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Coastal upwelling events in front of the Ivory Coast during the FOCAL program

Surface winds
Temperature
Currents
Upwelling
Ivory Coast
Vents de surface
Température
Courants
Remontée d'eaux froides
Côte d'Ivoire

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ABSTRACT

In situ wind, current and temperature measurements carried out on and off the continental shelf of the Ivory Coast during the FOCAL (Français Océan Climat de la zone équatoriale AtLantique) program in 1983 and 1984, are described. The thermal structure at the coast mainly depends on both the intensity and the meridional extension of the Guinea current. In 1983, except for mid-January and mid-November, the thermocline is closed to the surface due to the yearlong presence of the Guinea current both onshore and offshore. In 1984, on the contrary, from the end of January through at least mid-May, the Guinea current is present on the shelf but is weak and narrow south of the shelf break; the thermocline at that time, compared to 1983, is some 15 m deeper. The eastward flow on the shelf alone is therefore unable to maintain a shallow thermocline. In summer (July-August) 1983 and 1984, the Guinea current is present on and offshore. Substantial changes are not, however, observed in the speed of the Guinea current at the coast in spring-summer, in comparison with the autumn-winter season, which could justify the larger amplitude of the surface cooling in summer than in winter. The upward displacement of the thermocline in spring-summer is amplified by the increase of the wind velocity component parallel to the coast. The mean upwelling rate induced by local wind forcing at the coast, in summer, through a simple linear model, is 1.12 m/day in 1983 and 0.83 m/day in 1984. In autumn-winter the secondary temperature minimum, which appears mainly subsurface, is linked to the second intensification of the Guinea current, both on and offshore. Horizontal advection does not explain the main surface cooling observed on the shelf.

Oceanol. Acta, 1988, **11**, 2, 125-138.

RÉSUMÉ

Étude des refroidissements saisonniers des eaux du plateau continental de Côte d'Ivoire pendant le programme FOCAL

Parallèlement aux observations hauturières effectuées dans le cadre du programme FOCAL (Français Océan Climat de la zone équatoriale AtLantique) en 1983 et 1984, il a été développé un programme côtier qui avait pour objet l'étude des refroidissements saisonniers qui affectent les eaux du plateau continental de la Côte d'Ivoire. Les mesures effectuées au-dessus et au large du plateau continental permettent d'affirmer que la variabilité du champ thermique à la côte est étroitement liée à l'intensité et à l'extension en latitude du courant de Guinée. En 1983, les observations montrent que la thermocline est proche de la surface toute l'année, conséquence d'une présence quasi-permanente du courant de Guinée sur le plateau, mais surtout au large de ce plateau continental. De janvier à mi-mai 1984, le courant de Guinée est présent sur le plateau, mais quasi-inexistant au large, surtout en avril-mai, et la thermocline se trouve, par rapport à la situation observée en 1983, à une immersion supérieure d'une quinzaine de mètres environ; le courant de Guinée, circonscrit uniquement au plateau continental, ne peut donc pas assurer seul un important déplacement vertical ascendant de la thermocline. En été (1983 et 1984), le courant de Guinée est à nouveau présent au large, et la thermocline se retrouve près de la surface, à la côte. Toutefois, par rapport à la situation observée en automne-hiver, aucun changement important, tant

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dans l'intensité que dans l'extension méridienne du courant de Guinée, ne permet de justifier la présence d'un minimum minimorum de température de surface à la côte en été. L'amplification du refroidissement de surface est dû à la rotation du vent du secteur sud-ouest au secteur ouest, qui a pour effet d'accroître la composante de la vitesse du vent dans une direction parallèle à la côte et, en aval, d'intensifier l'effet d'Ekman. Le déplacement vertical moyen de la thermocline, à la côte durant l'été boréal, déduit d'un modèle simple de circulation forcé par le vent local, est de 1,12 m/jour en 1983 et de 0,83 m/jour en 1984. Le minimum thermique secondaire, qui apparaît principalement en subsurface, en automne-hiver boréal, est lié à la seconde intensification du courant de Guinée, sur et au large du plateau continental. L'advection horizontale d'eaux froides, en surface, ne permet pas d'expliquer les forts refroidissements observés à la côte.

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INTRODUCTION

Surface and subsurface temperature variations observed along the continental shelf of the Ivory Coast are dominated by a strong semi-annual signal (Morlière, 1970). Coolings are observed during the boreal winter and summer; the main one occurs from May through September. They are characterized by a coastally trapped cold water tongue which, at 4°W during the summer, can extended from the coast (5°17'N) to the equator (Voituriez, 1981). Several physical mechanisms have been proposed to explain the summer cooling: *a*) Ekman divergence at the coast (Ingham, 1970; Verstraete, 1970); and *b*) geostrophic adjustment of the thermal field to the increase of both the Guinea current and climatic coastal wind (Ingham, 1970). The relative weakness and lack of substantial seasonal variability of the local winds recorded at Abidjan Airport led, however, to consideration of wind forcing over the whole Atlantic equatorial basin as an explanation of the onset of the coastal upwelling (*see* Cane, Sarachik, 1983 for a detailed review). An impulsive equatorial wind forcing produces an equatorial Kelvin wave which, at the eastern boundary, reflects as a poleward coastally trapped Kelvin wave. Picaut (1983), from coastal sea surface temperature (SST), computed a mean westward phase speed between the coastal stations located in front of Ghana and Ivory Coast. However there are some inconsistencies: 1) the phase speed computed along the coast is different from one year to the other; 2) an eastward phase speed appears to the east of Cape Three Points; and 3) no obvious phase lag is observed alongshore between the coastal stations in front of Ivory Coast (*see* Fig. 8 *in* Picaut, 1983). Houghton (1983) showed that the vertical displacement of the thermocline in the Gulf of Guinea is maximum both at the equator and along the northwestern boundary, west of 2°E. Houghton and Colin (1986) found that: 1) the time-lag observed between the vertical displacement of the isotherms at the equator (4°W) and at the coast (5°N-4°W) is different in 1983 and 1984; 2) the length scale of the sloping thermocline greatly exceeds the local Rossby radius of deformation and is in agreement with the latitudinal extension of the Guinea current; and 3) within the layers both above and below the thermostad (125-200 m), the amplitude and phase of the upwelling signal appear to be independent of depth. Cane and Patton (1984), using a linear numerical mode forced by a realistic wind forcing, found: 1) no phase variation of the cooling along the northwestern boundary of the Gulf located at 5°N; and 2) a small phase difference between the equatorial and coastal coolings. The non-linear multi-level model of Philander (1979) and Philander and Pacanowski (1981), showed an adjustment of the coastal thermal structure to the increase of both the Guinea current and the climatic cross-equatorial winds in the Gulf of Guinea. However, the amplitude of the simulated cooling is smaller than the amplitude of the summer cooling observed at the coast. In a more recent study, Philander and Pacanowski (1986) pointed out that if the winds along the equator determine the response of the surface equatorial layer in the Gulf of Guinea, they play, however, only a minor role in the seasonal upwelling along the coast near 5°N.

The aim of this study, based on a coherent data set obtained in 1983-1984 on and off the continental shelf of the Ivory Coast during the program Français Océan Climat équatorial AtLantic (Focal) is simply to emphasize the relations which exist locally (both on and offshore), on a seasonal time scale, between the temperature and both currents and wind. The major findings are that: 1) the current distribution observed on the shelf alone is insufficient to infer the vertical displacement of the isotherms – the distribution of the Guinea current off the shelf has to be considered; 2) the horizontal advection of surface cold waters from the south, east or west is not important; 3) winter cooling is related to the second increase of the Guinea current (GC) in autumn and winter, on and offshore; 4) summer cooling is associated with the increase of both the Guinea current and the zonal component of the wind at the coast.

This paper is organized as follows: the data set is presented; the temperature fluctuations are then described; a general description is given of the seasonal variability of both the currents and the wind as observed onshore and offshore; their relations with the temperature variability are emphasized; summary and conclusions follow.

