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Implications of changes in the benthic environment and decline of macro-benthic communities in the inner part of Ariake Bay in relation to seasonal hypoxia

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Abstract: In the inner part of Ariake Bay, located on the west coast of Kyushu, in western Japan, red tides have occurred with more frequency since the second half of the 1990s. Hypoxic waters have occurred during the summer months since the 2000s, despite the fact that nutrient loading from the land to the bay has not increased over the last five decades. We monitored water conditions at nine stations in the inner part of the bay, conducted benthic environmental surveys, and quantitative samplings of macro-benthic communities at the innermost four stations between 2002 and 2008. Each summer, the water was well-stratified due to the development of a halocline and a thermocline. The DO of the water below the pycnocline fell to hypoxic conditions. At the innermost three stations in the bay, the mud content and organic matter content of the sediment increased significantly, and the carbon stable isotope ratios of the organic matter contained in the sediment ranged between -21.3 ± 0.5‰ and -20.7 ± 0.5‰ of δ^{13}C. These facts indicated that the organic matter was derived photosynthetically from marine phytoplankton. The increase in the mud content of the sediment indicates a deceleration in the tidal current. This may be a key event that induces a series of environmental changes and disturbances, including the stratification of the water, the more frequent occurrence of red tides, the progress of the organic enrichment of the sediment, and the occurrence of hypoxic water during the summer.

Key words: Ariake Bay, halocline, red tide, stratification of the water, tidal current

Introduction

Ariake Bay is an enclosed coastal sea located off the west coast of Kyushu, Japan. It has a large tidal amplitude of over 6 m in the innermost areas of the bay during the spring tide. A large amount of soil and earth is transported from the land to the bay via the six major rivers (Kikuchi River, Yabe River, Chikugo River, Kase River, Rokkaku River, and Honmyo River). Mega-tidal flats of over 20,000 ha in total area have developed around the mouths of the aforementioned rivers (Sugano 1981). The inner part of the bay, with an area of approximately 370 km^2, has a depth of less than 20 m in most parts, and the fast tidal current caused by the large tidal amplitude brings with it the strong mixing power of the tidally-influenced water. The water of these areas is extremely muddy due to the continual resuspension of mud from the sea floor. There were very few reports of the occurrence of large-scale red tide events in the bay until the first half of the 1990s (Shirota 1980, Tsutsumi 2005, 2006), and hypoxic water occurred on a limited basis in the western part of the innermost area of the bay until the same time frame (Kyushu Regional Agricultural Administration Office 2014). In those days, the inner part of Ariake Bay, including the mega-tidal flats, was praised as a “fertile sea”, due to the occurrence of high densities of various organisms as well as extremely large catches of fish and shellfish (Inoue

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1980, Sugano 1981, Kikuchi 2000).

However, in Ariake Bay, the frequency and the total duration of red tides per year have increased significantly since the second half of the 1990s, despite the fact that nutrient loading from the land to the bay has not increased, and may have even decreased slightly since the 1960s (Tsutsumi 2005, 2006, 2011, Ministry of the Environment 2006). As a result of an analysis of the relationship between the scale of red tides and precipitation in the coastal areas of the bay during the 40 days preceding the occurrence of each large-scale red tide, which occurred in autumn and early winter (October to December), Tsutsumi et al. (2005) clearly found a further increase in the scale of red tides in the bay since 1998. From this time on, the scale of red tides suddenly increased by a factor of two to three to the same amount of precipitation in the coastal areas of the bay.

Both an increase in the frequency and size of red tide events tend to lead to organic enrichment of the sediment through an increase in organic loading on the sea floor, which in turn results in hypoxic conditions due to the increase in oxygen consumption caused by the decomposition of organic matter deposited on the sediment (Diaz & Rosenberg 1995, 2008, Karlson et al. 2002, Tsutsumi et al. 2003, 2007). Here, we define hypoxia as water with dissolved oxygen (DO) levels of less than 3.0 mg L^{-1}. In the case of Ariake Bay, the maximum water temperature in summer reaches 28°C to 32°C at the surface, and 26°C to 28°C in the benthic waters (Tsutsumi 2006, Tsutsumi et al. 2003, 2005, 2007). Macro-benthic animals are more sensitive to the negative impacts of decreases in the DO of the water in such warm conditions.

The occurrence of hypoxic waters over wide areas of the inner part of Ariake Bay was first observed in August, 2001 (Sato et al. 2001, The Nature Conservation Society of Japan 2001, Tsutsumi et al. 2003). Since then, hypoxic conditions have been reported every summer (Tsutsumi 2006, Tsutsumi et al. 2007, Hamada et al. 2008). Seikai National Fisheries Research Institute has monitored the DO levels of bottom waters continuously at several stations in the inner part of the bay during the summer months since 2004, using an automatic water quality monitoring system, and found that the DO of the water fluctuated markedly following the tidal cycle, and was often depleted during the neap tide (Ministry of the Environment 2006, Seikai National Fisheries Research Institute 2010).

The occurrence of hypoxic conditions of benthic waters tends to follow the development of reduced conditions in the sediment. The surface layer of the sediment turns black, smelling of hydrogen sulfide. Under such conditions, macro-benthic communities are likely to be poor and are comprised mainly of small and short-lived polychaetes (Pearson & Rosenberg 1978, Tsutsumi & Kikuchi 1983, Tsutsumi et al. 1991, Diaz & Rosenberg 1995, Rosenberg et al. 2001). Therefore, through quantitative surveys of the macro-benthic communities, we are able to evaluate the negative impact of increased organic enrichment of the sediment and the occurrence of hypoxic waters on the benthic ecosystem.

In this study, we established nine stations arranged on a longitudinal axis in the inner part of Ariake Bay, and monitored seasonal fluctuations of water conditions between 2002 and 2008. At the innermost four stations, we also assessed the benthic environment, and conducted quantitative samplings of macro-benthic communities. We report the occurrences of red tides and hypoxic waters in the bay during the summer months, changes in the physicochemical conditions of the sediment (including organic enrichment) and the development of reduced conditions, and the responses of macro-benthic communities to changes in the benthic environment in the innermost areas of the bay during the period of the study. We discuss the mechanisms that have led to the development of hypoxic conditions in the inner part of the bay during the summer months, resulting in changes in the benthic environment and the marked decline of macro-benthic communities in the innermost areas of the bay.

2. Materials and Methods

2.1 Study areas

In this study, we established nine sampling stations at intervals of approximately three kilometers on the longitudinal axis that runs midway between the eastern and western shores of the inner part of the bay (Stns S2, A, B, C, D, E, F, G, and H; Stn S2: 33°05′01″N, 130°16′55″E; Stn H: 33°01′10″N, 130°13′14″E) (Fig. 1).

2.2 Monitoring and sampling methods

We monitored water conditions (temperature, salinity, dissolved oxygen concentration (DO), and the fluorescence intensity of Chlorophyll-*a* (Chl *a*)) with a probe (Model 6600, YSI/Nanotech, Inc.) at depth intervals of 1 m from the surface to 10 m, and at depth intervals of 2 m in deeper layers, and collected water samples at the nine sampling stations set in the inner part of Ariake Bay (Stn S2 to Stn H) from the five different layers (surface, −2 m, −5 m, −10 m, and 1 m above the sea floor), from a boat, with a Van Done water sampler. Samples were collected at neap tide, or just after, on a monthly basis (with the exception of winter) between 3 August 2001 and 5 November 2008 (the data between 3 August 2001 and 6 November 2004 were referred from Tsutsumi et al. (2007)). We also conducted samplings of bottom sediments in order to monitor the physicochemical conditions of the sediment as well as quantitative surveys of macro-benthic animals at the innermost four sampling stations (Stn S2 to Stn C) of the bay, for a total of 39 times between 2002 and 2008 (28 April, 5 June, 8 July, 31 July, 25 September, 14 October, 14 November, and 14 December in 2002; 7 February, 7 April, 10 May, 7 June, 23 July, 3 August, 1 October, 1 November,

