Seasonal and Interannual Changes of Indian Oil Sardine, *Sardinella longiceps* Landings in the Governorate of Muscat (the Sea of Oman)

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Introduction

Oman is one of the most important countries engaged in fishing in the Middle East. The 3,240 km coastline, with a commercial fishing area of 350,000 km^2, has rich fishing grounds, the potential of which has yet to be fully evaluated. A 200 nmi exclusive economic zone extending seaward from the baseline from which the territorial waters are determined, has been declared. Omani fisheries may be divided into two broad categories, traditional (artisanal) and commercial, with the former representing the cornerstone of the national industry and accounting for 96% of landings (Fishery Statistics Book, 2011).

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ABSTRACT—Monthly data on Muscat's landings of the Indian oil sardine, Sardinella longiceps, *along with 23 environmental parameters (sea surface temperature, temperature of the mixed layer, wind speed, kinetic energy of mesoscale eddies, concentration of nitrates, dissolved oxygen, chlorophyll-*a, *abundance of phytoplankton, zooplankton, and several others) were analyzed for the period 1994–2011. Seasonal changes were associated with the time of the winter (Northeast) monsoon, with maximal landings in February. The multiple regression analysis of the statistically significant variables selected through the Principal Component Analysis has implied that 51% of seasonal variability in sardine landings might be approximated by the seasonal variations of the zonal component of wind speed and chlorophyll-a concentration in the coastal and open-sea regions. In terms of interannual changes, sardine landings exhibited a declining trend from 2001 to 2011 (the time covered by the most complete data set). Rising sea temperature, thermal stratification of the water column, and the trophic pressure imposed on sardine populations by large pelagic predators (talang queenfish,* Scomberoides commersonnianus*; kingfish,* Scomberomorus commerson; *longtail tuna,* Thunnus tonggol*; and some others) might be the factors mediating this trend.*

Given the high abundance of fish in Omani waters and its importance to the livelihood of thousands of people, the fisheries sector is a significant sector in the Omani economy. There is a strong fishing tradition in Oman, and a large number of small villages scattered along the coast, from which, in 2011, around 40,161 fishermen were directly employed in the fisheries sector operating 18,731 fishing boats of which 96% were fiberglass, 8–10 m in length (Fishery Statistics Book, 2011).

Small pelagic fish are an important component of the artisanal fishery in Oman (Al-Barwani et al., 1989). In some regions, coastal pelagic fish contribute directly to human consumption of fresh, dried, canned, smoked, or frozen fish, hence a large proportion of protein and nutrition needed for poor communities, as well as providing income for fishermen. Purse seining is a major fishing method for these species, including large-scale fishing for conversion of fish into fish meal and oil (particularly by Peru and Chile).

In Omani waters, small pelagic fish, including the Indian oil sardine, *Sardinella longiceps*, occur in large quantities (Haleem et al., 2011). Small pelagic stocks in Oman waters appear to be sustainably fished at the moment, and research surveys suggest that there is room for some further expansion in the Arabian Sea. These species form an important component of the marine food web because they comprise the bulk of the forage for large fish and other predators (Al-Barwani et al., 1989). They also contribute significantly to the Omani marine fishery: in 2011 about 27,931 metric tons (t) of sardines were landed along the coast of Oman valued at 5.8 million RO (~15 million USD).

Sardines are exploited primarily with beach seines, cast nets, and gill nets. Small-scale sardine purse seining is already conducted in some locations (in particular in south and north Al-Batinah regions) along the Sea of Oman as a result of a recent modification by adding rings and a drawstring to gillnets, thereby forming encircling gill nets. Because they require little investment in manpower and equipment, and are efficient in catching pelagic fish, encircling gillnets are widely used by traditional fishermen. Due to sardine schooling behavior (Misund et al., 2003), beach seines, purse seine, and encircling gillnets are an efficient and effective method of harvesting. Schooling can also be facilitated through fish aggregating devices (FAD's) emitting strong light at night (Fréon and Dagorn, 2000).

Fishmeal and oil are essential ingredients in feeds used by the aquaculture industry, which grew at an average rate of 8–20% per year. If this trend continues, the demand and prices for fishmeal are likely to increase in the future, noting that this will also fluctuate at decadal scales because of the fluctuations in supply, especially from the major producers. In Oman, due to the decline in the catch of large pelagics, human consumption of sardines has increased, resulting in increased market prices. These issues may result in over-exploitation of sardines, possibly endangering the stocks in the future.

In 2011 and 2012, Oman exported about 76% of its small pelagic catch. The biggest market for all species is United Arab Emirates followed by Saudi Arabia, Qatar, and Thailand. Regionally, sardines contribute over 50% to total landings reported for the western and eastern sides of the Arabian Sea (Samuel, 1967; Dhulked et al., 1982; Fishery Statistics Book, 2011). Along the coast of Oman, approximately 80% of sardine landings from the traditional fishery are contributed by the Indian oil sardine (Al-Abdessalam, 1995).

An attempt to explain interannual variations of sardine landings on the basis of fluctuating environmental characteristics has a 100 year history (Hornell, 1910; Longhurst and Wooster, 1990; Kawasaki, 1991; Al-Jufaili, 2007; George et al., 2012). The approach stems from the ecology of sardines exhibiting rapid turnover rates of populations (with a doubling time of about 15 months), as well as their vulnerability to changes of thermal and productive properties of habitats.

