

An unexpected nitrate distribution in the tropical North Atlantic at 18°N, 30°W—implications for new production

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Abstract—During a R.V. *Meteor* JGOFS-NABE cruise to a tropical site in the northeast Atlantic in spring 1989, three different vertical regimes with respect to nitrate distribution and availability within the euphotic zone were observed. Besides dramatic variations in the depth of the nitracline, a previously undescribed nose-like nitrate maximum within the euphotic zone was the most prominent feature during this study. Both the vertical structure of phytoplankton biomass and the degree of absolute and relative new production were related to the depth of the nitracline, which in turn was dependent on the occurrence/non-occurrence of the subsurface subtropical salinity maximum (S_{\max}). The mesoscale variability of the nitracline depth, as indicated from a pre-survey grid, and published data on the frequent occurrence of the S_{\max} in tropical waters suggest higher variability of new production and F -ratio than usually expected for oligotrophic oceans. The importance of salt fingering and double diffusion for nitrate transport into the euphotic zone is discussed.

INTRODUCTION

SINCE DUGDALE (1967) the euphotic zone of subtropical and tropical open ocean systems has been characterized as a two-layered system with respect to biological processes. In the upper nutrient-depleted layer phytoplankton production relies primarily on regenerated nutrients (EPPLEY, 1981) and small size classes dominate the phytoplankton (VENRICK, 1982; HERBLAND *et al.*, 1985). Nitrate-dependent new production (DUGDALE and GOERING, 1967) is usually thought to be restricted to the nitracline at the base of the euphotic zone (McCARTHY and ALTABET, 1984). This nitracline layer is characterized by a distinct chlorophyll *a* (Chl *a*) maximum (RILEY *et al.*, 1949; VENRICK *et al.*, 1973; HERBLAND, 1983) and an increased proportion of larger phytoplankton size classes (HERBLAND *et al.*, 1985). For both the Pacific (ANDERSON, 1969; SHULENBERGER and REID, 1981) and the tropical Atlantic (cf. HERBLAND and VOITURIEZ, 1979) oxygen maxima have been observed between the nitracline and the mixed surface layer. Phytoplankton biomass expressed as Chl *a* (LE BOUTELLER, 1986), nitrate concentrations (for values <40 nmol; EPPLEY *et al.*, 1990) and integrated nitrate content of the euphotic zone (EPPLEY and KOEVE, 1990) have been observed to control rates of nitrate use in the tropical and subtropical North Atlantic. Vertical structures, particularly the depth of the nitracline, have been found to be of great importance for integrated primary production and Chl *a* biomass (HERBLAND and

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VOITURIEZ, 1979). Recently, LE BOUTELLER (1986) showed that the nitrate uptake index (EPPLEY *et al.*, 1979) was significantly correlated with photosynthetic available radiation (PAR) in the tropical North Atlantic.

In the tropical North Atlantic the hydrographic variability of the upper thermocline reflects the frequent occurrence of a subsurface salinity anomaly (WORTHINGTON, 1976; EBBESMEYER *et al.*, 1986). Since DEFANT (1936) and MONTGOMERY (1938) this subsurface salinity maximum (S_{\max}) is a well known feature of tropical oceans that occurs between the seasonally mixed surface layer and the North Atlantic Central Water. The salinity maximum water is formed in the central subtropical North Atlantic gyre due to an evaporation/precipitation imbalance (DEFANT, 1936; MALKUS, 1962). Oxygen and nutrient signatures of the source water are typical for surface waters in the subtropical gyre, i.e. oxygen saturated (WORTHINGTON, 1976; TOPOGULF, 1986) but depleted with respect to nutrients, particularly nitrate (FRAZEL and BERBERIAN, 1990). From the source region, the subsurface salinity maximum water spreads out mainly in a southwest-directed tongue (WORTHINGTON, 1976; KAWASE and SARMIENTO, 1985), and has been observed even in Caribbean Sea waters (LAMBERT and STURGES, 1977). In the eastern North Atlantic it has been found between 20 and 8°N, 35 and 17°W, respectively (DEFANT, 1936; WILLENBRINK, 1982; BAUER and SIEDLER, 1988).

A recently reported unexpected nitrate distribution in the euphotic zone (EPPLEY and KOEVE, 1990) at 18°N, 30°W has been related to the occurrence of subsurface salinity maximum water at the base of the euphotic zone (PODEWSKI *et al.*, 1993). In this paper we attempt to relate observed variability in new production rates in the area (EPPLEY *et al.*, 1990; EPPLEY and KOEVE, 1990) to hydrographical and chemical patterns within the upper 200 m which were influenced by the frequent occurrence of S_{\max} water.

