

Ocean Bottom Electromagnetometer Carried From Bonin to Ryukyu Islands by Sea Currents

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Title page:

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Abstract

Ocean bottom electromagnetometers (OBEMs) installed on the seafloor around Nishinoshima Island (Bonin Islands) were missing after a December volcanic eruption. In February 2021, one was found on a beach on Iriomote Island (Ryukyu Islands), implying that it drifted westward for 1,700 km. The reason(s) for the disappearance of the OBEMs and the path followed by the recovered OBEM while drifting are important information for future ocean bottom observations and seafloor volcanology in general. We conducted particle drifting simulations with and without horizontal eddy diffusion to estimate the possible drift path and duration of the recovered OBEM. Our simulations show that particles transported from Nishinoshima have a 7-10 % probability of arriving at Iriomote Island, which is thus not a rare occurrence. Transport durations in our simulations varied widely between 140 and 602 days depending on the drift paths. The most likely drift duration in our simulation was 150 – 180 days, with or without eddy diffusion, corresponding to the release from the seafloor of the OBEM between 22 August and 21 September 2020. These dates follow shortly after intensifying eruptions at Nishinoshima, which may have affected the seafloor around the island. A similar drift duration and path was reported for pumices that erupted from Fukutoku-Oka-no-Ba submarine volcano (northern Bonin Islands) during 18-21 January 1986 and arrived in the Ryukyu Islands in late May 1986. Such drifting simulations may prove useful for identifying the sources of drift pumices, and thus otherwise undetectable eruptions. Finally, the Fukutoku-Oka-no-Ba submarine volcano erupted on 13 August 2021, producing abundant pumice rafts that, based on our results, will likely arrive in the Ryukyu Islands in the coming months.

Keywords

Ocean bottom electromagnetometer (OBEM)

Nishinoshima volcano

Iriomote Island

Drifting simulation

Pumice

Fukutoku-Oka-no-Ba

Main Text

1. Introduction

Seafloor observations are essential to Earth sciences because oceans cover about 70% of the Earth's surface and most major earthquakes and other geological events occur beneath the seafloor. Seafloor observation equipment often encounters unexpected trouble in deep-water locations; some instruments are lost during recovery whereas others disappear suddenly during their observational period. In the latter case, it is difficult to find and retrieve them, and precious scientific data and the instruments can be lost. Although such cases are not generally reported in scientific or official literature, they are known to occur during submarine volcanic eruptions and/or earthquakes, most likely while the instruments are recording indispensable data. For instance, ocean bottom seismometers recording at the time of the 2011 Tohoku-Oki earthquake (Mw 9.0) could not be retrieved because they were either entrained in earthquake-generated turbidites (e.g., Japan Agency for Marine-Earth Science and Technology 2011, 2012) or dislodged from their installation locations. Some of those seismometers were retrieved during a special operation using a remotely operated vehicle and were found to have recorded the

passing of the tsunami while trapped in the turbidites (Arai et al. 2013). Hence, it is essential to retrieve lost instruments, and thus to investigate the reason(s) for their loss and the paths and durations of their drifting at the sea surface.

The Izu-Bonin (Ogasawara) Arc is one of the most active volcanic areas in the world (e.g., Tamura et al. 2016). For instance, Nishinoshima, an uninhabited volcanic island in the Bonin archipelago (~1,000 km south of Tokyo, Japan; Fig. 1), has intermittently erupted since November 2013 (e.g., Maeno et al. 2016; Kaneko et al. 2019). Most recently, a caldera-forming eruption occurred at Fukutoku-Oka-no-Ba, a submarine volcano about 250 km south of Nishinoshima (~5 km northeast of Minami Iwo Island; Figure 1), on 13 August 2021 (Japan Meteorological Agency 2021). These volcanos offer an exceptional opportunity to study ongoing island-forming eruptive processes and the structures of active submarine volcanoes.

It is difficult to study such submarine volcanoes because we generally do not know their precise eruption histories. A few literature reports attributed pumices found on the coasts of Ryukyu, Kyushu, and Shikoku Islands to eruptions in the Bonin Islands (e.g., Kato 1988; Nakano and Kawabe 1992). These pumices might have drifted from east to west along unimaginable routes. Determining the origin of such pumices and their drift times and paths might reveal previously unknown volcanic eruptions.