In following Longhurst and Wooster (1990) and George et al. (2012), we hypothesized that in the case of the Omani traditional fishery, sardine landings are representative of stock abundance. The assumption might be adequate if the number of fishing boats in the region does not increase. In our analysis (carried out in very general terms), we also hypothesized that on one hand the phytoplankton biomass (assessed by chlorophyll-*a* concentration) will characterize the availability of food for sardines, known to be the phytoplankton consumers in the region (Haleem et al., 2011). On the other hand, sardines are exposed to the press of diverse predators represented by large pelagic species, such as the longtail tuna, *Thunnus tonggol*; sawtooth barracuda, *Sphyraena putnamae*; kingfish, *Scomberomorus commerson*; queenfish, *Scomberoides commersonnianus*; Indo-Pacific sailfish, *Istiophorus platypterus*; and some other species. Using statistical analysis of environmental variables, we have attempted to estimate the trends and factors driving seasonal and interannual changes in sardine landings in the governorate of Muscat.

Materials and Methods

Sardine landings 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 landings data for sardines and the other major fish populations in the Sea of Oman are available from the annual reports published by the Ministry of Agriculture and Fisheries Wealth (Fishery Statistics Book, 2009). Common names of the large pelagic species represented in these reports correspond to the names given in Table 1.

To assess the relationship between sardine landings and environmental variables, a set of monthly time series was assembled. These time series were selected to characterize coastal and open sea waters. The coastal time series were represented by stations BK and F sampled by the Sultan Qaboos University team of researchers over the past 8 years (Al-Azri et al., 2009). These stations (BK, lat. 23.51ºN, long. 58.72ºE, and F, lat. 23.67ºN, long. 58.5ºE) are located in the Muscat region, 25 km apart along the coast, with an average depth of 10 m and 20 m, respectively. Monthly data on the concentration of nitrates, dissolved oxygen, chlorophyll-*a*, abundance of phytoplankton (total diatoms and dinoflagellates), and zooplankton (copepods) obtained at these stations were used for the Principal Component Analysis (Jolliffe, 2002).

Table 1.—Common and scientific names of the large pelagic species.

Common names	Species
Sawtooth barracuda	*Sphyraena putnamiae*
Blacktail barracuda	*Sphyraena qenie*
Pickhandle barracuda	*Sphyraena jello*
Sharpfin barracuda	*Sphyraena acutipinnis*
Yellowtail barracuda	*Sphyraena flavicauda*
Striped bonito	*Sarda orientalis*
Sailfish	*Istiophorus platypterus*
Frigate tuna	*Auxis thzard thzard*
Longtail tuna	*Thunnus tonggol*
Yellowfin tuna	*Thunnus albacares*
Kingfish	*Scomberomorus commerson*
Queenfish	*Scomberoides commersonnianus*

Data on sardine landings were complemented by the monthly frequency of fish kill incidents and algal blooms along the Omani coast, available from the archives of the Marine Science and Fisheries Research Center (Muscat, Oman) and Al-Gheilani et al. (2012).

Zonal and meridional components of wind speed were retrieved from the NCAR/NCEP reanalysis database (Kistler et al., 2001), in which the daily averages of wind speed at 10 m above sea level were extracted for the Sea of Oman region with coordinates lat. 22.5–25.0ºN; long. 57.5–60.0ºE. The meridional 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.

For the assembly of historical data on temperature in the Sea of Oman, we compiled the database on 7,000 vertical profiles resulting from onboard casts carried out from 1950 to 2009. These data, were selected to estimate monthly averaged temperatures in the upper 20 m layer for the open sea region in the central part of the Sea of Oman (lat. 23–26ºN, long. 57–60ºE). All of the other remotely sensed variables were extracted for the same region.

Satellite derived (4 km and 9 km spatial resolution SeaWIFS and MODIS Aqua) monthly Level-3 products for sea surface temperature and chlorophyll-*a* concentration are avail-

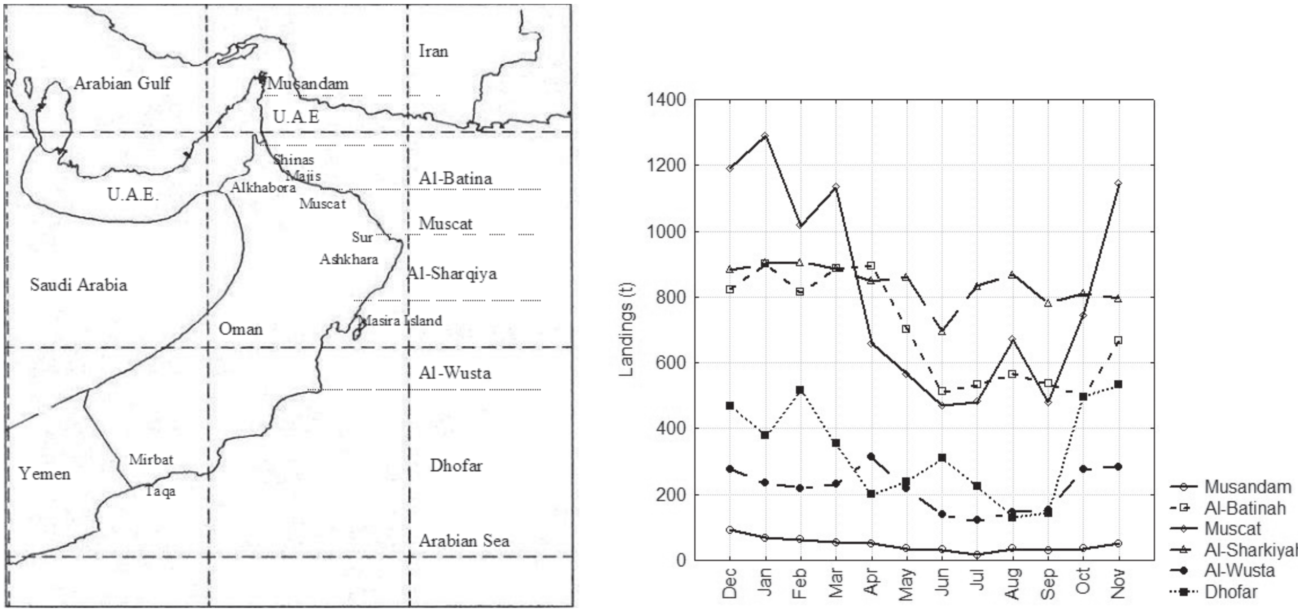

Figure 1.—The map of Oman coast with governorates (left) and averaged seasonal cycles of sardine landings over these governorates (2000–11) (right).

