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Climate and pelagic fisheries in the Canary and Guinea currents 1964-1993: the role of trade winds and the southern oscillation

Pelagic fisheries
West Africa
Trade winds
Oceanic currents
Southern Oscillation

Pêches pélagiques
Afrique de l'ouest
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ABSTRACT

Upwellings off the coasts of western Africa provide abundant but fluctuating marine resources. Sea surface temperature and wind stress, monitored by the ship-of-opportunity observation network, are compared to fishery statistics from 1964 onwards. In the Canary Current, off Sahara and Mauritania, upwellings are mostly wind driven. In the Guinea Current, off Côte d'Ivoire and Ghana, the link with local wind is very weak.

In the southern Canary Current, two wind-intensification periods occurred in the early 1970s and from 1986 onwards. On each occasion, *Sardina pilchardus* landings were multiplied approximately threefold. During the first event, catches of species living at the periphery of the upwelling, *Sardinella, Trachurus, Decapterus* and *Scomber*, decreased slightly. During the second event, interrupted by some warming, catches of sardinelle increased, those of horse-mackerel decreased; mackerel landings increased only during the warm years. Sardine catches are correlated to the alongshore wind stress of the year (n–2), except during the very early months of larval life. Each wind stress increase induces an enrichment which favours larval survival, except just after hatching, when the adverse effects of turbulence and offshore advection prevail.

In the part of the Guinea Current submitted to seasonal shoaling of the thermocline, a dramatic increase of the *Sardinella aurita* catch began at the beginning of the 1980s. Nevertheless, the SST warming trend does not indicate an intensification of deep-water uplift. Another hypothesis, based on the change of sign of the Southern Oscillation Index since 1976, is proposed. The tropical Atlantic would be in a long-term, warm, El Niño-like phase, with strengthened eastward circulations in the vicinity of the equator. Coastal surface and subsurface currents, linked to this eastward flux, would be intensified. Therefore, the number and/or the surface of eddies formed in these currents by Cape Palmas and Cape Three Points would be increased. Since sardinelle spawning occurs in these regions, which play the role of retention cells, enlargements of the turbulent structures would enable a larger number of larvae to thrive and sustain a larger population, according to the Sinclair hypothesis.

RÉSUMÉ

Influence du climat sur les pêcheries pélagiques du courant des Canaries et de Guinée de 1964 à 1993. Rôle des alizés et de l'oscillation australe.

Les remontées d'eaux froides qui se produisent le long des côtes d'Afrique occidentale sont des lieux de pêche intensive, mais très fluctuante. Les observations recueillies par les navires marchands permettent d'y suivre l'évolution du vent et de la température de surface et de les comparer aux statistiques de pêche depuis 1964. Dans le courant des Canaries, au large du Sahara et de la Mauritanie, les remontées d'eaux sont essentiellement dues à un upwelling induit par le vent. Le lien avec le vent local est beaucoup moins net dans le courant de Guinée, devant la Côte d'Ivoire et le Ghana.

Dans le sud du courant des Canaries, deux périodes d'intensification de l'alizé se sont produites vers 1970-1976 et depuis 1986. Chaque fois, les captures de *Sardina pilchardus* ont été multipliées par trois environ. Lors du premier événement, il s'est produit une légère régression des prises de *Sardinella, Trachurus, Decapterus* et *Scomber,* mieux adaptées à la périphérie des upwellings ; lors du second événement, interrompu par un certain réchauffement, les prises de sardinelles ont augmenté, celles de chinchards ont diminué, et celles de maquereaux ont augmenté uniquement lors du réchauffement. Les captures de sardine sont corrélées à la tension de vent parallèle à la côte au cours de l'année (n–2), à l'exception des premiers mois de la vie larvaire. Toute augmentation de vent induit un enrichissement bénéfique à la survie larvaire, sauf pendant les tout premiers mois suivants l'éclosion, où la turbulence et l'advection vers le large entraînent davantage de pertes.

Dans la région du courant de Guinée sujette à des remontées saisonnières de la thermocline, un fort accroissement des captures de *Sardinella aurita* s'est produit depuis le début des années 1980. Cependant on n'observe pas de baisse de la température de surface qui indiquerait une intensification des résurgences. Une autre hypothèse est proposée, basée sur le changement de signe de l'oscillation australe depuis 1976. L'Atlantique tropical serait depuis plusieurs années dans une période chaude, de type El Niño, avec une circulation vers l'est intensifiée autour de l'équateur. Les courants côtiers de surface et de subsurface du golfe de Guinée, liés à ce flux vers l'est, en seraient accrus. Par conséquent le nombre et/ou la surface des tourbillons, formés dans ces courants par les caps des Palmes et des Trois Pointes, serait accru. Or les sardinelles se reproduisent dans ces régions qui jouent le rôle de structure de rétention pour leurs larves. L'agrandissement de ces structures tourbillonnaires permettrait donc la survie d'un plus grand nombre de larves et le développement d'une population plus abondante, conformément au schéma de Sinclair.

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INTRODUCTION

The principal fishing areas along the western coasts of Africa, are situated in the Canary, Guinea and Benguela currents, where upwellings or thermocline shoalings induce strong new primary production, due to the uplift of the nutricline to the photic layer. The Canary and Benguela upwellings belong to the oceanic boundary systems, as parts of the intertropical anticyclonic gyres, in both hemispheres. The currents are largely wind-driven, at least in their mid-latitude range, and their surface waters flow equatorwards. Conversely, the eastward-flowing Guinea Current (GC) is fed by the North Equatorial Countercurrent (NECC), which is a part of the return circulation of waters accumulated on the western side of the tropical Atlantic under the influence of the trade winds. The distantly-forced NECC is located in the doldrum area and is driven against the prevailing trades by the meridional shear of the zonal winds (Katz, 1993) (Fig. 1). In the Guinea Current, seasonal shallowings of the thermocline induce pulses of biological production along the shelves of Côte d'Ivoire and Ghana. Therefore large changes in basin-scale atmospheric pressure may be supposed to induce important oceanological and ecological variations in these areas.

The corresponding ecosystems yield important but highly variable fishing resources, especially among pelagic species. The idea that large-scale fluctuations of pelagic fisheries depend firstly on recruitment and then on the variability of larval survival is now widely accepted. The fate of an individual larva depends on its immediate environment: small-scale turbulence, availability of edible plankton, presence or absence of predators, etc. But, due to scale transfer problems, attempts to predict the strength of a stock at recruitment on the basis of fine-scale plankton observations would be hazardous. So, an opposite approach will be used. Just as large-scale oceanic turbulence is known to break down into smaller eddies, so we may suppose small-scale biological events to be steered by large-scale physical perturbations.

This paper seeks to demonstrate possible relationships between planetary climate changes and two pelagic stocks in the Canary and Guinea currents, during the past thirty years. In the Canary Current, on two occasions with a 12-year interval, a maximum of *Sardina pilchardus* catches followed a period of trade wind strengthening (Fig. 2, 4).

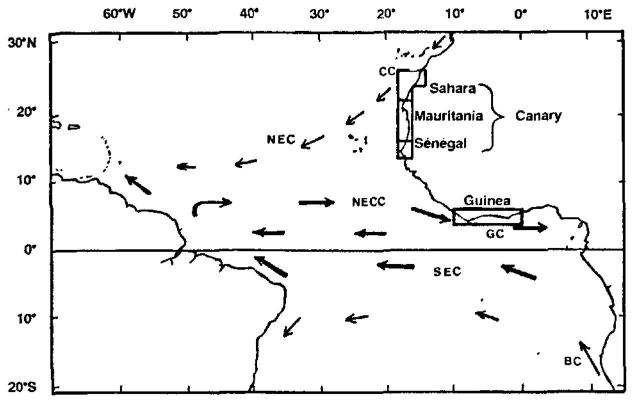

Figure 1

Map of the tropical Atlantic Ocean, location of the study areas: Canary (Sahara, Mauritania, Senegal) and Guinea (see Tab. 1). Surface currents in boreal summer: CC, Canary current, NEC, north equatorial current, NECC, north equatorial countercurrent, SEC, south equatorial current, GC, Guinea current, BC, Benguela current.

