

Retirement Commemorative Volume

Oceanographic Research Vessel

MIRAI

1997–2025



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Oceanographic Research Vessel MIRAI
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Hiroyuki YAMATO
President,
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On the Retirement of the Oceanographic Research Vessel Mirai

On the occasion of the publication of the Mirai Retirement Commemorative volume, I would like to extend my greetings on behalf of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

This vessel was launched in 1972 as Japan's first nuclear-powered ship, Mutsu. After undergoing various technical trials, its nuclear reactor was removed in 1995, and it was subsequently operated as the oceanographic research vessel Mirai from 1997 to the present day. It is a historic vessel that has greatly contributed to the advancement of Japan's science and technology. Since its commissioning as Mirai, it has played a crucial role in global oceanographic research. From the Arctic Ocean to the tropics and across the Atlantic and Indian Oceans, Mirai has collected invaluable data and contributed to our understanding of sea ice reduction in the Arctic Ocean, the mechanisms of the El Niño phenomenon, and the detection of deep-ocean warming and ocean acidification, as well as broader issues such as global warming, climate change, ocean physics, and biogeochemistry. As a central observational platform in numerous international intensive observation projects, Mirai has made significant contributions to the international community through numerous scholarly publications and research outcomes.

Another prominent aspect of Mirai is its role as a site for human resource development. Long-term expeditions aboard one of the world's largest research vessels offered many young researchers, engineers, and students rare opportunities to handle actual observational equipment, collect and analyze data in the field, and directly experience the realities and challenges of oceanographic research. JAMSTEC has actively provided development opportunities to young researchers and promoted international joint studies through Mirai. The cruises of Mirai also involved numerous technical and observational support staff, whose efforts were integral to advancing seawater analyses, maintaining instruments, processing data in real time, and establishing safe and efficient observation practices. Thus, Mirai has significantly contributed to the cultivation of highly skilled technical personnel whose practical expertise has underpinned the progress of science. The body of scientific achievements and legacy of human resource development left behind by Mirai has laid an indispensable foundation for future oceanographic research.

I would like to express my deepest respect and gratitude to all who have been involved in the operation, maintenance, observation, and research of and by Mirai over the years, including the local residents of Mutsu City, Aomori Prefecture, among other regions, as well as the companies that provided operational and observational support. The dedication and passion of all these individuals were the greatest driving force sustaining Mirai. Mirai's wake is a symbol of our knowledge and the challenges ahead. I am confident that this spirit will be carried on by Mirai II, which will continue to serve as a core element of JAMSTEC's mission.



Introduction

Makio HONDA
Chair,
Editorial Committee for
the Mirai Retirement Commemorative
Volume

*Please note that this English version contains only the main research cruises in Chapter 1 and contributions from abroad in Chapter 3.

Structure of This Retirement Commemorative Volume

Mirai was conceived as a platform to advance the four priority infrastructural research themes as presented in Report No. 4 of the Council for Ocean Development (December 1993), "Japan's Promotion Measures for Oceanic Research". Following its entry into service in October 1997, Mirai embarked on a familiarization training cruise in November. By February 1998, research subjects corresponding to the four themes were consolidated under a Long-Term Observation and Research Plan. In October 1998, full-scale operation began in the form of open collaborative research.

● Thermal Circulation

- Observational studies in the western Tropical Pacific Ocean
- Observational studies on air-sea interaction
- Observational studies on the variabilities of the Subtropical Gyre and the Subpolar Gyre in the North Pacific Ocean
- Observational studies in the Arctic Ocean

● Material Cycle

- Observational studies on the material cycle in the high latitude seas
- Observational studies on primary productivity in the Equatorial Pacific Ocean

● Marine Ecosystems

- Observational studies on the plankton community
- Observational studies on the ecosystems of deep-sea organisms

● Ocean Crust Dynamics

- Observational studies on the ocean crust dynamics of the sea floor

Chapter 1 introduces research cruises that remain heavy users of Mirai in the present day, despite changes in observational focus, survey regions, and associated project names.

1. Time-series observation for biogeochemistry cruises in the western North Pacific
2. Arctic Ocean observational study cruises
3. High-precision global oceanographic observational cruises
4. Tropical and subtropical observational study cruises
5. Air-sea interaction study cruises

Beyond the vessel's initial priority themes, Mirai undertook various one-off cruises tailored to the needs of different periods, as well as cruises that leveraged the ship's distinctive capabilities. Additionally, within the Long-Term Observation and Research Plan, continuous observation utilizing Mirai was recommended in addition to the core themes. Chapter 2 highlights representative examples of such initiatives.

1. Solid Earth observational study cruises
2. Marine resource survey and observational study cruises
3. Atmospheric material cycle observational study cruises

Chapter 3 presents recollections of Mirai from individuals closely connected to the vessel, including the director of the Mutsu Institute for Oceanography at Sekinehama, Mirai's home port, as well as those involved in the ship's construction and operation, onboard and onshore observational support staff who sustained the cruises, and JAMSTEC alumni and participants from external institutions in Japan and overseas.

Finally, Chapter 4 serves as a reference section, compiling a wide range of information related to Mirai cruises.

Readers are also encouraged to consult previously published special issues on Mirai (only in Japanese) together with this volume. These publications offer a more detailed retrospective on Mirai's origins, history, scientific achievements, and the many memories associated with her.



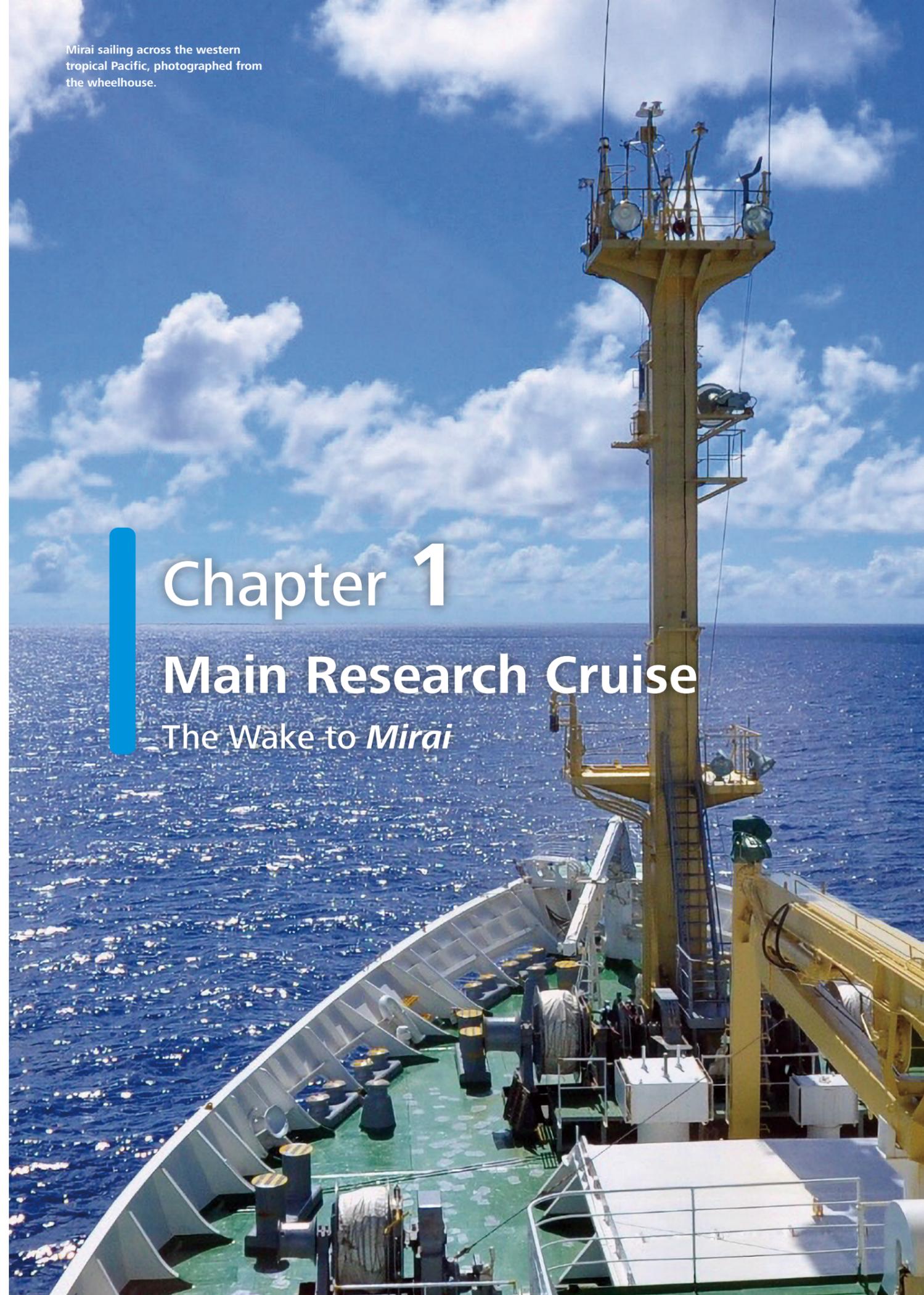
R/V MIRAI launching ceremony, August 21, 1996

Mirai sailing across the western tropical Pacific, photographed from the wheelhouse.

Chapter 1

Main Research Cruise

The Wake to *Mirai*



1 Time-series Observations for Biogeochemistry in the western North Pacific

Makio HONDA



MR19-02 was conducted from May 24 to June 14, 2019 (Reiwa 1). Glass balls used in the mooring system were arranged to form the characters “Reiwa” in celebration of the new era name (actually a fake image).

Introduction

The global “boiling” due to the increase in atmospheric carbon dioxide (CO₂) is emerging as a global problem, destroying environments and ecosystems worldwide. Covering approximately 70 percent of the Earth’s surface, the ocean absorbs about one quarter of the CO₂ emitted annually by human activities and stores roughly 60 times the amount of CO₂ currently accumulated in the atmosphere. Therefore, the ocean regulates the concentration of atmospheric CO₂. However, the ocean’s capacity to absorb CO₂ varies significantly across time and space. With recent changes in the global environment—including ocean warming, acidification, and deoxygenation—this capacity may decline significantly. Accordingly, to evaluate the ocean’s CO₂ absorption ability and predict its future trajectory, it is essential to conduct time-series observations of the air–sea and intra-ocean dynamics of CO₂ and related substances across diverse marine regions.

The subarctic region of the western North Pacific is the terminal point of the global deep-water circulation. With nutrient-rich deep waters supplied to the ocean surface, biological productivity in this region is high. According to surveys conducted by universities and research institutions in Japan and abroad, this region has long been considered to have a strong capacity for CO₂ absorption through biological activity. However, observations have generally been sporadic, and systematic time-series observation studies have not been conducted. To address this, JAMSTEC established observational stations in the western North Pacific subarctic and subtropical regions with the commissioning of Mirai. Since then, the time-series observations for biogeochemistry centered on these stations have been conducted to examine the dynamics of CO₂ and various other substances across the air–sea interface and within the ocean interior. Mirai’s distinguished history began with our MR97-02 cruise in November–December 1997 (Fig. 1). The sections present a retrospective of the time-series observations for biogeochemistry cruises conducted over the past three decades, organized by the principal research projects and themes of the time.

KNOT Project (1997–2000)

In the 1980s, global warming caused by increasing atmospheric CO₂ had begun to attract worldwide attention, and the ocean’s capacity to absorb atmospheric CO₂ soon became an area of interest. To understand the role of the ocean in the global carbon cycle and climate change, numerous international organizations and scientists participated in an international marine biogeochemical research program “Joint Global Ocean Flux Study (JGOFS)” conducted from 1987 to 2003. The US JGOFS team conducted biogeochemical observational studies over several years using research vessels and mooring



Fig. 1. MR97-02 group photo. The history of R/V Mirai begins here.

systems in various regions, including the northern North Atlantic and equatorial regions, as well as the Indian and Southern Oceans. Meanwhile, to understand the role of the western North Pacific in the carbon cycle and climate change, the Japan JGOFS team undertook the North Pacific Process Study (NPPS), a joint effort among universities and national research institutes. An observational station designated KNOT (44°N, 155°E) was established at the southwestern edge of the North Pacific Subarctic Gyre (NPSAG). Collectively referred to as the KNOT Project, from 1997 to 2000, biogeochemical time-series observational studies were conducted at this site using multiple research vessels and mooring systems. KNOT is the acronym for Kyodo (“Joint”) North Pacific Ocean Time-series Station. As an aside, the fact that the acronym’s first letter derives from Japanese may be considered somewhat unrefined, especially because the name was coined rather informally by senior professors and research directors representing Japan over drinks after a committee meeting.

Several vessels were used for the fixed-point (revisit) observations, including Hokkaido University’s T/S Hokusei-Marui, Tokai University’s T/S Bosei-Marui, and the University of Tokyo’s (at the time) T/S Hakuho-Marui. However, the newly commissioned R/V Mirai quickly became the central platform, particularly for the cruises in the characteristically rough seas of the autumn and winter seasons. With a gross tonnage of approximately 8,700 tons, R/V Mirai was the largest research vessel in Japan and among the largest in the world. Equipped with an anti-rolling system comprising a 100-ton weight that moved along rails to stabilize the vessel, R/V Mirai was uniquely suited for long-term observations even under stormy conditions. With accommodations for over 40 researchers and marine technicians, and laboratories permanently outfitted with analytical instruments for nutrients, total carbon, pigments, mass spectrometry, CO₂, and continuous surface monitoring, Mirai enabled the collection of high-quality data at sea. The first and second buoy hangars enabled indoor maintenance of observation equipment and allowed the vessel to carry a large volume of gear. Unlike

other JAMSTEC vessels, Mirai featured wooden decks, which were gentler on the feet and did not become scorching hot like steel decks in summer. Its expansive deck space, multiple working winches, and tall A-frame facilitated the efficient and safe deployment and recovery of various mooring and drifting systems, including sediment traps.

During the MR99-K02 cruise in May 1999, the team encountered an extraordinary increase of phytoplankton (spring bloom) in the open ocean, with chlorophyll concentrations exceeding 10 mg/m^3 —an exceptionally rare phenomenon. Intensive observations were conducted, successfully capturing detailed changes in primary productivity and seawater CO_2 concentrations associated with the rise and fall of phytoplankton populations. Despite the late hour and to the dismay of the chief scientist and captain, a principal investigator from a national research institute, thrilled by the unusual opportunity to observe a spring bloom, insisted on making an unscheduled stop and taking water samples. Conversely, the MRO0-K01 cruise in January–February 2000 was marked by heavy snowfall on deck. Observation work required constant snow removal, and deployment of drifting systems for primary productivity and shallow-depth particle collection had to be started just be-

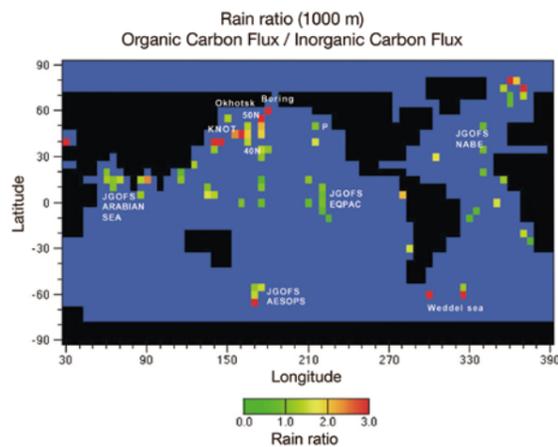


Fig. 2. Rain ratio (adapted from Honda et al., *Deep-Sea Research II* 49, 5595–5625, 2002)

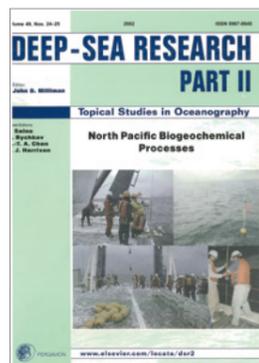


Fig. 3. Cover of the KNOT Project *Deep-Sea Research Part II* special issue

fore sunrise. With wind chills around -10°C , venturing onto the deck before dawn was daunting. Although the standard practice on board was to assemble ten minutes before operations, most researchers lingered indoors until the last moment, leaving only the Chief Officer (observation officer) waiting outside, snow accumulating on him like Captain Kanda in Death March on Mount Hakkōda.

Over a period of four years, 21 observations were conducted at KNOT, covering all seasons. These observations yielded high-density time-series data revealing substantial seasonal variations in phytoplankton and zooplankton populations, primary productivity, CO_2 and carbonate system parameters, and nutrients. The magnitude of seasonal variation observed at KNOT ranks among the biggest in the world, largely attributable to phytoplankton blooms following spring and the intense vertical mixing in winter.

Seafloor-moored sediment trap experiments and drifting sediment trap observations, led by JAMSTEC and Nagoya University, revealed that KNOT's export production rate (the proportion of organic carbon flux at the base of the surface mixed layer relative to primary productivity) and its rain ratio (the ratio of organic to inorganic carbon flux) were higher than those observed at the US time-series stations ALOHA and BATS, or Canada's OSP. These results suggest that the biological carbon pump of the western North Pacific, including KNOT, is highly efficient by global standards (Fig. 2).

Occasional intrusions of subtropical or coastal waters into KNOT were observed—the site did not always represent the broader characteristics of the NPSAG.

The results of the KNOT Project, along with findings from other domestic projects—such as the A-line observations by the Fisheries Agency and volunteer ship observations by the National Institute for Environmental Studies—were published in a special issue of *Deep-Sea Research Part II* in 2002 (Fig. 3).

HiLATS Project (2001–2006)

In October 2000, the Mutsu Office was reorganized into the Mutsu Institute for Oceanography. As one of its major research initiatives, and based on a proposal by the late Dr. Susumu Honjo (Senior Scientist at the Woods Hole Oceanographic Institution [WHOI] and Part-time Executive Director of JAMSTEC at that time), the project (High Latitude Time-Series study: HiLATS) was launched to investigate material cycles in the western North Pacific. This project was conducted through the combined use of advanced mooring systems equipped with state-of-the-art automated sampling and measuring devices, together with R/V Mirai.

In its first year (FY 2000), in addition to sediment traps already used for time-series observations, new equipment was procured, including a Remote Access water Sampler (RAS), instruments for phytoplankton and

zooplankton sampling (PPS/ZPS), an automated incubation system for primary productivity measurements (SID), an underwater optical measurement system (BLOOMS), and a profiling CTD/ADCP system (MMP). At the end of the fiscal year, an international workshop on material cycles in the North Pacific was attended by approximately 50 researchers from Japan and abroad. Within the HiLATS Project, the new time-series station “K2” (47°N , 160°E) was established near the center of the NPSAG, replacing the less stable KNOT station. (The “K” in K2 derives from the Kamchatka Peninsula.)

In August 2001, Mirai loaded four 40-foot containers of observation equipment and mooring components transported from WHOI at Dutch Harbor, Alaska, USA. On August 28, she departed along with WHOI researchers and marine technicians (MR01-K04 Leg 2). The project required deploying mooring arrays extending from the seafloor at $\sim 5,000 \text{ m}$ to precisely 30 m below the sea surface (the lower euphotic zone), held under one-ton tension. Upon arrival at the site, wide-area acoustic surveys were conducted to identify a flat seabed, and precise depth determination was made with a CTD and an altimeter mounted on the rosette water sampling system. Mooring operations were performed under the direction of WHOI marine technicians. Although concerns had been raised about potential difficulties due to language barriers and differences in operational approaches, the collaboration among R/V Mirai's crew, MWJ marine technicians, and WHOI marine technicians proved friendly, accurate, efficient, and safe. Consequently, three mooring arrays were successfully deployed within $\pm 10 \text{ m}$ precision—one biogeochemical mooring (BGC) and two physical oceanographic moorings (PO) at two locations (K1: 51°N , 165°E and K2) in the western North Pacific. During the final phase of the cruise, the 9/11 terrorist attacks occurred in New York. The event was a profound shock for the WHOI researchers and marine technicians who had come from Boston. Owing to the closure of Boston Logan Airport, they were forced to remain in Mutsu for a week after disembarkation.

In October 2002, another cruise (MR02-K05 Leg 2) departed from Dutch Harbor again. Despite severe weather, coordinated operations among WHOI marine technicians, MWJ staff, and R/V Mirai's captain, observation officers, and deck officers enabled the safe recovery of the previous year's moorings. As R/V Mirai's deck is located 7 m above the sea surface, a work boat was expected to be necessary to secure the 2 m diameter surface buoy (the “red ball”). However, a WHOI technician successfully hooked the buoy's eye with a 10 m bamboo pole alongside the ship's hull, a feat that impressed Japanese staff as uniquely characteristic of America as the “country of cowboys.”

Subsequently, six mooring arrays (BGC and PO combined) were deployed at three locations (K1, K2, and K3: 40°N , 160°E) in the western North Pacific. At



Fig. 4. Time-series observation instruments, featured on the cover of *Sea Technology* for their uniqueness.

K2, a heavily instrumented mooring—equipped with an RAS, an SID requiring special permits due to the use of radiocarbon, and ten time-series sediment traps spanning from just below the euphotic zone to the deep sea—was deployed to investigate the vertical transformation of marine snow. The appearance of the mooring was likened to a “decorated truck” (dekotora) (Fig. 4).

In 2003, Mirai was assigned to the BEAGLE2003 (MR03-K04), with our observations conducted via the research vessel R/V Kairei (KR03-11). Unlike R/V Mirai, R/V Kairei specializes in geological and geophysical surveys. Its narrower deck and lack of facilities, such as traction winches, rosette (or carousel) water sampling system, and radiation-controlled “Isovan” containers, required considerable adaptation for mooring operations.

In late September, we once again embarked from Dutch Harbor. However, strong winds prevented our flight from Anchorage from landing; several aborted attempts (“touch-and-go”) eventually made us return to Anchorage after a three-hour journey. Compounding difficulties, a shipment of battery packs for Argos transmitters failed to arrive, requiring improvised replacements—an omen of the misfortune to come. After successfully recovering moorings deployed at K1 the previous year and conducting oceanographic observations, we moved on to K2. There, the PO mooring with the MMP was retrieved without difficulty, followed by the recovery of the heavily instrumented “dekotora” mooring with ten sediment traps. After successful acoustic communication with the release system and transmission of the release command, we confirmed that the release had functioned normally. Under ordinary conditions, the surface buoy (“red ball”) at 30 m depth would have surfaced within seconds; nevertheless, it did not. After two hours, only the acoustic releaser supported by only a few buoyant glass spheres floated to the surface, revealing the catastrophic loss of the $\sim 5 \text{ km}$ mooring string and all its attached instruments. The following days were filled with frantic activity as we reported the loss and conducted searches, while successfully recovering two moorings at K3. The workload was so intense that there was barely time for bathing. Onshore, the incident triggered major

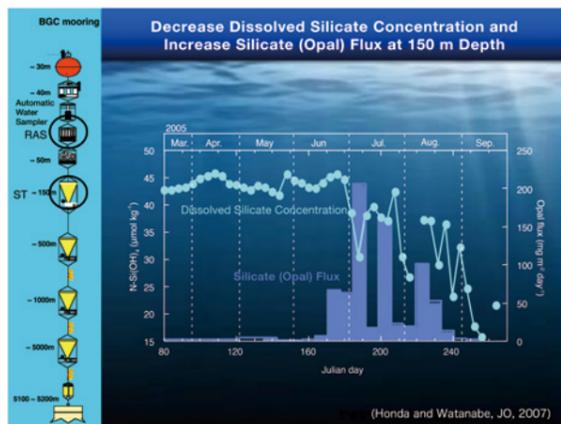


Fig. 5. Changes in dissolved silicate and opal flux (adapted from Honda and Watanabe, *Journal of Oceanography* 63, 349–362, 2007)

repercussions: while the lost radiocarbon posed no ecological risk, the fact that radioactive material was involved required formal reporting to the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and managing the media response, imposing heavy burdens on the director and administrative section of the Mutsu Institute for Oceanography, the Yokosuka Headquarters' Safety Management Office, and Operations Department, among other divisions. Despite searches at sea, no trace

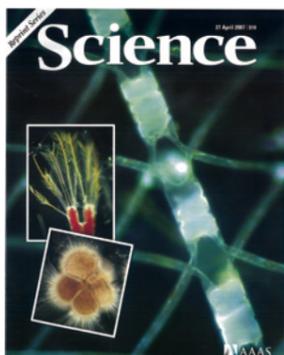


Fig. 6. VERTIGO, K2 observation results published in *Science*.

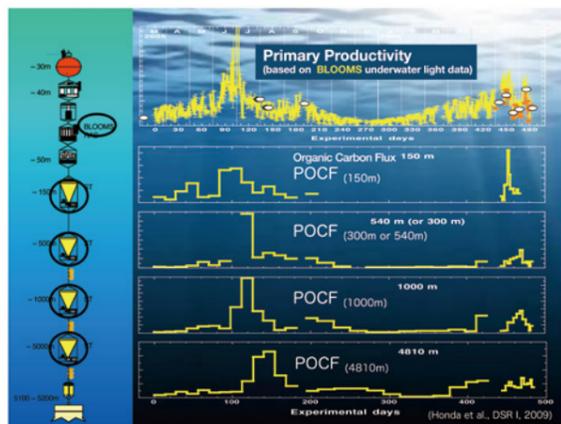


Fig. 7. Time-series changes in primary production and organic carbon flux at various depths. (adapted from Honda et al., *Deep-Sea Research I* 56, 2281–2292, 2009)

of the mooring was found. Ultimately, without redeployment, R/V Mirai returned to Yokosuka in disappointment. As most of the equipment had been procured in the US with the expectation of at-sea deployment and recovery, the unplanned return of instruments entailed extensive import procedures and a substantial tariff burden, further damaging the project.

Consequently, mooring observations were suspended for about a year and a half, during which accident investigations and preventive measures were undertaken.

In March 2005, short-term mooring deployment trials were conducted on the MR05-01 cruise with enhanced safety measures. Later, in September–October, two moorings were successfully recovered during the MR05-04 cruise. Although limited to six months, the project obtained valuable high-frequency time-series data and samples. Notably, the simultaneous observation of changes in nutrient concentrations in the surface ocean and fluxes of sinking particles at a depth of 150 m, made possible by the RAS, was the first of its kind worldwide (Fig. 5).

This cruise traversed the North Pacific from Sekinehama to San Diego, so it enabled the collection of comparative datasets on ecosystem and material cycle processes between NPSAG (including K2) and the Alaska Gyre (including the Canadian time-series station OSP).

Owing to the HILATS Project, Station K2 was globally recognized as a leading biogeochemical time-series station in the NPSAG and registered as part of the international OceanSITES network. In 2005, K2 was used in the VERTIGO project, an international study of the biological carbon pump led by WHOI scientists. Results showed that the efficiency of the biological carbon pump at K2 was higher than that at Station ALOHA near Hawaii; these findings were published in *Science* (Fig. 6).

The following year, the MR06-03 cruise was conducted over two months, May–July 2006. The MIRAI spent about two weeks at K2 conducting repeated observations, aiming to monitor the changes in material cycling and the biological pump during the spring bloom. This enabled the monitoring of evolving processes of material cycling and biological carbon export. Consequently, valuable data were obtained on primary production, nutrients, phytoplankton pigments, carbonate chemistry, and related parameters. The previously deployed moorings were also successfully recovered, yielding high-frequency time-series data on seawater, marine snow, and underwater light conditions from March 2005 through mid-2006 (Fig. 7).

K2S1 Project (2010–2014)

Just as the global environment is undergoing profound change, the ocean is experiencing multiple, interacting stresses, including warming, acidification, and deoxygenation, raising concerns about the future capacity of the ocean to absorb atmospheric CO₂. However,

the impacts of these stresses on ecosystems and biogeochemical cycles may differ across oceanic regions. Accordingly, in addition to the subarctic gyre region of the western North Pacific, a new time-series station was established in the subtropical gyre, which has different ecosystem characteristics and water mass structures. A comparative biogeochemical research program was launched under the theme “Change in material cycles and ecosystem by the climate change and its feedback.” As a counterpart to Station K2, a new subtropical observation site, S1 (30°N, 145°E), was established south of the Kuroshio Extension. This initiative became known as the “K2S1 Project.” To achieve its objectives, shipboard observations covering all seasons using Mirai, mooring observations, satellite observations, and numerical simulations were conducted.

The first cruise took place in January–February 2010 (MR10-01). Although severe winter weather posed difficulties (Fig. 8), comprehensive biogeochemical observations were successfully conducted at K2 and S1, including water sampling, in situ primary productivity measurements, particle collection using drifting arrays, and plankton sampling. At both stations, time-series sediment traps were deployed at depths of 200 m, 500 m, and 4,810 m. At S1, a specialized mooring (POPPS) was also deployed, featuring a profiling buoy that repeatedly traveled between the surface and 200 m depth to measure temperature, salinity, oxygen, chlorophyll, and primary productivity. The deployment coincided with Setsubun, the traditional “bean-throwing” day. A ritual bean-scattering ceremony was held to pray for safety and success, although those in charge of the sediment traps were slightly anxious about beans accidentally contaminating the samples.

The next cruise, MR10-06, which occurred in autumn 2010, marked a return to departures from Dutch Harbor. Again challenged by rough seas, the sediment-trap and POPPS moorings at K2 and S1 were safely recovered and redeployed. Despite the physically demanding nature of observations at sea, the high-calorie diet onboard led to gradual weight gain among participants. As a countermeasure, “Billy’s Boot Camp” workouts became popular during the cruise, with men and women of all ages exercising nightly in the ship’s gym.

The MR11-02 cruise, conducted in late winter (February–March 2011), included the recovery and redeployment of the POPPS mooring, inspection of NOAA’s KEO buoy, and recovery and deployment of JAMSTEC’s JKEO buoy.

A distinctive feature of the K2S1 Project was the use of a large, multi-net plankton sampler (IONESS) for collecting zooplankton and small fish. Resembling a giant koinobori (“carp streamer”), this system comprised eight nets, each with a 2 m² opening and a total length of approximately 5 m. The nets could be opened and closed at chosen depths and towed horizontally for ~20 minutes, collecting organisms in the cod end. Recovery re-



Fig. 8. Voyage in rough seas (MR10-01)



Fig. 9. Nadeshiko MIRAI

quired eight to twelve people to haul the device onto the deck by hand, followed by washing the nets in large buckets. To capture diel vertical migration patterns of zooplankton, operations were conducted during the day and night. At K2, nighttime IONESS work often meant laboring in subzero temperatures and falling snow—conditions reminiscent of the harsh world evoked in the Japanese enka ballad Kita no Ryoba (“Northern Fishing Grounds”).

