THE CÔTE D'IVOIRE AND GHANA COASTAL UPWELLINGS DYNAMICS AND CHANGES

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Abstract :

This document is a review of the facts and theories about the origin and mechanisms of the seasonal upwellings occurring off Côte d'Ivoire and Ghana. The two seasons of upwellings, the major during boreal summer and the minor during boreal winter are considered. New insights show that the impact of wind, although being not the unique cause of upwelling, could be more important that previously thought. But dynamics of each upwelling appear to be different, complex and not definitely explained. Long term environmental changes could have affected the minor upwelling in a small way, but it could be sufficient for inducing changes in the Sardinella populations during the last decade.

Résumé :

Ce document passe en revue les faits et théories concernant l'origine et les mécanismes des upwellings saisonniers qui se produisent au large de la Côte d'Ivoire et du Ghana. Deux saisons d'upwellings, le majeur durant l'été boréal, le mineur durant l'hiver boréal sont examinées. Des études récentes montrent que l'effet du vent, bien que n'étant pas la cause unique de remontée d'eaux froides pourrait être plus important que ce que l'on pensait. Mais la dynamique de chaque upwelling est différente, complexe et reste encore non totalement élucidée. Des changements environnementaux à long terme semblent avoir affecté l'upwelling mineur, de façon faible, mais suffisante pour induire des changements dans les populations de Sardinelles au cours de la décade récente.

1 - Mean Patterns in the Côte d'Ivoire and Ghana Upwelling Ecosystems.

The Cote d'Ivoire and Ghana ecosystem is located between 0 and 8°W at a low latitude (5°N). The large continental shelf (60 km) east of Cape Three Points narrows on the western side of the Cape and is less than 20km wide off Côte d'Ivoire. The East-West orientation of the coast is a singular characteristic of this tropical upwelling ecosystem. However, the eastward flow of the Guinea current and the westward undercurrent make the structure of the surface and subsurface circulation quite similar to the other upwelling areas. The depth of the thermocline is shallow, it varies seasonally between 10 to 60 meters. The seasonal amplitude of the sea surface temperature (SST) is large, SST varies between 21°C during the austral winter and more than 29°C in April. The southwest monsoon wind is the dominant wind regime, wind speed is maximum (around 5 m/s) during the austral winter. On the eastern side of Cape Three points in Ghana and Cape Palmas in Côte d'Ivoire, the wind is upwelling favorable all year round, maximum values of the upwelling index are observed during the austral winter (fig. 1). Due to the latitude dependency of the Ekman transport, upwelling indices can reach large values in equatorial regions. Off the Cote d'Ivoire and Ghana ecosystem, the wind intensity remains below 5 m/s but the value of the upwelling index is similar to values observed on other eastern boundary currents. Nutrient concentration is high and comparable to what is found is other upwelling areas. Perhaps, the most important feature of this ecosystem is the occurrence of two upwelling seasons : the main one from June to October and a second one of minor amplitude in February-March.

Table 1 and figure 1 summarize the main characteristics of the Côte d'Ivoire and Ghana ecosystem; information on other upwelling areas are also given to allow comparison between ecosystems.

	LATITUDE	UPWELLING	SST (°C)	WIND SPEED (m/s)	UPW. INDEX (m3/s/m)	WIND MIXING (m3/s3)
COTE D'IVOIRE -GHANA	5°	JAN-FEB	**27.8** 21.4 30.0	**3.7** 1.7 6.1	**1.0** -0.3 26	**95** 8 359
		N JUNE-OCT.	**27** 21.4 29.9	**3.7** 0.5 6.7	**1.3** -0.5 3.6	**95** 1 335
SENEGAL (Cap Vert)	15°N	DEC.-JUNE	**25.8** 17.9 29.2	**4.8** 2.6 7.8	**1.0** -06 2.6	**197** 50 683
CAP BLANC	21°N	PERMANENT	**19.3** 16.9 249	**7.2** 4.0 10.7	**1.7** 0.5 3.9	**627** 160 1548
BAJA CALIFORNIA (Punta Eugenia)	27°N	PERMANENT	**18.7** 15.1 25.4	**5.9** 4.1 8.7	**0.7** 0.1 1.5	**359** 137 1017
PERU : Trijillo	8°S	PERMANENT	**20.4** 16.3 28.4	**4.9** 1.6 7.9	**1.2** 0.1 3.3	**188** 10 613
PERU : Callo	12°S		**19.3** 15.0 26.7	**5.5** 2.6 8.3	**1.0** 0.2 3.2	**276** 28 789
NAMIBIA	23°S	PERMANENT	**15.9** 12.8 20.0	**6.0** 1.7 12.0	**1.1** 0.1 4.4	**432** 19 2698

