

Seasonal Distribution of Nutrients and Primary Productivity on the Eastern Continental Shelf of Venezuela as Influenced by the Orinoco River

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Nitrogenous nutrients, dissolved silicate, and salinity were measured in surface waters and shallow hydrocasts along similar cruise tracks during the spring (dry season) and fall (wet season) of 1988. Both cruises transected the eastern Caribbean, transited the Gulf of Paria, ran parallel to the Orinoco Delta and into the main channel of the Orinoco River. Trends in primary productivity were also measured by daily carbon 14 incubations. In both seasons, samples covered the range from highly oligotrophic and transparent to highly productive and rich in biogenic and abiogenic particulate matter. Most of the Orinoco outflow appears to turn N to NW and remains in shallow waters off Venezuela and surrounding Trinidad, permitting benthic regeneration of river-borne nutrients. However, the role of the Orinoco and associated low-salinity coastal waters in fertilizing large areas of the eastern Caribbean basin, as suggested by satellite imagery, can be approximated crudely from the nutrient composition at Boca de Dragon, which is representative of the nutrient status of these waters as they flow into deeper Caribbean waters. Additional nutrients may be supplied to the area primarily from Amazon-derived water entering the Caribbean Basin further north, with some coastal upwelling along the continental shelf in the dry season.

INTRODUCTION

Coastal oceanic water masses, especially those located in the tropics, are among the most fertile and productive. This biological and organic richness may result from high loads of nitrogen, phosphorus and silicon supplied by hydrodynamic processes resulting from continental drainage, or from coastal upwelling processes during seasons of winds favoring this process. Within the context of coastal bioecosystems, estuarine-deltaic zones are notable as transition environments between the ocean and the continent. The Orinoco River system in Venezuela provides one of the largest-scale examples of these interactions. It has a major influence on the hydrographic and biological conditions of the estuarine system of the Gulf of Paria and the Caribbean Sea.

The Orinoco River begins near Brazil, at the junction of Sierra Párima and Sierra Unturan, and flows over an area of 2560 km², of which 1670 km² are navigable. It irrigates a flood plain of 981,000 km² in Venezuela, Colombia, and Brazil, is the only South American river with a true delta, and has an ocean front of 300 km. Its principal affluent is the Caroní River, with a brown-ochre color, which is mixed with the waters of the Orinoco, which are yellow. The Orinoco flow is turbulent and contains a large amount of suspended clay. These Orinoco-Caroni waters are rich in organic and inorganic matter which is transported to the Atlantic Ocean and the Caribbean Sea through the estuarine-deltaic system. The Orinoco River contributes a large amount of suspended sediments (86.3 × 10⁶ tons yr⁻¹), with an average water flow

of 33.95 × 10³ m³ s⁻¹ [Salazar, 1989], second only to that of the Amazon. The flow regime is characterized by precipitation throughout the year, with maximum flow in August and minimum flow in March.

The estuaries formed in the delta are known as Boca Ajíes and Boca Bagre in the Gulf of Paria, and Boca Grande or Boca de Navíos, where the navigation channel is located (Figure 1). Knowledge of the estuarine-deltaic system of the Orinoco and the Gulf of Paria dates from 1954, when Van Andel and Postma described the hydrographic, climatological and sedimentary conditions of the area [Morelock, 1972; Eisma *et al.*, 1978]. The formation of muddy plains in the deltaic coast is due to deposition of sediments transported to the northwest by the Guyana current. Butenko *et al.* [1981] reported the formation of a clay wedge in the delta area up to about 80 km into the adjoining Atlantic, with additional organic clays and inorganic input from the Amazon River. This was confirmed by Milliman *et al.* [1982], who found montmorillonite characteristic of the clay sediments of the Amazon River in the Orinoco delta, also transported by the Guyana current. Herrera and Masciangioli [1984] determined that the predominant circulation in the coastal area of the delta consists of surface currents generated by the trade winds moving to the west and northwest. The hydrographic and chemical conditions of the sediments in the Gulf of Paria were studied by Benitez and Okuda [1976], Bonilla [1977], and Bonilla and Lin [1979]. The geochemical characteristics of the sediments in parts of the river and delta were studied by Bonilla *et al.* [1985]. Müller-Karger and Varela [1988] determined that the nutrient influence of the Orinoco River on the Caribbean Sea reaches Puerto Rico, based on the concentration of pigments during the high flow season for the Orinoco (August–October). Salazar [1989] studied the hydrogeochemical conditions of the estuarine-deltaic region of the Orinoco, from the island of Curiapo inside the river to 180 km into the Atlantic Ocean.

In these tropical bioecosystems there are two seasons: a dry season from December to April, and a rainy season from

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Paper number 92JC02761.
0148-0227/93/92JC-02761\$05.00

