OCEANOLOGICA ACTA, 1987, N° SP

The distribution of nutrients in the equatorial Atlantic : relation to physical processes and phytoplankton biomass

Nutrients
Physical processes
Vegetal biomass
Equatorial Atlantic

Sels nutritifs
Processus physiques
Biomasse végétale
Atlantique équatorial

Claude OUDOT [a], Pascal MORIN [b]
[a] Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM), B.P. 1386, Dakar, Sénégal.
[b] Laboratoire d'Océanographie Chimique, Université de Bretagne Occidentale, 6, Avenue Le Gorgeu, 29283 Brest Cedex, France.

Received 2/7/85, in revised form 20/5/86, accepted 27/5/86.

ABSTRACT

In the Gulf of Guinea (4°W), the equatorial upwelling, generated by the divergence of surface current meridional components, appears only during the boreal (northern) summer (June to September) south of the Equator and exhibits a considerable enrichment in nitrate and phosphate at the sea surface. At the Equator below the surface, there is also a seasonal nutrient enrichment due to vertical mixing or/and vertical motion of the thermocline. Zonal advection from the African coastal zone, often advanced to explain the equatorial fertility, does not completely agree with the observed surface distributions of nitrate.

In the western equatorial Atlantic (35°W), the seasonal surface nutrient enrichment does not appear in July and the surface layer seems to remain impoverished in nutrient throughout the year. Here, the thermocline is deeper than at 4°W and the equatorial divergence does not seem sufficiently strong to raise the nutrient into the euphotic zone ; consequently, the phytoplankton biomass is reduced. Westward along the Equator, a sharp deepening of the thermocline occurs between 20° and 25°W.

Oceanol. Acta, **1987.** Proceedings International Symposium on Equatorial Vertical Motion, Paris, 6-10 May 1985, 121-130.

RÉSUMÉ

La distribution des sels nutritifs dans l'Atlantique équatorial : relation avec les processus physiques et la biomasse phytoplanctonique

Dans le Golfe de Guinée (4°W), l'upwelling équatorial, engendré par la divergence des composantes méridiennes du courant de surface, apparaît seulement durant l'été boréal (juin à septembre) au sud de l'équateur, et montre un important enrichissement en nitrate et phosphate à la surface de la mer. Mais à l'équateur proprement dit, en subsurface, un autre enrichissement momentané en sels nutritifs, dont l'origine est discutée, se produit : mélange vertical ou/et élévation de la thermocline. L'advection zonale à partir de la zone de l'upwelling côtier africain, souvent mise en avant pour expliquer la fertilité équatoriale, ne s'accorde pas complètement avec les distributions de surface observées de nitrate.

Dans la partie occidentale de l'Atlantique équatorial (35°W), l'enrichissement superficiel saisonnier en sels nutritifs n'apparaît pas en juillet, et la couche de surface semble rester appauvrie toute l'année. A cet endroit, la thermocline est plus profonde qu'à 4°W, et la divergence équatoriale ne semble pas assez forte pour amener les sels nutritifs dans la couche de surface bien éclairée : la biomasse phytoplanctonique est alors réduite. C'est entre 20 et 25°W que l'enfoncement de la thermocline est le plus accentué, le long de l'équateur.

Oceanol. Acta, **1987.** Proceedings International Symposium on Equatorial Vertical Motion, Paris, 6-10 May 1985, 121-130.

INTRODUCTION

Nutrient distribution has long been used in hydrological studies to show the vertical motions in the surface layer of the ocean. First determined by biochemical processes (consumption — regeneration), this distribution within the ocean can afterwards be modified by physical processes (vertical and horizontal advection — turbulent mixing).

In tropical regions, in contrast with what happens in mid-latitude regions, the production cycle is continuous throughout the year and the thermocline is permanent. Nonetheless the surface circulation induced by the trade winds is subject to seasonal variations which can affect the structure of the thermocline. For a long time these seasonal variations in the equatorial area of the Atlantic Ocean were unknown because consistent reference was made to the Equalant cruises, of which the summer one (Equalant 2 in August 1963) subsequently appeared to have been carried out in abnormal conditions for that season.

Since the beginning of the 1970, the work of the ORSTOM oceanographers in the Gulf of Guinea has shown that the eastern equatorial Atlantic area undergoes seasonal variations. Data collected during the five CIPREA cruises carried out in the eastern part between August 1978 and January 1980 (Fig. 1) and during five FOCAL cruises to the west as far as the South American coast between July 1982 and August 1984 have improved our knowledge of variations in nutrient distribution in the equatorial Atlantic and of the influence of different physical processes on such distribution. A quantitative comparison of nutrient and chlorophyll pigments helps to clarify the role of nutrient in the observed variability of phytoplankton biomass in the equatorial Atlantic.

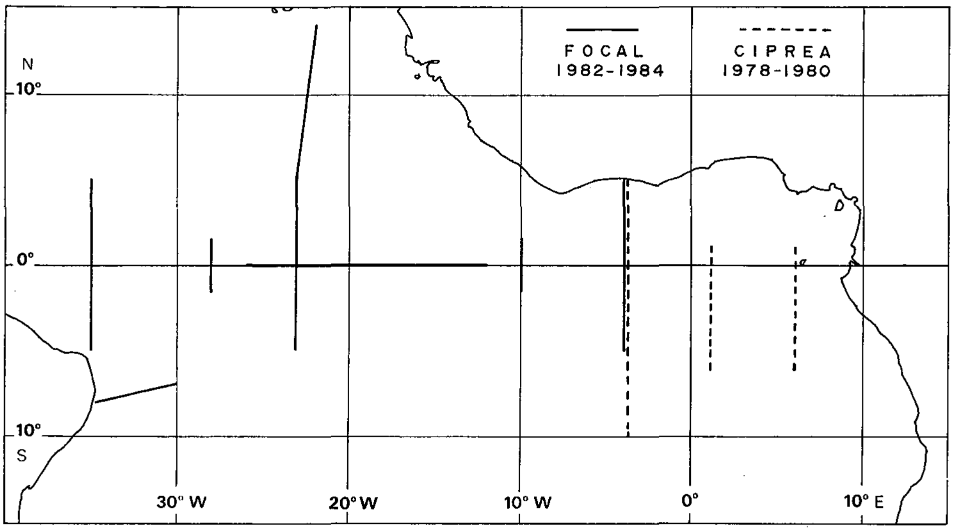


Figure 1

Location of the observation tracks in the equatorial Atlantic: CIPREA cruises (1978-1980) et FOCAL cruises (1982-1984).

Localisation des rails d'observations dans l'Atlantique équatorial : campagnes CIPREA (1978-1980) et FOCAL (1982-1984).

SEASONAL VARIABILITY

Surface

It has long been accepted that in the three oceans, the equatorial belt is subject to the effects of the divergence of the surface current meridional components, and is consequently the centre of a vertical upward transport, called upwelling. This upwelling, distinguished in the first place by a cooling of the surface layer, is more or less pronounced according to the season and the longitude. According to the analysis of the historical data (Mazeika, 1968 ; Merle, 1978), the equatorial upwelling in the Gulf of Guinea appears usually in northern summer. Between April and August at 4°W (Fig. 2) the surface temperature drops from more than 28°C to less than 22°C in the band of 0°-5°S latitude. The cooling of this band is accompanied by a nitrate and phosphate enrichment of the surface layer above the thermocline : within this band the superficial concentration of nitrate, inferior to 0.1 $\mu mol.l^{-1}$ during the warm season, becomes higher than 2.0 $\mu mol.l^{-1}$ in the cold season from 0° to 5°S, with a maximum value exceeding 6.0 $\mu mol.l^{-1}$ (Fig. 2 in the middle) ; at the same time, the phosphate concentration increases from 0.1 to 0.4 $\mu mol.l^{-1}$ (Fig. 2 at the bottom). Thus, at the 4°W longitude, the area cooled and enriched in nutrient lies completely to the south of the Equator, contrary to what generally happens further to the west, where this area overlaps the Equator, as we shall see later (Fig. 7). This shift of the upwelling zone, reported time and again (Hisard *et al.*, 1977 ; Voituriez, 1980 ; Oudot, 1983), is in agreement with the qualitative model proposed by Cromwell (1953), which forecasts a divergence and consequently an upwelling south of the Equator when the wind blows from the southeast : this is the case south of the Equator in the Gulf of Guinea, where southeasterly trade winds are the usual rule.

