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RESEARCH ARTICLE

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Simulated distributions of pumice rafts in Japan following eruptions at volcanic islands and submarine volcanoes

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Abstract

Voluminous pumice rafts produced by the 2021 phreatomagmatic eruption of Fukutoku-Oka-no-Ba, a submarine volcano located in the Izu-Bonin Islands, reached many Japanese ports and islands, damaging fisheries and hindering marine traffic and trade. This event emphasized the necessity for governments and stakeholders to develop plans in advance and prepare disaster mitigation measures before an eruption. To investigate when and to what extent pumice might intersect trade routes and arrive at islands after future eruptions, we conducted particle tracking simulations of eruptions at major volcanic islands and submarine volcanoes near Japan using the velocity field from the ocean reanalysis dataset. Seven major volcanoes that have produced pumice rafts in the past century were selected: the submarine volcano NNE of Iriomote Island, Izu-Tobu Volcanoes, Miyakejima, Bayonnaise Rocks, Nishinoshima, Kaitoku Seamount, and Fukutoku-Oka-no-Ba. We partly reproduced the distribution of pumice arrivals recorded after the 1986 Fukutoku-Oka-no-Ba eruption, demonstrating the potential effectiveness of the simulations. We report likely pumice raft arrivals and drifting durations for the investigated eruptive scenarios, which may aid future risk assessments for pumice arrivals.

Keywords Pumice, Submarine volcano, Fukutoku-Oka-no-Ba, Particle tracking experiment, Dispersion, Natural hazard

1 Introduction

Pumice is generated by the vesiculation and quenching of silicic magma during volcanic eruptions. Due to its low density, pumice is often buoyant in water, and pumice erupted from volcanic islands or submarine volcanoes is occasionally found adrift at sea (Kato 2009; Bryan et al. 2012), often in large (a few square meters to several hundreds of square kilometers), mobile accumulations called pumice rafts (e.g., Jutzeler et al. 2014, 2020). Some pumice rafts drift several thousands of kilometers over months to years, whereas others sink to the seafloor or become stranded on shorelines (Jutzeler et al. 2014; Fauria et al. 2017; Fauria and Manga 2018; Whitham and Sparks 1986). These rafts have been recognized as natural hazards impacting human life, local industries (impeding marine traffic and operations in harbors and ports), and coastal ecosystems (Hurlbut and Verbeek 1887; Jutzeler et al. 2014, 2020; Oppenheimer 2003; Sigurdsson et al. 1987).

The 13 August 2021 phreatomagmatic eruption of Fukutoku-Oka-no-Ba submarine volcano (the Izu-Bonin islands, Japan) erupted a large volume of pumice that accumulated in rafts (e.g., Yoshida et al. 2022a; Maeno et al. 2022; Fauria et al. 2023) and drifted to the Ryuku Islands ~ 1400 km

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to the west, arriving about two months after the eruption (Japan Coast Guard 2021; Geological Survey of Japan 2021; Tada et al. 2021). The pumice rafts impeded local activities and industries and damaged ecosystems for several months after arrival, with some local effects persisting until the present day (e.g., Yoshida et al. 2022a, b, c; Ohno et al. 2022), becoming a temporary societal problem in Japan that was widely reported in various media. For example, pumice rafts blocked harbors by covering coasts and surface waters, and individual pumice clasts obstructed the water intakes of motor vessels and damaged hulls and propellers, hindering the operation of fishing boats and maritime traffic. In addition, the pumice rafts impacted the fish farming and tourism industries by killing fish and rendering beaches inaccessible due to abundant flotsam, respectively. Some papers also reported significant impacts on coastal ecosystems (e.g., Akiyama et al. 2022; Ohno et al. 2022; Sato et al. 2022).

To reduce the damage caused by pumice rafts, advanced preparation is essential, including numerical simulations predicting their movements. Jutzeler et al. (2014, 2020) demonstrated that combining satellite observations of pumice raft movements with real-time predictive simulations is effective for predicting raft drift directions. More recently, Asami and Takahashi (2023) presented a simulation model that predicts pyroclast behavior in the marine environment with practical accuracy. Because it takes time for local government agencies and stakeholders to prepare mitigation measures, it is important to estimate the likelihood, magnitude, and drift duration of pumice rafts for a target location using predictive numerical simulations before a potential eruption.

Here, we conducted numerical simulations of drifting pumice rafts to clarify the likelihood and duration of drift to important areas along the Japanese coast. We focused on volcanic islands and submarine volcanoes near Japan that have produced giant pumice rafts in past eruptions. We first conducted a numerical drifting simulation for the 1986 Fukutoku-Oka-no-Ba eruption to validate the effectiveness of our simulation by comparing the results to observations of pumice raft arrivals at several locations in Japan. Then, we conducted the same drifting simulations for potential future eruptions at seven volcanoes known to have produced pumice rafts. By dissipating the tracked particles from the starting point each month over several tens of years, we incorporated seasonal and annual ocean current variations into the analysis.

2 Data and methods

2.1 Volcanic islands, submarine volcanoes, and target areas

We conducted two particle simulation experiments. Hereafter, we call the simulated particles 'virtual pumice clasts'. In the first experiment, virtual pumice clasts were tracked from Fukutoku-Oka-no-Ba to Iriomote Island, Okinawa, Genkainada, Bungo Channel, off Cape Shionomisaki, and Hahajima Island (Table 1). The purpose of this experiment was to validate our simulation by comparing the simulated pumice raft arrival dates at the six target locations with those that followed the January 1986 Fukutoku-Oka-no-Ba eruption, which produced floating pumice during 18–21 January (Ossaka 1991). Pumice clasts produced by that eruption were observed at Hahajima on 15 March, Okinawa and Iriomote Island in late May, Bungo Channel on 26 June, off Cape Shionomisaki in August, and at Genkainada in October (Yoshida et al. 1987; Kato 1988).

In the second set of experiments, virtual pumice clasts were tracked from major volcanic islands and submarine volcanoes near Japan known to have produced pumice rafts in the past few decades. We selected seven volcanoes: the submarine volcano NNE of Iriomote Island (V1); the Izu-Tobu volcanic range (V2); Miyakejima (V3); Bayonnaise Rocks (V4); Nishinoshima (V5); Kaitoku Seamount (V6); and Fukutoku-Oka-no-Ba (V7; Table 2). From these volcanoes, we released virtual pumice clasts to 16 target areas (Table 3) to estimate pumice raft arrivals. We selected 11 areas important to sea traffic based on the ship-tracking site https://www.marinetraffic.com/: Osumi Strait; Koshiki Strait; Bungo Channel, off Cape Shionomisaki, Irago Channel; off Izuoshima Island; off Cape Omaezaki; off Onahama; off Sakaiminato; Wakasa Bay; and Tsugaru Strait. We selected Iriomote Island, Minami-Daito Island, Okinawa, and Amami Oshima Island because their economies depend on marine activities and beach tourism, and Chichijima Island because the only transportation to the island is by sea. The locations of the selected volcanoes and target areas are shown in Fig. 1. Figure 1 also shows the paths of the Kuroshio Current and the Kuroshio Recirculation, which are known to affect pumice dispersals (e.g., Tada et al. 2021).

Table 1 Target areas selected for the first particle tracking simulation experiments

Name	Latitude, longitude
Iriomote Island	23.98–24.58°N, 123.55–124.15°E
Okinawa	26.00–27.00°N, 127.47–128.47°E
Genkainada	33.30–34.00°N, 129.35–130.35°E
Bungo Channel	32.87–33.27°N, 131.83–132.53°E
Off Cape Shionomisaki	33.20–33.50°N, 135.46–136.06°E
Hahajima Island	26.35–26.95°N, 141.85–142.45°E

Table 2 Volcanic island and submarine volcano pumice sources used in this study. Descriptions are based on Ossaka (1991)

Name	Code	Abbrev.	Latitude, longitude	Years in which pumice rafts were produced
Submarine volcano NNE of Iriomote Island	V1	IR	24.5°N, 123.8°E	1924
Izu-Tobu Volcanoes	V2	IZ	35.0°N, 139.1°N	1989
Miyakejima	V3	MI	34.1°N, 139.5°E	1983
Bayonnaise Rocks	V4	BA	31.9°N, 140.0°E	1952–1953, 1970
Nishinoshima	V5	NI	27.2°N, 140.9°E	1973–1974
Kaitoku Seamount	V6	KA	26.1°N, 141.1°E	1981
Fukutoku-Oka-no-Ba	V7	FU	24.3°N, 141.5°E	1917, 1986, 2021

Table 3 Target areas selected for the second particle tracking simulation experiments

Name	Latitude, longitude
(A) Iriomote Island	23.98–24.58°N, 123.55–124.15°E
(B) Okinawa	26.00–27.00°N, 127.47–128.47°E
(C) Amami Oshima	27.64–28.64°E, 128.82–129.82°E
(D) Minami-Daito Island	25.57–26.17°N, 130.92–131.52°E
(E) Koshiki Strait	31.54–32.14°N, 129.88–130.18°E
(F) Osumi Strait	30.73–31.23°N, 130.70–131.20°E
(G) Bungo Channel	32.87–33.27°N, 131.83–132.53°E
(H) Off Cape Shionomisaki	33.20–33.50°N, 135.46–136.06°E
(I) Irago Channel	34.07–34.67°N, 136.88–137.38°E
(J) Off Cape Omaezaki	34.40–34.70°N, 137.94–138.34°E
(K) Off Izuoshima Island	34.60–35.10°N, 138.86–139.86°E
(L) Off Onahama	37.10–37.70°N, 141.00–141.30°E
(M) Off Sakaiminato	35.48–35.88°N, 132.75–133.35°E
(N) Wakasa Bay	35.46–35.86°N, 135.20–136.10°E
(O) Tsugaru Strait	41.20–41.80°N, 139.92–141.07°E
(P) Chichijima Island	26.77–27.37°N, 141.91–142.51°E

2.2 Particle tracking experiments

In our particle tracking simulations, we used horizontal velocities, sea temperatures, and salinities from the ocean reanalysis dataset, a daily dataset with a horizontal resolution of $0.1^\circ \times 0.1^\circ$ provided by the operational numerical weather prediction of the Japan Meteorological Agency (JMA 2013; http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2019-nwp/index.htm). The dataset region is 117°E–160°W, 15°N–65°N. We released virtual pumice clasts at 0.5 m depth in all simulations because pumice clasts are usually observed drifting on the sea surface.

Virtual pumice 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 virtual pumice location (x and y being the east–west and north–south coordinates, respectively) at time step n; u_n and v_n are the eastward and northward velocities, respectively; and Δt is the time step, taken here to be 20 min. (λ_x, λ_y) is the random walk displacement represented by Eq. (3), in which $(A_{\mathrm{H}}^x, A_{\mathrm{H}}^y)$ and P_{N} are the horizontal eddy diffusion coefficients and the probability function of the normal distribution, respectively. The magnitude of the lateral diffusivity is 100–10,000 m²/s (Nummelin et al. 2021). We conducted tests using various diffusivities within that range and compared the results with the record of pumice raft arrivals from the 1986 Fukutoku-Oka-no-Ba eruption. Based on the results of those tests, we set both A_{H}^x and A_{H}^y to be 1,000 m²/s in all experiments.

