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A Newly Emerging Environmental Issue: Development of Hypoxia in the Bottom Water of Ariake Bay

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Abstract—Ariake Bay is one of the most important shallow seas for fisheries in the western Japan. The large tidal range in combination with large freshwater discharge into this sea could play a crucial role in maintaining the productive environment and have contributed to prevention of red-tide outbreaks and to rare incidence of hypoxia in the bottom water. However, the situation has been rapidly changing in recent years and the fisheries catch of this sea showed a remarkable decline, possibly due to various coastal development such as reclamation and dike construction in Isahaya Bay, part of the estuary head of Ariake Bay. In this paper, we discuss the development of hypoxia in the bottom water of Isahaya Bay, as a newly emerging environmental issue. Detailed analyses of the existing time-series data obtained from hourly observation in Isahaya Bay has revealed that development of density stratification, associated with wind-induced intrusion of high-density bottom water into the bay, could accelerate the hypoxia formation in the bay. Prevailing offshore wind pushes the hypoxic water further into the bay, and forces it to upwell near the dike, often leading to eventual occurrence of Aoshio (namely, upwelling of the anoxic water to the surface). This could do damage to a wider range of habitat environment in and around Isahaya Bay. Implication of recent environmental changes such as hypoxia formation for the recent decline in fisheries resources and future tasks for the environmental restoration are also discussed in detail.

Keywords: Ariake Bay, Isahaya Bay, hypoxia, wind-induced current, environmental restoration, fisheries resources

1. INTRODUCTION

Recent environmental changes in Ariake Bay

Ariake Bay (Ariake Sound) is one of the most important shallow waters for fisheries in the western Japan (Fig. 1). The estimated fisheries catch per unit area of this bay

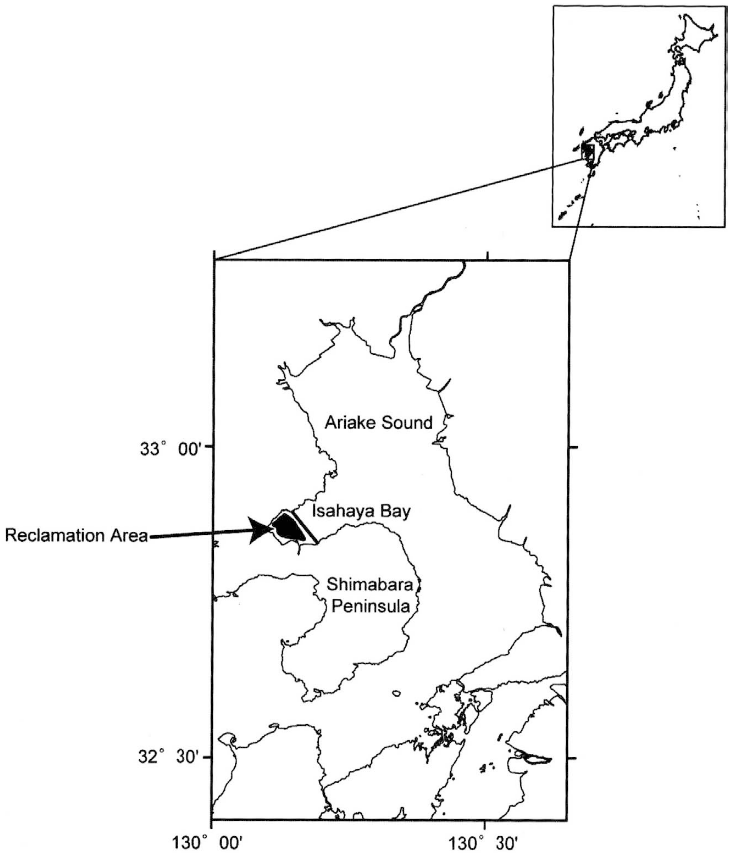

Fig. 1. Location of Ariake Bay (Ariake Sound). A reclamation project with dike construction was undertaken in Isahaya Bay, part of the estuary head of Ariake Bay.

