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Oxygen Minimum Zone and Fish Landings along the Omani Shelf

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ABSTRACT

Historical data on vertical distribution of temperature, salinity, dissolved oxygen concentration, eco-soundings and artisanal fish landings were used, to investigate the relationship between characteristics of the oxygen minimum zone and fish landings along the Omani shelf (in the western Arabian Sea). It was shown that seasonal shoaling of the oxycline shifts the deepened layer of myctophids up to the surface and closer to the coast which in turn favors accumulation of pelagic predators in the same locality. Both phenomena lead to a compressing of the habitat and increasing artisanal landings. The factors mediating seasonal changes of the oxygen minimum zone are discussed here.

Key words: Arabian sea, fish landings, oxygen minimum zone

INTRODUCTION

Persistence of the Oxygen Minimum Zones (OMZ) exerts gradual impact on spatial and temporal distribution of pelagic organisms. This refers zooplankton (Sameoto, 1986; Bottger-Schnack, 1996; Smith *et al.*, 1998; Wishner *et al.*, 1998), as well as mesopelagic and epipelagic fish (Ekau *et al.*, 2010; JGOFS, 2002). In the Arabian Sea, the OMZ is delineated by a dissolved oxygen concentration of less than 4.5 μM (0.1 mL L^{-1}) and is well pronounced, from the interior part of the sea to the coasts of Oman, Iran, Pakistan and India (Herring *et al.*, 1998; Morrison *et al.*, 1999; Karuppasamy *et al.*, 2010; Naqvi and Jayakumar, 2000).

In being one of the most prominent oxygen depletions of the World Ocean, the Arabian Sea OMZ is also notorious for the other peculiarity which is the largest stock of mesopelagic lantern fish (myctophids) associated with the upper boundary of OMZ or inhabiting this zone. The stock is believed to consist of roughly 100 million tonnes (Nair *et al.*, 1999). In terms of trophic relationships, myctophids play an important role as the diet of large pelagic fish (Gjosaeter, 1984), 1179 species of which inhabit the waters of Oman (Al-Jufaili *et al.*, 2010).

The artisanal fishery of large and small pelagic fish accounts for 96% of Oman landings. Numerous small villages are scattered along the Omani coast, from which around 40,161 fishermen are directly employed in the fisheries sector operating 18,027 fishing boats. Of these, 90% are fiberglass boats 8-10 m in length (MFW, 2011).

Oxygen depletions pronounced in Omani coastal waters reach extremes, evident through periodic fish kill incidents. Some of them end up in huge losses; tonnes of fish harvested in aquaculture farms along the coast are killed annually (Al-Gheilani *et al.*, 2011). As far as the

Omani shelf is concerned, the relationship between characteristics of OMZ and fish catches is still poorly investigated. Our goal was to elucidate seasonal changes of the OMZ parameters and to understand whether these changes could influence landings of commercial fish species.

MATERIALS AND METHODS

Data for the analysis come from 53 oceanographic expeditions carried out in the Western Arabian Sea, from 1960-2002 (Table 1). In terms of national inputs, 38% of CTD vertical profiles come from the US expeditions, 34% of data was contributed by the UK and the rest is the contribution of the USSR, Germany, Japan, the Netherlands and India.

The location and number within a gridded pattern of 2117 vertical profiles of the dissolved oxygen is shown in Table 1. In order to evaluate intra-seasonal changes, these profiles were averaged for each season, from 1960-2002.

The seasonal averaging gave 447 vertical profiles characterizing the north-east (winter) monsoon, 551 profiles characterizing the south-west (summer) monsoon, 498 profiles collected during the spring inter-monsoon and 618 profiles obtained during the fall inter-monsoon season. Along with onboard measurements, the archives of the Ministry of Agriculture and Fisheries Wealth were analyzed. In particular, we used materials on CTD and oxygen casts carried out by the research vessel "Al Mustaqila 1" from August 2007 to September 2008 (Baird *et al*., 2009). The survey included shelf waters between cape Ras Al Hadd and the Yemen boarder between depths of 20 and 250 m. Some casts were carried out on the continental slope upto 160 km offshore. Five seasonal surveys were complemented (Table 2).

Conductivity, temperature, depth and dissolved oxygen measurements were carried out using an RBR CTD probe deployed from the vessel.

A Simrad EK60 acoustic backscatter with 38, 120 and 200 kHz transducers was used for routine acoustic surveys. The nearshore transects across the shelf began at a 200 m depth and extended upto 8 km offshore. When deep-scattering layers were identified on the sounder, pelagic trawls were used to catch the organisms. Later on, catches were sorted by species. The P55 midwater trawl with a 10 mm liner in the cod end was used to sample mesopelagic organisms.

Along with data on field surveys, we used historical records on fish landings which are routinely monitored by the Department of Fisheries Statistics, based on a sampling system established by the Oman-American USAID project (Mathews *et al*., 2001). Monthly traditional (artisanal) landings were retrieved from the annual reports published by the Ministry of Agriculture and Fisheries Wealth (MFW, 2008).

Statistical analysis: As far as the statistical methods applied are concerned, the averaged over seasons vertical profiles of dissolved oxygen were approximated by the Distance Weighted Least Squares method which is aimed to minimize the sum of the squares of the deviations of the points from the curve (Wolfram/MathWorld, 2014). The distance-weighted least squares method fits a curve to the data by using a polynomial (second-order) regression calculated for each value on the X variable scale to determine the corresponding Y value such that the influence of the individual data points on the regression (i.e., the weight) decreases with their distance from the particular X value (McLain, 1974).

