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Long-term observations of iron-oxyhydroxide-rich reddish-brown water in Nagahama Bay, Satsuma Iwo-Jima Island, Kagoshima, Japan

Takuya Ueshiba and Shoichi Kiyokawa

Abstract

Nagahama Bay, in the southern part of Satsuma Iwo-Jima Island (38 km south of Kyushu Island, Japan), contains an active hydrothermal system along the beach and at the fishing port. The construction of a breakwater around the bay has resulted in a semi-closed body of water with an entrance from the south. From this bay, reddish-brown seawater enriched in iron-oxyhydroxides is discharged to the Pacific Ocean constantly. The greenish-blue seawater of the Pacific Ocean occasionally enters the bay and mixes with the reddish-brown water. The daily flow pattern of the reddish-brown seawater in the bay has been monitored previously during storms and periods of heavy rain. However, greenish-blue seawater is sometimes observed in the bay at low tide. Therefore, we monitored the color of the sea surface and water at the seafloor for periods of 26 and 12 days during spring and autumn, respectively, using automatic still cameras to compare the water color with meteorological data recorded at Iwo-Jima Island.

The results show that a southerly wind is associated with the trapping of reddish-brown surface water in the bay. In contrast, a northerly wind brings greenish-blue water from the open ocean into the bay, even at low tide. The factors that control the color of seawater in Nagahama Bay are not only the tidal cycle and storm waves, but also wind speed and direction.

Keywords: Satsuma Iwo-Jima Island, iron-oxyhydroxides, hydrothermal system, shallow-water, tide, wind

1. Introduction

Iron deposits of various ages are found in many regions worldwide (Robb, 2005); however, little is known about the mechanism of iron sedimentation (Konhauser et al., 2002), especially the details of the suspension of iron hydroxide in seawater and its mode of accumulation on the seafloor.

Nagahama Bay on Satsuma Iwo-Jima Island, Japan, contains iron-rich reddish-brown seawater and modern-day hydrothermal iron-oxyhydroxide sediments on the seafloor (Nagata, 2011). Observations of turbidity in the bay have shown that the seawater color is controlled by tidal level, storm waves, and heavy rain (Ninomiya and Kiyokawa, 2009; Kiyokawa et al., in press); however, greenish-blue seawater is observed in the bay at low tide during periods of fine weather, and this cannot be explained by previous models of the daily flow pattern of iron-rich reddish-brown seawater in the bay. Moreover, no previous study has compared the seawater color in the bay with meteorological data. In this study, we observed the daily flow pattern of reddish-brown iron-rich water in Nagahama Bay for 26 days in autumn and 12 days in spring using one or two automatic still cameras, in order to compare the pattern of color change in the seawater with the record of wind speed and direction.

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2. Location and geology of Nagahama Bay

Nagahama Bay, Satsuma Iwo-Jima Island, is located about 38 km south of Kyushu Island, Japan (Fig. 1). Iwo-Jima Island contains the Kikai-caldera rim, extending NE–SW (Matumoto, 1943), and two active volcanoes: the rhyolitic Iwo-dake and basaltic Inamura-dake (Ono et al., 1982). Reddish-brown to white water is discharged from the eastern and southern coasts of Satsuma Iwo-Jima Island. These waters are colored because they contain complex molecules of Si–Fe–Al after neutralization of hot spring waters with seawater (Nogami et al., 1993). The reddish-brown iron-oxyhydroxide-rich seawater remains on the surface, maintaining the high temperature of the hot spring water. In Nagahama Bay, therefore, the reddish-brown seawater overlies colder seawater from the open ocean (Ninomiya and Kiyokawa, 2009). A large volume of reddish-brown seawater containing iron-oxyhydroxides is constantly discharged from Nagahama Bay to the open ocean (Sikaura and Tazaki, 2001); however, the construction of a breakwater in the bay, to protect against strong waves, means that the reddish-brown seawater is retained in the bay to a greater degree than at other parts of the coast around Iwo-Jima Island.

