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Geophysical Approach to Marine Coastal Ecology

The Case of Iriomote Island, Japan

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ISSN 2365-7677 ISSN 2365-7685 (electronic)
Springer Oceanography
ISBN 978-981-15-1128-8 ISBN 978-981-15-1129-5 (eBook)
https://doi.org/10.1007/978-981-15-1129-5

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Preface

The presence of a coral reef, a sea grass bed of a shallow sea, a tidal flat, and a mangrove river will form a diverse tropical/subtropical coastal marine ecosystem and provide various benefits to humans. However, several coastal marine ecosystems are currently on the verge of crisis all over the world. In particular, the large-scale bleaching of coral due to the rising temperature of seawater observed in 2016 in all parts of the world is still fresh in our memory. Therefore, there is a strong demand for the global conservation of the coastal marine ecosystems and for environmental impact assessments.

Furthermore, the Iriomote Island, which is the target area of this book, has witnessed an increasing number of tourists in recent years after the inauguration of a new airport on the adjacent Ishigaki Island, and concerns regarding the impacts on the natural environment are intensifying. In addition, the Government of Japan is planning to register the area that includes the Iriomote Island (official name of the area: Amami-Oshima Island, Tokunoshima Island, the northern part of Okinawa Island, and Iriomote Island) as a world natural heritage site. Therefore, elucidating the relation between the ecology of organisms concerning the coastal marine ecosystem in the Iriomote Island, the physical environment corresponding to the ecological distribution of these organisms as well as the environmental impact assessment based on it is valuable immediate requirements.

To satisfy those requirements, investigations on the ecological distribution, observations of the ocean, atmosphere, and rivers, and numerical simulations have become important. Research with a comprehensive approach that combines the above has not necessarily been sufficient so far because close cooperation is required among specialists in different disciplines. Since 2011, the editors of this book, who are specialists in geophysics (Shinya Shimokawa and Tomokazu Murakaki) and ecology (Hiroyoshi Kohno), have been conducting a joint research on oceanographic observations during the occurrence of typhoons on the Iriomote Island, which is considered to be prone to typhoons. We noted that such a comprehensive research was possible, and we intended to contribute to the research on the conservation of the coastal marine ecosystem in areas, such as coral reefs, which are in a critically vulnerable situation.

Although the normal state and spatial environmental gradient related to coastal marine ecosystems, such as corals, are obviously important, the temporal environmental gradient of the oceanographic and meteorological phenomena and weather events, such as typhoons and monsoons, occurring in the region are also important. In particular, unlike tropical regions, subtropical regions, such as the Ryukyu Islands, which include the Iriomote Island, serve as the northern or southern limit for various marine species. In other words, for such species, a subtropical region offers marginal survival conditions. In such an area, the temporal environmental gradient of the oceanographic and meteorological phenomena can critically influence the distribution of marine species. For example, a strong wave and current due to a typhoon may destroy a coral. However, if no typhoon has occurred for a long time, the seawater temperature remains high, which may cause bleaching of the coral. Thus, all of the average state, spatial, and temporal environmental gradients are important to understand the physical environment, including the coastal marine ecosystem.

The Sakiyama and Amitori Bays in the Iriomote Island are the only nature conservation areas in the ocean environment in Japan. Because there is no land route to reach the area, the natural environment with minimal artificial influence is preserved and contains diverse coastal marine ecosystems such as coral. The Painta, Ubo, Ayanda, and Udara Rivers flow into the inner parts of the bays. The Amitori Bay is characterized by a sudden change in the depth of water and exhibits the second largest water depth in Okinawa. They yield various spatial environmental gradients. This area also provides a temporal environment gradient; the typhoons are surrounded by high-pressure systems in the Pacific Ocean in summer and by the northeasterly monsoon winds from continental anticyclones in winter. All these occurrences make the area very suitable to perform field research aimed at understanding the physical environment involving the coastal marine ecosystem.

For more than nine years since 2011, we have energetically promoted research on the physical environment involving the coastal marine ecosystems, such as coral, mainly in the Sakiyamawan–Amitoriwan Nature Conservation Area. We have benefited from the help of many researchers, and this book is the outcome.

In Part I, we introduce common basic items for specific research that are to be covered after Part II. It also describes the target areas of this book, including the Iriomote Island and the Sakiyamawan–Amitoriwan Nature Conservation Area, and their meteorological fields. Further, it provides an overview of the organisms that are studied in this book (coral, *Enhalus acoroides*, and *Coenobita brevimanus*), the observation equipment used for obtaining the physical environment data, and the numerical model used for replicating the oceanic flow and sediment transport fields. In Part II, we cover the physical environment of the Iriomote Island elucidated using various types of observation equipment and numerical models. It describes the oceanic flow field, sediment transport from rivers flowing into the inner parts of the bays, and underwater three-dimensional measurement using the SfM technique. Parts III and IV, which constitute the core of this book, present the research results obtained using a comprehensive approach by combining the investigations of ecological distribution, observations of ocean, atmosphere, and rivers, and numerical simulations. In Part III, we study the relations between the distribution of the coastal marine ecosystem and the physical environments. The relation between the distribution of coral as well as *Enhalus acoroides* and the physical environment, particularly the relation between the oceanic flow and sediment transport fields, and a method to estimate the distribution of coral based on its physical environment are obtained. In Part IV, we study the relations between the physical environments and the retention and dispersion of eggs, larvae, seeds, and fruit of marine organisms. The bundles of *Acroporidae* that spawn simultaneously, the seeds and fruits of *Enhalus acoroides* whose male and female flowers bloom simultaneously and pollinate on the sea surface, and the larvae of *Coenobita brevimanus* simultaneously discharged on the seashore are described along with the relation of them with the physical environment, especially the oceanic flow field.

This book was completed not only with the help of each chapter's author but also with the help of several collaborators. We would like to extend our gratitude to all such collaborators. In particular, Prof. Dr. Ryohei Misumi and Mr. Ken Sakihara provided tremendous support while advancing the research work presented in this book. In addition, the research activities on which this book was based were supported by the following: the research project of National Research Institute for Earth Science and Disaster Resilience ("Development of the Water-Related Disaster Prediction Technology Based on Multi Sensing"); a research and education grant for Okinawa Regional Research Center, Tokai University ("Species Diversity and its Maintenance Mechanisms of the Coral Community in the Ocean Area Northwest of Iriomote Island"); and the joint study conducted by Tokai University and the National Research Institute for Earth Science and Disaster Resilience ("Elucidation of the Relationship Between Coastal Marine Ecosystem and Temporal–Spatial Gradient of Physical Environment in the Ocean Area Northwest of Iriomote Island"). We would like to take this opportunity to express our gratitude to all of them.