In plotting monthly fish landings, statistical quartiles of data distribution were used. These quartiles denote the spread around the center (median), in the form of lower and upper limits

Table 1: Research vessels and voyages assembled and contributed to the historical database on dissolved oxygen measurements

Country	Institution	R/V name and voyage No.	Year	No. of oxygen profiles
UK	BODC	Discovery (D10)	1994	15
UK	BODC	Discovery (D12)	1994	29
UK	UKNO	Discovery	1963-1964	89
UK	UKNO	Charles Darwin	1986	4
USSR	IORAS	Vytyaz	1960	13
USSR	YugNIRO	Vladimir Vorobyev	1961-1967	185
USSR	YugNIRO	Marlin	1964-1969	90
USSR	MHI	Mikhail Lomonosov (19)	1966	18
USSR	YugNIRO	Ariel	1969-1970	45
USSR	YugNIRO	Zheleznyakov	1970,1971,1980	55
USSR	IORAS	Akademik Shokalskiy	1973	6
USSR	IORAS	Akademik Kurchatov	1976	6
USSR	YugNIRO	Nauka	1983,1985	145
USSR	YugNIRO	Nikolay Reshetnyak	1983-1985	139
USSR	YugNIRO	Skif	1986	128
USSR	YugNIRO	Kometa Galleya	1987-1988	69
USSR	YugNIRO	Dmitriy Stefanov	1989	74
Unknown	NODC	GODAR Project	1960-1971	238
USA	NODC	Thomas G. Thompson (TTN-043)	1995	15
USA	NODC	Thomas G. Thompson (TTN-045)	1995	22
USA	NODC	Thomas G. Thompson (TTN-049)	1995	40
USA	NODC	Thomas G. Thompson (TTN-050)	1995	20
USA	NODC	Thomas G. Thompson (TTN-053)	1995	40
USA	NODC	Thomas G. Thompson (TTN-054)	1995	17
USA	NODC	Knorr	1995	56
USA	WHOI	Atlantis II	1963,1965,1975	45
USA	WHOI	Anton Bruun	1963-1964	21
USA	WHOI	Chain	1970-1971	3
Germany	FM-GEOMAR	Meteor 32_1	1995	22
Germany	FM-GEOMAR	Sonne 89_1	1993	32
Germany	FM-GEOMAR	Meteor 32_4	1995	8
Germany	FM-GEOMAR	Meteor 32_6	1995	32
Germany	FM-GEOMAR	Sonne 118	1997	33
Germany	FM-GEOMAR	Sonne 119	1997	24
Germany	FM-GEOMAR	Sonne 120	1997	22
Netherlands	NIOZ	Tyro (D2)	1992	31
Netherlands	NIOZ	Tyro (D3)	1993	27
Japan	JODC	Umitaka Maru	1994	2
India	NCAOR	Sagar Kanya	1994-1997	25
Oman	MSFC	Coastal stations	2001-2002	232

Table 2: General characteristic of the r/v “Al Mustaqila 1” voyages along the Omani shelf

Voyage No.	Voyage acronym	Time range	No. of acoustic files	Trawl survey stations	CTD stations
1	OMA0701	17/09/07-15/10/07	725	114	215
2	OMA0702	01/11/07-17/12/07	812	113	253
3	OMA0801	29/01/08-18/03/08	1458	131	348
4	OMA0802	19/04/08-10/06/08	1589	127	319
5	OMA0803	01/08/08-23/09/08	1487	129	265

pointed out that from 25-75% of all measurements were in the vertical black boxes displayed in figures. All statistical estimates and plots were generated by means of the "Statistica-v9" software (http://www.statsoft.com).

RESULTS

Whilst regional circulation of the Omani shelf waters is subjected to substantial changes driven by monsoonal winds, various subsets of data that spanned an annual cycle were used. The first subset amalgamated historical data on dissolved oxygen sampled in 1960-2002. Vertical profiles of the oxygen concentration were averaged for each season (Fig. 1) which allowed us to analyze the annual cycle.

The upper 30 m layer was well ventilated during the winter monsoon; the mixed layer had the highest values of dissolved oxygen. Further on, the oxygen concentration as well as the oxycline depth-both declined during the spring (inter-monsoon) season but the most prominent decline was observed during the summer monsoon. The differences between neighboring periods (summer and autumn profiles or winter and spring profiles) were much less pronounced than between two inter-monsoon seasons. For example, vertical profiles pointed out, that the 2 mL L^{-1} concentration has shifted up by 25 m (from spring to autumn) which exceeded the difference between any of two "Monsoon-inter-monsoon" periods. Overall, the two fold change of the 2 mL L^{-1} concentration depth was observed throughout a seasonal cycle. No seasonal differences in oxygen concentration were noticed at 250-300 m.

The variation coefficient was used to characterize seasonal changes in vertical profiles. The latter one represented the standard deviation-to-mean ratio computed over depths of oxygen concentration (Table 3). In analyzing this data, two tendencies were noticed. The first one pointed

Table 3: Variation coefficients of averaged vertical profiles of the oxygen concentration showed in the Fig. 1

Depth (m)	Winter	Spring	Summer	Autumn
0	0.21	0.35	0.16	0.20
5	0.29	0.67	0.16	0.19
10	0.18	0.48	0.20	0.19
20	0.13	0.46	0.31	0.29
30	0.13	0.48	0.42	0.38
40	0.16	0.61	0.50	0.48
50	0.17	0.52	0.61	0.61
60	0.21	0.65	0.72	0.75
70	0.27	0.59	0.81	0.81
80	0.32	0.60	0.89	0.87
100	0.46	0.73	1.10	0.98
120	0.51	0.90	1.23	0.98
140	0.65	1.00	1.24	1.19
160	0.70	1.08	1.23	1.30
180	0.64	1.17	1.34	1.30
200	0.68	1.13	1.31	1.40
220	0.54	1.23	1.37	1.14
240	0.56	1.31	1.43	1.16
260	0.50	1.34	1.39	1.15
280	0.45	1.33	1.42	1.24
300	0.62	1.20	1.32	1.12