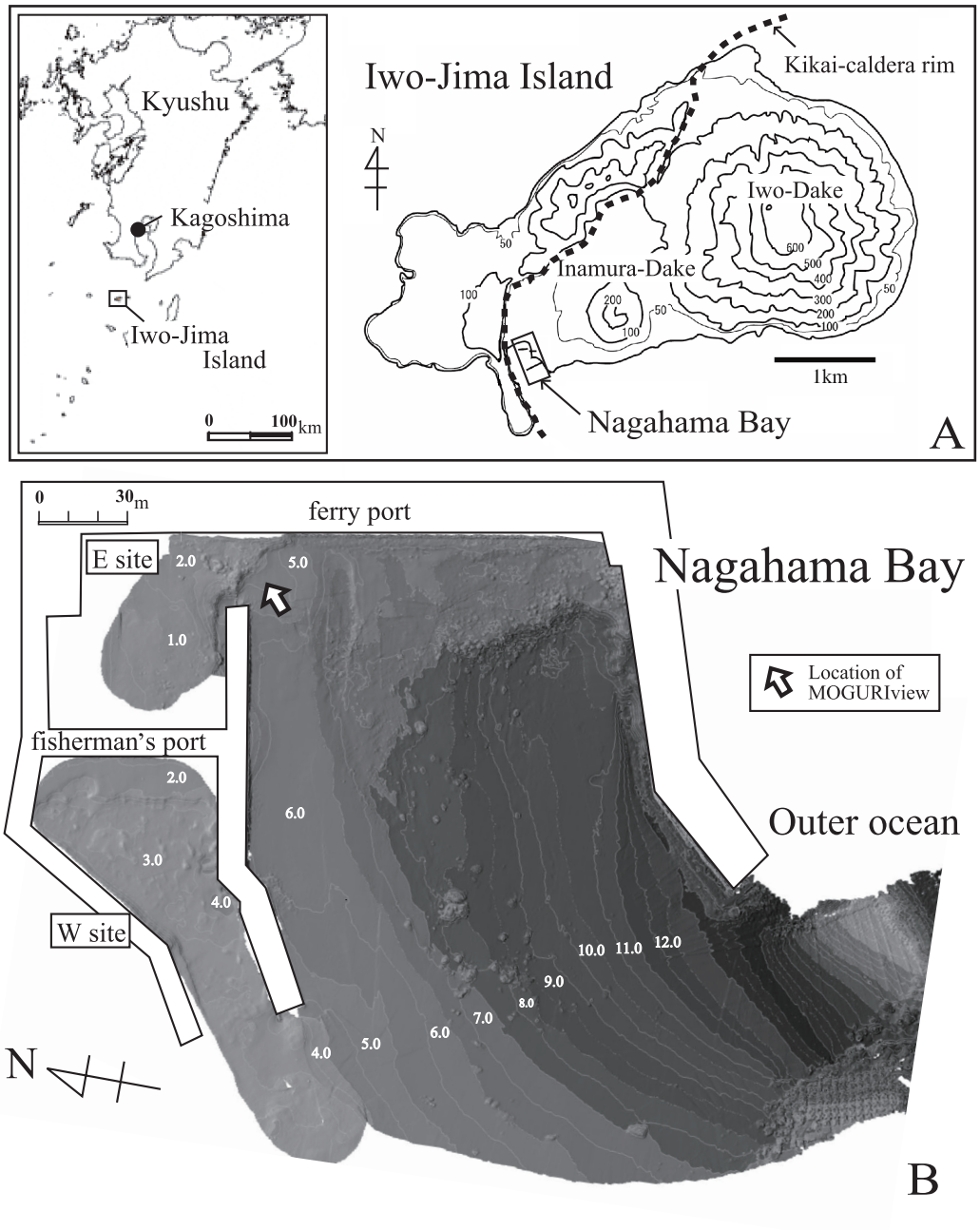

Fig. 1. (A) Locality map of Iwo-Jima Island and Nagahama Bay. (B) Sea Bat bathymetric map of Nagahama Bay in September 2010 (by Windy Network Co.).

