The meanders of equatorial currents in the Atlantic Ocean : influence on the biological processes

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ABSTRACT

During a SOP cruise (Special Observation Period) of the GARP program, a 14 days station was occupied in the equatorial Atlantic Ocean (0°-4° W).

Vertical oscillation of the hydrological structure (thermocline, nitracline, nitrite maximum) was observed according to the south-north oscillations of the equatorial current system (surface current and undercurrent). Chlorophyll distribution and primary production values are greatly influenced by these oscillations.

From our data, it seems that the core of the Lomonosov current is the most productive part of the equatorial area.

An "Ecological Equator", (between 0° 30 S and 0° 30 N) is introduced; in this area, the primary production changes from 1 to 2 g C m^{-2} d^{-1} in few days with a constant solar radiation (Total irradiance: 2100 J cm^{-2} d^{1-}).

KEY WORDS : Equator — Primary production — Currents.

RÉSUMÉ

LES MÉANDRES DES COURANTS ÉQUATORIAUX DANS L'OCÉAN ATLANTIQUE : INFLUENCE SUR LES PROCESSUS BIOLOGIQUES

Pendant une campagne SOP (Special Observation Period) du programme GARP, une station de 14 jours a été réalisée dans l'océan Atlantique Équatorial (0°-4° W).

L'oscillation verticale de la structure hydrologique (thermocline, nitracline, maximum de nitrite) a été observée et mise en relation avec les oscillations sud-nord du système des courants équatoriaux (courant de surface et sous-courant de Lomonosov). Les distributions et les valeurs de la production primaire sont grandement influencées par ces oscillations.

D'après nos données, il semble que le cœur du courant de Lomonosov soit la partie la plus productive de la zone équatoriale.

Un « Équateur Écologique » (entre 0° 30 S et 0° 30 N) est introduit; dans cette zone, la production primaire varie de 1 à 2 g C m^{-2} j^{-1} en quelques jours, avec un ensoleillement constant (Rayonnement global = 2 100 J cm^{-2} j^{-1}).

MOTS CLÉS : Équateur — Production primaire — Courants.

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INTRODUCTION

It now seems well established that the equatorial region of the Atlantic shows seasonal variations (Hisard, 1973; Katz *et al.* 1977; Lass and Hagen, 1980). These variations have been ignored or underestimated, because the exceptional conditions found during the cruise Equalant II (August, 1963) have been considered for long time, as the rule.

During the GATE cruises (1974) and the O.R.S.T.O.M. cruises of the R.V. Capricorne between 1970 and 1978, Hisard *et al.* (1977), and Voituriez and Herbland (1977) observed important surface coolings (<21 °C in summer 1975, 1977, 1978) with spectacular nutrients enrichment (NO_3=4.6 µgat l^{-1}) in the summer period. In the Gulf of Guinea, the year divides into two main periods: a warm season from October to May without upwelling, and a cold period from June to October with an equatorial and sub-equatorial upwelling. During the cold season the primary production is mainly located in the superficial waters (0-30 m layer) where the sufficient light and nutrients allows the increase of biomasses (Tchmir, 1971). During the warm season, the primary production is mainly located in the thermocline where the nitrate appears. The phytoplankton is less lighted and less productive: it is a "Typical Tropical Structure" (TTS) described by Herbland and Voituriez (1979); during that season, the equatorial area of the Atlantic does not differ from the whole Tropical Atlantic Ocean. However, Voituriez and Herbland (1977) found that compared with the other TTS the primary production values in the equatorial area are very variable, but they were enable to give any satisfactory explanation for the surprising amplitude of the variations. These variations were hypothetically attributed to the changes of turbulence, which fixes the depth of the nitrate rich layer in the euphotic zone. Sedikh and Loutockhina (1971) observed an important interannual variation of the stability in warm season, but no reason was given.

It seems well admitted also that the surface equatorial current (Westward flowing current) and the underequatorial current (Eastward flowing current) have not a right and well located path: these two currents show South-North oscillations, first observed by Rinkel (1969). Duing *et al.* (1975) confirmed from GATE observations, that the South Equatorial current and the Equatorial undercurrent reveal large scale meandering with a preferential period of 15-16 days. Meandering of the flow pattern was found to be related to corresponding displacements of the high salinity core of the undercurrent. The aim of this paper is to show the evidence of relation between the south-north oscillations of the current system and the variations of the vertical distribution of nutrients. An attempt is made to estimate the effects of oscillation upon the primary production processes.

MATERIAL AND METHODS

The study was carried out in February 1979 on R.V. Capricorne during the second part of the first SOP (Special Observation Period) of the GARP program. The station (0°-4° W) was occupied for 14 days (fig. 1). Some complementary results have

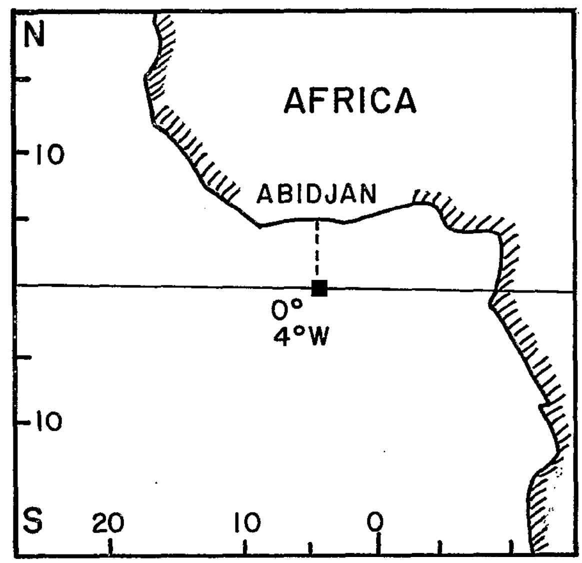

Fig. 1. — Position of the long duration station and section used in the study.

