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Have the recent hydrological changes in the Northern Gulf of Guinea induced the *Sardinella aurita* outburst?

Climatic change
Pelagic fisheries
Upwelling
West Africa

Changements climatiques
Pêcheries pélagiques
Upwelling
Afrique occidentale

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ABSTRACT

Sea surface temperature along the northern coast of the Gulf of Guinea drops abruptly twice a year, with a moderate decrease in boreal winter and a greater one in summer. Several mechanisms have been proposed to explain these coolings: Ekman upwelling due to local wind, remote wind forcing in the western Atlantic, geostrophic adjustment to the Guinea current variations or eddies created by headlands in the current. The resulting seasonally-induced plankton production has led to the development of pelagic fisheries, with dramatic increases in *Sardinella aurita* catches in Côte d'Ivoire and Ghana during the last decade and new spatial and seasonal distributions. A study to account for these changes was undertaken on the basis of wind and temperature data recorded by merchant ships from 1964 to 1990 and coastal temperature measurements from 1978 to 1990. During the study period, pseudo-wind stress increased by 0.23 (m^2/s^2)/year and sea surface warming by about 0.03°C/year. The main changes occurred during the 1980s; in coastal waters, warming was very marked in the western area (0.069°C/year), even during the cold seasons, and the eastern side experienced a slight cooling (- 0.034°C/year). The latter change is compared to westerly wind intensification (increased speed and slight rotation) which should have enhanced Ekman pumping. These developments are viewed in the context of recent data concerning warming in tropical regions, controversial increased speed of trade winds and changes in oceanic circulation. More frequent Ekman upwelling events in the east of the Ivorian gulf might have favoured an expansion of the *S. aurita* stock of Ghana towards the Côte d'Ivoire. This possibility does not exclude the hypothesis of a circulation change which has been proposed to explain the settlement of sardinelles up to the western side of the gulf.

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RÉSUMÉ

Les récents changements hydrologiques de la côte nord du Golfe de Guinée ont-ils induit l'expansion de *Sardinella aurita* ?

La température des eaux de surface de la côte nord du Golfe de Guinée connaît un régime saisonnier à deux minima, avec un refroidissement léger en hiver et plus fort en été boréal. Divers mécanismes ont été proposés pour expliquer ces refroidissements : upwelling d'Ekman induit par le vent local, forçage à distance par le vent sur l'ouest de l'Atlantique, ajustement géostrophique en phase avec l'intensification du courant de Guinée, turbulences dans la circulation créées par effet de cap. Une pêcherie de poissons pélagiques exploite la production issue de ces remontées d'eaux. Au cours de la décennie 1980, les débarquements de *Sardinella aurita* de la pêcherie ivoiro-ghanéenne se sont brusquement accrus et ont montré une nouvelle répartition spatiale et saisonnière. On a cherché une explication dans l'examen des séries de température de surface mesurées à la côte (1978-1990) ainsi que dans les données de vent et de température recueillies par les navires marchands. Après établissement d'une climatologie (1964-1990), on observe une élévation générale de la température de l'ordre de 0,03°C/an et une augmentation de la tension de vent de 0,23 (m^2/s^2)/an. Les principaux changements se produisent au cours des années 1980 ; dans les eaux côtières, le réchauffement est très marqué dans l'ouest du golfe ivoirien (0,069°C/an), y compris lors des saisons froides, tandis que dans l'est il se produit un léger refroidissement (- 0,034°C/an). Celui-ci est comparé à l'intensification des vents d'ouest (accélération et légère rotation), susceptible de créer un pompage d'Ekman. Ces observations sont replacées dans le contexte des acquisitions récentes sur le réchauffement des zones tropicales, l'accélération controversée des alizés et les modifications de la circulation océanique. Il est possible qu'une plus grande fréquence d'épisodes d'upwelling d'Ekman, dans l'est du golfe ivoirien, ait favorisé l'expansion du stock ghanéen de *S. aurita* vers la Côte d'Ivoire. Ceci n'est pas contradictoire avec l'hypothèse d'une modification de la circulation qui a été émise pour expliquer l'implantation des sardinelles jusque dans l'ouest du golfe.

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INTRODUCTION

Changes in climatic conditions can lead to dramatic alterations in fish population and/or their regional distribution. Large interannual variations in catches have recently been recorded in the Côte d'Ivoire and Ghana, two countries located along the northern coast of the Gulf of Guinea, roughly between 8°W and 0° (Fig. 1). The stock of *Sardinella aurita*, one of the main pelagic species along this coast, yielded variable but moderate catches during the 1960s. Recruitment overfishing in 1972 led to a stock collapse the following year (Fig. 2). Binet (1982) suggested that *S. aurita* was usually protected from heavy fishing in avoiding low salinity coastal waters, but the severe drought which struck western Africa in 1972 suppressed this natural protective behaviour and young *S. aurita* were fished in great quantities by canoe fishermen, near the shore. The stock recovered only in 1976. In the early 1980s, the stock recruitment variability seemed to be related to the upwelling intensity; meanwhile availability of fishes was correlated directly to the surface cooling but negatively to the river runoff (Mendelssohn and Cury, 1987 ; Fréon, 1988). Since then, catches have been growing, despite interannual variations, and surprisingly, during the last decade, the stock has been able to sustain a high level of catch, without suffering a new collapse. Other changes have occurred in the pelagic fisheries (Binet *et al.*, 1991), the most striking of them being the outburst of *Balistes carolinensis*, now in regression (Caverivière, 1991).

In parallel with yearly catch variations of *Sardinella aurita*, seasonal and regional patterns have changed in these fisheries during the last decade (Binet *et al.*, 1991). It was previously considered that the appearance of *S. aurita* was related to seasonal coolings which increased plankton production (Binet, 1976; 1979), but this species is now fished throughout the year. Moreover, the fishing grounds, former-

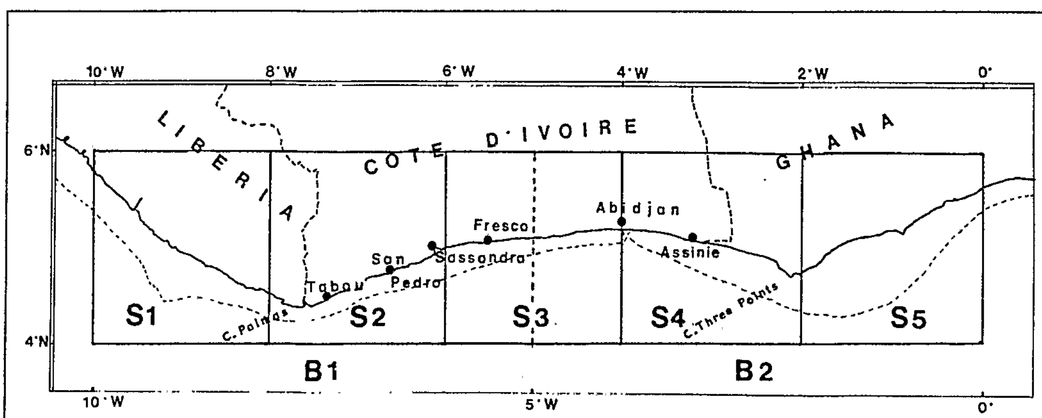


Figure 1

Map of the northern part of the Gulf of Guinea indicating the positions of coastal stations along the Ivorian gulf and the 5° x 2° (B1, B2) and 2° x 2° (S1 to S5) grids used in the processing of ships observations.

Carte de la région nord du golfe de Guinée, indiquant les positions des stations côtières le long du golfe ivoirien ainsi que les grilles 5° x 2° (B1, B2) et 2° x 2° (S1 à S5) utilisées dans le traitement des observations des navires.

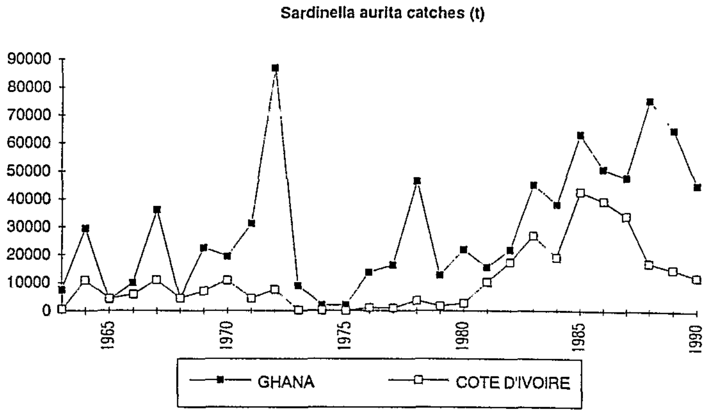


Figure 2

Annual catches of Sardinella aurita *in Ghana and Côte d'Ivoire from 1963 to 1990 (according to Binet* et al., *1991 and Pezennec and Bard, 1992).*

Captures annuelles de *Sardinella aurita* par le Ghana et la Côte d'Ivoire entre 1963 et 1990 (d'après Binet *et al.*, 1991 et Pezennec and Bard, 1992).

ly limited to the Ghana shelf, *i. e.*, the eastern region of the Gulf, now extend towards western Côte d'Ivoire (Fig. 2).

The basic question is whether such a biomass increase in stock and the extension of its geographical range resulted mainly from internal changes in the species population or alteration of the physical environment. Several hypotheses have been proposed concerning the latter possibility: increased wind speed and intensification of upwellings (Roy, 1992), changes in the regional temperature pattern (Herbland and Marchal, 1991), changes in the system of currents (Binet *et al.*, 1991) or lengthening of the short cooling periods (Pezennec and Bard, 1992).

The purpose of this paper is to examine previously reported results concerning the intensification of coastal cooling and the shift in these areas. Near-ocean and coastal data sets were used to update the study of local climatic variations along the northern coast of the Gulf of Guinea from the mid-1960s to 1990. After a presentation of these data sets and a brief reminder of the normal physical conditions in the region, long-term climatic changes are considered in the entire area. The following section indicates the major climatic changes between the eastern and western parts of the region studied. In the discussion section, these results are related to recent data on global changes, including rising air/sea temperatures, increased atmospheric water content and greater tropospheric circulation. The controversial question of strengthening in the wind speed is debated. Regional changes in the oceanic circulation system are also considered. Finally, possible explanations are discussed for the observed changes in *Sardinella aurita* catches during the last three decades.