Tsukuba, Japan Shinya Shimokawa
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November 2019

Contents

Part I
Basic Information

Chapter 1
Iriomote Island, Japan

Shinya Shimokawa, Hiroyoshi Kohno, Akira Mizutani, Masako Nakamura and Wataru Doi

Abstract This chapter gives basic information on Iriomote Island, the target area of Iriomote Island. Sections 1.1–1.3 describes geophysical aspect of Iriomote Island: the geographical characteristics, Sakiyamawan–Amitoriwan Nature Conservation Area, and the meteorology, respectively. Sections 1.4–1.6 describe biological aspects of Iriomote Island: Corals, Tropical sea grass *Enhalus acoroides*, *Coenobita brevimanus*, respectively.

Keywords Iriomote Island · Sakiyamawan–Amitoriwan Nature Conservation Area · Coral · *Enhalus acoroides* · *Coenobita brevimanus*

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S. Shimokawa et al. (eds.), *Geophysical Approach to Marine Coastal Ecology*, Springer Oceanography, https://doi.org/10.1007/978-981-15-1129-5_1

1.1 Geographical Characteristics of Iriomote Island

Shinya Shimokawa

Iriomote Island is located southwest of Japan at 24° 15–20′ N and 123° 40–55′ E on the East China Sea. It is around 100 km from the Tropic of Cancer and around 200 km from Taiwan, which is closer to it than Okinawa Island, Japan (Fig. 1.1a). The island belongs to the Ryukyu Islands, Okinawa, Japan and is included among the Yaeyama Islands with Ishigaki, Taketomi, Kohama, and other small islands.

Geologically, Iriomote Island belongs to the Ryukyu Arc. The Ryukyu Arc–Okinawa Trough system is one of several arc–backarc systems along the margin of the western Pacific and eastern Asia (Kizaki 1986). Ryukyu Arc is divided into the north, middle, and south Ryukyu arcs. The respective boundaries are the Tokara strait and the Miyako depression. The Yaeyama Islands, including Iriomote Island, belongs to the south Ryukyu Arc. The deepest area of the Okinawa Trough is at the submarine rift valley near the Yaeyama Islands: It reaches 2300 m depth.

The main target area of this book is the northwestern part of Iriomote Island (Fig. 1.1b), particularly Sakiyama and Amitori bays (Fig. 1.1c). Neither bay has a

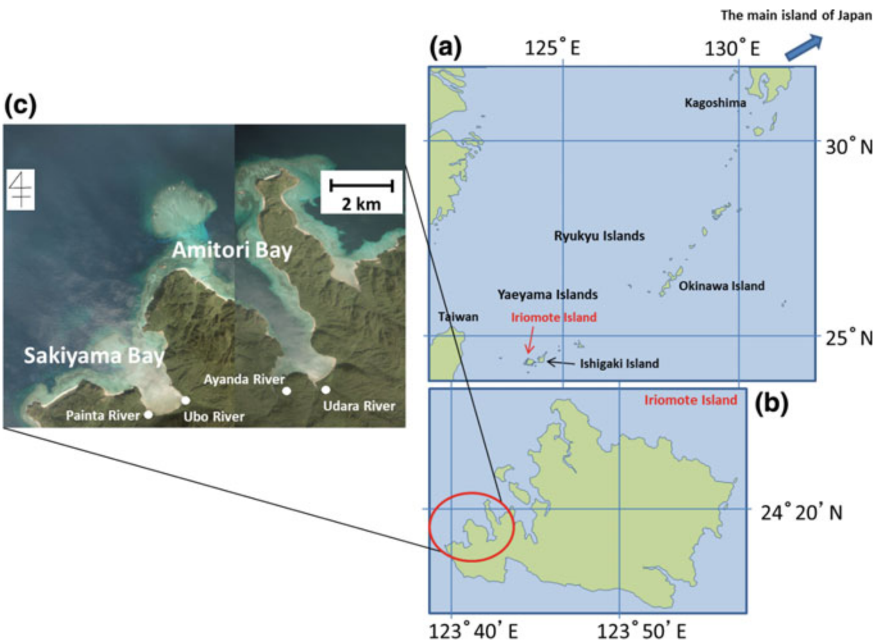


Fig. 1.1 Locations of Iriomote Island, Sakiyama Bay, and Amitori Bay. Our main study region lies on the southernmost tip of the Ryukyu Islands, Japan (**a**) and on Iriomote Island (**b**), and in the northwestern part of Iriomote Island, which includes the Sakiyamawan–Amitoriwan Nature Conservation Area (**c**) with its two bays: Sakiyama Bay and Amitori Bay. The white points in (**c**) show the river mouths of the four rivers: Painta, Ubo, Ayanda, and Udara rivers

road for access. Moreover, the bay perimeters are uninhabited. Consequently, the bays conserve widely diverse natural environments with little human impact. They belong to Sakiyamawan–Amitoriwan Nature Conservation Area. Details of the area are described in Sect. 1.2.

Iriomote Island, with an area of 290 km^2, is the second-largest island of Okinawa prefecture after Okinawa Island, with a shoreline length of 130 km. Over 90% of its mountainous topography is covered by subtropical virgin forest. Nevertheless, it has no steep mountains. The highest, Komi-dake, has height of 469.5 m. The second and third, Tedou-dake and Goza-dake, have respective heights of 441.2 and 420.4 m. These mountains overlap, with ridges extended, forming the complicated topography. Flatlands exist only around the mouths of the large rivers, as described later, and along the coast. They are used as residential areas, farmlands, and stock farms. The island has around 2000 residents.

On Iriomote Island, rivers are well developed by many rains and the complicated topography. Its many rivers and swamps include the 18.8 km long Urauchi River, which is the longest river in Okinawa prefecture. Nakama River is 7.45 km long. Urauchi River flows northwestward on the island from its southeastern origin. The Nakama River flows eastward from its southwestern origin. Many waterfalls are formed by their water flows and the complicated topography. Particularly Pinaisahra, which has the maximum height in Okinawa prefecture, and the Mariyudu and Kanbire waterfalls are famous as sightseeing spots. In addition, mangrove forests have developed around the riverbank near the river mouth. A mangrove forest in Nakama River is the largest in Japan.

