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ORIGINAL RESEARCH

Decadal changes of the Western Arabian sea ecosystem

Sergey A. Piontkovski · Bastien Y. Queste

Abstract Historical data from oceanographic expeditions and remotely sensed data on outgoing longwave radiation, temperature, wind speed and ocean color in the western Arabian Sea (1950–2010) were used to investigate decadal trends in the physical and biochemical properties of the upper 300 m. 72 % of the 29,043 vertical profiles retrieved originated from USA and UK expeditions. Increasing outgoing longwave radiation, surface air temperatures and sea surface temperature were identified on decadal timescales. These were well correlated with decreasing wind speeds associated with a reduced Siberian High atmospheric anomaly. Shoaling of the oxycline and nitracline was observed as well as acidification of the upper 300 m. These physical and chemical changes were accompanied by declining chlorophyll-*a* concentrations, vertical macrofaunal habitat compression, declining sardine landings and an increase of fish kill incidents along the Omani coast.

Keywords Arabian Sea · Fish landings · Chlorophyll-a · Sea surface temperature

Introduction

As an acknowledged concept of the Large Marine Ecosystems, the Arabian Sea is recognized as a unique ecosystem within the Indian Ocean (Sherman and Alexander 1990) with very pronounced fluctuations in physical, chemical, and biological properties. Seasonal dynamics of the Arabian Sea have drawn interest from the international scientific community over the past 50 years; however there has been a paucity of studies in the last two decades due to logistical constraints. In terms of changes, the region exhibits strong seasonal dynamics in which monsoonal winds force periodic modes of ocean–atmosphere coupling with dominant annual and semiannual periods (Morrison et al. 1998). Ultimately, these modes of atmospheric and hydrophysical processes are reflected in corresponding fluctuations of biological productivity (Banse and English 2000; Barber et al. 2001). What is currently less understood, namely due to reduced sampling in the last 20 years, are dominant patterns of variability over decadal timescales.

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Srivastava et al. (2000) investigated decadal trends in cyclonic disturbances across the Arabian Sea and the Bay of Bengal from 1891 to 1997 and identified a significant decrease in the annual frequency of storms across both basins. The decrease in storm frequency was particularly pronounced from 1970 to the present. In parallel, Zveryaev (2002) recorded an increase in sea surface temperature over the last few decades resulting in decreased land–sea heat gradients and weaker low-level westerlies over the northern Indian Ocean.

Gomes et al. (2014) reported a gradual change in dominant phytoplankton species during algal blooms in the northern Arabian Sea. Diatom-dominated communities were replaced by the dinoflagellate, *Noctiluca scintillans,* since the early 2000s. The authors associate this shift in community composition to more frequent upwelling of hypoxic waters into the euphotic zone. Over the same period (1998–2012), a decadal declining trend in global pelagic ocean chlorophyll was evaluated by Gregg and Rousseaux (2014), with a reference to the north Indian Ocean as well. However, their time series were relatively short.

Empirical evaluation of regional decadal trends is important for their subsequent assimilation by three-dimensional coupled physical-biogeochemical models which allow a multilateral understanding of physical-biological interactions and accurate long-term forecasts to be achieved (Peňa et al. 2010; Francis et al. 2013). These models would clarify the causes of global and regional warming, expanding hypoxia, declining primary production of the open ocean and many other phenomena which are currently under investigation.

The main constraint to identifying variability of ocean properties on decadal timescales is the availability of a well quality controlled regional database. In our case, this database is focused around the western Arabian Sea and assembles data from all available oceanographic expeditions to the region. In the present paper we put together the main decadal trends identified for the western Arabian Sea over the past 50–60 years, highlighting the changes which occurred between the first and forthcoming second International Indian Ocean Expeditions (Snider, 1961; Intergovernmental Oceanographic Commission 2013). We also describe the ecological impacts of the physical and chemical changes observed over decadal timescales, particularly with respect to Omani fisheries.

Materials and methods

Atmospheric pressure, sea surface temperature, outgoing longwave radiation, zonal and meridional wind speed components were retrieved from the NCEP/NCAR reanalysis database (Kistler et al. 2001), which is a joint product from the National Center for Environmental Prediction (NCEP, USA) and the National Center for Atmospheric Research (NCAR, USA). The product represents gridded data from 1948 to the present time. Each variable was extracted to cover the region bounded by 10°N–26°N and 50°E–64°E. 10 m wind speed, air temperature, water temperature, salinity, pH, dissolved oxygen, nitrate and chlorophyll-*a* concentrations, measured both in situ and remotely, were collected from 1950 to 2010 in a region previously mentioned.

The meridional wind component has a positive value when the wind is blowing from south to north. A south wind has a positive meridional constituent, while a north wind has a negative one. In case of zonal component, values are positive when the wind is blowing from west to east. Thus, a west wind has a positive zonal constituent while an east wind has a negative one.

The pH of seawater was measured by means of standard pH-meters "pH-262", "pH-340" (Methods on hydrochemical investigations of the ocean 1978) and by using the spectrophotometric techniques (Clayton and Byrne 1993). In the latter case, the pHT of samples using m-cresol purple (mCP) was determined from $pH_T = pK_{ind} + \log[(R-0.0069)/(2.222-0.133\,R)]$, where pK_{ind} is the dissociation constant for the indicator, $[H+]_T = [H+] + [HSO4-]$, and R (A_{578}/A_{434}) is the ratio of the absorbance of the acidic and basic forms of the indicator corrected for baseline absorbance at 730 nm.

The major part of the onboard measured concentration of nitrates and dissolved oxygen came from the UK and USA expeditions with an appropriate description of chemical analysis given elsewhere (JGOFS 1996; JGOFS Protocols 1994). 72 % of the data collected originates from US and UK expeditions (Table 1). The location and number of casts within a 2° grid square of all 29,043 vertical temperature profiles is shown in Fig. 1. In order to evaluate decadal changes, these data were arranged in the form of time series or decadal subsets, from 1950 to 2010. Vertical profiles of physical and chemical parameters were smoothed by cubic spline (Craven and Wahba 1979).