DATA SETS

The two data sources used in this study are designated as "ships" and "coastal" data sets. Observations of wind and sea-surface temperature (SST) obtained through an international network of ships-of-opportunity provided the first type of information. These raw data were processed for the entire tropical Atlantic basin in order to determine monthly fields of pseudo-wind stress (1) and SST. The data base was started in 1964 and is continuously updated. Details on the data processing procedures can be found in three sequential atlases (Picaut *et al.*, 1985; Servain *et al.*, 1987; Servain and Lukas, 1990). Here, only the following steps need be considered. The monthly values of wind stress and SST were calculated in 5° longitude by 2° latitude quadrangles. An objective analysis method, based on the successive correction type (Cressman, 1959) and taking into account the number of observations (2), was then used to create a 2° x 2° gridded monthly data base. This method associates the current 5° x 2° monthly field with both 5° x 2° and 2° x 2° monthly climatic averages. The region under study here corresponds to two 5° x 2° primitive blocks ranging from 4° to 6°N latitude and respectively from 10° to 5°W and 5°W to 0° longitude (Fig. 1). Interpolation and smoothing were performed to take into account the regional field of each parameter, so one must realize that wind stress and SST values from contiguous 2° x 2° squares were far from independent. Though two 5° x 2° contiguous blocks were not also completely independent (the radii of influence used in the objective analysis were 1400, 1 000 and 600 km successively), the most significant comparisons were between the 2° x 2° squares from different primitive 5° x 2° blocks, especially between squares S1 or S2, and S4 or S5 (Fig. 1, Tab. 1).

The second data source, based solely on nearshore SST, was provided by six coastal stations sampled by the Centre de Recherches Océanographiques of Abidjan (Côte d'Ivoire). Observations were performed daily at about 9 a. m. by casting a bucket into the surf, and data were averaged on a monthly basis. These six stations (Fig. 1) are situated along the very open Ivorian gulf, from Tabou (near Cape Palmas)

Table 1

Geographical squares from gridded ships data; coastline angles from the north (cf. *Fig. 1).*

Carrés géographiques issus de la grille de la base de données «navires marchands». Orientation de la côte par rapport au Nord (*cf.* fig. 1).

Primitive box	Longitude range	Squares	Longitude range	Coast direction/N
		S1	10°-8°W	120°
B1	10°-5°W	S2	8°-6°W	67°
		S3	6°-4°W	85°
B2	5°W-0°	S4	4°-2°W	115°
		S5	2°W-0°	67°

Table 2

Ivorian coastal stations: lengths of SST series.

Stations côtières ivoiriennes : dates du début et de la fin des séries de température de surface de la mer.

Stations	Length of SST series
Tabou	1/01/1978 - 31/12/1990
San Pedro	7/05/1982 - 31/12/1990
Sassandra	1/01/1978 - 31/12/1990
Fresco	1/01/1978 - 31/12/1990
Abidjan	27/07/1978 - 31/12/1990
Assinie	1/07/1978 - 31/12/1990

to Assinie (near the border of Ghana). Their positions and the period of their record-keeping (most operations began in 1978) are indicated in Table 2.

BACKGROUND CLIMATOLOGY

The observed climatic system

In the eastern Atlantic area, the Intertropical Convergence Zone (ITCZ), roughly separating the northern and southern trade wind systems (Hastenrath and Lamb, 1977), migrates seasonally between a southern position just north of the equator during boreal winter and a northern position up to 20°N along the African continent during boreal summer. The northern coast of the Gulf of Guinea, though located about 5°N, is thus largely under the climatic influence of the southern hemisphere. Mainly as a result of the prevailing low pressure system over the northern African continent, the eastern part of the southern trade winds veers progressively to the right when crossing the equator and reaches the African coast in a southwesterly direction. However, there is great seasonal variability in wind stress direction (Fig. 3 *a*) and intensity (Fig. 3 *b*). Wind stress is strongest (about 30 m^2/s^2) in boreal summer when the southern hemisphere trade system is powerful, and weakest (about 10 m^2/s^2) in winter.

Seasonal coolings of surface waters occur along the northern coast of the Gulf of Guinea, approximately between Cape Palmas (7°40 W) and Cotonou (2°26 E). SST climatology computed from the merchant ship data set (Fig. 4) indicates a bimodal curve with a slight drop in temperature in February and deep cooling from July to September. With respect to the waters off Côte d'Ivoire, Morlière (1970) referred to these periods as the "short" and "long" cold seasons. The surface coolings, accompanied by a rising of isotherms, are strongest on the eastern sides of Cape Palmas and Cape Three Points (Ingham, 1970; Morlière and Rebert, 1972). Arfi *et al.* (1991) computed, from the shoreline bucket samples, a sea surface cooling index, taking into account the temperature difference between 26°C and SST (when lesser than 26°C) and the length (days) of that occurrence. This index shows, during cold seasons, two clear cooling gradients, decreasing from west to east. The pattern found between Cape Palmas and Cape Three Points, is repeated eastwards of this headland, up to Keta in Ghana (1°00 E).

The ships data set shows, during the long cold season, a 2°C zonal gradient, from 0° to 10°W, the coldest area (S5) being situated to the east of Cape Three Points, the warmest to the west of Cape Palmas (S1). This zonal SST gradient, deduced from ships observations, appears to be different from that observed in the shoreline bucket samples. Indeed, during the long cold season, the cooling areas have a larger latitudinal extent, off Cape Three

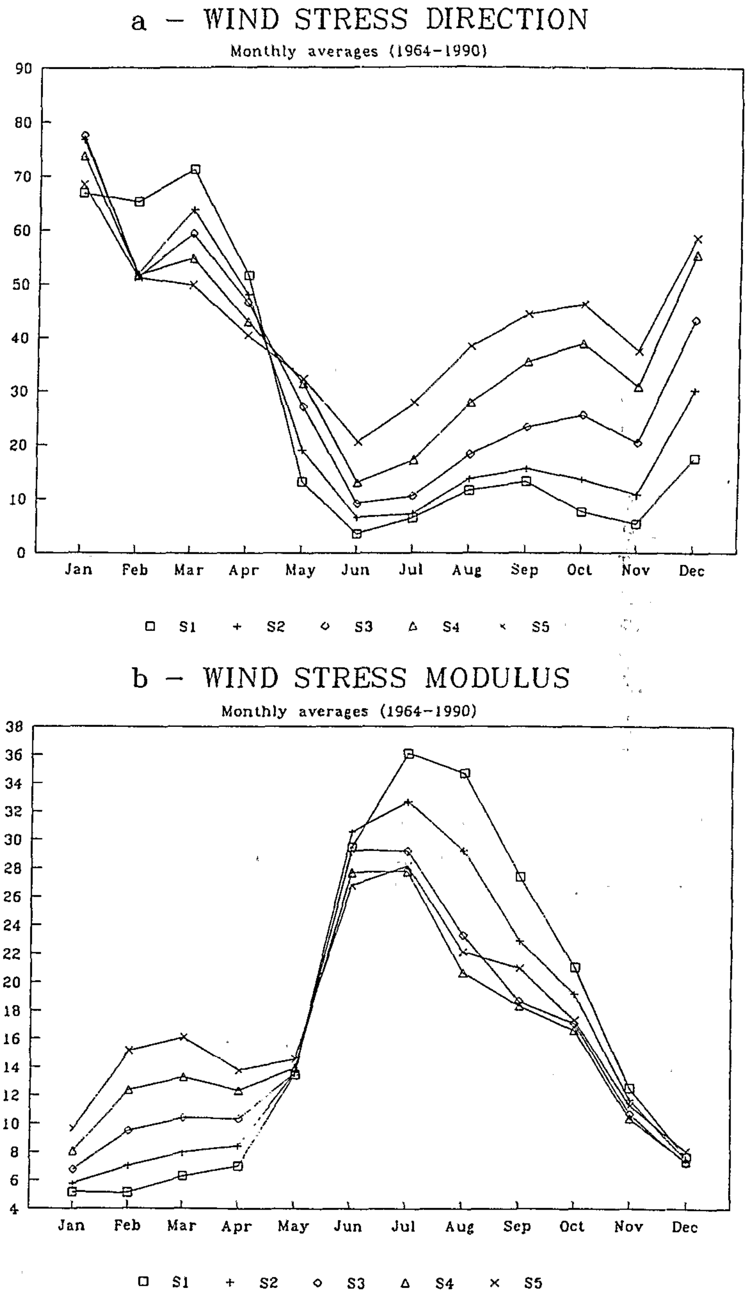


Figure 3

Monthly climatology (1964-1990 average) of wind stress based on ships observations in the five 2° x 2° squares S1 to S5: a) wind stress direction (direction where the wind blows) in degrees from the North; b) wind stress modulus in m^2/s^2.

Climatologie mensuelle (moyenne 1964-1990) de la tension de vent basée sur les observations des navires dans les cinq carrés 2° x 2° (S1 à S5) : a) direction de la tension de vent (direction vers laquelle souffle le vent), en degrés à partir du Nord ; b) module de la tension de vent en m^2/s^2.

Points (S5) than off Cape Palmas (S2), according to oceanographic cruises (Ingham, 1970) and remote sensing pictures (Pezennec and Bard, 1992; Le Loeuff *et al.*, 1993). Thus, the ships lanes cut across the coldest area off Cape Three Points, while they pass to the south of the coolest waters off Cape Palmas. The processing of ships data smooths spatial heterogeneities and creates an apparent increase in SST from east to west, while the shoreline bucket samples indicate the contrary (3).
During the short cold season the [ships] SST gradient is very weak and not significant. Conversely, two warm seasons occur from March to May ("long warm season") and in November and December ("short warm season"). Two periods of transition, in June and October, are linked to the twice-yearly migration of the ITCZ above the coastline latitude, corresponding to heavy rainfall in the region.

