

Sardine and horse mackerel recruitment and upwelling off Portugal

A. Miguel P. Santos, Maria de Fátima Borges, and Steve Groom



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The results of preliminary investigations on the possible relationships between coastal upwelling variability observed with satellite remote sensing, and sardine and horse mackerel recruitment dynamics in the west coast of Portugal are presented. The analysis of a sardine-recruitment time-series for the period 1976–1998 shows that there has been a decreasing trend since 1983 (with the exceptions of 1991 and 1992), the years from 1993–1995 representing the lowest values in that time series. Horse mackerel exhibited a decrease from 1986 until 1990, and from 1992–1995, the latter representing the lowest value for the period 1986–1998. Sea surface temperature (SST) derived from satellite data were used to compute monthly SST upwelling indices along the Portuguese west coast over a period from 1987–1997. The analysis focused on seasonal and annual upwelling variability off Portugal, and its possible effects on sardine and horse mackerel recruitment to the fishery. An increasing trend in SST upwelling indices during the winter (January–March), especially between 1992 and 1995 was found. The upwelling events observed off Portugal during winter months, which correspond to the spawning season for sardine and horse mackerel, had a negative impact on the recruitment of these fish species. This effect on recruitment could be due to an increase in conditions favourable to the offshore transport of larvae and consequently an increase in their mortality. Prior to 1992, when no upwelling events occurred during winter, recruitment dynamics was closely linked with the spring–summer seasonal upwelling variability off the Portuguese west coast.

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Key words: coastal upwelling, horse mackerel, Portugal, recruitment, sardine, *Sardina pilchardus*, satellite remote sensing, *Trachurus trachurus*.

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A. Miguel P. Santos and Maria de Fátima Borges: Instituto de Investigação das Pescas e do Mar (IPIMAR), Avenida de Brasília, 1449-006 Lisboa, Portugal. Steve Groom: Plymouth Marine Laboratory, Prospect Place, Plymouth, Devon, PL1 3DH, United Kingdom. Correspondence to A. Miguel P. Santos: tel.: +351 21 302 7067; fax: +351 21 301 5948; e-mail: amsantos@ipimar.pt

Introduction

The location of the Portuguese west coast at the eastern boundary of the subtropical North Atlantic determines many of its atmospheric and oceanographic characteristics, including the occurrence of coastal upwelling during summer in response to the intensification and steadiness of favourable equator-ward winds (e.g. Wooster *et al.*, 1976; Fiúza *et al.*, 1982). The Portuguese coastal upwelling is part of a more general system that extends southward to 15°N (Wooster *et al.*, 1976) – the Canary Current Large Marine Ecosystem.

The reproductive strategies of some pelagic fish adapted to coastal upwelling ecosystems, such as sardine (*Sardina pilchardus* Walbaum, 1792) and horse mackerel (*Trachurus trachurus* Linnaeus, 1758) on the Portuguese continental shelf, minimise Ekman offshore transport effects to assure inshore transport and larval retention (e.g. Roy *et al.*, 1989).

The maximum intensity of sardine spawning off Portugal takes place predominantly from November to April, inclusive (Figueiredo and Santos, 1989; Ré *et al.*, 1990). Ichthyoplankton studies carried out along the Portuguese coast showed that sardine spawning occurs in two well-defined areas (Ré *et al.*, 1990): (i) off the

western coast, mainly during winter; and (ii) on the southern coast, mainly in the spring. According to the monitoring of adult maturity stages (Borges and Gordo, 1991), horse mackerel spawning period off Portugal is mainly during winter, from December to March–April. The egg surveys carried out in 1992 and 1995 indicated the presence of horse mackerel eggs in two well-defined spawning areas: one north of Lisbon and the other south of Lisbon including the Algarve (Farinha and Borges, 1994).

