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On some factors influencing dissolved silicon distribution over the northwest African shelf

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ABSTRACT

Nitrate concentrations in the upwelling source waters observed near Cabo Corbeiro during the JOINT-I experiment were more than twice as high as dissolved silicon concentrations, but dissolved silicon concentrations in the surface layers fell below $0.5 \mu\text{g-atoms } l^{-1}$ less frequently than inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^- + \text{NH}_3$). An analysis of the average nutrient fields observed during the JOINT-I experiment suggests that this situation arises partly from relatively rapid silicon regeneration rates in the sub-surface waters overlying the shelf. By combining the available information on the cross-shelf advective-field with average nutrient gradients in the sub-surface onshore flow, we calculated a net input of about $0.5 \mu\text{g-atoms } l^{-1} \text{ day}^{-1}$ for dissolved silicon and about $0.3 \mu\text{g-atoms } l^{-1} \text{ day}^{-1}$ for inorganic nitrogen.

Mixing diagrams enabled us to calculate a net dissolved silicon uptake rate in the photic zone over the shelf. This result conflicts with the implications of a few direct measurements of silicon uptake vs. dissolution, but we are able to show that the spatial distribution of these samples favored an excess of solution over uptake.

1. Introduction

While advection of deeper waters into the photic zone supplies upwelling areas with the "new" inorganic nutrients necessary for their high primary productivities, recycling of these nutrients within the upwelling system can also be quite important (Dugdale and Goering, 1967). Although dissolved silicon is not required by all primary producers, observations have been made linking dissolved silicon depletion with decreased primary productivity (Dugdale and Goering, 1970). Consequently, a better understanding of the processes that control dissolved silicon concentrations over the northwest African shelf should help us understand the productivity of this ecosystem. Silicon dissolution and uptake can be measured directly (Nelson and Goering, 1977), but we will show that it is useful to complement the relatively small number of these difficult-to-obtain observations with an interpretation of the more abundant nutrient and hydrographic data.

The nutrient and hydrographic data that we will emphasize were taken from the

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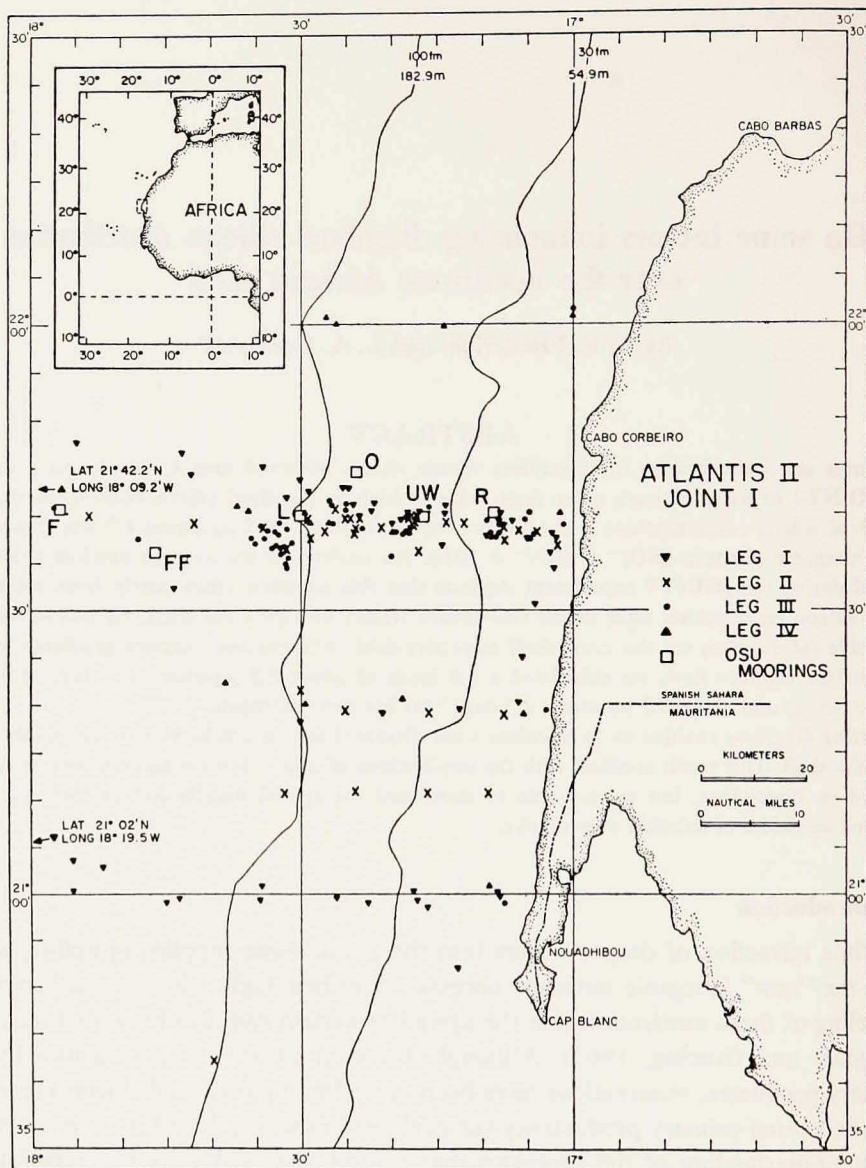