A debated explanation for the seasonal cooling occurrences

Along the north-western coast of Africa, from Morocco to Senegal, the seasonal coolings result mainly from local wind-driven dynamics. In the same forcing conditions, a computed Ekman transport index (Roy, 1991) is six times as great at 5°N (Côte d'Ivoire latitude) as at 30°N (Morocco latitude). Nevertheless, a true Ekman-type wind-driven upwelling cannot be considered as the unique explanation of seasonal coolings along the northern coast of the Gulf of Guinea (Houghton, 1976; Bakun, 1978). Other dynamic processes could be involved, *e. g.*, downstream eddies created in the Guinea current by the cape effect (Marchal and Picaut, 1977), coastal shallowing of the thermocline by geostrophic adjustment to the strengthening of the Guinea Current during boreal summer (Ingham, 1970), or westward propagation of alongshore-trapped Kelvin waves (Moore *et al.*, 1978). According to Colin (1991), the cool seasons cannot be solely due to the Kelvin wave; the surface coolings are in phase with the maxima of the Guinea Current, and the thermocline rise near the coast is accentuated by an increase of the wind component parallel to the shore.

Ekman-upwelling intensity depends on the angle between wind-stress direction and the coastline. Roughly eastward wind stress along the northern coast of the Gulf of Guinea should favor upwelling, but from Liberia to Ghana the coastline is not regularly west-east. In our study, there is a rough correspondence between the boundaries of each square box and the inflexion points of the coastline (Fig. 1; *see* Tab. 1 for successive shoreline directions). A projection of climatic wind stress along these lines (Fig. 5) emphasizes the considerable differences between the five boxes, implying that there are areas of likely yearly upwelling effect (S2, S3, S5 squares) and areas of seasonal change between

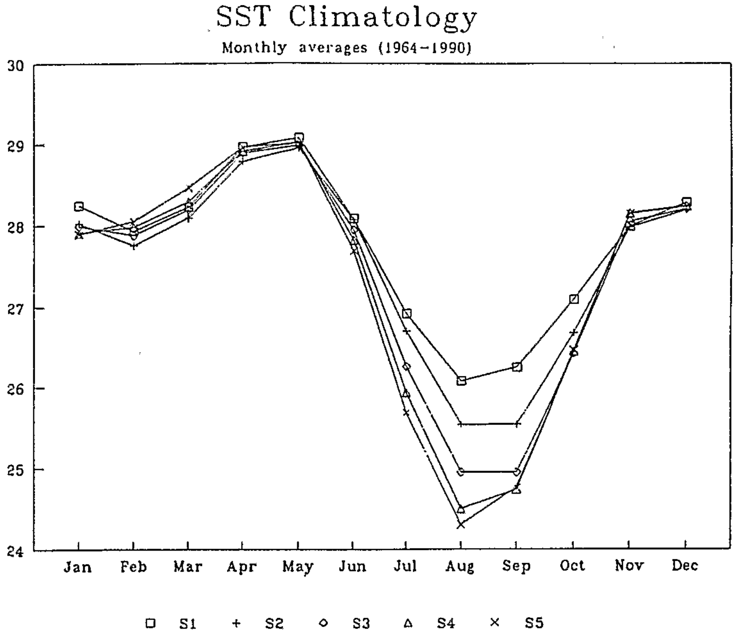


Figure 4

Monthly climatology (1964-1990 average) of sea surface temperature (SST in °C) based on ships observations in the five 2° x 2° squares S1 to S5.

Climatologie mensuelle (moyennes 1964-1990) des températures de surface de la mer (°C), basée sur les observations des navires marchands dans les cinq carrés 2° x 2°, S1 à S5.

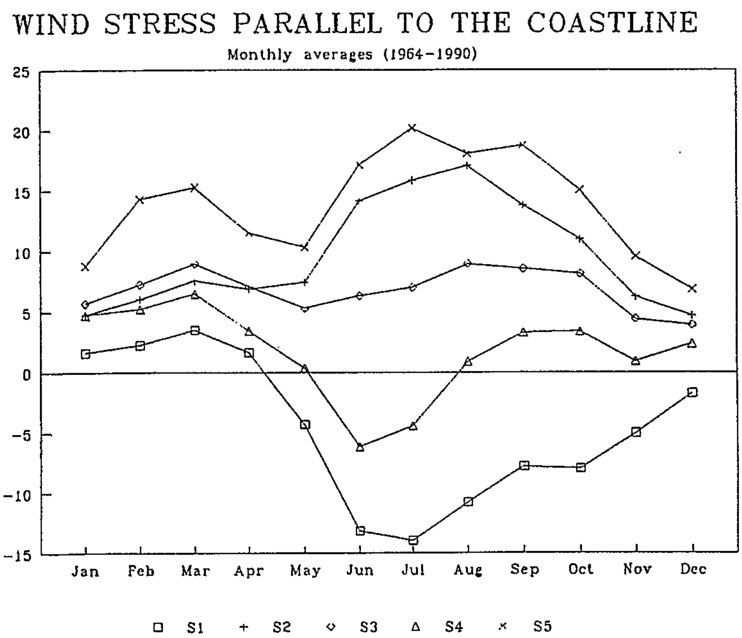


Figure 5

Monthly climatology (1964-1990 average) of the component of wind stress parallel to the coast (m^2/s^2) based on ships observations in the five 2° x 2° squares S1 to S5 (positive: eastwards).

Climatologie mensuelle (moyennes 1964-1990) de la composante de la tension de vent parallèle à la côte (m^2/s^2), basée sur les observations des navires marchands dans les cinq carrés 2° x 2°, S1 à S5 (valeurs positives vers l'Est).

upwelling and piling effects (S1 and S4). During boreal summer (long cold season), the wind stress component parallel to the coast is maximum east of Cape Three Points (S5) and Cape Palmas (S2), which is propitious to an upwelling process. The opposite effect occurs in the western part of these capes (S4 and especially S1). Nevertheless, the S4 area also undergoes sustained cooling in boreal summer (Fig. 4); this has been attributed to an eastward drift of the plume of upwelled waters from Cape Palmas (Morlière and Rebert, 1972).

Numerically it has been demonstrated (Busalacchi and Picaut, 1983) that the semi-annual wind-driven response in the idealized Gulf of Guinea is largely a result of local wind stress fluctuations. On the other hand, the oceanic annual signal is mainly due to equatorial zonal wind stress fluctuations, west of the gulf, as suggested by Moore *et al.*, (1978). Supporting this remote forcing theory, Picaut (1983) claimed that a westward propagation of alongshore-trapped Kelvin waves is an important factor affecting the temperature along the northern coast of the gulf. Indeed, in the whole Gulf of Guinea (and this is particularly evident in the present study region), local and remote dynamics may coexist and it is difficult to determine the respective importance of each.

LONG-TERM GLOBAL TRENDS: APPARENT INCREASED WIND SPEED AND WARMING

In this section we examine the results directly derived from our analysis. The reality of long term trends will be debated in the *Discussion* section.

Wind-stress direction showed some changes during the period studied. Greatest frequency of westerlies and southwesterlies (*i. e.*, clockwise rotations favoring upwelling) were observed before 1968, in 1974 and during the 1980s. The largest changes were recorded during boreal winters (Fig. 6 *a*). From 1978 onwards, the average winter wind direction progressively became more westerly. Noticeable changes also occurred from spring to fall of 1983-1985 (Fig. 6 *a*, *b*).

Yearly wind-stress modulus and [ships] SST anomalies averaged between 10°W and 0°, show obvious trends from the 1960s onwards (Fig. 7). They corresponded respectively to a wind-stress strenghtening of about 6 m^2/s^2 [0.23 (m^2/s^2)/year] and a sea surface warming of about 0.8°C (0.030°C/year).

However, these increases did not seem regularly distributed over the different seasons. The slope of the long-term trends of standardized anomalies in wind-stress components and SST measures the rate of change during the four quarters of the year (Tab. 3). These measurements were associated with "t" tests to assess the probability of positive long-term increases. The hypothesis of a 0 slope was rejected except for the winter SST and meridional stress. The speeding up of wind stress was significant throughout the year, but especially during spring and summer when the zonal wind stress component increased faster than during the rest of the year. The warming of the near-ocean area was stronger during summer and strongest during fall, *i. e.*, the long cold and short warm seasons.

Average SST for the six coastal stations shows the same slight increasing trend from 1978 to 1987 (0.031°C/year) (Fig. 8). As in the near-ocean area, long-term warming was stronger during the summer and fall than during spring, while no trend was evident during winter.

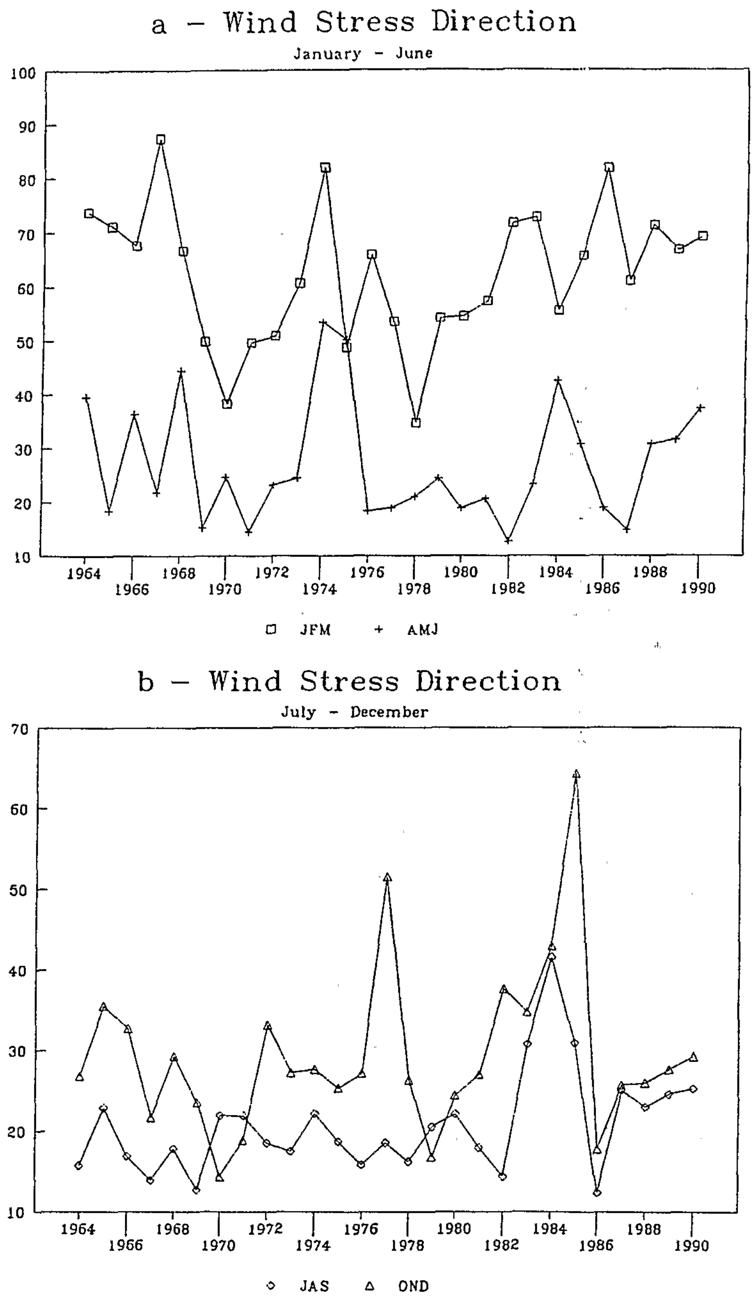


Figure 6

Wind stress direction averaged from S1 to S5 in degrees from the north: a) January-March and April-June averages; b) July-September and October-December averages.