On the day before the cruise ended, the team paid a courtesy visit to the deep-sea scientific drilling vessel D/S Chikyu, which was docked in Hachinohe. The following day, March 9, 2011, R/V Mirai returned to Sekinehama. During the unloading of a bunch of equipment from the ship, an earthquake struck, although it caused no tsunami and resulted in minimal disruption. That afternoon, the staff proceeded to Tokyo by Shinkansen, unaware that this tremor was a foreshock of the 2011 off the Pacific coast of Tohoku Earthquake. Two days later, D/S Chikyu and the onboard scientists from the International Coastal Research Center (Atmosphere and Ocean Research Institute, The University of Tokyo) in Otsuchi, Iwate Prefecture were directly affected by the disaster.

The MR11-03 Cruise (April–May 2011) served partly as a survey of the Fukushima nuclear accident. A nota-



Fig. 10. Commemorative message flag



Fig. 11. MR13-04 cruise report cover

ble feature of this cruise was the frequent release of radiosondes along the north–south transect track, prompting participants to dub it the “Zonde Festival.”

On MR11-05, Leg 1 (June 27–July 16, 2011) covered subarctic sites such as KNOT and K2, while Leg 2 (July 17–August 4, 2011) included S1 and the waters off Tohoku. At K2 and S1, in addition to water sampling and plankton collection, the program included mooring recovery and redeployment, drifting array experiments, and sediment coring with a multiple corer. On Leg 2, for the INBOX project, which focused on three-dimensional analysis of subtropical water masses such as mode water, approximately 20 Argo floats were deployed near S1. Leg 2 also included 13 women (marine technicians, students, and ship officers). In anticipation of the following day’s FIFA Women’s World Cup final, the crew donned face paint and posed with the ship’s Hinomaru flag, proudly cheering for the Japanese team, Nadeshiko Japan (Fig. 9). In the early hours of July 18 (JST), as Nadeshiko equalized in extra time and ultimately triumphed in the penalty shootout to claim their first-ever World Cup title, cheers erupted throughout the ship. Morning greetings took the form of jubilant “Congratulations!”, as festive as a New Year’s morning.

The MR12-02 cruise was likewise conducted in two legs. Leg 1 (June 4–24, 2012) focused on the recovery and redeployment of sediment-trap moorings at K2

and the JKEO moorings of JAMSTEC’s air-sea interaction research group. Leg 2 (June 24–July 12, 2012) conducted observations at S1 as well as observations off Tohoku, including a new time-series sediment trap station, F1 (36.5°N, 141.5°E), established on the MR11-05 cruise. Later analysis revealed that sediment-trap samples from F1 contained radiocesium at levels an order of magnitude higher than those from K2 and S1. At KEO, NOAA’s mooring was recovered and redeployed. A senior NOAA marine technician onboard shared his experience surviving the catastrophic 1980 Mount St. Helens eruption, illustrated with vivid photographs—an event that had brought him media attention and financial benefit at the time.

Although shorter than typical material cycle cruises, the MR13-04 cruise enjoyed good weather and recovered and redeployed three mooring systems at K2 and S1, as well as a sediment-trap mooring off Fukushima. Additional water sampling was conducted at K2, S1, KEO, JKEO, and KNOT; plankton collection, primary production measurements, and in situ filtration were conducted at K2 and S1. CTD and water sampling were also performed inside a mesoscale eddy off eastern Hokkaido. During this cruise, a banner of “messages of support,” prepared at JAMSTEC’s Yokosuka open house, was hoisted (Fig. 10). As was customary at the end of time-series cruises, a shipboard barbecue was held before arrival. These gatherings, which brought together crew, marine technicians, researchers, and students in a relaxed setting with games and the cruise report cover contests, provided valuable opportunities for camaraderie and mutual appreciation (Fig. 11).

In 2014, mooring operations were primarily conducted by other vessels: T/S Hakuho-Maru at K2, R/V Kaiyo at S1, and T/S Shinsei-Maru at F1. With this, the K2S1 Project came to an end. Through the K2S1 Project, the biogeochemical characteristics of subarctic and subtropical regions of the western North Pacific were investigated in detail. The project also revealed new issues, including the following: (i) unexpectedly high supply mechanisms of nutrients to the oligotrophic subtropical region and (ii) a mismatch between the carbon demand of midwater organisms and available supply. The outcomes of the K2S1 Project were published on various platforms, including a special issue of the *Journal of Oceanography*.

Fukushima Nuclear Accident Investigation (2011–2015)

On March 11, 2011, the 2011 off the Pacific coast of Tohoku Earthquake (M 9.0) and subsequent tsunami struck, causing the cooling systems of the Tokyo Electric Power Company’s Fukushima Daiichi Nuclear Power Plant (FDNPP) to fail. Venting operations, hydrogen explosions, leakage of externally supplied cooling water, and intentional discharges led to the release of excessive

amounts of artificial radionuclides into the environment. The MEXT requested JAMSTEC, with its many research vessels, to conduct investigations into the dispersion and accumulation of these radionuclides in the ocean. By late March, water sampling and aerosol monitoring off Fukushima had begun.

R/V Mirai was also mobilized for this investigation. As is well known, R/V Mirai had been converted from *N/S Mutsu*, Japan’s first nuclear-powered vessel, which suffered a radiation leak accident in 1974. Initially, some sneeringly suggested that R/V Mirai might be contaminated with radiation. Predictably, contamination tests found no evidence of any such problem.

The MR11-03 cruise, originally scheduled for April as part of the K2S1 Project, was modified to incorporate FDNPP accident investigations. Departing from Yokohama in mid-April, the ship diverted to waters off Fukushima. Full-depth water sampling was conducted at several points from the continental slope toward the open ocean. During this process, a high-turbidity layer was observed near the seafloor—sediments had been resuspended by the earthquake. News of aftershocks continued to flow from land throughout the cruise, casting a somber mood over the vessel.

R/V Mirai proceeded to the observation sites KNOT, K2, and S1. While underway, regular surface water sampling and aerosol collection were conducted; at the observation sites, these activities were supplemented with full-depth water sampling, plankton sampling, zooplankton and small fish collection using IONESS, and particle sampling with in situ filtration systems. Prior to recovery, shipboard and atmospheric contamination checks were conducted using survey meters. After recovery, samples were screened using survey meters and Geiger counters, with the utmost caution taken to prevent any exposure (Fig. 12).

At the time, measuring radioactive cesium in seawater required 20 liters of water per sample. Over the course of the cruise, approximately 100 seawater samples were collected to map the horizontal and vertical distribution of radioactive cesium, amounting to roughly two tons in total. Offloading and loading these samples onto transport trucks was laborious, and one could not help but sympathize with those at the National Institute of Radiological Sciences, who would have to unload and carry them into the laboratory. These efforts revealed that concentrations of accident-derived radioactive cesium in surface seawater were highest off the coast of Tohoku. Within one month of the accident, radioactive cesium had already reached the subarctic station K2 (~2,000 km from FDNPP) and the subtropical station S1 (~1,000 km from FDNPP) (Fig. 13).

In July 2011, the sediment trap moorings deployed at K2 and S1 in November 2010 were recovered and redeployed during MR11-05. Subsequent analyses showed that radioactive cesium first appeared in sinking particles collected at 500 m between March 25 and April 5,



Fig. 12. Contamination inspection

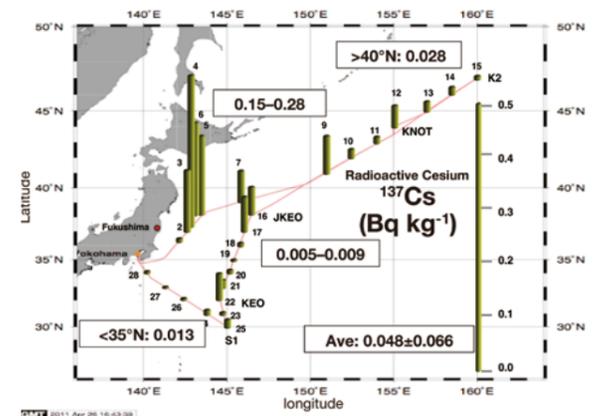


Fig. 13. Horizontal distribution of radioactive cesium concentrations one month after the accident (adapted from Honda et al., *Geochemical Journal* 46, e1–e9, 2012)

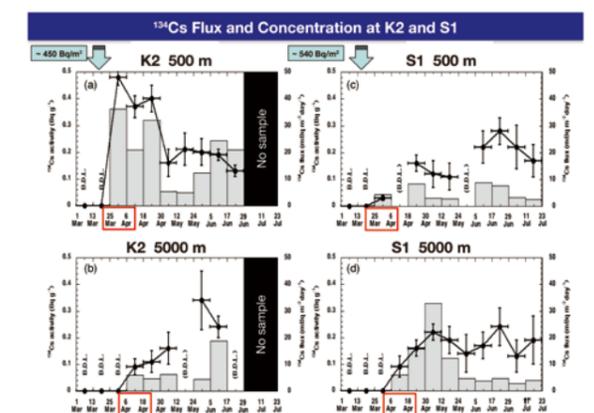


Fig. 14. Radioactive cesium concentration (black circles) and flux (bar graph) in sediment trap samples (adapted from Honda et al., *Biogeosciences* 10, 3525–3534, 2013)

2011, and 4,810 m between April 6 and 17, 2011 (Fig. 14). Numerical simulations indicated that this dispersion had occurred via aerosols through the atmosphere rather than by ocean currents and that the sinking velocities of particulate cesium were on the order of tens of meters per day from the surface to 500 m and hundreds of me-

ters per day from 500 m to 4,810 m.

Off the coast of Miyagi, the ship suddenly jolted with a “bang” followed by shaking. “What was that?” Moments later, a news ticker confirmed that an earthquake had occurred off Miyagi. It was the first time many aboard had experienced a vessel vibrating due to seismic activity.

Throughout these cruises, the principal investigator (PI) and chief marine technician (Kururi) carried pocket dosimeters, constantly checking radiation levels onboard. On one occasion, Kururi approached the PI, his face pale—a normally near-zero reading had suddenly turned positive. Where was the radiation coming from? After retracing his movements, the readings of the sampling room, laboratory, and storage room remained unchanged; the dosimeter suddenly spiked at the flying bridge. The culprit, it turned out, was not radiation but electromagnetic waves from the ship’s radar. Kururi had gone there earlier in the morning to replace aerosol filters, inadvertently exposing the dosimeter to radar signals. While pocket dosimeters were known to react to mobile phones, few had anticipated their response to radar. While the incident became a lighthearted anecdote, it also served as a reminder that even radiochemists engaged in marine research have blind spots.

During MR11-05, a new observation site, F1 (36.5°N, 141.5°E, 1,350 m deep), was established approximately 100 km southwest of FDNPP on the continental slope. There, in collaboration with WHOI, a mooring with sediment traps at 500 m and 1,000 m was deployed to monitor particulate radionuclide dynamics. The recovery and redeployment of this mooring were repeated during MR12-02 and MR13-04. The operations were conducted jointly with WHOI marine technicians, one of whom also happened to be an employee of an American sediment trap manufacturer. By chance, an employee of a Japanese manufacturer was also on board during MR12-02. Although the two companies had a history of rivalry, the technicians shared a cordial rapport; they were even photographed together, with both sediment traps visible in the background.

Observations at F1 continued until 2015. Four and a half years of time-series data revealed the following: (i) fluxes of radioactive cesium in sediment trap samples were more than an order of magnitude higher at F1 than at K2 or S1; (ii) while cesium concentration had been under detection limit from sediment traps at K2 and S1 within a year, it was being detected at F1 five years after the accident; and (iii) cesium fluxes tended to increase in autumn and winter. It was estimated that typhoons and low-pressure systems passing near FDNPP resuspended radiologically-contaminated sediments, which were then transported laterally to the continental slope and captured in the F1 traps.

When these results were published and announced to the press, criticisms such as “let sleeping dogs lie” appeared on online forums like 2channel. Members of par-

liament inquired about the results of the investigation, and the results were in danger of being used as a “political tool.” On the other hand, as this was a joint Japan-US observation, I was given the opportunity to meet and report to Ms. Caroline Kennedy, who was then the US Ambassador to Japan.

At the outset, with little precedent or information available, embarking on FDNPP-related investigation cruises must have required courageous decision-making. Nonetheless, Mirai was among the first to initiate such cruises, securing invaluable data on the behavior of anthropogenic radionuclides in the ocean.

It is sobering to reflect that N/S Mutsu, once crippled by a radiation accident and unable to fulfill its purpose for nearly two decades, would, as R/V Mirai, make significant contributions to investigating the aftermath of the Fukushima nuclear accident. Who could have imagined such a reversal of fate?

Observational Study of Nutrient Supply Mechanisms: KEO Observations (2014–present)

As mentioned, the K2S1 Project revealed that primary productivity in the oligotrophic subtropical ocean is unexpectedly high. This prompted new research seeking to clarify the mechanisms of nutrient supply sustaining such productivity. Possible mechanisms include mesoscale eddies, typhoons, and aerosols. Accordingly, in June 2014, time-series sediment trap observations were initiated at the KEO station (32.5°N, 144.5°E), located approximately 2.5 degrees north of S1. KEO is an observation site established by NOAA’s Pacific Marine Environmental Laboratory (PMEL), where a surface buoy (the KEO buoy) has been moored to conduct meteorological observations, estimate air–sea heat fluxes, and study the physical oceanography of the region since 2003. Thus, it was anticipated that variability in sinking particles collected by JAMSTEC’s time-series sediment traps would be elucidated in relation to the meteorological and oceanographic variability observed by the KEO buoy.

Results from three years of sediment trap observations at ~5,000 m depth beginning in 2014 showed an increase in sinking particles which are thought to have formed during summer and autumn, when nutrients are typically depleted. Analysis of KEO buoy data revealed that during these periods, cold, nutrient-rich mid-depth waters (~500 m) upwelled into the subsurface layer (~100 m). Satellite data also showed a marked decrease in sea surface height at such times (Fig. 15). These findings suggest a scenario in which mesoscale cyclonic eddies passing near KEO during nutrient-depleted seasons induce upwelling of nutrient-rich mid-depth waters to the subsurface, enhancing subsurface primary production and ultimately increasing sinking particle fluxes. The frequency of mesoscale cyclonic eddies estimated by numerical simulation, along with the increase in nutrient

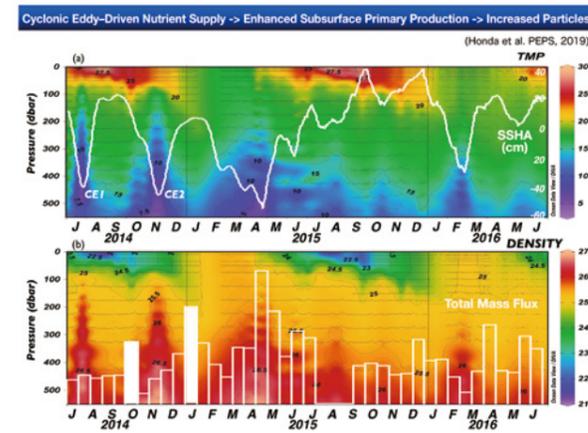


Fig. 15. Time-series vertical distribution of temperature (upper) and density (lower) observed by the KEO buoy at 5,000 m depth (bar graph below). The white line in the upper panel shows sea surface height anomalies. (adapted from Honda et al., *Progress in Earth and Planetary Science* 5, 42, 2018)



Fig. 16. MR21-01 cruise report cover

supply and primary productivity caused by them, was consistent with the observed increases in sinking particles. During MR21-06 Leg 2, which extended across the New Year, high-frequency sampling of seawater, plankton, suspended particles, and particle imaging was conducted across a mesoscale eddy near KEO to investigate its biogeochemical impact and the role of downwelling in particle transport. This cruise marked the first time this author had eaten Christmas cake on board, and enjoyed a lavish New Year’s feast “osechi.”

Aerosols were examined as a potential nutrient source. Past reports had described increases in phytoplankton following episodes of Asian dust deposition and the eruption of Miyakejima, and numerical simulations likewise suggested that aerosols enhance primary productivity in the subtropical ocean. The main objective of the MR21-01 cruise (February 13–March 24, 2021) was to evaluate the biogeochemical impacts of aerosols transported from Asia under the IMPACT-SEA project (Fig. 16). In addition to conventional high-volume air sampling, observations included a time-series rain sampler, a tethered balloon (nicknamed “Ottotto”) equipped with a camera and a fog collector (nicknamed “Yoko’s Harp”), and even “rain chase” operations to track rain clouds to assess aerosol deposition via rainfall and its biogeochemical effects. While most onboard hoped for clear skies, the research team secretly prayed for rain. As this cruise was conducted during the COVID-19 pandemic, strict protocols were in place: PCR testing and a week-long hotel quarantine with solitary meals prior to embarkation. Onboard protocols included mask wearing, daily temperature checks, prohibition of sauna use, silent meals with no unnecessary conversation, online meetings in separate rooms, and a ban on group social events. The saving grace was permission to use the exercise room. In the early morning hours, when no one else was around, this author diligently ran on the treadmill, covering 160 km over the 40-day cruise.

Meanwhile, the subtropical western North Pacific has also attracted attention as an accumulation zone for marine plastic debris. JAMSTEC’s Marine Plastics Research Group joined the R/V Mirai cruise to investigate the

three-dimensional distribution of marine plastic debris and the role of mesoscale eddies, using nets and in situ filtration devices. The group also attempted to measure microplastics in sediment trap samples collected at KEO, successfully quantifying the vertical transport of microplastics mediated by marine snow in the region.

Acidification, Ecosystems, and Biogeochemical Cycle Studies: Hybrid Mooring System and BGC-Argo Observations (2014–present)

Following the K2S1 Project, a hybrid moored system was deployed at K2 for time-series observations. This large, complex mooring system comprised a primary production profiler (POPPS), RAS, ADCP, CTD, pH sensor, sediment traps, a recovery buoy, and glass spheres. The efficient, rapid, and safe deployment and recovery of such a sophisticated system was made possible by Mirai’s large and highly skilled crew. Moreover, numerous BGC-Argo floats capable of measuring biogeochemical components such as oxygen, fluorescence, and backscatter were deployed near K2, enabling observations of seawater properties and the seasonal variability of the biological carbon pump from the surface to the deep ocean. Despite occasional issues, such as the loss of a primary production profiler, the system allowed time-series observations of underwater properties that cannot be captured by satellites, particularly the vertical distributions of phytoplankton, suspended particles, and ocean structure during the stormy and observationally challenging winter season. Data revealed two annual blooms of phytoplankton in late spring and autumn (Fig. 17). Analysis suggested that the autumn bloom was likely driven by the resupply of trace iron, which is a micronutrient (see below).

The western North Pacific subarctic region, including K2, is a high-nutrient, low-chlorophyll (HNLC) area. Despite the abundance of major nutrients, phytoplankton biomass remains low due to iron limitation. Onboard Mirai, clean seawater sampling and the establishment of simple clean sections enabled iron-addition incubation experiments. While iron supply to the region had tradi-

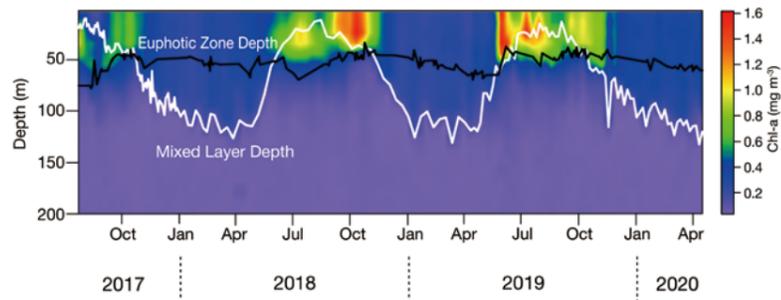


Fig. 17. Seasonal variation in vertical distribution of phytoplankton concentration near K2 (NPSAG) observed by BGC-Argo floats (adapted from Fujiki et al., *Journal of Oceanography* 78, 63-72, 2022)

tionally been attributed to lateral transport from the Okhotsk Sea, analyses of mineral particles and iron isotopes in aerosols and suspended particles near the sea surface revealed that iron in aerosols also contributes to the regional iron supply.

Meanwhile, analysis of carbonate system data collected at KNOT and K2 since R/V Mirai's commissioning in 1997 confirmed that ocean acidification is progressing in this region (Fig. 18). This result was reported in the IPCC's Fifth Assessment Report (AR5). To assess the ecological impacts of acidification, particularly on calcifying zooplankton, shell densities of planktonic foraminifera collected via sediment traps and plankton nets were analyzed using JAMSTEC's micro-focus X-ray CT system (MXCT). Results revealed seasonal and depth-dependent variability in shell density. To detect long-term changes caused by ocean acidification (Fig. 19) and predict future trends, a new CREST project, Carbon cycle and Lower trophic level oceanic organisms Investigation for Future Environments (C-LIFE), was launched in 2024, continuing analysis, modeling, and observational research using new moored systems.

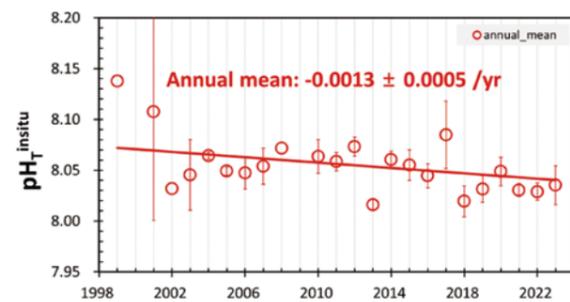


Fig. 18. Ocean acidification progressing at NPSAG (based on Wakita et al., *Biogeosciences* 10, 7817-7827, 2013)

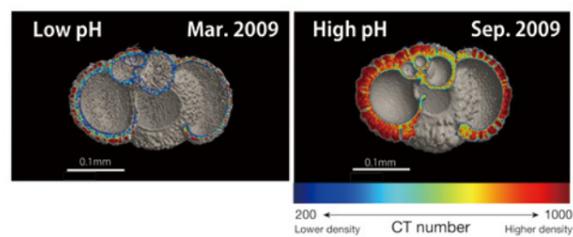


Fig. 19. Foraminiferal shell "bone density" changes with seasonal variations in acidity (adapted from Kimoto et al., *Frontiers in Earth Science* 11:1184671, 2023)

Conclusion

Owing to Mirai, many researchers, students, and marine technicians could embark on and utilize onboard instruments and laboratories, enabling numerous analyses and experiments to be conducted during each cruise. The rapid and safe execution of mooring operations made time-series observations possible, providing extensive insights into the biogeochemistry of the western North Pacific. Mirai has also contributed to the academic achievements of many researchers and students, including this author, and facilitated the completion of degrees.

However, although the mean state of material cycles in the western North Pacific has been elucidated, ongoing changes in response to current multi-stress conditions have yet to be detected. Just as continuous atmospheric CO₂ measurements in Hawaii revealed the increase in atmospheric CO₂ due to human activities, the principle of "continuity is power" applies to ocean observations as well. The time-series observations at station K2, which have been passed down through the generations by various people, have now reached over 20 years, and in 2025 the North Pacific Marine Science Organization (PICES) awarded the Marine Monitoring Service Award (POMA). Nevertheless, the ocean is even more variable than the atmosphere, with strong physical, chemical, and biological interactions—detecting such changes requires even longer-term time-series observations. Collaborating with long-term observation sites such as ALOHA and BATS in the US and ESTOC in Europe, JAMSTEC considers it a mission to continue biogeochemical time-series observations in this region using the Arctic research vessel Mirai II, as well as other research vessels.



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From the 2016 Arctic Cruise

Introduction

Takashi KIKUCHI

On August 18, 1998, the oceanographic research vessel (R/V) *Mirai*, which had entered service the previous year, departed from Sekinehama, made a stop at Seward, Alaska, and made its maiden voyage through the Bering Strait into the Arctic Ocean. As of 2025, R/V *Mirai* has made 23 Arctic cruises in the 28 years since its first cruise (Fig. 1). Although JAMSTEC began research in the Arctic Ocean as early as 1990, until R/V *Mirai* became operational, observations were carried out by accompanying the research projects of US universities and institutions. With the entry into service of R/V *Mirai*, it became possible for JAMSTEC to plan independent cruises and advance research by traveling to the field directly and obtaining data firsthand. Thus, the ability to conduct Arctic cruises with R/V *Mirai* represents a major milestone for JAMSTEC and the advancement of Japanese Arctic research.

With contributions from Motoyo Itoh, Shigeto Nishino, and Amane Fujiwara, who have played central roles in leading R/V *Mirai*'s Arctic cruises, this chapter presents stories from these 23 cruises over 28 years. Itoh focuses on observations from the Barrow Canyon mooring, which began around the same time as R/V *Mirai*'s entry into service and is active today, describing the Pacific-side Arctic Ocean environment, particularly ocean warming. Nishino discusses the importance of international collaboration, essential for Arctic research, alongside findings from Arctic physical and biogeochemical studies. Representing

the “third generation of R/V *Mirai*,” Fujiwara, who grew from student to chief scientist onboard, recounts the practical operations of Arctic cruises and insights gained from the Arctic Ocean. Finally, Kikuchi reviews the ship's 28 years and 23 cruises with various quantitative data, providing an overall summary and reflection.

R/V *Mirai* Continues to Capture Environmental Changes in the Pacific-Side Arctic Ocean

Motoyo ITOH

The 28 years from 1998 to 2025, during which R/V *Mirai* conducted Arctic observations, coincided with a period of rapid environmental change in the Arctic Ocean, including sea ice decline. R/V *Mirai* faced the Arctic climate change. I joined JAMSTEC Arctic research group in 2002 and participated in six Arctic cruises on R/V *Mirai*, as chief scientist on the 2010, 2022, and 2024 cruises. During this period, I also participated in eight cruises aboard foreign icebreakers, Canadian Coast Guard Ships (CCGS) *Louis S. St-Laurent* and *Sir Wilfrid Laurier*, as well as the US Coast Guard Cutter (USCGC) *Healy*—and observed sea ice decline and ocean warming in the Arctic Ocean.

On R/V *Mirai*'s Arctic cruises, geological, oceanographic, and meteorological observations were conducted. The Barrow Canyon mooring is one of the major oceanographic observations (Fig. 2). In the late 1990s, Mr. Kiyoshi Hatakeyama and Prof. Koji Shimada initiated this mooring and I continued it from 2008 to the present. Over two decades of long-term observations by this mooring overlap

with the history of R/V *Mirai*. Although Arctic sea ice has largely declined in recent years, shipboard observations remain limited to summer and autumn. To capture seasonal and interannual variations in the ocean, year-round time-series observations via moorings are essential. Long-term time-series observations over 20 years in the Arctic Ocean are rare. The four moorings — the University of Washington's Bering Strait moorings, JAMSTEC's Barrow Canyon moorings, and Woods Hole Oceanographic Institution's Canada Basin and Beaufort Slope moorings — are the only long-term mooring observation sites in the Pacific Arctic Ocean, capturing recent environmental changes.

The overall achievements and history of R/V *Mirai*'s Arctic cruises are detailed in the sections by Drs. Takashi Kikuchi and Shigeto Nishino; here, I focus on the Arctic change captured by R/V *Mirai*, primarily through mooring observations.

Since the late 1990s, Arctic sea ice thickness and sea ice extent have decreased under the influence of global warming, with particularly dramatic declines in the Pacific-side Arctic Ocean. In the early 2000s, thick multiyear ice remained in the northern Canada Basin and the observational area by R/V *Mirai* was limited to the southern basin. However, as sea ice retreated, R/V *Mirai* gradually expanded its observation area, continuing to set new northernmost records almost every year from 2002 to 2010. During my first Arctic cruise in 2002, thick multiyear ice remained that could only be navigated by icebreakers such as the CCGS *Louis S. St-Laurent* using “charging” (or ramming) techniques. By 2004, such thick multiyear ice regions had shrunk, and icebreakers could proceed by breaking thinner ice, a change that left a strong impression on me.

The Bering Strait, which connects the Pacific and Arctic Oceans, is a shallow strait with a depth of 50 m. The Pacific side is at a higher water level than the Arctic side, creating an average northward flow of approximately 1 Sv (Woodgate, 2018), through which Pacific-origin surface and subsurface waters enter the Chukchi Sea. These Pacific waters exhibit pronounced seasonal variations: in summer, warm, low-salinity Pacific water transports heat and freshwater, whereas in winter, nearly freezing, high-salinity Pacific water delivers nutrients to the Chukchi Sea and the Canada Basin. In the Canada Basin, these waters spread beneath the surface and subsurface layers below melting ice and river inflows. Heat in summer Pacific water accelerates summer sea ice melting and suppresses winter ice formation, while freshwater strengthens stratification, and nutrients in winter Pacific water affect primary production—contributing to environmental changes in this region.

Barrow Canyon lies along the main pathway of Pacific water flowing northward through the Chukchi Sea. In summer, 80–90 percent of Pacific water flowing into the basin passes through this canyon (Itoh et al., 2013), making it an ideal location for monitoring Pacific water variations. It is also one of five biological “hotspot” areas in

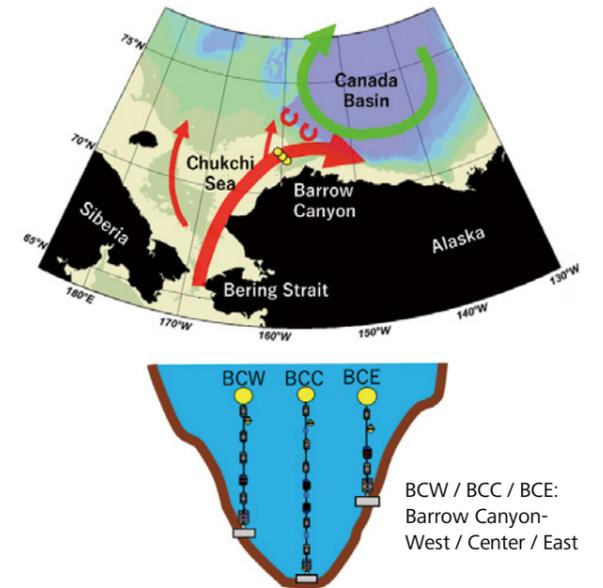


Fig. 2. Schematic diagram of ocean circulation in the Chukchi Sea (top) and Canada Basin, and the Barrow Canyon mooring system.

the Arctic selected in 2010 by the Distributed Biological Observatory (DBO), an international project under the International Arctic Science Committee (IASC) involving Japan, the US, Canada, China, South Korea, and Russia, and attracting repeat observations from multiple countries each year.

