

# Chapter 10

## Coral Distributions and Physical Environments in Sakiyama Bay



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**Abstract** This study was conducted to clarify the relation between coral distributions and physical variables in Sakiyama Bay, Iriomote Island, Japan. First, the distributions of coral coverage by the colony shapes and coral areas by the community types were investigated at 72 points around the bay. Next, physical variables such as oceanic flow and soil particle numbers were analyzed by numerical simulation under average summer and winter conditions in the region. The results were compared with the obtained coral distribution. From those results, we inferred the following: (1) Coral coverage shows a direct relation with bottom flows in the region; the bottom flows differ among coral community types. (2) Coral coverage shows an inverse relation with soil particle numbers in the region. *Enhalus acoroides* mainly inhabits areas with greater numbers of soil particles.

**Keywords** Reef building coral · Sakiyama Bay · Physical environment · Soil particle · Bottom flow · Numerical simulation

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This chapter is based on the work reported by Shimokawa et al. (2016).

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## 10.1 Introduction

Sakiyama Bay, a part of the Amitoriwan–Sakiyamawan Nature Conservation Area (see Sect. 1.2), is adjacent to Amitori Bay. An earlier chapter (Chap. 9) described the relation between coral distributions and physical environments in Amitori Bay (Murakami et al. 2012; Shimokawa et al. 2014; Ukai et al. 2015; Shimokawa et al. 2015). Sakiyama Bay has Iriomote Island’s leading communities of branching coral and a kind of seagrass (*Enhalus acoroides*; see Sect. 1.5), but Sakiyama Bay differs considerably from Amitori Bay in terms of its geographic characteristics such as depth, length, and shape. The relation between coral distributions and physical environments in Sakiyama Bay has remained unknown. Investigations of its characteristics have been strongly needed. Therefore, to clarify those various relations, we conducted investigations of distributions of coral coverage by colony shape and coral area for community types at 72 points around the bay. Then, we compared the obtained coral distributions with physical variables such as oceanic flow and soil particle numbers using numerical simulations under average summer and winter conditions in the region (Shimokawa et al. 2016).

## 10.2 Investigation Method of Coral Distributions

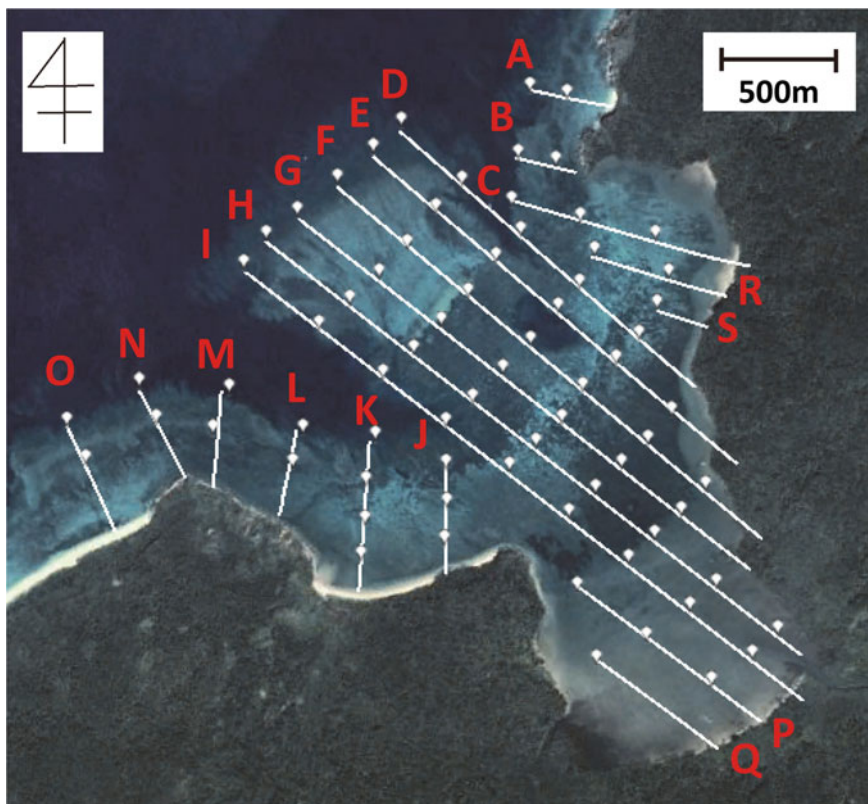
We conducted the following investigations of coral distributions during May–November in 2015.

