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The effect of low oxygen conditions on biogeochemical cycling of nutrients in a shallow seasonally stratified bay in southeast Korea (Jinhae Bay)

Young-Sug Kim [a,*], Yong-Hwa Lee [b], Jung-No Kwon [a], Hee-Gu Choi [a]

[a] National Fisheries Research & Development Institute, Marine Environment Research Division, 216, GijangHaean-ro, Gijang-Up, Busan 619-705, Republic of Korea

[b] East Sea Fisheries Research Institute, Fisheries Resources and Environment Division, 1194, Haean-ro, yeongok-myeon, Gangneung-si, Gangwon-do 210-861, Republic of Korea

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ABSTRACT

The formation and distribution of oxygen-deficient water mass (ODW) in Jinhae Bay exhibited seasonal patterns similar to those of the summer thermocline, indicating a close mutual relationship, and the influence of ODW formation conditions appeared prominently in the bottom water. The principal factors analysis indicate that dissolved oxygen and NO_2 in the bottom water during the time of ODW formation were highly correlated with NH_3 and dissolved inorganic phosphorus. The findings clearly illustrate the effects on ODW of seasonal physical and chemical changes. ODW that formed in the bottom water of Jinhae Bay during summer produced high concentrations of nutrients in the bottom water; since the growth of phytoplankton was limited by the strong stratification and low concentrations of dissolved oxygen (<3 mg/L) in the bottom layer, these nutrients (especially NH_3 and DIP) were retained and accumulated, serving as a major source of nutrients during the dry winter.

1. Introduction

Hydrographic factors are key determinants for the occurrence of hypoxia and eutrophication. If oxygen is not supplied by advective and vertical mixing, then declining oxygen concentration leads to hypoxia or ODW, which is defined as water containing less than the normal 3 mg/L dissolved oxygen (DO) concentration (Pearson et al., 1978). The areas in which ODW occurs are frequently those with poor exchange of water. ODW occurs when algae and other organisms die, sink to the bottom, and are decomposed by bacteria, using the available dissolved oxygen (Rabalais et al., 2002; Middelburg et al., 2009). Thus again, the effects of interactions between oxygen, nutrients only occur below hypoxia, and these are released into the water (Gray et al., 2002). There, productivity arises from wind-driven upwelling of nutrient-rich water to the surface of coastal waters, and upwelling also transports oxygen-poor waters onto productive continental shelves.

Many studies have estimated the effects of hypoxia but, in the field, other environmental co-factors often make it difficult to estimate the actual impact of hypoxia. As organic enrichment leads to lowered oxygen concentration through degradation, oxygen depletion can be the result of a number of factors including natural ones, but is of most concern as a consequence of eutrophication in coastal waters, and is also likely to occur at the organically enriched bottom as a result (Diaz and Rosenberg, 1995; Chan et al., 2008). If oxygen concentration in the bottom layer becomes sufficiently low for hypoxia to occur, areas particularly prone to this include shallow waters of semi-enclosed water bodies such as the Gulf of Mexico (Scavia et al., 2003). Compared with DO, no other variable is of such ecological importance for marine environments or displays such magnitude of change over short time scales. What might/might not return to normal levels, before eutrophication began to spread dead zones (Diaz and Rosenberg, 2008).

The duration of seasonal hypoxia then becomes the primary influence on environmental parameters that display strong seasonal cycles. Generally, a spring or autumn algal blooms; populations normally decline from a combination of resource depletion and predation (Graf and Rosenberg, 1997). During persistent hypoxia, there is a drastic reduction in secondary production, and microbes remineralize virtually all organic matter. The inflow of organic matter undergoes slow precipitation in waters that marine active circulation, causing contamination in the sediment layer. When the water temperature rises in summer, decomposition and chemical reactions by microorganisms in the contaminated sediment layer lead to increased oxygen consumption and elution of contaminants. The amount of contaminants eluted from these sediments is an important factor that affects the trophic levels of

* Corresponding author. Tel.: +82 32 560 7664; fax: +82 32 569 2053.
E-mail address: youngsugkim@korea.kr (Y.-S. Kim).

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the bottom layer water mass, based on stratification during the circulation of nutritional salts (Boström et al., 1982). Furthermore, the elution flow from the sediment layer to the water stratum exceeds the amount absorbed into the sediment or moved by precipitation at the water stratum; thus, in contaminated waters, when the internal load becomes excessive, it can impede self-cleansing, which can then lead to eutrophication.

Jinhae Bay is representative of aquaculture regions of Korea, with active farming of oysters, mussels, etc. However, due to an extensive and protracted period of oxygen-deficient water mass (ODW) or hypoxia that began in 1989, the biological habitat of farmed aquatic organisms in the bay has been heavily degraded (Hong, 1987; Lim et al., 2006). Additionally, because the flow of seawater does not smoothly in Jinhae Bay, there is the possibility of mortality in cage-type fish farms.

This study examines the behavior of environmental variables for physicochemical aspects of eutrophication, based on the seasonal formation of ODW in Jinhae Bay. Furthermore, the study analyzes seasonal nutrient concentrations resulting from changes in environmental states caused by the formation, dispersion, and dissipation of ODW in Jinhae Bay, in order to clearly identify their impact on environmental conditions in the bay.

