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Impacts of Oxygen-Deficient Water on the Macrobenthic Fauna of Dokai Bay and on Adjacent Intertidal Flats, in Kitakyushu, Japan

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Dokai Bay is surrounded by the city of Kitakyushu, Japan. We assessed the chemical conditions of its waters and sediments, and carried out quantitative samplings of the macrobenthic fauna of the bay and on adjacent intertidal flats from 1992 to 1993. Large amounts of organic matter were deposited on the floor of the bay and intertidal flats due to eutrophication, and resulted in the occurrence of oxygen-deficient water from the bottom to the middle layer during the summer. On the tidal flats, the sediments were kept oxygenated and accessible to benthic animals throughout the year. However, the macrobenthos declined markedly in summer. The oxygen-deficient water of the bay seemed to temporarily upwell onto the intertidal flats causing a catastrophic environmental disturbance. Following this, only a few polychaete species survived, in extremely low densities. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: eutrophication; organic enrichment; macrobenthic fauna; intertidal flats; oxygen-deficient water; enclosed coastal sea.

Introduction

The coastal areas of the ocean, especially intertidal flats at the interface between land and sea, are areas of highest primary production in the marine ecosystem (Carefoot, 1977; Kikuchi, 1993; Valiela, 1995). The amounts of primary production by macroalgae and benthic microalgae that proliferate on intertidal flats are equivalent to tropical rain forests (Pomeroy, 1959; Mann, 1973). The extremely high productivity of intertidal flats is able to abundantly support various aquatic organisms. Many intertidal flats, however, have been reclaimed in Japan as waterfront areas with high commercial value. Japan, with limited land and a dense population, is a good example of intertidal flat destruction due to reclamation (Takahashi, 1994). Following rapid economic growth since the 1960s, intertidal flats adjacent to large cities have been reclaimed, modified rapidly and turned into industrial and commercial sites, agricultural lands, and residential areas. Surveys by the Environmental Agency of the Japanese government in 1988 reported that approximately 40% of the original intertidal flats had disappeared from Japanese coasts within the last half century (Kikuchi, 1993; Takahashi, 1994).

In Japanese coastal areas, remaining intertidal flats are valuable and necessary to preserve the functions of the coastal ecosystem. They are not, however, necessarily healthy. In many enclosed coastal seas near large cities, such as Tokyo, Osaka, Nagoya, and Kitakyushu, eutrophication of the water column occurs, and, consequently, there is excessive organic loading on the sea bed resulting in the development of hypoxic, even anoxic, conditions in the benthic environment, especially during the summer months (Ochi and Takeoka, 1986; Suzuki and Matsukawa, 1987; Joh, 1989; Sasaki, 1989, 1993; Omori *et al.*, 1994; Suzuki *et al.*, 1998; Higashi *et al.*, 1998). The hypoxic (or anoxic) water tends to cause a catastrophic environmental disturbance in the benthic ecosystem of coastal waters (Arntz, 1981; Baden *et al.*, 1990; Rosenberg *et al.*, 1990; Tsutsumi *et al.*, 1991; Llanso, 1992; Desprez *et al.*, 1992; Nilsson and Rosenberg, 1994; Diaz and Rosenberg, 1995; Tsutsumi, 1995). In the Japanese enclosed seas such as Tokyo Bay and Mikawa Bay, the hypoxic or anoxic bottom waters containing high levels of hydrogen sulphide often

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upwells onto the shores from late summer to the beginning of autumn causing, for example, a mass mortality of commercial molluscs on intertidal flats (Kakino, 1986; Kakino *et al.*, 1987; Furota, 1987; Aoki, 1994; Aoki, 1999).

In the Japanese enclosed coastal seas, the upwelling of anoxic bottom water seems to be a much more common event than the number of cases reported from such areas. Recent studies have clarified the mechanisms by which anoxic water (with a high sulphide content), is formed on the sea floor and upwells onto the shore (Furota, 1987; Ohta *et al.*, 1987; Samukawa *et al.*, 1987; Tominaga *et al.*, 1988; Otsubo *et al.*, 1991; Takeda *et al.*, 1991). Little information is, however, available related to environmental disturbances caused by the upwelling of anoxic water onto the shore ecosystem.