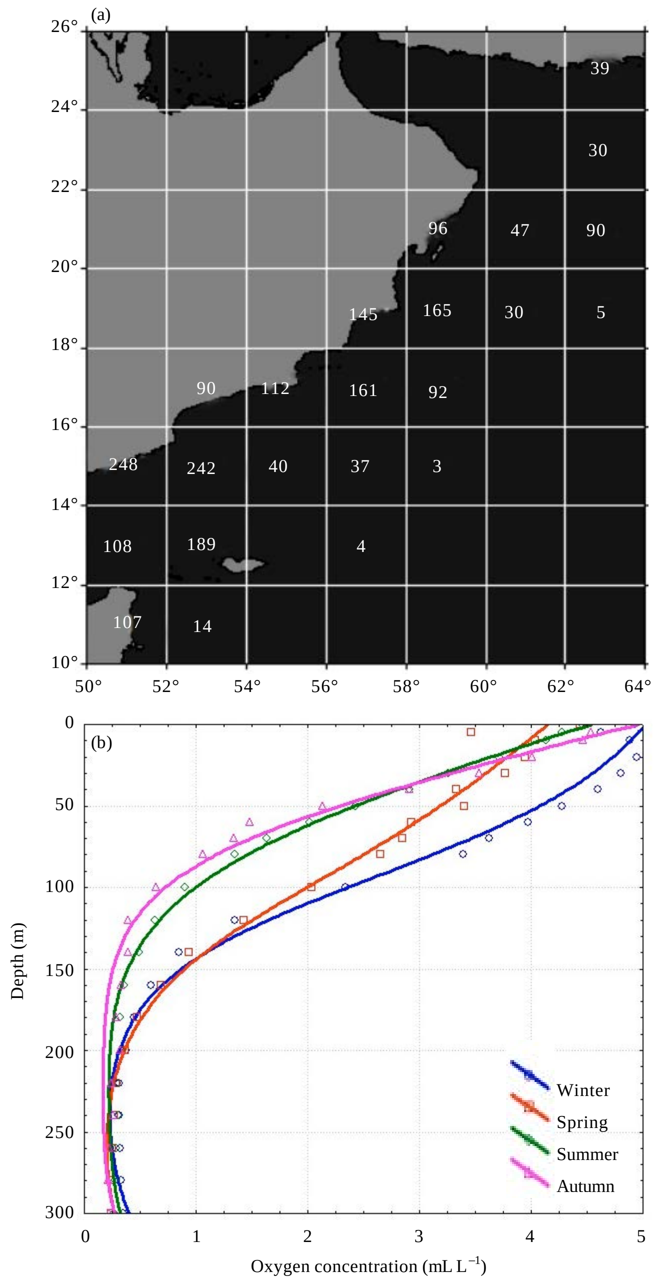

Fig. 1(a-b): Gridded data on (a) Oxygen sampling and (b) Vertical distribution of the dissolved oxygen concentration. Vertical profiles were averaged over seasons and approximated by the Distance Weighted Least Squares method. Winter: 447 vertical profiles, Spring: 498, Summer: 551 and Autumn: 618

out that the winter vertical profile was less variable compared to three others (especially the summer one). The second tendency implied a general increase in oxygen variation from the upper layers towards the maximal depth sampled. This tendency was less pronounced for the winter monsoon compared to the other seasons.

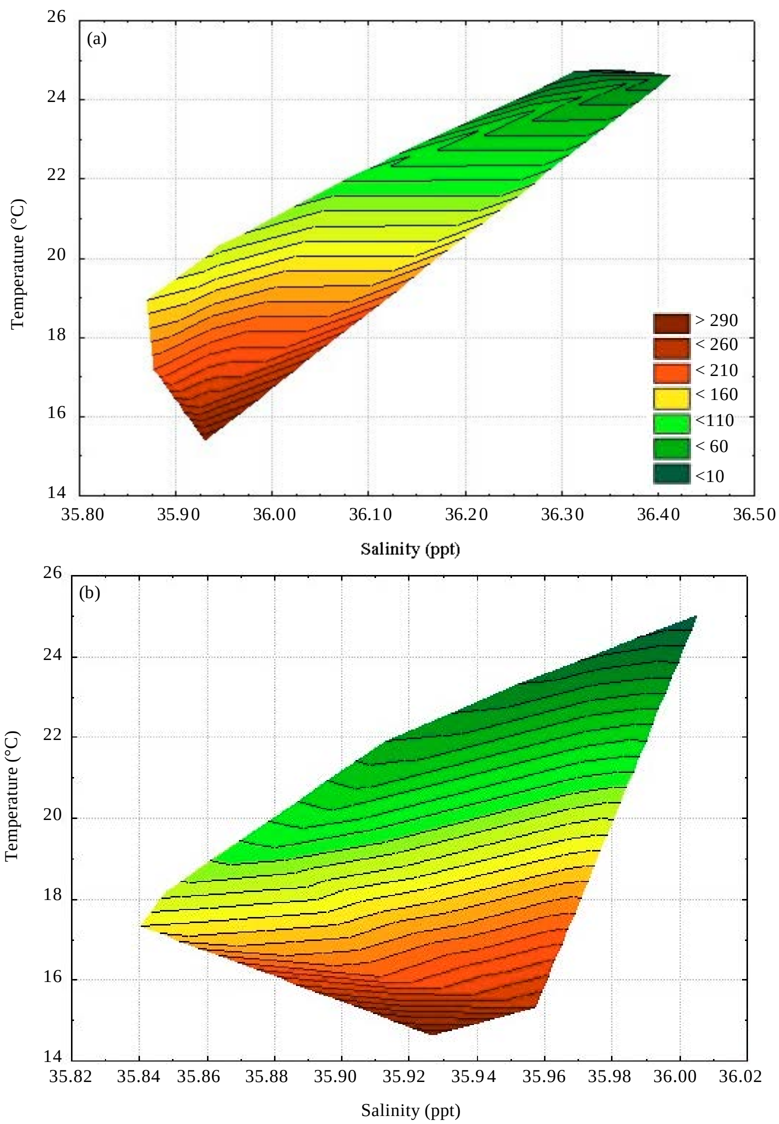

Fig. 2(a-b): Thermohaline characteristics of the (a) Winter and (b) Summer monsoons. Color spectrum represents depths, in meters

Along with oxygen, temperature and salinity casts averaged over seasons were also analyzed. In this study, data is presented for the winter and summer monsoons, in the form of T-S contours (Fig. 2). The color scale and isolines denote various depths. What made these contours different is the salinity, indicating that the range of depths from 60-160 m (which spanned the oxycline) has experienced maximal salinity variations. This variation was high during the summer compared to the winter monsoon season. As for the temperature, the latter one exhibited quite conservative properties; the range of temperatures from 60-160 m was approximately same for both seasons.