Figure 1. Station locations for R.V. *Atlantis-II* Cruise 82 (JOINT I), March-May 1974, and the Oregon State University (OSU) current meter array locations.

R. V. *Atlantis-II* during March-May 1974. These observations formed a portion of the JOINT-I experiment. Barber (1977) has described this multi-ship, multi-national effort in some detail. Here, it is sufficient to note that the observations were concentrated along a zonal line at $\sim 21^{\circ}40'N$ (near Cabo Corbeiro, Fig. 1), and that

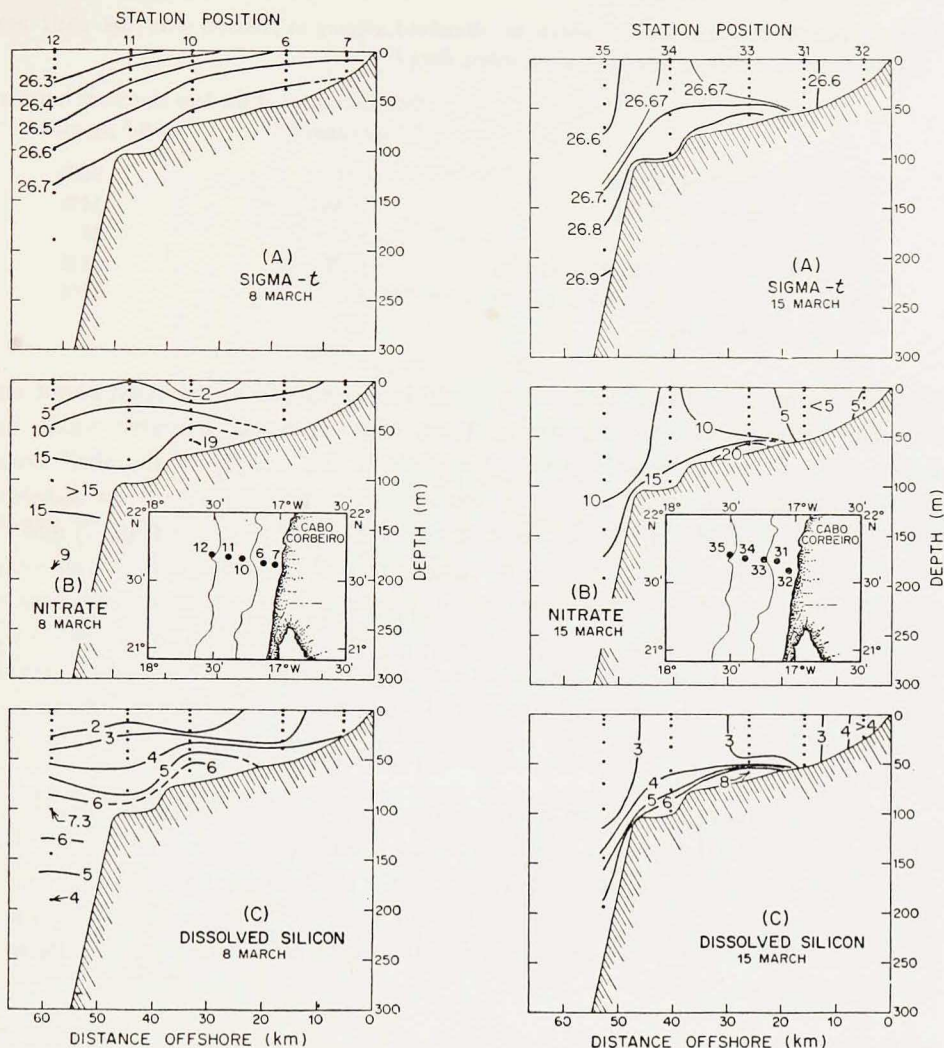


Figure 2. Sigma- t (A), nitrate (B) and dissolved silicon (C) sections taken on 8 March 1974.

Nitrate and dissolved silicon concentrations are in $\mu\text{g-atoms l}^{-1}$.

Figure 3. Sigma- t (A), nitrate (B) and dissolved silicon (C) sections taken on 15 March 1974.

Nitrate and dissolved silicon concentrations are in $\mu\text{g-atoms l}^{-1}$.

the shipboard efforts were supported by observations from moored instrument arrays, shore-based meteorological stations and aerial surveys.

Much of the variability in dissolved silicon distributions can be related to the same variations in physical processes that influence the nitrate concentrations which we have previously explained (Codispoti and Friederich, 1978). For example, during the two major upwelling events that we described, dissolved silicon, reactive

Table 1. Nitrate and inorganic nitrogen vs. dissolved silicon at stations over the shelf near 21°40'N where surface nutrient concentrations were low.

	Concentration of the less abundant nutrient	
	$\leq 1 \mu\text{g-atom l}^{-1}$	$\leq 0.5 \mu\text{g-atoms l}^{-1}$
Nitrate < dissolved silicon	73%	86%
Nitrate > dissolved silicon	27%	14%
Number of stations	37	29
Inorganic nitrogen < dissolved silicon	57%	68%
Inorganic nitrogen > dissolved silicon	43%	32%
Number of stations	37	22