Our study area, Dokai Bay, is virtually surrounded by Kitakyushu, a city with a population of approximately one million. The marine environment of this bay has suffered from extremely eutrophic conditions, due to discharges of large amounts of nutrients caused by the outflow of effluents from chemical factories and wastewater treatment plants (Yamada *et al.*, 1991; Ueda *et al.*, 1992, 1994; Kajiwara and Yamada, 1997; Higashi *et al.*, 1998). Eutrophication of the water often causes the growth of phytoplankton blooms, and results in the deposition of large amounts of organic matter onto the sea floor. In the innermost areas of the bay, where water tends to stagnate, dissolved oxygen of the bottom water is depleted during the summer (Ueda *et al.*, 1994; Kajiwara and Yamada, 1997; Higashi *et al.*, 1998). In a recent study (Ueda *et al.*, 1994), we reported that hypoxic waters with DO levels of < 1.5 mg l^{-1} had upwelled into the middle (between 1.5 and 6.0 m in depth) of the water column in areas offshore from the bay's intertidal flats. It is likely that oxygen-deficient water further upwelled toward the surface layer, and moved towards the shore, causing a catastrophic impact to the benthic ecosystem of the intertidal flats in the innermost parts of the bay.

In this paper, we focus on the occurrence of oxygen-deficient water at the innermost areas of Dokai Bay during the summer, and the subsequent multi-seasonal change in the density of macrobenthic animals in the bay and on the adjacent intertidal flats. We assessed the chemical conditions of the water and sediments, and carried out quantitative sampling of the macrobenthic fauna in the bay and on the adjacent intertidal flats, four times, between April 1992 and April 1993. Here, we report upon the results of the environmental assessments, and clarify the impact of oxygen-deficient water on the seasonally changing abundance and species composition of the macrobenthic fauna of the intertidal flats.

Study Area

Dokai Bay is located in a corner of Kyushu, Japan (33°56′N, 130°57′E) (Fig. 1). The bay is approximately 13 km in length, 1.2 km in width at the bay mouth and 0.3 km wide at the head. The first heavy and chemical industrial areas in Japan were established along this bay during the 1900s. Three separate intertidal flats with a

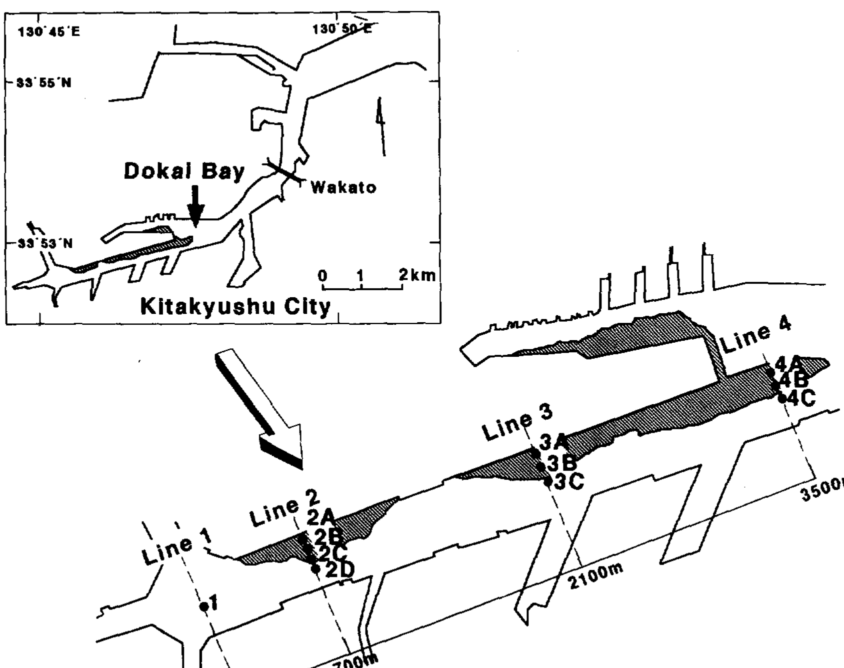

Fig. 1 Map of the study area in Dokai Bay (Kitakyushu, Japan).

total area of 40 ha are distributed along the northern shore at the head of the bay. The maximum width of the intertidal flats at the extreme low water spring tide (ELWST) is approximately 150 m. The depth of water offshore from the intertidal flats is approximately 8–10 m. In this study, we placed four sampling stations in the offshore areas (Stations 1, 2D, 3C, 4C) and seven more on the intertidal flats (Stations 2A, 2B, 2C, 3A, 3B, 4A, 4B), arranged in four transect lines.