able from the National Aeronautics and Space Administration (NASA) Ocean Color Group (http://oceancolor.gsfc.nasa.gov). Monthly time series of chlorophyll-*a* and sea surface temperature were acquired for the period 1997–2011 using the GES-DISC Interactive Online Visualization and Analysis Infrastructure software as part of the NASA's Goddard Earth Sciences Data and Information Services Center.

Since mesoscale eddies markedly affect monthly variations in chlorophyll-*a* sea surface temperature, and the other characteristics of the upper layer (Piontkovski et al., 2012b), their energetic characteristics were calculated. The sea surface height anomalies (required to estimate the kinetic energy of eddies) were produced from TOPEX/Poseidon, Jason-1 and Jason-2 altimeter data and acquired from the Archiving, Validation and Interpretation of Satellite Oceanographic data center website (http://www.aviso.oceanobs.com). The assessment of the kinetic energy of eddies was based on the altimeter-derived sea surface heights for the western Arabian Sea (lat. 18–25ºN, long. 58–62ºE), for the period 1997–2009. The methodology of calculations of eddy kinetic energy per unit mass was that used by Sharma et al. (1999).

Results

Among the governorates of sardine fishery in the Sea of Oman, Muscat and Al-Batinah lead the landings. Unfortunately, no plankton and physical-chemical sampling has been carried out in Al-Batinah so we were focused on the data available for Muscat. Also, this is the region with pronounced seasonal fluctuations (Fig. 1). The maximum matches the time of winter monsoon lasting from December to March. In all the other Sea of Oman regions maximal landings coincide with the winter monsoon as well. The seasonality of landings with dominant winter maximum is the pattern pronounced throughout the years. The reports of the Ministry of Agriculture and Fisheries Wealth enabled us to analyze this pattern retrieved from regular (monthly) data from 2000 to 2011. Earlier data are fragmented and did not allow us to construct monthly time series. Even the time range from 1994 to 2000 had data missing, so the continuous seasonal pattern was analyzed predominantly for the time range from 2000 to 2011 (Fig. 2, 3).

In the seasonal cycle of landings, variations were most pronounced in 2000–02, when seasonal gradient between winter and summer values reached one order of magnitude (Fig. 2). From 2002 to 2009, the seasonal gradient declined, as did the annual landings.

To evaluate the components comprising the variance of landings, a spectral analysis was employed (Fig. 4). This statistical procedure enables one to break down the total time series variance into characteristic components with their own periods.

In transforming data for the analysis, the Tukey smooth window with 0.36, 0.24, 0.45, 0.24, and 0.04 Hamming weights was used. One could notice three major peaks contributing to the total spectral density of the sardine landing variance. The first peak could not be treated as statistically reliable because the period corresponding to this peak is close to the duration of the

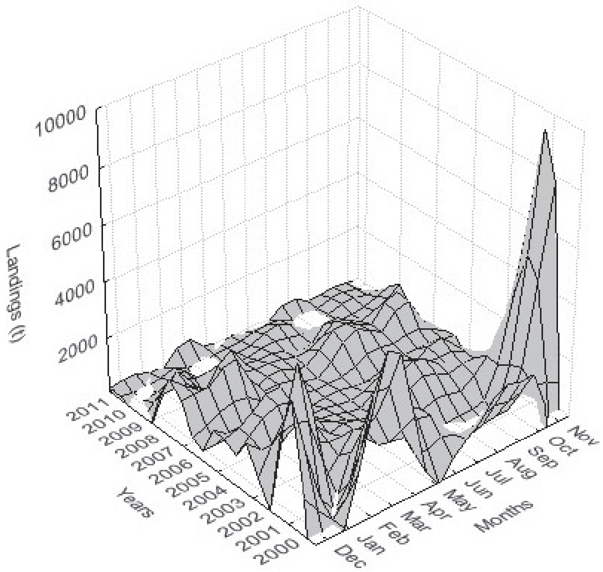

Figure 2.—Seasonal cycles of sardine landings in the governorate of Muscat.

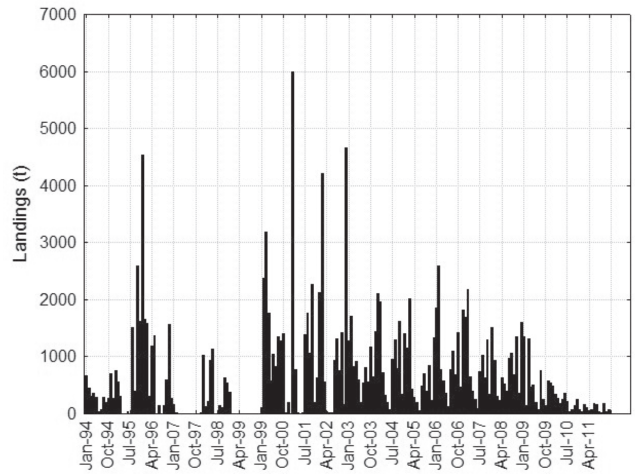

Figure 3.—Long-term monthly fluctuations of sardine landings in the governorate of Muscat.

