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THE NORTH EQUATORIAL COUNTERCURRENT OBSERVED DURING THE PROGRAMME FRANCAIS OCEAN CLIMAT DANS L'ATLANTIQUE EQUATORIAL EXPERIMENT IN THE ATLANTIC OCEAN, JULY 1982 TO AUGUST 1984

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Abstract. Observations from Programme Francais Océan Climat dans l'Atlantique Equatorial (FOCAL) cruises in 1982 and 1984 have confirmed that in the central Atlantic Ocean the North Equatorial Countercurrent (NECC) has a well-defined seasonal regime with a very reduced flux during spring. The main core of the NECC always lies between 4°N and 6°N. Focal observations have also shown that a long-term change of NECC may occur and contribute to the development of an "El Niño" type event in the eastern Atlantic Ocean.

1. Introduction

The North Equatorial Countercurrent (NECC) is the main eastward equatorial current of the Atlantic and Pacific Ocean. It is located generally between 3° and 10°N in the vicinity of the Intertropical Convergence Zone (ITCZ), between the North and South Equatorial Currents, which are driven by the trade winds. The NECC carries eastward the large amount of water, heat, and salt accumulated in the western part of equatorial oceans.

In the Atlantic, ship drift data [Richardson and McKee, 1984] have shown that the NECC is a continuous eastward flow across the entire ocean between 5° and 8°N from July to December. East of 20°W it is observed all year long. In contrast, west of this longitude it disappears between January and June, when the surface flow is westward. At this time there is a true reversal of the current. Studies of Garzoli and Katz [1983] using dynamic height difference between 3°N and 9°N from historical data have shown this reversal in the western part of the equatorial Atlantic. They assumed that the NECC is geostrophically balanced, and they concluded that the variations of meridional slope of the thermocline mirror the dynamic height and are directly correlated with the NECC eastward transport. Thus the redistribution of heat and salt is directly related to the transport fluctuations.

Up to now, various studies [Katz and Garzoli, 1982; Richardson and McKee, 1984] have shown that the equatorial Atlantic currents and particularly the NECC have a very well marked seasonal cycle. It seems, however, from the new Programme Francais Océan Climat dans l'Atlantique Equatorial (FOCAL) data set, that this strong seasonal cycle can be largely modified by interannual changes.

2. Data

We shall use in this paper the observations made during the oceanographic cruises of the FOCAL Experiment. This program was undertaken first to describe, then to model, the response of the tropical Atlantic to the wind stress on a seasonal scale. Nine cruises from the research vessels Capricorne of the Institut Francais de la Recherche pour l'Exploitation de la Mer (IFREMER) and Nizery of the Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) made a seasonal survey (every 3 months) of the equatorial Atlantic from the Brazilian coastline to the Gulf of Guinea (Figure 1). Temperature, salinity, and dissolved oxygen were measured between the surface and 500 m with a Neil Brown conductivity-temperature-depth-oxygen (CTDO) system, while horizontal velocity was simultaneously obtained by current profiling using a free floating surface buoy. The methods used, as well as the meridional sections of temperature, salinity, dissolved oxygen and zonal components of the currents, were described in an hydrologic atlas of FOCAL cruises published by Hénin et al. [1986]. The dates of the FOCAL cruises are given in Table 1.

FOCAL and the joint U.S. Seasonal Response of the Equatorial Atlantic (SEQUAL) operations resulted in many other measurements during the same period. For the first time an equatorial ocean was globally monitored over a period of two years. In the NECC region, observations consisted of drifting buoys [Richardson, 1984], current meter moorings [Levy and Richardson, 1984 a, b], inverted echo sounders (IES) [Katz and Garzoli, 1984], and surface (temperature and salinity) and subsurface (expendable bathythermograph, or XBT) observations along shipping lines from ship of opportunity programs [Rual and Jarrige, 1984; Bruce, 1984].