In the first experiment, batches of 49,000 virtual pumice clasts were released from Fukutoku-Oka-no-Ba once per day during 18–21 January 1986. In the second set of experiments, batches of virtual pumice clasts were released from the seven selected volcanoes on the 15th day of each month from 1982 to 2015. Batch sizes were 49,000 virtual pumice clasts for V1 (the submarine volcano NNE of Iriomote Island), V3 (Miyakejima), V4 (Bayonnaise Rocks), V5 Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba), and 18,000 virtual pumice clasts for V2 (the Izu-Tobu range). We defined a square area (each side measuring 0.7°) containing 49 grid squares centered at each volcano. The grid spacing was 0.1°, the same as the horizontal resolution of the ocean dataset. One thousand virtual pumice clasts were put in each grid. We selected only 18 grids near V2 (Izu-Tobu), because that volcano is close to land, thus the batch size was 18,000 virtual pumice clasts for V2. In

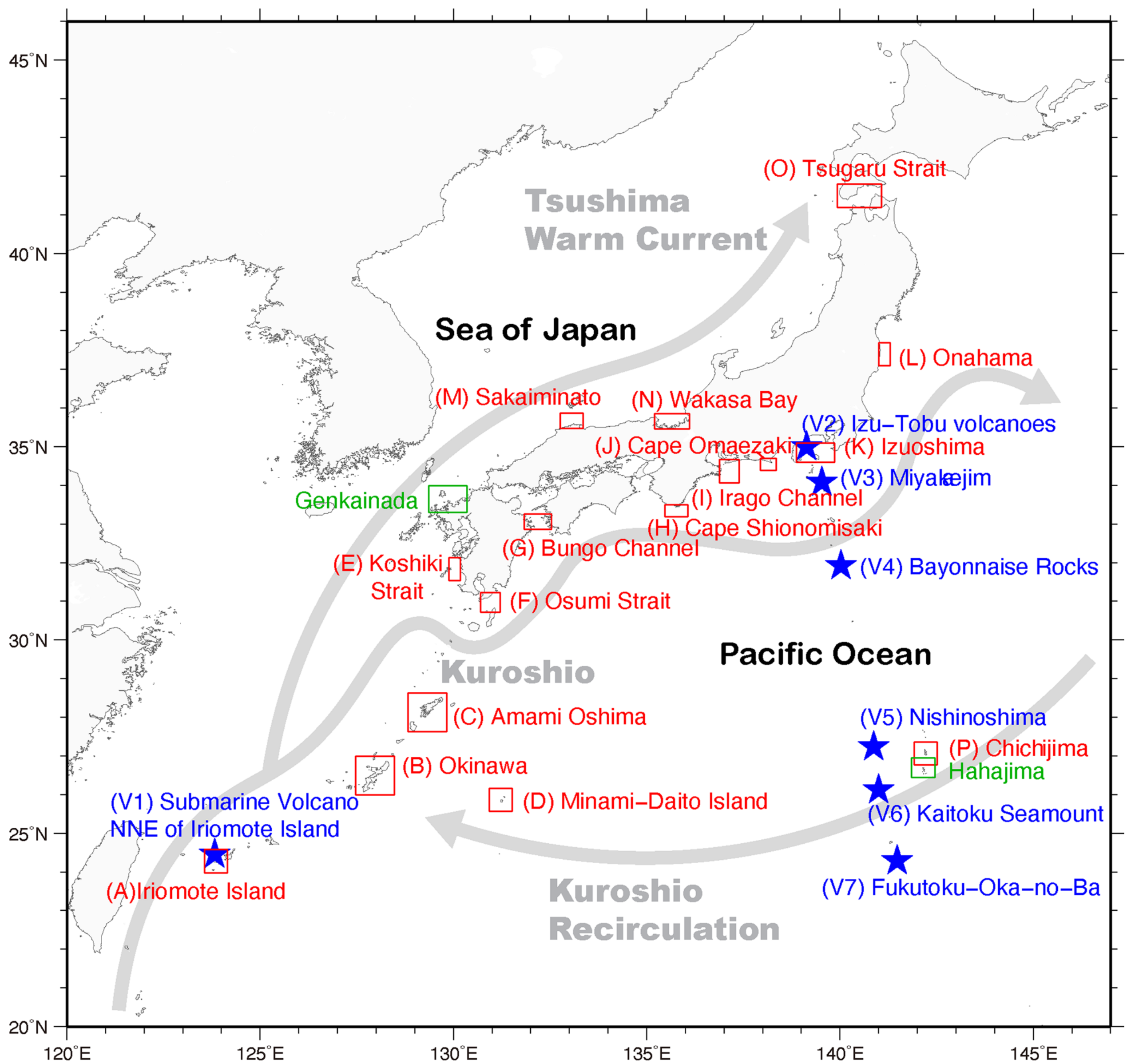


Fig. 1 Submarine volcano and volcanic island sources (blue stars) and target areas (red squares) used in our particle tracking simulations. Green squares are target areas that were only used in our simulation of the 1986 Fukutoku-Oka-no-Ba pumice raft. Major ocean currents around Japan are also shown

both experiments, the virtual pumice clasts were assigned drift duration of 365 days, because drifting pumice clasts tend to weather into smaller fragments that are no longer buoyant within a year (Kuroda 1987). The location of each virtual pumice clast was recorded every day, and the first day that any virtual pumice clast arrived in a target area was recorded as a pumice raft arrival. Some virtual pumice clasts continue to drift, and they might arrive at another target area. The others stop as landing when the surface horizontal velocity of the nearest grid of them is zero. In this study, we did not consider the remobilization process that the landing pumices restart to drift.

We calculated the monthly and yearly mean values of the number of virtual pumice clasts arriving at each target location and their drift durations. Monthly means were taken as the average from 1982 to 2015 for each month, and yearly means as the average monthly mean value from January to December. We considered the mean drift duration and the shortest drift duration (i.e., the shortest recorded time during all tracking experiments). We confirmed that the mean drift durations roughly correspond with the median value of the drift durations from its distributions for all paths. Thus, the particles that are transported to the target area in the mean drift duration could be considered as a large majority. The question of whether disaster mitigation measures should focus on the shortest or mean drift duration is apt, because an amount of pumice large enough to impede marine traffic will not always reach a port along the shortest route. Thus, we regard both the mean and shortest times as approximate times to be alert for pumice arrivals. For the first experiment, in which we validated our particle tracking simulation method, we compared the mean and shortest drift durations with the dates on which pumice clasts were reported in the target areas for the first time, because those are the only records of pumice arrivals.

3 Results

3.1 Pumice arrivals from Fukutoku-Oka-no-Ba in 1986

The number of virtual pumice clasts that arrived at each target area during each month and the month in which pumice clasts were reported in the area for the first time are illustrated in Fig. 2. Virtual pumice clasts reached Iriomote Island, Okinawa, and Genkainada later than the recorded arrivals, whereas virtual pumice clasts reached Cape Shionomisaki and Hahajima earlier than the recorded arrivals. The closest arrival dates to the record are 19 July (first reported pumice arrival late May) for Iriomote Island, 6 June (reported in late May) for Okinawa, 22 June (reported 28 June) for Bungo Channel, 5 August (reported in August) for Cape Shionomisaki, 8 November (reported in October) for Genkainada, and 15 March (reported 15 March) for Hahajima Island. The virtual pumice paths from Fukutoku-Oka-no-Ba to the arrival locations are shown in Fig. 3. These are the paths in which the pumice arrived at the nearest date to the record date. Except for Iriomote Island and Genkainada, the discrepancies between the simulated and recorded arrival dates are less than 1 month, although the actual discrepancy at Genkainada might also be less than 1 month because only the arrival month was recorded. Of the 49,000 virtual pumice clasts released from Fukutoku-Oka-no-Ba every day during the period 18–21 January 1986, 117 (0.060%) arrived at Iriomote Island, 215 (0.110%) at Okinawa, 7 (0.004%) at Genkainada, 22 (0.011%) at Bungo Channel, 140 (0.071%) at Cape Shionomisaki, and 14,756 (7.53%) at Hahajima Island.

3.2 Pumice drift paths for potential eruptions from 7 volcanoes

Figure 4 shows example drift paths for 50 randomly selected virtual pumice clasts released from V1 (the submarine volcano NNE of Iriomote Island) in March 2004; similar examples for other volcanoes are provided in the Appendix. The yearly mean number of virtual pumice clasts released from each source volcano that arrived at each target area and their yearly mean drift durations (i.e., numbers and durations averaged over the entire study period) are illustrated in Fig. 5.

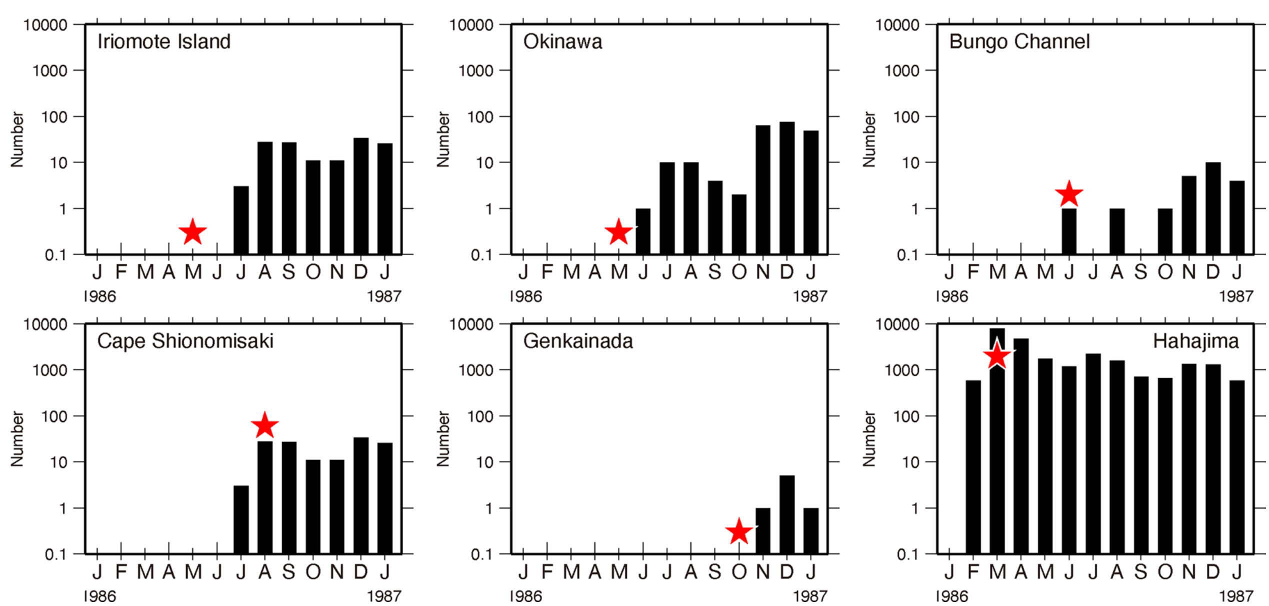


Fig. 2 Number of virtual pumice clasts that arrived at each target area from the Fukutoku-Oka-no-Ba 1986 eruption. The red stars represent the dates on which the first pumice clasts were reported at each location