3. Methods

3.1. Long-term monitoring system

To monitor the color of seawater in Nagahama Bay, we prepared two long-term automatic monitoring systems: MOGURIKU, which observes the bay from on land, and MOGURIview, which observes the seawater from the seafloor (Fig. 2). MOGURIKU is a fixed camera that was used to capture an image of Nagahama Bay at 5-min intervals for 26 and 12 days. MOGURIKU was attached to Misaki Bridge, from where it could capture an image of all of Nagahama Bay from an elevation of about 100 m. MOGURIview is a submarine automatic camera with an LED flash, and in the present study it was used to capture an underwater image of the seawater at the seafloor in Nagahama Bay at 10-min intervals for 12 days. MOGURIview was set at a water depth of about 4.5 m, at a site located east of the fishing port in the bay (Fig. 1).

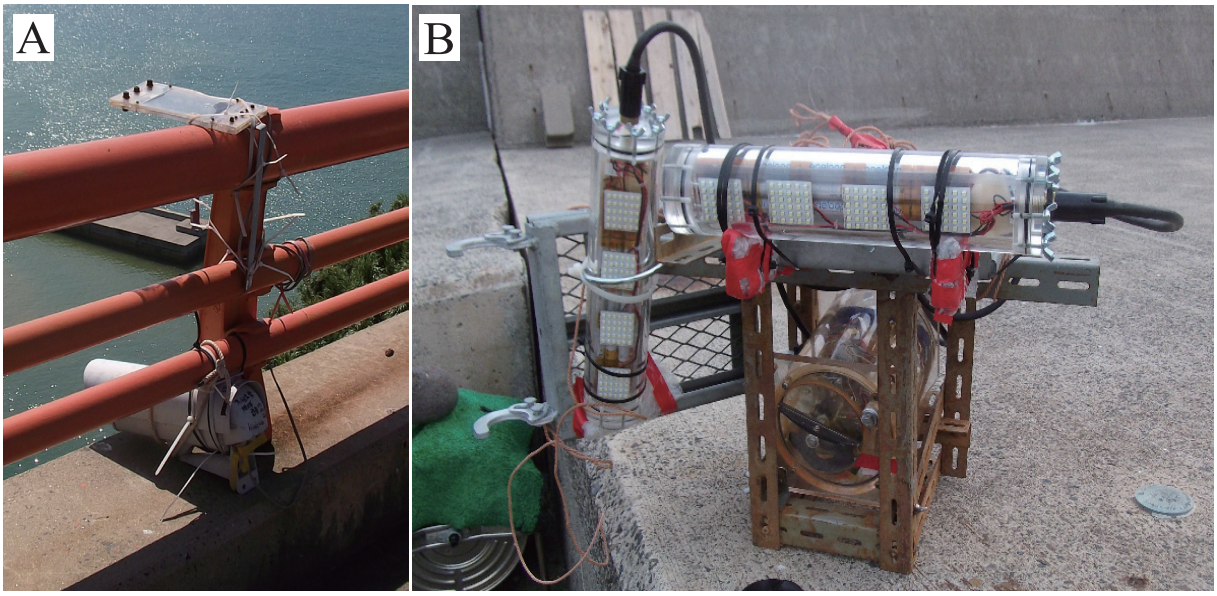

Fig. 2. (A) The sea surface automatic monitoring camera "MOGURIKU" installed on Misaki Bridge. (B) The seafloor automatic monitoring camera "MOGURIview".

3.2 Observation period

Monitoring of the sea surface and seafloor was performed during two periods: 3–28 October 2009 and 5–16 April 2011 (Figs. 3-4). In first period, MOGURIKU alone recorded changes in the color of surface water within the bay. In the second period, we used both MOGURIKU and MOGURIview (Fig. 4). Unfortunately, iron-oxyhydroxides adhered to the lens of MOGURIview, obscuring the images taken after 14 April.

3.3. Meteorological data

We analyzed wind data recorded at Mishima Center, approximately 30 m north of Nagahama Bay, where analog meteorological data are recorded hourly. We compared these data with the long-term observation images and tide data (Figs. 3-4) from the Makurazaki tidal station, as reported by Japan Meteorological Agency (2011).

4. Results

Figures 3 and 4 compare the sea surface and seafloor image data with tide, wind speed, and wind direction data. As Nagahama Bay is located between very steep cliffs of the caldera rim to the west and the mountain Inamura-Dake to the east, wind direction in the bay is almost always from the north or south. Wind speed is generally 0.0–5.0 m s^{-1}, although speeds of more than 10 m s^{-1} are recorded during storms.