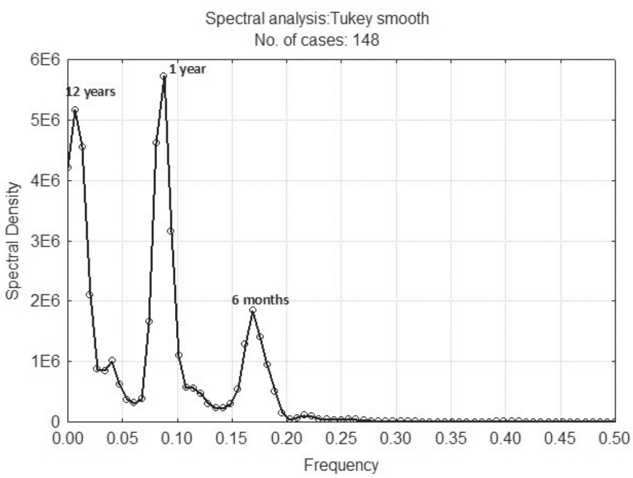

Figure 4. —The power spectrum of sardine landings in the governorate Muscat.

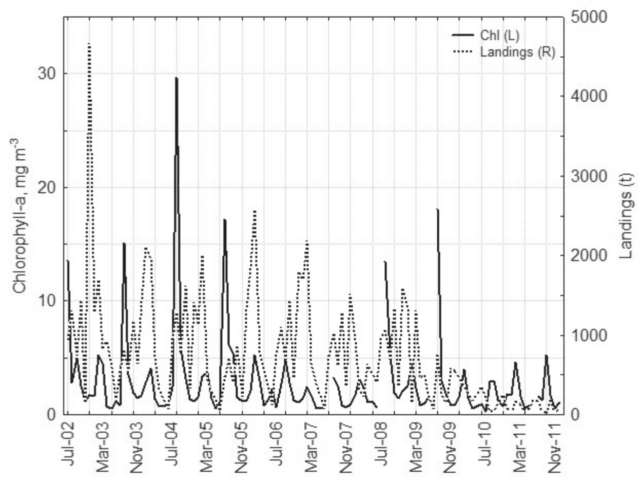

Figure 5.—Monthly time series of chlorophyll-*a* concentration (from MODIS-Aqua) and sardine landings in the governorate of Muscat.

time series (15 year). Among the other peaks, the annual periodicity seems to be the major contributor, followed by the semi-annual variations. As it was shown in Fig. 1, the seasonal changes are mostly associated with the time of winter monsoon during which sardine landings (in February) markedly exceeded all the others.

In Omani waters, sardines mostly feed on phytoplankton (Haleem et al., 2011). With this regard we used the chlorophyll-*a* concentration as the indicator of phytoplankton biomass. Our previous studies implied that remotely sensed chlorophyll-*a* (from the SeaWIFS scanner) is statistically correlated with the chlorophyll-*a* from the coastal time series of the Muscat region (Piontkovski et al., 2011). In comparing monthly time series of sardine landings and remotely sensed chlorophyll-*a*, we retrieved data from the SeaWIFS and MODIS-Aqua archives. The time series for the later one is exemplified in Fig. 5.

One could notice a certain agreement in monthly fluctuations of chlorophyll and sardine landings which might be represented in a quantitative

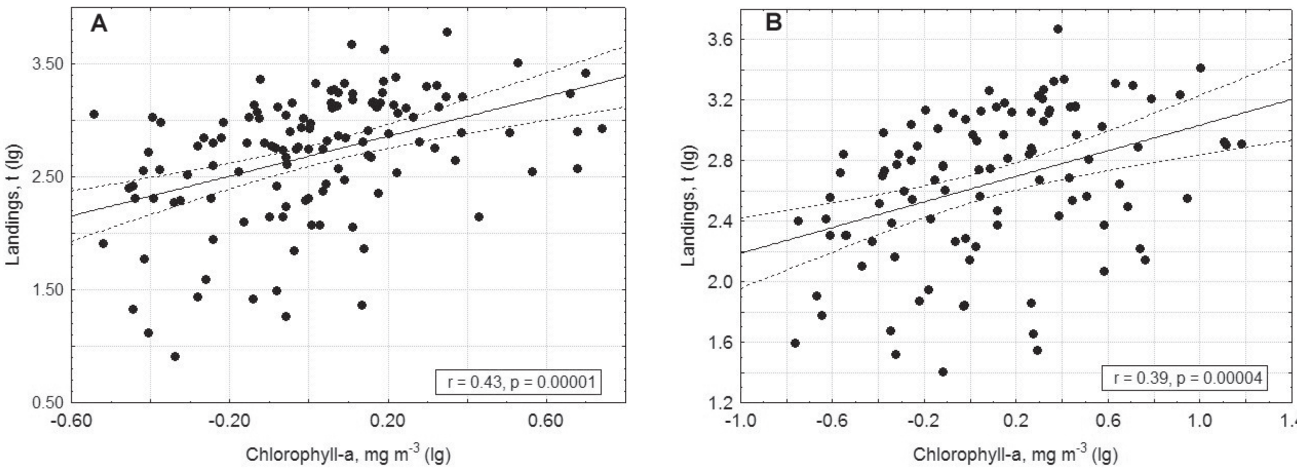

Figure 6.—Scatterplots of sardine landings vs. chlorophyll-*a* concentration estimated for two chlorophyll datasets (a: SeaWIFS and b: MODIS scanners) for the Sea of Oman (lat. 23-25^{o}N; long. 58-60^{o}E).

form as indicated in the scatter plots of landings versus chlorophyll concentration (Fig. 6). The scatter plots characterize the agreement in a very general form, averaged over various scales of parameter variations. The breakdown of covariance of two variables over these scales might be assessed through the coherency spectrum (Fig. 7). In a given case, the coherency spectrum implies the major periods (or frequencies) at which both parameters exhibit maximal correlation. Obviously, these periods are the annual and semiannual.