Ocean bottom electromagnetometers (OBEMs) measure seafloor magnetic and electric fields variations, and are the only available means of estimating the detailed electrical conductivity structure beneath the seafloor. Because electrical conductivity is sensitive to temperature and presence of volatiles and aqueous pore fluids, OBEMs provide invaluable information on the thermal, hydrological and mineralogical structure beneath the seafloor (e.g., Tada et al. 2016; Naif et al. 2013). We installed OBEMs on the seafloor around Nishinoshima to estimate the electrical conductivity structure of the volcanic body and identify the location and dimensions of the magma chamber. However, some OBEMs were missing after a volcanic eruption in December 2019. Surprisingly, in February 2021, one was found on Takana beach on Iriomote Island, about 1,700 km west of Nishinoshima (Figs. 1, 2). We retrieved this OBEM in perfect condition and recovered the data recorded at Nishinoshima. The recovery of this OBEM on Iriomote Island demonstrates that materials can drift from the Bonin to the Ryukyu Islands.

Determining the reason(s) for the disappearance of OBEMs and their subsequent

drifting routes and durations is important for ocean bottom observations and seafloor volcanology in general because this information can be used to (1) find and recover future missing instruments and (2) constrain the origins or forecast the routes of drifting pumices.

Here, we report on the installation, loss, and subsequent recovery on Iriomote Island of an OBEM installed at Nishinoshima. We also performed simulations to estimate its drift path and duration. Based on our simulations, we relate the OBEM's disappearance to volcanic activity at Nishinoshima and discuss implications for drifting pumices.

2. Installation, loss, and recovery of the OBEM

OBEMs are generally installed for a few months to a few years depending on the objective of the project and power limitations. In the OBEM devices used in our studies, most of the instruments are contained within two 17-inch glass spheres under vacuum, each covered by a plastic sphere; one sphere contains a fluxgate magnetometer, two tiltmeters, a thermometer, and a data logger, and the other contains batteries and a transducer circuit. Each device has four orthogonally attached pipe arms containing five Ag-AgCl electrodes and is supported by an aluminum frame containing an acoustic transponder, a radio beacon, a xenon flasher, and an anchoring weight (Figure 2a; e.g., Seama et al. 2007). Our OBEMs measure time series of magnetic field (three components), electric field (two components), and instrument tilt.

During their installation, OBEMs are dropped off a ship, free-fall to the sea surface, and settle to the seafloor under their own weight. Because OBEMs encounter water currents while settling, their final installed positions differ from their launch positions. Once on the seafloor, OBEMs typically couple with seafloor sediments and remain stationary. Thus, their installed positions are generally calibrated in three dimensions only once (at the time of installation) by sounding with the acoustic transponder on the OBEM and a shipboard transducer. On completion of the project, a release command triggers an electrical current through the thin metal wire connecting the OBEM to its anchor, and the OBEM floats to the sea surface for recovery.

We initiated OBEM observations around Nishinoshima in 2016 to estimate the electrical conductivity structure of the island (Baba et al., 2020). In September 2018, we deployed six more OBEMs around Nishinoshima from the Japan Meteorological Agency

(JMA) weather ship *Keifu Maru* (cruise KS18-07). After verifying that each OBEM had settled to the seafloor, their positions were determined by sounding.

About nine months later, in June 2019, we attempted to retrieve the six OBEMs during cruise KS19-05 of the *Keifu Maru*. In this particular operation, we recalibrated the positions of the OBEMs because it was known that some of them had moved, perhaps due to volcanic activity and/or slope collapse (Baba et al., 2020). We recovered four OBEMs but were unable to recover the other two (JM4 and JM6) during that cruise.

JM4 was deployed on 10 September 2018 on the eastern flank of Nishinoshima (observation site NS15, 27°16.1222'N, 140°59.5671'E, ~2,033 m water depth). Upon recalibration on 10 June 2019, the position of JM4 was 27°16.1303'N, 140°59.5779'E (Figure 1c), about 23.3 m downslope to the N49.8°E from its installation position. After recalibrating its position, we sent the release command and the transponder responded normally. However, after more than 28 h, JM4 had not surfaced; we inferred that it was trapped on the seafloor by overlying sediments, as was the case for the OBEM that was buried in thick mud during the 2011 Tohoku-Oki earthquake (Japan Agency for Marine-Earth Science and Technology 2012).