Carte de l'Atlantique intertropical, localisation des régions étudiées: Canaries (Sahara, Mauritanie, Sénégal) et Guinée, (Cf. Tab. 1). Courants de surface en été boréal : CC, courant des Canaries, NEC, courant nord équatorial, NECC, contre courant nord equatorial, SEC, courant sud équatorial, GC, courant de Guinée, BC, courant de Benguela.

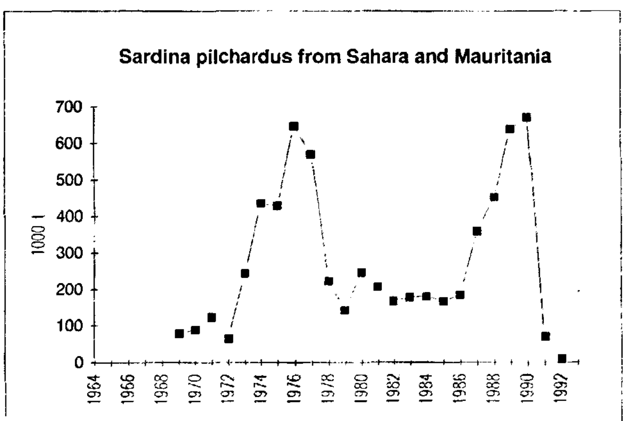

Figure 2

Sardina pilchardus *catches off Sahara and Mauritania, from FAO (1990) and Binet* et al., *(in press).*

Prises de *Sardina pilchardus* au large du Sahara et de la Mauritanie, d'après FAO (1990) et Binet *et al.*, (sous presse).

The reinforcement of wind-induced upwelling increased the nutrient content and planktonic production in the euphotic layer: this probably improved the survival rate of juvenile fish. In the Guinea Current, the stock of a closely related species, *Sardinella aurita*, has sustained inexplicably high catches for more than a decade (Fig. 3); but the same hypothesis, based on an increase in nutrient content, does not entirely explain the new state of this fishery.

In the Pacific Ocean, a climate change has been observed since 1976: the southern oscillation index (SOI) – *i.e.* the difference of the sea-level pressure between Tahiti and Darwin – which is a monitoring index of El Niño,

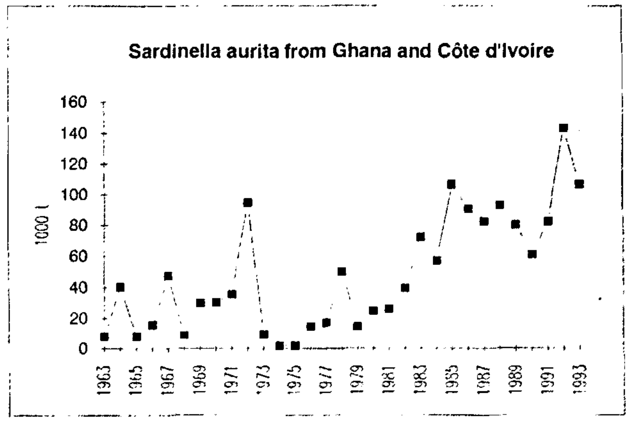

Figure 3

Sardinella aurita *catches off Côte d'Ivoire and Ghana, from Bard and Koranteng (1995).*

Captures de *Sardinella aurita* en Côte d'Ivoire et au Ghana, d'après Bard et Koranteng (1995).

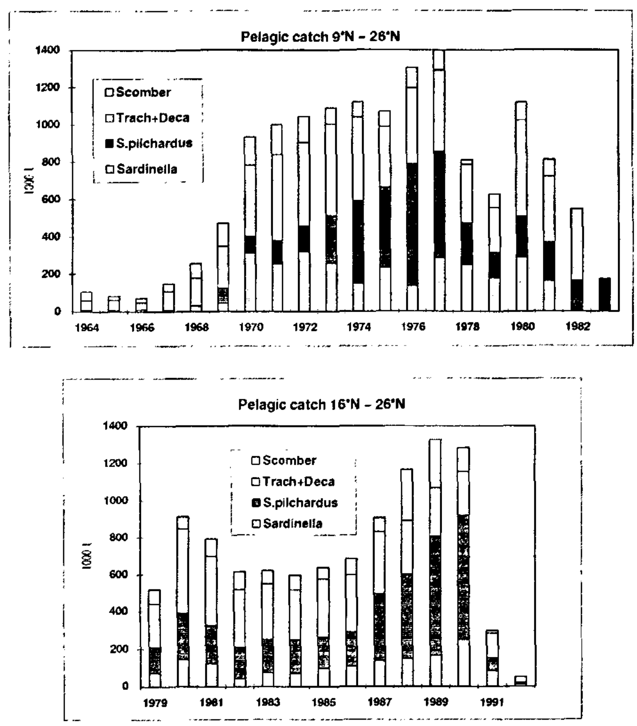

Figure 4

Catches of the main pelagic species in the Canary area during the first and the second sardine boom, from different sources. Top: catches from 9°-26° N (Fréon, 1988); bottom: catches off Mauritania, approximately 16-22° N (Samb, pers. comm.; Binet et al., *in press). The main species are* Scomber japonicus *(mackerel),* Decapterus rhonchus, Trachurus trecae *and* T. trachurus *(horse-mackerel),* Sardina pilchardus *(sardine),* Sardinella aurita *and* S. maderensis *(sardinelle).*

Captures des principales espèces pélagiques dans la région Canarie durant le premier et le second boom des sardines, à partir de différentes sources. Haut : prises de 9° à 26° N (Fréon, 1988); bas : prises au large de la Mauritanie, approximativement de 16° à 22° N (Samb, comm. pers.; Binet *et al.*, sous presse). Les principales espèces sont *Scomber japonicus* (maquereau), *Decapterus rhonchus*, *Trachurus trecae* et *T. trachurus* (chinchard), *Sardina pilchardus* (sardine), *Sardinella aurita* and *S. maderensis* (sardinelles).

has for the most part remained in a negative phase. The hypothesis of an Atlantic El Niño has long been proposed, notably to explain the seasonal thermic cycle in the Gulf of Guinea and the interannual variability of the Eastern Tropical Atlantic (Merle, 1980; Hisard, 1980) and along the northwestern African coast (Michelchen, 1985). After the strongest 1983-1984 Atlantic warm event had been thoroughly investigated (Hisard, 1988), the idea of connections between oceans clearly emerged. Anomalies in the sea-level pressure field and in the seasonal shifts of the Intertropical Convergence Zone (ITCZ) induce wind, current and sea-surface temperature modifications in the Atlantic equatorial belt (Merle and Hisard, 1990; Katz, 1993; Carton and Huang, 1994; Bakun, 1996). We shall see that the coastal pelagic fish populations are probably also affected by these changes.

DATA SETS

Data on fishery landings were provided by the *Centre National de Recherches sur l'Océanographie et les Pêches* (CNROP) at Nouadhibou (Mauritania), the *Centre de Recherche Océanographique* at Dakar-Thiaroye (Senegal) and at Abidjan (Côte d'Ivoire), and the Fishery Research Unit of Tema (Ghana). Previously published statistics were also used (FAO, 1990; Bard and Koranteng, 1995). A composite series including FAO and unpublished data of sardine landings was used for correlation calculation.

Wind values and sea-surface temperature (SST) data were obtained from the database of J. Servain, computed from the ships-of-opportunity network. The raw data were processed in order to obtain monthly fields of SST and of pseudo wind stress (Servain and Lukas, 1990). The pseudo wind stress t (hereafter referred to as "wind stress"), is $t = |W|W$; W being the wind speed. It differs from the true wind stress by a constant (the density of the air x the drag coefficient). The monthly values of wind stress and SST were calculated in 5° longitude by 2° latitude quadrangles. An objective analysis method was used to create a 2° × 2° gridded monthly data base. Then, averages were calculated between the 2° squares closest to the shore. In the Canary Current, the three strips will be referred to respectively as "Sahara", "Mauritania" and "Senegal". In the Guinea Current, the study area ranges from Liberia to Ghana (Tab. 1). In order to appreciate the part played by the wind in the upwelling of deep waters, we compared the SST to alongshore wind stress, *i.e.* approximately the eastward and southward components in the Guinea and Canary currents respectively; except along the coast of Sahara, oriented at 208°, where the wind stress was projected on to this direction.