3. The Wind Field

The FOCAL cruise period (July 1982, August 1984) is characterized by a well-contrasted meteorological regime which differs from the mean

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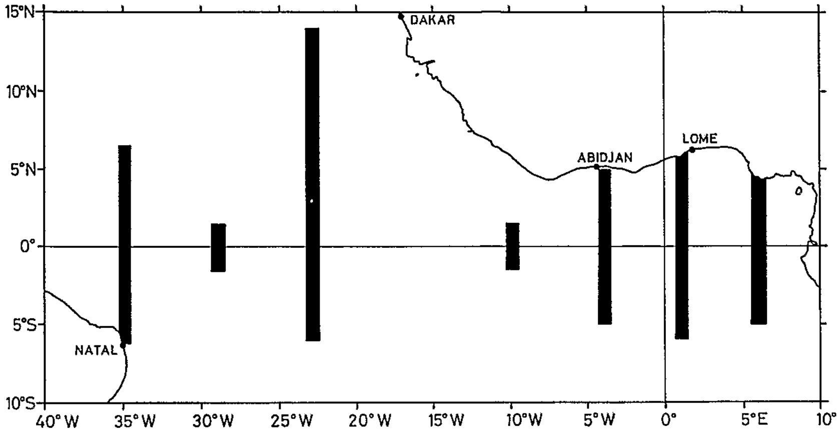


Fig. 1. Distribution of R/V Capricorne and Nizery sections during the FOCAL experiment.

climatology [Horel et al., 1986]. In 1983, very strong northern hemisphere trade wind prevailed north of Brazil, then a sudden relaxation of the wind occurred from December 1983 to January 1984 in the equatorial band.

Following Ekman pumping theory, the thermocline is raised on the north side of the ITCZ, lowered on south side. If geostrophy is assumed, the depth of thermocline, the dynamic topography, and the surface currents are directly related to the position of the ITCZ. This convergence zone of the winds, which presents a general NE-SW axis from west Africa to Brazil, shifts meridionally during the year. Its northern position occurs in July-October, and it reaches its southernmost position during January-April when it crosses the equator in the western Atlantic.

The curl of wind stress during the FOCAL period has been computed from the 10-m level wind stress which was provided by the European Meteorological Center in Reading, England, on a 1.875° X 1.875° grid and was processed by Tourre and Charvy [1985]. The first version of wind data set was used by S. Arnault (personal communication, 1986) to produce $d\tau_y/dx - d\tau_x/dy$ for the 22.5°-24.375°W and the 35.625°-33.750°W bands (Figure 2) from

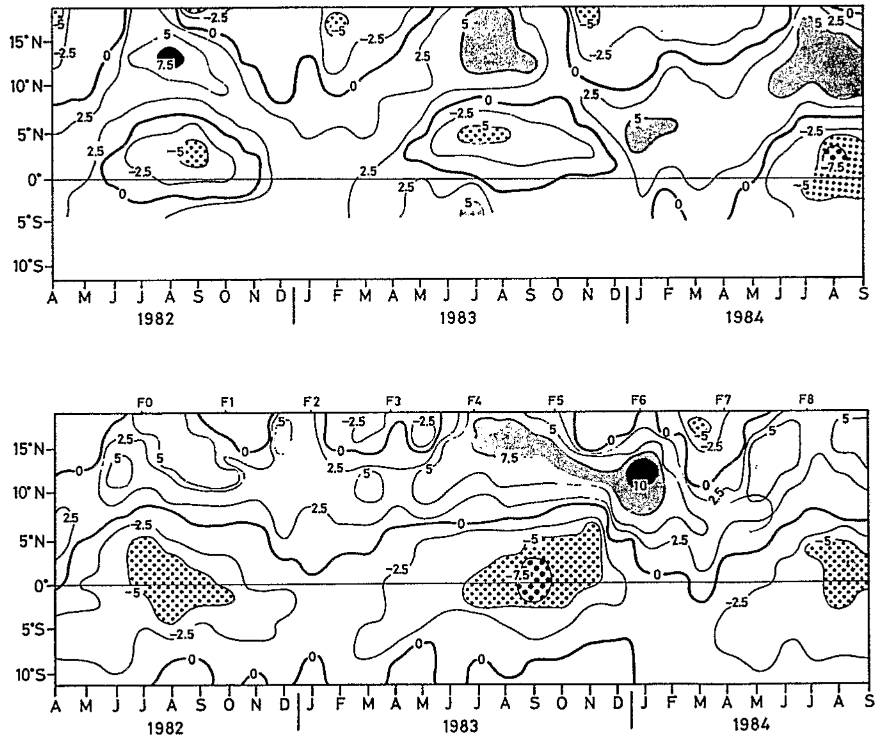


Fig. 2. Wind stress curl in 10^8 International System units issued from European Meteorological Center in Reading (top) along 35°W and (bottom) along 23°W.

