Bull. Plankton Eco-Eng. Res. 3: 47-50, 2023

Note

Surface nutrient regime and bottom hypoxia in Manila Bay during the southwest monsoon

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Received April 25 2023, Accepted April 30 2023

Abstract We examined the surface nutrient regime and hypoxia in Manila Bay, Philippines, during the southwest monsoon along a transect from off Limay, Bataan Peninsula, to Metro Manila. The water column showed stratification, with warm, less saline water in the top 10 meters overlying cold, saline bottom water. Hypoxia was present in the bottom waters along the entire transect, and anoxic conditions were observed off Manila. Ammonium concentrations ranged from 6.7 to 40.2 μM, exceeding those of nitrate and nitrite, both of which were nearly depleted at almost all stations except off-Manila, with levels below 0.1 μM. Phosphate varied from 0.1 to 1.9 μM, resulting in a stoichiometrically nitrogen-rich condition at the surface, with N:P ratios ranging from 17.1 to 149.7 and an average of 37.4. This is in contrast to the phosphate-rich conditions reported during the northeast monsoon period. A plume with high nutrient concentrations and high chlorophyll *a* was observed off Manila, indicating freshwater inflow from sewage and the Pasig River. Diatoms, including the *Skeletonema costatum* complex and *Chaetoceros* spp., were abundant, and these eutrophic conditions likely favored the occurrence of green *Noctiluca,* while it was not observed during our study.

Keywords: Manila Bay, nutrient, chlorophyll *a*, hypoxia, southwest monsoon

The discharge of sewage from land areas around the world has increased due to human activities and population growth. This has caused eutrophication in coastal areas and various environmental issues, as noted by Glibert et al. (2005). In the South China Sea, the situation is particularly serious, as anthropogenic activities have resulted in the inflow of large amounts of nutrients via river water, leading to the formation of eutrophic waters (Huang et al. 2003, Wang et al. 2008, Qiu et al. 2010). This cultural eutrophication in coastal areas is responsible for the proliferation of harmful algal blooms (HABs) and the formation of a hypoxic or anoxic layer in the bottom layer during the stratification period in enclosed waters. In this study, we investigate the characteristics of the surface nutrient regime and hypoxia in Manila Bay, one of the most important semi-enclosed waters in the South China Sea during the southwest monsoon.

Manila Bay is a semi-enclosed water body that spans an area of 1,700 square kilometers and has an average depth of 17 meters. The climate of Manila Bay can be divided into two distinct seasons: a dry season from November to April and a rainy season from June to September. Additionally, three prevailing wind periods exist: the northeast monsoon from October to January, the southwest trade winds from March to May, and the southeast monsoon from June to September (Jacinto et al. 2006).

Observations were conducted on September 3 and 4, 2019 (Fig. 1). A CTD (Sea-Bird 19 Plus) was used to obtain profiles of water temperature, salinity, dissolved oxygen (DO), and in vivo fluorescence of chlorophyll from the surface to the near-bottom. Water samples were collected from the surface using a bucket to measure chlorophyll *a* (Chl *a*) and nutrient concentrations. The samples were filtered through GF/F filters (Whatman) on board a ship and then measured for Chl *a* using a fluorometer (Aquafluor, Turner Designs) after extraction with acetone in the dark at ice temperature for 24 h, and sonication. Nutrient concentrations were measured using an autoanalyzer (TRAACS, BL-TEC) after being frozen for transportation back to a land laboratory. Phytoplankton was observed by fixing seawater with neutral formalin (final concentration 2.0%).

The bay was stratified with less saline water in the top 10 meters overlaying cold, saline bottom water (Fig. 2). At Stn. 15, a significant decrease in salinity relative to the neighboring stations was observed at the surface, indicating an inflow of river water. DO concentrations were relatively high near the surface and diminished with depth (Fig. 2). DO concentrations fell below the standard value of 2.8 mg L^{-1} for hypoxia at depths of approximately 10-18 meters, confirming the formation of hypoxic conditions (Jacinto et al. 2011). Moreover, the bottom water at Stn. 16 displayed an extremely low DO concentration of less than 0.01 mg L^{-1}, signifying the development of anoxic conditions. This was in contrast to the supersaturation of DO observed at a depth of 3 meters above the anoxic zone.

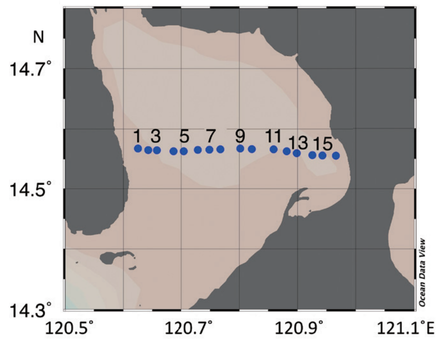

Fig. 1. Station locations. For simplicity, even-numbered stations are not labeled on the map.