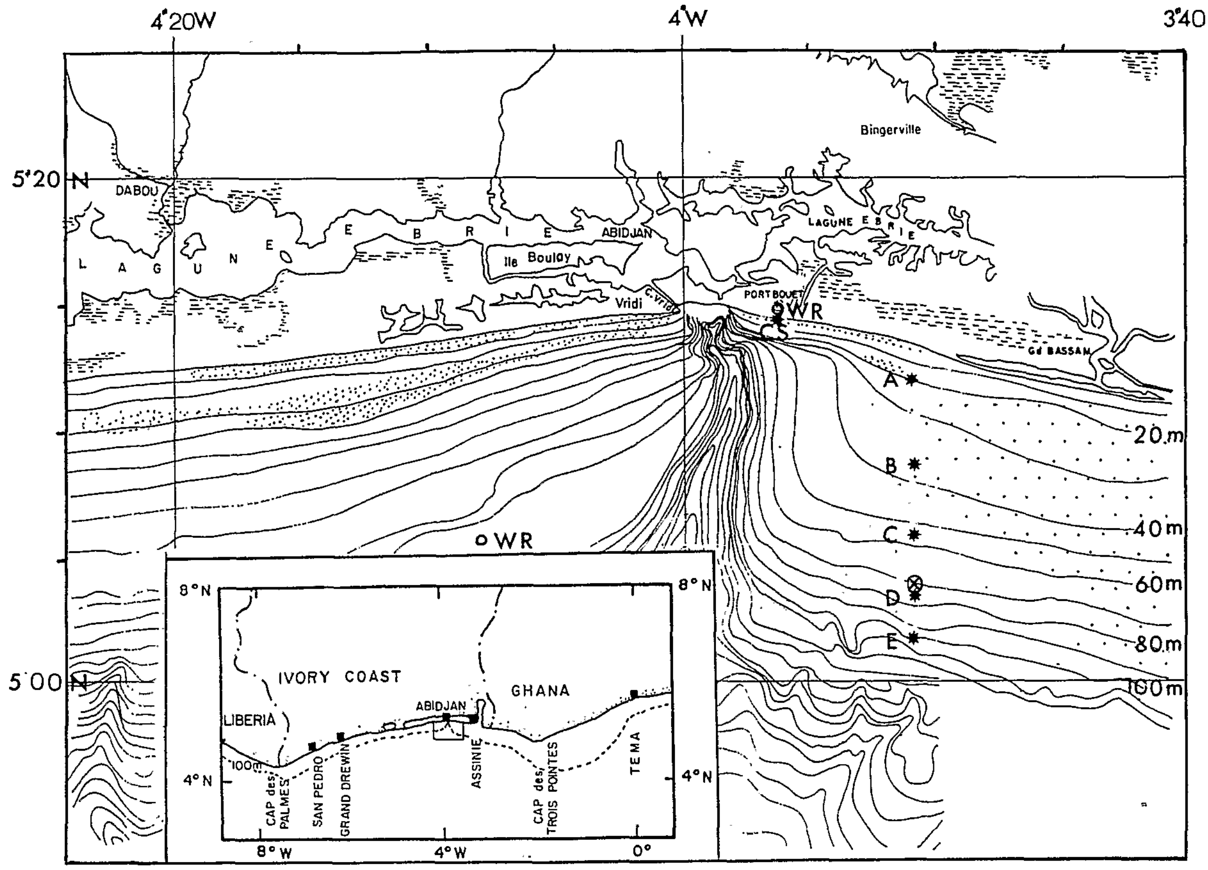

Figure 1

Map of the bathymetry of the continental shelf of Ivory Coast in front of Abidjan. Superimposed are the geographical positions of the:
- *wind recorders at the coast (WR 1) and on the shelf (WR 2);*
- *subsurface mooring (cross in an open circle);*
- *coastal stations along the coast (Tabou, Grand Drewin, Abidjan (CS) and Assinie);*
- *five stations (A, B, C, D, E) visited quasi-weekly at distances of respectively* 2.6, 8.7, 13.9, 18.9 *and* 21.5 *km offshore.*

Carte bathymétrique du plateau continental de Côte d'Ivoire en face d'Abidjan. Sont indiquées la(es) position(s) :
- des enregistreurs de vent à la côte (WR 1) et sur le plateau continental (WR 2);
- du mouillage de subsurface (croix entourée d'un cercle);
- des stations côtières (Tabou, Grand Drewin, Abidjan et Assinie);
- des cinq stations situées sur le plateau continental et occupées en moyenne une fois par semaine; ces stations sont localisées respectivement à 2,6, 8,7, 13,9, 18,9 et 21,5 km de la côte.

DATA

Different data sets are used in this study (*see* Fig. 1 for the geographical positions of the stations):

- Quasi-weekly temperature and current measurements at points (A, B, C, D, E) located respectively at distances of 2.6, 8.7, 13.9, 18.5 and 21.5 km offshore, along longitude 3°51′W and at bottom depths of 20, 35, 55, 75 and 100 m respectively, from 23 December 1982 through 2 December 1983 and from 25 January through 17 August 1984; there are gaps in the records from 16 September to 7 October 1983 and from 21 May to 22 June 1984. Temperature and current measurements were made with an Aanderaa current-meter (RCM 4) every 5 meters from the surface to 15 m depth, every 10 m from 15 to 35 m depth and every 20 m from 35 to 95 m depth. At each station, the boat was anchored during the measurements. At site E, a hydrological cast (6 bottles every 20 m from the surface to the bottom) was systematically carried out in order to calibrate the temperature measurements from the Aanderaa current-meter and to obtain a description of the salinity offshore. The salinity values were obtained at the lab using a Neil Brown salinometer.
- Hourly temperature values from a subsurface mooring deployed between sites C and D at a bottom depth of 70 m from 7 February through 17 September 1983. Five Aanderaa temperature sensors were fixed on the mooring line at 8, 18, 30, 45 and 60 m depths;
- Daily SST at four coastal points located along the shelf (Assinie, Abidjan, Grand Drewin and San Pedro) from 1 January 1983 through 31 December 1983. At the coastal station of Abidjan (CS), SST and sea surface salinity values are available from 1 January 1983 through 31 December 1984.
- Wind measurements from a wind recorder (WR 1) placed at the top of the lighthouse of Abidjan (27 m above sea level) from 27 February through 16 August 1983 and from 25 April through 31 December 1984. Wind measurements from a recorder (WR 2) fixed at the top of a surface buoy (2.5 m above sea level) moored at 16.3 km southwest of Abidjan by the Veritas company (Norway) were available from 1 October 1982 through 15 June 1983.

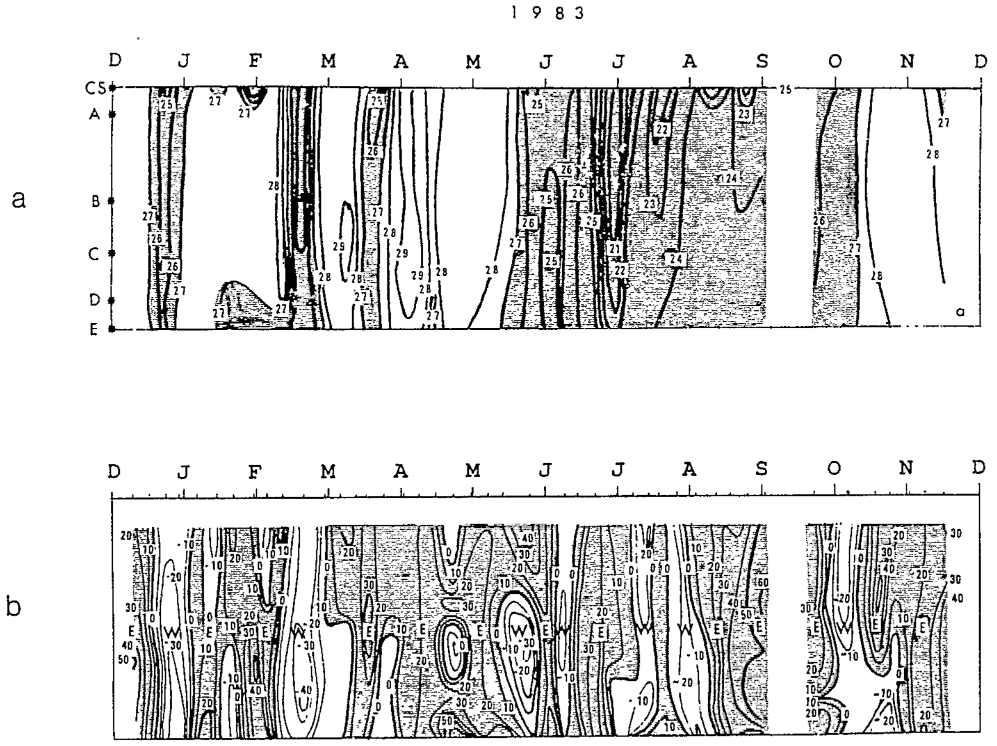

Figure 2

Distributions of the sea surface temperature (SST): a) and zonal component of the current velocity; b) as a function of latitude (sites A, B, C, D and E) from 23 December 1982 through 2 December 1983. The gap in the record occurs from 16 September to 7 October; SST at CS has been included in the horizontal distribution (shaded areas correspond to temperature less than 27°C and to eastward flows; stick marks on top of lower panel indicate the date of measurements; first letters of the month correspond to day 15).

Distributions horizontales (points A, B, C, D et E) : *a*) de la température de surface de la mer (SST); et *b*) de la composante zonale de la vitesse du courant du 23 décembre 1982 au 2 décembre 1983 (il n'y a pas eu de sorties à la mer du 16 septembre au 7 octobre; les valeurs de la SST à la côte (CS) ont été incluses dans le tracé de la température; les traits verticaux fins situés dans la partie supérieure du panneau inférieur correspondent aux dates des mesures; la position des premières lettres du mois indique le 15ᵉ jour de ce mois; les parties ombragées se réfèrent respectivement aux plages de température inférieures à 27°C et de courant est).