Known as Utqiagvik in the local language, Barrow is an Inuit town along the Alaskan coast, located along whale migration routes. As an aside, my first encounter with R/V *Mirai* was off Barrow in September 2002, when I transferred by Zodiac boat from a month aboard the CCGS *Louis S. St-Laurent*. From the sea surface, R/V *Mirai* appeared immense and beautifully white, leaving a strong impression.

Recently, increased Arctic ship traffic due to sea ice decline has led to stricter regulations on entering coastal areas during whaling seasons. In 2018, the timing of Barrow Canyon mooring operations coincided with the fall whaling season. I participated in the Inuit whaling meeting in Utqiagvik as the only non-local participant seeking permission to enter the coastal areas. I emphasized the importance of long-term observation in Barrow Canyon, but I feel that what came across was only the enthusiasm of having come all the way from Japan. I am deeply grateful to the local people for their understanding and cooperation in granting us permission. Some of my collaborators told me that such permission would be hard to get; therefore, the experience was something of a “miracle” and remains a cherished memory. Good relations with the whaling association have been maintained, and Utqiagvik has become one of my favorite towns.

Over 20 years of mooring observations at Barrow Canyon have revealed many insights. Here, I briefly present variations in heat transport, which influence sea ice decline (Fig. 3).

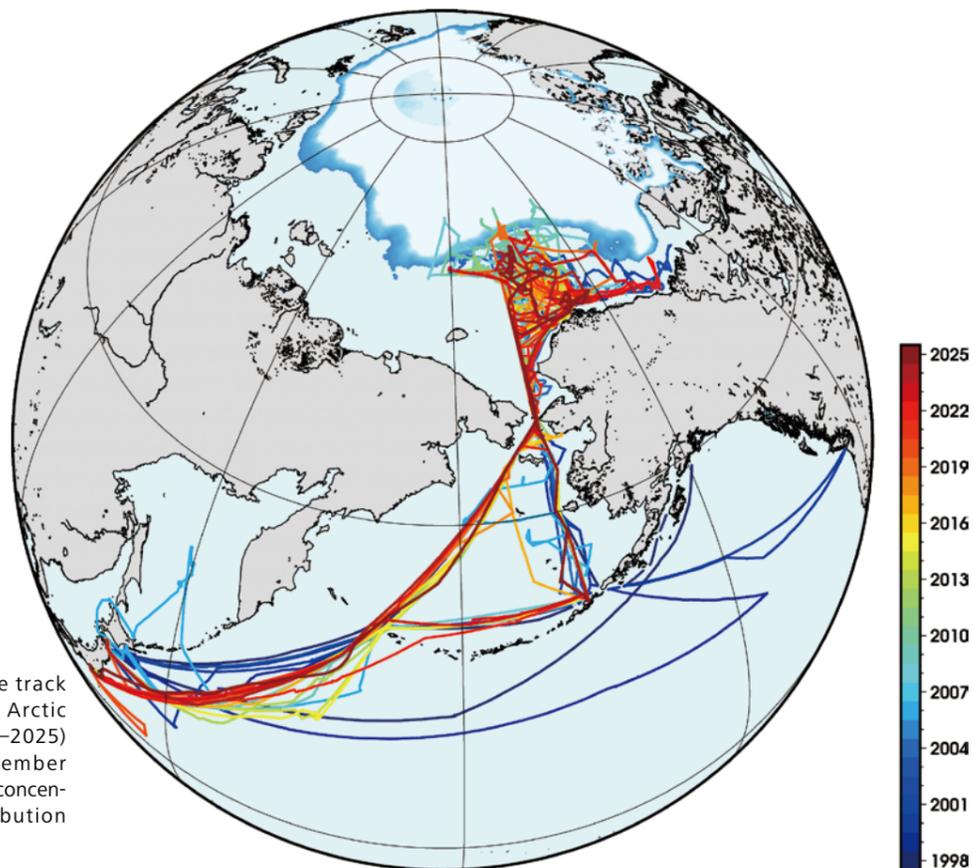


Fig. 1. Cruise track of R/V *Mirai*'s Arctic cruises (1998–2025) and the September mean sea-ice concentration distribution (2015–2025)

As I mentioned above, Barrow Canyon is a primary pathway for warm Pacific Summer Water flowing into the basin. Mooring observations show that summer Pacific water heat transport increased 1.5-fold from 2000 to 2020. Further analysis combining mooring data with satellite-derived sea surface temperatures and wind fields suggests that heat transport doubled from the 1980s to the 2020s. There is no trend in volume transport through Barrow Canyon—the heat transport increase is primarily due to the warming of Pacific Summer Water. Interannual variations are largely driven by early-summer sea ice changes in the Chukchi Sea rather than by Bering Strait heat transport (Itoh et al., in press). Heat exported from Barrow Canyon accumulates in the subsurface layer in the Pacific-side Arctic Ocean basin. In the Canada Basin, subsurface ocean heat content nearly doubled from the late 1980s to the late 2010s (Timmermans et al., 2018). Observations by R/V Mirai also revealed that in the previously unmonitored Chukchi Borderland region, subsurface heat content increased 1.8-fold from 1999 to 2020 (Muramatsu et al., 2025). In this way, large amounts of heat are stored in the subsurface layer in the Pacific Arctic Ocean and it can lead to a drastic reduction of sea ice, if it is supplied directly beneath the ice.

Finally, I would like to reflect on R/V Mirai's Arctic cruises. While it is equipped with extensive observation instruments and laboratories and is among the largest oceanographic vessels in the world, capable of withstanding harsh conditions, I believe its greatest strength lies not in its hardware but in the skill and dedication of the people who operate it. The captain, crew, ice pilots advising on ice navigation and marine technicians managing instruments and collecting data, the knowledge and expertise of the personnel are essential for successful research cruises. As R/V Mirai's navigable area depends on sea ice,

high-resolution satellite imagery and forecasts of ice, weather, and waves are indispensable. Chief scientists, including myself, have continuously updated cruise plans to maximize R/V Mirai's performance based on current ice conditions. The combined efforts of all these people have made R/V Mirai's cruises successful and remarkable.

I would like to extend my sincere gratitude to the captains and crew of R/V Mirai, Cap. Duke Snider, the marine technicians from Japan Marine Enterprise and Marine Work Japan who supported these cruises, and Mr. Hirokatsu Uno, Mr. Keisuke Matsumoto, and Mr. Hiroki Ushiomura of Marine Work Japan for their support with mooring operations. My husband, Dr. Minoru Kitamura also has experience being on board R/V Mirai as chief scientist. The cruise plan review meeting eventually led to our marriage. For this, I am also grateful to R/V Mirai.

A Repeat R/V Mirai Cruise's Perspective on International Collaboration and Future Prospects

Shigeto NISHINO

No discussion of Arctic Ocean observations is complete without mentioning international collaboration. From July to August 1994, two icebreakers from the US and Canadian coast guards (USCGC Polar Sea and CCGS Louis S. St-Laurent) took turns breaking through thick Arctic sea ice to conduct the first modern Arctic Ocean transect observations (1994 Arctic Ocean Section: 1994 AOS). Sea ice was considerably thicker than it is today, and success required the combined strength of these large icebreakers, exemplifying the "power of international collaboration."

About four years later (July–September 1998), R/V Mirai conducted its first Arctic observations in the Bering and Chukchi Seas. Leveraging its ice-capable design, R/V

Mirai could conduct highly precise, multi-parameter observations in the Pacific-side Arctic Ocean, particularly in shelf and ice-edge regions (Fig. 4), earning its reputation as a "laboratory at sea." At the time, a major research theme was the formation and maintenance of the Arctic Ocean stratification that allows summer sea ice to persist. Investigating water mass exchanges between the shelves and basins, which characterize this stratification, was crucial. As the central Arctic basins are covered by ice, international collaboration with icebreakers was indispensable.

Against this backdrop, in February 1998, prior to R/V Mirai's first Arctic cruise, JAMSTEC hosted an international workshop in Yokohama titled, "Exchange Processes Between the Arctic Shelves and Basins." Knut Aagaard (University of Washington), a leading Arctic researcher and principal investigator of the 1994 AOS aboard USCGC Polar Sea, delivered the keynote on Arctic shelf-basin interactions. Eddy Carmack (Institute of Ocean Sciences, Canada), the chief scientist on the 1994 AOS aboard CCGS Louis S. St-Laurent, presented on water mass exchanges in the Beaufort Sea and Canadian Arctic Archipelago. The networks and information established at this workshop facilitated R/V Mirai's international collaborative observations.

From its inception, R/V Mirai collaborated with the CCGS Louis S. St-Laurent and Sir Wilfrid Laurier, conducting observations from the Pacific-side Arctic shelf to the Canada Basin. In 2002, 2004, and 2008, R/V Mirai's Arctic cruises were conducted under a collaborative study between Japan and Canada named Joint Western Arctic Climate Studies (JWACS). By this time, the effects of global warming had become visible in dramatic sea ice reductions, and ocean warming was progressing. Consequently, the research focus shifted from "Arctic conditions allowing summer sea ice" to the "Arctic with catastrophic sea ice loss," and R/V Mirai's observation area expanded to the southern Canada Basin, where ice decline was pronounced. It became clear that the spread of warm Pacific-origin water was a key factor in the Pacific-side Arctic sea ice reduction (Shimada et al., 2006).

The 2008 R/V Mirai Arctic cruise was conducted as part of the Fourth International Polar Year (IPY, 2007–2008), enabling an expedition as far as the Makarov Basin off Siberia. Comparing Canada and Makarov Basin data revealed that, in association with ice loss, the nutricline deepened in the Canada Basin but remained shallow in the Makarov Basin, suggesting differences in the response of lower trophic ecosystems (Nishino et al., 2013). Routine data collected by R/V Mirai, including nutrients, were measured by specialized marine technicians. Some of this expertise was shared with JWACS collaborators, and the outcomes of joint research (e.g., Nishino et al., 2013) can be considered the result of "international technical collaboration."

Although JWACS primarily focused on hydrographic observations of ocean physics and chemistry, the DBO project initiated in 2010 targeted biologically active areas ("biological hotspots") in the Pacific-side Arctic. DBO initial-

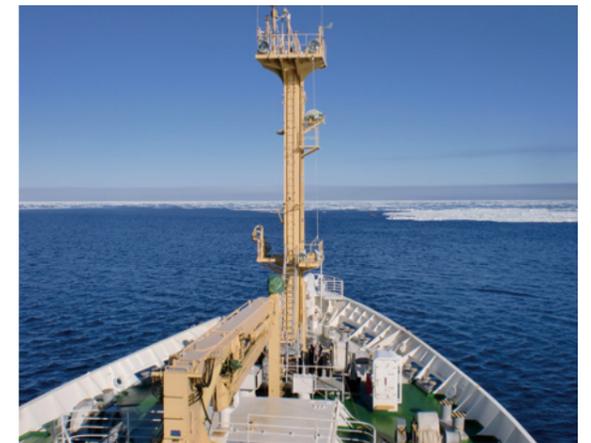


Fig. 4. Sea-ice field stretching out before R/V Mirai (taken during the 2016 Arctic cruise)

ly involved vessels from the US, Canada, Japan, South Korea, China, and Russia, taking turns observing multiple biological hotspots. Currently, four countries, excluding China and Russia, are involved. R/V Mirai focused on the waters off Pt. Hope, Alaska (southern Chukchi Sea). High-nutrient Pacific waters flowing in from the Bering Sea were known to trigger spring phytoplankton blooms supporting the hotspot, but the seasonal variations were poorly understood. Thus, JAMSTEC installed a mooring in addition to participating in DBO collaborative observations. Results showed that nutrients generated from decomposed organic matter on the seafloor triggered autumn phytoplankton blooms, sustaining the biological hotspot (Nishino et al., 2016, Fig. 5).

Furthermore, the mooring observations revealed that zooplankton biomass peaks in autumn rather than spring (Kitamura et al., 2017). Decomposition of organic matter in Hope Valley produces CO₂, and it was also found to cause localized acidification at the seafloor (Yamamoto-Kawai et al., 2016). This raises concerns about the effects of acidification on calcifying organisms and higher trophic levels via the food web. Plankton in the southern Chukchi Sea serve as prey for seabirds and marine mammals—the seasonal dynamics revealed by these studies are linked to seabird migrations and mammal movements (Tsujii et al., 2021). As marine mammal harvests are essential for indigenous livelihoods, this research has not only environmental but also social policy relevance. DBO recently initiated dialogue with Alaskan indigenous communities to integrate traditional knowledge with scientific insights—a move reflecting the broader need for "interdisciplinary and international collaboration in knowledge" in Arctic research.

While DBO covers the Pacific-side Arctic, in 2015, a pan-Arctic scale Synoptic Arctic Survey (SAS) providing comprehensive international Arctic observations was proposed. After three workshops and multiple meetings at international conferences, a science plan was finalized in 2018. The survey's goal is to create an integrated dataset covering Arctic ocean stratification, circulation, chemical budgets (carbon, nitrogen), ocean acidification, biological

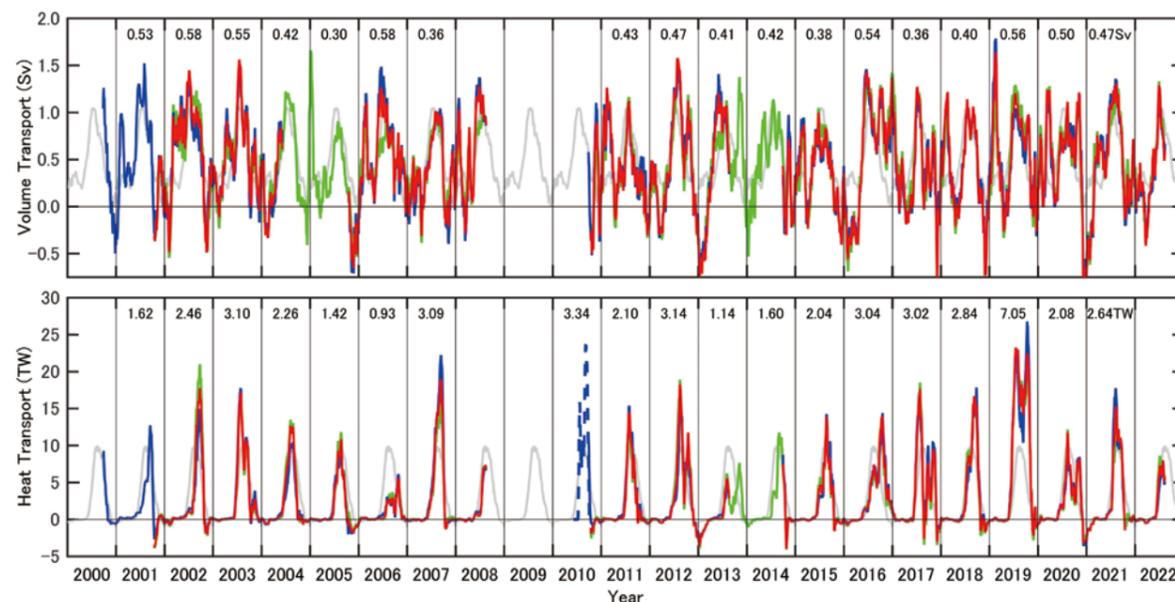


Fig. 3. Volume (top) and heat transport (bottom) through the Barrow Canyon into the Canada Basin of the Arctic Ocean

productivity, and ecosystem changes. SAS required an unprecedented undertaking of simultaneous, multi-ship, wide-area, high-precision observations.

Execution began in 2020 but was heavily impacted by COVID-19, which led to the cancellation of many SAS cruises. Only R/V Mirai, South Korea's icebreaker Araon, and CCGS Louis S. St-Laurent were able to conduct cruises. For R/V Mirai, the operational and observational plans were repeatedly revised, and permission for a foreign ice pilot—essential for Arctic entry—was granted just eight days before departure. Amid these challenges, I lost 5 kg (later regained) while managing the cruise as chief scientist. A 14-day quarantine in Japanese coastal waters reduced Arctic observations to just 16 days. Fortunately, operating as a SAS cruise, the three vessels could collaboratively cover a wide area of the western Arctic. Subsequently, SAS cruises by European and US teams were conducted in 2021–2022, with R/V Mirai participating for three consecutive years. Completion of the SAS project, across the entire Arctic Ocean, ultimately took place from 2020 to 2022.

Despite these difficulties, the 2020 R/V Mirai SAS cruise captured unprecedentedly low-oxygen, acidified waters over the Chukchi Plateau in the central Arctic's high seas (Nishino et al., 2023). Integrated analysis of R/V Mirai, Araon, and CCGS Louis S. St-Laurent data revealed that Arctic Ocean circulation—strengthening due to sea ice loss—transported low-oxygen, acidified waters, previously

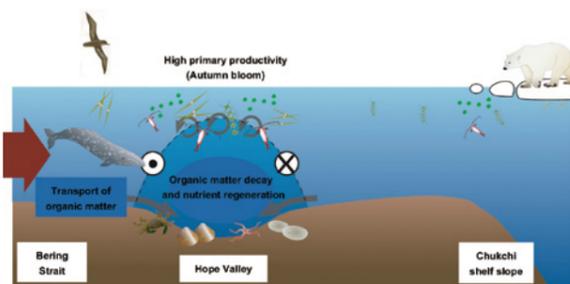


Fig. 5. Schematic of the autumn bloom observed in the Hope Valley (Nishino et al., 2016)

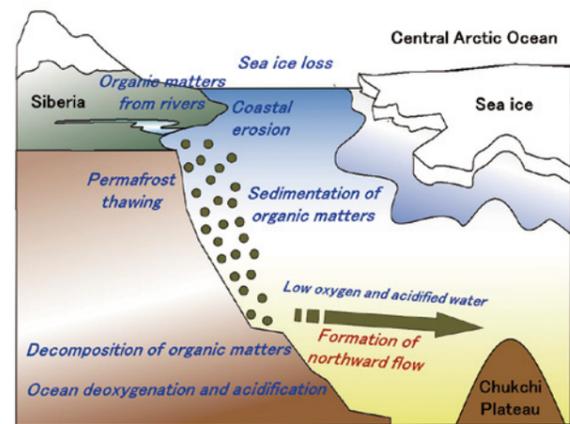


Fig. 6. Schematic showing low-oxygen, acidified waters transported from the Siberian coastal region to the Chukchi Plateau (Nishino et al., 2023)

confined near the Siberian coast, into the high seas (Fig. 6). The Chukchi Plateau is now the Arctic region experiencing the fastest rate of deoxygenation and acidification, raising concerns about future marine environmental and ecosystem impacts.

These findings informed the “Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAOFA),” guiding the selection of critical areas for scientific monitoring under the agreement. This contribution was highlighted in the ArCS II newsletter as an example of successful social implementation. Additionally, a paper co-authored by international law researchers that detailed Japan's role in CAOFA was published (Nishino et al., 2025).

Currently, SAS is integrating multinational data for pan-Arctic scale analyses. Plans are underway for a second SAS (SAS II) around 2030, with JAMSTEC serving as the secretariat. Early analyses indicate that during SAS, the Transpolar Drift current from Siberia toward Greenland was shifting toward North America, potentially altering freshwater export pathways to the Atlantic. As the Greenland region is critical for global deep-water formation, changes in Arctic freshwater export could affect deep-water formation and the associated transport of carbon and nutrients—key topics for SAS II. There are also plans for new DBO (Baffin Bay/Davis Strait-DBO) activities in the Greenland Atlantic region, opening opportunities for “interoceanic international collaboration” linking the Arctic Ocean and the Atlantic between SAS II and the new DBO. R/V Mirai will retire after its 2025 cruise, but its mission will continue on the Arctic Research Vessel Mirai II, enabling Japan to make significant contributions to SAS II.

Finally, I would like to express my heartfelt gratitude to everyone who supported R/V Mirai's operations until its retirement, including the captains and crew, marine technicians who collected world-class high-precision data, and collaborators across diverse fields, including the social sciences.

“Third Generation of Mirai” Arctic Cruises

Amane FUJIWARA

My entire research career has been nurtured by R/V Mirai. Since my debut on the 2008 MR08-04 Arctic cruise as a second-year master's student at Hokkaido University, I have participated in 12 Arctic cruises, up to the final MR25-05C. If we consider those who worked tirelessly to commission R/V Mirai as “the first generation” and those who mastered its observational capabilities as “the second generation,” then I—having joined as a student and serving as chief scientist in its retirement year—belong to “the third generation of R/V Mirai.” Here, as a representative of this third generation, I wish to reflect on my cruises and share my feelings about R/V Mirai's retirement.

I was far from an “elite student” who continuously produced outstanding research, and also faced employment difficulties as a young researcher. Nevertheless, fate

brought me to the Arctic and to R/V Mirai. The year I began serious ocean research as a graduate student happened to coincide with the 2007–2008 International Polar Year, when Arctic observations were a global priority. This serendipity allowed me to join R/V Mirai's Arctic cruises. That same period witnessed unprecedented sea ice loss, with most of the Arctic ice replaced by first-year ice. Public attention turned to Arctic research, and in 2012, coinciding with the completion of my PhD, the GRENE Arctic Climate Change Research Project began, providing postdoc opportunities and additional Arctic cruises. In 2015, with the start of the ArCS project and the launch of JAMSTEC's Arctic Environmental Change Research Center, I joined JAMSTEC as a researcher. In fact, I received an invitation to the 2015 Arctic cruise meeting before my official employment notice arrived—a unique experience. On my first day at JAMSTEC, I was asked for my work uniform and safety shoe size. I realized the role I was expected to play and resolved to dedicate myself entirely to R/V Mirai's observations.

Throughout my career, pivotal environmental changes and large-scale projects coincided with key moments, offering opportunities for research and work. Witnessing the Arctic's dynamic nature deepened my love for the ocean and its life (Fig. 7), exemplifying the principle “What you like, you will do well” that guided me toward becoming a marine researcher.

I initially assumed that the standard R/V Mirai Arctic cruise style was typical, but I gradually learned that the Arctic's unpredictability makes “plans are almost always tentative” a maxim. While ocean observations generally adjust for weather and sea conditions with a rough two-to-three-day forecast, in the Arctic, unexpected ice appearances can alter plans within hours. Believing the announcement that “the next station is in five hours,” I'd doze off, only to jump awake at the call: “Sea ice has appeared, so we'll conduct a CTD here!” ...and so on. When I was an external participant, I had to remain on alert for sudden CTD announcements.

Later, as part of JAMSTEC, I gradually became part of the “criminal” side, relaying sudden schedule changes from Chief Nishino to the team. Students would often express frustration at frequent changes, and sometimes they would get quite angry at me. I was very doubtful as to why I was the one getting scolded, but back then, I could still understand their feelings, so I had to act as the supportive senior. However, when I myself became chief scientist, I ended up repeatedly issuing sudden plan changes. I recall announcing “No CTD day” for crew-intensive mooring operations, only to hear international collaborators say, “I don't trust you.” Since then, I have always added the precautionary phrase, “Everyone, please prepare for CTD just in case.” Fortunately, from around 2020, daily updated and high-quality ice charts and near-real-time SAR images became available. Onboard networks enabled visualization of sea ice conditions at resolutions of several hundred meters via web browsers, and GIS software made

it possible to calculate ice-edge distances instantly (Fig. 8).

High-speed internet connectivity has also been introduced. Compared with R/V Mirai's early Arctic cruises, it is considerably easier to plan several days ahead, for which I count myself fortunate. This is entirely owing to the sustained efforts of those who support our expeditions, including the National Institute of Polar Research and Weathernews Inc., among many others.

Even back in the 2010s, advanced systems for obtaining voyage support information had already been established, spearheaded by Jun Inoue (now at the National Institute of Polar Research). I recall being astonished by R/V Mirai's capabilities at the time. Nonetheless, when it came to sea ice, we often had to rely on sea ice concentration images with resolutions of 12 km from AMSR-E, or sometimes as coarse as 25 km from SSM/I. Since then, the social implementation of the scientific knowledge accumulated through Arctic research, including past R/V Mirai cruises, has advanced considerably. By the time I became chief scientist, voyage support information was exceptionally well developed, with robust backing from many directions. Data once used primarily for safe navigation, for instance, to avoid sea ice, now serve additional purposes, such as identifying the ideal ice edge for conducting observations safely. Looking back, I am deeply aware that my ability to conduct research and observations in relative comfort rests upon the knowledge and technologies painstakingly developed by those who came before me.

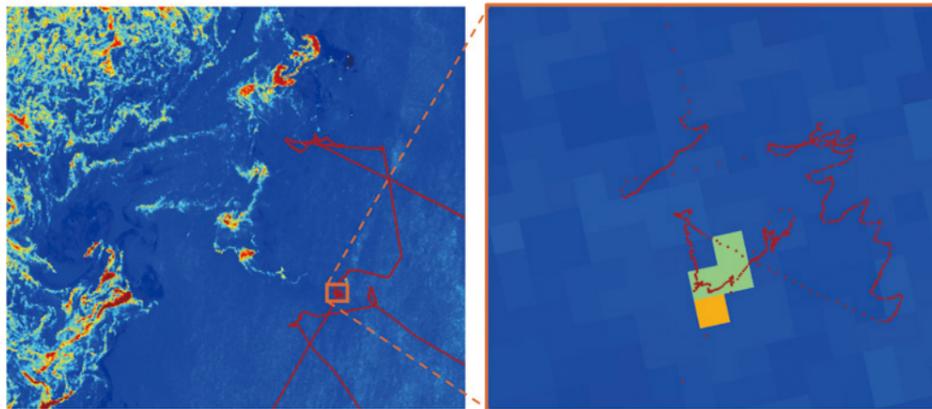
Before I knew it, I had been participating in R/V Mirai's Arctic cruises for nearly twenty years, long enough to be considered a veteran. In recent years, I began to feel that I had acquired a kind of “local sense” and seasonal intuition for the Chukchi Sea region—similar, perhaps, to the way weather forecasts speak of conditions being “around average” or at a “once-in-ten-years level.” From surface water monitoring (SOJ) data and preliminary analysis reports, I can roughly gauge whether variables such as air and water temperature, salinity, nutrient concentrations, and chlorophyll-a concentrations are relatively high or low for a given place and season. I can even broadly sense whether biological activity is abundant or scarce.

This intuition has occasionally produced direct research results. For instance, during the standard R/V Mirai transect along the north-south line across the Chukchi shelf at 168°W, I noticed remarkably high chlorophyll-a concentrations near the seafloor. On the spot, we improvised a cultivation experiment simulating benthic conditions with the equipment available, ultimately discovering that diatoms can use light penetrating to the seafloor to proliferate in near-bottom environments (Shiozaki, Fujiwara et al., 2022). In the 2021 and 2024 cruises, while transiting the Chukchi shelf, casual remarks like “Doesn't the salinity look low this year?,” made while glancing at the SOJ monitor during mealtimes, sparked further investigation. We decided to collect additional samples of oxygen isotopes and colored dissolved organic matter throughout the cruise to clarify the extent and causes of



Fig. 7. The majestic Arctic landscapes that captivated the author (Fujiwara) during R/V Mirai's Arctic cruises

Fig. 8. High-resolution synthetic aperture radar (SAR) sea-ice distribution map and R/V Mirai's cruise track (red line) on a day when ice-edge observations were conducted. As shown in the magnified image on the right, the SAR resolution is high enough to resolve the outline of R/V Mirai itself. Such near-real-time data were transmitted directly to the ship during operations.



the observed low-salinity water; as of 2025, the data analysis is underway.

I believe that such seemingly small qualitative observations made in the field can hold important scientific clues. Casual conversations with crew members and marine technicians, who have often witnessed the Arctic Ocean for even longer than we researchers, may likewise contain valuable insights, such as “There seem to be a lot of seabirds this year.” It feels somewhat akin to the way people rejoice or lament over the varying abundance of clams gathered during annual shellfish digging. Having had the good fortune to be involved in Arctic cruises for many years, I wish to continue valuing these field-based observations and the communication with fellow shipmates that nurtures them.

Once I begin recalling memories, there is no end, and some of the more mischievous moments, which I probably should not mention, bring tears to my eyes when I remember them. I am deeply indebted to R/V Mirai and the related institutions, as well as to the crew members who were always so supportive. I can state unequivocally that I would not be who I am today without R/V Mirai. When I was invited to contribute to this article, my first and clearest sense was a feeling of gratitude toward all those with whom I have shared experiences through R/V Mirai and its Arctic cruises. I intend to repay these debts through research results, and as part of the “Arctic Research Vessel (ARV) Mirai II first generation,” by passing the torch to the next generation of researchers.

Finally, allow me this opportunity to extend my

heartfelt gratitude to the captains, crew, and Capt. Duke Snider who operated R/V Mirai for a quarter century in hazardous ice seas without major accidents, Mr. Takao Oshima, Director of Marine Operations, and all those at Nippon Marine Enterprises who sustained the vessel's operations, even through a historic global pandemic, my colleagues at JAMSTEC's Research Platform Operations Department and other related divisions, the marine technicians who provided high-quality measurement data, “R/V Mirai first generation,” who laid the foundations, and the “R/V Mirai second generation,” who elevated the observations to a world-class standard, all our collaborators, my academic mentors who guided me into Arctic research, and, above all, to R/V Mirai herself. My deepest gratitude to you all. Truly, thank you.

Some Statistics and notes from the R/V Mirai Arctic Cruises

Takashi KIKUCHI

Reading the above sections, I'm satisfied that Itoh, Nishino, and Fujiwara have covered most of what ought to be conveyed about the Arctic cruises. I thus decided to look back through the 22 cruise reports up to 2024. (As this piece was written before the 2025 Arctic cruise, any information about that year is based on the draft of the cruise plan. Data from the 2025 cruise were not available at the time.) Using these records, I reviewed what we had done over the years and used this information for this final summary. Several names are mentioned below, but I hope readers will forgive me for omitting honorifics for the sake of brevity. Moreover, the numbers presented here were painstakingly calculated by Kikuchi while going through the cruise reports. So, there may be counting mistakes, transcription errors, or simple miscalculations. Consider the figures as approximations and read them as such. A table summarizing cruise schedules and participant numbers is appended at the end of this section (Table 1).