phosphorus, and nitrate concentrations would increase close to the coast about one day after the onset of upwelling winds. Then, with continued favorable winds, the center of most intense upwelling would migrate to the vicinity of the shelf break where it would remain until the system relaxed. This correlation between dissolved silicon, nitrate, and sigma- t is illustrated in the sections of 8 March (Fig. 2) and 15 March (Fig. 3), demonstrating cases of relaxation and intensification of upwelling, respectively. The apparent parallelism is not complete, however, and an analysis of the JOINT-I nutrient data reveals trends that help to explain why low ($<0.5 \mu\text{g-atoms l}^{-1}$) dissolved silicon concentrations occurred less often than low inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^- + \text{NH}_3$) concentrations (Table 1) even though nitrate concentrations in the upwelling source waters were more than twice as high as the dissolved silicon concentrations.²

Our analysis focuses on some average cross-shelf nutrient gradients. It demonstrates that dissolved silicon is regenerated more quickly than nitrate, nitrite, and ammonia in the subsurface waters moving onto the shelf; and it indicates that silicon dissolution may not exceed uptake near Cabo Cabeiro as suggested by Nelson and Goering's (1977) results. We also make an attempt to rationalize their results with our observations.

2. Data and methods

Hydrographic casts aboard the R. V. *Atlantis-II* were made using 5-liter Niskin bottles equipped with protected and unprotected thermometers. Standard collection and handling procedures were followed (Duxbury and Dinkins, 1966). Salinities were measured aboard ship with a Woods Hole salinometer. Nutrient analyses were made using a Technicon AutoAnalyzer system with procedures based on the manual method of Murphy and Riley (1962) for reactive phosphorus and the AutoAnalyzer techniques of Armstrong, Stearns, and Strickland (1967) for dissolved silicon, nitrate,

2. Although we do not treat reactive phosphorus concentrations in detail in our analysis, we have multiplied them by the 16/1 (by atoms) $\Delta\text{N}/\Delta\text{P}$ ratio frequently assumed (Redfield *et al.*, 1963) and compared the resulting values with inorganic nitrogen concentrations. From this analysis, it is clear that reactive phosphorus was relatively more abundant than inorganic nitrogen.