Positions de la station de longue durée et de la radiale.

been collected from sections of the first part of the SOP (January 1979), and from moorings of the CIPREA program. Every morning the ship came near the equatorial mooring and the following sampling was made: water was collected at 8-10 levels in the euphotic zone with a 30 l Niskin P.V.C. bottle. The nutrients (NO_3, PO_4, NO_2) were immediatly analysed with autoanalyser (Technicon); the chlorophyll *a* was measured after filtration, grinding and extraction in 90 % acetone by fluorometry (Turner). Particulate carbon was measured with a C.H.N. analyser (Hewlett Packard 185B) and particulate phosphorus after persulfate oxydation, with PO_4 analyses. Temperature and current profiles were obtained with Aanderaa currentmeter rigidly locked on a current profiler (Miami model).

The primary production was determined by *in situ* incubation from sunrise to sunset with C^{14} method, the radioactivity of filters being counted by liquid scintillation technique.

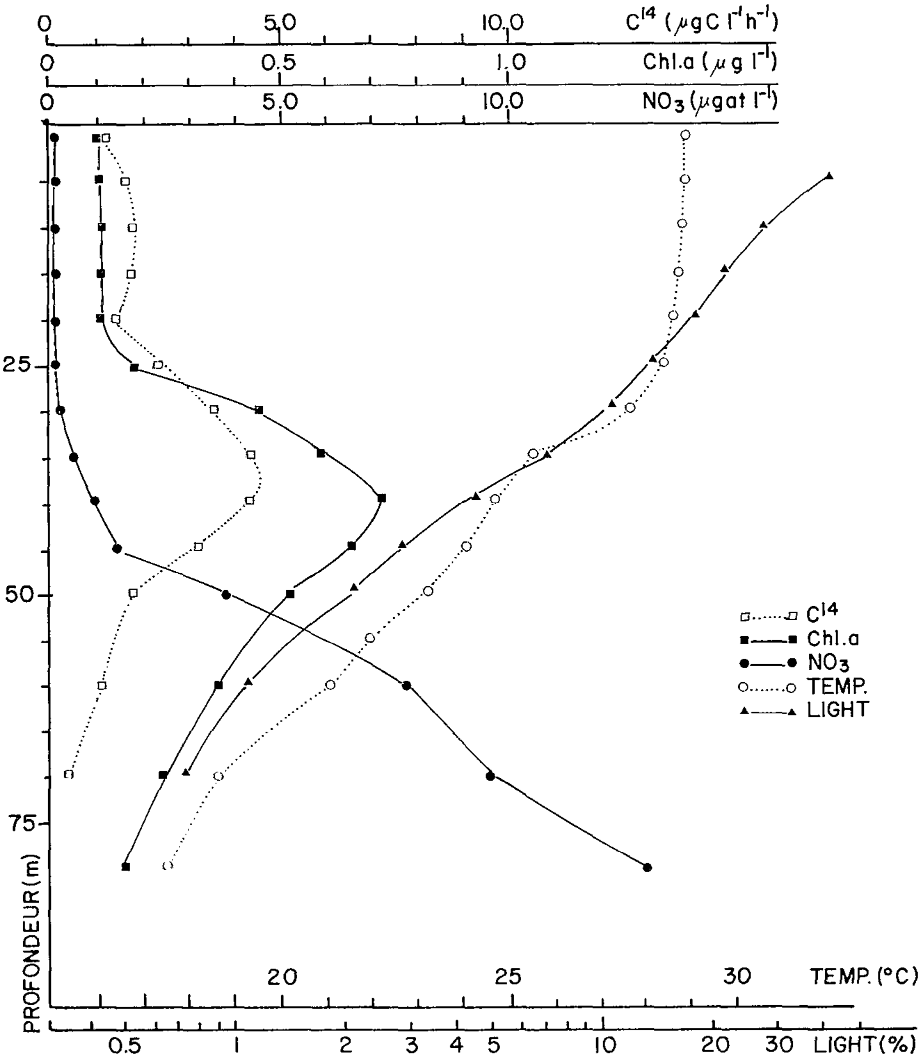

Fig. 2. — The mean profiles of temperature, nitrate, chlorophyll *a*, primary production and light at 0°-4° W during the 14 days station (from Herbland et Leboutelller, 1981).

Profils moyens de température, nitrate, chlorophylle a, *production primaire et lumière à 0°-4° W pendant la station de 14 jours* (d'après Herbland et Leboutelller, 1981).

