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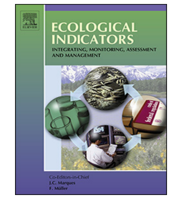

Ecological indications of copepods to oxygen-deficient near-shore waters

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ABSTRACT

Dissolved oxygen deficiency and its impacts on marine organisms is an important research topic world over. In this study, we utilized the advantage of a shallow seasonal hypoxic zone occurring along the Southwest Coast of India. Also, we adopted the standard live staining technique to assess the ecological responses of copepods to oxygen-deficient waters. Based on 18 weekly/biweekly sampling sessions in the nearshore-waters along the Southwest coast of India, spanning over the Pre-Southwest Monsoon (April) to Late-Southwest Monsoon (September) of 2014, this study showed a noticeable decrease in the total abundance of copepods in the hypoxic subsurface waters associated with coastal upwelling. This feature was noticed particularly during the Peak-Southwest Monsoon (July–August), which was contrary to the usual temporal abundance pattern of copepods in the aerated surface waters. During the Southwest Monsoon, the percentage of dead copepods was noticeably high in the study area, especially in the subsurface waters, due to the physiological stress from hypoxic waters. Indicator Value (IndVal) analysis of copepods demarcated 8 indicator species (IndVal > 40) under different environmental conditions. During the Pre-Southwest Monsoon, the indicator species were *Acartia erythraea*, *A. danae, Centropages orsini* and *C. furcatus*, whereas *Oithona similis* was the indicator during the Peak-Southwest Monsoon. *Pseudodiaptomus serricaudatus* and *Centropages tenuiremis* were the indicators during the Late-Southwest Monsoon, whereas *Temora turbinata* was an indicator during both the Early- and Late- Southwest Monsoon periods. The overall pattern in the distribution of copepods evidenced the dominance of calanoids during the Pre-Southwest Monsoon and that of cyclopoids (*O. similis*, *Oithona* sp.,) during the Peak-Southwest Monsoon. Multivariate analysis showed that the observed temporal shift in the composition and increase in the number of dead individuals of copepods in the study region were mainly governed by the coastal upwelling-associated hydrographical settings.

1. Introduction

Oxygen-deficient (hypoxic to anoxic) waters exist in the Oxygen Minimum Zones (OMZs) of oceans as a consequence of intense and prolonged organic matter decomposition in poorly-mixed subsurface layers (Ekau et al., 2010; Levin et al., 2009). The major causative factor for these pollution events in the OMZs is believed to be the high organic production in the euphotic layer facilitated by natural or anthropogenic eutrophication events (Naqvi et al., 2000, 2006; Ekau et al., 2010; Levin et al., 2009). Studies in the past have raised an alarm about an imminent increase in the spread of oxygen-deficient zones across the globe (Diaz and Rosenberg, 2008; Stramma et al., 2008; 2010). In the northern Indian Ocean, the Arabian Sea has a well-defined thick perennial OMZ in the mid-depths (~150–1200 m), especially in its central and northern part, believed to have resulted from high plankton production in the euphotic layer during most of the year (9 out of 12 months), augmented by poor mixing in the subsurface waters (Naqvi et al., 2000, 2006; Ekau et al., 2010; Levin et al., 2009; Jyothibabu et al., 2010). The perennial mid-depth oxygen-deficient waters get elevated/expanded eastward during the Southwest Monsoon associated with coastal upwelling, causing the formation of seasonal oxygen-deficient zones in the nearshore waters along the west coast of India (Naqvi et al., 2000; Gupta et al., 2016; Jyothibabu et al., 2018). It has been documented that oxygen-deficient zones in the water column can significantly influence the distribution, predation and food web structure of organisms living in such environments (Longhurst, 1967; Pihl et al., 1992). However, the research community is still struggling to comprehend the adverse impacts of oxygen-deficient waters on organisms, mainly due to the inadequate discrete sampling of the OMZ pelagic community, which usually occurs along ocean mid-depths. It is a

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fact that world over, much more information in this regard is available for benthic organisms as compared to the pelagic ones (Banse, 1968; Ekau et al., 2010; Levin et al., 2009 and references therein).

Copepods are the most abundant crustaceans in the world oceans, usually contributing > 60% of the total zooplankton abundance (Padmavati et al., 1998; Queiroga and Blanton, 2004; Jagadeesan et al., 2013). They act as a trophic link between phytoplankton and fishes in the food chain and thus, play a crucial role in ocean biogeochemical cycles (Campos et al., 2017). Usually, changes in the surroundings get reflected in the community composition, diversity, and geographical distribution of copepods (Queiroga and Blanton, 2004; Jagadeesan et al., 2013; Campos et al., 2017). Copepods are sensitive to even subtle changes in the environment and are, therefore, suitable indicator organisms of environmental change and ecosystem functioning (Campos et al., 2017). However, in the present study domain of the eastern Arabian Sea, information on copepods that inhabit the OMZ waters is rather limited (Padmavati et al., 1998; Smith and Madhupratap, 2005) compared to those from the rest of the world (Smith, 1982; Smith et al., 1998; Ekau et al., 2010 and references therein). Most of the earlier studies on copepods from the eastern Arabian Sea focused mainly on their abundance and compositional aspects and, therefore, there is virtually no conclusive information available on how OMZs influence copepods in the region. One of the major reasons for the scarcity of such information, not only from Indian waters but from other parts of the world as well, seems to be the methodological inadequacy in assessing the physiological status of copepods living in the OMZ waters in the ocean mid-depths. In this context, studies on the physiological status (live and dead status) of plankton are advantageous in shallow OMZs in the near-shore waters as the sample collection from such shallow waters can be done rapidly, minimizing the sampling stress on the experimental organisms.

