Sardine and other Pelagic Fisheries Changes Associated with Multi-Year Trade Wind Increases in the Southern Canary Current

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ABSTRACT

Two periods of high abundance and southward spreading of sardines (*Sardina pilchardus*) and accompanying changes of other pelagic fish are described through the landings of an industrial fishery off Sahara and Mauritania. In the mid-1970s, the catches increased six-fold, exceeding 600 000 t in 1976-1977, then they decreased to 200 000 t, before rising again, in 1989-1990, to the same level. Afterwards, eastern bloc fishing effort was severely reduced and the catch dropped. Wind and sea surface temperature series obtained from ships-of-opportunity show that each of these booms followed a multi-year intensification of the northeasterly trades and upwelling.

An explanatory hypothesis is proposed, which relies on the alongshore and cross shelf circulation and on patterns primary of secondary production rate. In strong upwelling and fast offshore advective situations, primary production prevails and can feed large populations of sardine which thrive on phytoplankton. While in weaker upwelling areas, counter-currents acting as large scale retention loops, improve the transfer of primary production to zooplankton and favor zooplankton filter feeders (*Sardinella*, *Trachurus*) and small predators (*Decapterus*, *Scomber*).

During the trade wind strengthening periods, increases in the southward circulation and Ekman upwelling modify the ecosystem so that sardines colonize newly upwelled waters, overwhelm other species and widen their range up to Senegal. While in relaxation intervals, the decline of sardine leads to the dominance of sardinella, horse mackerel and mackerel.

Correlation analysis show that the yearly catches of sardine lag two years behind the alongshore wind stress. This means that larval and young fish survival is improved by increases of wind induced upwelling. Comparing catches to the monthly wind stress shows that strong wind always favors recruitment except during the first three months of larval life where the detrimental effect of the offshore losses overwhelms the improvement of feeding conditions.

RÉSUMÉ

Les données de captures d'une pêcherie industrielle établie au large du Sahara et de la Mauritanie permettent de décrire deux périodes de forte abondance et d'expansion de la sardine (*Sardina pilchardus*) vers le sud, ainsi que les changements concomittants qui se sont produits parmi les autres espèces pélagiques. Dans le milieu des années 70, les prises ont été multipliées par six jusqu'à dépasser 600 000 t en 1976-1977, puis elles ont diminué jusqu'à 200 000 t avant de retrouver en 1989-1990 le même niveau. Ensuite l'effort de pêche des pays de l'Est a été fortement réduit et la prise s'est effondrée. Les données de vent et de température de surface recueillies par les navires marchands montrent que chacune de ces expansions a suivi un renforcement de plusieurs années des alizés et de l'upwelling.

Une hypothèse explicative est proposée, basée sur les schémas de circulation parallèle et perpendiculaire à la côte et sur le rapport des productions primaire et secondaire. Dans des situations d'upwelling intense et de forte advection vers le large, la production primaire l'emporte et peut alimenter de grandes populations de sardines phyto-planctonophages. Au contraire, dans les régions d'upwelling faibles, des contre-courants agissent comme des boucles de rétention et augmentent le temps de résidence des eaux au dessus du plateau, ce qui améliore le transfert de la production primaire vers le zooplancton et favorise donc les filtreurs de zooplancton (*Sardinella, Trachurus*) et les prédateurs (*Decapterus, Scomber*).

Pendant les périodes de renforcement du vent, l'accroissement de la circulation vers le sud et l'intensification des upwellings d'Ekman modifie l'écosystème de telle façon que les sardines colonisent les eaux nouvellement remontées et étendent leur aire de répartition jusqu'au Sénégal. Cependant, dans les intervalles de relaxation, le déclin des sardines conduit à la dominance des sardinelles, chinchards et maquereaux.

Des calculs de corrélation montrent que les prises annuelles de sardine suivent la courbe de l'intensité du vent avec un retard de deux ans. Ce qui signifie que la survie des larves et des jeunes poissons est améliorée par l'upwelling induit par le vent pendant les deux premières années de leur vie. La comparaison des prises aux tensions de vent mensuelles montre que le vent favorise le recrutement à toutes les périodes de l'année, sauf pendant les trois premiers mois de la vie larvaire où l'effet négatif de l'entraînement au large prévaut sur l'amélioration des conditions trophiques.

INTRODUCTION

Clupeoid fish, and particularly sardines, are well known to be highly variable resource and the analysis of scales records from anoxic sediments showed that large variations in stock size have occurred before the development of fisheries (Soutar and Isaacs, 1974). On the other hand, similarities between the fluctuations of several sardine fisheries, in different oceans, suggest that climatic factors, at a quasi-planetary scale, might control these populations (Cushing, 1982).

Stock increases in density are frequently associated with geographic spreading, as the case of the north eastern Atlantic sardine. The northern boundary of *Sardina pilchardus* is approximately the entrance of the British Channel (Southward *et al.*, 1988). During the 1950s, the French sardine fishery was bountiful and large quantities of sardine were caught all the way to the North Sea. The fishery of Northern Morocco was then considered as most southern fishery for this species. However, at the same time (1953), the regular occurrence of small number of *S. pilchardus* was established in Mauritanian waters (Cadenat and Moal, 1955), and some individuals were occasionally caught as south as Dakar (Fréon, 1988). During the 1960s catches from the North Sea to the Gulf of Biscay declined. Also, at the end of the 1960s, a strong southward extension of the sardines occurred in the Canary Current (Fig. 1) leading to the emergence of a new fishery off the Western Sahara, which had been initially directed towards horse mackerels (*Trachurus spp.*), mackerels (*Scomber japonicus*) and scads (*Decapterus ronchus*), (FAO, 1985, 1990). The sardine catches, mainly due to eastern bloc trawlers, (Fig 2) increased quickly from 80 000 to 650 000 tonnes, then decreased below 200 000 t during the late 1970s and early 1980s. Again, in the late 1980s, catches reached approximately the level of the preceding maximum (FAO, 1990). But, from 1992 onwards, political changes and economic problems led the eastern bloc countries to dramatically reduce their fishing effort and, consequently, the catch has declined considerably (FAO, 1994).

An apparent relationship between the southwards expansion of sardine, the strong catch increase and a drop in sea surface temperature was noticed by Domanovsky and Barkova (1976) and Fréon (1988). The latter equally observed a change in

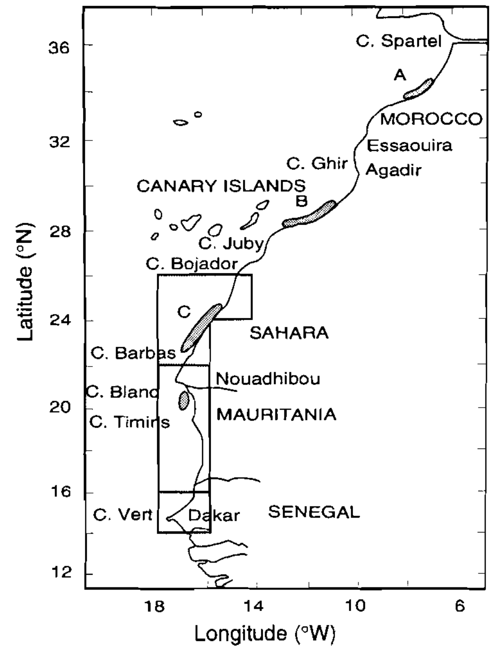


Fig. 1: Location of the spawning areas of stocks A, B, C (shaded), (from FAO, 1985) and of Banc d'Arguin (south of Cape Blanc). These areas are henceforth called 'Sahara', 'Mauritania' and 'Senegal'. The SST and wind data presented here stem from these areas.

the specific composition of the pelagic catch, and hypothesized probable causes for these changes. Also, a review of ecological knowledge in this area led Binet (1988) to explain how the trade wind acceleration increased offshore and southwards surface transport, enhanced the primary/secondary production rate, favoring phytoplankton feeders and the southwards expansion of temperate species.

