NUTRIENT–DENSITY RELATIONSHIPS IN THE WESTERN NORTH ATLANTIC BETWEEN CAPE LOOKOUT AND BERMUDA[1]

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ABSTRACT

A study of the nutrient–density relationships of Sargasso Sea water reveals a close correlation; Gulf Stream waters are anomalously higher and more variable in nutrients for a given density. Nutrient anomalies can be used in the same way as oxygen anomalies to map the distribution of Caribbean water in sections across the Gulf Stream. They show that contributions of Caribbean water to the Gulf Stream vary greatly from time to time. Oxidative ratios of $\Delta O : \Delta N : \Delta P = (-233) : 16.3 : 1.0$ were derived from the correlation between oxygen anomalies and nutrients anomalies of Gulf Stream water in the sigma-*t* range 25.0–26.8.

INTRODUCTION

In a variety of ocean areas, water masses can easily be identified by their characteristic temperature–salinity relationships. While this familiar technique works well for distinguishing between Gulf Stream and slope waters, it fails to differentiate the waters of the Gulf Stream system from those of the adjacent Sargasso Sea.

The only chemical methods so far used with success to trace the distribution of Gulf Stream water involve the correlation of oxygen with temperature, salinity, or density (Dietrich 1937; Rossby 1936; Richards and Redfield 1955). Of these methods the oxygen–density relationship has proved most advantageous. Richards and Redfield (1955) found a well-defined correlation between the oxygen content and density in the Sargasso Sea, while the waters of the Caribbean Sea, Yucatan Channel, and Strait of Florida were anomalously lower in oxygen for a given density. The oxygen deficiencies could be used to trace the presence of these waters of southern origin along the course of the Gulf Stream and to delineate its right-hand boundary. The oxygen anomalies have also been useful for studying seasonal changes in the distribution of these waters along the continental slope of North Carolina (Stefánsson et al. 1971).

Since the principal nutrients, phosphates and nitrates, are normally inversely related to oxygen, the subsurface Gulf Stream waters would be expected to be anomalously high in nutrients as compared to Sargasso Sea water of the same density. To test this supposition and to investigate the possibility of using nutrient anomalies for tracing the distribution of Caribbean water in sections across the Gulf Stream, we have examined the relationships between nutrients and density for Gulf Stream and Sargasso Sea water. This communication describes the results and some of their applications.

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MATERIALS AND ANALYTICAL METHODS

Samples for dissolved constituents were collected in the years 1966–1969 during 12 RV *Eastward* cruises from the region between the North Carolina continental shelf and 69° 50′ W (Fig. 1).

Salinity was measured conductometrically with an inductive salinometer, temperature

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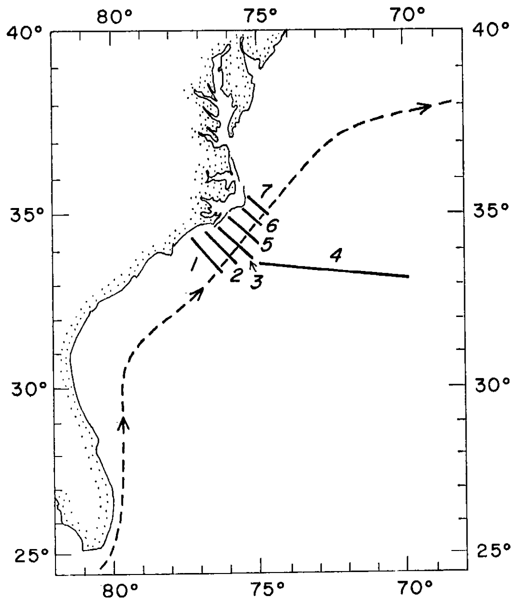

FIG. 1. Location of stations in study area. Sections 1, 2, 5, 6, and 7 were occupied six times in the period February 1966 to April 1967, section 3 twelve times in the period February 1966 to August 1969 and parts of section 4 were occupied in August 1967, 1968, and 1969. The broken line indicates the mean axis of the Gulf Stream as given by von Arx et al. (1955).

with high-precision reversing thermometers, and oxygen was determined by Winkler titration. The nutrient samples were drawn into polyethylene bottles, quick-frozen, and stored in a deep-freezer until thawed and analyzed spectrophotometrically ashore. Nitrate was determined by the method of Mullin and Riley (1955) and phosphate according to Murphy and Riley (1962).