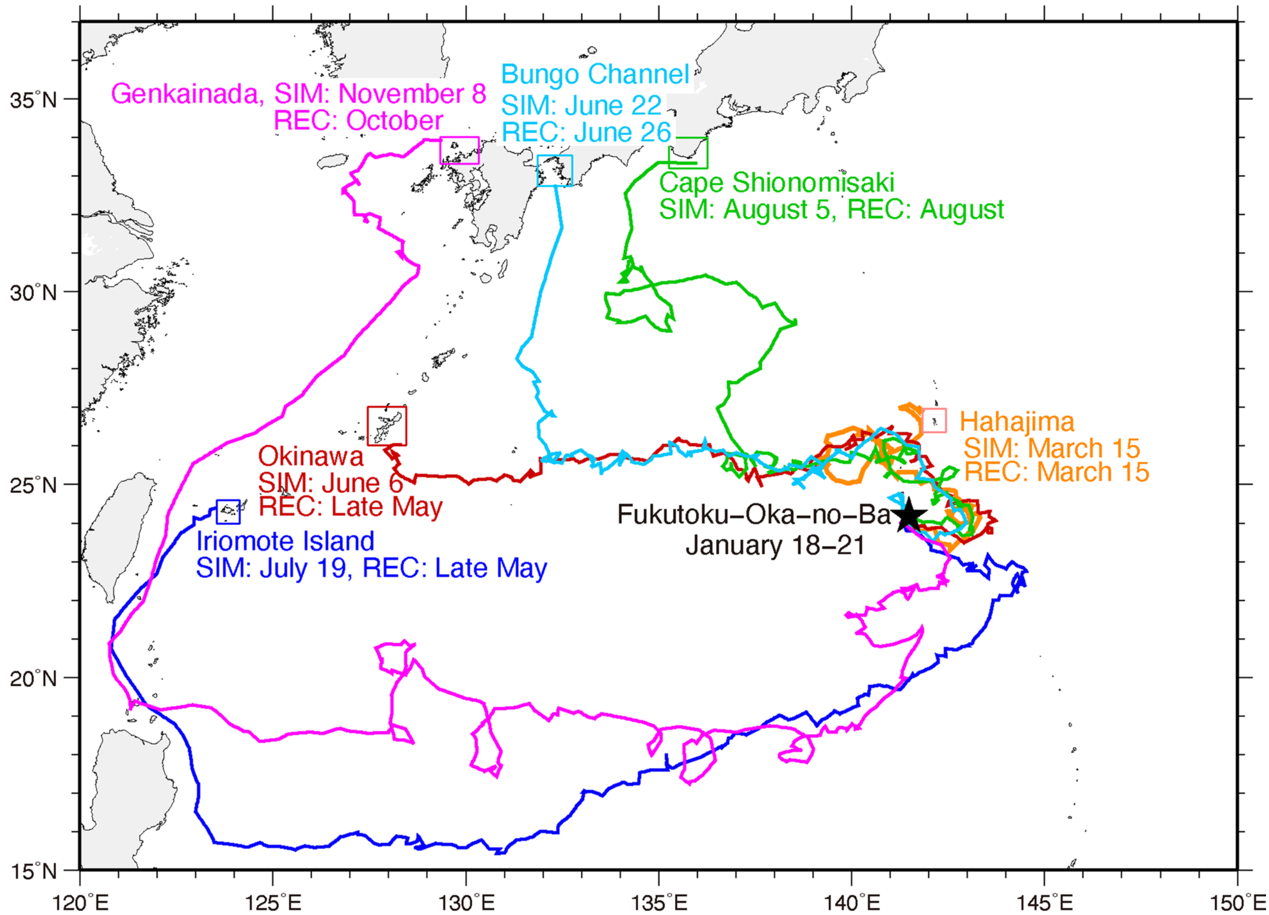


Fig. 3 Simulated trajectories and arrival dates of virtual pumice clasts released during 18–21 January 1986 from Fukutoku-Oka-no-Ba (black star). The illustrated paths are those of the virtual pumice clasts that arrived nearest the date that pumice clasts were reported for the first time. Simulated and recorded arrival dates are denoted by 'SIM' and 'REC,' respectively

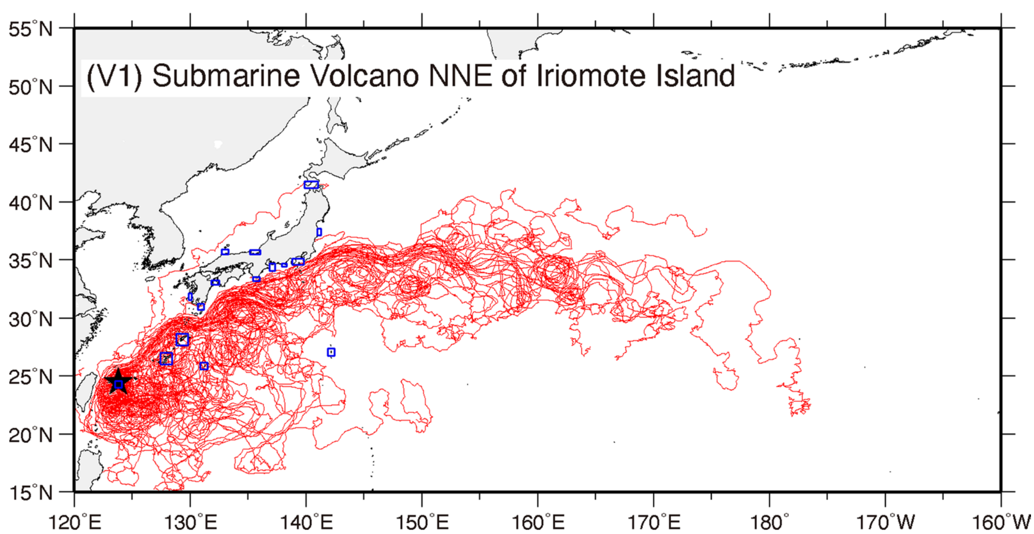
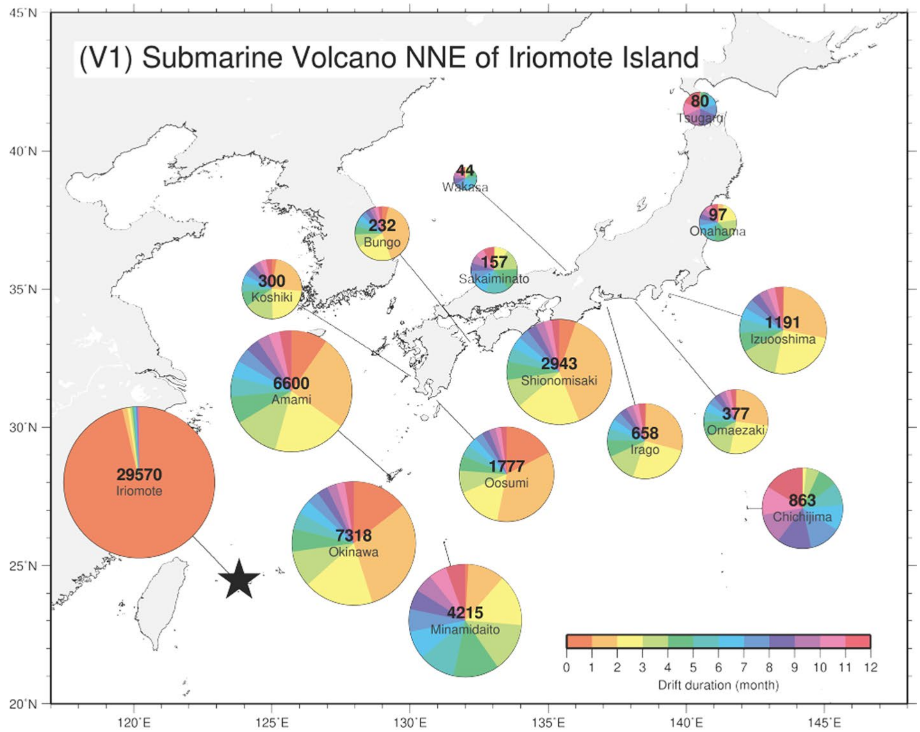


Fig. 4 Simulated drift paths of 50 randomly selected virtual pumice clasts released from V1 (the submarine volcano NNE of Iriomote Island, indicated by the black star) on 15 March 2004. Blue rectangles indicate target areas



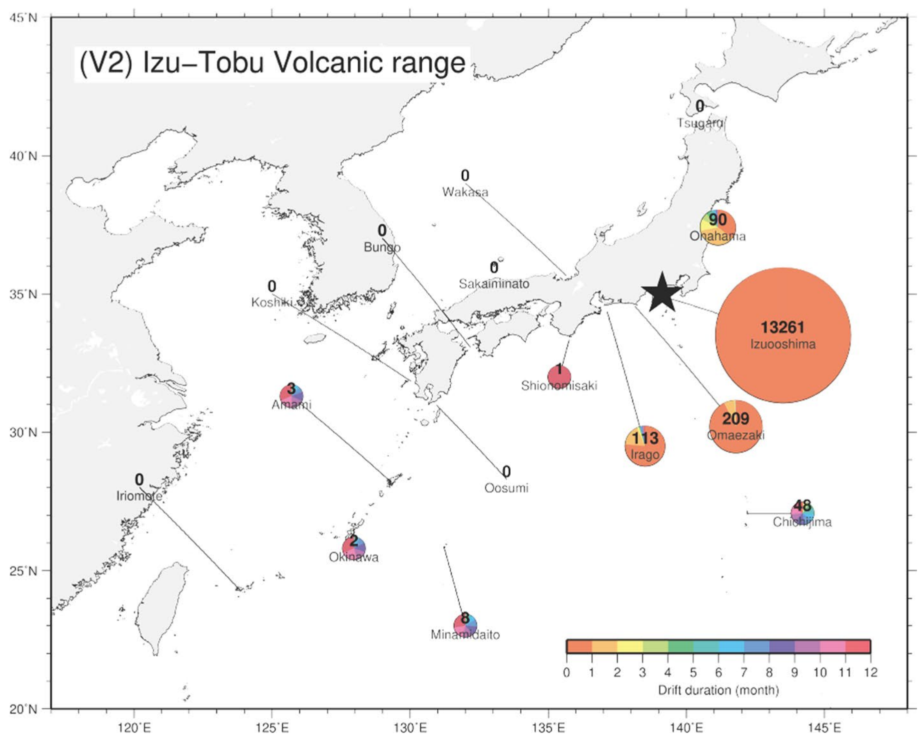
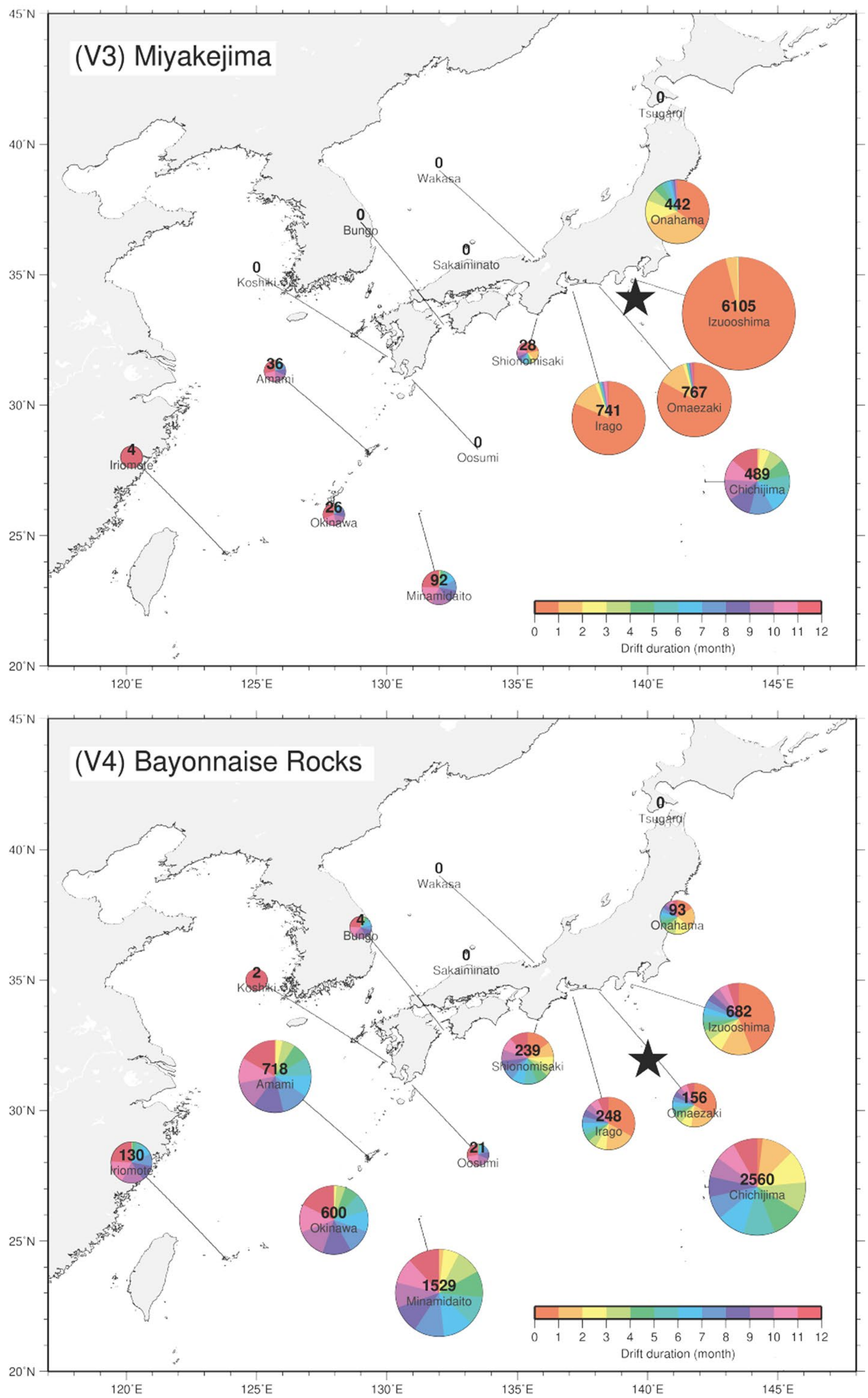