Dias (1994) has shown that during the period of 1947–1987 there was a significant change in the monthly wind distribution pattern on the Portuguese west coast, namely an increase in the frequency of equator-ward winds, the driving force of coastal upwelling in the region, in winter (January–March). One hypothesis is that these conditions lead to the increase of favourable conditions for offshore transport during the spawning season of sardine and horse mackerel off Portugal and probably to the increase in larval mortality.

During summer (June–September) more active and persistent coastal upwelling conditions prevail and, in consequence, there is a high level of phytoplankton and zooplanktonic production inducing more favourable feeding conditions for juveniles and adult zooplanktonic feeders.

According to the climatological analysis (1959–1969) conducted by Fiúza *et al.* (1982) wind-induced upwelling conditions tend to be more stable, frequent and intense from June–August, and upwelling indices tend to be higher between July and September. However, the analysis performed by Dias (1994) of the annual mean values of upwelling indices in April–September computed using wind observations obtained by the Portuguese Meteorological Office at the meteorological station of Cape Carvoeiro (Portugal) between 1947 and 1992, revealed that a very significant decreasing trend of the April–September indices occurred during the 45 years. Thus, the mean value of the last 12 year period was less than a half the mean of the first 12 year period. Dias (1994) also recognised a significant warming trend from the analysis of the mean annual values (May–September) of the sea surface temperature (SST) off Cape Carvoeiro, which confirms the decreasing upwelling index.

The physical and biological characteristics of the ocean surface produced by coastal upwelling have been identified successfully using satellite remote sensing instrumentation (e.g. Abbott and Chelton, 1991; Sousa and Bricaud, 1992; Nykjaer and Schrimpf, 1993; Nykjaer and van Camp, 1994; Peliz and Fiúza, 1999).

This paper investigates the existing relationships between upwelling indices derived from satellite remote sensing observations and recruitment, in order to identify an environmental index which could be

incorporated into stock assessment models and used to predict recruitment.

Materials and methods

Recruitment data

The recruitment data series used for sardine and horse mackerel were estimated using Virtual Population Analysis (VPA) as accepted by the “ICES Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy” (ICES, 2000). This analytical assessment used the total commercial catch data from ICES Divisions VIIIc and IXa, catch in numbers-at-age group tuned with fishery independent information on biomass and stock abundance-at-age group from research surveys. For sardine the population in number-at-age group was estimated using two sources of independent information: biomass estimates from egg surveys using the Daily Egg Production Method (DEPM), and acoustic surveys carried out during the recruitment and spawning season (autumn and winter). For horse mackerel the fishery independent data are abundance indices from trawl surveys, and spawning stock biomass estimates based on egg surveys using the Annual Egg Production Method (AEPM).

The spawning and juvenile areas of sardine are mainly located in ICES Division IXa, therefore the VPA recruitment estimates are in accordance with the direct recruitment estimates from acoustic surveys performed to the west of Portugal in Division IXa.

Exploratory data analysis on VPA using only the ICES Division IXa catch matrix and the acoustic surveys performed in the same area in November and March indicate the same order of recruitment estimates at age 0 (Azevedo, 2000). A significant linear relationship ($r^2=0.901$ and $p\leq 0.001$) was detected between independent recruitment estimates for the Atlantic coast of the Iberian Peninsula (ICES Divisions VIIIc and IXa) from ICES (2000), and for the west of Portugal and Galicia (ICES Division IXa) from Azevedo (2000) (Figure 1). It was decided, therefore, to perform further analysis using ICES (2000) VPA estimates of recruitment in both ICES Divisions VIIIc and IXa.