### (1) Investigation of coral coverage distributions by colony shape.

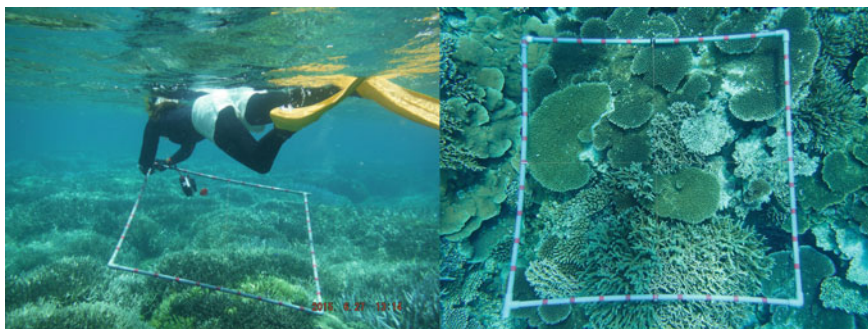
Coral distributions were investigated for 72 points on 19 lines, A–S in Sakiyama Bay (Fig. 10.1). Three quadrats measuring 2 m on each side were placed. Photographs were taken from just above at each point irrespective of the presence or absence of corals (Fig. 10.2). Then, according to the previous studies (Murakami et al. 2012; Shimokawa et al. 2014, 2015; Ukai et al. 2015), the types of coral life forms were classified as branching, tabular, massive, foliose, or encrusting corals as shown in Fig. 9.2. Subsequently, the coverage was calculated as the average on the three quadrats with 1% of the pitch width.

### (2) Investigation of distributions of coral areas by community type.

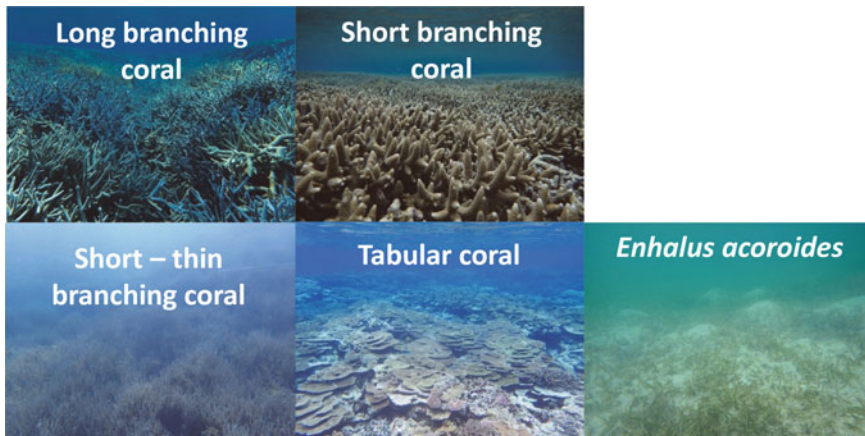
We specifically examined branching and tabular corals with higher appearance frequencies in Sakiyama Bay. Particularly for branching coral, the community types were classified as long, short, or short–thin branching corals based on the measurement of lengths of the living parts and widths of the bases for randomly selected branches. To make an addition of *Enhalus acoroides* community to these communities, the areas of five community types (Fig. 10.3) were calculated using GPS measurements.



**Fig. 10.1** Lines and points for investigating coral distributions. On lines A, B, J–O, investigation points were set approximately every 100 m; on other lines, they were set around every 200 m. Map data © 2016 Google (referred from Shimokawa et al. 2016)



**Fig. 10.2** Photographs of coral investigations (left) and quadrats (right) in Sakiyama Bay. A photograph of quadrats was taken at the offshore side point on line B (Fig. 10.1) (referred from Shimokawa et al. 2016)



**Fig. 10.3** Community types treated in this study (referred from Shimokawa et al. 2016)

### 10.3 Calculation Method of Physical Environments

Various factors such as physical, chemical, and biological factors affect the diverse distributions of corals (Motokawa 2008; Sheppard et al. 2009). Among them, this study addresses physical factors including ocean waves, ocean currents, sediments, salinity, and illuminance. Especially, the present study specifically elucidates the bottom flow speed and soil particle number because the distributions of corals inhabiting on sea bottom are affected by the bottom flow speed rather than the surface flow speed and wave strength. Moreover, in Sakiyama Bay, soil particle inflow from rivers at the inner bay can spread because of the flat bottom of the bay (Kawana 1990, see also Sect. 10.6).