MATERIALS AND METHODS

During the first leg of R.V. *Meteor* cruise 10, a site at about 18°N, 30°W had been occupied. Between 26 March and 6 April 1989 a Langrangian drift study with hydrographical, chemical and biological measurements was carried out. The euphotic zone was sampled every morning before sunrise next to a drifting array, consisting of two sediment traps, various *in situ* fluorescence probes and a surface buoy. Discrete water samples for oxygen and nutrient determinations, and for incubations were taken using a hydrocast equipped with Neil Brown CTD-sensors (Mark III-CTD-unit) and 24 10-l Niskin bottles. Samples for Chl *a* measurements were taken from a subsequent hydrocast with six 30-l Niskin bottles. Nitrate concentrations and nitrate utilization were measured using the chemoluminescence technique (GARSIDE, 1982, 1985; EPPLEY *et al.*, 1990; for details on sample handling see EPPLEY and KOEVE, 1990). Nitrate and other nutrients were additionally measured according to GRASSHOFF *et al.* (1983). Oxygen concentrations were measured with the modified Winkler technique (GRASSHOFF *et al.*, 1983) using a photometer controlled automatic titration system. Relative oxygen saturations were calculated according to WEISS (1970). Chlorophyll *a* samples were gently filtered onto Whatman GF/F and measured with a spectrophotometer (STRICKLAND and PARSONS, 1972; JEFFREY and HUMPHREY, 1975). Primary production measurements (^{14}C) were provided by F. Jochem and are described in JOCHEM and ZEITZSCHEL (1993). The depth of the euphotic zone (1% light level) was estimated based on Secchi depth readings. Fluorescence profiles were measured using the Kiel-FISH system, equipped with ME-CTD-sensors and a backscatter

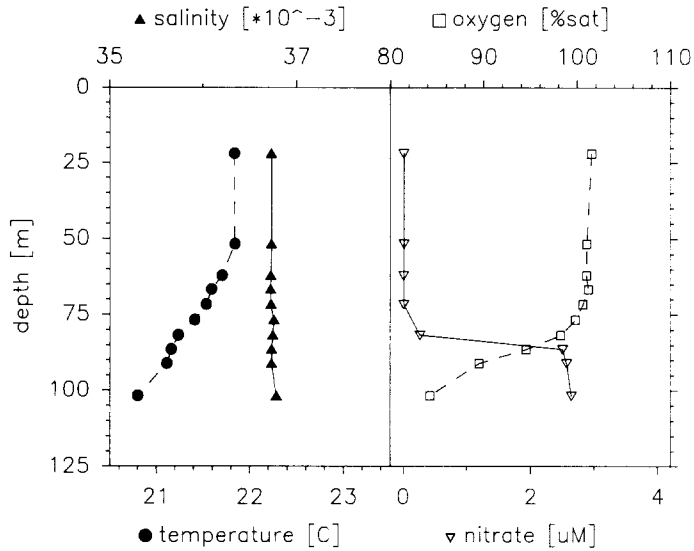


Fig. 1. Representative profiles of temperature, salinity, nitrate and oxygen at a T-station from the beginning of the drift experiment (Sta. 241, 27 March 1989).

fluorescence probe. Sample depths for water property measurements and incubations were selected according to the fluorescence profile. *In situ* incubations for nitrate utilization and ^{14}C -primary production were carried out in connection with a second drifting sediment trap array (JOCHEM and ZEITZSCHEL, 1993). Polycarbonate bottles (250 ml) were incubated at eight to ten depths in the upper 100 m with a high resolution within the layer of maximum fluorescence. Incubations lasted from sunrise to sunset (about 12 h).

RESULTS AND DISCUSSION

Vertical distribution of nitrate and oxygen

During the 12-day study, the drifting array moved in an approximately northwesterly direction, which corresponds quite well with the direction of the seasonal Ekman-transport of the surface layer in the study area (STRAMMA and ISEMER, 1988). The speed of the drifter varied and objective analysis of density fields and geostrophic calculations in deeper water layers (120 and 300 m) showed that the drifter crossed a subsurface frontal structure between 29 March and 1 April (PODEWSKI *et al.*, 1993). During the study we observed three different vertical regimes with respect to nitrate distribution, which we classified as T-, N- and D-stations (see Figs. 1–3 for examples, Fig. 4 for a schematic representation and Table 1 for boundary conditions of different water layers).

At the beginning of the drift study, vertical profiles of chemical and biological properties in the upper 150 m resembled those typical for tropical waters (Figs 1 and 4a; Table 2; T-stations). The winter mixed surface layer extended over the upper 60 m and was nitrate depleted and oxygen saturated. The nitracline (defined as the $0.5 \mu\text{mol l}^{-1}$ isoline of nitrate), which was usually observed between 60 and 80 m, coincided with decreasing temperature and oxygen saturations. Salinity profiles of T-stations did not show significant