was remarkably high in 1979 in comparison with the other enclosed seas in the world (Yanagi, 2002). The large tidal range, 5–6 m during the spring tide, and strong tidal mixing, in combination with a large amount of freshwater discharge into the innermost area, could play a crucial role in providing a variety of habitats like a tidal flat and maintaining the environment as productive for fisheries resources such as shellfish and cultured laver (*Nori* in Japanese). These features of this sea, mentioned above, apparently contributed to prevention of red-tide outbreaks and to rare incidence of oxygen depletion in the bottom water in the past. However, the situation has been rapidly changing in recent years, possibly due to various coastal development. The time-series of fisheries catch in this sea showed a rapid decline in 1980s, mainly due to the reduction in shellfishes (Fig. 2), while the number of incidence of red tides increased in 1980s and in 1990s as well (Nakata, 2004). In winter of 2000–2001, a

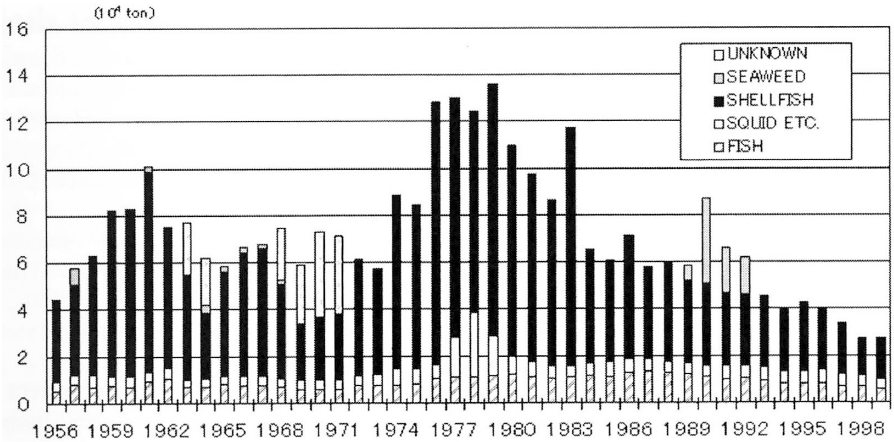

Fig. 2. Time-series of fisheries catch (1956–1999) in Ariake Bay.

large-scale diatom red tide occurred and did serious damage to Nori culture (Ishizaka, 2003 ; Ishizaka et al., 2006). A reclamation project with dike construction, which was undertaken in the tidal flat region of Isahaya Bay (see Fig. 1), is now under severe public debate on its environmental impact (Sato et al., 2001; Unokisgi, 2002, for example) .

In this context, the 5-year research group for "Integrated Study on the Effect of Environmental Change on the Fisheries Resources in Ariake Bay" (2001–2005) was organized at the Faculty of Fisheries, Nagasaki University. According to this study, recent environmental changes in Ariake Bay were summarized as follows; (1) In 1970s–1980s, rapid increase of reclamation of tidal flats in the estuary head of Ariake Bay could result in a stagnant condition, in addition to reduction in shellfish habitats, possibly degrading the environment and causing frequent red-tide outbreaks by more harmful species (Matsuoka, 2004). (2) In 1990s, reduced turbidity, accompanied with reduced tidal current/mixing (possibly enhanced stratification) could accelerate further environmental degradation and increase the number of incidence of red-tide outbreaks especialy in winter (Kiyomoto et al., 2008).

2. HYPOXIA IN THE BOTTOM WATER: A NEWLY EMERGING PROBLEM

In addition to the above problems, depletion of dissolved oxygen (DO) in the bottom water has been often reported and seriously threatening habitat environment during summer in a wider area of the innermost part of Ariake Bay (Tsutsumi et al., 2003, 2007; Hamada et al., 2008). The DO depletion could be a trigger of red-tide outbreakes through increased nutrient resolution from the bottom sediment, followed by further degradation of the habitat environment. It is therefore an urgent task to explore the mechanism behind the development of hypoxia and to take preventive measures against it.