Direction de la tension de vent, moyenne de S1 à S5, en degrés à partir du Nord : a) moyennes de janvier à mars et avril à juin; b) moyennes de juillet à septembre et octobre à décembre.

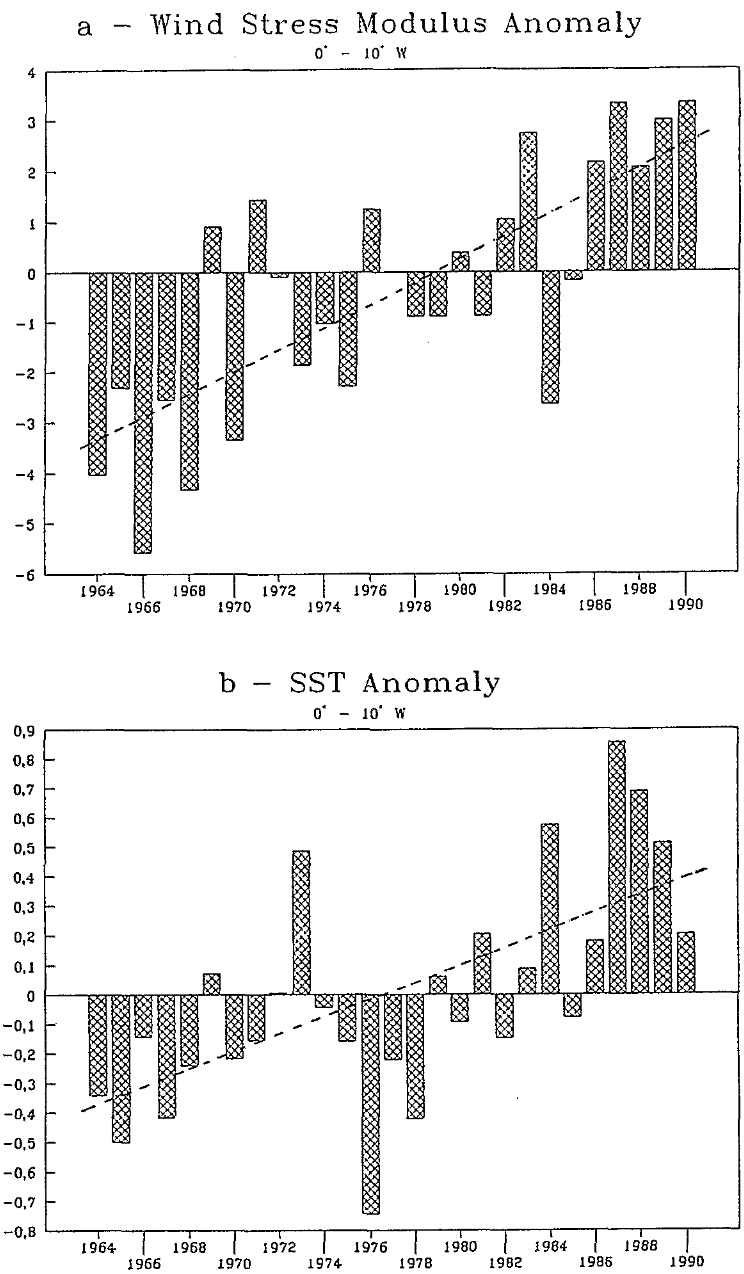


Figure 7

Annual anomalies of: a) wind-stress modulus (m^2/s^2) ; and b) SST (°C) averaged between 0° and 10°W (S1 to S5) from ships data (1964-1990). Dashed lines represent linear adjusting functions.

Anomalies interannuelles du module de la tension de vent en m^2/s^2 (a) et de la température de surface de la mer en °C (b), moyennes entre 0° et 10°W (S1 à S5), à partir des données des navires (1964-1990). Les tiretés représentent les ajustements linéaires.

In the hypothesis of local wind-driven upwelling, increase in eastward wind stress would reinforce Ekman transport and drops in coastal surface water temperatures might be expected. The warming observed even during the major cooling season tends to demonstrate that the local wind is not the main driving force of the thermocline rise. This point will be given further consideration in the *Discussion* section.

EAST-WEST DIFFERENCES

Alongshore SST differences

Insofar as alongshore distribution of *Sardinella aurita* changed during the last decades, it seems obvious to look at a possible variation in the SST zonal gradient observed by Morlière and Rebert (1972) and by Arfi *et al.* (1991). Herbland and Marchal (1991) have noted a reversal of this gradient. The regular pattern of decreasing alongshore SST, from Cape Palmas to Cape Three Points, was clearly observed in 1979 and 1980 but altered progressively until 1983-1984 when it was completely reversed. During these last years the waters off Assinie were cooler than those off Tabou during the long cold season. To assess the durability of this new pattern, we updated the work of Herbland and Marchal by computing the yearly SST averages of two groups of stations (Fig. 8): one on the western side of the Ivorian gulf (SSTTbSd for Tabou, San Pedro, Sassandra) and the other on the eastern side (SSTAbAs for Abidjan-Assinie). Missing values not exceeding a period of one month were replaced by the interannual daily means. It would appear that the western area is warming (0.069°C/year), whereas the eastern area is cooling slightly (- 0.034°C/year). Quarterly differences SSTAbAs-SSTTbSd were then computed for each year (Fig. 9). Downward variation means that cooling on the eastern shore of the gulf (near Cape Three Points) is intensifying or that the western shore waters (near Cape Palmas) are warming. During all seasons except summer, the differences between eastern and western temperatures decreased regularly from 1978 to 1990. The summer was somewhat different, with a stronger decrease from 1980 until 1986 and two sharp increases in 1978-1979 and 1986-1987. From 1987 onwards, the slope of the summer curve was similar to that of the other seasons.

Elements of such atypic seasonal change in the alongshore SST gradient can be observed in the near-ocean data set. Temperature differences between two squares of the gridded set (S2 and S4) were calculated. As these two squares come from two independent 5° x 2° quadrangles, their data may be compared. The winter and summer differences (SSTS4-SSTS2) are plotted in Figure 10. In winter (short cold season), there was a decreasing trend in zonal temperature differences during the 1980s, whereas in summer (long cold season) these differences were more strongly negative during a five-year period between 1980 and 1986.

Finally, the changes observed during the last decade onshore and along shipping routes show strong similarities. The western side of the Ivorian gulf became warmer and the eastern side cooler. At shoreline stations these changes occurred during all four seasons (although stronger during cold seasons). In near-ocean [ships] data, changes were also most evident during boreal winter and summer.

Table 3

Linear trends (slope) of sea surface temperature and wind stress increases computed on standardized anomalies between 1964 and 1990 for the whole area (0-10° W) and separately for the different seasons. The null hypothesis (slope ≤ 0) was tested by the one tailed t test (t = slope/standard error) with 25 degrees of freedom.
*, **, *** *indicate respectively that Ho is rejected at the 5; 1 or 0.1% level.*

Tendances linéaires des accroissements de température de surface de la mer et de la tension de vent, calculées sur les anomalies standards entre 1964 et 1990 pour chaque saison et sur l'ensemble de la région (0°-10°W). L'hypothèse nulle (pente ≤ 0) est testée par le test t unilatéral (t = pente/écart-type) à 25 degrés de liberté.
*, **, *** indiquent respectivement que Ho est rejeté au niveau 5 ; 1 ou 0,1 %.

	Quarter	Slope	t
SST	JFM	0.015	0.805
	AMJ	0.046	2.434 *
	JAS	0.053	3.089 **
	OND	0.083	4.982 ***
Wind stress modulus	JFM	0.160	2.312 *
	AMJ	0.258	4.334 ***
	JAS	0.209	4.605 ***
	OND	0.168	2.450 *
Zonal stress	JFM	0.135	1.883 *
	AMJ	0.185	3.098 **
	JAS	0.250	4.507 ***
	OND	0.113	1.922 *
Meridional stress	JFM	0.042	0.626
	AMJ	0.213	3.361 **
	JAS	0.157	3.223 **
	OND	0.131	1.990 *

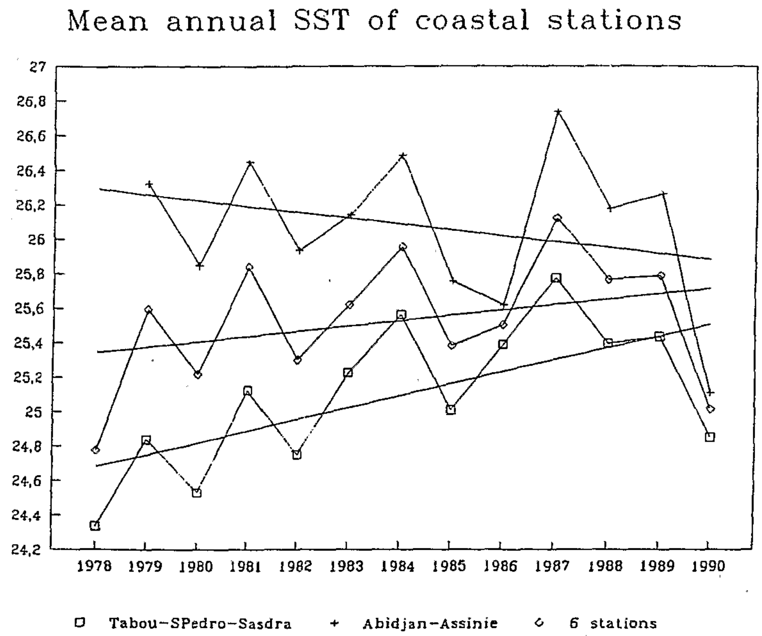


Figure 8

Mean annual SST (°C) from coastal station data: western group (Tabou, San Pedro and Sassandra), eastern group (Abidjan, Assinie) and the set of 6 Ivorian stations. Straight lines represent linear adjusting functions.

