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The use of the salinity maximum of the Equatorial Undercurrent for estimating nutrient enrichment and primary production in the Gulf of Guinea

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Abstract—In the Atlantic Ocean the summer equatorial nutrient enrichment seems due to the increased vertical mixing induced by the vertical shear between the westward South Equatorial Current and the eastward Equatorial Undercurrent. The high salinity core of the undercurrent is a good indicator of the intensity of vertical mixing: its salinity decreases as vertical mixing increases. There is a linear relationship between the salinity of the core and the nitrate enrichment of the surface layer, and at times when nitrate is limiting, the salinity maximum of the Equatorial Undercurrent can be used as a measure of the primary production.

INTRODUCTION

THE HISTORICAL data mapped by MAZEIKA (1968) and the results of the last 20 years' cruises (KOLESNIKOV, 1973; SEDIKH and LOUTOCHKINA, 1971; VOITURIEZ and HERBLAND, 1977) showed that there are two seasons in the equatorial Atlantic Ocean: a warm season from October to June and a cold one from July to September. Mazeika's maps also show that during the cold season equatorial surface cooling is most intense in the Gulf of Guinea around 10°W.

It now seems that the equatorial cooling and the nutrient enrichment of the surface water at the equator in summer could be due to an increase in vertical mixing rather than an actual upwelling. HISARD, CITEAU and VOITURIEZ (1977) reported that the wind alone could not account for the equatorial enrichment because there is no important change in the year of the wind conditions at the equator in the Gulf of Guinea, but the equatorial surface cooling occurs only in summer and is at a maximum in the Gulf of Guinea. On the other hand, there seems to be a significant relationship between equatorial enrichment and the high vertical velocity shear between the westward South Equatorial Current and the eastward Equatorial Undercurrent. In summer, the vertical shear is increased by the acceleration of the South Equatorial Current [25 cm s^{-1} in January 1975 and 110 cm s^{-1} in August 1975 at 4°30′W, according to VOITURIEZ and HERBLAND (1977)] and by the shoaling of the Equatorial Undercurrent (HISARD *et al.*, 1977), both acting to increase vertical mixing and consequently the cooling and nutrient enrichment of the surface water. The Richardson numbers in the pycnocline at the equator (4°30′W) give evidence of such an increase of vertical mixing in summer: $Ri = 5$ in March 1975 and $Ri = 0.3$ in August 1975 (VOITURIEZ and HERBLAND, 1977).

Salinity is conservative and the value of the salinity maximum of the Equatorial

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Undercurrent (Fig. 1) can be used to predict the amount of vertical mixing. The Equalant cruises in 1963 to 1964 (KOLESNIKOV, 1973, 1976) showed the seasonal variations of this salinity maximum. In the warm season it occurs all along the equator and is higher than 36‰, whereas in the cold season it vanishes in the Gulf of Guinea east of 5°W (NEUMANN, 1969). It was previously thought that the disappearance of the salinity maximum was associated with the absence of the undercurrent in the eastern Atlantic, but now it is obvious that the Equatorial Undercurrent reaches the far eastern part of the Atlantic even in summer when the salinity maximum fades in the Gulf of Guinea (HISARD and