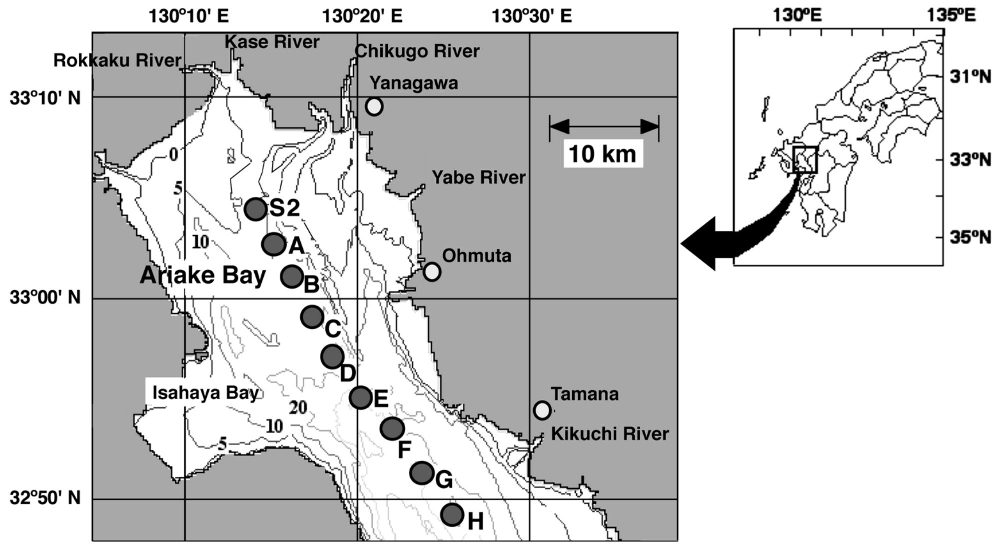

Fig. 1. Study areas and sampling stations in Ariake Bay.

and 24 December in 2003; 11 February and 9 June in 2004; 28 August, and 1 December in 2005; 18 April, 28 June, 5 August, 22 August, 18 October, and 24 December in 2006; 29 April, 23 May, 25 July, 7 August, 24 August, and 14 November in 2007; and 15 April, 27 May, 7 June, 25 July, 10 October, and 5 November in 2008). Notable exceptions to the sampling schedule are as follows: sampling was carried out at Stn A only on 22 August 2006, 25 July and 24 August in 2007, and 7 June 2008; at two stations excluding Stn S2 and Stn B on 28 April 2002; and at three stations excluding Stn S2 on 5 June, 8 July, and 31 July in 2002, and 23 July 2003.

At each station for the benthic surveys, we collected one grab sample with an Eckman-Berge-type grab sampler (20 cm×20 cm). We subsampled one sediment sample with a handy sampler (5 cm×5 cm×5 cm) for a particle size composition analysis of the sediment, and five sediment samples with a handy core sampler (18 mm in diameter) for a chemical analysis of the sediment from the grab sample. The surface layer of the sediment core samples (up to a depth of 1 cm) was cut and put in a plastic bag. The bags were kept in a cooler box until they were brought to the laboratory. For quantitative surveys of the macro-benthic communities, we collected five grab samples. Each of them was sieved with a 1.0 mm opening mesh screen, and put in a plastic bag. At the laboratory, samples were fixed using a 10% formalin solution with a dye (Rose Bengal) for staining macro-benthic animals.

2.3 Sample analysis

For measurement of the concentration of Chl *a*, water samples were filtered through glass-fiber filters. Each filter was put into a test tube with 10 ml of 90% acetone. Test tubes were kept in a freezer at −20°C for 12 to 24 h to extract Chl *a*. The extracts were sonicated for 10 min and the concentration of the Chl *a* was determined spectrophotometrically with a fluorometer (Turner Design, 10-AU) according to Lorenzen (1967) before and after acid treatment with 1 N HCl (cf. Parsons et al 1984). To visualize the vertical profile of Chl *a* concentration in the water, we derived a correlation equation between the fluorescence intensity measured by the probe and the measurement of Chl *a* concentration with data collected from the same layers, translating the data from the vertical profile of fluorescence intensity to Chl *a* concentration.

Compositions of particle size from sediment samples were determined by wet sieving. Acid Volatile Sulfide (AVS) content (which serves as an indicator of the development of reduced conditions), organic matter content, and carbon stable isotope ratios of the sediments were determined by analyzing the sediment for chemical conditions. To determine the AVS content of the sediment, approximately 0.5 g of the sediment was collected from each plastic bag, weighed, and put in a test tube. Fifty percent sulfuric acid was added to the test tube arbitrarily, and hydrogen sulfide gas released from the sediment into the test tube was syphoned into to a column tube (Gastec corp., Hedorotec 201H). Approximately, three grams of sediment sample were collected from the plastic bag, weighed, dried at 55°C for several days, and weighed to determine the water content. The AVS content of the sediment was expressed as the value per gram of dry sediment.

The remaining sediment samples for the chemical analysis were freeze-dried, treated with 2N hydrochloric acid to remove inorganic carbonate, and vacuum-dried. Total Organic Carbon (TOC) content of the treated sediment samples and the carbon stable isotope ratios of the organic matter contained within were determined with an elemental analyzer (Fisons, NA1500 or Thermo Fisher Scientific, Flash EA1112) and a stable isotope analyzer (ThermoQuest, DELTAPlus), respectively.

The carbon stable isotope ratios of the sediment samples were expressed as $\delta^{13}C$, which is calculated from the following equation:

$$\delta^{13}C\ (‰) = (RSA/RST\text{-}1) \times 1{,}000$$

RSA: carbon stable isotope ratio of the sediment sample ($^{13}C/^{12}C$), RST: carbon stable isotope ratio of the standard material. In this study, we use glycine as the working standard.

Samples for the quantitative surveys of the macro-benthic communities were sieved with a 1.0 mm mesh screen at the laboratory again. Macro-benthic animals were sorted from the residues retained on the sieve, and kept in a 75% alcohol solution. These specimens were identified, counted, and weighed.

The statistical analysis of the results was performed using the computer software, StatView 5.0 (Hulinks).

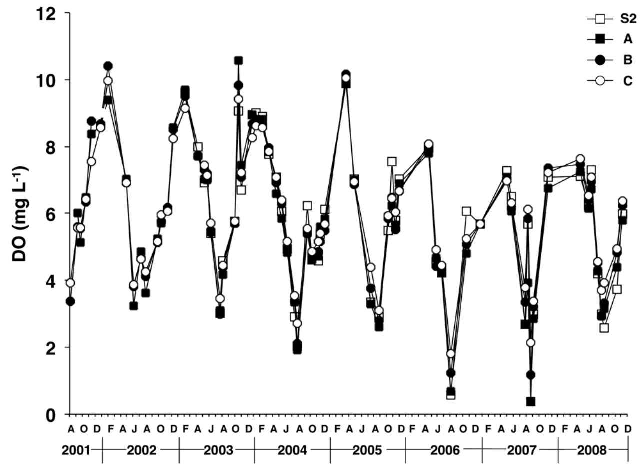

Fig. 2. Seasonal fluctuations in DO of the water just above the sea floor at the four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between 2001 and 2008. The data between August in 2001 and November in 2004 are referred from Tsutsumi et al. (2007).

Results

Occurrence of hypoxic water during the summer months

Figure 2 shows the seasonal fluctuations in the DO of the water just above the sea floor at four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between August 2001 and November 2008. The dissolved oxygen concentration of the water just above the sea floor tended to decrease markedly during the warm seasons, and hypoxic conditions (DO <3 mg L^{-1}) occurred at all four stations every August since 2003. At Stn S2 and Stn A, which were located in the innermost areas of the bay, the water fell to near anoxic conditions: 0.57 mg L^{-1} and 0.69 mg L^{-1} on 5 August 2006, and 0.39 mg L^{-1} and 0.37 mg L^{-1} on 24 August 2007, respectively.