Table 1 : The physical characteristics of several upwelling areas. For each parameter, minimum, median and maximum values are given. Source COADS data set.

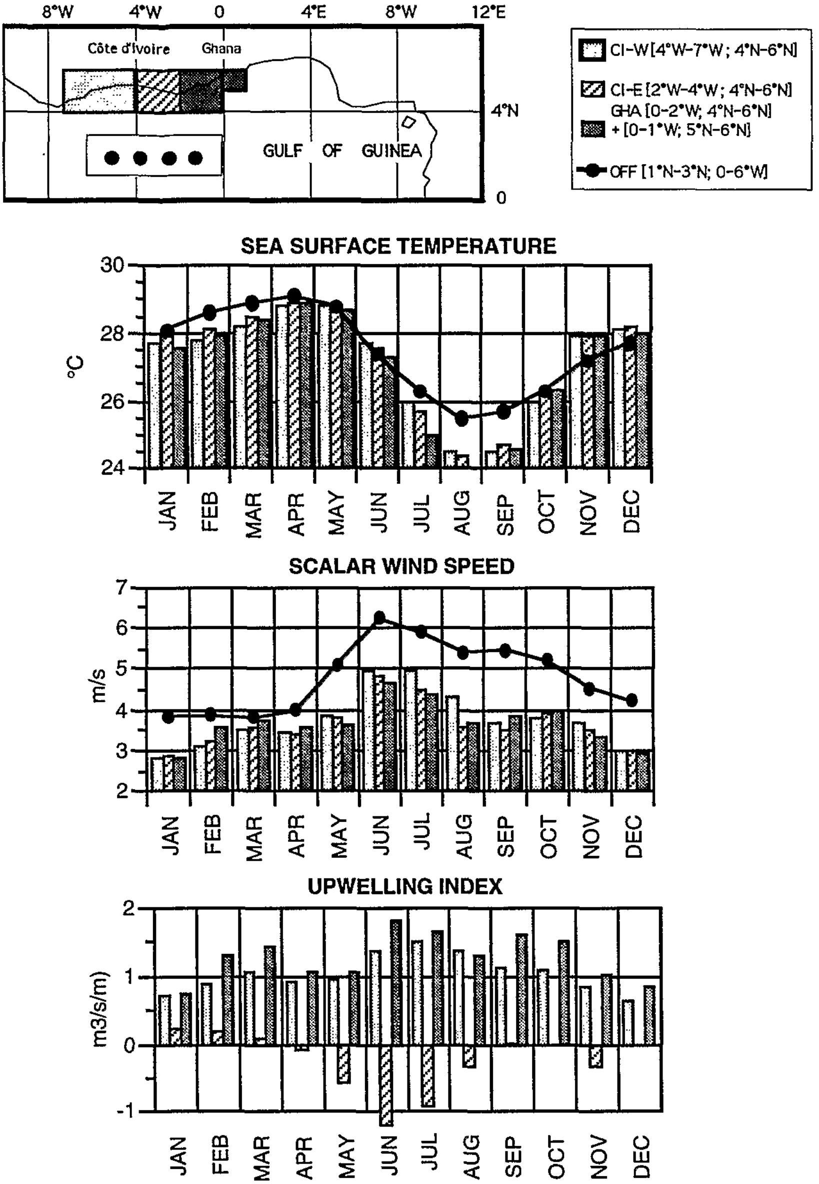

Figure 1 : Mean seasonal cycle of sea surface temperature, wind speed and upwelling index for three coastal areas off Côte d'Ivoire and Ghana and one offshore area. Mean values calculated using data extracted from the COADS dataset.