The Ryukyu Islands, including Iriomote Island (Fig. 1.1a), have a subtropical marine climate, although they belong to humid subtropical climate (Cfa) according to the Köppen–Geiger Classification. Influenced by Kuroshio, among the world's major warm currents, and monsoons, among the world's major seasonal winds, annual precipitation reaches over 2000 mm. Subtropical rainforests thrive there. This is a distinguishing feature in the subtropical zone between 20–30° N and 20–30° S (Shimizu 2014). Much of the subtropical world is in the mid-latitude dry zone with low precipitation. Its vegetation is mostly dry series, including monsoon forest, savanna, steppe, and desert. Details of the atmospheric fields are presented in Sect. 1.3.

Many primitive characteristics have remained on Iriomote Island, home to characteristic and various animals and plants. One reason that the biome of the island has maintained its uniqueness up to the present day is that the Ryukyu Arc, including Iriomote Island, was separated from the Asian Continent and Japanese Islands (i.e., the Okinawa Trough was formed) at an early time: from Late Miocene to Early Pleistocene (Miki et al. 1990; Gallagher et al. 2015). It also was not submerged during the subsequent marine transgression periods (Ota 1998; Okamoto 2017). The Iriomote wildcat (*Prionailurus bengalensis iriomotensis*) and crested serpent eagle (*Spilornis cheela*) are designated as special national natural treasures. Also, the yellow-margined box turtle (*Cuora flavomarginata*), Kishinoue's giant skink (*Plestiodon kishinouyei*), Sakishima habu (*Protobothrops elegans*), and others are designated as national natural treasures. Most of those are species endemic to Yaeyama Islands, although species endemic to Iriomote Island also exist, such as the Iriomote wildcat.

Moreover, the abundant ecosystems of Iriomote Island extend from land into the circumjacent coastal marine regions. Its biological environmental factors can be characterized mainly by coral reefs, seaweed forests, and tidelands. They can supply habitats and food for various living things beginning with fish and shellfish. Particularly, the coastal marine ecosystem in this region can be characterized mainly by the coral reefs which have been formed by sea level changes and accompanying glacial and interglacial cycles in Pleistocene and inflow of Kuroshio into the back arc side of the Ryukyu Arc at around 2 million years ago (Iryu et al. 2006). Details of the targets of this book, coral, *Enhalus acoroides* (a species of sea grass) and *Coenobita brevimanus* (a species of land hermit crab), are described, respectively, in Sects. 1.4, 1.5, and 1.6.

Iriomote Island has been designated as Iriomote Ishigaki National Park, Iriomote National Wildlife Sanctuary, and the Sakiyamawan–Amitoriwan Nature Conservation Area. Great efforts have been dedicated to the protection of the island's animals and plants and to the conservation of their habitats. Recently however, tourists are increasing rapidly with the opening of an airport on Ishigaki Island, neighboring Iriomote Island. Since then, concerns about nature destruction have intensified. In addition, the Government of Japan aims to register the region, including Iriomote Island (Amami-Oshima Island, Tokunoshima Island, the northern part of Okinawa Island, and Iriomote Island), on the world nature heritage list (Government of Japan 2017). Registration on the world heritage list can lead to the intensification of nature conservation and economic development through increased tourism, but such recognition can bring burdens to the natural environment with increased tourism. It should be recognized strongly that economic development by tourist businesses is based on nature conservation in the relevant area. For that purpose, assessments of environmental impact and consideration of measures for reducing environmental loads will be increasingly necessary for the area.

For environmental impact assessment, relations between distributions of living things there and physical environments of their habit must be investigated. This book specifically examines the relations among coastal marine ecosystems such as coral, sea grass, and land hermit crab, with the intention of providing basic information in support of assessments.

1.2 Sakiyamawan–Amitoriwan Nature Conservation Area

Hiroyoshi Kohno

The Sakiyamawan–Amitoriwan Nature Conservation Area is located at the westernmost end of Iriomote Island, the Yaeyama Islands, Okinawa-ken (Fig. 1.2). It consists of a marine area of 1077 ha including Sakiyama and Amitori bays opening

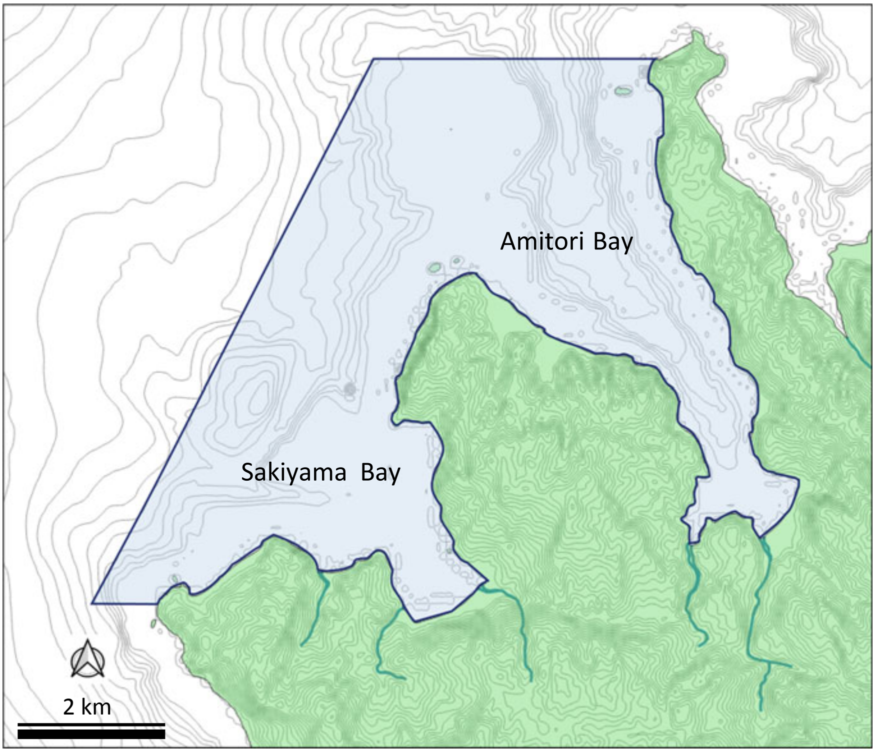


Fig. 1.2 Location of the Sakiyamawan–Amitoriwan Nature Conservation Area. Created by editing Geospatial Information Authority of Japan, 2017. http://fgd.gsi.go.jp/download/mapGis.php

to the northwest and their circumference, forming a clear sea area with rich natural beauty subject to little anthropogenic impact (Ministry of Environment 2015).