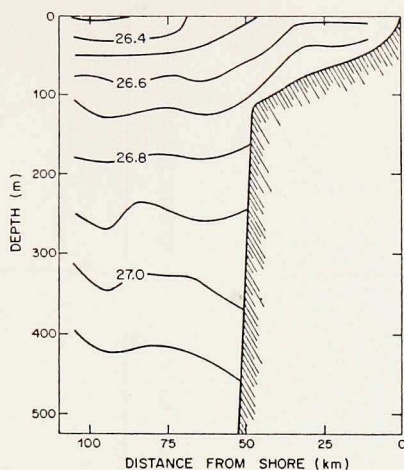


Figure 4. Average sigma- t distribution along $21^{\circ}40'N$ as observed from R.V. *Gilliss* during JOINT-I, February-April 1974 (from Barton *et al.*, 1975).

and nitrite. Ammonia was measured by the method of Koroleff (1970), as automated by Slawyk and MacIsaac (1972). All the *Atlantis-II* hydrographic data for JOINT-I have been compiled by Friebertshauser *et al.* (1975). These authors present a comprehensive account of the methods employed and discuss the quality of the data. Vertical sections based on these data have been presented by Codispoti *et al.* (1976). Those sections chosen for use here have been redrawn on a common base in the manner described by Codispoti and Friederich (1978) to facilitate intercomparison. The wind and current data were taken from reports by Barton *et al.* (1975), and Halpern *et al.* (1975). The silicon uptake and dissolution data used in this paper were reported by Nelson (1975) and the carbon productivity data by Barber and Huntsman (1975).

3. Results

The physical investigations of Mittelstaedt *et al.* (1975), Barton *et al.* (1977), Halpern (1977), and Halpern *et al.* (1977) have shown that during periods of enhanced upwelling there was a tendency toward a balanced, two-layered, cross-shelf flow and also toward an alignment of surface isotherms parallel to the coast. While these observations make it reasonable to suggest that there is a net offshore flow in the surface water and a net onshore flow at depth (Fig. 9), the lack of complete two-dimensionality must be taken into account throughout our analyses. For example, the tendency toward two-dimensionality was not so evident in the nutrient distributions because the study region was strongly influenced by the front between North Atlantic Central Water (NACW) and South Atlantic Central Water (SACW); and these water masses differ considerably in their nutrient content (e.g., Anderson,

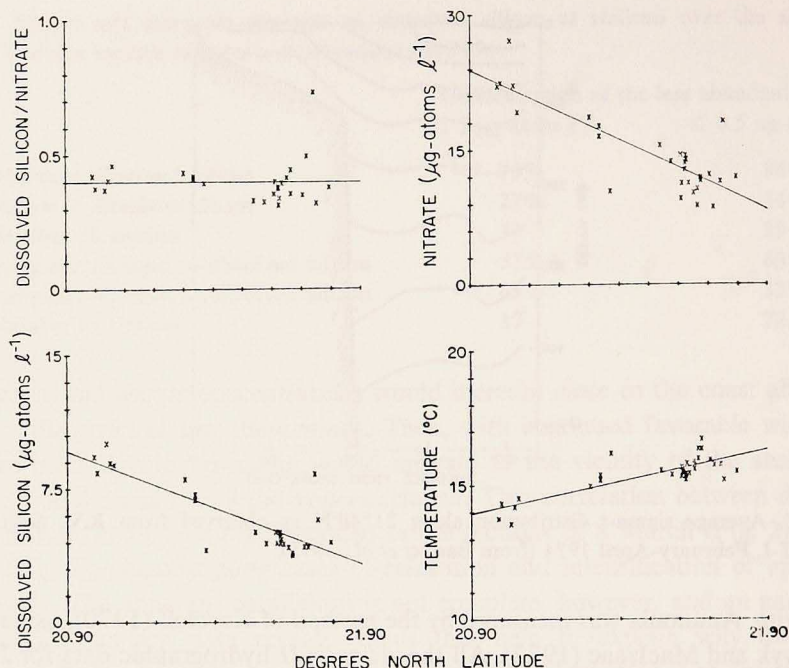


Figure 5. Temperature, nitrate, dissolved silicon and dissolved silicon/nitrate vs. latitude for depths ≥ 150 m and sigma- t 's ≥ 26.6 and ≤ 26.8 . The lines are least squares linear.