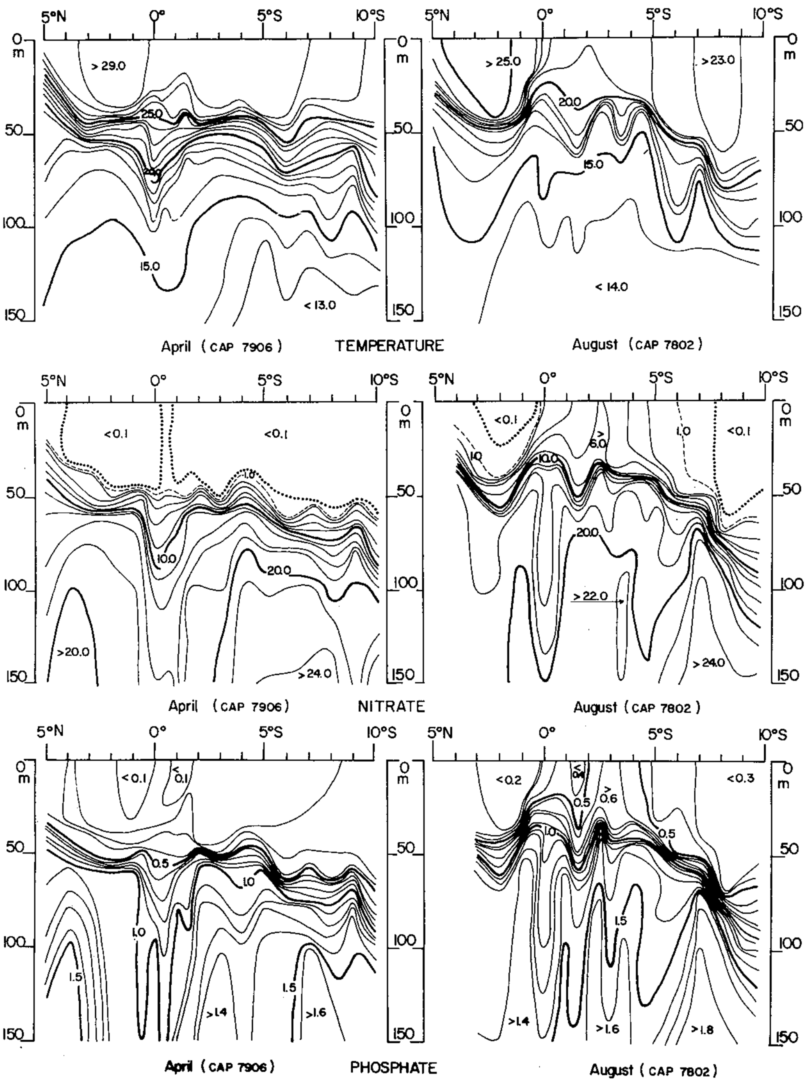


Figure 2

Meridional distributions along 4°W of temperature (°C), nitrate ($\mu mol.l^{-1}$) and phosphate ($\mu mol.l^{-1}$). Right in August 1978 (CIPREA 1) : upwelling season ; left in April 1979 (CIPREA 2) : warm season.

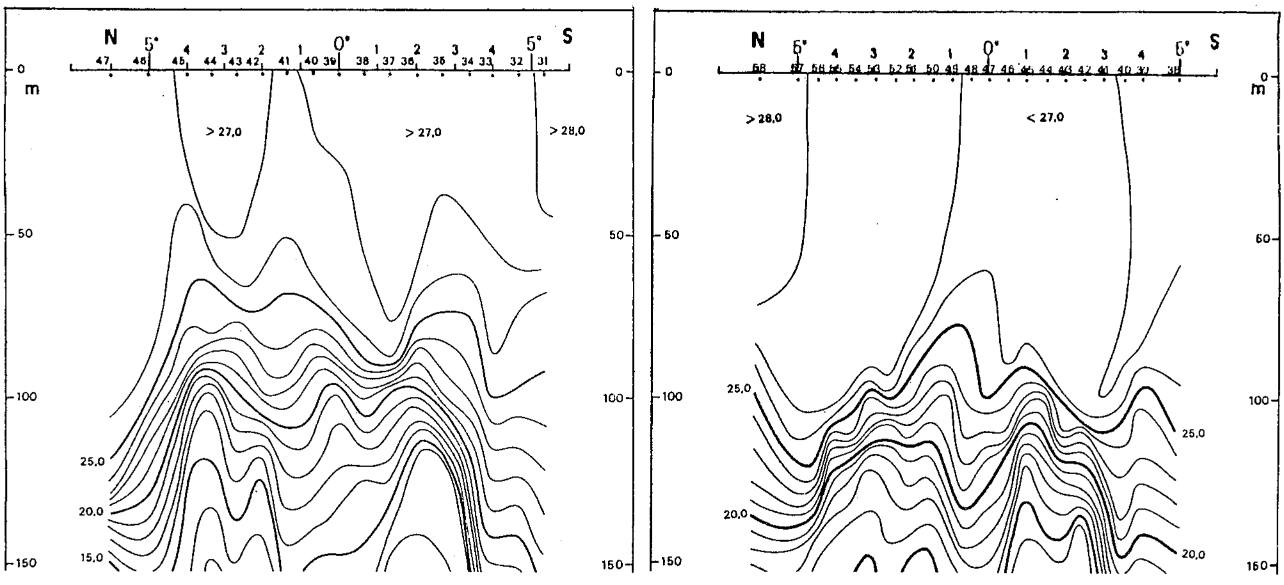
Distributions méridiennes le long de 4°W de la température (°C), du nitrate ($\mu mol.l^{-1}$) et du phosphate ($\mu mol.l^{-1}$). A droite en août 1978 (CIPREA 1) : saison d'upwelling ; à gauche en avril 1979 (CIPREA 2) : saison chaude.

To the west (35°W), off the coast of Brazil (Fig. 3) there is no large seasonal cooling of the sea surface and no large nutrient enrichment of the surface layer to match that at 4°W. There, the thermocline, nitracline and phosphacline are much deeper than at 4°W. The absence of seasonal variations in the western equatorial area has been pointed out before by Kaiser and Postel (1979) at 30°W. We may, however, notice a light nutrient enrichment in January against July : the surface concentrations of nitrate and phosphate exceed 0.1 and 0.2 $\mu mol.l^{-1}$ respectively in January, but not in July (Fig. 3). In support of a seasonality opposite to that observed at 4°W, we note that the thermocline is slightly shallower in January than in July. We shall return to this topic later.