The surface solar radiation was continuously measured with an Eppley pyranometer, and each day, around 12 h local time, a profile of the penetration of P.A.R. (Photosynthetic Available Radiation) was measured in terms of quanta for the 350-700 nm band (Lambda quantum meter).

RESULTS

(*a*) The mean hydrological structure and amplitude of variations

The mean profiles are shown in fig. 2: there is a warm mixed layer of 20-25 m, without nitrate and low values of chlorophyll. The thermocline is well developped. The chlorophyll *a* and primary production maxima are located in the top of the nitracline (gradient of nitrate), at the beginning of the thermocline where high mean values of chlorophyll (0.75 µg l^{-1}) and primary production (4.5 µg C l^{-1} h^{-1}) have been observed.

The light profile shows clearly a change of the slope between 30 and 45 m, which corresponds to the productive layer where the diffuse attenuation coefficient is higher (Morel, 1980). The 1 % of surface light, which usualy defines the bottom of the productive layer, is near the depths from 60-65 m.

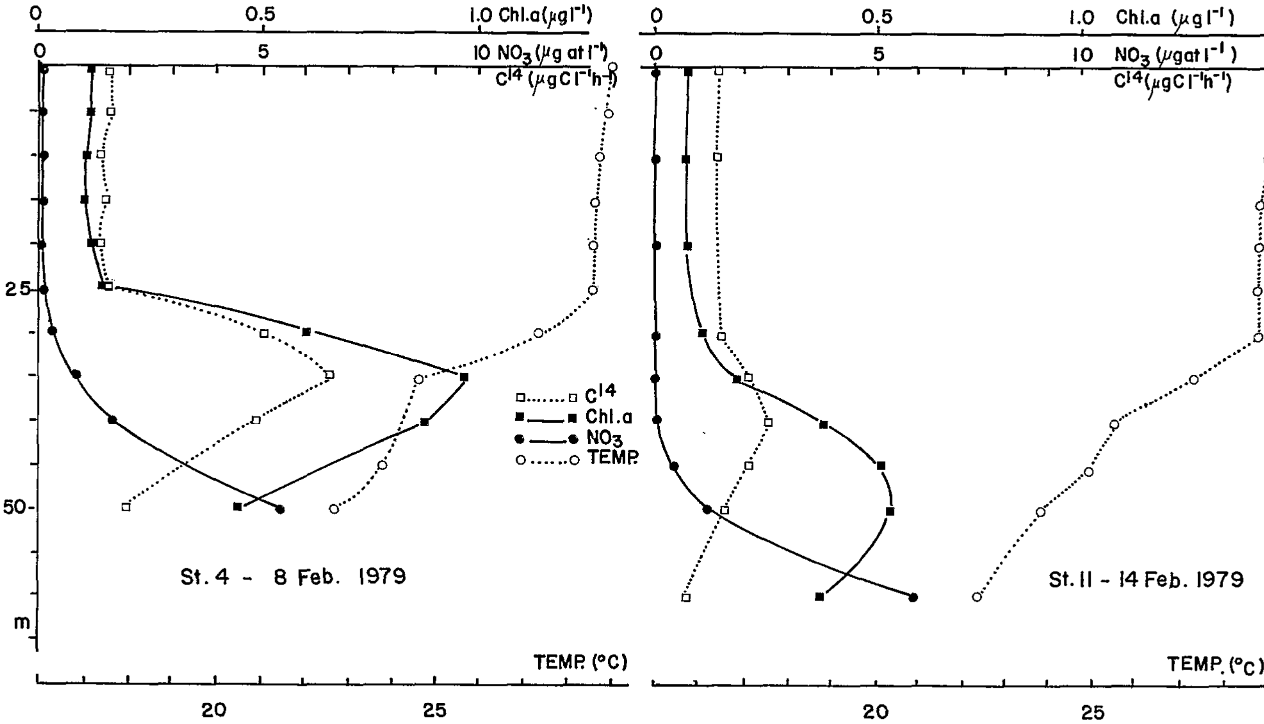

Fig. 3. — Profiles of temperature, nitrate, chlorophyll *a* and primary production at two opposite stations (station 4 and station11) with 7 days time intervall.

Profils de température, nitrate, chlorophylle a *et production primaire à 2 stations contrastées (station 4 et 11) à 7 jours d'intervalle.*

These mean profiles mask a high variability : for example (fig. 3) 7 days separate the station 4 and the station 11. At station 11 the mixed layer is thicker (10 m), the nitracline is deeper (20 m), the chlorophyll and primary production maximums are also deeper whereas their values have decreased : from 1.05 to 0.50 $\mu g\ l^{-1}$ for chlorophyll *a* and from 7.5 to 2.5 $\mu g\ C\ l^{-1}\ h^{-1}$ for primary production.

(b) Hydrological structure and current oscillations

The evolution with time of some characteristic levels of the structure is shown in fig. 4. The depth of the mixed layer, the depth of the reversal of current (between the surface current and the undercurrent), the depth of the nitrite maximum are in phase (fig. 4a), and roughly follow a sinusoïde curve (10-20 m of amplitude, and 15 days of period). The current measurements (fig. 4b) show that the maximum speed of the E.W. component (>70 cm s^{-1}) of the Lomonosov current occurs when the curves of the fig. 4a are shallower. In the surface layer the phenomenon is opposite: low current occurs ($\simeq 30$ cm s^{-1}) when the Lomonosov current is rapid, and high current (>70 cm s^{-1}) when Lomonosov vanishes.