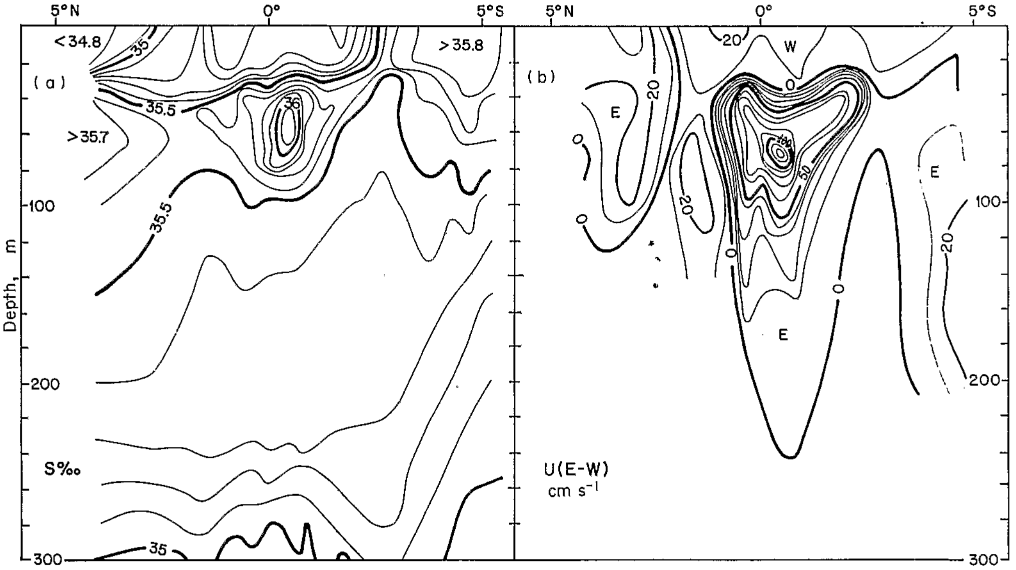

Fig. 1. The east–west component of the velocity (U) and the salinity distribution in the Gulf of Guinea along 4°30′W in January 1975. (a) Salinity. (b) East–west component of velocity.

MORLIÈRE, 1973). Figure 2 is an illustration of this fact at 4°30′W: in August the salinity maximum has almost disappeared by mixing of the upper layer while the eastward Equatorial Undercurrent is always present. According to the Equalant Atlas the values of the salinity maximum are similar during both seasons (36.8‰) in the western part of the Atlantic. Therefore the variations observed in the eastern Atlantic, i.e. the summer disappearance of the salinity maximum in the Gulf of Guinea and its strong decrease along the equator from west to east in summer [0.5‰ from 30 to 17°W in the summer 1963 and only 0.4‰ from 30°W to 8°E in the winter of 1963 according to NEUMANN (1969)], can be explained by vertical mixing variations. SEDIKH and LOUTOCHKINA (1971) and HISARD (1973) have noted this relationship between salinity values and vertical mixing, and they have also shown the increase of the surface salinity that is concomitant with the decrease of the salinity maximum of the undercurrent.

It can be concluded that the erosion of the salinity maximum of the Equatorial Undercurrent is a qualitative indicator of the intense vertical mixing at the equator during summer. The aim of this paper is to show that it can also be used to assess nutrient enrichment and primary production at the equator.