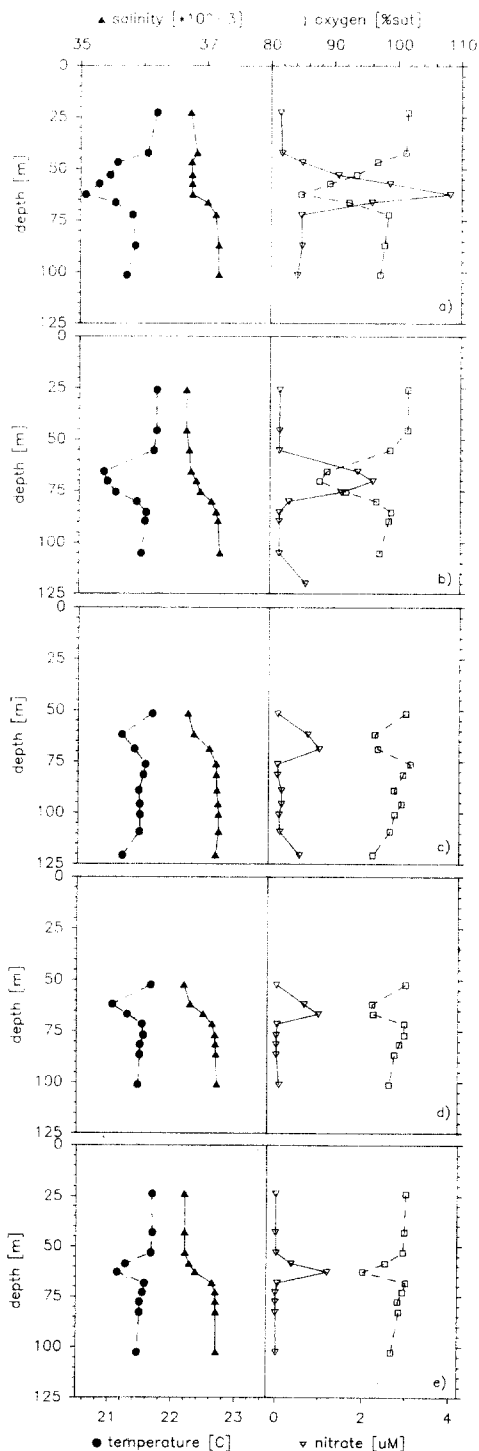


Fig. 2. Depth distribution of temperature, salinity, nitrate and oxygen at representative stations with nose-like temperature, nitrate and oxygen structures (N-stations): (a) Sta. 249, 29 March; (b) Sta. 279, 3 April; (c) Sta. 282, 3 April (evening); (d) Sta. 283, 4 April; (e) Sta. 287, 5 April. The lower nitracline was sampled at Stas 279 and 282 (b, c).

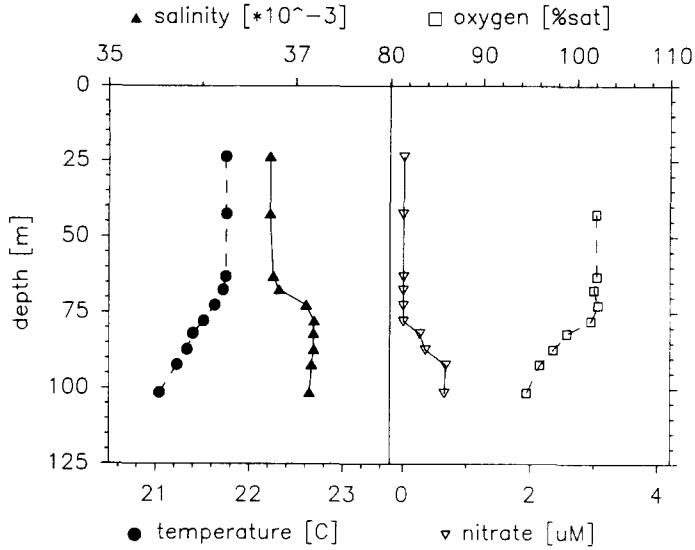


Fig. 3. Temperature, salinity, nitrate and oxygen profiles at a D-station with deep nitracline at the end of the drift study (Sta. 292, 6 April). Nose-like structures of nitrate and oxygen have disappeared. Note the very low nitrate concentration even at 120 m ($0.88 \mu\text{mol NO}_3 \text{ l}^{-1}$).

contributions of S_{max} water. Mainly during the second half of the drift study, we observed a very different pattern of nitrate and oxygen distribution in the upper 150 m (Figs 2 and 4b; Table 2, N-stations). Vertical profiles of nitrate showed a nose-like nitrate maximum with an upper nitracline at the base of the winter mixed surface layer at 57 ± 7 m depth. Between 75 and 100 m a secondary nitrate minimum was observed where nitrate was at the

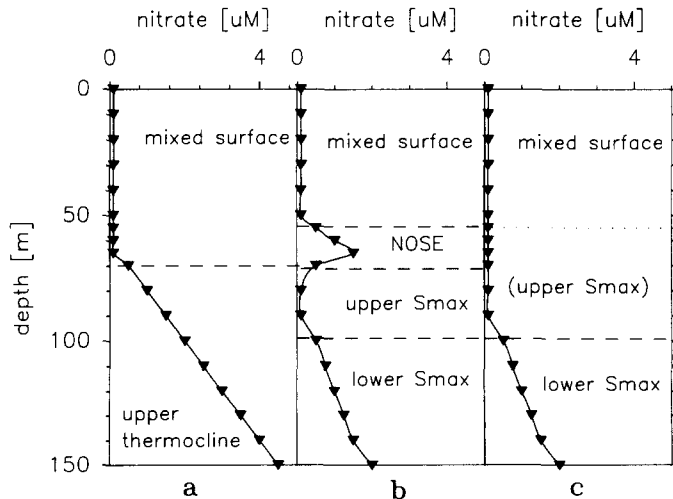


Fig. 4. Schematic presentation of the different vertical nitrate regimes observed during our study. T-(typical tropical)-stations (a), N-(Nose-like structures)-stations (b), D-(deep nitracline)-stations (c).

