Chapter 7
Transport Properties of Soil Particles in Sakiyama and Amitori Bays

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Abstract The actual states of soil particle transport in and exchange between the Sakiyama and Amitori bays, Iriomote Island, Japan, were investigated using atmosphere–ocean–river observations and numerical simulations. Results show that in both bays in summer, large particles (≥ 15 μm) do not move from areas near the river mouths. Small particles, however, do move to the respective east sides of the bays. In winter in both bays, large particles move to the respective centers of the bays from areas near the river mouths, whereas small particles move to the respective west sides of the bays. Furthermore, soil particles move mainly from Sakiyama Bay to Amitori Bay in summer, but this direction is reversed in winter. These features are explainable mainly by seasonal differences in wind speed and direction, but the combination of seasonal differences in wind speed and direction, the wind-driven current and the topography are also important for them. The results are useful for assessing soil particle effects on coastal oceanic ecosystems, such as those containing reef-building coral and *Enhalus acoroides*, and their effective conservation in natural conservation areas of the Sakiyama and Amitori bays.

Keywords Coastal oceanic ecosystem · Environmental impact assessment · Iriomote Island · Sakiyamawan–Amitoriwan Nature Conservation Area · Soil particle

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7.1 Introduction

The Sakiyamawan–Amitoriwan Nature Conservation Area of Iriomote Island is the only oceanic nature conservation area in Japan. Sakiyama Bay was designated as a nature conservation area in 1983. In 2015, the area was extended to include the adjacent Amitori Bay (Ministry of the Environment, Government of Japan 2015a, b; see also Sects. 1.1, 1.2 and Fig. 1.1). The area has no access roads. The bay perimeter is uninhabited. Therefore, it is a natural environment with very little human impact. Additionally, it has various environmental gradients, such as freshwater and soil inputs from rivers at the innermost parts of the bays, the existence of mangrove forests aside from the rivers, and differences of water depth, length, and reef slope zones between the bays (Kawana 1990; Ukai et al. 2012). The environmental gradients affect the distribution of coastal marine systems such as those including reef-building corals (see Sect. 1.4, Chaps. 9, 10 and 11) and *Enhalus acoroides* (see Sect. 1.5 and Chap. 12). For example, soil particles provide nutrients to them, but disturb the respiration of corals and photosynthesis of zooxanthellae. Consequently, the conservation and the assessment of environmental impact are urgently and critically necessary.

Previous reports have described that the distributions of reef-building corals (Murakami et al. 2012; Shimokawa et al. 2014b, 2015, 2016; Ukai et al. 2015) and *Enhalus acoroides* (Murakami et al. 2014, 2015a, b; Nakase et al. 2015, 2016) are influenced strongly by the environmental gradients. They vary with location in the Sakiyama and Amitori bays. However, the effects of soil input from rivers on the coastal marine ecosystems have not been investigated thoroughly in the area, especially in Sakiyama Bay.

This study was conducted to provide transport properties of soil particles in the region as basic information for analysis. Because of the remoteness of the study area and limited access, broad and continuous observations are difficult to obtain. Therefore, in addition to the observations conducted on site, we used numerical modeling that integrated observational data into the models. Based on the results, we were able to elucidate the transport properties of soil particles in the study area and the exchange properties between the Sakiyama and Amitori bays in summer and winter.

7.2 Numerical Model and Method

First, we conducted observations of wind speed, wind direction, and precipitation at point A (continuous meteorological observation station, Fig. 7.1), and flow rates at the four rivers using an acoustic Doppler current profiler (see Chap. 2). Tables 7.1 and 7.2 show average meteorological field data observed at point A in the summer and winter, with average flow rates observed respectively at the four rivers in the summer and winter. For flow rates of the Painta and Ubo rivers (Fig. 7.1) in