Originally, a sea area of 128 ha at the center of inner Sakiyama Bay was designated by the Environmental Protection Agency as the first marine Nature Conservation Area of Japan on June 28, 1983 (Marine Park Center Foundation 1984). Sakiyama Bay, about 1.3 km wide, with length of as little as 1.4 km, is shallow. It has a huge Galaxea colony at its mouth and well-developed reef-building coral assemblages to the center, comprising *Acropora*, *Montipora*, and *Porites*. Collectively, they form a complicated and rich marine biota in which one species among them is dominant and grows thickly at one place while several species are intermingled at other places. A submarine seaweed forest has formed at the bay head, mainly comprising communities of *E. acoroides*, a tropical sea grass for which the northern limit of distribution is the Yaeyama Islands. Furthermore, tidal flats around the mouth of small rivers flowing into the bay head are well developed (Ministry of Environment 2015). However, Amitori Bay is long and deep, with an inner bay environment that is affected little by waves and tidal currents or by northeast monsoons in winter (see Sect. 1.3). Mangrove forests grow at the bay head, with the Udara and Ayanda rivers with developed tidal flats flowing there. This steep environmental gradient accompanying the length and water depth of the bay is also a notable characteristic of Amitori Bay. Moreover, coral assemblages are developed according to diverse environments inside the bay. There is a large-scale assemblage of *Leptoseris amitoriensis*, an endemic species of Iriomote Island in the depth of the bay. Consequently, both Sakiyama and Amitori bays have outstanding natural environments with rich natural character, large coral assemblages, seagrass meadows, and various species thriving and expanding. Those commonalities notwithstanding the bays differ in geographical features and environments inside the bays, so that a characteristic biocoenosis for each bay reflects their differences (Ministry of Environment 2015). The characteristics of physical environments such as waves, tidal current, and sediment transportation from rivers in both bays are described in Part 2.

This area including both bays and their circumference falls under "sea areas that sustain well-preserved nature including native flora and fauna, e.g., tropical fishes, corals, and seagrasses" prescribed by item 5, paragraph 1, Article 22 of Nature Conservation Act, so that it is necessary to conserve this whole area as a nature conservation area. For this reason, the area was re-designated as a nature conservation area with substantial expansion from the original Sakiyamawan Nature Conservation Area on February 17, 2015 (Ministry of Environment 2015).

Nature conservation areas are extremely important for the conservation of natural environments. However, it is fundamentally important to comprehend local ecosystems unerringly as well as the characteristics of flora and fauna with peculiarity, endemism, and scarcity, to preserve them for years to come. Therefore, the Ministry of Environment has been conducting surveys continuously since the re-designation (Marine Park Center Foundation 1984; Nature Conservation Bureau of Environmental Protection Agency 1990, 1999; Nature Conservation Bureau of Ministry of Environment and Kaiyu Ltd. 2004; Naha Natural Environmental Office of Ministry of Environment and Okinawa Regional Research Center of Tokai University 2016, 2017, 2018).

Coral assemblages and seagrass meadows, constituting the principal biological environment of the Sakiyamawan–Amitoriwan Nature Conservation Area, have so far undergone the influences of feeding damage of coral by a huge outbreak of corallivorous starfish, *Acanthaster planci* sensu lato, coral bleaching by high water temperature, and feeding damage to *E. acoroides* by green turtles *Chelonia mydas*. For example, although feeding damage of *A. planci* sensu lato was confirmed as only slight in Amitori Bay until 1979, a huge outbreak of this starfish arose in 1980–1982, entailing destructive feeding damage to the coral assemblage (Kohno 1984). These populations were assumed to have invaded Sakiyama Bay gradually since 1983, but they left without imparting severe feeding damage; a sound coral reef survived (Marine Park Center Foundation 1984; Ogura et al. 1989). This is one aspect of the background of Sakiyama Bay, designated as the first marine nature conservation area of Japan. The coral assemblages of Amitori Bay, once almost annihilated but on the road to recovery, suffered from wide-area coral bleaching by high water temperatures in 1998, 2007, and 2016, so that coverage has been declining consistently. Especially, bleaching by high water temperature during the summer of 2016 extended to even the lower reaches of reef slopes. Coverage and egg production rates, as well as the number of Acropora larvae, recruited decreased extremely in 2017. Consequently, the influence of bleaching lasted into the following year. Details of coral issues are discussed in detail in Sect. 1.4. Medows of *E. acoroides* with monospecific or dominantly are formed scattered along the northwestern coast of Iriomote Island. However, the decline and disappearance of meadows because of overgrazing by herbivorous green turtles *C. mydas* are rapidly advancing recently (Takeyama et al. 2014; Naha Natural Environmental Office of Ministry of Environment and Okinawa Regional Research Center of Tokai University 2016, 2017, 2018). The ecological characteristics of habitat and sexual reproduction of *E. acoroides* at the northern limit of distribution and more detailed recent status are described in Sect. 1.5.

1.3 Meteorology of Iriomote Island

Akira Mizutani

Iriomote Island, located around 24° north latitude and 123° east longitude, is one island among the Yaeyama Islands of the southernmost end of the Ryukyu Islands from Kyushu, Japan to Taiwan. The Kuroshio Current (warm current) flows northward between Iriomote Island and Taiwan. By virtue of this warm current, heat flows into the atmosphere from the sea in winter, so that atmospheric temperatures do not drop to any great degree even during a southing cold snap; also, heat flows into the sea from the atmosphere in summer, so that atmospheric temperature does not rise remarkably. The Okinawa province including Iriomote Island belongs to such a “subtropical oceanic climate.” However, the Okinawa province is also governed by the East Asian monsoon belt: Northerly and southerly winds prevail, respectively, in winter and summer.