NUTRIENT–DENSITY RELATIONSHIPS OF SARGASSO SEA AND GULF STREAM WATERS

The phosphate–density and nitrate-density correlations for the Sargasso Sea were based on 156 and 80 samples respectively, collected between the right-hand boundary of the Gulf Stream and 69° 50′ W (section 4, Fig. 1). The Sargasso Sea side of the Gulf Stream was assumed to be where the density surfaces no longer sloped downward from west to east.

Within the Sargasso Sea both nitrates and phosphates are almost constant in the density range $\sigma_t = 24.0–26.0$ (Figs. 2 and 3). At higher densities the values increase progressively, reaching a maximum [$(NO_3^-$-N] ≈ 25 μg-atom/liter, [PO_4^{3-}-P] ≈ 1.60 μg-atom/liter) at σ_t 27.30. In the range $\sigma_t = 27.30 - 27.90$ the values decrease gradually with density. For densities between $\sigma_t = 24.0$ and 26.30 nutrient concentrations remain within narrow limits, between $\sigma_t =$ 26.30 and 26.80 the concentration range for a given density is somewhat greater, and at higher densities there is a wide scatter in the values, especially of samples from the deepest water strata.

In contrast to the water of the Sargasso Sea, concentrations of samples taken within the Gulf Stream were found to be highly variable for a given density and anomalously high in the σ_t range 25.0–26.6 (Figs. 2 and 3). At densities exceeding $\sigma_t = 26.80$ the nutrient–density relationships do not distinguish Gulf Stream water from that of the Sargasso Sea.

NUTRIENT ANOMALIES

Phosphate and nitrate anomalies were estimated by subtracting the nutrient concentration of water from the Sargasso Sea for a given density, as determined from the curves shown in Figs. 2 and 3, from the observed concentration of the sample. Having computed the anomalies for each sample, we plotted their distributions on sections across the Gulf Stream. Examples of such distributions are given in Figs. 4 and 5. Oxygen anomalies determined as described by Richards and Redfield (1955) are shown for comparison.

It is evident from Figs. 4 and 5 that a) the phosphate, nitrate, and oxygen anomalies show almost identical features, oxygen deficiencies corresponding to nutrient excesses as referred to Sargasso Sea water, b) numerically the anomalies reach a maximum at the core of the Gulf Stream, where they are centered around $\sigma_t = 26.0$, disappearing gradually as the right-hand bound-