Table 1 Research vessels and cruises assembled and contributed to the historical database on CTD casts

Country	Institution	R/V name and cruise #	Year
UK	BODC	DISCOVERY(D10)	1994
UK	BODC	DISCOVERY(D12)	1994
UK	UKNO	DALYMPLE	1960, 1963
UK	UKNO	HYDRA	1976, 1984
UK	UKNO	ROYAL NAVY NON-SURVEY VESSELS	1960, 1995
UKRAINE	MHI	MIKHAIL LOMONOSOV, 19	1966
UKRAINE	IBSS	PROFESSOR VODYANITSKIY, 30	1990
UKRAINE	YugNIRO	NAUKA	1967–1980
UKRAINE	YugNIRO	SKIF	1969–1970
USA	NODC	THOMAS G. THOMPSON (TTN-043)	1995
USA	NODC	THOMAS G. THOMPSON (TTN-045)	1995
USA	NODC	THOMAS G. THOMPSON (TTN-049)	1995
USA	NODC	THOMAS G. THOMPSON (TTN-050)	1995
USA	NODC	THOMAS G. THOMPSON (TTN-053)	1995
USA	NODC	THOMAS G. THOMPSON (TTN-054)	1995
USA	NODC	USCGC RELIANCE	1961
USA	NODC	COMMANDANT ROBERT GIRAUD	1961
USA	NODC	KNORR	1995
USA	WHOI	ESSO AFRICA	1976
USA	WHOI	ESSO GENEVA	1976–1977
USA	WHOI	ESSO KAWASAKI	1975–1977
USA	WHOI	ESSO WILHELMSHAVEN	1976–1977
USA	WHOI	ESSO HONOLULU	1976, 1979
USA	WHOI	ESSO MADRID	1978–1977
USA	US NAVY SHIPS OF OPPORTUNITY	NAVY SHIPS*	1960, 1992
GERMANY	FM-GEOMAR	METEOR 32_1	1995
GERMANY	FM-GEOMAR	SONNE 89_1	1993
GERMANY	FM-GEOMAR	METEOR 32_4	1995
GERMANY	FM-GEOMAR	METEOR 32_6	1996
GERMANY	FM-GEOMAR	METEOR 74_3	2007
GERMANY	FM-GEOMAR	SONNE 118	1997
GERMANY	FM-GEOMAR	SONNE 119	1997
GERMANY	FM-GEOMAR	SONNE 120	1997
THE NETHERLANDS	NIOZ	TYRO, LEG D2	1992
THE NETHERLANDS	NIOZ	TYRO, LEG D3	1992
PAKISTAN	NIOPK	NASEER1	1992
PAKISTAN	NIOPK	NASEER2	1992
PAKISTAN	NIOPK	NASEER3	1993
PAKISTAN	NIOPK	NASEER4	1994
PAKISTAN	NIOPK	NASEER5	1994
JAPAN	JODC	UMITAKA MARU	1994
CANADA	CANADIAN NAVY	ROYAL CANADIAN NAVY SHIPS	2001–2005
FRANCE	NHOS	BEAUTEMPS-BEAUPRE	2004–2010
AUSTRALIA	AUSTRALIAN NAVY	ROYAL AUSTRALIAN NAVY SHIPS	2001–2010
OMAN	MSFC	COASTAL WATERS STATIONS	2001–2010

Table 1 continued

Country	Institution	R/V name and cruise #	Year
	FREE-DRIFTING PROFILING FLOATS ARGO		2002–2010

* NAVY research vessels: MT MITCHELL, AYLWIN. BAINBRIDGE, BROWN, BROWNSON, BRUMBY, CAPODANNO, DECATUR, ESSEX, FANNING, HEWES, J., KITTY HAWK, LA SALLE. MOBILE BAY, MULLINNIX, NEW, NOA, PASSUMPSIC, EARY, R. E., PHARRIS, REQUISITE, SEMMES, STRIBLING, TANNER, USS GEORGE K. MACKENZIE, VALDEZ, VOGELGESANG, ARCO JUNEAU, KIRK, KOELSCH, LAWRENCE, MOALE, MONTGOMERY, E., PAUL, TAYLOR, AIRCRAFT, BERKELEY, HOLT, H. E., and SOMERS

Data on industrial and traditional landings from Omani fisheries are based on a sampling system established by the Oman-American USAID project (Mathews et al. 2001) and have been regularly collected by the Department of Fisheries Statistics. Data on annual landings of sardines in the Sea of Oman were taken from the annual reports published by the Ministry of Agriculture and Fisheries (Fishery Statistics Book 2010). Fisheries data were complemented by data on fish kill incidents along the Omani coast, available from the
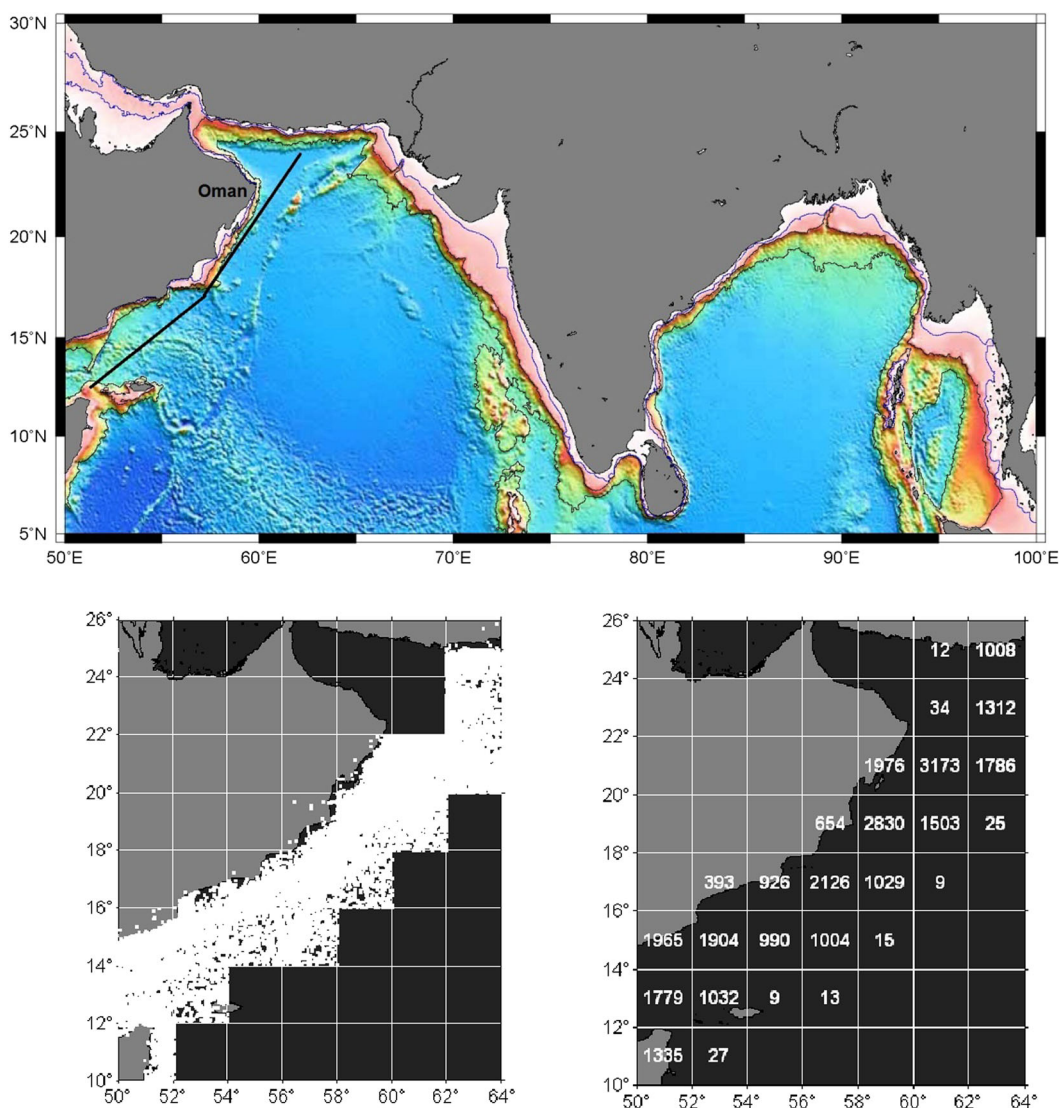