JM6 was also deployed on 10 September 2018, but on the southern flank of Nishinoshima, between the main edifice and submarine volcano. Its initial installation position was 27°11.7955'N, 140°52.4258'E at about 991 m depth. Upon recalibration on 8 June 2019, its position was 27°11.8011'N, 140°52.3908'E at about 989 m depth, 58.6 m to the N79.8°W from its initial position. As with JM4, JM6 did not surface even though it responded normally to the release command.

We later tried to recover JM4 and JM6 using the remotely operated vehicle (ROV) *KM-ROV* on 13 and 14 December 2020 during cruise KM20-11 of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) ship R/V *Kaimei*. Before deploying *KM-ROV*, we called the transponders of JM4 and JM6 using the ship's transducer, but did not receive any signal. We searched the seafloor for JM4 and JM6 around their last known positions using the sonar and video cameras on *KM-ROV*; after about two hours of searching for each, we called off the search.

One of the authors (H. Ichihara) received an email on 19 February 2021 from the Iriomote Ecotourism Association (Iriomote Island, Okinawa prefecture) reporting that an OBEM had drifted ashore there. The OBEM (Fig. 2b) was discovered on a beach on the

northeast part of the island (Fig. 1b) during beach cleaning on 18 February. We visited the island to retrieve the OBEM on 11 March 2021 and found it to be JM4.

Its surface was fully covered with lugworms (serpulid polychaetes), and several stalked barnacles of the genus *Lepas* were attached to it. The capitular lengths of *L. anserifera* exceeded 10 mm, suggesting that the barnacles had been attached to the OBEM for more than 50 days before its retrieval (Inatsuchi et al. 2010). Upon inspecting the glass spheres, we found that the vacuum had been maintained until we opened them. Therefore, JM4 maintained its buoyancy after releasing its anchor, and it must have drifted on the sea surface from around Nishinoshima to Iriomote Island. Time-series data were recorded until late August 2019, when the batteries were most likely exhausted. The data logs contained no direct information related to the release of its weight or JM4's ascent to the sea surface.

3. Drifting simulations

We conducted drifting simulations to estimate the possible route and duration of JM4's travel from Nishinoshima to the Iriomote Island. We used horizontal velocities, sea-surface temperatures, and salinities from the ocean reanalysis dataset of the JMA's operational numerical weather prediction model (Japan Meteorological Agency 2013). This daily dataset has $0.1^\circ \times 0.1^\circ$ horizontal resolution.

We set particles around Iriomote Island and conducted backward particle tracking experiments because the timing of JM4's stranding on Iriomote Island is much better constrained than that of its departure from Nishinoshima. We released particles at 1 m depth in the simulations because JM4 never lost its buoyancy and sank. Particles were released on 18 February 2021, the date JM4 was found on Iriomote Island, and tracked until 10 June 2019, the last date of contact with JM4 at Nishinoshima.

We conducted two experiments: one using 200 particles without horizontal eddy diffusion and the other using 2,000 particles and accounting for horizontal eddy diffusion. These two experiments correspond to end-member cases of random Brownian motion resulting from waves, wind, and other forces in the natural system.

Particle locations were tracked using the formulae:

$$x_{n+1} = x_n + u_n \Delta t + \lambda_x \quad (1)$$

$$y_{n+1} = y_n + v_n \Delta t + \lambda_y \quad (2)$$

$$(\lambda_x, \lambda_y) = P_N \sqrt{2\Delta t} \left(\sqrt{A_H^x}, \sqrt{A_H^y} \right) \quad (3)$$