Table 1. *Boundary conditions of water layers observed during the drift study*

	Nitrate ($\mu\text{mol l}^{-1}$)	Oxygen (% Sat.)	Salinity $\times 10^{-3}$		Temperature ($^{\circ}\text{C}$)
Mixed surface	<0.5	98–102	36.7	lower boundary	>21.1
Upper thermocline	>0.5	<98	36.7	upper boundary	<21.1
Nose-like structure	>0.5	<98	>36.7	upper boundary	<21.1
	>0.5	<98	<37.1	lower boundary	<21.3
Upper S_{max}	<0.5	98–102	>37.1	both	>21.3
Lower S_{max}	>0.5	<98	<37.1	upper boundary	<21.3

detection limit even with the sensitive chemoluminescence method. Between 90 and 120 m we observed a lower and main nitracline (see Fig. 2b,c and Table 2). Oxygen profiles at these stations showed significant subsurface minima at depths where nitrate was high (Fig. 2). At the depth of the subsurface nitrate minimum, oxygen saturations were as high as at the surface (i.e. about 100% saturation). The vertical temperature distribution showed a minimum in the nitrate maximum. Salinity profiles were characterized by the occurrence of an “intrusion” of high saline water usually between 70 and 150 m (see Fig. 2), which was identified to be water of the subtropical salinity maximum (S_{max} ; PODEWSKI *et al.*, 1993). Highest observed nitrate concentrations in the nose-like structure were about $4 \mu\text{mol NO}_3 \text{ l}^{-1}$ at Sta. 249, and integrated nitrate values in this structure decreased with time/stations (see Table 3). The concentrations of nitrate and oxygen in the subsurface nitrate minimum layer compared well with measured and expected performed values of the subtropical salinity maximum (POHL, 1991; B. KLEIN, personal communications). During the last days of the drift study the nose-like nitrate, oxygen and temperature structures had disappeared, the lower nitracline became the principal one and was still located at about 100 m depth (see Figs. 3 and 4c; Table 2 D-stations). The S_{max} layer was still present and the nitracline was well established below the mixed surface layer. The nitrate distribution found on these stations resembles the nitrate profiles typical for truly oligotrophic sites, like the Sargasso Sea (e.g. ALTABET, 1989).

Biological effects

A change in the depth distribution of maxima of Chl *a*, corresponding to maxima in autotrophic biomass and primary production (JOCHEM and ZEITSCHEL, 1993), was evident during the T-, N- and D-stations, characterized above. Absolute Chl *a* concentrations at the depth of the Chl *a* maximum decreased during the drift study from up to $1.12 \mu\text{g Chl } a \text{ l}^{-1}$ at T-stations down to values as low as $0.37 \mu\text{g Chl } a \text{ l}^{-1}$ at D-stations (Table 2). A closer look at selected *in situ* Chl *a* profiles from the FISH-system reveals a more detailed picture of the transition from N- to D-stations. A second, deeper, maximum in Chl *a* appeared between Stas 279 and 291 (Fig. 5), becoming the principal Chl *a* maximum after the disappearance of the upper one. A close correlation between the depth of the Chl *a* maximum and the nitracline depth was evident at the study site (see Fig. 6). This observed relationship between Chl *a*, phytoplankton biomass, primary production and the depth of the nitracline resembles the “typical tropical structure” described by HERBLAND and VOITURIEZ (1979), indicating the importance of nitracline depth to pelagic dynamics at the study site.

Table 2. Depth of the euphotic zone (Z_{eu}), depth of upper and lower nitraclines, depth of Chl *a* maximum and maximum Chl *a* concentration (T-, N- and D-stations are indicated)

Station	Date	Z_{cu} (m)	Upper nitracline (m)	Lower nose boundary (m)	Lower nitracline (m)	Depth of Chl a_{max} (m)	max[Chl <i>a</i>] ($\mu\text{g l}^{-1}$)	Stage	Note
239M	03/26/89	ND	80	ND	ND	75	0.77	T	
241E	03/27/89	ND	82	ND	ND	80	0.64	T	
245M	03/28/89	ND	81	ND	ND	65	0.78	T	
247E	03/28/89	ND	63	ND	ND	65	1.12	T	*
249M	03/29/89	62	44	70	>100	45	0.99	N	
252E	03/29/89	ND	73	ND	ND	78	0.53	T	*
254M	03/30/89	62	52	ND	ND	70	0.78	T	
258E	03/30/89	ND	67	ND	ND	78	0.86	T	*
260M	03/31/89	89	58	s.note	s.note	60	0.87	(N)	†
264E	03/31/89	ND	72	ND	ND	78	0.91	T	
266M	04/01/89	84	76	ND	ND	65	0.62	T	
270E	04/01/89	ND	62	ND	ND	67	0.79	T	*
273M	04/02/89	87	62	s.note	s.note	65	0.70	(N)	‡
277E	04/02/89	ND	s.note	s.note	90	67	0.62	(N)	§
279M	04/03/89	65	54	74	120	65	0.64	N	
282E	04/03/89	ND	59	71	120	67	0.67	N	*
283M	04/04/89	79	59	67	>100	60	0.67	N	
286E	04/04/89	ND	—	—	105	75	0.51	D	*
287M	04/05/89	84	56	63	>120	50	0.55	N	
290E	04/05/89	ND	—	—	110	88–109	0.45	D	
291E	04/05/89	ND	—	—	100	NV	NV	D	
292M	04/06/89	92	—	—	90	80/120	0.37	D	
Mean Values									
Upper nitracline mean		S.D.	<i>n</i>	Depth Chl a_{max} mean	S.D.	<i>n</i>	[Chl <i>a</i>] mean	S.D.	<i>n</i>
T71		10	10	72	6	10	0.78	0.17	10
NS7		7	8	63	6	7	0.71	0.14	7
D90–120				100			0.37		

