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Effects of Freshwater Stratification on Nutrients, Dissolved Oxygen, and Phytoplankton in the Bay of Bengal

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ABSTRACT. The Bay of Bengal (BoB) is strongly density stratified due to large freshwater input from various rivers and heavy precipitation. This strong vertical stratification, along with physical processes, regulates the transport and vertical exchange of surface and subsurface water, concentrating nutrients and intensifying the oxygen minimum zone (OMZ). Here, we use basinwide measurements to describe the spatial distributions of nutrients, oxygen, and phytoplankton within the BoB during the 2013 northeast monsoon (November–December). By the time riverine water reaches the interior bay, it is depleted in the nutrients nitrate and phosphate, but not silicate. Layering of freshwater in the northern BoB depresses isopycnals, leading to a deepening of the nutricline and oxycline. Oxygen concentrations in the OMZ are lowest in the north (<5 μM). Weak along-isopycnal nutrient gradients reflect along-isopycnal stirring between ventilated surface water and deep nutrient-replenished water. Picoplankton dominate the phytoplankton population in the north, presumably outcompeting larger phytoplankton species due to their low nutrient requirements. Micro- and nanoplankton numbers are enhanced in regions with deeper mixed layers and weaker stratification, where nutrient replenishment from subsurface waters is more feasible. These are also the regions where marine mammals were sighted. Physical processes and the temperature-salinity structure in the BoB directly influence the OMZ and the depth of the oxycline and nutricline, thereby affecting the phytoplankton and marine mammal communities.

INTRODUCTION

The Bay of Bengal (BoB) receives immense freshwater runoff from major rivers such as the Ganges, Brahmaputra, Godavari, Mahanadi, Cauvery, Irrawaddy, and Krishna (1.6×10^{12} m^3 yr^{-1}; UNESCO, 1979). Surface water salinity in the BoB is on average 3–7 psu lower than the neighboring Arabian Sea (La Violette, 1967; Varkey et al., 1996). Although precipitation and runoff are most intense during the southwest monsoon (June–September; Unger et al., 2003), the transit time for riverine water to reach the interior of the Bay is several months, and freshwater content in the interior BoB peaks during the northeast monsoon (October–December). This freshwater leads to strong, salinity-controlled stratification in the near-surface layer that inhibits vertical mixing and results in the prevalence of oligotrophic conditions (Shetye et al., 1991; Shetye, 1993; Rao et al., 1994).

Rivers are major sources of nutrients to the BoB. Annually, the Ganges and Brahmaputra Rivers supply 133×10^9 mol yr^{-1} of dissolved silicate, which is ~2% of the riverine input to the world ocean (Sarin et al., 1989). Recently, Krishna et al. (2015) estimated the nutrient flux from rivers to the northern Indian Ocean to be 1.84, 0.28, and 3.58 Tg yr^{-1} (1 Tg = 10^{12} g) of dissolved inorganic nitrogen, phosphate, and silicate, respectively. However, roughly 91% of the dissolved inorganic nitrogen is retained within the estuaries before reaching the coastal ocean, and riverine water is nutrient poor by the time it reaches the interior of the BoB.

Although primary production in the BoB is comparable to the Arabian Sea during northeast and post-monsoon seasons, it is significantly lower in the BoB during the southwest monsoon (Gauns et al., 2005). Throughout the year, the BoB is characterized by oligotrophic conditions, which have been attributed to weak vertical mixing (Ramaiah et al., 2010). Strong stratification within the BoB contributes to a quiescent environment, which may limit the overall nutrient supply to the system, resulting in lower productivity (Prasanna Kumar et al., 2002). Because strong stratification inhibits exchange between surface waters and those at depth, intense forcing, such as that during cyclones, may be required to erode the stratification and inject nutrients into the euphotic zone to enhance primary production (Madhu et al., 2002; Maneesha et al., 2011; Latha et al., 2015). Studies indicate that cold-core eddies play an important role in uplifting nutrients to enhance primary production (Prasanna Kumar et al., 2004; Vidya and Prasanna Kumar, 2013). Recent work suggests that frontal zones in the Arabian Sea harbor high phytoplankton biomass due to increased nutrient input through vertical mixing and advection (Roy et al., 2015; Vipin et al., 2015). Fronts are commonly observed in the BoB as well, but they are largely due to lateral variations in salinity. Their importance for primary production is yet to be explored.

Here, we present data from a basin-wide cruise conducted in November–December 2013 that demonstrates how water column stratification influences the nutrient and phytoplankton size distributions in the Bay of Bengal. Strong near-surface stratification inhibits vertical exchange of oxygen, creating a sharp and more intense OMZ in the northern bay. An opportunistic marine mammal survey was also conducted during the approximately two-week-long cruise. This study was supported through India's National Monsoon Mission (NMM).

MATERIALS AND METHODS

The research cruise, sponsored by the US Office of Naval Research-funded Air-Sea Interactions Regional Initiative (ASIRI), took place on R/V *Roger Revelle* from November 29 to December 12, 2013 (Figure 1). Atmospheric forcing during the cruise was influenced by the passage of Cyclone Madi, which developed in the western BoB in early December. Peak cyclone wind speeds were reached on December 10, 2013. The local wind stress at the ship exceeded 0.4 N m^{-2} on December 7, 2013.