Monthly time series of chlorophyll-*a* and sardine landings both exhibited a tendency to decline over years, from 2002 to 2011 (Fig. 3, 5). In fact, the tendency might be traced back to 2001 (Fig. 3). As for the earlier data, they are fragmented which does not allow them to be the part of the time series we analyzed.

The other potentially important factor is the trophic pressure imposed on sardines by large pelagic predators. We analyzed annually averaged historical data on landings of large pelagic species acting as potential predators for sardines (Fig. 8). Obviously, all the relationships evaluated are negative; they all imply the tendency of sardine landings to decrease when landings of sardine predators are going up.

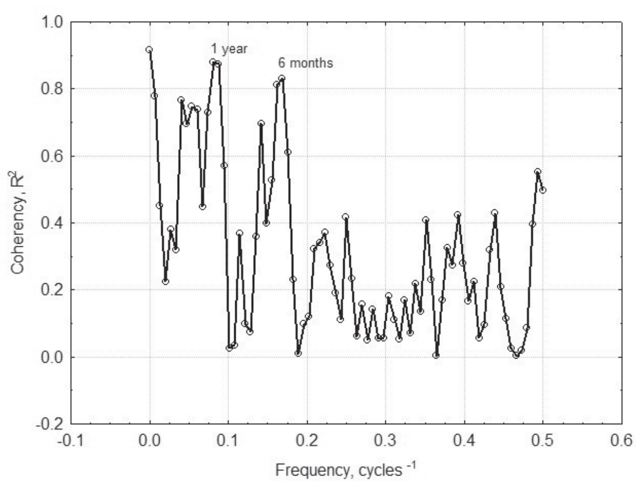

Figure 7.—The coherency spectrum: sardine landings vs. chlorophyll-*a* concentration (from SeaWIFS).

To estimate a potential role of the other environmental factors contributing to seasonal variance of sardine landings we analyzed 23 environmental variables (Table 2) featuring the coastal and open-sea regions. The selection of variables, based on previous investigations, reported a marked role of these variables in physical-biological coupling in the Arabian Sea and elsewhere (Madhupratap et al., 1994; Logerwell et al., 2001; Logerwell and Smith, 2001; Gaol et al., 2004; Haleem et al., 2011; George et al., 2012). The variables were log-transformed and subjected to the Principal Component Analysis (PCA), which is the data compression procedure enabled to reduce the number of variables (used to describe the variability of data) to a few Principal Components (Factors) reflecting the compression result (Jolliffe, 2002).

Since seasonal periodicity is one of the most pronounced signals in all the above variables, data for the PCA were arranged in the form of a seasonal cycle (from January to December), averaged from 2004 to 2008. This was the time range with minimal number of missed data for all the variables listed. For the assessment of factor loadings, the Varimax normalized matrix was applied to the logarithmically transformed variables listed in Table 2. We constrained the PCA analysis by the extraction of three Factors (components), which explained 76% of the total variance in the system of selected variables. In Table 3, variables with statistically significant loadings are given in bold.

Apparently, all three Factors are different by the variables driving the factor load. For instance, Factor 1 is a complex of interacting atmospheric and hydrophysical variables; Factor 2 is mainly associated with the interplay between three variables significantly contributing to this Factor, which is the zonal component of wind speed, concentration of chlorophyll-*a* in the open and coastal waters, and sardine landings. Eventually, Factor 3 is loaded primarily by seasonal variation of the concentration of diatoms in coastal waters (the Muscat region).

A group of variables contributing to Factor 1 has explained 52% of the total variance. Factor 2 contributed an additional 15%, which came to 67% of the total variance explained. Factor 3 has added 9% which raised the level of explained variance up to 76% (Table 4). Overall, the three principal components (three Factors) employed, have explained the major part of seasonal variation within the system of proposed variables (Table 2). A subsequent stepwise multiple regression analysis of the statistically significant variables denoted by the PCA has implied that 51% of seasonal variation in sardine landings might be approximated by the seasonal variations of the zonal component (east-west) of wind speed and chlorophyll-*a* concentration in the coastal and open sea regions.

Predictive properties of the above multiple regression might be exemplified by the plot of predicted values of sardine landings as the function of actual reported landings (Fig. 9). The model is aimed at forecasting seasonal changes of sardine landings in the Muscat region. It should be noted, however, that seasonal patterns of sardine landings are distinctly different along the Omani coast (Fig. 1), and the same goes to the seasonal patterns of chlorophyll-*a*. This means that a series of regional models on sardine landings should be worked out in the future.

Discussion

In the Sea of Oman, the sardine is one of the major fishery components which comprised about 84% of the total landings of small pelagic fish averaged for 2001–11 (Fishery Statistics Book, 2011). We used historical data to describe seasonal and interannual trends in landings. Apparently, in the case of sardine landings, both patterns might be interpreted in terms of environmental factors rather than the pressure on fish stocks. Seasonal fluctuations of landings are correlated with the forcing imposed by monsoonal winds on the upper mixed layer of the sea (in our case, the zonal component of the wind speed). The winter (northeast) monsoon is the major force mediating the seasonality of photosynthetically active radiation, wind speed, sea surface temperature, nutrients, and chlorophyll-*a* concentration in the region (Piontkovski et al., 2011). All of these parameters exhibit pronounced seasonal patterns in the Sea of Oman and a certain group of environmental parameters correlate well with sardine landings.

