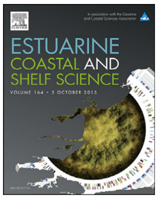
Estuarine, Coastal and Shelf Science 164 (2015) 204–213

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss



Contribution of the development of the stratification of water to the expansion of dead zone: A sedimentological approach

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form
12 June 2015
Accepted 25 July 2015
Available online 31 July 2015

Keywords:
Stratification
Sedimentary environments
Benthic communities
Hypoxia
Plankton blooms
Western Japan
Ariake Bay

ABSTRACT

To test a hypothesis that the development of the stratification of water enhances the phytoplankton blooming and hypoxia without any increase in the nutrient loading in an enclosed bay, the present study examines the spatial relationship among the hydrographic structures, physico-chemical conditions of the sediments, and macrobenthic communities at 21 stations in the inner part of Ariake Bay, Kyushu, Japan in August 2010, and compares the distribution of the mud content of the sediment in 2014 with those of last few decades focusing on the succession of sedimentary environment. The stratification of water developed in the innermost part of Ariake Bay, and hypoxia occurred below the well-stratified water. The distribution of the muddy bottom with high content of organic matter derived from phytoplankton almost overlapped with the stratified water. Cluster analysis concerning the grain size composition of the sediment corresponded greatly to that of the macrobenthic communities. These results indicate that the development of the stratification of water strongly influences the sedimentary environments and the community structure of macrobenthic animals in the inner part of Ariake Bay. Comparison with the past distribution of mud content revealed eastward expansion of the muddy sediment, and it suggests the distribution of the well-stratified water has expanded recently. The results of the present study show the possibility that the development of the stratified water causes a series of phenomena, which closely resemble ones following the development of the eutrophication of the water, without any increase in the nutrient loading in an enclosed bay or estuary.

1. Introduction

In recent years, coastal ecosystems tend to decline markedly due to various negative impacts of anthropogenic activities on the lands caused by urbanization, development of industries and agriculture, and other reasons throughout the world (Lotze et al., 2006; Halpern et al., 2008). In particular, in enclosed coastal seas (and/or bays) where the water exchange with open sea is restricted, effluents with high concentration of nutrients discharged from the lands often cause serious eutrophication, following the frequent blooming of phytoplankton and increase of organic loading on the sea floor (e.g., Graf et al., 1982; Rosenberg et al., 1990; Kemp et al., 2005; HELCOM, 2009). As the organic enrichment of the sediment progresses, reductive bottom environment tends to expand into wider areas (Nilsson and Rosenberg, 2000; Rosenberg et al., 2001; Gray et al., 2002; Middelburg and Levin, 2009), and larger animals with calcareous shells that dominate in the macrobenthic communities in the healthy oxidative environment are apt to be replaced by small polychaetes with opportunistic life history characteristics (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986).

On the sea floor with the organically enriched sediment, oxygen consumption of the bottom water is accelerated in the warm season. In addition, halocline and thermocline tend to develop in enclosed coastal seas, restrict the vertical mixing of the water, and result in the occurrence of hypoxia or anoxia below the pycnocline

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http://dx.doi.org/10.1016/j.ecss.2015.07.028
0272-7714/

in the water (Turner et al., 1987; Seliger and Boggs, 1988). The seasonal occurrence (or year-round occurrence in some cases) of hypoxia or anoxia in the bottom water often causes a catastrophic disturbance on the macrobenthic communities (e.g., Jørgensen, 1980; Diaz and Rosenberg, 1995; Karlson et al., 2002; Laine, 2003; Baustian and Rabalais, 2009; Seitz et al., 2009). The region under these circumstances is referred to as “dead zone” and has spread in the world's coastal ocean (Diaz and Rosenberg, 2008; Rabalais et al., 2014).

The dead zone tends to develop due to not only the increase of the effluents discharged by the anthropogenic activities, but also the recent global warming (Boesch et al., 2010; Altieri and Gedan, 2015). In particular, thermocline and halocline will be developed more by factors including greenhouse effect and the increase of freshwater input, respectively (Harley et al., 2006). The stratification of water will be developed in estuaries and coastal seas, since it is often caused by both of thermocline and halocline. However, the combination pattern of these two factors changes in temporal and spatial scales depending on the regional topography (Holt et al., 2010; Najjar et al., 2010). Hence, more information based on the regional scale is necessary for understanding of the impacts of the development of water stratification on the ecosystem in estuaries and coastal seas.

Ariake Bay in the present study area is located in the west coast of Kyushu, western Japan, and is one of the typical enclosed coastal sea. The ecosystem of this bay has been praised as “fertile sea” because of the extremely large fishery productivity, and has supported the coastal fisheries for a long time (Tsutsumi, 2006). However, since the later half of the 1990s, a large scale of phytoplankton blooming has occurred repeatedly in the inner part of the bay irrespective of season, even though the amount of nutrient loading from the land to the bay did not increase at least in the past five decades (Tsutsumi, 2006; NPO Ariake Bay Rehabilitation Organization, 2011; Fig. A1 in Appendix A). Since the 2000s, hypoxia has occurred in the wide areas of the inner part of Ariake Bay every summer, and consequently has resulted in the marked decline of the macrobenthic communities (Yoshino et al., 2010, 2014).