Materials and Methods

We carried out a chemical assessment of the water and sediments and undertook quantitative benthic samplings of the macrobenthic fauna at five stations on the intertidal flats (Stations 2A, 2B, 2C, 3A, 4A) on 22 April 1992, and at all 11 sampling stations on 31 August 1992, 18 December 1992 and 15 April 1993. At each station, we measured the vertical profiles of temperature and dissolved oxygen (DO) of the water at depth intervals of 1.0 m with a DO meter (Central Science UC-12) at the time of high tide, and took three grab samples with an Eckman–Barge grab sampler (15 × 15 cm) from a boat.

At each station, we subsampled the surface layer of the sediment to a depth of 1 cm from one grab sample, and determined its AVS (Acid Volatile Sulphide) level with an AVS test column (Gastec, Hedorotec 201H), and total organic carbon (TOC) level with a CHN analyser (Yanaco, MT-500). The remaining two grab samples were sieved on a 1 mm mesh screen, and the residues fixed in a 10% solution of formalin with Rose Bengal. The macrobenthic fauna was sorted, identified, counted and weighed.

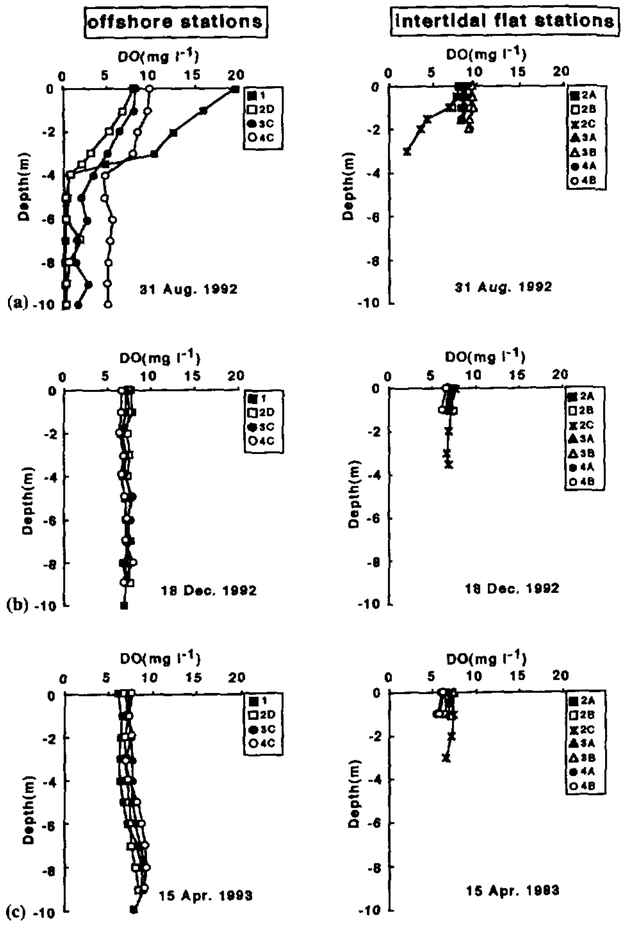

Fig. 2 Vertical profiles of DO levels in the water at 11 sampling stations on (a) 31 August 1992, (b) 18 December 1992, and (c) 15 April 1993.

Results

DO levels in the water

Figure 2 indicates the vertical profile of DO in the water column. In August 1992, the DO profiles at four offshore stations (Stations 1, 2D, 3C and 4C) showed a distinct signature between the surface and bottom. DO of the surface layer to a depth of 2 m was oversaturated within the range of 5.2–19.8 mg l^{-1}, while that of the layers deeper than 4.0 m was depleted at Stations 1 and 2D, within the range of between 0.1 and 0.8 mg l^{-1}. Dissolved-oxygen-deficient water extended from the sea floor to a depth of 6 m above it, and for a length of at least 2100 m from Stations 1 to 3.

Dissolved-oxygen-deficient water was not identified during high tide on any of the six intertidal flat stations except 2C. DO of the bottom water at these stations was always either saturated or near-saturation within the range of 7.1–9.5 mg l^{-1}. Station 2C was located at the seaward edge of the intertidal flats and, during high tides, bottom water was found within a transition zone between two distinct layers in the water column with strikingly different DO signatures, at the head of the bay.

In December 1992 and April 1993, the water column was well mixed at all sampling stations and DO levels in all layers were >5.4 mg l^{-1}.