During the first monitoring period (26 days), when just the sea surface was observed (Fig. 3), the seawater in the bay was reddish-brown when the wind blew from the south, and greenish-blue when from the north. During spring tide (13–18 October), the water in the central part of the bay was greenish-blue during high tide and when the wind blew from the north. The water was reddish-brown when the wind blew from the south.

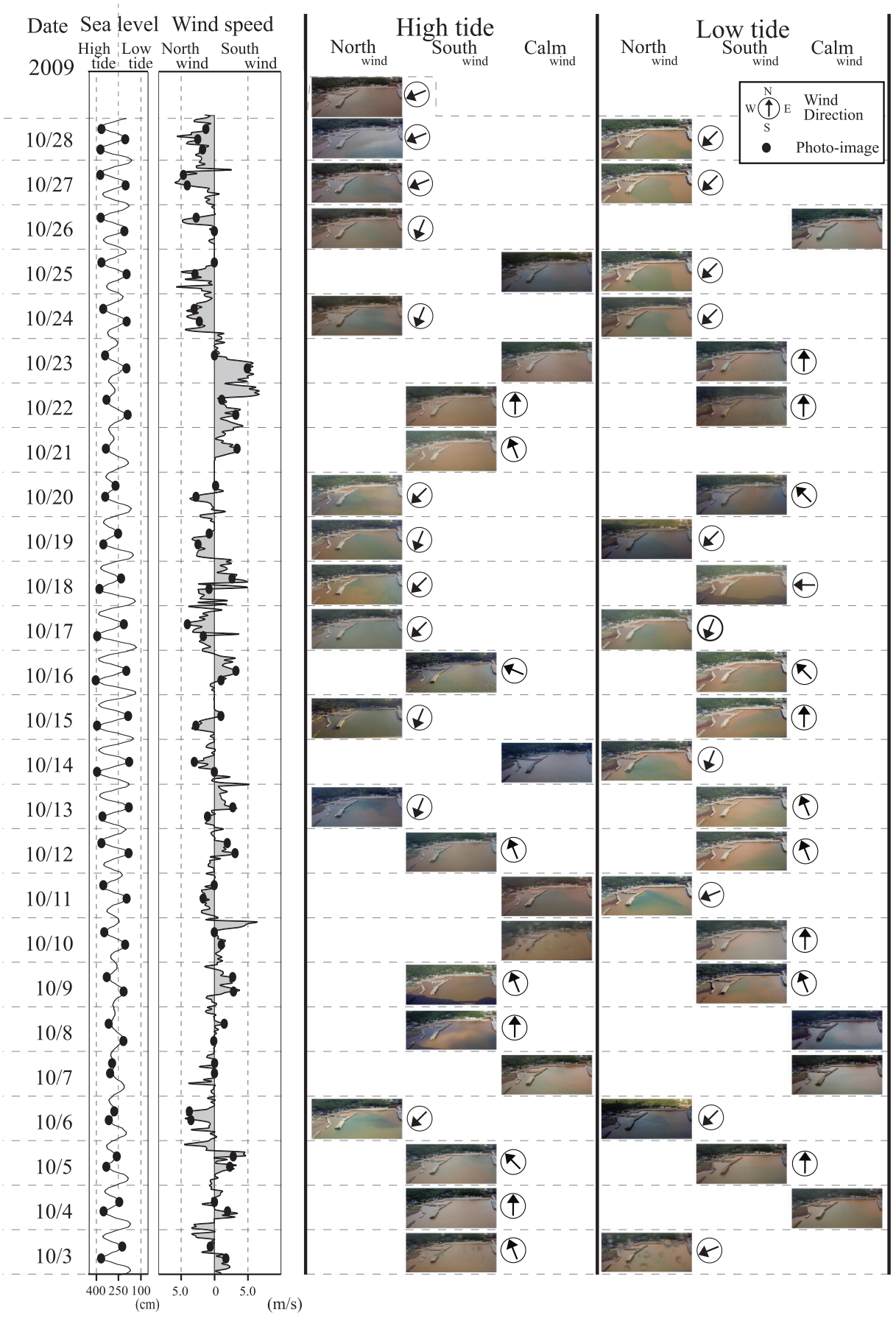

Fig. 3. Water color compared with sea level (cm) (JMA, 2011) and wind speed (m s^{-1}) for Nagahama Bay during the autumn monitoring period.