Satellite remote sensing data

Satellite estimates of sea surface temperature (SST) from coastal and offshore regions in selected locations along the Portuguese west coast (Figure 2) were obtained from the NASA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder data-set (Vazquez *et al.*, 1994) which provided global SST for 1987–1993, and from the NERC Satellite Receiving Station at the University of Dundee, Scotland (June 1993–April 1997). Those locations were chosen because the ocean environment

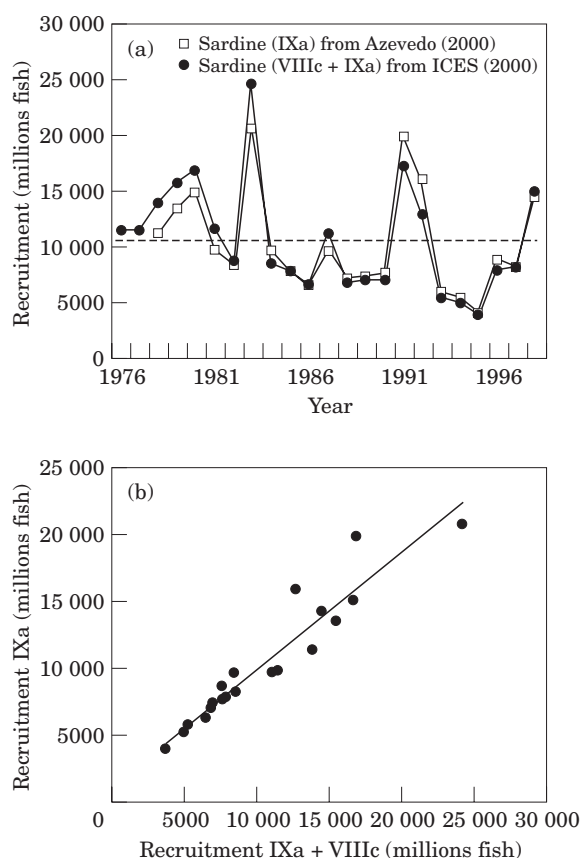


Figure 1. Sardine (*Sardine pilchardus*) recruitment for the period 1976–1998. (a) recruitment time-series in ICES Divisions IXa and VIIIc. The horizontal broken line is the long-term mean of the time-series. (b) linear regression between sardine recruitment in ICES Division IXa from Azevedo (2000) and in ICES Divisions IXa+VIIIc from ICES (2000) ($y = 1342.4 + 0.8479x$; $r^2 = 0.9005$, $p = 0.0$).

appears to respond rapidly to upwelling-favourable equator-ward winds and upwelling filaments reappear each year at such places (e.g. Sousa, 1995). The assumption made was that they could be used as good indicators of the presence or absence of the phenomenon.

In order to calculate a monthly cooling anomaly due to the coastal upwelling, NASA Pathfinder SST (Vazquez *et al.*, 1994) was averaged in a box 0.5 degree latitude and 0.34 longitude for each point along the coast, and at an oceanic location approximately 15 degrees west at the same latitude (i.e. separated by about 500 km within a direction inshore–offshore). The Dundee AVHRR full resolution (1 km) data were processed to SST according to the methodology described in Miller *et al.* (1997) using NOAA SST algorithms (hereafter the Miller approach). Monthly composites were produced from the cloud-free parts of the individual SST images at a 4-km resolution, and SST was averaged within the coastal and oceanic boxes described above.

Due to differences in the form of the algorithms, and in the validation data-sets used to construct the algorithms, the NOAA and Pathfinder algorithms give slightly different results for SST from the same input satellite data. Although the comparison of SST values extracted with the different algorithms showed that the NASA Pathfinder-SST values were in general lower than the ones obtained with the Miller methodology, they both show a very consistent linear relationship when statistically compared. Therefore, in order to merge the two sets of data for further analysis, a simple least-squares linear regression analysis was performed. The regression line was used to estimate the NASA Pathfinder-SST values for the period 1994–1997 because the statistical regression analysis was very highly significant (F test with $p \leq 0.001$) explaining 92% of the variability of the relationship of the two SST data sets.

Zonal SST upwelling indices, hereafter referred as “upwelling index” or simply “index”) were derived during the period 1987–1997 from the SST monthly-mean data. The index was calculated as the temperature difference between coastal and oceanic locations at the same latitude. The sign of the anomalies was changed in the figures below so that larger positive values were associated with more intense coastal upwelling conditions.