TABLE 1. FOCAL Cruise Schedule

Cruise	Start Date	End Date	Year
0	July 6	July 23	1982
1	Oct. 13	Nov. 21	1982
2	Jan. 11	Feb. 18	1983
3	March 16	April 29	1983
4	July 1	Aug. 6	1983
5	Oct. 3	Dec. 2	1983
6	Jan. 11	Feb. 15	1984
7	April 2	May 14	1984
8	July 3	Aug. 7	1984

April 1982 to September 1984. The seasonal cycle of the upward pumping north of 10°N and of the downward sinking is well delineated at both longitudes. A maximum meridional gradient of wind stress curl occurs in July-September every year, which implies a maximum NECC flux. Along 23°W this gradient is, however, the strongest in January 1984 and shifts toward the south (4°N instead of 6°N, approximately). This is due to the drastic relaxation of the tradewind. This topic is also covered by Hisard and Hénin [1987].

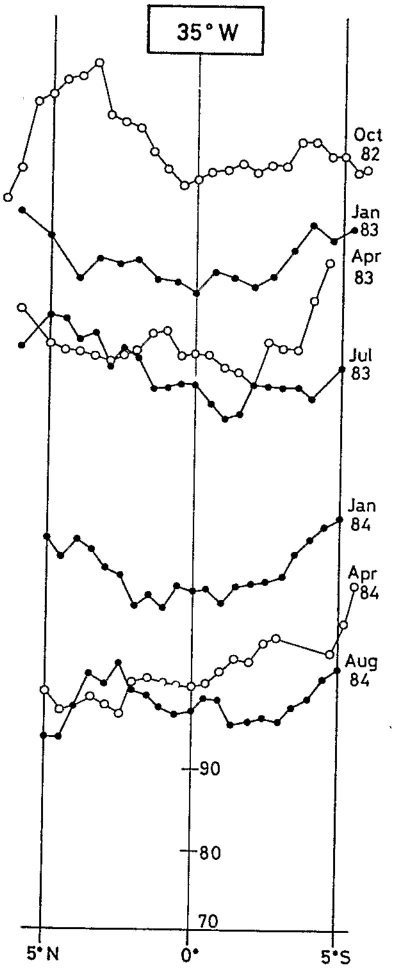


Fig. 3. Surface dynamic height along 35°W relative to 500 dbar. Dynamic scale is reported for August 1984 cruise; each cruise is shifted vertically to 10 dyn cm.

4. Dynamic Topography

The dynamic topography may be used to determine the geostrophic circulation outside of the strictly equatorial band (2°N to 2°S). Dynamic topography was calculated for the surface relative to 500 dbar along 35°W, 23°W, and 4°W meridional sections (Figures 3, 4, and 5). Eastward surface velocities correspond to dynamic height values increasing equatorward. In the central and eastern sections, the NECC and the Guinea current were correctly monitored by our cruises, but at the western section north of Brazil along 35°W the observations were unfortunately limited to the south of 5°-6°N.

4.1. The 23°W Section

In the central Atlantic (Figure 4) a dynamic crest is always observed between approximately 3°N and 5°N while a minimum (trough) is located at 7°N (January 1984) or further north. During some cruises no trough was observed when it occurred north of 14°N, the northern limit of measurements.

The north-south maximum dynamic height gradient is quite variable in strength and in latitude. These two parameters (amplitude of meridional gradient and latitude) are both of primary importance to determine the geostrophic velocity which is given by

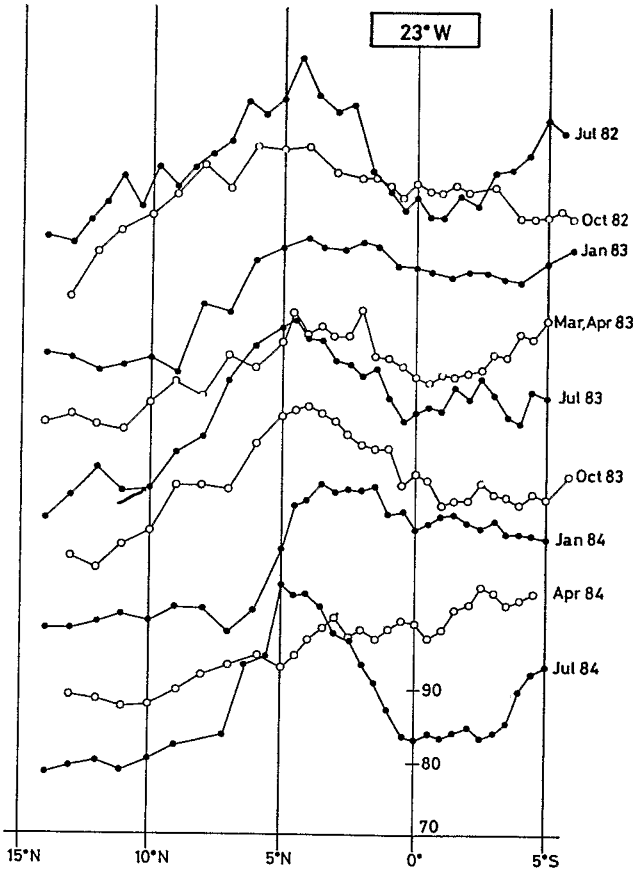


Fig. 4. Same as Fig. 3, except along 23°W.