A complementary data set of nearshore SST was provided by five coastal stations sampled by the *Centre de Recherche Océanographique* (CRO) of Abidjan (Fig. 14). Observations were performed daily by casting a bucket into the surf, and data were averaged on a monthly basis (Arfi *et al.*, 1991).

Table 1

Geographical areas in which wind stress and SST from the gridded ships data were averaged. The assumed coast directions are approximations for alongshore wind stress estimates. The referred areas do not correspond to political entities.

Aires géographiques dans lesquelles les moyennes des tension de vent et de température de surface issues des données « navires », ont été calculées. Les moyennes portent sur les valeurs précédemment calculées par bloc de 2° × 2°, selon la procédure indiquée. Les directions du trait de côte sont des approximations pour l'estimation de la tension de vent parallèle à la côte. Les régions indiquées ne font pas référence à des entités politiques.

Areas	Latitude range	Longitude range	Coast direction/N
"Sahara"	22°-26° N	14°-16° W and 16°-18° W	208°
"Mauritania"	16°-22° N	16°-18° W	180°
"Senegal"	14°-16° N	16°-18° W	180°
"Guinea"	4°-6° N	0°-10° W	90°

RESULTS

Canary Current: *Sardina pilchardus*

In the late 1960s, pelagic trawlers, mainly from the eastern-bloc, began to fish sardine, mackerel and horse-mackerel along the Saharan and Mauritanian coasts, south of the areas previously exploited. Starting at 80 000 t, the catch quickly peaked at 650 000 t in 1976. It then fell and fluctuated around 200 000 t from 1978 to 1986. Again, in 1989 and 1990, more than 600 000 t of sardines were landed. More recently, political and economic problems led to a sudden interruption of this fishery in 1992 (Fig. 2, Binet *et al.*, in press).

At the time of the highest catches, the latitudinal range of *Sardina pilchardus* showed the farthest southward extensions. Considered to be 28° N in 1966, the southern boundary of sardine distribution then moved equatorwards: 21° N in 1970, 18° N in 1973 (Domanovsky and Barkova, 1976), reaching Senegal (15° N) in 1974 (Boely and Fréon, 1979). Subsequently, the species progressively retreated northwards, and in 1982-1983 disappeared from Mauritanian waters. In 1984, however, it was again fished off the Banc d'Arguin (20° S), and in 1991 it appeared in the Senegalese small-scale fisheries and accounted for the bulk of certain beach-seine catches south of Dakar in 1994 (Petitgas, pers. comm.). Although Senegalese sardine catches were very limited, they clearly showed on two occasions during the past 25 years, a southward extension, following the boom off Sahara and Mauritania.

During the peaks of the sardine fishery, the catches of other pelagic species behaved differently. During the first sardine boom (1973-1978), catches of *Sardinella*, *Trachurus*, *Decapterus* and *Scomber* slightly decreased; during the second sardine boom (1987-1990), *Trachurus* and *Decapterus* decreased slightly, while *Sardinella* showed a small increase and *Scomber* peaked in 1988-1989 (Fig. 4).

Although these changes relate to commercial landings rather than a sampling survey, we may suppose that they

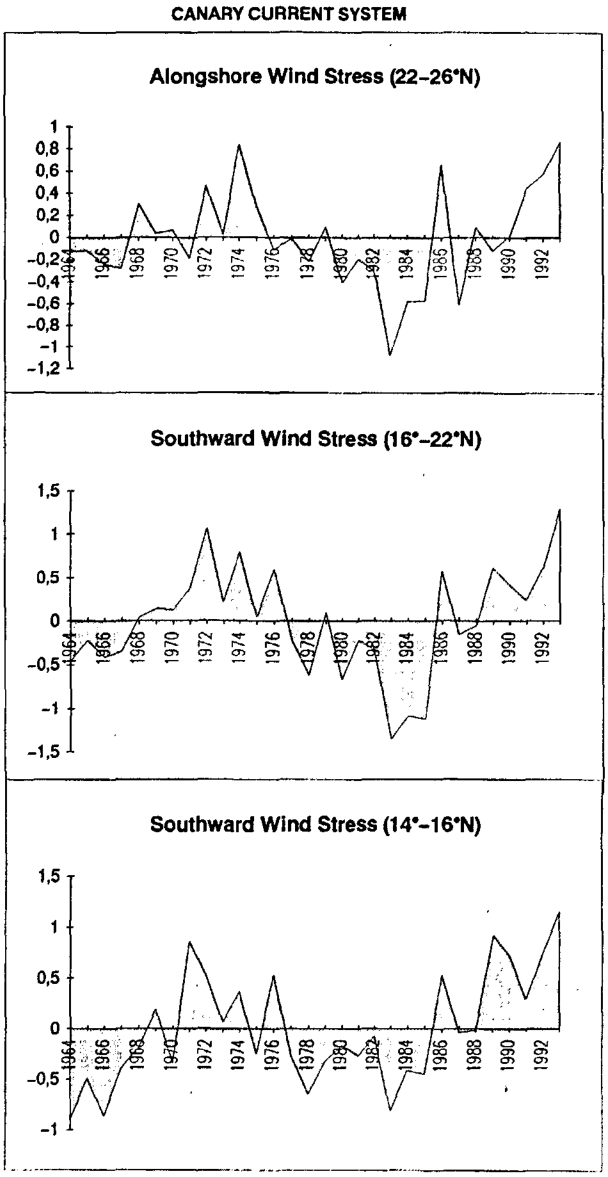

Figure 5

Pseudo wind stress in the Canary region (14°-26° N), Standardized anomaly of the alongshore component in Sahara region (22°-26° N) and of the southward component in Mauritania and Senegal regions (22°-16° N and 16°-14° N). See Table I. From the J. Servain database.

Pseudo tension de vent dans la région Canaries (14°-26° N). Anomalies normalisées de la composante parallèle à la côte dans la région Sahara (22°-26° N) et de la composante sud dans les régions Mauritanie et Sénégal (22°-16° N et 16°-14° N). Cf. tableau I. D'après la base de données de J. Servain.

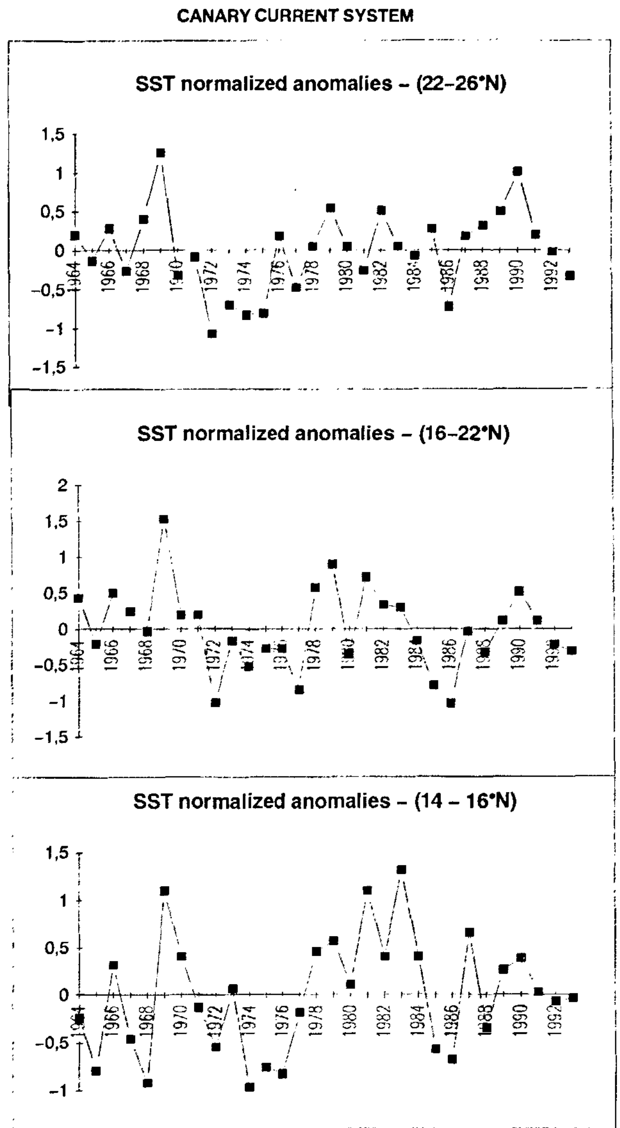

Figure 6

Sea surface temperatures in the Canary region (14°-26° N). SST standardized anomalies in the Sahara (22°-26° N), Mauritania (22°-16° N) and Senegal (16°-14° N) areas. From the J. Servain data base.

