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Drift of an ocean bottom electromagnetometer from the Bonin to Ryukyu Islands: estimation of the path and travel time by numerical tracking experiments

Noriko Tada^{1*} , Haruka Nishikawa^{2,3} , Hiroshi Ichihara^{1,4} , Hiromi Kayama Watanabe⁵  and Tatsu Kuwatani¹ 

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 1700 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 arriving at Iriomote Island have a 7–10% probability of having been transported from Nishinoshima; thus, such transport is not a rare occurrence. Transport durations in our simulations varied widely between 140 and 602 days depending on the drift paths. More detailed insight into the path and duration of drift of the OBEM will require further comparison between drifting simulations and growth histories of barnacles attached on the OBEM. A similar drift duration and path was reported for pumices that erupted from Fukutoku-Oka-no-Ba submarine volcano (southern 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, would likely arrive in the Ryukyu Islands. In fact, the beginning of October 2021, they began to arrive in the Ryukyu Islands.

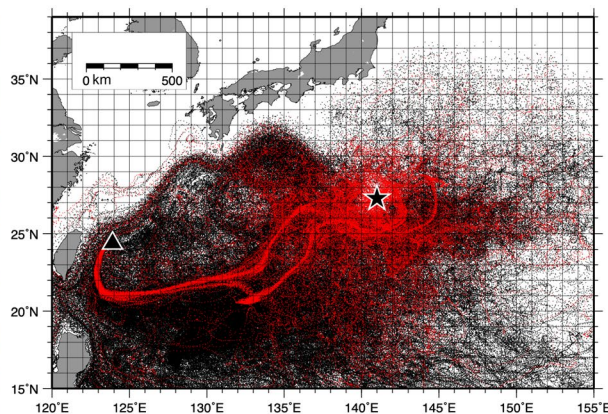
Keywords: Ocean bottom electromagnetometer (OBEM), Nishinoshima volcano, Iriomote Island, Drifting simulation, Pumice, Fukutoku-Oka-no-Ba

*Correspondence: norikot@jamstec.go.jp

¹ Research Institute for Marine Geodynamics (IMG), Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan

Full list of author information is available at the end of the article

Graphical Abstract



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 (~1000 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, an eruption occurred at

Fukutoku-Oka-no-Ba, a submarine volcano about 335 km south of Nishinoshima (~5 km northeast of Minami Iwo Island; Fig. 1), on 13 August 2021 (Japan Meteorological Agency 2021a). 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 Kawanabe 1992). These pumices might have drifted from east to west along unknown 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., Naif et al. 2013; Tada et al. 2016). 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 sometime after a volcanic eruption in December 2019. Surprisingly, in February 2021, one was found on Takana beach on Iriomote Island, about 1700 km west of Nishinoshima (Figs. 1, 2). We retrieved this OBEM in perfect condition and recovered

