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Equatorial upwelling at 4°W during the FOCAL program

Surface winds
Temperature
Current
Equatorial area
Atlantic Ocean

Vent de surface
Température
Courants
Zone équatoriale
Océan Atlantique

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ABSTRACT

Data from an equatorial surface mooring are combined with seasonal equatorial cross sections in order to determine the local physical processes involved in the onset of the equatorial upwelling as observed at 0-4°W during the FOCAL (programme Français Océan-Climat dans l'Atlantique équatoriaL) experiment. On a seasonal time scale, local wind and current measurements may explain, in part, the cooling observed in 1983 and 1984 during the boreal summer. When the trade winds intensify, the sea surface temperature decreases and remains low as long as the wind velocity has a westward component. The secondary temperature minimum which appears between October and December, 1983 is not related to the local wind observations. Through a simple linear model, the climatic zonal component and the divergence of the surface wind stress observed at 0-4°W induces an upwelling over the period of June-July but a downwelling over the period of October-November-December. The intensification of the South Equatorial Current at the surface and the corresponding decrease of the Equatorial Undercurrent below are associated on a seasonal time scale with a decrease of the temperature at and below the surface ; the abrupt increase and decrease of the surface and subsurface currents in February-March 1983 lead, by geostrophic adjustment, to an uplift of the 20°C isotherm, contained within the thermocline, of 14 m. In October-November, the decrease of the equatorial undercurrent at 85 m depth induces by the same way a vertical displacement of the 17°C isotherm of 16 m. Vertical mixing takes place during the two cooling periods ; maxima and vertical shear are found for both years in June-July between 10 and 35 m depths and in October-November between 35 and 60 m depths.

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RÉSUMÉ

L'upwelling équatorial à 0-4°W pendant Focal

Une analyse des mesures continues de vent, de température et de courants, obtenues à partir d'une ligne de mouillage de surface déployée à 0-4°W de février 1983 à septembre 1984 pendant Focal (programme Français Océan-Climat dans l'Atlantique équatoriaL), a permis, en liaison avec les mesures de température et de courants obtenues le long du méridien 4°W et entre les latitudes 1°30N et 1°30S, lors des campagnes océanographiques effectuées en février, avril, août, novembre 1983 et février, mai et juillet 1984, de préciser la variabilité saisonnière de la structure thermique à 0-4°W, et de montrer que les refroidissements observés à la surface durant l'été boréal, pouvaient être, en partie, expliqués par les distributions locales du vent et des courants. L'intensification des alizés du Sud-Est en avril et leur maintien jusqu'en juin-juillet, la divergence positive des tensions de vent qui apparaît en juin-juillet, l'intensification du courant équatorial Sud en surface et la décroissance simultanée de l'intensité du contre-courant équatorial intermédiaire en subsurface (undercurrent dans la terminologie anglo-saxonne) de février-mars à juillet-août, enfin l'augmentation du mélange vertical à la partie supérieure de la thermocline à cette période, contribuent au déclenchement et au maintien du refroidissement de surface, en été boréal, à 0-4°W. En automne boréal, la décroissance de la température observée en subsurface en octobre et en décembre n'est pas liée au vent local. L'apparition simultanée d'un maximum secondaire de courant Ouest en surface et d'un minimum de courant Est en subsurface, ainsi que l'accroissement du mélange vertical en subsurface, contribuent au refroidissement observé en subsurface en cette saison.

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INTRODUCTION

Many studies have been devoted to the description of the seasonal variability of the atmospheric and oceanic fields in the equatorial Atlantic Ocean ; most of them are related, however, to the thermal field variability. Hastenrath and Lamb (1977), from monthly mean historical data, exhibited the presence in the east of a large annual signal in the time dependence of the sea surface temperature (SST) with a mean amplitude of 4-5°C. Minimum SST is observed from April through September ; the tongue of cold water extends along the Equator to the east of 20°W and from 4°S to 2°N to the west of 10°E. Merle (1980), from monthly mean temperature data derived from all the vertical temperature profiles available along the Equator, found an annual signal in the time evolution of the depth of the 20°C isotherm (D20), which is contained within the thermocline ; in particular he showed a deepening of the thermocline from spring to summer, in the west and a shoaling in the east, although at that time, the mean zonal component of the wind stress is larger in the west than in the east (Hellerman, 1979). Houghton (1983), averaging the SST and the D20 in the domain delimited by the longitudes 3°W and 6°W and the latitudes 1°30N and 1°30S, found a bimodal structure for the D20 and an annual signal for the SST. The decrease of the D20 is, however, spread over May and June, showing an interannual variability in the onset of the equatorial upwelling in that area. Miller (1981) inferred, from an inverted echo-sounder record at 0-4°W, an uplift of the thermal structure in March despite the weakness of the trade winds in the Gulf of Guinea at that time. Voituriez (1981) described at 0-4°W, from data collected by the RV Capricorne between 1971 and 1979, at different periods of the year, the seasonal variability of the SST in relation with the intensity of the trade winds : SST is minimum in boreal summer when the total wind stress is maximum ; the zonal component of the wind stress is, at that time, maximum and negative. The thermal fluctuations may also be affected by the currents through horizontal and vertical advection or by vertical mixing. Voituriez (1983) showed, from vertical sections of temperature and current measurements carried out in the Gulf of Guinea during the Ciprea program (1978-1980), that the surface cooling at 0-4°W is maximum when : 1) the South Equatorial Current (SEC) is developed in summer ; this current carries cold water upwelled both south of the Equator (2°S) and along the Southwestern African coast ; 2) the Equatorial Undercurrent (EUC) is minimum, the core of the EUC staying however at the same depth all along the year. He also pointed out, because of the lack of a seasonal signal in the vertical gradient between the zonal components of the SEC and EUC, that the surface cooling, in summer, is independent of the vertical mixing ; this is however in contradiction with previous results (Crawford, Osborn, 1979 ; Hisard *et al.*, 1977).

The object of this paper is, through the longest continuous time series ever provided by an equatorial surface mooring site at 4°W and through seasonal cross equatorial sections along 4°W (Fig. 1), to describe the surface wind and upper ocean temperature and current fluctuations as sampled during the program Français Océan Climat dans l'Atlantique équatoriaL (FOCAL) and to point out the relations which prevail, on a seasonal time scale, between the tempe-

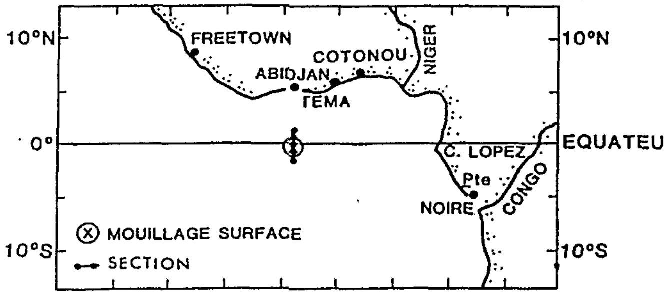

Figure 1

Map of the Gulf of Guinea showing the geographical positions of the surface mooring and of the meridional section during the FOCAL experiment.