1973; Fraga, 1974; Codispoti and Friederich, 1978). The more dense upwelling source waters along the $21^{\circ}40'N$ line, where most of the JOINT-I nutrient data were taken, had a sigma- t range of about 26.6 to 26.8 (Figs. 2-4) and consisted chiefly of NACW as defined by Sverdrup *et al.* (1942). However, in many sections, influences of the colder, less saline, nutrient-rich SACW were observed, and as Cape Blanc was approached, the importance of SACW as a constituent of the upwelling source waters increased (Fig. 5). A study of *in situ* changes of dissolved silicon must take this complication into account, and we are fortunate that the relationship between nitrate and dissolved silicon in the upwelling source waters appears to be rather constant and unrelated to origin (Fig. 5). Consequently, the use of dissolved silicon/nitrate (Si/NO_3^-) ratios allows us to normalize for the varying composition of the source waters and considerably reduces the longshore effects that are caused by the front between SACW and NACW.

The data indicate that nitrate concentrations in the deeper waters of the continental shelf were not greatly affected by *in situ* processes (Fig. 6), so the use of these ratios should give some idea of the *in situ* changes in dissolved silicon in the deeper waters. This conservative tendency in the deeper nitrate concentrations might be

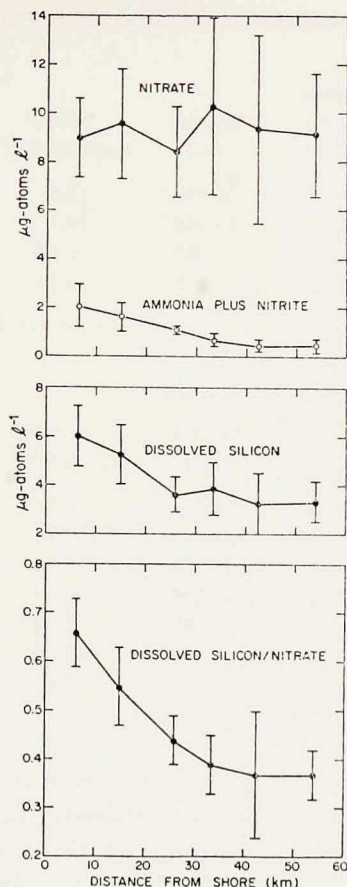


Figure 6. Average nitrate, nitrite plus ammonia, dissolved silicon and dissolved silicon/nitrate along $21^{\circ}40'N$. Sigma- $t \geq 26.65$ and ≤ 26.75 , depth ≥ 20 m within 15 km of the coast and ≥ 30 m everywhere else. Bars indicate ± 1 s.d.

expected since most of the inorganic nitrogen regenerated from organic matter produced in the photic zone is initially present as ammonia and nitrification is a slow process (Vaccaro, 1971) when compared to the short (\sim one week) residence time of these waters that is derived from an onshore flow of $\sim 8 \text{ cm sec}^{-1}$ (Fig. 9) and a shelf width of ~ 50 km. Nitrite (generally $<1 \mu\text{g-atom l}^{-1}$) was present in the deeper water, but this does not necessarily indicate significant nitrification (Blasco, 1971). Although there was some nitrate input from the bottom, inorganic nitrogen input from this source appeared to be mainly in the form of ammonia. If the nutrient input from the bottom is distributed over the average thickness of the onshore flow over the shelf (~ 30 m, Fig. 9), the nitrate contribution from the bottom was considerably less than the $0.13 \mu\text{g-atoms l}^{-1}\text{day}^{-1}$. In fact, this is the value that one

Table 2. Temperature, salinity and nutrient data from the section of 8 March 1974, interpolated to the 26.7 σ_t surface.