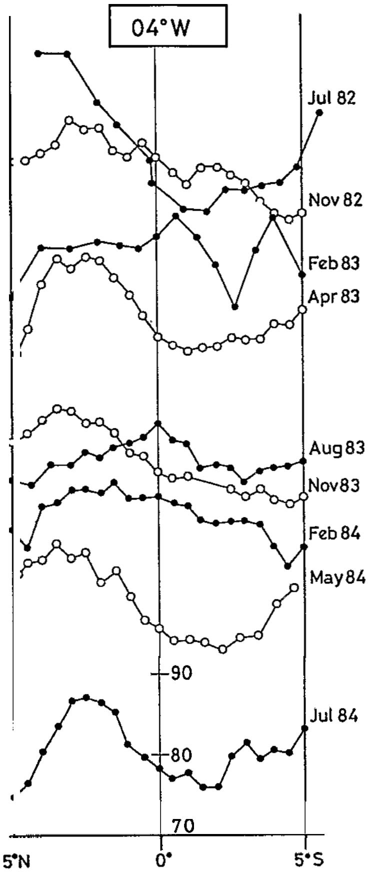


Fig. 5. Same as Fig. 3, except along 4°W.

$$V = (1/2\ \omega \sin \Phi) * (dH/dy)$$

where ω is rotation of the earth, Φ is latitude, and dH is dynamic height difference for a north-south variation dy.

Because the relative variation of the Coriolis parameter (f=2 ω sin (Φ)) is large at low latitudes, the meridional location of the dynamic height maximum gradient is essential to determine the eastward geostrophic core, which is represented in Figure 6 for every FOCAL cruise.

Therefore it is not surprising, even if the dynamic height of the ridge presents a seasonal signal with maximum in July-October and minimum in January-April [Hénin and Hisard 1984], that a very large eastward velocity core is observed in January 1984. At this time the meridional dynamic height gradient was stronger than usual and had shifted toward the equator.

The wind stress curl along 23°W (Figure 2) showed a very strong Ekman pumping further south than usual and in January instead of August-September. Therefore the NECC seems directly associated with wind stress forcing.

Studies carried out with various climatologies, ship drifts by Richardson and McKee [1984], Hellerman wind stress [du Penhoat and Treguier, 1985], hydrologic atlas [Merle, 1978; Garzoli and Katz, 1983], concluded that the NECC shows a very well marked cycle and even reversal in winter in the western Atlantic.

FOCAL observations have confirmed these structures and have confirmed the much reduced flow in spring in 1983 and in 1984. The NECC was shifted toward the equator and was associated with a flat dynamic topography.

Another feature of FOCAL observations is the very weak NECC in October 1982, which was unfortunately not corroborated by other FOCAL and SEQUAL operations because a large number of observations started only in early 1983.

Comparing October 1982 and October 1983 confirms the interannual changes of the NECC regime as well as the extreme development of the wind field.

Mass fluxes of the NECC along 23°W (Figure 6 and Table 2) show the very large difference between the two annual cycles observed during the FOCAL experiment. During the first period (July 1982 to July 1983) the flux is almost half the flux of the second period (July 1983 to July 1984).