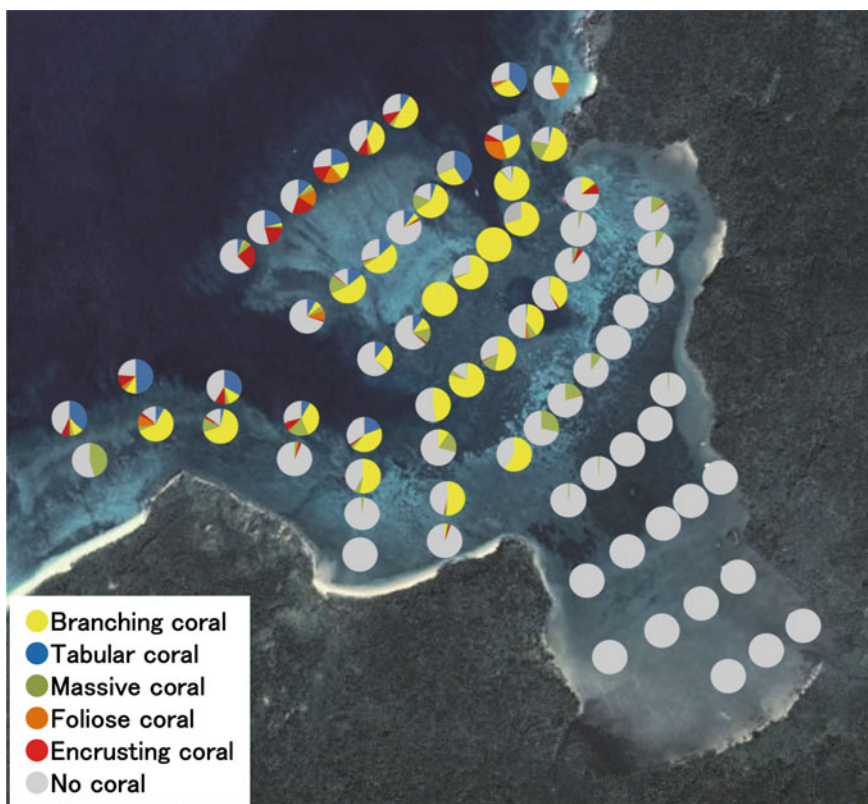
For that purpose, we re-analyzed the results reported from earlier studies (Murakmai et al. 2013; Nakase et al. 2015) conducting numerical simulations for bottom flow speed and soil particle number under average conditions of summer and winter in Sakiyama Bay. Here, the Simulating Waves Nearshore (SWAN, Booji et al. 1999) and Coastal Ocean Current Model (CCM, Murakmai et al. 2015c) were used for simulations of the bottom flow speed (amplitude of orbital velocity). Lagrange particle tracing method (e.g., Cushman-Roisin and Beckers 2011) was used for the soil particle number. Details related to the simulation method are presented in Chap. 3 and in the original articles described above.