Both phytoplankton blooming and hypoxia are phenomena followed by the development of halocline (pycnocline) caused by the inflow of a large amount of freshwater from the rivers during the rainy seasons (Tsutsumi, 2006). However, these rainy seasons are just annual meteorological phenomena, which have not changed notably in the recent three decades, judging from precipitation data of the Japan Meteorological Agency in the areas around the bay. The recent frequent occurrence of phytoplankton blooming and hypoxia in the inner part of Ariake Bay, therefore, suggests that the pycnocline tends to develop in the water during the rainy seasons or continue for a longer time than before despite the same amount of inflow of the river water to the bay, and it is very likely that this phenomenon brings a serious negative impact on the benthic ecosystem in the inner part of the bay.

In the present study, we propose a hypothesis that the development of the stratification of water enhances the phytoplankton blooming and hypoxia without any increasing of the nutrient loading in an enclosed bay, and approach this hypothesis, being based on the data obtained from the field surveys, and fundamental knowledge of sedimentology that benthic environment reflects the dynamics in the water column in the estuary or coastal seas (cf. Gray and Elliott, 2009). To test the hypothesis, the present study (1) examines the spatial relationships among the hydrographic structures, physico-chemical conditions of the sediment, and macrobenthic communities in the inner part of Ariake Bay in August 2010 just after the rainy season, when the pycnocline developed well in the water, (2) compares the spatial distribution of mud content of the sediment in 2014 with those of the previous studies reported during the past 25 years, and we discuss how the benthic ecosystem is affected by the development of the stratification of water.

2. Materials and methods

2.1. Study sites

Ariake Bay is located in the west coast of Kyusyu, western Japan (Fig. 1). It is an enclosed bay approximately 1700 km^2 in area and a mean depth of 20 m. In spring tide, the mean tidal range reaches about 6 m in the innermost part of the bay, the tidal current exceeds 1 m s^{-1} at a maximum, and large tidal flats (ca. 190 km^2) emerge on the coasts of the bay. The river mouths of five major rivers (Chikugo River, Kikushi River, Yabe River, Kase River, Rokkaku River) concentrate on the inner part of the bay. Among them, Chikugo River has the largest catchment areas of about 2860 km^2, and discharges about 4.5 × 10^9 m^3 of freshwater to the bay per year, which accounts for approximately 66.0% of the total amount of freshwater input from the five major rivers (Ministry of the Environment Government of Japan, 2006).

2.2. Sampling methods

The monitoring of hydrographic conditions was conducted at the 21 sampling stations in the inner part of the bay including three stations in Isahaya Bay on August 4, 2010 (closed circle in Fig. 1). At each station, the vertical profiles of water (temperature, salinity, and dissolved oxygen (DO)) were measured with a multi-probe (YSI 6600, Yellow Springs Instruments, USA) at depth intervals of 1 m from the surface to the depth of 10 m, and at depth intervals of 2 m in the further deeper layers. At the five stations on the longitudinal line (Stn S2, A, B, C and D), water samples were collected at the five different layers (the surface, -2 m, -5 m, -10 m, and 1 m above the sea floor) with a Van Dorn water sampler. From each of the water samples, 200 ml of water was subsampled to determine the concentration of chlorophyll *a* (Chl-*a*), and a duplicate of 500 ml of water was subsampled to determine the amount of suspended solids (SS) of the water, respectively. All these water samples were kept in a cooler box, and brought back to the laboratory. These surveys were carried out with two boats, and finished within six hours.

Sampling of the sediment for assessments of physico-chemical conditions of the sediment and quantitative surveys of macrobenthic animals was conducted at the 21 stations on August 5 and August 6 in 2010 (closed circles in Fig. 1). At each station, four sediment samples were collected with an Ekman-Birge grab sampler (20 × 20 cm). One of them was used for physico-chemical analysis of the sediment, and the other three were used for the quantification of macrobenthic animals. The sediment sample for the physico-chemical analysis was subsampled once with a core sampler (5 × 5 × 5 cm) for determination of the grain size composition of the sediment, and ten times with plastic cores with a diameter of 29 mm, and their surface layers up to the depth of 1 cm were used for chemical analysis of the sediment. Each of the sediment samples for the quantification of macrobenthic animals was sieved on a 1 mm opening mesh, and the residues retained on the mesh were put in a plastic bag. On September 17 and September 18 in 2014, additional samplings of the sediment were conducted at the 23 stations (triangles in Fig. 1) for the comparison of the spatial distribution of the mud content with the previous reports, in the same manners with the samplings conducted in 2010. All these samples were kept in a cooler box, and transported to the laboratory.