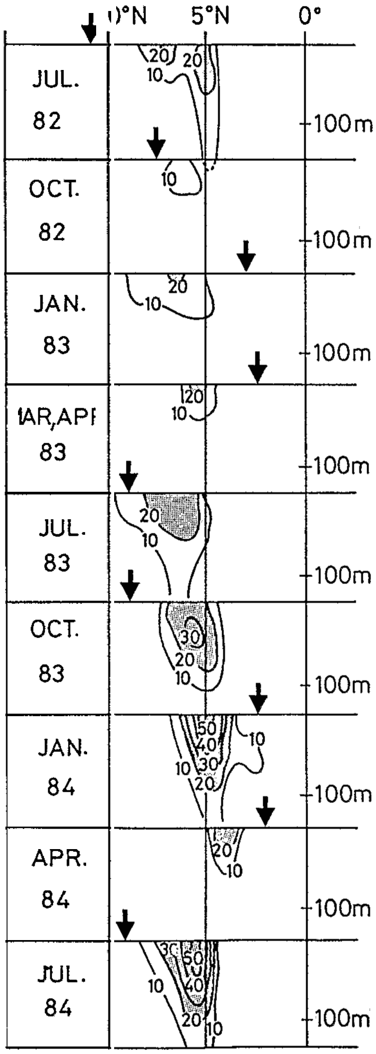


Fig. 6. Zonal geostrophic velocity for each FOCAL cruise along 23°W. Only contours of eastward velocities >10 cm/s are drawn. Velocities greater than 20 cm/s are shaded. The ITCZ is indicated by vertical arrows.

TABLE 2. Eastward Geostrophic Fluxes of NECC (0-100 m) Along 23°W

	FOCAL Cruise								
	0	1	2	3	4	5	6	7	8
Date	July 1982	Oct. 1982	Jan. 1983	April 1983	July 1983	Oct. 1983	Jan. 1984	April 1984	July 1984
Flux U									
>10 cm/s	4.8	1.1	4.0	1.8	7.8	7.8	10.1	1.6	10.1
>0 cm/s	7.3	4.2	6.8	3.8	9.1	10.0	11.1	3.6	11.6

Fluxes are in 10^6 m^3/s.

We may mention here the effect of the wind stress anomaly described by Tourre and Charvy [1985] and Horel et al. [1986], that is a large development of trade winds during 1982-1983 followed by a sudden relaxation in early 1984.

4.2. The 35°W Section

Although this section is limited to the south of 5° - 6°N and is inappropriate to monitor correctly the NECC, we observe that during the two spring cruises (April 1983 and April 1984), dynamic heights suggest an eastward current located close to the equator and just north of it. Direct current observations confirm that this eastward surface core is distinct from the Equatorial Undercurrent core (Figure 7). At this time the ITCZ crossed the equator north of Brazil, and this suggests that the NECC may be dramatically pushed toward the equator. This spring current structure is confirmed by two years of observations with quite different meteorological regimes.

4.3. The 4°W Section

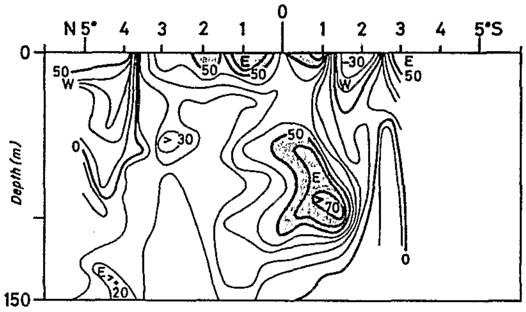
Along 4°W south of the African coastline and north of the equator, the eastward Guinea Current is observed throughout the year, but its true seasonal cycle is not very evident from our measurements.

The FOCAL sections along 4°W revealed very large dynamic height values (Figure 5) and a very large heat content for the 0-100 m upper layer during January and April 1984 at, and north of, the equator (Figure 8). This suggests an advection from the NECC, which was exceptionally well developed in the central Atlantic and whose southernmost position facilitates its penetration in the Gulf of Guinea.

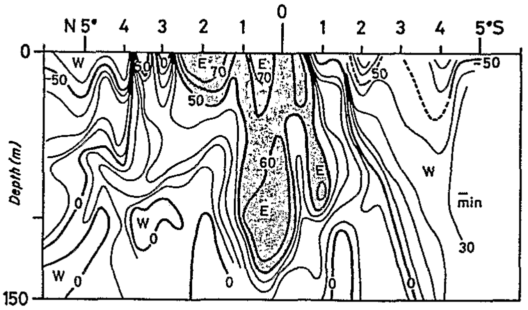
5. Direct Current Measurements

During FOCAL cruises on board R/V Capricorne, direct current profiles were obtained in the upper 500 m with a current profiler working in conjunction with a free floating buoy. When possible, observations with this system were compared with data from FOCAL and SEQUAL current meters under moored buoys [Colin, 1987; R. H. Weisberg, personal communication, 1985]. They agreed very well on the equator [Hénin and Hisard, 1986].