Températures de surface dans la région Canaries (14°-26° N). Anomalies normalisées de la température dans les zones Sahara (22-26° N), Mauritanie (22°-16° N) et Sénégal (16°-14° N). D'après la base de données de J. Servain.

reflect species rearrangement in the ecosystem. *Sardina pilchardus* is partially a phytoplankton feeder; *Sardinella* is a tropical vicariant, mostly a zooplankton feeder; *Trachurus*, *Decapterus* and *Scomber* are strict zooplankton feeders or predators. Changes in fish species abundances can also be viewed as the consequences of a trophic web reorganization (Binet, 1988).

Anomalies of alongshore wind stress off Sahara are very coherent, with southward wind stress changes along the coasts of Mauritania and Senegal from 1964 to 1993 (Fig. 5). Two wind maxima, in the early 1970s and late 1980s-early 1990s, are separated by a relaxation period. The SST anomalies exhibit a similar, inverted, pattern. Multi-year periods of trade wind strengthening correspond to low SST (Fig. 6). The correlation between monthly values of wind and SST (Fig. 7*a*) are negative, which denotes an Ekman upwelling, except during the monsoon season, off Senegal and to a lesser degree off Mauritania, which agrees with Wooster *et al.*, (1976) and Rebert (1983).

To quantify the relationships between upwelling and sardine recruitment, it is preferable to compare wind rather than SST to the sardine catch, because wind stress is the driving force of upwelling, and temperature decrease only a consequence. Cross-correlations between annual values show the best result with a time lag of two years (Tab. 2): increases in the north-easterlies annual mean lead to commercial catch enlargement two years later. This means that the recruitment of two-year old sardines would be favoured by any strengthening of upwelling during their first year of life.

Table 2

Cross-correlations between the yearly catch of sardines (Sahara and Mauritania) and the alongshore wind stress annual averages (22°-26° N).

Corrélations croisées entre les prises de sardines (Sahara et Mauritanie) et les moyennes annuelles de la tension de vent parallèle à la côte (22°-26° N).

	year n	year n–1	year n–2	year n–3
r	0.126	0.242	0.354	0.237

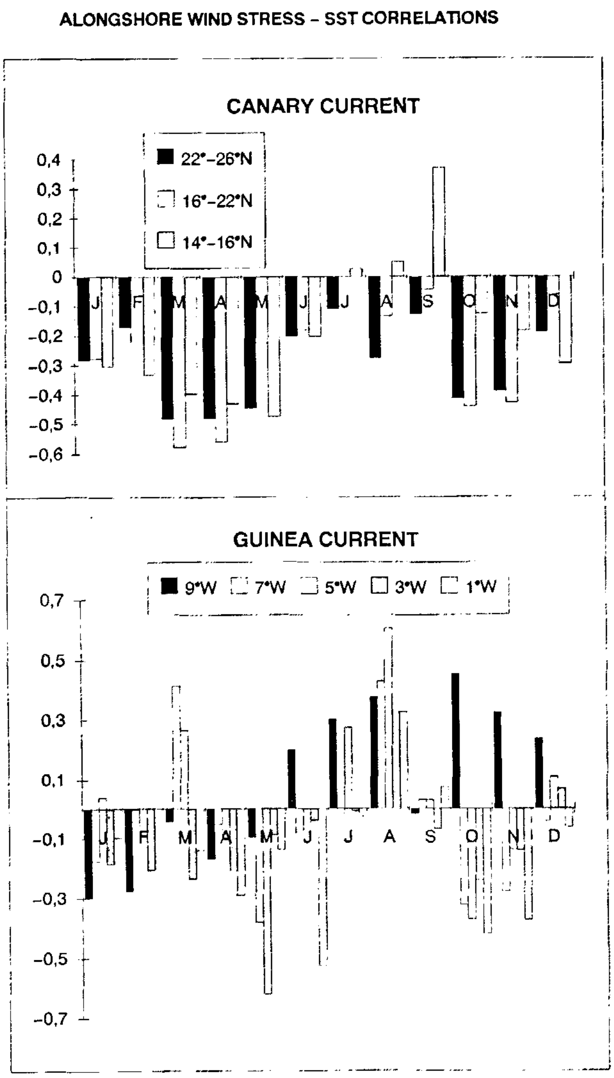

Figure 7

Along shore wind stress – SST monthly correlations in the different areas. Top: Canary region, bottom: Guinea region. In the Guinea data set, correlations were calculated on the 12th differences, in order to eliminate the interannual trend (from Binet and Servain, 1993).

Corrélations mensuelles entre la tension de vent parallèle à la côte et la température de surface. Haut: région Canaries, bas: région Guinée. Dans l'ensemble des données « Guinée », les corrélations ont été calculées sur les différences douzièmes, pour éliminer la tendance à long terme (d'après Binet et Servain, 1993).

When we correlate the annual sardine catches of years n to the monthly wind stress of years n to n–3 (Fig. 8), the catch appears positively correlated to the wind virtually every month and at any time lag, except in May, July, August and especially December, when the correlations are negative. Now, the spawning periods occur principally in October-December and to a lesser extent in April-May (FAO, 1990). Then, wind strengthenings when larvae are less than three months old could negatively affect their survival, whereas they would be beneficial at any time of year. In other terms, strengthenings of the Ekman upwelling are beneficial to the food web and hence to the sardine, in so far as they do not occur within the very first months of larval life. During these early months, superficial offshore transport associated to the upwelling cross-shelf circulation leads to a loss of eggs and larvae which is not compensated by the food chain improvement in terms of larval survival. It is possible that turbulence also has a direct detrimental effect on young larvae.

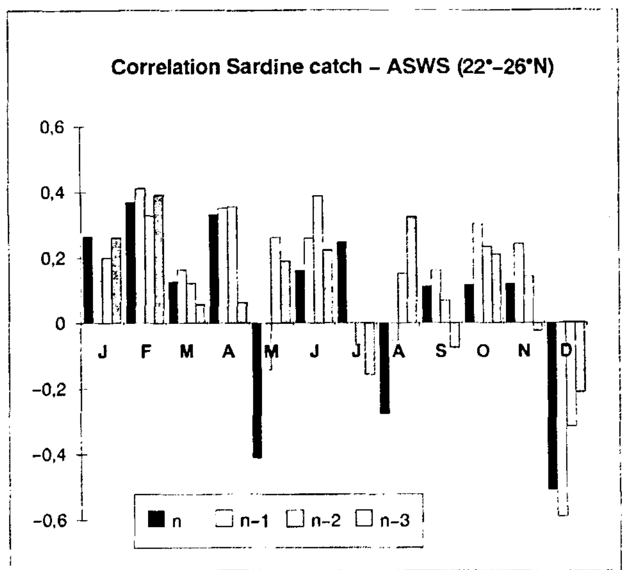

Figure 8

Cross correlations between annual catches of sardine off Sahara and Mauritania and alongshore wind stress monthly means (22°-26° N), at different time lags (years n, n–1, n–2, n–3).

Corrélations croisées entre les captures annuelles de sardines au large du Sahara et de la Mauritanie et la moyenne mensuelle de la tension de vent parallèle à la côte (22°-26° N), pour différents pas de temps (corrélations avec le vent de l'année n, n–1, n–2).