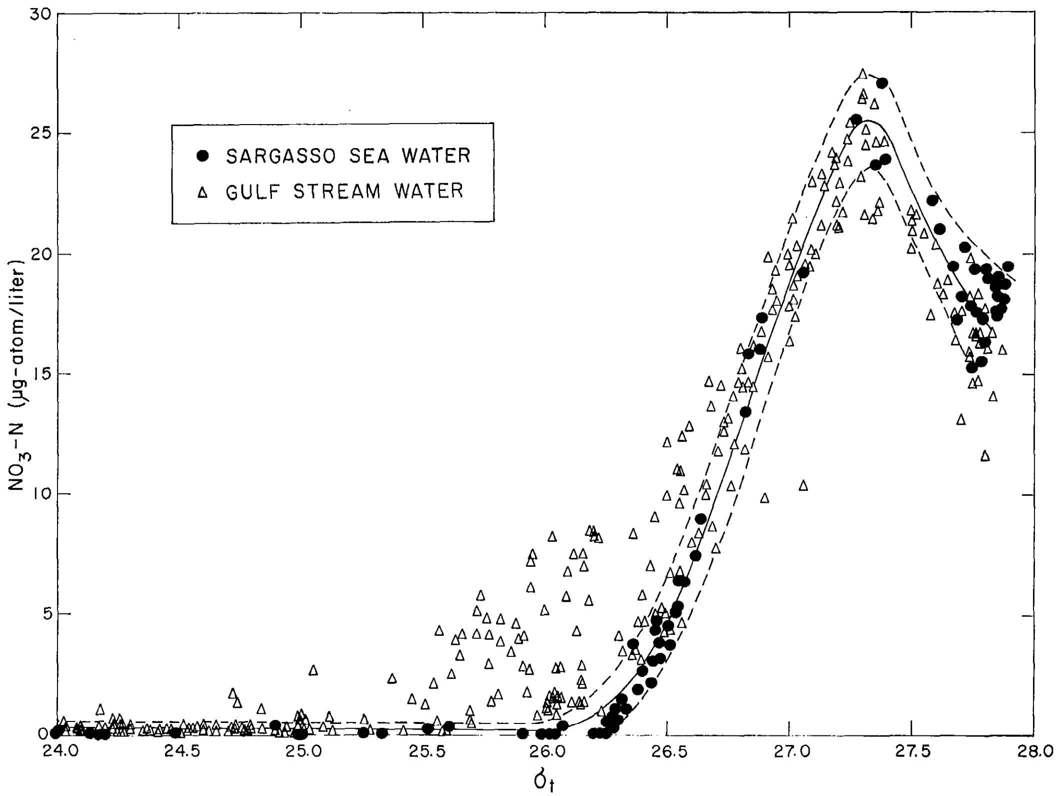

FIG. 2. Correlation between nitrate concentrations and density (σ_t). Circles denote Sargasso Sea observations made in section 4 in August 1967, triangles denote Gulf Stream observations made in section 3, February 1966–August 1967.

ary of the stream is approached, and c) marked variations with time exist in the magnitude and distribution of Caribbean water in the section.

A comparison of the anomalies found during all 12 cruises suggests seasonal variations in the distribution of Caribbean water: Summer observations showed an intrusion of this water to the bottom layers over the shelf, while winter observations indicated its absence in the shelf area and near the edge of the continental shelf. The apparently small contribution of Caribbean water observed in March 1967 represents a unique situation, probably arising from intense vertical mixing of the surface layers, as was indicated by almost constant temperature, salinity, and density from the surface down to 130 m in the region off the shelf break (Stefánsson et al. 1971).

The largest oxygen, nitrate, and phosphate anomalies observed during these investigations were: −1.27 ml/liter (−113 μg-atom/liter), 7.9 μg-atom/liter, and 0.53 μg-atom/liter respectively.

DISCUSSION

The application of oxygen anomalies to study seasonal variations in the distribution of Caribbean water along the continental slope off North Carolina has been described (Stefánsson et al. 1971). Nutrient anomalies could also be used for this purpose and provide a check on the method of oxygen anomalies. Although nutrients are less easily determined than oxygen, their concentrations are less affected by seasonal warming and cooling processes than is that of oxygen. Consequently, the nutrient anomaly distribution may provide