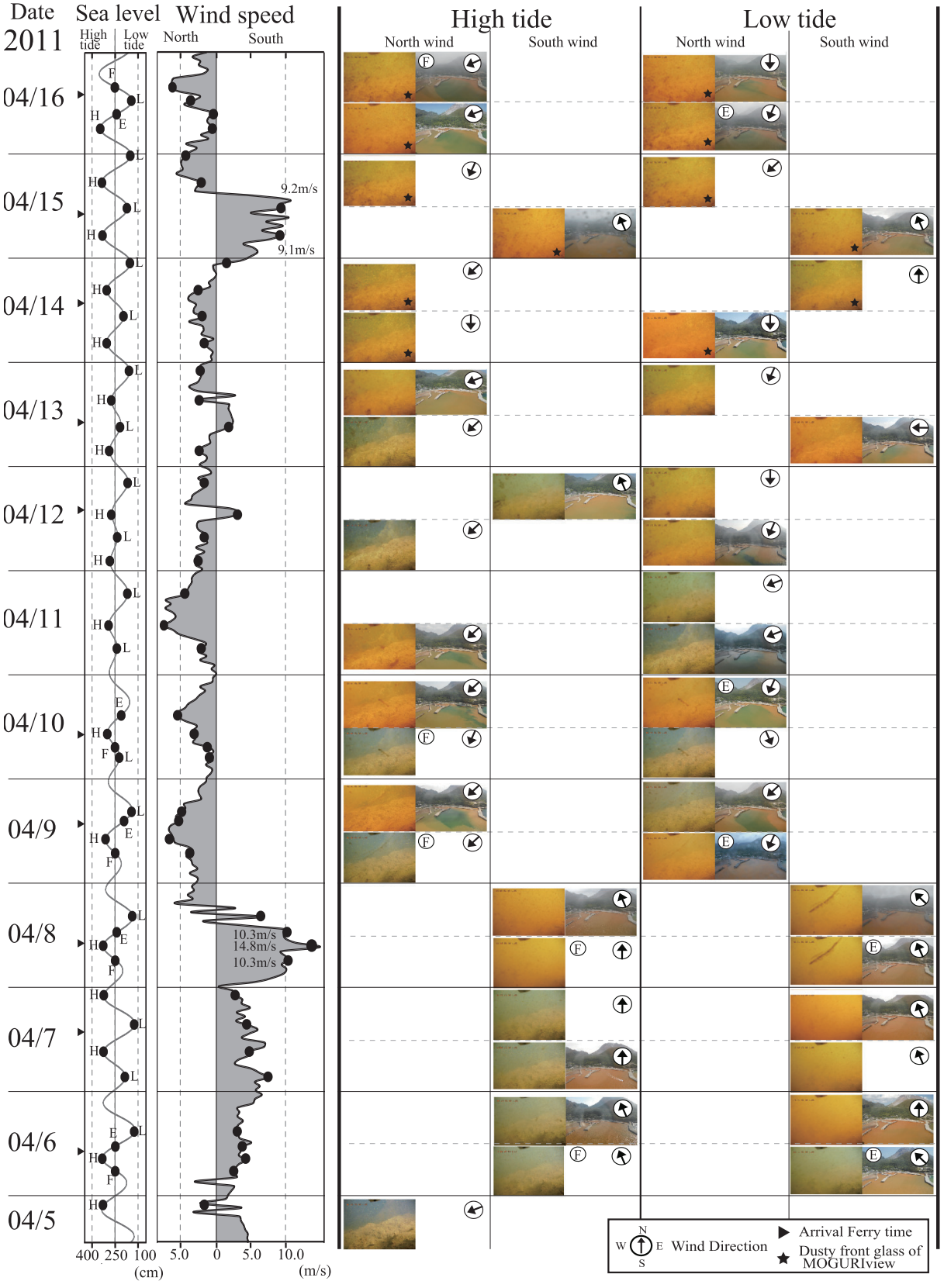

Fig. 4. Water color at the seafloor and sea surface compared with sea level (cm) (JMA, 2011) and wind speed (m s^{-1}) during the spring monitoring period. Black dots are observation points. H=high tide. F=flowing tide. E=ebb tide. L=low tide. The influence of sunlight reflection affects the color tone in the seafloor images taken during daytime.