Sampling and Measurements

Repeat conductivity-temperature-depth (CTD) profiles were obtained from the surface to 220 m depth at 86 stations spaced approximately 20 nm (~37 km) apart along the ship's track in international waters (Figure 1). Fluorescence (WET Labs, USA) and dissolved oxygen were measured using sensors attached to the CTD. Water samples for dissolved oxygen and chlorophyll-*a* (Chl-*a*) were acquired at 44 stations, and samples from 29 stations were analyzed for nutrients and pigment levels.

Chl-*a* was sampled by passing 5–10 L of seawater through 0.7 µm glass fiber filters and extracting the chlorophyll with 90% acetone. Concentrations were measured using high pressure liquid chromatography. Nutrient concentrations were measured by the colorimetric technique following Grasshoff et al. (1992). Following the pigment biomarker grouping method of Uitz et al. (2006), we assessed the contributions of different size classes to total phytoplankton abundance.

Satellite Data

Surface features of the study region were mapped from satellite observations, including sea surface temperature (SST), sea surface salinity (SSS), sea surface height (SSH), and surface Chl-*a* (Figure 1). Surface temperature data (10 km^2, 15-day mean) were obtained from the US National Oceanographic Data Center and Group for High Resolution Sea Surface Temperature (GHRSST; http://pathfinder.nodc.noaa.gov) using Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Version 5.2 (PFV5.2) data (Casey et al., 2010). Surface salinity (110 km^2, 21-day mean) was from the NASA Aquarius Project (2015). Sea surface height data (25 km^2, 15-day mean) were produced and distributed by Aviso (http://www.aviso.altimetry.fr), as part of the Ssalto ground processing segment. Finally, surface Chl-*a* data (5 km^2, 15-day mean) were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS; Ocean Biology Processing Group, 2003). Additionally, merged SSH and derived geostrophic currents were obtained from US National Oceanic and Atmospheric Administration (NOAA) websites (http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset; http://pathfinder.nodc.noaa.gov) using AVHRR PFV5.2 data (Casey et al., 2010).

Marine Mammal Observations

A team of eight observers collected marine mammal observations from the 03 deck of R/V *Roger Revelle* by rotating through four positions every half hour during daylight hours: port and starboard observers used 25 × 150 deck-mounted "big-eye" binoculars to scan from their respective beams to 10° past the bow

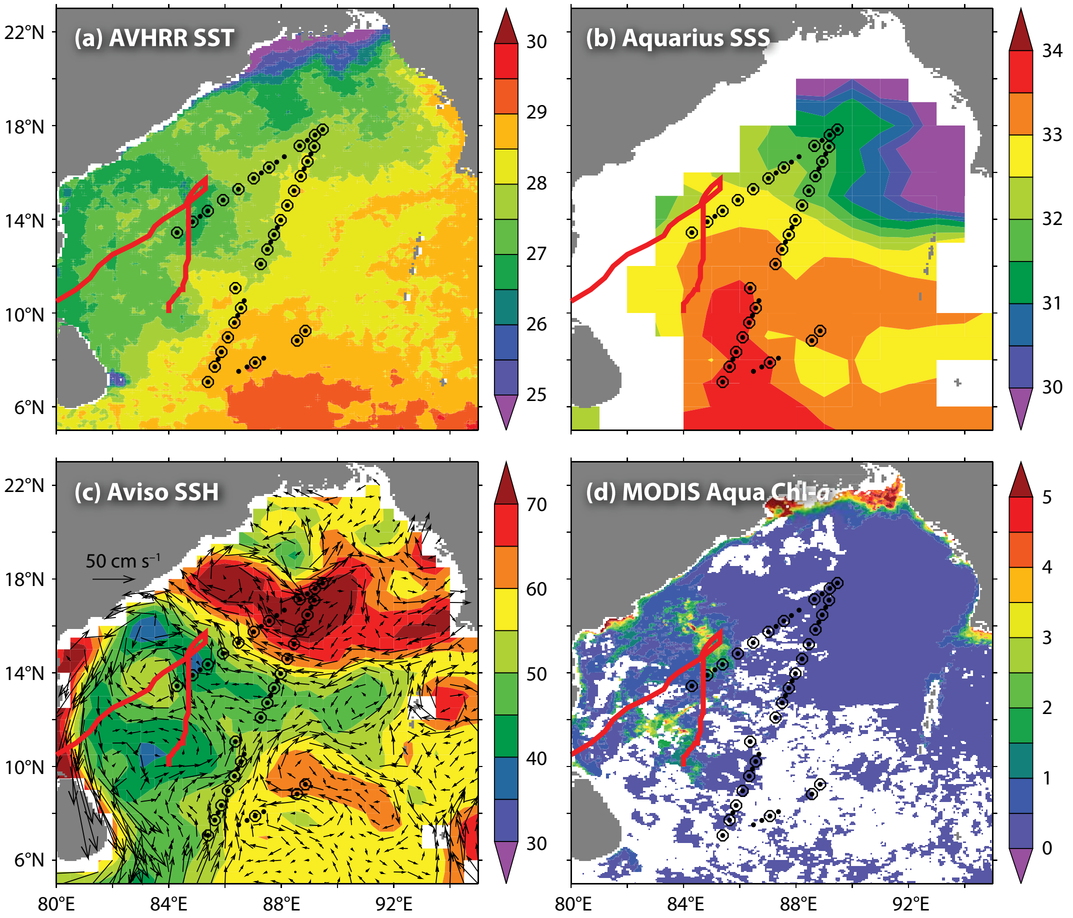

FIGURE 1. Maps of (a) AVHRR sea surface temperature (0.1° × 0.1° resolution; Nov 28–Dec 12, 2013) with cruise track and station numbers, (b) Aquarius sea surface salinity (1° × 1°; Nov 26–Dec 17, 2013), (c) Aviso sea surface height (0.25° × 0.25°; Nov 28–Dec 12, 2013), and (d) MODIS chlorophyll-*a* (0.05° × 0.05°; Nov 25–Dec 11, 2013) in the study region. The red line indicates the track of Cyclone Madi.