Thus, the second boom of the sardine fishery, south of 26°N, during the late 1980s, following another multi-year strengthening of the trade winds and concomitant with a new southward expansion of this species all the way to Senegal, is of particular interest, as it corroborates the previous hypotheses. This paper generalizes these through a hypothesis linking trade winds and pelagic fisheries, from a literature review, then presents the climate and fishing changes observed along the north west coast of Africa, from 26°N to 14°N, during the last three decades.

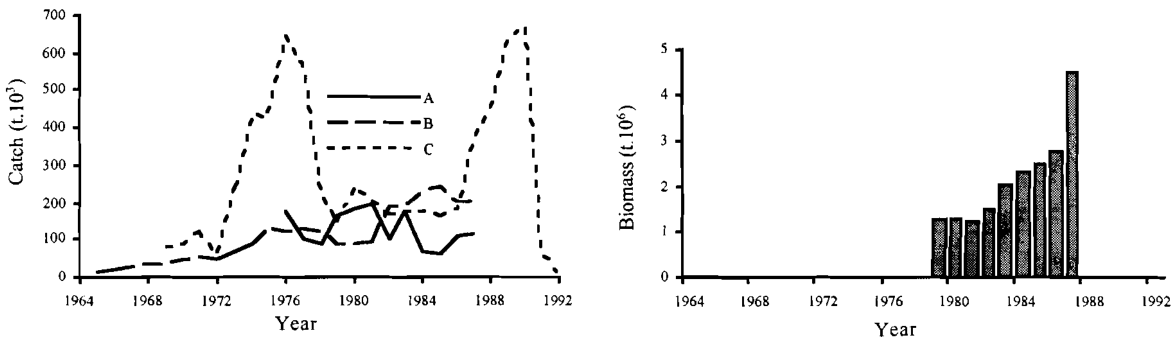


Fig. 2: Sardine catch of stocks A, B and C (see Fig. 1), Biomass of the stock C computed from a VPA. After FAO (1990 and 1994).

1. HYDRODYNAMICS AND PRODUCTION CHANGES INDUCED BY CHANGES IN WIND STRENGTH

An increase in trade wind velocity strengthens Ekman upwelling, offshore and southwards transport and could explain the settlement of *Sardina pilchardus* beyond its usual range, by enhancing the drift towards southern areas and in modifying the ecosystems such that sardines can overwhelm other pelagic species (Binet, 1988).

1.1. Alongshore circulation

Along the northwestern coast of Africa, surface transport is driven by currents that are usually equatorward: the Canary Current and the Guinea Current. Under this surface layer, a poleward counter-current, situated near the edge of the shelf, sinks progressively from the Bay of Biafra (where it is still a surface current) to Morocco. The core of this poleward circulation is located between 25 and 60 m depth, off Côte-d'Ivoire (Lemasson and Rébert, 1973), 50-100 m off Senegal (Rébert, 1983), 100-200 m off Banc d'Arguin, 200-300 m north of Cape Blanc, 400-500 m at 25°N and 500-1000 m between 30 and 34°N (Mittelstaedt, 1982, 1983) (Fig. 3).

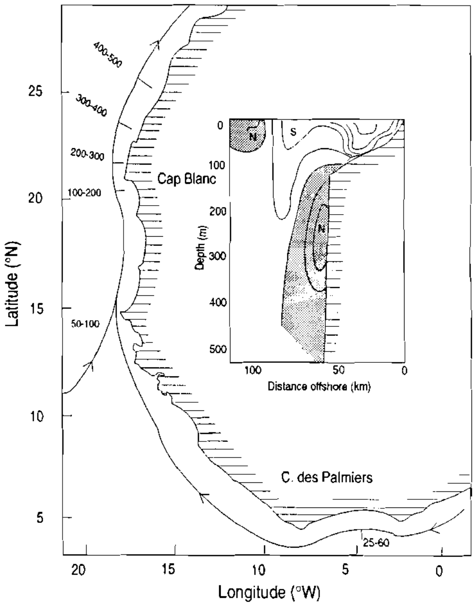


Fig. 3: Depth of the subsurface circulation (in m) along the coast of Northwest Africa. The polewards current progressively sinks north of Cape Blanc. The insert shows the alongshore components of the current (northwards and southwards, in cm/s), along a cross-shelf transect, north of Cape Blanc (21° 40'N). After Mittelstaedt (1982), Lemasson and Rébert (1973) and Teisson (1983).

However, the surface circulation fluctuates and seasonal reversals are known from Mauritania to the Bay of Biafra. On the shelf, between Cape Timiris and Cape Blanc, the flow is essentially wind-driven, and enhanced by a southward jet of 10 to 20 cm/s. However, offshore, a counterflow moves northwards opposite to the wind (Fig. 3). Inshore, there is also a superficial countercurrent, during summer and autumn (Mittelstaedt, 1976). The variability of the currents over the shelf and the slope is mainly determined by the interactions between the wind-driven flow and the countercurrent (Mittelstaedt *et al.*, 1975). Off

Saint-Louis du Sénégal (16°N), Catewicz and Siwecki (1985) found that currents in both northwards and southwards directions take the place of the general equatorward transport from June to November, in relation with seasonal interruption of the trade-wind. The velocities are low and the direction variable from June to August, while, during the following months, the current flows southwards and is faster. Teisson (1983) showed, similarly that during periods of strong trades, there is a fast southward flux, from the shore to beyond the continental slope, while during weak trades, a slow southwards vein flows in the middle of the shelf, between two northwards counter currents (Fig. 4).

Finally, a northward flow occurs along the Northwest African coast, due to the large-scale pressure gradient; however on the shelf, this effect is masked when the trade winds are strong enough to maintain the equatorward flow. The offshore undercurrent and the inshore near-surface countercurrent thus appear to be one and the same current system (Mittelstaedt, 1982).

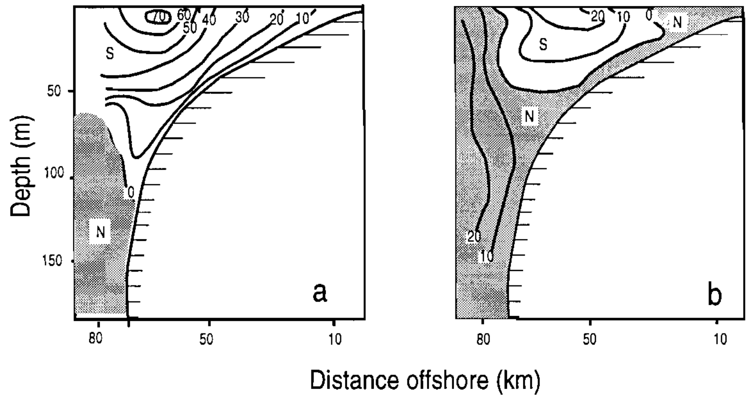


Fig. 4: Current section across the Senegalese shelf, at 14°N. North-South components (cm/s) during (a) strong trades and (b) weak trades, (from Teisson, 1983).

1.2. Upwelling and cross shelf circulation

There is no superficial countercurrent along the coast of Western Sahara, where the upwelling pattern is reduced to a two-cell system (Fig. 5a). In the coastal cell, the residence time of water in the euphotic layer, over the shelf is short, about 10 days (Jacques and Tréguer, 1986).

Off Mauritania, the cross circulation due to the coastal upwelling system is more complex. It has a horizontal diameter of 50 to 100 km (twice the shelf width), depending on the strength of the local winds. The most intense ascending motions occur at the shelf break, between 100 m and 150 m. The water masses rising up along the slope are trapped by the subsurface onshore flow of the compensation layer and upwelled on the shelf, close to the coast (Mittelstaedt *et al.*, 1975). The near-surface offshore flow ranges vertically over 15 m near the Banc d'Arguin to about 50 m at 20 km further seaward. Within the compensation layer, the upwelling waters come from the North at shallower depth and from the South at lower depths, due to the poleward-flowing current. (Mittelstaedt, 1982).