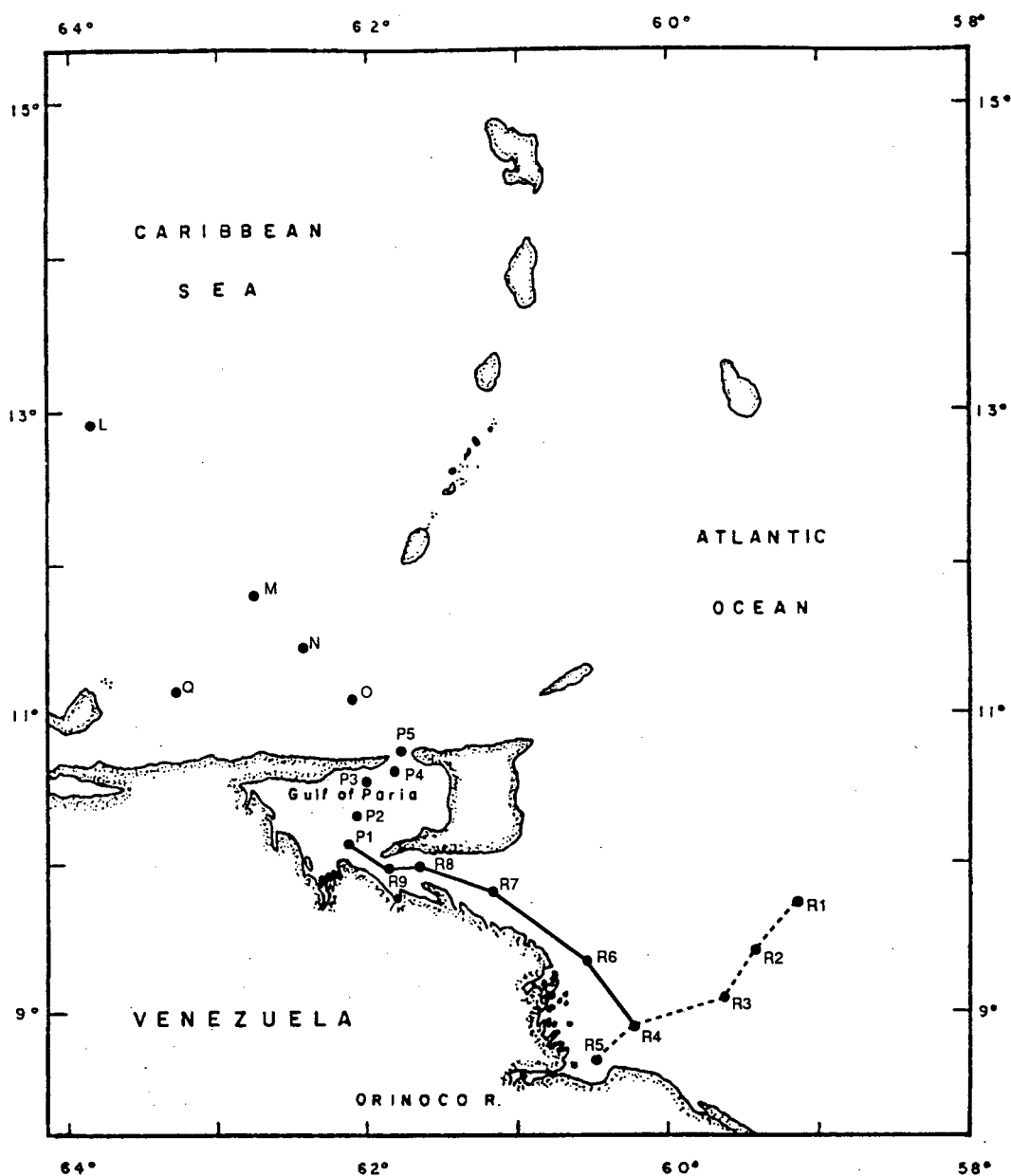


Fig. 1. Location of the sampling sites from *Colombus Iselin* cruises CI-8805 and CI-8816, spring and fall 1988 (solid line, E-W transect; dashed line, NE-SW transect).

May to November. Evaporation is highest in February (129 mm) and lowest in November (76 mm), while precipitation is highest in August (127 mm) and lowest in April (19 mm). Thus the timing of the two cruises reported here nearly coincided with the two extremes. Westerly winds are prevalent, with an eastern component during most of the year. A semi-diurnal tide regime dominates in the estuarine-deltaic region [Salazar, 1989].

Here we summarize the saline stratification, nutrient distributions, and primary productivity measurements from the spring (April 1988) and fall (September 1988) cruises. We focus on longitudinal transects NE-SW and E-W from the mouth of the Orinoco. This paper focuses on the near-shore data (all data S of $\approx 11^\circ\text{N}$), as studies in that area were the most intensive and the riverine impact is strongest. For effects in the Caribbean N of 11°N , see the accompanying paper [Zika *et al.*, this issue]. In order to better understand

the hydrochemical mechanisms of the delta, conservative and nonconservative processes resulting from the runoff of the Orinoco during high and low flow are considered.

METHODS

Source of Samples

Water samples were collected in the estuarine-deltaic system of the Orinoco River, Gulf of Paría, and adjacent areas (Figure 1) during research cruises CI-8805 in the spring (April 1988) and fall CI-8816 (September 1988) on board the *R/V Columbus Iselin*. Seawater samples were taken using a rosette sampler (General Oceanics, Miami, Florida) consisting of twelve 5-L teflon-lined polyvinyl chloride Niskin bottles. The rosette was fitted with a Neil Brown conductivity, temperature, and depth (CTD) probe. Additional surface

(2 m) samples were collected from the through-the-hull teflon bow pumping system.

Nutrient Analyses

Water samples were collected in 60-mL Nalgene bottles and refrigerated until analyzed. Samples were analyzed within 24 hours after collection. Turbid samples were filtered using 0.45 μm pore-size Acrodisc disposable filter assemblies (Gelman Sciences, Ann Arbor, Michigan).

Nutrient determinations (NO_2^- , NO_3^- , $\text{Si}(\text{OH})_4$) were performed on an Alpkem RFA-300 nutrient analyzer (Alpkem Corp., Clackamas, Oregon). All nutrient determinations were measured against internal standards according to the RFA methodology handbook (Alpkem).

Primary Productivity Measurements

Surface water (≈ 0 –2 m) samples were collected in BOD bottles to which 0.95 mL of $\text{NaH}^{14}\text{CO}_3$ ($2.5 \mu\text{Ci mL}^{-1}$, 42.37 nmol mL^{-1} , Amersham Corp., Arlington Heights, Illinois) was added. The samples were irradiated in full sunlight in a flowing seawater bath for 3 hours (dark controls were covered with aluminum foil). After irradiation the samples were filtered through GF/F glass fiber filters (Whatman International Ltd., Maidstone, England), rinsed with 50 mL of 1 N HCl and stored for further analysis. Integrated photosynthetically active radiation (PAR) was measured with a LI-COR (model 1800) calibrated spectroradiometer. Radioactivity was determined with a Beckman LS 3801 liquid scintillation counter (Beckman Instruments, Fullerton, California). Primary productivity values were calculated as $\mu\text{gC fixed per m}^3 \text{ h}^{-1}$.

RESULTS

Spring and Fall Salinity Distributions

The spring-fall salinity distributions (Figures 2–5) are dramatically different. In spring there was a sharp freshwater-seawater interface within the navigation channel and upstream of Pt. Barima, so that the NE-SW transect (Figure 2) never encountered pure river water ($S_{\text{min}} = 8$ ppt at R5 at ebb tide). The E-W transect (Figure 4), as close inshore as feasible navigationally, also encountered only relatively saline waters ($S > 30$ ppt) because the saltwater-freshwater gradient was centered close inshore in the nonnavigable waters of the Orinoco's extensive deltaic system and distributaries in spring.

In fall, both sections were within the core of the near-field freshwater-saltwater mixing zone (Figures 3, 5). The E-W transect and the Gulf of Paria was roughly 50% saltwater at that time, while the NE-SW transect encountered $S = 0$ ppt water from surface to bottom at R5. The surface distribution of salt (not shown) on these two cruises thus resembled that given by Rodriguez [1975] for April, but in September the E-W transect and Gulf of Paria waters were already almost twice as saline as those reported for August, suggesting that the peak flow was already well past and the gradual advection and mixing of this large input with seawater were underway. Where there was sufficient water for navigation by the R/V *Iselin*, the delta region of the Orinoco River exhibited a typical salt wedge circulation which governs hydrographic and chemical conditions in deeper waters. Thus the spring versus fall effects of the riverine inflow are

limited primarily to a shallow surface layer and are hardly detectable even at 50 m. This factor can be seen clearly by comparing salt, silica, and nitrate seasonal differences along both transects: NE-SW (Figure 2, spring; Figure 3, fall) and E-W (Figure 4, spring; Figure 5, fall). The tendency to upwelling in the spring and its relaxation in the fall are clearly indicated in the NE-SW (onshore-offshore) sections by the sloping and horizontal (respectively) isolines for $S = 36$ ppt, and silicate or nitrate $1 \mu\text{M}$. The E-W transect comparison most clearly shows the much larger extent of freshwater influence: the spring top-bottom contrast is ≈ 31 –36.5 ppt, while in the fall the range is ≈ 13 –36.6 ppt.

The sloping isolines indicate the dry season upwelling of intermediate water from the southeastern Atlantic in the platform at Boca Grande. Water of salinity 35.5 ppt at 30 m (R1) ascends to the surface layers (2–10 m), pushing the freshwater mass into the river (Figure 2) from the surface (R3) with changes in salinity, delineating this area of the estuary from the salt wedge towards the bottom at R5, where the wedge's apex is formed. The mixing zone was between R5 and R6 near the platform at Boca Grande. At a depth of 90 to 140 m there was a cold, deep-water mass from the southeastern Atlantic which was higher in salinity (36.8–37.15 ppt) between R1 and R2, rich in nitrogenous compounds (nitrite, 0.18–0.16 μM ; nitrate, 0.47–6.2 μM) and low in silicate (0.12–0.35 μM). Thus, during the dry season, when the Orinoco has its lowest flow, its influence is limited to a narrow fringe stretching along the estuarine-deltaic area (Figures 2 and 3).