Guinea Current: *Sardinella aurita*

During the 1960s, the Côte d'Ivoire and Ghana *Sardinella aurita* fisheries yielded moderate but highly variable catches, ranging from 8000 to 47 000 t. Then, in 1972, 90 000 t were fished, due to an unusual availability of immatures in coastal waters, which has been related to the dramatic decrease of the river flows (Binet, 1982).

The stock then suffered a collapse which lasted several years, but recovered during the late 1970s. Surprisingly, since 1983 it has sustained continuous high production (Fig. 3). Off Côte d'Ivoire, the fishing areas have spread westward, and the fishing season is virtually year-long. Acoustic surveys confirm that these high catches are supported by an increased biomass of pelagic fish whose geographical distribution matches the new spatial pattern of fisheries (Binet and Marchal, 1992). Finally, the relative abundance of the two sardinelles has changed: *Sardinella maderensis*, dominant during the 1960s and 1970s, became a subordinate species in the 1980s (Pezennec and Bard, 1992).

DISCUSSION

The preceding hypotheses are based on landing series. Although it is difficult to appreciate the respective roles of recruitment and availability in the figures cited, we shall consider them as reflections of real changes in fish populations.

Eastern boundary upwelling

Following the first boom of the sardine fishery off Sahara and Mauritania (1974-1977), a hypothetical explanation linking wind stress, cross-shelf and alongshore circulations, and primary and secondary production, was proposed, based on a review of the literature (Binet, 1988). Twelve years later, another multi-year windy event led to a very similar situation (Binet *et al.*, in press), with trade wind increases modifying circulation, temperature and the primary/secondary production rates.

The direction and velocity of the circulation between the coast and the shelf break is clearly related to the strength of the trade winds. Under the influence of strong northerly winds, equatorward surface circulation is intensified, whereas northward countercurrents appear in moderate wind conditions (Teisson, 1983, Huyer, 1976; Mittelstaedt, 1983; Catewicz and Siwecki, 1985). This means that pelagic larvae of temperate species (notably *Sardina pilchardus*) were spread to the south of their former boundaries during the windy years, while a smaller number of tropical fish (such as *Sardinella aurita* and *S. maderensis*) reached the Mauritanian or Saharan nurseries. Advection of northerly waters and intensified upwelling cool the surface layer, and Mauritanian and Senegalese waters more closely resemble the sardine's biotope.

The upwelled, turbulent, nitrate-rich waters of the photic layer are a source of new primary production dominated by small diatoms and large flagellates. This production is consumed by copepods which are themselves eaten by filter feeding fish. Cushing (1989) opposes this traditional food chain to the microbial loop occurring in stratified, low-nutrient waters where the regenerated primary production depends on ammonia. The traditional, shorter food chain supports the world's major fisheries, while the microbial loop is a longer food web characteristic of a steady-state environment, unable to support large stocks.

Does this mean that any upwelling strengthening results in higher primary and secondary production and larger fish stocks? A review of the literature concerning observations along western Africa (Binet, 1988) shows that the answer depends on the possibility of synchronization of secondary and primary production. Apart from Thaliacea and Cladocera, which are able to multiply rapidly by budding or parthenogenesis, most zooplankton taxons reproduce sexually and their numbers cannot match the phytoplankton pulses. In the strongest upwelling off Sahara, the cross-shelf circulation creates a fast helicoidal movement and upwelled waters do not remain in the euphotic layer over the shelf for more than ten days (Jacques and Tréguer, 1986). Diatomites on the sea bed show that a large part of the primary production is not consumed. In the weaker upwellings off Mauritania, however, countercurrents create large loops, increasing the residence time of waters over the shelf up to one month (Mittelstaedt, 1982), which permits the development of a copepod generation, from hatching to spawning. In fact, the higher values of zooplankton biomass are not situated near the core of the strongest upwellings but on their fringes, offshore (Blackburn, 1979, Grall *et al.*, 1974) or south of Cape Blanc (Alcaraz, 1982), where complex circulation slows the offshore advection and induces a better transfer from phytoplankton to zooplankton.

Therefore, if the wind stress pulses and relaxations are not matched with the generation time of copepods, primary production will exceed zooplankton feeding capacities and will favour phytoplankton feeders instead of carnivorous fish. Sardines are plankton feeders, distinguished from most clupeids by their longer digestive tract which enables them to digest phytoplankton cells as well as copepods. So, when strong primary production pulses occur during windy years, sardines can thrive and outnumber other fish. During these stronger upwelling events, the transfer of primary to secondary production occurs further offshore and zooplankton eaters such as horse-mackerel and mackerel are less abundant over the shelf. Finally, the alternation of strong and moderate trade wind conditions over several years led to a succession of sardine vs mackerel and horse-mackerel dominance, marking a regime shift.

Similar alternations of *Sardina pilchardus* with mackerel and/or horse mackerel are observed in different ecosystems. Off northern Spain, two sardine and two horse mackerel periods occurred between 1952 and 1986 (Villegas and Lopez-Areta, 1988), but the relationships with climate change were not the same. Off central Morocco (Kifani and Gohin, 1992), the alternance was explained by differences in availability related to climate change and to a stock depletion. In the Benguela Current, an equatorward shift of the pilchard (*Sardinops sagax*) fishery was observed in the late 1960s, and later, the sardine was replaced by anchovy in southern Benguela and by horse-mackerel in the northern Benguela (Crawford *et al.*, 1987). These changes, often sustained over several years, have been related to large-scale trends in temperatures and wind stress and to the Southern Oscillation Index (Shannon *et al.*, 1988), giving rise to "regimes" in the ecosystem structure (Crawford *et al.*, 1995). Off the coast of Chile, Draganik *et al.* (1995) noticed that the strong 1982-1983 El Niño favoured the occurrence of strong year-classes of *Trachurus murphyi.*

In the southern Canary Current, small differences between the two booms affected the catches of pelagic fish other than the sardine. During the first event, the climatic anomaly favourable to upwelling lasted almost six consecutive years; while during the second event, the duration of the 1986 wind reinforcement did not exceed one year and water cooling was interrupted, for several (2-4) years, by a positive SST anomaly. Accordingly, sardinelle, horse-mackerel and mackerel catches decreased during the first event, while showing various behaviours during the second: sardinelle catch increased steadily, horse-mackerel decreased and mackerel increased strongly in 1988 and 1989, just after the mid-event wind relaxation, then decreased when the upwelling intensified again (Fig. 4). Surveys from RV *Fridtjof Nansen*, carried out off Senegal in 1981, 1986, and 1992, confirm that landing variability reflects abundance changes; the last cruise detected a fourfold increase in the biomass of sardinelle, and a decrease in the biomass of horse-mackerel and mackerel (Samba and Samb, 1995).

Up to a certain threshold, the strengthening of eastern boundary upwellings enhances planktonic production and consequently the recruitments of plankton feeders. Cury and Roy (1989) showed that the best recruitments are obtained with an annual mean wind speed of about 5-6 m/s. Stronger winds would increase turbulence and offshore losses, detrimental to the wealth of sardine stocks. Except for May, July, August and December, the present results show positive relationships between the wind speed for any month and the sardine catch two years later (Fig. 8). The climatic wind speed maximum off Sahara is in July, about 8 m/s, and the minimum is in November, near 5.5 m/s (Binet *et al.*, in press). In other terms, the wind is throughout almost the whole year above the Cury and Roy optimum and these authors'assertion should be modified; strong winds have probably detrimental effects on recruitment, during the very first months of fish life, after which they favour the survival of larvae and juveniles.