To explain these complex features, Mittelstaedt (1982) proposes a three-cell pattern, consisting of a strong inshore upwelling and of a weak offshore divergence, separated by a convergence over the slope (Fig. 5b). The subsuperficial waters of the undercurrent may rise in the onshore as in the offshore upwellings while the surface waters of the countercurrent may be involved in the upwelling circulation of the shelf by downwelling along the convergence zone and rising along the slope in the compensation layer. The existence of an occasionally closed inshore upwelling circulation cell makes it possible for some of the upwelled water to recirculate in two to three weeks. Mittelstaedt (1982) computes the residence time of the water on the shelf to one month, starting from the entry of subsurface water on the shelf and ending when the surface layer leaves the shelf, after having passed two upwelling cycles. This pattern associates vertical and horizontal recycling with the latter, an anticyclonic cell, probably being the more effective.

Off Mauritania, complex hydrographic patterns, including a countercurrent near the surface enables the recycling of water, both vertically and horizontally, in a manner different from that off the Sahara (Fig. 5).

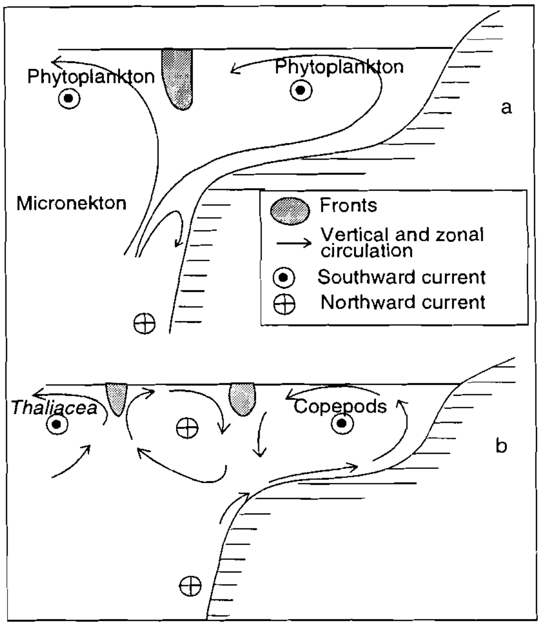


Fig. 5: Pattern of the cross shelf circulation off Sahara, 25°N (a) and Mauritania, 18°N (b). After Jacques and Tréguer (1986), Mittelstaedt (1982) and Weikert (1984).

1.3. Balance between phyto and zooplankton productions

Phytoplankton production can quickly follow a nutrient enrichment of the euphotic layer, provided that turbulence has sufficiently decreased. Off Morocco, Grall *et al.* (1982) observed a lag of 4 to 10 hours between the maximum wind impulse and the arrival of deep water at the surface. Chlorophyll then increases 6 hours after the wind relaxes, and stratification begins. Indeed, phytoplanktonic cells need only a few hours for division. Thus, maximum chlorophyll areas are situated very close to the core of upwelling plumes. Frequently, a large part of this primary production is lost for consumption by herbivores, on ends in dead ends. In some areas, large swarms of *Thaliacea* can exploit quickly the huge amount of biomass produced, because Salps and doliolids may short-circuit sexual reproduction and multiply very quickly by budding. Cladocerans too, can reproduce parthenogenetically and ensure a rapid utilization of the primary production. However, the bulk of the zooplankton is made of Copepoda, whose life cycles are much too long (2 to 4 weeks in tropical seas) to ensure an efficient transfer of a bloom of primary production to secondary production. This is probably the reason why zooplankton is not very abundant in regions of strong upwellings.

Along the north western coast of Africa, the maxima of zooplankton and of phytoplankton are closely matched in areas with weak, seasonal upwelling, while there is mismatch in permanent strong upwellings.

Off Morocco, Grall *et al.* (1974) measured the rate ATP/Chl*a*, (roughly equivalent to the sum of autotrophs plus heterotrophs, divided by chlorophyll *a*). This rate was lowest near the core of the plume and increased southward, to a maximum 60 nautical miles from the core. In the two-cell upwelling system off Sahara, there are only small copepods over the shelf. The strongest zooplankton biomasses are found offshore (Vives, 1974; Hargreaves, 1978; Weikert, 1984; Olivar *et al.*, 1985), contrarily of what is currently observed. Larger species (notably Euphausiacea) live off the shelf (Blackburn, 1979). On the contrary, south of Cape Blanc (Mauritania), larger zooplankton biomasses are found on the shelf, or nearby (Alcaraz, 1982).

The seasonal maxima of phytoplankton and zooplankton occur approximately at the same time in Mauritania (south of Cape Timiris), off Dakar and Abidjan, while off Morocco, the phytoplankton and zooplankton peaks are dissociated (Fig. 6).

This probably means that when the residence time of zooplankton near the bloom of phytoplankton is too short, the copepods are not able to transform efficiently the primary production into eggs and to lay these near the richest phytoplankton areas. This is so mainly because phytoplankton is concentrated in the euphotic layer, while zooplankton,

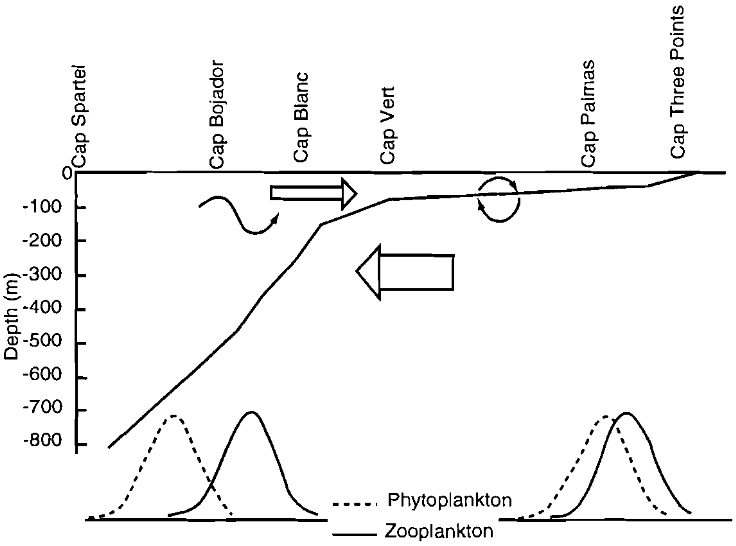


Fig. 6: Surface and subsurface circulation along the West Africa (broad arrows). Mean depth of the subsurface polewards circulation. Zooplankton drift is related to ontogenetic vertical migration (sinusoid and circular arrows). South of Cape Vert, ontogenetic migration can retain zooplankton populations in high primary production areas, because the undercurrent brings back older stages near their hatching place; phytoplankton and zooplankton annual cycles are matched. North of Cape Blanc, the polewards current sinks deeper and ontogenetic migration of most copepod species cannot retain them in the most productive areas; moreover the residence time of waters over the shelf is short and high zooplankton biomasses are found offshore. In coastal areas the zooplankton peak lags several months after the phytoplankton bloom (adapted from Binet, 1988, 1991).

distributed over the whole water column, is scattered by the currents. The efficiency of transformation of phytoplankton into animal biomass is low and the zooplankton seasonal maximum lags behind the phytoplankton bloom. However, certain copepods perform an ontogenetic migration; the young stages remain near the surface, while the older stages dwell in a deeper, opposite current. This behaviour can retain the population in a given area, or at least weakens its dispersion (Binet and Suisse de Sainte-Claire, 1975; Binet, 1977). Vertical migrations, when coupled to an appropriate currents system, are probably the reason why maxima of phyto- and zooplankton do occur at the same time in moderate upwelling areas, where offshore transport is slow or where two opposite currents are superposed (Binet, 1988, 1991), (Fig. 6).