Vertical profile of the water during hypoxic conditions

Figure 3 shows cross-sections of the salinity, temperature, Chl *a*, and DO of the water at the nine stations along a longitudinal axis in the inner part of Ariake Bay in August between 2005 and 2008, when the most severe hypoxic conditions occurred in the bottom layer each year. The water structure of the bay was characterized by the development of a halocline due to the inflow of a large amount of river water into the bay during the rainy season between the second half of June and the first half of July and/or a thermocline caused by solar radiation in summer. The salinity of the surface water tended to decrease further in the innermost areas of the bay, as the mouth of the largest river in Kyushu, the Chikugo River, was located at the north-eastern corner of the innermost area of the bay (Stn S2 to Stn C; 21.0 to 23.7 in 2005, 14.7 to 17.3 in 2006, 19.6 to 28.4 in 2007, and 23.5 to 23.7 in 2008). The temperature of the water reached 29.1 to 32.7°C and 29.6 to 32.6°C at the surface. It was 5.2 to 8.9°C and 3.5 to 7.1°C higher than that of the benthic water in the whole study area in 2006 and 2007, respectively. These results indicate that the water was distinctly stratified due to both the halocline and the thermocline, and that vertical mixing of the water was limited over extensive areas in the inner part of Ariake Bay in August between 2005 and 2008.

Phytoplankton bloomed in the surface layer of the stratified water following the occurrence of the hypoxic conditions commonly observed during these four years. We define the occurrence of a red tide as the water condition that contains Chl *a* higher than 10 $\mu g\ L^{-1}$. The highest concentrations of Chl *a* reached were 106 $\mu g\ L^{-1}$ and 135 $\mu g\ L^{-1}$, at a depth of 2 m below the surface at Stn A and Stn B on 28 August 2005, 17.7 $\mu g\ L^{-1}$ at the surface of Stn S2 on 5 August 2006, 76.6 $\mu g\ L^{-1}$ and 109 $\mu g\ L^{-1}$ at the surface of Stn S2 and Stn C on 24 August 2007, and 40.3 $\mu g\ L^{-1}$ and 23.0 $\mu g\ L^{-1}$ at a depth of 1 m below the surface at Stn S2 and Stn E on 10 August 2008. The red tide plankton was made up mainly of the raphidophyte, *Chattonella antiqua*, and the dinoflagellate, *Akashiwo sanguinea,* in 2005 (Kyushu Fisheries Coordinate Office 2007a); the diatoms, *Skeletonema* sp. and *Chaetoceros* spp. in 2006; the raphidophyte, *C. antiqua*, in 2007 (Kyushu Fisheries Coordinate Office, 2007b); and the raphidophytes, *C. antiqua* and *C. marina*, and diatoms, *Thalassiosira* spp., in 2008 (Kyushu Fisheries Coordinate Office 2009). These phytoplankton blooms tend to increase organic discharge to the sediment on the sea floor, and increase the oxygen consumption of the overlying water of the sediment due to decomposition of the organic matter deposited on the sea floor.

The cross-sections of DO in the water column indicate two major characteristics of the occurrence of hypoxic water in the inner part of the bay. Firstly, hypoxic water was observed in the deeper layers of stratified waters with both haloclines and thermoclines at the innermost four stations (Stn S2 to Stn C), where the depth of the water was shallower than 15 m. Secondly, the DO of the water; however, did not always decrease consistently with depth.

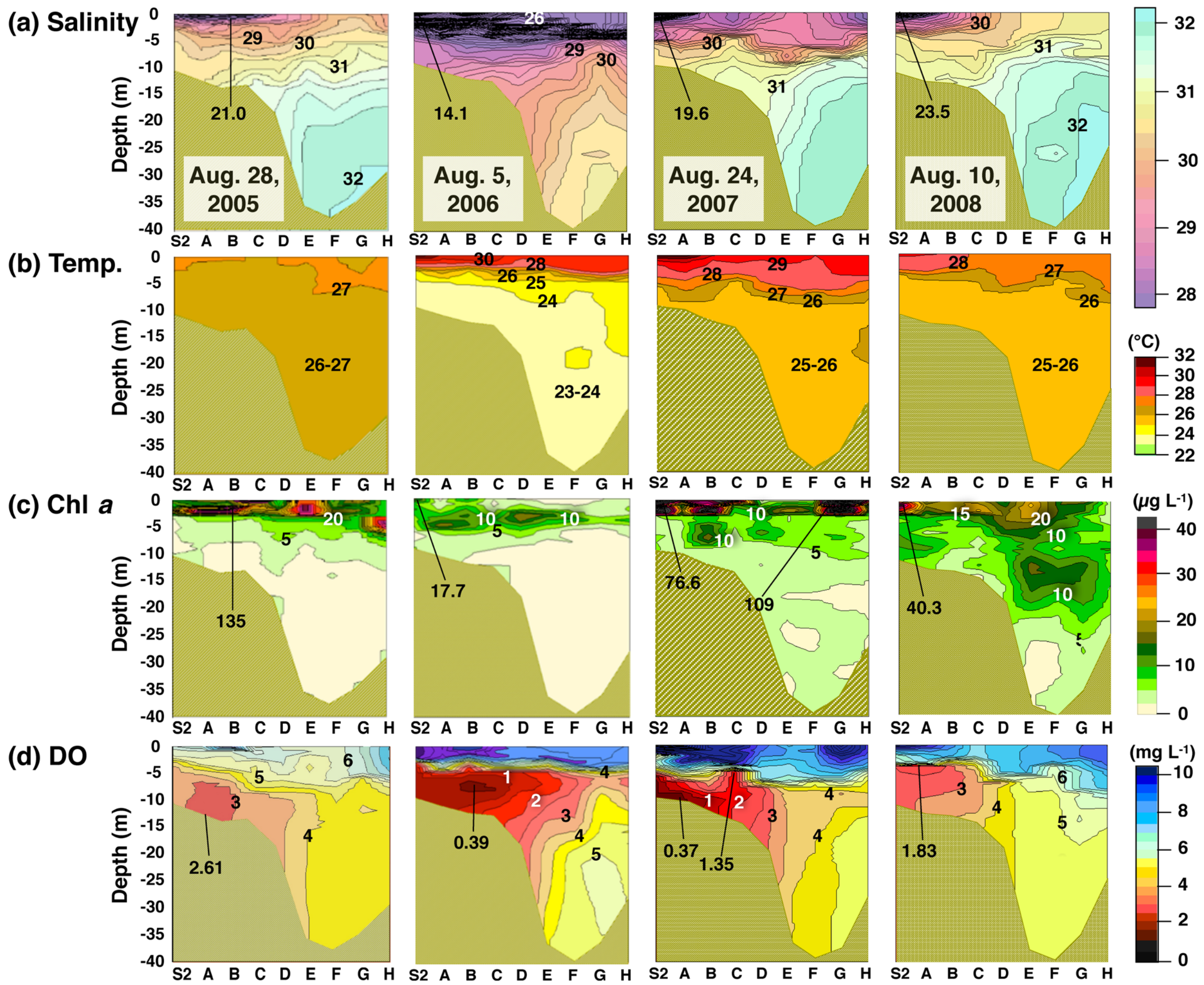

Fig. 3. Cross-sections of (a) salinity, (b) temperature, (c) Chl *a*, and (d) DO of the water at the nine stations along a longitudinal axis in the inner part of Ariake Bay in August, between 2005 and 2008 (coinciding with the most severe hypoxic conditions occurring in the bottom layer of the water each year).

For example, the lowest DO concentration was recorded in the bottom waters above the sea floor on 28 August 2005 (2.61 mg L^{-1} at Stn A, Fig. 4a) and on 24 August 2007 (0.37 mg L^{-1} at Stn A, Fig. 4b), while the oxygen minimum layer formed at mid-depth, just below the halocline and thermocline on 5 August 2006 (0.39 mg L^{-1} at a depth of 7 m from the surface at Stn B, Fig. 4c), at Stn C on 24 August 2007 (1.35 mg L^{-1}), and on 10 August 2008 (1.83 mg L^{-1} at a depth of 3 m from the surface at Stn A, Fig. 4d).

Changes in the bottom environment

Figure 5 indicates the changes in the annual mean values of mud content of the sediment, at the four stations (Stn S2 to Stn C), in the inner part of Ariake Bay between 2002 and 2008. In 2002, the mud content of the sediment was 16.1±3.2% (mean±S.D., n=4) at Stn S2, 53.5±10.3% (n=8) at Stn A, 29.4±15.5% (n=7) at Stn B, and 12.4±3.6% (n=7) at Stn C. The sediment of these four stations was identified as sand at Stn S2 and Stn C, muddy sand at Stn B, and sandy mud at Stn A. The mud content of the sediment increased markedly at Stn A and Stn B, and the sediment changed to mud by 2008 (the mud content in 2008 was 92.0±3.7% (n=5) (+38.5%) at Stn A, and 86.7±6.1% (n=5) (+57.3%) at Stn B). At the remaining two stations, Stn S2 and Stn C, the mud content increased slightly in this period. In 2008, it was 29.1±1.9% (n=4) (+9.0%) at Stn S2 and 25.8±8.0% (n=5) (+13.4%) at Stn C. The increase in the annual mean value of the mud content between 2002 and 2008 is statistically significant, even at Stn S2 and Stn C (Mann-Whitney's U-test, Stn S2: $U=0.000$, $z=-2.309$, $p=0.0209$, Stn C: $U=2.500$, $z=-2.650$, $p=0.0080$, respectively), even though the sediment was still identified as sandy (muddy sand) at both stations.