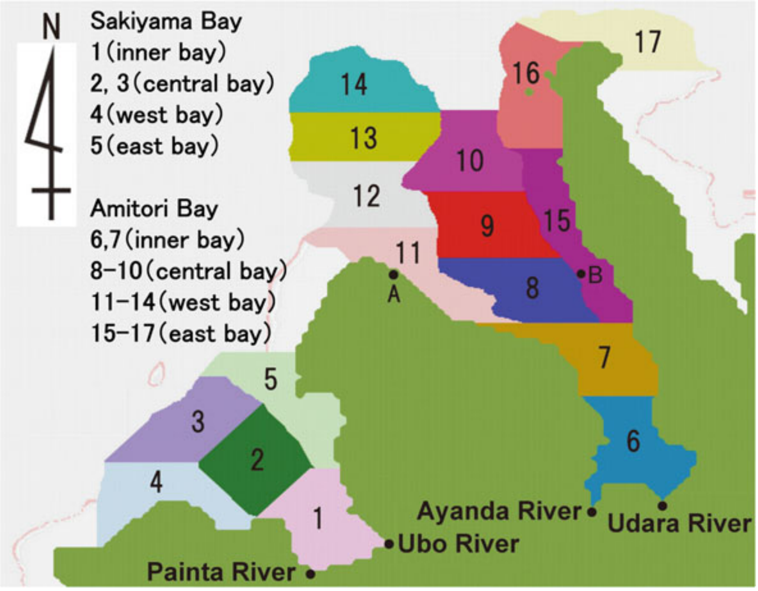

Fig. 7.1 Calculated domain and 17 regions investigated in this study. Particles are released from the mouths of the Painta, Ubo, Ayanda, and Udara rivers. A and B, respectively, show the meteorological observation point and oceanic flow observation point (Shimokawa et al. 2014b). Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

Table 7.1 Average meteorological field observations at point A (Fig. 7.1) in the summer and winter

	Summer	Winter
Ayanda river (m^3/s)	0.012	0.041
Udara river (m^3/s)	0.010	0.023
Painta river	0.011 m^3/s	Same as that in summer
Ubo river	0.097 m^3/s	Same as that in summer

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Table 7.2 Average flow rates observed at the four rivers (Fig. 7.1) during summer and winter

	Summer	Winter
Average wind speed (m/s)	3.1	5.8
Maximum wind speed (m/s)	8.6	13.5
Average wind direction (°)	SSE (160)	ENE (73)
Average precipitation (mm/day)	1.5	2.9
Maximum precipitation (mm/day)	15.5	42.5

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Sakiyama Bay, we used the same values for both summer and winter because winter observations could not be conducted.

Next, we reproduced current velocity fields in the Amitori and Sakiyama bays using CCM (Coastal ocean Current Model with a multi-sigma coordinate system, see Chap. 3; Murakami et al. 2011; Shimokawa et al. 2014a) with our field observations, the astronomical tide calculated using a tide model (Matsumoto et al. 2000) as the boundary values, and the water temperature and salinity observed using a conductivity–temperature–depth profiler (see Chap. 2; Murakami et al. 2012) for initial values. The calculated domain is portrayed in Fig. 7.1. Time periods of the calculations were June 9 to June 29, 2014, and November 1 to November 22, 2014, which are, respectively, periods of typical summer and winter atmospheric conditions in this area. The space resolution is 50 m horizontally and 42 layers vertically. The time step is 1 s.

Then, using the calculated current velocity fields, Lagrangian particle tracing analysis (see Chap. 3; Cushman-Roisin and Beckers 2011) was applied. The mass percentage passing of soil particles from the Ayanda and Udara rivers (Fig. 7.1) in Amitori Bay, obtained by sediment trap observation at the mouths of the rivers (Shimokawa et al. 2014b) demonstrated that the soil particle diameters were distributed mainly from 0.1 to 50 μm. This study specifically examines soil particle distributions. To investigate the soil particle distributions, the size difference of soil particles must be included because fine particles reach distant places, but coarse particles do not. Therefore, soil particles with diameters of 0.1, 1, 3, 5, 8, 10, 15, 20, and 30 μm were released every 10 s from the river mouths of the four rivers (Painta, Ubo, Ayanda, and Udara rivers, with six grid points for each river. Therefore, 24 particles were released every 10 s for each diameter value. See also Fig. 7.1.). We assumed that total sediment loads are equal among the four rivers in numerical experiments because no exact data are available, although the actual loads and the watershed sizes might be different. The initial state is that with no particle. Then, the states of the soil particles were classified into bottom (on the seafloor), floating (in the sea), and landed (from the sea). Time series of soil particle positions was obtained. Additional information for the numerical models and methods is presented in Chap. 3.