Températures moyennes de surface (°C) aux stations côtières : groupe occidental (Tabou, San Pedro et Sassandra), oriental (Abidjan, Assinie) et ensemble des six stations ivoiriennes. Les droites représentent les fonctions d'ajustement linéaire.

Alongshore wind-stress differences

It was noted above (Fig. 7 *a* and Tab. 3) that wind stress averaged over the total study area increased during the last three decades. Local deviations in climatology provide additional information about this change. During northern winters (January, February and March), wind stress parallel to the coast in S4 was usually weaker than in S2 (Fig. 5 and 11 *a*). There were slight exceptions during the 1960s and 1970s, but in the last decade there was a 4-year strong anomaly (1985-1988), with alongshore wind stress becoming stronger in S4 than in S2 (Fig. 11 *a*). Moreover, the spring (April, May and June) and summer (July, August and September) alongshore wind stress in S4 was mainly positive (*i. e.* favorable to upwelling) from 1983 onwards (Fig. 11 *b*, *c*), whereas it had been negative during the previous decade. During the fall (October, November and December) an increasing trend has also been noticed (Fig. 11 *d*).

It would thus appear that changes in wind force and direction on the eastern side of the Ivorian gulf at the beginning of the 1980s tended to replace piling up by a near-upwelling situation.

DISCUSSION

Long-term trends

An increase of SST over the last 30 years has already been reported in tropical oceans, particularly in the Atlantic (Flohn and Kapala, 1989; Citeau *et al.*, 1989; Servain *et al.*, 1990). The cause and importance of this warming is debatable, but the rise in SST is unquestionable though not uniformly distributed at once in space and time. Thus, performing an empirical orthogonal functions (EOFs) analysis of the ships data in the 5°N-5°S zonal strip, (Servain and Legler, unpublished manuscript, 1987), a local specificity was noted for SST around Cape Three Points, leading to a raw 0.5°C rise from the 1970s to the first half of the 1980s. This is in agreement with our Figure 7 *b*.

A strengthening of the winds has also been recorded during the last decades over several parts of the world ocean and particularly in tropical areas (*e. g.* Servain and Séva, 1987; Flohn and Kapala, 1989; Bakun, 1990). However such strengthening is debated since some authors (*e. g.* Ramage, 1984 and 1987; Postmentier *et al.*, 1989; Cardone *et al.*, 1990) have expressed doubts, citing bias in the wind recording, due to the use of anemometer measurements in place of the sea-state estimates. One specific cause should be the widespread assumption that the height of the shipborne anemometers is 10 m, whereas the actual mean height is 20 m. This should lead to an about one m/s overevaluation of the "anemometer" data against the "estimated" data. A gradual increasing use of anemometer measurements among the whole recorded data, should have induced a slow rising of the velocity in the

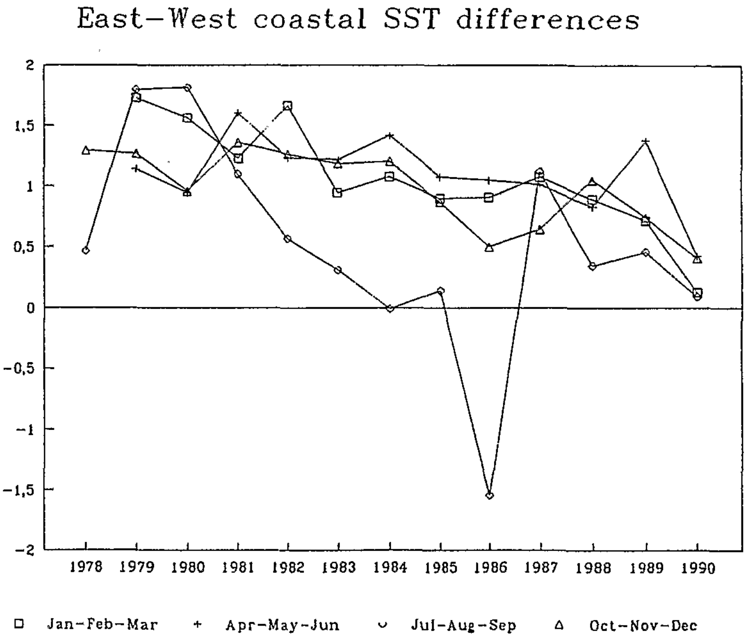


Figure 9

Difference in SST (°C) between eastern (Abidjan, Assinie) and western (Tabou, San Pedro, Sassandra) coastal stations during the four seasons.

Différences entre les températures de la mer (°C) des stations côtières du groupe oriental (Abidjan, Assinie) et occidental (Tabou, San Pedro, Sassandra) au cours des quatre saisons.

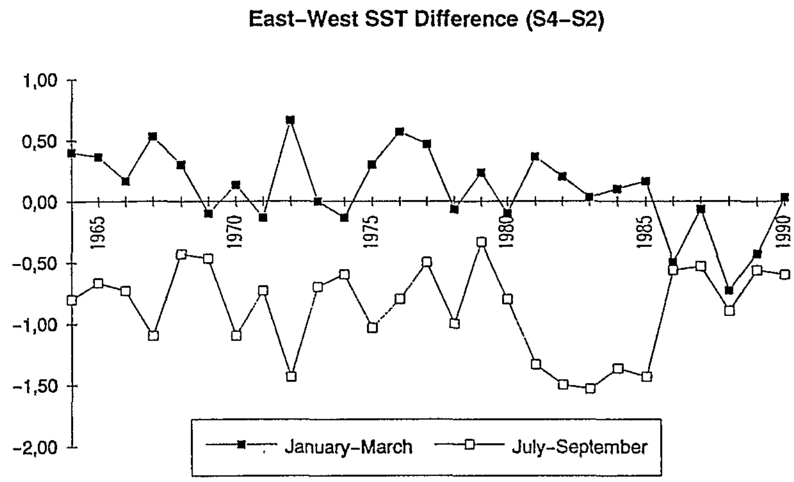


Figure 10

Eastern minus western SST (°C), from ships data (SSTS4-SSTS2) from January to March and July to September.

Différences entre les températures de l'Est et de l'Ouest (température S4 - température S2), en °C, au cours du premier et du troisième trimestre; données navires marchands.

wind data base during the last past decades. Unfortunately, a correct information about the type of recorded wind data is often missing in the ships records. In that condition, the possible bias due to the change of the measurement procedure is very arduous to estimate and the result not certain.

As most of the wind data base available all over the world, the wind data base used in this study (Picaut *et al.*, 1985 and updated works) has been created without taking such problem into account and no differenciation was made between anemometer data and sea-state estimates. As a consequence, the wind increase noted in our data set is probably partially due to the instrumental bias discussed above. However, similar strengthening has been noted in tropospheric geostrophic wind computed from air pressure data observed during the same period, and this was especially obvious during the 1980s (Diaz *et al.*, 1992). These authors, as well as Flohn and Kapala (1989) and Flohn *et al.*, (1990; 1992) considered that at least a part of the apparent increase is due to real changes. For a belt selected in the tropical Atlantic (14-26°N; 20-50°W), i.e. close to our study region, the linear trend of the directly observed easterlies during fourty one years (1948-1988) is practically identical (0.773 m/s against 0.778 m/s) to the calculated geostrophic easterlies (*see* Fig. 14 of Flohn *et al.*, 1992). These last authors related both wind and temperature increases to the greenhouse role of atmospheric increases in water vapour content. This additional energy input would lead to an acceleration of ocean warming in low latitudes and a strengthening of most tropical circulations, particularly the Hadley circulation. Along most eastern boundaries of oceans, Bakun (1990) observed also an increase of wind speed recorded by ships. He attributed this acceleration to a growing difference in atmospheric pressure between sea and land due to the greenhouse effect and inferred an intensification of Ekman upwellings along the coasts of California, Peru, Portugal and Morocco. However, he did not quote temperature decrease in the sea.

SST regional changes

The inversion of the SST east-west gradient observed in coastal data by Herbland and Marchal (1991) may be questionable. Such rough measurements obtained by unsophisticated means may suffer from various biases. For example, a change in reading time or the use of a thermally non-protected bucket can modify the temperature recorded. Nevertheless, the reversal in coastal temperatures was determined from six stations spread along a 450 km coastline and recorded by independent observers. The changes in this data set were progressive from one to the other. On the other hand the analysis procedure for ships data smoothed or altered differences between nearby areas. But the fact that ships temperatures corroborate coastal measurements gives them more credit and confirms the existence of a pluri-annual SST zonal anomaly on the Ghana and Côte d'Ivoire shelf and offshore.

What are the reasons for such changes ? Although wind stress is not the sole driving force, it is possible that local wind stress changes have altered the spatial pattern of SST.