Key: M, morning stations; E, evening stations; ND, not determined; Z_{cu} , depth of the euphotic zone (1% light depth); T, stations with "typical tropical" nitrate and oxygen profiles; N, stations with "nose-like" nitrate and oxygen profiles; D, stations with only a "deep" nitracline.

* Only few Chl *a* data available.

† At 100–120 m lower nitrate, higher oxygen concentration and USSM-salinity signature.

‡ At 100 m depth only, lower nitrate, higher oxygen concentration and USSM-salinity signature.

§ At 67 m (the depth of Chl a_{max}) low oxygen but high nitrate values.

|| Second Chl a_{max} at 100 m depth with $0.43 \mu\text{g Chl } a \text{ l}^{-1}$.

Rates of new production peaked at the nitracline, and integrated new production in the euphotic zone correlated well with integrated nitrate concentrations (EPPLEY and KOEVE, 1990). Highest integrated nitrate utilizations (Table 4) were found at stations with shallow nitracline depths, situated well above the 1% isolume (T-stations 254 and 260) and at the station with the largest nitrate maximum observed (N-station 249). Lowest nitrate utilization rates were observed at the end of the drift period after the disintegration of the

Table 3. Integrated nitrate content, vertical extension of the nose-like nitrate maximum, and maximum concentration of Chl *a* at several N-stations

Station	Int. NO ₃ (mmol NO ₃ m ⁻²)	Vertical extension (m)	max [Chl <i>a</i>] (μg l ⁻¹)
249	53.2	26	0.95
279	29.9	20	0.64
282	9.4	12	0.67
283	6.1	8	0.67
287	5.94	7	0.55

nitrate maximum when a deep nitracline at 90 m (Sta. 292) was observed. Mean *F*-ratios of the upper 100 m (Table 4) varied between 0.1 and almost 1, with highest values at stations with a shallow nitracline depth. Typical *F*-ratios for oligotrophic oceans are in the range of 0.1–0.2 (EPPLEY and PETERSON, 1979), which agree only with our lowest values. For the north equatorial Atlantic, LE BOUTEILLER (1986) has shown that nitrate use and, particularly, the nitrate uptake index (nitrate use per unit Chl *a*) was significantly correlated with photosynthetically available radiation (PAR). Assuming optical properties of clearest ocean water (Jerlov Typ 1, JERLOV, 1976) with an attenuation coefficient of 0.036 m⁻¹ (cf. SMITH and SAKSHAUG, 1990), the 1% light depth is at about 125 m. A Chl *a* content of 30 mg m⁻² or less, typical for oligotrophic sites (e.g. ALTABET, 1989), will raise this depth to about 115 m (assuming an average specific absorption coefficient of 0.010 m² (mg Chl *a*)⁻¹ (MASKE and HAARDT, 1987). The typical depth of the nitracline at truly oligotrophic sites like the Sargasso Sea is about 110 m (ALTABET, 1989); hence it is situated at about the 1% light level. During our study the nitracline depth was as shallow as the 20% light depth at

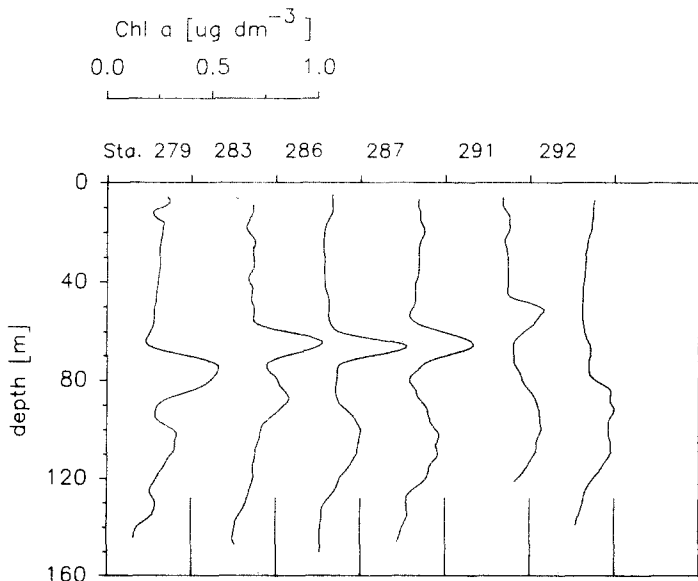


Fig. 5. *In vivo* Chl *a* profiles on several N- and D-stations. (Stas 279/N, 283/N, 286/D, 287/N, 291/D, 292/D are shown. See Table 2 for additional data.)

those stations with high new production and F -ratios (T- and N-stations). At our D-stations, however, the nitracline was situated at the depth of the 1–5% isolume, and F -ratios were as low as those expected for oligotrophic sites.