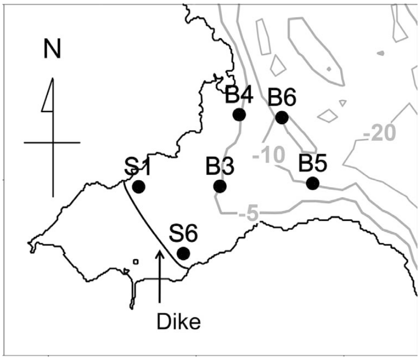

Fig. 3. Stations for hourly observation of sea surface temperature, salinity and DO in Isahaya Bay by the Kyushu Regional Agricultural Administration Office. Wind speed and direction are measured at B3.

In recent years, the hypoxia started to occur in the bottom water of Isahaya Bay, a part of the head of Ariake Bay, where dike construction was completed in 1997, resulting in serious damages to cultured short-neck clams in the tidal flats of the northern bay (Hirano et al., 2010). It could be resulted from reduction of the tidal current and subsequent enhancement of vertical stratification in the bay, possibly due to the dike construction (Tsutsumi et al., 2007). In fact, maximum tidal currents at both the ebb and the flood in Isahaya Bay appreciably reduced after dike construction (Matsuoka, 2004), which was also evident in the numerical simulation made by Manda and Matsuoka (2006).

In these contexts, in order to look at the present situation of the development of hypoxic water in this bay, we have analyzed existing time-series data (in July–August of 2004–2008) on temperature, salinity, DO, and wind direction and speed, which were obtained from hourly observation by the Kyushu Regional Agricultural Administration Office (Fig. 3). Data from direct current measurement made at the central bay (B3) in August 2006 were also used for the present analysis.

Figure 4 shows the time-series of wind (a), velocity of residual current in the bottom water (b), and vertical distributions of sigma-t (c) and DO (d) from 17–27 August 2006. A storm hit Ariake Bay on 18–19 August 2006, followed by flooding in the head of Ariake Bay on 18–21 August. Responding to the storm, prevailing wind changed from southward to northeastward and residual current in the bottom water reversed the direction from north to south-southwest (Fig. 4b), showing that bottom water tended to move windward and intrude into Isahaya Bay under the offshore wind. During this period, in fact, density of the bottom water rapidly increased and DO in the bottom water decreased, corresponding to the intrusion of the offshore water. This further suggests that stratification in Isahaya Bay could be intensified by the wind-induced bottom intrusion, followed by the surface intrusion of low salinity water as was evident after the flooding in the time-series of density profiles (Fig. 4c).