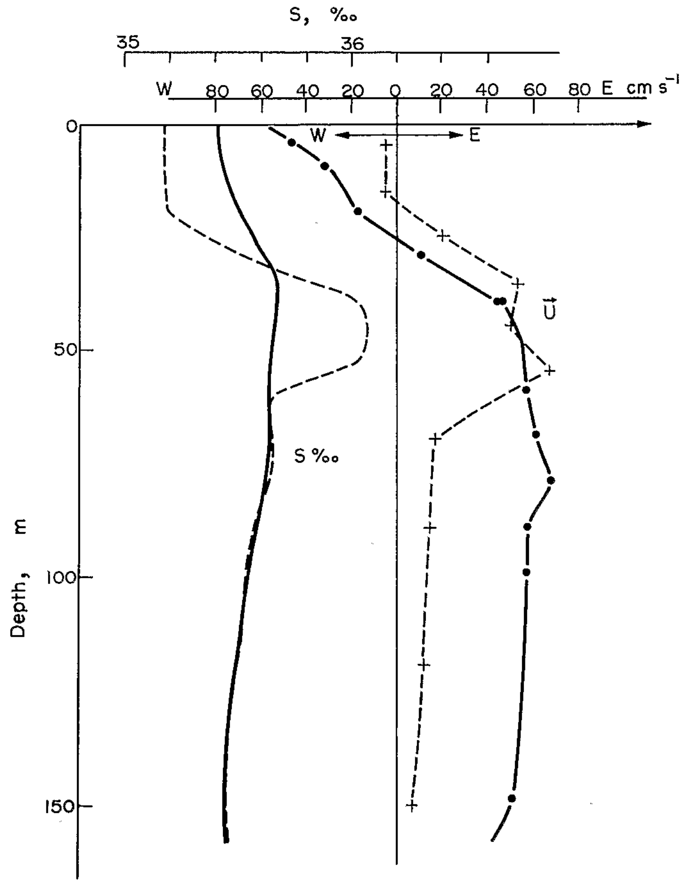

Fig. 2. The salinity core of the equatorial undercurrent at 4°30′W in March 1975 (warm season) and in August 1975 (cold season). U is the east–west component of velocity. ----, CAP 7502, 2 March 1975. Sta. 47. $\phi = 0°44'S$, $G = 4°35'W$. ——, CAP 7506, 8 August 1975. Sta. 56. $\phi = 0°23'S$, $G = 4°26'W$.

EQUATORIAL NITRATE ENRICHMENT AND THE SALINITY MAXIMUM OF THE UNDERCURRENT AT 4°W

In tropical areas where the mixed layer is usually nitrate depleted, nitrate is often the factor limiting primary production and can be used to estimate nutrient enrichment of the euphotic layer. If vertical mixing is the main process in the equatorial enrichment, we can expect a relationship between the nitrate enrichment and the value of the salinity maximum of the undercurrent. During cruises around 4°W by the R.V. *Jean Charcot* and *Capricorne* such a relationship was found between the nitrate content of the upper 100 m at the equator and the value of the salinity maximum (S) of the undercurrent (Fig. 3).

$$\sum_{0}^{100\,m} NO_3\text{-}N(\text{mgatoms}\,m^{-2}) = -1102.7S + 40398, \quad (r = -0.98), \tag{1}$$

where $35.66‰ < S < 36.43‰$.

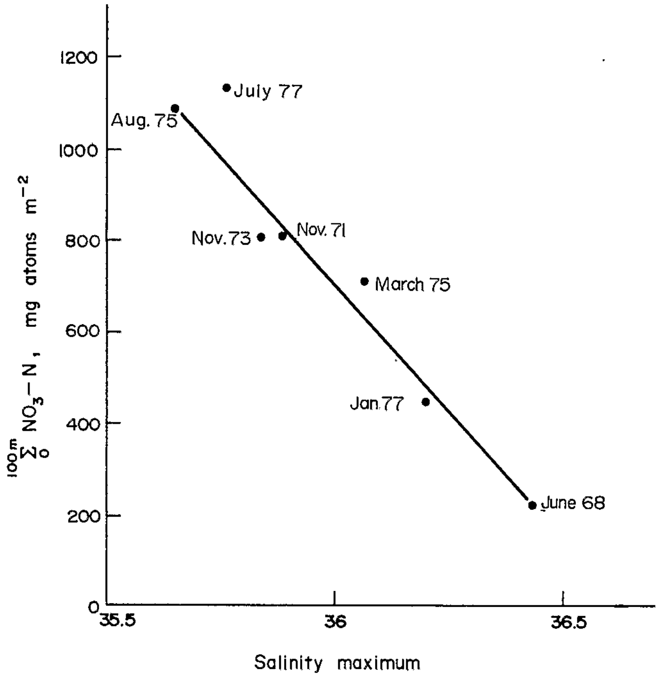

Fig. 3. Relationship between the nitrate content of the upper 100 m and the value of the salinity in the maximum salinity core of the Equatorial Undercurrent around 4°W.

$$\sum_{0}^{100\,m} NO_3-N = -1102.7S+40398, r = -0.98.$$

The annual evolution of the equatorial nitrate enrichment at 4°W is shown in Fig. 4, where all the nitrate values are calculated from equation (1) from the values of the salinity maximum compiled by HISARD (1973) for the period 1962 to 1973 and measured by the R.V. *Capricorne* from 1973 to 1977. The three seasons of production described by TCHMIR (1971) are shown here: maximum from June to September, decreasing from October to January, and minimum in spring. The low nitrate content in June 1968 is associated with the highest value of salinity observed in the undercurrent at 4°W (36.43‰) and with a speed of the undercurrent unusually high (100 cm s^{-1}) for that season (HISARD, 1973). It is probably an exceptional extension of an extremely poor warm season.