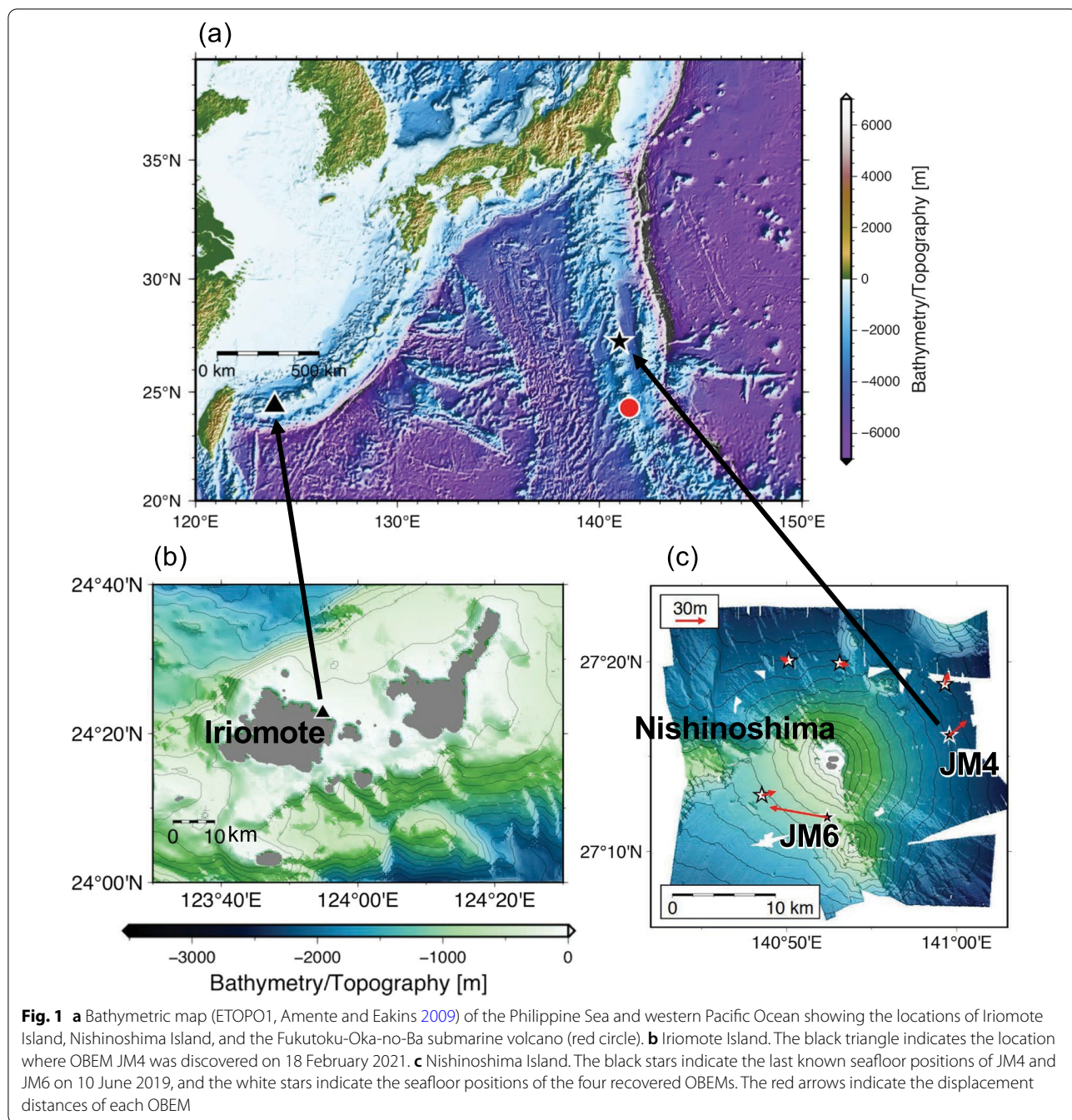


Fig. 1 **a** Bathymetric map (ETOPO1, Amante and Eakins 2009) of the Philippine Sea and western Pacific Ocean showing the locations of Iriomote Island, Nishinoshima Island, and the Fukutoku-Oka-no-Ba submarine volcano (red circle). **b** Iriomote Island. The black triangle indicates the location where OBEM JM4 was discovered on 18 February 2021. **c** Nishinoshima Island. The black stars indicate the last known seafloor positions of JM4 and JM6 on 10 June 2019, and the white stars indicate the seafloor positions of the four recovered OBEMs. The red arrows indicate the displacement distances of each OBEM