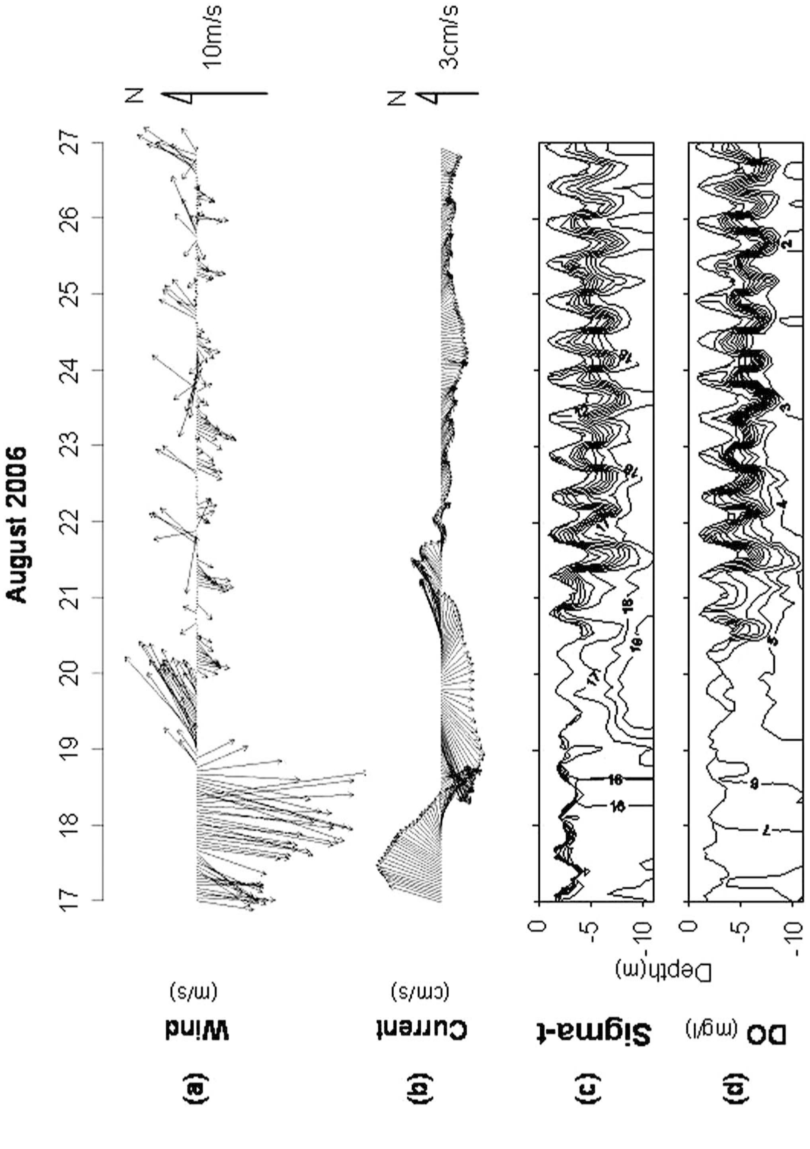

Fig. 4. Time-series of wind (a) and residual currents (25-hour running means) in the bottom water (b), and vertical profiles of density (sigma-t) (c) and DO (d) at the central Isahaya Bay (B3), from 17–26 August 2006.

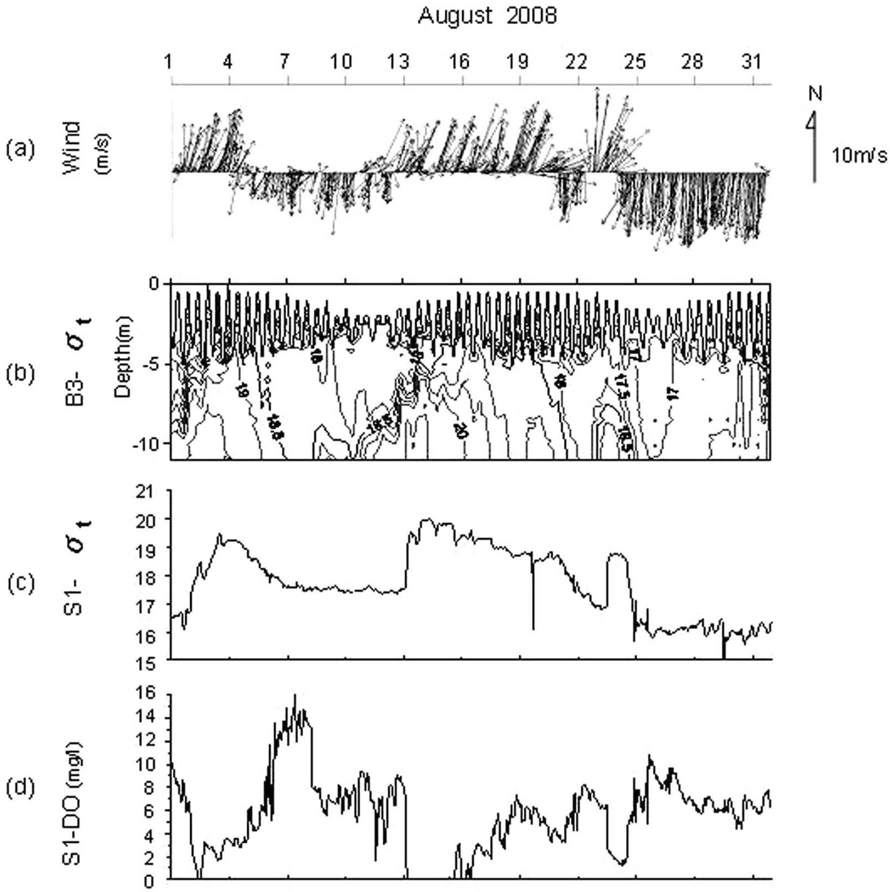

Fig. 5. Time-series of wind (a) and vertical profiles of density (sigma-t) (b) at the central Isahaya Bay (B3), and time changes of density (sigma-t) (c) and DO (d) in the bottom water near the dike (S1, see Fig. 3) in August 2008.