Sediment TOC

Figure 3 shows the surface layer sediment TOC levels at all sampling stations in August 1992. The lowest sediment TOC levels (31.9, 21.3, 28.2 mg g^{-1} dry sediment, respectively) were recorded at the most landward stations on the intertidal flats (Stations 2A, 3A and 4A) on each transect line. Sediment TOC tended to increase

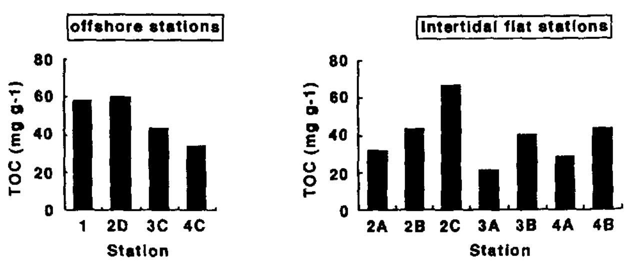

Fig. 3 Surface layer sediment TOC values at 11 sampling stations on 31 August 1992.

at those stations on the seaward side of the intertidal flats and at offshore stations. On the inner two transect lines (transect lines 1 and 2) of the stations, sediment TOC reached extremely high levels of 58.0 and 60.1 mg g^{-1} dry sediment (at offshore stations 1 and 2D) and 66.5 mg g^{-1} dry sediment at Station 2C located at the seaward edge of the intertidal flats, respectively.

Sediment AVS

Figure 4 shows seasonal fluctuations in surface layer sediment AVS at all stations. The sediment AVS levels between 0.6 and 4.8 mg g^{-1} dry sediment at the offshore stations (Stations 1, 2D and 3C) in August 1992 indicate that reducing conditions developed in summer, when dissolved oxygen levels were low in the bottom water (Fig. 2). Sediment AVS levels at these three stations were >1.5 mg g^{-1} dry sediment in December 1992, although bottom water DO levels had already recovered to saturation levels. Thus, on the sea floor in offshore areas, highly reduced sediments were not easily oxidized even after recovery of DO levels in the bottom water.

On the intertidal flats, the sediments were kept well-oxygenated at three stations (Stations 2A, 2B and 4A) throughout the year. Sediment AVS levels at these stations were never >0.6 mg g^{-1} dry sediment. At four other stations on the intertidal flats (Stations 2C, 3A, 3B and 4B), the development of reducing conditions in the sediment was similar to those of the offshore stations in August 1992. The sediment AVS levels at these stations ranged between 1.0 and 1.8 mg g^{-1} dry sediment. Oxidation of the sediments on the intertidal flats proceeded much faster than at offshore stations. This is likely due to aerial exposure and saturated surface water. In December 1992, sediment AVS levels of >1.0 mg g^{-1} dry sediment were recorded only at Station 3B.

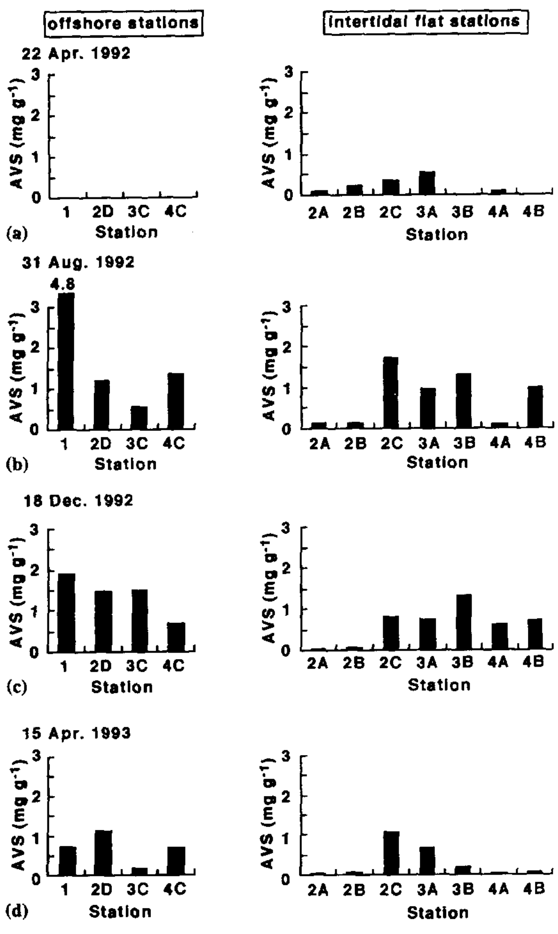

Fig. 4 Surface layer sediment AVS values at 11 sampling stations on (a) 22 April 1992, (b) 31 August 1992, (c) 18 December 1992, and (d) 15 April 1993.