2 - What Causes the Upwellings ?

The mechanism responsible for the occurrence of the seasonal upwellings in the Côte d'Ivoire and Ghana ecosystem remains unclear. For the summer upwelling, several processes are proposed. Along the Côte d'Ivoire and Ghana coasts, Ekman transport induced by South-West winds is directed offshore and may be responsible for creating the coastal upwelling (Ekman type upwelling, see fig. 2). However, Bakun (1978) pointed out that maximum values of offshore Ekman transport occur to the east and downstream (in reference to the Guinea current) of the location of the summer minimum temperature. The low values of the coastal wind and the absence of seasonal cycle seem also to question the importance of the local wind to the upwelling process (Verstraete et al. ,1980). All attempts to correlate the intensity and duration of the upwelling with the local coastal winds have failed (FRU, 1970; Houghton, 1976). However, Colin (1988) using data collected a few miles offshore with moored buoys showed that the offshore wind is stronger than the wind measured at coastal stations and also has a pronounced seasonal cycle. By looking at the correlation between SST and alongshore wind stress, Binet and Servain (1993) concluded that there is no apparent relationship between the interannual variability of the offshore wind and the intensity of the summer cooling.

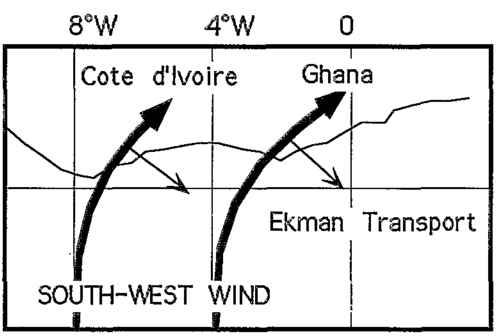

Figure 2 : Schematic diagram of the offshore Ekman transport created by the South-West wind regime over the North coast of the Gulf of Guinea.

Hingham (1970) proposed the idea of a current induced upwelling along the North coast of the Gulf of Guinea (fug. 3). The Guinea Current, in geostrophic balance, is associated with an upward slope of the thermocline toward the coast. The acceleration in summer of the eastward flow of the Guinea current increase the slope and thus could give favorable conditions for a coastal upwelling. This idea was tested using a numerical models (Philander, 1979) but insignifiant coastal upwelling is produced because all subsurface isotherms are undisplaced at the coast. The lack of continuous surface and subsurface measurement over a long time period is also a strong limitation to carry a comprehensive analysis of the effect of the coastal circulation on the dynamics of this ecosystem.

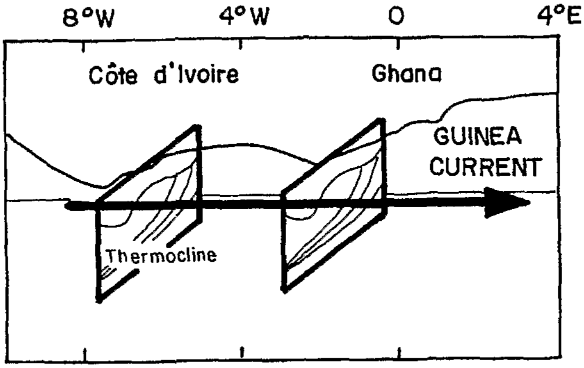

Figure 3 : A schematic diagram of a current induced coastal upwelling by the eastward flow of the Guinea Current.

Marchal and Picaut (1977) proposed another type of current induced upwelling. Dynamic interactions between the flow of the Guinea Current and Cape Palmas and Cape Three Points can induce a shallowing of the thermocline downstream of the two capes and an accumulation of water upstream (fig. 4). This would be enhanced on the wide and shallow shelf east of Cape Three Points.