From earlier measurements obtained during the first leg of the SOP, it is possible to localise the positions and the displacements of the Lomonosov current during our observation period: around January 15, the undercurrent is centered on 0° 30 S (fig. 5a). During the following days, it was minimum at the equator (salinity maximum=35,8 at 40-45 m). Then a sharp increase of Lomonosov current was observed at 0°. It reached 85 cm s^{-1} at 50 m associated with a salinity maximum of 36.10 ‰ at 60 m on January 25. Four days later, the core of the current appears at 0° 30 N (max.=90 cms^{-1}, salinity maximum=36.20 ‰ (fig. 5b). It was probably near its northern position. Consequently, at the begining of the second leg of the SOP (February 5), the current of Lomonosov came from the north, crosses the equator on 9-10 February (fig. 4b) and reaches its southern position on 15-16 February, when the nitracline, and the different maxima are near to their deepest position (fig. 4a).

According to these observations, it seems that the south-north oscillations of the equatorial current

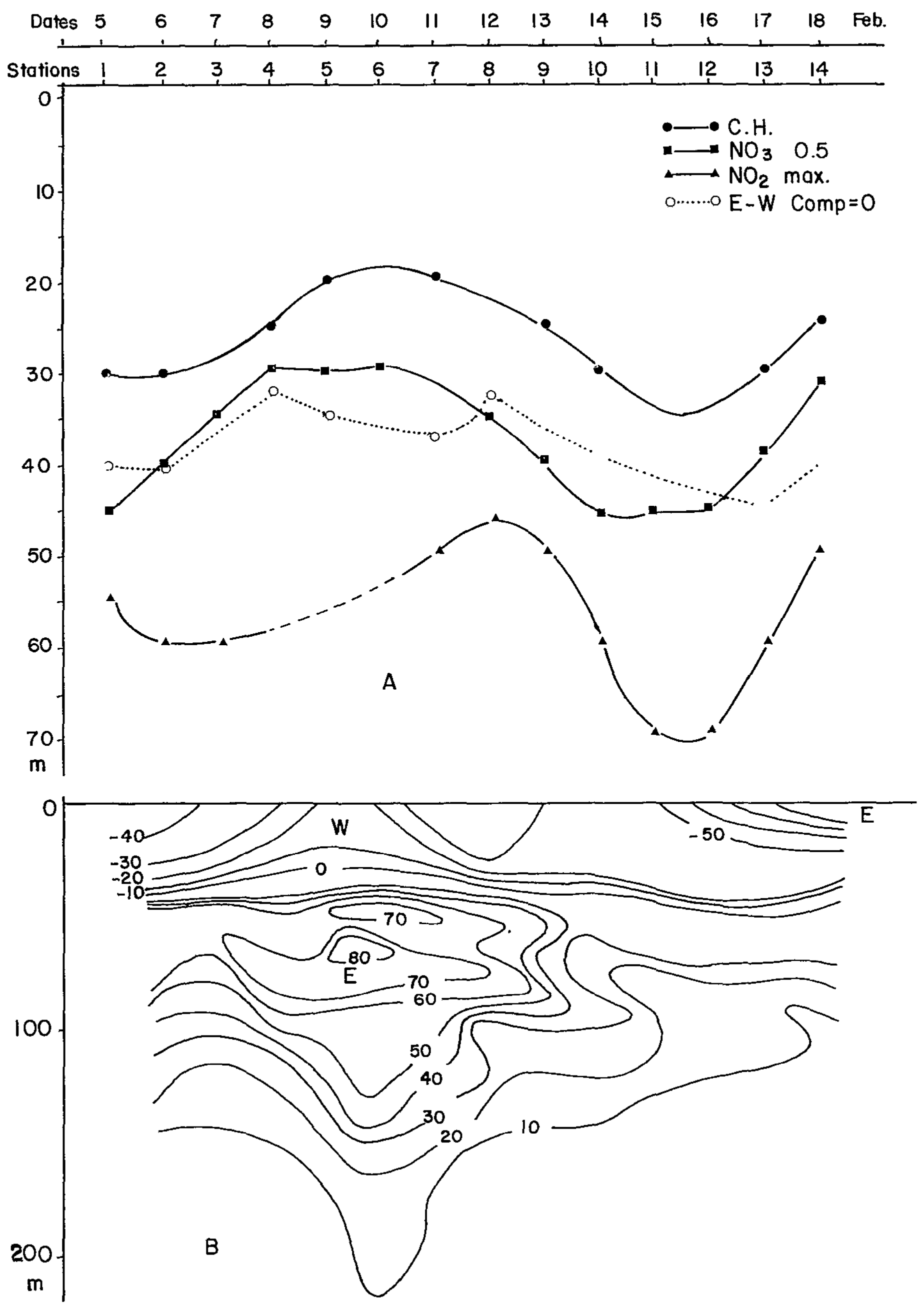

Fig. 4. — The time evolution of the depths of mixed layer, nitracline, turn of current and nitrite maximum during the 14 days study, with regard to the evolution of the E-W components of the current system.