TEMPERATURE

Seasonal variability

Surface coolings are present on the shelf from 23 December 1982 through 2 December 1983 (Fig. 2*a*). In 1983, relative SST minima (T<27°C) are observed from the beginning of January through mid-April and absolute SST minima (T<25°C) from the end of May through mid-October. These two periods are often referred to as the semi-annual and annual signals respectively. The SST distribution exhibits lower SST at the shore than offshore, except in mid-June; the SST minimum is observed at the shelf break. Along the coast (Fig. 3), SST starts to decrease in mid-May and to increase in mid-September at all stations. Differences appear at San Pedro in comparison with the other coastal stations: 1) SST does not increase in March-April; and 2) the duration of the surface cooling, in summer, is longer. These discrepancies, as qualitatively pointed out by Morlière and Rebert (1972), can be related to cape effects. The depth of the isotherms at site E (Fig. 1) also exhibits seasonal fluctuations (Fig. 4*a*); the isotherms are deep in mid-January, March-April, at the end of both May and August and in mid-November. On the other hand, the isotherms are shallow in February-March, June-July and September. The daily mean temperature values obtained from the subsurface mooring located some two nautical miles northward of site E (Fig. 1) show similar features (Fig. 5). Subsurface, the vertical gradients are weak in mid-February (only 5°C decrease between 8 and 60 m depth) and mid-July (only 3°C between the same levels); large temperature differences (4.5°C and 5°C) are, however, [illegible]served during these periods between the surface ([illegible] D) and 8 and 18 m depth respectively. On

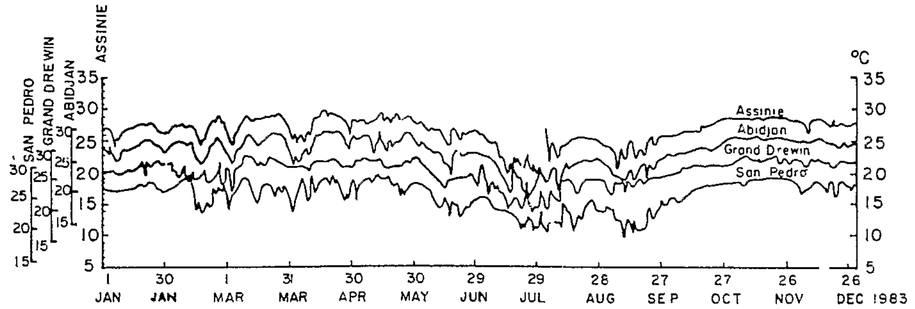

Figure 3

SST distributions at Tabou, Grand Drewin, Abidjan (CS) and Assinie from 1 *January through* 31 *December* 1983.

Distributions de la SST à Tabou, Grand Drewin, Abidjan et Assinie du 1ᵉʳ janvier au 31 décembre 1983.

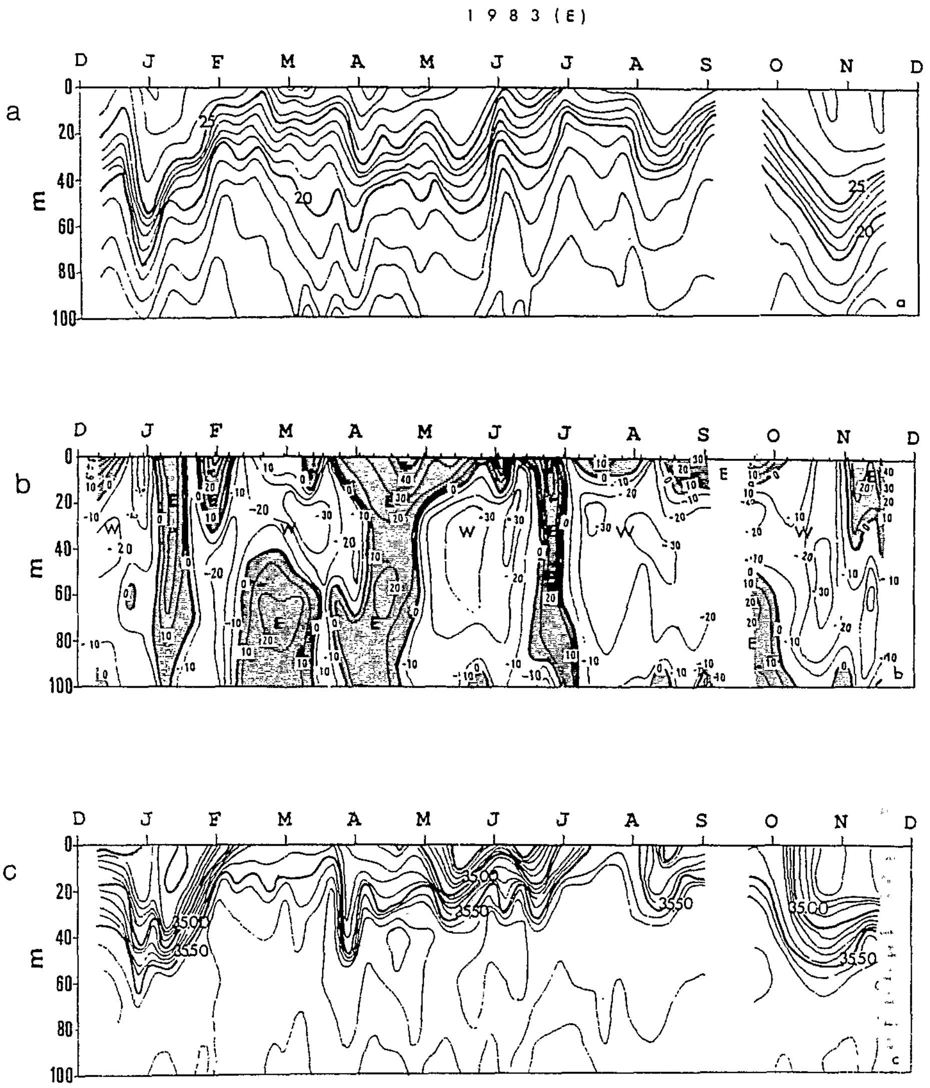

Figure 4

Distributions of the isotherms (a) zonal component of the velocity of the currents (b) and salinity (c) as a function of time and depth at site E (duration identical as in Figure 2; shaded areas correspond to eastward flows; tick marks on top of central panel indicate the date of measurements; first letters of the month correspond to day 15).

Distributions, en fonction du temps et de la profondeur, au point E, de la (*a*) température, (*b*) composante zonale de la vitesse des courants et (*c*) salinité (durée des mesures identiques à celle de la figure 2; la partie ombragée correspond aux périodes de courant est; les traits verticaux fins situés dans la partie supérieure du panneau central indiquent les dates des mesures; la position des premières lettres du mois se réfère au 15ᵉ jour de ce mois).

the other hand, surface (0-18 m depth) homogeneous layers appear in mid-April and at the end of August. This is in agreement with the AXBT profiles obtained off the shelf break by Houghton and Colin (1986) during 1983.

Interannual variability

The main features described in summer 1983 are observed in 1984 both at the surface (Fig. 6 *a*) and at depth (Fig. 7 *a*): a temperature minimum occurs at the surface in July-August and a temperature maximum in April-May. A relative SST minimum appears in January at the coast (Fig. 8 *a*). The two-year observations exhibit, however large differences both at and below the surface. At the surface, the mean SST is higher by around 1.5°C in 1984 than in 1983 from mid-April through the end of June (Fig. 8 *a*). High SST values have been also reported at that time in the northeastern part of the Gulf of Guinea (Piton, 1985) and at the equator (Colin *et al.*, 1986). In July, if SST is roughly the same at the coast for both years, the southward extension of the cold waters on the shelf is however less in 1984 than in 1983 (Fig. 6 *a*, 2 *a*). Subsurface (Fig. 4 *a*, 7 *a*), the depth of the 25°C (D 25) and 20°C (D 20) isotherms are, from mid-February to mid-March, respectively 25 and 45 m deeper in 1984 than in 1983. Interannual variability also affects the distribution of salinity, particularly at the surface (Fig. 8 *b*); contrary to the temperature, the main differences now occur during the second part of the year. The very low salinity values observed at that time obviously reflect the strong influence of run-off from the Abidjan lagoon located nearby (Fig. 1).

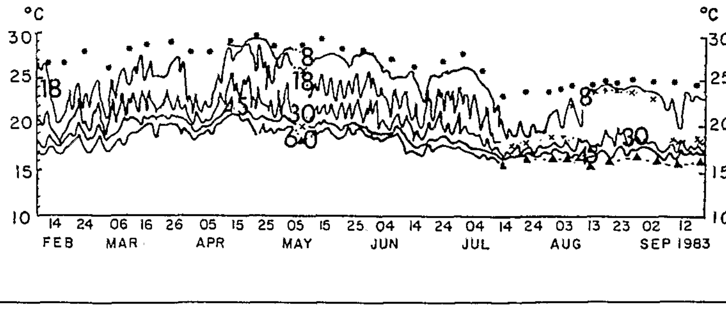

Figure 5

Temperature distributions at 8, 18, 30, 45 *and* 60 *m depth (subsurface mooring) from* 8 *February through* 16 *September* 1983. *Stars, crosses and triangles represent respectively temperature values at* 0, 20 *and* 60 *m depth at site* D.