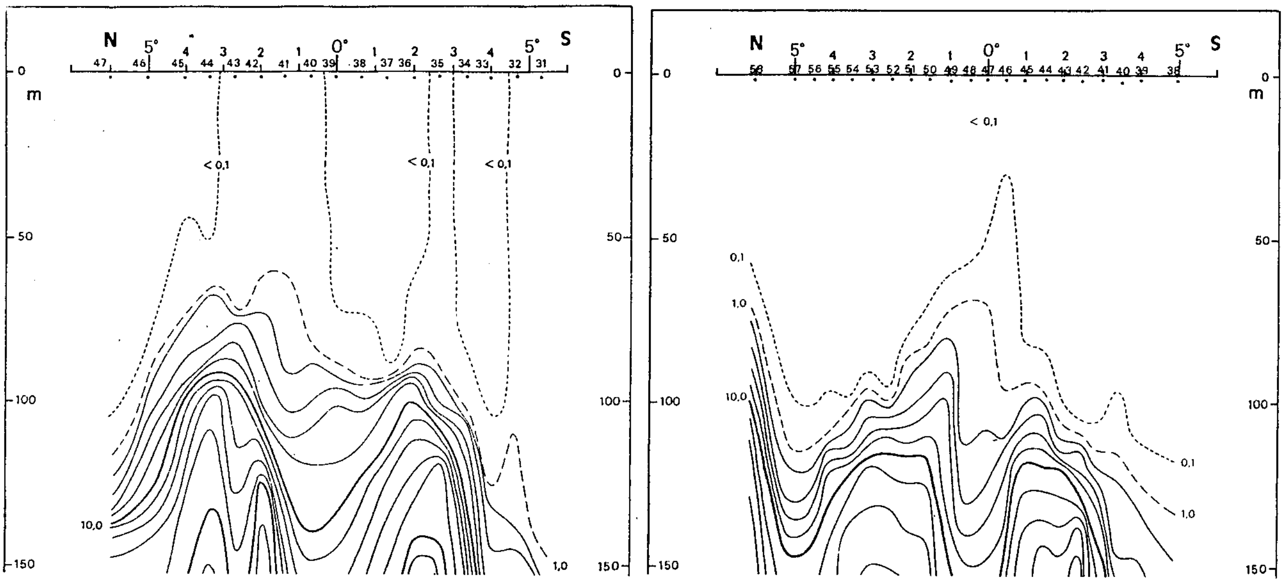
Subsurface

Along the 4°W meridian (Fig. 2) on the Equator at about 50 m depth, *i.e.* at the mean level of the Equatorial Undercurrent (Voituriez, 1983), the seasonal variation of the nitrate and phosphate distributions is also quite clear. In August the Undercurrent is carrying waters much richer in nutrient than in April : at 60 m (Fig. 2), mean depth of the core of the Undercurrent constant throughout the year according to Voituriez (1983), nitrate and phosphate concentrations increase from less than 6 $\mu mol\ NO_3.l^{-1}$ and 0.6 $\mu mol\ PO_4.l^{-1}$ to more than 14 $\mu mol\ NO_3.l^{-1}$ and 1.2 $\mu mol\ PO_4.l^{-1}$. This enrichment, which is important from an ecological point of view because it affects the euphotic layer, is different from the upwelling process.

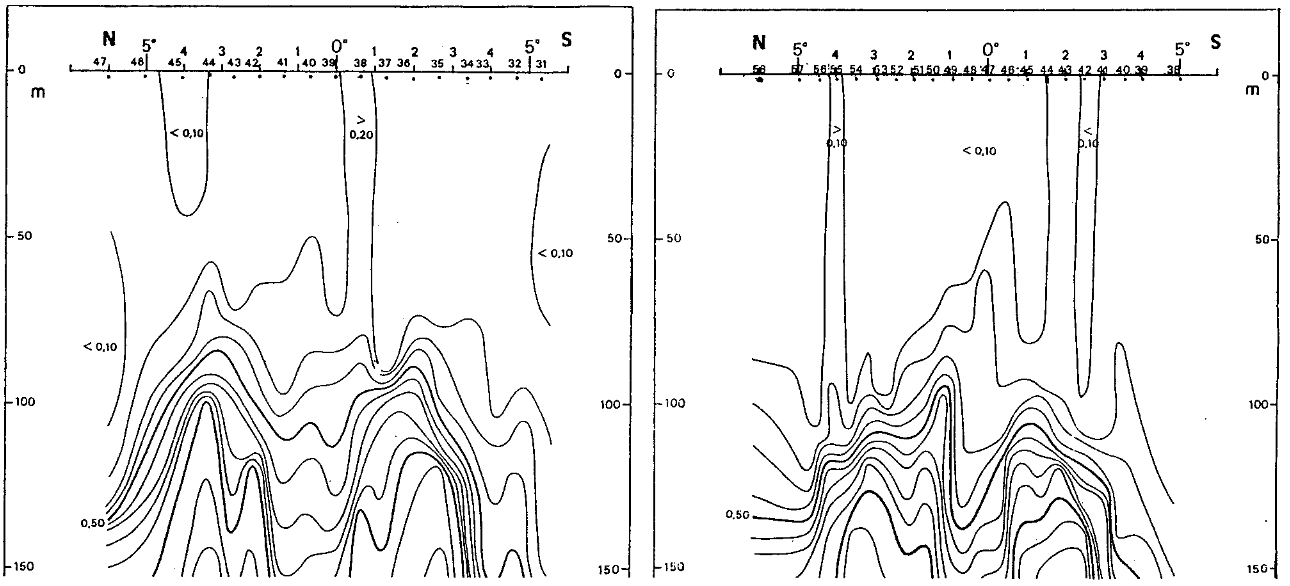
For a long time, seasonal variations of the hydrological properties and nutrient within the Equatorial Undercurrent were interpreted as resulting from increased vertical mixing in boreal summer between the Undercurrent and the surface Equatorial Current (Hisard *et al.,* 1977 ; Voituriez, Herbland, 1979). The resulting nutrient enrichment of the euphotic layer could be important because it lasts longer than the upwelling itself, as is suggested by the analysis of the meridional distributions of nitrate during six months of the year (relatively to different years). We can see from figure 4, taking as reference the shape of the 1.0 $\mu mol\ NO_3.l^{-1}$ isopleth (which corresponds approximatively to the upper limit of the Equatorial Undercurrent), that the strict equatorial enrichment, allegedly the result of vertical mixing, lasts longer (it appears in June and it is still present in January) than the enrichment south of the Equator associated with the upwelling (from June to September). This would confirm at 4°W the hypothesis of Kaiser and Postel (1979), for whom at 30°W vertical mixing is more important than vertical advection in the process of