Carte du Golfe de Guinée montrant les positions géographiques du mouillage de surface et de la radiale occupées pendant le programme FOCAL.

rature and both the wind and the current fields. The paper is organized as follows: 1) the data will be presented; 2) a description of the low frequency variability of the thermal field will be made; 3) the seasonal variability of the thermal field will be compared to the seasonal variability of both the wind and the current fields; 4) summary and discussions will follow.

DATA SET

The wind observations (Fig. 2 *b*, 2 *c*, 2 *d*) at 0-4°W were obtained using meteorological units mounted on a surface mooring; in addition to the observations of the wind speed and wind direction, the atmospheric pressure, air temperature and SST (Fig. 2 *a*) were also measured. The sensors were positioned at 2.5 m above sea level. During the experiment two units were used. The first developed by EERM (Meteorologie Nationale Française) and deployed from February 13, 1983 to February 5, 1984; the data were transmitted through the ARGOS system and sampled every 3 hours. The second developed by Aanderaa Instruments and deployed from February 23 to September 27, 1984; the sampling interval was in that case 1 hour and the data were then averaged every 3 hours. The temperature and current measurements (Fig. 3, 4, 5) were collected using Vector Averaging Current Meters (VACM's) manufactured by EG & G Sea

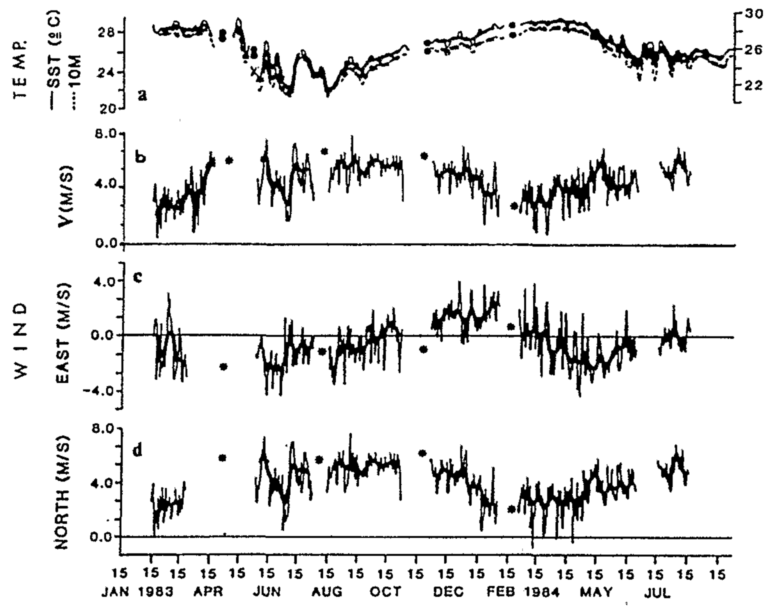

Figure 2

Distribution of the 10-day running mean superimposed on the daily mean values of the surface layer (0-10 m) temperature (a), wind speed (b) and of the zonal (c) and meridional (d) components of the wind velocity (using the oceanographical convention) at 0°, 4°W from February 1983 to October 1984 for the temperature and from February 1983 to September 1984 for the wind data. Dots and crosses indicate temperature values observed at the surface and at 10 m depth during the FOCAL cruises and AXBT SEQUAL flights; stars represent the wind speed (b) and wind velocity components (c and d) measure at the Equator by the R. V. Capricorne during the FOCAL cruises.

Séries chronologiques, données moyennées sur 1 et 10 jours, de la température (a) dans la couche de surface (0-10 m), de la vitesse du vent (b) et des composantes zonale (c) et méridienne (d) de la vitesse du vent (convention océanographique) à 0°, 4°W de février 1983 à octobre 1984 pour la température et de février 1983 à septembre 1984 pour le vent. Les points et croix indiquent respectivement les valeurs de la température observées en surface et à l'immersion 10 m pendant les campagnes FOCAL et les vols AXBT ; les étoiles représentent l'intensité (b) et les composantes horizontales de la vitesse du vent (c et d) mesurées à 0°, 4°W par le N. O. Capricorne lors des campagnes FOCAL.

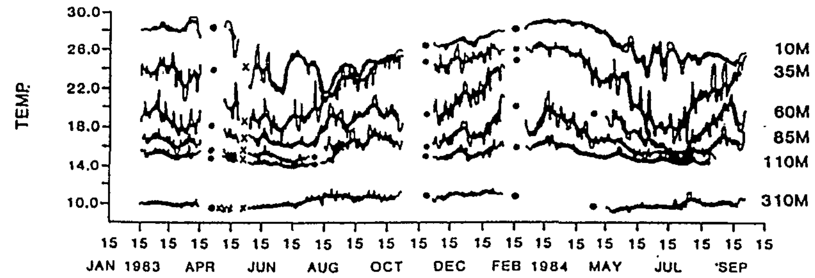

Figure 3

Vertical distribution of the 10-day running mean superimposed on the daily mean temperature values at 10, 35, 60, 85, 110 and 310 m depth from February 1983 to October 1984 at 0° 4°W (dots and crosses indicate temperature values from the CTD and AXBT vertical profiles obtained during the FOCAL/SEQUAL experiment).

Distribution verticale des enregistrements de température moyennés sur 1 et 10 jours aux immersions 10, 35, 60, 85 et 110 m de février 1983 à octobre 1984 à 0°, 4°W (les points et croix indiquent respectivement les valeurs de température déduites des profils verticaux CTD et AXBT obtenus lors des campagnes FOCAL et vols SEQUAL).

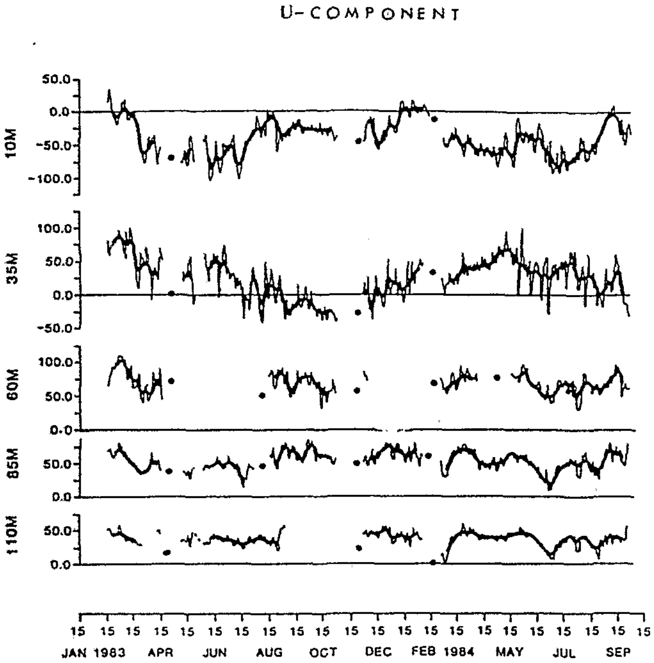

Figure 4

Time series of the 10-day running mean superimposed on the daily mean values of the zonal component of the current velocity at 0°, 4°W from February 1983 to October 1984 (the levels of measurements are : 10, 35, 60, 85 and 110 m) ; dots indicate the zonal components of the current velocity observed during the FOCAL cruises.