Distributions en fonction du temps, de la température aux immersions 8, 18, 30, 45 et 60 m (mouillage de subsurface), du 8 février au 16 septembre 1983. Les étoiles, croix et triangles correspondent aux valeurs de la température en surface et aux immersions 20 et 60 m au point D.

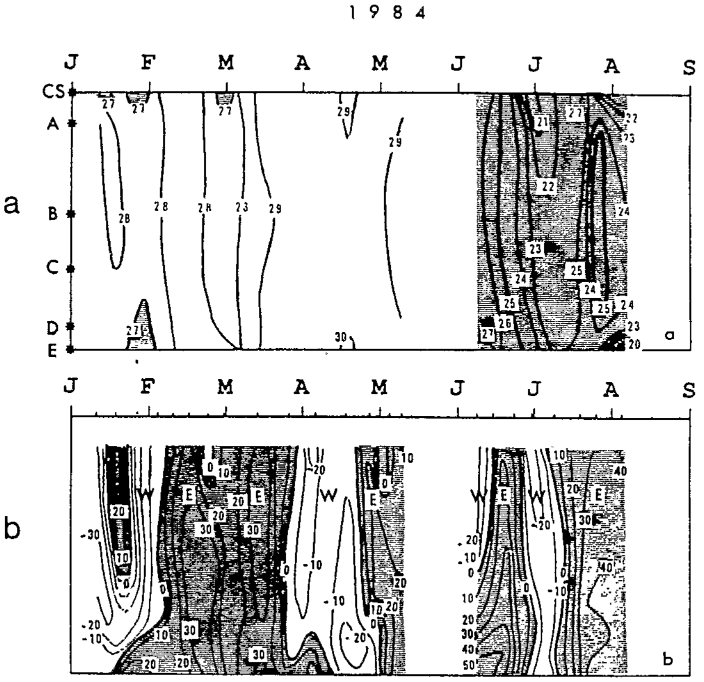

Figure 6

Distributions of SST: a) zonal component of the current velocity; b) as a function of latitude (sites A, B, C, D and E) and time (25 January through 16 August 1984). SST at CS have been included; the gap in the record occurs from 21 May to 26 June (shaded areas correspond to temperature less than 27°C and eastward flows; stick marks on top of the month indicate the date of measurements; first letters of the month correspond to day 15).

Distributions horizontales (points A, B, C, D et E) de la (*a*) SST, et (*b*) de la composante zonale de la vitesse des courants du 25 janvier au 16 août 1984 (il n'y a pas eu de sorties à la mer du 21 mai au 26 juin; les valeurs de la SST à la côte (CS) ont été incluses dans le tracé de la température; les traits verticaux fins situés dans la partie supérieure du panneau inférieur correspondent aux dates des mesures; la position des premières lettres du mois indique le 15ᵉ jour de ce mois; les parties ombragées se réfèrent respectivement aux périodes de température inférieures à 27°C et de courant est).

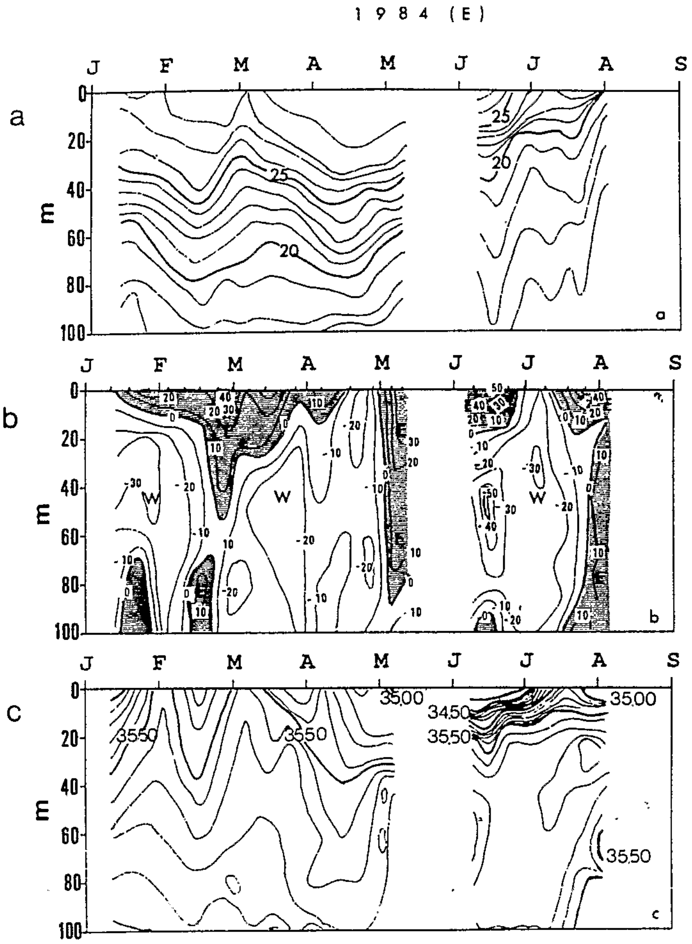

Figure 7

Distributions of the isotherms (a) zonal component of the velocity of the currents (b) and salinity (c) at site E as a function of depth and time (same duration as in Figure 6; shaded areas correspond to eastward current; tick marks on top of central panel indicate the date of measurements; first letters of the month correspond to day 15).

Distributions, en fonction du temps et de la profondeur, (*a*) de la SST, (*b*) de la composante zonale de la vitesse des courants et (*c*) de la salinité au point E (durée des mesures identique à celle de la figure 6; la partie ombragée correspond aux périodes de courant est; les traits verticaux fins situés dans la partie supérieure du panneau central indiquent les dates des mesures; la position des premières lettres du mois se réfère au 15ᵉ jour de ce mois).

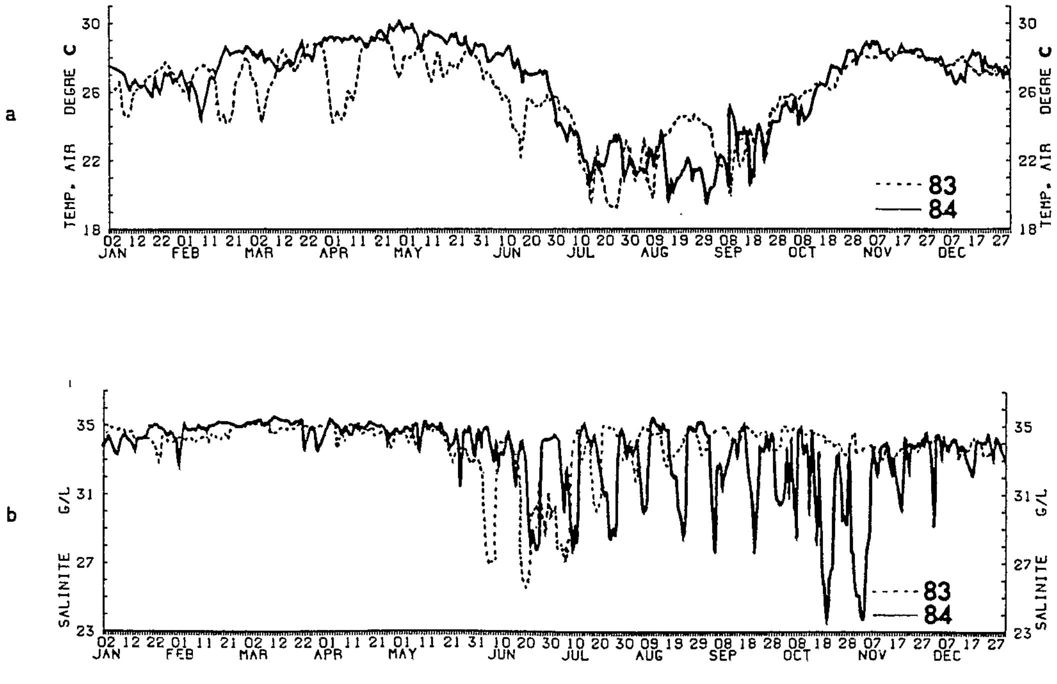

Figure 8

SST (a) and sea surface salinity distributions (b) at the coast (CS) in 1983 and 1984.

(*a*) SST et (*b*) salinité de surface à la côte (CS) en 1983 et 1984.