Nutrients and Primary Productivity

The vertical nutrient distributions are also shown in Figures 2–5, while the surface values and primary productivity data are given in Figures 6 and 7. Table 1 presents a highly condensed summary of the data for both seasons in the vicinity of the Orinoco River.

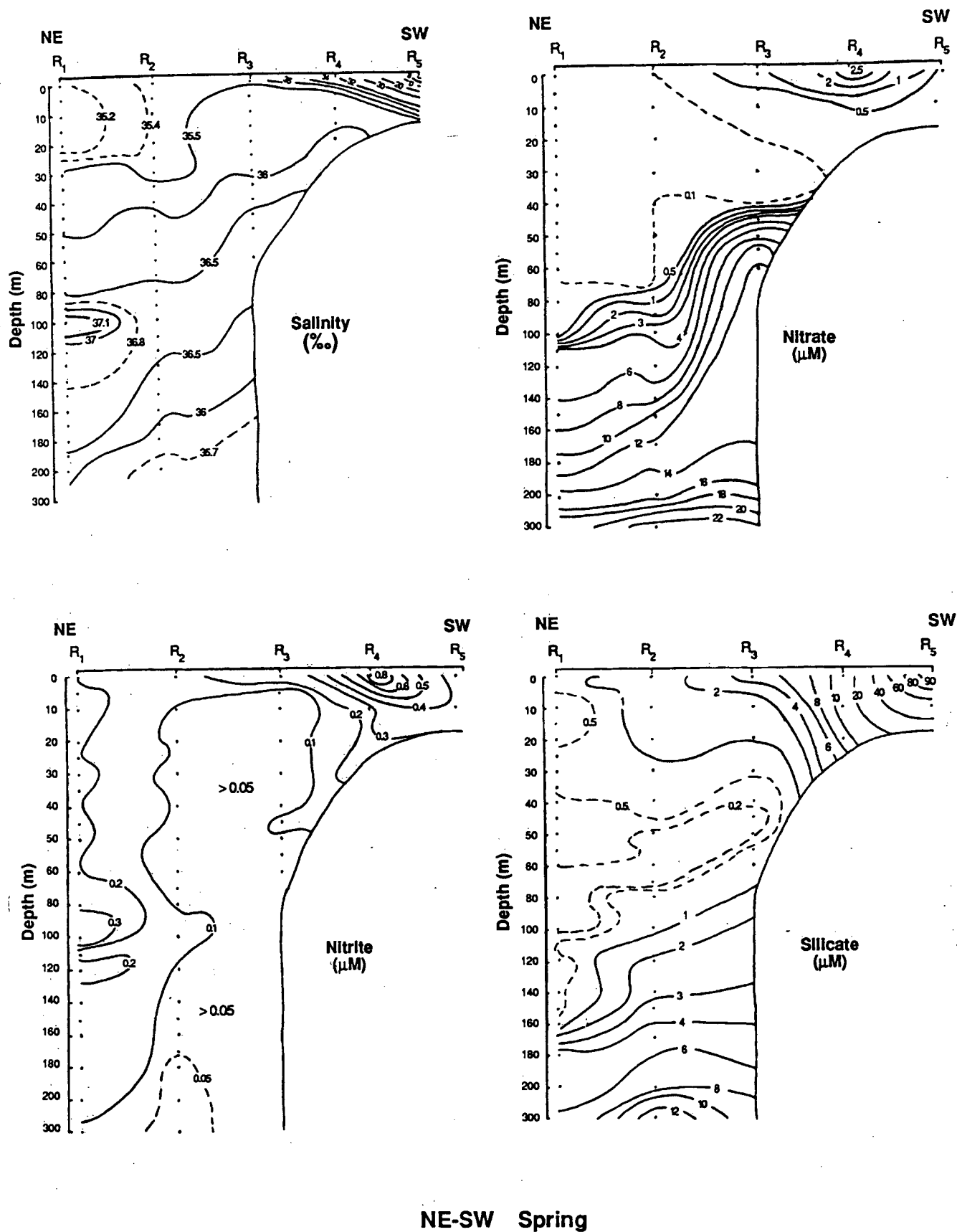
Given the restrictions imposed in the spring by navigation requirements and the strong tendency of the river water to spread over the salt water in a thin difficult-to-sample sheet in both seasons, these data are obviously too sparse and unrepresentative of the river-delta-coastal system as a whole to permit a detailed characterization of the region in either season, or a detailed interseasonal comparison. The purpose of gathering these data was rather to provide ancillary information for the more detailed process-oriented studies reported in other papers in this Special Section.

Nevertheless, a few issues of general interest to the biogeochemistry of this fascinating but relatively little-studied region can be addressed with this data set. They are discussed below. Some of these same issues are also addressed from different perspectives in some of the accompanying papers (e.g., the Si budget and Ra-Si relationships [Moore and Todd, this issue]; primary productivity, nutrients, and specific pigment distributions [Bidigare et al., this issue]).