The intensified stratification resulted in hypoxia development in the bottom water as seen in the DO profiles (Fig. 4d).

The upper two panels of Fig. 5 show the time-series of wind (a) and density (sigma-t) profiles (b) in August 2008 at central Isahaya Bay (B3, Fig. 3). It is clearly seen that high density water appeared in the bottom water when the offshore (north-northeastward) wind prevailed, and that pycnocline moved upward and downward responding to offshore wind and onshore (southward) wind, respectively. This indicates that prevailing offshore wind in Isahaya Bay induced bottom intrusion of high density offshore water with low oxygen concentration into the bay, enhancing vertical stratification and subsequently leading to development of hypoxia in the

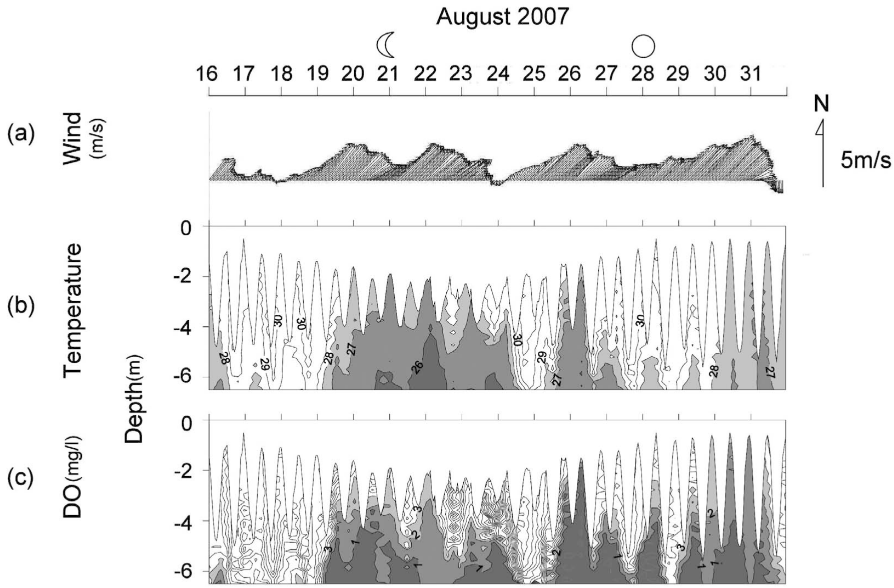

Fig. 6. Time-series of wind speeds (25-hour running means) (a) and vertical profiles of water temperature (b) and DO (c) near the dike (S1) from 16–31 August 2007.

bottom water. When onshore wind prevailed, on the other hand, offshore current was induced in the bottom water and the situation was reversed; the pycnocline was lowered and the hypoxic water disappeared from the bay. It should be also noted from Fig. 5(c,d) that appearance of the bottom water with high density corresponded to severe decline in DO near the dike (S1, Fig. 3), suggesting that rapid consumption of DO occurred as high density water moved inward to the dike from the central bay.

It is noticeable that when offshore wind further prevailed, this hypoxic water continued to move inward to the dike and upwelled to the surface, often inducing Aoshio (upwelling of anoxic bottom water) as was actually reported near the dike in mid-August 2008. Figure 6 further shows the time-series of wind (a) and vertical distributions of temperature (b) and DO (c) in the vicinity of the dike (S1) from 16–31 August, 2007. It should be noted that bottom water with low temperature and low DO upwelled to the surface, responding to prevailing offshore (northeastward) wind. The upwelling velocity roughly estimated from the theory for this case (about 6 m/h at maximum) was consistent with the observation (sea surface temperature near the dike dropped after 4–5 hour continuous blows of the offshore wind). When onshore wind prevailed, on the other hand, offshore current was induced in the bottom water and the situation was reversed.