We may reasonably suppose that the complex hydrological mechanisms enabling the water to recirculate in upwelling cells or slowing southward and offshore transports, lengthen the residence time of zooplankton near productive areas and improve the energetic transfer from primary to secondary production. It appears that in the strongest upwelling areas (Morocco, Sahara), where no subsurface layer counter acts the southwards transport, the upwelling leads mainly to a phytoplanktonic production. Off Mauritania on the other hand, as long as the countercurrent is not too deep, recirculating cells and vertical migrations enhance zooplankton production. The same, occurs, a fortiori, on the shelves off Senegal and Côte-d'Ivoire, where the countercurrent comes close to the surface.

Off Mauritania, the northwards surface transport develops when the trade winds relax, while the southwards transport strengthens and spreads up to Senegal during strong northerly periods. Then, phytoplankton production is probably favored instead of the zooplankton, and a shift of the upper levels of the food webs, from zooplankton-feeders to phytoplankton feeders, becomes likely.

1.4. Pelagic fish feeding and spawning

Clupeids are microphagous and most feed on zooplankton. Nevertheless, diatoms, and to a lesser extent dinoflagellates, are regularly consumed by Californian sardine along with zooplankton (Lewis, 1929). In the Canary Current, the contribution of phytoplankton to stomach contents of *Sardina pilchardus* is far from being negligible (Nieland, 1980) and this species frequently schools near diatoms blooms. Moreover, Cushing (1978) notes that the digestive tract of *S. pilchardus* is longer than that of strictly zoophagous clupeoids, which enables this species to digest phytoplanktonic cells. On the contrary, *Sardinella* spp. are mainly zooplankton filter-feeders, *Trachurus* spp. are only zooplankton feeders and *Decapterus rhonchus* and *Scomber japonicus* are predators. Thus, *Sardina pilchardus* can feed on phytoplankton and colonize newly upwelled waters, where secondary production is weak; this contrasts with the others species which tend to occur in the more mature ecosystems at the boundaries of the upwellings.

Along the northwestern coast of Africa, *Sardina pilchardus* has three main spawning areas (Fig. 1) corresponding to the three stocks A, B (north of Cape Juby) and C (south of Cape Juby). Reproduction does not occur in the strongest upwelling areas, between Essaouira and Cape Ghir and the larvae are less abundant between Cape Barbas and Cape Blanc where offshore advection is very strong. In the C stock (Sahara), the spawning area spreads between Cape Bojador and Cape Barbas (26° to 22°N). Off Cape Blanc *S. pilchardus* spawns from the center to the edge of the shelf. Eggs are distributed over the first 60 m, but after hatching, most larvae occur in the first 30 m (John *et al.*, 1980; John, 1985). Some of the deeper eggs are driven shoreward by the return circulation, then drift south westwards. The main spawning period is in October-December, a secondary spawning bout occurs in April-May. Concentrations of spawners appears to be associated with small turbulent eddies in autumn and winter (Barkova and Domanevskaya, 1990), the seasons during which wind speeds are at their minimum.

Egg production is regulated by a thermic threshold and starts at temperature ranging from 15 to 17°C. Thus, spawning cannot happen in the very center of an upwelling. In weak upwellings, eggs tend to be abundant over the entire shelf, while in strong upwellings, eggs tend to occur over the shelf break, in warmer waters (John *et al.*, 1980). This regulating mechanism improves odds for the larvae to find a suitable environment for their development.

Sardinella aurita is another abundant pelagic fish from the intertropical belt including West Africa. It inhabits coastal waters, seasonally enriched by upwellings, and also spawns in Mauritania. The Banc d'Arguin and coastal region south of Cape Timiris include nurseries. The main reproduction season is in July-October, when the upwelling declines (Conand, 1977). *S. aurita* feeds mainly on zooplankton (Nieland, 1982).

Thus, while all of these species can live in upwelling, the feeding and reproductive strategies of *Sardina pilchardus* give it a better ability to colonize newly upwelled waters. On the other hand, any strengthening of southwards transport and correlated weakening of northwards surface currents, favours the settlement of new populations of sardine south of their usual latitudinal range and weakens the northwards migration of *Sardinella* spp.; and any cooling of the shelf waters favours temperate species (sardine) against tropical ones (sardinella).

2. DATA SETS

2.1. Climatic observations

Winds and sea surface temperatures (SST) were obtained from the international network of ships-of-opportunity. These raw data were processed for the entire tropical Atlantic basin to determine monthly fields of pseudo-wind stress[1]. The database was started in 1964 and is continuously updated (Picaut *et al.*, 1985; Servain *et al.*, 1987; Servain and Lukas, 1990). The monthly values of wind stress and SST are calculated in 5° longitude by 2° latitude quadrangles. An objective analysis method is then used to create a 2° x 2° gridded monthly data base. Afterwards, the calculated data of the nearshore squares were averaged in three larger latitudinal strips, herafter called 'Sahara', 'Mauritania' and 'Senegal' to allow comparisons with the available fisheries statistics (Fig. 1, Table 1).

To obtain time series of a wind-induced upwelling index, monthly values of alongshore wind stress were computed. In Sahara region the wind vector was projected onto the shoreline direction. In other areas, where the coastline is assumed to be North-South, we used the southwards component of the wind stress. Climatologies were computed for the different areas (Fig. 7 a,b,c).

[1] *The wind stress vector is the product of the density of air, the drag coefficient, the wind velocity vector and the absolute value of observed wind speed. The pseudo wind tress, hereafter named "wind stress" is equal to the product of the last two terms (wind velocity vector by absolute value of the wind speed).*

Areas	Latitude range (°N)	Longitude range (°W)	Coast direction (°N)
'Sahara'	22 - 26	14 -16 and 16 - 18	208
'Mauritania'	1° - 22	16 - 18	180
'Senegal'	14 - 16	16 - 18	180

Table 1: Geographical areas in which wind stress and SST from the database of J. Servain were averaged (these areas do not correspond to political entities).

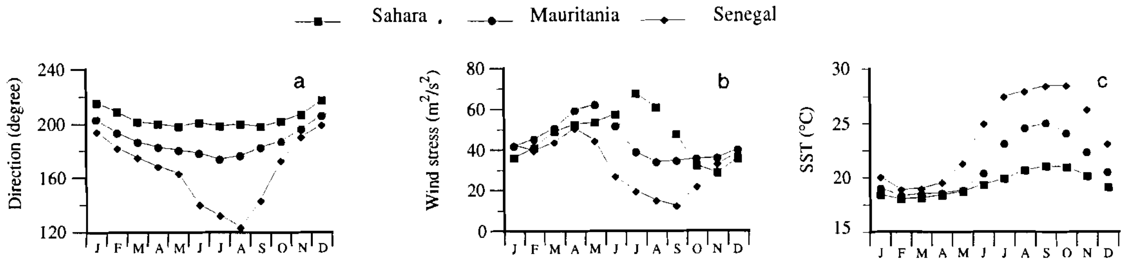


Fig. 7: Climatology from the ships of opportunity (database of J. Servain, 1964-1993): a) Wind direction, b) Alongshore wind stress, c) sea surface temperature.

2.2. Fisheries statistics

From 1964 to 1987, the catches in 'zone C', (26°N to 19°N, i.e., approximately from Cape Bojador to Cape Timiris), were obtained by WECAF working groups (FAO, 1990). *Sardina pilchardus* appeared in this area from 1969 onwards. The bulk of the catch was made up by eastern bloc countries, mainly the Soviet Union and including the former German Democratic Republic (GDR; Fig. 8). Boats were large pelagic trawlers (RTMA, BMRT and RTMS) and purse seiners associated to carriers (FAO, 1990).

Catches of mackerel (*Scomber japonicus*), scad (*Decapterus rhonchus*), Atlantic horse mackerel (*Trachurus trecae*), Cunene horse mackerel (*T. trachurus*) and *Sardinella* spp. from 1964 up to 1981 are known from a broad latitudinal range, corresponding to the WECAF divisions 34.1.3 and 34.3.1, (9°N to 26°N) (*in* Fréon, 1988).