Séries chronologiques, données moyennées sur 1 et 10 jours, des composantes zonales de la vitesse du courant à 0°, 4°W de février 1983 à octobre 1984 (immersions : 10, 35, 60, 85 et 110 m) ; les points indiquent les valeurs de la composante zonale de la vitesse du courant obtenues aux mêmes immersions lors des campagnes océanographiques FOCAL.

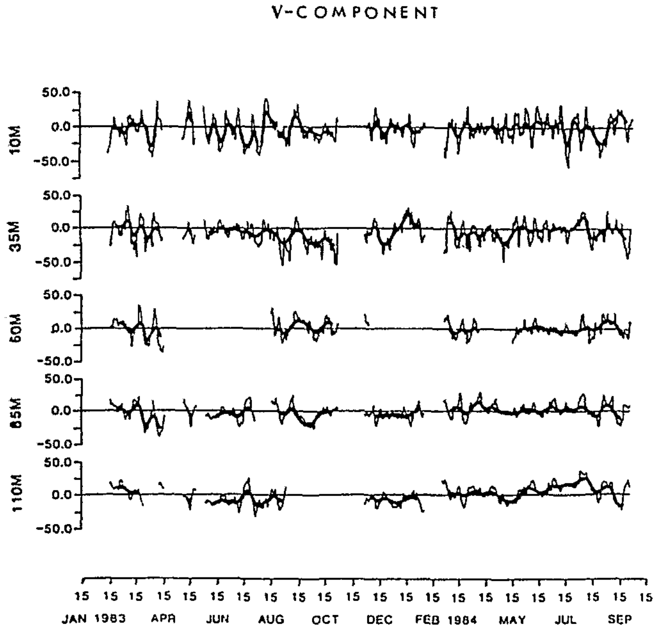

Figure 5

Time series of the 10-day running mean superimposed on the daily mean values of the meridional component of the current velocity at 0°, 4°W from February 1983 to October 1984 (same levels of measurements : as in Figure 4).

Séries chronologiques, données moyennées sur 1 et 10 jours, des composantes méridiennes de la vitesse du courant à 0°, 4°W de février 1983 à octobre 1984 (immersions identiques à la figure 4).

Links Inc. suspended from taut wire surface mooring of the type described by Halpern (1986). The current meters were placed at 10, 35, 60, 85 and 110 m depth and the data were sampled every 15 minutes. From two to four Aanderaa temperature and depth sensors were fixed on the mooring line to : 1) get a better description of the upper thermal field ; 2) know the time evolution of the temperature in the second thermocline (310 m depth) and 3) check the vertical stability of the scientific equipment (*see* Colin, 1983 for a detailed description of the surface mooring line). The records start February 13, 1983 and end September 27, 1984. The gaps which appear in April, May, November, 1983 and in February, 1984 in the wind, temperature and current records are due to cuts of the mooring line by tuna boats ; the other gaps correspond to electronic failures of the scientific equipment. All the wind, temperature and current time series presented in this paper are 10 day running mean superimposed to daily mean values. The cross equatorial sections (1°30°N-1°30°S) of the temperature (Fig. 6 *a*) and current measurements (Fig. 6 *b*) were obtained by respectively a Neil Brown CTD recorder lowered from the RV Capricorne and by a current profiler developed by the University of Miami and equipped with an Aanderaa current meter RCM4, sliding along a taut wire of 550 m length suspended from a free surface drifting buoy. The sections were carried out along 4°W in February 15-18, April 25-29, August 2-6, November 21-30, 1983 and in February 11-15, May 9-15, July 17-21, 1984. The temperature and current profiles were made every 55.6 km from the surface to 550 m depth (Henin *et al.*, 1986). In this paper, the measurements obtained between the surface and 150 m depth, are presented ; the temperature measurements at 310 m depth have been superimposed on the moored 310 m depth temperature record (Fig. 3).

TEMPERATURE

Low frequency variability

The time series of the 10-day running mean temperature values, recorded at 10, 35, 60, 85, and 110 m, are shown in Figure 3 ; the dots and crosses indicate respectively the temperature values obtained at the same levels, from CTD and AXBT profiles. The temperature records (Fig. 3) exhibit a large annual signal in the first 110 m : minimum temperature is observed in July and maximum temperature in February-March, for both years. This annual variability also appears in the Meridional and Vertical Distributions of the Temperature (MVDT) along 4°W (Fig. 6 *a*) ; the thermocline shallows from winter to summer and deepens (in 1983) from summer to winter.

The temperature at 60, 85 and 110 m depth starts to decrease at the beginning of March, 1983 and around mid-March, 1984, at 85 and 110 m depth (Fig. 3). At the surface (Fig. 2 *a*) and at 10 m depth (Fig. 2 *a*, 3), the temperature, thereafter named SLT at this level, starts to decrease around one month later. In 1983, the SLT is decreasing 3 days before the cut of the surface mooring line. The MVDT (Fig. 6 *a*) show at 1°S, an uplift of the depth of the 20°C isotherm,