In summary, as shown in Fig. 7, development of density stratification, associated with wind-induced intrusion of high-density bottom water into the bay, could

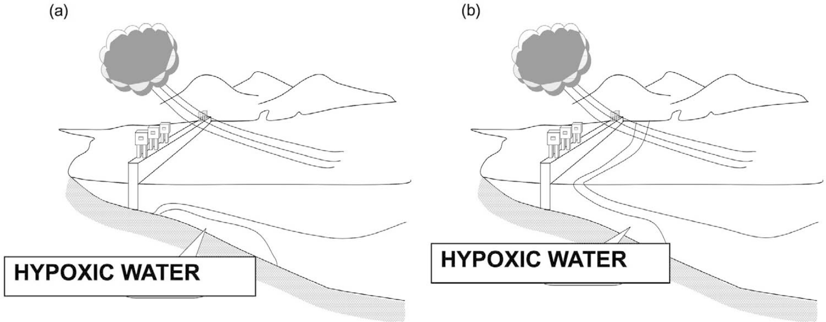

Fig. 7. Schematic diagrams of hypoxia development (a) and upwelling of hypoxic water (b) near the dike in Isahaya Bay, responding to prevailing offshore (north-northeastward) wind.

accelerate the hypoxia formation in Isahaya Bay (Fig. 7a). Prevailing offshore wind pushes the hypoxic water further into the bay, and forces it to upwell near the dike (Fig. 7b), often leading to eventual occurrence of Aoshio. The upwelling of the hypoxic water to the surface could do damage to a wider range of habitat environment in and around Isahaya Bay.

3. IMPLICATION OF RECENT ENVIRONMENTAL CHANGES SUCH AS HYPOXIA FORMATION FOR THE DECLINE IN FISHERIES RESOURCES

In parallel with marked decline in shellfish catches in 1980s, fish catches also showed continuous reduction after late 1980s (see Fig. 2). Figure 8 demonstrates four examples of the time change in fisheries catch of some dominant species. It should be noted that the declining trend in the catch of these species became more prominent in late 1990s.

Most of the species which showed a rapid decline in recent years have several common characteristics. They depend much on the bottom habitat environment and also have similar early life history; they have spawning sites in the central bay (off Shimabara, for example) and mostly spend larval and juvenile stages in the innermost part of the bay. This suggests that continuous reduction in the fisheries catch in 1990s could be resulted from rapid degradation of habitat environment near the bottom possibly due to increased incidence of red-tide outbreaks and subsequent enlargement of hypoxic bottom water in summer (Fig. 9). According to unpublished data from Dr. A. Yamaguchi, Nagasaki University, many fish larvae were still distributed in and around Isahaya Bay, after the completion of dike construction. This suggests that environmental degradation in Isahaya Bay could be critical for survival and recruitment of fish larvae which are possibly on the way of transport from the spawning sites in the central bay to the nurseries in the innermost part. It is therefore necessary to take notice with a negative influence of hypoxic water on the survival of those fish larvae in possible connection with declining trend of fisheries resources in Ariake Bay.