where (x_n, y_n) is the horizontal particle location (x and y are east–west and north–south coordinates, respectively) at time step n , u_n and v_n are eastward and northward particle velocities, respectively, and $\Delta t = 20$ min is the time step. In Equation (3), (λ_x, λ_y) is the random walk displacement, and (A_H^x, A_H^y) and P_N are the horizontal eddy diffusion coefficients and the probability function of the normal distribution, respectively. Both A_H^x and A_H^y were set at $0 \text{ m}^2/\text{s}$ for the experiment without horizontal diffusion and at $10 \text{ m}^2/\text{s}$ for the experiment with horizontal diffusion. The ‘initial’ positions (i.e., on 18 February 2021) of the 200 particles in the experiment without horizontal diffusion are shown in Figure 3a. In the experiment with horizontal diffusion, we set ten particles at each of the same 200 positions. We judged particles as having ‘arrived’ (i.e., having originated) at Nishinoshima if they were back-transported into a $1^\circ \times 1^\circ$ area centered on the island (Fig. 3b). We set this large target area because the bathymetry around Nishinoshima has changed dynamically in recent years, and the reanalysis velocity data that we used did not account for recent uplift that would influence the velocity field around Nishinoshima.

Figure 4a shows all particle trajectories for the two experiments. In the experiments without and with horizontal diffusion, 23 and 137 particles were back-transported into the target area, respectively. Figure 4b shows the ‘arrival’ points and transport durations of those particles. The shortest and longest transport times were 140 and 602 days, respectively. The transport times of particles that ‘arrived’ to the west of Nishinoshima tended to be longer than those of particles that ‘arrived’ to the south. There was no specific tendency among the transport times in the experiment without diffusion, whereas transport times of 150–180 days were by far the most common in the experiment with diffusion (Fig. 4c).

4. Discussion

4-1. Circumstances of the OBEMs on the seafloor and implications for volcanic

activity at Nishinoshima

In addition to finding JM4 on Iriomote Island, our simulation results with and without horizontal eddy diffusion indicate that 7–10% of the particles around Iriomote Island on 18 February 2021 were transported from around Nishinoshima within the preceding two years. Thus, we suggest that sea-surface transport from the Bonin Islands to the Ryukyu Islands and Taiwan is not a rare occurrence. In addition, the shortest transport time we obtained (140 days) is consistent with the lengths of barnacles attached to JM4, which must have been attached for at least 50 days before its retrieval. However, the simulated transport durations varied widely between 140 and 602 days depending on the drift path. Indeed, Nishinoshima and Iriomote Island are situated in the North Pacific Subtropical Gyre; a particle transported from Nishinoshima can arrive at Iriomote Island in half a year if it is carried by a relatively strong sea current, whereas one trapped in medium-sized eddies will take much longer. More detailed insight into the path and duration of drift of JM4 will require further comparison between drifting simulations and barnacle growth histories. Here, we discuss what may have happened to the OBEMs on the seafloor and constrain the period during which JM4 must have floated to the sea surface, which might be related to previously unknown submarine volcanic activity. This information will be useful for detecting when pumices were erupted from the Bonin Islands and how long they drifted before reaching the Ryukyu Islands.

OBEMs JM4 and JM6 were not recoverable by conventional means in June 2019 (see section 2). The other four recovered OBEMs were not installed between JM4 and JM6 and had only moved 9 – 15 m, much shorter distances than JM4 and JM6. Therefore, these two OBEMs were probably moved by external forces such as a failure of the unstable volcanic slope and/or crustal deformation associated with the intrusion of magma. Such seafloor occurrences might not be correlated with known activity at Nishinoshima, may have occurred locally to the south and east of the island, and may not have been detectable above the sea surface.

There are three possible reasons why JM4 and JM6 did not ascend from the seafloor in June 2019: (1) the release systems did not work, even though they responded normally to the release commands; (2) the weights may have been released, but the glass spheres containing the fluxgate sensors and recorders may have been flooded, preventing the

buoyant rise of the OBEMs; or (3) the weights may have been released, but the OBEMs were stuck in sediments and could not ascend. Because JM4 was found without its weight and with its two glass spheres still under vacuum, we reject the first two possibilities and conclude that JM4 had become stuck in sediments. Unfortunately, JM6 has not yet been found and we cannot say whether it remains on the seafloor or is adrift in the ocean.