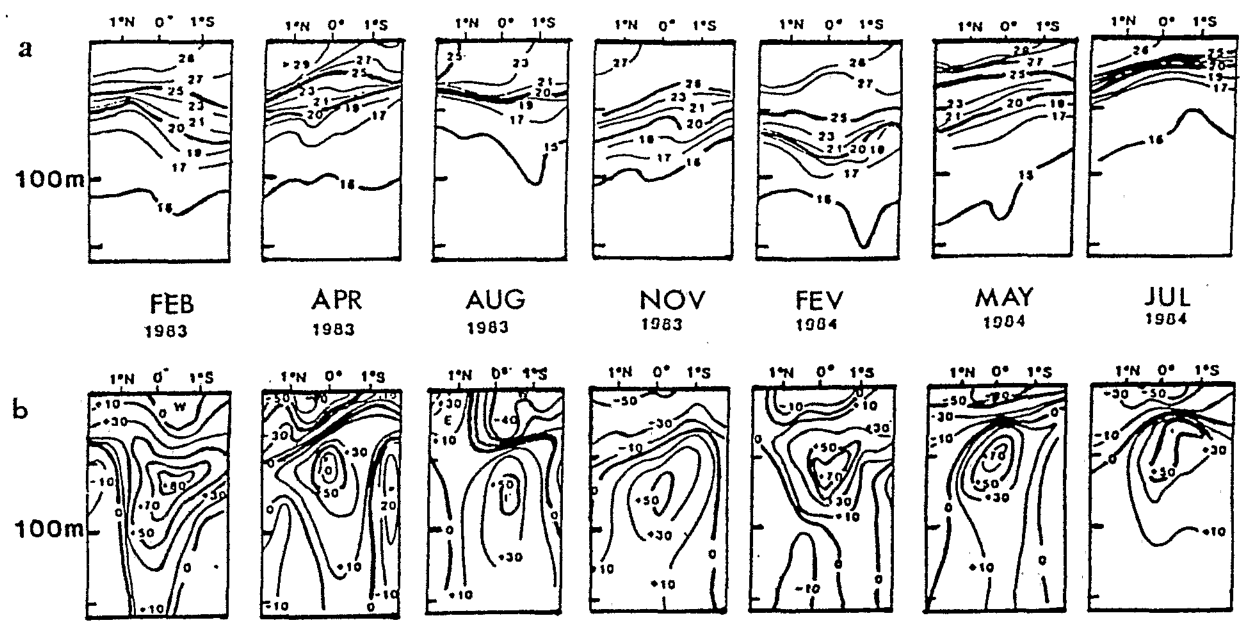

Figure 6

Meridional (1°30N-1°30S) and vertical (0-160 m) distributions of the temperature (a) and of the zonal component of the current velocity (b) along 4°W, in February, April, August and November 1983 and in February, May and July 1984.

Distributions méridienne (1°30N-1°30S) et verticale (0-160 m) de la température (a) et de la composante zonale de la vitesse du courant (b) le long de 4°W en février, avril, août et novembre 1983 et en février, mai et juillet 1984.

contained within the thermocline, of 35 m from mid-February through the beginning of May 1984 ; the 15°C isotherm exhibits an identical behavior during the same period of time, suggesting the presence of a strong southward meridional pressure gradient at the surface. From spring to summer, the temperature decreases monotically ; minimum temperature is observed at 60, 85 and 110 m depth, mid-July, 1983 and a week later in 1984. At 35 m, the minimum is observed around three weeks earlier for both years. Temperature values at 35 and 60 m are slightly lower in 1984 than in 1983 (15.5°C *versus* 15.9°C at 60 m depth). The large temperature difference which appears between the 10 and 35 m levels, indicates the position of the thermocline, close to the surface. The MVDT carried out in August, 1983 and July, 1984 (Fig. 6 *a*) clearly indicate : 1) a shallower position of the thermocline in summer than during the other seasons ; the depths of the 25 and 15°C isotherms reveal this upward displacement ; 2) the presence of a strong meridional gradient (1°C/degree of latitude) at the surface indicating a maximum cooling south of the Equator. At 310 m (Fig. 3), a depth which is located in the lower part of the second thermocline (Fig. 7), the temperature first evolves in the same way : maximum values are found in February-March, 1983 and January 1984 ; minimum temperature is recorded in May for both years. At that depth, the temperature increases from the beginning of June through the end of August, 1983, and from mid-May through the end of July, 1984 ; thereafter, the temperature remains constant. A comparison between the dates of occurrence of the temperature minimum both at 60 and 310 m depth, indicates a phase lag of about 2 months which corresponds to a vertical phase speed or vertical component of the velocity of 5-6 m/d or 6-6.5 × 10^{-3} cm/s. A similar tendency was also found at the same location during the same period of time from AXBT profiles (Houghton, Colin, 1986). From August to November 1983 and from August to the end of the records in 1984 (Fig. 3), the temperature at 60 and 85 m depth increases ; this occurs however 2 to 3 weeks earlier at 35 m depth. One month, in 1983 and 2 months, in 1984 after the increase of the temperature at 35 m depth, a homogeneous layer of at least 35 m thickness is observed ; this phase corresponds to an abrupt deepening of the thermocline. At the surface and at 10 m depth, the temperature remains however constant ; this is particularly obvious from mid-July to mid-September, 1984. A similar behavior was also noted at 0-28°W (Weisberg, Colin, 1986). Beginning in October 1983 and except for the SLT, the temperature starts to decrease again at 60 and 85 m depth until the end of October. At 35 m and above, the temperature continues to increase indicating the presence of a steep thermocline between these two levels ; this is confirmed by the MVDT obtained in November 1983 (Fig. 6 *a*). From the end of November 1983 to the beginning of February 1984, the temperature increases at all levels. The secondary temperature minimum does not appear in the SLT ; at 35 m depth and in 1983, the temperature record is however lower at the end of November than at the end of October, indicating the presence of the thermocline just below the surface. At 310 m depth, there is no tendency of a decreasing of the temperature from mid-August 1983 to the beginning of February 1984. The climatic vertical displacement of the 11°C isotherm however exhibits a semi-annual signal, with a second minimum depth occurring in January (Houghton, Colin, 1986).

Interannual variability

If most of the energy is contained in the seasonal frequency band, the amplitude of the annual signal at

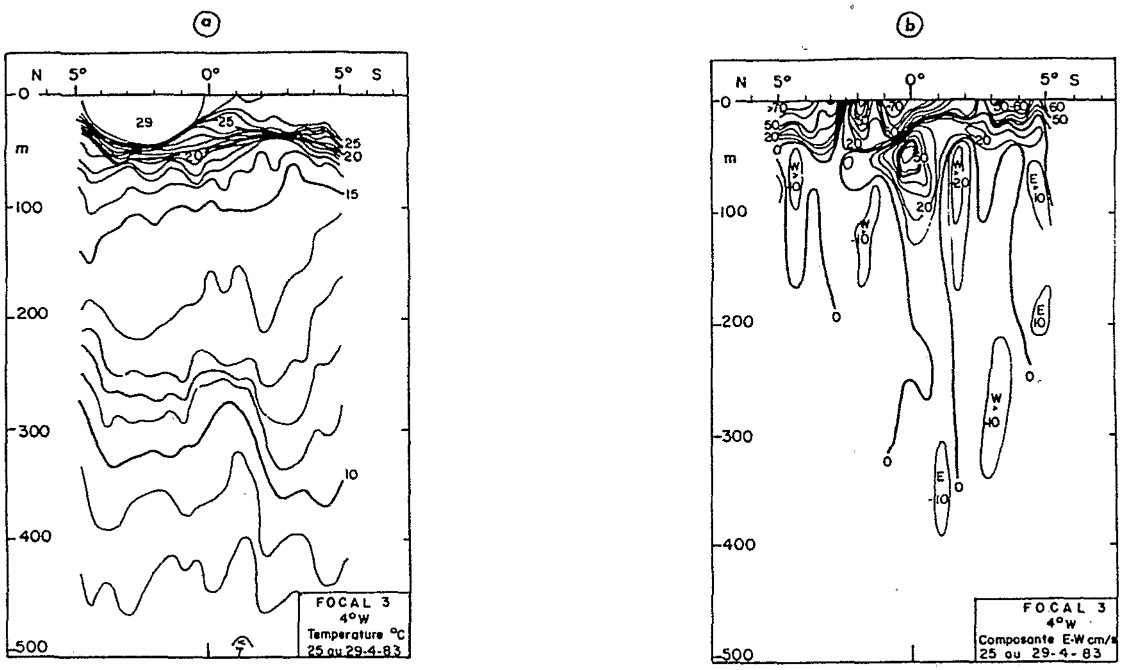

Figure 7

Meridional (5°N-5°S) and vertical (0-550 m) distributions of the temperature (a) and of the zonal component of the current velocity (b) along 4°W , in April 1983.