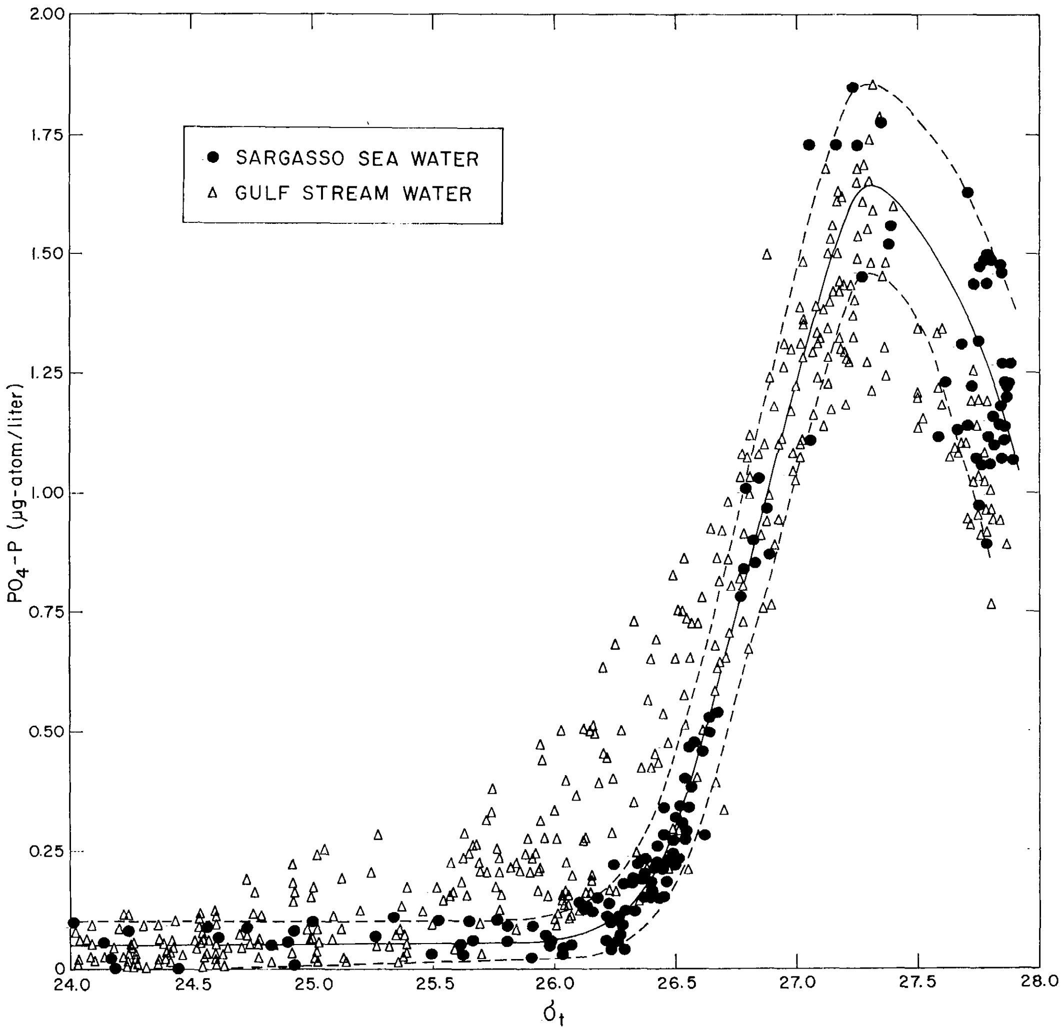

FIG. 3. Correlation between phosphate concentrations and density (σ_t). Circles denote Sargasso Sea observations made in section 4 in August 1967, 1968, and 1969, triangles denote Gulf Stream observations made in section 3, February 1966–August 1967 and August 1969.

a more suitable water mass tracer, especially in areas where the Gulf Stream is near the continental slope and seasonal temperature variations are greater than in the open sea. With modern autoanalyzer techniques such surveys could easily be carried out routinely on multistation cruises.

Assuming that the oxygen deficiencies of Gulf Stream water result from oxidation of organic matter with accompanying nutrient release, it follows that the correlation between nutrient anomalies and oxygen anomalies provides a means to evaluate the oxidative ratios. If it can also be postulated that the concentrations of preformed nutrients[4] are the same in Sar-

[4] Following the definition by Redfield (1942), preformed nutrient refers to that fraction of dissolved inorganic nutrient which was present in the water at the time it sank from the surface. Since preformed nutrients are entirely independent in origin of processes of organic decomposition and oxidation taking place after the water left the surface, they are by definition conservative properties of seawater.