The second subset of data was contributed by a number of transects with oxygen vertical profiles across the shelf which were retrieved from a series of linked voyages, carried out during a relatively short period of time (Fig. 3). Figure 3 exemplified the spatial distribution of temperature

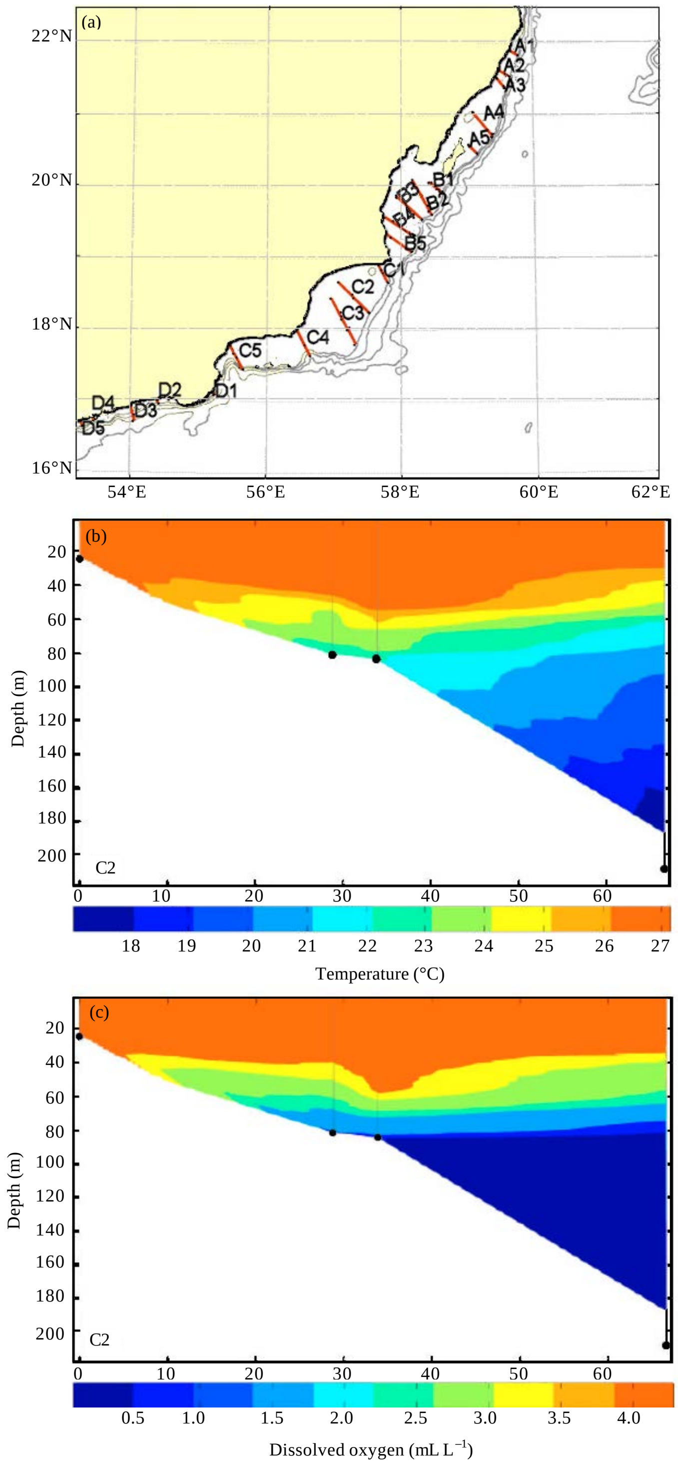

Fig. 3(a-c): Scheme of (a) Transects and distribution of (b) Temperature and (c) Dissolved oxygen along the shelf. CTD transect C2 (Baird *et al.*, 2009). R/v "Mustaqila 1" (voyage OMA 0701, September-October, 2007). Dots with vertical lines denote spatial location of CTD casts