Let us start with the cruise duration. Between 1998 and 2025, R/V Mirai carried out 23 Arctic cruises, totaling 1,069 days—roughly three years at sea. The total distance sailed is estimated to be about 400,000 km, the equivalent of traveling approximately ten times around the Earth. (Admittedly, the cruise reports do not record distance; this figure relies on Kikuchi's hazy recollection.) That is quite the distance! Of these, a total of 572 days were spent conducting observations in the Arctic Ocean (north of the Bering Strait). The remaining 497 days were needed to go there and back. As it takes about 10–12 days for R/V Mirai to travel between Japan and the Bering Strait, the numbers make sense. It is a reminder that, when traveling by ship, the Arctic Ocean is not exactly “close” to Japan. However, that transit time was by no means wasted. Those days were used productively for observation preparation, instrument testing, onboard seminars, and even “Arctic board games.” On the return leg, we often used the time to compile the cruise report

or hold debriefing sessions (celebratory gatherings, perhaps?). I can say with confidence that this time was crucial for strengthening the camaraderie among researchers, marine technicians, and crew members alike. The yakiniku barbecue parties were great fun! (Sadly, they have not been held in recent years.)

The earliest R/V Mirai ever entered the Arctic Ocean was August 18, 1998. That year, she returned to the Bering Strait on August 28, where she encountered sea ice drifting in from the Siberian side. On her very first Arctic cruise, Mirai risked becoming trapped in the ice. Captain Masaharu Akamine, who was in command of the vessel, wrote about this episode in the Newsletter of the Oceanographic Society of Japan (February 2022 issue); please refer to that piece if you are interested. The latest Mirai ever returned through the Bering Strait was November 25, 2018. That cruise took place during the early winter, just as the seasonal sea ice was beginning to form. For further details, please see Jun Inoue's contribution on the subject.

As part of international outreach activities, R/V Mirai was opened to the public overseas: first in Seward, Alaska (United States) in 1998, then in Seattle, Washington and Victoria, British Columbia (Canada) in 2000. The many visitors were given the chance to see the R/V Mirai up close and learn about JAMSTEC's oceanographic investigations. Hosting public exhibitions abroad offered an important opportunity to raise R/V Mirai's international profile, and interacting with people overseas was truly enjoyable.

As for the extent of R/V Mirai's Arctic observations, the northernmost latitude reached was 79°11' N in 2010. For reference, the 2008 cruise reached 78°50' N, and the 2009 cruise reached 79°00' N. One of the objectives during this period was to cover as broad an area of the Arctic Ocean as possible, resulting in a series of record-breaking northernmost observation points year after year. From 2012 onward, however, cruises were conducted according to specific research themes and available observation days, so extending the northern limit was no longer a goal. The easternmost point reached was 127°W in 2002. R/V Mirai entered the Canadian Exclusive Economic Zone (EEZ) twice: once in 2002 and again in 2022. The westernmost point was 174°E in 2008. Although R/V Mirai's activities were constrained by sea ice, the vessel nonetheless conducted observations across a wide area of the Pacific sector of the Arctic Ocean almost every year, publishing significant results. This is an exceptional accomplishment, even by international standards, and one which we should be proud of.

From the perspective of improving operational efficiency, and, of course, reducing costs, some Arctic cruises were scheduled back-to-back with cruises in the North Pacific, such as biogeochemical time-series observations or Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) expeditions. In these cases, crew changes were made at Dutch Harbor, Alaska, meaning that some Arctic cruises either began or ended there. Of

the 23 Arctic cruises, 11 had Dutch Harbor as either their departure or arrival port. The only way to reach Dutch Harbor is by plane from Anchorage. However, as these flights are notoriously prone to cancellations and delays, participants generally planned their itineraries with extra time to spare. Consequently, when things went smoothly, many researchers found themselves with some leisure time in Dutch Harbor before boarding. Quite a few researchers spent that time exploring the small town or climbing the hill behind the airport. That said, it is a small place, and after a few visits, even Dutch Harbor can lose its novelty. Whenever a cruise began or ended in Dutch Harbor, the transit time between the harbor and the first or last observation station (usually near the Bering Strait) was roughly two days. This made both the preparation and cleanup phases especially busy, leaving little room for rest. Some researchers, buried in post-cruise work and analyses, even missed the traditional barbecue party, a minor but heartfelt tragedy of every Arctic cruise.

A total of 440 researchers and 506 marine technicians—some 946 individuals in total—participated in the Arctic cruises aboard R/V Mirai. When divided by the 23 cruises, this figure indicates that there were approximately 41 people on each cruise. In other words, there were more than 40 researchers and technicians onboard at any given time. On many occasions, every available berth was filled. The Arctic cruises were typically highly interdisciplinary, bringing together specialists in physical oceanography, chemistry, biology, meteorology, atmospheric chemistry, geophysics, geology, sea ice, and engineering. There were always many requests to board, and some researchers and projects could not be accommodated, a situation that often required careful coordination. This was particularly true after 2015, when the cruises began operating as part of Japan's national Arctic research project. Thanks to the cooperation of everyone involved, R/V Mirai's Arctic cruises became truly distinctive, uniting experts across diverse fields. I would like to express my sincere gratitude to all who participated in and supported these efforts.

In addition to the pre-cruise coordination, the chief scientist of each R/V Mirai Arctic cruise had to constantly



Fig. 9. Group photo of the 2023 Arctic cruise

adjust daily observation plans on-site, carefully monitoring the sea-ice conditions, responding to onboard issues, and making quick and informed decisions (see Fujiwara's section for further details). After the cruise, they were responsible for preparing the Cruise Report and presenting to various audiences. Serving as chief scientist on a R/V Mirai Arctic cruise was never easy.

The nine people who served as chief scientists for R/V Mirai's Arctic cruises, in chronological order, were: Takatoshi Takizawa, Koji Shimada, Naomi Harada, Takashi Kikuchi, Motoyo Itoh, Shigeto Nishino, Jun Inoue, Kazutoshi Sato, and Amane Fujiwara. (While several others served as chiefs on transit legs, their names are omitted here. Please forgive the exclusion.) Among them, Nishino was the chief scientist on five cruises, including three consecutive years (2015, 2016, and 2017). During this period, the cruises were part of Japan's national Arctic project (ArCS, FY2015–2019) and international initiatives such as DBO, all while producing significant research results. Truly remarkable! I actually invited Nishino to co-author this article so that he could share some of his reflections on those demanding years, but being the earnest person he is, he instead wrote a detailed summary of the international projects he contributed to. Thank you, Nishino-san.

Next in number of chief scientists are Takizawa, Shimada, Itoh, and Fujiwara, each serving three times. In recent years, Itoh and Fujiwara alternated as chief scientists, especially over the past five years—a period marked by the COVID-19 pandemic, which brought about various restrictions, limitations on cruise days, and the need to adapt to new forms of international collaboration. I extend my deepest gratitude to both for their extraordinary efforts during such unprecedented times.

The person with the highest total number of Arctic cruises overall is, by far, Captain Duke Snider, who appears to have served as ice pilot on about 18 Arctic cruises. Including other R/V Mirai cruises, he partook in more than 20 cruises aboard R/V Mirai. Snider first joined R/V Mirai's Arctic cruise in 2002, and ever since, he has worked tirelessly with the ship's captains and chief scientists to ensure the safe execution of observations in ice-covered waters. He also contributed an essay to this commemorative volume. Here, I express to him my gratitude—deeper than any ocean on Earth. I sincerely hope we will continue to work together in the future.

As for researchers, the record for most Arctic cruises is shared by Nishino and Fujiwara, each with 12 cruises, meaning they took part in more than half of R/V Mirai's Arctic cruises. They are followed by Jonaotaro Onodera (11), Inoue (7), and Kohei Matsuno (7). Both Fujiwara and Matsuno first joined R/V Mirai's Arctic cruise in 2008 as master's students. Over the years, they participated in numerous cruises, published their findings, and became distinguished researchers and university faculty members. I firmly believe that this generation, which Fujiwara fondly refers to as the "third generation of Mirai," will continue

to lead and shape the future of Arctic research in Japan.

Incidentally, some 150 postdoctoral researchers, graduate students, and undergraduate students participated in R/V Mirai's Arctic cruises, an invaluable contribution to human resource development. The cruise with the largest number of student participants (14) occurred in 2012, when I served as chief scientist. On a personal note, I was 45 years old at the time and realized, to my shock, that I was the oldest researcher onboard. As it turned out, that cruise was the last time I participated in one of R/V Mirai's Arctic cruises. The next highest number of student participants (12) was on a cruise in 2023. Of these, six were early-career researchers from overseas, selected through an open call for proposals targeting Early Career Scientists (ECSs). The participants belonged to the United States (2), Denmark (2), the United Kingdom (1), and Portugal (1). Both the foreign and the Japanese ECSs onboard remained in touch after the cruise. Although it was a demanding expedition in many ways, it left a lasting impression as a cruise that fostered new forms of international collaboration (Fig. 9).

Members of the media also joined some of the cruises to support public outreach. During the 1998 shakedown cruise, seven journalists participated and shared in the experience of Mirai's first Arctic cruise. In more recent years, a representative from NHK joined in 2020, and a journalist from Jiji Press joined in 2024. Their coverage contributed to television programming and special feature articles highlighting the cruise. Notably, Ryota Dei of Jiji Press, who joined the 2024 Arctic cruise, received the Vaughn–Uyeda Memorial International Journalistic Prize for his series of feature articles on the Arctic, which included reports from the cruise. This recognition constitutes one of the major achievements of R/V Mirai's Arctic research activities.

Now, I would like to reflect on the observations conducted during the cruises. As this article is being written prior to the 2025 cruise, the following data reflect the 22 Arctic cruises up to 2024.

During R/V Mirai's Arctic cruises, a total of 2,355 CTD casts were conducted. Note that this figure refers to the number of casts, not the number of observation stations, the latter of which is estimated to be around 2,300 locations. On average, each cruise recorded 107 casts, with the highest number being 260 casts in 2008. That particular cruise, which also set both the westernmost and (at the time) northernmost observation records, included the longest duration of stay in the Arctic Ocean (40 days), covering an exceptionally wide area. In contrast, in recent years, as the cruises have become increasingly interdisciplinary, and with more observation days allocated to non-oceanographic studies (and cruise durations constrained by budgetary factors), the number of casts has declined to around 40–70 per cruise. Incidentally, a total of 1,582 XCTD probes were launched. From the perspective of physical oceanographers, XCTD probes are particularly useful tools, as they allow data collection without

requiring additional ship time, making them a valuable resource.

The total number of plankton net hauls, encompassing all net types, was 1,022. The yearly variation in haul counts was significant, likely reflecting the individual research preferences of the scientists onboard. Naturally, the number of hauls increased when researchers who were highly motivated to conduct sampling, even at the expense of sleep, joined the cruise. Some of the challenges and joys of these sampling efforts may be described in Matsuno's contribution in this volume. Similarly, the number of seafloor sediment and core samples, combining all methods such as piston corers, multi-corers, and Smith–McIntyre grab samplers, totaled 176. Notably, the years 2022 and 2024, when seafloor core sampling served as a primary observation focus, each recorded more than 30 core retrievals.

Mooring recovery and deployment were also among the essential missions of the Arctic cruises, with 49 recoveries and 53 deployments conducted over the years. The slight discrepancy between these figures stems from occasions when recovery operations were performed using vessels from other nations. The over 20 years of continuous observation data accumulated through these moorings are of tremendous scientific importance. For further details, please refer to Itoh's section.

Regarding meteorological observations, a total of 1,917 radiosonde launches were conducted, encompassing both Arctic and transit periods. The number of radiosonde soundings depended on whether specialists in atmospheric observations were aboard. A total of 14 cruises included radiosonde observations, typically performed twice daily, and up to eight times per day during intensive observation campaigns. Notably, during the Years of Polar Prediction (YOPP) in 2018 and 2019, R/V Mirai successfully collected and disseminated valuable late autumn to early winter atmospheric data, contributing significantly to global polar research efforts.

As mentioned at the beginning, it was around 1990, during the formative or "launch" phase of Japan's Arctic research, that JAMSTEC and Japan as a whole began exploring how to conduct scientific observations in the Arctic. It was in 1998 that they had finally reached a stage where they could independently carry out Arctic Ocean observations based on their own research goals and capabilities. This marked the beginning of what could be called JAMSTEC's "independence phase" in Arctic research. As the international importance of Arctic research grew, so Japan began launching its own national Arctic research projects from 2011 onward, ushering in a "developmental phase." Throughout all these stages, there was always R/V Mirai. Indeed, the progress of JAMSTEC and Japan's Arctic research would not have been possible without R/V Mirai. The upcoming 2025 Arctic cruise will mark R/V Mirai's final cruise to the Arctic. Just as with every cruise before it, I sincerely hope for a safe journey, successful observations, and the ship's safe return home.

Table 1. Summary of R/V Mirai's Arctic Cruises: Cruise Schedules and Number of Participants

	Cruise ID	Chief Scientist	Departure		Arrival		Remarks	cruise duration	Number of researchers	Number of marine technicians	Number of participants from abroad
1	MR98-06	Takizawa	7/30	Sekinehama	9/10	Sekinehama	Shakedown cruise, Public open day at Seward.	43	15	7	
2	MR99-K05 (Leg 2)	Takizawa	9/11	Dutch Harbor	10/05	Sekinehama		25	20	15	
3	MR00-K06	Takizawa	8/03	Sekinehama	10/13	Sekinehama	Public open day at Seattle and Victoria.	72	22	24	
4	MR02-K05 (Leg 1)	Shimada	8/24	Sekinehama	10/10	Dutch Harbor	Including the Canadian EEZ. Westernmost (127°W)	48	26	22	12
5	MR04-05	Shimada	9/01	Dutch Harbor	10/13	Dutch Harbor		43	10	25	2
6	MR06-04 (Leg 2)	Harada	8/21	Kushiro	9/29	Sekinehama		40	24	19	
7	MR08-04	Shimada	8/15	Sekinehama	10/09	Dutch Harbor	Easternmost(174°E)	56	20	22	2
8	MR09-03	Kikuchi	8/28	Sekinehama	10/25	Sekinehama		59	18	24	2
9	MR10-05	Ito	8/24	Sekinehama	10/16	Dutch Harbor	Northernmost (79.2°N)	54	16	27	
10	MR12-E03	Kikuchi	9/03	Sekinehama	10/17	Sekinehama	GRENE Arctic Climate Change Research Project	45	21	25	1
11	MR13-06	Nishino	8/28	Dutch Harbor	10/20	Sekinehama		54	21	25	1
12	MR14-05	Inoue	8/31	Dutch Harbor	10/10	Yokohama		41	18	28	2
13	MR15-03	Nishino	8/23	Sekinehama	10/21	Sekinehama	ArCS	60	16	29	
14	MR16-06	Nishino	8/22	Hachinohe	10/05	Sekinehama	ArCS	45	18	28	
15	MR17-05C	Nishino	8/24	Dutch Harbor	10/01	Hachinohe	ArCS	39	17	28	4
16	MR18-05C	Inoue	10/24	Sekinehama	12/06	Shimizu	ArCS, Early Winter (November)	44	8	13	
17	MR19-03C	Sato	9/27	Sekinehama	11/09	Hachinohe	ArCS, Early Winter (October)	44	18	21	1
18	MR20-05C	Nishino	9/19	Shimizu	11/01	Shimizu	ArCS II	44	16	23	
19	MR21-05C	Fujiwara	8/31	Shimizu	10/21	Shimizu	ArCS II	52	19	26	
20	MR22-06C	Ito	8/12	Shimizu	9/28	Shimizu	ArCS II, Including the Canadian EEZ.	48	22	20	3
21	MR23-06C	Fujiwara	8/25	Shimizu	10/04	Dutch Harbor	ArCS II, Proposals for overseas young researchers.	41	25	15	6
22	MR24-06C	Ito	8/26	Sekinehama	9/30	Dutch Harbor	ArCS II, Proposals for overseas young researchers.	36	26	19	1
23	MR25-05C	Fujiwara	8/31	Dutch Harbor	10/05	Shimizu	ArCS III (Plan)	36	24	21	1
	23 times in 28 years							1,069	440	506	38

Compiled from cruise reports archived in DARWIN (https://www.godac.jamstec.go.jp/darwin_cruise/view/base?lang=en).

The number of "researchers" includes ice pilots, bear watchers, and media representatives.

"Participants from abroad" refers to researchers and graduate students affiliated with overseas institutions, companies, or universities.

Foreign nationals based at Japanese institutions or universities are not included in this count.



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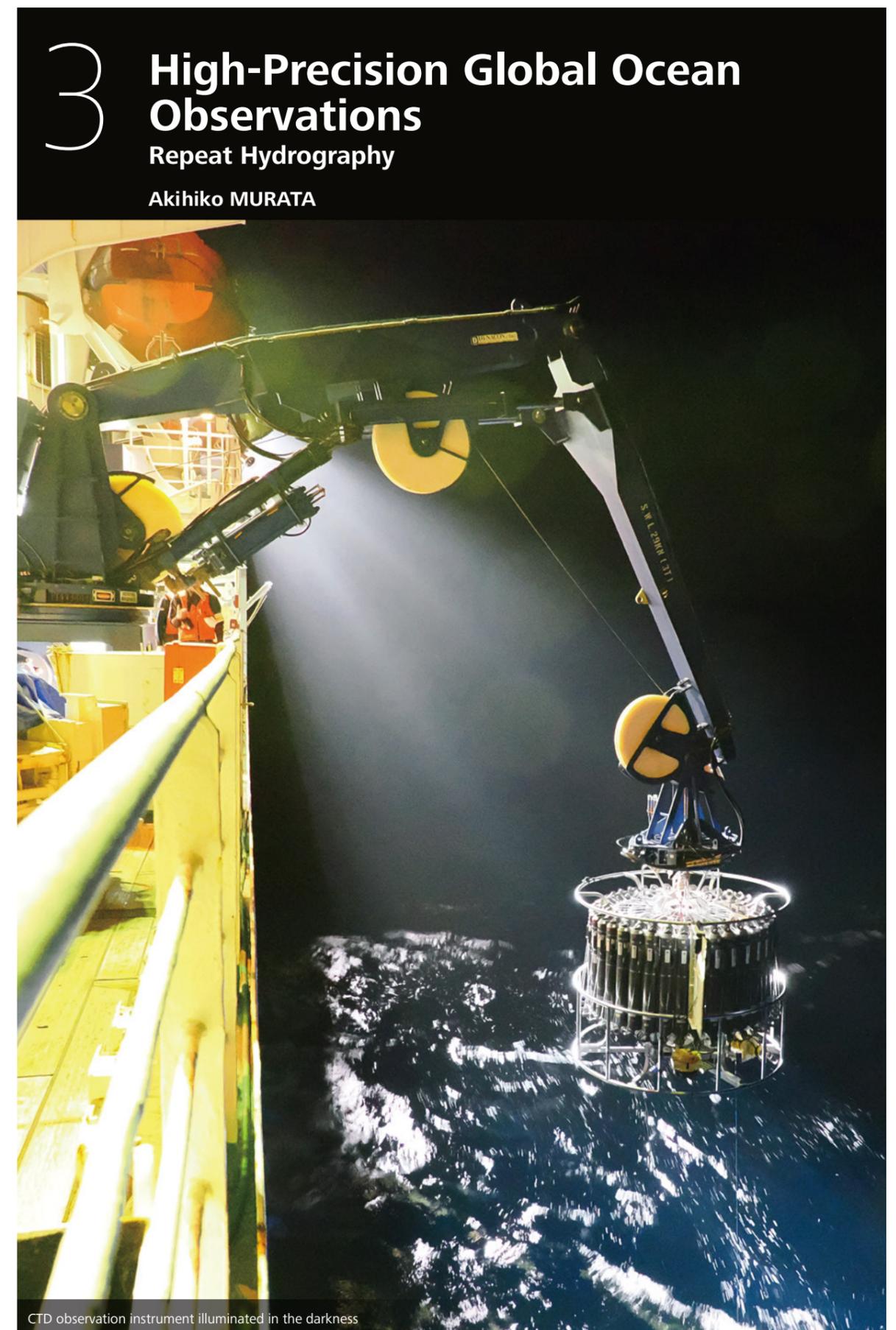
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CTD observation instrument illuminated in the darkness

Introduction

The term in the title “repeat hydrography” may not be familiar even among oceanographers, and there may not be a universally shared understanding of what it actually entails. While “repeat” means “to conduct repeatedly,” “hydrography” is often translated as “hydrographic surveying” or “marine mapping,” which gives a strong impression of a discipline dealing with the topography of water bodies.

In this context, however, the repeat hydrography cruises introduced here refer to oceanographic observations conducted along lines predefined by the international oceanographic community that cross-cut between continents. They are sometimes called intercontinental transect observations. At closely spaced observation stations along these lines (Fig. 1), precise measurements are taken from the surface to just above the seafloor, including temperature, salinity, dissolved oxygen, nutrients (e.g., nitrate, nitrite, phosphate, and silicate), CFCs, and carbonate system parameters (e.g., total inorganic carbon, total alkalinity, and pH), and the data are made publicly available.

Since the late 1990s, JAMSTEC has carried out such cruises approximately every other year using the research vessel *Mirai* (Table 1 and Fig. 2). As the same observation lines are revisited, the surveys are literally “repeated.” While most parameters are standard in oceanography, biological measurements have also been added in recent years, broadening the scope of observation.

The origins of repeat hydrography can be traced to the World Ocean Circulation Experiment (WOCE) program primarily conducted in the 1990s, specifically the WOCE Hydrographic Programme (WHP) One-Time Survey, which carried out one high-precision survey on each line during the WOCE period. As climate change became a global concern, there was growing recognition that understanding ocean circulation was essential for identifying and predicting long-term climate variability. To this end, measurements of parameters such as temperature, salinity, dissolved oxygen, and nutrients—then routine in oceanographic observation—were required at unprecedented levels of precision. In addition, various chemical tracers were analyzed to uncover the history of ocean circulation, most notably CFCs and radiocarbon

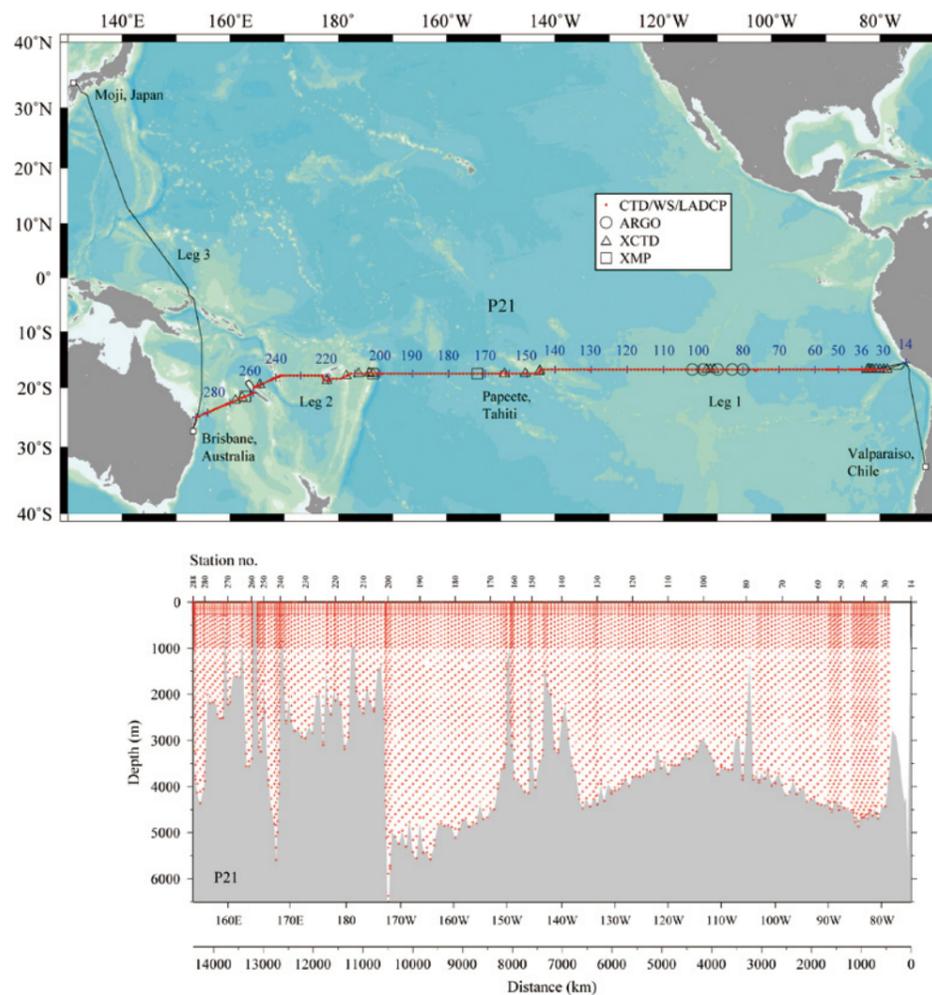


Fig. 1. 2009 Cruise (MR09-01) observation lines (top) and sampling depths (bottom)

Table 1. Repeat hydrography cruises conducted by *Mirai*

Implementation year	Ocean	Cruise ID	WOCE Line
1999	North Pacific	MR99-K05 Leg 1	P01
2001	North Pacific	MR01-K04	P17C, P17N
2003	South Pacific	MR03-K04 Leg 1	P06
2003	South Pacific	MR03-K04 Leg 2	P06
2003	South Pacific	MR03-K04 Leg 4	A10
2003/2004	Indian Ocean	MR03-K04 Leg 5	I04, I03
2005	North Pacific	MR05-02	P10
2005	North Pacific	MR05-05 Leg 1	P03
2005/2006	North Pacific	MR05-05 Leg 2	P03
2006	North Pacific	MR05-05 Leg 3	P03
2007	North Pacific	MR07-04	P01
2007	North Pacific	MR07-06 Leg 1	P01, P14N
2007	North Pacific/South Pacific	MR07-06 Leg 2	P14N, P14C
2009	South Pacific	MR09-01 Leg 1	P21
2009	South Pacific	MR09-01 Leg 2	P21
2011/2012	North Pacific/South Pacific	MR11-08 Leg 2	P10
2012	North Pacific	MR11-08 Leg 3	P10
2012	South Pacific/Southern Ocean	MR12-05 Leg 2	P14S, S04I
2012/2013	Southern Ocean	MR12-05 Leg 3	S04I
2014	North Pacific	MR14-04 Leg 2	P01
2015/2016	Indian Ocean	MR15-05 Leg 1	I10
2017	South Pacific	MR16-09 Leg 3	P17E
2019	Indian Ocean	MR19-04 Leg 2	I08N
2019/2020	Indian Ocean/Southern Ocean	MR19-04 Leg 3	I07S, S04I
2021	North Pacific	MR21-04	P01
2023	North Pacific	MR23-07	P14N
2025	North Pacific	MR25-02	P04W

(^{14}C), both of which continue to be measured on *Mirai*'s repeat hydrography cruises today.

Multiple vessels from government agencies and universities participated in the WOCE one-time surveys. Today, however, only JAMSTEC and the Japan Meteorological Agency continue these observations in Japan. Leveraging its advantages as one of the world's largest oceanographic research vessels with long cruising range and capacity for many researchers and technicians, *Mirai* has conducted surveys across the Pacific Ocean, as well as in the Indian and Southern Oceans (Table 1). That repeat hydrography cruises are now a routine part of *Mirai*'s schedule was made possible by the ship's major refit during the early years of the program. (For details, see the contribution by Masao Fukasawa, who led the modification project.)

The guiding principles of these cruises are “from land to land” and “from the surface to just above the seafloor,” with high-precision measurement being a given. Achieving these goals requires not only the cruise itself but also meticulous preparation and post-cruise work. The following sections discuss *Mirai*'s repeat hydrography cruises and related topics.

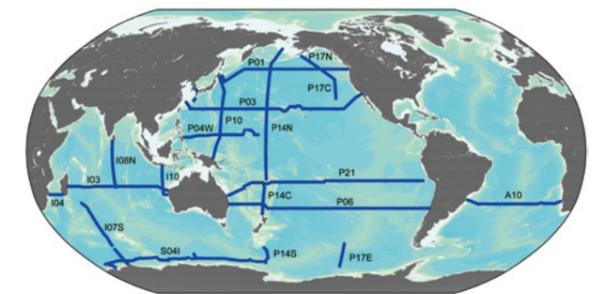


Fig. 2. Repeat hydrography lines covered by *Mirai*

Preparations

The first step in a repeat hydrography cruise is deciding which observation lines to survey. This is discussed within JAMSTEC's research groups (currently the Physical and Chemical Oceanography Research Group, Global Ocean Observation Research Center, Research Institute for Global Change) and requires coordination among the international community. As noted, repeat hydrography originated in the WOCE One-Time Survey—a community that continues today under GO-SHIP (Global Ocean Ship-based Hydrographic Investigations Program). This program facilitates information exchange to avoid, for example, Japan repeating a line immediately after the US

has surveyed it. As the goal is to detect long-term basin-scale changes over decades, repeating a line within a year or two would be of little scientific value. This is es-



Fig. 3. CTD being recovered from the ocean using a winch, with sensors at the bottom and 36 Niskin bottles at the top (top right photo). The winch was newly installed for BEAGLE2003.



Fig. 4. CTD preparation



Fig. 5. Bottles arranged on deck for seawater sampling



Fig. 6. Seawater sampling from Niskin bottles, in a space that feels somewhat cramped given the size of Mirai.

pecially true in the Pacific, where “land-to-land” lines are very long, making them difficult for a single institution to survey alone. In such cases, GO-SHIP coordinates international cooperation. For instance, the Pacific P04 line (along 10°N) is being re-surveyed with JAMSTEC covering the western half (MR25-02, completed in May 2025, P04W, Fig. 2) and the US covering the eastern half.

Another critical preparatory task for “land-to-land” lines is obtaining survey clearance within foreign EEZs. In the Pacific, many countries have prior experience granting JAMSTEC such clearances, making the process relatively smooth. However, this is not the case with countries applying for the first time. For first-time countries, formal diplomatic channels are required, and procedures vary by country. Preparation begins with identifying the appropriate local authorities and often involves careful planning.