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

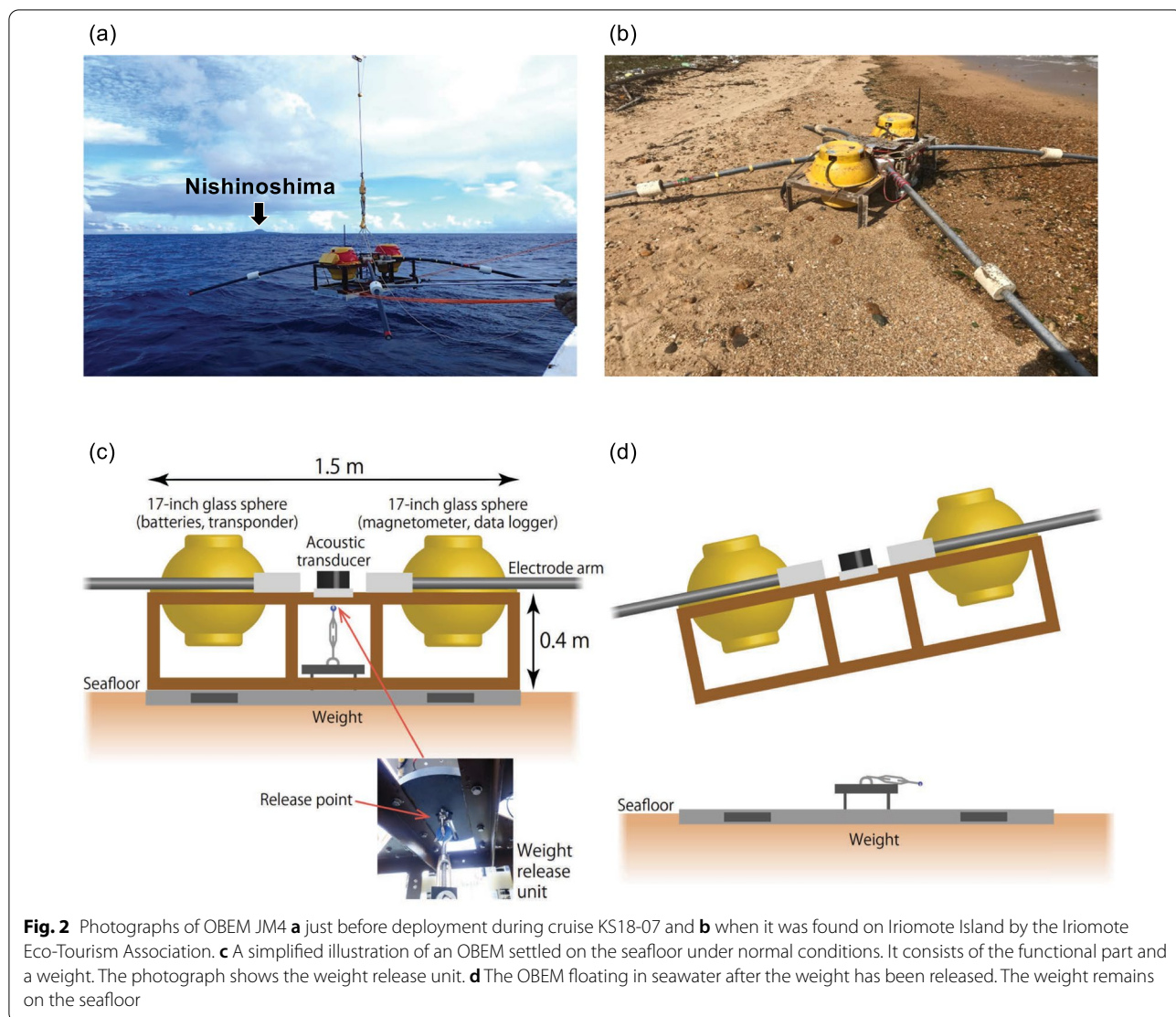


Fig. 2 Photographs of OBEM JM4 **a** just before deployment during cruise KS18-07 and **b** when it was found on Iriomote Island by the Iriomote Eco-Tourism Association. **c** A simplified illustration of an OBEM settled on the seafloor under normal conditions. It consists of the functional part and a weight. The photograph shows the weight release unit. **d** The OBEM floating in seawater after the weight has been released. The weight remains on the seafloor

volcanic activity at Nishinoshima and discuss implications for drifting pumices.

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-in. glass spheres under vacuum, each covered by a plastic sphere; one sphere contains a flux-gate 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 transducer, a radio beacon, a xenon flasher, and an anchoring weight (Fig. 2a; e.g., Seama et al.

2007). Our OBEMs measure time series of magnetic field (three components), electric field (two components), and instrument tilt.

OBEMs are released from a ship on the sea surface, from which they sink freely by their weight and settle to the seafloor. Because OBEMs drift along subsurface ocean currents as they fall, 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 transducer 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 weight, 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). As usual, the positions of the OBEMs were measured only one time, when the OBEMs settled on the seafloor. However, the 2016 observation data of one OBEM indicated that it had shifted laterally on the seafloor (Baba et al. 2020). Therefore, we decided to measure the locations of OBEMs two times, specifically in Nishinoshima observation: just after installation and just before recovery. 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 9 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, ~2033 m water depth). Upon recalibration on 10 June 2019, the position of JM4 was 27° 16.1303' N, 140° 59.5779' E (Fig. 1c), about 23.3 m downslope to the N49.8° E (49.8° from the north to east) from its installation position. After recalibrating its position, we sent the release command and the transducer 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 (JAM-STEC) ship *R/V Kaimei*. Before deploying *KM-ROV*, we called the transducers 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 2 h 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 weight, and it must have drifted on the sea surface from around Nishinoshima to Iriomote Island (Additional file 1: Fig. S1). Time-series data were recorded until 24 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. Thus, the longest possible drift time of JM4 was 544 days, from 24 August 2019 to 18 February 2021.

