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Patterns of distribution of inorganic nutrients in Red Sea and their implications to primary production

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ABSTRACT

This paper presents data on inorganic nutrients obtained in several transects within Saudi Arabian waters of the Red Sea in 2012–2015. Increase in their concentrations from north to south is not monotonously linear but is punctuated by regions of high concentrations alternating with those of low concentrations, regardless of the type of nutrient (N, P or Si), season and location. Such a type of distribution could be only explained in terms of eddy circulations within the Red Sea basin. The enrichment with nutrients of the boundary currents of the eddies could be explained partly by entrainment of Gulf of Aden Intermediate Water in the eddies and the mixing of the latter with the underlying Red Sea Deep Water, and partly by a higher biological productivity in the peripheries of the eddies. These results have two major implications for our understanding of biogeochemical cycles in the Red Sea. The first is that the eddy-associated injection of nutrients into the euphotic zone could cause higher levels of production over a substantial spread of the Red Sea. The second is that the anticyclonic eddies may function as traps of nutrients and in that event, their peripheries and centers may function as independent mesocosms.

1. Introduction

The Red Sea is a marginal sea of the Indian Ocean, communicating with the latter through the narrow Strait of Bab al Mandab. It is also one sea area where the biological and chemical oceanographic features and processes remain even now poorly studied (Qurban et al., 2014). A perusal of the literature shows that what is available as data on inorganic nutrients are mostly from the Strait of Bab Al Mandab (Grasshoff, 1969; Souvermezoglout et al., 1989), extreme northern end of Gulf of Aqaba (Badran, 2001; Badran et al., 2005) and, in one instance, along the axis of the Gulf of Aqaba and few stations in the northern Red Sea (Häse et al., 2006). But for the measurements made in some local studies where anthropogenic impacts were considerable (ex. Al-Farawati, 2010), there does not exist any comprehensive dataset of nutrients or a better understanding of their dynamics in the whole of the Red Sea basin.

The first full section on distribution of total phosphorus along the axis of the Red Sea from 26°N to 12°N was presented by Newmann and McGill (1962) based on data collected by *R.V. Atlantis* and *R.V. Vema* in 1958 and this remains, till date, the only presentation of basin-long distribution of any nutrient. Their data (Newmann and McGill, 1962) showed that the concentrations of phosphorus in the southern Red Sea were slightly higher than those in the north. The next set of measurements was made during the International Indian Ocean Expedition, notably during the *Meteor* Cruise (Grasshoff, 1969), but most of the stations occupied were in the southern Red Sea, Strait of Bab Al Mandab and Gulf of Aden, with only a few in the northern and central Red Sea. These data, and similar ones from other studies (ex. Khimitsa and Bibik, 1979), were used to suggest that the flow of nutrient-rich Gulf of Aden Intermediate Water (GAIW) in the shallower depths, and remineralization in deeper waters during their transit from north to south (Morcos, 1970), could account for the relatively higher concentrations of nutrients in the southern Red Sea. Reviewing the meager data available on the distribution of nutrients in the Red Sea until then, Weikert (1987) concluded that 'as a general feature nutrient concentrations throughout the water column in the southern Red Sea are higher than those in the central and northern regions'. The only other study where measurements of nutrients (nitrate, phosphate and silicon) along the entire axis of the Red Sea, from about 27°N to 13°N, were made was during the *ORV Sagar Kanya* cruise in 1983 (Naqvi et al., 1986) but unfortunately the data were only used to examine oxidative ratios without any distribution maps. There have been no measurements of nutrients or reports on their distribution anywhere in the main body of the Red Sea in the four decades since then.

Between 2012 and 2015, we undertook four cruises in the Saudi Arabian waters of the Red Sea when concentrations of inorganic nutrients were measured at closely spaced stations and depth intervals. These constitute the first comprehensive dataset in recent years for

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the Red Sea waters and with these, we discuss the pattern of changes in the concentrations of nutrients and their relevance to primary productivity.

2. Material and methods

Fig. 1 shows the location of the stations occupied during the four cruises. During the cruise in 2012 (13–27 November), stations at quarter degree intervals from 27.5°N to 25°N and at half degree intervals between 25°N and 23°N in four transects (A–D) were occupied. Transect A was along the axis of the basin, transect D was near the coast and the other two were in between. In the 2013 cruise (6–30 November), stations placed at half degree intervals from 17°N to 27°N along the axis of the basin (transect A) and near the coast (transect C), with one station in between, were sampled. The cruise in 2014 was in summer (27 June–6 July) and the stations (23°N to 28°N) were located closer to the coast and spaced at quarter degree intervals. In the cruise in spring of 2015 (9–21 March), the stations were placed at half degree intervals along the axis from 20°N to 28°N. The longitudinal limits of the stations sampled were 40° 53′E at 17°N and 34° 58′E at 27°N. The transects occupied in the 2013 cruise were the longest possible within the Saudi waters.