Such tasks cannot be handled by researchers alone and often require collaboration with administrative staff, who sometimes even accompany us to negotiations. Occasionally, we were notified of clearance only after the cruise had begun, so the ship waited near the EEZ boundary. These EEZ applications go through the diplomatic channels from the relevant department at JAMSTEC via MEXT and the Ministry of Foreign Affairs. Even though we rarely met in person, sincere thanks go to everyone involved.

Beyond these logistical arrangements, scientific preparation is also essential. As the name “WOCE re-survey” suggests, repeat hydrography has continually strived for the same or higher precision as the original WOCE surveys. If Mirai’s oceanographic data are regarded as high-quality, this owes to the experience gained through repeat hydrography cruises.

Repeat Hydrography Cruises on Mirai

In essence, repeat hydrography involves taking Conductivity, Temperature, and Depth (CTD) measurements at high-density observation points (30–50 km spacing) along intercontinental lines.

Each CTD instrument is equipped with Niskin bottles for collecting seawater at selected depths, 36 bottles each with a capacity of 12 liters, allowing up to 36 discrete depth samples per cast (Fig. 3). Preparation begins about 15 minutes before reaching a station: the CTD sensors are checked and the Niskin bottles are set (Fig. 4). In the open ocean, depths can reach 5,000–6,000 m, so a single CTD cast from deployment to recovery can take four to five hours. Roughly 30 minutes before recovery, the sampling bottles are placed into baskets corresponding to Niskin bottle numbers 1–36 (Fig. 5). Once the CTD is back on the Mirai’s deck, the ship proceeds to the next station, during which water sampling is performed (Fig. 6). Stations with many parameters or special sampling can take longer. Initially, the process could take about two hours, but crews gain efficiency over time,

reducing it to around one hour. This routine is repeated three or four times a day, typically for a week. As ship time is strictly scheduled from departure to arrival, any delay in CTD operations affects the overall plan. In the open ocean, travel between stations usually takes two to three hours, allowing the CTD and sampling teams to rest during transit.

While CTD measurements are conducted on other cruises, repeat hydrography is uniquely demanding. Every station conducts CTD casts to just above the sea-floor, and few other cruises routinely do so; typical surveys reach only about 2,000 m. This process is physically and mentally challenging for researchers, technicians, and crew.

It also places stress on the equipment. The CTD equipment is subject to daily round trips from atmospheric pressure to 6,000 m (~600 atm) three to four times a day. In the early 2010s, JAMSTEC conducted two repeat hydrography cruises per year. On one occasion, repeated CTD sensor malfunctions were traced to usage beyond what the manufacturer had designed the equipment to withstand—a level of operation not carried out by any other institution worldwide. Onboard analytical instruments are also subject to intense demands. With continuous sample inflow, critical measurement systems operate in dual setups to manage the workload efficiently.

While repeat hydrography cruises are undoubtedly demanding, they are not exclusive to Mirai. During the 1990s, multiple government and university research vessels were used to conduct WOCE one-time surveys. The key advantage of Mirai lies in its size and efficiency. With a gross tonnage of 8,706 tons, Mirai can accommodate over 40 researchers and technicians, plus a total of 80 personnel including crew. This allows 24-hour shift operations for CTD deployment and recovery, water sampling from Niskin bottles, and onboard analyses. A crucial part of crane operations is wire maintenance, which requires constant monitoring and dedicated personnel.

On most other cruises, researchers and technicians collect and analyze their own samples at their stations. This works fine when stations are sparse, but on a repeat hydrography cruise, where stations are close together and samples arrive in rapid succession, separating sampling and analysis teams is essential. Experienced researchers and technicians handle analysis, while sampling—which is relatively easier but requires precision—is assigned to temporary personnel, often students. Each sampler collects all parameters from every Niskin bottle. Although considered “simpler,” careful handling is crucial for high-precision data. At the start of each cruise, all samplers gather for training; they receive instructions from parameter specialists and practice the procedure (Fig. 7). Some groups, especially collaborative projects from within and outside JAMSTEC, collect special or unusual samples, and the sampling processes are similarly practiced for about two days before actual sam-

pling begins.

Regarding the dispensing of seawater from Niskin bottles, different bottles are used for different parameters, and each requires a slightly different handling method (Fig. 8). As one person collects all samples from a single bottle, mistakes occur easily. Additionally, because samples come from depths of 5,000–6,000 m, they must be processed quickly on deck to prevent alteration. Gas components such as oxygen, CFCs, and carbonate parameters require particular care; they are assigned to the earliest sampling positions, and each sampling bottle is checked to ensure no bubbles are present. If sampling fails, the process is repeated. The sampler-in-charge (two per cruise) verifies all collected samples. As proper sampling affects analysis precision, onboard analysts provide feedback on measurement quality. Taking two bottles from the same Niskin yields duplicate samples, which should match within the expected error range; large discrepancies trigger a review of the sampling procedures.

Ensuring high-precision measurements is a central goal of repeat hydrography cruises. As part of an international program, one objective is to accurately monitor global long-term ocean changes. For this, data from different groups must be scientifically comparable, that is, measured using the same scale—just as centimeters and inches cannot be compared if mixed. While this seems obvious, truly comparable datasets are rare. Physical pa-



Fig. 7. Focused on sampling practice, with international participants



Fig. 8. Seawater sampling bottle

rameters like temperature and salinity have long been standardized, allowing robust studies of long-term variability. Chemical components, however, are more challenging. For instance, while nutrients have been measured alongside temperature and salinity since the late nineteenth century, long-term studies remain scarce due to the low comparability of nutrient data. Even during the high-precision WOCE surveys of the 1990s, comparability was limited. Although standard procedures were established, there were no certified reference materials for these measurements at the time.

Nutrient reference materials were introduced to the oceanographic community in the 2010s as Japan-originated and Japan's first marine environmental standard materials. They were developed through over 30 years of effort by the late Michio Aoyama (Meteorological Research Institute; later affiliated with Fukushima University and Tsukuba University; concurrently a JAMSTEC Visiting Senior Researcher). On *Mirai*, precursor reference materials were already in use from the BEAGLE2003 cruise onward, and have been employed on every JAMSTEC repeat hydrography cruise ever since. Through international promotion led by JAMSTEC, these nutrient standards have now become globally recognized. Their value lies precisely in their widespread use, and *Mirai*'s cruises have played a key role in ensuring the comparability of nutrient data, a significant contribution to the international oceanographic community.

Researchers experienced with repeat hydrography on other vessels have commented on *Mirai*, noting that while procedural details differ slightly, *Mirai*'s large capacity for personnel and equipment and ability to conduct long-duration cruises make it advantageous as a large ship.

Thus far, we have outlined the unique features of repeat hydrography on *Mirai*. As this program targets the global ocean, its operational range exceeds that of any other *Mirai* cruise. Observations are conducted far from Japan, covering five of the seven oceans: the North Pacific, South Pacific, Indian Ocean, South Atlantic, and Southern Ocean. (The Arctic is covered by the Arctic Group cruises.) Although the cruises may have seemed repetitive, each left distinct impressions. Several of these will be highlighted below.

■ BEAGLE2003

The BEAGLE2003 cruise departed Brisbane, Australia, on August 3, 2003. It sailed eastward roughly along 30°S, with port calls at Papeete (Tahiti), Valparaíso (Chile), Santos (Brazil), Cape Town (South Africa), Tamatave (Madagascar), and Port Louis (Mauritius), before finally arriving in Fremantle (Australia) on January 24, 2004. Conducted to mark JAMSTEC's 30th anniversary, the cruise was named after the HMS *Beagle*, on which Charles Darwin circumnavigated the globe.

Its primary goal was to reveal decadal-scale variability in the Antarctic overturning system. Prior to

BEAGLE2003, a group led by Masao Fukasawa, who also contributed to this commemorative volume, had discovered an unusual warming of bottom waters at P01 and P17N (WOCE lines, Fig. 2), located at the northern edge of the North Pacific and in the terminal regions of global ocean circulation. Physical oceanographic interpretation suggested the origin of this warming lay in the Southern Ocean, prompting the planning of BEAGLE2003 to circumnavigate that region.

The cruise covered WOCE lines P06 (Southern Ocean), A10 (South Atlantic), I03 (Indian Ocean), and I04 (Indian Ocean) (Fig. 9). JAMSTEC assigned it the cruise number MR03-K04, dividing it into six legs. Legs 1, 2, 4, and 5 were designated repeat hydrography legs: Leg 1, 34 days and 121 CTD stations; Leg 2, 38 days and 116 stations; Leg 4, 30 days and 111 stations; and Leg 5, 27 days and 145 stations. During these legs, CTD observations were conducted almost continuously, putting both equipment and personnel to the test. This was made feasible by prior modifications to *Mirai*, particularly the upgrade of the observation winch (Fig. 3), which greatly improved CTD deployment efficiency.

From start to finish, from Brisbane to Fremantle, *Mirai* did not stop in Japan. Before the BEAGLE2003 cruise starting in Brisbane, several other cruises had taken place. *Mirai* had departed Yokohama on May 21, 2003, and the ship spent 307 days away from Japan. Such a long mission required multiple backup instruments in case of failure, careful planning for the storage of the enormous number of water samples, and space for disposal of post-analysis waste brought back to Japan. In some cases, additional sampling bottles were purchased, with used bottles washed on board. The demands on the workforce for tasks such as sampling, analysis, and cleaning exceeded any previous cruise. In this context, it was *Mirai*'s large size and capacity that made the success of BEAGLE2003 possible.

The Partnership for Observation of the Global Oceans (POGO) is a forum of major ocean research institutions worldwide. In 2001, POGO adopted the São Paulo Declaration to strengthen Southern Hemisphere ocean observations. As a follow-up, BEAGLE2003 included many researchers and technicians from Southern Hemisphere countries. Notably, one participant later became a university advisor, and 22 years later, their student, supported by a POGO scholarship, joined MR25-02 (*Mirai*'s final repeat hydrography cruise). In this way, BEAGLE2003 made a lasting multi-generational contribution to education.

Although preparations were demanding, the extended time away from Japan and visits to seldom-explored regions (e.g., the South Atlantic) allowed for enjoyable port stays. While recent cruises typically allocate only three days in total per port (i.e., arrival, one day in between, departure), BEAGLE2003 allowed longer stays, including three full days in between in Papeete and Cape Town. Being a commemorative cruise, several

ceremonies were held at ports, and a grand achievement ceremony marked the end of the voyage (Fig. 10). One memorable experience was disembarking in Valparaíso on October 16, after Leg 2, and remaining in South America until Leg 4 began in Santos on November 6, which also involved the mishap of having to renew a Brazilian visa. Others included climbing Table Mountain in Cape Town through fog (or clouds from a distance), discovering that the ice cream stored in the shared fridge had mysteriously disappeared, continuing analyses because replacement personnel failed to show up (apparently after a night of heavy drinking), helping a Latin crew member set up an electric guitar amplifier, and nightly dance parties hosted by the same group.

Although over 20 years have passed and such silly memories often come to mind before the observations themselves, the data collected during BEAGLE2003 have been preserved and continue to support future research.

■ P01 Re-Observation

The P01 line stretches from off Hokkaido to off Seattle, roughly along 47°N (Fig. 11). This line is notable because Japan has conducted observations there four times: 1999, 2007, 2014, and 2021. P01 is one of the lines designated by the community for roughly decadal repeat observations. Since one end of the line is Japan, it is convenient for Japanese researchers. However, execution has seldom been smooth: in 1999, equipment malfunctioned; in 2007, a fishing net got caught in the propeller, forcing a return to port; in 2021, circumstances prevented the vessel from reaching Seattle. Only 2014 went smoothly. Even internationally, few lines have been repeated four times. P01 is also where bottom-water warming was first observed (as mentioned in BEAGLE2003), making it especially interesting to track changes 10–20 years later. It is hoped that observations will continue even after *Mirai*'s retirement.

■ Indian Ocean Cruises

Fewer historical observations have been conducted in the Indian Ocean than in the Pacific and Atlantic, partly due to its distance from countries with long oceanographic history. Japan's relative proximity allowed it to conduct not only BEAGLE2003's I03 and I04 lines but also plan three observations of the I08 line (Fig. 12). For unclear reasons, the first two planned cruises ended up being little more than phantom voyages and never materialized. As some observations fall within Sri Lanka's EEZ, negotiations involved two visits there. When the cruises were canceled, Japan conveyed to Sri Lanka—at least as I recall—that the cancellation was provisional rather than final. Eventually, the I08 line was successfully observed in 2019, coinciding with a rare occurrence of the Indian Ocean Dipole (IOD). By chance, this allowed high-precision observations of the IOD for the first time globally, providing valuable data.

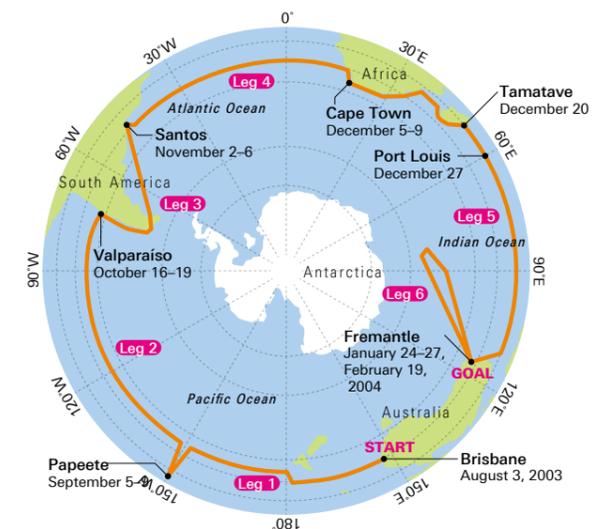


Fig. 9. Cruise track of BEAGLE2003



Fig. 10. BEAGLE2003 completion ceremony at Yokohama Port, March 23, 2004

Post-Cruise Work

At an international meeting, one researcher remarked, "Oceanography isn't oceanography if you don't make your data open." I wholeheartedly agree. In repeat hydrography cruises, data are fully open and free to use. However, releasing data indiscriminately is not enough. Each dataset is carefully reviewed by the responsible analysts, and quality assessments are assigned before publication. In repeat hydrography datasets, a column next to each measurement indicates the results of quality control. For example, for dissolved oxygen, the column with measured values (header: OXYGEN) is accompanied by a quality flag column (header: OXYGEN_FLAG_W), where numbers denote data quality (e.g., "2" for good data, "4" for bad). Before WOCE, flagged datasets were rare, and openly accessible data even rarer. JAMSTEC publishes quality-controlled datasets as data books (Fig. 13), including explanations of measured parameters, distribution maps, and accompanying optical discs containing flagged numerical data for user convenience. The flagged data files introduced in repeat hydrography cruises are called seafiles, and this format is often used

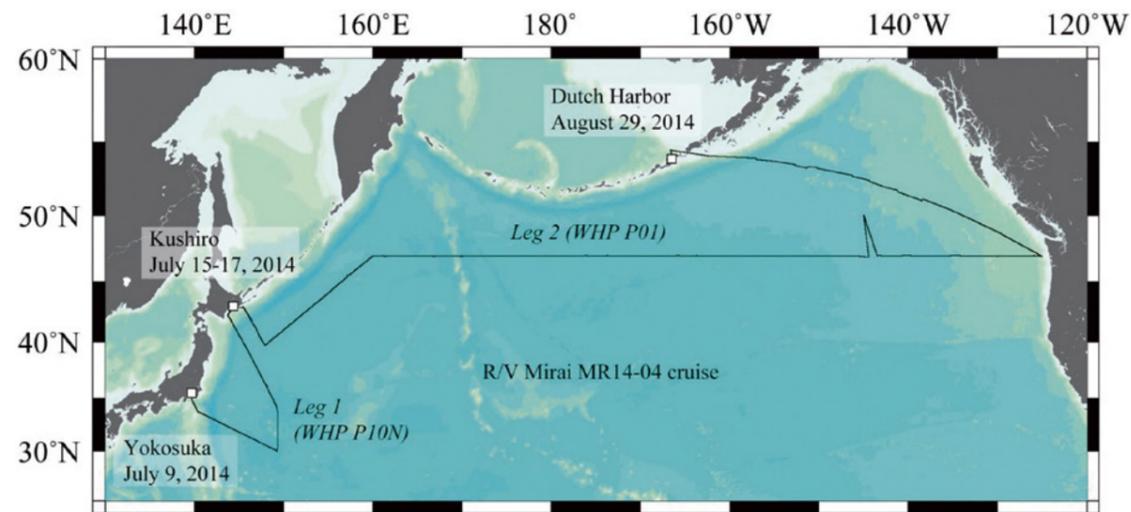


Fig. 11. P01 observation line, conducted in 2014 as MR14-04 Leg 2

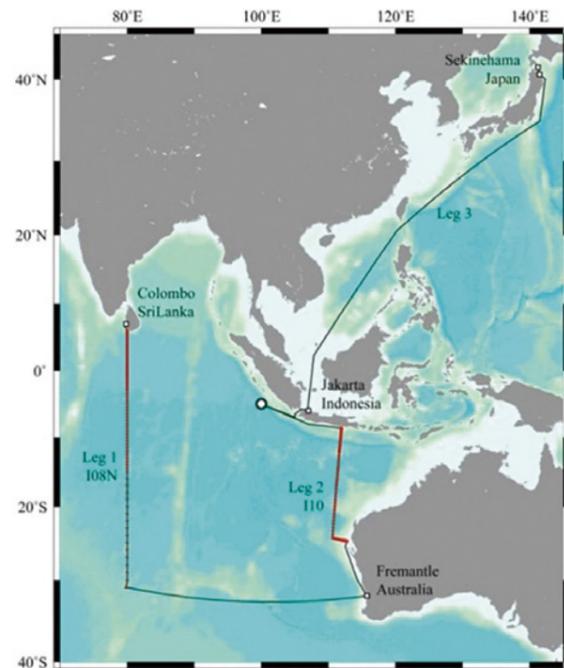


Fig. 12. I08 observation line. Planned in 2011, 2015, and 2019. The figure shows the 2015 observation. The 2011 observation was canceled, and the 2015 cruise (MR15-05 Leg 1) included only I10 in the eastern Indian Ocean. In 2019 (MR19-04 Leg 2), the northern part of I08 above 20°S was observed.

in other cruises as well.

Post-cruise work does not end with the publishing of the data book. Each group's quality control is inherently subjective, and comparison with data from other groups requires adjustment when necessary. This step is crucial for estimating material budgets. For example, estimating how much atmospheric CO₂ the oceans absorb relies on accurate seawater CO₂ measurements. Even small measurement errors can propagate into large un-

certainties when scaled to the entire ocean volume. As CO₂ is a key driver of global warming, inaccurate data could compromise future projections.

In repeat hydrography, the Global Ocean Data Analysis Project (GLODAP) collects datasets from each group and applies secondary quality control. The datasets included are not limited to repeat hydrography cruises. Its goal is to produce basin- and global-scale datasets with consistent quality. The QC method compares data below 1,500 m for each cruise and adjusts them using inverse analysis. Collected data are mixed in quality, but data measured with standard reference materials are highly comparable. In this respect, Japan's development and first provision of nutrient standard materials to the international oceanographic community represent a major contribution. Data from Mirai's repeat hydrography cruises serve as reference datasets in GLODAP.

GLODAP datasets up to version 2 are publicly available and widely used, and the paper introducing GLODAP is highly cited. Version 3 is currently being developed, again using Mirai's data as a standard.

Conclusion

Repeat hydrography originated with WOCE, planned in the mid-1980s. Reviews of the program describe it as "the first comprehensive global survey of physical properties of the oceans," highlighting its initial focus on understanding ocean physics. In the 2000s, the International Ocean Carbon Coordination Project (IOCCP) began observing ocean CO₂, placing repeat hydrography within the Ocean Interior Observations, with an increased focus on chemical parameters. In the 2010s, Bio-GOSHIP was launched to collect global-scale biological data. Therefore, the scope of repeat hydrography expanded from physics to chemistry to biology. Today, the

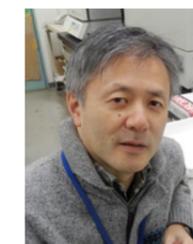


Fig. 13. Data book collection

term "repeat oceanography" better reflects reality: the ocean has flows (physics), contains various dissolved substances (chemistry), and hosts marine ecosystems (biology). The evolution of repeat hydrography to encompass all these dimensions is natural and necessary.

The period from 2021 to 2030 has been declared the UN Decade of Ocean Science, aimed at addressing the declining health of the oceans caused by human misuse. The initiative seeks solutions based on ocean science, encompassing both natural and social sciences. One of its seven objectives, the "Seven Seas," is "a predictable ocean," focusing on climate change and ocean acidification. Mirai's repeat hydrography cruises have contributed to this goal by providing high-precision datasets. Although Mirai has retired, its mission is passed on to Mirai II.

The content of this report was completed with contributions and comments from participants of Mirai's repeat hydrography cruises: Yuichiro Kumamoto, Hiroshi Uchida, Masahito Shigemitsu, and Mio Akamatsu.



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4 Tropical and Subtropical Observations

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TRITON Buoys Deployed by Mirai

Tropical observation cruises by Mirai

Iwao UEKI

Introduction

Work on the TRITON buoys begins with the call, "Let's go for zero accidents today, too! All right!" Depending on the station, deployment and recovery operations often exceed five hours. With hopes for a safe day, the crew watches as the TRITON (Triangle Trans-Ocean Buoy Network) buoy is lifted by the A-frame crane (Fig. 1). Deck and engine crew work skillfully, inspiring confidence, while the following procedures are checked. Once the surface buoy is in the water, the marine technicians attach approximately 13 underwater sensors to a wire rope (Fig. 2). Next, recovery buoys and nylon ropes are connected, and finally the acoustic releases and anchor are attached to complete the mooring system. The vessel then moves to the target location with the anchor positioned at the deck end, and the mooring system is finalized by deploying the anchor. Positioning the anchor accurately at the target location requires the expertise and experience of the bridge crew. Through these operations, the TRITON mooring system with a mooring line longer than the height of Mount Fuji is completed.

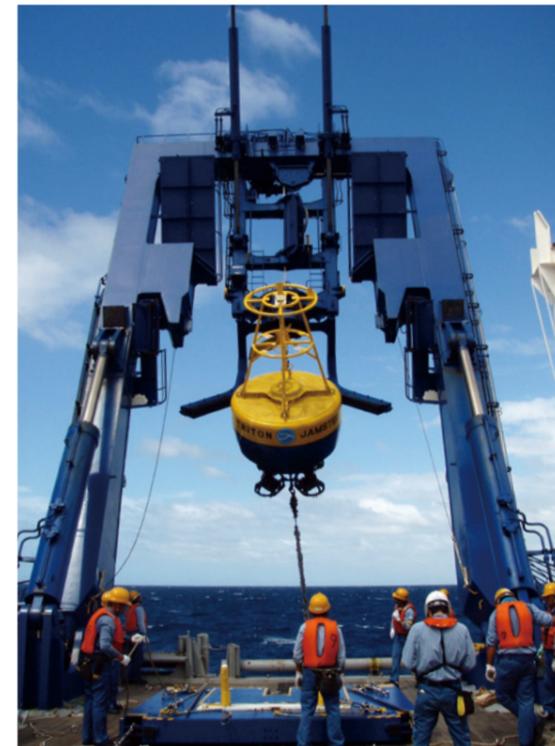


Fig. 1. Lifting a surface buoy of TRITON mooring
A TRITON's surface buoy weighs about 2.4 tons, requiring great care when handled on a rolling vessel. Once lifted from the trolley into the position shown in the photo, the buoy becomes stable, marking the completion of one hazardous stage. After pausing to confirm safety, the A-frame is lowered seaward, initiating the surface buoy deployment and subsequent mooring operations.

During tropical observation cruises, much of the work revolves around deploying TRITON buoys. On cruises with a high number of buoys, over 20 days of the 45-day cruise could be spent on mooring operations. Mirai has large storage spaces for buoy equipment, including the second buoy warehouse and the rope storage. At that time, the second buoy warehouse—large enough to resemble a gymnasium—was often completely filled with surface buoys. Being in the tropics, operations were often conducted under harsh conditions, either under a cloudless, blazing sun or in torrential squalls where visibility dropped to nearly zero.

The tropical observation cruises witnessed scenes like the TRITON buoy operations described earlier. Here, we reflect on these cruises while highlighting some of Mirai's contributions.

Tropical Observation Research in Mirai's Long-Term Observation and Research Plan

Mirai was designated based on the fourth report of the Council for Ocean Development as a research vessel advancing four key objectives: understanding thermal circulation, material cycle, marine ecosystems, and ocean crust dynamics. The observational studies in the Western Tropical Pacific are a key part of Mirai's long-term observation and research plan for understanding thermal circulation.

The Tropical Ocean Climate Study (TOCS) program is linked to three research topics of observational studies in the Western Tropical Pacific mentioned above: air-sea fluxes in the tropical ocean, variabilities of currents in the tropical ocean, and the Indonesian Throughflow and ocean structure in and around the Indonesian Seas. Mirai serves as the central platform for these observational

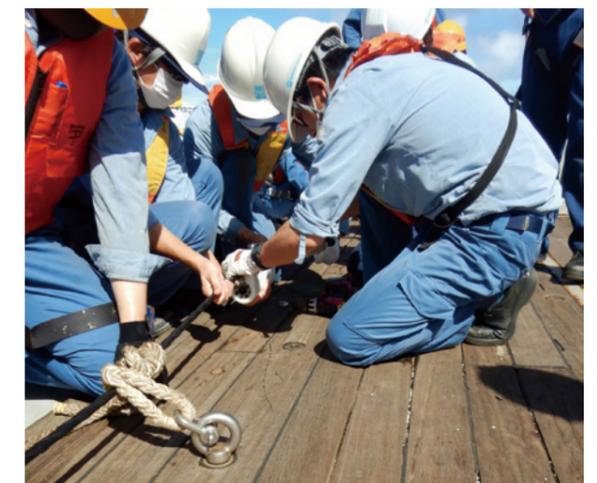


Fig. 2. Sensor installation by marine technicians
After the surface buoy is deployed, underwater sensors are attached to the wire rope. Once the rope payout stops and safety is confirmed, several marine technicians—each assigned roles such as sensor transport, support, fixture assembly, and bolt tightening—work swiftly and efficiently, much like a Formula 1 pit crew, to complete the sensor installation.



Fig. 3. Facilities Supporting Buoy Operations

Second Buoy Storage (upper left) is primarily used to store buoy bodies, with capacity for nine units. They are transported to the upper deck via a dedicated elevator when needed for deployment preparation. Rope Storage (lower left) stores mooring wire and nylon ropes wound on iron reels, which are moved two decks up by elevator for use. First Buoy Storage and Tower Storage (center top) are used for buoy assembly and tower storage; the staircase at the back leads to the tower storage area. The TRITON Transfer Trolley (center bottom) is used to move buoys between the first buoy storage and beneath the aft A-frame. Traction Winches (white rollers beside the trolley) are used to reel in ropes during mooring recovery. Rope Winding Machine (upper right) is used to wind or unwind ropes from iron reels. The Hoist Winch (lower right), the white winch on the right side, is used for stabilizing the buoy with wire ropes and transferring tension within the mooring line.



Fig. 4. Subframe Attached to the A-Frame

Mirai's A-frame is equipped with an auxiliary "subframe" shaped like the letter "H." When the A-frame winch lifts the buoy, the subframe fits closely against it, functioning as a stabilizer to prevent swaying.

studies. Initially focused on the tropical Pacific, the program later expanded to the Eastern Indian Ocean, reflecting discoveries such as the Indian Ocean Dipole mode. As the research targets climate variability, it balanced long-term observations via the TRITON array with short-term process studies. These process studies included: low-latitude western boundary currents (e.g., New Guinea and Mindanao Currents) and equatorial waves, freshwater fluxes and upper-ocean salinity variations, ocean mixed-layer variability and surface fluxes, tropical ocean circulation and water mass variability, and air-sea interactions at the northern and eastern edges of the warm pool. All of these processes are characteristic of the tropical region.

Specific observations conducted during tropical cruises included long-term mooring with TRITON buoys. These also included ocean structure surveys using CTD (Conductivity-Temperature-Depth profiler), LADCP (Lowered Acoustic Doppler Current Profiler), and turbulence measurement systems. Additionally, observations of low-latitude western boundary currents and equatorial current systems using hull-mounted ADCP and subsurface ADCP moorings were conducted, as well as lower-atmosphere measurements using Doppler radar and various meteorological instruments.

Mirai was exceptionally well-equipped to support these observations. The vessel's infrastructure for handling large TRITON buoys was particularly notable. For instance, the second buoy storage room and rope storage could accommodate the deployment and recovery of nine TRITON buoys per cruise. Other equipment in-

cludes elevators for retrieving surface buoys and ropes from the second buoy storage or rope storage to the upper deck, a tower warehouse on the second floor of the first buoy storage, overhead cranes for lowering towers onto buoy floats from the tower warehouse, and a mobile cart used to move surface buoys to the A-frame at the stern of the upper deck. Mirai was well equipped with facilities to carry out operations efficiently.

Mirai was equipped with two rope-reeling winches, a high-power traction winch, an air hoist for sway control, and other equipment. These pieces of equipment provided a safe working environment for mooring operations (Fig. 3). A key feature is the sub-frame mounted on the large A-frame, which restrains surface buoys during lifting and lowering to the sea surface and thereby prevents them from swaying (Fig. 4).

No other vessel combined such comprehensive capabilities, which enabled the safe deployment and recovery of more than 200 large-size moorings. Beyond observations with moorings, Mirai supported diverse observations with its Doppler radar, multiple meteorological instruments, stabilized CTD winch systems, and high-performance multibeam sonar. Equally important was the human resources. Indeed, the professionalism of the crews and marine technicians enabled careful organization of observation procedures, accumulation of operational know-how, and a deep understanding of the scientific significance of each measurement. Together, these hardware and human resource environments made Mirai a highly respected platform among global oceanographic research institutions.

Deployment of the TAO/TRITON Array and International Contributions

Mirai's operational philosophy explicitly included contributing to the international research community. Specifically, Mirai was expected to play a key role in programs such as the Global Ocean Observing System (GOOS) for understanding and predicting global ocean variability and environmental change, and Climate Variability and Predictability (CLIVAR) for research on climate variability and its predictability. During the 1990s, climate phenomena such as El Niño attracted significant attention. Scientific and societal demands called for accurate monitoring systems and improved climate prediction, and Mirai was envisioned as a research platform to meet these needs.