During our cruise, mesoscale horizontal variability was investigated within a $1 \times 1^\circ$ triangular grid prior to the drift study (Fig. 7). Since nitrate and oxygen measurements were not conducted within this grid, the depth of the nitracline was estimated from the depth of the Chl a maximum (*sensu* Fig. 6 and STRASS and WOODS, 1991) and the upper boundary of the main temperature gradient (compare Figs 1–3). Accordingly, we separated four groups of stations, three of which corresponded to our T-, N- and D-stations during the drift study. Estimates of nitracline depth based on structural analysis during the pre-survey grid compared well with measured nitrate profiles during the drift study at nearby stations. From this analysis a strong heterogeneity in nitracline depth and vertical Chl a distribution is evident (Fig. 7). The central and the northern areas, which showed shallow nitracline depth and nose-like maxima, respectively, are supposed sites of higher new production, compared with areas in the southwestern part of the grid.

Nose-like nitrate profiles: a unique situation?

Nose-like structures of nitrate and oxygen in the upper 100 m of the open ocean such as those reported here are, to the best of our knowledge, as yet undescribed in the literature. The only similar observation with respect to subsurface minima in nitrate profiles comes from the EASTROPAC expedition (THOMAS, 1972) where South Pacific S_{\max} water with almost undetectable concentrations of nitrate was observed between 50 and 150 m at several stations between 15 and 10°S and 119°W. With surface nitrate concentrations of

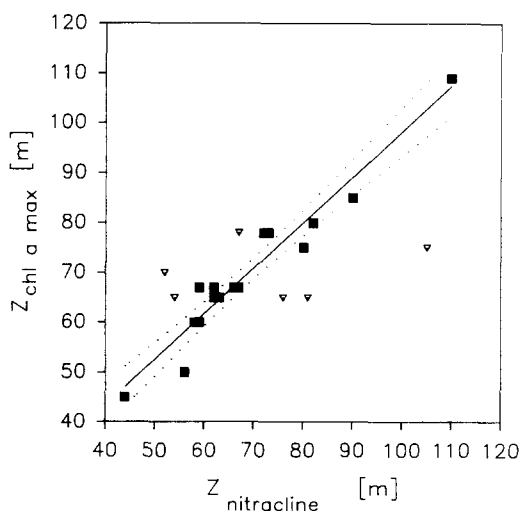


Fig. 6. Correlation between the depth of the Chl a_{\max} and the depth of the nitracline during our drift study at 18°N, 30°W. Squares indicate stations where both nitrate and Chl a samples came from the same CTD-cast. Linear regression formula was $y = 0.91x + 6.87$, $r = 0.97$. On several morning stations (triangles) Chl a and nitrate were sampled from different casts, spaced about 2 h apart. The apparent non-systematic deviation of $Z_{\text{Chl } a_{\max}}$ and $Z_{\text{nitracline}}$ at these stations is ascribed to internal wave activity which was observed during this study (PODEWSKI, unpublished).

Table 4. Integrated nitrate utilization rates ($\text{NO}_3\text{-use}$), primary production and depth weighted mean F-ratio in the euphotic zone. F-ratios calculated as $(\text{NO}_3\text{-use} \cdot \text{Redfield-ratio})/\text{primary production}$, with Redfield-ratio = 6.7 (REDFIELD *et al.*, 1963). 1% light depth (Z_{eu}), based on Secchi-Disk readings and depth of nitracline (0.5 $\text{mmol NO}_3 \text{ l}^{-1}$) are given for comparison. Nitrate utilization rates are from EPPLEY and KOEVE (1990), primary production values are from JOCHEM (1990) and JOCHEM and ZEITZSCHEL (1993)

Station	1% Isolume (m)	$Z_{\text{nitracline}}$ (m)	$\text{NO}_3\text{-use}$ ($\text{mmol m}^{-2} (12 \text{ h})^{-1}$)	Primary production ($\text{mg C m}^{-2} (12 \text{ h})^{-1}$)	F-ratio
241	60	82	1.97	268	0.59
249	62	44	3.91	429	0.73
254	62	52	4.81	411	0.94
260	89	58	4.79	437	0.88
266	84	76	0.50	336	0.12
273	87	62	2.67	—	—
279	65	54	—	1102	—
292	92	90	-0.26	447	0

2–5 $\mu\text{mol l}^{-1}$, being non-limiting to autotrophic growth, we postulate that this inversion in the South Pacific did not affect pelagic growth to the extent reported in our nitrate poor waters.