Density and biomass of macrobenthic fauna

Figures 5 and 6 show the seasonal changes in density and biomass, expressed in terms of wet weight of the macrobenthic fauna. Both density and biomass indicate similar patterns of fluctuation. At the offshore stations, where dissolved oxygen levels in the bottom water were depleted in summer (Fig. 2), the density and biomass of the macrobenthos were poor throughout the period of study. In August 1992, density and biomass were only 40–710 ind. m^{-2}, and 0.3–8 gWW m^{-2}, respectively. Even after dissolved oxygen levels in the bottom water had became saturated (after December 1992), the macrobenthos recovered only slightly.

On the intertidal stations, a relatively abundant macrobenthic fauna was identified in April 1992. At five stations on the flats (Stations 2A, 2B, 2C, 3A and 4A), the densities were 5110–16 160 ind. m^{-2} and the biomass was 88–1621 gWW m^{-2}. However, the macrobenthic fauna catastrophically declined at all seven stations in August 1992 (20–1130 ind. m^{-2} and 0.02–15 gWW m^{-2}), although the DO levels remained at saturation levels,

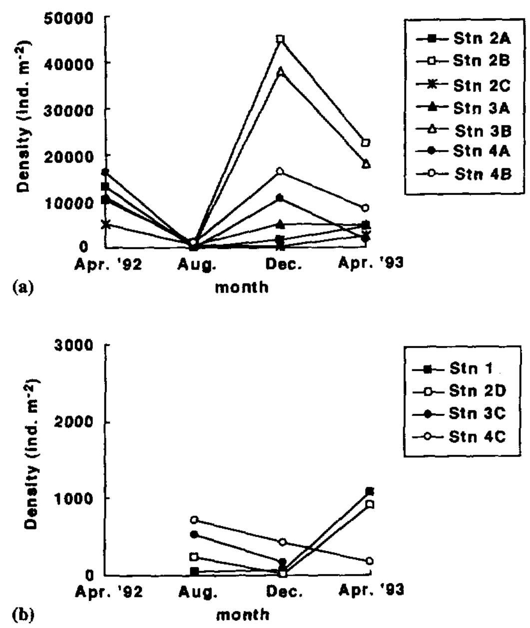

Fig. 5 Seasonal changes in density of the macrobenthic fauna at (a) the seven intertidal stations, and (b) the four offshore stations.

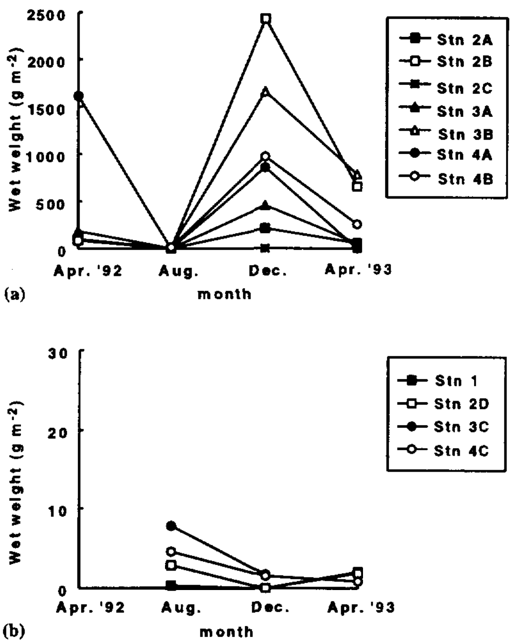

Fig. 6 Seasonal changes in biomass (in terms of wet weight) of the macrobenthic fauna at (a) the seven intertidal stations, and (b) the four offshore stations.