Distributions méridienne (5°N-5°S) et verticale (0-550 m) de la température (a) et de la composante zonale de la vitesse du courant (b) le long de 4°W en avril 1983.

0-4°W varies more or less from one year to the other. Houghton (1983) showed, from historical data, that the depth of the 20°C isotherm displays an interannual variability with an amplitude which is around half the amplitude of the seasonal signal. The changes that occur in the thermal field during the FOCAL program are also important. The mean temperature difference observed in March between the two years is 2.4°C at both 35 and 85 m depth. At the surface and at 10 m depth (Fig. 2 *a*) this temperature difference is maximum (1.5°C) in March with higher SLT in 1984 than in 1983. The MVDT also show a deeper position of the D20 in Februay 1984 than in February 1983 and a higher SST at the beginning of May 1984 than at the end of April 1983. This feature does not concern only the upper layer ; at 310 m depth (Fig. 2), the temperature recorded in February is around 1°C higher in 1984 (beginning of February) than in 1983 (mid-February). A higher SLT and a deeper thermocline in the winter and spring 1984 were also observed in the whole equatorial area of the Guinea Gulf with a maximum amplitude at the equatorial 6°E site (Colin *et al.*, 1987) and also along the northwestern African coast, at least to the east of Abidjan (Piton, 1985 ; Colin, pers. comm.). During the boreal summer, the values of the temperature minima observed at both 35 and 60 m depths, are smaller in 1984 than in 1983 (15.7°C *versus* 16.5°C at 60 m depth for example). At 85 and 110 m depths, the reverse is observed ; at 110 m the value of the temperature minimum is higher in 1984 than 1983 (14.3°C *versus* 13.9°C) ; in the surface layer, the mean SLT is 2°C higher in 1984 than in 1983. The different behavior of the temperature records in the first 110 m leads to a thinner and steeper thermocline in 1984 than in 1983. The MVDT obtained in July 1984 and in August 1983 clearly emphasize this feature (Fig. 6 *a*). They however overestimate the amplitude of the interannual variability at that season. Two sections carried out in mid-July 1983 and at the end of July 1984 would, to the contrary, lead to similar values of the SST, depth, and thickness of the thermocline and therefore to minimal interannual variability. Surface and subsurface continuous temperature measurements are essential to resolve the amplitude of both seasonal and interannual variability. In the same way, inferring the strength of the equatorial upwelling from the depth of the thermocline may also lead to mistaken interpretations: minimum SST at 0-28°W, as at 0-4°W, does not necessarily coincide with a persistent position of the thermocline close to the surface (Weisberg, Colin, 1986). Warm events are not only located in the equatorial areas. Higher SST has also been observed, in 1984, at Pointe-Noire (Fig. 1) during the boreal summer and in Abidjan (Fig. 1), during the winter and spring. Equatorial warm events therefore are associated with coastal warm events, north of the Equator in winter and spring and south of the Equator, in boreal summer. This discrepancy between the two SST time evolutions observed on either side of the Equator, is not particular to the 1984 year (Colin *et al.*, 1987).

In summary the persistence of the warm events observed in 1984 at 0-4°W from February through June below the surface layer and from February through mid-September at the surface, had no major influence on: 1) the period of the onset of the summer cooling ; it occurs in April either in 1983 or in 1984 ; 2) the occurrence of the temperature minima which appear during the second half of July for both years ; 3) the strength of the cooling below the surface layer. However, warm surface waters induced : 1) an important rainfall over the western part of Africa, particularly in Ivory Coast where the drought had been widespread for three years ; and 2) a poorer tuna fish season in the Gulf of Guinea, especially in winter and spring due to a deeper position of the thermocline in 1984.

WIND

To interpret the seasonal fluctuations which appear in the temperature field, the *in situ* seasonal variability of the surface wind, as observed during the same period of time, will now be considered.

Low frequency variability

The time series of the wind speed and of the zonal and meridional components of the wind velocity are shown in Figure 2 *b*, 2 *c*, 2 *d*. They all exhibit a large annual signal as observed during the same period of time, in the central (Payne, 1984) and in the western (Garzoli, Katz, 1984) Atlantic. At 5°N-4°W, the wind speed record presents a bi-harmonic structure (Colin, pers. comm.) which does not exist further south, at the Equator. Colin and Garzoli (1987) described in details the wind observations obtained simultaneously at 0°-4°W during the FOCAL program and at 0°55'N-29°W (St Peter and St Paul Rocks) during the SEasonal response of the eQUatorial AtLantic (SEQUAL) experiment. They compared, on a seasonal time scale, the steadiness of the wind velocity components and the intensity of the total wind stress and wind stress components inferred from the wind observations at both sites. They also made a comparison at each location, between the monthly mean wind stress values inferred from the *in situ* observations and from climatology. Finally they emphasized the ocean response to the local and far field wind forcing. Their results at 0°-4°W may be summarized as follows : The SLT, on a seasonal time scale, is highly correlated with the zonal component of the wind velocity (Fig. 2 *a*, 2 *c*). When the southeasterly winds increase during the first half of April, 1984 which correspond to higher negative values (positive is eastward) of the zonal component, the SLT decreases around one week later ; in 1983, the SLT starts to decrease 8 days after the increase of the wind speed (Fig. 2 *b*) ; unfortunately the decrease occurred only 3 days before the cut of the mooring line. During FGGE (First GARP Global Experiment) a similar behavior between the wind and the surface temperature was also observed (Colin *et al.*, 1987). Then the SST remained low so long as the zonal component of the wind was negative. This happened until the end of September, 1983 and until at least mid-August, 1984. The SST increases as soon as the zonal component is positive which corresponds to southwesterly winds ; this situation appears in October, 1983. The highest SST are observed during the relaxation period of the trade winds (January through April, 1984) ; they are induced by the important equatorial eastward transport of warm waters just before the relaxation of the eastward zonal pressure gradient (Cane, 1980 ; Philander, Pacanowski, 1980).