The transition zone between cold upwelling waters and warmer oceanic waters has been observed to be located 100–300 km offshore from the coast (Fiúza, 1983; Sousa, 1995; Amraoui, 1997). Moreover, Wooster *et al.* (1976), Nykjaer and Schrimpf (1993) and Nykjaer and van Camp (1994) found good agreement between offshore Ekman transport and the zonal (shelf-offshore) temperature anomaly. For this reasons we adopted those methodologies for the study of upwelling variability. The seasonal upwelling cycle along the Portuguese coast described by several authors (e.g. Wooster *et al.*, 1976; Fiúza *et al.*, 1982) is illustrated in Figure 3, which presents the monthly mean index (SST anomaly) for the period 1987–1997 on the Portuguese west coast calculated using the methodologies described above.

Results

Figure 4 shows the plots of inter-annual variability of recruitment to the fishery of sardine and horse mackerel in ICES Divisions VIIIc and IXa for the periods 1976–1998 and 1985–1998, respectively.

Sardine exhibits large fluctuations of the recruitment strength during the period 1976–1998. During the 1970s recruitment was above average with an extremely high year class in 1983, followed by a period of low recruitment from 1984–1990. During the 1990s there were alternating periods of values above (1991–1992, and 1998) and below (1993–1995) the average of the time

