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Re-evaluation of 'paradox of mesozooplankton' in the eastern Arabian Sea based on ship and satellite observations

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ABSTRACT

In the central and eastern Arabian Sea (EAS), biomass and production of phytoplankton are known to vary spatially and seasonally whereas, biomass of mesozooplankton (MSP) is reported to be constant. This apparent contradiction has been called 'Arabian Sea Paradox'. However, it is important to note that the paradox is based on a very limited seasonal data (from 5 to 7 locations). Therefore, we reconsidered the paradox based on intensive in-situ observations at 37–40 locations in the EAS. In agreement with the known seasonal difference in phytoplankton standing stock in the EAS, we analysed the MSP data in two ways using two-way nested ANOVA. In 'basin scale' analysis, MSP data from the EAS were pooled and seasonal and inshore–offshore variations were analysed for the entire region. In 'regional scale' analysis, MSP data were analysed separately for (a) northern region (north of 15°N) and (b) southern region (15°N and south of it). Satellite data of chlorophyll *a*, SST and wind speed were also analysed to show the major differences in oceanographic features in the northern and southern EAS. The analyses showed prominently high chlorophyll *a* (av. 1 mg m^{-3}) in the northern region during most of the year through winter convection, open ocean upwelling and lateral advection from the Arabian coast. On the other hand, chlorophyll *a* was low (av. 0.2 mg m^{-3}) in the southern region during most of the year mainly due to thermohaline stratification. The MSP biomass was distributed almost in a similar way as that of phytoplankton stock with statistically significant spatial and seasonal variations in the northern and southern regions. In this paper, we review the 'paradox of MSP' and present clear and new evidences to show that this concept is not logically applicable for EAS.

1. Introduction

1.1. An overview of the scientific background

Mesozooplankton (MSP; 200–2000 μm) plays a significant role in marine pelagic food web, and their ecological, trophodynamic and biogeochemical roles have been well recognised (Buitenhuis et al., 2006). The EAS, the western boundary of the Indian subcontinent, has several distinctive features in its plankton community compared to the rest of the Arabian Sea (Sarma, 2004). The first intensive effort that generated scientific knowledge on MSP community of the EAS was the International Indian Ocean Expedition (IIOE; 1960–1965). This programme with intensive observations in the EAS (Fig. 1a) showed that MSP biomass varies seasonally and geographically. This feature is clearly seen in the plankton Atlas prepared subsequent to IIOE (Fig. 1b and c, Panikkar, 1968), with high biomass values along the southwest coast of India during the summer monsoon (April 16 to October 15) and along the northwest coast of India during the winter monsoon (October 16 to April 15). The open ocean regions of EAS had apparently low biomass during both the summer and winter monsoon periods (Panikkar, 1968; see the review by Madhupratap and Parulekar, 1993).

Subsequent to IIOE, several studies have confirmed the occurrence of high MSP biomass along the southwest coast of India during the summer monsoon period (May to September), and attributed this to the result of phytoplankton blooms caused by coastal upwelling (Johansen et al., 1978; Haridas et al., 1980; Raj and Ramamithram, 1981; Madhupratap et al., 1990; Jyothibabu et al., 2008a,b; Ashadevi et al., 2009-unpublished). However, a few earlier studies have observed that even in the absence of coastal upwelling, MSP biomass remains high along the southwest coast of India during the summer monsoon, due to land and river runoff (see the review by Madhupratap and Parulekar, 1993). Similarly, a few studies conducted in the northern Arabian Sea showed high MSP standing stock during the winter monsoon (November–February) and spring intermonsoon period (March–April), which was attributed to the winter blooms of phytoplankton (Haq et al., 1973; Paulinose and Aravindakshan, 1977).

Almost three decades after the IIOE, Madhupratap et al. (1992), based on observations along the shelf and slope regions of the southeastern Arabian Sea (SEAS), reported that MSP biomass remains

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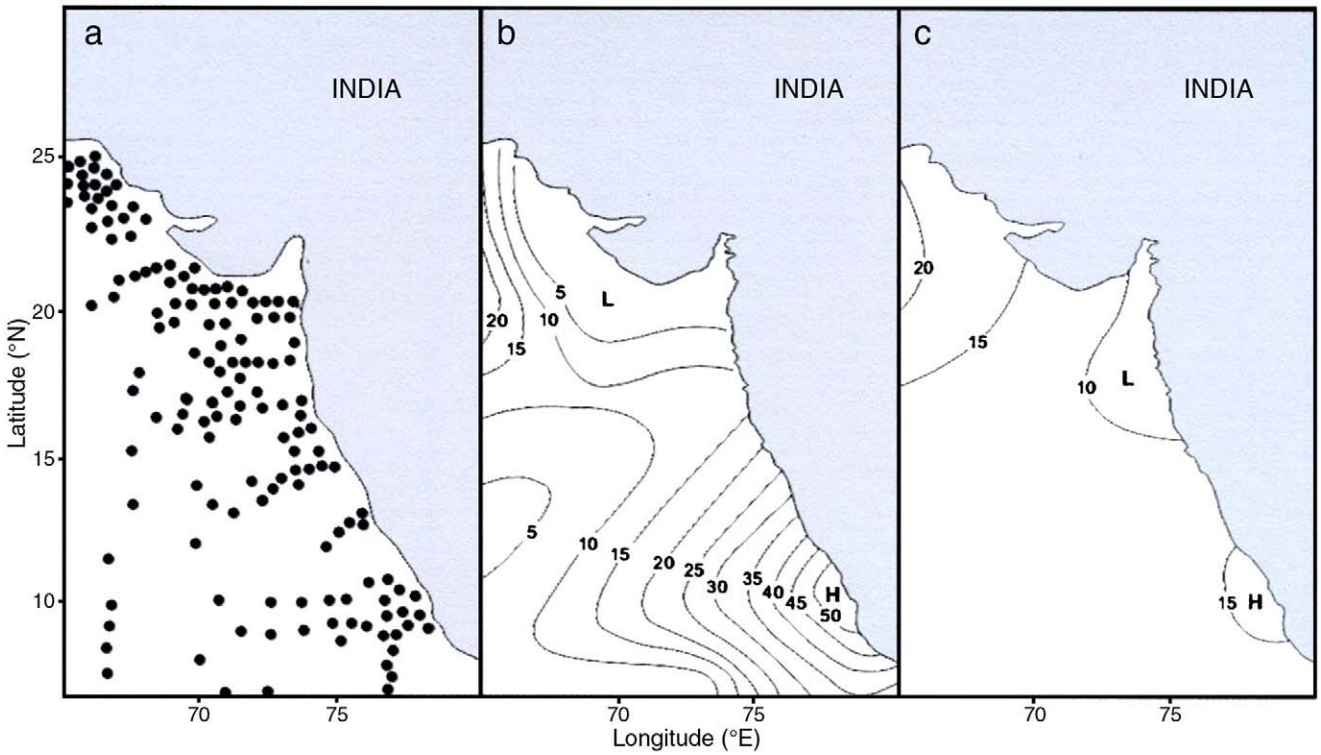