In the mid-1990s, before the construction of Mirai, JAMSTEC launched the Tropical Ocean Climate Study (TOCS) project to study tropical climate. The project employed subsurface moored ADCPs for long-term observations of equatorial currents and low-latitude western boundary currents. It also coordinated with NOAA to maintain the TAO (Tropical Atmosphere and Ocean) array, forming the basis for the subsequent development and operation of TRITON buoys.

After Mirai entered service, the project focused on

deploying the TRITON buoy array. This required continuous collaboration with NOAA as well as gaining the understanding and cooperation of coastal nations, including the Federated States of Micronesia, Republic of Palau, Republic of Indonesia, and Independent States of Papua New Guinea. Early efforts were exploratory, but opportunities for onboard participation and local seminars gradually gained researchers' and officials' support. Over time, both Mirai and TRITON buoys became widely recognized and accepted by government authorities, port authorities, and national meteorological agencies.

The deployment of TRITON buoys began with MR98-02 in February 1998. Despite initial troubles, vandalism, and many other difficulties, the persistent efforts of many stakeholders enabled JAMSTEC to develop world-class expertise in moored buoy technology and operations. Trial and error during Mirai's mooring operations was essential to achieving this level of capability.

Owing to Mirai's efforts during MR02-K04, the initially planned network of 18 TRITON buoys was successfully completed in August 2002 (Fig. 5). The TRITON array coordinated with NOAA's TAO buoy array and later became the core of tropical ocean observation as the TAO/TRITON array, playing a major role in tropical research, climate variability studies, and climate prediction (Fig. 6). Beyond the Pacific, Mirai also played a major role in constructing the RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) array in the Indian Ocean through multinational collaboration, creating a new ocean basin-scale tropical buoy network. Maintaining these arrays over many years represents a major achievement befitting the name Mirai. The data from these arrays have not only advanced oceanographic research but also supported



Fig. 5. Commemorative Photo of TRITON Buoy Network Completion

During MR02-K04 cruise (Captain: Takaaki Hashimoto; Chief Scientist, Leg 1: Yoshifumi Kuroda, Leg 2: Hideaki Hase), the initially planned 18 TRITON buoys were successfully deployed, completing the network. The TRITON buoy project was a collaborative effort among multiple departments, including the Ocean Observation and Research Department, the Engineering Development Department, and the Planning and Coordination Section at the time.

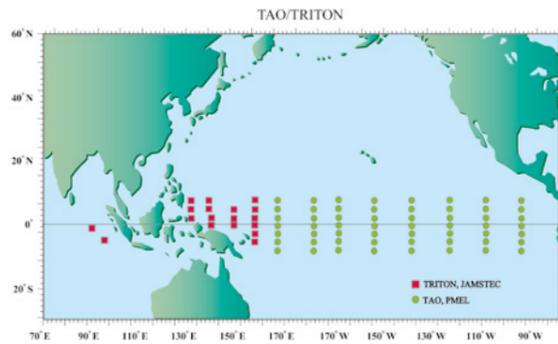


Fig. 6. TRITON Buoy Network

The tropical TRITON network was designed with 16 stations in the Pacific and 2 in the Indian Ocean. Based on the characteristics of the warm pool region, noted for strong air–sea interactions and heavy precipitation, the system enhanced observation of marine meteorology on finer time scales and expanded ocean salinity measurements compared with existing TAO mooring. Later, one additional station was added in both the Indian and Pacific Oceans.



Fig. 7. Public Access to TRITON Data

TRITON data are made available to researchers in near real time (with about a one-day delay) through JAMSTEC and its partner, the US NOAA. For operational meteorological agencies, data are simultaneously distributed in real time via the Global Telecommunication System (GTS) and used for weather forecasting.

operational meteorological and climate prediction agencies in the world, producing tangible societal benefits (Fig. 7). For instance, Japanese distant-water fishermen mentioned higher catches from using buoy data to plan voyages. Moreover, Australian agricultural groups were grateful for the data because it allowed them to take proactive measures against drought.

In this way, Mirai’s long-term climate observations, carried out in cooperation with the global ocean observation community and coastal nations, have made important contributions extending beyond the research community to global weather and climate prediction as well as related societal efforts worldwide. Through this achievement, Mirai exceeded its original goal of contributing to international research, leaving a lasting legacy in both science and society.

■ Continuous Observations in the Indian Ocean and the Indian Ocean Dipole Mode

In 1999, a research group at the Center for Frontier Research on Global Environment (at the time) discovered

the Indian Ocean Dipole (IOD) phenomenon, a short-term climate variability originating in the tropical Indian Ocean. The IOD is a short-term climate variability driven by air–sea interactions, similar to the ENSO in the Pacific, in which basin-scale oceanic structures and atmospheric fields in the tropical Indian Ocean shift from normal conditions. Typically, the IOD alternates between positive and negative phases every two to three years, affecting the weather and climate in coastal countries around the Indian Ocean, in Japan, and in other parts of the world, similar to ENSO. In the early 2000s, when the TAO/TRITON array in the Pacific began operations, oceanographic data in the Indian Ocean were extremely scarce, highlighting the need for a similar observation system in the tropical Indian Ocean.

Against this backdrop, JAMSTEC began deploying two TRITON moorings in the eastern tropical Indian Ocean during MR01-K05 in October 2001. One buoy was set at 5°S, 95°E, corresponding to the eastern pole of the IOD. This deployment enabled monitoring of the ocean’s internal structure associated with the eastern IOD pole—a pioneering initiative that later informed the construction of the RAMA buoy array, significantly contributing to the global oceanographic community.

In addition to TRITON moorings, continuous observations using ADCP moorings near the equator were conducted, revealing equatorial currents and wave phenomena. For example, the Wyrčki Jet, which is associated with upper-ocean warm water transport, was previously thought to occur semiannually. However, observations revealed that it actually exhibits shorter intraseasonal variability, demonstrating the value of high-temporal-resolution observations in situ. These observational phenomena and the theoretical waves were further verified by subsequent “Mirai” observations.

Although the Indian Ocean is relatively remote from developed nations, Mirai’s commissioning enabled regular observational cruises to this region. “Mirai” subsequently played an active and significant role in international observational projects, including MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset), CINDY2011 (Cooperative Indian Ocean Experiment on intraseasonal variability in the Year 2011)/DYNAMO (Dynamics of the Madden-Julian Oscillation), YMC (Years of the Maritime Continent), and IIOE-2 (Second International Indian Ocean Expedition). These achievements built on its long-standing track record.

■ Scientific Achievements from Tropical Observations

Here, I present some of the scientific achievements obtained from Mirai’s cruises, the deployment of TRITON moorings, and tropical climate research.

Research on low-latitude western boundary currents, such as the Mindanao Current system and the New Guinea Coastal Current system, was advanced before the TRITON network became fully developed. These

currents, located in the western part of low-latitude tropical ocean circulation, transport mid-latitude water toward the equator and are closely related to the heat balance and material circulation in the low-latitude tropics. Analyzing moored ADCP data, Mirai’s hull-mounted ADCP, and CTD observations clarified the seasonal characteristics of these currents and their relationship with El Niño events. Normally, the equatorward transport by these currents balances the poleward transport generated by winds across the tropical Pacific. Observational data demonstrated that during El Niño events, this balance is disrupted, elucidating the mechanisms of the heat budget of the entire tropical Pacific basin.

With the accumulation of data from the TRITON moorings, research utilizing their continuous monitoring of marine meteorology and salinity became feasible. Specifically, studies were conducted on the upper-ocean heat budget, considering air–sea interactions, freshwater and salinity budgets, and water mass variability. The variability below the mixed layer and the large-scale vertical structures near the thermocline spanning from north to south were also analyzed. Previously undetectable due to the lack of high-resolution time series data, these variability processes could now be identified using the TRITON datasets. These long-term datasets also enabled process studies using Mirai, which allowed investigations of variability in the tropical upper ocean and ENSO-related processes.

As an example of ENSO-related research, a study based on observational data showed that around 2000, the previously strong correlation between El Niño events and the variation of warm water accumulation in the tropical upper ocean declined. This change in correlation was concluded to be related to a decadal modulation of El Niño. Research also found that the decay of the 1997–1998 El Niño was significantly influenced by WES (Wind-Evaporation-SST) feedback associated with the characteristic sea surface temperature distribution in the western tropical Pacific. Another study hypothesized that coastal upwelling along northern New Guinea contributes to the onset of El Niño.

Observational studies on the IOD also achieved significant results. A representative achievement was producing observational data elucidating the details of the upper-ocean heat balance at the eastern pole during positive and negative IOD events, accumulated via long-term observations using TRITON moorings at the eastern pole. The detailed ocean data obtained from mooring observations enabled much more accurate estimates of the heat budget. Further research indicated that coastal upwelling off Indonesia–Sumatra, which had previously received little attention, contributes to the occurrence of the IOD, greatly advancing our understanding of the phenomenon.

Other research groups participating a sub-missions achieved results in their respective fields, such as biogeochemistry, material cycling, atmospheric observation in-

cluding the upper atmosphere, solid Earth studies, and technical development (e.g., performance evaluation of instruments attached to moorings). Information exchange broadened the scope of research in the tropical region.

Broadly speaking, the aforementioned achievements can be divided into two categories: long-term observations using the TRITON network and process studies using Mirai. For observational studies of phenomena on relatively longer time scales, such as climate variability, it is important to advance both harmoniously. Mirai’s ability to contribute to both types of observation made it possible to obtain significant scientific achievements.

■ Recent Activities

As data from the TRITON network accumulated, it became possible to approach longer-period variability. One major variability that strongly controls the heat balance of the tropical Pacific upper ocean is the ENSO, but fluctuations with a period of around ten years are also recognized to have a relatively large impact. Studies using CTD datasets have shown the existence of a circulation of heat content with a decadal period in the tropical Pacific, with an increase in heat content observed at the northern edge of the warm pool east of the Philippines. This reflects the supply of heat flux from the atmosphere and highlights the importance of air–sea interaction behavior in that region. Meanwhile, the ENSO research community focused on the decadal modulation of ENSO as possibly related to the frequent occurrence of ENSO-like events since 2000. Research targeting longer-period variability in ENSO began to increase. Against this background, in December 2016 (MR16-08), long-term mooring observations were initiated at a new site called PHSMO (Philippine Sea Mooring, 13°N, 137°E). This site also functions as a flux reference site within OceanSITES, an international long-term observation network (Fig. 8).

The TPOS2020 (Tropical Pacific Observing System 2020) project, initiated in 2014, involved discussions within the international tropical observation research community about renewing the Pacific observation system. Discussion topics included reconfiguring the TAO/TRITON array, establishing “super sites” with enhanced flux and upper-ocean observations like PHSMO, complementary observations using platforms other than moorings such as Argo floats, strengthening biogeochemical observations, and expanding process studies at the northern and eastern edges of the warm pool and the Peruvian upwelling region. Following these discussions, we have been advancing observation studies on air–sea interactions in the upper ocean and lower atmosphere, particularly at the northern and eastern edges of the warm pool. By integrating shipboard observations using Mirai with moorings, Wave Gliders, and Argo floats, it is now possible to conduct densely resolved spatiotemporal process studies. In addition to physical observations, biogeochemical observations have also been implement-



Fig. 8. A moored buoy installed at the PHSMO site near the northern edge of the warm pool

ed. *Mirai* proved to be an excellent platform for efficiently conducting multi-parameter observations, providing great confidence in research planning.

Conclusion

Finally, I would like to record my impressions of crewing *Mirai* over many years. Those who have boarded her will understand that *Mirai* is truly a large research vessel. At first, with few boardings, the vessel felt so vast that one could easily get lost. As I went on more cruises, this sense of vastness diminished, and I became impressed by the well-designed facilities and increasingly aware of thoughtful details throughout the ship. This usability is partly due to careful design at the planning stage. It also reflects the continuous improvements made by the deck and engine crews during each cruise. Tasks that were difficult on one cruise were often made easy the next year through the introduction of new procedures or tools. I was deeply impressed by the dedication of the crew. These examples underscore the fact that *Mirai's* capabilities as a research vessel were supported by its people. Personally, the collaborative environment—where crew, marine technicians, and researchers worked together to enhance observation efficiency and accuracy—was extraordinarily comfortable. Furthermore, through *Mirai's* cruises, I was able to improve my observation skills and related knowledge, which was remarkable. With the current trend of reducing research vessels both domestically and internationally, I sincerely hope that many others will have similar opportunities to mine.

Acknowledgements

First, I would like to express my gratitude to all personnel involved in ship operations and observations during the cruises. In particular, the process of continuous improvements, carried out together with the bridge crew, deck crew, engine crew, and marine technicians, to ensure the safe execution of relatively high-risk and labor-intensive activities such as large buoy mooring became an extremely valuable and lasting asset. Although

not directly involved in observations, the delicious meals prepared by the galley were a daily source of energy. I would also like to thank those who provided extensive support from shore, from before to after each cruise, assisting with operations and observations. Additionally, I wish to express deep gratitude to those involved in the initial *Mirai* Operation Review Committee and other committees, as well as the many research groups that participated in the cruises. Thanks to all of you, I can confidently say that tropical observation research advanced significantly alongside *Mirai's* activities.

Mirai and Kuroshio Extension Flux Buoys

Yoshimi KAWAI

The seas around Japan have high sea surface temperatures due to the warm water transported by the Kuroshio Current, and in winter, strong cold air outbreaks from the continent result in the largest air–sea heat fluxes in the world. While the influence of mid-latitude oceans on weather and climate had long been underestimated, around 2000, their importance began to be recognized. It is now clear that the seas around Japan strongly influence phenomena ranging from global atmospheric circulation to heavy rainfall and snow in Japan.

Despite being an important region, ocean-based meteorological observations were extremely limited. Accordingly, in June 2004, NOAA's PMEL, led by Dr. Meghan Cronin, installed a mooring buoy at a fixed point near 32.5°N, 144.5°E on the southern side of the Kuroshio Extension, namely KEO (Kuroshio Extension Observatory), and began continuous observations. In February 2007, JAMSTEC's Kuroshio Transport and Surface Flux Group (at the time) collaborated with PMEL to begin mooring observations at a fixed point on the northern side of the Kuroshio Extension (38.0°N, 146.4°E), known as JKEO (Japanese Kuroshio Extension Observatory) (Fig. 9). The first mooring at JKEO was a donut-shaped buoy similar to the PMEL KEO buoy, deployed during MR07-01. From February 2008, a K-TRITON buoy, a strong-current version slightly larger than the tropical m-TRITON buoy, was used at JKEO (first deployment: MR07-07 Leg 3). From FY2009, under JAMSTEC's second mid-term plan, Air-Sea Interaction Research Team (at the time) assumed buoy observations. In June 2012, a K-TRITON buoy was deployed near the axis of the Kuroshio Extension between KEO and JKEO, at 33.8°N, 144.9°E (NKEO [New NEO]), as a one-year project (MR12-02 Leg 1). This was made possible by funding from the Grant-in-Aid for Scientific Research on Innovative Areas (MEXT), "A "hot spot" in the climate system: Coupled Ocean-Atmosphere Variability over Monsoonal Asia due to Contiguity between the Tropical Warmness and Arctic Coolness," which began in FY2010. Unfortunately, observations at NKEO ended just over eight months later, when the mooring line broke

and the buoy drifted in March 2013. The drifting surface buoy was recovered on the return cruise from the tropics (MR13-01), marking *Mirai's* final involvement with K-TRITON buoys in the Kuroshio Extension.

The Kuroshio Extension region is a busy fishing area, and fishing gear entanglement and mooring line breakage often caused drifting buoys. Additionally, winter monsoons, typhoons, and strong winds from developing extratropical cyclones frequently damage meteorological instruments, often preventing data collection at critical times. Consequently, mooring observations at JKEO concluded in July 2013, the final year of JAMSTEC's second mid-term plan. As a result of this and the use of the vessel *Kaiyo*, *Mirai's* involvement in Kuroshio Extension buoy observations was limited. The author personally experienced K-TRITON buoy operations on *Mirai* only once (MR11-02), during which we recovered a mooring remnant that had sunk to the seafloor after a line break, a rare but invaluable experience, though one that would have been better to have avoided.

The drifting surface buoy was recovered in October 2010, during the emergency *Kairei* cruise (KR10-E04). However, the wire cable had broken at around 4 m below the sea surface, and it was assumed that nearly the entire mooring line had sunk. The water depth at the site was approximately 5,250 m, and the total length of the mooring line was about 7,800 m. In principle, by activating the acoustic release near the seafloor and detaching it from the anchor, the glass floats above should rise to the surface and be recoverable. However, in the Kuroshio Extension region, the strong current can exceed several knots. If the current was strong, the glass floats would be swept sideways and fail to reach the surface. The day before recovery, current velocity data were obtained using an LADCP mounted on a CTD frame, and a simulation based on that data suggested that the floats would barely reach the surface. Consequently, recovery was decided.

On the day of recovery, the release was conducted at 05:00, and the team waited for the float to surface. Based on prior experience in tropical regions, it was expected to take three to six hours. Immediately after the release, the glass floats ascended rapidly, making it difficult to capture the transponder signal, and causing a moment of panic. Once the signal was successfully acquired, the float ascended smoothly to about 2,500 m depth; however, its rise then slowed, which was unusual. It took approximately two hours to ascend from 2,000 m to 1,000 m, and the speed further decreased in shallower water, exacerbating concern. As the process was taking longer than expected, the C/O (Chief Officer) stated that if recovery could not be completed by sunset, a workboat would be deployed to attach a buoyancy device and a flasher to the glass floats for monitoring overnight. Just as preparations for this were about to begin, the glass floats finally reached the surface shortly before

14:00. They were not immediately visible despite being afloat; a crew member spotted them just forward of the bow, which was a close call, as they might have collided with the propeller if slightly off. Although waves were high, the crew successfully deployed a workboat, and recovery was finally completed after 17:30, as the daylight faded. Large amounts of nylon line, likely from fishing gear, were tangled in the floats, indicating interference from fisheries. Aside from one CTD used for the mooring system being damaged by seawater, the instruments remained intact. Later, the captain mentioned that tracking the transponder with SSBL prevented use of thrusters, requiring the ship to slowly zigzag for over eight hours while following the transponder—a demanding task.

Recalling various troubles, a KEO buoy that had been installed in 2009 malfunctioned due to a typhoon, and two NOAA technicians boarded MR10-02 to repair it (the author was not aboard). This involved the risky task of bringing the surface buoy on deck while still attached to the anchor. Thanks to the experienced crew, repairs were completed safely, earning the gratitude of the NOAA technicians and personnel. *Mirai's* spacious deck and elevator system, suitable for large buoy operations, impressed even veteran NOAA staff.

Both *Mirai* and *Kaiyo* supported valuable buoy observations in the Kuroshio Extension region. Surface moorings require significant effort and cost, and in fishing-heavy regions, surface buoys are prone to drifting due to gear interference. Instrument damage often leads to extended data gaps. Currently, only NOAA's KEO buoy

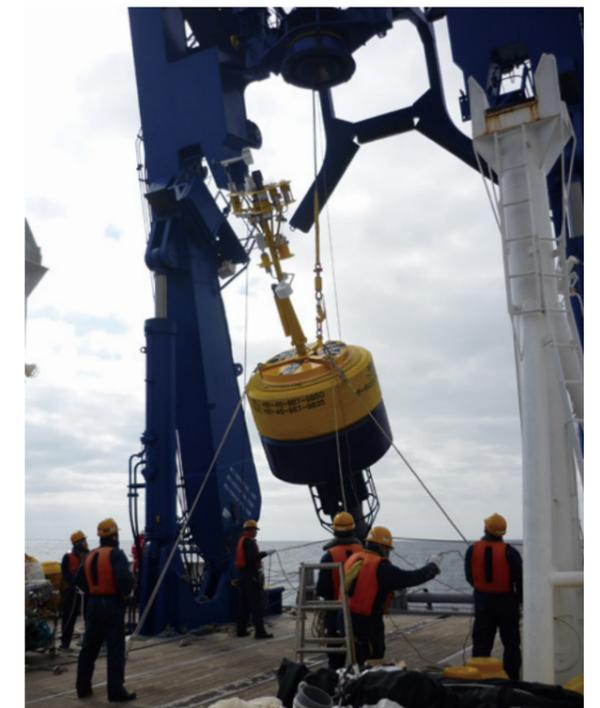


Fig. 9. A K-TRITON mooring being deployed at the JKEO site during MR11-02 cruise

remains in the Kuroshio Extension. In recent years, off-shore meteorological observations using sail drones and wave gliders have been conducted, but such platforms are still unsuitable for continuous observation in mid-to-high latitude regions where storms, high waves, and strong currents coincide. In the future, large mooring equipment may be needed again, and it is expected that Mirai II will play a role in mooring operations similar to those conducted by Mirai.

Behind the Scenes of TRITON Buoy Operations with Mirai

Yasuhisa ISHIHARA

Mirai has the capability to deploy and recover nine TRITON buoys per cruise. However, as maintenance cruises carry one spare buoy, in practice, ten buoys are prepared, shipped, and loaded for each cruise. With Mirai's buoy maintenance cruises scheduled sequentially, on-site personnel faced the enormous challenge of sustaining the buoy network while gradually reducing maintenance costs. Although the initial TRITON moorings were robust systems, operational challenges existed.

Regarding handling challenges, TRITON moorings introduce a taut-moored system, which requires a large surface buoy to maintain tension across the mooring line (Figs. 10 and 11). Therefore, only vessels with sufficient surface-buoy handling capability, such as Mirai, could conduct maintenance cruises. As the Indian Ocean buoy network far from Japan expanded, the introduction of smaller-size of the surface buoys that could be handled by relatively smaller local ships was considered, leading to the development of m-TRITON mooring system.

Basically, the TRITON's electrical system had a high total power consumption. Although deployed in sun-rich tropical regions, frequent vandalism prevented the use of solar panels. Consequently, lithium primary batteries, with high energy density per volume, were necessary for long-term observation in open ocean. Naturally, these expensive consumables posed operational cost issues.



Fig. 10. A TRITON mooring under maintenance on Mirai



Fig. 11. Mirai's A-frame crane and a TRITON surface buoy

Around 2004, with the start of m-TRITON development, major updates to the electrical system began. JAMMET sensors (Fig. 12), which reduced power consumption while using the same sensor head as the original TRITON, were introduced along with low-power data loggers (Fig. 13) managing scheduled operations and low-voltage Argos satellite transmitters (Fig. 14) for data communication, gradually from 2006 onward. These developments significantly reduced operational costs, even though lithium primary batteries continued to be used. Sequentially, TRITON and m-TRITON systems standardized onboard electronics. The TRITON systems were outwardly similar, but their internal electrical systems were entirely replaced, which reduced operational costs and supported the maintenance of the TRITON network.

To operate the 18 TRITON observation sites, nearly 500 underwater sensors made by Sea-Bird Scientific were deployed. Since these sensors were installed around the same time, it was anticipated that they would need to be replaced simultaneously, leading to the consideration of cost-effective domestic sensors. JAMSTEC began developing JES-10 CTD sensors, with performance comparable to that of Sea-Bird Scientific's sensors (Fig. 15). By 2013, practical comparative operations began. JES-10 sensors were originally developed for TRITON mooring, and were then downsized, optimized for low-power consumption, and developed profile-capable versions. These sensor lines are now commercialized by a JAMSTEC venture company. Alongside JES-10, JAMSTEC also developed a high-precision calibration tank, achieving national standard traceability for temperature, which is now used for calibrating underwater sensors domestically.

Numerous other efforts supported the TRITON network via Mirai. Despite operational cost reductions, sustaining the network remained challenging. In June 2021, with the recovery of buoys during MR21-03, TRITON buoy network operations were suspended. From March 1998 to the date of suspension, TRITON had journeyed alongside Mirai for 23 years and 3 months.

• JAMSTEC Meteorological sensor system : JAMMET



Fig. 12. JAMMET and its dedicated data processing board



Fig. 13. Low-power data logger



Fig. 14. Low-voltage Argos satellite transmitter



Fig. 15. JAMSTEC's original underwater sensor, JES-10 (IM type)

Although TRITON operations by Mirai were paused, the various technologies developed during this period—including maintenance and operation of Wave Gliders as an alternative to the mooring observations, and development of small multi-purpose observation floats—remain foundational technologies for the current Observation Technology R&D group.

Looking back, though not literally “led by the ox to Zenkoji,” my involvement in the behind-the-scenes operations of Mirai and the TRITON network entailed working alongside the teams at the technical support companies, continuously improving and taking on challenges, which allowed me to gain many invaluable experiences. For this, I express my heartfelt gratitude.

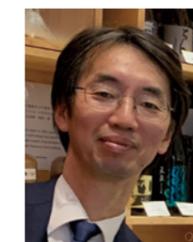
Thank you, Mirai. And well done.



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5 Air-Sea Interaction Study

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Introduction

Kunio YONEYAMA

This article is written by three JAMSTEC researchers who took a role of chief scientist during the R/V Mirai cruises for the study on air-sea interaction in the tropics (hereafter, we briefly mention this as “air-sea cruise”). Since our main research target was large-scale atmospheric disturbances developed over the ocean, it required us to form a large enough observation network which can capture those phenomena in space and time under the international collaborative framework. Thus, we describe air-sea cruises from the viewpoint of international field campaigns for the first four sections focusing on their background to tell why and how they happened (drafted by KY). Then, we review the recent cruises conducted in the tropical western Pacific Ocean (by SY). In addition, since C-band (and polarimetric-type since 2014) Doppler radar is a symbolic observation tool for our cruise, we have a special section which describes it in detail (by MK). Finally, instead of concluding remarks, we’d like to leave several key words which might tell how and what our air-sea cruises were like (by KY).

Nauru99

I (KY) speculate that many foreign scientists knew the launch of the R/V Mirai earlier than many Japanese scientists, as they had a plan to use the Mirai since mid-1990s. I had a chance to study at the U.S. NSF National Center for Atmospheric Research (NCAR) for one year from March 1995 under the JAMSTEC scholarship. One of my research themes there was to learn how to operate a shipborne Doppler radar from NCAR and Colorado State University, which had experience using such ship-

borne radar during the international field experiment in the tropical western Pacific Ocean in 1992-1993. To obtain such knowledge I met many researchers not only in these two but also in several institutes of the U.S. National Oceanic and Atmospheric Administration (NOAA) and others in Colorado, so information about our ship being constructed was immediately spread out among their community. One day, my mentor at NCAR asked me to sign in a proposal sheet. I did not care about it at all at that time, but later I realized that it led to our ship’s participation in the field experiment called Nauru99. In 1998, the U.S. Department of Energy’s (DOE’s) Atmospheric Radiation Measurement (ARM) program deployed their meteorological observation site at Nauru Island in the tropical western Pacific. Nauru99 was first designed to evaluate its island effect on measured atmospheric parameters by deploying the NOAA’s new ship Ronald H. Brown and a Flinders University of Australia Cessna aircraft. NOAA also deployed surface moorings along 165°E. After we at JAMSTEC formally decided to join this experiment, Nauru99 became a collaborative international field experiment led by DOE/ARM, NOAA and JAMSTEC. Researchers from U.S., Japan, Australia, UK, Germany, and Samoa joined. Two ships’ participation enriched the experiment, as both had a shipborne Doppler radar. Its observational configurations were set in three phases: 1) two ships in the vicinity of the island (about 500 m off the coast) for intercomparison, 2) triangle array with two ships and Nauru, 100km apart from each other for surface flux measurement, and 3) two ships 50km away for dual Doppler radar measurement (Figs. 1 and 2). Since Nauru99 was our first experience of joining the international field campaign using the Mirai, hereafter we write several topics which affected our future activities beyond this cam-

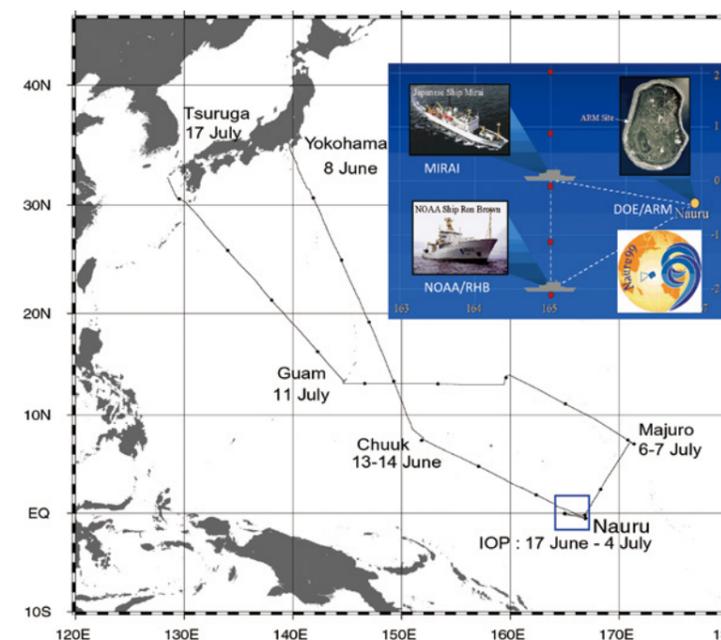


Fig. 2. R/V Mirai seen from Nauru

Fig. 1. Cruise track of the Mirai MR99-K03 and Nauru99 observational configuration

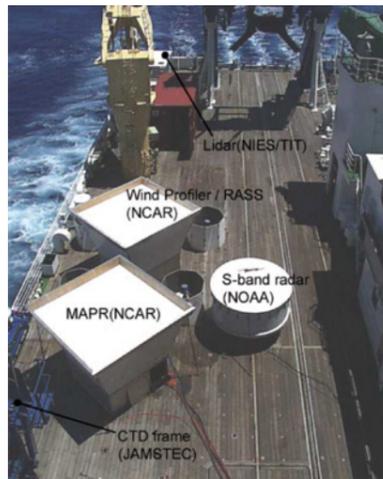


Fig. 3. Remote sensing instruments deployed for the Nauru99 campaign

paign.

First, I'd like to note that we learned much about project management through Nauru99. Although we could set planning the cruise from scientific aspects, we did not have any knowledge about logistics. For example, NCAR deployed several remote sensing instruments onboard the Mirai (Fig. 3). To make this happen, we needed to get a domestic (Japanese) license for operation onboard a Japanese-registered ship. In addition, since those instruments were stored in the bonded warehouse before the Mirai's departure in Yokohama, Japan, special treatments were required. Fortunately, we could get strong support from the Japanese authorities, ship operating company, couriers, and others, so that we could get approval. This experience paved the road for broader collaborative options for foreign researchers in the coming decades.