Fig. 1 Historical data and regions: (*Upper panel*) the map with the transect indicating the main axis of sampling sites near Oman; (*Left low panel*) location of oceanographic stations with *vertical* profiles of temperature (1950–2010); (*Right low panel*) actual number of CTD casts over 2° *squares*

archives of the Marine Science and Fisheries Research Center (Muscat, Oman) and published by Al-Gheilani et al. (2011).

Results

Atmospheric parameters

The outgoing longwave radiation (OLR) features the total radiation emitted by the atmosphere to space. It is believed that the OLR variations are affected by the Earth's skin temperature, atmospheric temperature, water vapor, and cloud cover (Susskind et al. 2011). Monthly time series were retrieved from NCEP database, in which they also stem from NCAR archives, with some missing values filled with temporal and spatial interpolation (Liebmann and Smith 1996). We used averaged values for January–February and July–August, to seek decadal trends of OLR during North-East and South-West monsoons (Fig. 2). Apparently, positive linear trends were pronounced for both seasons over five decades.

As far as the atmospheric pressure characteristics are concerned, the Siberian High acts as one of the dominant atmospheric pressure systems affecting winds over Asia and the northern Indian Ocean during North-East (winter) monsoon (Gong and Wang 1995; Gong and Ho 2002; Kim et al. 2005). Annual characteristics of Siberian High were kindly provided by R. (D'Arrigo et al. 2005). The anomaly is defined by the value above 1028 hPa over the middle to higher Asia continent. The regression we elucidated implies a negative trend of the Siberian High index over the past five decades (Fig. 3). A Spearman rank correlation analysis of the annual time series of atmospheric pressure shows a negative correlation with sea surface temperature in winter (with $r = -0.4$, at $p < 0.05$).

The wind field in our study was characterized by zonal and meridianal components of the wind speed (Fig. 4). A characteristic pattern pronounced in both components is a declining trend covering the time range from 1960 to 2010.

Sea temperature

Two data sets were used to investigate long-term temperature trends: 60 year of SST from the NCEP-NCAR Reanalysis database and the historical database on vertical profiles of temperature we assembled for the
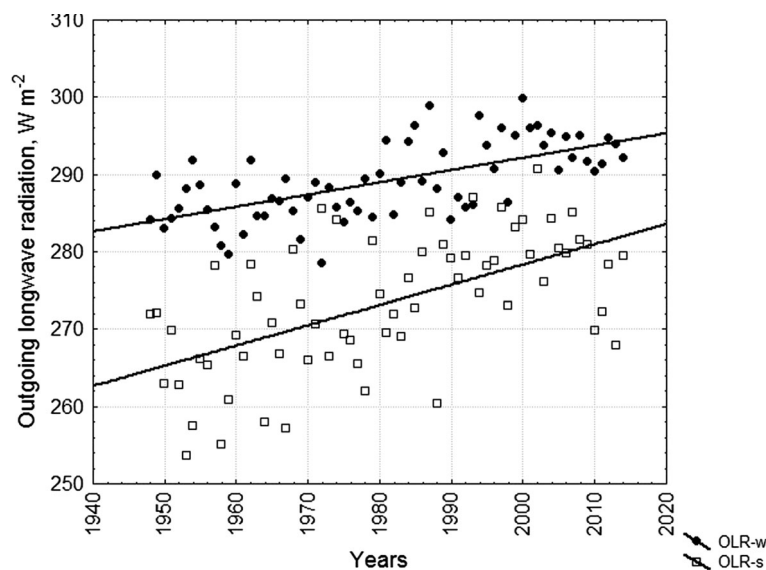

Fig. 2 Interannual changes of the outgoing longwave radiation in the western Arabian Sea during summer (OLR-s, averaged July–August) and winter monsoons (OLR-w, averaged January–February). Annual data for the period 1948–2014 retrieved from the NCEP-NCAR database
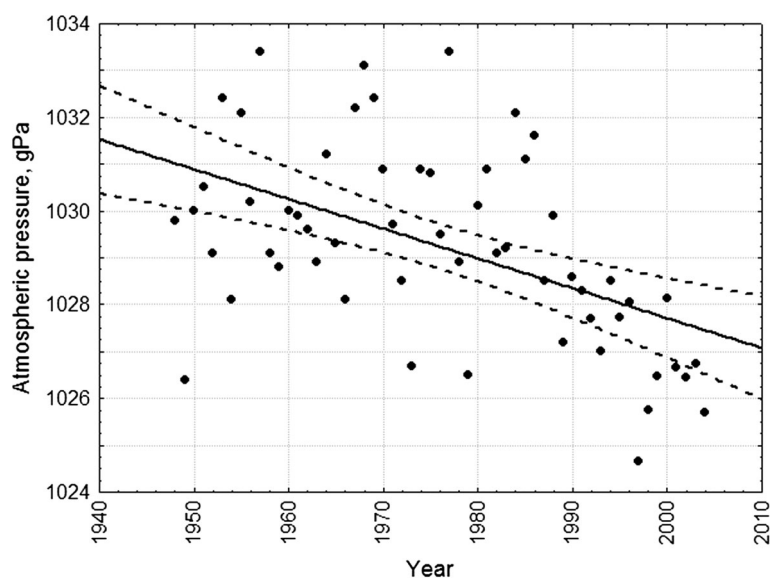
Fig. 3 Interannual changes of atmospheric pressure in the region of Siberian High (data from D'Arrigo et al. (2005). Regression parameters: $r = -0.5$; $p = < 0.05$. *Dashed lines* are 95 % confidence limits
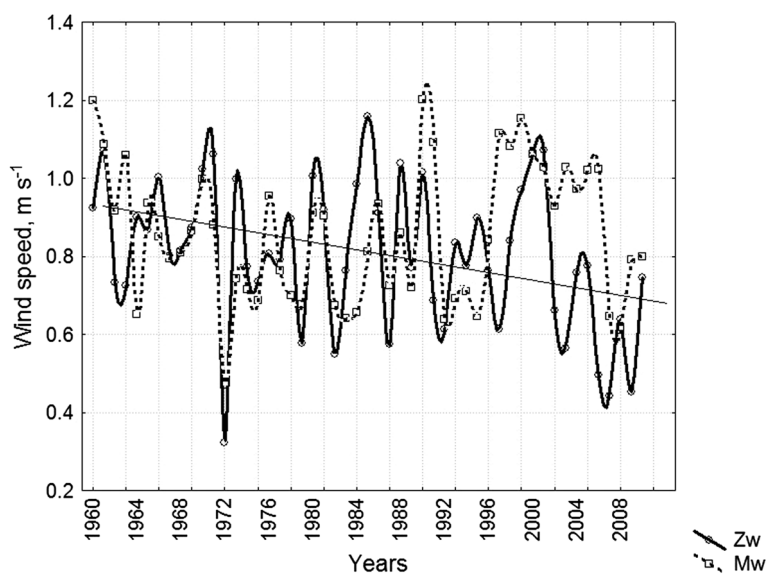