Near-equatorial, coastal upwelling

Several surplus production models, accounting for the effects of upwellings and river flows on the *Sardinella spp.* fishery in the Guinea Current, were performed by Cury and Roy (1987) and Fréon (1988). But these models failed after 1981, suggesting that something had changed in the sardinelle – environment relationships (Binet, 1995). The central hypothesis was the same as in the case of the Canary Current sardines: an increase in the upwelled nutrient input should enhance new production and feed more fish. Seasonal shoalings of the thermocline, off Côte d'Ivoire and Ghana, are induced by forces other than the local wind stress. Geostrophic adjustment of isotherms associates a southward thermocline slope to the eastward Guinea Current (Ingham, 1970). Kelvin waves, generated by the wind stress over the western side of the Atlantic, cross the ocean, trapped along the equatorial wave guide before splitting on the African coast and moving poleward, uplifting the thermocline along the African coasts (Picaut, 1983; Verstraete, 1992). Finally, the cyclonic turbulent eddies created in the Guinea Current, downstream from Cape Palmas and Cape Three Points, also induce a thermocline doming at their centre (Marchal and Picaut, 1977).

At first sight, the time series of *Sardinella aurita* catch and wind stress could appear to be related by a causal mechanism, as in the Canary Current (Fig. 3, 9*a*). The westerlies being favourable to upwelling along this coast, enhanced plankton concentration could be expected following wind strengthening. But the warming trend of the SST (Fig. 9*b*), discourages acceptance of this hypothesis without careful examination. When examining the monthly relationships between alongshore wind stress and SST (Fig. 7*b*), Binet and Servain (1993) noticed that wind and SST were weakly but negatively correlated, except during the long cold season (boreal summer). Thus, the eventuality of a strengthening of the Ekman upwelling during the long cold season has to be rejected. But short upwelling events, occurring sporadically in the course of the boreal winter, raise the thermocline and increase the nutrients in the euphotic layer. If the thermocline does not reach the surface, these short events do not display any signature in SST series. Pezennec and Bard (1992) pointed to the possible role of the minor upwelling season in

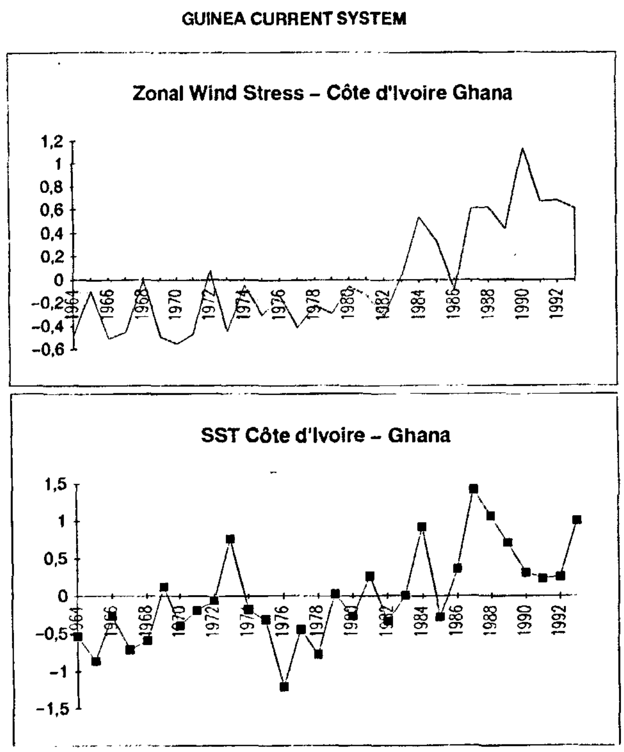

Figure 9

Guinea region (0°-8° W). Top: zonal component of the pseudo wind stress (eastward positive). Bottom: SST standardized anomalies, from the J. Servain database.

Région Guinée (0°-8° W). Haut : composante zonale de la pseudo tension de vent (comptée positivement vers l'est). Bas : température de surface, anomalies standards, d'après la base de données de J. Servain.

recruitment improvement. Indeed, these brief shoalings of the thermocline momentarily interrupt the impoverishment of plankton which normally occurs from November to May (Binet, 1993). Pezennec and Bard supposed that increases in these minor upwellings could improve the survival of sardinelle larvae and their recruitment in the fishery. However, neither the plankton samples collected near Abidjan between 1969 and 1980 (Binet, 1993), nor the series of Tema (Ghana) from 1969 to 1992 (Mensah, 1995) show any plankton biomass increase during the years of the sardinelle boom. Therefore, non production-related hypotheses cannot be dismissed.

Seasonal variability in the equatorial Atlantic

According to recent works, reviewed by Verstraete (1992) and Longhurst (1993), the seasonal variation of SST and circulation in the equatorial Atlantic may be viewed as a response to local and distant forcing of the wind stress. A remote equatorial response mainly affects the eastern equatorial region and a local north equatorial response is associated to the seasonal migration of ITCZ (Merle, 1983).

Resulting from the mean zonal wind stress, an east to west rise of the annual mean dynamic surface is observed along the equator, with a low point about 10° W and a reverse slope eastwards (Merle 1983). An east-to-west tilt of the thermocline, whose upper point is below the dynamic height minimum, is associated to the surface topography, and a reverse slope is observed eastwards of the upper point of the thermocline. In the eastern equatorial ocean (the Guinea gulf), low-salinity warm waters overlie the thermocline for most of the year (Merle and Arnault, 1985).

Among the seasonal variations of wind stress, the most significant for the SST variations is the sudden increase of the westward stress in the western part of the basin, during the boreal spring. This generates an equatorially-trapped wave movement which travels into the gulf and is reflected first poleward along the coast of Africa, in the form of Kelvin waves and then back in a westerly direction, in the form of Rossby waves. These waves uplift the thermocline during boreal summer in the eastern equatorial Atlantic. If the thermocline is sufficiently shallow, the intensified southerly winds erode its upper layer and cool the SST.

The presence of low-salinity warm waters over the thermocline, during most of the year in the eastern equatorial Atlantic, is indicative of an Atlantic El Niño (Hisard, 1980; Merle, 1980). The distantly-forced seasonal rise of the thermocline in the eastern basin is another point of similarity with the Pacific. But the Pacific is three times as wide as the Atlantic at the equator and, given the time required for the waves to cross the ocean, a seasonal zonal thermocline tilt is forced by the seasonality of wind stress in the Atlantic, whereas in the Pacific the basin-scale thermocline tilt occurs only on the interannual El Niño scale, when zonal wind stress is relaxed for longer than normal season (Philander, 1979). Therefore, it can be advanced that the Atlantic exhibits an El Niño-like event each autumn, or, reciprocally, that an "Atlantic summer" occurs every 4-6 years in the eastern Pacific with each new El Niño (Longhurst, 1993).

The North Equatorial Countercurrent (NECC) and its seasonal change form part of the ocean response to seasonal wind forcing (Richardson and Reverdin, 1987). The current starts up in May-June and flows eastward across the Atlantic, into both the Guinea Current (GC) and the North Equatorial Current (NEC). The NECC disappears or reverses from about January-June, west of 18° W. It has a rapid onset in the northwestern equatorial Atlantic, and changes from a weak westward flow in spring to an intense eastward flow during summer. The rapid summer intensification of the NECC coincides with a simultaneous intensification of the westward flow in the South Equatorial Current (SEC) which continues in the North Brazil Current before turning eastwards to form the western NECC (Richardson and Reverdin, 1987). Its flow is controlled by changes in the curl of the wind stress (Garzoli and Katz, 1983) and its meridional shift parallels the ITCZ seasonal migration.

Warm events and Atlantic El Niños

Moreover, it has recently been shown that the equatorial and tropical Atlantic Ocean is also forced at the ENSO time scale by the atmospheric pressure gradient of the eastern Pacific. This may partly be interpreted as exaggerations of the seasonal cycle.

The eastern equatorial Atlantic undergoes warm events every few years. In calculating a composite from eight years of anomalously warm equatorial SST, Carton and Huang (1994) show that these events are associated to particular anomalies of wind stress and SST spatial pattern. In the equatorial belt, westerly anomaly of winds in the west and reduced northward trades in the east are associated to a strong warm SST anomaly during boreal summer in the Gulf of Guinea, while in the northeastern tropical Atlantic (from the African coast to 40° W), a strengthening of the north-east trade winds is observed. In addition, the Intertropical Convergence Zone (ITCZ) is intensified and shifted southwards.