Figure 6 indicates the changes in the annual mean values of TOC content of the surface layer of the benthic sediment at the four stations (Stn S2 to Stn C) between 2002 and 2008. The mean TOC content of the sediment in 2002 was 5.4±1.8 mg C g^{-1} (mean±S.D., n=4) at Stn

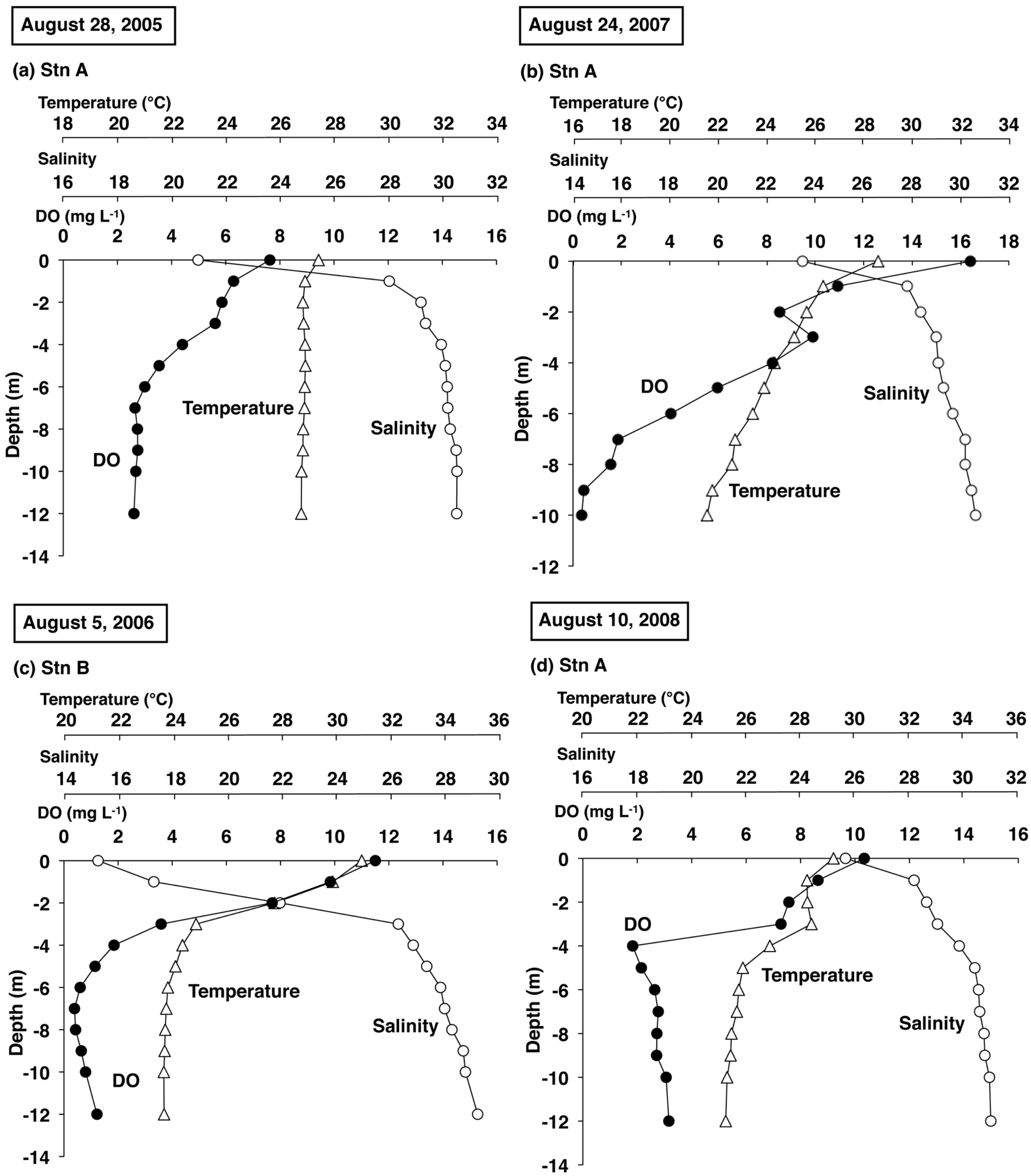

Fig. 4. Vertical profiles of water conditions (temperature, salinity, and DO)

S2, 18.1±2.2 mg C g^{-1} (n=8) at Stn A, 11.8±3.4 mg C g^{-1} (n=7) at Stn B, and 4.9±1.3 mg C g^{-1} (n=7) at Stn C. At the three stations, excluding Stn C, a statistically significant increase in the TOC content of the sediment was found between 2002 and 2008 (Stn S2: r^2=0.776, F=17.66, p<0.01, ANOVA; Stn A: r^2=0.899, F=10.19, p<0.02, ANOVA; Stn B: r^2=0.898, F=43.46, p<0.01, ANOVA, respectively). In 2008, the annual mean TOC contents of the sediment were 13.2±4.4 mg C g^{-1} (n=4) at Stn S2, 27.3±1.0 mg C g^{-1} (n=5) at Stn A, and 22.3±5.1 mg C g^{-1} (n=5) at Stn B, and 2.4 times, 1.5 times, and 1.9 times larger than those measured in 2002, respectively. These differences were also statistically significant (Mann-Whitney's U-test, Stn S2: z=−2.928, p=0.003, Stn A: U=0.000, z=−2.932, p=0.034, Stn B: U=2.000, z=−2.517, p=0.012). At Stn C, the annual mean TOC content of the sediment increased slightly between 2002 (4.9±1.3 mg C g^{-1}) and 2008 (6.0±2.2 mg C g^{-1}), but the difference was not sta-

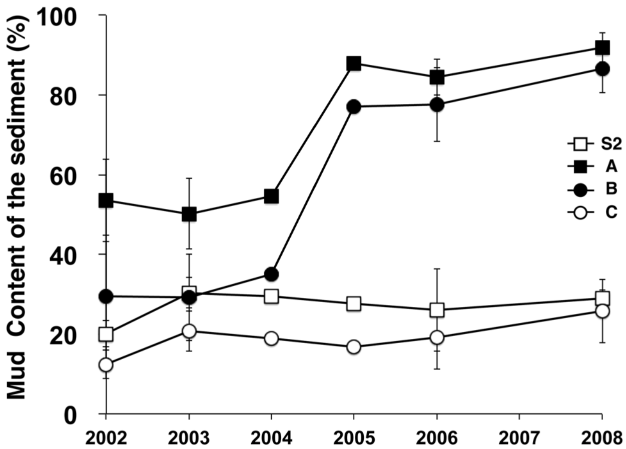

Fig. 5. Changes in the annual mean values of mud content of the sediment at the four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between 2002 and 2008. Error bars indicate standard deviations of mean values.

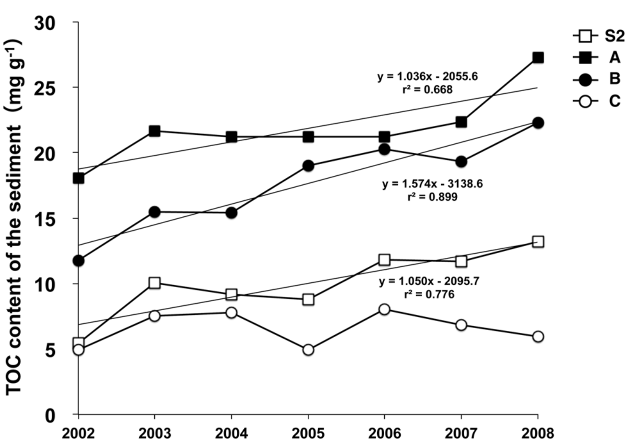

Fig. 6. Changes in the annual mean values of TOC of the surface layer of the sediment at the four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between 2002 and 2008.

tistically significant (Mann-Whitney's U-test, Stn C: U=14.000, z=−0.878, p=0.380).