From 1979 up to 1992, all pelagic catches made in the Mauritanian EEZ and off Western Sahara were collected by the Centre National de Recherches sur l'Océanographie et les Pêches (CNROP), Nouadhibou and compiled during the November 1993 working group held at Dakar (FAO, 1994).

Total catch of sardine was preferred to catch per unit of effort (CPUE) as an index of long term abundance variations because some effort data were missing or difficult to standardize and especially because the use of CPUE has proved to be hazardous to assess the abundance of highly variable pelagic resources. Fish are non randomly distributed, they frequently aggregate and their CPUE remains stable even when abundances decline. The fishing effort dramatically dropped after 1990 (Fig. 8).

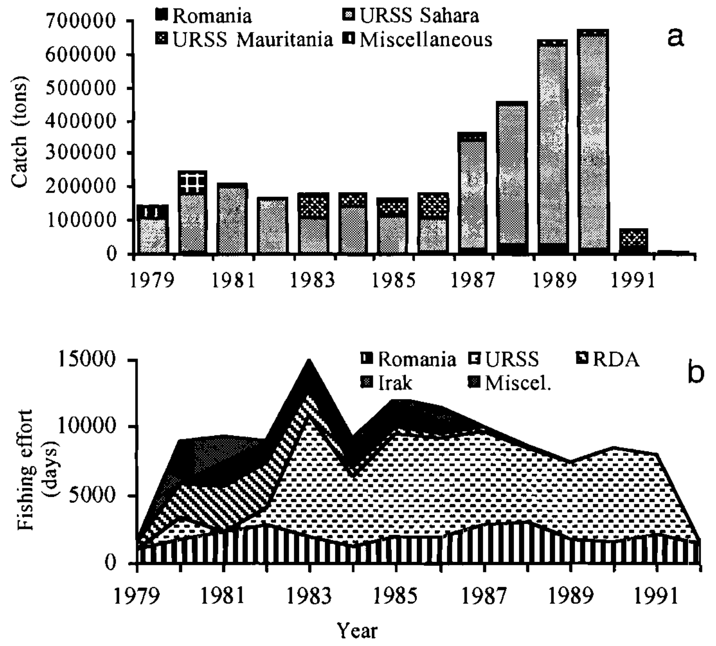


Fig. 8: Data on the sardine fishery: a) sardine catch off Mauritania and Sahara by different countries (1979-1992); b) fishing effort by different countries off Mauritania (1979-1992).

Available data do not allow a clear separation between what has been fished off Mauritania and off Sahara. The Romanians fished only off Mauritania since 1979, meanwhile the Soviet fleet operated mainly off Sahara. As the Soviet catch largely exceeds all others, we compared the whole catch made off Mauritania and Sahara to the alongshore wind stress recorded off Sahara. The differences between the two sardine catch series, during their overlapping period, are small, compared to the peaks observed in 1976-77 and in 1989-90. Thus, we created a composite catch series including the first data set for the 1969-78 period and the second one, from 1979 onwards (Fig. 2). The dramatic decrease of the Soviet fishing effort after 1991 led us to discard the values of 1991 and 1992 from the correlation versus wind stress (section 4.4), as they probably did not reflect a real decrease in stock abundance.

The fishing strategy and the seasonal variations of availability of the different species off Mauritania were studied based on the mean monthly CPUEs of the Romanian fleet (1979-1992).

Off Senegal, *Sardina pilchardus* is caught only by small scale fisheries. It has been previously recorded as a very rare species (Fréon, 1988; Fréon and Stequert, 1979) and appeared in the small scale fishery statistics only in 1991. Unfortunately *Sardina pilchardus* is not appreciated by Senegalese consumers and, due to its low price (5 FCFA/kg), fishers do not target this species. Thus, its real abundance is not well known.

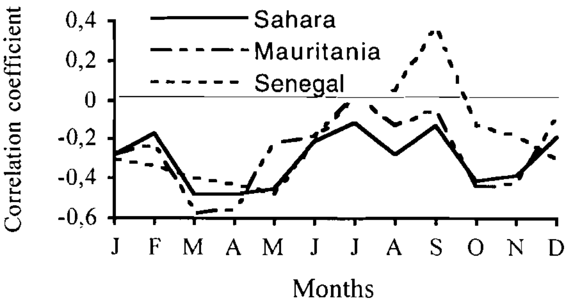
3. CLIMATE

3.1. Wind stress and SST climatologies

The meridional migration of the Intertropical Convergence Zone (ITCZ, which separates the northern and southern trade wind systems) determines wind and SST seasonal variations. ITCZ moves from a near equator latitude, during boreal winter, to a northern position, around 15°N on the coast and 20°N in the continent, during boreal summer. The northeasterly trade winds blow all over the year along the Saharan coast, while along the Senegal, winter and spring northerly alternate with variable, frequently westerly winds from June to October (Fig. 7a). The average wind speed increases from the south to the north, reaching their maxima in April to July, from the Senegal to the Sahara (Fig. 7b).

Along the northwestern coast of Africa, upwelling is considered to be a basically wind-driven process (Wooster *et al.*, 1976). Indeed, almost all correlations between monthly values of alongshore wind stress and SST are negative (Fig. 9). The only exceptions are found off Senegal, in July, August and September, during the monsoon season (Fig. 7). Nevertheless, it is of interest to notice the weakness of the correlation in summer and winter, in the three areas. These weak correlations probably mean that SST depends not only on local winds but also on remote events carried southwards by the Canary Current (Rébert, 1983). Wooster *et al.* (1976) observe that the field of offshore Ekman transport and those of coastal temperature anomalies are basically similar. However, a discrepancy occurs between 20° and 25°N, where the coastal temperature anomaly continues through the last quarter of the year even though the offshore transport has decreased significantly. That probably means that cold upwelled waters are strongly advected from the north at this time. Then the waters of the Saharian shelf are probably more mature (in an ecological sense) than waters that have been just upwelled and thus, more suitable for the feeding of early larvae.

Fig. 9: Correlations between monthly values of alongshore wind stress and sea surface temperature. Negative correlations indicate Ekman upwelling.



3.2. Changes during the last three decades

Then we consider the alongshore wind stress (ASWS) series as a broad scale proxy for upwelling intensities. From 1964 up to 1993, ASWS (Fig. 10) and SST (Fig. 11) show roughly inverted patterns. Positive anomalies of ASWS (upwelling favorable) occurred at approximately the same time in the three study areas : from 1971 to 1975, in 1986 and from 1991 onwards. Strong negative anomalies of SST were clearly associated to the first two events, while period of strong winds in the early 1990s corresponds only to a slight cooling.

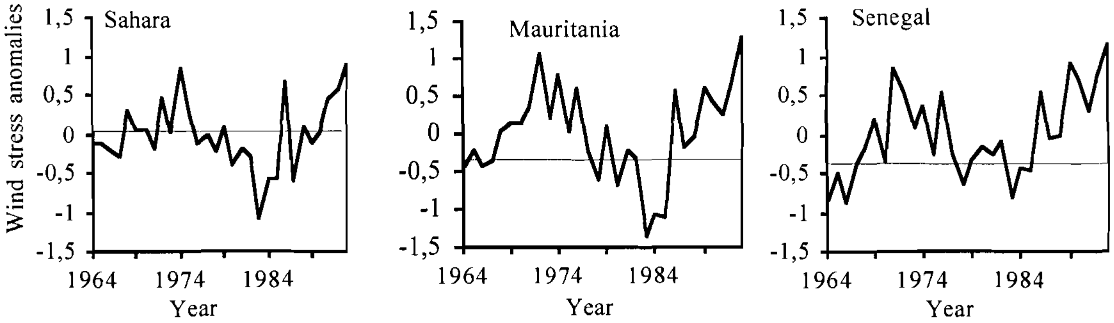


Fig. 10: Normalized series of alongshore mean annual wind stress anomalies (1964-1993). The wind stress is parallel to 208° off Sahara, and is southwards off Mauritania and Senegal.