In a 13-year study of the time-space evolution of SST and heat storage, Tourre and White (1995) observe that the lowest frequency signal of the SST is approximately out of phase with the ENSO in the Pacific Ocean. Warmest surface temperatures occur approximately 18 months after the peak phase of El Niño and can last for more than one year. Katz *et al.* (1986) found a tendency for the south-east Atlantic trade winds to increase during the peak phase of El Niño, when the sea level pressure is minimum in the eastern Pacific.

A hypothetical mechanism connecting Pacific ENSO to Atlantic anomalies could explain these Atlantic warm events and wind field anomalies. During the warm phase of a Pacific ENSO, Atlantic trade winds are strengthened due to the anomalous expansion of the zone of rising air over the South American continent (Bakun, 1996). The equatorial upwelling is intense and the Atlantic is in a cool phase. Equatorial currents build up an anomalous transoceanic slope of the sea surface (Fig. 10). When the Pacific reverts to a post-El Niño situation, the large amount of sinking air over the South America weakens the

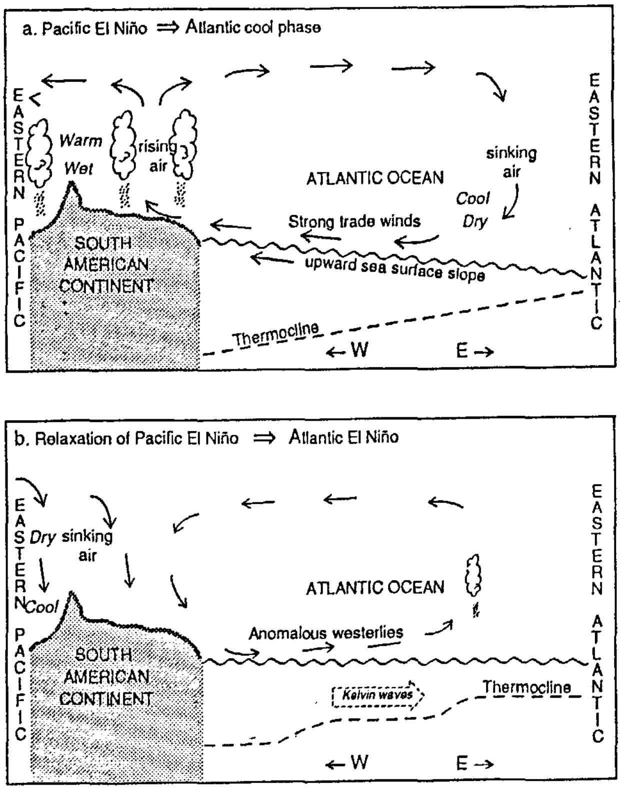

Figure 10

Hypothetical tropical ENSO teleconnection between the Pacific and the Atlantic, the figure represents the vertical plane along the equator, from Bakun (1996).

Schéma de téléconnection hypothétique entre les évènements ENSO du Pacifique et ceux de l'Atlantique dans la région tropicale. Coupe verticale au niveau de l'équateur, d'après Bakun (1996).

Atlantic trades or even gives way to anomalous westerlies. The sea slope is cancelled and equatorial upwelling is weakened or interrupted. This constitutes an El Niño-like, warm phase.

In 1983-1984, the consequences of the Pacific El Niño in its final stage were observed as previously described, and strong anomalous eastward circulation was measured. The ITCZ was in a very southern latitude, leading to a trade-wind relaxation at the equator. So, the NECC was strengthened and fed a stronger Guinea Current (Hisard *et al.*, 1986). At the same time the eastward flow along the equator was reinforced, and an unusual amount of very saline subsurface waters was observed in the eastern Gulf of Guinea (Piton and Wacongne, 1985). Anomalous height in the sea surface topography was observed east of the Greenwich meridian (Katz *et al.*, 1986) and led to an anomalous southward circulation along the coast of Namibia. The Benguela upwelled waters were covered by warmer waters. This event was called the "Benguela Niño"; although rare, it had occurred previously in 1934, 1950 and 1963 (Shannon *et al.*, 1986), *i.e.* during years following strong Pacific ENSO.

No direct measurements of the return, poleward circulation were done, just north of the equator, during the 1983-1984 Atlantic El Niño. But some observations off Abidjan (Binet and Marchal, 1992) indicate that the Guinea Under-current (GUC), which originates in the Bay of Biafra (Lemasson and Rebert, 1973*a*, *b*) from a part of the Equatorial Under-current (Hisard and Morlière, 1973), was probably also strengthened.

An ENSO-NECC connection?

Sharp increases of the NECC were observed in 1983 and again in 1987, just after the Pacific ENSO events. In an average year, the NECC attains a maximum transport of 20 sverdrup for at least one month, while in 1983 and 1987 it sustained this value for over half the year (Katz, 1993). A rough negative relationship between the Southern Oscillation Index (SOI) and the NECC is observed from 1983 to 1989 (Fig. 11, from Katz). And we can suppose that low SOI values are correlated with stronger NECC transport, through an anomalous wind field, proper to Atlantic El Niños.

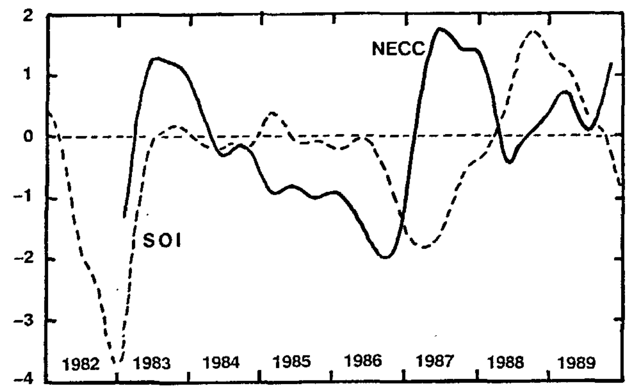

Figure 11

Comparison between North Equatorial Countercurrent dynamic height (solid line) and Southern Oscillation indices (dashed line). The ordinates is in terms of each series standard deviation. From Katz (1993).

Comparaison entre la hauteur dynamique du Contre Courant Nord Equatorial (trait plein) et l'Oscillation Australe (SOI, tirets), ordonnées en écarts-type, d'après Katz (1993).

Now, the SOI has remained at low values since 1976, except in 1988-1989, and since 1990 has been locked in a negative phase (Kerr, 1993), (Fig. 12). It may be presumed that on average, but not consistently, the return eastward circulation in the equatorial belt (NECC and Equatorial Undercurrent) is strengthened, and the same is true for the coastal Guinea Current and Undercurrent which depend on them.

Eddies in the coastal circulation and retention areas

The spawning areas of both *Sardinella* species are situated east of Cape Palmas and Cape Three Points (Marchal, 1993), where large eddies were observed by Marchal and Picaut (1977), downstream of the capes, supposedly created by these headlands in the Guinea Current. Lemasson and Rebert (1973*a*) observed opposite currents near the coast and over the shelfbreak, on both sides of Cape Palmas.

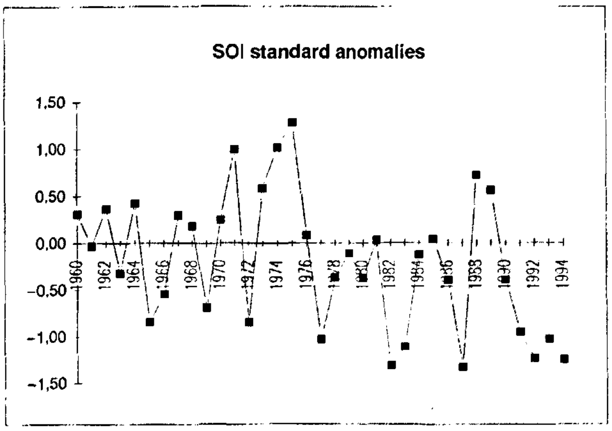

Figure 12

Southern oscillation index (SOI) 1960-1994, sea level pressure difference between Tahiti and Darwin. From the Climate Diagnostic Bulletin.

Indice de l'Oscillation Australe (SOI) de 1960 à 1994, différence de pression entre Tahiti et Darwin, d'après le Climate Diagnostic Bulletin.