Another point I remembered well is related to data policy. In recent years, an open data policy has become popular, rather mandatory in the scientific community. However, it was not three decades ago. Three Pls (DOE/ARM, NOAA, and JAMSTEC) needed to develop a policy for data quality control and sharing. Since the Mirai operation was designed for collaborative use by various scientists, we already had a data policy and regulation for the Mirai that quality-controlled data should be opened within two years after the cruise. I think this was very challenging, as most scientists, who obtained data, usually kept it to themselves in that era. So, I insisted on the application of this idea for Nauru99. On the other hand, DOE had its own data policy, which regulates that all data should be immediately shared with the public. In their regulation, such quick open data did not require quality-control. After deep controversy within three (actually, with the help from other Nauru99 members), we could reach the consent that quality control procedures should be completed within one year after the campaign, then those data should be shared with broader

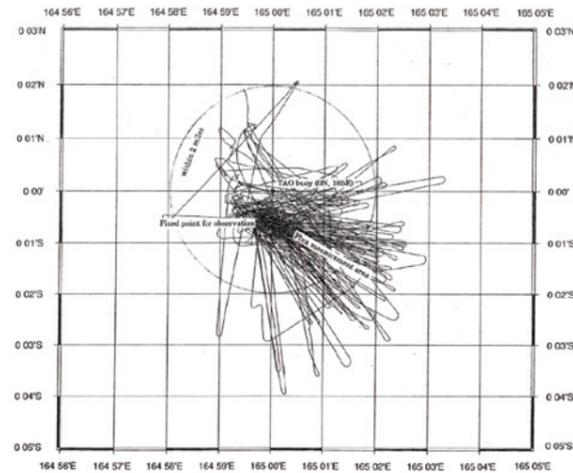


Fig. 4. Cruise track during the Nauru99 on-station observing period

(not limited to Nauru99 participants) scientific community. Since then, this data policy has become a basis for any international campaigns we are involved in. Incidentally, as for Nauru99 data, we found that only Japanese participants were punctual and provided data within this deadline.

The next is related to data quality itself. Since the main purpose of Nauru99 was to evaluate whether data obtained on island can be used as data over the ocean based on the comparison among different platforms, ship's data are basically expected to be true. However, since the Mirai is a huge vessel and consists of iron mass, it is easily affected by the ship body structure for temperature measurement. Even if the sensor measures temperature correctly, there is a possibility that the air mass around the Mirai has already been modulated. Besides, surface flux measurement systems are equipped at the top of the foremast, so we must keep the bow upwind. Thus, during on-station period at the designated location, we always steam against wind with 1-2 knots, then return to the original position with higher speed to obtain wind from bow, which allows us to keep the Mirai's position within a couple of miles from the designated point. Figure 4 is taken from the cruise report, where the ship master kindly provided figure and text describing how to operate for the accurate surface measurements. You can see we really did not stay in one place. In addition, we introduced NOAA's scientific computer system and Shipboard Oceanic and Atmospheric Radiation measurement system developed by the Brookhaven National Laboratory as the Mirai's standard system based on experience of Nauru99 owing to their reliability.

As for upper-air sounding, whereas the semi-auto launcher system is stored in the sea-container, we do lots of launch procedures manually to ventilate air inside the container to avoid any ship body structural influences. We also sought the best direction (azimuth) against

the wind for launching, as it might be possible that radiosonde hits the ship's protrusions. Above are just examples of how we tried to establish methods for obtaining accurate data. In early years of the Mirai operation, technical staff from the Global Ocean Development Inc. (GODI) made tremendous effort to establish several ways to obtain correct data. We do appreciate their effort, which made Mirai data more reliable during her entire cruises.

Finally, I had to note the sad accident. On the way back to Japan after departing Majuro, Marshall Islands, where most participants disembarked, one student had an accident falling from the lower deck of foremast after the maintenance work there. We immediately decided to make an emergency port call in Guam. We are deeply sorry for her tough time. After this accident, stairs to the lower deck were installed instead of ladders and several safety protocols have been developed and/or strengthened to avoid possible risks.

MISMO

After Nauru99 cruise, we focused on air-sea interaction study over the tropical western Pacific, where the warmest sea surface temperatures exist. For this purpose, we collaborated with the Frontier Observational Research System for Global Change, who deployed their land-based observation site in Palau Islands. From 2000 through 2004, we studied the inner structure of cloud systems associated with the Madden-Julian Oscillation or MJO, which is known as a dominant intraseasonal variation in the tropics. It is usually observed as a large-scale ($O(1,000\text{km})$) cloud ensemble which mainly develops over the Indian Ocean, then propagates eastward along the equator and typically recurs about 30–60-day interval. It is well known that the MJO has a great impact not only over the tropics but also all over the world through changing pressure patterns and interacting with other phenomena. Whereas papers on moisture variations have been published, several papers on the development mechanism of the MJO-convection were rejected. Reviewers insisted that initiation process can be discussed only from data over the Indian Ocean. This fact motivated us to dispatch the Mirai to the Indian Ocean. Then, we proposed to conduct MISMO field campaign, where MISMO stands for Mirai Indian Ocean cruise for the Study of the MJO-convection Onset. Incidentally, we named it after Spanish ¡Ahora Mismo! meaning "just now." This is because in early 2000s I was personally studying Spanish, as I thought I might have a chance to speak in Spanish when I visit the Southern Hemisphere countries, if I joined Beagle2003 cruise. After all, I could not have such a chance, but I learned several words and thought it was adequate to express our action.

Since the MJO is usually observed as a huge cloud ensemble whose spatial scale exceeds 1,000 km, we are not sure when and where it occurs. Namely, there is no

guarantee to capture their convection onset by the Mirai alone. So, we sought collaboration from domestic and international research communities. While we visited Maldives to get support from their Met Office, we also advertised our plan at CLIVAR Indian Ocean Panel meeting to get their endorsement. Then, we asked many scientists about their contribution to this campaign. For example, the Institute of Low Temperature Science of Hokkaido University kindly offered their X-band radar to deploy at Gan Island on the equator. Finally, we could get participation of 19 institutes/universities from Japan, Maldives, India, and the U.S. We could deploy meteorological observation sites at three islands in Maldives to form atmospheric flux array with the Mirai and could deploy surface and sub-surface moorings around the Mirai to monitor oceanic responses to the atmospheric intraseasonal disturbances (Fig. 5). The period and location of the Mirai stationary observation was set based on preliminary analyses using satellite data as well as previous studies. Since we could form a configuration with two land-based sites for atmospheric sounding, we could measure mass convergence/divergence over this array, which is an inevitable component to discuss the development of cumulus convection associated with the MJO.

After the warming up cruise from Sekinehama to Singapore, where we prepared various new instruments such as GPS-based water vapor measurement and the ISAR infrared sea surface temperature autonomous radiometer, the Mirai departed Singapore on October 16, 2006, as a start of MISMO field campaign. At the same time, we noticed that the MJO-convection was about to develop and to propagate to the east in the central Indian Ocean. Of course, we had no choice. When we arrived at the stationary point at the equator, 80.5°E after deploying moorings and floats, a calm sea was there. Then, Mirai observations with many instruments such as C-band Doppler radar, radiosonde, wind profiler (by Kyoto University), lidar (NIES), cloud radar (Chiba University), sky radiometer (University of Toyama), turbulent flux measurement (Kobe and Okayama Universities), two types of special radiosondes (high accurate water vapor by Hokkaido University, and video-sampling by Yamaguchi University), as well as CTD started in conjunction with land-based observations in Maldives for about one month.

In mid-November, at last, we could capture the onset of the MJO-convection. Frankly speaking, however, we did not notice this fact onboard. Daily report from the Mirai is still available at the MISMO website (<https://www.jamstec.go.jp/mismo/>) and it says "symptom" on November 16, and "super cloud cluster" on the next day. But it follows "fine, later rain" on November 18. Namely, we were not convinced that the situation is associated with the MJO-convection onset. Maybe, this was due to limited precipitation observed onboard the Mirai apart from satellite images. Later, we realized it was the onset

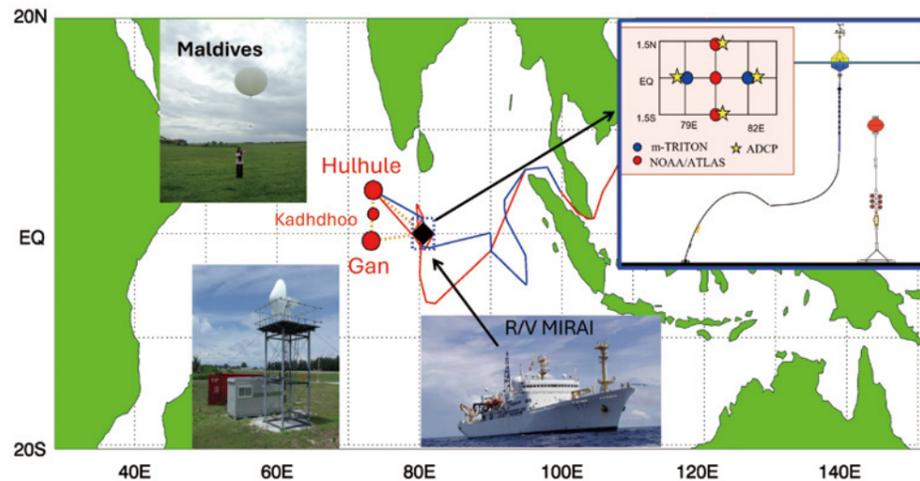


Fig. 5. MISMO observation network. Circle indicates land-based sites, while diamond indicates ship site.

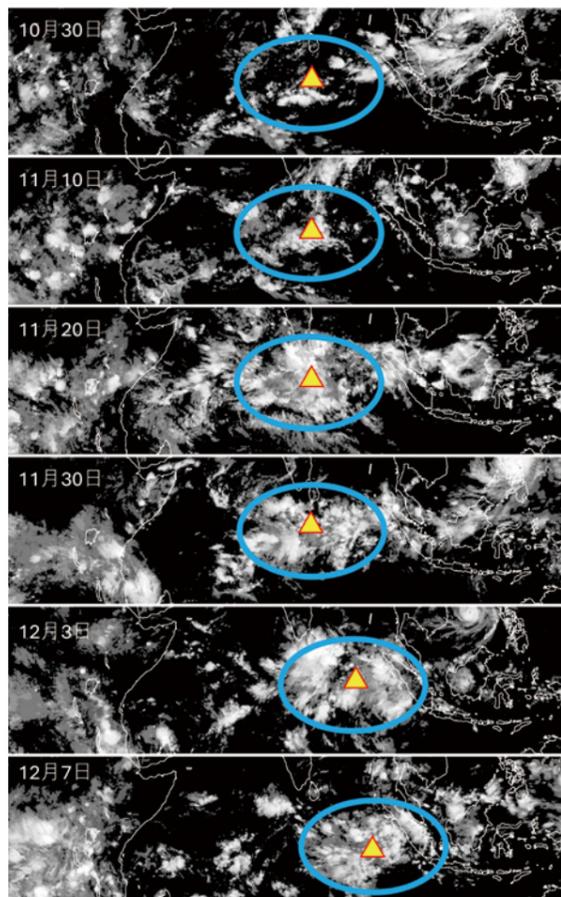


Fig. 6. Cloud development during MISMO. Triangle indicates Mirai, and blue circle is targeted area. Background cloud images are derived from infrared brightness temperature data (Janowiak et al., 2017, doi:10.5067/P4HZB9N27EQU).



Fig. 7. Clouds observed during the MISMO cruise

owing to the analysis after the cruise, and leg-2 observations.

MISMO cruise consisted of two legs with a stationary observation in leg-1 and cruising to the east after calling at Male, Maldives to maintain the moorings deployed in the eastern Indian Ocean as leg-2. I must confess we did not expect this situation during the planning stage at all. I must say, "Simply, we were very lucky." As shown in Fig. 6, Mirai could cruise to the east accompanied with the MJO-convection. Since clouds embedded in the MJO consist of cumulus, cumulonimbi, and stratiformis, clouds taken by a photo do not mean entire MJO clouds. However, we can easily imagine that the onboard members enjoyed seeing clouds developed in front of the ship (Fig. 7) and were convinced that they were observing the MJO-convection.

Analyses of MISMO data revealed the detailed features of convection development associated with the MJO. Particularly, radar data taken during the rendezvous in leg-2 demonstrated the reason for cloud hierarchy within the MJO-convection.

CINDY2011

I believe MISMO had a great impact on the MJO research community and let them know Mirai's name. On the one hand, while we produced scientific papers using MISMO data, some members were eager to conduct observations again. This was partly because after the MISMO campaign, another big MJO event occurred in the Indian Ocean and some scientists insisted this December event was a real event and MISMO's case was just one of the intraseasonal variations. In addition, our analysis demonstrated that triangle array deployed during the MISMO might underestimate the flux component from some equatorial wave modes. Then, we decided to make it happen again as a new campaign called CINDY2011 (Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011).

When we started to promote our new campaign, responses from the MJO community were quite different

from MISMO, namely, it was very welcomed. I believe everybody recognized that in-situ observation by ship is meaningful as one MJO study approach owing to MISMO. After all, participants from 69 institutes/universities of 16 countries and regions joined the campaign. We had four research vessels, two aircraft, and land-based sites from south (Diego Garcia) to north (Sri Lanka), and from west (Kenya) to east (Papua New Guinea), that covered the entire Indian Ocean to monitor the behavior of the MJO convection (Fig. 8). We set the intensive observing period (IOP) from October through January (and to March at some land-based sites). There is a small story on the naming. When we discussed how to name the new campaign, we concluded that it should be easier to pronounce (MISMO is named after Spanish, but some U.S. colleagues called it in English pronunciation). So, we chose CINDY, as we thought it was easy for everyone to pronounce. However, while European and Asian colleagues joined the campaign as part of CINDY, U.S. colleagues needed to launch their own project DYNAMO (Dynamics of the MJO) and adopted a style to join CINDY through their own project. Then, we call it CINDY/DYNAMO. Later, other U.S. projects DOE's ARM MJO Investigation Experiment (AMIE) and Littoral Air-Sea Process (LASP) by the Office of Naval Research also joined. So, we find various names in published articles which use the 2011-2012 field campaign data, though they are the same-effort entity.

CINDY/DYNAMO campaign captured the three MJO events during the four-month IOP and collected unprecedented observations to promote the MJO study. As of the end of April 2025, over 300 scientific papers have been published since this campaign. For example, their data support a theory called "moisture mode," and data are used as a benchmark for the intercomparison of the MJO simulations. However, as we felt during the MISMO, onboard personnel during the Mirai CINDY cruise were also not sure they were observing the developing stage of the MJO, as the Mirai occupied one apex of a square-shaped sounding array and most of the time

was under fine-weather conditions. Even so, all members kept good conditions and enjoyed the ship life. We could confirm this from the memorial group photos taken at the end of each leg (Fig. 9). I think this is because we could confirm the observation went well from the NICAM forecast products sent to the ship by the CINDY numerical modelling team (Fig. 10), and we enjoyed on-board seminar every 2 days or so, which made us intimate with each other.

YMC

We have thousands of photos like Fig. 11. This photo, however, is quite different from others.

After CINDY2011 field campaign, we focused on analyzing data and made presentations at various international meetings. Davos Atmosphere and Cryosphere Assembly 2013 (DACA-13), which was held in Davos, Switzerland famous for the venue of the World Economic Forum in July 2013, was one of such meetings. During DACA-13, an idea of the Years of the Maritime Continent or YMC was initially brought up by the DYNAMO PI, and then quickly grew up when CINDY/DYNAMO colleagues enjoyed the discussion as well as cheese fondue dinner. As shown in the previous section, while CINDY/DYNAMO main observation area was formed over the central Indian Ocean, we could get various support and data from west (Kenya, Seychelles) to east (Indonesia, Papua New Guinea). Among them, it is very impactful for U.S. colleagues about collaboration with Indonesia, as usually it is difficult for them to obtain data there. This happened because the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) was very supportive and eager to obtain scientific knowledge to improve weather forecast and climate prediction skills. In addition, strong leadership by the Director-General of BMKG made it possible. Also, JAMSTEC has a long history of collaboration with the Agency for the Assessment and Application of Technology (BPPT), which is currently known as the

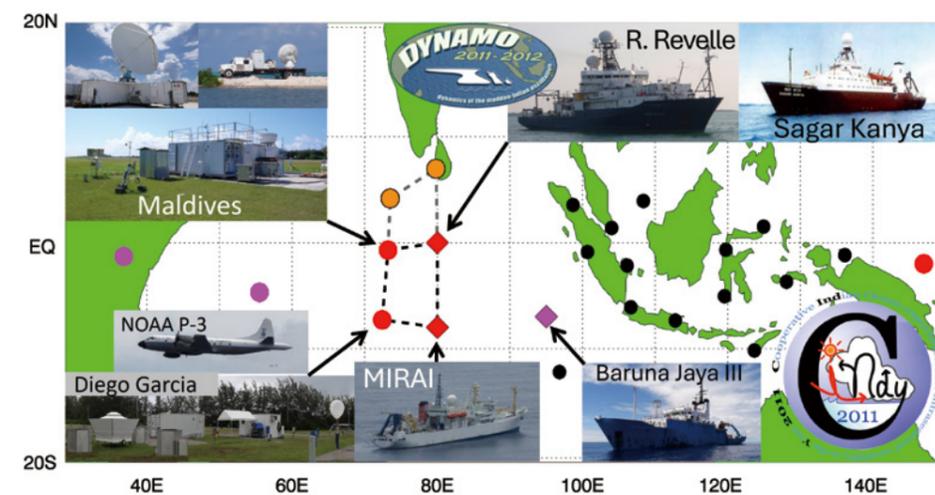


Fig. 8. Same as Fig. 5, but for CINDY2011 campaign.



Fig. 9. Group photos taken at the end of CINDY2011 cruise (left) leg-1 and (right) leg-2

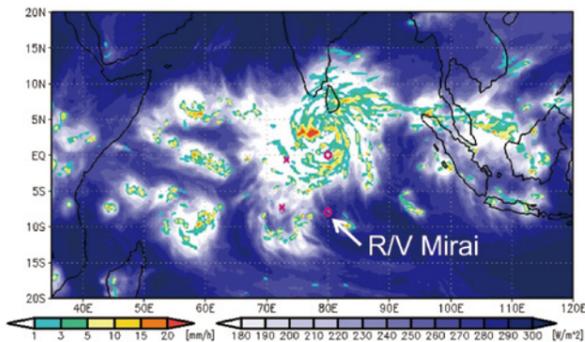


Fig. 10. An example of NICAM forecast during CINDY2011. Taken from CINDY2011 website (<https://www.jamstec.go.jp/cindy/>)

National Agency for Research and Innovation (BRIN).

The Maritime Continent (MC), which spans over the equatorial region from the eastern Indian Ocean through western Pacific, is often referred as a heat engine of the globe due to huge heat release from active cumulus convection. However, its geographical complexity made weather forecast and climate prediction challenging without detailed observations. We agreed to have another field campaign over the MC based on the good relationship with MC countries, which developed through CINDY/DYNAMO campaign.

After DACA-13, we immediately moved forward. Frankly speaking, forming research community on the YMC and negotiating with international bodies for endorsement were not big tasks at all, as we experienced through previous campaigns. The biggest challenge was solely dependent on the fact of whether we can conduct observations along the coast in the MC countries. The significant precipitation pattern over the MC region is characterized by diurnally developed rainfall along the coast and their offshore propagation. We need to know how such diurnal cycle of rain interacts with the MJO. However, even if we can get strong support from local research agencies/universities, it does not guarantee that we can conduct the observation in those areas, as logistics are completely different and difficult. We must com-

ply with many domestic regulations in addition to getting an approval for marine scientific research within respective Exclusive Economic Zones (EEZs).

YMC was originally set as a two-year campaign since July 2017, as we have several research targets such as diurnal cycle of rain, MJO, monsoons, Indonesian throughflow, and so on. However, due to logistical difficulties and COVID-19, some research groups could not start in time. Then, we expanded the IOP to early 2020 as phase-1 and set phase-2 for additional observations and follow-up activities by 2 more years.

We at JAMSTEC decided to have two targets during the YMC campaign period. First one is interaction between diurnal cycle of rain and the MJO in the west coast of Sumatra Island, and the second one is boreal summer intraseasonal oscillation (BSISO) in the vicinity of Philippines and Palau. For the former target, we designed two campaigns in 2015 and 2017. To be honest, the reason why we set one campaign before the YMC IOP is not only for scientific motivation but also for our experience of logistics. Namely, we needed the 2015 campaign as a test for 2017 and intended to learn how to get research permission for observation in the territorial waters.

I would say that YMC can be expressed by one

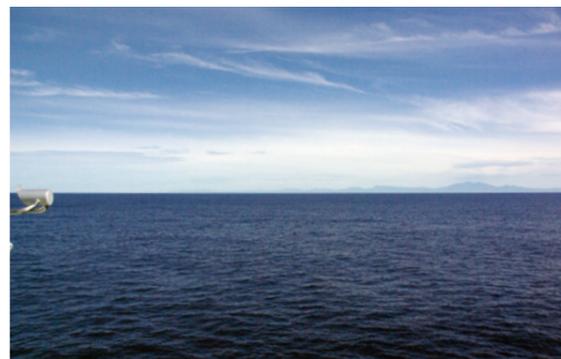


Fig. 11. A photo taken from the Mirai off Bengkulu during pre-YMC (MR15-04) cruise

word “negotiation.” We visited Indonesia, Philippines, Malaysia, Singapore and so on for explanation about YMC scientific strategy and how YMC can contribute to local weather and climate prediction, and life. Since we wanted to conduct observations along the coast of Sumatra Island, my colleagues visited to seek suitable locations to deploy our land-based site in conjunction with the Mirai’s observation. Colleagues from BPPT greatly helped with this survey. We also had several meetings with local authorities and stakeholders, because we recognized we cannot conduct observations smoothly without their understanding and support. To get research permissions and marine scientific research clearance as well as security clearance, we were deeply indebted to the Embassy of Japan. For this complicated procedure, our administrative staff made a special effort, and some members visited the MC countries and helped inside and out.

Now you can see how we could get a photo in Fig. 11. We could get a research permit on the day when the Mirai departed Japan in October 2015, then the security officer embarked the Mirai when she just entered the Indonesian EEZ. Finally, we could reach the off west coast of Sumatra, where we deployed a land-based site in Bengkulu (Fig. 12). We could observe the most precipitation events ever experienced in the air-sea cruise history. Since the Mirai occupied near the coast, simultaneous observation between video-sonde observation launched from Bengkulu (Fig. 13) and the Mirai’s radar (Fig. 14) could be performed.

The lessons learnt through pre-YMC campaign were successfully followed by the YMC-Sumatra 2017 campaign, which resulted in the success of observations with Indonesian colleagues. By considering the fact that several field campaigns were canceled due to COVID-19 and other reasons, our data available from the YMC website (<https://www.jamstec.go.jp/ymc/>) could provide other YMC participants who could not get data by themselves with research opportunities. Data sharing among YMC community is of course one important component to promote our science, and we are proud of Mirai’s contribution.

BSISO

Satoru YOKOI

In recent years, efforts have been focused on understanding the nature of Boreal Summer Intraseasonal Oscillation (BSISO), a type of tropical intraseasonal variability observed over the tropical Western North Pacific and Indian Ocean during the boreal summer season. The BSISO is a phenomenon characterized by a band-shaped region where vigorous deep cumulus convection occurs. The region extends over several thousand kilometers and slowly migrates northward from near the equator to around 20°N. The BSISO influences daily weather in Japan through, for example, modulation

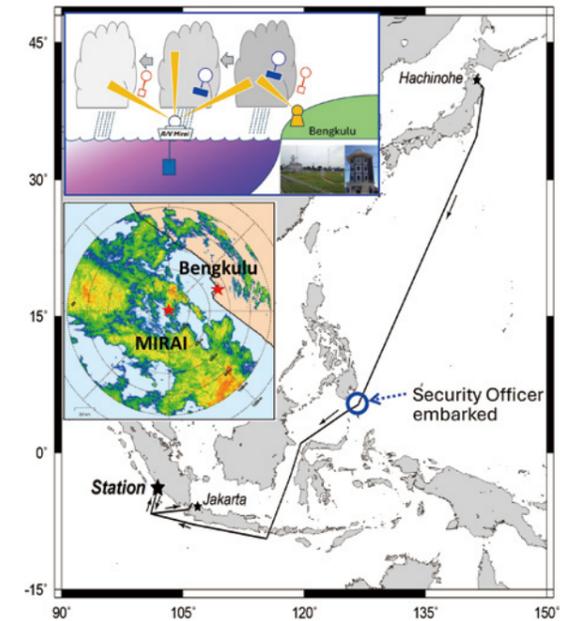


Fig. 12. Cruise track of MR15-04 and observation strategy along the coast of Sumatra Island

of typhoon genesis frequency and promotion of northward migration of Baiu front. Despite such significant impacts, many aspects of the mechanisms behind the behavior of BSISO remain unclear. Therefore, we conducted research cruises using the R/V Mirai in the boreal summer of 2020 and 2024 (MR20-E01 and MR24-04 cruises, respectively) to obtain detailed observation data of the atmosphere and ocean over the tropical Western North Pacific that are helpful in elucidating the mechanisms.

A remarkable aspect of these cruises is that we deployed Wave Gliders, a type of uncrewed surface vehicle, and m-TRITON moored buoys, which JAMSTEC has developed over many years, around the R/V Mirai (Fig. 15) during the station observation periods. By combining observations taken by these platforms with those by weather radar, it became possible to capture the relationship between precipitation activity and underlying conditions of the atmospheric boundary layer and the ocean surface layer at a fine horizontal scale of tens of kilometers.

One of the true thrills of field observation is that we cannot always capture the phenomenon we are aiming for. That uncertainty might be what keeps us coming back again and again. During the MR24-04 cruise, clear skies persisted from the beginning through the middle of the station observation period. The possibility that we might not be able to observe the BSISO during this cruise made us anxious and frustrated. Then, one morning in the latter half of the period, thick clouds started to cover the sky and wind direction shifted dramatically; the BSISO had arrived! We were overjoyed, gathering beneath the rain-splashed radome, eager to physically experience the wind and rain.

When I first boarded the R/V Mirai in 2013, I was



Fig. 13. Launch of video-sonde at Bengkulu

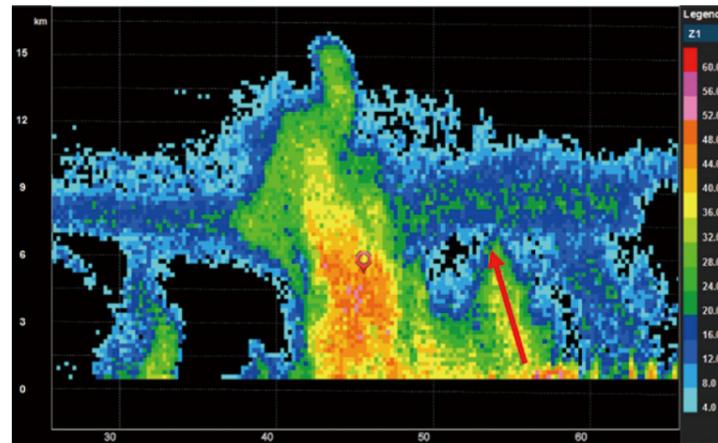


Fig. 14. Radar intensity RHI (Range/Height Indicator) section observed from the Mirai

deeply impressed by how sophisticated the observation procedures were. Regarding radiosonde observation (Fig. 16), for example, there was detailed knowledge about favorable relative wind conditions for balloon launches, ship maneuvering to create such conditions, and techniques to obtain data from as low an altitude as possible. Expertise and ingenuity for ensuring the acquisition of high-quality observational data were evident throughout. I felt respect and gratitude toward the predecessors who, with a strong sense of responsibility as observation experts, had devoted great effort.

This may be a bit of a digression, but I'd like to introduce a tool related to the ingenuity behind the radiosonde observation. The tool is used to gently push out a balloon that gets stuck inside the launch tower due to overfilling with helium. The tool was named after one of my senior researchers. Here is the reason. When he joined cruises in the 2000s, he repeatedly got balloons stuck and then poked them out with a nearby broom.

Eventually, the crew who learned about this situation kindly created this tool for him. Later, the researcher became a university professor and sent his student to join the MR20-E01 cruise. When the student found the tool, he said, "Oh, this is the legendary..." and took a commemorative photo with it. A vessel with such a long history, boarded by so many passionate individuals, seems suited to having stories like this across generations.

Radar

Masaki KATSUMATA

When one looks over Mirai's exterior, the white radome in the central hull section is one of the most eye-catching features (Fig. 17). This is the housing for the parabolic antenna of so-called "Doppler radar". I wrote "so-called" because the name "Doppler radar," which was given based on the function of the first radar when the Mirai was launched, is still used now even af-

Fig. 15. Arrangement of three Wave Gliders and the m-TRITON buoy during the MR20-E01 cruise

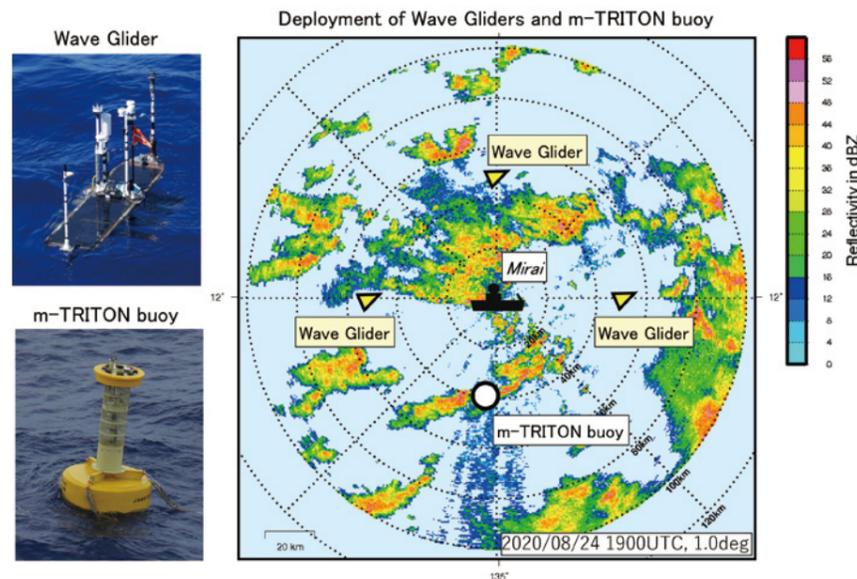


Fig. 16. Snapshot of radiosonde launch

ter the 2014 upgrade. The upgrade gave new function to make the radar a "dual-polarization radar" not just a "Doppler radar". This article is good chance to promote that the Mirai's dual-polarization radar is internationally known as "MPOL": "POL" is widely used as an abbreviation meaning polarization radar. The "M" stands for "Mirai" and "Marine". The name of the world's three shipborne polarimetric radars are paired as SEA-POL (US), OceanPOL (Australia), and M(arine)POL (Japan). However, this article covers the original non-dual-polarimetric radar as well, so in this article I use the familiar common name or simply call it "the radar."