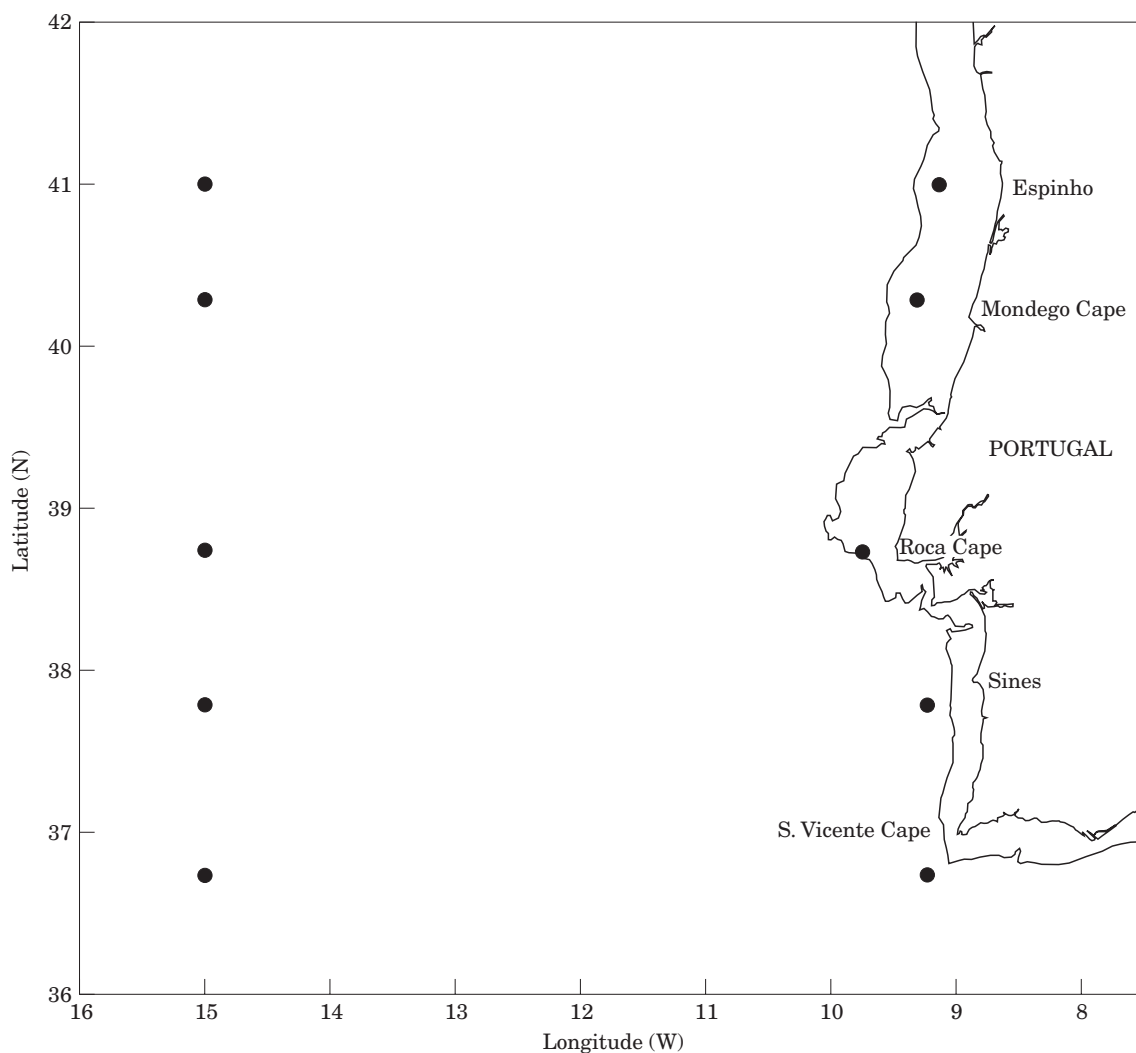


Figure 2. Chart of the Portuguese coast showing the selected locations (●) for the extraction of sea surface temperature (SST) values.

series. The years from 1993–1995 exhibited the lowest values of the last 20 years (Figure 4). Horse mackerel recruitment exhibited a decrease from 1986 until 1990, and from 1992–1995, the latter representing the lowest value for the period 1986–1998 (Figure 4).

Figure 5 illustrates the variability of the recruitment of sardine and horse mackerel respectively, and the upwelling conditions, represented by the SST upwelling index, occurring in the period 1987–1997 during: (i) April–September [Figure 5(a) and (b)], which is the typical upwelling season of the Portuguese west coast; and (ii) winter [January–March; Figure 5(c)], which is the spawning season of these small pelagic fish species off Portugal.

Table 1 presents the correlation coefficient matrix of the association between upwelling conditions (index) in

different seasons and sardine and horse mackerel recruitment for the periods 1987–1992 and 1993–1997.

For the period 1987–1992, sardine and horse mackerel recruitment strength at age 0 is positively correlated with the April–September upwelling index, with r values equal to 0.66 and 0.76, respectively (Table 1). However, the significant positive relationships disappear after 1993 (Table 1) due to recruitment failure in both species, despite the continuation of favourable juvenile feeding conditions, as indicated by the high upwelling index in summer [Figure 5(a) and (b)].

Upwelling indices below the average occurred during the spawning seasons (winter) of 1988–1991 [Figure 5(c)]. These indices turned to a positive anomaly during the period 1992–1995 [Figure 5(c)], corresponding to more intense upwelling conditions. The

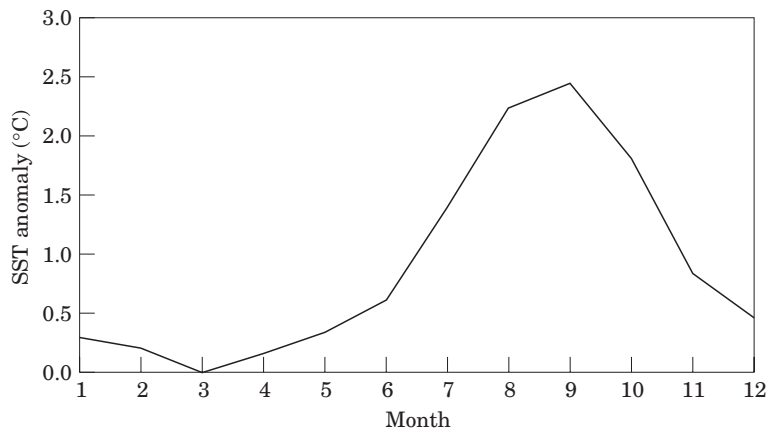


Figure 3. Monthly-mean sea surface temperature (SST) anomaly between coastal and offshore areas (upwelling index) along the Portuguese west coast in the period January 1987–April 1997, derived from the NASA Pathfinder and “Miller” method satellite-derived SST. Higher values indicate more intense coastal upwelling conditions.