CURRENTS

Longhurst (1962) stated that: 1) the seasonal variability of the Guinea current (GC) is linked to the seasonal variability of both the North Equatorial Countercurrent (NECC) and the Canary Current (CC); and 2) the maximum development of GC occurs during the boreal summer. In addition, he pointed out a tri-monthly period in the reversal of GC in front of the Cape Palmas and Cape Three Points areas. Donguy and Prive (1964) showed reversals in their computed geostrophic surface current off Abidjan in May-June and September-October, 1962. Boisvert (1967) stated that GC appears constant in direction, except from December through February when easterly winds cause the current to reverse. Ingham (1970) showed from a climatic seasonal current data set an increase (35 cm/s) of GC in summer (July-September) from off Cape Palmas to Abidjan (Fig. 1). In winter (January through March) no such increase was observed. Bakun (1978), Richardson and Philander (1987) from monthly mean climatic shipdrift observations (hereafter designated as MMCS) along the coast in front of Ivory Coast, showed a maximum development of GC from May to July (75 cm/s) and a minimum in November; the surface westward current never appears in this climatic data set at 4.30°N (Fig. 9). Lemasson and Rebert (1968) gave a vertical description of the currents on the continental shelf of Ivory Coast in December 1967; they observed at the surface the eastward Guinea current and, below, a current flowing to the west and named thereafter Ivoirian Undercurrent (IU); this current was found at the lower part of the thermocline and associated with a high salinity core. In July 1969, Lemasson and Rebert (1973 *a*) observed a similar current scheme with, however: 1) a higher speed for GC offshore than onshore; and 2) a decrease and a shoaling of the salinity core, still associated with a westward component of the current, from east to west, along the coast. The presence of a westward current at the surface along the coast, as pointed out earlier by Longhurst (1962), could therefore correspond to the surfacing of IU and not to the reversal of GC which would be, in that case, displaced seaward,

Ingham (1970) explained the north-south sloping of the thermocline along the continental shelf of the northwestern Gulf of Guinea in summer by the geostrophic adjustment of the thermal structure to the increase; the observations were, however, scarce and random both in time and space. Direct measurements carried out onshore and offshore will permit comparison, on a seasonal time scale, of temperature with current fluctuations.

Observations

Figures 2 *b* and 6 *b* show the surface distributions of the zonal component of the currents as a function of time and latitude at sites A, B, C, D and E. In 1983, a large high-frequency variability is observed which can be attributed in part to the large amplitude oscillations previously observed at the same location by Picaut and Verstraete (1976; 1979). In 1983, maxima eastward flows are preferentially observed on the shelf at the end of summer, autumn and winter and at the shelf break (site E), in spring and at the beginning of summer. In 1984, the surface current distribution exhibits similar behaviour from January through August. These observations are in agreement with the MMCS computed off the continental shelf.

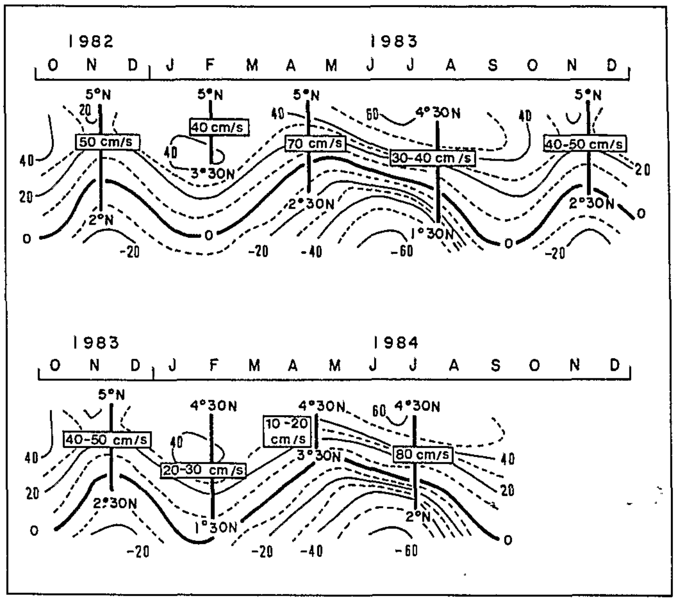

Figure 9

Mean surface eastward velocity and latitudinal extension of the Guinea current during the FOCAL cruises in 1982 (*XI*/17-20), 1983 (*II*/15-19; *IV*/25-29; *VIII*/2-6; *XI*/21-*XII*/6) *and* 1984 (*II*/11-15; *V*/1-3; *VII*/17-21) *from direct current measurement north of the equator. Superimposed are the monthly mean shipdrift eastward (positive) velocities (cm/s) from* 4°30 *N to the equator (after Richardson, Philander,* 1987).

Composantes est moyennes et extensions méridiennes associées des courants observés au nord de l'équateur en novembre (17-20) 1982, février (15-19), avril (25-29), août (2-6), novembre (21)-décembre (6) 1983 et février (11-15), mai (1-3) et juillet (17-21) 1984. Les isotachs déduits des dérives mensuelles moyennes des navires sont en surimpression (d'après Richardson, Philander, 1987).

The surface eastward (westward) component of the flow, on the shelf, is associated with a southward (northward) component (Fig. 10).

The vertical distribution versus time of the zonal component of the currents (Fig. 4 *b*, 7 *b*) at site E reproduces the gross features found by Lemasson and Rebert (1968) on the shelf: eastward flow at the surface and westward flow below (the thickness of the Ekman layer varies on the shelf from 13 to 22 m using a common value for the coefficient of the vertical eddy viscosity in the range 10-30 cm^2/s). Compared to this schematic vertical current distribution, there are, however, periods of time during which: 1) the current system is still baroclinic but with the westward flow at the surface and the eastward flow underneath; this occurs in March and October 1983; and 2) the current is barotropic either eastward (end of January, April-May, July, end of November 1983 and March 1984) or westward (beginning of January, June, August, November, 1983 and May, July 1984). Maxima westward flow are observed every 2 to 3 months; this seems to confirm the previous observations of Longhurst (1962) off Cape Palmas and Cape Three Points.

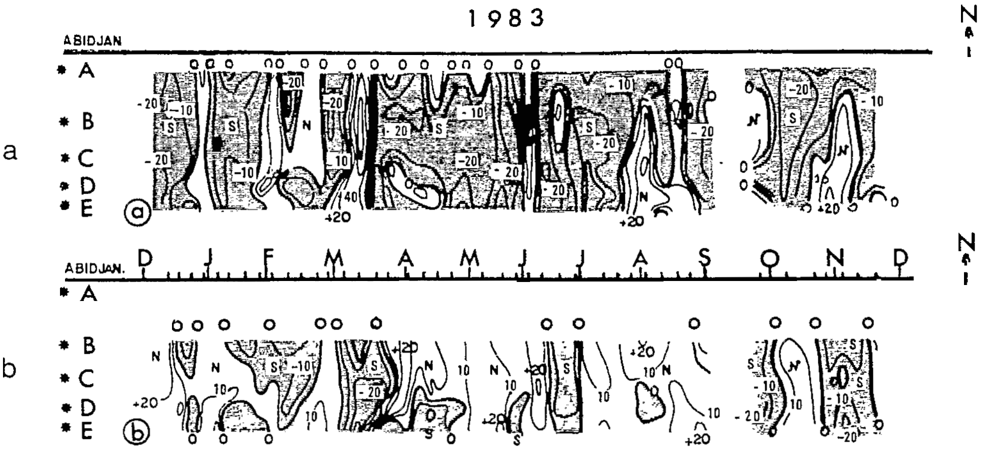

Figure 10

Horizontal distributions of the meridional component of the velocity of the current at the surface a) and at 35 m depth b) from 23 December 1982 through 2 December 1983. For b) only current measurements at sites B, C, D, and E have been used (shaded areas correspond to southward flows; tick marks on top of lower panel indicate the date of measurements; first letters of the month correspond to day 15).

Distributions de la composante méridienne de la vitesse du courant : (*a*) à la surface et (*b*) à l'immersion 35 m du 23 décembre 1982 au 2 décembre 1983. Pour le cas (*b*), seules les mesures aux points B, C, D et E ont été prises en considération (la partie ombragée correspond à la composante sud du courant; les traits verticaux fins situés dans la partie supérieure du panneau inférieur indiquent la date des mesures; la position des premières lettres du mois se réfère au 15ᵉ jour de ce mois).

Relation between the zonal component of the current velocity and the temperature

On the shelf

SST and surface current distributions (Fig. 2,6) are not related in a simple manner. If SST minima follow, by one to two weeks on average, maxima of eastward flow (February, May-June, July, beginning of September 1983 and June, August 1984) there are periods of time during which: 1) SST minima are associated with weak eastward or westward flows (beginning of both March and August 1983, mid-July 1984; and 2) the lowest SST values are not associated with the highest eastward velocities (beginning of both September and November 1983, March 1984).

As pointed out for the surface, the depth of the thermocline is not simply related both to the strength and the vertical extension of the Guinea current; if shoalings of the isotherms occur with the increases of the eastward flow (end of January, mid-February, beginning of May and July, end of November 1983 and beginning of July, mid-August 1984), there are, however, periods during which: 1) maxima vertical extension of GC are not related to maxima tilt of the isotherms (April-May 1983 and March 1984); and 2) minima depths of the thermocline are associated with strong westward flows (February-March, from June to September 1983, July 1984).

In summary, temperature fluctuations observed on the continental shelf of Ivory Coast cannot be easily inferred alone both from the surface and vertical distributions of the currents on the shelf. Larger space scales of these currents (larger than the 69 km internal Rossby radius of deformation) have to be considered.