Fig. 5 The average number of virtual pumice clasts arriving at each target area after being released from (V1) the submarine volcano NNE of Iriomote Island, (V2) the Izu-Tobu volcanic range, (V3) Miyakejima, (V4) Bayonnaise Rocks, (V5) Nishinoshima, (V6) Kaitoku Seamount, and (V7) Fukutoku-Oka-no-Ba. In each frame, the black star represents the location of the volcano source. The numbers reported were averaged over all simulations; for example, an average of 7318 of the total 49,000 virtual pumice clasts released from the submarine volcano NNE of Iriomote Island were transported to Okinawa per simulation. The radii of the pie charts are proportional to the logarithm of the average number of virtual pumice clasts that arrived at each target area. The color scale of the pie charts indicates the average drift duration of each proportion of the virtual pumice clasts that arrived. If the mean number of virtual pumice clasts was below 1, a value of 0 is reported



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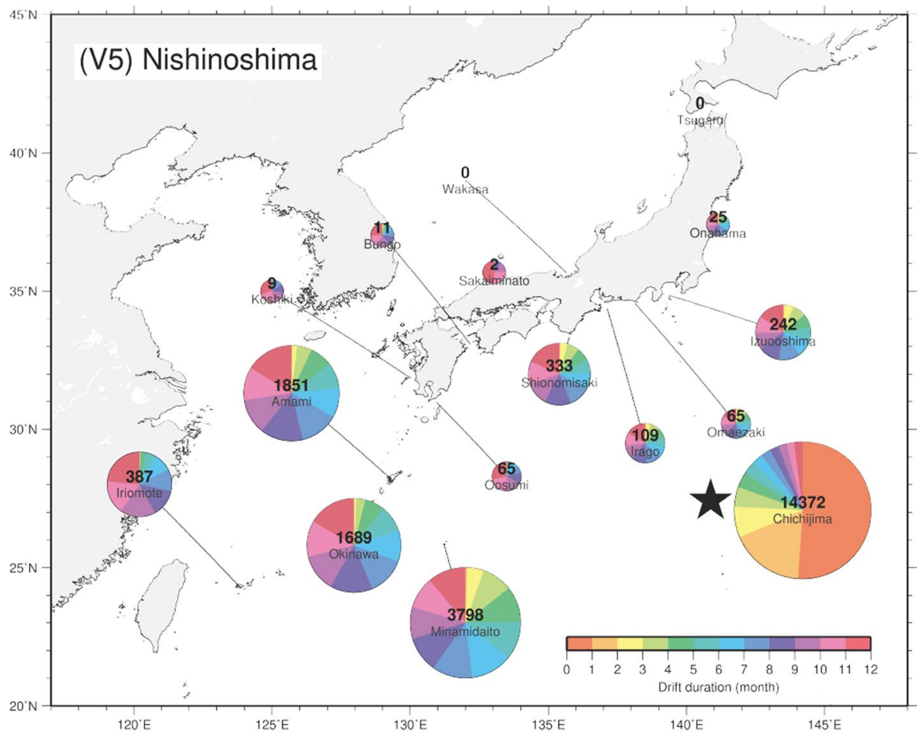

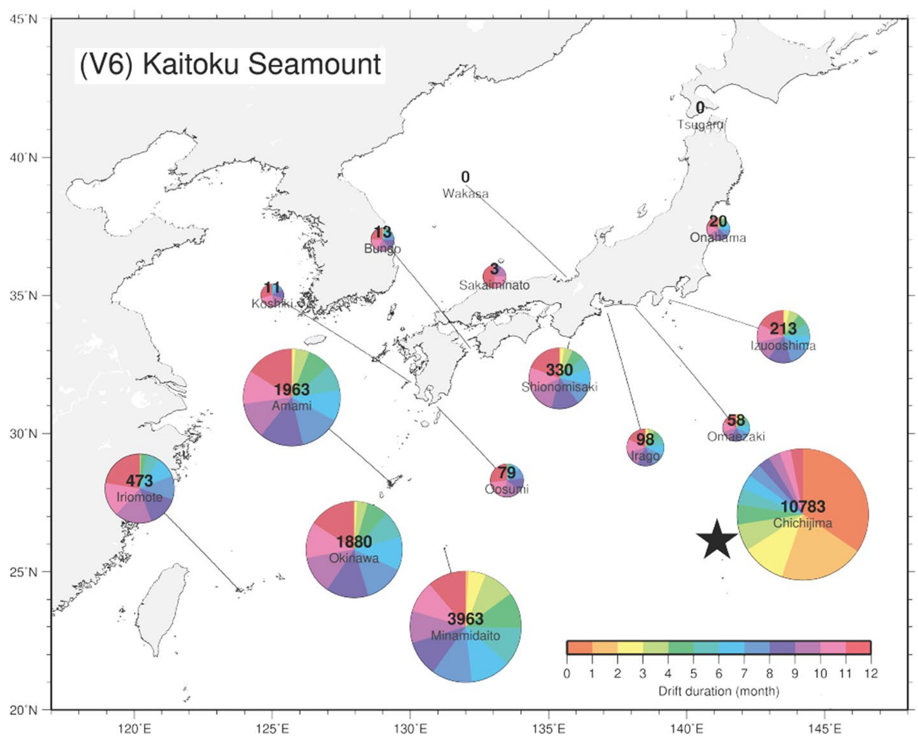

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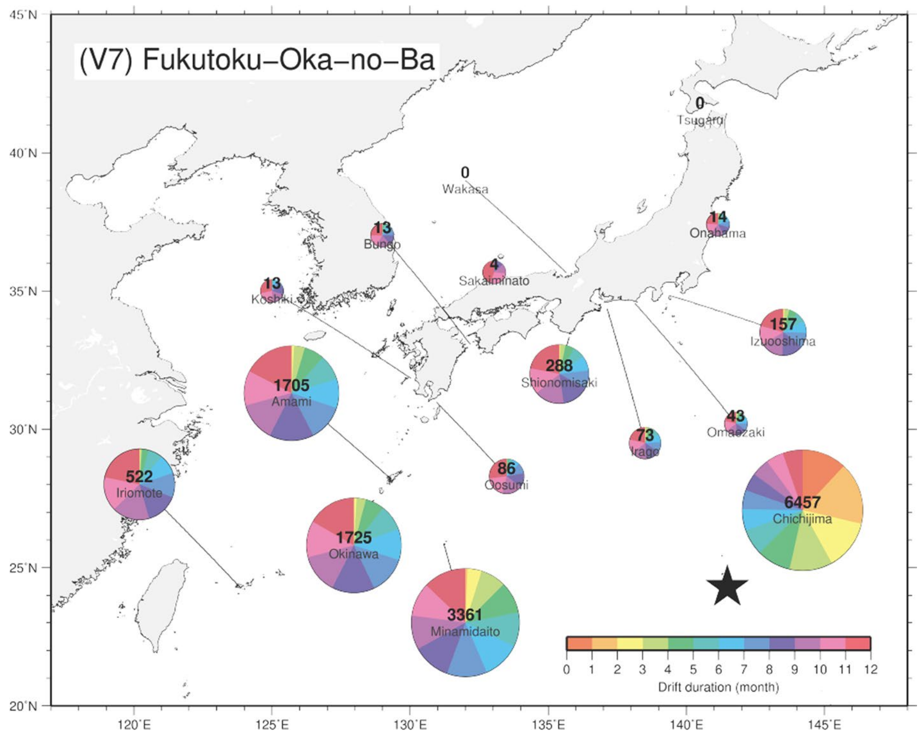

Fig. 5 continued

Greater numbers of virtual pumice clasts arrived at target areas along or in the Pacific Ocean than at target areas along or in the Sea of Japan because, other than V1 (the submarine volcano NNE of Iriomote Island), all investigated volcanoes are in the Pacific Ocean. To arrive in the Sea of Japan, virtual pumice clasts must become entrained in the Tsushima Warm Current (Fig. 1). Because the submarine volcano NNE of Iriomote Island is located south of the divergence of the Kuroshio Current and Tsushima Warm Current, virtual pumice clasts released there are more easily transported to targets in the Sea of Japan (M, Sakaiminato; N, Wakasa Bay; and O, Tsugaru Strait) than are virtual pumice clasts released from other volcanoes (Figs. 1, 4, 5a).