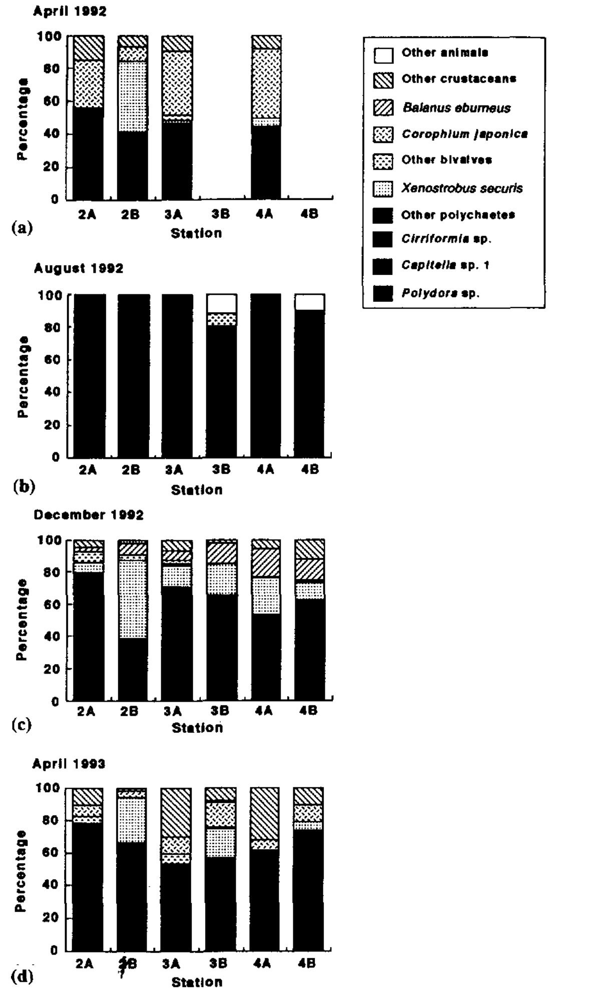

Fig. 7 Percentage composition of individual macrobenthic animal species at the six intertidal stations on (a) 22 April 1992, (b) 31 August 1992, (c) 18 December 1992, and (d) 15 April 1993.

(except Station 2C (Fig. 2)), and the surface sediments also remained in a well-oxygenated condition at three stations (Stations 2A, 2B and 4A) (Fig. 4(B)). In December 1992, the densities and biomass of the macrobenthos rapidly recovered to 1840–44 840 ind. m^{-2} and 211–2431 gWW m^{-2} at six stations, except Station 2C, respectively.

Dominant species and percentage composition of the macrobenthic fauna of the intertidal flats

Figures 7 and 8 indicate the percentage composition of individual macrobenthic species and percentage biomass (wet weight) at the six intertidal stations. In April 1992, polychaetes accounted for between 40% and 53% of the density of the macrobenthos at all four sampling stations. The dominant species were *Polydora* sp., *Capitella* sp. 1 and *Cirriformia* sp. The other 50% of the macrobenthos composed of the bivalve, *Xenostrobus securis*, an amphipod, *Corophium japonica* and several other species of crustaceans. In terms of percentage biomass, the polychaetes, including *Cirriformia* sp. and *Neanthes succinea*, dominated the macrobenthos at Station 2A. At three other stations, the bivalves, including *Ruditapes philippinarum* and *X. securis* accounted for 60–90% of the biomass.

In August 1992, when the macrobenthic fauna markedly decreased in density and biomass at the intertidal stations (Figs. 5 and 6), the community was mostly made up of polychaetes, including *Polydora* sp., *Capitella* sp. 1, *Cirriformia* sp., and *N. succinea*. The polychaetes accounted for between 81% and 100% of the density of the macrobenthos at all six stations, and between 83% and 100% of the biomass, except at Station 3B.

In December 1992, the abundance and biomass of the macrobenthos rapidly recovered (Figs. 5 and 6). The percentage of polychaetes decreased to between 38% and 80% at all six stations, when several species of molluscs and crustaceans, including the bivalve, *X. securis*, and a barnacle, *Balanus eburneus*, densely recolonized. In terms of percentage biomass, the ratios of these molluscs and crustaceans also increased and accounted for between 93% and 98% of the biomass of the macrobenthos at all six stations.

In April 1993, the dominant macrobenthic species-group, in terms of density, were: *Polydora* sp., *Capitella* sp. 1 and *Cirriformia* sp. (Polychaeta); *X. securis* (Bivalvia); and *C. japonica* (Crustacea). These species first appeared as the dominant species-group in April 1992. The dominant species-group, in terms of biomass, were *Cirriformia* sp. and *N. succinea* (Polychaeta), and *R. philippinarum* and *X. securis* (Bivalvia). These were also the dominant species-group, in terms of biomass, in April 1992. Thus, the species composition of the re-established macrobenthos in the spring was almost the same as the previous spring.