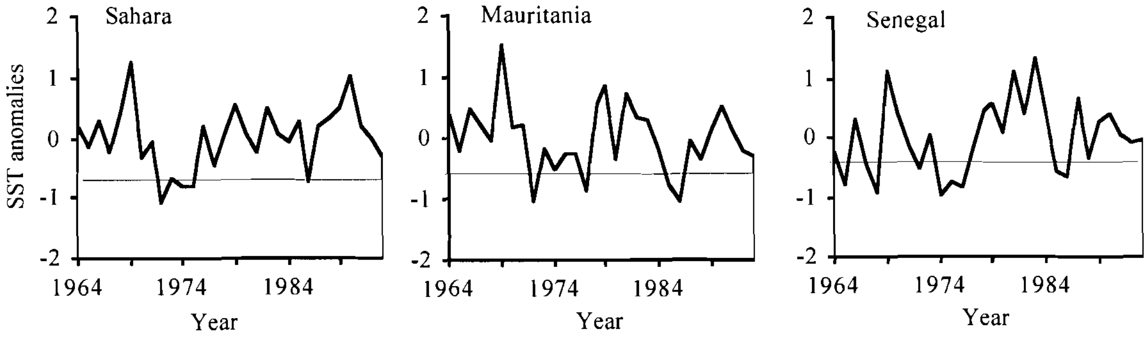


Fig. 11: Normalized series of mean annual sea surface temperatures anomalies, 1964-1993.

4. SMALL PELAGIC FISHERIES

4. 1. Southwards spreading of Sardine

The fishery for *Sardina pilchardus* in northern Morocco is relatively recent, as it began only during the 1920s (Belvèze, 1984). The fishing area progressively spread southwards, into what has been called zone A (32° to 30°N), (Belvèze, 1984). Occasional occurrence of small sardines was recorded farther south, in the Baie du Lévrier (near

Nouadhibou) as early as 1923 by Monod. In June 1941, Spanish trawlers caught some small specimens (7-8 cm) off the Cape Blanc; in September 1952, a stomach of *Orcynopsis unicolor* provides another record. In 1953, the regular presence of sardine in the Baie du Lévrier was established by beach seine sampling from April to July (Cadenat and Moal, 1955). All were of small sizes (7 to 12 cm) but they reached sexual maturity and the catch of very small fish (3 cm) proved that a population has established itself. Furnestin (1955) attributed the small size of these fish to a low growth rate in the southern limit of their province, and he thought that no commercial yield was foreseeable in this area.

From 1965 a second fishery developed between 29° and 27°N (zone B), then a third, south of 26°N, after 1969 (zone C). Catches of several tons were obtained in the Baie du Lévrier and north of Cape Blanc in 1972 and 1973 (Maigret, 1974). The southern boundary of the sardine fishery was estimated at 28°N in 1966, 21°N in 1970 and 18°N in 1973 (Domanovsky and Barkova, 1976). In 1974 some sardines were caught off Senegal (Conand, 1975; Boëly and Fréon, 1979). Then the schools came back northwards and the species almost disappeared from Mauritanian waters in 1982-83.

However, from 1984 the species was again fished off the Banc d'Arguin (20°N) and a new southward displacement appeared to begin (FAO, 1985). Indeed, the Senegalese small scale fisheries caught 77 t of *Sardina pilchardus* in 1991, and 1100 t in 1994, mainly by purse-seines. During a short period of the winter 1994, sardines were the main species caught in certain beaches south of Cape Vert, (Petitgas, pers. comm.). The present expansion of *Sardina pilchardus* in Senegalese waters is by no means comparable with the preceding scarce records. The rare records of sardine concerned mainly young fish, caught in waters between 16°C and 19°C, during the cold season, although, in 1954 and 1976, young fish were fished in the Bay de Gorée, in 25°-28°C waters (Fréon, 1988). On the contrary, the beach seine sampling, between January and March 1994, proved that the schools were made of 20-23 cm ripe sardines, weighing 100-130 g. Remote sensing thermographs indicate a strong cooling of superficial waters during the winters from 1986 onwards (except 1990). In 1986 and 1994, surface cold waters spread southwards from the Mauritania to southern Senegal (Demarcq, this vol.). This cooling may be responsible of the exceptional abundance of sardine south of Dakar. In the course of May 1994, the species was also caught in the bottom nets of the small scale fisheries, and it disappeared soon after, probably escaping in deeper waters as the warm season was advancing. On the contrary, the first months of 1995 were rather warm and no sardine was reported.

Although the Senegalese catch was very limited until 1994, it has clearly demonstrated, twice in twenty years, a southwards spreading of the geographical range of the sardine, following, one or two years later, the huge catch off Sahara in 1976-1977 and in 1989-1990. Moreover, each of these peaks was approximately in phase with a strengthening of the trade winds.

4.2. Seasonal pattern of catches and CPUE off Sahara and Mauritania

Seasonal and spatial distribution of pelagic catches can be used to infer ecological preferences of different fish species. The fishing strategy, i.e. the distribution of fishing days north and south of Cape Timiris, was approximately the same for the Soviet and Romanian fleets (Fig. 12). Most of the effort was in the south from April to June, then the boats moved northwards until the end of the year. This shift of the fishing boats is related to the seasonal displacement of the strongest upwelling. Chavance *et al.* (1991) observed that the fleet mainly worked in the region of the steepest SST gradients. Indeed, *Trachurus* spp. are the main catch of pelagic trawlers and this fishing strategy enables a regular yield of either of the two main *Trachurus* species. On the 1985-1991 Romanian catch averages (Fig. 13), the CPUE of the temperate species

T. trachurus highest during winter and almost null in summer, while the tropical *T. trecae* was mainly fished in the southern area, all along the year. Chavance *et al.* (1991) noted that the two peaks of yield correspond respectively to arrival of spawning concentrations of each of these two species into Mauritanian waters.

The seasonal patterns of CPUE for *Decapterus rhonchus* and *Scomber japonicus* differ from the preceding (Fig. 13). The higher catches occur after the maximum upwelling period. The seasonal changes in CPUE are related to temperature optima and feeding regimes. Phytoplankton predominates during period of maximum upwelling intensity, while heavier concentrations of zooplankton are delayed until wind stress and offshore transport relax (See Section 1.3). *S. japonicus* and *D. rhonchus* having a carnivorous diet avoid the newly upwelled waters, more than do *Trachurus* spp.

The tropical species *Sardinella aurita* and *S. maderensis* are more abundant during the summer non-upwelling period and higher concentrations of these two species are encountered south of Cape Timiris (Fig. 13).

The best catches of *Sardina pilchardus* clearly come from northern Mauritania, though the fishing effort of Romanians and Soviets were roughly equivalent in north and south areas (Fig. 12). The best fishing months were January-May and, secondly November-December. In other words, sardine was mainly fished during its two spawning seasons, and the catch were almost null from June to September, during the warmer period.