Évolution dans le temps des profondeurs de la couche homogène, de la nitracline, de la renverse du courant et du maximum de nitrite, en rapport avec l'évolution de la composante E-W du système des courants.

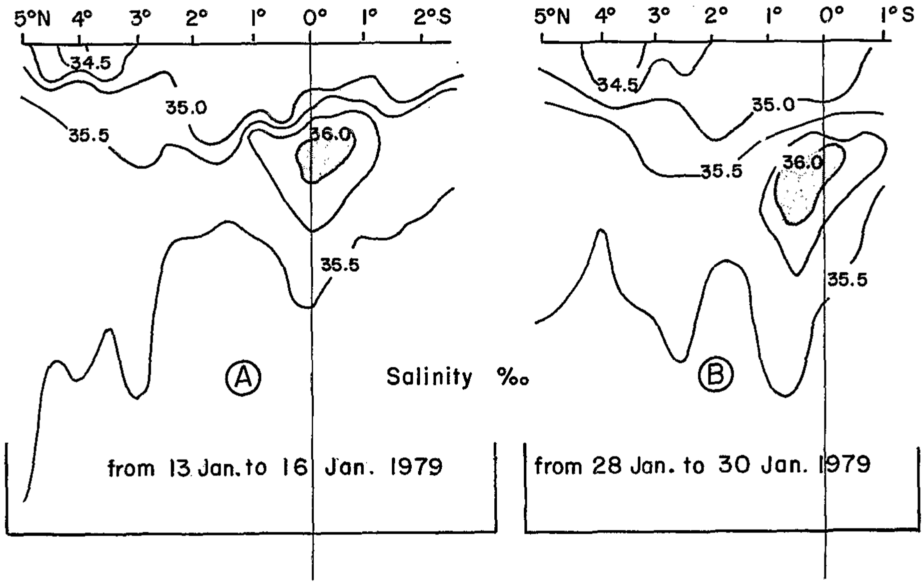

Fig. 5. — Two sections of salinity during the first part of the SOP (January 1979) showing the displacement of the salinity core. RV Capricorne SOP 1/1 two sections, from J. Citeau

Deux coupes de salinité pendant la première partie de SOP montrant le déplacement du noyau de salinité du courant de Lomonosov. RV Capricorne SOP 1/1 deux sections, d'après J. Citeau

system (surface current+undercurrent) are linked with the vertical displacements of the hydrological structure.

(c) Consequences on the primary production

Herbland and Voituriez (1979) pointed out that, in the Tropical Atlantic ocean, hydrological structure and primary production values were closely associated: the depth of the nitracline is a good indicator of the intensity of the integrated primary production of the water column. Since the depth of the nitracline changes in terms of the current oscillations, it is likely that the values of primary production will be affected by these variations.

As a matter of fact, the chlorophyll maximum presents a spectacular evolution with time (fig. 6). It reaches a maximum value ($\simeq$1.00 μg l^{-1}) on 7-11 February (Stations 3-6) and a minimum value (0.30 μg l^{-1}) on 17 February (St. 13). There is an half period of the Lomonosov oscillation between the two extreme values. The evolution of the maximum value is associated with an evolution of the shape of the profiles (fig. 7). The sharper profiles during the first week correspond roughly to the passage of the Lomonosov current (Stations 4-5-6) on 8-10 February. The maximum of flatness occured

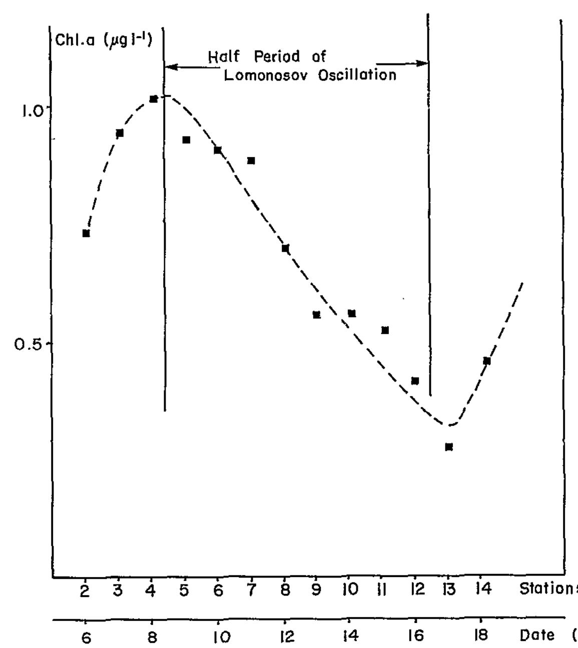

Fig. 6. — Evolution of the chlorophyll *a* maximum values during the 14 days station.