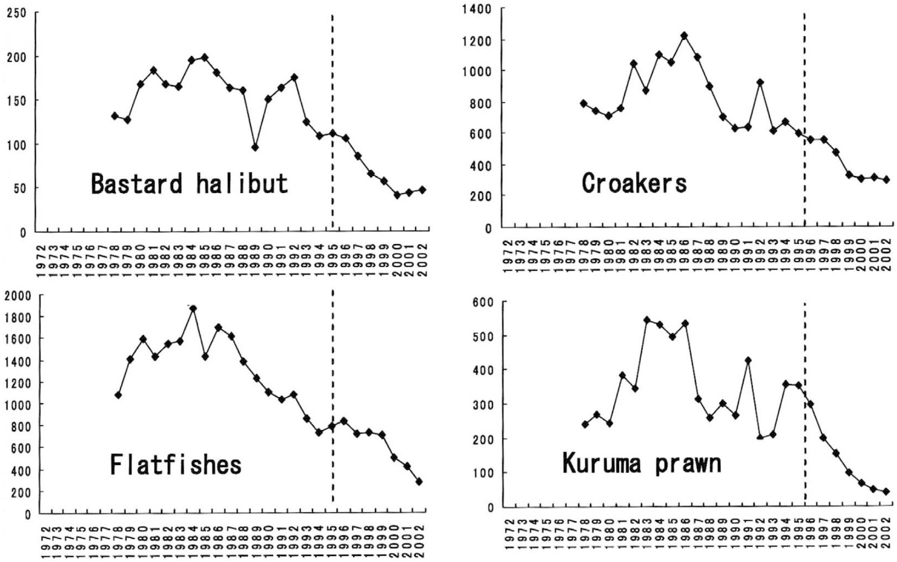

Fig. 8. Time changes in the fisheries catch of four dominant species (or fish groups). The broken line in each panel indicates the year 1995.

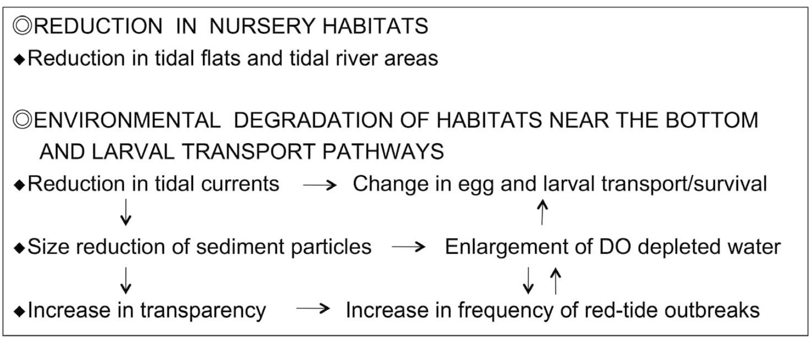

Fig. 9. Possible causal processes of recent decline in the fisheries resources in Ariake Bay.

On the other hand, Fig. 10 demonstrates the environmental conditions associated with mass mortality of short-neck clams cultured on the tidal flats in northern Isahaya Bay (Hirano et al., 2010). Those include daily tidal range, wind speed, red tide incidence and occurrence of hypoxia in the bottom water, and as is seen easily, hypoxia occurred under the smallest tidal ranges (actually corresponding to the neep tide) and week winds (less than 5 m s^{-1}) during the period of *Chattonella* red-tide