Relationships between wind and SST

To investigate that question, regressions between SST and alongshore wind stress have been calculated in the ships data set. In order to avoid apparent correlations due to the similar long-term trends in wind and SST series, autocorrelations must be removed. Thus, 12th-differencing each monthly series (*i. e.* substracting each January value from the value of January of the previous year, each February value from the previous February value, *etc.*) has been done prior to analysis. The slopes of the linear regressions of SST *versus* wind stress parallel to the coast are shown for every square and month (Fig. 12). They are generally negative; even though poorly significant, they mean a weak association of inter-year SST variability to Ekman-type upwelling events, almost all the year round. The most surprising is the higher apparent linkage during the warm seasons and the apparent lack of interannual effect of wind induced cooling during the long cold season.

Pezennec and Bard (1992), using coastal stations SST and ships wind measurements, noticed a positive relationship between SST and wind speed during the long cold season and no significant correlation in the short cold season, which is rather similar to our results. Although the one-month time step of the ships data is not suited to determining possible wind effects on short upwelling events, the present results indicate a weak association of interannual SST change to wind induced upwelling, except during the long cold season. The driving mechanisms of the interannual-scale temperature changes in the the short and the long cold seasons thus appear to be different.

The previously quoted work of Servain and Legler (unpublished manuscript, 1987) indicates a change in the respective importance of the short and long cold season. During the 1970s, the long cold season of the boreal summer was the coldest, afterwhat the ranges of the previously called short and long cold seasons become of the same order.

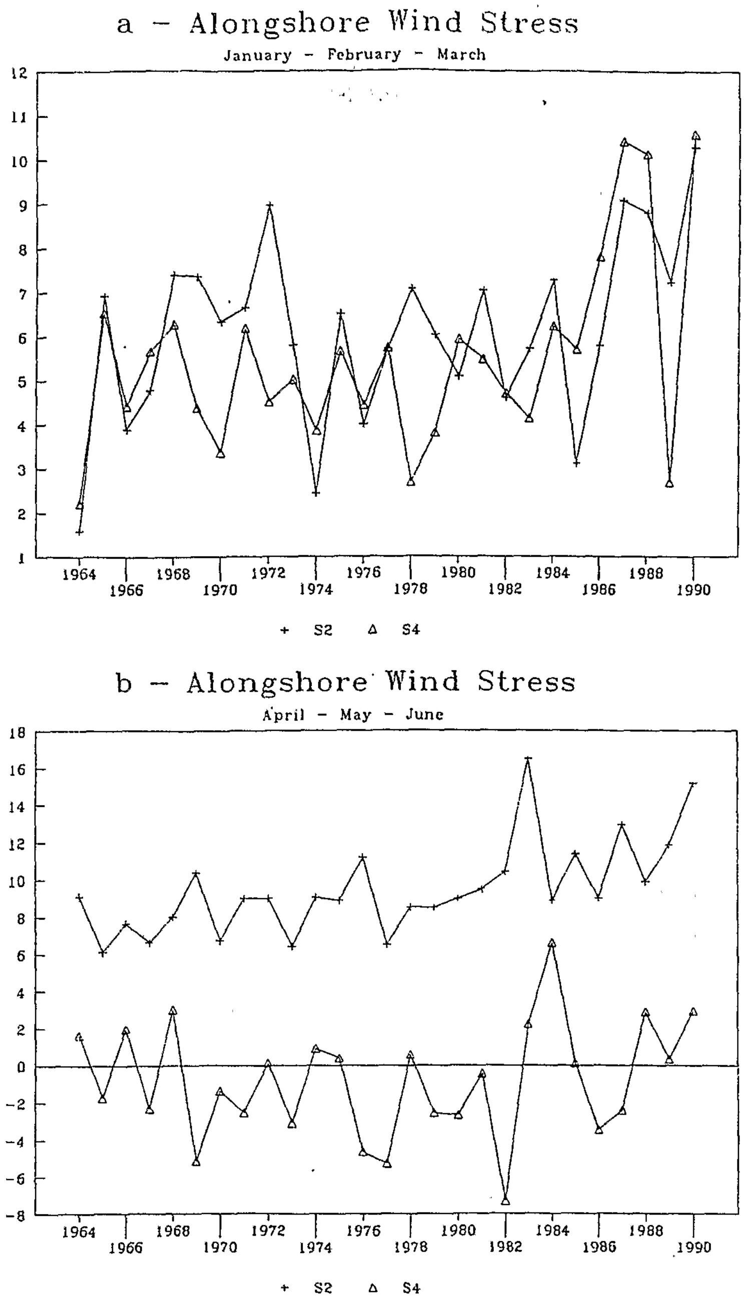
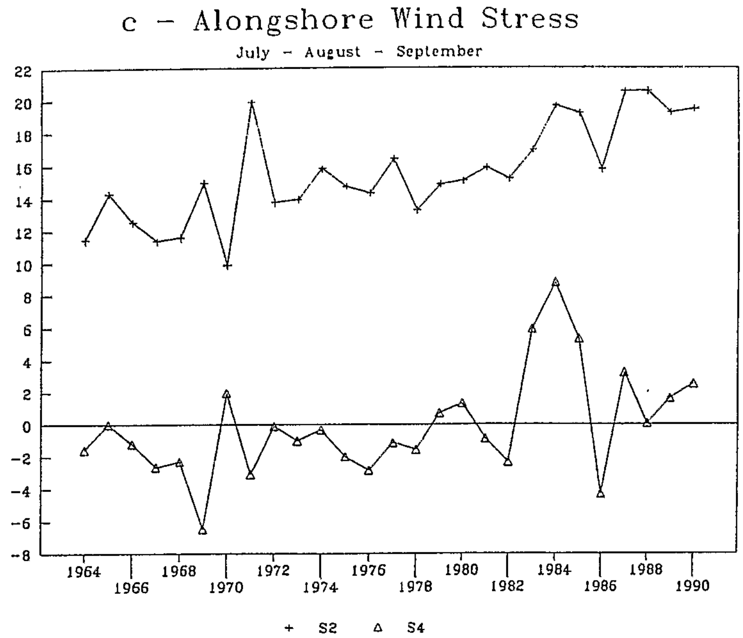


Figure 11 *a, b, c, d*

Alongshore wind stress in S2 and S4 squares in m^2/s^2: a) January-February-March; b) April-May-June; c) July-August-September; and d) October-November-December. Note the changes on the eastern side of the gulf (S4), during the last decade: wind stress parallel to the coast (favourable to upwelling) became higher than in S2 during the short cold season (a) and changed from negative to positive in the long warm (b) and long cold (c) seasons.

In coastal regions along 5°N, according to Philander and Pacanowski (1986): "the winds are favourable for coastal upwelling throughout the year. The coastal upwelling is nonetheless a seasonal phenomenon because it depends on the depth of the thermocline, which is determined by large-scale, not local conditions". Then, the cooling of surface waters cannot solely be explained by the Ekman transport, but the local wind stress could weaken SST during the short cooling events which occur mainly during the first term and sometimes later, breaking the warming up. Surprisingly, it seems that the wind has no effect on the interannual surface cooling in the long cold season. The



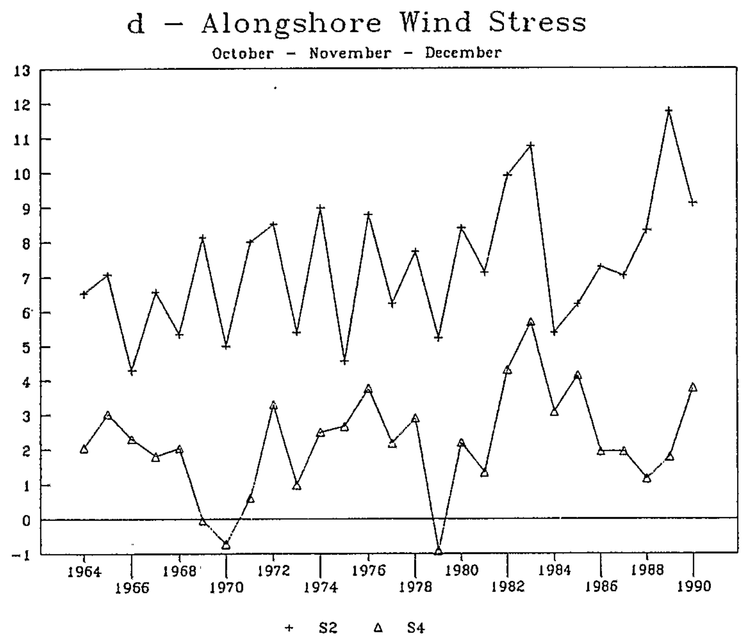


Figure 11 *a, b, c, d (following)*

Tension de vent parallèle à la côte (m^2/s^2) dans les carrés S2 et S4 en : a) janvier-février-mars ; b) avril-mai-juin ; c) juillet-août-septembre ; et d) octobre-novembre-décembre. Noter les changements dans l'est du golfe pendant la dernière décennie : en S4 la tension de vent parallèle à la côte (favorable à l'upwelling) devient plus forte qu'en S2 pendant la petite saison froide (a) et, de négative, devient positive pendant les grandes saisons chaude (b) et froide (c).

lack of coincidence between wind freshening and temperature may be the effect of global warming in hiding a possible wind-induced lowering of SST, particularly east of Cape Palmas. On the other hand, the small changes in the wind direction, observed during the last decade, would reinforce the cooling on the eastern side of the Ivorian gulf.

Changes in the current system?

Another hypothesis is that fluctuations in the tropical Atlantic circulation pattern occurred during the 1980s. Along the northern coast of the Gulf of Guinea, surface current flow is usually eastward (Guinea Current), and the westward-flowing Guinea Undercurrent corresponds to underlying cold waters with maximum salinity (Lemasson and Rebert, 1973 *a*). However, sporadic reversals of surface current are well-known along the coast from Nigeria to Liberia. The undercurrent is probably fed by subsurface water from the Bight of Biafra (Lemasson and Rebert, 1973 *b*).

An Atlantic El Niño-like event culminated during 1983-1984 (Philander, 1986; Hisard *et al.*, 1986; Hisard, 1988). An acceleration of zonal trade winds until mid-1983 raised the east-west slope of the sea surface along the equator (Katz *et al.*, 1986). Then, from mid-1983 to mid-1984 the trade winds collapsed, with the result that eastward surface transport was increased and equatorial upwelling reduced. Similar to what happens in Pacific El Niños, a strengthening of polewards circulation was recorded along the African coast. Such an anomaly has been observed during the summer of 1984 in the southern Atlantic along the Namibian coast (Shannon *et al.*, 1986). Furthermore, high salinity subsurface cold waters have spread up along the northern Gulf of Guinea to more westerly longitudes and have moved nearer the coast and the surface than previously (Piton and Wacongne, 1985).