Évolution des valeurs du maximum de chlorophylle a *pendant les 14 jours de station.*

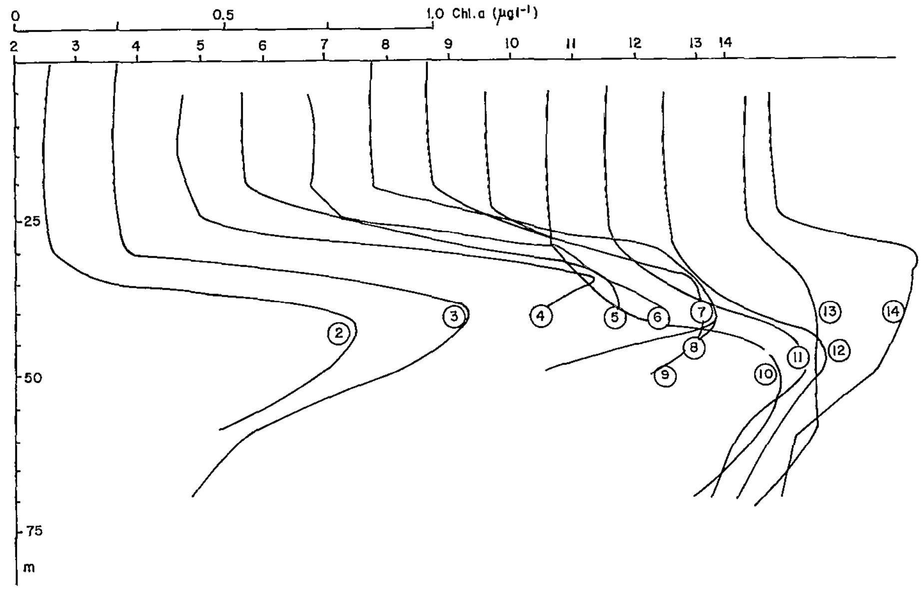

Fig. 7. — Evolution of the chlorophyll *a* profiles during the 14 days station.
Évolution de la forme des profils de chlorophylle a *pendant les 14 jours de station.*

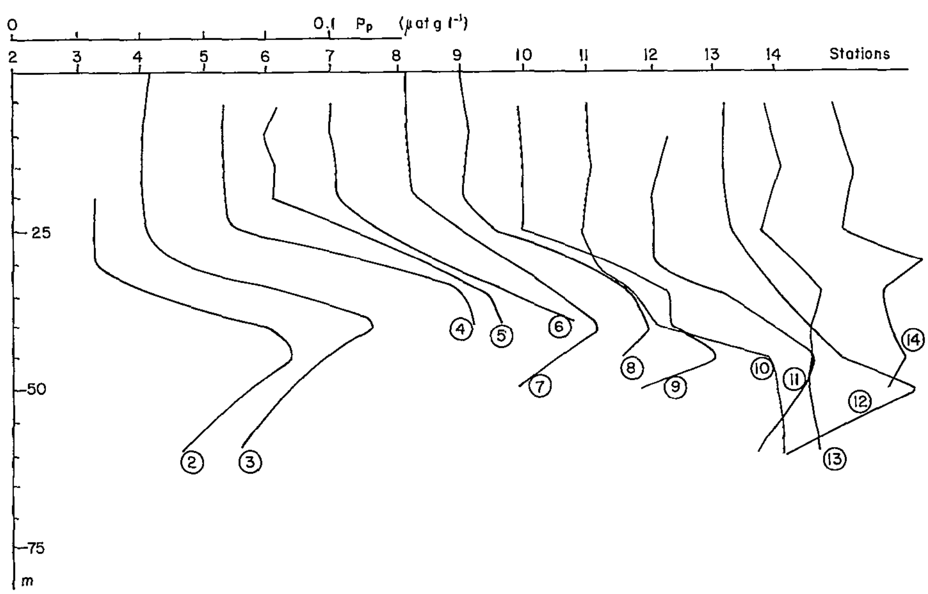

Fig. 8. Evolution of the particulate phosphorus profiles during the 14 days station.
Évolution de la forme des profils de phosphore particulaire pendant les 14 jours de station.

on 17 February (St. 13) when the Lomonosov current would be near from its southern most position. This spectacular evolution could be spurious. Fortunately, the particulate phosphorus measurements, made on the same samples give very similar results (fig. 8): sharp profiles during the first week and round profiles during the second week, without maximum at the station 13.

The observations made for chlorophyll *a* distributions are very similar for primary production. The main difference is that the primary production measurement gives an instantaneous value, which can be changed if the light conditions from one day to the other are different. During the 14 days station, the solar radiation has been nearly constant (2100 J cm^{-2} d^{-1}), two days excepted (St. 11: 963 and

St. 12: 247 J cm^{-2} d^{-1}). At these two stations, the primary production profiles are not consistent with the TTS profiles: the integrated value decreases, and the nitraclinal maximum of CO_2 uptake vanishes and forms higher in the mixed layer, in a better lighted zone. In spite of the disparate values of the stations 11 and 12, it is possible to follow the evolution of the primary maximum values (fig. 9) and that of the shape of profiles (fig. 10). The results are very similar to those of chlorophyll and particulate phosphorus: high values during the first week and lower values during the second.