(average observer eye height was 12.8 m above the water), a center observer viewed the area near the ship with naked eyes and 7 × 50 handheld binoculars, and an independent observer viewed the area near the ship with naked eyes and 7 × 50 handheld binoculars to verify all species identifications and to report any sightings missed by the three primary observers. The center observer also logged weather conditions, visibility, and sighting data into a computer. The survey effort consisted of active searching in Beaufort 5 or less sea conditions while the ship was steaming at speeds of 8 knots or greater. All survey effort was conducted in passing mode; the ship was never diverted to identify species or estimate group sizes.

OBSERVED PHYSICAL AND BIOGEOCHEMICAL STRUCTURE

Physical Setting: Lateral Variability and Vertical Structure

Figure 1 shows that surface salinity in the northern BoB (north of 15°N) is lower than that in the southern part of the bay. The low-salinity water to the north is also relatively cool compared to the south and east. Satellite SSH variations and the computed geostrophic surface circulation show higher SSH by 20 cm and an associated east-west elongated anticyclonic eddy located north of 14°N (Figure 1). Two cyclonic features were located further south, offshore of the equatorward East India Coastal Current. The satellite SST showed a patch of cooler water (by 1°C) compared to surrounding regions around 15.5°N on the northwestern part of the transect (Figure 1). This region is also marked by a patch of elevated Chl-*a* at the surface, one of the few locations with a significant signal in remotely sensed Chl-*a* (Figure 1). This region was influenced by the passage of Cyclone Madi from December 6 to 13, 2013; however, at this time the ship was on the eastern side of the BoB, outside the region of strong forcing.

The satellite-derived salinity (Figure 2) is consistent with the vertical salinity structure (Figure 3), which shows low-salinity waters in the upper 50 m in the northern bay. Salinity variations govern the lateral and vertical density gradients