Fig. 4 Interannual changes of the wind speed in the western Arabian Sea; zonal (Zw) and meridianal components (Mw). Data were retrieved from the NCEP-NCAR database. *Curves* were smoothed by cubic spline

region. According to NCEP-NCAR data, decadal changes of the sea surface temperature in the western Arabian Sea during the South–West Monsoon can be characterized by a positive trend of 0.2 °C per decade ($r = 0.5$, $p < 0.05$).

In the western Arabian Sea, the surface mixed layer extends to ∼30 m with a seasonally variable in depth thermocline extending below. The thermocline layer is underlied by the Persian Gulf Water Mass which originates in the Persian Gulf and flows out through the Strait of Hormuz. Persian Gulf Water Mass outflow is mediated by the atmospheric pressure gradient between the Gulf and the Sea of Oman (Yao and Johns 2010). This water mass propagates eastwards between 150 and 350 m to the western Arabian Sea. The decadally averaged temperature profiles show a gradual warming of the entire water column with no change in mixed layer depth (Fig. 5). The rate of warming in the upper 30 m layer is approximately 0.6 °C per decade ($r = 0.8$, $p < 0.1$). Warming at depth is less pronounced with rates approaching 0.4 °C per decade ($r = 0.8$, $p < 0.1$).
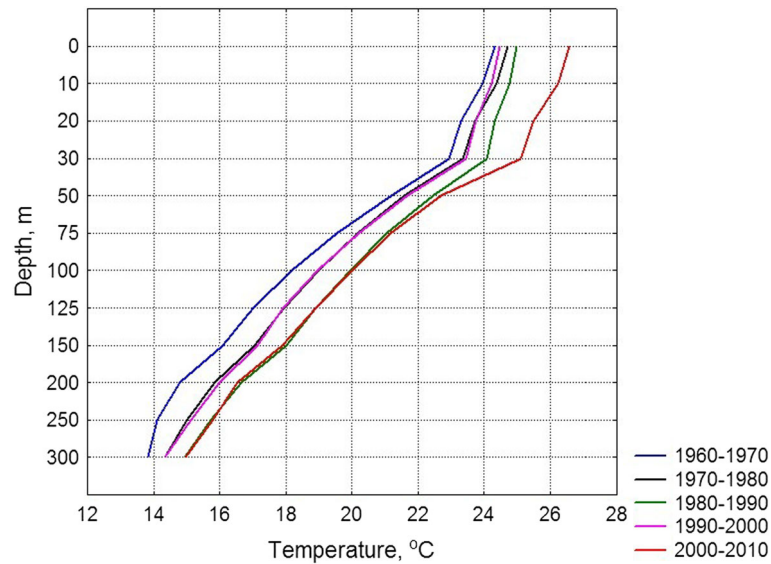
Fig. 5 *Vertical* profiles of summer temperature in the western Arabian Sea (**b**), averaged over decades
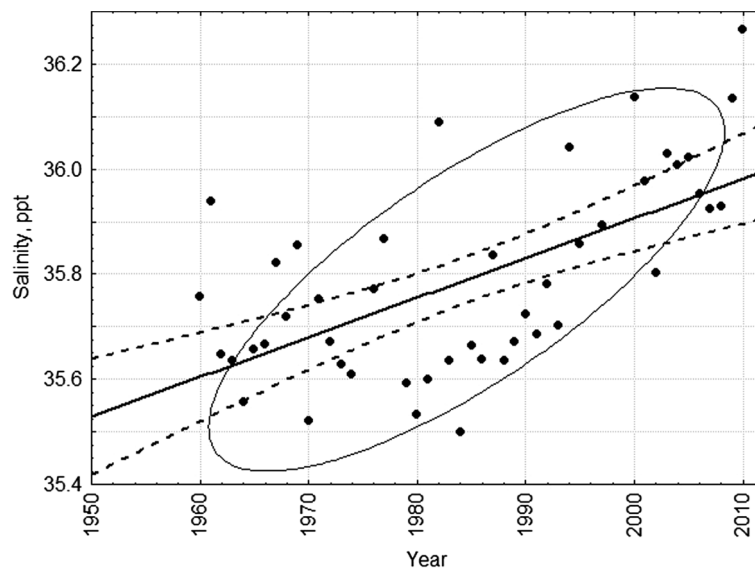

Fig. 6 Interannual changes of salinity at a 300 m depth. Regression parameters: $Y = 2.82 + 0.0075X$; Number of annually averaged measurements: $n = 676$, $r = 0.62$, $p < 0.05$. *Dashed lines* are 95 % confidence limits. The correlation ellipsis and regression *curve* are given by *solid lines*

Salinity

No decadal trends in upper mixed layer salinity were pronounced, however changes were observed at depth. A characteristic feature of the western Arabian Sea is the presence of warmer high salinity waters originating in the Persian Gulf and forming the Persian Gulf Water Mass which resides at depths of ∼ 150–350 m (Fig. 6). Changes in salinity at this depth are indicative of varying Persian Gulf Water properties or flow. We investigated decadal changes of salinity at a 300 m depth. The data indicate increased Persian Gulf Water Mass outflow during the past five decades as illustrated by the warming and increasing salinity of 0.3 signatures between 200 and 300 m (Figs. 5, 6).
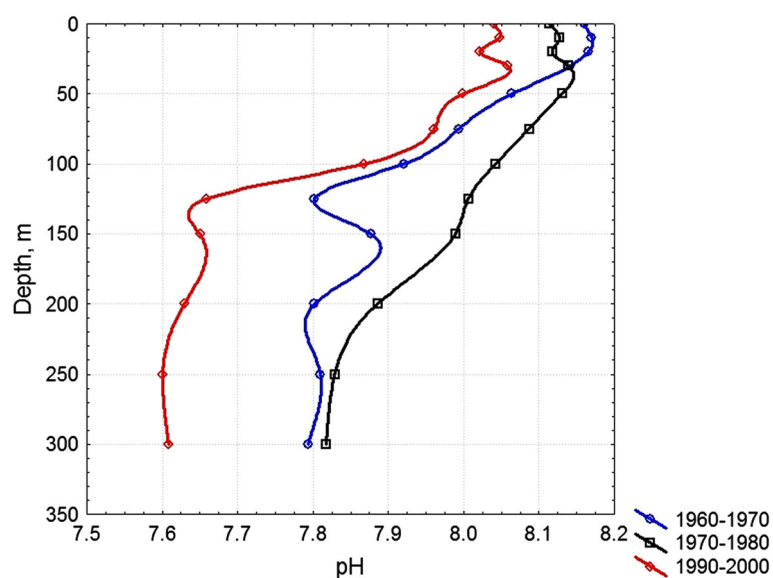
Fig. 7 Decadal changes of the pH *vertical* distribution in the western Arabian Sea. *Curves* were smoothed by cubic spline. Number of stations per decade: $n = 38$ (1960–1970); $n = 28$ (1970–1980); $n = 43$ (1990–2000)