Inversions such as the intrusion of high saline waters yielding subsurface salinity maxima are a common and well known phenomenon in tropical and subtropical waters (DIETRICH *et al.*, 1975). The depth of the S_{max} layer is critical for the distribution of nitrate within a “potential euphotic zone” of 115–125 m. Usually, the core of the S_{max} water in the tropical North Atlantic is observed between 80 and 150 m (WORTHINGTON, 1976; BAUER and SIEDLER, 1988), however, it rises towards the Equatorial Counter Current, where it can be found at 50 m depth (PETERS, 1978; BAUER and SIEDLER, 1988). WORTHINGTON (1976) showed that the S_{max} water keeps its oxygen signature of about 100% saturation for a great distance from its formation at the surface. Due to autotrophic N-uptake in the source region of the S_{max} water, it also should be nitrate depleted, a relationship also evident from Fig. 8. Information on the distribution of nutrients and particularly nitrate in the upper 100 m of the open ocean is poorly documented, the depth of the nitracline, however, may be inferred from the depth of the subsurface Chl *a* maximum (e.g. STRASS and WOODS, 1991). GIESKES *et al.* (1978) observed a subsurface Chl *a* maximum at about 100 m at stations at 20°N, 30°W, with maximum concentrations of about 0.25 mg m^{-3} ; the Chl *a* maximum and presumably the nitracline was situated below the core of the S_{max} (BAARS *et al.*, 1979). More recent observations from stations at 21°N, 34.5°W and 16°N, 36.5°W indicate that during late August 1988 both the nitracline and the Chl *a* maximum were below 100 m depth and below the core of the S_{max} water (FRAZEL and BERBERIAN, 1990; FRAZEL *et al.*, 1989). Neither of the two studies indicates any nose-like structure of nitrate between the seasonally mixed surface layer and the S_{max} layer. Furthermore, FRAZEL and BERBERIAN (1990) observed that total primary production in the area was restricted to the upper nitrate-depleted 50–70 m, indicating that new production at the nitracline, which was below the 1% isolume, was low. Nitrate concentrations during winter 1989 were below the detection limit at least in the upper 40–50 m at the study site (B. KLEIN, personal communication). Preliminary inspection of salinity profiles from this cruise reveals that the S_{max} layer directly underlies a shallow (30–50 m) seasonal mixed layer. Nose-like structures in temperature, which could be used as an indication of nitrate maxima (see Fig.

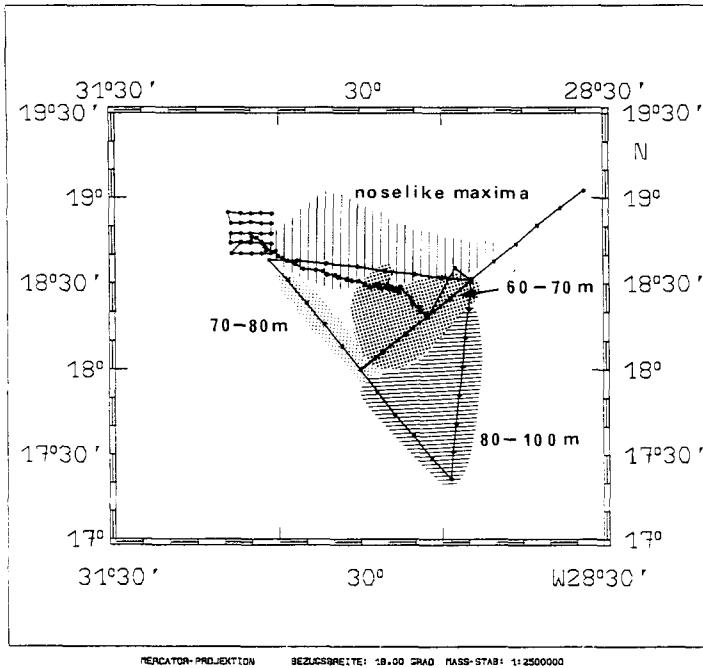


Fig. 7. Mesoscale horizontal variability of the nitracline depth in the study area, as inferred from the depth of the Chl *a* maximum and temperature structure. The map shows the expected depth of the nitracline during the pre-survey grid (large triangle) and the measured depth of the nitracline at stations along the drift track. The analysis is based on a separation of the profiles into the following groups. (1) Nitracline expected at 60–70 m: stations with shallow (60–70 m) upper boundary of main temperature gradient and Chl *a* maximum depth; Chl *a* concentrations are high and a pronounced maximum is present. This group corresponds to T-stations during the drift study. (2) Nose-like nitrate maximum expected: stations with nose-like temperature structures and well established Chl *a* maximum (corresponds to N-stations). (3) Deep nitracline (80–100 m) expected: stations with deep (80–100 m) and less pronounced Chl *a* maximum (corresponds to D-stations). (4) Intermediate nitracline depth expected: stations with intermediate (about 80 m deep) Chl *a* maxima.

2 and the mesoscale analysis, Fig. 7), were not seen in their CTD-profiles. An examination of published and unpublished upper ocean data thus reveals that (a) S_{\max} water as a typical water mass in large parts of the tropical ocean usually underlies the mixed surface layer and thus deepens the nitrate-depleted water layer, and (b) nose-like nitrate maxima within the euphotic zone are previously unreported in the literature.