To briefly recap the radar on the "Mirai": it is equipment that transmits microwaves and receives signals backscattered by precipitation particles (raindrops, snowflakes, etc.). Information about the quantity, shape, and movement of these particles is obtained from the amplitude and the phase of the received signals. A major feature of radar is its ability to determine the "spatial distribution" of precipitation systems and their internal structure, as shown in Figs. 12, 14 and 15, by scanning (continuously changing the antenna direction) and identifying distances based on the time difference between

transmission and reception. Obtaining spatial distribution is quite a fascinating characteristic of the radar (unlike most other shipboard sensors typically measuring at 'point' or "vertical profile"). The radar repeated such observation every few minutes to enable obtaining four-dimensional distribution of the precipitation.

This powerful instrument was equipped when Mirai was launched. It was before my participation in JAMSTEC, so all I hear about the tremendous hardships endured by those who worked tirelessly to install such radar on the Mirai. On the other hand during the 2014 upgrade (see Fig. 17), there were almost no apparent problems (while the tremendous quiet efforts were made by all involved). Finally, the radar completed its observations throughout two generations—from the Mirai's commissioning to its decommissioning—thanks to the dedicated efforts of many: those involved in fieldwork, those securing the necessary budgets, and those handling administrative tasks. Particularly, the technical staff of the former operator GODI provided meticulous support. As a user, I express my deepest gratitude to all of you involved.

From here on, I'd like to share my several memorable cruises with the radar.

First one is MR99-K03. This was the first research cruise focused primarily on atmospheric observations joining the international project "Nauru99." This was also my very first experience aboard the research vessel. However, it hardly rained throughout the entire observation period, without any signals on radar screen. On the other hand, other observational data yielded numerous significant results concerning conditions under clear skies. This memory became a strong lesson (and emotional scar) that one must design observation plans that can be considered successful under any conditions. That emotional scar was gradually healed by subsequent voyages: MR00-K04 in the following year (observing orga-



Fig. 17. The radome and antenna of the radar: First one is at upper left (taken in MR13-03), while the upgraded one is at lower left (taken in MR24-04). Right one was shot during the upgrade when the radome was set onto the antenna (taken in May 2014).

nized rain clouds in the intertropical convergence zone [ITCZ] over the western Pacific in early summer) and MR00-K07 (observing the trailing edge of convectively active phase of the Madden-Julian Oscillation [MJO] near the equator in the western Pacific), both of which captured suitable and exciting rain clouds for radar observation.

The following year's MR01-K05 remains my most memorable voyage. This month-long stationary observation near the equator in the western Pacific captured remarkable variations: It began during a clear weather period, captured a tornado midway through, and concluded with the arrival of an active phase of the MJO during the final third. In fact, radar problems arose simultaneously with the arrival of the active phase. Working through day and night with the onboard technical staff and the manufacturers in Japan and the US, we finally secured the observation data. During this same period, actually, we coordinated and executed the recovery of an optional rain gauge installed on a nearby TRITON buoy (which led to me becoming a buoy rider), and managed recreational activities (including the notorious "sports festival") in parallel. Perhaps it was because of

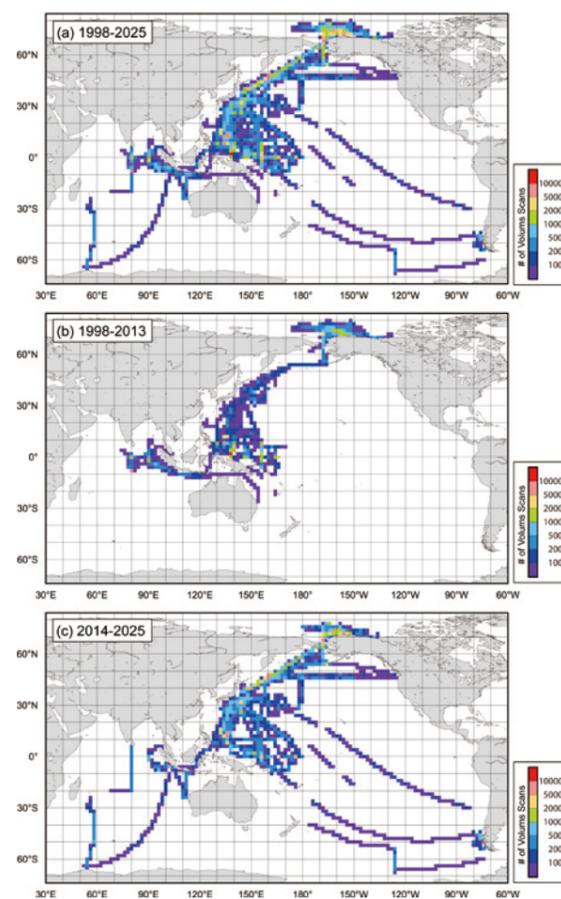


Fig. 18. Distribution of all the obtained radar data. The total number of the volume scan was gridded to each 2-degree grid in latitude and longitude. (a) All period, (b) first-generation radar (1998-2013), and (c) upgraded radar (2014-2025)

our youth (both myself and other onboard members, and both in physical age and experiences aboard the Mirai). Note that I don't consider it as a mistake like a dialogue by the red-suited masked guy: we're wearing blue work clothes.

The most outstanding achievement was undoubtedly the MR11-07 cruise for the international project "CINDY2011". We conducted totally nearly 50 days of stationary observations at 8°S over two consecutive legs, forming part of an observation network alongside other ships and islands. During the first half of Leg 1, the frequent heavy rainfall data brought by the ITCZ over the southern Indian Ocean made me think, "This observation is going to be great...!" However, from the middle of Leg 1 through the final stretch of Leg 2, there was no significant rainfall. I as the chief scientist maintained a strong stance, but I as a rain cloud specialist was inwardly disappointed. However, the radar onboard U.S. research vessel at the equator captured entirely different raincloud variations. Combining both sets of data allowed us to clarify the north-south structure of the MJO, which was one of the major successes of the international project.

Capturing spectacular rain clouds by our own shipboard instruments was finally achieved during the MR15-04 cruise (part of Project Pre-YMC), which conducted stationary observations off Sumatra using an upgraded dual-polarized radar. The observed features were greatly fascinating for both as the chief scientist and as a raincloud scientist: Rain clouds propagated offshore daily, with stronger and taller echo than any I'd ever seen onboard. Furthermore, in the latter half of the period, rainclouds switched their characteristics entirely to be the element of the convectively active phase of MJO. Capturing these variations yielded rich data, not just from the radar alone, but also through simultaneous observations by video sondes capturing precipitation particle shapes, the satellite radar GPM/DPR, and lidar with enhanced water vapor measurement capabilities. I believe MR15-04 offered the most spectacular and enjoyable precipitation phenomena of any voyage to date. The next most impressive and dramatic rain clouds were possibly related to the typhoon embryos during MR13-03, MR20-E01, and MR24-04.

On the other hand, there have been many cruises without spectacular rain clouds. During MR25-01, NO rainfall occurred at all within the two-weeks period at the equator. On MR02-K06, although satellite and objective analyses indicated the convectively active phase of MJO should have been passing overhead, no organized rain clouds were found over the Mirai station. Also aforementioned MR99-K03 was... However, these cruises provided the certain evidence of "no rain" under these conditions.

To further leverage this accumulated data, works continue today on improving data quality control and developing new parameter calculations. The vast radar dataset collected over 27 years and 62,000+ hours (Fig.

18) is the crowned monument of the dedicated efforts by many involved, and it will continue to be utilized. We continue to contribute a bit more to working with the dataset.

Finally, I'd like to touch on the situation around the radar equipment during the air-sea interaction cruises. Many of the onboard researchers on these cruises were interested (more or less) in clouds, precipitation and sky. It is natural that such people often gathered on the top deck (near the radar room or antenna mounts) to check the radar data and/or to observe the outside conditions (Fig. 19). With those who want to meet someone, or those who wait for next observation works, the bustling top deck was a major characteristic of the air-sea interaction research cruises. I believe the memories at the top deck with sky, cloud, rain, stars and talks under them, are the greatest achievements for all who joined, as well as the scientific data, over these 27 years.

Epilogue

Kunio YONEYAMA

As we wrote in Introduction, this article was drafted only by three air-sea cruise chief scientists. Thus, we must admit that the contents are solely from each subjective impression. We also had one guy who took a chief scientist role for air-sea cruise. Prof. Hiroyuki Yamada, who left JAMSTEC in 2012 then joined the faculty of University of the Ryukyus, passed away in 2024. We are deeply saddened with his loss, and we could not ask him to give his messages for the Mirai retirement. However, we know that he also enjoyed much the Mirai cruise in his own style. So, even if we could ask him, another personal impression would have been added to this article, we guess. After all, we realized it is almost impossible to sum air-sea cruise up as a whole. Thus, we gave up concluding air-sea cruise with one direction. Instead, we leave several key words chosen by one author (KY), which may help the readers to imagine how and what the air-sea cruises were like.



Fig. 19. Examples of onboard people (incl. scientists, tech staff and crew) observed at the top deck, shot at MR24-04 (upper left), MR11-07 (lower left), and MR02-06 (top and bottom right)

The first key word is "Kami-zumo (paper crafted Sumo wrestling)." I know you cannot imagine what it is supposed to mean. Until early 2000s, radiosondes were packed in hard papers and plywood. To reuse those papers and plywood, we enjoyed kami-zumo tournaments during lunch breaktime. Wrestlers were made of paper, while a sumo ring was made of wood (Fig. 20). This event was meant to be not only for fun but also for another mission. As we repeatedly wrote, air-sea cruise basic observation style is a stationary observation, which consists of 3-hourly routine work of radiosonde sounding and CTD casting in addition to continuous atmospheric and oceanic observations. We kept this about one month or so. Based on my personal experience in my early career on board, we had a hazardous accident after long-time routine work due to loss of concentration. Thus, I felt we needed to refresh ourselves to avoid possible risks. I'm not sure kami-zumo tournaments could refrain from facing any risks, at least we could relax and enjoy, which might help onboard personnel being intimate with each other. Since package of radiosonde was changed, kami-zumo faded away by 2010. Anyway, I felt the reason why we could enjoy such small events might come from the fact that our cruise is occupied by monotonous works except enjoying watching the changing sky and ocean (Fig. 20).

The next keyword is "Impression notes" in informal cruise reports. We request the first-time participants in the air-sea cruise to write their impression and put them in the Appendix of the "informal" cruise report, which is shared among only cruise participants. We adopted this style from the TOCS (Tropical Ocean Climate Study) cruise. Many participants wrote how their image before the cruise had been changed through the air-sea cruise. Many young guys often write about nice meals served onboard. Some technical staff confessed how they struggled with their day and night reversal working time. All are impressive and can be equally shared among the same cruise participants. I wrote it is almost impossible to sum up air-sea cruise in one word. This is because



Fig. 20. The Osaka Grand Tournament

when he/she hears about Mirai's retirement, they should remember their cruise and notice the time since then. All such memories on their own are crucial parts of air-sea cruise. They are countless.

Finally, I'd like to nominate "westerly winds." Since the main target of air-sea cruises is to capture precipitation systems, most scientists onboard seek rain. Weather is often used as a starter of greeting in Japan like "It is nice weather, isn't it?" Of course, it means we have fine weather with sunny skies. However, the definition of "nice weather" during our cruise is different from standard daily life. When we had continuous fine weather, we sometimes put a reversed talisman, which is believed in Japan to make rain happen. Of course, we did it as a joke. Since our main target was rain associated with the MJO, whose convectively active phase comes after long convectively suppressed period, we needed to wait for most of our observation time. Strictly speaking, fine day conditions are very important research parts of the MJO. So, it is okay from the scientific viewpoint even with no rain, and we do not care about such situation so seriously. However, as our observation time was approaching an end and no rain we had, many people were wondering whether we could really capture the rain event during this cruise or not. As a result, many members hesitated to use the terms "fine" and "rain" in our conversation. Even if I said that "I don't worry," it seemed they heard like "I do mind." I clearly remember the following conversation. One fine day, when I chatted with a ship crew on the deck, he asked me "When can we have westerly winds?" Do you know the reason why I'm proud of our research vessel Mirai? No need to explain it other than his word.

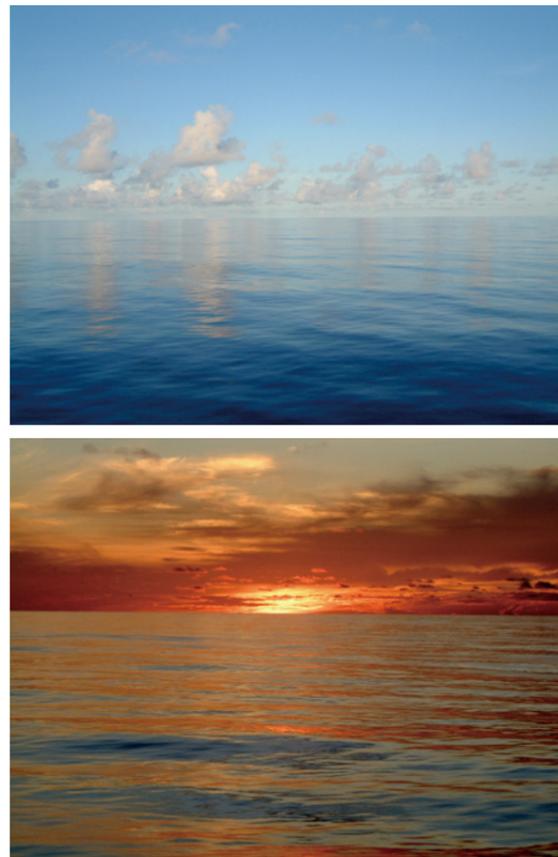


Fig. 21. The sea reflecting the sky. Both photos were taken on November 2, 2006 during the MISMO cruise.



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Marine and Coastal Meteorology Research Group
Group Leader

Mirai sailing in the northwestern North Pacific during winter. MR10-01 cruise.



Chapter 3

Retirement Messages

Mirai for Everyone



Steven J. Manganini
Emeritus Research Scholar,
Woods Hole Oceanographic Institution

Mirai Retirement 2025

David (Duke) Snider
Ice Pilot
Martech Polar Consulting Ltd.



Commemorative photo of the MR24-06C cruise



Steven J. Manganini, Emeritus Research Scholar
Geology & Geophysics

To: Dr. Makio Honda
JAMSTEC, Yokosuka, Japan

March 29, 2025

Subject: RV Mirai Retirement letter

Dear Dr. Honda,

I thank you for inviting me to write this letter about my cruise participation on the RV Mirai, as she will be retiring soon. I am greatly honored to share my very productive, and pleasant experiences on the RV Mirai during my time as Research Specialist at the Woods Hole Oceanographic Institution.

As you probably recall, it was an exciting time during those past cruises as new discoveries in the deep ocean were being made with the use of newly developed time-series equipment. The late Dr. Susumu Honjo was a pioneer in this innovative research with the development of Time-Series Sediment Traps (shown in photo) to collect settling particles on an annual basis in the deep ocean, significantly contributing to our understanding of biogeochemical process. We also realized that these time-series data needed to be integrated within the global ocean requiring simultaneous deployments in all oceans. To achieve this goal, collaboration with our institution and JAMSTEC was necessary and the RV Mirai was an important factor in achieving this goal. The RV Mirai had the equipment and personnel to be successful!

I participated on (2) RV Mirai cruises, where we deployed and recovered several time-series equipment at several stations in the North Pacific. The RV Mirai was the perfect ship to successfully accommodate our research. Precise locations as well as depths were needed along with specialized deck deployment and recovery equipment and personnel and the Mirai had everything we needed. In addition, the preparation of the highly sensitive electronic profiler, large volume pumps, and geochemical sediment traps needed dedicated laboratories requiring a range of top quality specialized equipment and personnel, which the Mirai always had on board. All our projects were very successful and we honor and congratulate the RV Mirai, and the Officers, Crew and Scientists who sailed on her during her extraordinary career and now retirement. Thank you RV Mirai!



Working on the deck of the RV Mirai, Dr. Makio Honda with colleague, and myself are preparing time-series sediment traps from JAMSTEC and the Woods Hole Oceanographic Institution for deployment in the North Pacific.

With fond memories,

Steven J. Manganini
Emeritus Research Scholar, WHOI

Our Ocean. Our Planet. Our Future.

who.edu

It is with a great deal of sadness that I write this short remembrance of more than 20 years working closely with the teams ashore and onboard RV Mirai in support of the ship's tremendous research activities in Polar waters, both Arctic and Antarctic. The ship and the people involved have become part of my life over these years, as friends, almost family and a home away from home for so long. It is sad to see this grand ship retire this year, in 2025.

My relationship with the ship and the people began in 2002, as an Ice Navigator onboard for the Arctic JWACS voyage, with Captain Masaharu Akamine and Chief Scientist Dr Koji Shimada. What an exciting way to begin my association with RV Mirai as this cruise worked in a joint multi-ship research project in the Canadian Basin that also included CCGS Louis S. St. Laurent and CCGS Sir Wilfrid Laurier. Onboard Mirai was an international team of researchers from Japan, Canada and United States. The crew of RV Mirai welcomed me into their "home" onboard with open arms on that first voyage. Many of the faces onboard were well known to me, having sailed together on previous Arctic research voyages on Canadian Coast Guard vessels. Back then I still had red hair though my beard was already turning "Arctic blonde". Since that first voyage, I have sailed onboard for almost all Mirai's Polar voyages, and every

cruise since 2013.

My role through the years has been two-fold. On one hand to serve the Captain of the ship, keeping the ship safe from ice beyond the ship's capabilities, while on the other hand working with the Chief Scientist to plan observations that are safe, but take advantage of Mirai's capabilities and ice conditions and maximize the research potential of the ship.

With climate change we have seen many changes over the more than twenty years of Arctic and Antarctic research. Amongst the changes, while consistently visiting many observation points continuously over the years, Mirai's research has amassed vital knowledge of trends and changes and made exciting and sometimes shocking new discoveries. In the first years, we were extremely excited to make a furthest north voyage in the region of 74°N, at the time considered exceptional. Now, Mirai routinely voyages well north of that as the Polar pack continues to reduce annual extent.

I have made many very good friends sailing onboard RV Mirai while proudly doing my part to both keep the ship safe and expand our global scientific knowledge of the Polar Regions. As I began writing this, I felt sad. As I close this, I feel great HAPPINESS and pride in being part of such an incredible international research program.



Captain Duke Snider and Little Diomed Island

Mirai: Illuminating the Ocean's Carbon Cycle for a Changing World

Christopher Sabine

Professor of Oceanography and Interim Vice Provost for Research, University of Hawai'i at Mānoa

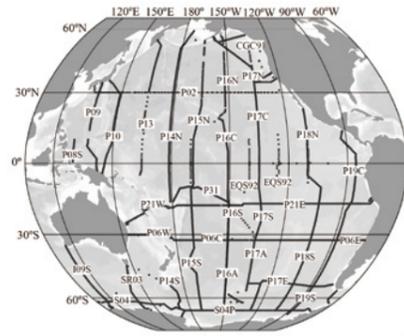


The Japan Agency for Marine-Earth Science and Technology's (JAMSTEC) research vessel R/V Mirai has played a key role in delivering high-quality physical and chemical oceanographic measurements to the global scientific community for nearly 30 years. Since its commissioning in 1997, Mirai has been a workhorse for deep-sea exploration and data collection, significantly contributing to our understanding of the ocean's complex processes, particularly concerning carbon cycling.

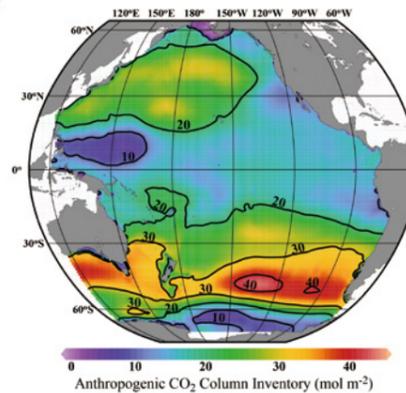
One of Mirai's most crucial contributions for the carbon community lies in its participation in international programs like the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) and its predecessor the Repeat Hydrography Program. These programs aim to establish a global baseline of oceanographic properties and track their changes over time. Mirai maintained several critical repeat oceanographic transects in the Pacific, Indian and Southern Ocean, consistently providing precise measurements of temperature, salinity, dissolved oxygen, nutrients, and carbon-related parameters like dissolved inorganic carbon (DIC), total alkalinity (TA), and pH.

These carbon measurements are vital for understanding the ocean's role in the global carbon cycle and in particular the accumulation of anthropogenic carbon, not just in the surface waters, but also deeper in the water column. The ocean acts as a massive carbon sink, absorbing a significant portion of atmospheric carbon dioxide (CO₂). However, increased anthropogenic CO₂ emissions are leading to ocean acidification, with potentially severe consequences for marine ecosystems. Mirai's data helps scientists monitor these changes, assess the ocean's capacity to absorb CO₂, and model future scenarios.

The data collected by Mirai is not only instrumental in understanding the ocean's current state but also in building comprehensive datasets like



The left figure shows the cruise tracks of the cruises used to evaluate the distribution of anthropogenic CO₂ in the Pacific. The bottom figure shows the column inventory of anthropogenic CO₂ in the Pacific (Sabine et al., 2002, doi: 10.1029/2001GB001639)



the Global Ocean Data Analysis Project (GLODAP). GLODAP synthesizes oceanographic data from various sources to create a global, internally consistent dataset of ocean chemistry. Mirai's high-quality measurements are crucial for ensuring the accuracy and reliability of GLODAP, which is used by researchers worldwide for various applications, including climate modeling and ocean acidification studies.

Furthermore, Mirai's capabilities extend beyond standard hydrographic measurements. It is equipped with advanced instrumentation for studying various aspects of ocean biogeochemistry, including trace metal distributions, particle fluxes, and microbial processes. This comprehensive approach allows scientists to gain a holistic understanding of the ocean's intricate workings and the interplay between physical, chemical, and biological factors. As an ice-hardened ship it was also instrumental in providing measurements in high-latitude waters.

In summary, Mirai has had an illustrious career as a critical platform for gathering essential oceanographic data, particularly regarding carbon and its related properties. Its participation in international programs and contributions to global datasets like GLODAP highlight its significance in advancing our understanding of the ocean and its role in the global climate system. The data it has provided is vital for informing policy decisions and developing strategies to mitigate the impacts of climate change and ocean acidification.

R/V Mirai and Her Very Important Contributions to Ocean Climate Studies

Fadli Syamsudin

Senior Scientist, National Agency for Research and Innovation, Indonesia



It was back on my first journey together our Indonesian team with R/V Kaiyo in 1996 steaming to western tropical Pacific waters under WCRP's "World Ocean Circulation Experiment (WOCE)". Japan was involved in this multi-national program and facilitated Indonesia to join. After this program, JAMSTEC continually invited Indonesian team for R/V Mirai to conduct CTD and many other physical, biogeochemical and meteorological sensors as well as current meter moorings in those regions under program "Tropical Ocean Climate Studies (TOCS)" starting in 1999 and ensuring my participation and our colleagues from the National Agency for Research and Innovation (BRIN), formerly known as the Agency for the Assessment and Application of Technology (BPPT). Joining the TOCS with R/V Mirai yearly ended in 2007 but followed by the MEXT program where we keep maintaining TRITON buoys in the Indonesian waters and its adjacent.

The last cruise I joined with R/V Mirai was during 2017 – 2019 where JAMSTEC initiated very important international campaign in studying Madden-Julian Oscillation (MJO) participated by US, Australia, UK, China, and Southeast Asian countries, such as Malaysia, Singapore, and many others not to mention. This is really big and important program, especially for Indonesia, where the western Sumatra water became the station of R/V Mirai conducting oceanographic and meteorological experiments to capture the nature of MJO development. Following by this experiment, R/V Mirai made a port call in Jakarta and open her facilities to the public at Tanjung Priok Port, so many Indonesian students and researchers gathered into the rooms and asked for many instruments installed. The Indonesian government was really appreciated with this opportunity.

Our cruises have put fundamental sciences and milestones to understand the role of these regions on climate in the near future so that many countries could take benefit by making better preparation for



Giving a word during the sayonara party at the end of the cruise expedition

the mitigating programs. This is R/V Mirai endeavour mentioning that our Indonesia Maritime Continent plays important role in distributing MJO energy from Indian to Pacific Oceans before traveling the whole equatorial region. The R/V Mirai has given in countless contributions to the scientific communities, and JAMSTEC will be remembered by this important footstep in climate studies.

In the personal perspectives, there are so many nice and spectacular memories that I will share some moments here but most importantly the R/V Mirai has trained me as a sea going scientist in physical oceanography and has given rigorous knowledge of how important our Maritime Continent and especially our Indonesian waters in improving the global climate models. To see the sunrise and especially sunset in the horizon of equatorial regions was always giving different stories from day by day. Waking up in the early morning to make a downcast CTD was a hard task, but this was actually a very interesting moment to see the physical properties and small benthic are still "active and awake" in the dark deep ocean. The rest time together with the crews and other members was also a never forget memory. Many unforgettable memories that I could write in this very short space, but I wanted to mention over whole of so many experiences, I personally really respect with the strong leadership given by the Chief Scientist and the Captain for every cruise I attended. The crews were professional to conduct the operational works to make success our expeditions.

Just as a final word, I am really in debt with many chances given by JAMSTEC through our Indonesian participations, and R/V Mirai has given many unforgettable memories. I believe the R/V Mirai has been bringing us to more understandable and predictable future climate changes as her duty accomplished together with her name JAMSTEC has given as "Mirai".

Observations taken from the R/V Mirai reveal the importance of small vertical scale flow features

Kelvin Richards

University of Hawai'i



I have fond memories of my time on the Mirai in both taking observations and the lifestyle onboard. My first cruise was MR07-07 leaving Auckland, New Zealand in late 2007. Two days into the cruise and we celebrated the New Year. I am very much indebted to Yuji Kashino, the Chief Scientist, in allowing me to participate and to bring along an instrument to measure the ocean currents at high vertical resolution (a high frequency LADCP). This allowed me to follow up on observations I had taken in the Western Equatorial Pacific in the 1980s and 90s that showed the presence of small vertical scale features in temperature and salinity.

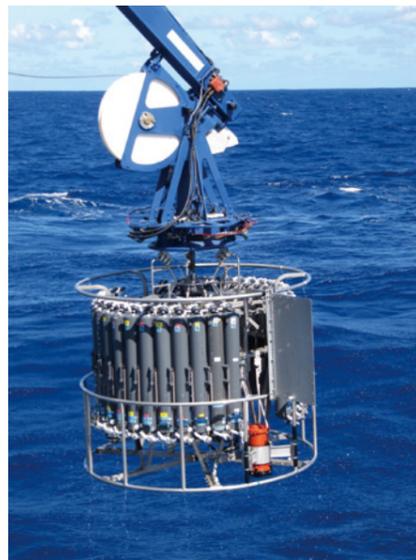
The Mirai proved to be an ideal platform to take the observations in terms of its frequent trips to the region to maintain the TRITON mooring array and the assistance of the officers, crew and technicians in deploying instruments. The measurements showed

that the small-scale features in temperature and salinity were associated with strong vertical shear in the currents. On subsequent cruises we had the use of a microstructure instrument that showed the strong shears produced turbulence. Being able to take measurements on a number of cruises showed how the strength of the small-scale features and associated turbulent mixing varied in time and ocean state.

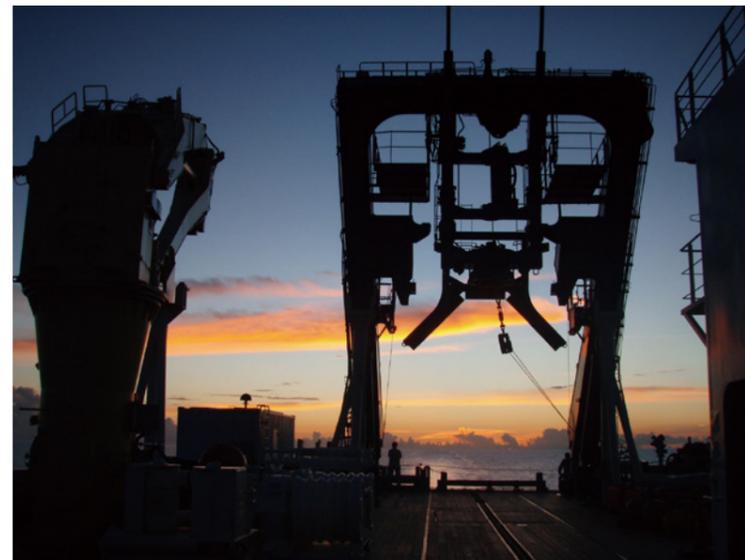
The measurements from the Mirai prompted the development of theory for why such flow features are present. Accounting for their presence in numerical models of the ocean and coupled ocean/atmosphere demonstrated their importance in shaping the ocean thermocline and the state of the ocean. That in turn affects coupled phenomena such as El Niño/La Niña.

I very much enjoyed my time on the Mirai and feel fortunate in having had the opportunity. As well as work, there is the social factor. The good food. Socializing after a hard day's work. Watching the catching of tuna and mahi mahi attracted by the TRITON moorings. And being invited by the crew to sample the freshly caught fish. Watching the sunset, and the occasional green flash.

Thank you, Mirai.



Deployment of the LADCP (orange cylinder) on the CTD frame



Sunset during the MR08-03 cruise (the author is found at the foot of A-frame portside)

Selected cruise reports with covers featuring figures and photographs