pH

In situ measurements of pH were much less numerous compared to vertical profiles of temperature and salinity. Only 38 oceanographic stations included pH measurements between 1960 and 1970, 28 between 1970 and 1980, and 43 stations for 1990-2000. Vertical profiles were averaged annually first, then over a decade, to calculate the decadal profile. The data indicate an overall decrease in pH, particularly at depth. However due to the paucity of data, it is not possible to state that this trend is significant and not an artifact linked to temporally biased sampling (Fig. 7). Over the past 40 years, pH has diminished by 0.2 units in the upper 50 m layer (df = 22, $t = 1.76$; $p = 0.1$). Acidification rates derived from these profiles are 0.1 unit pH per decade.

Dissolved oxygen

2117 dissolved oxygen profiles were averaged over each decade (Fig. 8). They indicated a gradual shoaling of the oxycline. For instance, the depth of the 1 ml L^{-1} concentration located at ~ 145 m in 1960–1990 has shifted to ~ 80 m in 1990–2010. The shoaling of the oxycline was verified by a t test showing statistically significant inter-decadal differences between vertical profiles, in particular the "oldest" and the "newest" (Table 2).

Nitrates

Data for the concentration of dissolved nitrates came from various expeditions cited in Fig. 1 and Table 1. Nitrate measurements require a specific sampling program and are therefore less numerous. The 1960–1970 decade contained 145 stations, 1970–1980 had 18 stations and 1990–2000 had 305 stations. Decadal mean profiles imply a decline in nitrate concentrations in the upper 30 m layer above the seasonal thermocline (Fig. 9). This decline has consisted of about 30 %, comparing the oldest versus the latest profiles (1960–1970 versus the 1990–2000). Both decades are relatively well fitted by measurements, with 81 and 76 vertical profiles correspondently. The concentration decline in the upper 30 m layer has consisted of 31 %, comparing the oldest versus the latest decadal profiles.
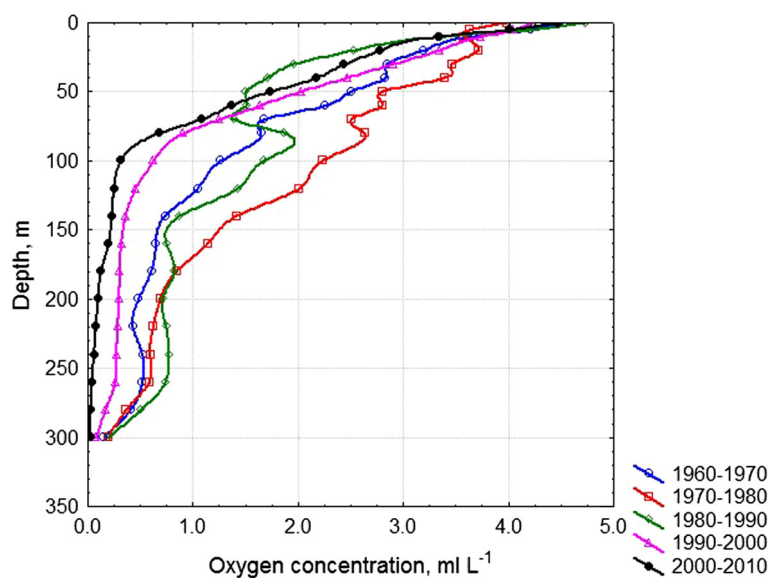
Fig. 8 Decadal changes of the dissolved oxygen vertical profiles in the western Arabian Sea during the South-west Monsoon season. *Curves* were smoothed by cubic spline

Table 2 Comparative statistics for the decadal profiles of dissolved oxygen concentration. *N* is the number of layers in the vertical profile, "*t*" is the *t* value, "df" is the degree of freedom, and "*p*" is the probability level

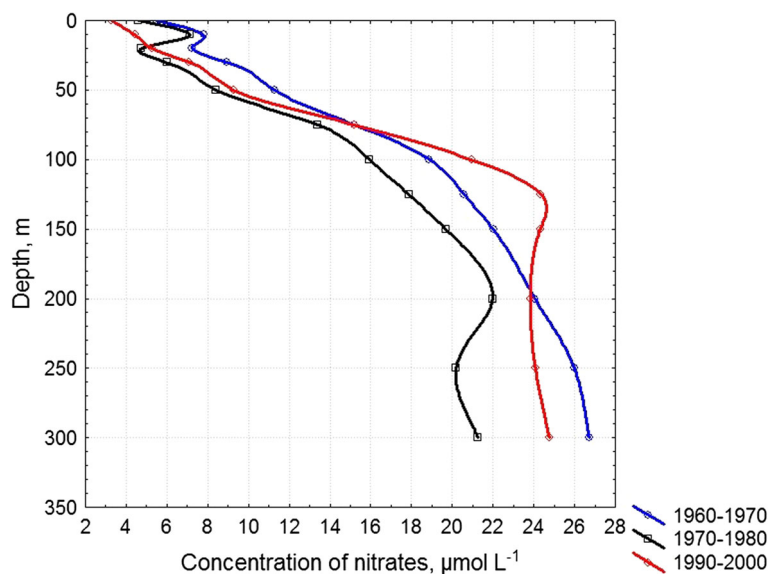| Decade	N	t	df	p
1960s vs 1970s	21	−3.48	20	0.0024
1970s vs 1980s	21	2.87	20	0.0095
1990s vs 2000s	21	5.94	20	<0.0001
1960s vs 2000s	21	8.89	20	<0.0001

Fig. 9 Decadal changes of annually averaged vertical profiles of the concentration of nitrates in the western Arabian Sea. *Curves* were smoothed by cubic spline. The number of stations per decade: $n = 145$ (1960–1970); $n = 18$ (1970–1980); $n = 305$ (1990–2000)

Chlorophyll "a"

Remotely sensed chlorophyll-*a* concentrations from the SeaWIFS scanner enabled us to analyze the time range from 1997 to 2010 only. The time series from 2002 to 2014 is available from the MODIS scanner. Both are too short to undertake an analysis over decadal timescales. The SeaWIFS time series revealed typical fluctuations of chlorophyll concentration with a dominant period of 1 year and 6 months (Piontkovski and Claereboudt 2012; Piontkovski et al. 2013). We observed a slight negative trend in chlorophyll-*a* concentrations interannualy. We also identified a strong negative correlation between sea surface temperature (Y) with chlorophyll values (X) obtained for the western Arabian Sea (Piontkovski et al. 2013): $Y = 7.41 - 0.23X$ ($r = -0.5$, $p < 0.05$). Sea surface temperatures for the region were retrieved from the NCEP-NCAR database.