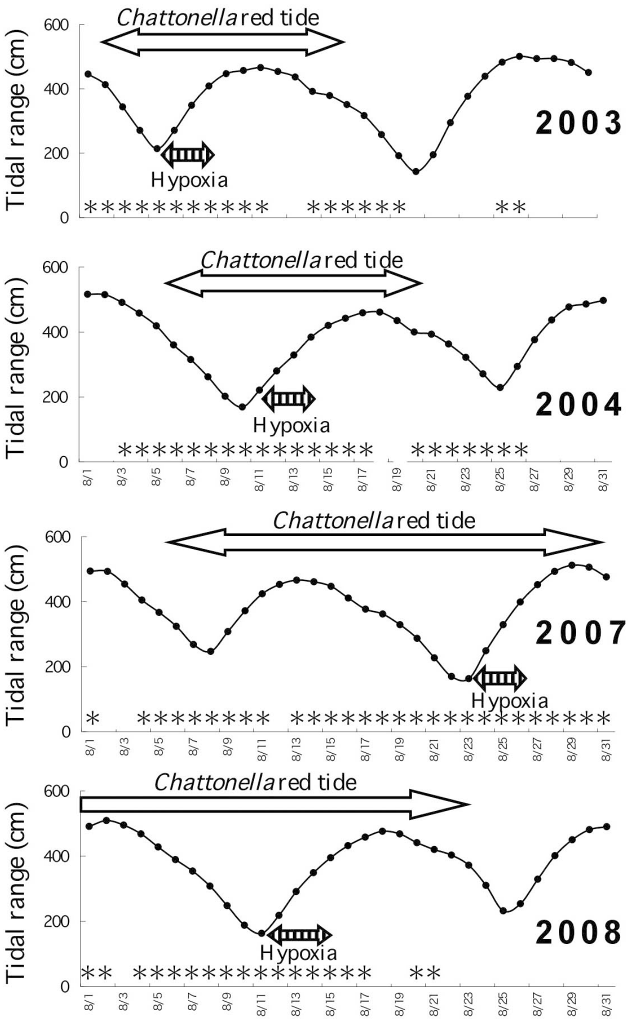

Fig. 10. Variations in the daily tidal range in the innermost area of Ariake Bay, corresponding to hypoxia formation in the tidal flat of northern Isahaya Bay in 2003, 2004, 2007 and 2008 (no hypoxia occurred in 2005–2006). Bold open arrows indicate the period of *Chattonella* red-tide outbreaks. Asterisks indicate that daily mean wind speed at B3 (see Fig. 3) was bellow 5 m s^{-1}. (Reprinted from *Fisheries Engineering*, **47**, Hirano et al., Fig. 4. © 2010, The Japanese Society of Fisheries Engineering.)

outbreaks. This may suggest that decrease in the DO supply rate due to low water exchange and week vertical mixing (enhanced stratification), and increase in the DO consumption rate due to red-tide outbreaks, both could contribute to hypoxia formation, leading to mass mortality of the clams. Further systematic field surveys are necessary to prove the above hypothesis on the hypoxia formation at the clam culture ground in the tidal flats. A hypoxia prevention system that is composed of barriers against the hypoxic water intrusion and a micro-bubble generator for aeration has recently been developed and experimentally deployed in the clam culture ground (Hirano et al., 2010).

4. FUTURE TASKS FOR ENVIRONMENTAL RESTORATION

It is of great importance, in general, to set-up a common goal for the restoration of damaged environment. Cosidering that the decline in the shellfish production was the most serious signal of the environmental degradation of Ariake Bay, it should have the first priority to restore high and sustainable productivity of shellfishes. It is needless to say that recovery of tidal flats and tidal current systems is essential to the rehabilitation of the shellfish production.

Another possible goal could be the restoration of ecological function of the estuarine system as a nursery habitat for various fisheries resources. However, there has been almost no study on the transport and survival process of fish eggs and larvae in Ariake Bay. It is therefore an urgent task to initiate the pilot study concerning recruitment mechanism of the fishes which spawn offshore and have their nurseries inshore. This will contribute to detecting causes of recent decline in the fisheries catch and also to finding the proper way to environmental restoration of this bay.

From a practical viewpoint for restoring hypoxic conditions in the bottom water, it is necessary to develop a nutrient budget model for making a quantitative diagnosis of the present situation and predicting the future. The nutrient budget of Ariake Bay is probably composed of three parts: benthic ecosystems in the tidalflat, plankton ecosystems in the water column and artificial systems related to Nori culture. In recent years, the benthic ecosystem has remarkably declined, while the plankton ecosystem has been dominated by more harmful algal species (Matsuoka, 2004). More detailed and quantitative information about these ecosystems is required to develop the effective restoration plan.

Future tasks from a management viewpoint must include reconsideration of ongoing/planned projects for coastal development such as reclamation, dredging and construction of harbors/dams. In that sense, it is necessary to develop a good management measure for environmental protection and restoration of Ariake Bay, on the basis of the scientific diagnosis of the present status. The monitoring networks for red tides, oxygen depletion in the bottom water and other properties related to fisheries production should be established in near future. In a longer-term, it will be required to integrate and coordinate various ongoing/planned projects for environmental restoration under the common goal as mentioned above. For this purpose, close cooperation among researchers and research organizations relevant to the projects will be also indispensable. The establishment of a common, open and unified database should be strongly recommended. Preliminary trials in this direction have just been made in various ways, however presently they have not yet been fully integrated.

Finally, large mudflat regions like those in Ariake Bay extend widely along the west coast of Korea, and there exist similar serious environmental problems related to reclamation projects. It is therefore of great importance for researchers working in Ariake Bay and the Korean coast to keep in close cooperation with each other and have a common opportunity to exchange relevant scientific information.

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