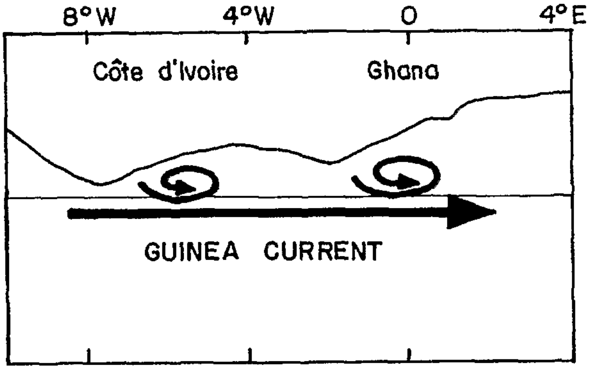

Figure 4 : A schematic diagram of a the «cape effect» induced by the eastward flow of the Guinea Current, as described by Marchal and Picaut (1977).

Remote forcing is also thought to play an important role in the dynamic of the Cote d'Ivoire and Ghana summer upwelling (Moore *et al.*, 1978) : an increase of the easterly wind in the western equatorial Atlantic creates an internal upwelling Kelvin wave that propagates eastward along the equator; when reaching the African continent, this wave reflects as coastal Kelvin waves and Rossby waves, the coastal Kelvin waves are trapped along the coast and propagate poleward, the Rossby waves propagate westward on both sides of the equator (fig. 5). Picaut (1983) showed that the phase lag observed in the SST signal from several coastal stations along the coast is in agreement with the idea of a westward propagation of the upwelling signal; vertical propagation was also observed. Servain *et al.*

(1982) found a correlation between the zonal wind stress in the western Atlantic and the SST in the Gulf of Guinea, this is also in agreement with the remote forcing mechanism. However, there is no apparent relationship between the onset of the equatorial upwelling and the onset the coastal upwelling (Houghton and Colin, 1987).The offshore extension of the thermocline vertical oscillation is also far greater than the Rossby radius.

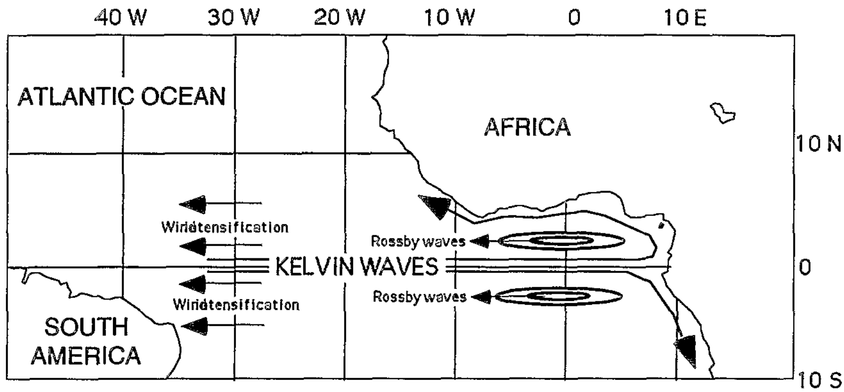

Figure 5 : Schematic diagram of the remote forcing of the summer upwelling in the Gulf of Guinea according to Moore *et al.* (1978).

The winter upwelling has received less attention than the summer upwelling. The intensity of this secondary upwelling is maximum in the surrounding of Cape Palmas and sharply decreases toward the east to become almost unnoticeable on the SST signal of the Ghana coastal stations (Arfi *et al.*, 1991). The intensification of the Guinea current in January and February is thought to contribute to the upward movement of the thermocline associated with this secondary upwelling (Morlière, 1970). The SST difference between an offshore area and a coastal area off Côte d'Ivoire is positively correlated with the offshore component of the Ekman transport (fig. 6). This result suggest that the local wind may also be an important contributor to the winter upwelling off Côte d'Ivoire: increasing offshore transport enhances the coastal upwelling, coastal SST decreases and as a result the temperature gradient between the offshore and the coastal areas increases.