Similar results were reported for the other regions. In the southeastern part of the Indian Ocean, fluctuations of sardine catches were positively correlated to the remotely sensed chlorophyll-*a* (Gaol et al., 2004). In the Mediterranean Sea, a set of remotely sensed parameters (chlorophyll-*a*, photosynthetically active radiation, sea surface temperature, sea level anomaly, and some others) was sufficient to explain the location of the juvenile grounds of European sardines. These areas were mostly located inshore and often in proximity to river mouths (Schismenou et al., 2008).

Nutrient enrichment of coastal waters through river runoff (which is gradually mediated by summer monsoon) and the reaction of sardine shoals to the increased abundance of diatoms and zooplankton biomass was reported for the Kerala coast of India. With the monsoon and coastal upwelling both progressing northward, the sardine shoals followed this trend to stay in the zones with maximal food for larvae (Madhupratap et al., 1994).

Being filter feeders, sardines are supposed to be tightly related to spatial-temporal changes of phytoplankton concentration. The gut content analysis of the sardines caught along the coast of the Sea of Oman (in the Muscat and Sohar regions) has indicated that phytoplankton comprise about 62–68% of their diet (Haleem et al., 2011). It is not surprising that seasonal fluctuations of sardine landings were statistically associated with the phytoplankton-related parameter used in our study (chlorophyll-*a* concentration). In the eastern Arabian Sea, in coastal waters of India, the remotely sensed chlorophyll-*a* could explain up to 39% of interannual variations in sardine landings (George et al., 2012).

In some way, seasonal fluctuations of sardine landings and their regional differences might be influenced by mesoscale eddies propagating through the coastal waters. In the California Current, the elevated densities of sardine larvae were associated with cyclonic eddies and the peripheries of anticyclonic eddies which are believed to be favorable areas for sardine recruitment (Logerwell and Smith, 2001; Logerwell et al., 2001). Warm eddies could often branch out warm streamers visible in satellite images of sea surface temperature with streamer structures of about 10 km in width. Simultaneous satellite measurements and aircraft observations on sardine schools have shown that sardines tend to use warm streamers for migration towards the coast, with the formation of dense schools at the head of warm streamers, in which fishing grounds are often formed (Sugimoto and Tameishi, 1992; Tameishi et al., 1994).