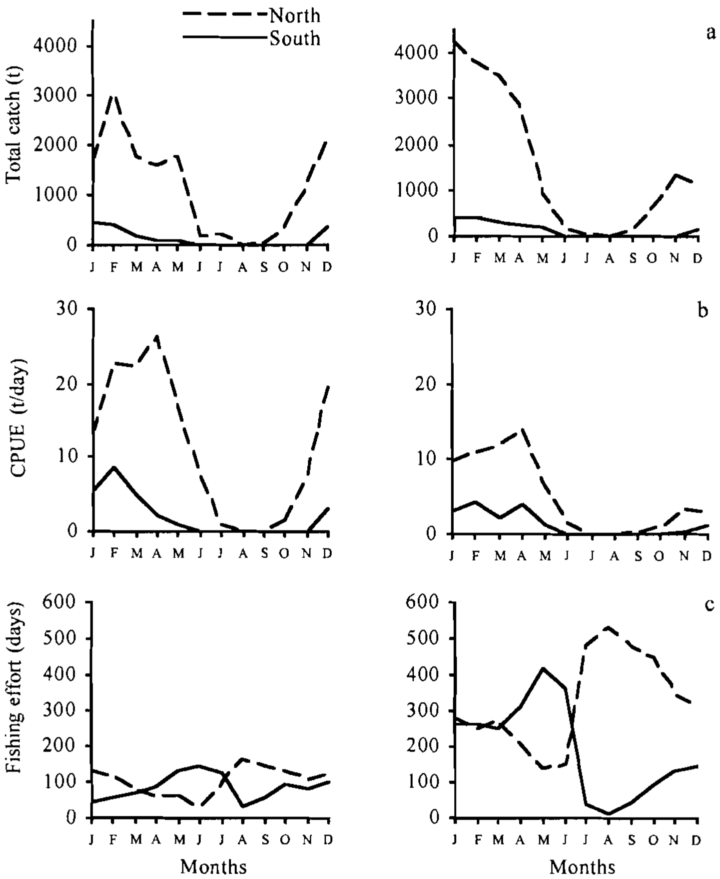


Fig. 12: Seasonal features of the Romanian (left) and Sovietic (right) sardine fisheries off Mauritania, North and South of 19°N:
a: total catch;
b: catch/effort;
c: fishing effort.

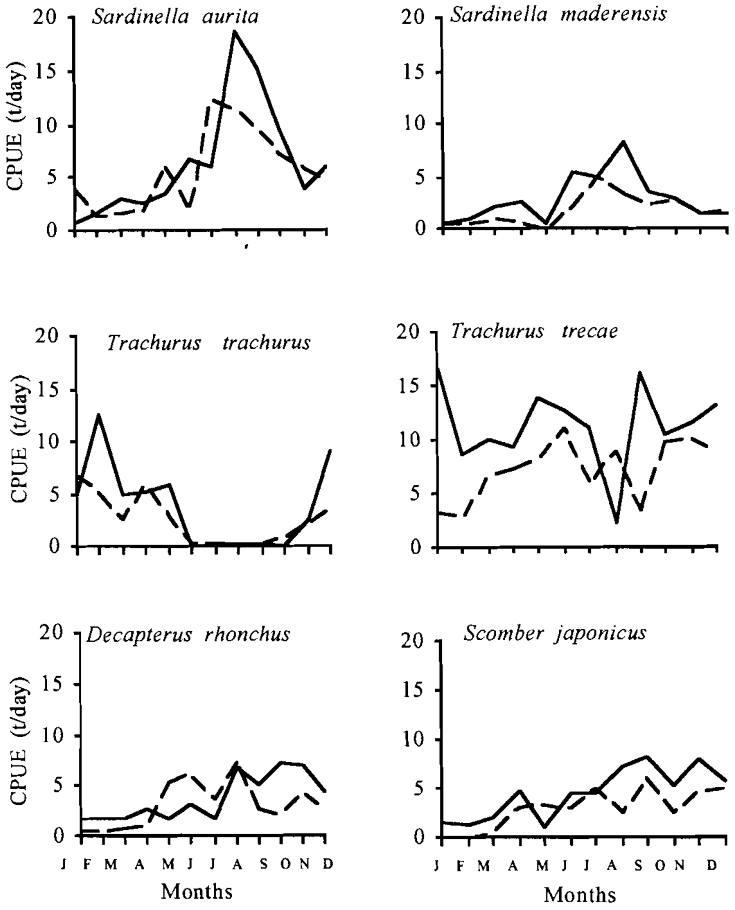


Fig. 13: Seasonal variation of catch per unit of effort (t/day) of the Romanian fishery off Mauritania (1979-1992) for *Sardinella aurita, S. maderensis, Trachurus trachurus, T. trecae, Decapterus rhonchus* and *Scomber japonicus*, off northern and southern Mauritania.

4.3. Changes in species dominance

A change in the relative abundance of pelagic species during the mid 1970s wind event was described by Fréon (1988) and Binet (1988). While the sardine landings were growing, the relative abundance of mackerels (*Scomber japonicus*), horse mackerels (*Trachurus* spp.), jack mackerels (*Decapterus rhonchus*) and *Sardinella* spp. were diminishing (Fig. 14). The new data set (1979-1992) shows a basically similar pattern. After the 1970s wind event, the proportion of sardine decreased, the catches were again dominated by *Trachurus* spp and *Decapterus*. Then, the 1986 ASWS peak was followed by a several year increase of *Sardina pilchardus* at the expense of the other species, up to 1989. These changes closely resemble those which happened 10 years earlier.

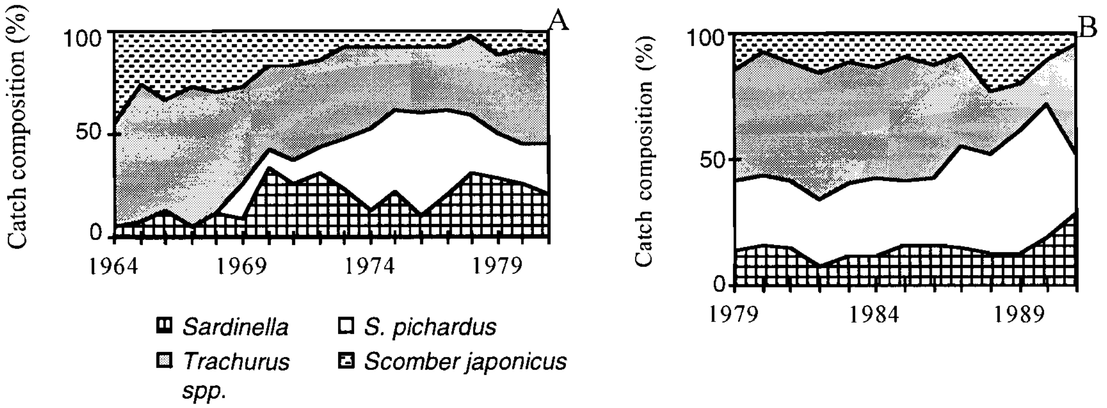


Fig. 14: Changes in the species composition of pelagic catches in the 9°-26°N area (left), from Fréon (1988) and Binet (1988); and off Mauritania (right), from FAO (1994).

4.4. Wind - sardine recruitment relationships

A linear correlation was sought between the time series of wind stress and sardine catch off Sahara and Mauritania (1969-1990), (Fig. 15). These were first calculated between annual values of ASWS and sardine catches. The best correlation is obtained between the annual catch and the wind of the previous years (Table 2). Assuming that catch variability reflects - to a certain extent - changes in the stock abundance, these correlations mean that if sardines are mainly recruited at two years old, the recruitment is favoured by increase, in the wind, induced upwelling during the first yearof life of the fish, and the result appears in the fishery two years later. According to Barkova (*in* FAO, 1990) stock biomass began to increase slowly in 1982, and quickly from 1987 (Fig. 2), that is only one year after the 1986 wind strengthening.

Year	year n	year n-1	year n-2	year n-3
r	0.126	0.242	0.354	0.237

Table 2: Correlations between the yearly catch of sardine (Sahara and Mauritania) and the alongshore wind stress between 22° and 26°N.

Then, in order to identify the season whose climate determines recruitment levels, the regressions were calculated between the annual catches and the twelve monthly ASWS series, with time lags ranging from zero to two years (Fig. 15). The correlations are weak, but positive for the largest part of the year. Negative values are observed only in May, July, August and particularly December. The coherence of these results has some significance. If the spawning periods are in October-December and April-May, strong winds when larvae are less than three months old, negatively affect their survival; on the other hand, strong winds during the rest of the year improve survival. In other words, strengthening of Ekman upwellings are beneficial to the food web and to sardine feeding, insofar they do not occur within the very first months after spawning of sardine.