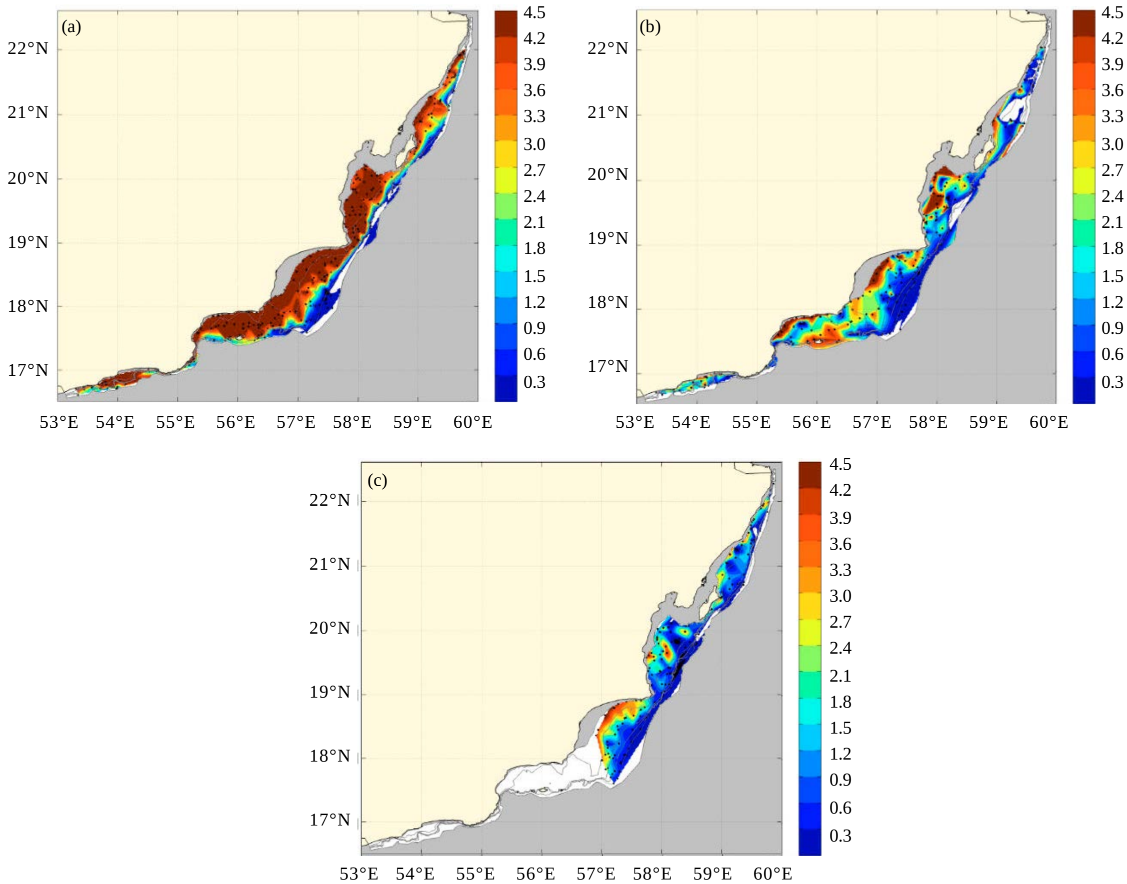

Fig. 4(a-c): Spatial distribution of the dissolved oxygen at the bottom along the Omani shelf in (a) February, (b) August and (c) September (Baird *et al*., 2009)

and oxygen concentration across the Al-Wusta shelf. A tongue of oxygen depleted waters penetrated far inshore, up to the depth of 20 m. Also, transects across the shelf resembled the mesoscale heterogeneity of temperature and oxygen distribution. For instance, a local increase of oxygen concentration is pronounced 35 miles offshore, in which the 4 mL L^{-1} zone has descended from 40-60 m deep. Deepening of high oxygen concentration was accompanied by a local decrease of temperature which indicated the upward motion of cold water. Overall, the figure implied how mesoscale heterogeneity could influence large scale spatial-temporal patterns.

The CTD casts along the shelf allow for analysis of a general pattern of spatial distribution of the dissolved oxygen, as well as its seasonal pattern (Fig. 4). Consecutive maps characterized two major constituents of the spatial-temporal structure: (1) Spatial heterogeneity in the oxygen distribution over the shelf and (2) Seasonal decline of the concentration from winter to fall, ending up in the bottom hypoxia; over 70% of the sampled shelf area was occupied by the oxygen minimum zone.

The third subset of the analyzed data was the sequence of CTD-oxygen casts repeated throughout the year in the same region (Fig. 5). This data provided insight into the process of OMZ development. Series of vertical profiles showed the tendency of shoaling of the oxycline, from

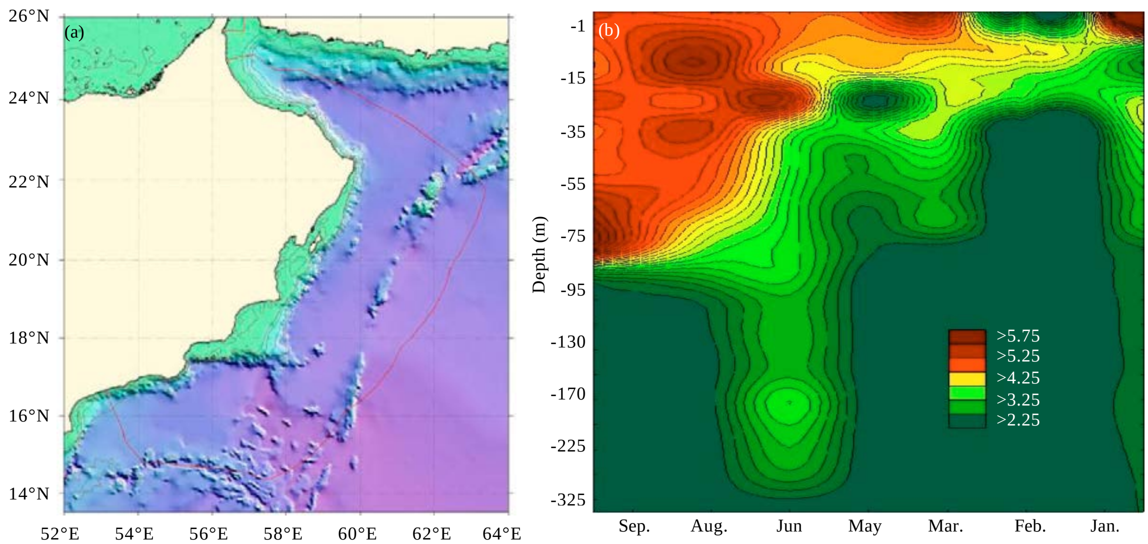

Fig. 5(a-b): Bathymetry, (a) Sampling strata (A-D) and (b) Vertical distribution of the dissolved oxygen concentration in January through September, 2008 (offshore stratum B). Red line: Oman Exclusive Economic Zone

January through September. In fact, this figure explains the previous one, in terms of how the bottom oxygen concentration changes its status, from highly saturated (in February) to the hypoxic realm (in September). It is noteworthy that in January, the OMZ was located at ~110 m while the boundary shifted upto ~35 m by September. Also, the figure captured patches of oxygen depletions as well as patches of well oxygenized waters-both nested on a general trend of shoaling oxycline. These patches were pronounced over various depths.

As far as the spatial pattern is concerned, the depth of the upper boundary of OMZ exhibited seasonal variations, alongshore. For instance, during winter monsoon, the depth changed from ~100 m near the Ras Al Had to ~400 m in the southernmost region (near the Oman-Yemen boarder) which reflected a basin scale trend of the oxygen concentration to increase southward (Morrison *et al.*, 1998).

The upper boundary of the oxycline is the barrier, configuring the location of the deep-scattering layer which has been sampled by a pelagic trawl during the “Mustaqila 1” expedition (Fig. 6). Shallow echo sound-scattering layers consisted predominantly of the myctophid species *Benthosema pterotum* (Alcock, 1890). Acoustic surveys carried out over 24 shelf transects gave the following averaged biomass of myctophids: About 0.14 million tonnes for winter, 0.92 for spring and 1.24 for autumn.