2. Material and methods

2.1. Study region

Jinhae Bay is a semi-enclosed coastal bay located on the southeast coast of Korea. It has winding coastlines and undulating coastal waters with an average depth of 20 m (NFRDI, 2009a). The amount of seawater exchange through Gaduk waterway during spring tide is (471–507) × 10^6 tons, which accounts for 86–90% of the total seawater exchange in Jinhae Bay (Kim and Kim, 2009). Among local tides, the semidiurnal tide is preeminent; the current speed during spring tide is known to be as high as 90 cm/s, and as much as 30 cm/s during neap tide, with an oscillatory current and a clockwise reflux current occurring in the center of Jinhae Bay (Kang et al., 1991). In inner bays that have low current speed, such as Jinhae Bay (<10 cm/s), salinity stratification is often observed with water temperature stratification, due to increased water temperature during summer and an inflow of freshwater from the basin (Cho et al., 2002).

In this study, a total of 31 stations from the southwestern (I), northern (II), and eastern and central (III) waters of Jinhae Bay were surveyed once a month from June to October 2010 (Fig. 1), which is when ODW usually forms in the bottom water layer; and in December, when dissipation occurs.

2.2. Analytical methods

Survey items included physicochemical factors, such as temperature (T), salinity (S), pH, dissolved oxygen (DO), dissolved inorganic nutrients, chemical oxygen demand (COD), total nitrogen (TN), and total phosphate (TP); as well as a biological factor, chlorophyll-*a* (Chl-*a*). The measurement methods are as follows.

T and S were observed onsite using a conductivity–temperature–depth sensor (CTD) (SBE 19 plus, USA) at differing water depths; pH and DO concentration were observed onsite using a multi-parameter monitoring system (YSI 6600-V2, USA) at differing water depths; and DO was evaluated via the Winkler titration analysis value. Seawater samples were collected from the surface and bottom layers of water using a Niskin water sampler, and sediment samples were collected from the surface layer of the bottom sediment using a grab type bottom sampler at the total of 13 stations (stations 1, 3, 8, 11, 13, 14, 16, 17, 19, 21, 23, 25, and 31). They were completely processed onsite before being transported to the laboratory, after which analysis of dissolved inorganic nutrients and others was performed according to the Marine Environmental Process Exam Standards (MOMAF, 2002).

Dissolved inorganic nutrient analysis was performed by filtering the sample through 0.45 μm membrane filter paper (nitrate cellulose), then measuring ammonia nitrogen (NH_3), nitrate nitrogen (NO_3), nitrite nitrogen (NO_2), and dissolved inorganic phosphate (DIP) with a nutrient auto-analyzer (QUATTRO four-channel, USA). Dissolved inorganic nitrogen (DIN) was expressed as the sum of NH_3, NO_3, and NO_2. TN and TP were measured from a non-filtered sample using the QUATTRO four-channel auto-analyzer. Chl-*a* was measured by filtering 500 ml of the sample through a 0.45 μm membrane filter paper (nitrate cellulose), then extracting the color dye with 90% acetone in a cold, dark room, and measuring with a fluorescence spectrometer (Tuner Design 10-AU, USA). COD of sea water was analyzed using the alkaline permanganate method on non-filtered samples that were transported to the laboratory while frozen COD is indicative of

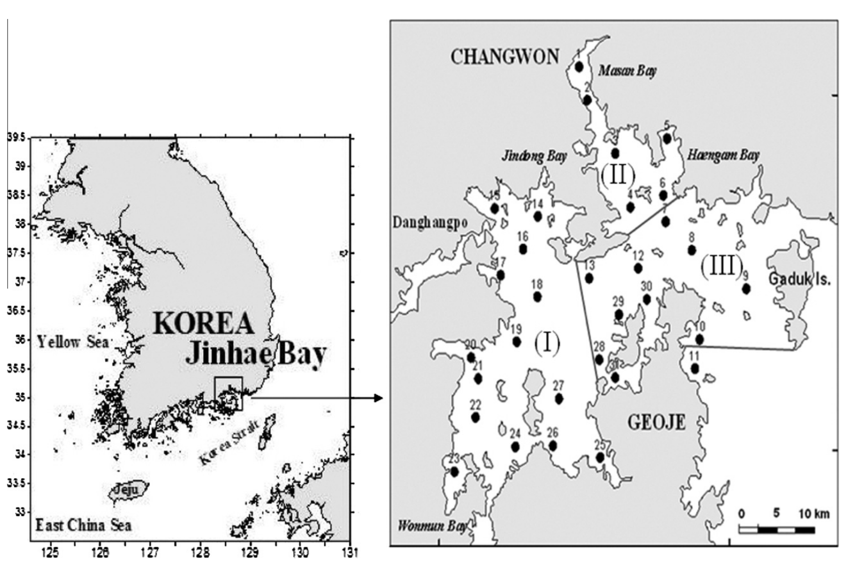

Fig. 1. Map showing the study sites (filled circles) in the inner area of Jinhae Bay.