THE DEPTH OF THE NITRACLINE AND THE SALINITY MAXIMUM OF THE UNDERCURRENT AT THE EQUATOR AT 4°W

In previous papers, HERBLAND and VOITURIEZ (1977a, in press) have shown the ecological significance of the nitracline in the so-called 'typical tropical situations' defined as tropical systems in which the mixed layer is nitrate depleted. They used data from cruises made by the R.V. *Capricorne* in the eastern tropical Atlantic between 1973 and 1977. During these cruises chlorophyll-*a* was determined at 12 levels of the euphotic zone by *in vivo* fluorescence with spectrophotometric calibration or by extracted fluorescence calibration with pure chlorophyll. Primary production was measured *in situ* at 8 or 10

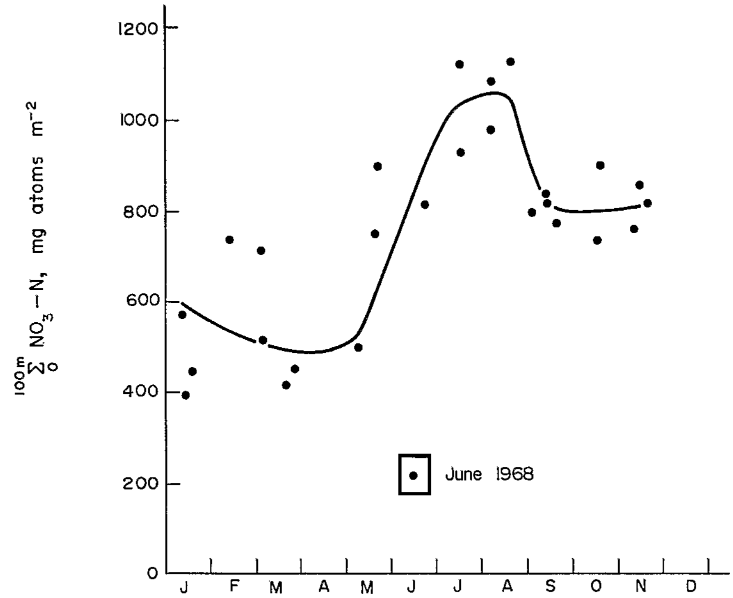

Fig. 4. Seasonal variation of the nitrate content of the upper 100 m at the equator around 4°W.

levels by the ^{14}C method; the incubation time was 8 or 10 h from sunrise to sunset. Their results for the typical tropical situations are summarized here:

The nitracline does not coincide with the pycnocline and usually the top of the nitracline is inside the pycnocline. The maxima of chlorophyll and primary production coincide with the top of the nitracline, which is the level where conditions for primary production are optimum because it is the best-lit nutrient-rich layer and it is inside the pycnocline where vertical stability is high. In such systems, the overall primary production depends on new production which, consuming nitrate, extends into the nitracline. Therefore in typical tropical situations primary production is controlled by the position of the nitracline in the euphotic layer and, as a first approximation, we can assume that the depth of the nitracline is both a measure of the light intensity at the nitracline level and an indirect measure of the primary production. From 28 primary production estimates with the nitracline depth varying from 15 to 100 m and including equatorial stations, the relationship between the total primary production and the nitracline depth is:

$$\text{Primary production} = -0.87\,ZNO_3(\text{m}) + 90, \quad 15\,\text{m} < ZNO_3 < 100\,\text{m}, \quad (2)$$
$$(\text{mg C m}^{-2}\,\text{h}^{-1})$$

where ZNO_3 is the nitracline depth defined by the first level where $NO_3-N > 0.1\ \mu\text{g atoms l}^{-1}$.