These two characteristics combine to produce the climate of the Okinawa province and Iriomote Island: roughly comprising a winter and a summer. In winter, high-pressure and low-pressure fronts pass over the Japanese Islands through the Sea of Japan by turns from the continent. The so-called pressure pattern of “high pressure to the west and the low pressure to the east” prevails when high-pressure areas cover the west side of the Japanese Islands and low-pressure areas cover the east side (Fig. 1.3a). Iriomote Island is located at the southern edge of this high-pressure zone; light rains fall; and a strong northeast winds are typical. Moreover, waves get higher and stormy weather comes from the sea under this pressure pattern. By contrast, in summer, the so-called pressure pattern of the “high

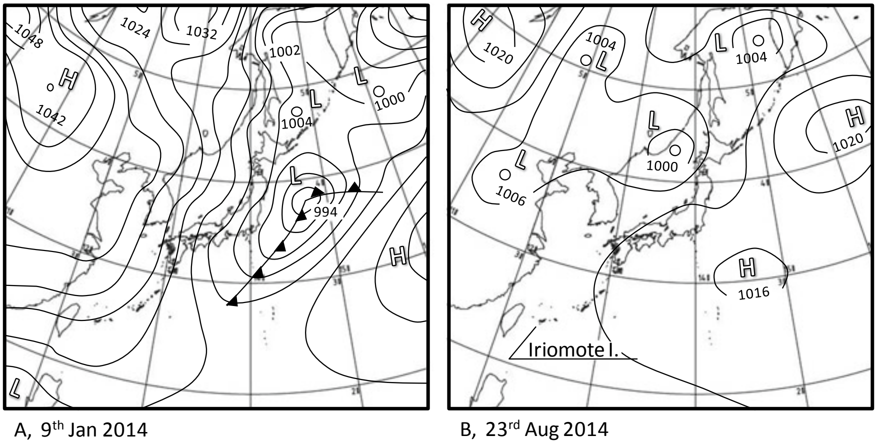


Fig. 1.3 Representative barometric arrangement in winter (**a**) and summer (**b**) around the Japanese archipelago. Created by editing Japan Meteorological Agency, 2014: https://www.data.jma.go.jp/fcd/yoho/hibiten/index.html

pressure to the south and the low pressure to the north" prevails when high-pressure areas cover the south side and low-pressure areas cover the north side, centering on the Japanese Islands (Fig. 1.3b). The weather on Iriomote Island is pleasant when covered by the Pacific High, and southeastern winds are typical.

However, a typhoon reverses the quiet oceanic conditions of a summer and produces a disturbance. Typhoons break out at around 15° north latitude to the east of the Philippines, move northwestward along the edge of the Pacific High, developing strength, and approach the Yaeyama Islands. The annual numbers of approaching typhoons at the Yaeyama Islands are reportedly 4.3 at Ishigakijima and 4.1 at Iriomote Island (Ishigakijima local meteorological observatory, Japan Meteorological Agency: http://www.jma-net.go.jp/ishigaki/obd/stats/sokuho/index_Stats.html browsed on August 3, 2018.).

This section presents an outline of a characteristic meteorological field in Iriomote Island based on records published during 2011–2016 (Mizutani and Sakihara 2012, 2014, 2015, 2016, 2017), from meteorological observations taken by the Okinawa Regional Research Center of Tokai University at Amitori Bay of Iriomote Island, providing research on natural and cultural sciences with environmental data.

Table 1.1 presents observation items and the outline of the equipment used. The observation equipment for atmospheric temperature and precipitation is placed on a lawn about 60 m inland from the seashore, and at the end of a pier for seawater temperature, wind direction, and wind velocity (Fig. 1.4). Seawater temperatures are measured on the sea bottom at about 3 m depth.

Table 1.1 Summary of observations

Observation equipment		Interval (min)
Data logger	CR1000 (Campbell)	
Air temperature and humidity	CVS-HMP155D-JM (Vaisala)	10
Precipitation	CTK-15PC-JM (Climatec)	10
Wind direction and speed	CYG-5106 (R. M. Young)	10
Water temperature	Tidvit v2 (Onset)	10

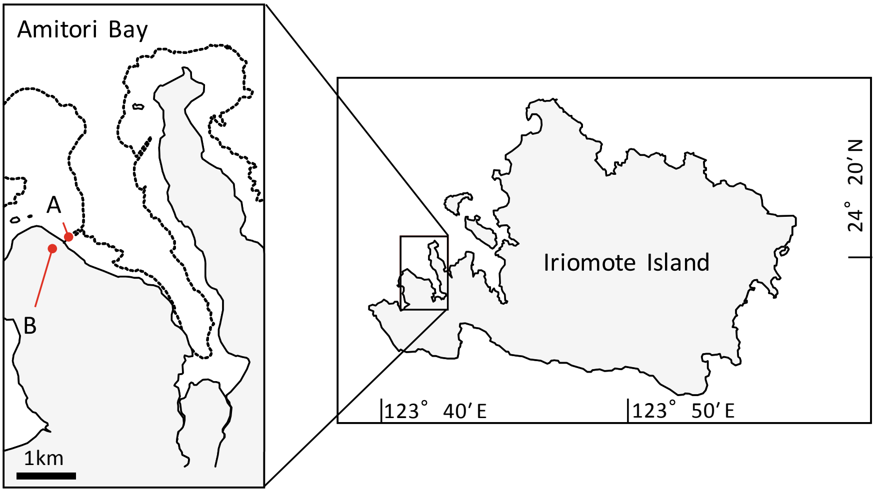


Fig. 1.4 Observation points at Amitori Bay, Iriomote Island: A, water temperature, wind direction, and speed; B, air temperature, humidity, and precipitation

For the period for which data were used, the observed values at Amitori for the six years of 2011–2016 indicate a warm and wet environment throughout the year, with average atmospheric temperature of 24.4 ± 4.44 SD °C (SD, standard deviation), average seawater temperature of 25.7 ± 2.72 SD °C, and average humidity of 80.1 ± 11.11 SD %. Annual accumulated rainfall was high, exceeding 1500 mm. Average wind velocity was 4.2 ± 2.83 SD m/s, and northeast and south–southeast winds prevailed, respectively, accounting for at 14.8 and 13.7% of all wind directions.