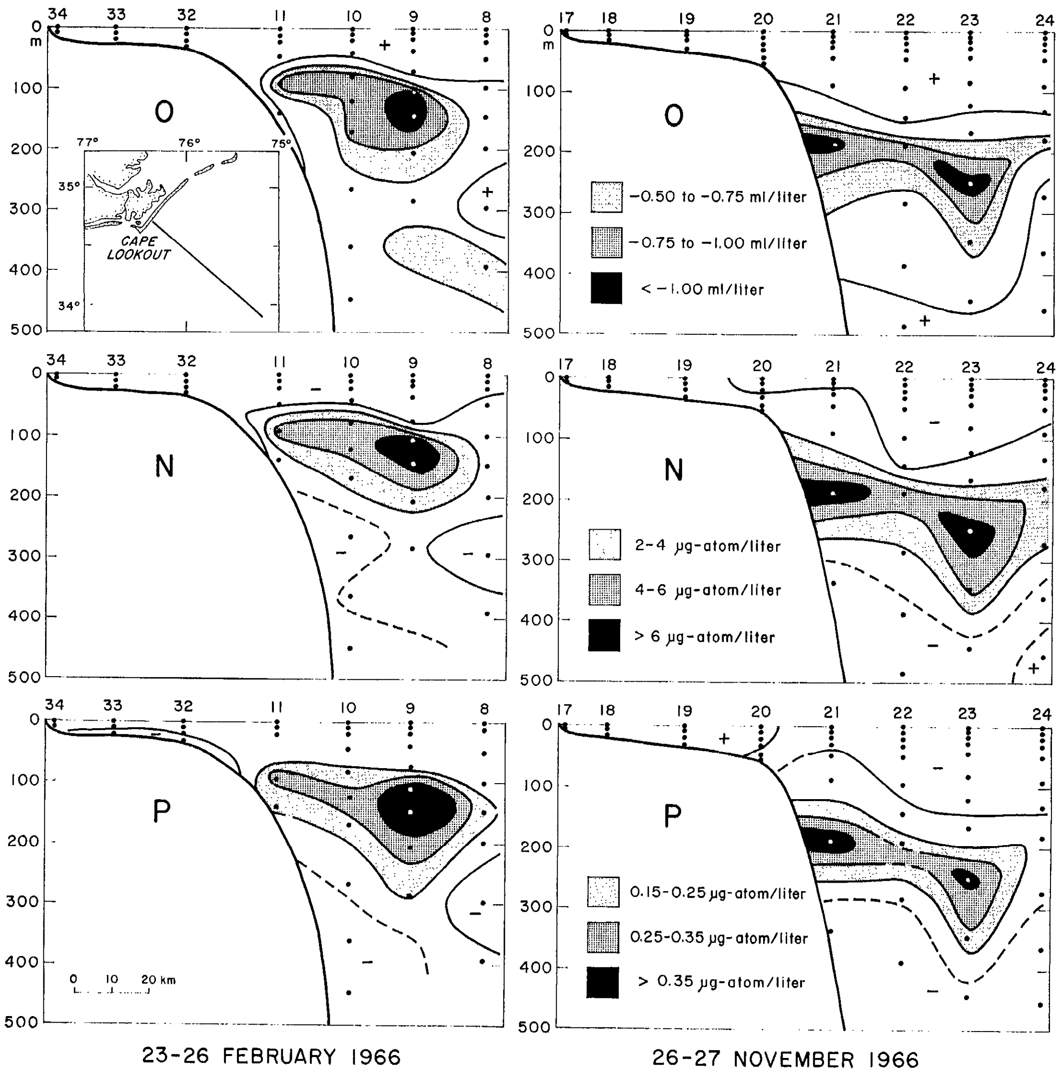

FIG. 4. Vertical distribution of oxygen anomalies (O), nitrate anomalies (N), and phosphate anomalies (P) in section 3 in February and November 1966. The location of the section is shown on inset map. Vertical scale shows depth (m). Horizontal scale shows station number.

gasso Sea and Gulf Stream waters for a given density, this approach should be more reliable than estimates based on the apparent oxygen utilization, which involve various errors and uncertainties (e.g., Redfield et al. 1963; Stefánsson 1968).

To investigate this application, a statistical analysis was made of the correlation between the anomaly values of oxygen and nutrients in section 3 for the σ_t range 24.0–26.8. In the surface layers the oxygen content varies seasonally, and reoxygenation from the atmosphere causes a disappearance of negative oxygen anomalies. Furthermore, phytoplankton uptake leads to reduction or even depletion of nutrients in the photic zone. To eliminate these surface effects, near-surface samples were omitted and only values with negative oxygen anomalies included in the regression analysis. The results (Figs. 6 and 7) indicate a close correlation between nutri-