During the second monitoring period (12 days), when both cameras were used (Fig. 4), seawater at the bottom of Nagahama Bay became clear during high and flowing tides, but was cloudy during low and ebb tides. During 10–12 April (neap tide), however, water at the seafloor was clear, and greenish-blue water entered the bay at both high and low tides. On these three days, the wind was from the north. The surface waters of Nagahama Bay were reddish-brown during periods of southerly wind, and greenish-blue during periods of northerly wind.

A storm struck the bay on 8 April (Fig. 4), when the wind speed exceeded 10 m s^{-1}. On this day, the surface seawater in the bay was reddish-brown and water at the seafloor was cloudy. The route of a ferry passed close to MOGURIview, mixing the reddish-brown water with the underlying greenish-blue water and depositing iron-oxyhydroxides on the seafloor (Fig. 4). On 9 April, water at the seafloor became cloudy after the passing of the ferry at 13:15 (all times are local time), and cleared by 16:00. The ferry also passed MOGURIview at 9:55 on 10 April, resulting in cloudy water near the seafloor from 10:00 to 13:00.

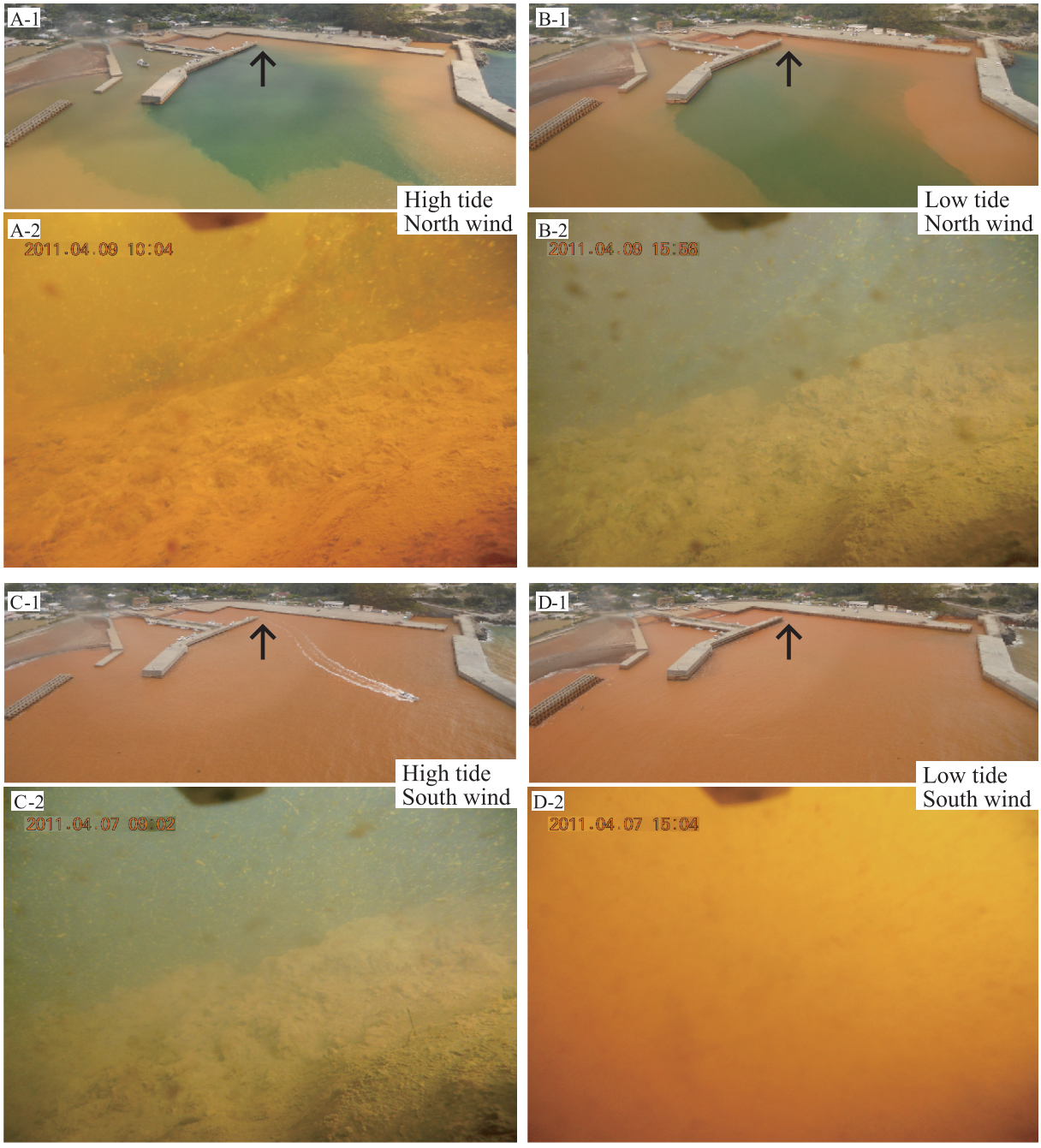

Fig. 5. Sea surface (upper photos) and seafloor (lower photos, 4.5 m water depth) images of water in Nagahama Bay. (A) Northerly wind and high tide on 9 April 2011. (B) Northerly wind and low tide on 9 April 2011. (C) Southerly wind and high tide on 7 April 2011. (D) Southerly wind and low tide on 7 April 2011. Arrows indicate the location of MOGURIview. Daytime photographs of the seafloor are much brighter (orange color) than those taken during the morning or evening.