7.3 Results and Discussion

Figure 7.2 portrays a snapshot of the soil particle distributions with a diameter of 3 μm calculated via Lagrangian particle tracing analysis in the final states for the summer and winter (0:00 UTC, June 30 and 0:00 UTC, November 23 in 2014, respectively). Particles with yellow, red, violet, and pink, respectively, represent sources of the Painta, Ubo, Ayanda, and Udara rivers. The results demonstrate that for both bays, soil particles tend to accumulate on the east side in summer and the west side in winter and move from Sakiyama Bay to Amitori Bay in summer and from Amitori Bay to Sakiyama Bay in winter.

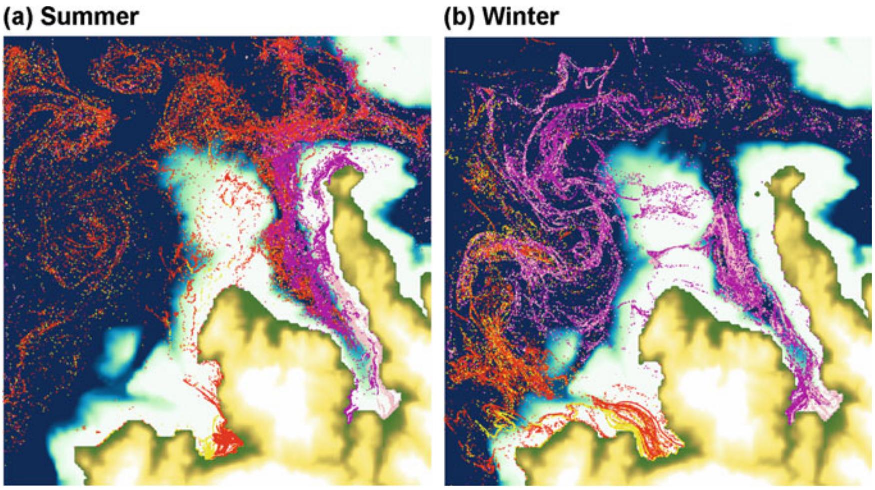
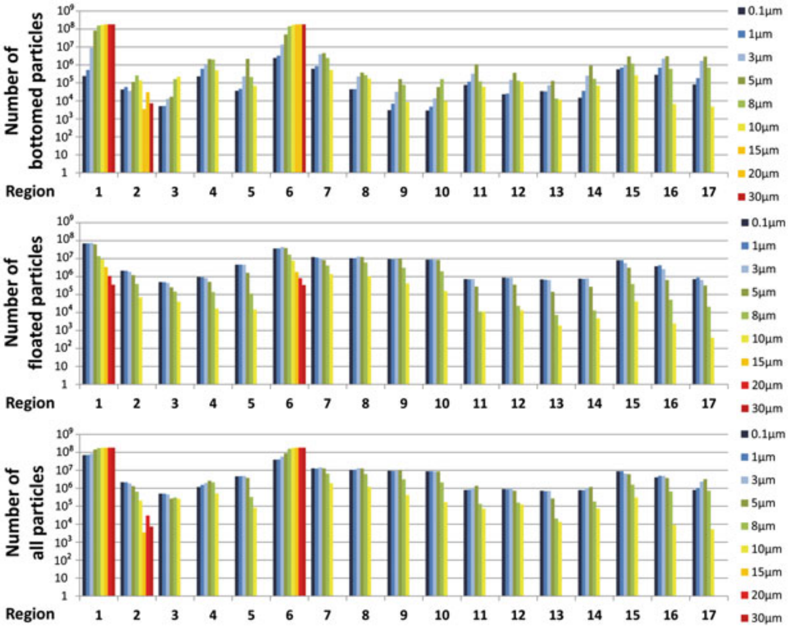


Fig. 7.2 Distributions of soil particles with a diameter of 3 μm in final states during **a** summer and **b** winter (0:00 UTC, June 30 and 0:00 UTC, November 23 in 2014, respectively). Yellow, red, violet, and pink dots, respectively, represent soil particles from the Painta, Ubo, Ayanda, and Udara rivers: Fig. 7.1. Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