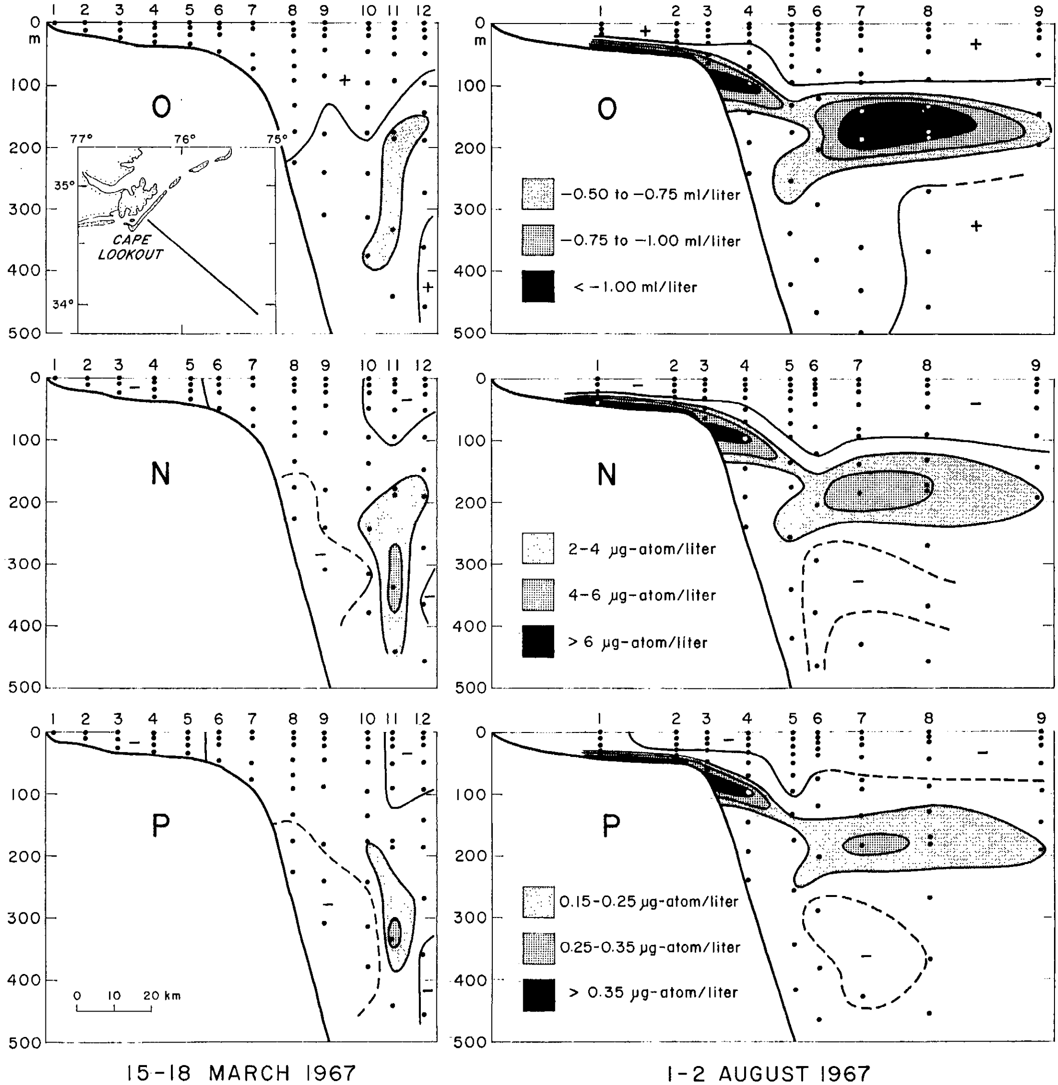

FIG. 5. Vertical distribution of oxygen anomalies (O), nitrate anomalies (N), and phosphate anomalies (P) in section 3 in March and August 1967. The location of the section is shown on inset map. Scales as in Fig. 4.

ent and oxygen anomalies. The calculated regression lines have the equations

NO_3^--N anomaly (μg-atom/liter)
$= -0.46 - 6.23\,O_2$ anomaly (ml/liter), (1)
PO_4^{3-}-P anomaly (μg-atom/liter)
$= -0.03 - 0.383\,O_2$ anomaly (ml/liter). (2)

The statistical data (Table 1) show that the nitrate to phosphate change derived from the anomalies is practically the same as that obtained from the regression of nitrate concentrations to phosphate concentrations, using all observations from sections 1–7 collected between February 1966 and March 1968. The oxygen to nutrients ratios of change are in good agreement with the findings of Richards and Vaccaro (1956) for the upper layers of the Cariaco Trench, but significantly lower than expected from the stoichiometric model of Richards (1965).