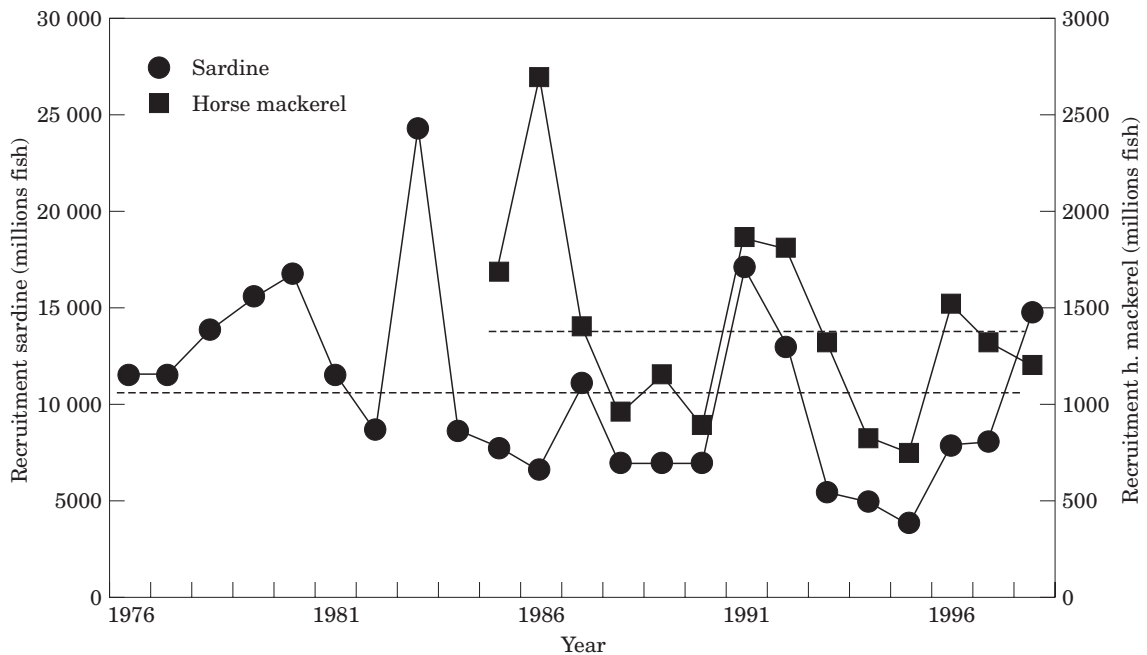


Figure 4. Sardine (*Sardine pilchardus*) and horse mackerel (*Trachurus trachurus*) recruitment to the fishery at age group-0 for the periods 1976–1998 (sardine) and 1986–1998 (horse mackerel) in ICES Divisions IXa+VIIIc. The horizontal broken lines are the long-term means of each time-series.

consequence of these more intense upwelling conditions during winter is revealed by an inverse relationship with sardine and horse mackerel recruitment (Table 1), with significant negative correlation for both sardine ($r = -0.958$) and horse mackerel ($r = -0.857$). A decrease to below average values in the winter upwelling index since 1996 [Figure 5(c)] parallels an increasing tendency in the recruitment values during 1997 and 1998 (Figure 4).