Inferred upward displacement for the bottom of the homogeneous layer

The thermal structure in the equatorial Atlantic Ocean adjusts to the general distribution of the wind forcing. When the trade winds intensify, the thermocline deepens in the west and shallows in the east (*see* Cane and Sarachik, 1983 for a detailed review) ; the shoaling of the thermocline in the east, is a necessary but not sufficient condition to induce a strong upwelling at 0-4°W, at the surface : maximum (minimum) SST is observed at 0-4°W when the thermocline is shallowing (deepening) ; local phenomena have therefore to be considered ; only non linear multi-level models can induce, in the presence of easterly or southerly winds, both an upward displacement of the thermocline and a cooling of the SST (Cane, 1979 ; Philander, Pacanowski, 1980 ; 1981). These models are however very complex to run. When the winds are southeasterly which correspond to the mean wind direction observed from spring to summer at 0-4°W and if the motion is assumed to occur on a time scale larger that the time required to set up the frictional boundary layer, a mean value for the vertical component of the velocity (w) can be obtained at the Equator. Following Webb de Witt and Leetmaa (1978) and using an Ekman type formulation, w is given by the relation :

$$w(D) = \frac{D^2}{2 * k}\left(\frac{d\tau_x}{dx} + \frac{d\tau_y}{dy}\right) - \frac{5 * D^4 * \beta * \tau_x}{24 * k^2}, \quad (1)$$

where x, y, z represent the coordinates positive eastward, northward and upward, D the depth of the quasi-homogeneous layer, τ_x, $d\tau_x/dx + d\tau_y/dy$ the zonal component and the horizontal divergence of the wind stress at the site, k and β the vertical coefficient of the eddy viscosity and the meridional derivative of the Coriolis parameter respectively. The wind stress quantities used in equation (1) are deduced from climatology. Colin and Garzoli (1987) made a comparison between the monthly mean wind stress values inferred from climatology (Hellerman, 1979) and from the *in situ* wind measurements made in 1983 and 1984. They found at 1°N-29°W and at 0-4°W a good agreement between the two zonal components ; differences however appear between the two meridional components ; the climatic meridional component at 0-4°W is larger than the *in situ* one by 0.2 dynes/cm^2 in winter and spring and by 0.1 dyne/cm^2 in summer and fall ; at 1°N-29°W, the discrepancy is more important. These differences do not affect however the value of the wind stress divergence. The climatic wind stress quantities, averaged over the two months period June and July, correspond to :

$$\tau_x = -0.10 \text{ dyne/cm}^2$$

$$\frac{d\tau_x}{dx} = 1.3 * 10^{-9} \text{ dyne/cm}^3$$

$$\frac{d\tau_y}{dy} = 5.5 * 10^{-9} \text{ dyne/cm}^3 .$$

The zonal gradient of the zonal components of the wind stress was calculated using the mean values at 0-

10°E ($\tau_x = 0.11$ dyne/cm^2) and at 0-28°W ($\tau_x = -0.59$ dyne/cm^2) respectively ; these two locations are 14° of longitude apart of 0-4°W and their wind stress components exhibit a low standard deviation at that time. The mean zonal gradient is the same ($1.4 * 10-9$ dyne/cm^3) as the one observed between 1°N-29°W and 0-4°W from the *in situ* observations. The meridional gradient along 4°W was obtained using the climatic meridional wind stress components at 2°N ($\tau_y = 0.59$ dyne/cm^2) and 2°S ($\tau_y = 0.40$ dyne/cm^2) ; in June-July, the meridional wind component presents a maximum at 2°N. The vertical coefficient of the eddy viscosity was determined through the position (1°30S) of the maximum cooling observed along 4°W (Fig. 6 *a*) ; this leads to $k = 200$ gr/cm/s. Using these values, we obtain at 40 m depth, a mean vertical speed of $w = 29 * 10^{-5}$ cm/s or 25 cm/day. This value corresponds to a mean vertical displacement of the interface of 15 m in 2 months. This quantity represents almost half of the total vertical displacement of the 20°C isotherm in 1983 (30-35 m) but only 1/3 in 1984 (Houghton, Colin, 1986).

Despite the large sensitivity of w at the Equator to the thickness of the homogeneous layer and to the vertical eddy viscosity coefficient, this simple linear model gives, because of its extreme simplicity, an easy and quick estimate of the vertical displacement of the interface. The temperature records exhibit the presence of a secondary minimum in November, 1983. If we apply, for that period of time, the relation (1) using : 1) the mean climatic wind stress values observed over the 3 months period October-November-December ($\tau_x = 0.01$ dyne/cm^2 and $d\tau_x/dx + d\tau_y/dy = -1. * 10-9$ dyne/cm^3) and 2) the same value of $k = 200$ gr/cm/s (the temperature sections still exhibit a shoaling of the thermocline south of the Equator at that time), we obtain for $w = -5.4 * 10-5$ cm/s or -4.7 cm/d at 40 m depth which, in that case, corresponds to a downwelling. The secondary temperature minimum cannot therefore be explained in terms of local climatic wind forcing ; Weisberg and Tang (1985) and Philander and Pacanowski (1986) suggested that the transients excited by the abrupt intensification of the trade winds, in the west, in April-May (this is the situation which prevailed in 1983) and which decay by November, could explain the semi-annual signal observed in the temperature field in November, 1983 in the Gulf of Guinea.

CURRENTS

The currents, through horizontal and vertical advection, influence the amplitude of the variability of temperature field. The time series of both the zonal (U) and meridional (V) components of the velocity of the currents, in relation to the meridional and vertical distributions of the zonal component of the velocity of the currents (MVDC), as observed during the FOCAL cruises, will now be considered.

Low frequency variability

The time series of the U and V components are shown in Figures 4 and 5 respectively. The U component exhibits, as seen in the temperature and wind fields, large seasonal fluctuations at all levels ; this is not the case for the meridional component, whether at the surface or below. In February 1983 and January 1984, the current is eastward, except at the surface where there is no motion. The MVDC (Fig. 6 *b*), also show in February a weak surface current in both years. At that time, which corresponds to the relaxation period of the trade winds, the vertical extension of the Equatorial Undercurrent (EUC), flowing eastward within the thermocline, is maximum with, however, a larger transport in 1983 than in 1984 (Weisberg, Colin, 1986) ; the MVDC also emphasizes this feature (Fig. 6 *b*). Maximum eastward values (90-100 cm/s) are observed at 35 and 60 m depth.

At the beginning of March, 1983 and in February, 1984, the South Equatorial Current (SEC), flowing westward at the surface, abruptly intensifies ; the velocity increases from 0 to 60 cm/s only within 2 weeks in 1983 and at the most within 3 weeks in 1984 (the gap in the record lasts from February 5 to February 23). The mean V component (Fig. 5) is zero at that time. Below, the EUC speed decreases at all levels for both years ; the meridional component is negative at 35, 60, and 85 m depth showing a southward displacement of the EUC associated with the increase of the SEC, at the surface ; the current sections made in April, 1983 and May, 1984, indicate, at and below the surface, a westward component of the current which is larger north of the Equator than south ; moreover, the core of the EUC has moved upward ; in May, 1984 the EUC surfaces at 2°30S (Fig. 7).