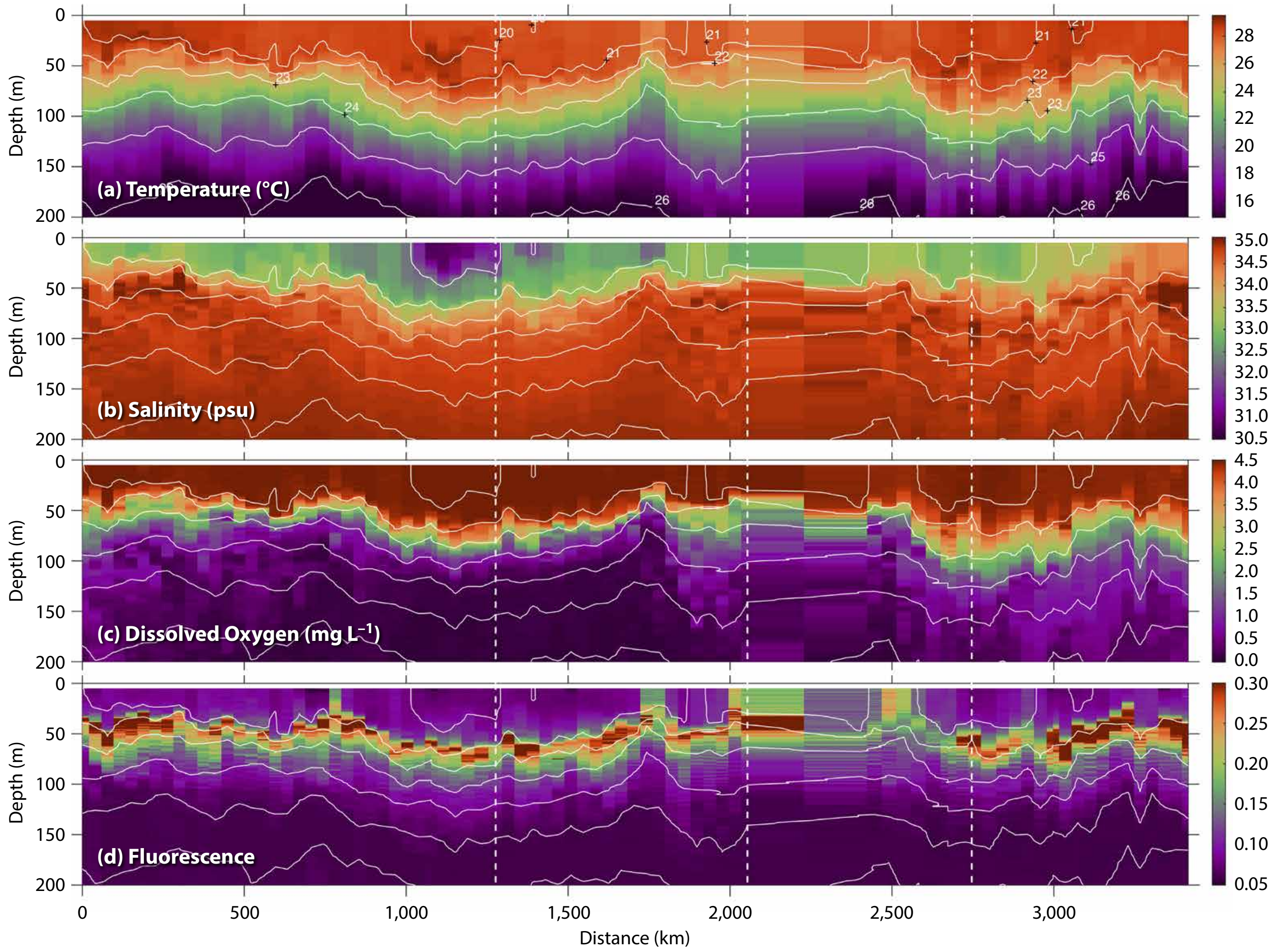

FIGURE 2. Depth-distance sections of (a) temperature (°C), (b) salinity (psu), (c) dissolved oxygen (mg L^{-1}), and (d) fluorescence in the upper 200 m layer along the cruise track. Isopycnals are plotted in each panel. Survey turns (at, from left, the northern, western, and eastern edges of the survey track) are plotted as vertical dashed lines.

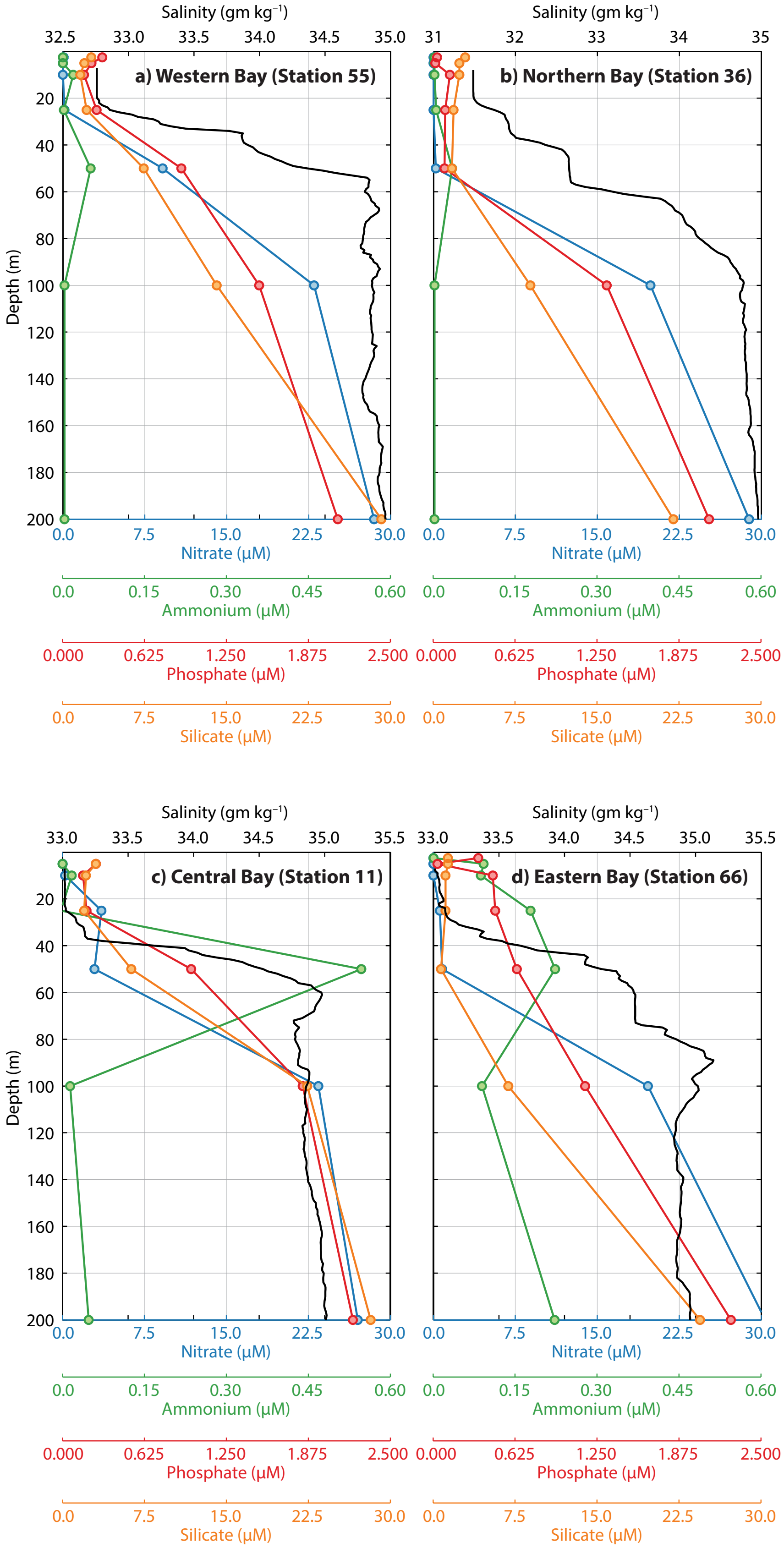

FIGURE 3. Representative profiles of nutrients—nitrate (μM, blue), ammonium (μM, green), phosphate (μM, red), and dissolved silicate (μM, orange)—and salinity (black) for geographic regions (a) western, (b) northern, (c) central, and (d) eastern Bay of Bengal.

in the upper 50–60 m of the ocean. The salinity difference between the surface and 100 m depth was ~1.5 psu in the south and 4 psu in the north along the central transect. Salinity dominates the density stratification near the surface, and the temperature often exhibits subsurface warm layers with temperatures in excess of 28°C (Figure 2).