In analyzing the relationship between myctophids and their predators, data was retrived on monthly traditional landings for 2008, for a number of species whose diet reportedly comprise myctophids, the major constituent of the deep-scattering layers (Rosas-Alayola *et al.*, 2002; Tsarin, 1997). Landings were averaged for three shelf regions-Sharqiyah, Al-Wusta and Dhofar (Fig. 7). In all graphs, the 25-75% quartiles of monthly landings were shown. In terms of seasonal changes, all three graphs pointed to the landings attaining maximal values in the fall of 2008. It goes without saying, not all large pelagic species had exhibited a similar tendency. For instance,

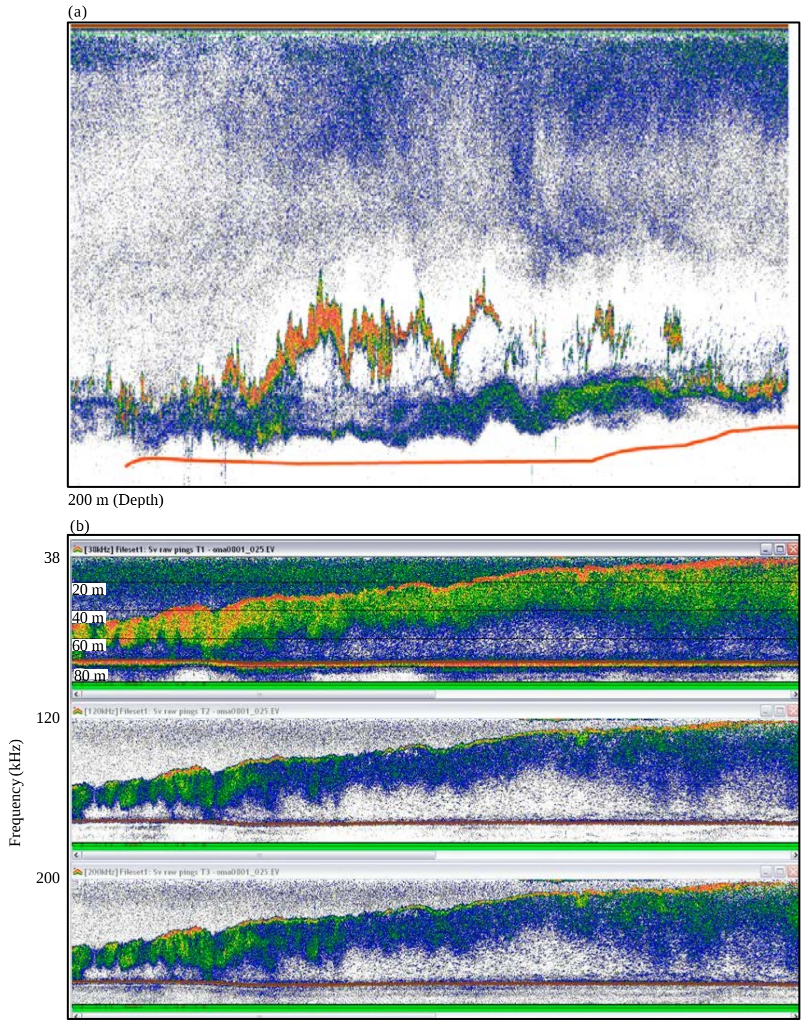

Fig. 6(a-b): Fragments of echograms recorded during the r/v “Mustaqila 1”, voyage OMA 0701. (a) A dense myctophid layer above the oxygen minimum zone (red line) during the day (Baird *et al*., 2009) and (b) Echograms of myctophid aggregations at 38, 120 and 200 kHz (Gauthier *et al*., 2009)

landings of Large Jacks (comprising 16% in total large pelagic landings) had maxima in July but the data on characterizing the contribution of myctophids to their diets on the Omani shelf was not found.

Large pelagic fish of the tropical ocean (like blue marlin-Makaira nigricans) require dissolved oxygen levels = 3.5 mL L^{-1} (Stramma *et al*., 2012). In order to present the relationship between the vertical distribution of dissolved oxygen and landings in the quantitative form, later ones plotted as the function of the 2 mL L^{-1} oxygen concentration depth, for two species (Fig. 8). In January, an oxygen concentration of this value has been recorded at ~90 m. By March 2008, the depth of the 2 mL L^{-1} oxygen concentration shifted upto 45 m and attained minimal depths later on in September which was delineated by maximal landings of Sailfish and Mullets.