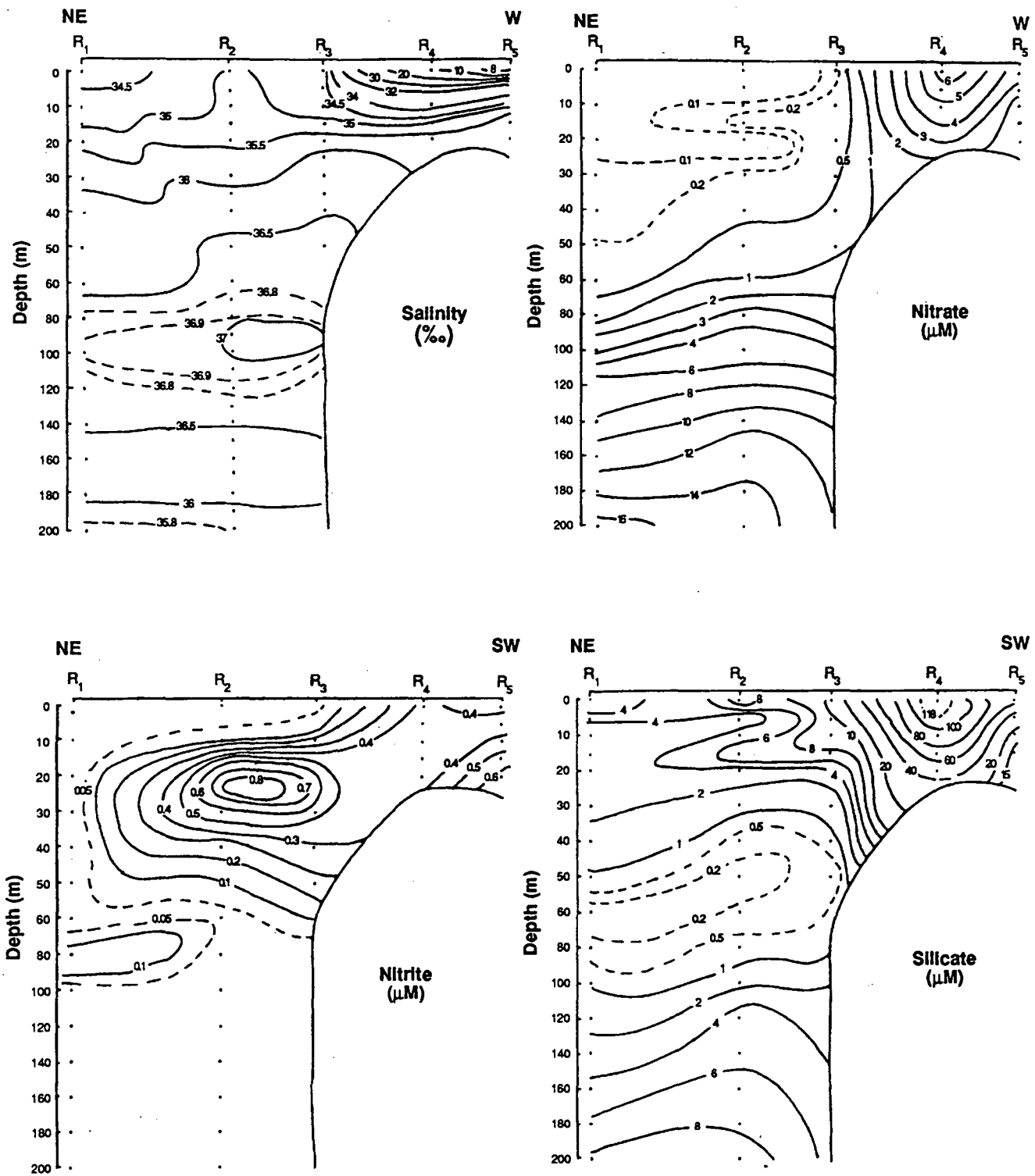
DISCUSSION

Silicate and (Nitrate Plus Nitrite) in Spring and Fall

Coastal nitrogen cycling is intense and complex [Carpenter and Capone, 1983]. The available data provide strong qualitative confirmation of the expected intense biological cycling in this region, as discussed previously [D'Armas,



NE-SW Spring
 Fig. 2. Depth profile of salinity, nitrite, nitrate, and silicate on a NE-SW transect, spring 1988.



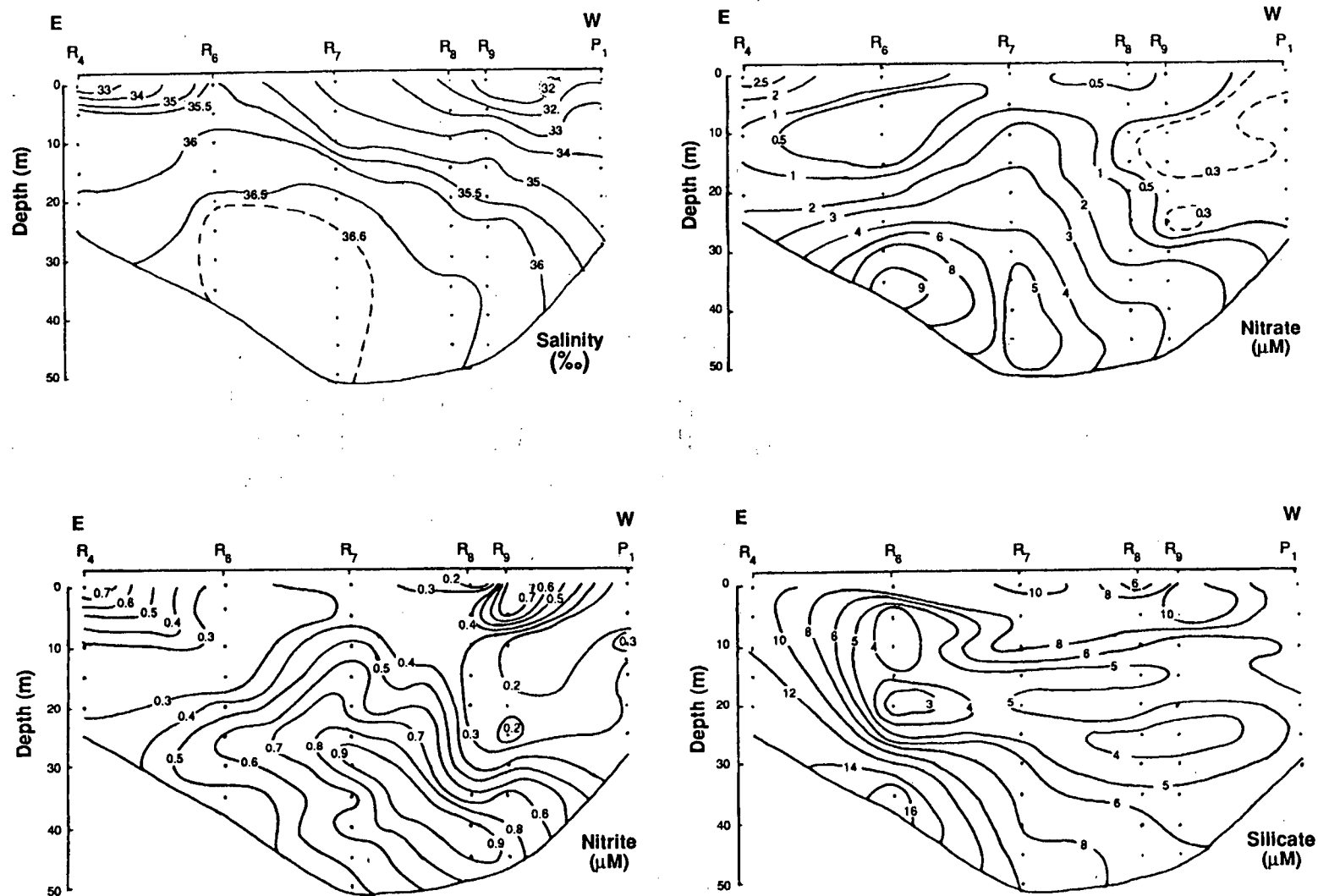
NE-SW Fall

Fig. 3. Depth profile of salinity, nitrite, nitrate, and silicate on a NE-SW transect, fall 1988.

1986; Salazar, 1989] for November conditions in the water column of the delta region. Sedimentary conditions there have been discussed by Milliman *et al.* [1982], Eisma *et al.* [1978], and Kennicut *et al.* [1987] and conditions in the Gulf