Virtual pumice clasts released from V2 (Izu-Tobu range), V3 (Miyakejima), and V4 (Bayonnaise Rocks) mainly arrived at eastern target areas (H, Cape Shionomisaki; I, Irago Channel; K, Izuoshima Island; and L, Onahama; Fig. 5b–d). These virtual pumice clasts were rarely transported to the Sea of Japan because their source volcanoes are near the mainstream of the Kuroshio Current. Larger numbers of virtual pumice clasts were transported to western target areas (A, Iriomote Island; B, Okinawa; C, Amami Oshima; D, Minami-Daito Island; and H, Cape Shionomisaki) from V4 (Bayonnaise Rocks) than from V2 (Izu-Tobu range) and V3 (Miyakejima), seemingly due to their locations relative to the axis of the Kuroshio Current: V2 and V3 are on the inshore side of the Kuroshio axis, whereas V4 is on the offshore side (Fig. 1). Some virtual pumice clasts released from V4 became entrained in the Kuroshio Recirculation, a westward current on the offshore side of the mainstream Kuroshio Current (Fig. 1). Westward transport by the Kuroshio Recirculation is also notable for virtual pumice clasts released from V5 (Nishinoshima), V6 (Kaitoku Seamount,) and V7 (Fukutoku-Oka-no-Ba) (Fig. 5e–g). Some virtual pumice clasts transported from these volcanoes by the Kuroshio Recirculation arrived near A (Iriomote Island) and were transferred to the Tsushima Warm Current, ultimately reaching M (Sakaiminato). A large proportion of the virtual pumice clasts from these three volcanoes was transported to nearby P (Chichijima Island).

The yearly and monthly means and standard deviations of the number of virtual pumice clasts that arrived at each target area from each volcano source are illustrated in Fig. 6. The range of interannual variations (black symbols) are within an order of magnitude except for virtual pumice clasts from V3 (Miyakejima) arriving at A (Iriomote Island), H (Cape Shionomisaki), I (Irago Channel), and J (off Cape Omaezaki) (Fig. 6A, H–J); virtual pumice clasts from V2 (Izu-Tobu range) arriving at C (Amami Oshima), I (Irago Channel), and J (off Cape Omaezaki) (Fig. 6C, I, J); and virtual

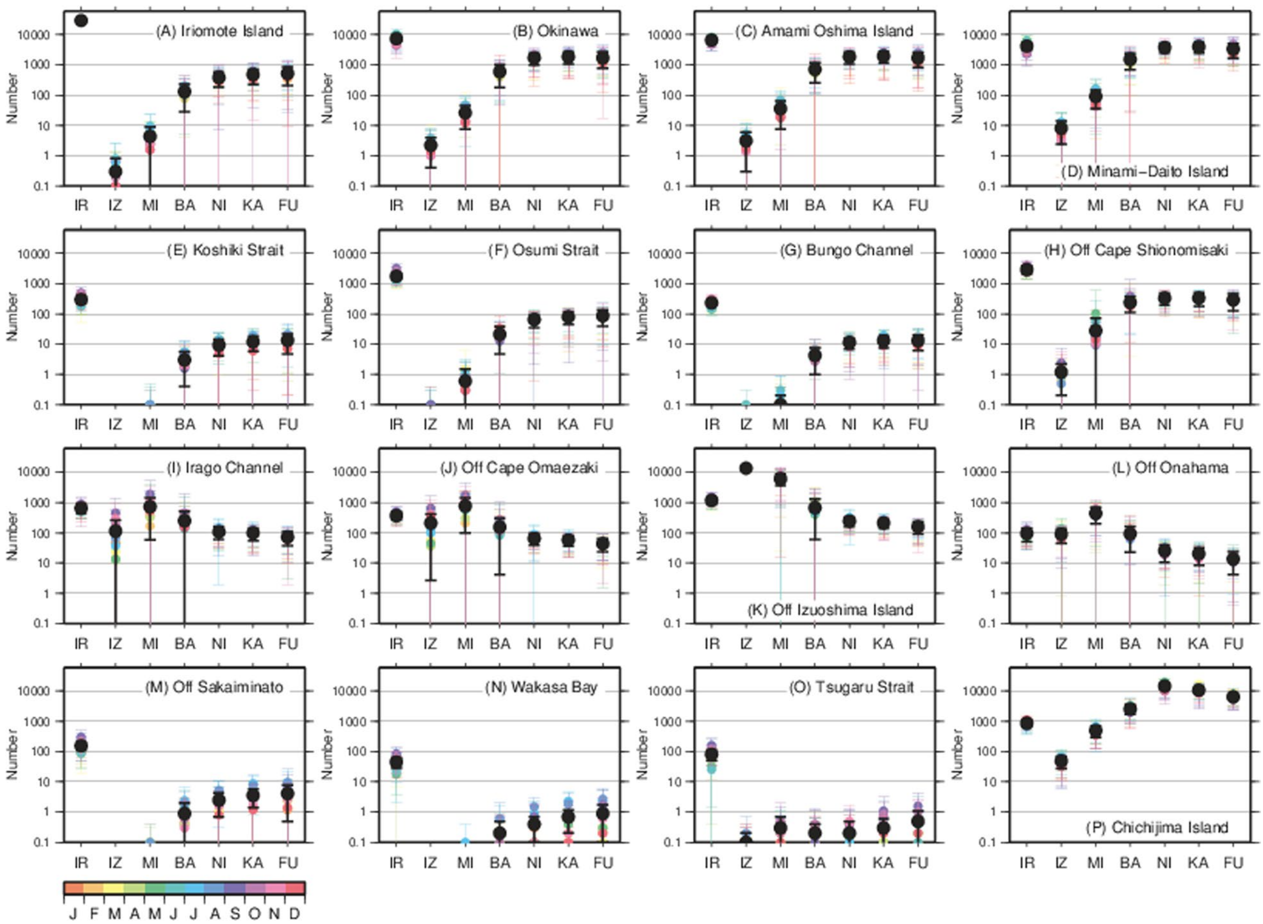

Fig. 6 Means and standard deviations (SDs) of the number of virtual pumice clasts that arrived at each target area from (V1) submarine volcano NNE of Iriomote Island (IR), (V2) Izu-Tobu volcanic range (IZ), (V3) Miyakejima (MI), (V4) Bayonnaise Rocks (BA), (V5) Nishinoshima (NI), (V6) Kaitoku Seamount (KA), and (V7) Fukutoku-Oka-no-Ba (FU). Black symbols and error bars are yearly means and SDs from 1982 to 2015; colored symbols and error bars are monthly means and SDs from 1982 to 2015

pumice clasts from V4 (Bayonnaise Rocks) arriving at I (Irago Channel), J (off Cape Omaezaki), K (off Izuoshima Island), and M (off Sakaiminato) (Fig. 6I–K, M). We expected the number of virtual pumice arrivals to change depending on the season because the seasonal monsoon should affect the flow field. For all paths, the yearly and monthly means of the number of virtual pumice arrivals are within an order of magnitude of each other; however, the monthly standard deviations of some paths are markedly larger than the yearly standard deviations, meaning that the interannual variation was large in specific months. We selected the paths and months for which the yearly mean virtual pumice number was larger than 100 and the monthly standard deviation was more than twice as large as the yearly standard deviation (Table 4). For the paths from V2 (Izu-Tobu Volcanoes), V3 (Miyakejima), and V4 (Bayonnaise Rocks) to H (off Cape Shionomisaki), I (Irago Channel), J (off Cape Omaezaki), and K (off Izuoshima Island), the standard deviations are large except during July–August. For the paths from V3 (Miyakejima) and V4 (Bayonnaise Rocks) to A (Iriomote Island), B (Okinawa), C (Amami Oshima), and D (Minami-Daito Island), and for the paths from V5 (Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba) to A (Iriomote Island), the standard deviations are large from October to December.

As we expected, the virtual pumice drift durations generally depended on the distance between the volcanoes and the target areas (Fig. 7). The virtual pumice drift durations also showed seasonal effects. Virtual pumice clasts released from V5 (Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba) during the summer generally exhibited notably shorter drift durations than those released during the winter. Seasonality is also apparent in the interannual

Table 4 Paths for which the yearly mean virtual pumice number was larger than 100 and the monthly standard deviation was more than twice as large as the yearly standard deviation

Volcano	(A) Iriomote	(B) Okinawa	(C) Amami	(D) M.Daito	(E) Koshiki	(F) Osumi	(G) Bungo	(H) Shionomisaki
(V1) IR								
(V2) IZ								
(V3) MI		Nov	Nov	Mar., Jun., Jul., Nov.				May
(V4) BA	Jul., Dec.	Dec	Dec	Dec				Feb., Apr., May, Jun., Sep., Oct., Dec.
(V5) NI	Oct							
(V6) KA	Oct							
(V7) FU	Oct., Nov.					Aug.		
Volcano	**(I) Irago**	**(J) Omaezaki**	**(K) Izuoshima**	**(L) Onahama**	**(M) Sakaiminato**	**(N) Wakasa**	**(O) Tsugaru**	**(P) Chichijima**
(V1) IR								
(V2) IZ	Sep., Oct., Nov., Dec.	Jun., Sep., Oct., Nov., Dec.		May				
(V3) MI	May, Jun., Jul., Sep., Oct., Nov.	Jan., Mar., Jun., Sep., Oct., Nov.	Mar., Apr., Jun.	Jan., Jun., Dec.				
(V4) BA	Jan., Feb., Apr., May, Jul., Sep.	Feb., Mar., Apr., Sep., Oct.	Feb., Apr., Aug., Sep., Oct., Nov., Dec.	Feb., Apr., Nov.				
(V5) NI								
(V6) KA								
(V7) FU								

variation. We selected the paths and months for which the number of yearly mean virtual pumice arrivals was larger than 100 and the standard deviation of the duration in a specific month was 2 months greater or less than that of the yearly mean (Table 5). Such paths are from V2 (Izu-Tobu), V3 (Miyakejima), and V4 (Bayonnaise Rocks) to H (off Cape Shionomisaki), I (Irago Channel), J (off Cape Omaezaki), and K (off Izuoshima Island) and appeared mainly from January to May and from October to December, i.e., other than in summer. This is the same tendency that is apparent in Table 4.

We note that the mean drift durations differed markedly from the shortest drift durations over all particle tracking experiments from 1982 to 2015 (Fig. 8). For 47.3% of the paths, the shortest drift durations were at least 6 months shorter than the mean drift durations.

4 Discussion

For the pumice drift, various factors that affect the pumice path are entangled in a complex manner. In this study, some factors (e.g., remobilization) are not included in the particle tracking experiments. Here we discuss the influence of such potential factors on our results and discuss how we understand the simulated results. First, we discuss the reproducibility of the virtual pumice dispersion from the January 1986 Fukutoku-Oka-no-Ba eruption. Then, we explain the potential factors, seasonality, and reliability of the drift duration.

4.1 Reproducibility of the January 1986 Fukutoku-Oka-no-Ba eruption

For this eruption, our simulated pumice raft arrival dates are generally consistent with the recorded arrival dates except for A (Iriomote Island). For Iriomote Island, the simulated arrival date was more than 1.5 months later than the recorded arrival date. There are two possible reasons why the simulation cannot reproduce the real drift duration. One is the uncertainty of the existence of the non-stational mesoscale eddy and the other is the lack of the remobilization.