It remains to consider the validity of

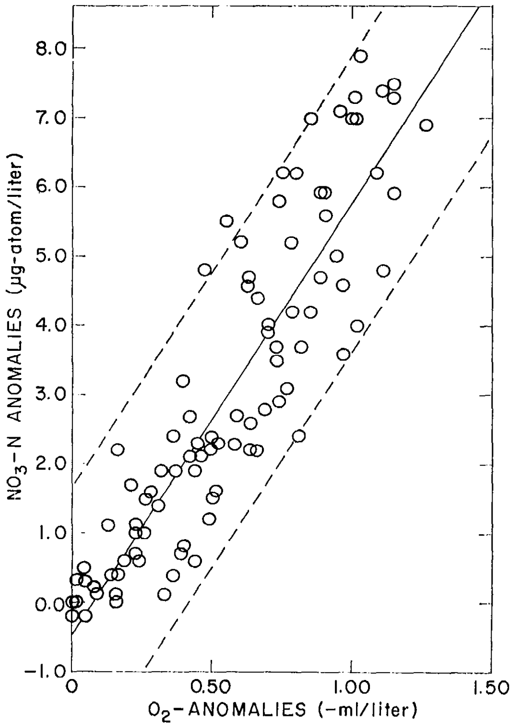

FIG. 6. Correlation between nitrate anomalies and oxygen anomalies based on 93 observations from section 3, 1966–1967. The broken lines indicate the 95% confidence limits.

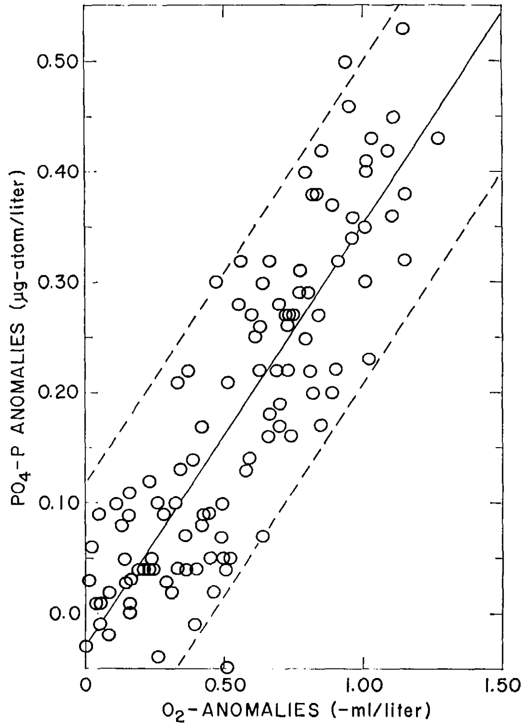

FIG. 7. Correlation between phosphate anomalies and oxygen anomalies based on 109 observations from section 3, 1966–1967 and 1969. The broken lines indicate the 95% confidence limits.

the postulate that preformed nutrients for a given σ_t value are the same in Sargasso Sea and Gulf Stream waters. Preformed nitrates estimated from the observed concentrations and the apparent oxygen utilization [based on Carpenter's (1966) solubility data], using a $\Delta N : \Delta O$ ratio of –16 : 276, increase with decreasing temperatures, as shown in Fig. 8. A similar relationship applies to preformed phosphates. This increase with decreasing temperatures can be explained by the fact that the deep

TABLE 1. *Oxygen–nutrient relationships*

Data	No. observ.	ΔO	ΔN	ΔP	Correlation coeff.	Reference
Phosphate anomalies vs. oxygen anomalies	109	–233 ± 13*		1.0	+0.86	This work
Nitrate anomalies vs. oxygen anomalies	92	–233 ± 12*	16.3		+0.89	This work
Nitrates vs. phosphates, all observations sections 1–7	1,279		16.22 ± 0.10*	1.0	+0.98	This work
Cariaco Trench, upper layers		–235	15	1.0		Richards and Vaccaro (1956)
Stoichiometric model		–276	16	1.0		Richards (1965)

* Standard error of estimate of the slopes ΔO : ΔP, ΔO : ΔN × 16.3, and ΔN : ΔP respectively.