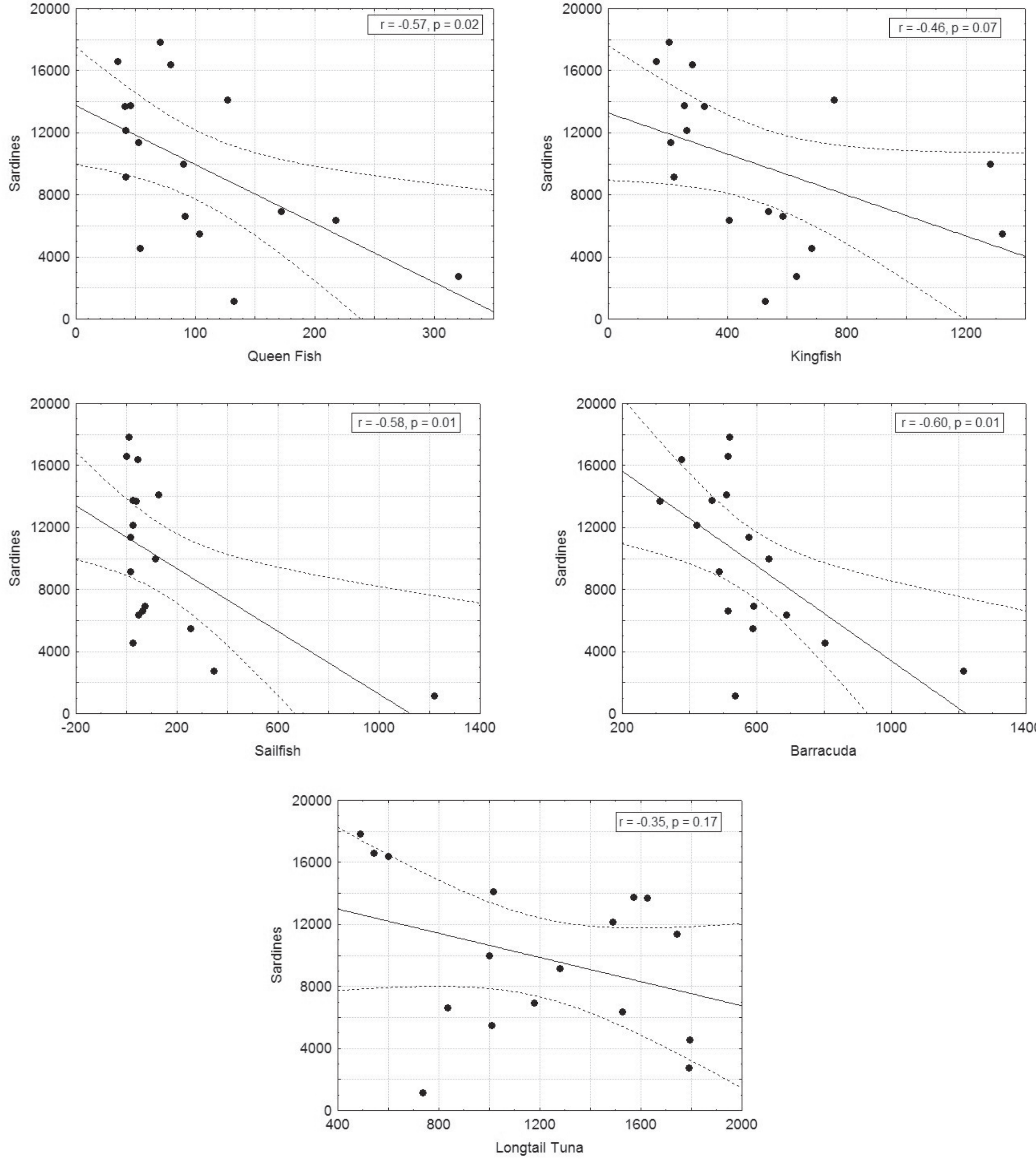

Figure 8.—The relationship between landings of sardines (t) vs. landings of the sardine predators (1994–2011).

Table 2.—Characteristics of the variables used for the Principal Component Analysis.

No.	Variable name	Variable abbreviation	Data source
1	Atmospheric pressure	Atm Press	NCAR/NCEP database
2	Atmospheric temperature	Atm Temp	NCAR/NCEP database
3	Outgoing low wave radiation	OLR	NCAR/NCEP database
4	Atmospheric precipitation	Precipitat	NCAR/NCEP database
5	Optical thickness of aerosol	Aerosol	MODIS database
6	Zonal component of wind speed	Z-wind	NCAR/NCEP database
7	Meridional component of wind speed	M-wind	NCAR/NCEP database
8	Concentration of dissolved oxygen	Oxy-20	SQU Historical database
9	Sea surface temperature	SST-MODIS	MODIS database
10	Temperature (20m deep; averaged for the central part of the Sea of Oman)	Temp-20	SQU database
11	Kinetic energy of mesoscale eddies	EKE eddy	SQU database
12	Concentrations of nitrates (coastal time series; station BK)	NO3-BK	SQU database
13	Concentration of dissolved oxygen (20m deep; averaged for the central part of the Sea of Oman)	Oxy-20	SQU database
14	Concentration of dissolved oxygen (coastal time series, station BK)	Oxy-BK	SQU database
15	Concentration of chlorophyll-*a* (coastal time series; stations F+BK)	Chl-F+BK	SQU database
16	Concentration of dinoflagellates (coastal time series; station BK)	Dino-BK	SQU database
17	Concentration of diatoms (coastal time series; station BK)	Diatom-BK	SQU database
18	Sardine landings	Sardine land	Ministry of Fisheries Reports
19	Concentration of chlorophyll-*a* (from SeaWIFS)	Chl-SeaWIFS	SeaWIFS database
20	Concentration of chlorophyll-*a* (from MODIS)	Chl-MODIS	MODIS database
21	Total copepod abundance (coastal time series; station BK)	Copepods-BK	SQU database
22	Frequency of algal blooms	Algal blooms	All Gheiani et al., 2012
23	Frequency of fish kill incidents	Fish kills	All Gheiani et al., 2012

Table 3.—Results of the Principal Component Analysis: factor loadings (Varimax normalized). Marked loadings are > 0.70. Variables with statistically significant loadings are given in bold.

Variable	Factor 1	Factor 2	Factor 3
Atm Press	0.60	0.53	-0.50
Atm Temp	**-0.77**	-0.55	0.26
OLR	**-0.82**	-0.47	0.20
Precipitat	**0.85**	0.34	-0.03
Aerosol	**-0.88**	0.12	0.24
Z-wind	0.09	**-0.73**	0.27
M-wind	-0.67	-0.35	0.57
SST-MODIS	**-0.87**	-0.43	0.15
Temp 20	**-0.82**	-0.36	0.15
EKE eddy	**0.92**	0.05	-0.01
NO3-BK	**0.81**	0.19	-0.03
Dino-BK	-0.55	-0.40	0.40
Diatom-BK	-0.27	0.20	**0.82**
Chl-SeaWIFS	0.40	**0.72**	-0.24
Chl -F+BK	0.09	**0.85**	0.27
Oxy-20	**0.91**	-0.12	0.00
Oxy-BK	-0.30	-0.45	0.68
Sardine Land	0.14	**0.75**	-0.13
HABs	0.42	0.52	0.22
Fish kills	-0.56	0.54	-0.20
Chl-MODIS	0.45	0.68	-0.07
Copepod-BK	0.13	-0.06	0.54

The western Arabian Sea is known for its vigorous field of mesoscale eddies that markedly affect phytoplankton and zooplankton distribution (Piontkovski and Banse, 2006). As far as the Sea of Oman is concerned, recent studies have shown an interannual increase in seasonal fluctuations of the kinetic energy of eddies as well as the increase in seasonal fluctuations of chlorophyll-*a* in 2000–08 (Piontkovski et al., 2012b). Perhaps both events were not favorable for sardines, so both may have contributed to a declining trend in sardine landings. This is consistent with the ranking of the kinetic energy of eddies as a powerful (high scored) variable in Factor 1 of our Principal Component Analysis (Table 2).

As for fishing pressure and its role in the formation of declining trend, the number of fishing boats in the region did not show steady gradual increase, with the reported number of 1,858 boats in 2004 vs. 1,624 boats in 2007, and 1,946 boats in 2011 for the Muscat governorate, for instance. In terms of the other factors affecting landings it should be noted that a ban on the use of encircling gear with rings was enforced for many years in the sardine fishery.