Off the shelf

The FOCAL current sections (Henin *et al.*, 1986) carried out along 4°W to the south of 5°N exhibit interesting features (Fig. 9). In 1983, the Guinea current is present and well developed in February, April-May, August and November-December 1983; velocity maxima are observed in spring (70 cm/s) and autumn (40-50 cm/s) and are associated with a latitudinal extension of GC from 5°N to 2°30 N; relative maxima of eastward flows are observed in February (Colin, 1983) and August; the flow in August extends from 4°30 N to 1°30 N. In 1984, GC is weak in February, absent in May but very strong in July during which velocity values up to 80 cm/s have been recorded between 4°30 N and 2°N.

Compared to the eastward component of the MMCS, the agreement is good for February and August 1983, May 1984. In November 1982, April and November 1983, July 1984, the zonal component of GC is larger. The opposite is observed in February 1984. The latitudinal extension of GC, on the contrary agrees well with that of the MMCS in November 1982 and 1983, February and May 1984. February 1983 and February through May 1984 are the periods which correspond both to a decrease and a southward position of the maximum of the wind curl at 4°W (Tourre, Chavy, 1987). According to Arnault (1987), the differences in velocity between the observed and the geostrophic currents, off the continental shelf, correspond to the Eklan drift.

In April-May 1983, GC is present on and offshore with a mean eastward component of 40 cm/s on the shelf and 50-60 cm/s off the shelf. Associated with this strong eastward current, the depth of the thermocline decreases at 4°W by 36 m between 3°30 N and 5°N. The corresponding dynamic height (DH) distribution shows an abrupt increase of DH (12 dyn. cm within 1°30) between the coast and 3°30 N along 4°W (Fig. 11 *a*). The same feature appears between 5°N and 3°N along 1°E and between 3°N and 2°N along 6°E. At 4°W, the zonal component of the geostrophic current at the surface associated with this meridional slope is u = 54 cm/s (Table) which is lower offshore but higher on the continental shelf than the observed eastward flows. For a wind stress value of 0.25 dyne/cm² at 5°N and using a mean coefficient in the range 10-30 cm^2/s for the vertical eddy viscosity, the Ekman drift varies from 25 to 15 cm/s. Geostrophic and observed eastward velocities are of the same order of magnitude in February 1983 and from February through May 1984, periods which correspond to the relaxation period of the wind (Colin, Garzoli, 1987; Tourre, Chavy, 1987). The observed mean Guinea current velocity on the shelf would only lead to a 5.5 m upward displacement of the thermocline over the 30 km width of the continental shelf which, alone, is unable to explain the important SST decrease observed on the shelf at the end of May 1983.

In August 1983, the meridional dynamic height distribution along 4°W shows a monotonic increase of DH from the coast to the equator (Fig. 11 *b*); the mean geostrophic velocity induced is 22 cm/s (Table).

The corresponding vertical displacement of the thermocline at the shelf break is only 29 m (less than that observed in April 1983), while SST presents an absolute minimum at that time on the shelf. Mid-July 1984, GC is weak onshore but well developed offshore; the maximum of the eastward flow is centered some 120 nautical miles off the coast (Fig. 9) and is associated with a meridional slope of the thermocline, large enough to place the thermocline close to the surface only a few nautical miles offshore. Starting in August, the MMCS indicate a decrease of GC at 4°30 N; on the shelf, the current is now preferentially westward both at and below the surface (Fig. 4 *b*). This is in agreement with the high salinity values measured at that time on the shelf (Fig. 4 *c*).

At the end of November 1982 and 1983, the eastward component of GC is again very high; values of 50 cm/s and 40-50 cm/s are observed. GC extends from the coast to 2°N and 2°30 S respectively (Fig. 9) and SST starts to decrease at the coast (Fig. 8 and 15). Subsurface, the core of the westward current deepens.

In February 1983 and 1984, compared to the situations observed in November 1982 and November 1983, the eastward component of GC is weaker. At that time, GC is stronger in 1983 than in 1984 (Fig. 9 and Tab.) and the thermocline at the shelf break remains closer to the surface in 1983 (10 m) than in 1984 (35 m). The MMCS values at 4°30 N exhibit a secondary eastward flow maximum, as observed on the shelf, in December-January, which corresponds to the secondary temperature minimum period at the coast (Fig. 8 *a*). In March-April 1983 and from February through May 1984, SST increases in average while the thermocline deepens on the shelf (Fig. 4 *a* and 7 *a*). The current, as observed in September-October, is westward (Fig. 4 *b* and 7 *b*). High salinity values are associated with the westward flow (Fig. 4 *c* and 7 *c*). GC is particularly weak and narrow in April-May 1984 (Fig. 9 and Tab.) due to the permanence of the relaxation period of the wind over the equatorial zone (Colin, Garzoli, 1987).

Horizontal advection

Surface coastal coolings can also be generated by horizontal advection of cold waters. As we shall see in this sub-section, this process seems negligible. In boreal summer, the potential sources of horizontal advection are:

– equatorial cold waters transported from the southeast area by the South Equatorial Current (SEC) and then advected by GC through the convergence zone located at 2°3°N; Piton and Fusey (1982), Richardson and Reverdin (1986) showed from drifter trajectories that such an exchange of water masses is possible in the Gulf of Guinea. The heat gain of the cold surface waters between the equator and the coast would lead to coastal SST higher than that observed at the equator. The temperature difference between the air and sea surface is positive and increases from the equator to the coast in summer. This is particularly obvious on the coast (Fig. 13 *a*, 14 *a*);

– surface coastal waters upwelled east of Cape Three Points and driven by the coastal westward current when it surfaces; in that case the cold waters have to be associated with high salinity values (Lemasson, Rebert, 1973 *b*). Le Floc'h (1970) found a perfect conti-

Table

Zonal component values (u_g) and latitudinal extension associated to the geostrophic velocity at the surface and north of the equator deduced from the dynamic height distribution (0/500 db) as obtained from the FOCAL seasonal cruises along 4°W.

Valeurs de la composante zonale et extensions méridiennes associées de la vitesse géostrophique de surface déduites des valeurs d'anomalie de hauteur dynamique (0/500 db), obtenues lors de campagnes saisonnières FOCAL.

Cruises	Date	u_g (cm/s)	Latitude extension
FOCAL 1	XI/17-20/1982	28	5°N-3°N
FOCAL 2	II/15-19/1983	37	5°N-3°30 N
FOCAL 3	IV/25-29/1983	54	5°N-3°N
FOCAL 4	VIII/2-6/1983	22	5°N-0°N
FOCAL 5	XI/21-XII/6/1983	29	5°N-3°N
FOCAL 6	II/11-15/1984	25	4°30 N-3°45 N
FOCAL 7	V/1-3/1984	18	5°N-3°N
FOCAL 8	VII/17-21/1984	57	5°N-2°30 N

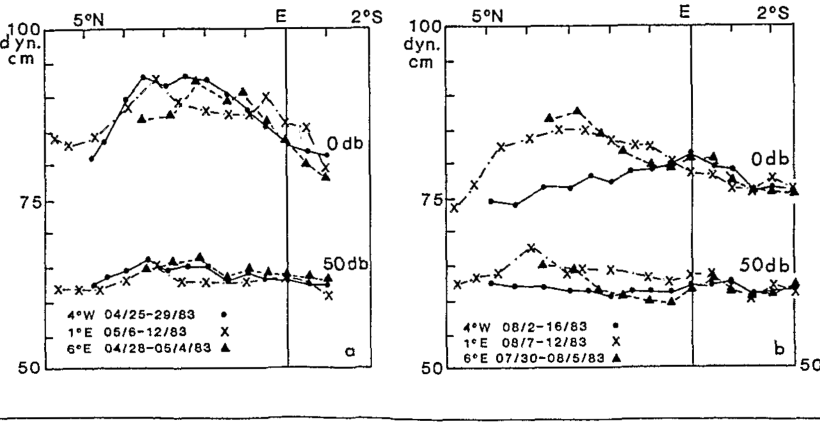

Figure 11

Dynamic height anomaly (dynamic.cm) at 0/500 db and 50/500 db along 4°W, 1°E and 6°E in April-May and August 1983.

Distribution méridienne de l'anomalie de hauteur dynamique en surface et à 50 db, par rapport à 500 db, le long des méridiens 4°W, 1°E et 6°E, en avril-mai et août 1983.

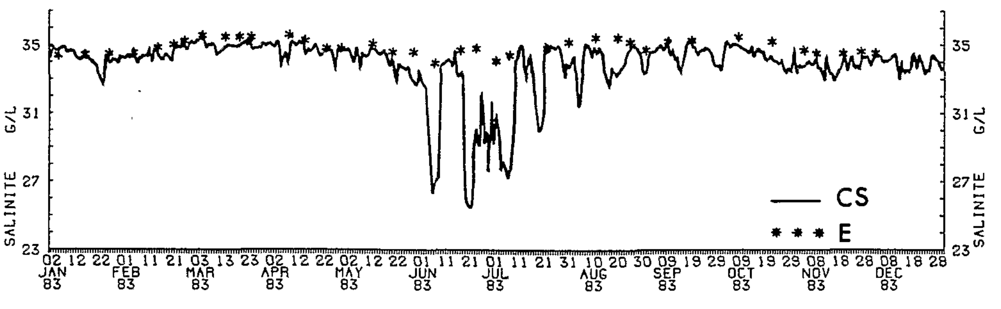

Figure 12

Sea surface salinity distributions at CS and E in 1983 (*same duration as Figure* 2).