January 1983 TEMPERATURE July 1983



January 1983 NITRATE July 1983

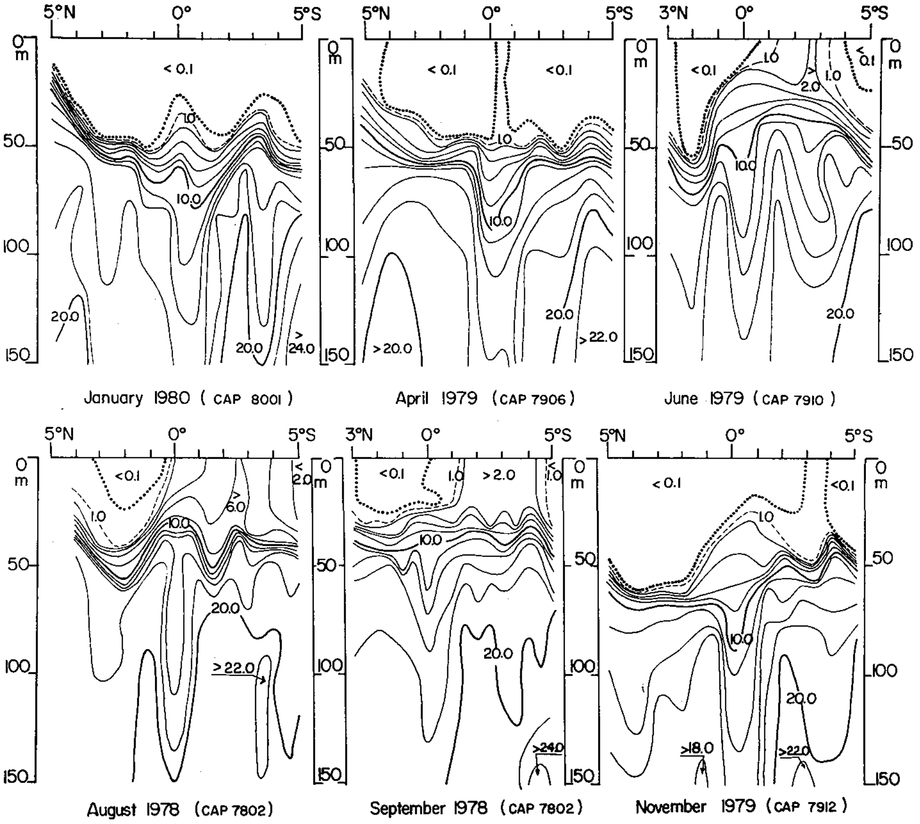


January 1983 PHOSPHATE July 1983

Figure 3

Meridional distributions along 35°W of temperature (°C), nitrate (µmol.l^{-1}) and phosphate (µmol.l^{-1}). Left in January 1983 (FOCAL 2) ; right in July 1983 (FOCAL 4).

Distributions méridiennes le long de 35°W de la température (°C), du nitrate (µmol.l^{-1}) et du phosphate (µmol.l^{-1}). A gauche en janvier 1983 (FOCAL 2) ; à droite en juillet 1983 (FOCAL 4).



January 1980 (CAP 8001) April 1979 (CAP 7906) June 1979 (CAP 7910)

August 1978 (CAP 7802) September 1978 (CAP 7802) November 1979 (CAP 7912)

Figure 4

Meridional distributions of nitrate (μmol.l^{-1}) along 4°W in six different months of the year (relatively to different years) (CIPREA cruises).

Distributions méridiennes de nitrate (μmol.l^{-1}) le long de 4°W en six différents mois de l'année (campagnes CIPREA), correspondant à des années différentes.

nutrient enrichment of the equatorial layer. Erosion of the salinity maximum of the Equatorial Undercurrent and the parallel increase of the surface salinity, decrease of the surface temperature and increase of the surface nitrate concentration have also been considered as an argument in support of the hypothesis of vertical mixing (Hisard, 1973 ; Voituriez, Herbland, 1979). A 13-day period of observations at the Equator in October 1979 (Fig. 5) shows the coupling between the cooling and the nitrate and salinity increases of the surface layer and the decrease of the salinity maximum at a 50 m depth. These short term variations (the cooling phase lasts from 23-31 October, *i.e.* 8 days) suggest a meandering of the Equatorial Undercurrent, which occurs with a period of ~ 16 days (Düing *et al.,* 1975). In reality, the decrease of the salinity maximum within the Undercurrent is accompanied by a decrease of the oxygen concentration, which cannot be ascribed to vertical mixing with the well-oxygenated surface layer (Voituriez, 1983). In his study of the Equatorial Undercurrent, this author proved that the modification of the hydrological structure of the Equatorial Undercurrent, and in particular the seasonal variation of the nutrient concentrations, is better accounted for by an elevation of the thermocline than by an increase of the vertical mixing during boreal summer. Merle (1980) showed the vertical motions of the thermocline with the season along the Equator from the African to the Brasilian coasts: the uplifting in summer east of 20°W is evident (Fig. 6), whereas west of 30°W there is a simultaneous deepening. For this author the vertical movement of the thermocline is associated with the dynamical response of the ocean to the seasonally varying winds. According to Figure 6, the upward motion of the thermocline in the eastern Atlantic occurs only between July and September, while the subsurface nitrate enrichment at the Equator continues in November and even into January (Fig. 4). In fact the two processes are not mutually exclusive, and we can admit a nutrient enrichment of the layer immediately beneath the surface by vertical mixing at the boundary between the surface Equatorial Current and the Equatorial Undercurrent and an enrichment of the core of this latter by an elevation of the thermocline and the associated nitracline.

At 35°W, within the Equatorial Undercurrent of which the core is deeper (100 m) than at 4°W, there is a small seasonal variation of the nutrient concentrations (Fig. 3). In January the Undercurrent is carrying waters slightly richer in nutrient than in July : at 100 m depth at the Equator, nitrate concentration increases from less than 2 μmol.l^{-1} to more than 5 μmol.l^{-1} and phosphate concentration from less than 0.3 μmol.l^{-1} to more than 0.4 μmol.l^{-1}. This enrichment corresponds to an uplifting of the thermocline in January in comparison with July : at 100 m on the Equator the temperature decreases from 25°C in July to less than 20°C in January (Fig. 3). These seasonal variations at 35°W agree well with the vertical motion of the thermocline in the western equatorial area showed by Merle (1980) and previously discussed in the eastern part (Fig. 6).

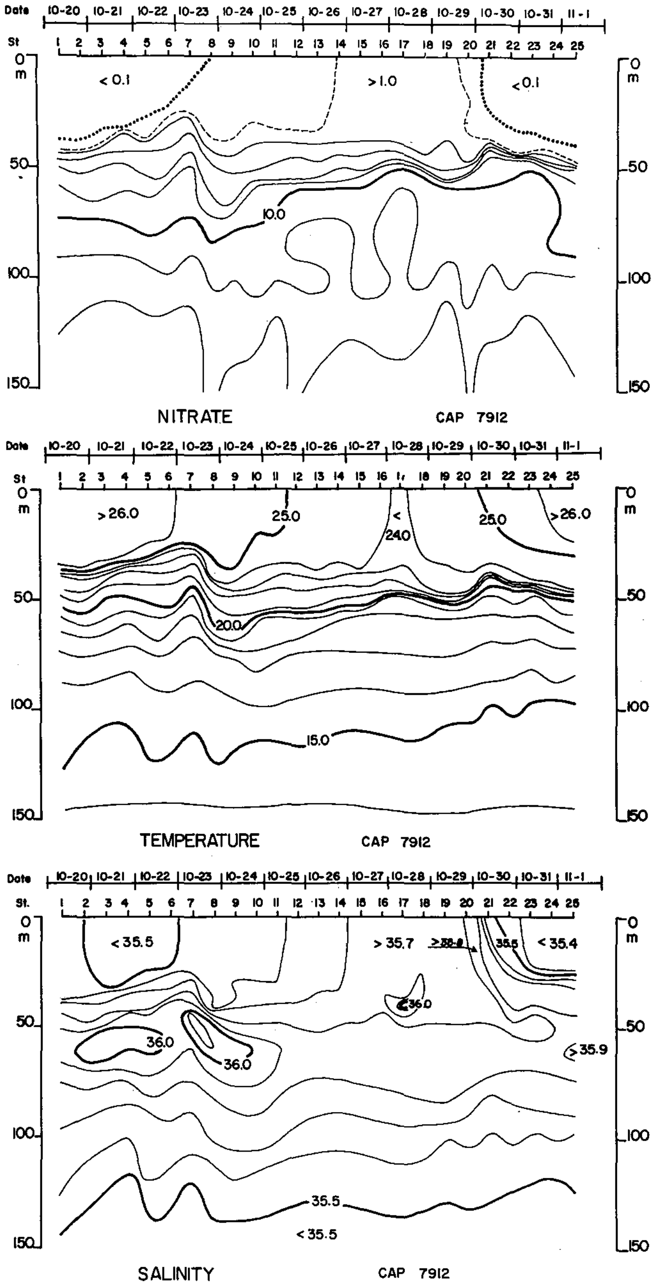


Figure 5

Temporal variations of the vertical distributions of nitrate (µmol.l⁻¹), temperature (°C) and salinity (‰) at the Equator (4°W) during a 13-day period of observations (October 1979 : CIPREA 4).