Studies elsewhere have presented the view that the response of copepods in OMZs could differ between taxa as many of them can avoid oxygen-deficient waters, whereas a few of them can adapt to the low oxygenated conditions (Castro et al., 1993; Auel and Verheye, 2007). Although some copepods (e.g., *Rhincalanus*, *Pleuromamma, Heterorhabdus, Aetideopsis* etc.) can adapt to oxygen-deficient waters (Castro et al., 1993; Auel and Verheye, 2007), most others suffer from varying degrees of adverse impact due to the hypoxic waters (Roman et al., 1993; Invidia et al., 2004; Marcus et al., 2004). On individual level, hypoxia could cause physiological changes in copepods, thereby altering their life cycle performance, reproductive success, disease vulnerability and longevity (Ekau et al., 2010 and references therein). As mentioned before, copepods are susceptible to significant changes in the environment and such changes could even lead to their death (Cervetto et al., 1999; Elliot et al., 2013; Jagadeesan et al., 2013; Martinez et al., 2014). Although routine zooplankton studies assume all individuals in the natural samples to be live, the presence of dead individuals (carcasses) is undeniable (Tang et al., 2009; Elliot and Tang, 2011; Frangoulis et al., 2011; Jyothibabu et al., 2016). Some data are available on the composition and abundance of copepods in the OMZs of the Arabian Sea (Goswami and Padmavati, 1996; Smith and Madhupradap, 2005), but information on the physiological status of copepods in oxygen-deficient subsurface waters remains unknown. Some of the biological characteristics of the present study area investigated under the AMPS program have been published recently (Karnan et al., 2017; Arunpandi et al., 2017; Jagadeesan et al., 2017a; Jyothibabu et al., 2018); in this paper, emphasis has been given to the ecological response of copepods to the hypoxic subsurface waters during the Southwest Monsoon (June–September). Considering the above aspects, focused attempts have been made here to track the ecological response of copepods to the seasonal oxygen-deficient conditions in the nearshore waters along the southwest coast of India during the Southwest Monsoon. The major objectives of the study are (a) to quantify the live and dead percentage of copepods (both adult and larvae) as an ecological response to the changing hydrographical setting and (b) to analyze the compositional changes of copepods, especially in the subsurface, so as to delineate the indicator species during different hydrographical settings.

2. Materials and methods

2.1. Study area

The study area is located off Alappuzha in the south-central coast of Kerala, along the southwest coast of India between 9.25 to 9.43°N and 76.3 to 76.4°E. It is typical of the near-shore waters along the west coast of India, which is influenced by coastal upwelling during the Southwest Monsoon. Coastal upwelling causes high nutrient availability in the surface water column, promoting luxuriant growth of phytoplankton, especially during the Peak and Late Southwest Monsoon (Ramasastry and Myrland, 1959; Silas, 1984; Jagadeesan et al., 2017a; Karnan et al., 2017; Jyothibabu et al., 2018). This study forms a part of the investigation 'Alappuzha Mud Bank Process Studies (AMPS)', a multidisciplinary oceanography program of CSIR-National Institute of Oceanography, India, carried out in 2014.

In addition to coastal upwelling, another littoral oceanographic feature that exists along the Southwest (Kerala) coast of India, albeit in fragmented stretches, is that of the 'Mud Bank.' Mud Banks may be defined as patches of semicircular calm littoral waters close to the coast formed due to the presence of a bottom fluid muddy layer in the region (Gopinathan and Qasim, 1974; Silas, 1984; Mallik et al., 1988; Jyothibabu et al., 2018). This fluid muddy layer significantly attenuates wave energy, causing wave-less, smooth sea surface conditions (Mud Bank) conducive for fishing operations when the rest of the region is exposed to heavy monsoonal waves (Mallik et al., 1988). Field sampling exercises were carried out in three locations (M1, M2 and M3) in the study area (Fig. 1); location M1 and M2 were in the onshore region (7m depth), but separated from each other by a distance of 8 km. Location M3 was located relatively in the offshore (12 m depth) perpendicular to M2. 18 field sampling sessions in these three locations were carried out from April (Pre-Monsoon) to September 2014 (Late Southwest Monsoon), consisting of 15 weekly samplings (April 22nd to 2nd August) and 3 biweekly samplings (16th August to 20th September).

2.2. Sampling methods

Vertical profiles of temperature and salinity were obtained using a conductivity, temperature and depth (CTD) profiler to understand the temporal hydrographical transformations in the study domain. Water samples collected from the surface (0.5 m) and subsurface (6m in M1 and M2 and 10 m in M3) waters using the Niskin samplers were used for measuring various chemical and biological parameters. Dissolved oxygen, nitrate and phosphate were measured based on standard procedures (Grasshoff, 1983). Chlorophyll *a* was measured using a Turner fluorometer following JGOFS protocol (UNESCO, 1994). Zooplankton samples were collected from two discrete layers, from the surface (0.5 m) and the subsurface (6m in M1 and M2 and 10 m in M3), adopting two different sampling methods. The surface sampling was done using horizontal tows of a standard meso-zooplankton net (200 μm mesh size); on the other hand, the surface sampling consisted of two net tows: the first short duration tow (2 min) was for quantifying live and dead copepods while the second tow was for normal duration (10 min) for the quantitative estimations of copepods. As per the staining methods adopted (Elliott and Tang, 2009), only short duration tow has the desired efficiency to quantify the live and dead copepods, as the long duration net tows can cause further mortality of copepods. The samples obtained through short duration net tows were immediately processed with the neutral red staining procedure (Elliott and Tang, 2009) and then stored at −20 °C until further microscopic analysis in the laboratory.

Mesozooplankton collected using long duration net tows were