Among the other trends reported, which might be ecologically important in the analysis of a declining trend in sardine landings, the frequency of fish kill and algal bloom incidents might be taken into account. Apparently, the annual frequency of fish kills and coastal algal blooms in Omani coastal waters had gradually increased in the past 30 years (Al-Azri et al., 2012; Al-Gheilani et al., 2012).

In the Sea of Oman, over 70% of coastal algal blooms are reportedly caused by the dinoflagellate, *Noctiluca scintillans*, which is a species actively avoided by the Indian oil sardine. High concentrations of *Noctiluca* usually lead to a scarcity of sardines (Nair, 1958). Furthermore, *Noctiluca* has not been reported in their stomachs (Prasad, 1953; Sekharan, 1966). Being a heterotrophic organism feeding on small phytoplankton, *Noctiluca* acts as the competitor for food with sardines.

It should be emphasized that the long-term declining trend in sardine landings (from 2001 to 2011) is a basin-scale phenomenon. It was reported for all the major fisheries regions along the coast, from Musandam, through Al-Batinah, to the Muscat (Haleem et al., 2011), which is in fact the Sea of Oman scale. On this scale, rising sea temperature and thermal stratification of the water column were reported (Piontkovski et al., 2012a) and might be the components partially explaining this trend.

The declining trend in sardine landings (from 2001 to 2011) could be a fragment of a more prolonged period of fluctuations. In the other geographical regions, the 30- to 60-year time series of sardine landings enabled a tight coupling to be elucidated, between landings and climatic indices featuring these regions. For instance in the northwestern Mediterranean Sea, the Western Mediterranean Oscillation index (WeMOi) is a sensitive indicator of climate variability. It was shown that positive WeMOi values were correlated with low sea surface temperature, high river runoff, and high landings per unit of effort. Conversely,

Table 4.—Results of the eigenvalue extraction by the Principal Component Analysis: the total and cumulative variance explained by three Factors (Table 2).

Factor	Eigen-value	% total variance	% cumulative variance
1	11.34	51.53	51.53
2	3.32	15.10	66.64
3	1.95	8.85	75.48

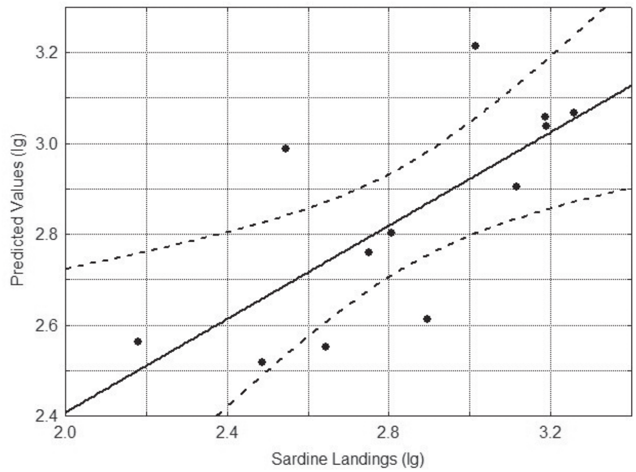

Figure 9.—A scatterplot of predicted vs. actual landings based on multiple regression model (Table 3). Y = 1.38 + 0.52X; R= 0.72. Dashed lines: 95% confident interval.

negative WeMOi values were associated with high sea surface temperature, low river runoff, and low landings per unit of effort. This means that the negative WeMOi was the phase with unfavorable environmental conditions and would decrease the survival, growth, and reproduction of sardines during their life cycle (Martin et al., 2012).

The Omani time series of sardine landings is yet to be sufficient for that kind of analysis. Nonetheless, a simple comparison of our data to the data characterizing the opposite site of the Arabian Sea implied that current interannual trends of sardine landings might be opposite, although both of them developed on the background of increasing temperature in the upper mixed layers. For instance, the declining trend in sardine landings reported for the Sea of Oman might be superimposed on a rising trend of landings along the southwestern coast of India (Vivekanandan et al., 2008). Does this mean that the Omani sardines migrated eastward, to the Indian coasts, or have they migrated southward, along the Omani coast? The distances of sardine feeding migrations could be thousands of kilometers (Schwartzlose et al., 1999; Wada and Kashiwai, 1991).

Understanding regional trends of interannual changes in sardine landings along the coast could provide useful information as well. For instance, the declining trend in the Sea of Oman tends to switch to the "no trend situation" in the neighboring Al-Sharqiya region (which is about 400 km to the south down the coast). Along the Indian coast stretched for 7,500 km, interannual trends of sardine landings vary greatly as well, from positive to fluctuations with no apparent interannual trends (Vivekanandan et al., 2008). Migrations of sardines along the coast are believed to be caused by changes of the preferential temperature zones and predator press (Armstrong et al., 1991; O'Donoghue et al., 2010). Both a temperature increase in the upper mixed layer over the past 50 years and a pronounced increase in predators affecting sardine have been reported for the Sea of Oman (Piontkovski et al., 2012a; Fig. 8).

As we noticed, the declining trend might be a fragment of a longer-term fluctuation. What are the typical periods of these fluctuations? Data from the Pacific Ocean imply naturally occurring periods in sardine landings of about 50 years (Chavez et al., 2003). Reconstruction of the history of Pacific sardine biomass over the past two millennia from sediments showed that sardines tend to vary over a period of about 60 years (Baumgartner et al., 1992). Recent estimates of typical fluctuations of temperature anomalies and fish landings in the world ocean report the period of 60–70 years as the most prominent in the past millennium (Klyashtorin and Lyubushin, 2007; Zhen-Shan and Xian, 2007; Lyubushin and Klyashtorin, 2012). The issue of how well the Sea of Oman fits this picture is yet to be investigated.

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