All the virtual pumices that were transported from Fukutoku-Oka-no-Ba to Iriomote Island from January 1986 in our simulation might take a circuitous path, which might be longer than the direct westward route, due to the existence of the non-stationary mesoscale eddy. Virtual pumices were trapped by an eddy that existed near Fukutoku-Oka-no-Ba and transported to the south by the eddy. Consequently, all virtual pumices

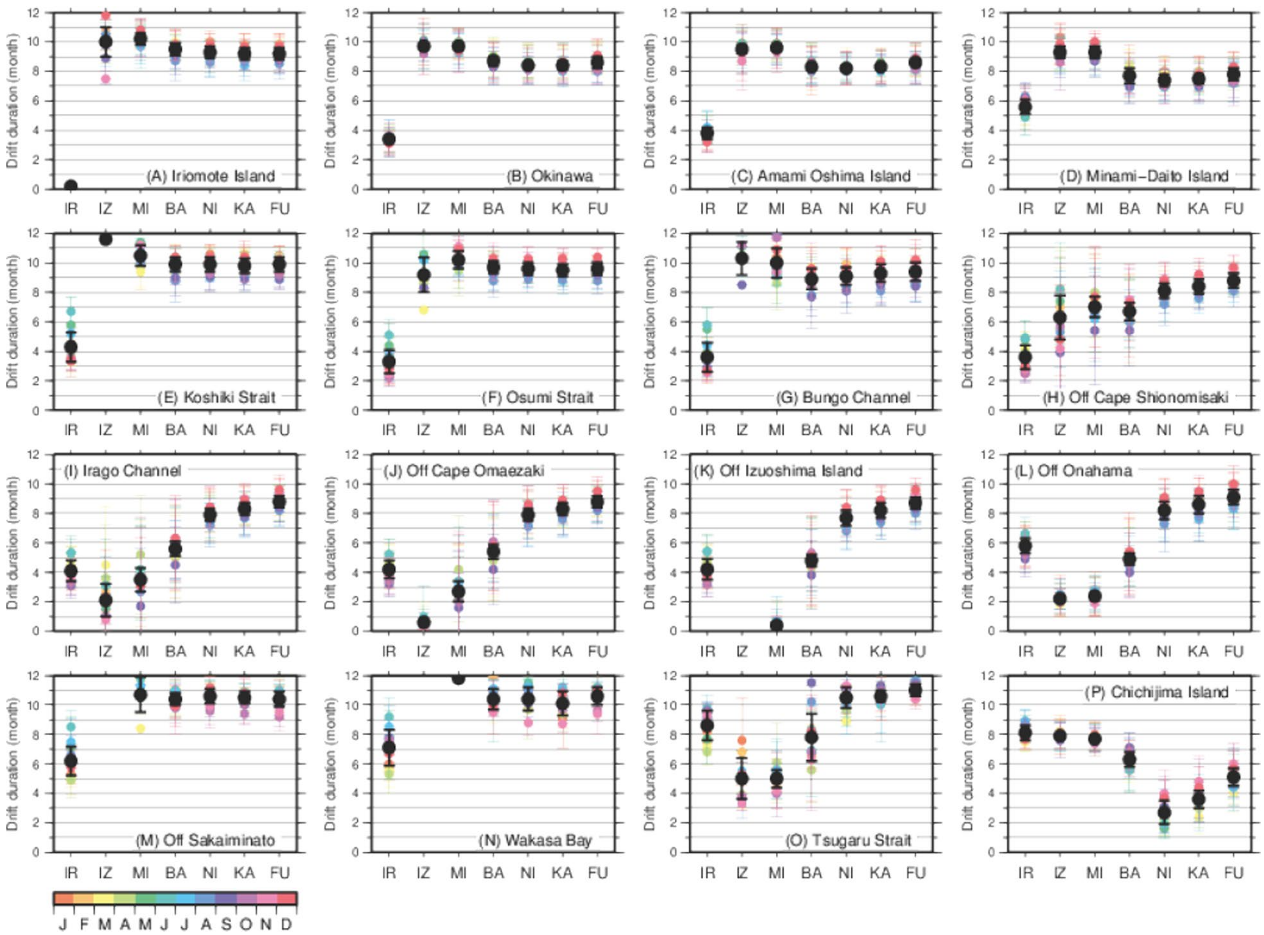

Fig. 7 Means and standard deviations (SDs) of the drift durations of virtual pumice clasts that arrived at each target area from (V1) submarine volcano NNE of Iriomote Island (IR), (V2) Izu-Tobu volcanic range (IZ), (V3) Miyakejima (MI), (V4) Bayonnaise Rocks (BA), (V5) Nishinoshima (NI), (V6) Kaitoku Seamount (KA), and (V7) Fukutoku-Oka-no-Ba (FU). Black symbols and error bars are yearly means and SDs from 1982 to 2015; colored symbols and error bars are monthly means and SDs from 1982 to 2015

could not take a direct route to Iriomote Island. Although the eddy had remained there from January to February in 1986 in the simulated velocity data, it is likely that there was no such eddy in the real ocean at that time. This is because, although the ocean reanalysis dataset can reproduce this mesoscale eddy, it could not have reproduced its exact position until corrections based on satellite data were incorporated in the 1990s (Takatsuki et al. 2017).

The above possibility was suggested by the long-term simulations for potential eruptions from 1982 to 2015. As shown in Figs. 7a and 8a, while the mean drift duration from V7 (Fukutoku-Oka-no-Ba) to Iriomote Island is 9 months, the shortest drift duration is 2 months. The reason why the drift duration varies in such a range is that there are two different transport paths. The longer path is alike the path in Fig. 3. After the start of drift, the pumice initially goes south, then turns west; when the pumice reaches the Philippines, the Kuroshio transports the pumice north to Iriomote Island. The shorter path is similar to that from V7 (Fukutoku-Oka-no-Ba) to B (Okinawa) (Fig. 3); some pumice goes north after the start of drift, then turns west and goes straight to Iriomote Island. The path of the pumice with the shortest drift duration shown in Fig. 8A followed this route, which takes only 2 months. According to the record of the 1986 eruption, the real pumice drift took about 4 months, which indicates that the pumice might be transported in the shorter path. On the other hand, all virtual pumices were transported in the longer path by trapping of an eddy in our simulation for the 1986 Fukutoku-Oka-no-Ba eruption.

The other factor that possibly caused the discrepancy is remobilization. According to the observations of the 2021 Fukutoku-Oka-no-Ba eruption, many pumice clasts arrived in the coastal area, but subsequently left the area and started drifting again (Yoshida et al.

Table 5 Paths for which the number of yearly mean virtual pumice arrivals was larger than 100 and the standard deviation of the duration in a given month was 2 months greater or less than the yearly mean

Volcano	(A) Iriomote	(B) Okinawa	(C) Amami	(D) M-Daito	(E) Koshiki	(F) Osumi	(G) Bungo	(H) Shionomisaki
(V1) IR								
(V2) IZ								
(V3) MI								
(V4) BA								Jan., Feb.
(V5) NI								
(V6) KA								
(V7) FU								

Volcano	(I) Irago	(J) Omaezaki	(K) Izuoshima	(L) Onahama	(M) Sakaiminato	(N) Wakasa	(O) Tsugaru	(P) Chichijima
(V1) IR								
(V2) IZ	Feb., Mar., Apr., Jun., Dec.							
(V3) MI	Jan., Feb., Mar., Apr., May, Jun., Jul., Aug., Oct., Nov., Dec.	Jan., Feb., Mar., Apr., May, Jun., Jul., Aug., Oct., Nov., Dec.						
(V4) BA	Jan., Feb., Mar., Apr., May, Sep., Oct., Nov., Dec.	Jan., Feb., Mar., Apr., Oct., Nov., Dec.	Jan., Feb., Mar., Apr., May, Oct., Nov., Dec.					
(V5) NI								
(V6) KA								
(V7) FU								

2022b). Such remobilization was not considered in this study. It means that we ignored the indirect path from Fukutoku-Oka-no-Ba to Iriomote Island. For example, it is possible that pumice once landed at an island near Iriomote Island (e.g., B: Okinawa) drifted again and arrived at Iriomote Island. In our simulation, the virtual pumice arrived at Okinawa on 6 June. If there is a strong southwest current from Okinawa to Iriomote Island, the remobilized pumice might arrive at Iriomote Island in June. If we considered such an indirect path, the virtual pumice possibly arrived at Iriomote Island earlier.

Since our simulation does not incorporate the short-term wind effect into the reanalyzed ocean current, wave and tidal mixing, it is difficult to reproduce the direct landing process and the following remobilization. Why we did not include such factors are explained in the following subsection.

4.2 Short-term wind effects on the current, windage, tidal mixing and Stokes drift

One of the purposes of this study was to reproduce the pumice drift of the 1986 Fukutoku-Oka-no-Ba eruption. Unfortunately, the ocean environmental dataset that includes 1986 is not suitable for considering short-term wind effects, including typhoon, on the current, dragging by wind, Stokes drift, tidal mixing, and remobilization, which impact pumice drift (Jutzeler et al. 2014, 2020; Yoshida et al. 2022a, b; Ohno et al. 2022; Kurogi and Hasumi 2019).

Before satellite observations, the spatiotemporal resolution of wind data was not sufficiently fine to consider the effects of typhoons, which alter ocean conditions on a scale of a few hours, or the wind itself, which changes direction within a few hours. The pumice that was thought to be transported under the influence of the typhoon was found after the August 2021 Fukutoku-Oka-no-Ba eruption. The drift duration was 2.5 months from V7 (Fukutoku-Oka-no-Ba) to Iriomote Island (Usami and Shinjo 2022). This drift path should be the shorter path that we discuss in 4–1. In addition to the position of the eddies and remobilization, the typhoon could affect the transport path because summer is typhoon season near Japan. After the eruption, many typhoons (e.g., Typhoon Chanthu and Typhoon Mindulle) passed near Fukutoku-Oka-no-Ba. Our simulation cannot reproduce the effect of typhoons perfectly because we used the daily mean flow field data; thus, the simulation may have missed abrupt changes (on the scale of a few hours) of the flow field associated with the passage of a typhoon. However, the report that the large amounts of pumice were found at Kita-Daito Island (near D, Minami-Daito Island; Fig. 1)