Because of deep subsurface currents in the NECC, the level of no motion is difficult to estimate. However, current profiles relative to 500 m seem to closely correspond to geostrophic velocities during all FOCAL cruises except during October 1982. At this time, geostrophy gives a very small eastward flow while direct measurements give the largest eastward NECC velocities of the FOCAL experiment (80 cm/s). As a result we may question the geostrophy of the NECC. The meridional smoothing of dynamic height reduces considerably the eastward geostrophic core, which is approximately at the same place as the very narrow core observed directly. Therefore the



FOCAL 3
10-14 APRIL 1983



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14-17 APRIL 1984

Fig. 7. Zonal component along 35 W from direct observations. (left) April 1983, (right) April 1984.

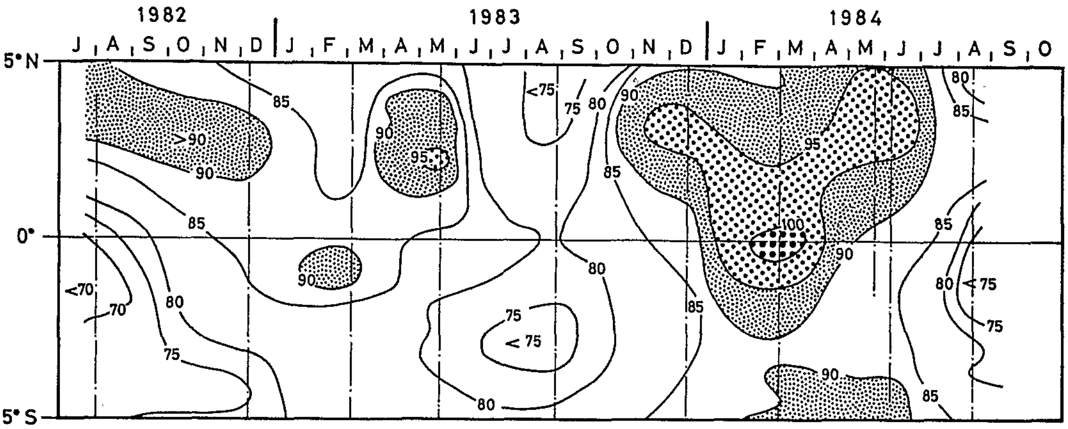

Fig. 8. Time latitude heat content of the 0-100 m layer along 4°W (in 10^8 J/m^2).

discrepancy between geostrophic and observed velocities may be due to a sampling problem.

In Figure 9 the upper 0-100 m profiles of temperature, salinity, and zonal component of direct current observed at two stations located within the NECC core show that the surface core is generally observed in the upper 50 m layer, but may be deeper on some occasions (October 1983).

The eastward velocity core may be under the surface (October 1983; it is also revealed by geostrophic currents in January 1984 and July 1984 (Figure 3)).

Direct observations of currents [Hénin et al. 1986] also confirmed that the main core of the NECC always lies near 4°-6°N, independent of the ITCZ latitude as revealed by geostrophy (Figure 6).

North of this main core, a few regions of eastward surface velocity were also observed during summer, facilitated by a westerly wind.

The seasonal regime of the NECC, as well as a larger zonal flux during the second period of the FOCAL experiment, is also confirmed by direct measurements [Hénin et al., 1986].

6. Salinity

The NECC is located in a salinity field that varies horizontally and vertically.

6.1. Horizontal

The salinity of the surface layer decreases from the South American coastline (35.8 ppt) to western Africa (< 34.0 ppt) [Merle, 1978]. North of South America, the Brazil Current supplies the western equatorial Atlantic with high-salinity waters from the South Atlantic.

The Atlantic NECC has long been associated with low-salinity surface waters as has the Pacific NECC [Hénin and Donguy, 1980]. However, observations made during the FOCAL experiment lead us to the conclusion that low-salinity water was directly related by rainfall to the location of the ITCZ rather than to the NECC. While the NECC core along 23°W during the nine FOCAL cruises was always observed between 4°N and 6°N, the surface salinity minimum was seen between 2°N and 9°N following the displacement of the ITCZ.

The surface salinity, shown by season in Figure 10, reveals that in April the minimum surface salinity lies near 3-5°N and in October near 8-9°N. Its smallest value (< 34.0 ppt) was observed in October 1982 at 8°N. Surface salinity of the core of NECC is approximately always near 35.0-35.5 ppt.