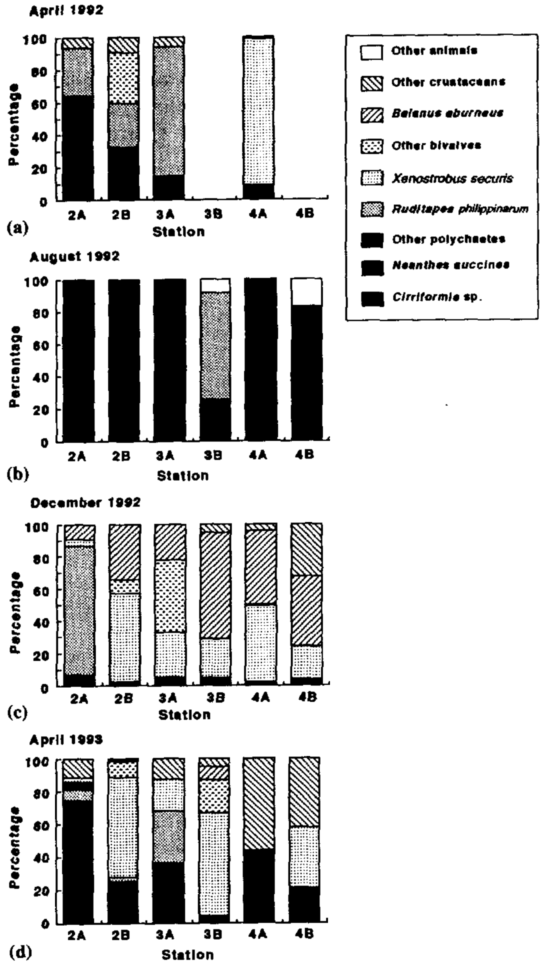

Fig. 8 Percentage composition of the biomass (in terms of wet weight) of the macrobenthic fauna at the six intertidal stations on (a) 22 April 1992, (b) 31 August 1992, (c) 18 December 1992, and (d) 15 April 1993.

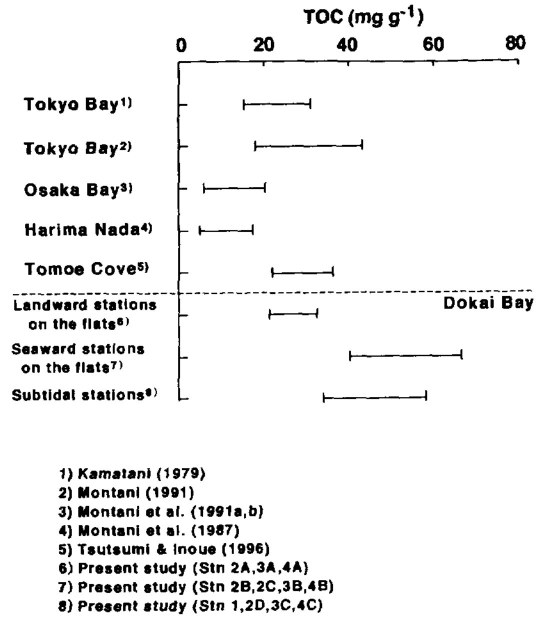

Fig. 9 A comparison of surface layer sediment TOC values recorded during this study and in previous studies in other Japanese enclosed coastal seas.

Discussion

Accumulations of organically enriched sediment are increasing in many enclosed coastal seas neighbouring large cities throughout the world, due to the inflow of wastewater and the dumping of organic matter (Diaz and Rosenberg, 1995). Dokai Bay in Japan, is a typical example of such an enclosed coastal sea (Yamada *et al.*, 1991; Ueda *et al.*, 1992, 1994; Higashi *et al.*, 1998). The results of this study revealed that the bottom sediments in the innermost areas of Dokai Bay were enriched in organic matter to a much greater degree (as high as TOC 66.5 mg g^{-1} dry sediment) than other Japanese enclosed coastal seas adjacent to major cities that have suffered from organic enrichment of the bottom sediments (such as Osaka and Tokyo) (Fig. 9). The highest sediment TOC levels reported upon from previous studies in Osaka Bay, Harima Bay, and Tokyo Bay, was <43.0 mg g^{-1} dry sediment (Kamatani, 1979; Montani *et al.*, 1987, 1991a,b; Montani, 1991).

In Japanese coastal waters, there is another important source of organic discharge into the sea, which is net pen fish farming (Tsutsumi and Kikuchi, 1983; Tsutsumi *et al.*, 1991; Tsutsumi, 1995; Tsutsumi and Inoue, 1996). Large amounts of cultured fish faeces and food residues have been deposited below the net pens over the past three decades (since net pen fish farming first began), across Japanese coastal seas. The organically enriched bottom sediments often exhaust dissolved oxygen of the bottom water during the summer. However, even these sediments (in one particular fish farm studied) did not contain organic matter of >36.0 mg g^{-1} dry sediment of TOC (Tsutsumi and Inoue, 1996). In the innermost areas of Dokai Bay, TOC levels in the bottom sediments reached 34.1–60.1 mg g^{-1} dry sediment in offshore areas and 28.2–66.5 mg g^{-1} dry sediment on the flats (Fig. 9). The sediments were thus organically enriched not only in the offshore areas but also on the flats.