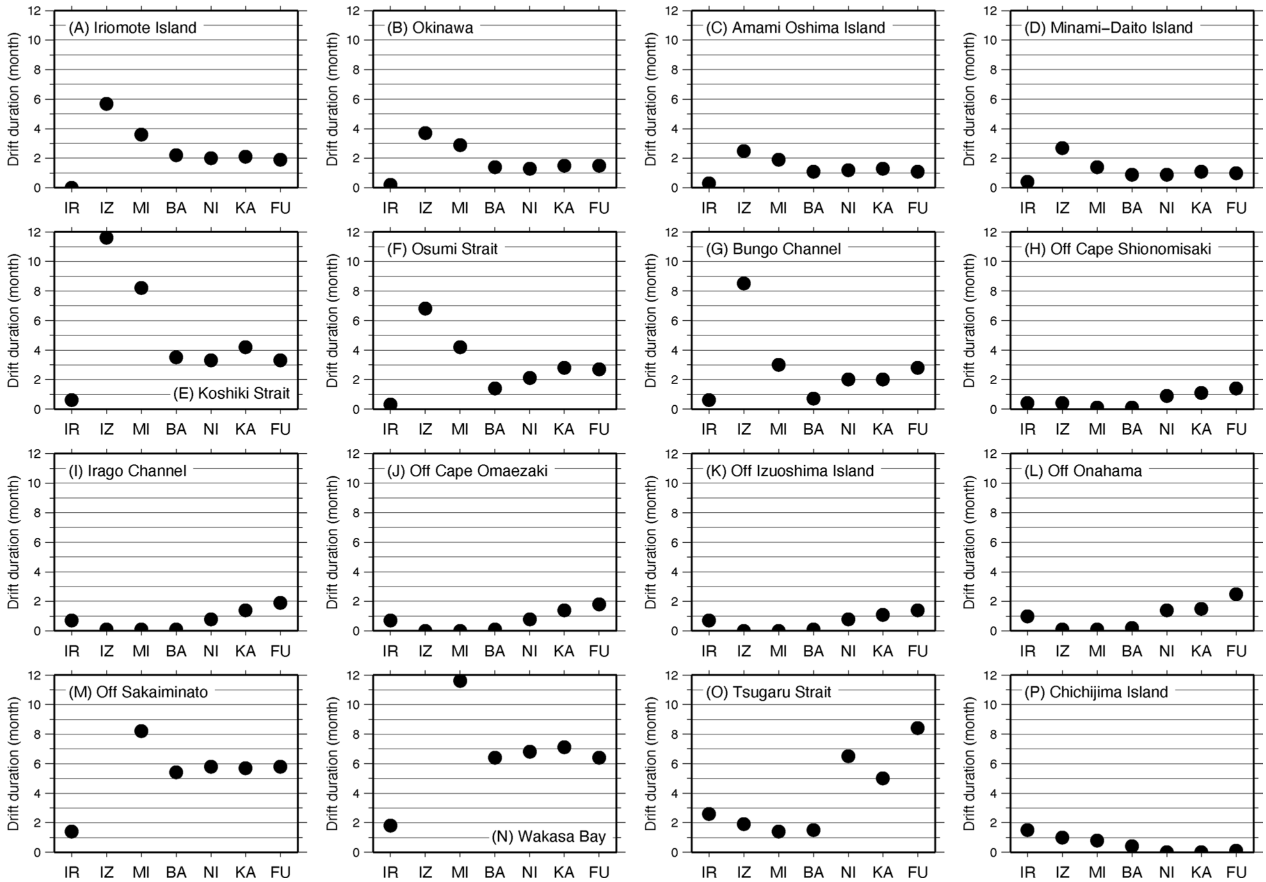

Fig. 8 The shortest drift durations of virtual pumice clasts that arrived at each target area from (V1) submarine volcano NNE of Iriomote Island (IR), (V2) Izu-Tobu volcanic range (IZ), (V3) Miyakejima (MI), (V4) Bayonnaise Rocks (BA), (V5) Nishinoshima (NI), (V6) Kaitoku Seamount (KA), and (V7) Fukutoku-Oka-no-Ba (FU) from 1982 to 2015

the day after the typhoon had arrived (Yoshida et al. 2022a) suggested that the typhoon affected the pumice distribution. Thus, it is possible that a typhoon could markedly change the flow field and it helped to transport pumice northward shorter path. Typhoon would also affect the pumice in a direct way, windage. However, since the wind data resolution is low, it was not included in our simulation.

The ocean reanalysis products we used do not include the tidal mixing and Stokes drift, which strongly affects near-coast flow fields. This is why we did not count the number of the virtual pumice clasts that stopped on the land but just count the number of the virtual pumice that passed the target areas. Sometimes stranded pumice left the beach and drift again especially in the case typhoon-induced wave overtopping occurred (Yoshida et al. 2022b). However, due to the lack of reliability for the exact number of stranded pumice and reproduction of the wave overtopping, we did not consider the remobilization. As we mentioned in the discussion of the 1986 eruption reproducibility, the lack of remobilization process possibly caused the underestimation of the number of pumice arrival at the target areas. Wave overtopping is a combined result of astronomic tide, storm surge and wave run-up and frequently occurs especially during the typhoon. To reproduce these processes, a specific model is needed that captures the finer-scale changes of wind and wave dynamics (e.g., 20 min. and 2 km scales used in Amunugama et al. 2020). The target area of such a finer-scale model is usually restricted in the coastal area. On the other hand, while the daily dataset with 10 km horizontal resolution, which we used does not reproduce these processes, the dataset can cover enough wider area to track the dispersion of the pumice near Japan. Integration of the coastal model and offshore model will be an issue in the future.

4.3 Seasonality

While our simulation cannot reproduce the effect of daily wind change, the simulation did reproduce the effect of the seasonal monsoon, which influences the flow field on a scale of a few days. In the Kuroshio region, the wind direction and velocity change seasonally (Nakamura 2017). The large interannual variations in the number of virtual pumice arrivals or of the drift duration in a specific month arise as a result of such seasonality. For the paths from V2 (Izu-Tobu Volcanoes), V3 (Miyakejima), and V4 (Bayonnaise Rocks) to H (off Cape Shionomisaki), I (Irago Channel), J (off Cape Omaezaki), and K (off Izuoshima Island), the interannual variations of arrival number and drift duration are large, except in summer (Tables 4, 5). As these target areas are located west of the source volcanoes, the virtual pumice clasts must go westward (Fig. 1). However, these volcanoes are located near the Kuroshio Current. Once the virtual pumice clasts are trapped by the Kuroshio, it is difficult for them to reach H (off Cape Shionomisaki), I (Irago Channel), J (off Cape Omaezaki), and K (off Izuoshima Island). If the virtual pumice clasts can escape from the Kuroshio and transfer to the westward current, it takes additional time for them to reach the target areas. Hence, whether the virtual pumice clasts are trapped by the Kuroshio is important, and this trapping depends on two factors. One factor is the variability of the Kuroshio path, which is not affected by seasonality. The other factor is the seasonal monsoon. Strong monsoonal winds induce Ekman transport (e.g., Wu and Hsin 2012), which forces virtual pumice clasts toward or away from the Kuroshio. For example, the usual wind direction is southwestward in October near these volcanoes (Nakamura 2017). Such wind induces southward Ekman transport at the sea surface, which moves virtual pumice clasts near Miyakejima toward the Kuroshio. In this area, although windy days continue during winter, spring, and autumn, the wind is weak during summer (Nakamura 2017). The weak summer monsoon could explain the small interannual variation during summer. For the paths from V3 (Miyakejima) and V4 (Bayonnaise Rocks) to A (Iriomote Island), B (Okinawa), C (Amami Oshima), and D (Minami-Daito Island), and for the paths from V5 (Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba) to Iriomote Island, the interannual variation of arrival number is large from October to December (Table 4). These target areas are west of V3 (Miyakejima), V4 (Bayonnaise Rocks), V5 (Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba). Near the target areas, the autumnal wind direction is southwestward, that is, the Ekman transport is westward. Thus, when the wind speed is higher, larger numbers of virtual pumice clasts can reach these target areas, and the number of virtual pumice arrivals depends on interannual wind variations.

Our simulation can reproduce seasonality other than that of wind. Virtual pumice clasts released from V5 (Nishinoshima), V6 (Kaitoku Seamount), and V7 (Fukutoku-Oka-no-Ba) in summer reached Pacific target areas relatively quickly (Fig. 7). As the Kuroshio Recirculation that flows near these volcanoes is strengthened in summer (Yoshida et al. 2022a), these shorter drift durations reflect the seasonality of ocean currents.

4.4 Reliability of the drift duration

As our final goal was to estimate the risk of pumice raft arrivals based on the results of our particle tracking experiments, it is important whether the mean or shortest drift durations are most representative of actual pumice rafts. We propose that both durations should be considered for two reasons. (1) The drift duration is vulnerable to the existence of non-stationary mesoscale eddies. For example, in our experiments, the mean and shortest drift durations from V7 (Fukutoku-Oka-no-Ba) to B (Okinawa) were 8.5 months (Fig. 7B) and 1.5 months (Fig. 8B), respectively. In comparison, pumice from the August 2021 eruption of Fukutoku-Oka-no-Ba arrived at Okinawa within 2 months, preventing fishing boats from sailing (e.g., Yoshida et al. 2022a). This case implies that the shortest drift duration is reliable. However, in contrast, pumice from the 1986 eruption took 4 months to travel from Fukutoku-Oka-no-Ba to Okinawa. The possible reasons why the 2021 drift time was shorter are that the pumice erupted that year was not trapped by the eddies that trapped the 1986 raft and/or seasonality. Since the eruption in 1986 is in winter and 2021 is in summer, seasonality includes the effect of the seasonal monsoon and typhoon. This difference suggests that pumice is not always transported along the shortest route. (2) The initial pumice arrival may not be large enough to impede marine traffic; this may explain the arrival of virtual pumice clasts at Cape Shionomisaki and Hahajima before real observations of pumice rafts (Fig. 2): it is possible that the first pumice arrival went unrecognized. Thus, following eruptions, particular attention should be paid during the period between the shortest possible drift duration and the mean duration.

We stress that the amount of pumice that arrives initially will not necessarily be small. A small number of virtual pumice clasts in our experiments does not necessarily translate to low real-world risk. We released only 49,000 particles, which is a small number considering the diverse and complex behavior of real pumice rafts. Therefore, warnings of pumice raft arrivals must be based on specific criteria regarding the number of particles arriving in tracking experiments and careful comparisons with historical records of pumice arrivals.

5 Concluding remarks

We conducted particle tracking simulations of eruptions at major volcanic islands and submarine volcanoes near Japan. In the case of the 1986 Fukutoku-Oka-no-Ba, the simulated drift durations are consistent with the records other than Iriomote Island. In addition, all recorded drift durations fall within the range of the shortest drift record and the mean drift duration derived from the simulations for the Fukutoku-Oka-no-Ba from 1982 to 2015. From these results, we concluded that a period following an eruption that warrants attention is from the shortest drift record to the mean drift duration, which was estimated for each volcano by the simulations from 1982 to 2015. On the other hand, our results indicate that in order to accurately predict drift duration within a precision of 1 month or less, we need to take certain factors into consideration, such as remobilization.

Appendix

See Figs. 9, 10, 11, 12, 13 and 14.