Nitrate supply to the euphotic zone in the tropical ocean

Nitrate distribution in the upper ocean of non-tropical regions of the Atlantic is characterized by a typical annual cycle of rapid depletion in the very top layer due to new production during spring phytoplankton growth, a gradual deepening of the nitracline during summer (STRASS and WOODS, 1991) due to new production at the nitracline, and the

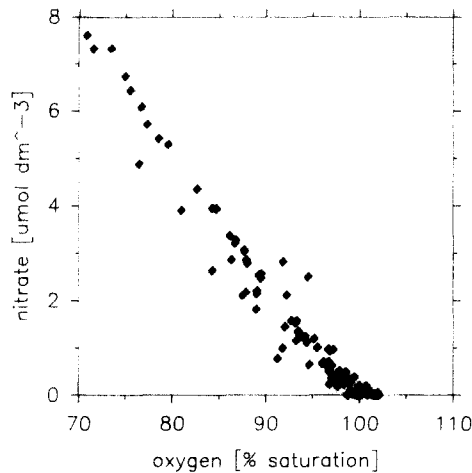


Fig. 8. Nitrate concentration versus oxygen saturation during the drift study at 18°N, 30°W. Values were determined from discrete water samples taken from the same bottle.

re-establishment of higher nitrate concentrations in the surface layer as a result of winter mixing. Initial spring nitrate concentrations, and hence annual new production, depend on the ratio of winter mixing depth to the summer mixed layer depth.

For tropical regions winter mixed layer depth is shallow compared with temperate domains of the ocean. Both LEVITUS (1982) and GLOVER and BREWER (1988) have suggested that the typical winter mixed layer in the study area is about 50 m deep. Comparing these climatological data with our observations that the nitracline was usually far below the winter mixed layer depth, we conclude that seasonal deepening of the mixed layer should be of minor importance for the nitrate flux into the euphotic zone, as evident also from model calculations (LEWIS *et al.*, 1988). Estimates of export production from the nearby beta triangle region (JENKINS, 1982) were equivalent to a mean nitrate utilization rate of $1.9 \text{ mmol N m}^{-2} \text{ day}^{-1}$. Both these data and our nitrate utilization rates of up to $4.81 \text{ mmol N m}^{-2} \text{ day}^{-1}$ require the existence of an additional nitrate source to the euphotic zone. Estimates of nitrate transport rates based on turbulent mixing yield low rates of $0.002\text{--}0.89 \text{ mmol N m}^{-2} \text{ day}^{-1}$ for the oligotrophic eastern Atlantic (LEWIS *et al.*, 1986), in agreement with a biologically unproductive oligotrophic ocean. Local wind-induced mixing events have been suggested to be a sporadic but important source for new nitrogen (JENKINS and GOLDMAN, 1985; WANGERSKY, 1986), however, model calculations reveal that this process might be a significant contribution to nitrate fluxes only if the nitrate-depleted surface layer is shallow (i.e. 50 m or less; KLEIN and COSTE, 1984; BIGG *et al.*, 1989).

Recently, HAMILTON *et al.*, (1989) suggested that salt fingers and associated double diffusion might be an important process in the vertical flux of nitrate. Diapycnal mixing due to salt fingering has been observed when warm and more saline water overlies cold and less saline water layers (BAUER and SIEDLER, 1988). Such a situation was given after intrusion of warm and saline S_{max} over cold and less saline Central Water during our drift study (PODEWSKI *et al.*, 1993). These authors discussed RROH values (SCHMITT, 1979) varying between 1.45 and 1.85, and stability angles (WASHBURN and KÄSE, 1987) of 0–45.

both indicating high salt-finger activity in the transition zone between the subsurface salinity maximum and the underlying nutrient-enriched North Atlantic Central Water. Staircases, particularly in salinity profiles, indicate that salt fingering was a usual phenomenon in this transition zone.

HAMILTON *et al.* (1989) compared the importance of double diffusive mixing and turbulent mixing for a more northern site in the eastern subtropical North Atlantic. When RROH values were 1.6, model calculations for their data gave vertical exchange coefficients due to salt fingering ($K_{s,t}$) that were six times higher than those for turbulent mixing ($K_{s,t}$). There are no microturbulence measurements available from our study, thus we can only speculate whether turbulent transport rates of nitrate are similar to those of LEWIS *et al.* (1986) or not. However, multiplying their turbulent transport rates with Hamilton *et al.*'s coefficient ratio ($K_{s,t}/K_{s,t}=6$ for RROH = 1.6) gives estimates for double diffusive nitrate fluxes of 0.012–5.4 mmol NO₃ m⁻² day⁻¹. At least the higher values could account for our high new production rates. We expect that RROH values between 1.45 and 1.85 which were found at the transition zone of S_{\max} water overlying nutrient-rich central water are typical for those areas of the tropical North Atlantic which are characterized by the subsurface salinity maximum water and hence double diffusive nitrate flux is a central process in replenishing of the nitrate contents of the lower part of the euphotic zone in this area.

In non-tropical systems vertical forcing (i.e. winter deep mixing) is central in controlling the annual cycle of nitrate in the euphotic zone and thus the annual new production. At our study site and presumably in large areas of at least the tropical North Atlantic the well known existence of the S_{\max} gives rise to high double diffusion as a very effective transport process for nitrate into the euphotic zone. Thus lateral forcing (i.e. the transport of high saline and warm, but nitrate-depleted water from the subtropical gyres) is a necessary prerequisite for higher nitrate fluxes from Central Water into the euphotic zone and supports higher new production rates than those expected from turbulent nitrate transport only.

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