In all cruises, in situ measurements of hydrographic parameters and collection of water samples were done from surface to a few m above bottom, except in the cruise in 2015 when sampling was restricted down to a depth of 400 m. Data on potential temperature (T_{pot}), salinity, density (σ_t) and dissolved oxygen were obtained at 1 m intervals from surface to bottom using a Sea-Bird SBE-9 CTD. Sensors for temperature and salinity had been calibrated before the beginning of the cruise at Hellenic Center for Marine Research, Greece. The values for dissolved oxygen obtained with the CTD were corrected by a factor determined by regression of the values obtained with the sensor on those obtained from water samples using Winkler's titration at all depths in two stations in each cruise. Water samples were collected using 5 L Niskin samplers mounted on the CTD rosette. Samples for nutrients were obtained at 10 m intervals down to 50 m depth, at 25 m intervals between 50 and 200 m depth and at 100 m intervals from 200 m to a few m above bottom. Concentrations of nutrients (nitrate, phosphate and silicon) were measured with a Skalar San Plus auto-analyzer using the methods given by the manufacturer. All measurements were done immediately on board. The analytical precisions were ±1% at a concentration of 1 μmol L^{-1} for nitrate and silicon, and ±2% at a concentration of 0.4 μmol L^{-1} for phosphate. A Shipboard Acoustic Doppler Current Profiler (SADCP) was used to obtain 10-min averaged data on directions and velocities of the currents at 20 m intervals down to 500 m while at stations. The data were not subjected to any tidal correction as the tidal current was relatively weak (maximum tidal range < 50–60 cm).

At all stations, additional water samples from 5 depths in the euphotic zone (0, 5, 10, 25 and 40 m) were obtained for measurements of the concentrations of photosynthetic pigments. Additional samples were obtained at a depth between 60 and 80 m characterized by a peak in fluorescence recorded by WetCDOM fluorescence sensor mounted on the CTD. Particulate matter from 1 L water sample was separated onto a GF/F filter pad and used for fluorometric determination of chlorophyll (Chl *a*) and phaeopigments in a Turner Designs Trilogy Fluorometer.

NO_3:PO_4 ratios at each station were calculated by linear regression of the data from surface to the bottom. In all instances, the relationship was highly significant ($p < 0.01$; $n = 10–20$).

3. Results

The transects sampled in 2013 were the longest and hence are considered first.

3.1. Along the axis

3.1.1. 2013 cruise

The water mass below about 400 m in the transect along the axis of the Red Sea basin was homogenous, characterized by a T_{pot} of 21.4–21.5 °C (Fig. 2). Above this depth, the isotherms showed vertical excursions through a range of 30–90 m, with prominent depressions at around 19°N, 23°N and 25°N (Fig. 2). Sections of salinity and density (not shown here) also showed the uniformity of the water mass (salinity of 40.5 and σt of 28.5–28.6) below 400 m and oscillations of isolines, similar to those of temperature, above.

Fig. 3 shows the profiles of nitrate, phosphate and silicon at the southernmost (17°N) and the northernmost (27°N) stations in this transect. Two features become remarkable. The first is the intrusion of the nutrient-rich GAIW at depths < 100 m in the south and its absence in the north. The second is the higher concentrations of all nutrients in the south than in the north, indicating a north–south gradient. Between these two end stations, the changes of the concentrations of nutrients showed interesting, highly variable patterns (Fig. 4). For example, the concentrations of silicon below 200 m at 17.5°N–18°N and at 20°N were >20 μmol L^{-1} than in between (<10 μmol L^{-1}). Likewise, the concentrations were also >10 μmol L^{-1} at 22–22.5°N, 23.5°N–24.5°N and 26°N whereas elsewhere north of 20°N, they were much lower (<10 μmol L^{-1}). The high concentrations of silicon at 18°N and at 20°N extended down to the bottom whereas they were restricted to shallower depths (<800 m) north of 20°N. The patterns of distributions of nitrate and phosphate were similar to those of silicon. In the first instance, the concentrations below 200 m at the stations located at ~18°N and at ~20°N were 2–3 times higher than in between. In the second, high concentrations, like those of silicon, could also be seen at 22–22.5°N, 24–24.5°N and near 26°N. Finally, the higher concentrations extended down to the bottom in the two instances south of 21°N but were limited to shallower depths in the north.

Concentrations of column Chl *a* (integrated down to 40 m depth) showed high values (20–25 mg m^{-2}) at 18°N and 21°N and these were separated by concentrations < 10 mg m^{-2} in between (Fig. 5). North of 21°N, the concentrations decreased to ~15 mg m^{-2} and continued to decrease to about 8 mg m^{-2} at 27°N but this decrease was punctuated by two instances of higher concentrations bracketing regions of lower concentrations (16 and 13 mg m^{-2} respectively at 22°N and 24°N with values < 13 mg m^{-2} in between, and 10 and 8 mg m^{-2} respectively at 25°N and 27°N with values < 7 mg m^{-2} in between).

The directions of zonal currents deduced with the data from SADCP (Fig. 6) showed a westward flowing current at about 18°N and an eastward flowing current at 19.5°N. Further north, two more pairs of west- and east-flowing currents, at 23 and 24°N, and at 24.5 and 26°N, also could be seen.

3.1.2. 2012 cruise

As was seen with the data of the 2013 cruise, the water mass below 400 m was homogeneous, with a T_{pot} of 21.4–21.5 °C, but above this depth, there was a distinct oscillation of the isotherms, from a depression at 24.5°N to an uplift at ~26.5°N (Fig. 7) in the transect A along the axis of the basin. The concentrations of all three nutrients were high on either side of the depression, at 23–23.5°N and at 24.5–25.5°N, and extended practically all the way to the bottom (Fig. 7). The differences between the high and low concentrations at any instance were by a factor of 2 (2 to >5 μmol L^{-1} of nitrate, 0.2 to 0.6 μmol L^{-1} of phosphate and 3 to 5 μmol L^{-1} of silicon). Another instance of high concentrations in the water column, down to about 800 m, was seen at 26–27°N, coinciding with the uplift of isotherms.

3.1.3. 2015 cruise

Only north of 23 °C was there a clear excursion of isotherms through several tens of meters, with a distinct depression at 26°N (Fig. 8).