5. Discussion

Turbidity in Nagahama Bay is affected by the tidal cycle, strong waves, and heavy rain (Kiyokawa et al., in press). In particular, water from the open ocean flows into the bay during high tide. Our observations on 6, 7, and 12 April 2011 show that greenish-blue seawater from the open ocean entered at high tide, whereas reddish-brown water was discharged from the bay at low tide. Ninomiya and Kiyokawa (2009) also reported the influence of the tidal cycle on the color of seawater. When a northerly wind blows, seawater at the bottom of Nagahama Bay is clear even during low tide (Fig. 5). In addition, when a southerly wind blew during the period 3–28 October, the sea surface in Nagahama Bay was reddish-brown, even at high tide. During periods with calm winds, iron-oxyhydroxides in the reddish-brown seawater are readily deposited on the seafloor in Nagahama Bay.

Our observations indicate that wind direction and speed are important controls on the movement of surface water. Consequently, during periods of northerly wind, greenish-blue water of the open ocean enters the bay, whereas reddish-brown seawater is trapped in the bay during periods of southerly wind (Fig. 6). Wind patterns are therefore the key to understanding the sedimentation of iron-oxyhydroxides in reddish-brown seawater at the seafloor in Nagahama Bay. Turbidity in the bay is highest at neap tide and during a southerly wind. These conditions may be the most favorable for the sedimentation of iron-oxyhydroxides in reddish-brown seawater.