Discussion

The typical pelagic fish life-history strategy in areas of coastal upwelling is tuned to favour spawning when the offshore transport is minimal and feeding later to profit from the increase of productivity due to summer coastal upwelling (Cushing, 1982; Roy *et al.*, 1989). We found that the decreasing trends in the recruitment of sardine and horse mackerel observed during the 1990s in the

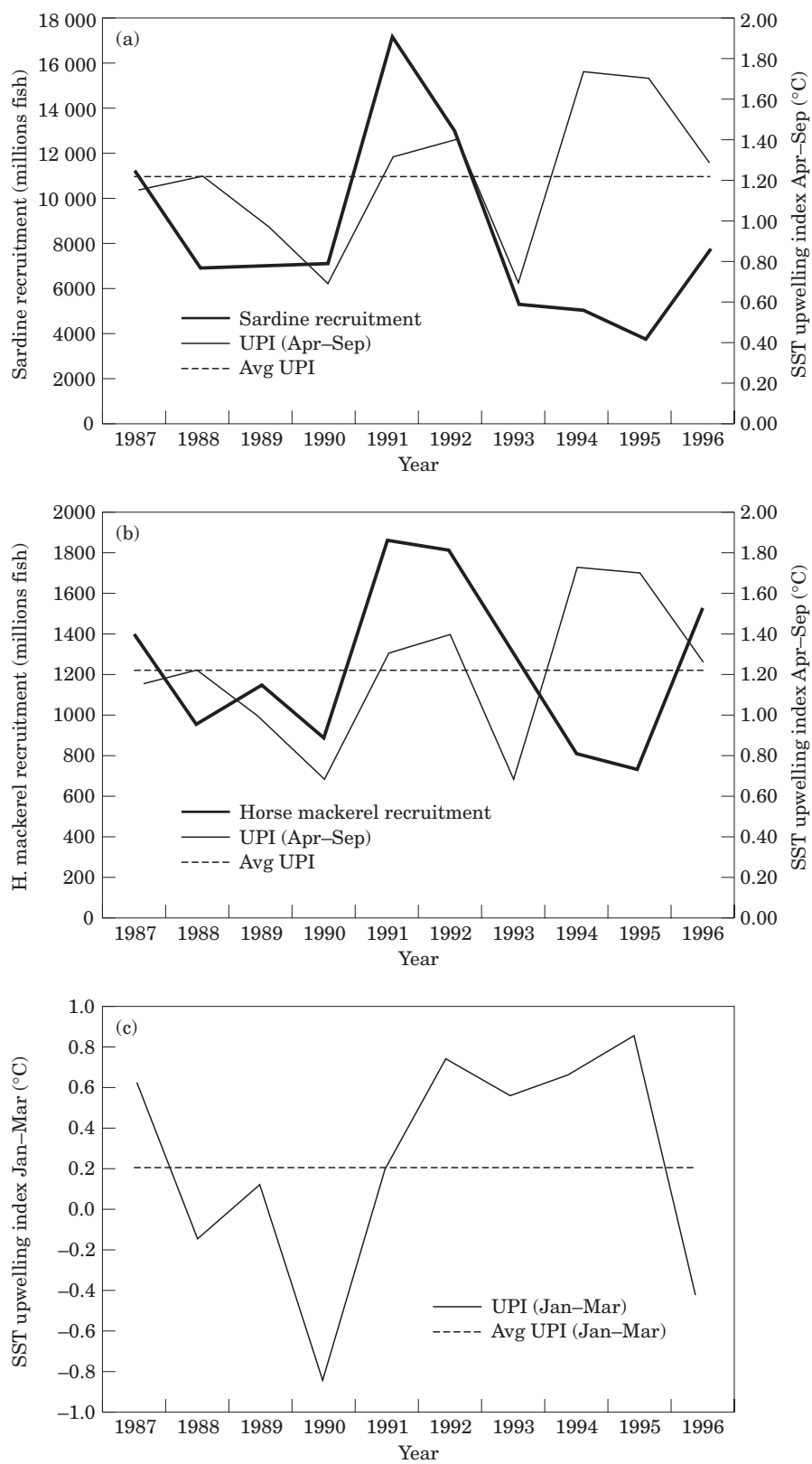


Table 1. Correlation matrix of the estimated linear association between upwelling index (UPI) during the winter (January–March) and the typical upwelling season (April–September) and the recruitment at age group-0 of sardine (*Sardine pilchardus*) and horse mackerel (*Trachurus trachurus*).