Distribution de la salinité de surface aux points CS et E en 1983 (période identique à celle de la Figure 2).

nuity on the surface $\sigma_t = 25.75$ between the high saline waters of both the Equatorial Undercurrent and the subsurface westward current north of the equator. Figures 4, 7, 8 show however that: 1) cold waters are associated at the surface with low salinity content; and 2) cold and less saline waters are observed preferentially when the surface current is eastward, even weak. The cold and saline waters associated with weak westward flows which appear at the beginning of March and mid-August should correspond in these cases to local vertical advection of westward momentum (the westward current is located at the lower part of the thermocline);

– surface cold waters upwelled east of Cape Palmas and driven by the Guinea current. Morlière and Rebert (1972) observed a zonal extension of the coastal cold water upwelled east of Cape Palmas, downstream of the Guinea current. These cold waters are associated with low salinity values at the surface (Fig. 4, 7, 8); Ingham (1970) attributed this fresh and cool water to the maximum run-off (July-August) of the coastal rivers, located west of Ivory Coast, following the west African monsoon. In front of Abidjan, the low surface salinity values observed at that time seem however mainly induced by the run-off from the lagoon (Fig. 12); moreover the positive temperature difference observed between air and sea surface at the coast (Fig. 13 *a*, 14 *a*), would lead to a heat gain of the ocean and therefore to an increase of SST from west to east; Figure 6 shows that the temperature minima remain alongshore of the same order of magnitude.

In summary, horizontal advection from the south, east or west does not seem sufficient to explain the very

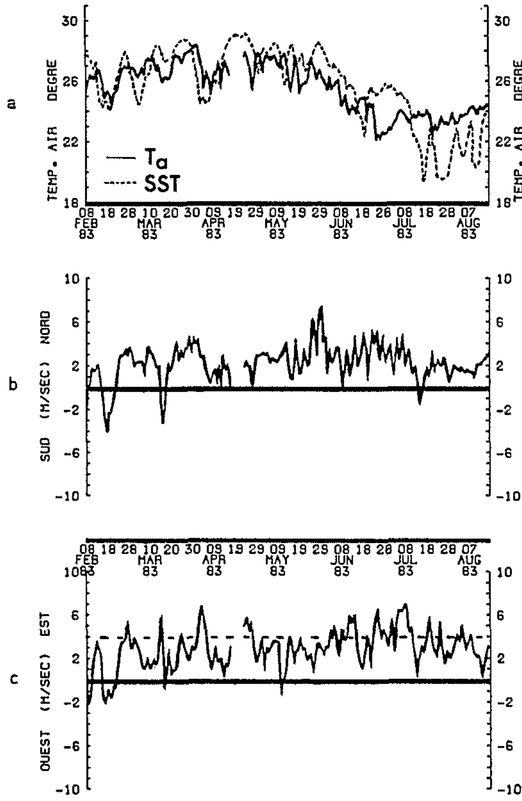

Figure 13

Distributions of the air temperature and SST (*a*), *meridional* (*b*) *and zonal* (*c*) *components of the wind at the top of the lighthouse of Abidjan* (*WR* 1) *from* 8 *February through* 16 *August* 1983 (*the sensors are at* 27 *m above sea level*). *The dashed line represents the value* 4 *m/s.*

Distributions (*a*) de la température de l'air et de la SST et des composantes (*b*) méridienne et (*c*) zonale de la vitesse du vent au sommet du phare (WR 1) d'Abidjan (hauteur 27 m au-dessus du niveau de la mer) du 8 février au 16 août 1983. La ligne en pointillés indique la valeur 4 m/s.

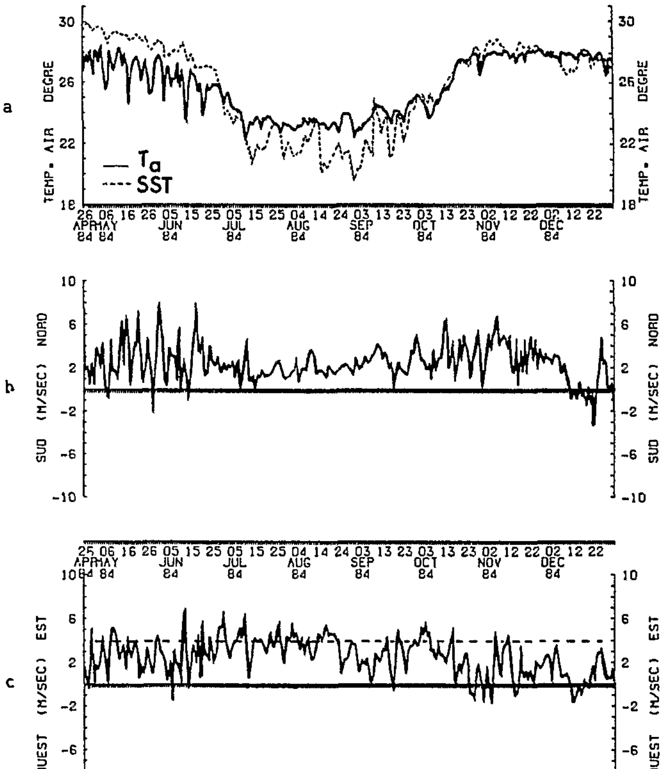

Figure 14

Same as Figure 12 *but from* 26 *April through* 31 *December* 1984.

Identique à la figure 12, mais pour la période allant du 26 avril au 31 décembre 1983. La ligne pointillée indique la valeur 4 m/s.

low SST values observed at the coast in boreal summer. Moreover, the distributions of the east component of the velocity of the Guinea current, as a function of time and latitude (Fig. 9), reveal that in August 1983 and July 1984, GC is maximum offshore while SST reaches its lowest minimum at the coast. Therefore other mechanisms have to be taken into consideration and among them, local wind forcing.

WIND

Verstraete (1970) modelled the summer coastal upwelling in front of Ivory Coast in terms of Ekman divergence; he obtained a mean vertical velocity component of 0.7 m/day. Houghton (1976) found, on the other hand, no apparent correlation between the wind and the temperature fluctuations, in front of Ghana, during summer 1974. Verstraete *et al.* (1979) observed, from mean tri-hourly wind observations obtained from 1966 through 1974 at Abidjan Airport, no obvious seasonal variations both in the north-south and east-west components. In contrast, they reported the presence of a large annual cycle in the meridional component of the historical monthly mean wind data (NOAA) computed at 4°10′N, 4°40′W (southwest of Abidjan) with a maximum in July. The zonal component exhibits however no seasonal signal. Comparing these two wind data sets, two questions arise: 1) is such a dramatic decrease in the wind speed (2-2.5 m/s) possible between 4°10 N and 5°15′N along 4°W?; and 2) are the wind observations at the airport representative of the wind field both at the coast and over the continental shelf? Ingham (1970), from climatic monthly mean wind data found, off the coast, a permanent southwesterly wind with a maximum wind speed in late summer. The wind observations carried out for the first time at the coast during the FOCAL program, will now be discussed.

Observations

The meridional (positive northward) and zonal (positive eastward) components of the wind velocity observed at the coast (Abidjan) are shown in Figures 13 and 14 (central and lower panels); it may be seen that both components are always positive. This is not the case further south, at the equator (4°W), where southeasterly wind has been observed in spring (Colin, Garzoli, 1987).

The wind components exhibit, on a seasonal time scale, interesting features. In 1984 (Fig. 14 *b*, 14 *c*): 1) the meridional component presents two maxima respectively in May-June and October-November while minima, on the other hand, appear respectively at the end of April-beginning of May, from the end of June through the beginning of October and after the end of November; and 2) the zonal component shows a maximum mean value of V = 4 m/s from the beginning of June to mid-August and from mid-September to the beginning of October. During the boreal summer, the direction of the wind is mainly parallel to the coast and therefore favorable to an Ekman-type upwelling. Minima of east-west component appear at the end of October and at the beginning of December. In 1983 (Fig. 13 *b*, 13 *c*), the maximum in the north-south component of the wind velocity is also observed from mid-May through the beginning of July; the east-west component is maximum from the end of June to the end of the record (beginning of August). From 8 February to 1 May, a period which corresponds to the southward position of the Confluence Zone of the trade winds (Hastenrath, Lamb, 1977; Tourre, Chavy, 1987) and to the associated increase of the air pressure over the Sahara, the zonal component of the wind velocity presents relative maxima due to travelling storms.