The survey passed through two eddies in the western BoB. The first eddy occurred near 1,750 km along-track distance, and was characterized by upwelled isopycnals and elevated fluorescence within the mixed layer (Figure 2). The second eddy was an intrathermocline eddy, characterized by upwelled isopycnals near the surface and depressed isopycnals at depth (Figure 2 near 2,100 km). The intrathermocline eddy was also marked by relatively high fluorescence in the mixed layer. (Note that only the western edge of the intrathermocline eddy appears in the CTD profiles, as stations were temporarily abandoned so that the ship could transit out of the path of Cyclone Madi.)

The thermocline was deeper in the oligotrophic region along the southernmost leg of the transect and within the low-salinity zone in the northern Bay (Figure 2). The second half of the cruise (>2,500 km alongtrack distance) took place after the development of Cyclone Madi in the western BoB. Upper-ocean stratification was reduced relative to conditions prior to the onset of Madi. In general, higher values of subsurface oxygen and mixed layer fluorescence were observed after the cyclone passed, even in regions far removed from the its track. This response is consistent with elevated vertical mixing observed after the development of the cyclone (not shown here).

Nutrient Distribution

The nitrate concentration in the surface waters was <0.1 μM at the western, northern, and eastern stations (Figure 3), but an enhancement was observed in the southern to central BoB early in the cruise (e.g., Central Bay Station, Figure 3). Density influences the vertical variation in nitrate concentration. For example, compare the relatively shallow nitrate-depleted layer in the western BoB with the deep nitrate-depleted layer in the eastern BoB (Figure 3). The northern BoB is characterized by two regions of weakly stratified water separated by a strongly stratified layer. Both of these layers are depleted in nitrate. The concentrations of phosphate follow nitrate, with a mean phosphate concentration of 0.13 ± 0.1 µM in surface layers, and relatively lower values <0.1 µM in the low-salinity region. The lower phosphate concentrations observed in the northern bay suggest that riverine water is either depleted in both nitrate and phosphate, or that these nutrients are consumed nearer the coast and are not resupplied from the subsurface due to the strong stratification induced by the surface freshwater. In contrast to nitrate and phosphate, silicate concentrations were close to or above 2 µM in the surface, suggesting that it was not a limiting nutrient during the study period. However, <2 µM of silicate was observed in the cyclone-influenced regions associated with high Chl-*a*, suggesting removal through biological processes. Relatively higher concentrations of silicate were observed in the low-salinity region, suggesting that freshwater is a strong source of silicate to the BoB (Figure 3). The N:P ratios (0.41 to 9.44) were below the Redfield value of 16 in the upper water column along the cruise track, indicating that nitrogen is a limiting nutrient in the photic layer. The Si:N ratios were above 10 in the upper water column with higher values (>20) in the low-salinity region, consistent with the interpretation that silicate is not a limiting nutrient in the entire study region.

Spatial Variations in Phytoplankton Biomass and Pigment Signatures

The vertical structure of Chl-*a* along the cruise track displayed lower values in the upper 20 m, with a persistent subsurface Chl-*a* maximum (SCM) throughout the study region (Figure 2). The depth of the SCM followed the mixed layer depth, indicating that physics (vertical mixing and stratification intensity) has a significant impact on variations in SCM. Relatively higher mixed layer Chl-*a* was observed in mesoscale eddies and at salinity outcroppings in the northern BoB (~750 km in Figure 2), suggesting that nutrient renewal by mixing or upwelling in these structures may be important for phytoplankton production throughout the BoB. Other profiles displayed enhanced mixed layer fluorescence associated with strong wind forcing during the passage of Cyclone Madi. Perhaps surprisingly, this response is no more intense than that observed in mesoscale eddies and at the northern salinity front.

The differentiation into phytoplankton size classes within the mixed layer showed that microplankton communities were low, between 10% and 15% of total phytoplankton, whereas nano- and picoplankton contributed 20%–40% and 50%–75%, respectively (Figure 4). The dominance of smaller size classes is particularly pronounced in low-salinity regions of the northern BoB, where picoplankton account for >50% of the phytoplankton biomass at all sampled depths. The enhanced contribution of picoplankton presumably resulted from low nutrient levels and a deeper nitracline in the north, while the relative increased contribution from nano- and microplankton was observed in the southeast associated with a shallower nitracline. This suggests