## 10.4 Distributions of Corals

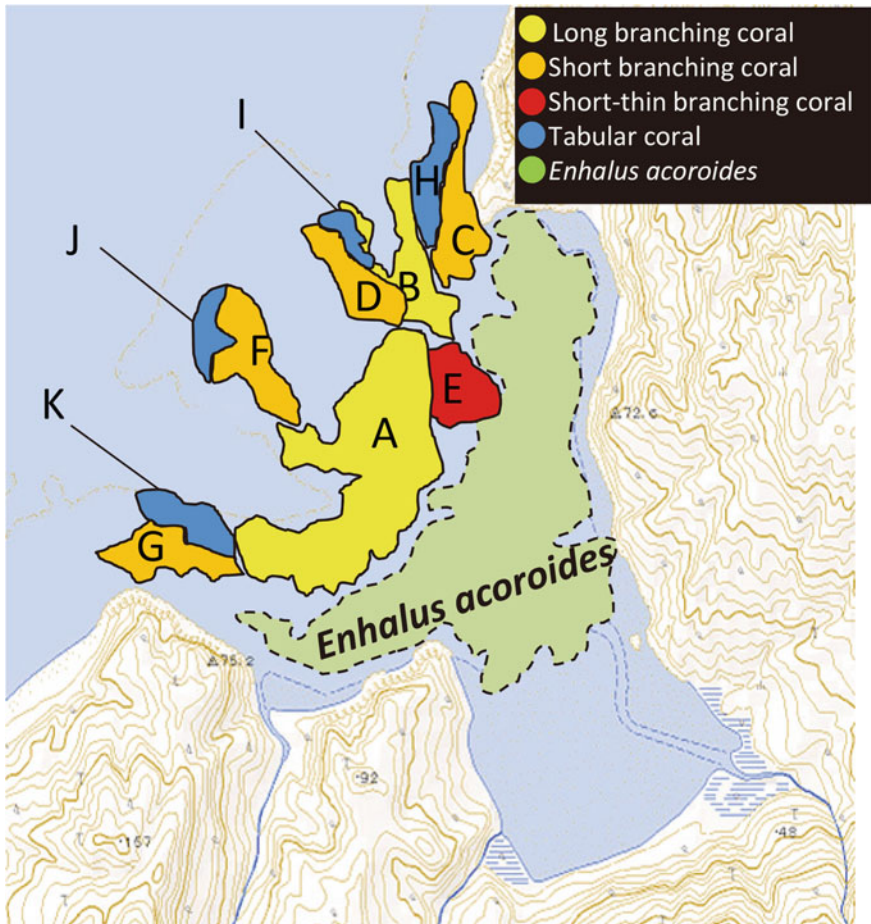
In this section, we state the results of investigations of the distributions of coral coverage by the colony shape and coral area according to the community type in Sakiyama Bay.

Figure 10.4 portrays the distributions of coral coverage by colony shape. Tabular, foliose, and encrusting corals distribute mainly at the reef margin. Branching corals do so at the reef margin and the mouth of the bay. Massive corals are distributed at the mouth and central parts of the bay.

Among all 72 points of investigation, the numbers of points with 0% and >1% coverage were, respectively, 17 and 55. The coverage averaged at points with >1% coverage is 48%. For branching corals, the average, minimum, and maximum coverage and the number of points with the appearance of corals are, respectively, 39%, 1%, 100%, and 41%. For tabular corals, they are 15, 1, 49, and 28%. For



**Fig. 10.4** Distributions of coral coverage by the colony shapes. The types of colony shapes are classified according to branching, tabular, massive, foliose, and encrusting corals shown in Fig. 9.2. Map data © 2016 Google (referred from Shimokawa et al. 2016)



**Fig. 10.5** Distributions of coral areas by community type. The community types were classified to long, short, short–thin branching, tabular corals, and *Enhalus acoroides* presented in Fig. 10.3 (referred from Shimokawa et al. 2016)

massive corals, they are 7, 1, 45, and 47%. For foliose corals, they are 6, 1, 29, and 19%. For encrusting corals, they are 7, 1, 24, and 25%.

Sakiyama Bay has seven branching coral communities (A–G in Fig. 10.5) and four tabular coral communities (H–K in Fig. 10.5). Average lengths of the living parts and width of the bases for the random selected branches in the branching coral communities are presented in Table 10.1. Based on the measurements, for the branching coral, the community types were classified as long, short, and short–thin branching corals. Average lengths of the living parts in the communities of long, short, and short–thin branching corals were, respectively, 15.9 cm, 9.4 cm, and

**Table 10.1** Average lengths and widths of branches in branching coral communities (referred from Shimokawa et al. 2016)

Community	A	B	C	D	E	F	G
Average length (cm)	14.7	17.1	9.1	9.3	9.8	9.9	9.4
Average width (cm)	1.2	1.2	0.9	1.0	0.4	1.1	1.0

9.8 cm. Average widths of the bases in the communities of long, short, and short–thin branching corals were, respectively, 1.2 cm, 1.0 cm, and 0.4 cm.