From April through June 1983, and from February through July 1984, the mean velocity of the SEC is around 70 cm/s. The speed has increased due to the intensification of the zonal component of the local wind. This current, despite its high speed, remains however confined to the surface layer. Subsurface, the EUC is still present at 35 m depth ; the U component however starts to decrease mid-June, 1983 and mid-July, 1984 ; at 85 m depth, the U component increases at that time, indicating a deepening of the EUC core mid-summer ; the same feature is also observed at 0°-28°W with however a larger amplitude (Weisberg, Colin, 1986) ; the current sections made in April and August 1983 (Fig. 6 *b*), also indicate a deeper position of the EUC core in August than in April. The vertical shear between the SEC and the EUC is maximum in spring and at the beginning of the summer ; the sections in April, 1983 and May, 1984 also show a large vertical shear between these two currents.

In August and for both years, the speed of the SEC substantially decreases ; the SEC is replaced in September by the Guinea Current (GC) which is flowing eastward and which spreads out at that time from the northwestern African Coast to at least the Equator (Voituriez, 1981, Richardson, Philander, 1986) ; the current sections in August, 1983 show that the Guinea Current already reached 1°N ; in July, 1984, the southern boundary of the GC is located at 2°N (Henin *et al.*, 1986). The horizontal shear between the SEC and GC is maximum in August, 1983. The V component exhibits at that time, an oscillation of around 30 day at 10 m depth (Fig. 5) ; this oscillation also appears at 0-28°W, both at and below the surface but with, in that case, a large amplitude (Weisberg, 1984). The necessary condition (β-$d^2U/dy^2 < 0$) for a barotropic instability, is achieved in August 1983, at 4°W. The same oscillation also appears in the V component, in August-September 1984. Subsurface, the EUC speed, at 85 meter depth, increases until mid-September for both years.

From the end of September 1983 to mid-November 1983, the SEC speed again increases ; the maximum speed (30-35 cm/s) is however half the speed observed in Spring. On the other hand, the SEC now extends deeper than in Spring ; the SEC is observed at 35 m depth ; the current section in November, 1983 shows that the zero line is around 40 m depth. The V component at that time is negative but larger at 35 than at 10 m depth, indicating a southward displacement of the SEC. Below, the speed of the EUC decreases but the velocity core is not weaker than 50 cm/s and remains centered, as in August, between the 60 and 70 m depth levels ; the maximum vertical shear is now observed between the 35 and 60 m depths. After November, 1983, the speed of the SEC (EUC) decreases and increases and the semi-annual cycle then begins again.

Relation between the temperature and the zonal currents

The fluctuations of both the temperature and the zonal components of the surface and subsurface current velocity are, on a seasonal time scale, related. When the SEC and EUC velocity cores increase and decrease respectively, the temperature decreases both at and below the surface. The reverse is observed when the speeds of the SEC and of the EUC decrease and increase respectively. The temperature and U component records at 85 meter depth clearly exhibit that feature : minima and maxima of temperature coincide with minimum and maximum values of the EUC velocity. Some differences appear however above the 85 m depth. At 35 m depth, the fluctuations between the temperature and current fields are out of phase from mid-July through the end of October, 1983 and in April-May, 1984. At 10 m depth, the SLT remains low in August-September even when the thermocline is deepening. These low temperature values are associated with cold waters upwelled, either south of the Equator (Voituriez, 1981) or along the southwestern African coast and transported by the SEC ; moreover, the decrease of the SLT does not immediately follow the increase of the SEC in March, 1983 and February, 1984 ; the same behavior is observed in October and December, 1983 when the SEC presents a secondary westward maximum. The discrepancy between the SEC and SLT fluctuations, in winter is due, following the relaxation period of the winds, to the overflowing to the west, of warm and fresh waters accumulated at the bottom of the Gulf of Guinea during the rainy season, both by the Guinea Current and the southwesterly winds ; a similar result was also found by Voituriez (1981). The accumulation of these warm waters in winter, induces in the Gulf of Guinea, a flattening (deepening) of the thermocline in 1983 (1984) along the Equator and as a consequence, a reduced eastward (intense westward) zonal pressure gradient (Hisard, Henin, 1987 ; Colin *et al.*, 1987).

The abrupt increase of the SEC ($\Delta U = +60$ cm/s at 10 m depth) and decrease of the EUC ($\Delta U = -45$ cm/s and $\Delta U = -20$ cm/s at 35 and 85 m depth respectively) observed in both years at 0-4°W in February-March, induce, by geostrophic adjustment ($\beta\Delta U = -d^2D/dy^2$), a decrease of the dynamic height anomaly at the Equator, compared to 1°N or 1°S, of respectively 8.2, 6.2 and 2.7 dynamic cm. For the corresponding measured mean temperature (28°C, 25°C and 17°C) and salinity (35.00, 35.50 and 35.75) values in February 1983 at 4°W, the decrease of these dynamic height anomalies lead respectively at the surface, to a vanishing of an homogeneous layer of 15 m thick, and subsurface, to an uplift of the 25°C and 17°C isotherms of 14 and 16 m respectively. These quantities are in good agreement with the vertical displacements of the 28°C, 25°C and 17°C isotherms observed from February through April, 1983 (Fig. 6 *a*). In October-November 1983, the mean decrease of the EUC velocity ($\Delta U = -30$ cm/s) at 85 m depth, leads to a vertical displacement of the 17°C isotherms of 16 m which represents 1.6 times that estimated from the moored linearly interpolated temperature data, from mid-September to mid-November, 1983 (Weisberg, Colin, 1986).

The total displacement of the 25°C, at 0-4°W, induced both by the increase (decrease) of the SEC (EUC) in March and the local wind forcing (both by the zonal component and divergence of the wind stress) in June-July, is 29 meters which is slightly less in 1983 and slightly more than half in 1984 than the total vertical displacement of that isotherm inferred from the direct observations from February through July (respectively 30-35 m and 50-55 m).

Relation between the temperature and the SEC/EUC vertical shear

As it has been pointed out before, a strong vertical shear is observed between the SEC and EUC at 0°-4°W. This vertical shear is able to enhance the surface cooling through vertical mixing. Maxima in vertical shear are found for both years from March-April through June-July between the levels 10 and 35 m and in October-December between the levels 35 and 60 m (Fig. 4). In June 1983, a difference of 110 cm/s is observed within a vertical distance of only 25 m (!). Figure 8 shows the 10 day running mean time series of : 1) the vertical gradient of the temperature (dT/dz) ; 2) the vertical gradient of the U component (dU/dz) and 3) the Richardson number deduced from the relation $R_i = ga(dT/dz)/(dU/dz)^2$ where *g* and *a* represent the gravity and the coefficient of thermal expansion (a = 0.0002/°C) respectively. The vertical gradients have been computed between the 10 and 35 m levels. R_i exhibits a large annual signal ; minima $R_i(R_i < 1)$ are observed from February 15 through July 15, 1983 and from February 1 through August 15, 1984 ; maxima $R_i(R_i > 1)$ are, on the other hand, observed from July 15, 1983 to February 1, 1984. Minima (maxima) R_i are associated with high (low) dU/dz values and correspond to a large (weak) vertical mixing. Despite the large values of dU/dz observed in June-July, dT/dz remains high at that time which indicates that the strong vertical mixing is opposed, in the surface layer, both to a vertical heat