Figure 7 indicates the annual mean values of the AVS content of surface sediments from the four stations (Stn S2 to Stn C) between 2002 and 2008. Acid-volatile sulfide consists of hydrogen sulfide, produced by the sulfate reducing bacteria, and iron sulfide, caused by the bonding of hydrogen sulfide to iron. It has been used as an indicator of reduced conditions in the sediment. The annual mean value of AVS content of the sediment fluctuated widely between 0.06 and 0.55 mg g^{-1} at Stn A between 2002 and 2008. There was an overall tendency for the AVS content of the sediment to increase at Stn S2 and Stn B during the period of this study. The highest values, 0.11 mg g^{-1} and 0.14 mg g^{-1}, were recorded at Stn S2 and Stn B in 2008, respectively. At Stn C, the AVS content of the sediment ranged between 0.00 and 0.02 mg g^{-1} throughout the period of this study. This indicates that the sediment remained

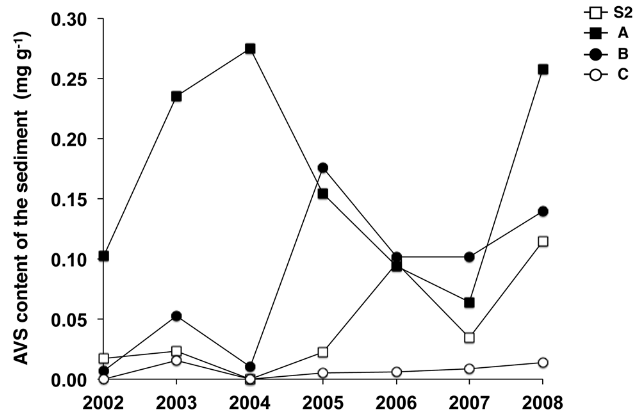

Fig. 7. The annual mean values of AVS content of the surface layer of the sediment at the four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between 2002 and 2008.

in an oxidized state.

In conclusion, the surface sediments became muddy and organically enriched, and fell to reduced conditions at Stn A and Stn B between 2002 and 2008. At Stn S2, the organic enrichment of the surface sediment gradually progressed with the development of reduced conditions over the course of this study, although the sediment remained sandy. At Stn C, no signs of changes in the physicochemical conditions of the sediment were found throughout the period of this study.

Sources of organic matter deposited on the surface layer of the sediment

Carbon stable isotope ratios of the organic matter contained in the surface sediment at the four stations (Stn S2 to Stn C) were determined with the six sediment samples collected between April 2006 and April 2007 (Table 1). δ^{13}C of the organic matter contained in the sediment was −21.3±0.5‰ (mean±S.D.) at Stn S2, −20.9±0.4‰ at Stn A, −20.7±0.5‰ at Stn B, and −20.8±0.5‰ at Stn C. Previous studies on the carbon stable isotope ratios of organic matter from various primary producers have revealed that they have significantly different ratios. For example, Yokoyama (2008) indicated that the carbon stable isotope ratios of the body tissues of marine phytoplankton occurring in mid-latitude region ranged between −24.4 and −17.8‰ (mean: −21.1‰), values for C3 terrestrial plants ranged from −28.0 to −24.9‰ (mean: −26.4‰), and values for benthic micro-algae ranged from −22.0 to −12.8‰ (mean: −16.4‰). The carbon stable isotope ratios of the organic matter contained in the sediment at the four stations nearly overlapped with that of marine phytoplankton. However, the ratio at Stn S2, which is the nearest station to shore, was slightly lighter than at the other three stations, most likely due to the contamination from organic matter produced by terrestrial plants. These results indicate that the organic enrichment of the sediment at the three stations (Stn S2, Stn A, and Stn B) was brought about by the de-

Table 1. Carbon stable isotope ratios of the surface layer of the sediment at the four stations (Stn S2 to Stn C) in the inner part of Ariake Bay between April 2006 and April 2007.

Date	Stn S2	Stn A	Stn B	Stn C
18 April, 2006	-21.3	-21.6	-21.4	-21.0
18 June, 2006	-22.0	-21.0	-21.1	-20.6
05 August, 2006	-20.7	-20.7	-20.6	-20.4
16 October, 2006	-21.2	-20.5	-19.9	-20.4
24 December, 2006	no data	-20.6	-20.4	-21.2
28 April, 2007	-21.2	-21.1	-21.0	-21.1
Mean ± S.D.	-21.3 ± 0.5	-20.9 ± 0.4	-20.7 ± 0.5	-20.8 ± 0.4

position of organic matter produced mainly by the marine phytoplankton in the bay.

Changes in macro-benthic communities

Figures 8 and 9 indicate the fluctuations in densities and wet weights of the dominant species and taxonomic groups of macro-benthic communities at the four stations (Stn S2 to Stn C) between 2002 and 2008. At Stn S2, the density was 5,275 ind. m^{-2} in April 2003, but decreased gradually from that point, repeating a small recovery. In November 2008, the density of macro-benthic organisms was recorded at 940 ind. m^{-2}. At Stn C, a similar downward trend in the density of the macro-benthic community was recorded. The highest density, 10,115 ind. m^{-2}, was recorded in April 2002. It decreased to only 590 ind. m^{-2} in November 2008. At Stns A and B, the macro-benthic communities were already sparsely populated at the density of 288 ind. m^{-2} in April 2002 and July 2002 and the densities fluctuated slightly, maintaining a low range between 25 and 1,413 ind. m^{-2} and between 160 and 1,950 ind. m^{-2} until November 2008, respectively.

The declining trends of the macro-benthic communities at Stn S2 and Stn C as well as their low abundance at Stn A and Stn B were reflected clearly in the fluctuations of wet weight as an indicator of biomass between 2002 and 2008. At Stn S2, the wet weight of the macro-benthic community was 212.6 gWW m^{-2} in April 2002. However, it decreased rapidly and fluctuated within a small range of 4.5 to 28.2 gWW m^{-2} between 2005 and 2008. At Stn C, the wet weight reached its maximum, 1,083.3 gWW m^{-2}, in March 2003, but decreased drastically, making a small recovery in June 2004 (68.0 gWW m^{-2}), December 2005 (166.7 gWW m^{-2}), and May 2007 (126.6 gWW m^{-2}). It fluctuated in an extremely small range between 4.1 and 7.9 gWW m^{-2} in 2008. At Stn A and Stn B, the wet weight of the macro-benthic community was low and ranged between 1.4 and 54.4 gWW m^{-2}, and between 0.3 and 39.7 gWW m^{-2}, respectively, throughout the period of this study.

The dominant species of the macro-benthic communities at the four stations in the early part of our study were replaced by several species of small bivalves and polychaetes during the period of this study. At Stn S2, the dominant species (by density) of the macro-benthic communities between July 2003 and June 2004 were two species of polychaetes, Maldanidae sp. (355 to 688 ind. m^{-2}) and *Scoletoma longifolia* (Imajima & Higuchi 1975) (88 to 363 ind. m^{-2}); and a brittle star, class Ophiuroidea (150 to 375 ind. m^{-2}). Amphipods, Corophiidae spp., were collected in high density in June 2004 (463 ind. m^{-2}) and in August 2005 (1,255 ind. m^{-2}). A small bivalve, *Raeta pulchella* (Adams & Reeve 1850), was recorded as having a wet weight of 167.6 gWW m^{-2} in April 2003, which accounted for 78.8% of the total wet weight of the macro-benthic community when it reached its maximum over the course of this study. In August 2003, the wet weights of Maldanidae sp. and the ophiuroids were recorded as 17.4 gWW m^{-2} and 19.1 gWW m^{-2}, respectively, making them the dominant species in the macro-benthic community. However, they were seldom collected after 2006 following the decline of the macro-benthic community. In October 2008, a small bivalve, *Veremolpa micra* (Pilsbry