Further on, the sea surface temperature was averaged for summer months for each year and correspondently (using the above mentioned equation linking sea surface temperature with chlorophyll), we obtained the chlorophyll concentrations characterizing the time of the South–west Monsoon (summer monsoon). A decadal trend was well pronounced in the retrieved time series (Fig. 10). The chlorophyll concentration has declined by about 40 %, from 1950s to 2010.

Fish landings (sardines and large pelagics)

Historical data on Omani fisheries go back to 1980s and ranked by several categories entitled in archived materials as "Large pelagics", "Small pelagics", "Demersal", "Unidentified Fishes", and etc. Within these categories, fish are distributed in groups such as "Barracuda", "King Fish", "Queenfish", "Sardines", etc. Sardines have dominated small pelagic fish catches over the Omani shelf. Approximately 80 % of artisanal landings within this group are contributed by the Indian oil-sardine *Sardinella longiceps* (Al-Abdessalaam 1995).

We retrieved monthly values and compiled data in the form of landings over the Arabian Sea, the Sea of Oman, and total Omani landings (Fig. 11). The time series obtained appeared to be relatively short. However, even in the range of the last two decades, one could observe a tendency of sardine catches to decline, over the Omani coast. In terms of decadal changes, a general decline of the magnitude of seasonal fluctuations might be observed. These fluctuations were much more pronounced in the 1990s compared to the next decade. Unfortunately, we were forced to construct the monthly time series by starting from 1994, because archived data from the 1980s were full of missed values.
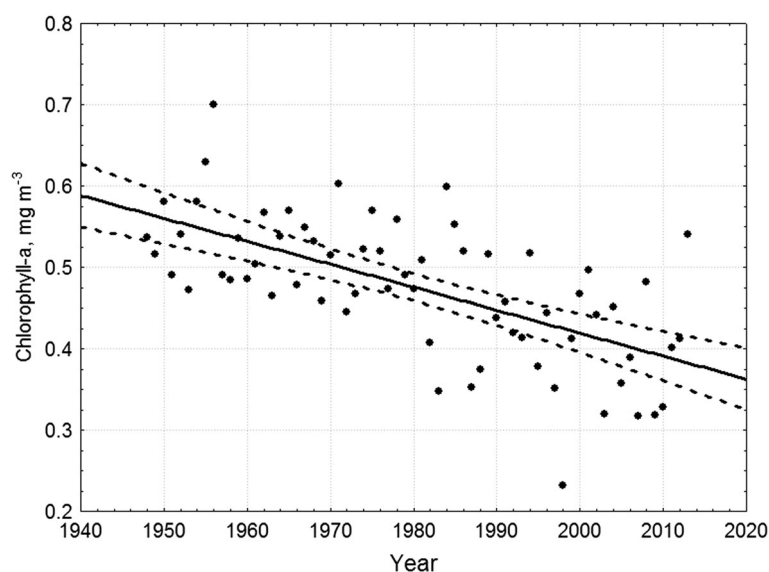

Fig. 10 Decadal changes of the chlorophyll-*a* concentration in the surface layer ($Y = 6.06 - 0.003X$; $r = -0.6$; $p < 0.05$). *Dotted lines* are 95 % confidence limits

Being intensive consumers of phytoplankton in Omani waters (Haleem et al. 2011), through fluctuations of landings, sardines demonstrate a positive correlation with monthly fluctuations of chlorophyll-*a* concentrations (Piontkovski et al. 2014). As for the chlorophyll-*a* concentration itself, we showed that this parameter has exhibited a declining decadal trend (Fig. 10).

Data on fish landings, despite their known errors and biases have been commonly used to infer associations between fish and their environment (Sundermeyer et al. 2005; O'Brien and Rago 1996). We analyzed interannual fluctuations of Yellowfin tuna and sardine landings. Being a planktivorous fishes, sardines are hunted down by large pelagic species such as the Yellowfin tuna. These trophic interactions dominate in the upper layer and are visible in landing statistics (Fig. 12). One could denote the fluctuations close to an inverted type, featuring the "Predator–Prey" interactions over the past 14 years. In this particular case, landing values might be treated as indicators of population abundance: a rising abundance in the population of predator
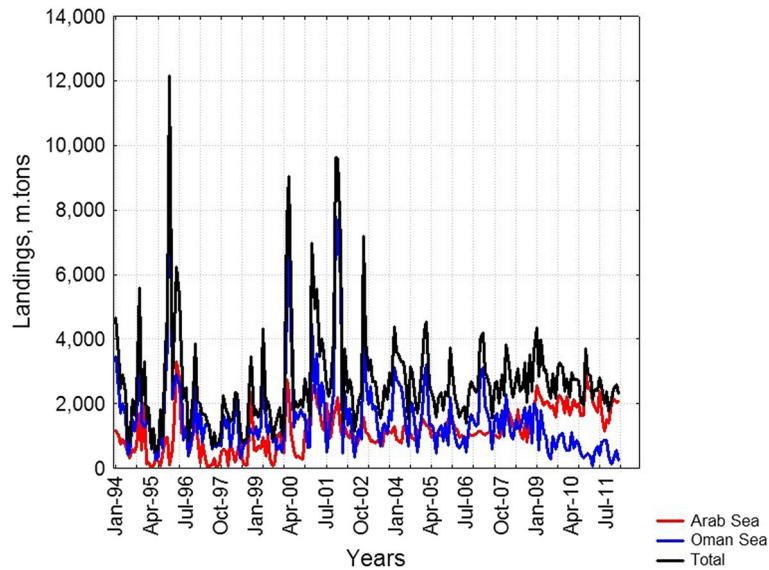