According to interannual simulation performed with an oceanic general circulation model (OGCM) by Morlière (pers. comm., 1992), other changes in the dynamics of the north equatorial Atlantic basin could have occurred during the last decade. Between 3° and 10°N, *i. e.*, in the latitudinal range of the North Equatorial countercurrent and of the Guinea current, an increase in eastward flow was observed in the first 30 metres at the beginning of the second half of the 1980s. These simulated results are not incompatible with the above hypothesis of a strengthening of return circulation (the westward Guinea undercurrent). Further, increases of both circulations enhances eddies near the capes and shear turbulences which bring colder waters towards the surface. Thus, large-scale oceanographic changes during the last decade appear likely, though their real nature remains unclear.

Consequences on *Sardinella aurita* stock

Herbland and Marchal (1991) observed that the cooling of the eastern Ivorian gulf modified the environment in a way favorable to the rather stenothermic and halophilic *Sardinella aurita*. Roy (1992) supposed that increased westerlies led to stronger upwellings and better feeding conditions for pelagic fish larvae and adults. Indeed, the largest population of Côte d'Ivoire-Ghana stock spawns in S4 and especially S5 during the two upwelling seasons (Marchal, 1991). Thus, the drop in summer and then winter SST in S4 during the 1980s may have indicated trophic situations successively favourable to recruitment from summer (1981-1985) and then winter spawning (1986-1989). The rapid

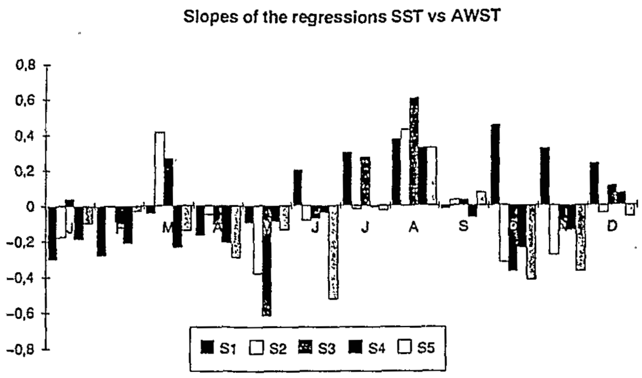


Figure 12

Regression coefficients of SST vs *alongshore wind stress, for every month and squares 1 to 5. Negative values indicate likely wind-induced upwellings. The surface waters cooling in the long cold season is unrelated to the wind stress, meanwhile weak upwelling trends occur during the rest of the year, except in S1.*

Coefficients de régression des températures de surface en fonction de la tension de vent parallèle à la côte, pour chaque mois et dans les carrés 1 à 5. Les valeurs négatives indiquent la possibilité d'un upwelling induit par le vent. Les variations interannuelles du refroidissement des eaux de surface en grande saison froide ne sont pas reliées à la tension de vent, tandis que de faibles tendances à l'upwelling existent tout le reste de l'année, sauf en S1.

increase and then sustained level of catches by Côte d'Ivoire fishing boats corresponds closely to this period (Fig. 2, 10).

The planktonic biomass depending on the nutrient input is negatively correlated to the temperature of surface water, except during the long cold season (Binet, 1976). Pezennec and Bard (1992) noticed that increased coolings in the short cold seasons of the last decade could lengthen planktonic production periods and benefit to pelagic fishes. The cooling of the eastern side of the Ivorian gulf improves larval and adult feeding and may also have facilitated the westward migrations of adults *Sardinella aurita* from the Ghana population. The appearance of fish near the surface, apart from the cold season, could be related to short upwelling events resulting from the change in the wind direction.

Nevertheless, the most striking changes in *Sardinella aurita* distribution are the biomass increase on the western shelf. Are the above-mentioned hydrological and meteorological changes sufficient to account for the demographic propagation of this species up to the western gulf? As suggested by Binet *et al.* (1991) and Binet and Marchal (1992; 1993), a slightly greater frequency of surface current reversals during some years could account for the westward extension of *Sardinella aurita*, with a second population developing in Guinea Current eddies created by the Cape Palmas headland.

SUMMARY

Several major changes have occurred in the ecosystem off the northern coast of the Gulf of Guinea during the last two decades:

1) The *Sardinella aurita* stock, object of an important fishery, has collapsed after an overfishing and then rebuilt itself. In the rebuilding process it has also expanded westward in a dramatic manner and became able to sustain higher catches than before.
2) The sea-surface temperature has undergone a rather monotonic long term increase. A 0.8°C rise in average SST in the studied area (10°W-0°, 4°N, northern coast of the Gulf of Guinea) was observed from 1964 to 1990.
3) The alongshore wind stress has also apparently undergone a long term increase, but in the sense that would increase wind induced upwelling and so tend to counter, rather than support, the observed sea surface temperature trend.
4) The eastern region of the Ivorian gulf (west of Cape Three Points) was an exception to the general warming trend, since SST decreased slightly during the cold seasons. This appears clearly in two separate data sets: along the shoreline area, where temperatures measured at one station were quite independent of those at other observation points; and in the near-ocean where the two sides of the gulf correspond to different primitive blocks for analysis of ships observations.

The last three points, although clearly settled, cannot be clearly logically connected according to our current understanding, for the following reasons : a) the seasonal cooling mechanism depends on several local and remote factors, which we are unable globally to apprehend; b) the space and time scale of the processed ships data are not fitted to detect possible short wind induced upwelling events.

The most prominent feature is the contradiction between rises in SST and apparent increases in the wind stress. The mean seasonal SST of the five blocks are in a rather good agreement with climatological wind stress, supposing locally wind driven upwelling, but this agreement disappears when observing interannual variations. The contradiction is the strongest during the long cold seasons, as the apparent wind increase came with a sea surface warming. Conversely, during the rest of the year, weak negative regressions between wind and SST indicate likely association with upwelling events.

During the last decade small clockwise rotations of the wind stress occurred, so that wind component parallel to the coast has risen in the eastern Ivorian gulf. These intensifications were apparent almost throughout the year. One can suppose that, even in a system where the main cooling season is not wind dependent, these changes might have favoured slight upwelling events in October-November and from January until May that would account for the temperature decrease of that area.

What would be the causes of wind increase and rotation? They may have been due to local climatic changes (deforestation and alteration of ground cover, both likely causes of soil heating and lowering of atmospheric pressure, particularly in the dry season, from November to May). They may also have been related to larger climatic events, *i. e.*, ITCZ seasonal displacement anomalies (Citeau *et al.*, 1989) or intensification of tropospheric circulation due to the greenhouse effect of an increase in atmospheric water vapour content. Further studies are required to evaluate the persistence of these patterns.

The *Sardinella aurita* outburst might have benefited from several factors. As suggested by Pezennec and Bard (1992), the lengthening of short cold seasons in the western area means a shortening of the forage-poor periods which favour the feeding of adult fish near the surface and the survival of their offspring. The cooling of the eastern region has probably the same effect in decreasing the unfavourable surface areas. The apparent contradiction is that short upwelling events would not counter the general warming but probably provide enough nutrients to inpulse short planktonic production events during the usually poor period from November to May.

The OGCM simulation indicating a growing eastward flow along the Atlantic Ocean during the last decade, especially until 1987, may agree with the hypothesis of a strengthening of return circulation on the shelf or near the slope (westward Guinea Undercurrent). These possible changes may have also favoured *Sardinella aurita* stock in improving containment of fish larvae in a feeding area and increasing the recruitment and settlement of a second population near Cape Palmas.

Aknowledgements

We thank the crews of all the ships who continuously gathered essential data at sea. We are also indebted to scientists and assistants at the Centre de Recherches Océanographiques in Abidjan who supplied us with daily coastal SST observations. Alain Morlière kindly provided us with the results of the OGCM performed at the LODYC (University of Paris 6) and Sabine Arnault updated for us an EOF analysis. We are also grateful to the reviewers of this manuscript for their help in finalizing our draft. This work was partly financed by IFREMER contract 91.1.430.023.

APPENDIX NOTES

1) Pseudo-wind stress, henceforth referred to as "wind stress", has two components: $\vec{\tau}_x = \vec{W}_x\ |W|$ and $\vec{\tau}_y = \vec{W}_y\,|W|$, where $|W|$ is the magnitude and $\vec{W}_x$ and $\vec{W}_y$ the two zonal and meridional components respectively of the wind vector $\vec{W}$.

2) During most of 1969, there was a dramatic decrease in the number of available observations in the northern gulf of Guinea (*see* Picaut *et al.*, 1985, pp. 14-15), including the region under study. This lack of data is not critical for SST because of its high temporal stability. However, previous analyses using original monthly mean data demonstrate that the wind stress signal was very different (more energetic) in 1969 than throughout our entire study period. As SST data did not take this anomaly into account, we made an artificial calculation of the wind stress field for each month of 1969 by averaging the corresponding months in 1968, 1969 and 1970. Our determinations indicate that this special circumstance did not significantly influence the average wind stress field. However, no reference will be made to the year 1969 in discussing the results of wind stress analysis.

3) There is another apparent discrepancy between SST climatologies in the near-ocean and coastal data sets. During the cold season, ships temperatures are about 4°C higher than those of the shoreline bucket samples but are similar during the warm season. These cold season differences can be explained by the way near-ocean climatology is computed from ships observations. Routes are generally located a few miles off the shoreline where coastal surface observations are collected, thus where sea surface cooling is most intense (Morlière and Rebert, 1972). Conversely, during the warm season, SST is practically uniform over a large offshore extent perpendicular to the coastline.

REFERENCES

Arfi R., O. Pezennec, S. Cissoko and M.A. Mensah (1991). Variations spatiale et temporelle de la résurgence ivoiro-ghanéenne. in: *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris, 162-172.

Bakun A. (1978). Guinea current upwelling. *Nature*, **271**, 147-150.