In subtidal areas offshore from the intertidal flats, dissolved oxygen levels in the water column were depleted from the bottom to the middle from August 1992 (Fig. 2), and the sediments fell into an extremely reduced condition, following the generation of high levels of hydrogen sulphide (Fig. 4). On the flats themselves, the bottom waters during high tide were, in contrast, either saturated or oversaturated with dissolved oxygen (Fig. 2). Interestingly, the sediments remained in a relatively oxygenated condition at three sampling stations (2A, 2B, 4A) (Fig. 4), even though the sediments were organically enriched at levels similar to those of the offshore areas (Figs. 3 and 9). This is one of the unique characteristics of the intertidal flat environment, when they are exposed to surface water with saturated dissolved oxygen levels during high tide and air during low tide.

Nevertheless, both benthic faunal density and biomass were equally poor in the offshore areas and on the intertidal flats in August 1992 (Figs. 5 and 6). At that time, innumerable freshly dead shells of bivalves, including *R. philippinarum* and *X. securis,* were found on the flats. Likewise, many freshly dead shells of bivalves can also be found on the intertidal flats of Tokyo Bay following upwelling of dissolved-oxygen-deficient water (Kakino, 1986; Furota, 1987; Aoki, 1994; Aoki, 1999).

The upwelling of dissolved-oxygen-deficient water onto the shore is easily observed in Tokyo Bay, as numerous molecules of sulphide compounds, having formed in the upwelling water, then reflect sunlight, and the water turns a milky blue colour. This phenomenon is known as 'Aoshio (blue tide)' (Kakino *et al.*, 1987; Ohta *et al.*, 1987; Tominaga *et al.*, 1988; Otsubo *et al.*, 1991; Takeda *et al.*, 1991). However, the phenomenon has never been reported from coastal areas of western Japan. It is likely that dissolved oxygen-deficient waters reach the intertidal flats of Dokai Bay, but the water remains colourless, even though it is exposed to sunlight; this is probably due to the low density of sulphide-compound molecules in the water. There is a need to monitor flood water DO levels on the intertidal flats throughout the summer to confirm when the dissolved-oxygen-deficient water first reaches them and how this influx causes the resulting catastrophic decline in the benthic ecosystem.

The benthic survivors on the intertidal flats after a 'crash' are dominated by several species of polychaetes (both in density and biomass), such as *N. succinea*, *Cirriformia* sp., *Capitella* sp. 1 and *Polydora* sp. (Figs. 7 and 8). These polychaetes seemed to be physiologically more tolerant of the short-term environmental disturbance that occurred on the flats during the summer than the other major components of the benthic fauna. On the other hand, in the benthic recovery process on the flats, from winter to the following spring, the bivalve, *X. securis*, and the barnacle, *B. eburneus*, exhibited a rapid increase in both density and biomass. These two species are exotic species from North America, and Australia/New Zealand, respectively (Asakura, 1992; Kimura *et al.*, 1999). In Dokai Bay, the larvae of these species are probably supplied by tankers that frequently arrive from foreign countries. These 'imports' find a relatively competition-free environment on the intertidal flats, due to the temporal environmental disturbance in summer. Many easily accessible habitats are available for these exotic species during the process of benthic ecosystem recovery over the winter-spring cycle.

There is another noteworthy phenomenon. At offshore stations from the intertidal flats, the density and biomass of macrobenthic animals remained extremely poor, even after bottom water DO levels had recovered to saturation by December (Figs. 5 and 6). The contrasting seasonal changes in abundance and biomass of the benthic animals on these intertidal flat areas indicate that there are other unidentified factors limiting the occurrence of the macrobenthic fauna in offshore areas of the bay. The macrobenthos once disappeared from the bay during the 1960s, due to severe water pollution from factory effluents, and wastewater from the city adjacent to the bay, but have recovered gradually by the enactment of environmental controls (Yamada *et al.*, 1991, 1992; Ueda *et al.*, 1992, 1994; Kajiwara and Yamada, 1997). However, the negative impacts of water pollution still depress the activities of the benthic fauna in the offshore areas of Dokai Bay. We suspect that there may be some unknown pollutants, contained in the water of the bay, that are affecting the early development of marine organisms.

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