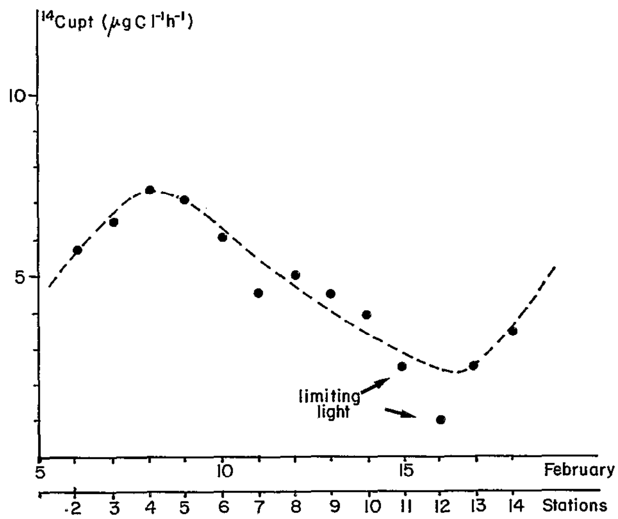

Fig. 9. — Evolution of the maximum primary production values during the 14 days station.

Évolution des valeurs du maximum de production primaire pendant les 14 jours de station.

The different productivity values seems to be correlated with differences in the composition of the particulate matter: Fig. 11 shows the relationship between chlorophyll *a* and particulate carbon. We can see distinctly two groups of points. The group of squares where the particulate matter is richer in chlorophyll than the group of dots. For example, when $C_p=60$ µg l^{-1}, Chla=0.75 µg l^{-1} the first week and 0.45 µg l^{-1} the second. But the slopes are not different. It would mean that the waters of the core of Lomonosov current are more "green" than the others.

An other interesting result is the size distribution of photosynthetic organisms: oligotrophic waters generally have a planktonic flora containing a high proportion of nanoplankton, while eutrophic waters generally have a standing crop much more dominated by the net plankton, although the proportions of the two groups are highly variable (MALONE, 1980). In our study, we have filtered the water of the chlorophyll maximum on 35 µm nylon net and 3 µm Nuclepore filters. The results must be confirmed, but there is a trend (fig. 12): during the first week, the chlorophyll containing organisms smaller than 3 µm are less than 50 %, whereas they are more than 60 % during the second week. In the same way, the fraction smaller than 35 µm is more important during the second week.

In brief, the south-north oscillation of the equatorial currents system is followed by chemical and biological consequences. Shallower and more

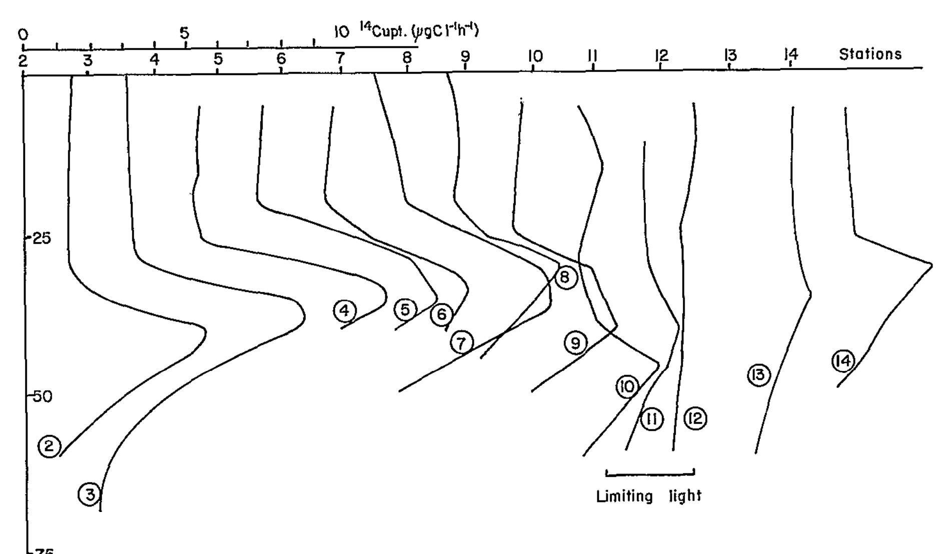

Fig. 10. — Evolution of primary production profiles during the study.

Évolution de la forme des profils de production primaire pendant les 14 jours de station.

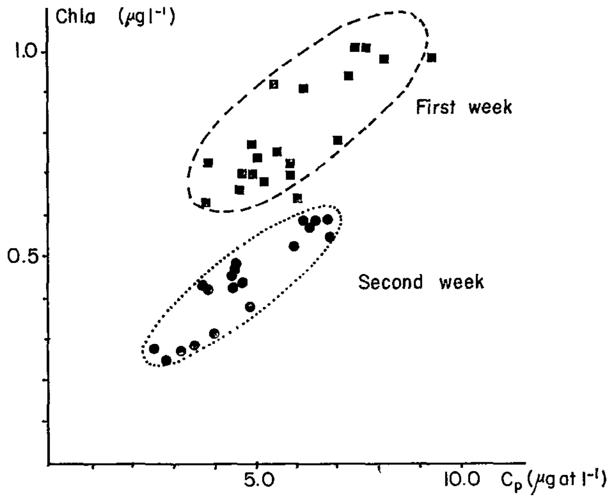

Fig. 11. — Relationship between particulate carbon (C_p) and chlorophyll *a* (chla) at the level of chlorophyll maximum.

