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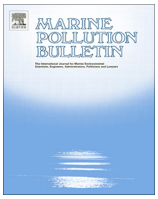

Spatiotemporal variability of hypoxia and eutrophication in Manila Bay, Philippines during the northeast and southwest monsoons

Lara Patricia A. Sotto *, Gil S. Jacinto, Cesar L. Villanoy

The Marine Science Institute, University of the Philippines, Diliman, Quezon City, Philippines

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ABSTRACT

Hypoxia in Manila Bay, Philippines was previously reported during the northeast monsoon (dry season) in February 2010. In this study, four more field surveys of the same 31 stations were conducted in July 2010, August 2011 and 2012 (wet season, southwest monsoon), and February 2011 (dry season, northeast monsoon). During the wet season, bottom hypoxia spread northward towards the coast with dissolved oxygen (DO) ranging from 0.12 to 9.22 mg/L and the bay-wide average reaching 2.10 mg/L. Nutrient levels were elevated, especially near the bottom where dissolved inorganic nitrogen reached 22.3 μM (July 2010) and phosphorus reached 5.61 μM (August 2011). High nutrient concentrations often coincided with low near-bottom DO content. Our work builds on the preliminary assessment of hypoxia in Manila Bay, the importance of repeated temporal studies, and shows hypoxia to prevail significantly during the southwest monsoon (wet season) when increased freshwater discharge caused strong water column stratification.

1. Introduction

Dissolved oxygen (DO) is an important aspect of the marine ecosystem that is essential for sustaining the majority of marine life. Hypoxia occurs when DO levels fall below 2 mg/L (or ∼30% saturation). At these oxygen levels, animals generally begin to feel the effects of suffocation (Diaz and Rosenberg, 2008). Eutrophication of coastal ecosystems, brought on by nutrient enrichment that causes increased primary production and hence accumulation of organic matter, contributes to the formation of hypoxia (Diaz and Rosenberg, 2008; Nixon, 1995; Rabalais et al., 2009). Water column stratification also contributes to the formation of hypoxia and anoxia by preventing the vertical diffusion of oxygen from the upper to the lower layers (Rabalais et al., 2001).

In Manila Bay, Philippines, fisheries and aquaculture are major sources of livelihood (PEMSEA and MBEMP-MBIN, 2007), and they can be adversely affected by the occurrence of hypoxia. At its worst, hypoxia can cause mass mortality of fish and lead to the formation of dead zones where very little marine life can survive (Diaz and Rosenberg, 2008). Hypoxia and eutrophication have been previously observed in Manila Bay, with near-bottom DO levels in the bay falling to 1 mg/L (June 2008) and nutrient levels exceeding the ASEAN water quality criteria (Chang et al., 2009; Jacinto et al., 2006). The bay is also affected by harmful algal blooms, persistent red tides, heavy metal pollution, and excess organic loads (Azanza et al., 2004; Chang et al., 2009; Jacinto et al., 2006; Prudente et al., 1994; Reichardt et al., 2006).

The occurrence of hypoxia in Manila Bay was previously observed during the cold and dry northeast monsoon (dry season) in February 2010 (Jacinto et al., 2011). In the current study, four more surveys were conducted, one during the dry season in February 2011 and three during the wet season in July 2010, August 2011, and August 2012. The goals of this study were to document the variation of near-bottom hypoxia across space and time, identify seasonal differences in the occurrence of hypoxia as influenced by salinity and freshwater discharge, and evaluate the role of eutrophication in promoting hypoxia in the bay.

2. Materials and methods

The watershed of Manila Bay has an estimated area of 19,268 km^2 and is home to 26 million people, or 30% of the total population (BSWM, 2012; EMB, 1992; NSO, 2007). Agricultural areas constitute 42%, miscellaneous land use areas (including built up or urban areas) make up 22%, grass/shrubland areas comprise 21%, forest and woodland areas constitute 11%, and wetland areas make up 4% (BSWM, 2012). Only about 16% of the households in the major cities around the bay have sewer coverage, making poor

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* Corresponding author. Address: The Marine Science Institute, University of the Philippines, Diliman, Quezon City, 1100 Philippines. Tel.: +63 2 393 9924.
E-mail address: lpasotto@msi.upd.edu.ph (L.P.A. Sotto).

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waste management a big part of the bay's environmental problems (Olchondra, 2011). The bay receives freshwater input from numerous rivers, including the Pasig and Pampanga Rivers, which contribute 70% of the freshwater influx (25 km^3/year) (PRRP, 1999). The organic matter load into the bay is estimated to be 250,000 t Biochemical Oxygen Demand (BOD)/year (PEMSEA and MBEMP-MBIN, 2007). The area is dry from November to April and wet during the rest of the year.

A total of 31 stations were sampled in Manila Bay during the four field surveys conducted during the dry season (northeast monsoon) in February 2011 and during the wet season (southwest monsoon) in July 2010, August 2011, and August 2012 (Fig. 1). These stations were the same stations sampled in February 2010 by Jacinto et al. (2011). Two replicate water samples from at least three depths (surface, mid depth, and near bottom) were collected using a 5 L Niskin sampler. Near bottom water samples were collected at 1 m above the recorded bottom depth from the echo sounder. Samples for analysis of inorganic nutrients were filtered through a 0.45 μM Sartorius CA membrane filter and kept frozen until analysis. In August 2011 and 2012, additional water samples for dissolved organic carbon (DOC) analysis were also collected, filtered through a pre-combusted 0.7 μM Whatman GF/F filter, preserved with concentrated phosphoric acid, and kept frozen until analysis. Depth, salinity, temperature, fluorescence, and DO profiles were obtained at each site using a SEABIRD SBE-25 CTD (February 2011, July 2010, and August 2011) and a SEABIRD SBE-19 CTD (August 2012).