Seasonally, the lowest temperature was recorded in January, with a monthly average of 18.5 ± 2.44 SD °C. Subsequently, atmospheric temperatures rise gradually, becoming the highest in July to reach a monthly average of 28.9 ± 2.15 SD °C (Fig. 1.5). The seasonal change of seawater temperature was synchronizing mostly with atmospheric temperature, the lowest at a monthly average of

Fig. 1.5 Monthly change of the air temperature on the Amitori Bay, Iriomote Island (2011–2016): circle, average; shorter line, SD; longer line, minimum and maximum

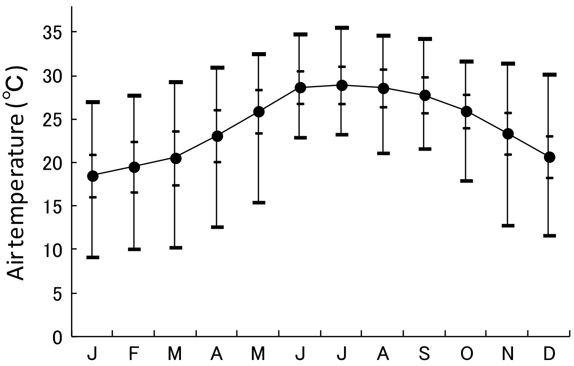
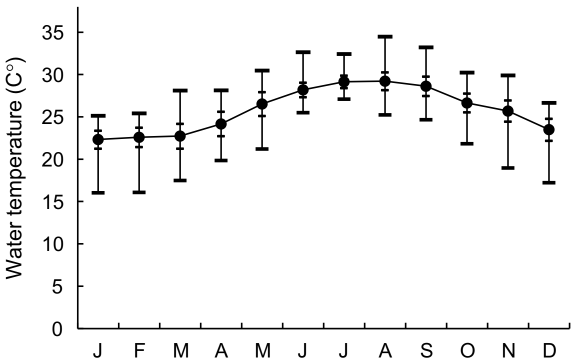


Fig. 1.6 Monthly change of the water temperature on the Amitori Bay, Iriomote Island (2011–2016): circles, average; shorter lines, SD; longer lines, minimum and maximum



22.3 ± 1.06 SD °C in January, and the highest at a monthly average of 29.2 ± 1.06 SD °C in August (Fig. 1.6). The ranges of atmospheric temperature and seawater temperature for the six years were 9.1–35.6 °C and 16.0–34.5 °C, respectively.

During October–March, northeast winds prevailed at 19–24% (Fig. 1.7), with wind velocity showing a monthly average of 4.7 ± 2.74 SD to 5.9 ± 3.01 SD m/s (Fig. 1.8). During April–August, south–southeast winds prevailed at 17–26%, with lower wind velocities showing a monthly average of 3.0 ± 1.50 SD to 3.9 ± 2.25 SD m/s. However, the maximum wind velocity (averaged for 10 min) of this period was over 20 m/s in July–October, where all cases were related to approaching typhoon phenomena.

Rainfall exceeded 100 mm almost every month. Especially, monthly accumulated rainfall of 200 mm or more was often recorded in August related to approaching typhoons and in May of the "rainy season" with enhanced rainfall under the influence of a stationary front stretching from east to west in the Okinawa

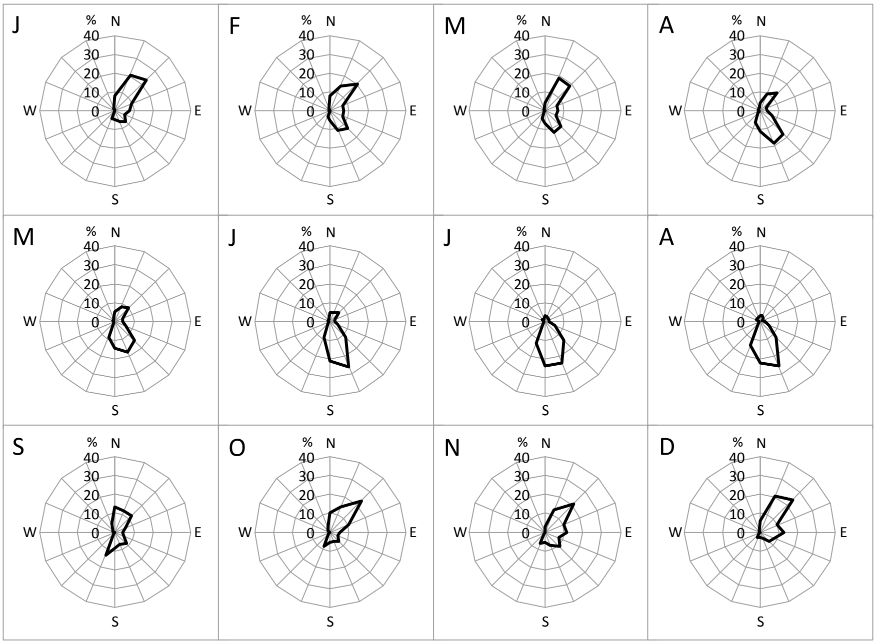


Fig. 1.7 Monthly change of the wind direction on the Amitori Bay, Iriomote Island (2011–2016)

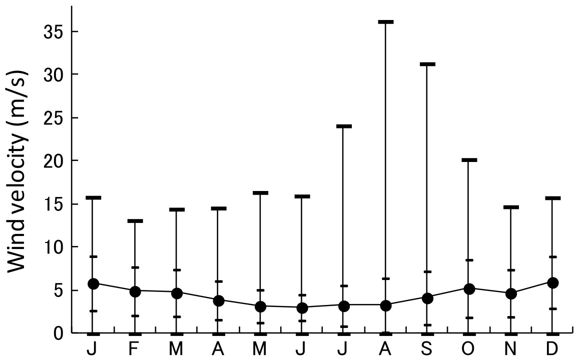


Fig. 1.8 Monthly change of the wind velocity on the Amitori Bay, Iriomote Island (2011–2016): circles, average; shorter lines, SD; longer lines, minimum and maximum

province (Fig. 1.9). Humidity was higher than 80% in April–September, and conversely lower than 80% in October–March (Fig. 1.10).