To examine the characteristics of soil particle distributions, including the difference of distribution by the diameters and moving state (bottomed or floated) of soil particles, Sakiyama and Amitori bays were divided into 17 regions: 5 regions for Sakiyama Bay and 12 regions for Amitori Bay (Fig. 7.1). The divisions reflected the distributions of reef-building coral (Murakami et al. 2012; Shimokawa et al. 2016) and *Enhalus acoroides* (Murakami et al. 2014; Nakase et al. 2015). Each region has almost equal areal extent. For example, the west (11–14) and east regions (15–17) of Amitori Bay, respectively, correspond to the top of the reef slope (Fig. 1.1). The inner region of Sakiyama Bay (1, 2) corresponds to the *Enhalus acoroides* habitat.

Figure 7.3 presents the number of soil particles by region, particle diameter, and particle state (bottomed or floated) integrated in summer and winter. In summer, large particles, defined here as particles with >15 μm diameter, moved only slightly from the river mouth of each bay. Particularly, floating large particles were found only in the innermost regions of the bays. For Sakiyama Bay, the total number of soil particles was large on the east side, although the number of bottomed particles was large in the west side and the floating particles were numerous on the east side. For Amitori Bay, the total number of soil particles was large in the central bay, but the number of bottomed particles was large on the east side. In winter, for Sakiyama Bay, large particles moved from the river mouth over a broad region of the bay. For Amitori Bay, large particles moved from the river mouths to the inner bay, although the region over which they were distributed was smaller than that for Sakiyama Bay. For Sakiyama Bay, the numbers of both bottomed and floated particles were greater on the west side than those on the east side. For Amitori Bay, the total


(a) Summer

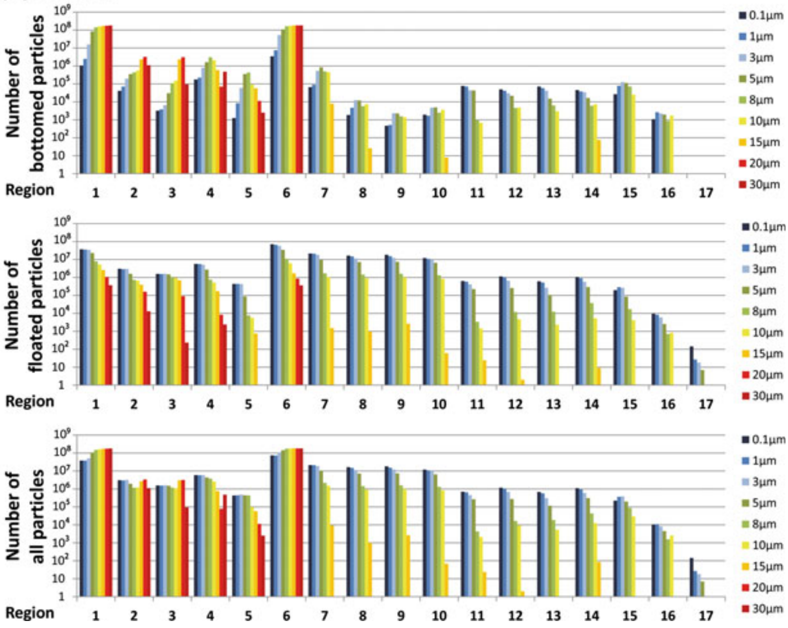

(b) Winter

Fig. 7.3 Numbers of soil particles by region, particle diameter, and particles state (bottom and floating) integrated into **a** summer and **b** winter. Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