Distance from Coast (km)	Station	Temperature ($^{\circ}\text{C}$)	Salinity (‰)	Nitrate ($\mu\text{g-atoms l}^{-1}$)	Dissolved Silicon ($\mu\text{g-atoms l}^{-1}$)	Dissolved Silicon/Nitrate
56	12	15.84	36.170	13.8	5.54	0.39
32	10	15.55	36.046	19.1	6.82	0.36
15	6	16.26	36.283	6.92	3.48	0.50
4	7	16.32	36.295	6.56	3.93	0.60

Temperature, salinity and nutrient data from the section of 1-2 April, interpolated to the 26.65 σ_t surface.

Distance from Coast (km)	Station	Temperature ($^{\circ}\text{C}$)	Salinity (‰)	Nitrate ($\mu\text{g-atoms l}^{-1}$)	Dissolved Silicon ($\mu\text{g-atoms l}^{-1}$)	Dissolved Silicon/Nitrate
93	68	16.63	36.311	6.34	2.54	0.40
55	67	16.31	36.249	6.49	3.03	0.47
48	66	16.28	36.241	5.68	2.67	0.47
43	65	16.31	36.245	5.74	2.53	0.44
32	62	16.14	36.197	7.24	3.31	0.46
12	63	16.16	36.199	8.09	5.45	0.67
4	64	16.28	36.235	7.65	6.02	0.79

would obtain from measurements close to the coast where pore water concentrations and bottom respiration were relatively high (Christensen and Packard, 1977; Rowe *et al.*, 1977). Effects due to denitrification are probably insignificant since all waters over the shelf were well oxygenated. Furthermore, owing to its greater abundance, changes in nitrate concentrations would have a relatively minor effect on Si/NO_3^- ratios when compared to similar changes in dissolved silicon concentrations. Nitrite and ammonia, on the other hand, showed definite cross-shelf variations (Fig. 6).

The above conclusions are substantiated not only by average conditions but also by individual hydrographic sections which indicate that nitrate concentrations below the photic zone for a given sigma- t surface either vary insignificantly or are closely related to water mass differences as indicated by temperature and salinity. Examples are given by the sections of 8 March and 1-2 April interpolated for the 26.7 and 26.65 sigma- t surfaces, respectively (Table 2). The latter example shows a situation where NACW dominated the chosen sigma- t surface, causing corresponding nitrate concentrations to be relatively uniform across the shelf. In the 8 March section, intrusions of SACW are indicated by the low temperatures and high nutrient concentrations at stations 10 and 12. In both cases, nitrate concentrations in the deeper waters roughly parallel the water mass composition while dissolved silicon increases beyond its expected values as the coast is approached.

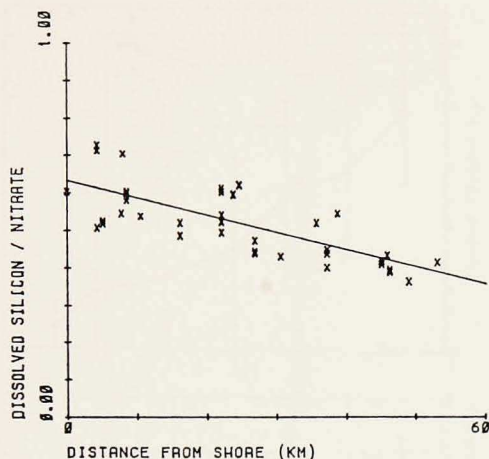


Figure 7. Dissolved silicon/nitrate vs. distance from the shore at 22N, 21°20'N, 21°10'N and 21N. Sigma $t \geq 26.65$ and ≤ 26.75 , depth ≥ 20 m within 15 km of the coast and ≥ 30 m everywhere else. Line indicates least squares linear regression.

Figure 6 has shown that although great variations exist in the sub-euphotic zone nitrate concentrations for the 26.65 to 26.75 sigma- t interval, there do not appear to be significant cross-shelf variations in the average concentrations. Average dissolved silicon concentrations, on the other hand, increase considerably over the inner half of the continental shelf (Fig. 6). As mentioned above, when Si/NO_3^- ratios are employed the effects of varying water mass composition are considerably reduced and much of the scatter in this data is eliminated (Fig. 6). This treatment strengthens the hypothesis that dissolved silicon concentrations in a given water mass increase toward the coast. The same general trend in Si/NO_3^- ratios was observed to the north at $\sim 22^\circ 00'\text{N}$ and to the south at $\sim 21^\circ 20'\text{N}$, $\sim 21^\circ 10'\text{N}$, and $\sim 21^\circ 00'\text{N}$ (Fig. 7), further indicating that the use of ratios eliminates much of the longshore nutrient variability. Data from these sections, however, are not used extensively in our analysis since there are no current meter records and little productivity data for these regions.