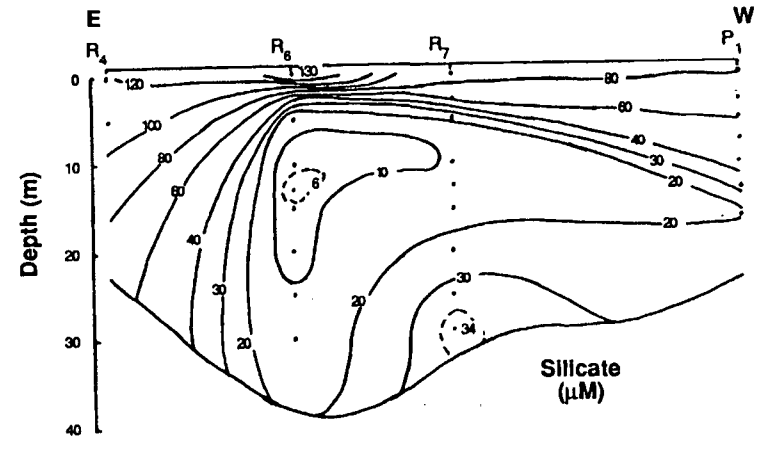
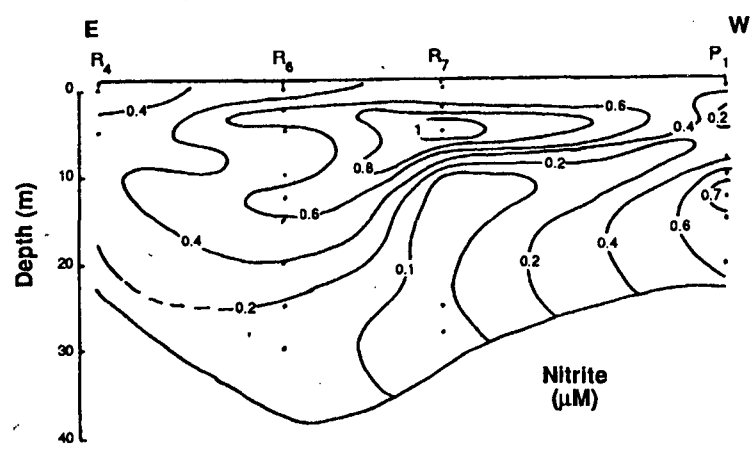
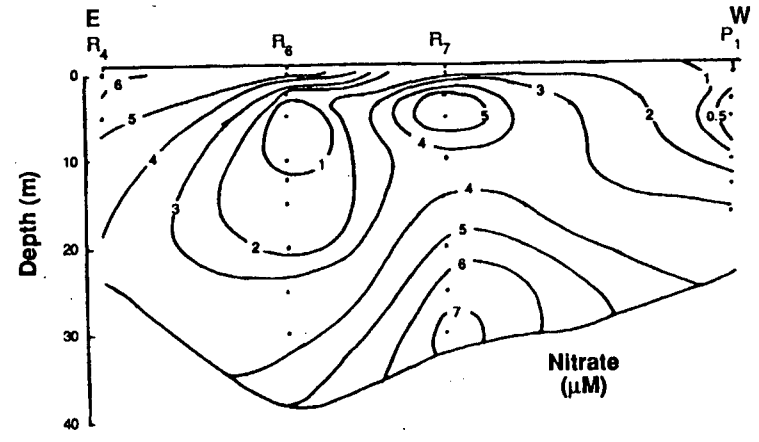
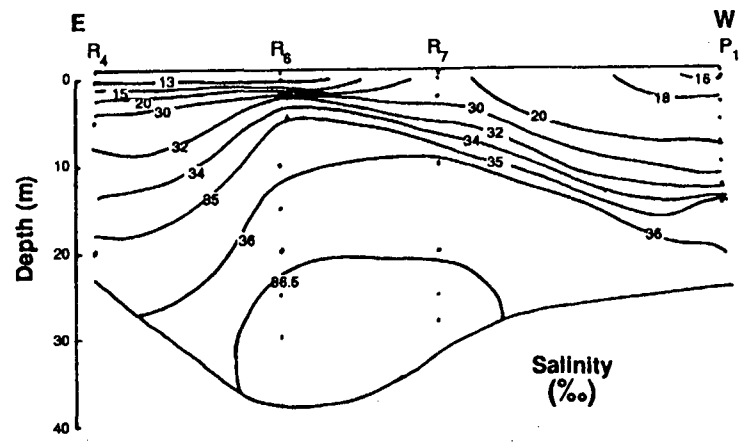
of Paria have been described by Bonilla and co-workers, as referenced in the introduction.

In addition to salt, other semiconservative tracers are useful in estuarine studies, most classically dissolved silicate



E-W Spring

Fig. 4. Depth profile of salinity, nitrite, nitrate, and silicate on an E-W transect, spring 1988.



E-W Fall

Fig. 5. Depth profile of salinity, nitrite, nitrate, and silicate on an E-W transect, fall 1988.

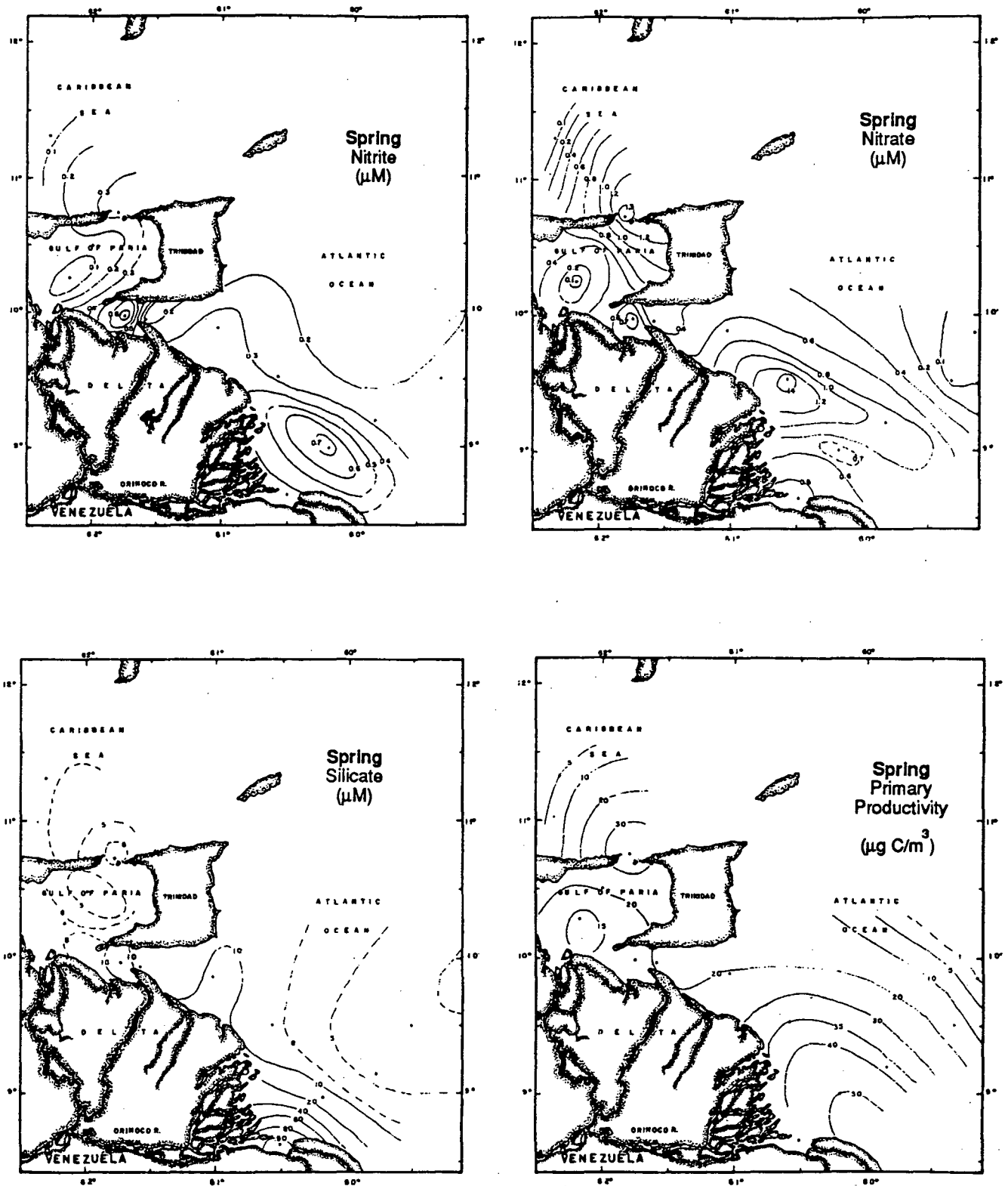


Fig. 6. Spatial distribution of nitrite, nitrate, silicate, and primary productivity in the surface water during the spring 1988. Primary productivity values are expressed as $\mu\text{g C m}^{-3} \text{ h}^{-1}$.