Variations temporelles des distributions verticales de nitrate (µmol.l⁻¹), de la température (°C) et de la salinité (‰) à l'équateur (4°W) au cours d'une période de 13 jours d'observations (octobre 1979 : CIPREA 4).

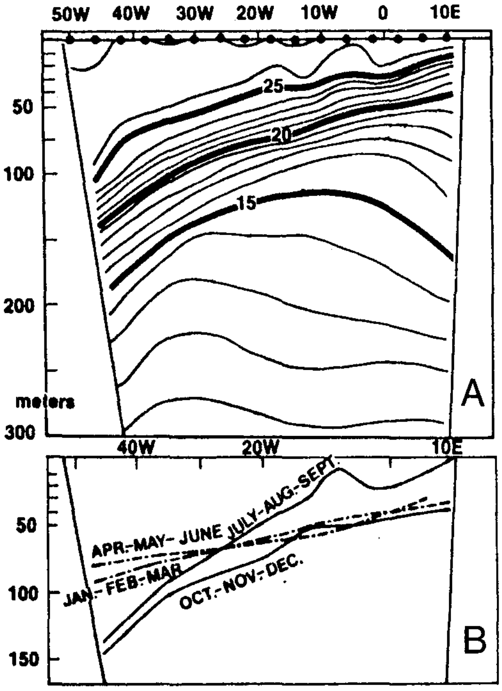


Figure 6

A) *Mean annual temperature in the 0-2°S band from the Brazilian coast (50°W) to the African coast (12°E) ;* B) *Depth variation of the 23°C isotherm for the four seasons of the year along the section shown in Figure 6* A *(after Merle, 1980).*

A) Température annuelle moyenne dans la bande 0-2°S de la côte brésilienne (50°W) à la côte africaine (12°W) ; *B)* Variation de la profondeur de l'isotherme 23 °C pour les quatre saisons de l'année le long de la section montrée sur la Figure 6 *A* (d'après Merle, 1980).

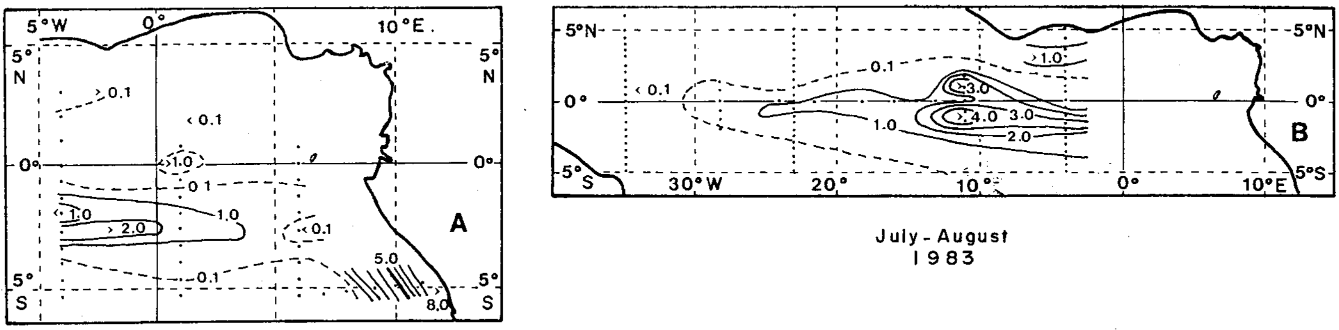
ZONAL EXTENSION OF THE EQUATORIAL ENRICHMENT

Large-scale maps of nutrient distribution at the surface of the oceans show most of the time a continuous decrease of the concentrations along the equatorial belt from the eastern boundary, which constitutes for most of the time the site of coastal upwelling. Seen in this way, nutrient distributions are nothing other than the reflection of the pictures of the surface thermal field derived from atlases (Hastenrath, Lamb, 1977 ; Merle, 1978) and from models (Philander, Pacanowski, 1981) according to which the cold waters observed just south of the Equator come from the coastal upwellings. Therefore, zonal advection from the rich coastal zone is often advanced to explain equatorial fertility. Our observations collected with the RV Capricorne (Fig. 7), both in the eastern part of the Gulf of Guinea (upper part) and in the central Atlantic (lower part), do not show a continuous decrease westwards. In 1979 (Fig. 7A), surface nitrate concentration is higher at 4°W than at 6°E and in 1983 (B) at 10°W than at 4°W. Zonal advection from the African coast is not sufficient to account for surface nutrient distribution along the Equator. There must be an other, more local, process which supplies the equatorial belt with nutrient. Increases in the nitrate concentration westwards are probably the results of local onsets of the equatorial upwelling, because they follow usually a cooling of the sea surface (Voituriez, 1980 ; Oudot, 1983).

We may note that the area of nitrate enrichment (concentration higher than 1.0 µmol.l⁻¹), completely south of the Equator in the Gulf of Guinea, overlaps the Equator west of 10°W. If now we take the 0.1 µmol.l⁻¹ isopleth, which marks generally the exhaustion of the surface layer, we can confirm the limit of the equatorial nutrient enrichment at about 30°W.

EQUATORIAL NUTRIENT ENRICHMENT AND PHYTOPLANKTON BIOMASS

It is important to examine the extent to which the seasonal nutrient enrichment previously described south of the Equator at 4°W affects the productive



June-July
1979

July-August
1983

Figure 7.

Horizontal distributions of nitrate (µmol.l^{-1}) at the sea surface in June-July 1979 (A : CIPREA 3) and in July-August 1983 (B : FOCAL 4).

Distributions horizontales de nitrate (µmol.l^{-1}) à la surface de la mer en juin-juillet 1979 (A : CIPREA 3) et en juillet-août 1983 (B : FOCAL 4).

potentiality of the area. As a criterion of biological productivity, we considered the quantity of chlorophyll *a* integrated in the euphotic layer the lower limit of which is assimilated to 0.1 µg Chl*a*.l^{-1}, *i.e.* down to a 90 m depth at 4°W and a 115 m depth at 35°W. At 4°W (Fig. 8) we see that the upwelling band (0-5°S) is not significantly more productive in July-August (mean value = 27 mg Chl*a*.m^{-2}) than in January-February (mean value = 26 mg Chl*a*.m^{-2}). Thus the onset of the upwelling which considerably increases the surface nitrate concentration has very little influence on the standing crop of the vegetal biomass. Herbland *et al.* (1983), according to the data of CIPREA cruises, have previously underlined the " paradox " of the equatorial zone, the global production of which is not increased during the upwelling season. These authors underlined that an increase of the phytoplankton biomass is possibly eliminated by an increased grazing pressure in the summer. North of the Equator (0-5°N) the situation is different because of the coastal upwelling, directly off the Ivory Coast, the onset of which in summer considerably increases both the nitrate levels (× 1.6) and consequently the phytoplankton biomass (× 1.6) of the adjacent area. Herbland *et al.* (1986) point to the difference of phytoplanktonic development, in intensity and in quality, between the " equatorial upwelling " and the " coastal upwelling ".