Relation between wind and temperature

In Figures 13 *a* and 14 *a*, the time variability of the wind components and SST are presented. On a seasonal time scale, the agreement between the temperature and the wind component fluctuations is good: 1) minima SST are observed during the boreal summer when the east-west component is maximum; 2) SST starts to decrease as soon as the zonal component is positive and increases; this occurs at the end of both May 1983 and April 1984. When the wind is southerly, the situation which is observed in October 1984, SST increases. The distributions of the wind components obtained in 1985 at the same place from January 1 until December 31 (not shown here) exhibit the same seasonal fluctuations as observed both in 1983 and 1984. As mentioned before for the climatic monthly mean NOAA data at 4.10°N-4.40°W and the direct wind measurements obtained during FOCAL at 0-4°W, the wind field at the coast also presents seasonal fluctuations in both components (semi-annual and annual respectively for the meridional and zonal components).

Vertical velocity component

Philander and Pacanowski (1986), pointed out that the coastal upwelling observed in boreal summer along the northwestern boundary of the Gulf of Guinea is mainly influenced by changes in both components of the local wind and in the curl of the wind over the Gulf of Guinea. At that time, on the shelf, the zonal component of the wind velocity is maximum.

Our purpose is to infer, through a simple linear model (Yoshida, 1955; Charney, 1955), the rate of the upwelling at the coast due to local wind forcing. Considering a uniform westerly wind blowing parallel to a coast oriented east-west (Fig. 1), the expressions of the horizontal components of the current and for the vertical displacement of the interface identified as the thermocline are, following Gill (1982):

$$v = -(\tau_s/fh_1)\,[1-\exp(-y/r)] \tag{1}$$

$$u = (\tau_s/\rho\, h_1)\,.\,t\,.\exp(-y/r) \tag{2}$$

$$\eta = (c\,\tau_s/g'\,h_1)\,t\,.\exp(-y/r), \tag{3}$$

where:

v, u : meridional and zonal components of the velocity;

η : vertical displacement of the interface;

τ_s : value of the wind stress at the surface;

x, y, z: coordinates respectively positive eastward, southward and downward;
c: SORT $[g' h_1 h_2/(h_1+h_2)]$ speed of long gravity waves;
f: Coriolis parameter (1.26×10^{-6});
g': reduced gravity ($=g\,\Delta\rho/\rho$);
h_1, h_2: thickness respectively of the upper and lower layers;
ρ: density;
y: distance from coast;
r: c/f (internal Rossby radius of deformation);
t: time.

In 1984 (Fig. 7 *a*), the mean depth of the thermocline from the end of January until the end of April is around 55 m (the bottom depth is 100 m) which leads to a mean value of $c=0.79$ m/s, using for $g'=0.0253\,\mathrm{ms}^{-2}$ deduced from the density observations. From the end of June to mid-August 1984, the mean wind velocity and the mean zonal component of the wind velocity are respectively 4.5 and 4 m/s. Following Bunker (1976) and Wu (1980), the corresponding mean wind stress component is 0.23 dyne/cm^2 using a drag coefficient of 0.98×10^{-3} (the wind recorder is at 27 m above the sea level and SST is lower than the air temperature in summer). The upwelling rate deduced from these different quantities at site E is 0.83 m/day; the thermocline takes in that case 66 days to surface. This theoretical value fits well the observed one (60 days in 1984). For 1983, using $h_1=40$ m (Fig. 2 *a*) and the same value for the surface wind stress, we get an upwelling rate at the same point of 1.12 m/day or 36 days for the thermocline to surface; in that particular case, the *t* years, the increasing of SST toward the south, occurs inside the Rossly radius of deformation ($r=69$ km). In January-February 1983, the mean zonal wind stress value is 0.05 dynes/cm^2 ($V_x=2$ m/s) and leads only to a 11 m mean vertical displacement of the thermocline from mid-January through the end of February which is less than half that associated with the Guinea current at that time (21 m between 2°30 N and 5°N). In October-November, the zonal component of the wind stress is weak at the coast and high SST values are observed.

In winter and spring 1983, peaks are observed in the zonal component of the wind velocity (Fig. 13 *c* and 15 *a*) and are associated with SST minima (Fig. 13 *a*). From the relation (3), we can infer during the gusty wind period, an upwelling rate at the end of March 1983, for example. Using a wind stress value of 0.66 dyne/cm^2 (the corresponding zonal wind component is 6.5 m/s and the drag coefficient used is 1.2×10^{-3} because the air temperature and SST are of the same order of magnitude in that case) relation (3) leads to an upwelling rate of 4 m/day; this high value is able to induce the very abrupt decrease of SST at the coast at that time, all the more easily because the depth of the thermocline is small.

Ekman transport

Relation (1) leads to a value of the Ekman transport (τ_s/f) on the continental shelf. Using the same surface wind stress and Coriolis parameter as before, the Ekman transport, if spread over a depth of 20 m, gives a mean offshore current of 9 cm/s. The increase of both the southward (Fig. 10 *a*) and eastward components in July on the shelf could be partly due to this effect. At 35 m depth, the meridional component is northward in agreement with the Ekman theory (Fig. 10 *b*). The real observed southward component of the current at the surface (v = 10-20 cm/s), at that time has to be increased by 3-4 cm/s due to the geostrophic northward velocity component induced by the increase of the zonal pressure gradient (2-3 dyn. cm) from April to August 1983, between 4°W and 1°E, along 5°N (Fig. 11).

SUMMARY AND CONCLUSIONS

Current and wind data collected during the FOCAL experiment, both on and offshore in front of Ivory Coast, permit the interpretation of the seasonal variability of the temperature field on the shelf. The depth of the thermocline on the shelf is very closely dependent on the strength (intensity and meridional extension) of the Guinea current. In 1983, the Guinea current is present most of the time, both on the shelf and off the coast and the thermocline is close to the surface all year round; along 4°W, the maximum eastward flow at and near the coast is observed in May; this current is associated with an observed 36 meters upward displacement of the thermocline at 5°N at the end of April-beginning of May 1983. The maximum latitudinal extension of the Guinea current is observed in summer. In 1984, the Guinea current is present from February through May on the shelf but in 1984 than in 1983; in July 1984, the eastward flow is well developed, more than that observed during the same period in 1983, but its latitudinal extension is slightly narrower. Lowest SST values on the shelf appear in July-August 1983 and July 1984 when the Guinea current velocity maximum is located off the continental shelf. Absolute SST

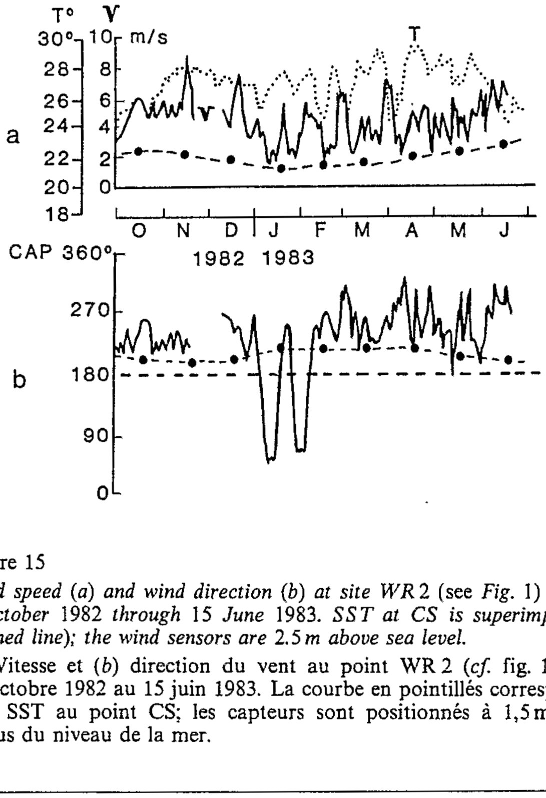

Figure 15

Wind speed (a) and wind direction (b) at site WR 2 (see *Fig.* 1) *from* 1 *October* 1982 *through* 15 *June* 1983. *SST at CS is superimposed (dashed line); the wind sensors are* 2.5 *m above sea level.*

(a) Vitesse et (*b*) direction du vent au point WR 2 (*cf.* fig. 1) du 1er octobre 1982 au 15 juin 1983. La courbe en pointillés correspond à la SST au point CS; les capteurs sont positionnés à 1,5 m au-dessus du niveau de la mer.

minima on the shelf cannot be therefore inferred only from the eastward flow distribution off the shelf. At that time, however, the zonal component of the wind velocity at the coast is maximum. In 1984, this maximum is observed from the beginning of June through the beginning of October; in 1983, this occurs from mid-May to the end of the record (end of July). The upwelling rate inferred from a simple linear model is 1.12 m/day in 1983 and 0.83 m/day in 1984, which corresponds in summer to the observed in 1983, and less so in 1984, vertical displacement of the isotherms on the shelf.

In conclusion, the onset of the cooling observed in winter on the continental shelf of Ivory Coast and which mainly appears subsurface is associated with the Guinea current both on and offshore. The cooling is weaker when the Guinea current is only confined on the continental shelf. In summer, the period which corresponds to the lowest temperature values, the cooling is first induced by the large scale structure of the Guinea current off the continental shelf which tilts the thermocline towards the coast and is then amplified by the increase of the zonal component of the wind at the coast. The horizontal advection of surface cold waters is not an important effect in the coastal upwelling phenomenon in front of Abidjan.

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