A total of 26 typhoons approached Iriomote Island during 2011–2016 (annual average: 4.3 times) (Ishigakijima Local Meteorological Observatory, Japan Meteorological Agency: http://www.jma-net.go.jp/ishigaki/obd/stats/sokuho/index_Stats.html browsed on August 3, 2018.). The maximum instantaneous

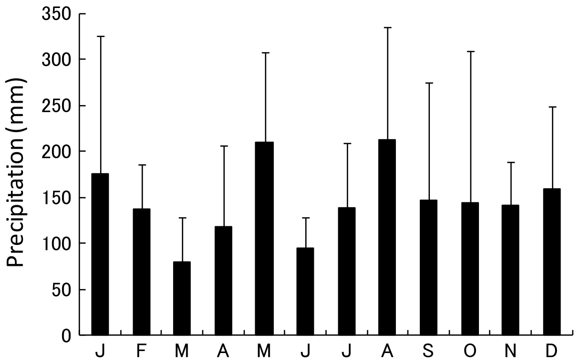


Fig. 1.9 Monthly change of the rainfall on the Amitori Bay, Iriomote Island (2011–2016): rod, average; bar, SD

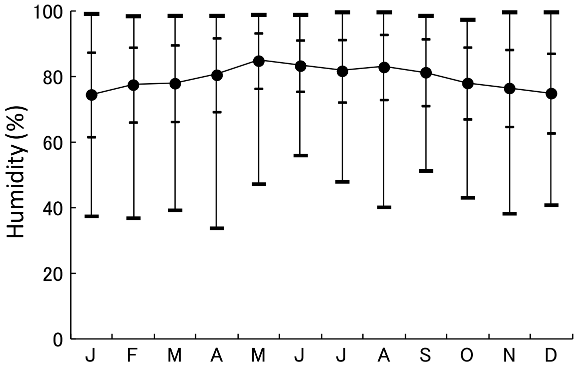


Fig. 1.10 Monthly change of the humidity on the Amitori Bay, Iriomote Island (2011–2016): circles, average; shorter lines, SD; longer lines, minimum and maximum

wind velocity of each year was recorded during the approach and passage of these typhoon storms. Noteworthy strong typhoons were No. 13 (SOUDELOR), No. 15 (GONI), and No. 21 (DUJUAN), all in 2015, with respective recorded maximum wind speeds and maximum instantaneous wind velocities of 28.9 m/s and 51.7 m/s, 36.3 m/s and 50.7 m/s, and 31.4 m/s, and 53.3 m/s (Fig. 1.11). Daily accumulated precipitation at the closest approach exceeded 100 mm in each case (Iriomote observation point, Ishigakijima local meteorological observatory, Japan Meteorological Agency: http://www.data.jma.go.jp/obd/stats/etrn/index.php). Furthermore, a storm and high surf occurred together and seawater temperatures dropped temporarily. Consequently, short-term disturbances in marine environments including seawater temperature are characteristic events of meteorological and oceanographic phenomena in this area, which has frequently approaching typhoons.

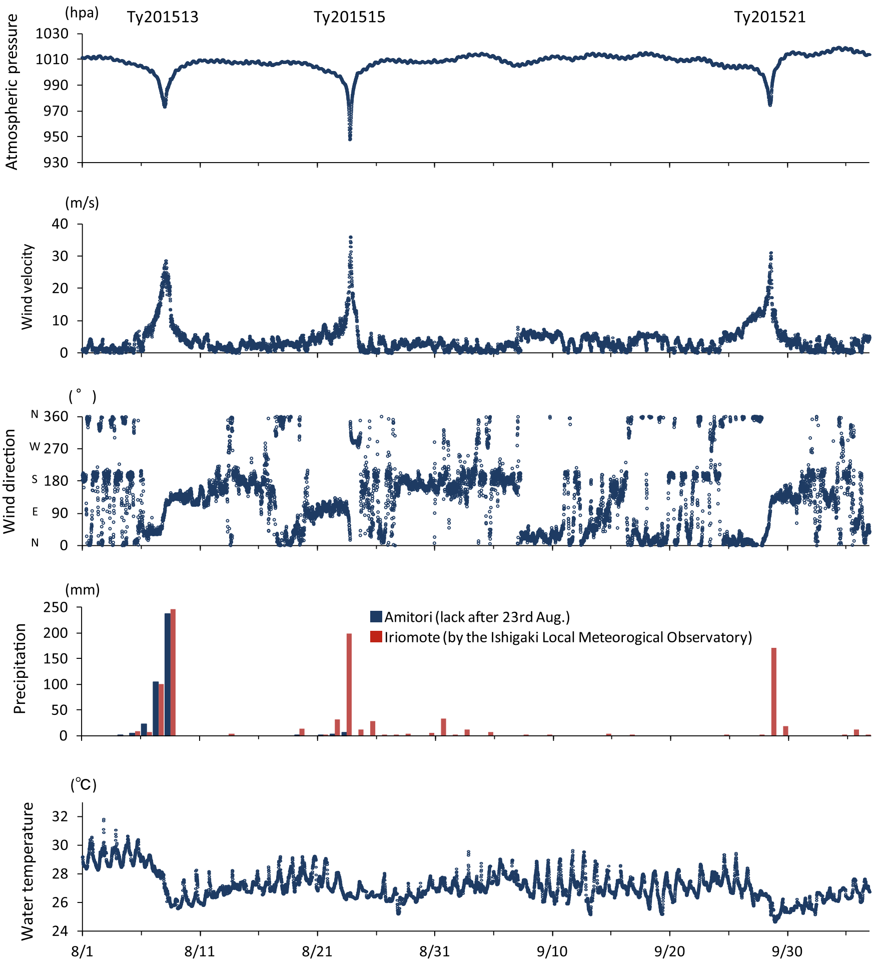


Fig. 1.11 Weather change with the three typhoons on the Amitori Bay, Iriomote Island in 2015. Precipitation on Iriomote was created by the author based on Ishigaki Local Meteorological Observatory, 2015. http://www.data.jma.go.jp/obd/stats/etrn/index.php?prec_no=91&blockno=47917&year=2015&month=09&day=&view= (referred from Mizutani and Sakihara 2016)