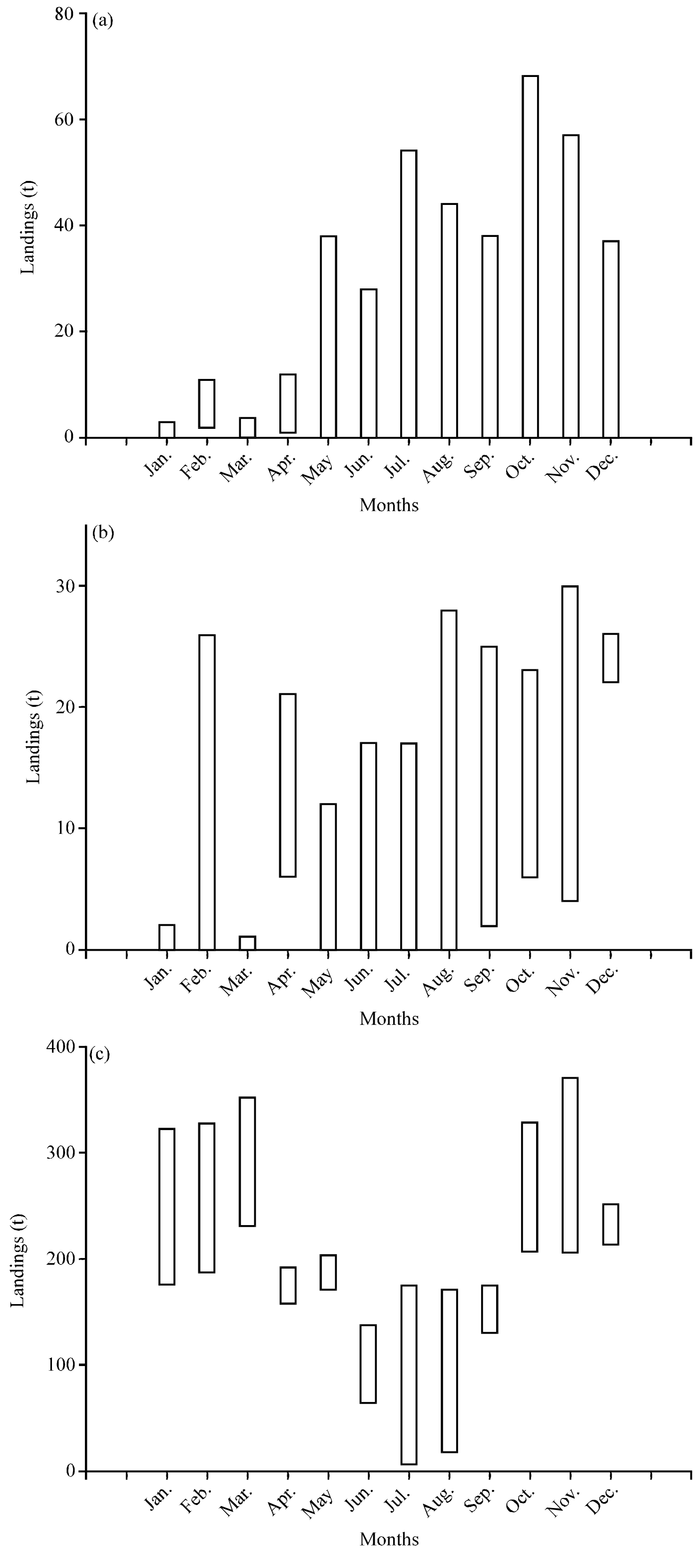

Fig. 7(a-c): Monthly landings of fish (a) Sailfish, (b) Mullet and (c) Emperor on the Oman shelf. Vertical bars are 25-75% quartiles encompassing three regions-Sharqiyah, Al-Wusta and Dhofar

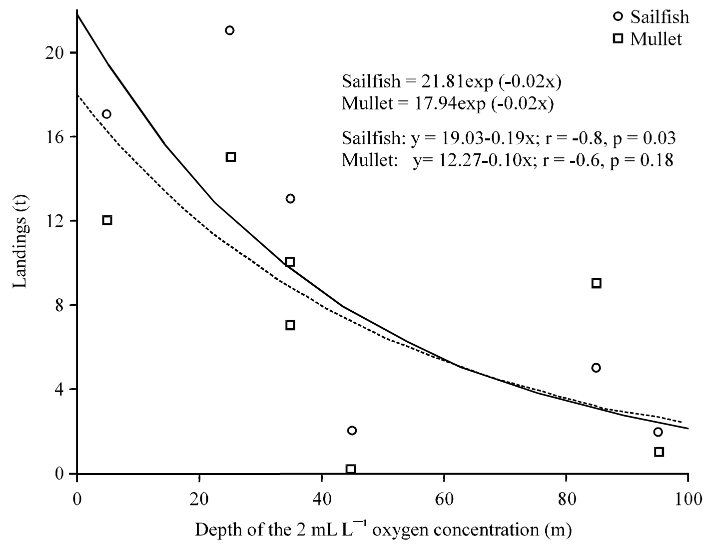

Fig. 8: Relationship between monthly landings and the depth of the 2 mL L^{-1} oxygen concentration

As for demersal fish, the processing of trawling carried out across the shelf (Table 1) indicated that most of the key demersal species in the "Mustaqila 1" trawl samples were concentrated closer to the coast in September-October while they were widely distributed over the shelf during the winter monsoon season.

DISCUSSION

In the western Arabian Sea, the upper 200 m layer is occupied by the Indian ocean surface water. Maps given by You and Tomczak (1993) imply that the annual salinity in the thermocline on the isopycnal surface σ_θ 25.7 located at a depth range of 150-200 m, is 35.6-35.8 ppt which falls into the range typical for the summer T-S (Fig. 2). The present results were slightly higher; the annual salinity in the depth range 150-200 m was 35.9 ppt.

In terms of seasonality of T-S contours, the summer monsoon variance was high compared to the winter monsoon pattern (Fig. 2). Presumably, the reason is a subsequent modification of the thermo-haline characteristics due to the reverse of the East Arabian Current. The latter one is directed north-eastward in summer and south-westward during the winter monsoon (Morrison *et al.*, 1998). The East Arabian Current is fed (in summer) by the Somali Current coming from the south, whereas in winter the reversed East Arabian Current is fed by the northern and central Arabian Sea waters transported by the North Monsoon Current (Beal *et al.*, 2013). Salinity variations mediated by horizontal advection are most intense in the northern Indian Ocean during the summer monsoon (Rao and Sivakumar, 2003).

In earlier studies of the region, the deepest mixed-layer depths were reported by the US JGOFS expedition during the winter monsoon (Morrison *et al.*, 1998). A 50% decline in the median saturation near the core of the North Arabian Sea High Salinity Water, from March to August and even larger between May and November, was noticed for the open waters of the northern Arabian Sea. This seasonal decline was suggested to be renewed early in the year, due to winter convection (Banse and Postel, 2009).

What causes oxycline shoaling in the fall? DiMarco *et al.* (2010) observed periodic fluctuations of oxygen concentration in the Gulf of Oman (Shinas region) and interpreted periodic decline of oxygen (from winter to fall) by the impact of monsoonal winds resulting in winter coastal upwelling raising already low oxygen water higher in the water column.

From our point of view, we are dealing with the basin scale mechanism mediating annual periodicity in oxygen fluctuations, rather than a regional phenomenon. This means a number of processes are involved. One of them is the reverse of monsoonal winds affecting the system of geostrophic currents. This forces the water mass to exert low-frequency oscillations due to which the thermocline and the oxycline-both exhibit vertical shifts.