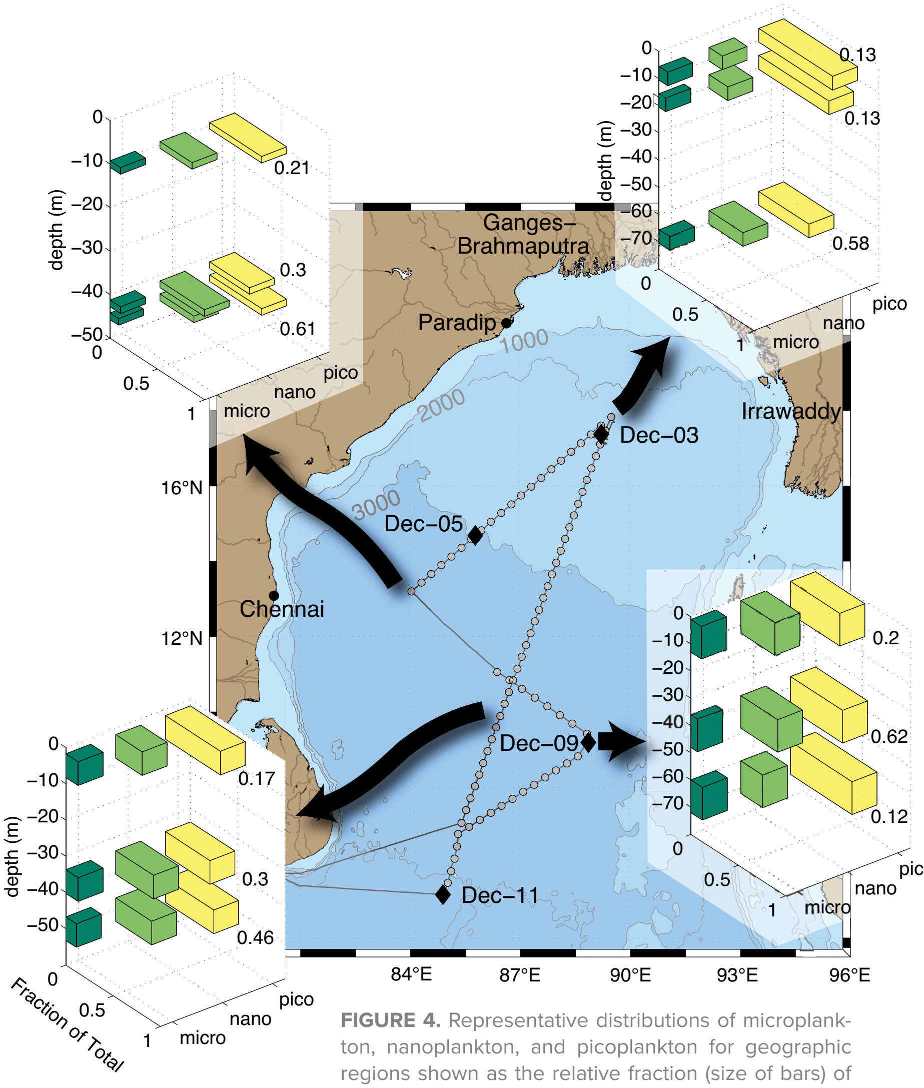

FIGURE 4. Representative distributions of microplankton, nanoplankton, and picoplankton for geographic regions shown as the relative fraction (size of bars) of the total phytoplankton concentration (as a fraction to total biomass). Black arrows indicate station locations.

a diversity of phytoplankton composition driven by stratification associated with the availability of nutrients in the Bay of Bengal.

Spatial Variations in Intensity of the OMZ in the Bay of Bengal

The upper boundary of the OMZ follows the thermocline, with a shallower oxycline in regions with a shallow thermocline and deeper oxycline in regions of depressed thermocline (Figure 2). The depth of the 20°C isotherm (D_{20}) shows a correlation with the depth of the 20 μM isoline of oxygen (DO_{20}) ($r^2 = 0.46$; $p < 0.001$) (Figure 5) and 26.3 isopycnal ($r^2 = 0.54$; $p < 0.001$). The intensity of the OMZ is the strongest to the north beneath fresh riverine water. The dissolved oxygen concentrations in the OMZ (between 100 m and 200 m depth) were significantly lower in the northern and southern regions of the bay (8.7 ± 6 μM). Dissolved oxygen concentrations in the OMZ (between 100 m and 200 m depth) were very low, due to poor ventilation.

Spatial Variations in Marine Mammal Distribution

A total of 1,669 km of trackline were surveyed in Beaufort 5 or less sea conditions, and 52 sightings of 12 different species were recorded (Table 1, Figure 6). The diversity of encountered species was quite high, but there were also numerous unidentified sightings (Table 1) owing to the survey's passing mode (the ship was not diverted from the trackline to identify species). The vast majority of sightings were concentrated along the westernmost transect line and just southeast of Sri Lanka, with only a few cetaceans encountered along the southernmost transect line and in the central to northern BoB (Figure 6a). However, it is important to note that sighting conditions were considerably better in the southern bay than in the central and northern bay (Figure 6b), so these broad patterns could be influenced by differences in detectability. The only species identified in the central BoB between 10°N and 18°N were sperm whales (*Physter macrocephalus*) and spinner dolphins (*Stenella longirostris*) at the northwestern edge of our survey, and a large group (~200) of spinner dolphins along the southern transect line.

DISCUSSION

Influence of Stratification on Concentrations and Ratios of Nutrients in the Bay of Bengal

The nutrient distribution shows significant geographic variation. Because river waters are a strong source of silicate to the interior of the Bay of Bengal, and both nitrate and phosphate are utilized within the estuaries (Sarin et al., 1989; Krishna et al., 2015), the low-salinity waters in the northern BoB contain high silicate concentrations but low nitrate and phosphate concentrations (Figure 3). Strong vertical stratification and weak diapycnal mixing limit the supply of nutrients from depth to the photic zone (Prasanna Kumar et al., 2002). The N:P ratios in near-surface water of riverine origin are <4 while Si:N ratios are >30, indicating that both nitrate and phosphate, but not silicate, are limiting to phytoplankton growth. An increase in the N:P ratio (>12) that is closer to the Redfield ratio of 16, is observed below 50 m depth, where regeneration of organic matter contributes to the nutrient pool (Figure 3). Enhanced vertical mixing was observed on the return transit south of 12°N (profiles 55 and greater) coincident with increased winds associated with Cyclone Madi. Enhanced nutrient concentrations are observed in these regions relative to the low-salinity water in the north, with N:P ratios of >8.