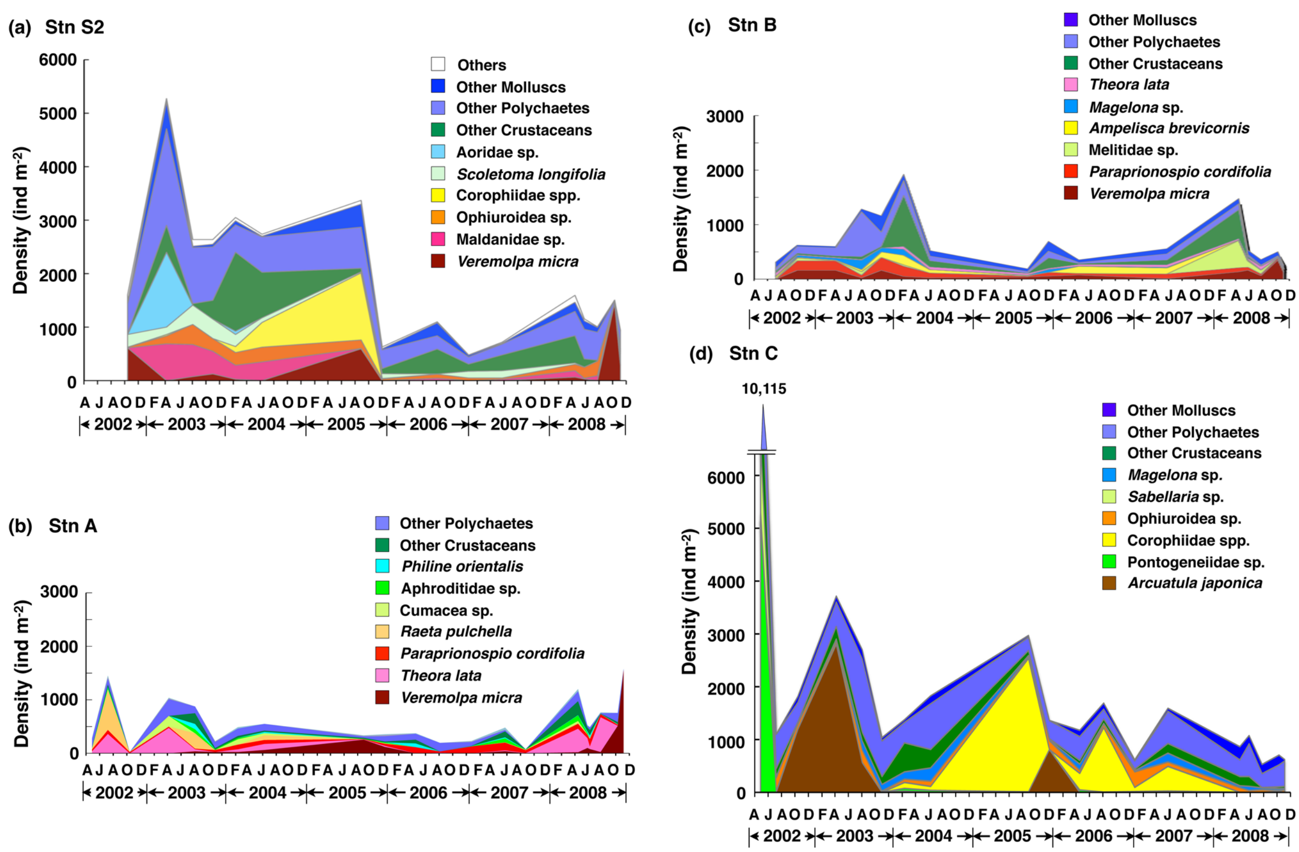

Fig. 8. Fluctuations in densities of the macro-benthic communities at the four stations (Stn S2 to Stn C) in the inner part of the bay between 2002 and 2008.

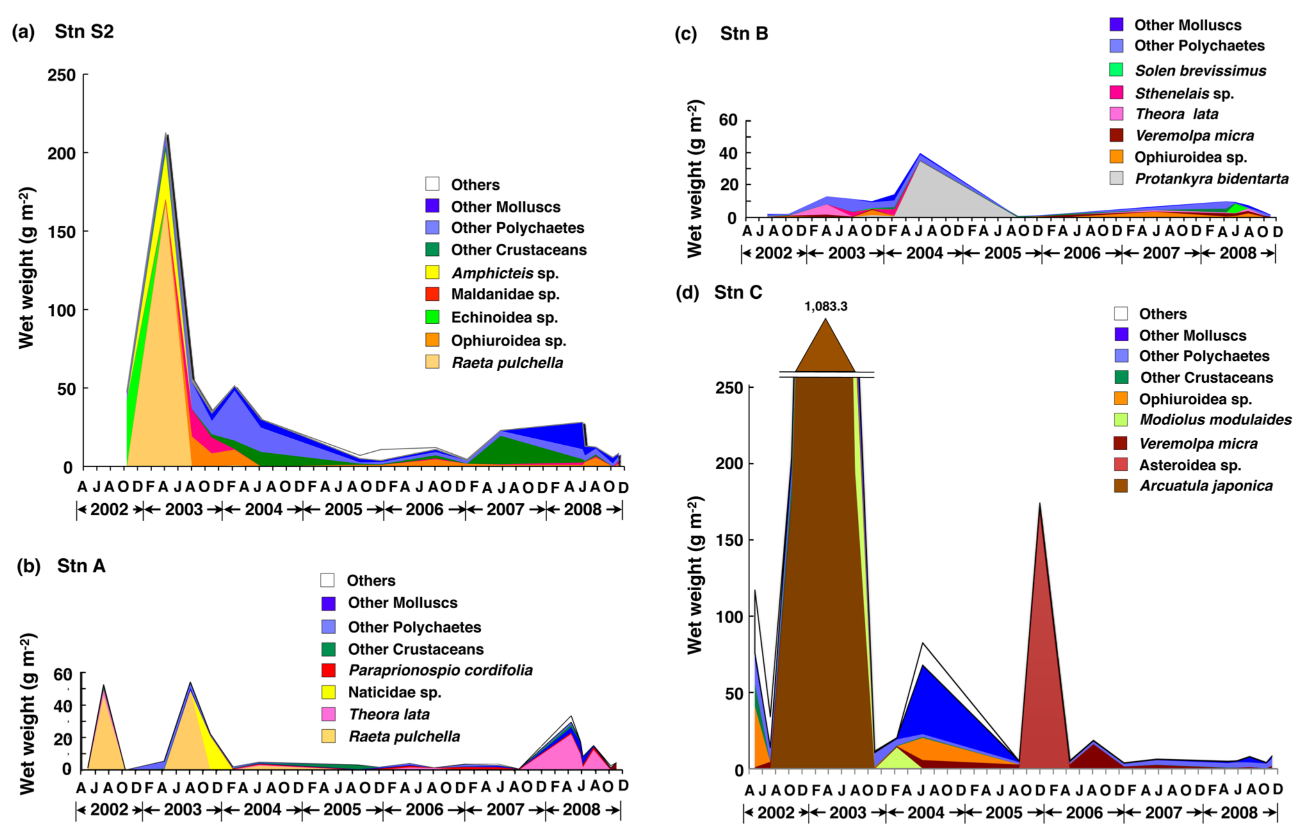

Fig. 9. Fluctuations in wet weights of the macro-benthic communities at the four stations (Stn S2 to Stn C) in the inner part of the bay between 2002 and 2008.

1904) was predominant in the macro-benthic community. The density of this species, 1,450 ind. m^{-2}, accounted for 96.3% of the total density of the community at that time, but its wet weight was only 3.6 gWW m^{-2}, as it is a small bivalve and most of the individuals were young juveniles with a shell length of several millimeters.

At Stn A, two small bivalves, *R. pulchella* and *Theora lata* (Hinds 1843) and a polychaete, *Paraprionospio cordifolia* (Yokoyama 2007) were the dominant species, but sparsely populated in both density (750 ind. m^{-2}, 362.5 ind. m^{-2}, 75 ind. m^{-2}, respectively) and wet weight (46.1 gWW m^{-2}, 3.6 gWW m^{-2}, 0.4 gWW m^{-2}, respectively) in the depressed macro-benthic community in July 2002. These three species occupied 81.4% of the total density and 94.8% of the total wet weight of the macro-benthic community. However, the most dominant species, *R. pulchella*, disappeared from the macro-benthic community by 2005. *Theora lata*, *V. micra*, and *P. cordifolia* dominated the macro-benthic community in 2008. In November 2008, *V. micra* was the predominant species in the macro-benthic community (1,520 ind. m^{-2}, 96.5%); however, its wet weight was only 4.0 gWW m^{-2} given that most of the individuals were young juveniles, similar to data from Stn S2.