[Burton *et al.*, 1970; Liss, 1976], as exemplified recently for the Mackenzie Shelf Estuary by MacDonald *et al.* [1989]. However, silicate distributions must be interpreted with care because biological uptake and subsequent sinking and redissolution of biogenic opal in the water and on the bottom can

lead to seriously nonconservative behavior on spatial and temporal scales that need to be defined empirically in each system [e.g., Edmond *et al.*, 1981].

However, use of Si as a tracer has a history in the greater eastern Caribbean basin with respect to understanding the

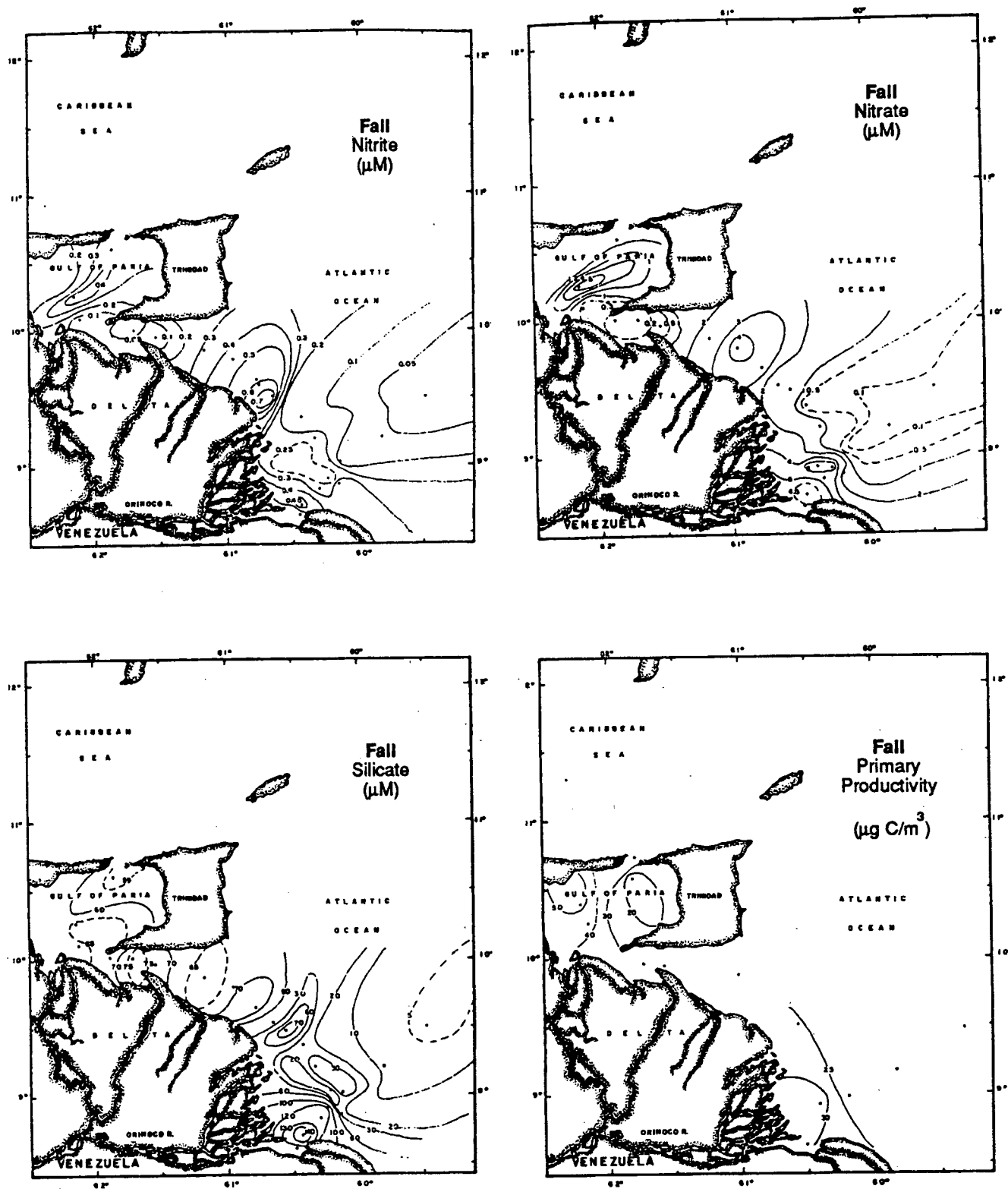


Fig. 7. Spatial distribution of nitrite, nitrate, silicate, and primary productivity in the surface water during the fall 1988. Primary productivity values are expressed as $\mu\text{g C m}^{-3} \text{ h}^{-1}$.

influence and seasonal variability of the great river systems to the southeast (Amazon and Orinoco) versus rain inputs. Froehlich *et al.* [1978] first used Si sections to suggest that rivers, not rainfall, were the principal cause of the seasonal surface freshening as far away as Puerto Rico. More re-

cently, Moore *et al.* [1986] used Ra-Si relationships to construct quantitative, sensitive tracers of the remote riverine inputs to this region. The radiochemistry approach was also applied on CI-8805 and 8816; the combined use of Si and radiochemical data to determine the "estuarine end mem-

TABLE 1. Nutrient Content and Primary Productivity in Different Offshore Regions of Estuarine-Deltaic Systems of the Orinoco

Region	Parameter Measured	Spring			Fall		
		Minimum	Maximum	Average	Minimum	Maximum	Average
Dragon's Mouth	NO ₂ ⁻	0.27	0.56	0.45	—	—	—
	NO ₃ ⁻	0.55	8.12	5.34	—	—	—
	Si(OH) ₄	3.21	6.42	4.76	—	—	—
	PP	31.0	31.0	31.0*	12.9	12.9	12.9*
Gulf of Paria	NO ₂ ⁻	0.16	0.60	0.34	0.06	1.01	0.41
	NO ₃ ⁻	0	1.00	0.41	0.26	7.03	3.25
	Si(OH) ₄	4.90	7.43	6.33	10.53	68.64	40.75
	PP	14.0	14.0	14.0*	26.0	52.8	38.0†
Serpent's Mouth	NO ₂ ⁻	0.12	0.92	0.42	—	—	—
	NO ₃ ⁻	0	3.37	0.98	—	—	—
	Si(OH) ₄	0.93	11.86	6.01	—	—	—
	PP	—	—	—	—	—	—
Shelf	NO ₂ ⁻	0.20	0.97	9.55	0.15	0.71	0.46
	NO ₃ ⁻	0	9.30	3.75	0	3.89	1.45
	Si(OH) ₄	2.05	17.92	6.83	4.61	28.00	9.41
	PP	35.0	35.0	35.0*	2.9	2.9	2.9*
River (surface transect DM)	NO ₂ ⁻	0.36	2.09	1.38	0.02	1.01	0.30
	NO ₃ ⁻	0.13	4.52	3.24	0	6.55	5.00
	Si(OH) ₄	10.84	98.26	41.46	12.20	149.80	110.46
	PP	50.0	50.0	50.0*	21.6	31.2	26.4‡
Ocean	NO ₂ ⁻	0.02	0.36	0.12	0	0.86	0.08
	NO ₃ ⁻	0	22.75	4.12	0	16.48	3.58
	Si(OH) ₄	0	12.00	1.50	0	9.86	3.52
	PP	1.0	1.0	1.0*	—	—	—

PP, primary productivity ($\mu\text{gC m}^{-3} \text{h}^{-1}$), NO₂⁻, NO₃⁻, and Si(OH)₄ (μM).