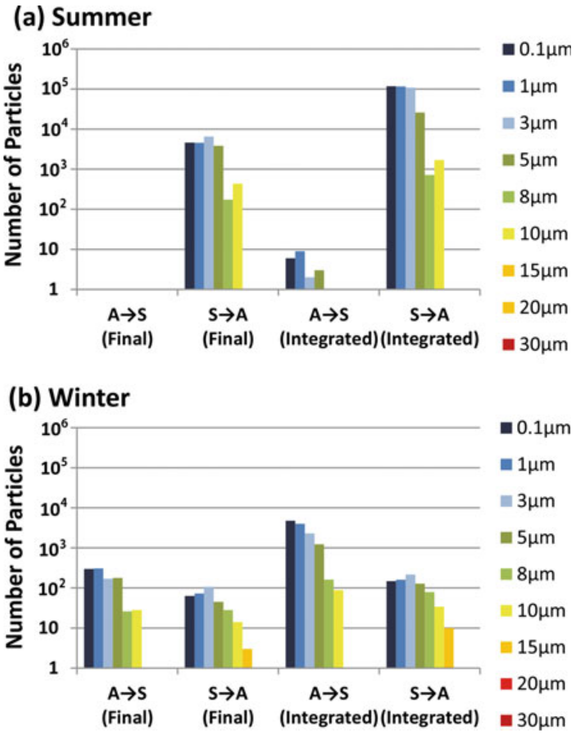


Fig. 7.4 Final and integrated numbers and size distributions of soil particles exchanged between Sakiyama and Amitori bays during **a** summer and **b** winter. Final and integrated values, respectively, represent the values at the end of the simulations and those integrated during the simulations. Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

number of soil particles was large in the central bay, but the number of bottomed particles was large on the west side. These characteristics of soil particle distributions and movements in winter were remarkably different from those in summer. The strong ENE winds in winter have the same effect on both bays. Therefore, the lengths along which the winds affect the soil transport are almost equal for both bays. However, the sizes and depths of the bays differ: Sakiyama Bay is smaller and shallower than Amitori Bay. Consequently, differences in soil particle transport between bays in winter are regarded as a cause.

Figure 7.4 shows the final and integrated numbers of soil particles exchanged between Sakiyama and Amitori bays in the summer and winter. Final and integrated values represent values at the end of the simulations and those integrated during the simulations. They are shown as respectively representative of instant and averaged values. For the soil particle exchange numbers, regions 13, 14, and 17 of Amitori Bay were excluded because they include open ocean regions. In summer, soil particles moved mainly from Sakiyama Bay to Amitori Bay. By contrast, in winter, soil particles moved mainly from Amitori Bay to Sakiyama Bay. However, in winter, movements from Sakiyama Bay to Amitori Bay also occurred for large particles, which is not observed in other cases examined in this study.

This fact agrees with the characteristics presented in Fig. 7.3, which shows that in winter for Sakiyama Bay, large particles moved from the river mouths to cover a broad region of the bay. Comparison of the final values with integrated values reveals that, in summer, the final values from Amitori Bay to Sakiyama Bay were not observed but the integrated values are present. In winter, the final values from Amitori Bay to Sakiyama Bay are on the same order of magnitude as those in the reverse direction, but the integrated values from Amitori Bay to Sakiyama Bay are a few orders of magnitude larger than those in the reverse direction.

Figure 7.5 presents a time series of wind speed and direction observed at point A (Fig. 7.1) during summer and winter. The averaged wind speed in winter is about two times larger than that in summer because of the existence of strong seasonal winds from the Asian continent in winter. The averaged wind direction is SSE in summer and ENE in winter. It is almost constant except for temporal variations that include the passage of low-pressure systems such as the storm event of June 12, 2014. The respective averaged values of wind speed and direction are 3.1 m/s and 160° in summer and 5.8 m/s and 73° in winter (Table 7.1). Comparing features of wind speed and direction (Fig. 7.5) with those of soil particles shown in the snapshot (Fig. 7.2), one might note that the soil particles released from the river mouth at the inner bay in summer flow in the direction of the wind (SSE). In winter, the spread soil particles shift to the direction of the wind (ENE) in both bays but those in Amitori Bay are apparently trapped in the center of the bay. Figure 7.6 shows ocean currents in winter. In Amitori Bay, the current flows to the west coast at 0 m, but it flows to the east coast at 30 and 50 m as the return flow. Therefore, the current rotates in the direction of depth. As time passes, the soil particles are trapped in the rotating current. In Sakiyama Bay, this mechanism does not occur because the bay is shallow: depths in most areas of the bay are within a few meters;