Drifting simulations

We conducted drifting simulations to estimate the possible route and duration of JM4's travel from Nishinoshima to Iriomote Island. We used daily horizontal velocities, sea-surface temperatures, and salinities obtained with the MOVE/MRI.COM-WNP ocean data assimilation system (Usui et al. 2006; Japan Meteorological Agency 2013). This system uses a multivariate 3DVAR scheme, in which coupled temperature–salinity empirical orthogonal functional decomposition in the vertical axis and a horizontal Gaussian structure are adopted for the background error covariance matrix. The horizontal resolution is 2/3° from 117° to 160° E and 1/6° from 160° E to 160° W zonally, and 2/3° from 15° to 50° N and 1/6° from 50° to 65° N meridionally. There are 54 vertical levels with thickness increasing from 1 m at the surface to 600 m at 6300 m depth.

We released 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 2000 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 Eq. (3), (λ_x, λ_y) is the random walk displacement, (A_H^x, A_H^y) are measures of the magnitude of uncertainty of horizontal velocity estimates, and P_N is the probability function of the normal distribution. 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 Additional file 1: Fig. S2a. In the experiment with horizontal diffusion, we released 10 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 (Additional file 1: Fig. S2b). We established 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 3a 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 3b 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. In our simulations, the drift duration showed a bimodal distribution with peaks at 150–180 and 330–390 days when horizontal eddy diffusion was ignored, whereas when horizontal eddy diffusion was included,

drift duration showed a dominant peak at 150–180 days (Fig. 3c). Therefore, transport times of 150–180 days were by far the most common in the experiment.

Discussion

Circumstances of the OBEMs on the seafloor and the OBEM drift duration

JM4 and JM6 were not recoverable by conventional means in June 2019 (see “Installation, loss, and recovery of the OBEM” section). There are three possible explanations for why OBEMs 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. JM4 and JM6 moved about 23.3 m and 58.6 m, respectively, downslope along the seafloor between September 2018 and June 2019 (Fig. 4). In contrast, the other four recovered OBEMs, which were not installed between JM4 and JM6 (Fig. 1c), had moved only 9–15 m. These large differences imply that external forces moved JM4 and JM6. In addition, JM4 was found without its weight and with its two glass spheres still under vacuum and retaining buoyancy. Thus, we reject possibilities (1) and (2) and conclude that JM4 had become stuck in sediments after it moved. Unfortunately, JM6 has not yet been found and we cannot say whether it remains on the seafloor or is adrift in the ocean.

To determine why JM4 got stuck and was later released from the sediments, it is necessary to constrain when JM4 rose off the seafloor. JM4 was confirmed to be on the seafloor on 11 June 2019, and it was found on Iriomote Island on 18 February 2021, 618 days later. However, its data log indicates that it was on the seafloor until at least 24 August 2019 (Fig. 4), when its sensor’s batteries became completely exhausted, because the temperature time series remained at $\sim 1.0^\circ\text{C}$ 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 ocean temperature increases at shallower depths. Therefore, JM4 must have remained on the seafloor until at least 24 August 2019. Unfortunately, the tiltmeters failed around the end of February 2019, so we cannot use tilt data to confirm this inference. From the recorded data, we can determine only that the longest possible duration of drift for JM4 was 544 days.