Ammonium, nitrate, nitrite, phosphate, and silicate concentrations of the seawater samples were measured using methods modified from Strickland and Parsons (1972) for use with a SKALAR SANS ++ segmented flow analyzer D5000. Total organic carbon content was determined as the non-purgeable organic carbon using a Shimadzu TOCV-5000 analyzer. The isosurface plots were generated using Golden Software Surfer 10 (Golden Software, Inc., 2012) while the scatter plot was generated using Ocean Data Viewer (Schlitzer, 2013). A principal component analysis (PCA) was also performed on the water quality data.

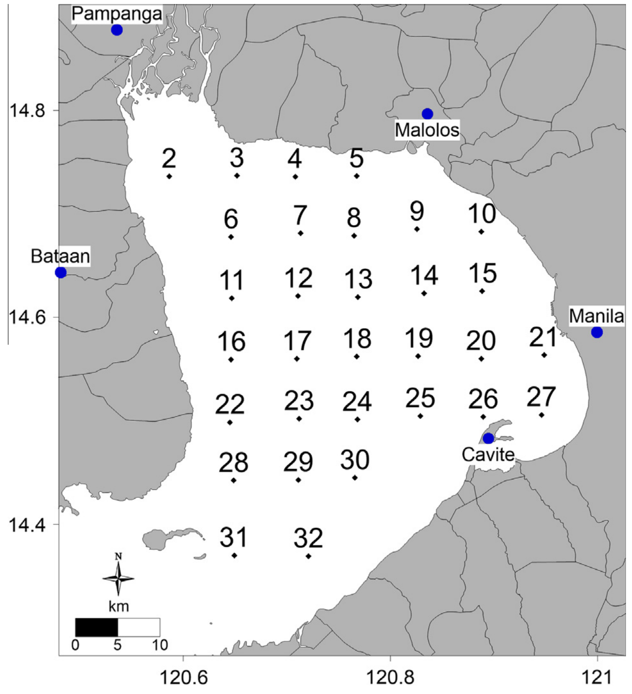

Fig. 1. Sampling stations in Manila Bay.

3. Results

3.1. Hypoxia

Near-bottom DO levels for Manila Bay were as low as 0.12 mg/L in August 2012 during the wet season (Fig. 2, Table 1). Waters near the coast and up to the middle of the bay during the wet season surveys were hypoxic, with-bay wide averages falling to as low as 2.10 mg/L (August 2011). In August 2012, DO concentrations improved along the coast, but the midsection of the bay remained hypoxic. No hypoxia was observed during the dry season in February 2011.

In the water column, the water depths at which hypoxia occurred ranged from 5 (wet season) to 36 m during the four surveys when hypoxia was observed. The DO minimum reached less than 1 mg/L, with the lowest value occurring during August 2012 (0.028 mg/L) at Station 11 offshore Bataan in the western part of the Bay.

In February 2010 during the dry season, the oxycline (the depth as which DO declines rapidly) started at around 10 m. In the succeeding wet season surveys, the oxyclines began as shallow as 5 m and more stations exhibited rapidly declining DO above 10 m; these results are indicative of worsening conditions for the bay. For example, the DO profiles for Station 19 show that the oxycline became shallower from February 2010 to July 2010 (Fig. 3). In February 2011, no hypoxia was observed, but in August 2011 the oxycline was again shallower (<10 m) and bottom hypoxia occurred. In August 2012, the oxycline was deeper but more of the water column near the bottom was hypoxic.

The thickness of the hypoxic layer (maximum depth minus the minimum depth at which DO <2 mg/L and remains hypoxic) averaged 3.5 m for the four surveys where hypoxia was observed (February 2010, July 2010, August 2011, and August 2012). The maximum thickness increased with time, reaching 15–18 m during the August 2011 and 2012 wet season surveys.

3.2. Eutrophication

Surface inorganic nutrient levels in general were higher near and along the coasts, especially offshore Manila, Cavite, Bulacan, and Pampanga where chlorophyll *a* levels are often elevated (Fig. 4). During the two dry season surveys, surface total inorganic nitrogen (TIN) increased whereas surface soluble reactive phosphate (SRP) and silicate levels decreased. For the three wet season surveys, surface TIN decreased from July 2010 to August 2011 and increased in August 2012, whereas surface SRP and silicate levels increased over time (Table 2).

Surface chlorophyll *a* values were usually higher near the coastal areas of the bay, especially near Manila, Cavite, Pampanga, and Bataan (Fig. 4). In February 2011, very high values (20–41 μg/L) were observed throughout the water column at Station 29, which lies at the southern area of the bay near Bataan. Over time, average surface chlorophyll *a* levels were relatively unchanged, although they were higher in August 2012 than during the other surveys (Table 2).

Near the bottom, nutrient levels were often higher at the midsection of the bay and near the coast, especially along the eastern side near Manila and Cavite (Fig. 5). These areas of high nutrient levels usually coincided with low near-bottom DO levels. TIN and SRP levels decreased from the first dry season survey to the second. No trend was observed for the wet season surveys, although nutrient levels were generally higher than those measured during the dry season. Near-bottom silicate levels remained relatively constant over time (Table 2).

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