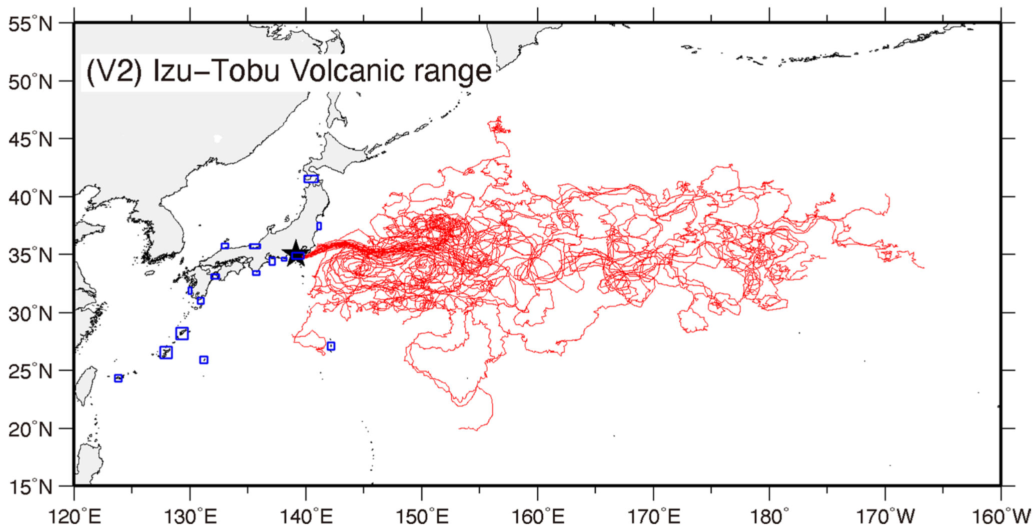

Fig. 9 Simulated drift paths of 50 randomly selected virtual pumice clasts released from the (V2) Izu-Tobu volcanic range (black star) on 15 March 2004. Blue rectangles indicate target areas

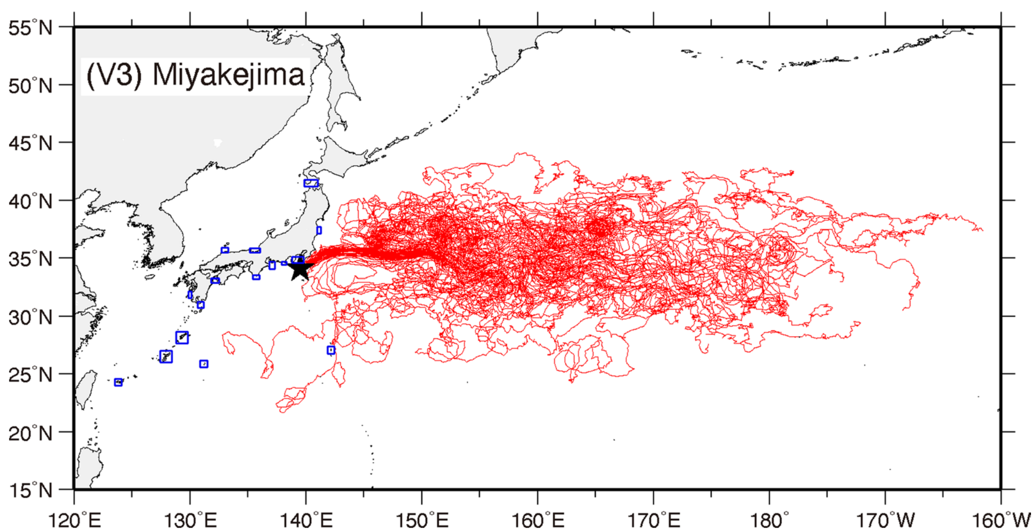

Fig. 10 Simulated drift paths of 50 randomly selected virtual pumice clasts released from (V3) Miyakejima (black star) on 15 March 2004. Blue rectangles indicate target areas

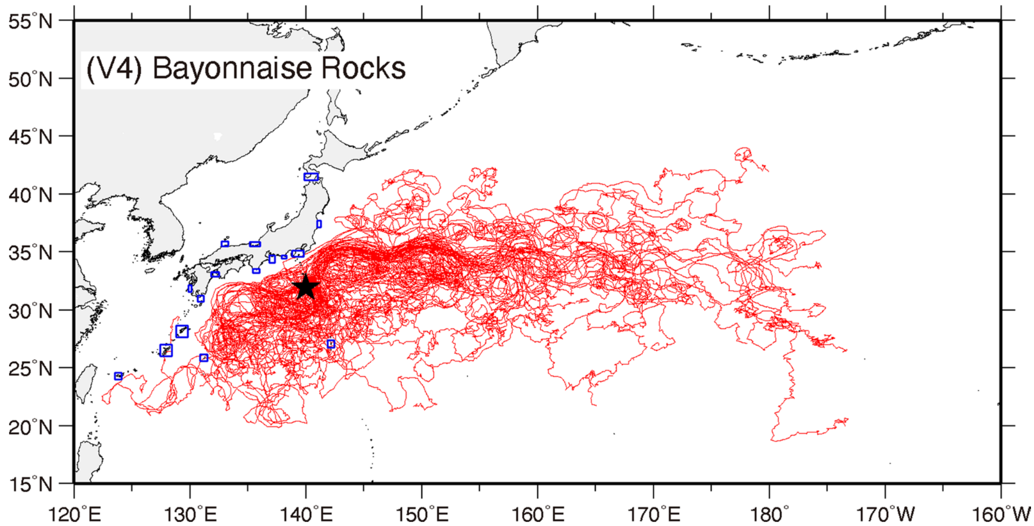

Fig. 11 Simulated drift paths of 50 randomly selected virtual pumice clasts released from (V4) Bayonnaise Rocks (black star) on 15 March 2004. Blue rectangles indicate target areas

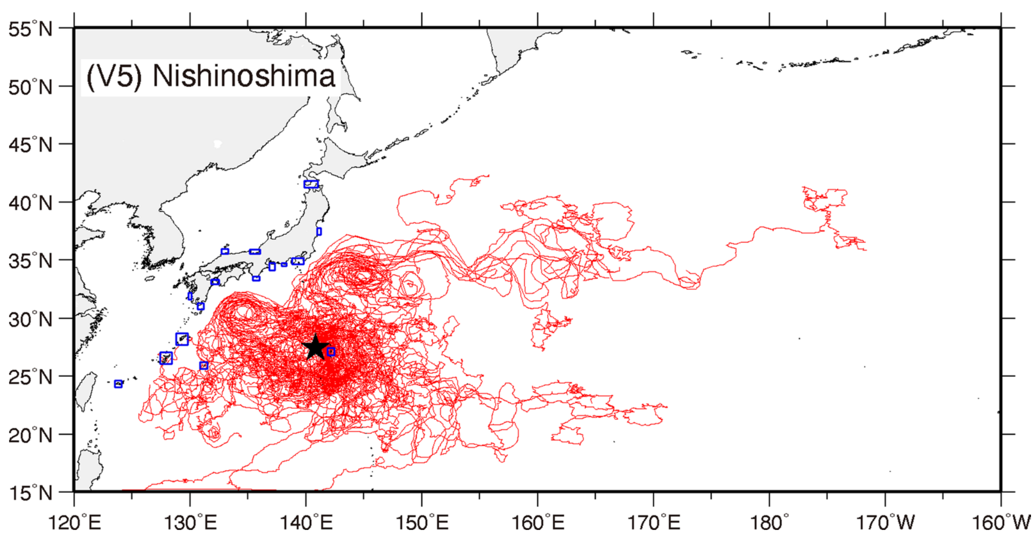

Fig. 12 Simulated drift paths of 50 randomly selected virtual pumice clasts released from (V5) Nishinoshima (black star) on 15 March 2004. Blue rectangles indicate target areas

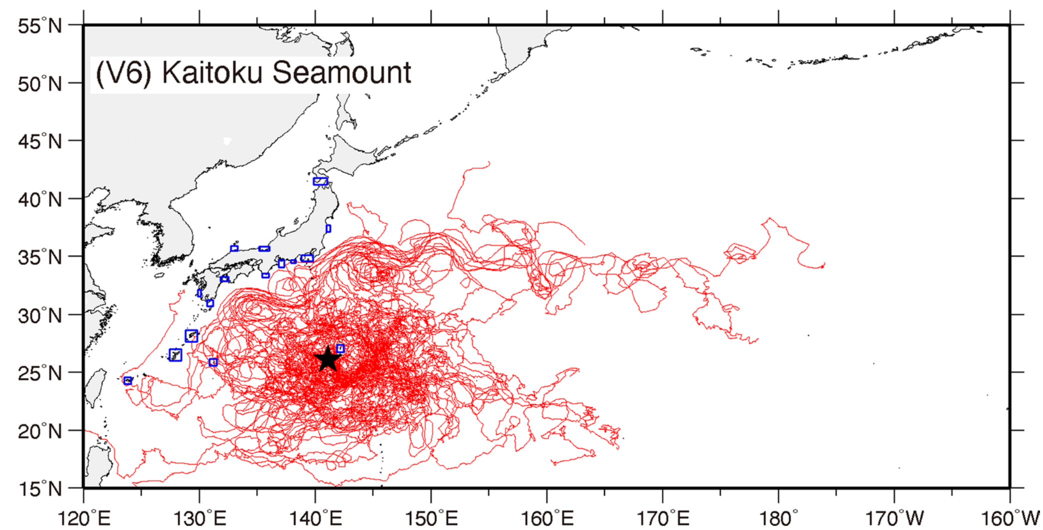

Fig. 13 Simulated drift paths of 50 randomly selected virtual pumice clasts released from (V6) Kaitoku Seamount (black star) on 15 March 2004. Blue rectangles indicate target areas

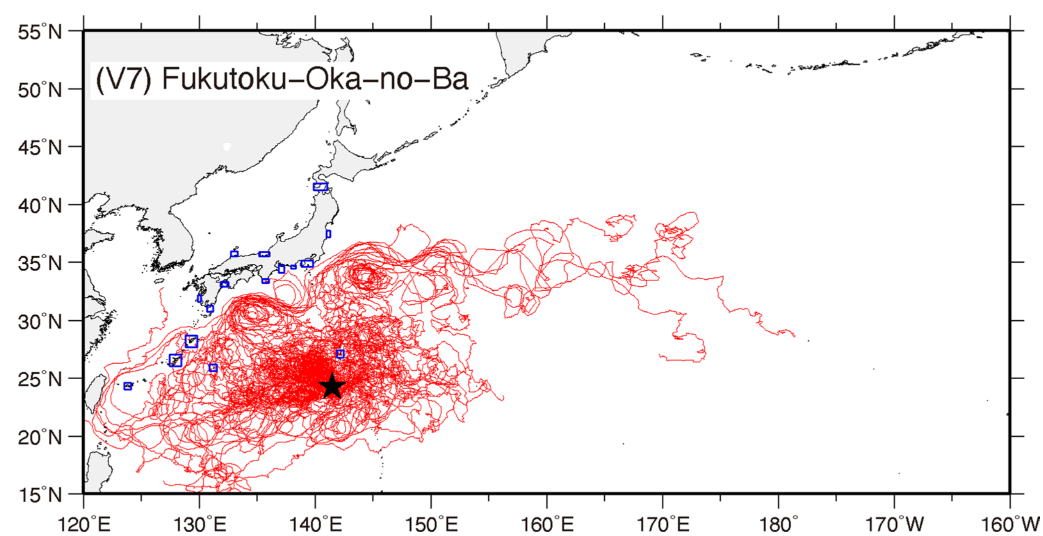

Fig. 14 Simulated drift paths of 50 randomly selected virtual pumice clasts released from (V7) Fukutoku-Oka-no-Ba submarine volcano (black star) on 15 March 2004. Blue rectangles indicate target areas

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The figures were produced using Generic Mapping Tools v4 (Wessel and Smith 1998).

Author contributions
HN conducted particle tracking experiments. TK and NT provided geological data (pumice transportation and volcanic activity). All co-authors collaborated with the corresponding author in the construction of the manuscript through several drafts. All authors participated in discussions about the results and commented on the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The ocean reanalysis dataset used in this study is available from the authors upon request. The request URL is http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2019-nwp/index.htm

Declarations

Competing interests
The authors declare that they have no competing interests.

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