In the western part (Fig. 8 on the left), the phytoplankton biomass is somewhat less than in the eastern part, as is to be expected from the much lower surface nitrate concentrations. Here, the impoverishment of the euphotic layer in nutrient, associated with the deepening of the nitracline and the phosphacline, seems to limit the standing crop of the phytoplankton biomass. There is no significant difference of the mean values of the latter between January-February and July-August, despite the much higher (×2-×3) nitrate levels in winter than summer. There is no satisfactory explanation of the equatorial spike of phytoplankton biomass (0°-1°S) noticed in July-August.

In the interpretation of these distributions of the integrated biomass, it seems interesting to take into account the quantity of nitrate present in the euphotic

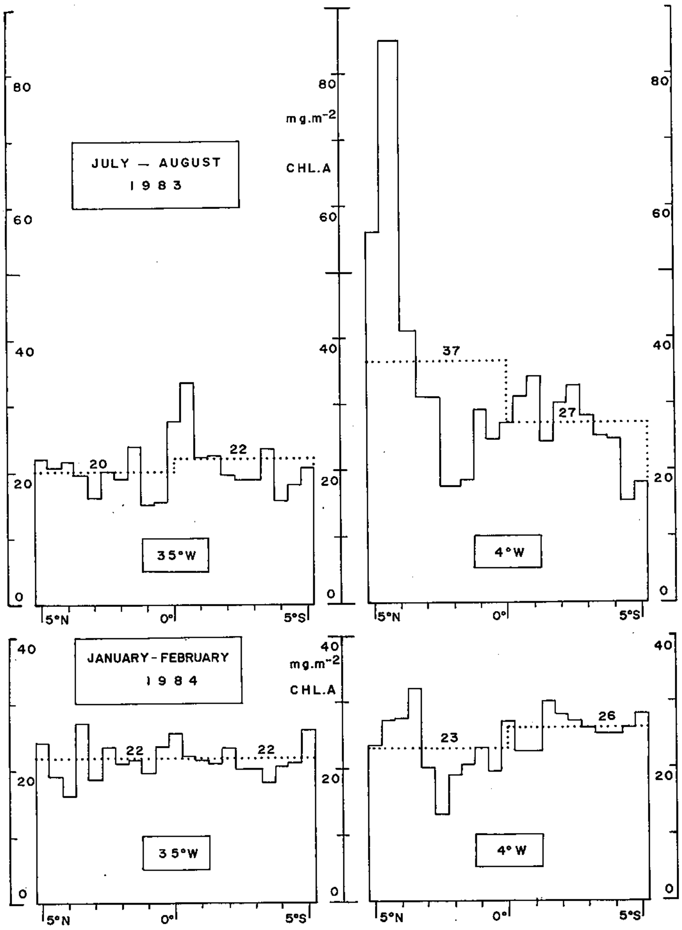


Figure 8

Meridional distributions of the quantity of chlorophyll a *(mg.m^{-2}) in the euphotic layer (lower limit : 0.1 µg Chla.l^{-1}) at 4°W (on the right) and 35°W (on the left), in July-August 1983 (at the top : FOCAL 4) and in January-February 1984 (at the bottom : FOCAL 6). Dotted lines and numbers indicate average values in the bands 5°N-0° and 0°-5°S. The limit 0.1 µg Chla.l^{-1} approaches 90 m depth at 4°W and 115 m depth at 35°W.*

Distributions méridiennes de la quantité de chlorophylle *a* (mg.m^{-2}) dans la couche euphotique (limite inférieure : 0,1 µg Chl*a*.l^{-1}) à 4°W (à droite) et 35°W (à gauche), en juillet-août 1983 (en haut : FOCAL 4) et en janvier-février 1984 (en bas : FOCAL 6). Les lignes en pointillés et les nombres représentent les valeurs moyennes dans les bandes 5°N-0° et 0°-5°S. La limite 0,1 µg Chl*a*.l^{-1} correspond à une profondeur voisine de 90 m à 4°W et de 115 m à 35°W.

layer rather than surface nitrate concentration: at 4°W (Fig. 9) the nitrate quantity available in the euphotic layer south of the Equator is — on average — as high in winter (684 mmol.m^{-2}) as in summer (732 mmol.m^{-2}). The onset of the equatorial upwelling, though it increases the surface nitrate concentration as previously seen (Fig. 2-4), does not affect to any great extent the nitrate quantity present in the euphotic layer: therefore the fact that the vegetal biomass remains unchanged between winter and summer is not surprising. On the other hand north of the Equator, the onset of the coastal upwelling in summer leads to a considerable increase in nitrate quantity (× 1.6), with respect to the winter situation: this could explain the biomass increase related previously (× 1.6).

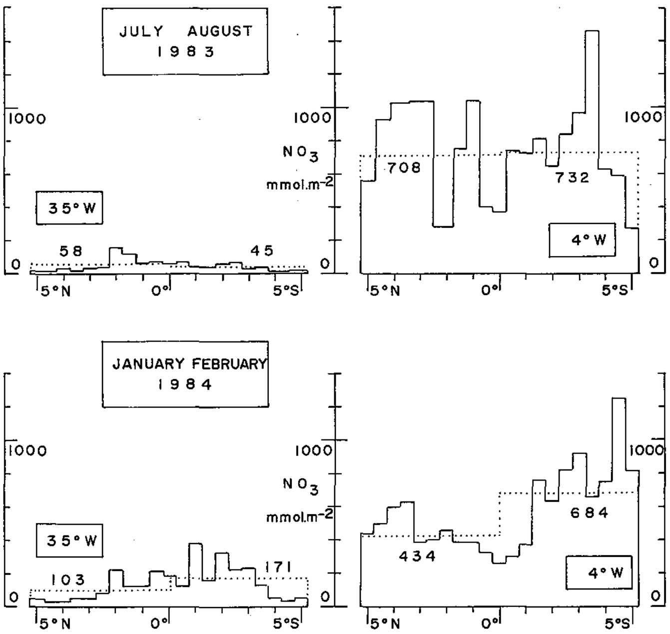


Figure 9

Meridional distributions of the quantity of nitrate (mmol.m^{-2}) in the euphotic layer (lower limit: 0.1 µg Chla.l^{-1}) at 4°W (on the right) and 35°W (on the left), in July-August 1983 (at the top: FOCAL 4) and in January-February 1984 (at the bottom: FOCAL 6). Dotted lines and numbers indicate average values in the bands 5°N-0° and 0°-5°S.

Distributions méridiennes de la quantité de nitrate (mmol.m^{-2}) dans la couche euphotique (limite inférieure : 0,1 µg Chl*a*.l^{-1}) à 4°W (à droite) et 35°W (à gauche), en juillet-août 1983 (en haut : FOCAL 4) et en janvier-février 1984 (en bas : FOCAL 6). Les lignes en pointillés et les nombres représentent les valeurs moyennes dans les bandes 5°N-0° et 0°-5°S.

At 35°W (Fig. 9 on the left), nitrate quantity, noticeably inferior to that at 4°W, is lower in average in July-August than in January-February (in a ratio of 2 to 3), without any further decrease in the phytoplankton biomass (Fig. 8 on the left) except for a very slight diminution north of the Equator. This diminution of nitrate quantity in summer results from the deepening of the nitracline following the deepening of the thermocline in July-August, as discussed previously.

On the other hand, when we compare the decreases of nitrate and chlorophyll quantity in the euphotic layer from 4°W to 35°W, we remark that the nitrate decrease is much more important than that of the biomass. The westwards zonal decrease of nitrate is in a ratio of about 10 in summer and 5 in winter (Fig. 9), whereas that of the phytoplankton biomass is in a ratio much lower than 2 (Fig. 8).