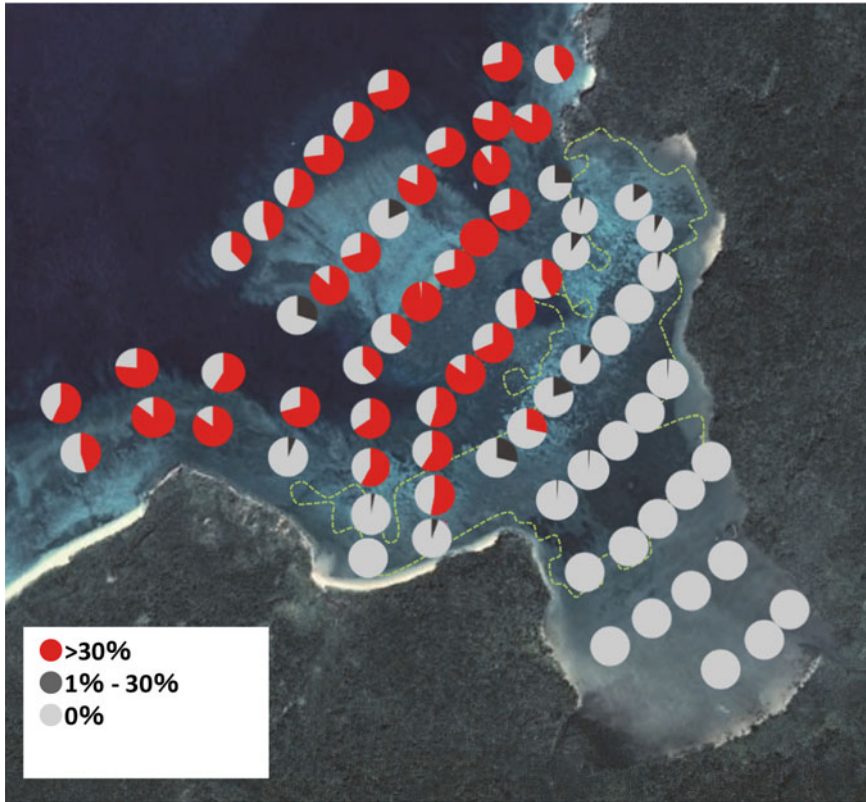
Figure 10.5 presents the distributions of coral areas by community type presented in Fig. 10.3. Long branching coral communities are located mainly at the mouth of the bay, slightly distant from the reef margin. The number and total area size are, respectively, 2 and 16 ha. Short branching coral communities are located mainly at the reef margin with strong wave breaks. Their number and total area are, respectively, 4 and 11 ha. Short–thin branching coral communities of 200 m diameter are mainly located at the margin of reef pond at around 13 m depth in the east of the central part of the bay. Their number and total area size are, respectively, 1 and 2 ha. *Enhalus acoroides* communities are located mainly at the central and inner parts of the bay, along a shallow and flat bottom at approximately 1.2 m depth (Kawana 1990).

## 10.5 Relation Between Coral Distributions and Physical Variables

In this section, we explain the relation between coral distributions described in the previous section. We also explain the bottom flow speed and soil particle numbers obtained from numerical simulations conducted for Sakiyama Bay.

Figure 10.6 shows the total coverage of corals without distinction of colony shape. Broadly speaking, the total coverage is over 30% from the mouth of the bay to the central part of the bay, under 30% from the central part of the bay to the habitat of *Enhalus acoroides* (shown by dotted yellow line), and 0% at the innermost bay area. Therefore, we classified the investigation points as those with total coverage of 0, 1–30%, and over 30%. Moreover, we analyzed the relation between the coral distributions and the physical variables.