	Recruitment h. mackerel	Recruitment sardine
Recruitment h. mackerel	1.000	
Recruitment sardine	0.853***	1.000
UPI (Jan–Mar) 1987–1992	0.743*	0.548 ^{ns}
UPI (Apr–Sep) 1987–1992	0.764*	0.663*
UPI (Jan–Mar) 1993–1996	– 0.858*	– 0.958***
UPI (Apr–Sep) 1993–1996	– 0.733*	– 0.359 ^{ns}

***Significant at the 0.1% level.

**Significant at the 1% level.

*Significant at the 5% level.

^{ns}Non-significant.

nursery grounds off the west coast of Portugal are linked with the increase of upwelling events in winter, i.e. during the spawning season of these species. This is corroborated by the significant inverse relationship of the winter upwelling index and the recruitment of sardine and horse mackerel during 1993–1996 (Table 1). The absence of coastal upwelling conditions in the winter after 1995 seems to have immediately favoured a noticeable increase of the recruitment strength of both species since 1995 [Figure 5(a) and (b)].

A good positive correlation was found between recruitment and upwelling until 1993 [Figure 5(a)], when active, typically summer, upwelling (April–September) occurs in the area (Figure 3). No correlation was found between 1993–1997 when enhanced coastal upwelling during spawning (winter) was observed. However, a significant negative correlation occurred with winter upwelling conditions (Table 1). Thus it would seem that if the recruitment has been adversely affected due to the unfavourable upwelling conditions during spawning in winter, it will not be relevant for recruitment success even if there are good conditions for feeding in the inshore nurseries in the summer.

Intermittent periods of positive and negative relationships between catches and summer upwelling indices off the northwestern Moroccan coast were reported by Kifani and Gohin (1992). Bakun (1990) also notes that off the Iberian Peninsula the 40 years fall–winter time-series of upwelling favourable winds exhibit a mixture of positive and negative trends, which appears to be in

accordance with the results of our analysis of the winter upwelling indices series for the period 1987–1997 [Figure 5(c)]. However, in winter, the surface changes caused by coastal upwelling could be mitigated by the greater depth of the upper mixed layer and consequently the coastal temperature deficit was not so evident, and might not even be if strong “events” take place.

These results confirm the fact that the variability of upwelling conditions during the winter, and spawning season is a crucial factor in the recruitment dynamics of these small pelagic fish species. Spawning stock biomass is a measure of potential recruitment but the variability of environmental factors can ultimately constrain the abundance of recruits. Appreciating this is potentially useful for fish stock predictions since it improves knowledge of the relationships between spawning stock biomass and recruitment (Shepherd *et al.*, 1984). Satellite remote sensing is, therefore, a tool that can be used to estimate coastal upwelling operationally for fish stock predictions.

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Figure 5. Annual upwelling indices (UPI) produced from satellite-derived sea surface temperature (SST) anomalies between coastal and offshore areas (larger positive values indicate more intense upwelling conditions), and sardine (*Sardine pilchardus*) and horse mackerel (*Trachurus trachurus*) recruitment at age group-0 for the period 1987–1996. (a) UPI for the typical upwelling season of the west coast of Portugal (April–September) and sardine recruitment; (b) UPI during the typical upwelling season (April–September) and horse mackerel recruitment; and (c) UPI during winter (January–March), the spawning season of these fish species. The long-term mean of the upwelling index series are indicated by the horizontal broken line.

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