*One value only, no average, depth 5 m.

†Average of four values, depth 5 m.

‡Average of two values, depth 0 m.

ber" by this approach is discussed in their paper [Moore and Todd, this issue]. Hence it is of interest to examine its behavior also in the estuarine region which may alter this water before it reaches the eastern Caribbean.

Figure 8 shows silicate versus nitrate plus nitrite plots for both seasons along with the mixing lines expected for spring and fall Orinoco river water plus oligotrophic seawater (nutrient-salinity plots cannot be used in spring, when all the low-salinity samples were acquired in rapid succession from the pumping system and could not be accurately matched with salinities). In spring (solid symbols) the data are from the vicinity of R4-R5, whereas in fall the same [Si] range was covered over much of the E-W transect outside of the Gulf of Paria. As noted above, the highest Si values in both seasons closely approximate those expected from the riverine data of Lewis and Saunders [1989]. In contrast, in both seasons NO₂⁻ + NO₃⁻ clearly cycles dynamically in waters of lower salinity (higher Si). The dominant cycling mechanisms appear to differ seasonally, as described below.

Proceeding from high to low Si values in spring, we initially encounter waters with very low NO₂⁻ + NO₃⁻/Si compared to that expected from the river-seawater mixing (Figure 8). These samples were from within the turbidity maximum, where photosynthetic uptake cannot be the nitrate sink. Rather, the associated high methane values in some samples (square symbols) strongly suggest that interactions with anoxic bottom and pore water environments were intense. Loss of NO₂⁻ + NO₃⁻ by denitrification (and possibly Si injection by redissolution) are likely the dominant processes redefining the NO₂⁻ + NO₃⁻/Si ratios here.

At intermediate [Si] the data fall on the high NO₂⁻ + NO₃⁻/Si side of the mixing line and the highest values are associated with unusually high nitrite concentrations (tri-

gles), often with NO₂⁻/NO₃⁻ approaching unity. This combination suggests that very active nitrification was converting ammonia and possibly DON to NO₂⁻ + NO₃⁻. Lewis and Saunders [1989] report $\approx 2.5 \mu\text{M}$ ammonia and $>11 \mu\text{M}$

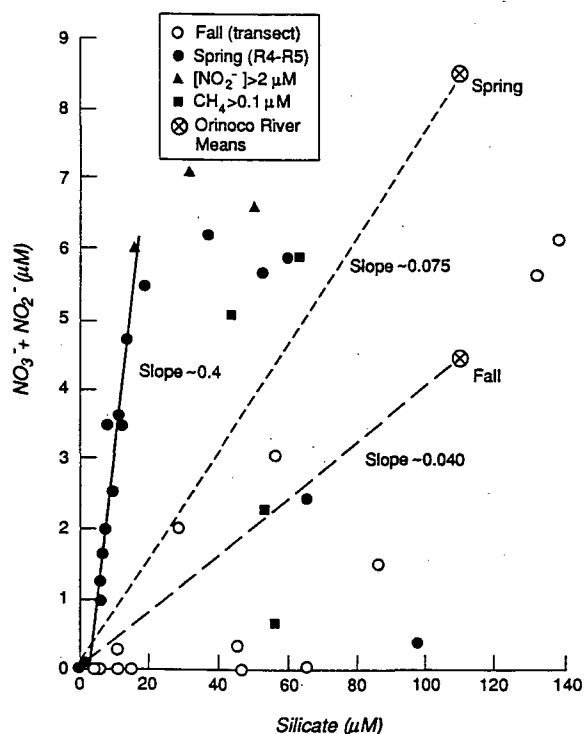


Fig. 8. Plot of nitrite and nitrate versus silicate in surface water for spring and fall 1988.

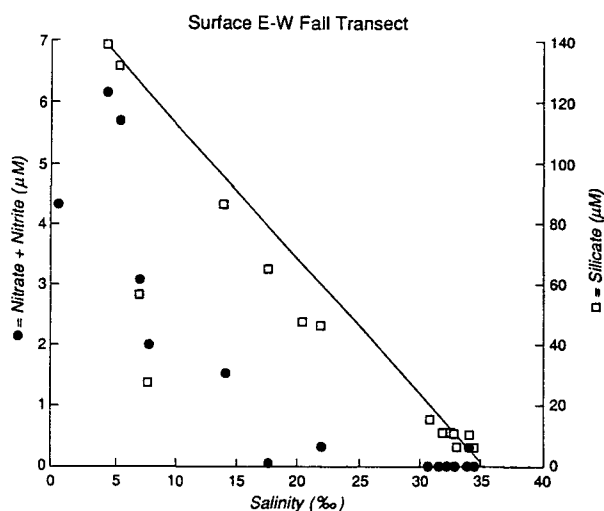


Fig. 9. Plot of nitrite plus nitrate versus salinity and silicate versus salinity from the surface water of E-W transect, fall 1988.

DON in the riverine end-member. Displacement of NH_4^+ /DON bound to clays by seawater cations in this zone of intense mixing would provide a mechanism to free new substrate for subsequent oxidation to nitrite by bacteria [Carpenter and Capone, 1983], while the high turbidity would minimize light inhibition [Olson, 1981; Vanzella et al., 1989]. Finally, at $<20 \mu\text{M}$ Si this high $\text{NO}_2^- + \text{NO}_3^-/\text{Si}$ water appears to mix conservatively with oligotrophic seawater, perhaps with some photosynthetic uptake of N at the very lowest [Si].

Thus these data show that in spring, nonconservative behaviors indicating biogeochemical cycling and input of N to coastal waters were intense in this very active zone, generating both relatively N-poor and N-rich waters (N/Si ratios ≈ 0.1 –5 of the riverine ratio). However, our sampling was far too sparse and unrepresentative to permit estimating the relative amounts of these two types of water input to the coastal zone over any significant area, and the absence of ammonia and DON data prevents a comprehensive mass balance approach.

In fall (Figure 8, open symbols) the much larger river flow pushed high-Si water out well beyond the core of the turbidity maximum; waters with strongly enriched $\text{NO}_2^- + \text{NO}_3^-/\text{Si}$ ratio were absent. The most Si-rich waters were also higher in $\text{NO}_2^- + \text{NO}_3^-$ than expected from the data of Lewis and Saunders [1989] but in the expected ratio. The fall data are plotted against salinity in Figure 9, revealing estuarine Si consumption and strong $\text{NO}_2^- + \text{NO}_3^-$ uptake, especially near ≈ 7 ppt salinity. This presumably reflects photosynthetic uptake by silicoflagellates (see Edmond et al. [1981] concerning this same situation in the Amazon plume). At higher salinities, Si is more nearly conservative and N + N is exhausted. These trends suggest remineralization of Si and continued uptake of N + N by nonsiliceous primary producers at higher salinity. However, in both seasons these interpretations must be tempered by the realization that the system was probably not at steady state, that significant vertical gradients which may have originated by non-conservative processes are ignored, and that the "riverine" (near Barrancas, at the head of the deltaic region) end-member data of Lewis and Saunders [1989] or our samples at

Boca Grande (R4–R5) may not typify the myriad other unsampled distributaries to the NE and entering the Gulf of Paria.