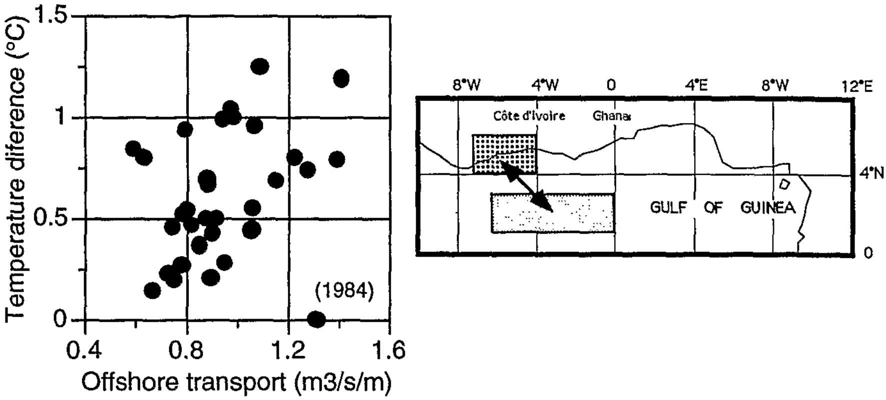

Figure 6 : The relationship between the offshore and coastal SST difference and the offshore Ekman transport off western Côte d'Ivoire. Increasing offshore transport enhances the temperature gradient between the offshore and coastal areas. 1984 is an outlier, also unusual conditions were recorded during 1984 in the tropical Atlantic ocean. (data extracted form the COADS database).

3 - Long Term environmental Changes in the Côte d'Ivoire - Ghana Ecosystems.

3. 1-Wind-Stress

Several studies suggest that there is a constant intensification of the wind stress along the coast of the Cote d'Ivoire-Ghana ecosystem (Roy, 1992; Binet and Servain, 1993). This increase is presented as being responsible for the changes observed in the sardinella fishery. However, the wind data used by these authors are extracted from meteorological observations collected by ships-of-opportunity, but they do not take into account changes in the measurement procedure that had occurred during the last 30 years. The velocity of the wind can be either estimated from the sea-state using the Beaufort scale («estimated» data) or directly measured using an anemometer («anemometer» data). However, when converted to m/s, wind velocity collected using the Beaufort scale («estimated» data) is generally lower than wind velocity given by an anemometer (fig. 7). Therefore, as the percentage of wind data collected using an anemometer is increasing over the past decades (fig. 8), a gradual increase of the mean wind velocity is observed when the measurement procedure is not taken into account in the calculation of the mean (see Ramage, 1984, Cardone et al., 1990, Diaz *et al.*, 1992 for a discussion of the possible bias encountered when using ships-of-opportunity data).

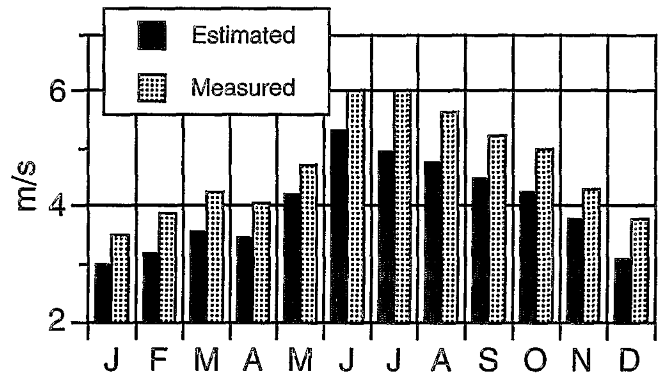

Figure 7 : Mean seasonal cycle of the wind in the coastal area (0-10°W and 4°N-10°N) calculated with :
a) the wind data collected using the Beaufort scale only (labeled «estimated»)
b) the «wind data collected using an anemometer only (labeled «measured»).
It is important to notice that the mean calculated using «measured» data is between 10% to 20% higher that the mean given by «estimated» data.
Source : COADS dataset; in this dataset, under the label «estimated» there is also an unknown percentage of data for which the indication on the measurement procedure is missing.