It is evident from these comparisons of the variations — in time as well as in space — of the quantities of nitrate and phytoplankton biomass, that in the equatorial belt the nitrate concentration does not affect to any great extent the phytoplankton standing crop, particularly in the west. In other words, in the equatorial area nitrate would not be the limiting factor of the phytoplankton biomass, and another link of food chain (*e.g.* grazing by zooplankton) must be examined. Under these conditions, we must be cautious when seeking to use nutrient distributions in discussing the fertility and the productivity of an area. Measured nitrate concentrations describe an instantaneous situation, the result of a balance between the physical and biological processes which supply and absorb nutrient, and do not give us any information about the fluxes set by these processes.

Voituriez and Herbland (1984) used the conservation of the nitrate/temperature linear relationship in all seasons, in the equatorial zone of the Gulf of Guinea, to show that there is no increase in nitrate uptake during the period of upwelling, and to explain the maintenance of planktonic production throughout the year. It is interesting to see in the western equatorial region the evolution of this relationship, indicating the balance between physical and biological processes. We plot all values of nitrate higher than 1.0 µmol.l^{-1} for all the stations between 5°N and 5°S at 4 and 35°W, in January-February and in July-August (Fig. 10). Irrespective of the season (winter or summer) the nitrate/temperature relationship in the western equatorial Atlantic is different from that in the eastern part, although the distinction is sharper during the summer upwelling. This difference is systematic, as shown in the Table which assembles the results for all the FOCAL cruises: the slope of the regression line nitrate versus temperature is always significatively lower (in absolute value) at 35 than at 4°W. Results at 4°W agree with those of the CIPREA cruises (Voituriez, Herbland, 1984): for comparison we exhibit (at the bottom of the Tab.) the cumulated average for all the CIPREA cruises (for the band 0°-5°S only). For the same temperature (Fig. 10), the upper layer of the nitracline is richer in nitrate to the west than to the east and the opposite for the deeper layers. This difference signifies a change, westwards along the Equator, of the equilibrium between physical and biological processes. This change could illustrate the decrease of the biological activity at 35°W, expressed by a diminution of nitrate consumption in the euphotic layer and of nitrate regeneration beneath. Lastly, we remark (Tab.) that at 35°W as well as 4°W there is no significant difference of the nitrate/temperature relationship according to season, which means that in both the western and eastern locations planktonic production is maintained all the year long.

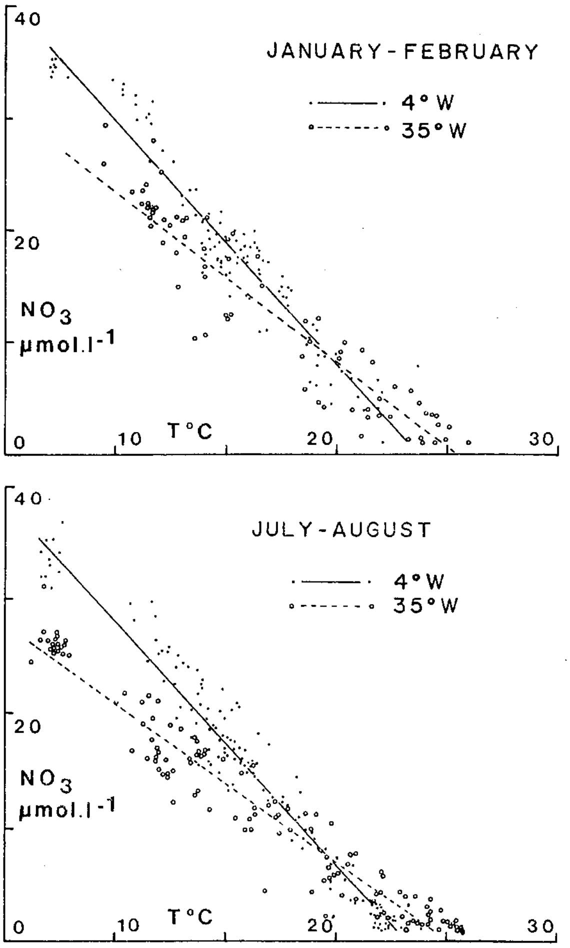


Figure 10

Relationships nitrate (NO_3 μmol.l^{-1})/temperature (T°C) along 4°W and 35°W in January-February 1983 (at the top: FOCAL 2) and in July-August 1983 (at the bottom: FOCAL 4). The nitrate values lower than 1 μmol.l^{-1} are extracted.

Relations nitrate (NO_3 μmol.l^{-1})/température (T°C) le long de 4°W et 35°W en janvier-février 1983 (en haut: FOCAL 2) et en juillet-août 1983 (en bas: FOCAL 4). Les valeurs de nitrate inférieures à 1 μmol.l^{-1} sont retirées.

ZONAL EVOLUTION OF NUTRIENT DISTRIBUTIONS

The zonal variation of the depth of the thermocline along the Equator, identified by the 23°C isotherm (Fig. 6) suggests a regular deepening of the thermocline from the African to the Brazilian coast. Our data collected in July-August 1983 (FOCAL 4 cruise) show in fact a breaking of the slope of the thermocline and the nitracline (Fig. 11). No anomaly of the wind field during that year can suggest that the sharp thermocline break is itself anomalous in 1983 rather than a possible permanent feature. The sharp deepening of the thermocline and the nitracline occurs between 20 and 25°W, where the surface nitrate concentration drops to less than 1.0 μmol.l^{-1}. An other important feature on this figure (at bottom) is the deepening and the vanishing of the nitrite maximum at the same place. West of 23°W the nitrite concentration is very low, less than 0.25 μmol.l^{-1}. This disappearance in the western equatorial Atlantic (35°W) of the high nitrite concentrations observed in the eastern part (4°W) is noted during each FOCAL cruise. This feature is interesting because nitrite has an ecological significance. Voituriez and Herbland (1977) have associated nitrite production with nitrate reduction by phytoplankton. Thus, the disappearance of the nitrite could be an indication of decreased phytoplankton activity in the western equatorial area, in turn related to the diminution of the standing crop mentioned above.

CONCLUSION

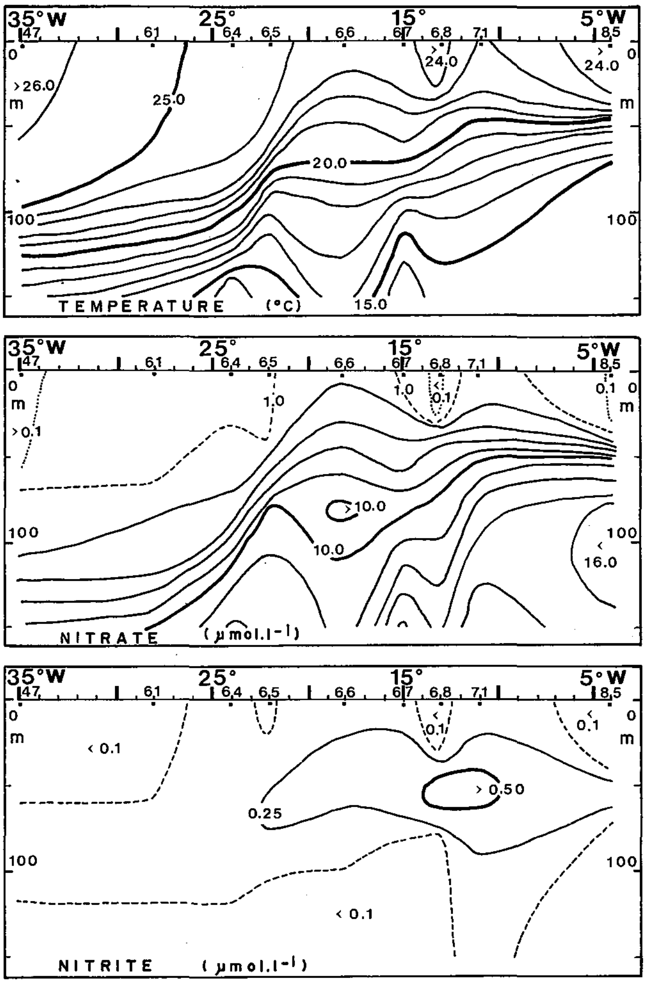
While the onset of the equatorial upwelling in boreal summer in the eastern equatorial Atlantic indeed increases the nitrate quantity available in the euphotic layer to stimulate photosynthesis (Fig. 9), this nutrient appears not to be limiting. It follows that the phytoplankton biomass is no higher in summer in the equatorial belt (5°N-5°S) at 4°W than in winter,

Table

Nitrate-temperature relationships along 4 and 35°W between 5°N and 5°S (nitrate higher than 1 μmol.l^{-1} and temperature in degrees C).