In the surface waters at $\sim 21^\circ 40'\text{N}$, the nutrient variability at any location on the shelf was extreme, but when overall averages are considered for the entire JOINT-I experiment a definite trend emerges (Fig. 8). The proportional change for dissolved silicon between the coast and shelf break appears to be about the same as that for nitrate or inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^- + \text{NH}_3$). Dissolved silicon shows a decrease of about 80% between the coast and a distance of about 45 km offshore, while nitrate and inorganic nitrogen decrease by about 70%. As suggested by Fig. 8, inorganic nitrogen concentrations frequently became lower than dissolved silicon concentrations during periods when low nutrient concentrations were encountered (Table 1).

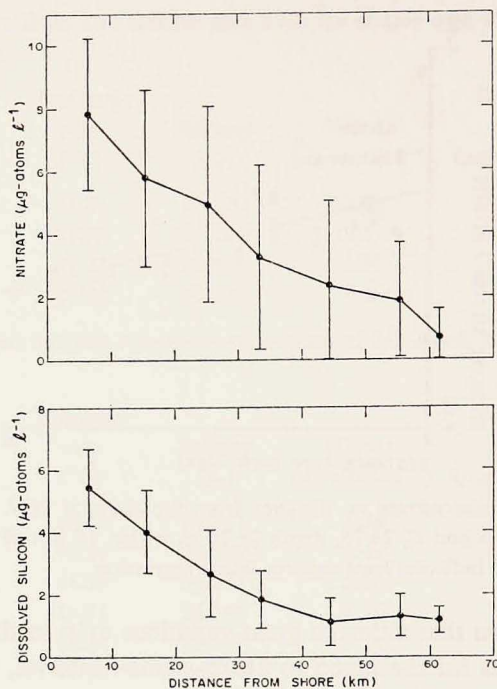


Figure 8. Near surface average nitrate and dissolved silicon concentrations along $21^{\circ}40'N$. Depth ≤ 20 m within 15 km of the shore and ≤ 30 m everywhere else. Bars indicate ± 1 s.d.

4. Discussion

On the continental shelf at $21^{\circ}40'N$, the average flow in the surface layer had an offshore component with the maximum velocity occurring very near the surface (Halpern *et al.*, 1975); but below a depth of about 30 m the currents had an onshore component with its maximum located about 45 km away from the coast at a depth of about 60 m (Fig. 9). For water in the 26.65 to 26.75 sigma- t interval contained in this flow, the observed change in Si/NO $_3^-$ ratios was from an average value of 0.37 near the shelf break to a value of 0.66 within 10 km of the coast (Fig. 6). The above change corresponds to an enrichment of approximately $2.75 \mu\text{g-atoms l}^{-1}$ of dissolved silicon, since the average nitrate concentrations had a value of $9.47 \mu\text{g-atoms l}^{-1}$ (Fig. 6). The onshore component of the currents at mid-depth over the shelf was about 8 cm sec^{-1} , giving the water within 10 km of the coast a residence time on the shelf of about 5.8 days and implying a net dissolved silicon input of about $0.47 \mu\text{g-atoms l}^{-1}\text{day}^{-1}$. Regenerated nitrogen in the form of ammonia and nitrite shows a net increase of only $0.28 \mu\text{g-atoms l}^{-1}\text{day}^{-1}$ over the same region even though the supply of inorganic nitrogen to the shelf by the upwelling source waters is much greater than that of dissolved silicon. The actual rates may be somewhat higher because we have not considered diffusive losses. However, including

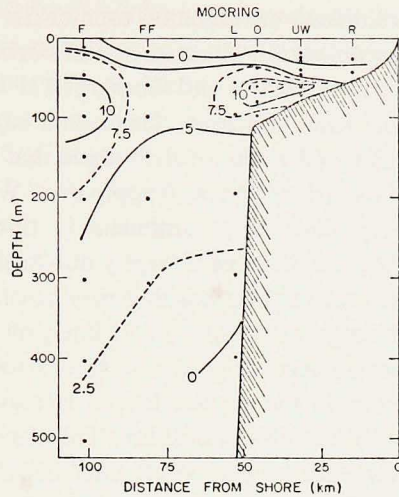


Figure 9. Average onshore velocity component, u (cm s^{-1}), from 23 February to 25 April (from Barton *et al.*, 1975).

diffusion would only enhance the difference between silicon and ammonia plus nitrite regeneration because the dissolved silicon gradients are relatively large.