It is important to constrain when JM4 rose from the seafloor because its release from the sediments might be related to previously unknown submarine volcanic activity that could not be otherwise detected (e.g., visually or by satellite). JM4 was confirmed to be on the seafloor on 11 June 2019 and was found 601 days later on Iriomote Island on 18 February 2021. However, its data log indicates that it was on the seafloor at least until 24 August 2019 when its sensor's batteries were completely exhausted, and the temperature time series remained at ~ 1.0 °C from the end of February 2019 through the end of August 2019. If JM4 had risen to the surface during this period, the temperature would have increased because the ocean temperature increases at shallower depths. Therefore, JM4 must have remained on the seafloor at least until 24 August 2019. Unfortunately, the tiltmeters failed around the end of February 2019, so we cannot use the tilt data to further confirm this conclusion. From the recorded data, we can only determine that the longest possible duration of drift for JM4 was 527 days. According to the results of our drifting simulations, it is unlikely that JM4 drifted for longer than 480 days; of the particles that 'arrived' at Nishinoshima, only 1 of 23 and 5 of 137 simulations without and with eddy diffusion, respectively, had longer residence times (Fig. 4c). Hence, JM4 most likely remained on the seafloor for at least a few months after February 2019.

Based on our simulations, the most likely duration of transport for JM4 is 150–180 days (Fig. 4c). These transport durations correspond to JM4 rising from the seafloor between 22 August and 21 September 2020. Nishinoshima began an eruptive period on 5 December 2019 that ceased at the end of August 2020. During that period, the eruptive style changed from Strombolian to violent Strombolian in mid-June 2020 (Yanagisawa et al. 2020). Violent Strombolian eruptions produce dense volcanic plumes, abundant ash, and lava flows (Pioli et al. 2008; Valentine and Gregg 2008). Indeed, Yanagisawa et al. (2020) observed a lava flow entering the sea on 20 July 2020. These eruptive events shortly precede the most likely dates for JM4 to have been released (22 August to 21 September 2020). Thus, we consider that volcanic materials entering the sea may have

dislodged JM4 either by disturbing the seafloor sediments or gently jostling it loose.

4-2. Implications for drifting pumices in the Ryukyu Islands

Just as JM4 was found on the beach on Iriomote Island, many pumices are found on beaches in the Ryukyu Islands (e.g., Kato 1980, 1988; Nakano and Kawanabe 1992). Kato (1988) reported that many pumices had been stranded on the Ryukyu Islands since late May 1986. Based on the mineralogy and geochemistry of the pumices, he concluded that they were effused during the 18–21 January 1986 eruption of Fukutoku-Oka-no-Ba (Fig. 1), thus indicating a distance and duration of drifting similar to those determined for OBEM JM4. This similarity indicates that in both cases, drifting was mainly affected by two currents: the Kuroshio counter-current, which flows from east to west at middle latitudes in the Pacific Ocean, and the Kuroshio current, which flows from the eastern shores of the Philippine and Taiwan to the Ryukyu islands.

It is generally difficult to specify the origin of drift pumices. For example, the origins of most drift pumices on Iriomote Island cannot be identified, although one type has been correlated to Fukutoku-Oka-no-Ba based on color, clast size, mineralogy, and geochemistry (Nakano and Kawanabe 1992). Our drifting simulation might therefore be used to quantitatively evaluate possible drift pumice origins. The tracking paths obtained in our simulation (Fig. 4a) reach Taiwan, the Philippines, and the Mariana Islands, which were mentioned as possible pumice origins by Nakano and Kawanabe (1992). Moreover, such drifting simulations might be useful in constraining the duration of volcanic activities and detecting otherwise undetectable eruptions of submarine volcanoes. Nakano and Kawanabe (1992) also reported that marine organisms were attached to drift pumices. As we have demonstrated, integrating biomarker analyses with drifting simulations can further narrow the possible origins and drift paths/durations of pumices.