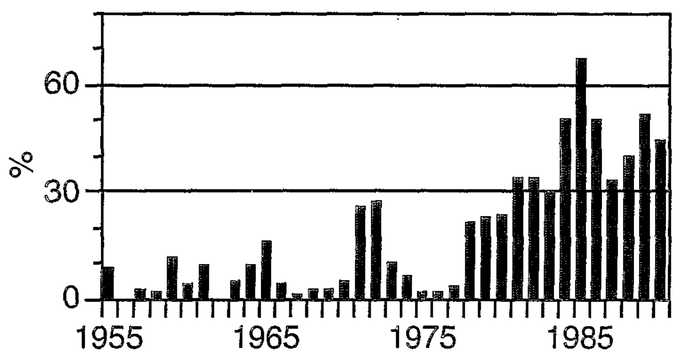

Figure 8 : Percentage of wind data collected in the Ghana-Côte d'Ivoire ecosystem (0-10°W and 4°N-10°N) using and anemometer in the COADS data base from 1955 to 1990.

Using the COADS dataset, the monthly mean components of the wind stress in the area defined by Binet and Servain (1993) are calculated, first with no restriction on the measurement procedure, a second time-series is created by selecting only «estimated» wind data. Following the same procedure than Binet and Servain (1993), the monthly wind stress modulus is calculated and averaged over a year for each time series (fig. 9). When considering all the available data with no restriction on the measurement procedure, our results are quite similar to those of Binet and Servain (1993) : from 1955-1990 there is a positive trend with a slope of 0.14 m/s per year, however when only «estimated» data are considered, the value of the slope is divided by two (Tab. 2).

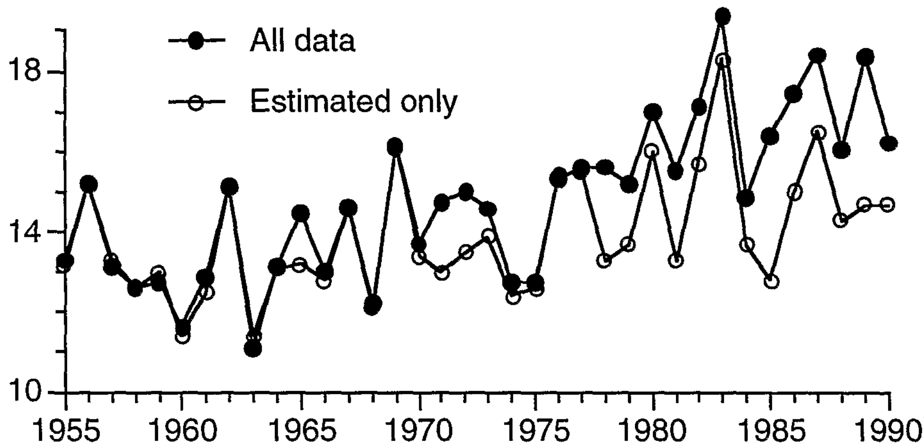

Figure 9 : Time-series of wind stress in the Ghana-Côte d'Ivoire ecosystem (0-10°W and 4°N-10°N) calculated from the COADS data set using :
a) all available data
b) data labeled «estimated» .

	R^2	Slope	Significance
all data	54 %	0.14	$p < 0.01$
«estimated» data	18 %	0.07	$p < 0.01$

Table. 2 : Statistical parameters of the adustment of a linear trend on the time-series of the mean annual wind stress in the Ghana-Côte d'Ivoire ecosystem (0-10°W and 4°N-10°N) calculated from the COADS data set using : a) all available data b) data labeled «estimated» .

Following Binet and Servain (1993), we also performed an analysis of the trend over the different seasons by considering the means by semester of the wind stress time-series calculated using «estimated» wind data. In that case the only statistically significant trend is observed during the first semester (table 3).

Estimated data	R^2	slope	Significance
JFM	12%	0.06	$p < 0.05$
AMJ	3 %	0.08	none
JAS	6 %	0.08	none
OND	0 %	....	none

Table. 3 : Statistical parameters of the adustment of a linear trend on the time-series of wind stress (mean by semester) in the Ghana-Côte d'Ivoire ecosystem (0-10°W and 4°N-10°N) calculated from the COADS data set using data labeled «estimated» .