Relations nitrate-température de 4 à 35°W, et entre 5°N et 5°S (concentrations de nitrate supérieures à 1 μmol.l^{-1}, et température exprimée en degrés C).

Cruise	Date	35°W	4°W
Focal 0	July 1982		$NO_3 = -2.25\,T + 52.2$ $r = -0.97 \quad n = 135$
Focal 2	January-February 1983	$NO_3 = -1.67\,T + 41.7$ $r = -0.94 \quad n = 79$	$NO_3 = -2.15\,T + 50.9$ $r = -0.96 \quad n = 102$
Focal 4	July-August 1983	$NO_3 = -1.36\,T + 34.6$ $r = -0.98 \quad n = 133$	$NO_3 = -2.07\,T + 49.2$ $r = -0.97 \quad n = 186$
Focal 6	January-February 1984	$NO_3 = -1.59\,T + 39.8$ $r = -0.95 \quad n = 126$	$NO_3 = -1.90\,T + 47.1$ $r = -0.98 \quad n = 145$
Focal 8	July-August 1984	$NO_3 = -1.72\,T + 40.9$ $r = -0.95 \quad n = 121$	$NO_3 = -2.10\,T + 48.7$ $r = -0.96 \quad n = 173$
Mean focal		$NO_3 = -1.57\,T + 39.1$ $r = -0.95 \quad n = 466$	$NO_3 = -2.07\,T + 48.8$ $r = -0.96 \quad n = 741$
Mean CIPREA (0°-5°S) (Voituriez, Herbland, 1984)			$NO_3 = -1.88\,T + 45.5$ $r = -0.95 \quad n = 540$



except in the narrow band (3-5°N) of the coastal upwelling (Fig. 8). In the western area (35°W), the deepening of the thermocline and the nitracline (especially in summer) makes the nitrate quantity less abundant in the euphotic layer ; the phytoplankton standing crop is found to be decreased in comparison with that at 4°W, without however reaching the same relative diminution as that of the nitrate, which is very great in summer (> 10) and winter (5). In the subsurface, the variation of nutrient concentrations within the Equatorial Undercurrent can be related to vertical motions of the thermocline. The sharp westward deepening of the thermocline along the Equator was observed between 20 and 25°W during FOCAL 4 (July-August 1983).

Zonal advection of nutrient-enriched water from the African coastal upwelling zone is not sufficient to account for the nitrate distribution in the surface equatorial belt, which must be partly determined by local vertical processes.

Evolution of the nitrate/temperature relationship and nitrite distribution from 4 to 35°W implies a relative reduction in the activity of the primary producers in the western equatorial Atlantic, in comparison with the stronger upwelling regions to the east.

◀ Figure 11

Zonal distributions along the Equator of temperature (°C), nitrate (μmol.l^{-1}) and nitrite (μmol.l^{-1}) in July-August 1983 (FOCAL 4).

Distributions zonales le long de l'équateur de la température (°C), du nitrate (μmol.l^{-1}) et du nitrite (μmol.l^{-1}) en juillet-août 1983 (FOCAL 4).

REFERENCES

Cromwell T., 1953. Circulation in a meridional plane in the central equatorial Pacific, *J. Mar. Res.*, **12,** 196-213.

Düing W., Hisard P., Katz E. J., Meincke J., Miller L., Moroshkin K. V., Philander G., Ribnikov A. A., Voigt K., Weisberg R., 1975. Meanders and long waves in equatorial Atlantic, *Nature*, **257,** 280-284.

Hastenrath S., Lamb P., 1977. *Climatic atlas of the tropical Atlantic and Eastern Pacific Oceans*, University of Wisconsin Press, Madison, 113 p.

Herbland A., Le Borgne R., Le Bouteiller A., Voituriez B., 1983. Structure hydrologique et production primaire dans l'Atlantique tropical oriental, *Océanogr. Trop.*, **18,** 249-293.

Herbland A., Le Bouteiller A., Raimbault P., 1987. Does the nutrient enrichment of the equatorial upwelling influence the size structure of phytoplankton in the Atlantic Ocean ? *Proc. Inter. Symp. on Equatorial Vertical Motion, Oceanol. Acta* this vol., 115-120.

Hisard P., 1973. Variations saisonnières à l'équateur dans le Golfe de Guinée, *Cah. ORSTOM, sér. Océanogr.*, **11,** 349-358.

Hisard P., Citeau J., Voituriez B., 1977. Equatorial Undercurrent influence on enrichment processes of upper waters in the Atlantic Ocean, *Report of the International Workshop on the Gate Equatorial Experiment, Miami, 28 February-1st March 1977.*

Kaiser W., Postel L., 1979. Importance of the vertical nutrient flux for biological production in the Equatorial Undercurrent region at 30°W, *Mar. Biol.*, **55,** 23-27.

Mazeika P. A., 1968. Mean monthly sea surface temperature and zonal anomalies of the tropical Atlantic, in : *Serial atlas of the marine environment*, Folio 16, American Geographical Society.

Merle J., 1978. Atlas hydrologique saisonnier de l'Océan Atlantique intertropical, *Trav. Doc. ORSTOM*, **82,** 182 p.

Merle J., 1980. Seasonal heat budget in the equatorial Atlantic Ocean, *J. Phys. Oceanogr.*, **10,** 464-469.

Oudot C., 1983. La distribution des sels nutritifs (NO_3-NO_2-NH_4-PO_4-SiO_3) dans l'Océan Atlantique intertropical oriental (région du Golfe de Guinée), *Océanogr. Trop.*, **18,** 223-248.

Philander S. G. H., Pacanowski R. C., 1981. The oceanic response to cross-equatorial winds (with application to coastal upwelling in low latitudes), *Tellus*, **33,** 204-210.

Voituriez B., 1980. The equatorial upwelling in the eastern Atlantic : problems and paradoxes, in : *Coastal upwelling research*, edited by F. A. Richards, American Geophysical Union, 95-106.

Voituriez B., 1983. Les variations saisonnières des courants équatoriaux à 4°W et l'upwelling équatorial du golfe de Guinée. I : Le sous-courant équatorial, *Océanogr. Trop.*, **18,** 2, 163-183.

Voituriez B., Herbland A., 1977. Production primaire, nitrate et nitrite dans l'Atlantique tropical. II : Distribution du nitrate et production de nitrite, *Cah. ORSTOM, sér. Océanogr.*, **15,** 57-65.

Voituriez B., Herbland A., 1979. The use of the salinity maximum of the equatorial undercurrent for estimating nutrient enrichment and primary production in the Gulf of Guinea, *Deep-Sea Res.*, **24,** 25-33.

Voituriez B., Herbland A., 1984. Signification de la relation nitrate/température dans l'upwelling équatorial du Golfe de Guinée, *Oceanol. Acta*, **7,** 2, 169-174.