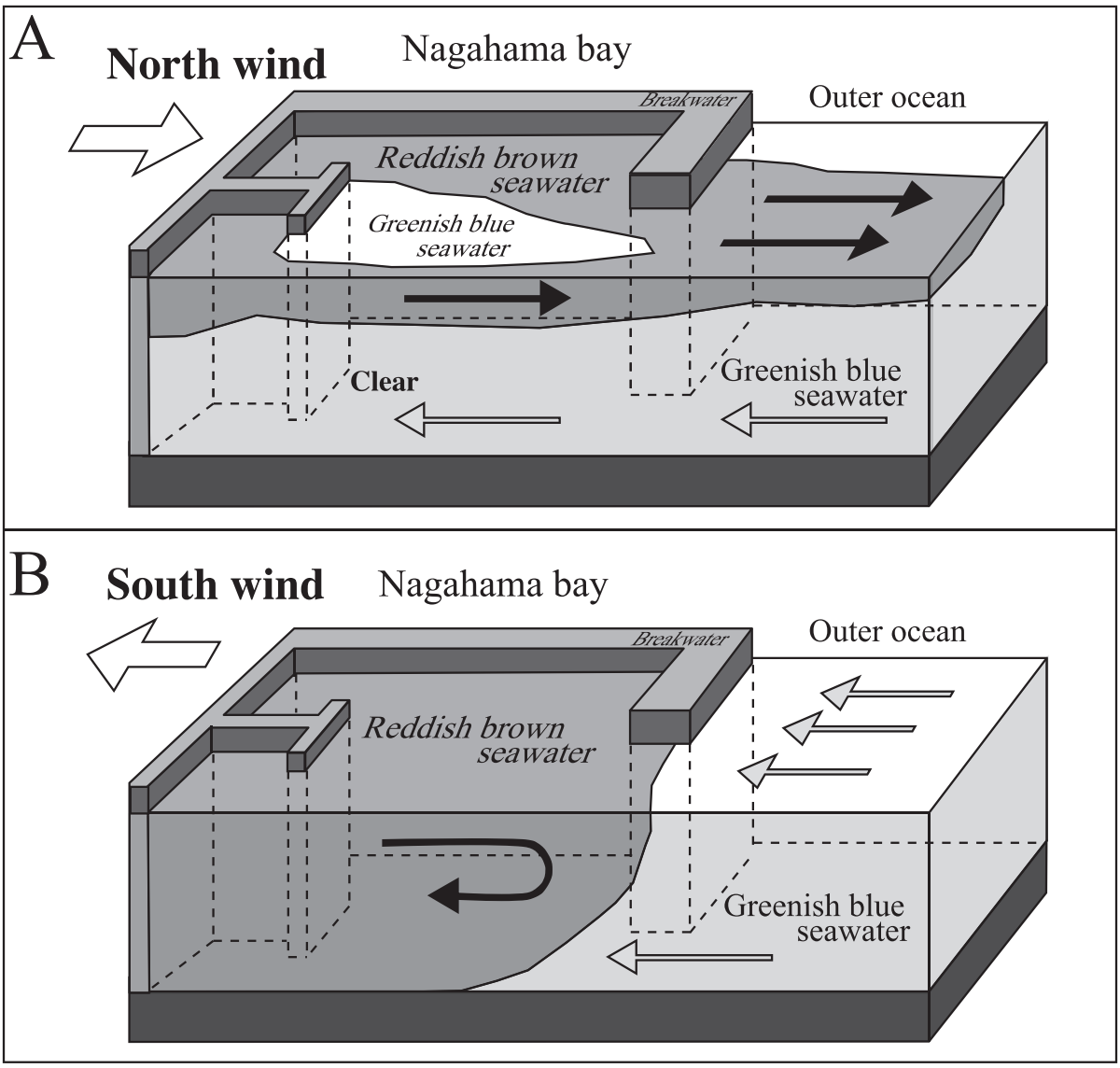

Fig. 6. Relation between the color of water in Nagahama Bay and wind direction. (A) During northerly wind, reddish-brown seawater flows out to the open ocean. (B) During southerly wind, reddish-brown seawater is trapped in Nagahama Bay. Arrows show the direction of seawater flow.

The seafloor in the bay is strongly affected by large waves during storms and typhoons. During the storm observed during the present study (8 April), water at the seafloor was cloudy, even during high and flowing tides. The passing of a ferry also resulted in cloudy seafloor water for about 3 hours.

6. Conclusions

1) The color of surface seawater in Nagahama Bay is significantly controlled by wind direction and speed. Reddish-brown seawater is trapped in the bay when a southerly wind is blowing. In contrast, greenish-blue seawater enters the bay when a northerly wind is blowing.

2) The color of seawater in the bay is also affected by the tidal cycle. It is likely that iron-oxyhydroxides are trapped in the bay during neap tide and when a southerly wind is blowing. These conditions may be favorable for the deposition of iron-oxyhydroxides on the seafloor.

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