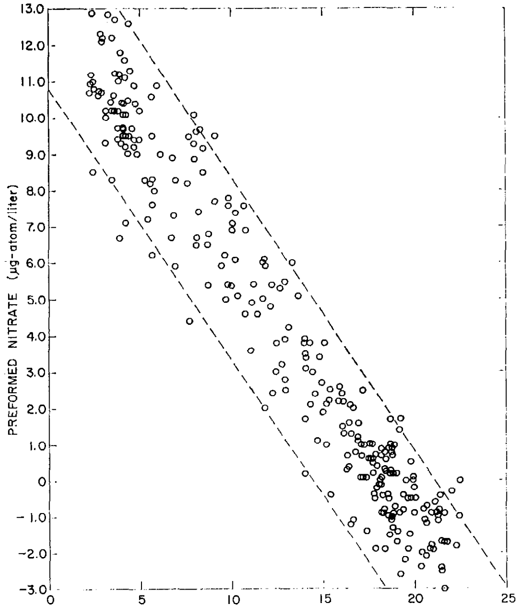

FIG. 8. Preformed nitrate–temperature relationship based on data from sections 1–7.

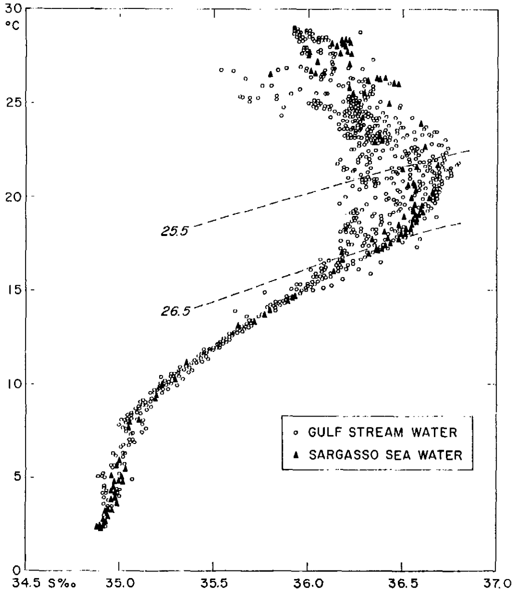

FIG. 9. Temperature–salinity relationships of Gulf Stream (open circles) for stations with depths >200 m and Sargasso Sea (triangles) waters based on data from sections 1–7.

water is formed in winter in high latitudes where light conditions limit growth. Consequently on sinking, the water contains the nutrients in the inorganic form in relatively large concentrations (cf. Redfield et al. 1963). It should be remarked, however, that the preformed nutrient values found for temperatures above 20C must be unrealistic, since most of them are negative. Even though the oxidative ratio were half of that used, "negative" values of preformed nutrients would still be obtained. This suggests that the estimates of the apparent oxygen utilization cannot be valid. The discrepancy, which cannot be explained by analytical errors, might be partly attributable to undersaturation of the water at the time it sank from the surface, and partly to the atmospheric pressure being then lower than normal. In spite of these errors, it seems almost certain that the assumption holds that the "true" preformed nutrients increase with decreasing temperatures as indicated by Fig. 8.

Plots of *in situ* temperature against salinity for all observations outside the 200-m isobath in sections 1–7 show a wide scatter in the values in the σ_t range 25.5–26.5 (Fig. 9). While a considerable overlapping exists, a great number of the Gulf Stream values tend to have a lower temperature (and a lower salinity) for a given σ_t than Sargasso Sea water. This would lead to slightly higher preformed nutrients of Gulf Stream water in this σ_t range and could possibly explain why the oxidative ratios found were somewhat lower than expected from the stoichiometric model.

Further studies of the nutrient-density correlations in the western North Atlantic are needed, not only to reexamine and improve the relationships here presented, but also to investigate to what extent the distribution of nutrient anomalies can be applied to trace waters of southern origin in various parts of the Gulf Stream system.

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