The other process which might be involved is a seasonal increase of evaporation (in particular during summer) which should affect salinity and density of the upper mixed layer. This reduces mixing, alters the sea level, sea surface slope and eventually the speed and direction of geostrophic currents. On the horizontal scale, the result is the penetration of oxygen depleted waters far inshore; oxygen vertical profiles are getting progressively shallow. For instance, in the Arabian/Persian Gulf, the sea surface slope is driven by the evaporation rate which affects regional circulation (Swift and Bower, 2003).

Noteworthy, shoaling of the oxycline in the fall of 2007 was reported for the central interior region of the Arabian Sea. The depth varied between 120 and 60 m with occasional values at 40 m. It was assumed that the observed decrease in the oxycline depth recorded by an ARGO float deployed in the oxygen minimum zone is caused by upwelling Rossby waves (wherein lowering of the thermocline shifts low-oxygen water to a shallower level). Triggered off the west coast of India and strengthened by the local wind stress curl, these waves propagate westward (Prakash *et al.*, 2012).

Along with physical-chemical forcing, the biological process mediating periodic decline of the dissolved oxygen should be taken into account. This decline is driven by bacterial decomposition of the organic matter-the algal bloom biomass. In studying the Omani shelf OMZ, Herring *et al.* (1998) pointed out that this zone is maintained in part by the high seasonal productivity at the surface. Periodicity of algal blooms in Omani shelf waters stems from seasonal availability of nutrients in the euphotic zone which in turn is mediated by summer and/or winter monsoons (Al-Azri *et al.*, 2012; Piontkovski *et al.*, 2013). We assume that footprints of biological activity markedly diminishing the dissolved oxygen concentration might be noticed in Fig. 1, in which the oxygen concentration during the highly productive summer monsoon is less than the concentration in a subsequent inter-monsoonal season (in autumn).

The difference in the structure of vertical profiles between summer and winter monsoons is most pronounced in the upper 30 m layer, in which the dissolved oxygen (in summer) starts to diminish linearly, to the depth of 100 m. Summer and winter monsoons impose different modes of physical-biological coupling in the western Arabian Sea, in which Ekman pumping associated with the offshore advection (in summer) or winter deep convective mixing mediate high productivity observed during monsoon periods (Kumar *et al.*, 2009; Wiggert *et al.*, 2000). These differences should be reflected in the oxidation and decomposition of organic matter produced by blooms which are footprinted in the structure of averaged vertical profiles of dissolved oxygen (Fig. 1). Moreover, the physical dynamics of waters mediated by the summer and winter monsoons induces a gradually different spatial variance of the dissolved oxygen concentration and thermohaline characteristics, with maximal values during the summer monsoon (Fig. 2, Table 3). This difference might be caused by a variable impact of mesoscale eddies on spatial distribution of these characteristics. In the western Arabian Sea, the highest frequency of eddy occurrence was reported for the summer period (Piontkovski and Al-Jufaili, 2013). Series of publications have provided insight into the impacts of eddies on the spatial variance of oxygen, temperature and salinity in this region (Banse and Piontkovski, 2006; Flagg and Kim, 1998; Morrison *et al.*, 1998; Piontkovski and Al-Jufaili, 2013).

Periodic changes of the oxygen spatial distribution affect the density of epipelagic and mesopelagic fish populations. Oxygen levels less or equal to 0.3 mL L^{-1} are considered physiologically limiting for many fish species (Ashjian *et al.*, 2002; Ekau *et al.*, 2010). In the western Arabian Sea, myctophids tend to be concentrated at the upper boundary of the oxygen minimum zone (Fig. 5). This means that populations follow seasonal displacement of the oxygen vertical profile. Once myctophids constitute a marked part of the diet of epipelagic and mesopelagic fishes, the upward shift of oxycline should make myctophids easier targets for pelagic predators. The echo-soundings and trawls carried out along the Oman shelf-both pointed out that in January, when oxycline is located deep (which points to well oxygenated shelf waters), fish are widely distributed throughout the shelf. In the fall, when oxycline moves up, most of the mesopelagic fish species shift up and closer to the coast. Since shallow water is well mixed, no oxycline is observed there. Consequently, one might expect the increase of fish catch in coastal waters. We tested this hypothesis through the analysis of monthly data on fish landings for some pelagic and demersal species (Fig. 6 and 7) which exhibited elevated values in fall. In the case of Sailfish, for instance, the vertical distribution is known to be correlated with the dissolved oxygen concentration so that hypoxic layers act as barriers to vertical movement (Prince and Goodyear, 2006).

Overall, the data discussed above partially clarify the seasonality in coupling between fish landings and the oxygen minimum zone characteristics. Seasonal shoaling of the oxycline shifts the deepened layer of myctophids up to the surface, as well as closer to the coast which in turn favors accumulation of their predators in the same locality. Both phenomena compress the habitat and increase artisanal landings reported by Oman fishery.

We suppose that the habitat compression is phenomenon pronounced over various spatial-temporal scales and regions. Eby and Crowder (2002) examined 10 estuarine fish species which all avoided areas with dissolved oxygen concentrations of <2.0 mg L^{-1}. They showed that fish may occupy the low concentration areas as conditions worsen and the size of the oxygenated refuge shrinks. It was proposed that this habitat compression may result in higher densities and greater overlap with potential competitors and predators. Prince *et al.* (2010) investigated the vertical habitat use of 32 sailfish (Istiophorus platypterus) and 47 blue marlin (Makaira nigricans) specimens monitored with pop-up satellite archival tags. It was shown that the near-surface density of billfish and tunas in the Eastern Tropical Atlantic increases as a consequence of oxygen minimum zone development, therefore increasing the vulnerability of populations to overexploitation by surface gears.

Not only the pelagic predators may be affected by the seasonal compression of shoaling oxycline, but the demersal fish as well. On the shelf of the Sea of Oman (Gulf of Oman), species diversity increased by 96% in March-2006 compared to November-2005. The authors argued that the upward migration of oxygen-depleted water to a shallow depth during the late monsoon displaced the demersal fish community along the coast (McIlwain *et al.*, 2011).

High traditional landings in fall are accompanied by another phenomenon: The frequency of fish kill incidents. In the western Arabian Sea, these incidents are reportedly high in fall compared to the other seasons (Piontkovski *et al.*, 2012). Oxygen deficiency is one of the major factors forcing this frequency.

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