These results shows that an important part of the changes in wind regime described by Roy (1991) and by Binet and Servain (1993) are related to changes in the wind measurement procedure; the increasing number of wind data collected using an anemometer during the last decade is responsible for an artificial increase of the wind intensity. When the change in the measurement procedure are taking into account, it appears that the only statistically significant trend of the wind stress is observed during the winter upwelling : over the last 50 years the wind stress shows a slight increase between January and March.

3. 2 - Intensification of the Undercurrent

Binet *et al.* (1991) and Binet and Marchal (1992) suggested that an intensification of coastal westward undercurrent occurred during the eighties. This hypothesis relies on current observations collected during 1983-1984. However, it is well known that the oceanographic conditions in the Gulf of Guinea during the last months of 1983 and the first quarter of 1984 were very unusual (see Hisard *et al.*, 1986). This warm event was related to the 1983 ENSO over the Pacific which was the strongest ENSO recorded during this century. No *in situ* current data are available since 1984. This hypothesis is based on data recorded during years with unusual climatic conditions and on other qualitative information; evidence of an intensification of the undercurrent over the last decade is still lacking.

	1968	1969	1970	1971-1982	1983	1984	1985-1993
Toward the East	77	93	91	no data	71	65	no data
Toward the West	**23**	7	9	no data	**29**	**35**	no data

Table. 4 : Occurences of eastward (Guinea Current) and westward (undercurrent) circulation over the shelf of Côte d'Ivoire (from Binet and Marchal,1992)

3. 3 - Intensification of the secondary Upwelling

Using data from ships of opportunity and coastal stations, Pezennec and Bard (1992) provided evidence of an intensification of the secondary upwelling during the last decade. In the western part of Côte d'Ivoire, a continuous decrease of the mean SST during the secondary upwelling starting in the mid seventies is apparent on figure 10. A similar result is found using the SST difference between an offshore and a coastal area (fig. 11). This increase of the intensity of the secondary upwelling seems to be associated with a slight increase of the offshore component of the Ekman transport (fig. 11).

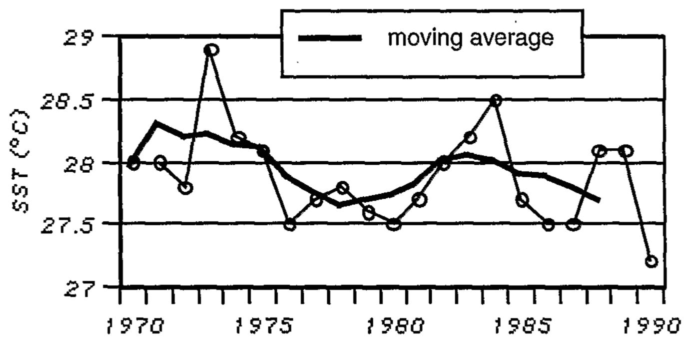

Figure 10 : mean SST between January and March from 1970 to 1990. Source : COADS data set.

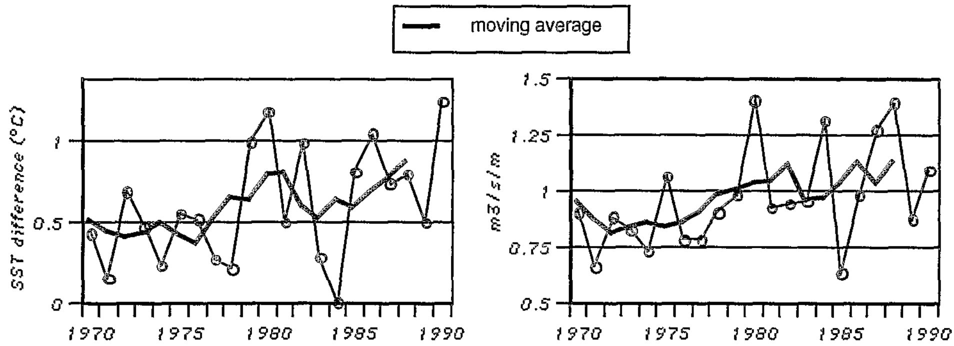

Figure 11 : -SST difference (mean value from January through March) between an offsore and a coastal area off Cote d'Ivoire (see fig. 6 for detail). Source : COADS data set.
-mean offshore transport between January and March from 1970 to 1990 off Cote d'Ivoire. Source : COADS data set.