Fig. 11 Monthly fluctuations of sardine landings along the Omani shelf (the Arabian Sea, the Sea of Oman, and the total landing by the sate)
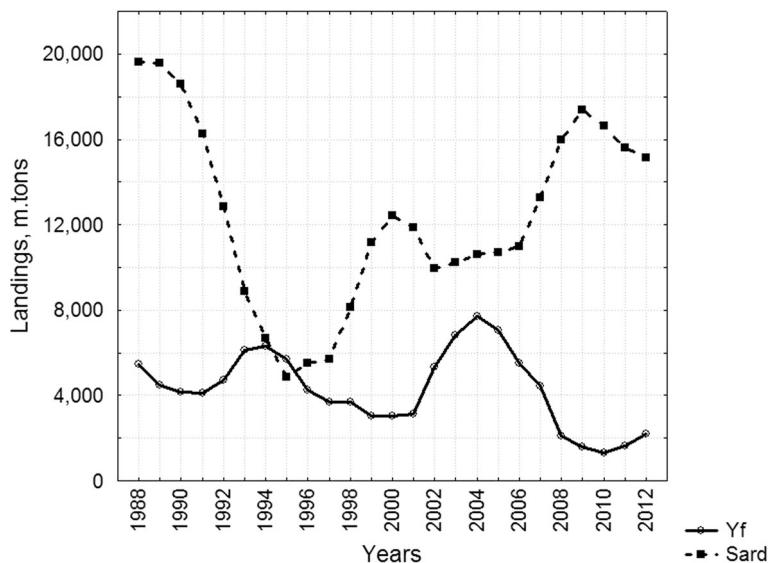

Fig. 12 Annual landings of Yellowfin tuna (Yf) and sardines (Sard) in the Arabian Sea. Time series were smoothed by the 3 year running mean

results in a decline of the prey population, and vice versa: a minimum in the abundance of predator is the time range for the population of prey to increase; exhibited by the plot. Interestingly, we did not find a similar type of the "Predator–Prey" interaction to be pronounced in landings of Yellowfin tuna in other subtropical regions, like southern latitudes of the western Indian Ocean, near Mauritius island (Dhurmeea et al. 2012) in which the oxycline is deepened, compared to the north-western Arabian Sea shelf.

Variability in Persian Gulf Outflow greatly influences the depth of the oxycline and thought that available vertical habitat for each species. It is possible that the fluctuations observed here are also affected by temporal patterns of habitat compression in the Sea of Oman.

Fish kills

The early records on fish kill incidents along the Omani coast overlooking the western Arabian Sea are date back to the mid 1970s. Since then, monitoring of algal blooms and fish kill incidents has been carried out by the Ministry of Agriculture and Fisheries at several points along the ~3000 km of the Omani coast. Records exhibit a threefold increase in the frequency of fish kill incidents (Fig. 13). In this regard, the latest decade appeared to be the most dramatic. Overall, the main contributors to fish kills were small pelagic fishes. Part of fish kills were observed during algal blooms, but also related to warm low oxygenized waters (Al-Gheilani et al. 2011).

Discussion

Linear (decreasing or increasing) decadal trends appeared to be well pronounced in a number of key environmental parameters characterizing the western Arabian Sea. In the Oman region, decadal changes in tropical rainfall and monsoon intensity are strongly related to variations in solar radiation (Neff et al. 2001). We observed positive trends in longwave radiation, air temperature at sea surface, and sea surface temperature. These trends were underlied by decadal declining trends of wind speed which in turn could be associated with a declining trend of the Siberian High atmospheric anomaly (Fig. 3). For instance, Panagiotopoulos et al. (2005) reported a statistically significant positive correlation between Siberian High and upper air zonal wind. Joseph and Xavier (1999) found a prominent linear decreasing trend in the frequencies of summer monsoon depressions, for the period of 1891–1998 (108 years).

A remote control partially mediating the atmospheric processes over the Arabian Sea region has been highlighted by a number of studies. Burns et al. (2002) reported decreasing monsoonal rainfall over the past century related to increasing sea surface temperature in the Indian Ocean. They concluded that decadal to
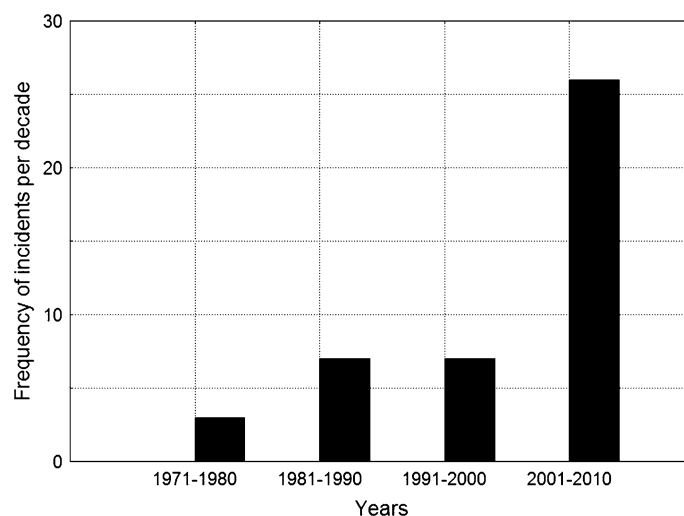

Fig. 13 Decadal changes of the frequency of fish kill incidents over the Omani coast

interannual cycles in their data appeared to originate in the tropical Pacific Ocean. For instance, the El-Niňo Southern Oscillation in the Pacific and the Indian Ocean Dipole in the southern tropical latitudes of the Indian Ocean both could contribute in part to long-term changes of sea surface temperature (Eremeev et al. 2012; Saji et al. 1999).

Warming of the water mass should theoretically result in increased acidification (Chierici and Fransson 2009). Both trends match this notion, in the aspect of decadal changes in the studied region. In analyzing decadal changes of salinity at a 300 m depth, we pointed out that not only the Persian Gulf Water Mass got warmer over past five decades; it also got saltier. This shelf-related phenomenon has its basin scale extension; salinity increase was reported for 1950–2008 in the poorly ventilated deep north Indian Ocean in the range of densities driven by the Red Sea Water mass and the Gulf Water mass (Durack and Wijffels 2010; Tomzac and Godfrey 1994).

Hypoxia is generally defined as <2 mg O_2 L^{-1} (Gray et al. 2002). In the western Arabian Sea, hypoxic zones over the shelf and eastwards, towards the oceanic regions, were reported for various seasons and were studied primarily in regards to seasonal changes (Herring et al. 1998; Morrison et al. 1998). We observed both a shoaling of the oxycline and general decline of oxygen concentrations in the upper mixed layer. From this, we speculate that both processes are mediated in part by basin scale zonal and meridianal advection of water masses. For instance, in the Arabian Sea, the phenomenon of zonal advection by the western boundary current was reported by Resplandy et al. (2012). The other potential contributor to the declining trend is the frequency of occurrence of mesoscale cyclonic eddies shifting oxycline upward. The western Arabian Sea is known for its vigorous eddy field denoted by high packed cyclonic and anticyclonic eddies (Piontkovski and Al-Jufaili 2013). However, the time range enabling the decadal trend of eddy occurrence to be statistically assessed is still short for the region.