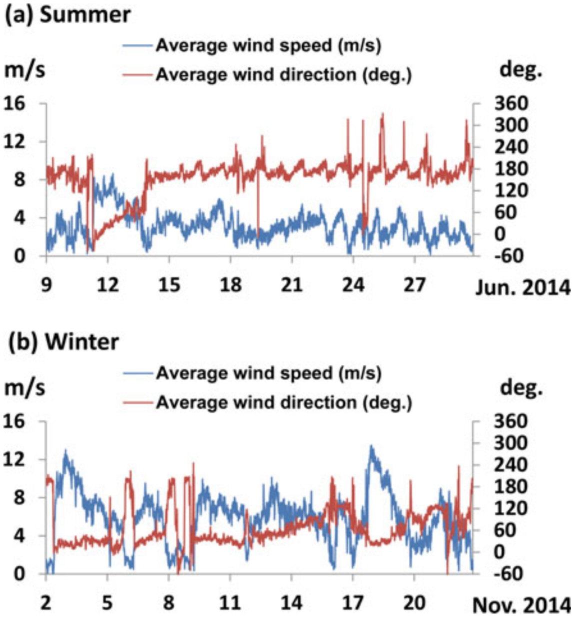


Fig. 7.5 Time series of wind speed and direction observed at point A (Fig. 7.1) in **a** summer and **b** winter. Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

the maximum is about 13 m at a reef pool of 200 m radius (Kawana 1990). In addition, comparison of the features of wind speed and direction with those of soil particles shown in Figs. 7.3 and 7.4 reveals differences in large particle movements for both bays between seasons. The differences are regarded as controlled mainly by differences in wind speed that occur with the seasons. Furthermore, differences in the number of soil particles exchanged between the Sakiyama and Amitori bays with the season are regarded as determined mainly by differences of wind direction that occur with the seasons. A certain amount of soil particle transport from Sakiyama Bay to Amitori Bay occurs in winter in the inverse direction of the winds. However, from Fig. 7.6, it is apparent that the averaged ocean currents, especially

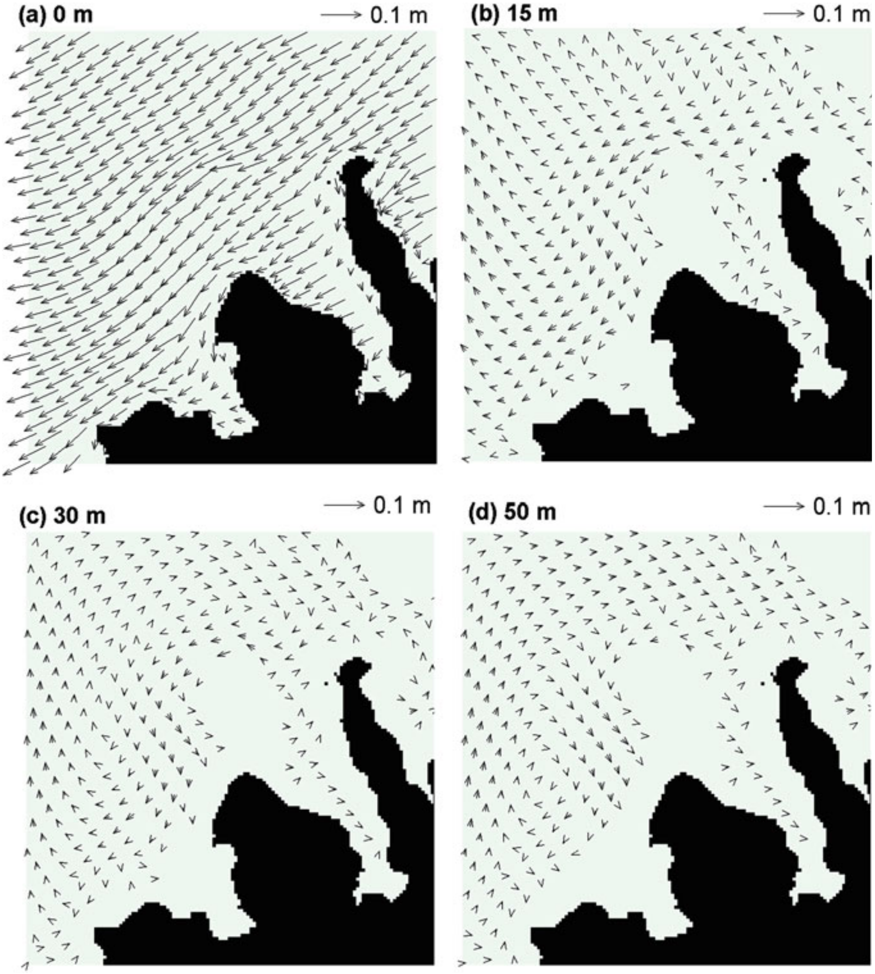


Fig. 7.6 Ocean current averaged in winter at depths of **a** 0 m, **b** 15 m, **c** 30 m, and **d** 50 m. Reprinted from Shimokawa et al. (2017) by The Authors licensed under CC BY 4.0