On 13 August 2021, a submarine eruption occurred at Fukutoku-Oka-no-Ba, and a new horseshoe-shaped island 1 km in diameter was observed on 16 August. Aerial photographs and satellite images show numerous pumice rafts drifting to the northwest (Japan Meteorological Agency 2021). Pumice rafts are known to cause various hazards, such as blocking harbors, ports, and marine traffic, and damaging hulls and propellers (e.g., Oppenheimer 2003; Jutzeler et al. 2014). Drifting simulations could also be used to

predict possible paths of pumice rafts, and thus potential risks (Jutzeler et al. 2014, 2020). Indeed, Jutzeler et al. (2020) recently tried to predict the ongoing dispersal of pumice rafts from the Tonga Arc (southwestern Pacific Ocean) using the latest-monitored ocean current data for forecast simulations.

We stress, however, that the drifting simulation have presented here does not provide a forecast; it is a hindcasting simulation. In addition, it does not consider the effect of wind, which likely impacts the paths of large, light drift pumices. Nonetheless, our simulation results and observational evidence that many pumices from Fukutoku-Oka-no-Ba, as well as the JM4 OBEM from Nishinoshima, arrive in the Ryukyu Islands suggest that the pumices rafts erupted in August 2021 will likely move westward and drift ashore in the Ryukyu Islands in several months. As of this writing (23 September 2021), we have begun drifting simulations to forecast such an eventuality.

5. Conclusions

OBEM JM4 was deployed on the seafloor near Nishinoshima in 2018 and was found ashore on Takana beach on Iriomote Island in February 2021, which motivated us to simulate its drifting path and duration. Our results indicate that material drifting from the Bonin Islands have a 7–10% probability of being carried by westward ocean currents to the Ryukyu Islands. Whether ignoring or accounting for horizontal eddy diffusion in our simulations, the most likely drift duration for JM4 was 150–180 days, corresponding to its release from the seafloor between 22 August and 21 September 2020. Nishinoshima volcano began erupting in late December 2019, and the eruptive style changed from Strombolian to violent Strombolian in mid-June 2020, producing lava flows that entered the ocean by late July 2020 (Yanagisawa et al. 2021). However, these activities were confirmed only from above sea level, and we do not yet know the extent to which they effected the submarine landscape around Nishinoshima. We hypothesize that this eruptive activity caused JM4 to rise to the sea surface. It is important to further constrain the drifting duration of JM4 because it will reveal when volcanic activities affected the eastern slope of Nishinoshima where JM4 was installed. More accurate information may be obtained from the growth record of the barnacles on JM4. The drifting path and duration of JM4 are similar to those of drift pumices from the Fukutoku-Oka-no-Ba

submarine volcano, which have been found in the Ryukyu Islands. Our drifting simulation may therefore also contribute to determining the origins of drift pumices and constraining the duration of related volcanism.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

JMA, Japan Meteorological Agency; OBEM, ocean bottom
electromagnetometer; ROV, remotely operated vehicle; JAMSTEC,
Japan Agency for Marine-Earth Science and Technology

Availability of data and materials

Contact the corresponding author to access the digital data for the
drifting simulation.

Competing interests

The authors declare that they have no competing interests regarding this
study.

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Authors' contributions

NT contributed to shipboard OBEM observations. NT and HI retrieved the JM4 OBEM from Iriomote Island. HN performed the drifting simulation. HW contributed to studying the marine organisms on the retrieved OBEM. NT, HN, and TK contributed funding to this study. All authors contributed to discussions and have approved the final manuscript.

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Authors' information

Not applicable

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Figure legends

Figure 1 (a) Bathymetric map (ETOPO1, Amante and Eakins 2009) of the Philippine sea and western Pacific Ocean showing the locations of Iriomote Island, Nishinoshima Island, and the Fukutoku-Oka-no-Ba submarine volcano (red circle). (b) Iriomote Island; the red star indicates where OBEM JM4 was discovered on 18 February 2021. (c) Nishinoshima Island; the blue star indicates the last known seafloor position of JM4 on 10 June 2019.

Figure 2 Photographs of OBEM JM4 (a) just before deployment during cruise KS18-07 and (b) when it was found on Iriomote Island by the Iriomote Eco-Tourism Association.

Figure 3 (a) Initial particle positions around Iriomote Island in the particle back-tracking simulations. Dots are the initial particle positions, and the center of the star

marks where the OBEM was found on the beach. These initial positions were set to include only the eastern side of the true arrival position because much of the western side includes the island itself, and because the arrival site faces the east. (b) Target area around Nishinoshima in the particle back-tracking simulations. The thick square encloses the $1^\circ \times 1^\circ$ target area around Nishinoshima (center of the star). Any particles that were traced back to this target area were considered to have originated from Nishinoshima.