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

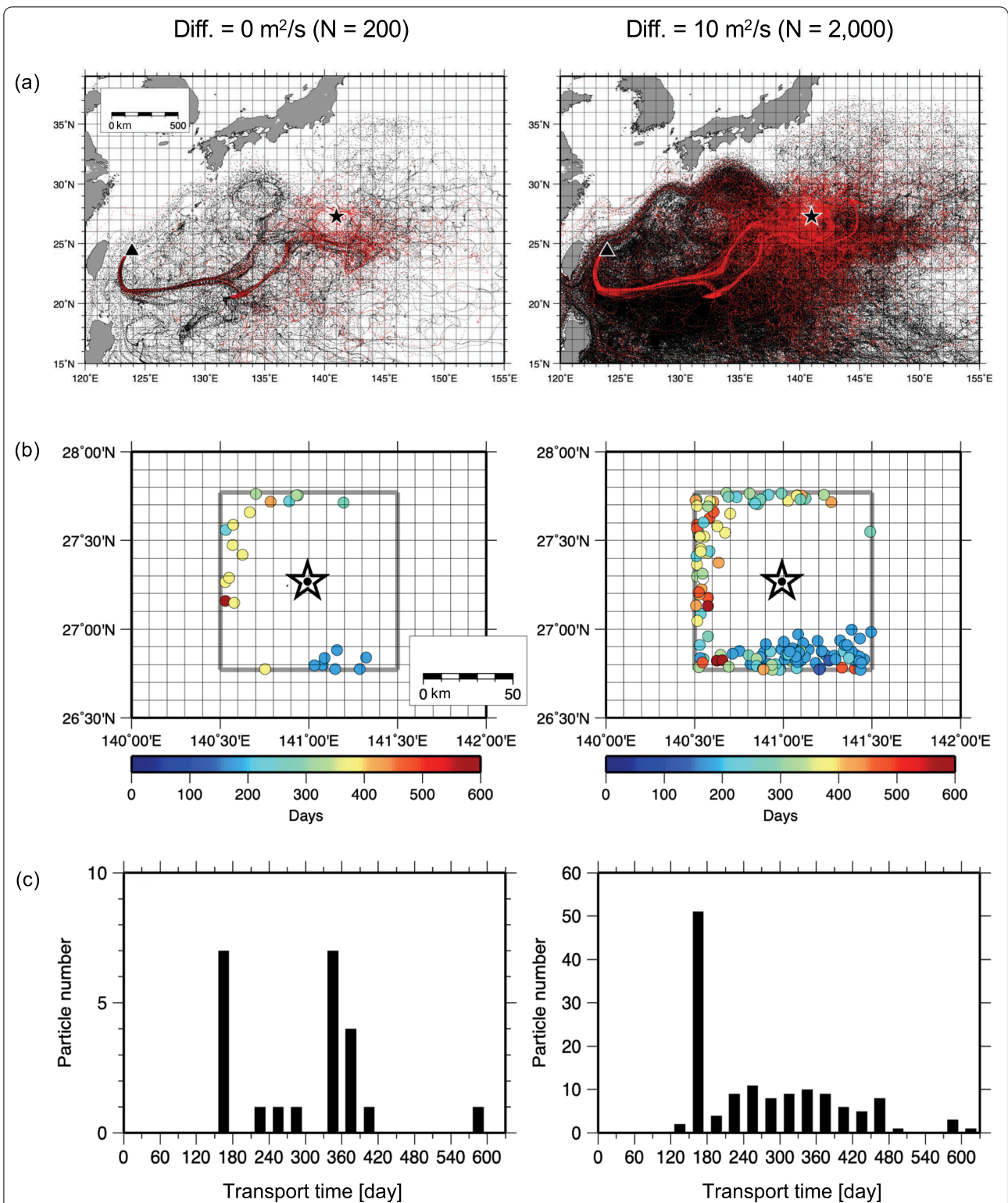


Fig. 3 Particle back-tracking simulations without (left, 200 particles) and with (right, 2000 particles) horizontal eddy diffusion (horizontal diffusion coefficient = 10 m²/s). **a** Daily particle positions from 18 February 2021 to 10 June 2019. Nishinoshima and Iriomote Islands are indicated by the 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