6.2. Vertical

The subsurface maximum salinity core, located at the base of the homogeneous layer, is quite constant near 36.1-36.2 ppt. This maximum of salinity is also often observed within the eastward flow (Figure 9) when the latitude of the ITCZ coincides with the NECC core; then the

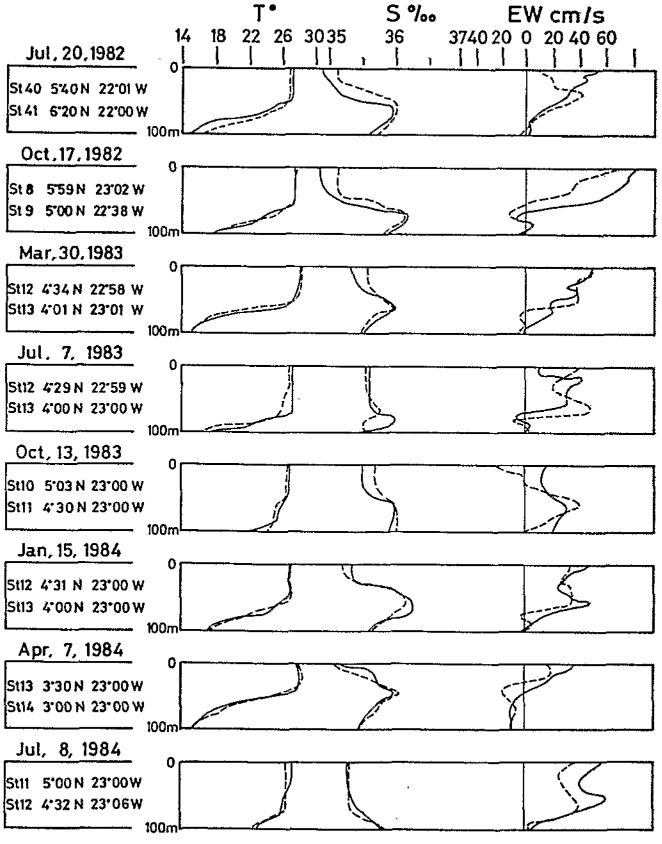

Fig. 9. Temperature, salinity and zonal velocity profiles of the 100 m upper layer at two characteristics NECC stations for each FOCAL cruise.