Figure 10.7 presents the relations among community type, total coverage, and bottom flow speed. Bottom flow is generated by waves, tides, wind, and river flows. Regarding the bottom flow speed by wave, irrespective of the season, the largest in terms of community type was tabular coral, followed in order by short branching coral, short–thin branching coral, and long branching coral (Fig. 10.7a). The largest in all coverage was points over 30%, followed in order by those of 1–30% and those of 0% (Fig. 10.7b). Particularly, the bottom flow speed in winter at points over 30% is twice as large as at points of 0%. However, for the bottom flow speed

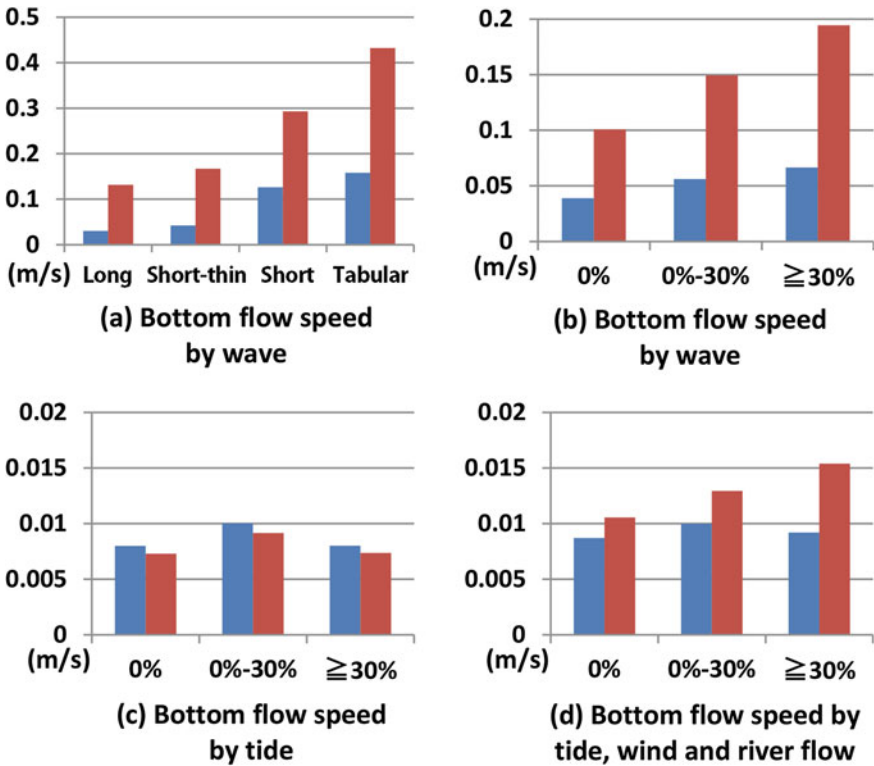


**Fig. 10.6** Total coverage of corals without distinction of colony shape. Red, dark gray, and light gray, respectively, portray over 30, 1–30, and 0%. The dotted yellow line shows the presence of *Enhalus acoroides*. Map data © 2016 Google (referred from Shimokawa et al. 2016)

by tide and that by tide, wind, and river flow, their correlation between total coverage and the values themselves is weaker than that by waves (Figs. 10.7b–d). Therefore, considering the relation between coral distributions and bottom flow speed, that by waves, is regarded as fundamentally important.

From the above, in Sakiyama Bay, it can be inferred that the bottom flow speed differs depending on points of each community type: Also, a higher bottom flow speed at a point indicates greater total coverage at that point. The results reflect the different shape tolerance of corals against ocean current: branching coral tends to be a dominant species because it grows rapidly (Stoddart 1969; Motokawa 2008), but at higher flow speeds (particularly at points near the mouth of the bay), the branch changes are more likely to be short than long (Fig. 10.5) because of their low tolerance against ocean current. By contrast, tabular coral tends to be more common (Fig. 10.4) because it has high tolerance against ocean currents by virtue of its shape (Goreau 1959; Woodley et al. 1981; Motokawa 2008). At higher flow speeds,