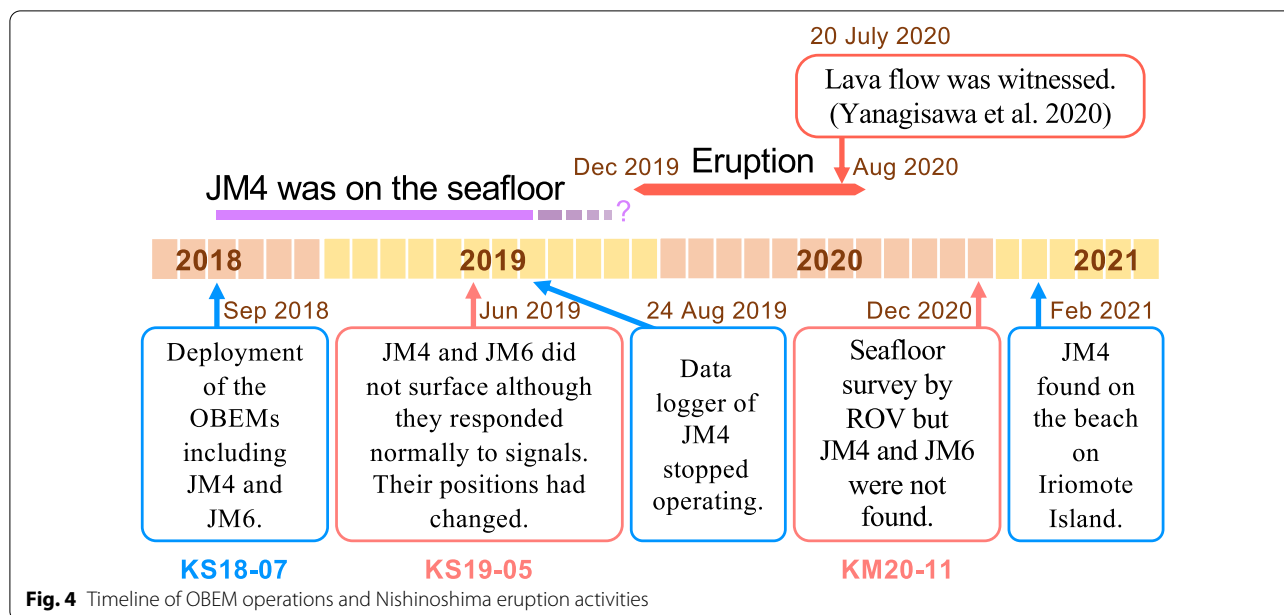


Fig. 4 Timeline of OBEM operations and Nishinoshima eruption activities

around Nishinoshima within the preceding 2 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, where mesoscale eddy activity is relatively strong (Aoki and Imawaki 1996); 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 mesoscale 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.

Based on our simulations both with and without eddy diffusion, Fig. 3c shows a peak in the 150–180 days bin, in which 2.6% and 3.5% of particles with and without eddy diffusion were achieved, respectively. These transport durations correspond to JM4 rising from the seafloor between 22 August and 21 September 2020. Because Nishinoshima began an eruptive period on 5 December 2019 that ceased at the end of August 2020 (Yanagisawa et al. 2020; Fig. 4), the peak is not consistent with the duration of this volcanic activity. By analyzing the observed data, Baba et al. (2020) inferred that one of five OBEMs deployed between October 2016 and December 2016 moved during the deployment period, which was

a quiet period between Nishinoshima eruptions in 2015 and in 2017. The other four OBEMs did not move, but the time series data of the three-component magnetic field and their instrumental tilts showed significant variations in the middle of November (Baba et al. 2020). They were not able to find related volcanic activities on Nishinoshima Island, so it is reasonable to consider the possibility of underwater activity (e.g., underwater volcanic activity or a slope collapse).

On the other hand, if the 180-day drift time corresponds to the release on 22 August 2020, the 180–441 days bins correspond to the release between 5 December 2019 and 21 August 2020, during the volcanic activity. The particles achieved in the 180–441 days bins account for 3.6% and 7.5% of the total number with and without eddy diffusion, respectively, which are larger than those in the 150–180 days bin. Indeed, Yanagisawa et al. (2020) observed a lava flow entering the sea on 20 July 2020 although there is no direct evidence such a lava flow made an OBEM move or release. In the future, to understand both above and under the sea surface volcanic activities, volcanic islands and submarine volcanoes should be studied by using underwater, onshore, airborne, and satellite instruments.