Relation entre le carbone particulaire (C_p) *et la chlorophylle* a *(Chla) au niveau du maximum de chlorophylle.*

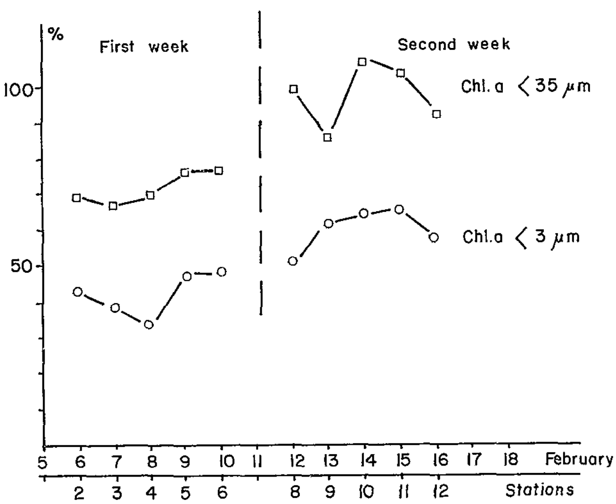

Fig. 12. — Size distribution of chlorophyll containing organisms during the study.

Distribution de la taille des organismes contenant de la chlorophylle.

pronounced chlorophyll and primary production maxima were observed in the core or very near the core of the Lomonosov current.

DISCUSSION AND CONCLUSIONS

(a) Seasonal variations and meanders variations

In a recent paper, Kaiser and Postel (1979) said that in the Equatorial Undercurrent Region at 30° W, the short terms variations are smaller than the seasonal period.

We have summarized in table I the main chemical and biological characteristics of the most different stations from a biological point of view (St. 4 and St. 13). A delay of 9 days, i.e. approximately the half period of the Lomonosov oscillation, exists between these two stations. Most of the ratios, values at station 4/values at stations 13 are greater than 2 or smaller than 0.5. The seasonal variations given by different authors for biological processes are of the same order of magnitude (Tchmir, 1971; Herbland and Voituriez, 1977; Leborgne, 1977).

Other observations are obviously necessary to confirm the amplitude and the regularity of the variation of biological meandering. It is also likely that the seasonal variations have been underestimated (see introduction of this paper) because samples of extreme situations are probably not available, but short term variations cannot be neglected. The observed variations, according to the south-north oscillation of the current system are sufficient to explain the large range of primary production values in the equatorial area (Voituriez and Herbland, 1977). Moreover, if we take the variations of solar radiations into account, the amplitude of variations increases: for example in our study, the extreme values for integrated primary production are 400-1800 μg C m^{-2} d^{-1}.

(b) Geographical and Ecological Equator

From these observations, it is obvious that the geographical equator does not correspond to an ecological entity. According to the current oscillations the strict equatorial area appears successively as a more or less productive area. It would be more correct to define an "Ecological Equator" delimited by 0° 40 S and 0° 40 N (approximately 150 km wide) where the biological processes are greatly affected by the current meanders. Recently, Cornus and Meinke (1979) and Kaiser and Postel (1979) concluded that the role played by turbulent exchange in the flow of nutrients is greater than that played by the mean vertical velocity in the undercurrent region at 30° W. Our observations agree with their results, since the maximum productivity occurs near the core of the Lomonosov current, where the vertical mixing is expected to be maximum in the thermocline.

(c) The trap of the long duration stations

When observations are made for several days at the same place, it must be kept in mind that the sampled water is not necessarily the same (in fact

TABLE I

Physical and biological characteristics of the most contrasting stations during the second part of the SOP cruise (5-20 February 1979,) at 0°-4° W St. 4 = 8 February, St. 13 = 17 February

Caractéristiques physiques et biologiques des deux stations les plus contrastées pendant la campagne SOP (5-20 février 1979) à 0°-4° W St. 4 = 8 février, St. 13 = 17 février

	St. 4	St. 13	ratio St. 4/St. 13
E-W component of surface current (cm s^{-1}).	— 30	— 78	0,4
E-W component of undercurrent (cm s^{-1})...	75	30	2.5
Max. value of:			
chlorophyll (µg l^{-1})....................	1.07	.28	3.8
part. carbon (µgat l^{-1}).................	8.2	3.5	2.3
part. phosphorous (µgat l^{-1})............	0.105	0.035	3.0
C/Chla (µg/µ g)........................	80	150	0.55
Integrated value (0-70 m) of :			
primary production (mgC m^{-2} d^{-1}).......	2,0	1.3	3.5
chlorophyll a (mg m^{-2}).................	27.5	13.5	2.0

never) from one day to the day after. If it is true for the equatorial area where two currents flow in the opposite E-W directions, and where both currents cross the equator, it is also valuable to consider such phenomena for other oceanic areas. The *in situ* development of phytoplankton population cannot be observed, because the rapid hydrological variations hide the biological evolution. For that reason, the prediction of biological events requires a better knowledge of the physical processes. Mathematical models for phytoplankton development which do not take the physical variability into account are therefore unable to predict the production of organic matter in the euphotic zone of the oceans.

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