Figure 4 Particle back-tracking simulations without (left, 200 particles) and with (right, 2,000 particles) horizontal eddy diffusion (horizontal diffusion coefficient = $10 \text{ m}^2/\text{s}$). (a) Daily particle positions from 18 February 2021 to 10 June 2019. Nishinoshima and Iriomote Islands are indicated by the blue and red stars, respectively. Red traces represent the tracks of particles that ‘arrived’ (i.e., originated from) within the Nishinoshima target area. (b) Original positions of particles calculated to have originated from within the target area. The center of the star represents Nishinoshima Island. The color scale represents the back-transport duration from Iriomote Island. (c) Distributions of back-transport times in each simulation.

Figures

Figure 1

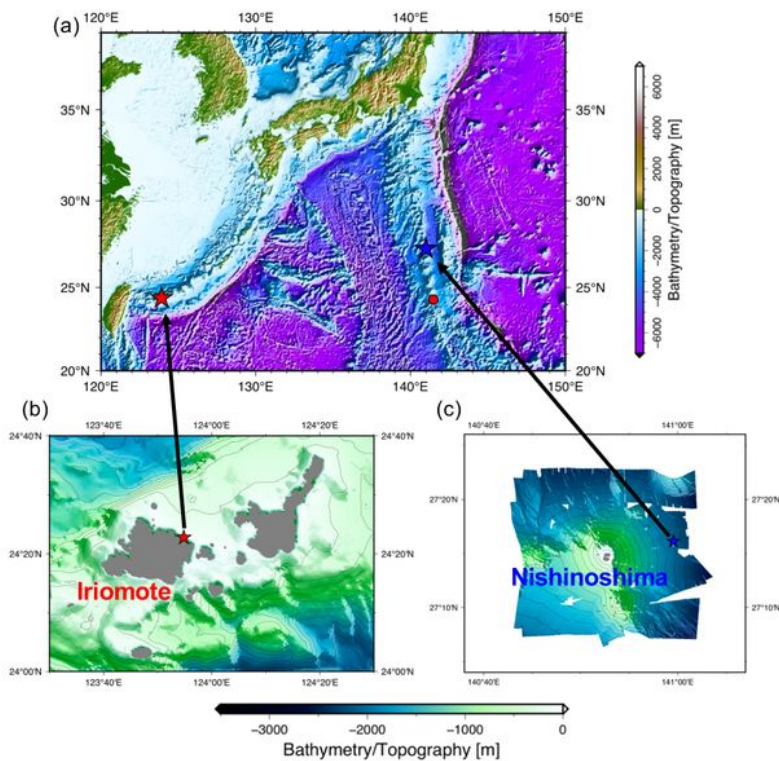


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Figure 2

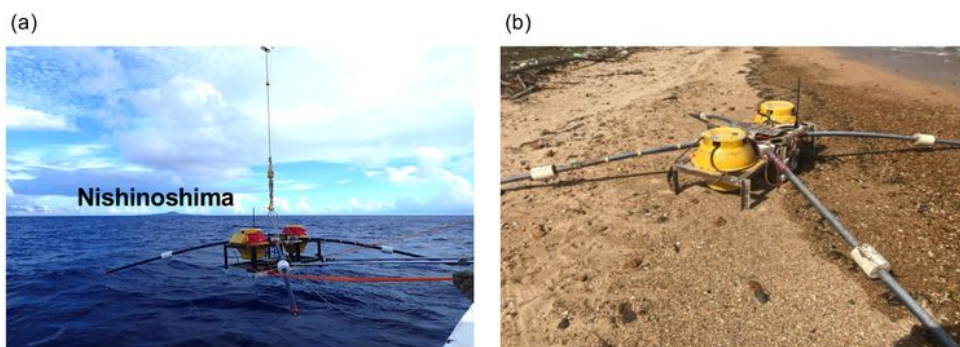


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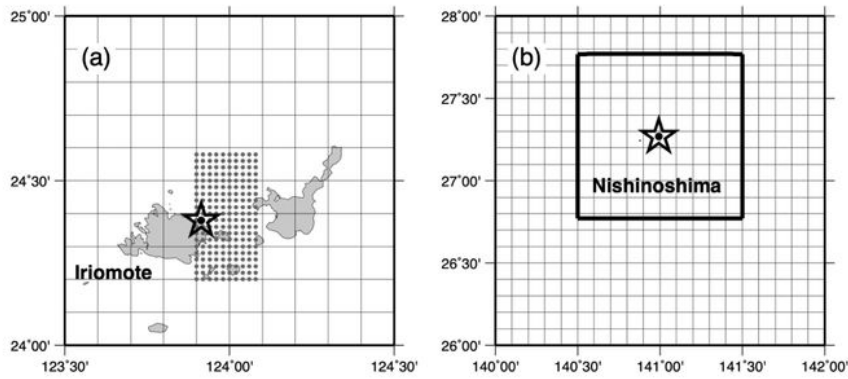


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Figure 4

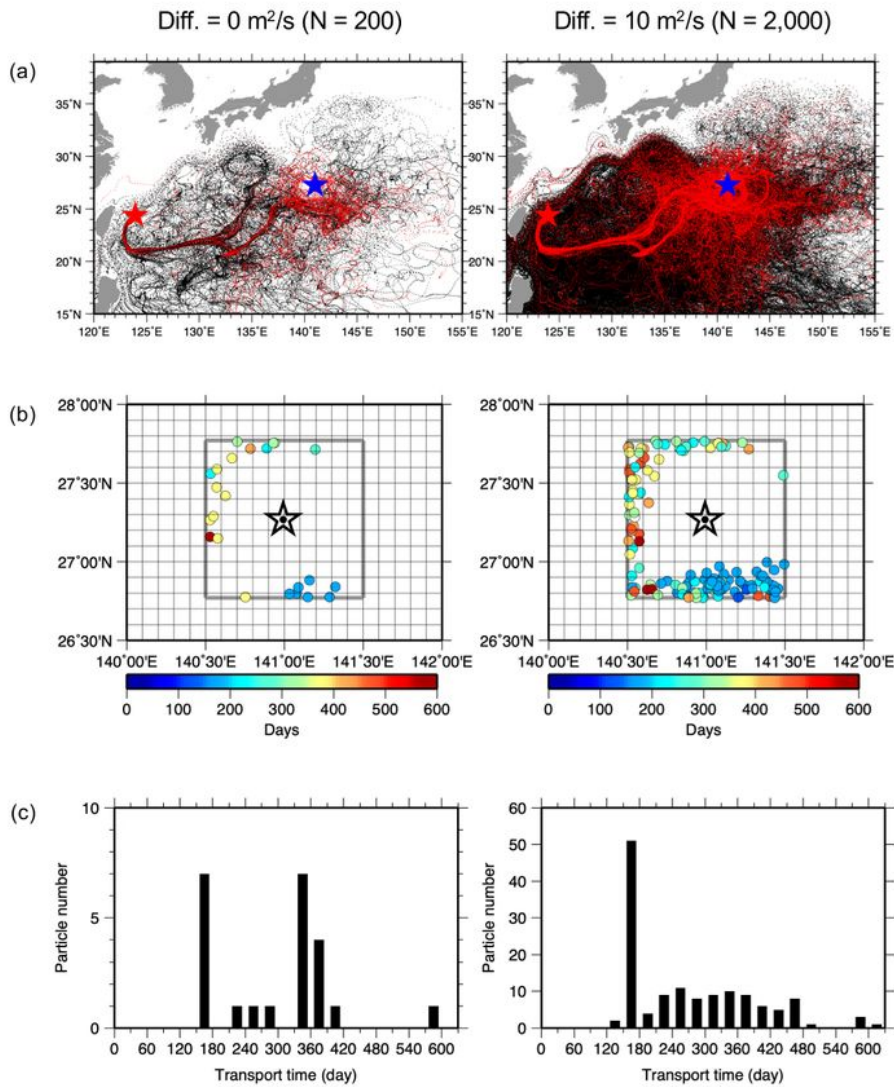


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