Gulf of Paria and Inputs to the Caribbean

Although some Orinoco and coastally trapped Amazon water enters the Caribbean by way of Galleons Passage N of Trinidad, efflux out of the Boca de Dragon is thought to represent a major component of the estuarine input to the Caribbean, as shown strikingly by satellite photographs [Müller-Karger et al., 1990].

The gyre circulation in this Gulf [Bonilla, 1977; D'Armas, 1986] tends to homogenize its waters, including the inputs of the northernmost distributaries discharging into the Gulf itself. Hence it is especially interesting to examine the behavior of Si on this scale. Taking our riverine end-member values and R1 as a seaward end-member for Atlantic water entering the Caribbean in the vicinity of the Grenada passage, conservative mixing of surface waters in spring predicts $\approx 18 \mu\text{M}$ silicate at P1; $<7 \mu\text{M}$ was present. Thus at low discharge, the residence time of water in the Gulf is apparently long enough that substantial biological removal occurs.

In contrast, in fall Si appears to be conservative along the coast and in the Gulf of Paria (Figure 10 inset), despite evidence for localized Si removal (Figure 9). Presumably, either this Si was regenerated and re-entrained in the flow (perhaps in the course of turbulent mixing in the Boca de Serpente), or the fraction of the total flow thus affected was minor. This mixing line thus defines the Gulf of Paria source water to the Caribbean (at this time) as having an end-member value of $\approx 120 \mu\text{M}$ Si representing river water (Orinoco plus coastally trapped Amazon flows) little modified by dilution by rainfall or biological removal. This differs from Froehlich et al. [1978] estimate of average freshwater input to the eastern Caribbean (for the entire eastern Caribbean, a significant amount presumably being Amazon water entering with the North Equatorial and Antilles currents through more northern passages) had an apparent end-member composition of $\approx 60 \mu\text{M}$ Si, corresponding mostly to three-component mixing of Amazon water (with nearly the same Si content as Orinoco water, $\approx 130 \mu\text{M}$), rainfall, and oligotrophic surface seawater.

Figure 10 is an Si-salt plot with our end-member mixing line (dashed), that of Froehlich et al. [1978] (heavy solid), and the surface Si data for the entire east. Caribbean cruise track (Figure 1) in fall 1988. Much of the data lie near the line of Froehlich et al. [1978], especially if adjusted to assume an end-member with $0.5 \mu\text{M}$ Si at 36.2 ppt rather than the value of 1 at 36.4 they used (light line). However, to the north (up to about 13°N) many points lie in between these two or along our mixing lines. If Si is nearly conserved in the E Caribbean, our Si data suggest a modified view of the three-component mixing concept to account for the fact that the Gulf of Paria component is apparently little diluted by rain, whereas the "offshore Amazonian" inputs supply rain-diluted riverine Si.

Thus our Si data more or less directly demonstrate the existence in fall of two freshwater/Si inputs and show that the source of high Si water is at least partly associated with the Orinoco input through the Gulf of Paria, up to $\approx 13^\circ\text{N}$. These findings thus reinforce the conclusion from ^{228}Ra data by Moore et al. [1986] that two discrete routes of delivery for

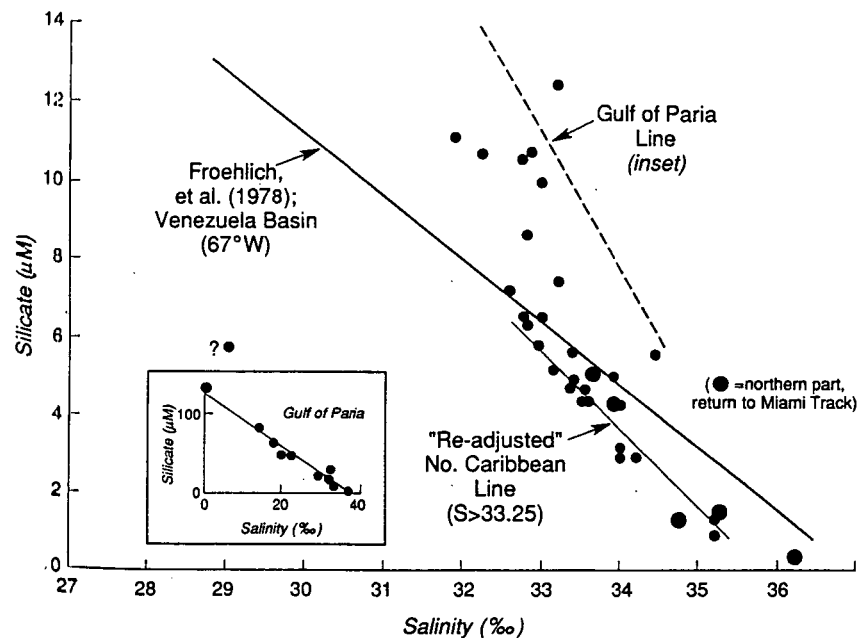


Fig. 10. Plot of silicate versus salinity for the surface waters of the East Caribbean cruise track and the Gulf of Paria, fall 1988.

the riverine waters exist [see also Moore and Todd, this issue].

Spring and Fall Distributions of Primary Productivity

On a larger scale, Ryther *et al.* [1967] suggested that Amazon water actually depressed productivity off Brazil by diluting N nutrients, whereas Müller-Karger *et al.* [1990] suggest a massive fertilization of the eastern Caribbean by Orinoco nutrients. As mentioned previously, the absence of ammonia and DON data do not permit us to evaluate the nitrogenous inputs to the eastern Caribbean, though clearly in fall there is massive nitrate depletion (Figure 9) before waters exit the Gulf of Paria. The absence of small primary productivity values close inshore in either season shows a normally enhanced coastal productivity, despite the fact that light, turbidity, and salinity stresses must be strong. The data by ~~Baigún~~ *et al.* [this issue] offer confirming evidence from pigment analyses. Thus the primary productivity data give an approximate indication that riverine fertilization takes effect close inshore (Figures 6 and 7). If sufficient N nutrients survive passage through the Gulf of Paria to fertilize the Caribbean Basin (as assumed by Müller-Karger *et al.* [1990]), this effect must be due to efficient biogeochemical recycling processes en route, not to an initially unproductive water mass.

Acknowledgments. This work was supported by National Science Foundation grants OCE 8700576 and OCE 8620249, ONR contracts N0001-14-87-K-0007 and N00014-89-J-1258. We thank the Captain and crew of the R/V *Columbus Iselin* for assistance at sea. This work is partially the result of research sponsored by NOAA National Sea Grant College Program Office, Department of Commerce, under grant NA86-AA-D-SG090, Woods Hole Oceanographic Institution Sea Grant Project R/O-15-PD. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear hereon.

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(Received May 10, 1991;
revised February 14, 1992;
accepted February 21, 1992.)