Fig. 1. (a) IIOE station locations in the eastern Arabian Sea, mesozooplankton biomass distribution during (b) summer monsoon and (c) winter monsoon: L — low; H — high (adapted from Panikkar, 1968).

unchanged during June–July (early summer monsoon) and November (early winter monsoon). They have observed low chlorophyll *a* during both monsoon periods; and opine that the observed 'high' MSP biomass during low chlorophyll *a* periods was a 'paradox'. Although the actual reasons for this 'high and unchanging' MSP biomass in low chlorophyll *a* regions had been obscure, they suggested the following plausible reasons for the observed disparity; (a) the high phytoplankton standing stock that would have existed a fortnight before the actual MSP measurement, (b) the high MSP grazing pressure during the sampling period that would have lead to low phytoplankton standing stock (top down control) and (c) the nutrition of MSP through a bacteria based food chain (microbial loop). However, none of these assumptions have been scientifically tested or proved so far. Moreover, a close observation of the data of this study reveals that the so-called 'high' MSP biomass was mostly restricted to the inshore regions, while the offshore regions had noticeably low values.

The Joint Global Ocean Flux Studies (JGOFS) was the most acclaimed oceanographic programme undertaken in the Arabian Sea during the recent past (1992–1997). The international scientific community, which participated in this programme, was mostly restricted to the central and western Arabian Sea. The Indian JGOFS measurements in the central and EAS (Fig. 2) reported that the MSP biomass did not vary seasonally and geographically, even when a pronounced seasonal and geographical variation existed in the phytoplankton standing stock (Madhupratap et al., 1996a). This peculiar situation (maintenance of high MSP biomass during low phytoplankton conditions) was termed as the 'Arabian Sea Paradox'. However, it is quite evident from Fig. 2, that this concept proposed was based on a limited number of observations without good seasonal coverage.

Subsequent to the IIOE, 'paradox of zooplankton' had also been referred from the western Arabian Sea (WAS). This was based on the

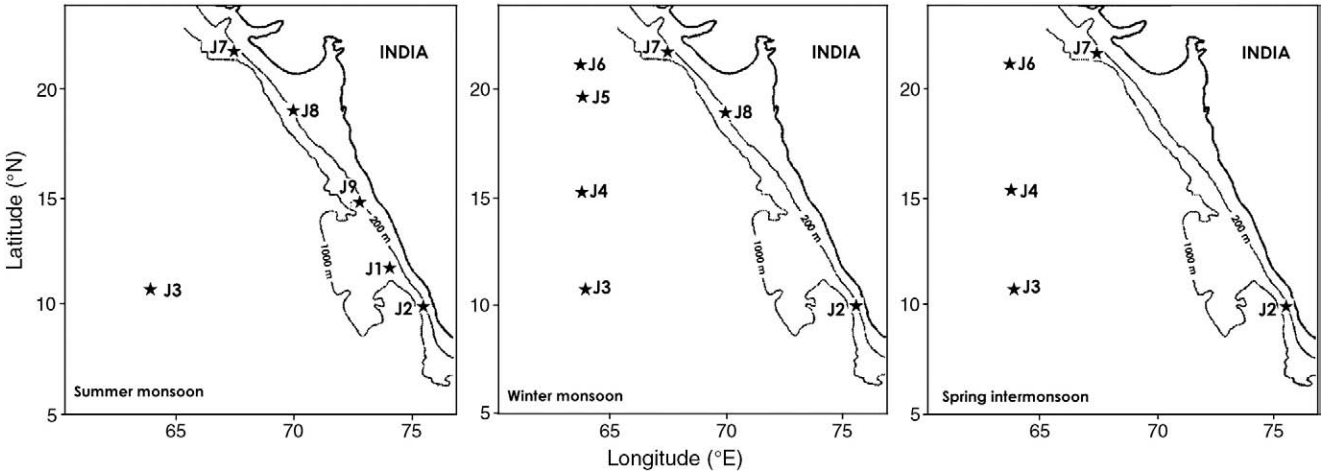

Fig. 2. Locations of zooplankton sampling during JGOFS India (redrawn from Madhupratap et al., 1996a).