During the warm season (from October to June) the equatorial area of the Atlantic Ocean is a typical tropical situation because there is essentially no nitrate in the surface layer (VOITURIEZ and HERBLAND, 1977). Therefore equation (2) can be applied at the equator during that period. The depth of the top of the nitracline is generally the result of an equilibrium between physical processes (vertical advection, vertical mixing) and nitrate

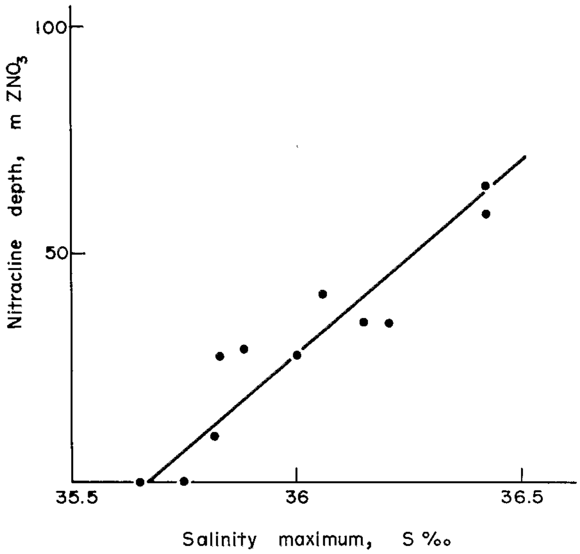

Fig. 5. Relationship between the depth of the nitracline and the salinity maximum of the undercurrent around 4°W. $ZNO_3 = 86.207S - 3075$, $r = 0.93$.

uptake by phytoplankton. However, it seems that vertical mixing is the more important because VOITURIEZ and HERBLAND (1977) have shown that at 4°W there is a relationship between the depth of the top of the nitracline and the depth of the maximum vertical density gradient, showing that the top of the nitracline is just below the maximum stability layer. Thus the thickness of the nitrate depleted layer is defined by the depth of the maximum stability layer through which rather low vertical mixing allows little nitrate diffusion. Under such conditions, a relationship also can be expected between the depth of the nitracline and the value of the salinity maximum of the undercurrent, which in turn indicates the amount of vertical mixing. From the measurements made by the R.V. *Jean Charcot* and *Capricorne* at the equator around 4°W such a relationship was found (Fig. 5):

$$ZNO_3(\mathrm{m}) = 86.207S - 3075, \quad (r = 0.93). \tag{3}$$

From equations (2) and (3), the following relationship between primary production (P_i) and the value of the salinity maximum of the undercurrent (S), valid only for the warm season at 4°W, can be deduced:

$$Pi(\mathrm{mg\,C\,m^{-2}\,h^{-1}}) = -75S + 2765, \quad 35.66‰ < S < 36.43‰. \tag{4}$$

Equation (4) shows that primary production increases with vertical mixing at the equator and can vary from 33 to 90 mg C m^{-2} h^{-1} during the warm season. During the cold season (July to September) when nitrate is present in surface water at the equator, equations (2) and (4) are not applicable, but VOITURIEZ and HERBLAND (1977) have shown that during that season measured primary production values (133 mg C m^{-2} h^{-1} in July 1977) were higher than those calculated using equation (2) for $ZNO_3 = 0$ (90 mg C m^{-2} h^{-1}), so that during the cold season the equation (4) gives a minimum estimate of primary production at the equator.

CONCLUSION

Relationships applied to specific examples show that one can evaluate primary production from simple physical or chemical parameters. Equation (2) relating primary production and nitracline depth is valid for the typical tropical situations of the Atlantic, and has been used to improve detailed primary production mapping in the Gulf of Guinea from the cruise GUINEE 1 of R.V. *Jean Charcot* in 1968 (HERBLAND and VOITURIEZ, 1977b) and in the tropical Atlantic Ocean from the Equalant data of 1963 (VOITURIEZ and HERBLAND, in press).

Equation (4) relating primary production and the salinity maximum of the undercurrent, is restricted to the equatorial area of the Gulf of Guinea, but insofar as vertical mixing is responsible for equatorial surface enrichment in the Atlantic Ocean, relationships similar to equations (1), (3), and (4) between nitrate enrichment, nitracline depth, primary production, and salinity maximum of the undercurrent should apply at each longitude. Unfortunately, the available nitrate and primary production data are too few to test the validity of such relationships at other longitudes.

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