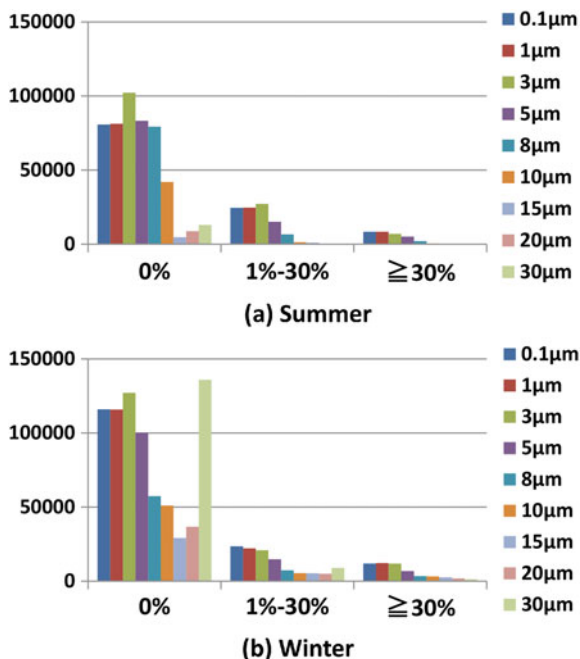


**Fig. 10.7** Relations among (a) community types, (b)–(d) total coverage, and bottom flow speed. The bottom flow speeds show averages for summer (blue) and winter (red) seasons on points with each range of coverage (referred from Shimokawa et al. 2016)

it becomes increasingly common (as the object point nears the reef margin); massive and encrusting corals tend to be more common (Fig. 10.4) because they have higher tolerance against ocean current by virtue of their shape, although they grow slowly (Stoddart 1969; Motokawa 2008). Consequently, in Sakiyama Bay, high coverage can persist in a broad area from the reef margin to the central part of the bay. Here, it is noteworthy that although short–thin branching coral communities are located at almost equal distance from the reef margin as long branching coral communities, they inhabit areas surrounding a reef pond: a special location in Sakiyama Bay with a flat bottom (Kawana 1990). That habitat is regarded as different from those found at other locations.

Figure 10.8 exhibits the relation between coral coverage and soil particle number. The soil particle number, irrespective of the season and soil particle diameter, is extremely large at points of 0%. Points with coral appearance of 1–30% are more numerous than points greater than 30%. In Sakiyama Bay, soil particle numbers are larger at coral inhibited areas, where coral coverage is low, probably

**Fig. 10.8** Relation between coral coverage and soil particle number in (a) summer and (b) winter. The soil particle numbers show values of total of soil particle numbers in calculation grids including investigation points with each range of coverage divided by the number of investigation points (referred from Shimokawa et al. 2016)



because soil particle inflow from rivers at the innermost part of the bay spreads a certain extent and affects the distribution of corals with low tolerance against soil particles (Rogers 1990; Motokawa 2008). This point will be discussed in greater detail in the next section in reference to the comparison with findings for Amitori Bay.

Here, it is noteworthy that the total numbers of soil particles of each diameter do not always match because soil particles of each diameter released from rivers can be counted only when the particles exist in a calculation grid that includes an investigation point. Additionally, the number of 30  $\mu\text{m}$  diameter soil particles in winter at points of 0% is extremely large because prevailing winds in winter in Sakiyama Bay are N-ENE (Kawana 1990). Therefore, large and heavy particles of 30  $\mu\text{m}$  diameter move only slightly from the innermost part of the bay (i.e., the region for total coverage of 0%), in addition to the above.

## 10.6 Comparison Between the Cases of Sakiyama and Amitori Bays

In this section, we discuss the difference between the distributions of corals and *Enhalus acoroides* in Sakiyama Bay presented in previous sections and those in Amitori Bay (Chap. 9 and Shimokawa et al. 2014).

Amitori Bay has various corals (Murakami et al. 2012; Shimokawa et al. 2014, 2015; Ukai et al. 2015), but their diversity (here, diversity in types of the colony shape, strictly speaking, equality; Ohgaki 2008) is maximal at the center part of the bay (Shimokawa et al. 2014). Few *Enhalus acoroides* inhabit the area; no large community exists (Murakami et al. 2014, 2015a, b; Nakase et al. 2015). By contrast, in Sakiyama Bay, although various corals also exist, their diversity is maximal at the reef margin (Fig. 10.4). *Enhalus acoroides* inhabits a broad area from the center part of the bay to the inner part of the bay (Fig. 10.5). These differences in distributions of corals and *Enhalus acoroides* between the bays are related not only to physical factors but also to various factors. They cannot be explained by a specific factor. However, the difference in soil particle inflow related to the geographic environment gradient between both bays is regarded as strongly affecting differences in the distributions of corals and *Enhalus acoroides* in the two bays.