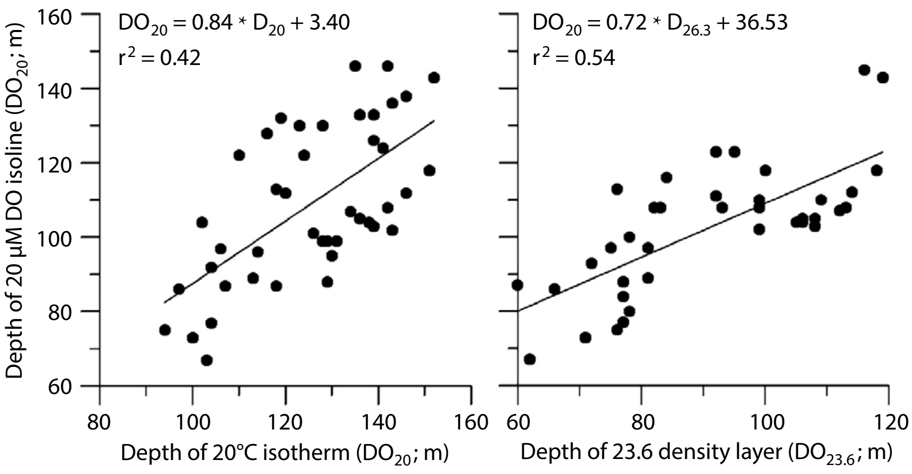

FIGURE 5. Scatter plots showing the relationship between the 20°C isotherm and the 23.6 density layer in the study region.

Influence of Stratification on Phytoplankton Biomass and Size Distribution

Physical processes significantly influence phytoplankton composition and size structure in the Bay of Bengal by modulating the availability of nutrients. The contribution of microplankton communities is low (10%–15%) compared to nano- (20%–40%) and picoplankton (50%–75%) in the entire study region (Figure 4). The dominance of picoplankton in the Bay of Bengal is related to the low concentrations of nitrate and phosphate (Figure 3). Strong stratification inhibits the supply of new nitrogen from subsurface to surface waters (Prasanna Kumar et al., 2002) as evidenced from the limiting near-surface concentrations of nitrate and phosphate. Hence, the biological production may largely be supported by regenerated nutrients (Gauns et al., 2005), as suggested by the ammonium concentrations (0.1–0.3 μM) in many of the profiles, particularly in the central and eastern bay (Figure 3).

Microplankton contribute a larger fraction of the phytoplankton in the central bay (~15%) as compared to other regions (8%; t_{stat} = 6.6; p <0.001). The variations in the contributions of micro-, nano-, and picoplankton follow the nitracline, with a significant linear relation between nitracline depth and fraction of picoplankton (r^2 = 0.58; p <0.001), and an inverse relation with fraction of microplankton (r^2 = 0.61; p <0.001). The nitracline depth, which governs the availability of nutrients and the size distribution of phytoplankton, is related to the physical structure and salinity stratification.

SCMs were observed in the entire study region (Figure 2) at the base of the mixed layer. SCM occurrence is reported in the literature and attributed to nutrient availability only below the mixed layer, which is shallower than the euphotic depth (e.g., Murty et al., 2002). Nano- and picoplankton contribute equally to the SCM compared to microplankton, possibly due to availability of nutrients and enough light at this depth.

Influence of Stratification on OMZ Intensity in the Bay of Bengal

Variations in the depth and intensity of the OMZ in the BoB are associated with stratification and production of phytoplankton biomass. The decomposition of sinking organic matter in the twilight zone removes dissolved oxygen from the water column and intensifies the OMZ. OMZ intensity is strongest below the low-salinity region (<5 μM), where stratification inhibits vertical mixing. Suppression of ventilation by stratification is a fundamental cause of the OMZ in the BoB (Sarma, 2002), and it is intensified in the north due to river discharge (Sarma et al., 2013). However, the low oxygen concentrations observed in this study have not previously been reported in the open ocean, and limited observations from other studies have suggested values in excess of 10 μM during the pre-southwest and northeast monsoon periods (Rao et al., 1994). In previous studies, these higher dissolved oxygen values in the northern BoB were attributed to faster sinking of organic river-borne suspended matter. Ballasting of organic particles leads to less bacterial degradation within the water column due to the lower residence time of sinking particles (Naqvi et al., 1994, 1996). Higher total suspended matter was reported in the northern BoB due to the influence of river discharge, as shown by the salinity decrease. Though picoplankton dominated the phytoplankton in the low-salinity, stratified surface

TABLE 1. Number of group sightings and group sizes.