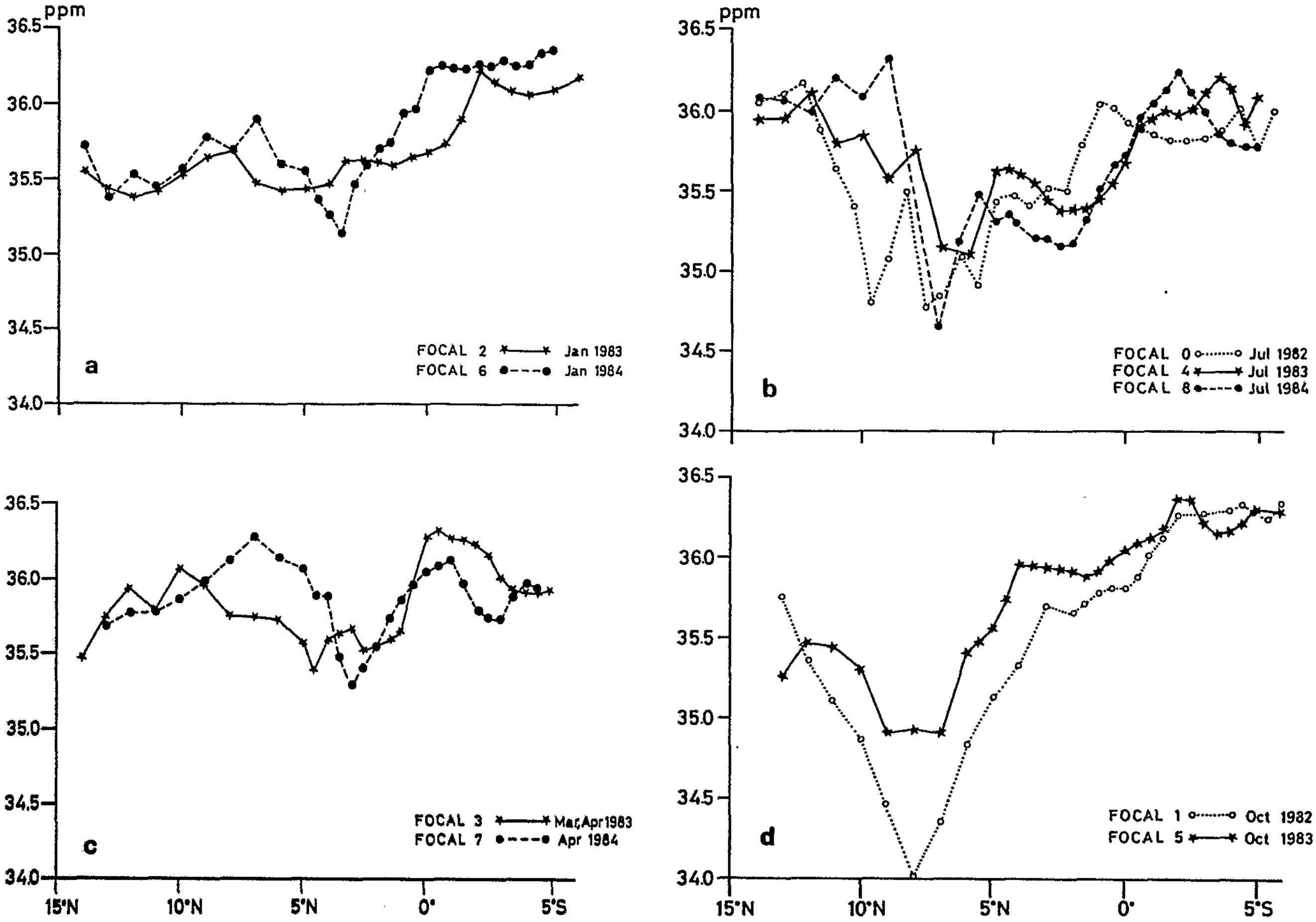

Fig. 10. Mean salinity of the upper 20 m layer along 22°-23°W (a) in January 1983 and 1984; (b) in July 1982, 1983 and 1984; (c) in April 1983 and 1984; and (d) in October 1982 and 1983.

vertical salinity gradient is very large even if temperature is constant. When the latitude of the ITCZ is quite different from the latitude of NECC core, as it is during July 1983, the vertical gradient is very small.

The transport of high-salinity water in the subsurface layers is well illustrated in January 1984 when, in the whole equatorial Atlantic, large eastward flows were developed, particularly the NECC. At this time in the upper 100 m layer, salinity was higher than it was during the other eight FOCAL cruises. Instead of isolated high-salinity cores at the base of the homogeneous layer, only one cell of salinity higher than 36.0 ppt was observed from 10°N to the equator [Henin et al., 1986]. Therefore the low salinity surface waters do not characterize NECC waters. However, the NECC is one of the major currents which redistributes eastward, under the surface, the high-salinity water accumulated in the western equatorial Atlantic.

7. Discussion

We may ask whether the reversal of NECC in winter is replaced by an eastward flow closer to the equator north of Brazil which contributes to the draining of the warm saline water accumulated in the west by the trade wind circulation. Although the size and meteorological regimes of the western Atlantic and Pacific oceans are different, this current near the equator is comparable to the western eastward surface current observed north of New Guinea in the western Pacific when the Asiatic monsoon occurs [Colin et al, 1973; Hisard and Hénin, 1984].

8. Conclusion

Observations from FOCAL cruises confirmed that in the central Atlantic along 23°W, the North Equatorial Countercurrent has a well-defined seasonal cycle with a much reduced flux in spring. The cruises reveal that the main core of the NECC always lies between 4° and 6°N.

Another result is the evidence of a long-term change of the NECC, which was abnormally well developed in January 1984. Because of its southernmost position at this time and its connection with the Guinea Current, the NECC may fill the Gulf of Guinea with warm, saline waters. This event is certainly connected with the "El Niño" type event observed off the Namibian coastline in March-April 1984 [Boyd and Thomas, 1984]. The volume of water of temperature higher than 20°C was estimated in the area delimited by the African coastline, 4°W, 4°S, and 6°E. It was only 38 X 10^{12} m^3 in January-February 1983 and more than 72 X 10^{12} m^3 in January-February 1984.

Simple linear models (Y. du Penhoat and Y. Gouriou, personal communication, 1986) driven by measured wind stress during FOCAL also found a large accumulation of warm water in January 1984 in the Gulf of Guinea. Because of the very restricted NECC core, and with the help of the XBT network actually developed for the Tropical Ocean and Global Atmosphere (TOGA) program (1985-1995), it should be therefore possible to correctly monitor (by close spacing of XBT launches between 3°N and 8°N) the NECC, which is one of the main sources of eastward flows and which contributes to the development of "El Niño" type events in the eastern Atlantic Ocean.

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