Offshore, the transport was eastward and closer to the coast a westward current was meandering. The currents in these areas are highly variable in space and time, and this complex pattern probably slows the advective losses of ichthyoplankton, acting as a retention structure. The transport of eggs and larvae from their spawning grounds would be more rapid in steady currents than in turbulent eddy areas.

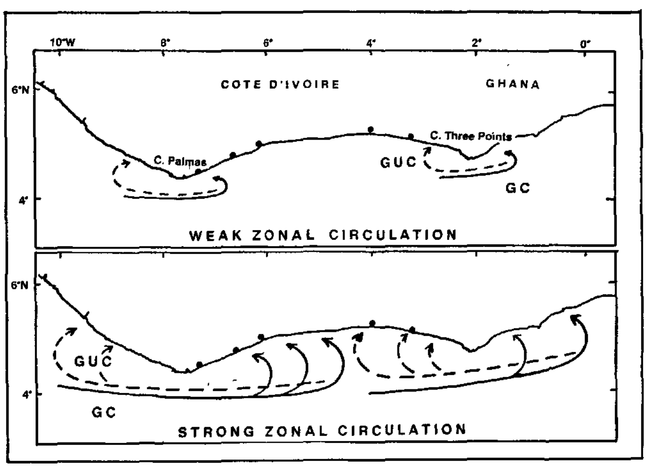

Figure 13

Hypothetical representation of the turbulent eddies created by headlands in the coastal circulation, downstream of Cape Palmas and Cape Three Points, for weak and strong oceanic circulations. GC: Guinea Current (solid line), GUC: Guinea Undercurrent (dashed line). Black dots indicate the position of the western and eastern groups of coastal stations.

Représentation hypothétique des turbulences créées par effets de caps dans la circulation côtière, en aval des caps des Palmes et des Trois Pointes, pour des circulations océaniques faible et forte. GC : courant de Guinée (trait plein), GUC : sous courant de Guinée (tirets). Les points noirs indiquent la position du groupe occidental et oriental de stations côtières.

Faster currents lead to higher plankton transport, but as broader areas are concerned by turbulent eddies, more ichthyoplankton are trapped in the turbulent retention area. Then, according to the relationships between larval retention area and spawning stock size established by Sinclair (1988), we can expect the amount of *Sardinella* recruits to vary with the surface of eddies.

The surface area covered by turbulent eddies probably depends on the speed of the current from which they were born. Then the areas covered by eddies around the capes are extended downstream for higher current speed. Eddies associated with the Guinea Current and Undercurrent have probably spread out respectively eastward and westward, each time the eastward oceanic transport increased, between 0° and 5° N (Fig. 13). Then the retention areas concern larger parts of the shelf than before and the SST regional differences are smoothed by increasing horizontal mixing. Morlière and Rebert (1972), who described an eastward increase in SST, from Cape Palmas to Cape Three Points, in a set of cruises carried out between

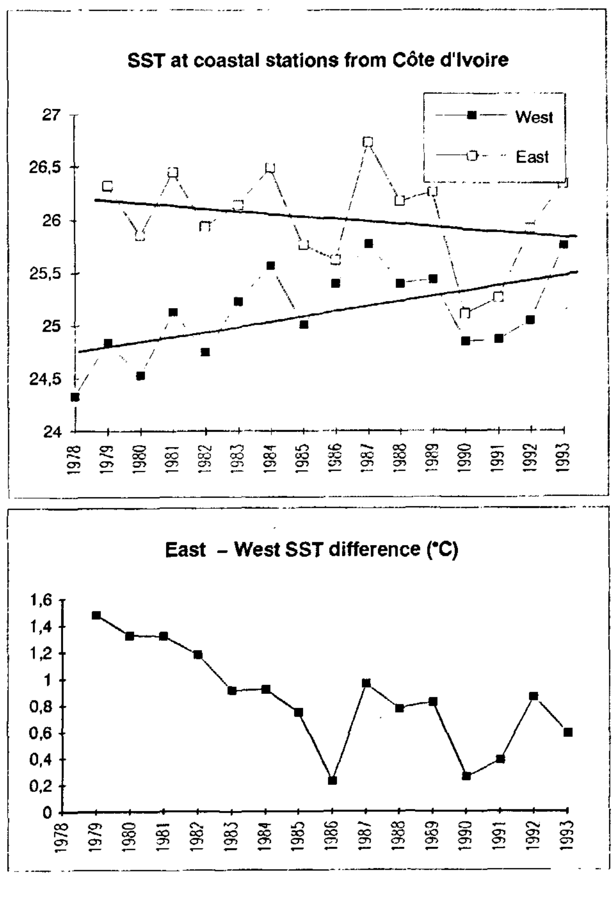

Figure 14

Top: mean annual sea surface temperature (° C) from coastal stations of the western group (Tabou, San Pedro, Sassandra) and eastern group (Abidjan, Assinie), see Fig. 12 for positions. Straight lines represent linear adjusting functions. Bottom: difference between the eastern and western SST.

Moyennes annuelles des températures de surface de la mer (°C) des stations côtières du groupe occidental (Tabou, San Pedro, Sassandra) et du groupe oriental (Abidjan, Assinie). Les droites représentent les fonctions d'ajustement linéaires. Bas: différence entre les températures de surface du groupe oriental et du groupe occidental.

1969 and 1972, explained this thermic gradient by the progressive warming of newly upwelled waters drifting in the Guinea Current. Now, the SST differences between the eastern and western sides of the Côte d'Ivoire coast have been decreasing continuously since 1978 (Herbland and Marchal, 1991; Binet, Servain, 1993 and Fig. 14). This indicates that a modification of some kind has been taking place since the mid-1970s, perhaps in the form of increased mixing between eastern and western waters.

CONCLUSION

Large-scale modifications in the climate of the tropical Atlantic have occurred since the mid-1970s, due to changes in the atmospheric sea level pressure field which are themselves more or less clearly related to the ENSO events in the Pacific Ocean. Warm events in the equatorial Atlantic appear every few years, possibly as consequences of ENSO. In a 28-year record of SST and wind stress, Carton and Huang (1994) show, along the central west equator, a gradual intensification of the westward component of the wind stress, particularly after 1976. This trend roughly parallels the SOI decrease. So, waters would be accumulated on the western side of the ocean due to a lack of return circulation. Now, in a composite year involving eight of these warm events, Carton and Huang (1994) show, during the boreal summer, an eastward anomaly of the wind stress along the Atlantic equatorial belt. So, an intensified return circulation during the summer could reduce the desequilibrium caused by the former long-term trend to water accumulation. Then NECC and Guinea Current strengthenings during this period are very probable. In the Guinea Current, extensions of the turbulent eddy area may be expected downstream of Cape Palmas and Cape Three Points, following a reinforcement of the NECC. These eddies probably concern also the Guinea Undercurrent, so they form on both sides of the capes. The ecological consequences will be: i) a broadening of the areas of cyclonic eddies generating thermocline shoaling, nutrient input in the euphotic layer and thus improved feeding conditions for sardinelle larvae; and ii) a widening of coastal gyres equivalent to retention areas, which means that a larger number of sardinelle larvae will reach the juvenile stage and will be recruited.

The same composite years of Carton and Huang (1994) show stronger than normal north-east trade winds during the equatorial warm event; but along the coast of north-western Africa, this strengthening is not very significant. During the stronger trade wind period, a reinforcement of the upwelling is observed and is probably associated to a southern extension of the equatorward circulation. In the Canary Current, the primary/secondary production rate increases in upwelling waters, sardine recruitment is improved and the catch will increase two years later. At the same time, the *Sardina pilchardus* geographical range extends 400 to 500 nautical miles southward, while the catch of sardinelles is reduced or increased according to the intensity and duration of the cooling events and as landings of predator fish such as mackerel and horse-mackerel decrease.

These hypothetical ecological processes appear evident in the Canary Current, where approximately the same succession of events was twice observed. In the Guinea Current, field studies and remote sensing observations would be necessary to validate the "eddy" hypothesis.

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