offshore, flow from Sakiyama Bay to Amitori Bay at 30 and 50 m, but flow from Amitori Bay to Sakiyama Bay at the surface. Moreover, the averaged wind direction was ENE in winter but, as portrayed in Fig. 7.5, the wind directions in winter changed considerably and became almost south around 2nd, 6th, 8th, 16th, 19th, and 22nd November. For the reasons described above, the soil particle transport from Sakiyama Bay to Amitori Bay in winter is regarded as occurring in winter. Consequently, the features in transport properties of soil particles in the Sakiyama and Amitori bays and soil particle exchange properties between the bays are explainable mainly by seasonal differences in wind speed and direction, but the combination among seasonal differences in wind speed and direction, wind-driven current and topography is also important for them.

However, some points of analyses must be improved to assess the actual states of soil particle transport in and exchange between the Sakiyama and Amitori bays more precisely. Particularly regarding the numerical simulations for the Painta and Ubo rivers in Sakiyama Bay, the flow rate used for winter was the same as that used for summer because we were unable to obtain a winter observational value, which is required as input for the numerical model. Furthermore, the critical Shields number was constant over the whole region in the numerical simulations conducted for the present study. Instead of them, observational values, which depend on the location, should be used in future studies.

7.4 Conclusions

For our target region, the only oceanic nature conservation area in Japan, conservation and environmental impact assessment are urgently and critically necessary. Nevertheless, investigations of the region, especially Sakiyama Bay, have not been thorough. To provide basic information for analyses, this study assessed the transport properties of soil particles in the region.

The Sakiyamawan–Amitoriwan Nature Conservation Area, designated as a nature conservation area in 2015 (Ministry of the Environment, Government of Japan 2015a, b), requires an immediate environmental impact assessment for its coastal marine ecosystems, such as those containing reef-building corals and *Enhalus acoroides*. As basic information for analyses, we assessed transport properties of soil particles in the region in this study. We conducted atmosphere–ocean–river observations and numerical simulations for the area to elucidate the transport properties of soil particles in the study area and the exchange of soil particles between the Sakiyama and Amitori bays during summer and winter.

The results are summarized as follows: (1) for each bay, soil particles tended to accumulate on the east side in summer and on the west side in winter; (2) for each bay, in summer, large particles (≥ 15 μm) did not move from areas near the river mouth, but in winter, large particles moved from the river mouth to the inner parts of the bay; and (3) soil particles moved mainly from Sakiyama Bay to Amitori Bay in summer, but the direction was reversed in winter.

These features are explainable mainly by seasonal differences in wind speed and direction, but the combination of seasonal differences in wind speed and direction, wind-driven current and topography also strongly affect them. For Amitori Bay, we conducted studies of soil particle effects on coastal oceanic ecosystems such as corals (Murakami et al. 2012; Shimokawa et al. 2014b; Ukai et al. 2015; Shimokawa et al. 2015, 2016) and *Enhalus acoroides* (Murakami et al. 2014, 2015a, b; Nakase et al. 2015, 2016). Those results provide basic information about whether the control of soil input from the rivers should be done or not and how much it should be done. Therefore, the results are expected to be useful to assess soil particle effects on coastal oceanic ecosystems and their effective conservation in the Sakiyamawan–Amitoriwan Nature Conservation Area.

Future studies will include observations related to the flow rate and critical Shields number described at the end of the preceding section. We shall assess soil particle effects on coastal oceanic ecosystems more precisely. Such results will enable us to clarify the relation between the distributions of coastal oceanic ecosystems, such as those containing reef-building corals *Enhalus acoroides*, and physical factors including the soil particle environment in the Sakiyamawan–Amitoriwan Nature Conservation Area.

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