The intensification of the secondary upwelling is also apparent on a decomposition of the observed SST into several components (varying seasonal, non-linear long-term trend, autoregressive and a residual) performed by Mendelssohn and Roy (1994). It should be noted that the intensification of the secondary upwelling occurs on the seasonal component (fig. 12), however the long term trend component of the SST in the area shows a continuous increase of the temperature (fig. 12).

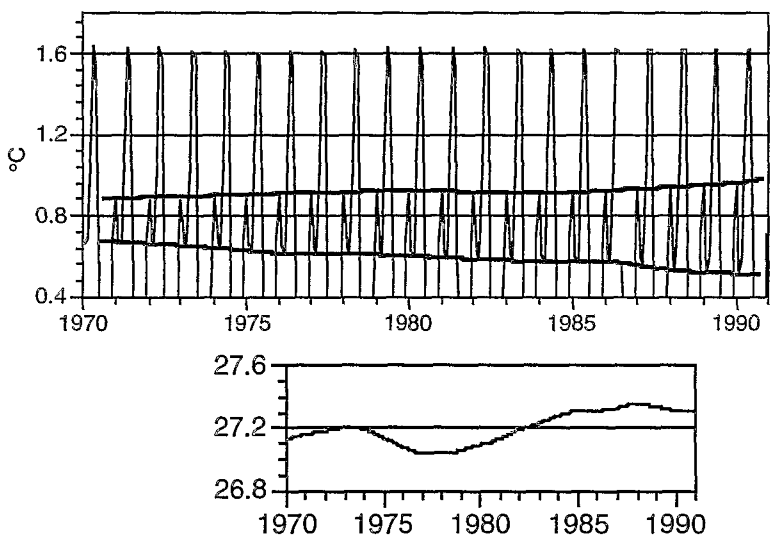

Figure 12 : Seasonnal component (upper) and long term trend (lower) of a decomposition of the SST signal off Western Côte d'Ivoire (from Mendelssohn and Roy, 1994).

4. Summary

The question «what causes the upwellings» has still no clear answer. The magnitude of the wind seems to be higher than one previously thought, specialy in the offshore area; there is also a pronounced seasonal cycle of the wind. However, during the summer upwelling, the relation between the upwelling intensity and the wind is in the wrong direction : more upwelling favorable wind gives warmer temperature. The Guinea current is thought to be an important contributor to the upwelling process; the interaction between the coastal topography and the coastal currents may also be an important factor. Continuous time series of current are still lacking to test these hypotheses. The remote forcing hypothesis is well documented and is supported by some numerical models and data analyses but the offshore scale of the thermocline oscillations along the coast suggests that local processes have to be considered. It should be noted that there is no correspondence between the onset of the equatorial upwelling and the onset of the coastal upwelling. Due to the equatorial location of the area a combination of both remote and local forcing is more likely to be at the origin of the upwelling process.

The dynamic of the winter upwelling is not well documented. There is an intensification of the eastward flow of the Guinea current in winter which may contribute to the upward movement of the thermocline. Both surface and subsurface data suggest that there is a significant correlation between interannual fluctuations of the wind and the intensity of the upwelling.

The long term environmental changes in the Cote d'Ivoire-Ghana ecosystems are well documented. Binet and Servain (1993) and Binet (this volume) presented a review of the changes that occurred in the coastal environment since the early sixties. However, a reanalysis of the wind data suggests that the intensification of the wind is weaker than previously thought. Changes in the current may have occurred but time series of surface and subsurface current data are lacking to investigate these changes. During the secondary upwelling, wind and SST data show that an intensification of the upwelling process had occurred since the mid seventies. Although the amplitude of the changes in the physical characteristics of the ecosystem remains quite small, the ecological impact of the intensification of the winter upwelling may be very important and may have induce the changes observed in the sardinella fishery during the last decade.

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