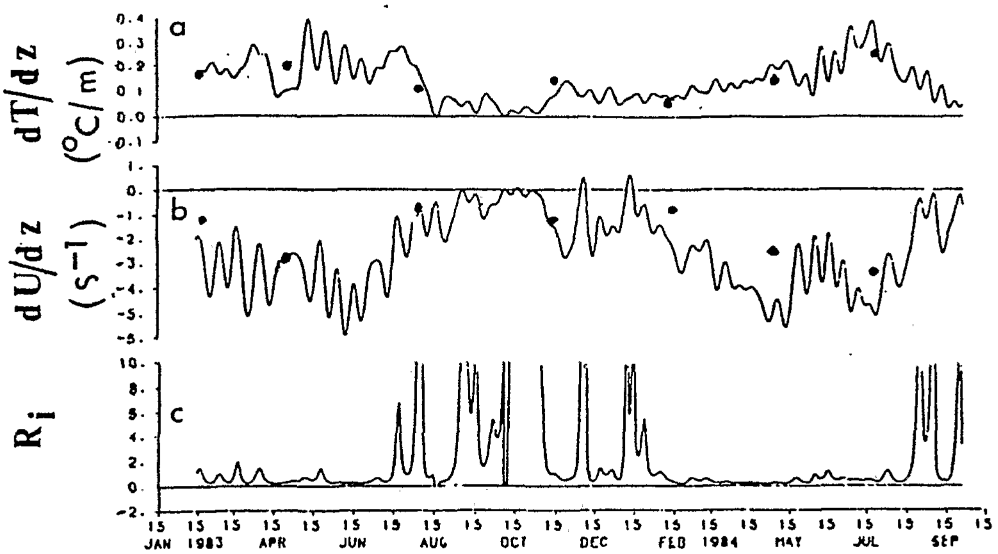

Figure 8

10-day running mean time series of the vertical temperature gradient (a), vertical shear between the zonal components of the currents (b) and of the Richardson number (c) inferred from (a) and (b), from February 1983 to October 1984 and between the 10 and 35 m depths (stars indicate values from the FOCAL cruises).

Séries chronologiques, données moyennées sur 10 jours, des gradients verticaux de la température (a) et de la composante zonale de la vitesse du courant (b) calculés entre les niveaux 10 et 35 m puis du nombre de Richardson (c) déterminé à partir de (a) et (b) de février 1983 à octobre 1984 (les étoiles représentent les valeurs déduites des campagnes FOCAL).

flux into the ocean across the sea surface ($T_{air} > T_{sea}$) and to an horizontal advection of surface waters upwelled south of the Equator in the divergence band (2°S-3°S). In October-December, the vertical shear between the 35 and 60 m levels leads to a Richardson number of $R_i = 0.42$ which indicates that the vertical mixing contributes to the subsurface cooling observed at that time. At the surface however, R_i remains large because of the presence of the SEC, both at 10 and 35 m depth ; the weakness of the vertical temperature gradient at that time, reflects the presence of a thick homogeneous layer. The vertical gradients dT/dz and dU/dz (stars in Fig. 8) derived from the seasonal temperature and current sections (Fig. 6 *a*, 6 *b*) and computed between the surface and the depth of the EUC core, also exhibit a large annual signal : minima dU/dz are observed from August 1983 through January 1984 and maxima in April 1983, May and July 1984. This result differs markedly from the one found by Voituriez (1983) at the same location during the CIPREA (CIrculation et PRoduction de la zone Equatoriale Atlantique) experiment (1978-1980) ; he did not find any seasonal variability in the time distribution of the vertical shear between the SEC and the EUC at 0°-4°W and concluded that the vertical mixing, in boreal summer, had no influence on the strength of the equatorial upwelling at 4°W.

SUMMARY AND CONCLUSIONS

The time series of the moored temperature measurements carried out at 0-4°W from February, 1983 through September, 1984, in addition with the temperature equatorial cross sections made along 4°W during the FOCAL experiment, exhibit a strong annual signal at and below the surface. Low values are found for both years from June through August with minima in July in the upper 110 meters and around two months earlier, at 310 m depth. Maxima temperature are observed from December through April above 110 m depth and from September 1983 through at least February 1984 at 310 m depth. Subsurface, a secondary temperature minimum appears between October and December 1983 at 35, 60, 85 and 110 m depth. The temperature records show differences in boreal winter and summer ; the 20°C isotherm, contained within the thermocline, is in February at greater depth in 1984 than in 1983 ; SST is also higher at that time in 1984. In Summer, SST is still higher in 1984 by 1°C in average.

The time fluctuations of the zonal components of both the wind and current velocities, are coherent with the seasonal variability of the temperature field. When the southeasterly wind intensifies at 0-4°W, the surface temperature remains low as long as the wind velocity has a westward component. The climatic zonal components and divergence of the wind stress, averaged over the 2 month period June-July, lead through a simple linear Ekman type model (Webb de Witt, Leetmaa, 1978), to a mean upward displacement of the interface (bottom of the homogeneous layer) of 15 m at that time ; in October-November-December, the wind distribution leads on the other and, to a downward displacement of the interface which is in contradiction with the presence of a secondary temperature minimum at that time, below the surface. When the South Equatorial Current intensifies in the spring and summer, the temperature decreases in the surface layer (0-10 m depth). Subsurface, the temperature also decreases when the velocity of the Equatorial Undercurrent decreases ; this occurs when the SEC velocity increases. The abrupt increase (decrease) of the SEC (EUC) in the spring lead through geostrophic adjustment, to a vanishing of an homogeneous surface layer of 15 m thick and an upward displacement of the 25 and 17°C isotherms of 14 and 16 m respectively ; in the fall, the vertical displacement of the 17°C isotherm, induced by the decrease of the EUC, is 16 m. The vertical shear between the zonal components of the SEC and EUC is maximum for both years, from March-April through June-July between 10 and 35 m depth and from October through December between 35 and 60 m depth. The Richardson number time evolution, inferred from the time series of the vertical gradient of the temperature and of the vertical shear between the zonal components of the SEC and EUC, both calculated between 10 and 35 m depth, show that the vertical mixing ($R_i\Pi l$) is large when the vertical shear is maximum. At that time, the vertical temperature gradient remains however relatively high indicating that the mixing is not strong enough to destroy density gradients being created by both the vertical heat flux across the surface ($T_{air} > T_{sea}$) and the horizontal advection by the SEC of surface warmer waters from the south and southeast. The horizontal advection effect is present in August-September when the thermocline is deepening while the sea surface temperature remains low.

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