At Stn B, the species present in the highest density from the sparsely populated macro-benthic community were two small bivalves, *V. micra* and *T. lata*; two polychaetes, *P. cordifolia* and *Magelona* sp.; and two amphipods, one from the family Melitidae and *Ampelisca brevicornis* (Costa 1853). A species of ophiuroid and two bivalves, *V. micra* and *T. lata*, showed the highest wet weight between 2002 and 2003. A holothuroid, *Protankyra bidentata* (Woodward & Barett 1858), increased the biomass of the macro-benthic community temporarily in June 2004 (34.7 gWW m^{-2}). In 2008, the species of the macro-benthic community present in the highest density were restricted to *V. micra*, *P. cordifolia*, and a melitid amphipod; while the species having the highest wet weights were *V. micra* and *P. cordifolia*.

At Stn C, various macro-benthic animals were collected in high densities in April 2002 (e.g., an amphipod from the family Pontogeneiidae, 5,175 ind. m^{-2}; two polychaetes, *Sabellaria* sp. and *Euchone* sp., 1,337.5 ind. m^{-2} and 712.5 ind. m^{-2}, respectively; and the amphipod, *Corophium* sp., 600 ind. m^{-2}). In April 2003, a bivalve, *Arcuatula japonica* (Dunker 1857) occurred at a density of 2,800 ind. m^{-2}. In August 2005, *Corophium* sp. occurred at a density of 2,525 ind. m^{-2}. In wet weight, *A. japonica* reached 997.1 gWW m^{-2} in April 2003; 86.9 gWW m^{-2} of the bivalve, *Modiolus modulaides* (Röding, 1798) was collected in August 2003; and 44.9 gWW m^{-2} of the bivalve, *Scapharca kagoshimensis* (Tokunaga 1906) was collected in June 2004. The wet weight of a sea star (class Asteroidea) was recorded as 166.7 gWW m^{-2} in December 2005. However, these macro-benthic animals had nearly disappeared by 2008, and the remaining community was made up of several small polychaetes including *P. cordifolia, Ophidromus* sp., and a species from the family Maldanidae.

Discussion

Occurrence of hypoxic water

In previous environmental studies of enclosed coastal seas, two different occurrence patterns of hypoxic conditions have been described. One is the phenomenon that occurs in benthic waters in the deepest areas, where the water is likely to be most stagnant owing to the restriction of water exchange with the open sea due to topographic factors, and/or during the warmest seasons when the vertical mixing potential of the water tends to decline markedly due to the development of a pycnocline following a thermocline and/or halocline (e.g., Baltic Sea in North Europe (Wulff et al. 1990), the Western Trough of the Lough Hyne Marine Reserve in southwestern Ireland (McAllen et al. 2009), Chesapeake Bay in the U.S. (Seitz et al. 2009), and Ise Bay (Takahashi et al. 2000). In these areas, oxygen consumption in the stagnant bottom water tends to be accelerated, and the water often becomes hypoxic or anoxic seasonally (or throughout the year), owing to the progress of organic enrichment of the sediment by the frequent blooming of phytoplankton (Rosenberg 1985, Rosenberg et al. 1990, Diaz & Rosenberg 1995, Karlson et al. 2002).

The other phenomenon is the occurrence of hypoxic waters near the shore in the innermost shallow areas, where a strong pycnocline tends to occur seasonally owing to large discharges of river water and increased solar radiation during the summer (e.g., Laholm Bay in the Southeastern Kattegat Sea in Sweden (Rosenberg et al. 1992); the western Long Island Sound (Welsh & Eller 1991); and the Tampa Bay Estuary, Florida in the U.S. (Malloy et al. 2007); as well as the estuarine areas of the Gulf of St. Lawrence Bay in Canada (Belley et al. 2010); Dokai Bay (Ueda et al. 1994, 2000), Tokyo Bay (Fujiwara et al. 2000, Kodama & Horiguchi 2011), and Osaka Bay (Tsujimoto et al. 2008) in Japan; Youngsan Estuary and Chinhae Bay in Korea (Lim et al. 2006); and Tolo Harbour in Hong Kong, China (Fleddum et al. 2011).

The occurrence of hypoxic waters in the innermost shallow areas of Ariake Bay is an example of the latter case (Fig. 3d). Hayami (2007) emphasized the importance of two different factors in the occurrence of hypoxic water in the bay. One is the formation of a river water plume that creates a distinct halocline in the water of the bay. The total precipitation during the rainy season, between the second half of June and the first half of July, reaches 420 to 650 mm usually in the coastal areas of the bay located in northern Kyushu (Fukuoka District Meteorological Observatory 2015). Since the mouths of four major rivers, including the largest one in Kyushu, the Chikugo River, are concentrated in the innermost areas of the bay, a large amount of freshwater discharged from these river mouths creates a large brackish water plume, with a depth of 5 to 10 m, extensively in the inner part of the bay during the rainy season. This extensive area of brackish water tends to remain until August (Tsutsumi 2006, Tsutsumi et al. 2007, Hamada et al. 2008, Fig. 3a), disturbing the vertical mixing of the oxygen-rich surface water (Fig. 3a, b) and the hypoxic water under the pycnocline.

Another factor is the effect of the influx of high salinity water from the outer side of the bay to the innermost areas during the neap tide, enforcing the halocline. The fine particles of sediment tend to be resuspended in water due to the fast tidal current, and they are likely to be transported toward the innermost areas of the bay along the estuarine circulation current, forming highly turbid waters with a high oxygen consumption rate (Abe et al. 2003, Tokunaga et al. 2005, Hayami et al. 2006).

In this study, the results of monitoring the vertical profile indicated the occurrence of hypoxic water with a DO minimum layer in the middle of the water column just below the thermocline and halocline at Stn B on 5 August 2006 (Fig. 4c), at Stn C on 24 August 2007 (Fig. 3d), and at Stn A on 10 August 2008 (Fig. 4d). The Ministry of the Environment (2006) noted the spread of hypoxic waters originating in benthic, near-shore areas outward toward off-shore areas was due to the fast tidal current in the inner part of Ariake Bay. It seems that the lateral advection of the hypoxic bottom water into the water of the offshore areas is one of the possible mechanisms that helps form the oxygen minimum layer in the middle of the water column. A similar phenomenon was also reported from Tokyo Bay (Fujiwara et al. 2000).

Many previous hydrological studies have also observed the oxygen minimum layer, referred to as "OML", in the mid-water column, documenting this phenomenon not only in deep waters (depths greater than 1,000 m) (Sanders & Childress 1990, Morales et al. 1999, Imasato et al. 2000) but in coastal waters as well (Welsh & Eller 1991, Krusel & Rasmussen 1995). Organic particles, including detritus, plankton, bacteria, etc., suspended in the water tend to be concentrated around the pycnocline caused by the halocline and thermocline in the middle layer of the stratified water (Mann & Lazier 1996). The combined effect of pelagic respiration by the suspended organisms and the restriction of vertical mixing of the stratified water resulted in the development of an oxygen minimum layer (Krusel & Rasmussen 1995). It is likely that the distinct pelagic consumption of oxygen occurred in the middle layer of the stratified water column with the oxygen consumption from the sediment of the sea floor simultaneously in the inner part of Ariake Bay under the conditions of high water temperature during the summer. In future studies, we hope to confirm the presence of the organic matter and micro-organisms that are responsible for creating the oxygen minimum layer around the pycnocline in the stratified water column.

Accelerated deposition of mud on the sea floor

One of the most distinct changes in the benthic environment noted in this study is the marked increase in the mud content of the sediment at Stn A and Stn B (Fig. 5). The sediment changed drastically from sandy mud and muddy sand, respectively, to mud at both stations. According to the results of the benthic surveys conducted in the inner part of the bay in 1989, there was a clear boundary of sediment type along the longitudinal axis in the center of the bay. The sediment east of the boundary was mainly made up of sand (the mud content was about 10% to 50%), while the muddy bottom with the mud content of more than 70% was widely distributed on the western side (Koga 1991). Stn A and Stn B in this study were located at the sandy bottom near the former east-west boundary judging from the distribution of the sandy bottom in the bay. The increase in the mud content at these two stations seemed to be caused by the expansion of the mud-type sediment toward the eastern side of the inner part of the bay.