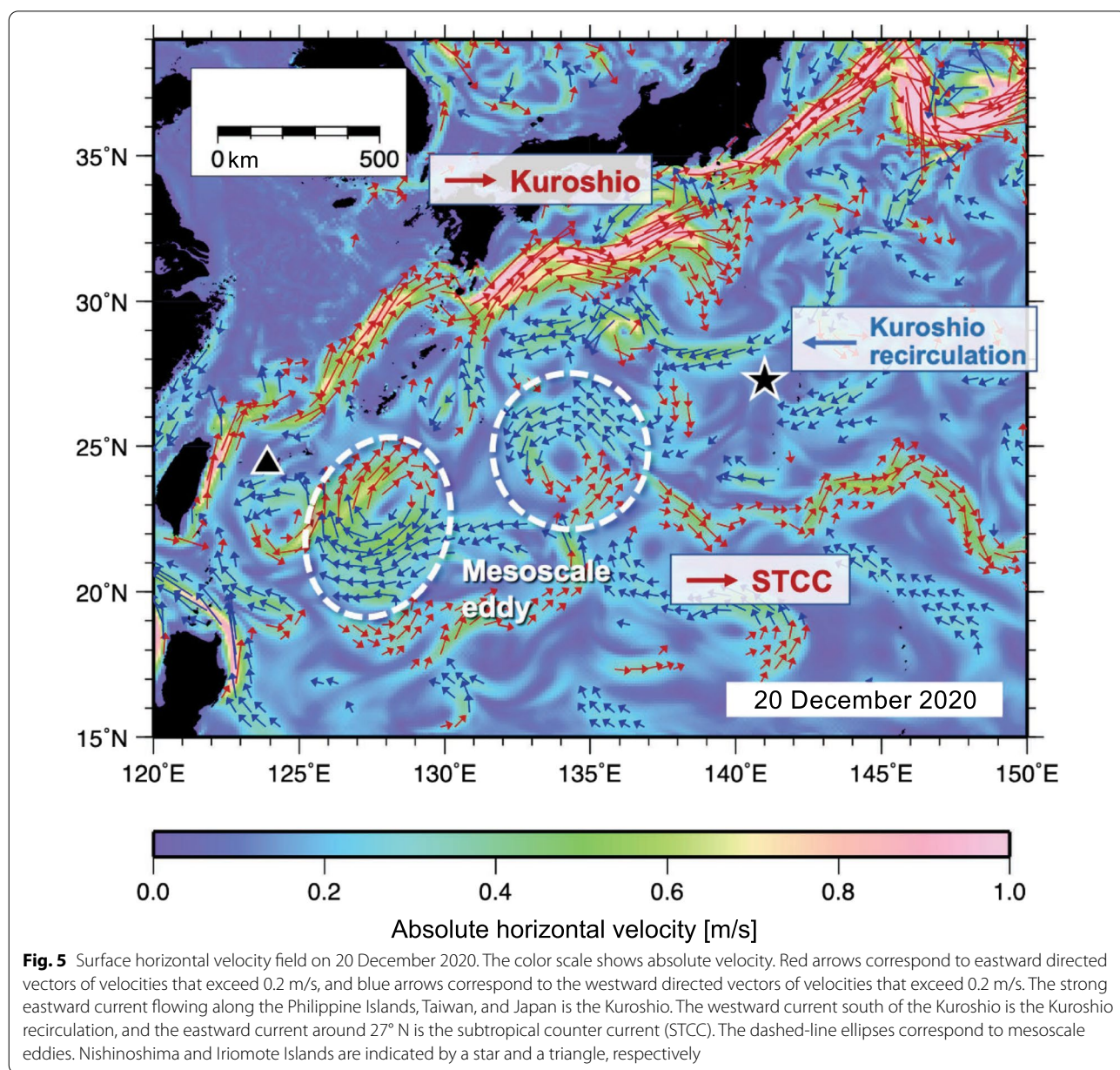
Implications for drifting pumices in the Ryukyu Islands

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 the westward current of the Kuroshio recirculation (Fig. 5). In addition to the dominant westward flow in the area between the Bonin and Ryukyu Islands, mesoscale eddies and the eastward-flowing subtropical counter current (STCC) may sometimes affect the drift paths and transport times of pumice (Fig. 5). In our experiments, some particles were trapped in eddies or

transported eastward from Nishinoshima for a certain period. On the other hand, depending on the location of mesoscale eddies and the STCC while it was drifting, the OBEM could have reached the Ryukyu Islands more quickly.

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 2021a). 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 presented here does not provide a forecast; it is a hindcasting simulation. In addition, though the wind effect was included as Ekman transport (Talley et al. 2011) in the velocity field that we used, the simulation did not consider the effect of direct wind drag on drifting pumice. Nonetheless, these simulation results and observational evidence that many pumices from Fukutoku-Oka-no-Ba, as well as the JM4 OBEM from Nishinoshima, arrived in the Ryukyu Islands suggest that rafts of pumice erupted in August 2021 should move westward and drift ashore in the Ryukyu Islands in several months.