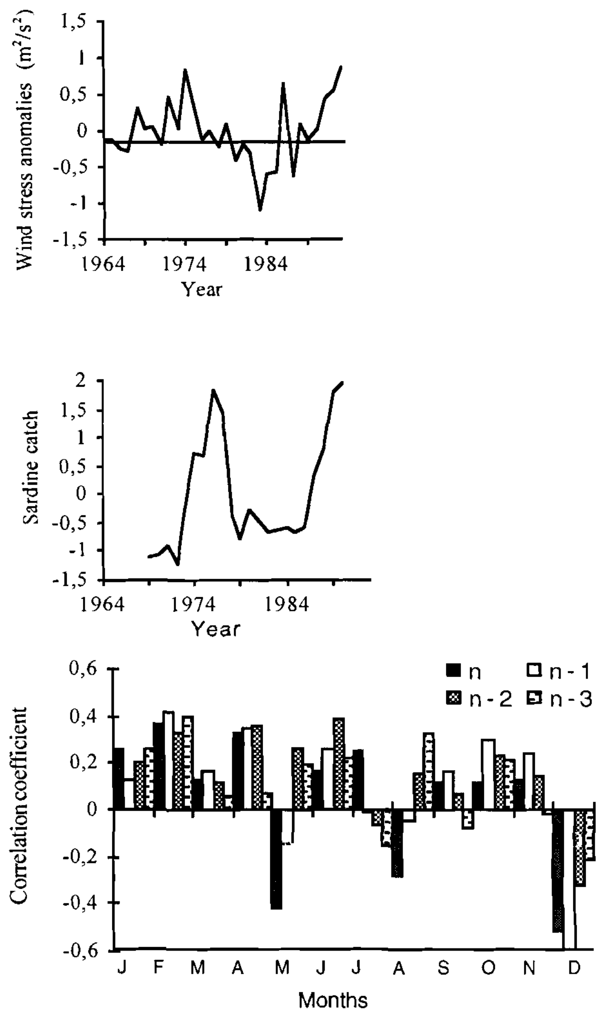


Fig. 15: Analysis of sardine recruitment: a) standardized anomalies of alongshore wind stress; b) total sardine catch off Sahara and Mauritania (1969-90); c) correlations between the annual sardine catch off Sahara and Mauritania and monthly alongshore wind stress, for time lags from 0 to 3 years.

CONCLUSION

In the southern part of the Canary Current a large fishery has developed off the Western Sahara, based on a sardine population, (stock C), which was absent before 1965. Two southwards expansions of this sardine occurred at 23 years interval. *Sardina pilchardus* was fished off Mauritania, where large industrial fleets were exploiting it and off Senegal, where moderate numbers were caught by the small-scale fishery. Southwards extensions are correlated to multi-year periods of trade wind strengthening which occurred in 1972-75, in 1986 and from 1991. We described likely environmental changes associated to the new climate pattern: intensification of upwelling regime, southward transport, and decline of SST. Phytoplankton production was probably boosted as well, but not matched by zooplankton grazing, due to the brevity of the residence time of waters over the shelf. Thus, sardines larvae were strongly advected towards the south and, as adult sardines are able to feed on phytoplankton, they were favoured instead of the zooplankton feeders, or the carnivorous small pelagic fish.

Off Northwest Africa, sardines spawn during the whole year, with a distinct maximum in winter. In the Cape Blanc area, larvae were abundant at SST between 16° and 17°C, scarce at temperature above 18°C and absent when the SST exceeded 21°C (John *et al.*, 1980). These authors described an absence or scarcity of larvae in 1968, 1970 and 1972, during weak or absent upwelling, while they record high catches of larvae in 1974, 1975 and 1977. These fluctuations are in good agreement with the changes of upwelling intensity, and corroborate the correlations we found between recruitment and annual wind stress.

However, spawning is limited by temperatures below 15.5°C (John *et al.*, 1980), and during strong upwellings, eggs are only found in small number over the shelf break. The negative correlation we found between catch and ASWS, during the spawning period, probably means that during early life, the advective losses are more deleterious for the larval survival than food limitations. This is in contrast to other parts of the year, when strong upwellings enhance the food content of coastal waters and the survival of young sardines.

In the Canary Current, the drift of fish larvae is basically directed southwards. Lloris *et al.*, (1979) propose a biological cycle of a demersal fish (*Pagellus acarne*) based on a latitudinal separation of adults (northern, upstream group) and juveniles (southern, downstream group). Eggs and larvae released by the adults drift southwards and lead to the southern group. The reverse link between young and adult is assumed to be a countercurrent migration off the edge of the shelf. (This return migration might be helped by the deep northwards current). The life span of *Sardina pilchardus* eggs is 2 to 4 days, while larvae may reach up to 9 weeks (John *et al.*, 1980). Along a transect parallel to the coast, from Morocco to Mauritania, the larger larvae were found in the south, indicating the direction of their drift. However, John *et al.* noted that, in 1977, the southern drift of near-surface larvae may be an exception due to the strong upwelling rather than a regular feature.

However, during the last decades of strong upwellings, a general trend to a southwards extension of the geographical ranges of pelagic species has occured (Ehrich *et al.*, 1987). Thus, we may reasonably suppose that the southwards circulation was enhanced and northwards surface transport inhibited during these windy years. It became unlikely for juvenile tropical fish to settle north of Cape Blanc. On the contrary, during wind relaxation periods, the slowing of alongshore and cross shelf circulations lengthen the residence time of water over the shelf, improves food web transfers and favours carnivorous fish. The decrease of northerlies enables a northwards surface transport and a colonization of the Mauritanian shelf by tropical species.

The first records of a species, out of its usual range, are generally from isolated individuals, which can be considered as vagrants, according to Sinclair (1988). If these vagrants are numerous enough, and if they encounter good environmental conditions, including circulation features enabling a complete life cycle on the shelf, their offsprings may initiate a new, self-sustaining population. The recent history of cod settlement off West Greenland, from larvae advected from the Iceland, is a similar example (Dickson and Brander, 1993). Thus, the southward extension of sardines from Morocco to Senegal, during the last decades, probably went off through the successive settlement of spawning areas, heading to self sustaining populations off Cape Bojador-Cape Barbas, Cape Blanc-Cape Timiris and possibly on the Senegalese Petite Côte, south of Cape Vert. This colonization was probably facilitated by the heavy exploitation of other fish stocks.

It required 20 years at least, between the first spawning, observed in 1950, in the Baie du Lévrier (Mauritania) and the first industrial fishing in 1970. Maigret (1974) noted that the three years preceding the first landings in Nouadhibou were especially cold. The first observations of *Sardina pilchardus* in Senegalese waters, previously reported by Fréon (1988), concerned young individuals probably carried by the southward circulation. In 1977 some ripe specimens were caught and again in 1994. Thus, it seems that a new population is settling south of Cape Vert, but due to lack of observation in 1995, we cannot confirm it. Although a Senegalese sardine fishery looks very unlikely in the future, let us remind that to Furnestin (1955) a regular sardine fishery off Mauritania was quite improbable.

It is satisfying to see that the same ecological relationships held during three decades and that chaotic dynamics did not prevail against them. The reasons are probably because upwellings are young ecosystems where any strengthening of Ekman pumping increases offshore transport, stops the maturation, and resets all the ecosystem, preventing chaotic evolution.

According to the 50 years wind stress time series compiled by Bakun (1990, 1992), it seems that the present climatic change was beginning at least 50 years ago. If, according to Bakun, this increase in the eastern boundaries trade winds is due to the increased contrast in temperature between heated land masses and the oceans, in relation to the 'greenhouse effect', we may expect a continuation and a strengthening of these phenomena during the coming years. Probably, the strengthening will not be regular but fluctuating, and we can expect a continuation of the alternance of sardine and horse mackerel-sardinella periods, with more frequent sardine periods.

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