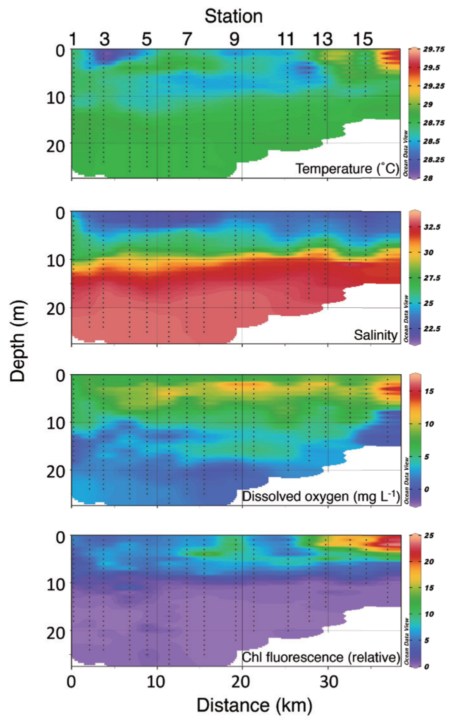

Fig. 2. Vertical profiles of temperature (upper), salinity (middle), dissolved oxygen (middle), and in vivo chlorophyll fluorescence (lower).

Ammonium exceeded nitrate and nitrite varying from 6.7 to 40.2 μM. In contrast, nitrate and nitrite were almost exhausted at Stns. 1 to 14 ranging below 0.1 μM (Fig. 3). Thus, the high ammonium concentrations produced an overall nitrogen-rich condition at the bay's surface despite the low concentrations of both nitrate and nitrite. Phosphate varied from 0.1 to 1.9 μM, making a stoichiometrically nitrogen-rich condition at the surface with the N:P ratio ranging from 17.1 to 149.7 with an average of 37.4. This was in contrast to the phosphate-rich condition observed during the northeast monsoon period (Furuya et al. 2006, Jacinto et al. 2011). The observed concentrations of nutrients were within the reported range for the southwest monsoon period (Chang et al. 2009), and the high ammonium concentrations are ascribable to loading from land. The maximum concentrations of ammonium, nitrate, and phosphate of 40.2, 4.0, and 1.9 μM, respectively, were observed at Stn. 15, which coincided with low salinity, indicating freshwater inflow presumably from Pasig River. This inference is compatible with the high fecal coliform counts in Pasig River estuary which indicate the discharge of untreated sewage from sewage pipes and direct sewage discharge from sheds along the coast (Jacinto et al. 2006). In the city of Manila, the sewerage system is not well developed and still has low coverage (Jacinto et al. 2006). In addition, a study on the origin of particulate organic matter in Manila Bay using stable isotopes showed that most of the nitrogen in Manila Bay comes from the Pasig River and is derived from urban sewage and industrial effluents (Miller et al. 2011). Thus, the southwest monsoon with high precipitation brings the nitrogen-rich conditions, particularly with high ammonium concentrations in Manila Bay.

Chlorophyll *a* was in the range between 6.9 and 111.3 μg L^{-1} (Fig. 3). The higher concentration was observed toward the urban district of Manila (Figs. 2 and 3). There was a drop of Chl *a* at Stn. 15 accompanied by a sharp increase in nutrients and the drop of salinity, indicating the inflow of freshwater (Figs. 2 and 3). The nutrient influx from rivers likely resulted in the blooming of phytoplankton. Diatoms including *Skeletonema costatum* complex and *Chaetoceros* spp. were most abundant. These species have been reported as the dominant diatom species in Manila Bay (Borja et al. 2019).

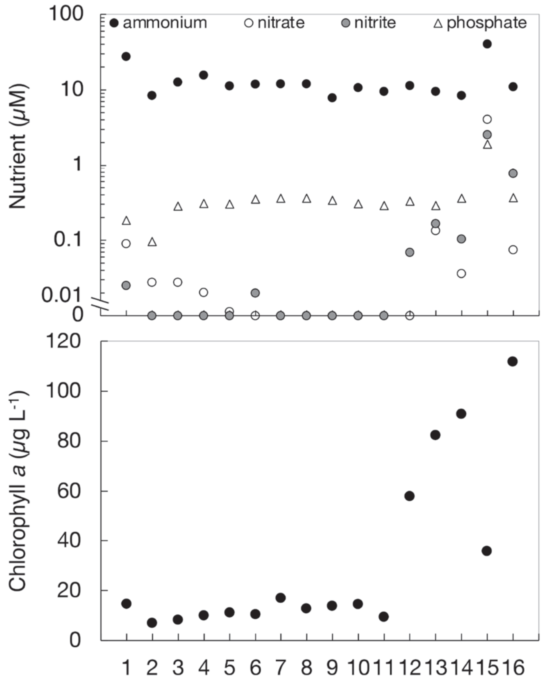

Fig. 3. Distribution of nutrients (upper) and chlorophyll *a* (lower) at the surface.

In Manila Bay, *Pyrodinium bahamense* var. *compressum* was the dominant bloom-forming species until the 1990s, but since 2001, green *Noctiluca* has emerged and become the dominant species (Hansen et al. 2004, Furuya et al. 2006, Harrison et al. 2011, Borja et al. 2019). Green *Noctiluca* grows by feeding on increased prey due to eutrophication (Sriwoon et al. 2008). Therefore, Manila Bay in the southwest monsoon period is considered to be suitable for the proliferation of green *Noctiluca* with an abundance of diatoms. While green *Noctiluca* did not occur during our observation, its recurrent bloom can be expected in the bay.

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