The Persian (Arabian) Gulf mediates, in part, the acidification of the north-western Arabian Sea, through horizontal advection of waters with high salinity and low pH values. A declining trend of pH reported for the Gulf in 2007–2010 (Uddin et al. 2012) is a regional fragment contributing to the basin scale phenomenon we discussed. The acidification rate we obtained (Fig. 7), has exceeded the ones reported for the other tropical and subtropical regions, i.e. during the BATS time series in the subtropical Atlantic and HOTS—Hawaiian time series in the subtropical Pacific Ocean (Doney et al. 2009), although these time series did not span the range of five decades. A pH time series of similar duration (1940–1999) was investigated recently by Shinjo et al. (2013). They provided insights into boron-isotope composition (δ11B) in massive Porites coral from Guam Island (in the North-western tropical Pacific). Interannual data showed a decreasing trend equivalent to $\sim$0.05–0.08 pH units for surface water pH.

Decadal vertical profiles of temperature pointed to a mean increase of 2.26 ± 0.91 °C at surface and 1.15 ± 0.48 °C at a depth of 300 m—both during summer period, from 1960s to 2010 (Fig. 5). The mean warming we observed over the past 60 years has exceeded the values reported for the near surface warming of the World Ocean (Gouretski et al. 2012); this highlights that regional trends do not necessarily reflect global trends. Perhaps the land-locked nature of the Arabian Sea, with no northward water mass transport contributes to a pronounced warming trend. Overall, the stratification of the water column has become more pronounced in the past 5 decades. Through increasing vertical gradient of temperature, this could contribute to a reduction of dissolved nitrate observed in the upper 30 m layer (Fig. 9). This would have direct ecological consequences; it is believed, excepting the South–West monsoon season, the concentration of nitrates in the upper layer could limit primary production (McCarthy et al. 1999)—the phenomenon reflected in part by a declining decadal trend of chlorophyll-a concentration (Fig. 10).

All in all, this suggests that the decadal trends we discussed are coupled. The weakening of the Siberian High atmospheric anomaly (Fig. 3) might be one of the reasons for the decline of wind speed (Fig. 4) and correspondent increase in atmospheric temperature. This in turn increases the temperature in the mixed layer, strengthening the thermohaline stratification of the water column (Fig. 5). More stratified conditions then reduced the penetration of nutrients into the upper mixed layer (Fig. 9). This would in turn affect primary production (assessed generally by the chlorophyll-a concentration, Fig. 10) and higher trophic levels (Fig. 11). Simultaneously, the size of high productive zones in the western Arabian Sea has decreased (Piontkovski and Claereboudt 2012; Piontkovski et al. 2013).

These environmental and habitat changes could also set up favorable conditions for some species to proliferate. For instance, there is a belief that in the past decade, the dinoflagellate *Noctiluca scintillans* has

expanded markedly over the Arabian Sea. Large blooms of this species were reported in the eastern and western Arabian Sea (Gomes et al. 2014). Noctiluca prefers higher temperatures, calmer waters, and is more competitive in oxygen depleted waters (Gomes et al. 2014). This is in agreement with the observed trends in environmental conditions. Expanding blooms of *N. scintillans* may also partially explain the declining trend in chlorophyll- *a* concentrations (Fig. 10) as the species is a mixotrophic organism actively consuming phytoplankton. This correlation has previously been reported in the literature (Huang and Qi 1997).

More stratified conditions, along with acidification of the upper 300 m layer (Fig. 7), shoaling of the oxycline (Fig. 8) and declining oxygen concentrations will directly contribute to increasing fish kill incidents (Fig. 13) and habitat compression for pelagic fishes over Omani shelf. This habitat compression is likely the cause of the reduced variability in sardine landings (Fig. 11). Oxygen concentrations below 3.5 ml L^{-1} are stressful for many larger tropical pelagic fish (Prince and Goodyear 2006; Stramma et al. 2012). Oxygen and a shoaling oxycline both result in pelagic populations compressed in the upper layer. This increases they susceptibility to trawling and traditional fishing practices. Consequently, artisanal landings of pelagic species in Oman are tightly linked to hydrophysical processes and their changes over the last 50 years. Landings for 13 major groups of large pelagic species (Yellowfin tuna, Longtail tuna, Kawakawa, Stripped bonito, Frigate tuna, Other tuna, Skipjack, Kingfish, Queenfish, Baracuda, Cobia, Sailfish, and Large jacks) displayed positive trends through the past 20 years (Fishery Statistics Book 2012). However, rising landings (markedly driven by increased number of boats) might end soon. A shoaling oxycline (Fig. 8) could reach an ecological threshold of oxygen depletion in the upper 50 m layer, pushing hypoxic waters further onto the Omani shelf in the coming decades. Further shoaling could cause a gradual decline or even a collapse of large pelagic fisheries as many species will move offshore. This is a critical issue as the artisanal fishery, accounting for 96 % of Omani landings, represents the cornerstone of the national industry, directly employing around 40,000 fishermen (Fishery Statistics Book 2012; Piontkovski et al. 2014).

At the same time, the amplitude of interannual changes is greater than that of decadal trends and our observations based on limited data. It is still possible that these conditions could be reversed in the coming decade. A decadal variation of atmospheric processes (like the intensity of Indian Ocean monsoonal winds) could be mediated by extra-terrestrial forces; for instance, lunar tidal actions which have the periodicity of 56, 95, 125 and 1470 years (Von Rad et al. 2006). These cycles were detected in some characteristics of sediment cores extracted from the Oxygen Minimum Zone of the Pakistan shelf. However, fluctuations of physical, chemical and biological processes of the Arabian Sea on the scale of hundreds of years are poorly understood so far.

Conclusion

In studying the western Arabian Sea, the following decadal trends were noticed, over the past 50 years (1960–2010): (1) decline of the wind speed associated with correspondent decline in the pronouncement of the Siberian High atmospheric anomaly, (2) increase of the atmospheric temperature at sea surface, water salinity and sea temperature in the upper 300 m layer, (3) intensive shoaling of the oxycline and nitracline, (4) intensive acidification of the water column, and (5) a decline of the concentration of dissolved nitrates.

Biological phenomena associated with and driven in part by the above decadal trends of physical–chemical processes were as follows: (1) compression of pelagic fish habitats and their progressive stratification due to increasing thermo-haline and oxygenic stratification in the upper 300 m layer, (2) a decline in the chlorophyll-a concentration (an indicator of biological productivity), (3) a decline of sardine landings over some regions, and (4) an increase of fish kill incidents.

Eventually, the economic and social consequences of these trends might result in a gradual decline or even a collapse of large pelagic fisheries; many species will move offshore because of intensive shoaling of the oxycline. The artisanal fishery, accounting for 96 % of Omani landings and directly employing around 40,000 fishermen would face problems.

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