According to Stoke's Law (cf. Gray 1981, Gray & Elliot 2009), mud particles with diameters of less than 63 μm require water movement with a velocity slower than 0.1 cm s^{-1} for sedimentation in the water, and a velocity faster than 10 cm s^{-1} for resuspension from the sea floor. The rapid increase in the mud content of the sediment indicates that the tidal current satisfied these hydrographic conditions for a significantly longer time during the tidal cycle than before, if the total amount of inflow of earth and soil to the bay per year has not changed markedly. The vertical mixing power of the water changes proportionally with the cube of the velocity of the tidal current (cf. Simpson & Hunter 1974). If such a deceleration of the tidal current occurred in the inner part of the bay as assumed from the increase of mud content of the sediment at Stn A and Stn B (Fig. 5), it would lead to further development of the stratification of the water, and most notably, immediately after a large amount of fresh water inflow from the rivers due to heavy rain. Therefore, the deceleration of the tidal current may have been a key event that induced a series of environmental changes and disturbances in the inner part of Ariake Bay. These environmental changes include more frequent occurrences of phytoplankton blooming in the surface layer of the stratified water (Ministry of the Environment 2006, Tsutsumi 2005, Tsutsumi et al. 2003), an increase in the deposition of fine particles on the sea floor (Fig. 5), the progress of the organic enrichment of the sediment (Fig. 6), and the occurrence of hypoxic water during the warm season (The Nature Conservation Society of Japan 2001, Tsutsumi et al. 2005, 2007, Fig. 3d). However, no previous studies have reported the deceleration of the tidal current in the inner part of the bay.

In our follow-up study, we have conducted benthic surveys to clarify how the distribution of benthic mud, which tends to be formed in the areas with restricted tidal current, has recently expanded in the inner part of the bay, as well as to elucidate the relationship between the distribution of muddy benthic sediment and the water structure in the bay. These results will be reported elsewhere.

Progress of organic enrichment of the sediment

At the three stations, excluding Stn C in the inner part of the bay, the annual mean values of the organic matter content (TOC) of the surface layer of the sediment increased significantly (1.5 to 2.4 times) between 2002 and 2008 (Fig. 6). The rate of increase in the TOC content of the sediment was estimated as 1.04 mg g^{-1} $year^{-1}$ at Stn A, 1.57 mg g^{-1} $year^{-1}$ at Stn B, and 1.05 mg g^{-1} $year^{-1}$ at Stn S2. The mean TOC content of the sediment at Stn C between 2002 and 2008 was 6.6 mg g^{-1}, where a significant increase in the TOC content of the sediment was not found. According to the rates of increase in the TOC content of the sediment, it is estimated that the TOC values of the sediment at Stn B and Stn S2 were almost equivalent to that of Stn C in 1998 and 2001, respectively. The sediment at Stn A seems to have originally been more enriched than that of Stn B or Stn C due to the higher mud content of the sediment. However, assuming that the rate of increase in the TOC content of the sediment was constant, the TOC content of the sediment at Stn A was estimated as 7.0 mg C g^{-1} in 1991, which is almost equivalent to the mean value at Stn C (6.6 mg C g^{-1}) between 2002 and 2008. Therefore, the organic enrichment of the sediment in the inner part of the bay seemed to have progressed since the 1990s, at the very least.

The results of the analysis of the carbon stable isotope ratio of the surface layer of sediment at the four stations in this study revealed that the organic matter deposited on the sediment was derived mainly from marine phytoplankton ($^{13}\delta$: −20.7‰ to −21.3‰, Table 1). In Ariake Bay, the number of occurrences and the total duration of red tides per year increased significantly since the second half of the 1990s(Tsutsumi 2005, 2012, Tsutsumi et al. 2005, Ministry of the Environment 2006).

It is, therefore, likely that the increase in organic loading on the sea floor, caused by an increased frequency of phytoplankton blooms, has resulted in the organic enrichment of the sediment in the inner part of the bay since the second half of the 1990s.

Decline of macro-benthic communities

Table 2 summarizes the changes in the benthic environment and macro-benthic communities at the four stations (Stn S2 to Stn C) in the inner part of the bay between 2002 and 2008, using the results of this study. Hypoxic water occurred commonly at these four stations every summer during this period. The macro-benthic communities had already become low in abundance and biomass at Stn A and Stn B in 2002, and had been declining rapidly at Stn S2 and Stn C for seven years between 2002 and 2008 (Figs. 8 & 9). These declining patterns of the density and biomass of the macro-benthic communities coincide with those characterized as typical phenomena caused by the progress of organic enrichment of the sediment following

Table 2. Summary of the changes of benthic environment and macro-benthic communities at the four stations (Stn S2 to Stn C) between 2002 and 2008. The data from this study, along with previous related studies (Tsutsumi 2006, Tsutsumi et al. 2003, 2005, 2007), were collected in the inner part of Ariake Bay between 2002 and 2008.

	S2	A	B	C
Occurrence of hypoxia of the bottom water	Every summer	Every summer	Every summer	Every summer
Mud content of the sediment	Slightly increased The sediment was still sandy.	Markedly increased The sediment changed from sandy mud to mud.	Markedly increased The sediment changed from muddy sand to mud.	Slightly increased The sediment was still sandy.
Level of organic enrichment of the sediment	Medium Rapidly progressing	High Gradually progressing	High Gradually progressing	Low
Development of reduced conditions of the sediment during the summer	Temporarily developed	Severe	Severe	none
Macro-benthic community	Rapidly declining	Already poor	Already poor	Rapidly declining
Changes of the macro-benthic community	The most dominant species in biomass, *Raeta pulchella*, disappeared.	The most dominant species changed from *Raeta pulchella* to *Theora lata.*	The most dominant species changed from small bivalves to *Veremolpa micra* and *Paraprionospio cordifolia*	The most dominant species, *Arcuatula japonica* disappeared.

the occurrence of hypoxia (Karlson et al. 2002). However, at Stn C, few signs of organic enrichment and reduced conditions of the sediment were found (TOC of the sediment was 6.0±2.2 mg C g^{-1} in 2008 (Fig. 6), and the AVS of the sediment was less than 0.02 mg g^{-1} throughout the period of this study (Fig. 7)), although hypoxia occurred in the water just above the sea floor during the summer (Figs. 2 & 3c). These results indicate that the rapid decline in the macro-benthic communities was not simply caused by the progress of organic enrichment of the sediment with the development of reduced conditions, but occurred even in the oxidic sediment with much less oxygen consumption of the overlying water.

Yoshino et al. (2010) examined the distribution of the macro-benthic communities and the major environmental factors that controlled their distributions in the inner part of Ariake Bay, and found that the changes in the structure of the macro-benthic communities were not caused by stress as a result of the increased TOC content of the sediment, but that they mainly arose from physiological stress caused by the occurrence of hypoxic water. Our results suggest a possibility that the transportation of hypoxic water by the tidal currents may explain these phenomena, since Ariake Bay has the largest tidal amplitude (over 6 m at the spring tide) on the Japanese coast, and it often generates a fast tidal current along the longitudinal axis of the bay (Inoue 1980, Odamaki et al. 2003). At Stn A and Stn B, the hypoxic water appears to be created in the benthic waters due to the oxygen consumption from the sea floor with the organically enriched sediment (Figs. 3d & 4). The hypoxic water is able to migrate in the direction of Stn C via the ebb tide, owing to the tidal current. If the hypoxic water created in nearby areas imposes a serious impact on the macro-benthic community, a marked decline of the macro-benthic community may occur without any signs of environmental deterioration in the sediment.

In our follow-up study, we have examined the distribution of water structure, physicochemical conditions of the sediment, and macro-benthic communities at 20 stations throughout the areas of the inner part of Ariake Bay and Isahaya Bay. The comparison of the benthic conditions described by these surveys with those made previously will describe the recent changes in the benthic environment and macro-benthic communities more clearly, and reveal the ultimate causes of the environmental disturbances occurring in the inner part of the bay in the past two decades.

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