In fact, in the beginning of October 2021, pumice rafts from the 2021 eruption of Fukutoku-Oka-no-Ba began to arrive in the Ryukyu Islands, where they have greatly interfered with the operation of ships and harbor functions, as reported by various social media outlets and news media. There is also concern that pumice rafts carried by the Kuroshio current will drift onto the coasts of the Honshu arc in the near future. The drift duration of pumice rafts from the 2021 Fukutoku-Oka-no-Ba eruption that drifted to Okinawa and the Amami Islands in the Ryukyu Islands was about 2 months. This drift duration is much shorter than that following the 1986 Fukutoku-Oka-no-Ba eruption (about 4 months) and also that of the drifting OBEM from Nishinoshima to Iriomote

Island (longer than four months) as estimated by our hindcasting simulation.

Potential causes of these large differences are the effects of surface windage and the STCC (Additional file 1: Fig. S3). The force driving drifting pumice depends on sea currents, windage, and waves (Jutzeler et al. 2014, 2020), but our drifting simulation for the OBEM did not take into account the effect of windage. The seasonal difference between the 1986 and 2021 eruptions (which occurred in January and August, respectively) might also have caused the overall direction of the windage to be different; in particular, typhoon No. 16 (Mindulle) in the area the drift path during September 2021 (Japan Meteorological Agency 2021b) might have sped up the westward drifting of the pumices. In addition, mesoscale eddy activity and the STCC, which show drastic seasonal and interannual variation (White et al. 1978; Kazmin and Rienecker 1996; Qiu and Chen 2010), are likely to be other important causes of the large difference in transport duration (Additional file 1: Fig. S3). Detailed investigations of actual observational cases and comparison of their results with numerical simulations of drifting pumices would improve understanding of the effect of windage and small sea currents and make it possible to construct better prediction models.

Conclusions

OBEM JM4 was deployed on the seafloor near Nishinoshima in September 2018 and was found ashore on Takana beach on Iriomote Island in February 2021, which motivated us to examine the circumstances of the OBEM on the seafloor and to simulate its drifting path and duration. Our simulation results indicated that materials drifting from Nishinoshima in the Bonin Islands have a 7–10% probability of being carried by westward ocean currents to Iriomote Island in the Ryukyu Islands. The drift durations of 180–441 days indicate that the release of the OBEM from the seafloor occurred during the eruption period between 5 December 2019 and 21 August 2020. In our simulation, releases of this duration were achieved by 3.6% of particles with eddy diffusion (7.5% without eddy diffusion). Also, 2.6% of particles with eddy diffusion (3.5% without eddy diffusion) traveled in 150–180 days, corresponding to the release time between 22 August and 21 September 2020, shortly after the eruption at Nishinoshima. 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.

Abbreviations

JMA: Japan Meteorological Agency; OBEM: Ocean bottom electromagnetometer; ROV: Remotely operated vehicle; JAMSTEC: Japan Agency for Marine-Earth Science and Technology; STCC: Subtropical counter current.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40623-021-01552-8>.

Additional file 1: Figure S1. Photo shows an OBEM float on the sea surface. It does not sink unless one of the glass spheres is broken or is flooded by water. **Figure S2.** (a) Initial particle positions around Iriomote Island in the particle back-tracking simulations. Dots are the initial particle positions, and the center of the triangle 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 S3.** (a) Two typical particle trajectories. The open star shows their confluence, and the black stars show their two end points, Nishinoshima and Iriomote Island. Dashed rectangular indicates the enlarged area. (b) Velocity field on 20 December 2020. The open star shows the confluence point. Red vectors in the left panel represent eastward flow, and blue vectors represent westward flow. The right panel shows the particle trajectories as same as Fig. S3a on the enlarged map of the area around the confluence point and the STCC. Shading highlights the remarkable eastward current. (c) Velocity field on 10 November 2020.

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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. TK contributed to the study of the drifting pumice. NT, HN, and TK contributed funding to this study. All authors contributed to discussions. All authors read and approved the final manuscript.

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Availability of data and materials

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

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

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

Author details

¹Research Institute for Marine Geodynamics (IMG), Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan. ²Research Institute for Value-Added-Information Generation (VAIG), Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan. ³PRESTO, Japan Science and Technology Agency (JST), 4-1-8 Honcho, Kawaguchi 332-0012, Japan. ⁴Earthquake and Volcano Research Center, Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan. ⁵Institute for Extra-Cutting-Edge Science and Technology Avant-Garde Research (X-Star), Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan.

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