Species	Sightings	Group size
Stenella longirostris	10	302, 200, 200, 180, 42, 40, 30, 30, 25, 13
Unidentified small dolphin	7	65, 50, 37, 30, 27, 13, 10
Unidentified dolphin	6	20, 7, 2, 1, 1, 1
Stenella coeruleoalba	5	80, 25, 15, 14, 5
Pseudorca crassidens	3	11, 1, 1
Stenella attenuata	3	200, 18, 13
Tursiops sp.	3	72, 20, 3
Grampus griseus	2	14, 8
Delphinus sp.	2	120, 50
Physeter macrocephalus	2	10, 1
Feresa attenuata	1	10
Orcinus orca	1	2
Balaenoptera musculus	1	1
Kogia sp.	1	1
Unidentified *Balaenoptera* sp.	1	1
Unidentified large whale	1	1
Unidentified large delphinid	1	2
Unidentified medium delphinid	1	11
Unidentified cetacean	1	1

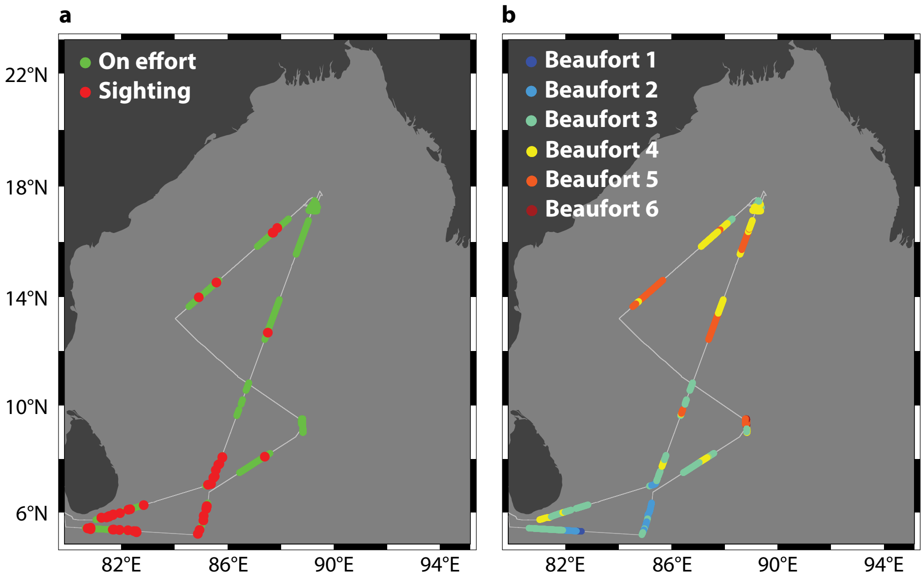

FIGURE 6. (a) Distribution of the marine mammal effort (green) and sightings (red). (b) Sea states on the Beaufort scale.

water, total organic carbon, as indicated by Chl-*a* (Figure 2), is lower than in other study zones. The lower availability of organic matter at the surface does not justify high oxygen demand as a cause of the intense OMZ. In this case, the intense OMZ is aggravated by the restricted supply of oxygen from the surface. In contrast to the ballast hypothesis, our study suggests that physical processes (stratification and lack of vertical mixing) control the depth and intensity of the OMZ rather than biological production and mineral ballast. Despite such low oxygen levels in the OMZ, denitrification was not observed, and nitrite concentrations were low (<0.1 μM). However, as discussed by Sarma et al. (2013), the occurrence of anammox may be possible without accumulation of nitrite in the water column. More work is needed to confirm the possible occurrence of anammox in the BoB.

> “This study suggests that stratification significantly influences the input of nutrients to the sunlit zone, resulting in variations in phytoplankton biomass and size structure in the [Bay of Bengal].”

Oceanographic Influences on Marine Mammal Distribution

Several authors have documented extremely high cetacean diversity in the waters near Sri Lanka (Leatherwood et al., 1984; Ballance and Pittman, 1998; de Boer et al., 2002). Our observations from the offshore waters to the east of Sri Lanka, where little marine mammal survey work has been conducted, confirm this. The waters we surveyed to the southeast of Sri Lanka and along the westernmost transect line had the highest abundance and diversity by far of any of the other surveyed areas. Sighting conditions were excellent in this region, facilitating both detection and positive identification of encountered species. Both visibility and sea states were poor in the central and northern BoB, and only two species, sperm whales and spinner dolphins, were identified there. While it is likely that the observed difference in marine mammal abundance and diversity between these two regions is real, the evidence for this is unfortunately only anecdotal, owing to the marked differences in sighting conditions between the regions and the small sample size. The differences in both physical and biological conditions between the southern and central/northern BoB observed during the cruise were certainly striking, with strong gradients in water masses as well as the depths of the thermocline, halocline, and OMZ. This variability can profoundly influence cetacean distribution via changes in both the vertical availability and the community composition of their prey (Reilly, 1990; Baumgartner et al., 2001, 2003). Despite a lack of strong observational support, it remains conceivable that the north/central region supports a different and smaller community of cetacean species than the southern BoB.

Summary and Conclusions

Our study examines the distribution of nutrients, dissolved oxygen, phytoplankton size distribution, and marine mammal diversity in the Bay of Bengal. Riverine-influenced near-surface water in the northern BoB was found to be relatively poor in nutrients. The study sampled two mesoscale eddies of variable structure: a cold core eddy and an intrathermocline eddy. Atmospheric forcing during the cruise was dominated by the development of Cyclone Madi, which affected the observed stratification and vertical mixing at distances far removed from the center of the storm. The OMZ was at its strongest to the north, where layering by riverine water intensifies stratification and depresses the thermocline. Though picoplankton dominated in the study region, the concentration of micro- and nanoplankton was greater in the western and central bay, possibly due to supply of nutrients from the subsurface by eddies, and mixing by cyclone-related winds. This study suggests that stratification significantly influences the input of nutrients to the sunlit zone, resulting in variations in phytoplankton biomass and size structure in the BoB. The marine mammal sightings recorded during our survey suggest that marine mammals predominate in regions of weaker stratification, higher phytoplankton productivity, and less-intense oxygen depletion, but further surveying is required to infer definitive relationships among biogeochemistry, the phytoplankton community, and faunal populations.

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