1.4 Corals in Amitori and Sakiyama Bay

Masako Nakamura and Hiroyoshi Kohno

1.4.1 State in the 1980s

Around Iriomote Island, outbreaks of corallivorous starfish, *A. planci* sensu lato have been observed since the beginning of the 1970s, e.g., Hatoma Island in 1972–1973 and Sekisei Lagoon in 1974–1981. In contrast, in Amitori and Sakiyama bays, damage caused by *A. planci* sensu lato has not been observed until the 1980s. First observations were made at the Amitori Bay entrance in the summer 1980. Branching acroporid corals and *Echinopora lamellosa* communities have largely been fed by *A. planci* sensu lato. Then, in the following year, coral communities in Amitori Bay were devastated by these corallivorous starfish. Only a part of the west side of the bay has not been affected (Marine Park Center Foundation 1984). In Sakiyama Bay, *A. planci* sensu lato were first observed 1983. In December 1983, *A. planci* sensu lato were observed, but only slightly, in Amitori Bay. However, fewer than 20 individuals per site were observed in Sakiyama Bay and northeastern areas of the entrance of Amitori Bay. The number of *A. planci* sensu lato in Sakiyama Bay increased toward August in 1984 (Ogura et al. 1989). According to the increase in the number of *A. planci* sensu lato, coral cover in Sakiyama Bay decreased in 1984. Coral communities in the northeast part of the bay showed 30–70% coverage in December 1983 (Marine Park Center Foundation 1984), but coral cover decreased to less than 10% in shallow waters in July (Ogura et al. 1989). Most of *Acropora* spp. were eaten in shallow lagoon to reef slope areas while branching and plate *Millepora* spp. and Fungiidae were not (Ogura et al. 1989). Ogura et al. (1989) estimated that the travel distance of *A. planci* sensu lato might be 0–15 m per day when there are corals on which to feed; they can travel for 6–10 h without prey. Moreover, the populations of *A. planci* sensu lato, which appeared in Amitori Bay in 1980, have been estimated as migrating to other areas along two routes, moving southwestward and northeastward (Marine Park Center Foundation 1984, Fig. 1.12). By the southwestward route, the population went to Sakiyama Bay and further west, passing through shallow areas of Yona-son or Sakuramizo. Along the northeastward route, the population followed reef edges and slopes to the end (closed-off section) of Amitori Bay and approached the bay entrance at the other bank (Sabasaki-side), subsequently proceeding northeastward.

In 1985, no *A. planci* sensu lato were observed; coral cover was less than 5% in most areas of Amitori and Sakiyama bays (Yokochi et al. 1991). Three years later, in 1988, coral cover started to increase from the entrance to the end of Amitori Bay (Habe 1989). In 1988, coral cover reached approx. 10%. In the entire bay, *A. planci* sensu lato was the dominant coral genus.

Fig. 1.12 Estimated migration routes at the beginning of the 1980s in Amitori and Sakiyama bays. Red arrows indicate southwestward route and blue arrows indicate northeastward route. A star shows the first area, where damage by *A. planci* sensu lato was first observed. Rewrite from Marine Park Center Foundation (1984). Map data© 2018 Google

The outbreaks of *A. planci* sensu lato in Amitori and Sakiyama Bays in the 1980s were expected to be attributable to numerous larvae entering the areas at the moment of increase of phytoplankton caused by heavy rainfall in 1976–1977 (Marine Park Center Foundation 1984).

1.4.2 State in the 1990s

At the end of the 1980s, coral cover in Sakiyama Bay varied from 1.1 to 21.6% (Nature Conservation Bureau 1999). However, 12.5–51.5% coral cover was observed in 1997, suggesting a recovery after the *A. planci* sensu lato outbreaks in the 1980s (Nature Conservation Bureau 1999). Dominant coral genera differed among sites in the bay. The highest coral cover was observed at S-RF.1, dominated mainly by branching *Acropora* spp. (Fig. 1.13). S-RS.1 and 2 were dominated by *Montipora* spp. and *Pocillopora* spp. Branching *Acropora* spp. were also dominant at S-EG.1. The lowest coral cover was observed at S-EW.1, where branching *Porites* spp. were the dominant coral genus.

Coral communities in Amitori Bay showed high cover: as much as those observed in Sakiyama Bay, which were 10–60% in 1995 (Nature Conservation Bureau 1999). Different from Sakiyama Bay, all of Amitori Bay were mostly dominated by *Acropora* spp. *Montipora* spp. were the second-most abundant coral genus in the bay. With lower cover, *Porites* spp. were also observed in the bay. At A-WM.1 and A-BB.1, acroporid coral covers decreased to 1997, although those at three other sites increased, especially at A-ER.1 and St.5; covers in 1997 were four

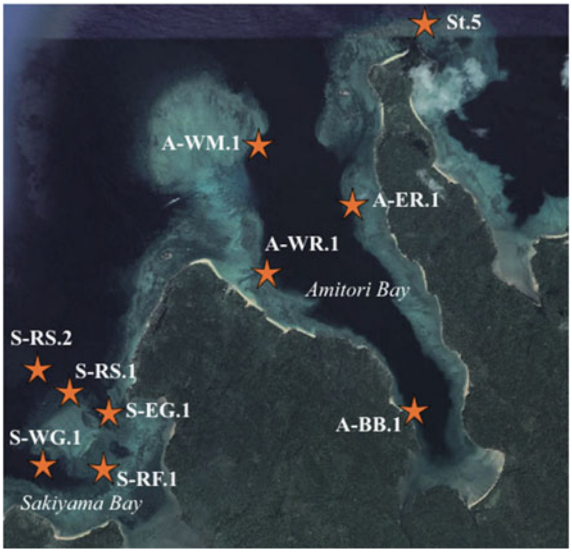


Fig. 1.13 Survey sites for observation of "State of Sakiyama Bay Nature Conservation Area, Okinawa, Japan" done by Nature Conservation Bureau, Environment Agency (Nature Conservation Bureau 1999). Map data© 2018 Google

times higher than those in 1995. As a result, coral cover was high in the bay, but it varied from 30 to 70% in 1997.

However, abnormally high seawater temperatures caused mass bleaching of corals in Ryukyu Islands, including Iriomote Is. More than 90% of branching *Acropor*a spp. and *Millepora* spp. in the lagoon in Sakiyama Bay died because of bleaching in 1998 (Nature Conservation Bureau 1999). However, coral communities at S-RS.1 and 2 were less affected.

1.4.3 State in 2000s

In spite of large coral losses because of mass bleaching in 1998, coral communities in Amitori and Sakiyama Bays already showed high coral cover and species diversity at the beginning of this century. Spot Check Surveys in 2004 found 40–60% coral cover at the entrances of the Sakiyama and Amitori Bays (Ministry of the Environment and Kaiyu 2004). In Sakiyama Bay, the maximum coral cover was 55%. The east side of Amitori Bay showed 60% coral cover. The communities in Sakiyama Bay consisted mainly of *Acropora* spp. and *Montipora* spp. In Amitori Bay, coral community compositions differed among areas. Reef flats around the entrance and middle of the bay were dominated by a mix of branching and table corals. Table corals were dominant at reef edges and reef slopes. In the shallow lagoon, there were mainly massive corals such as Poritidae. At the end of the bay, a mix of poritid corals, and branching and corymbose acroporids were major constituents of the community.