Bakun A. (1990). Global climate change and intensification of coastal ocean upwelling. *Science*, **247**, 198-201.

Binet D. (1976). Biovolumes et poids secs zooplanctoniques en relation avec le milieu pélagique au-dessus du plateau ivoirien. *Cah. ORSTOM. sér. Océanogr.*, **14**, 301-326.

Binet D. (1979). Le zooplancton du plateau pélagique ivoirien. Essai de synthèse écologique. *Oceanologica Acta*, **2**, 397-410.

Binet D. (1982). Influence des variations climatiques sur la pêcherie des *Sardinella aurita* ivoiro-ghanéennes : relation sécheresse-surpêche. *Oceanologica Acta*, **5**, 4, 443-452.

Binet D. and E. Marchal (1992). Le développement d'une nouvelle population de sardinelles devant la Côte d'Ivoire a-t-il été induit par un changement de circulation ? *Annls Inst. océanogr., Paris*, **68**, 1-2, 179-192.

Binet D. and E. Marchal (1993). The large marine ecosystem of shelf areas in the gulf of Guinea: long-term variability induced by climatic changes. in: Large marine ecosystems : stress, mitigation and sustainability, Ed. by K. Sherman, L.W. Alexander and B.D. Gold. AAAS Press, 104-118.

Binet D., E. Marchal and O. Pezennec (1991). *Sardinella aurita* de Côte d'Ivoire et du Ghana: fluctuations halieutiques et changements climatiques. in: *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris, 320-342.

Busalacchi A.J. and J. Picaut (1983). Seasonal variability from a model of the tropical Atlantic Ocean. *J. phys. Oceanogr.*, **13**, 1564-1588.

Cardone V.J., J.G. Greenwood and M.A. Cane (1990). On trends in historical marine wind data. *J. Climate*, **3**, 113-127.

Caverivière A. (1991). L'explosion démographique du baliste (*Balistes carolinensis*) en Afrique de l'Ouest et son évolution en relation avec les tendances climatiques. in: *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris, 354-367.

Citeau J., L. Finaud, J.-P. Cammas and H. Demarcq (1989). Questions relative to ITCZ migrations over the tropical Atlantic Ocean, sea-surface temperature and Senegal river runoff. *Met. atmos. Phys.*, **41**, 181-190.

Colin C. (1991). Sur les upwellings équatorial et côtier (5°N) dans le golfe de Guinée. *Oceanologica Acta*, **14**, 3, 223-240.

Cressman G.P. (1959). An operational objective analysis system. *Mon. Weath. Rev.*, **87**, 367-374.

Diaz H.F., F. Congbin and Q. Xiaowei (1992). A comparison of surface geostrophic winds with COADS ship wind observations. *Proceedings of the international COADS workshop, Boulder, Colorado, 13-15 January 1992*. H.F. Diaz, K. Wolter and S.D. Woodruff, editors. US Department of Commerce, NOAA/ERL, 131-141.

Flohn H. and A. Kapala (1989). Changes of tropical sea-air interaction processes over a 30-year period. *Nature*, **338**, 244-246.

Flohn H., A. Kapala, H.R. Knoche and H. Mächel (1990). Recent changes of the tropical water and energy budget and of midlatitude circulations. *Climate Dyn.*, **4**, 237-252.

Flohn H., A. Kapala, H.R. Knoche and H. Mächel (1992). Water vapour as an amplifier of the greenhouse effect: new aspects. *Meteorol. Zeitschrift N.F.*, **1**, 122-138.

Fréon P. (1988). Réponses et adaptations des stocks de clupéidés d'Afrique de l'Ouest à la variabilité du milieu et de l'exploitation. Analyse et réflexions à partir de l'exemple du Sénégal. Études et Thèses, ORSTOM, Paris, 287 pp.

Hastenrath S. and P.J. Lamb (1977). Some aspects of circulation and climate over the eastern equatorial Atlantic. *Mon. Weath. Rev.*, **105**, 8,1019-1023.

Herbland A. and E. Marchal (1991). Variations locales de l'upwelling, répartition et abondance des sardinelles en Côte d'Ivoire. in: *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris, 343-353.

Hisard P. (1988). El Niño response of the tropical Atlantic Ocean during the 1984 year. in : *International Symposium on Long-Term Changes Mar. Fish Pop. 1986*, T. Wyatt and M.G. Larraneta, editors. Vigo, 273-290.

Hisard P., C. Hénin, R. Houghton, B. Piton and P. Rual (1986). Oceanic conditions in the tropical Atlantic during 1983 and 1984. *Nature*, **322**, 243-245.

Houghton R.W. (1976). Circulation and hydrographic structure over the Ghana continental shelf during the 1974 upwelling. *J. phys. Oceanogr.*, **6**, 910-924.

Ingham M.C. (1970). Coastal upwelling in the northwestern gulf of Guinea. *Bull. mar. Sci.*, **20**, 1-34.

Katz E.J., P. Hisard, J.-M. Verstraete and S. Garzoli (1986). Annual change of sea surface slope along the Equator of the Atlantic Ocean in 1983 and 1984. *Nature*, **322**, 245-247.

Le Loeuff P., E. Marchal and J.-B. Amon Kothias (1993). *Environnement et ressources aquatiques de Côte d'Ivoire. I: Le milieu marin.* ORSTOM Editions, Paris, 588 pp.

Lemasson L. and J.-P. Rebert (1973 *a*). Les courants marins dans le golfe ivoirien. *Cah. ORSTOM, sér. Océanogr.*, **11**, 67-96.

Lemasson L. and J.-P. Rebert (1973 *b*). Circulation dans le golfe de Guinée. Étude de la région d'origine du sous-courant ivoirien. *Cah. ORSTOM, sér. Océanogr.*, **11**, 303-316.

Marchal M. (1991). Un essai de caractérisation des populations de poissons pélagiques côtiers: cas de *Sardinella aurita* des côtes ouest-africaines. in : *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris, 192-200.

Marchal M. and J. Picaut (1977). Répartition et abondance évaluées par écho-intégration des poissons du plateau ivoiro-ghanéen en relation avec les upwellings locaux. *J. Rech. océanogr.*, **2**, 4, 39-57.

Mendelssohn R and P. Cury (1987). Forecasting a fortnightly abundance index of the Ivorian coastal pelagic species and associated environmental conditions. *Can. J. Fish. aquat. Sci.*, **44**, 408-421.

Moore D.W., P. Hisard, J.P McCreary, J. Merle, J.J. O'Brien, J. Picaut, J.-M. Verstraete and C. Wunsch (1978). Equatorial adjustment in the eastern Atlantic. *Geophys. Res. Letts*, **5**, 637-640.

Morlière A. (1970). Les saisons marines devant Abidjan. *Doc. scient. Cent. Rech. océanogr,. Abidjan*, **1**, 2, 1-15.

Morlière A. and J.-P. Rebert (1972). Étude hydrologique du plateau continental ivoirien. *Doc. scient. Cent. Rech. océanogr,. Abidjan*, **3**, 1-30.

Pezennec O. and F.-X. Bard (1992). Importance écologique de la petite saison d'upwelling ivoiro-ghanéenne et changements dans la pêcherie de *Sardinella aurita*. *Aquat. liv. Resour.*, **5**, 249-259.

Philander S.G.H. (1986). Unusual conditions in the tropical Atlantic ocean in 1984. *Nature*, **322**, 236-238.

Philander S.G.H. and R.C. Pacanowski (1986). A model of the seasonal cycle in the tropical Atlantic Ocean. *J. geophys. Res.*, **91**, C12, 14192-14206.

Picaut J. (1983). Propagation of the seasonal upwelling in the eastern equatorial Atlantic. *J. phys. Oceanogr.*, **13**, 18-37.

Picaut J., J. Servain, P. Lecomte, M. Séva, S. Lukas and G. Rougier (1985). Climatic Atlas of the Tropical Atlantic Wind Stress and Sea Surface Temperature 1964-1979, Université de Bretagne Occidentale, Brest, France, 467 pp.

Piton B. and S. Wacongne (1985). Unusual amounts of very saline subsurface water in the eastern Gulf of Guinea in May 1984. *Trop. Ocean-Atmos. Newslett.*, **32**, 5-8.

Postmentier E.S., M.A. Cane and S.E. Zebiak (1989). Tropical Pacific Climate trends since 1960. *J. Climate*, **2**, 731-736.

Ramage C.S. (1984). Can shipboard measurements reveal secular changes in tropical air-sea heat flux ? *J. Clim. appl. Met.*, **23**, 187-193.

Ramage C.S. (1987). Secular changes in reported surface wind speed over the ocean. *J. Climate appl. Met.*, **26**, 525-528.

Roy C. (1991). Les upwellings : le cadre physique des pêcheries côtières ouest-africaines. in: *Pêcheries ouest-africaines. Variabilité, instabilité et changement.* P. Cury et C. Roy, editors. ORSTOM, Paris. 38-66.

Roy C. (1992). Réponses des stocks de poissons pélagiques à la dynamique des upwellings en Afrique de l'Ouest: analyse et modélisation. Études et Thèses. ORSTOM, Paris, 146 pp.

Servain J. and M. Séva (1987). On relationships between tropical Atlantic sea surface temperature, wind stress and regional precipitation indices: 1964-1984. *Ocean-air Interactions*, **1**, 183-190.

Servain J. and S. Lukas (1990). Climatic atlas of the tropical Atlantic wind stress and sea surface temperature: 1985-1989. Océans tropicaux Atmosphère globale. IFREMER, ORSTOM, JIMAR, 133 pp.

Servain J., M. Séva, S. Lukas and G. Rougier (1987). Climatic atlas of the tropical Atlantic wind stress and sea surface temperature: 1980-1984. *Ocean-air Interactions*, **1**, 109-182.

Servain J., M. Séva and P. Rual (1990). Climatology comparison and long-term variation of sea surface temperature over the tropical Atlantic Ocean. *J. geophys. Res.*, **95**, 9421-9431.

Shannon L.V., A.J. Boyd, G.B. Brundrit and J. Taunton-Clark (1986). On the existence of an El-Niño-type phenomenon in the Benguela system. *J. mar. Res.*, **44**, 495-520.