As explained in the *Introduction*, Sakiyama Bay is adjacent to Amitori Bay, but it differs considerably from Amitori Bay in terms of its geographic characteristics such as the depth, length, and shape. Amitori Bay has a large geographic environmental gradient: great length compared to the width of the mouth of the bay and a deep valley reaching 70 m depth at the center of the bay (Shimoji et al. 1990). Because of these geographic characteristics, the effects of soil particle inflow are strong at the innermost part of the bay and the deep valley in the center of the bay, and weak at the east and west sides of the bay, where the corals live (Murakami et al. 2013). By contrast, Sakiyama Bay has a small geographic environmental gradient: a short length compared to the width of the mouth of the bay, shallow depth of around a few meters from the innermost part of the bay to the mouth of the bay, with a flat bottom except for the reef pond of around 13 m depth and 200 m diameter just east of the central part of the bay (E in Fig. 10.5) (Kawana 1990). Therefore, the soil particle inflow effects are spread easily throughout the bay, compared to Amitori Bay. In fact, the sediment is a mixture of fine brown sand and gray-black mud in the entire region of the inner part of the bay (Shimoji et al. 1990). That is, in Sakiyama Bay, the effects of soil particle inflow from rivers at the innermost part of the bay are widespread because of its smaller geographic environment gradient than that of Amitori Bay. Therefore, in the inner part of the bay, a coral community, which is difficult to grow at the place with much soil, cannot develop, but the *Enhalus acoroides* community, of which roots and subterranean stems easily take root on muddy sediments (Komatsu et al. 2004), can develop. Moreover, branching coral has high tolerance against soil particles because of its shape, which renders the soil particles more difficult to accumulate than tabular coral (Rogers 1990; Motokawa 2008). Consequently, the distribution in the order of *Enhalus acoroides*, branching coral, and tabular coral with distance from the river at the innermost part of the bay is clearer in Sakiyama Bay.

For tabular and branching corals, different effects of their tolerances against soil particles on their distributions are approximately proportional to their distance from the river mouth. Differences in their tolerances against ocean currents, which affect their distributions, as stated in the preceding section, are approximately proportional to their distance from the bay mouth. Therefore, if rivers are located at the

innermost part of the bay, as they are in Amitori and Saliyama Bays, then similar effects can be expected on their distances from the mouths of the respective rivers and bays.

In Amitori Bay, the diversity index is highest at the center part of the bay, although the intermediate disturbance hypothesis (IDH) (Connell 1978), which postulates that local species diversity is maximized when environmental disturbances are neither too weak (or infrequent) nor too strong (or frequent), is supported for waves, but not for soil particles; IDH is supported as a whole. The reason is the following. First, the locations where the two effects above can be reached are separated because the geographic environmental gradient is large (i.e., Amitori Bay has a greater length than the width of the mouth of the bay). As a result, the environment in which corals of various types can coexist (i.e., the diversity is high) can be realized in the center part of the bay, where the disturbance of waves is of an intermediate degree. By contrast, in Sakiyama Bay, locations at which the two effects above can be obtained are overlapped because the geographic environmental gradient is small (i.e., Sakiyama Bay has a small length compared to the width of the bay mouth). Therefore, works constructed in a direction to strengthen the two similar effects and to create an environment for their coexistence cannot be realized in any specific location of the bay. Consequently, the distribution areas of tabular corals, branching corals, and *Enhalus acoroides* must be regarded as distinctly and necessarily separate.

## 10.7 Summary

This study clarified the relation between coral distributions and physical variables in Sakiyama Bay, Iriomote Island, Japan. The results were compared to those obtained for Sakiyama Bay. Differences of geographic environmental gradients between both bays are regarded as affecting the distributions of corals and *Enhalus acoroides*. These results are expected to provide useful information for the assessment of the effects of physical variables on coastal marine ecosystems in the Sakiyamawan–Amitoriwan Nature Conservation Area.

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