Because we are dealing with a productive continental shelf and because biogenic silica may sink more rapidly than organic nitrogen (Redfield *et al.*, 1963), our results are not surprising. One can envision a scenario in which biogenic silica produced over and just offshore of the shelf sinks into the onshore flow relatively rapidly and is kept in contact with the onshore flow even during relatively quiescent periods by the presence of the bottom.

The dissolved silicon input may arise from two sources, diffusion out of the bottom and dissolution of suspended particulates. Bottom input was measured at two stations near the coast by Rowe *et al.* (1977); if distributed over a 30-m layer, the average daily flux was $0.44 \mu\text{g-atoms l}^{-1}$, close to our estimated input. This could be a considerable overestimate for the major portion of the shelf, however, since the measurements were made near the coast in an area of pore water with relatively high dissolved silicon gradients (Rowe *et al.*, 1976). Dissolution of suspended particulate silicon may also play an important role in the establishment of the observed dissolved silicon distribution over the shelf. This hypothesis is supported by the high estimated upwelling velocities that were common during JOINT-I. During periods of enhanced upwelling, vertical velocities may have exceeded $10^{-2} \text{ cm sec}^{-1}$ (Mittelstaedt *et al.*, 1975; Barton *et al.*, 1977), a value comparable to the sinking velocities of diatoms (Margalef, 1961). In addition, the turbidity of the nearshore waters indicated considerable sediment resuspension (Milliman, 1977). Consequently, suspended particles may have had a relatively long residence time.

The high nearshore turbidities were common even at the surface. This resulted in a poor light regime for phytoplankton (Huntsman and Barber, 1977), and it may be useful to note that about half of Nelson and Goering's (1977) silicon dissolution vs. uptake measurements came from this zone. These data suggest an excess of water column solution over uptake, and while we shall argue that this may not be the case for the entire shelf, their conclusions may well apply here. We have previously shown that there may be a net production of ammonia in this region (Codispoti and Friederich, 1978) and suggested that this is largely due to the poor light regime.

So far, we have discussed the implications that may be drawn from the subsurface nutrient distributions. Although more difficult to interpret, the average cross-shelf surface gradient of dissolved silicon (Fig. 8) also merits some discussion. As noted above, silicon concentrations in the surface layers decreased by $\sim 80\%$ between the coast and a distance of about 45 km offshore. The absolute size of this gradient is enhanced by the relatively efficient regeneration in the subsurface waters: the upwelling waters with the highest dissolved silicon concentration rise to the surface over the inner shelf. It may also be enhanced by the possible excess of silicon solution over uptake in the nearshore surface waters.

It is difficult to reconcile this steep decrease in dissolved silicon as the surface waters move offshore with Nelson and Goering's (1977) suggestion that silicon dissolution may exceed uptake between the surface and the 0.1% light level (approx. 40 m) off Cabo Corbeiro. The steep decrease in dissolved silicon suggests a considerable net uptake in the surface layers. Moreover, the shape of this gradient provides an additional hint as to why Nelson and Goering's observations may not produce a realistic idea of average conditions over the shelf. We have mentioned that about half of their measurements are from a nearshore region where conditions favor an excess of solution over uptake, but it is also interesting to note that the remainder of their observations were concentrated along the outer shelf and slope where the cross-shelf silicon gradient is flat. Consequently, these measurements may also have been taken in a zone with a relatively high solution/uptake ratio. Their measurements did not include the mid-shelf zone where carbon productivity was highest (Huntsman and Barber, 1977) and where there was a steep offshore decrease in surface dissolved silicon concentrations.

To test the hypothesis that Nelson and Goering's (1977) results may have been biased by not including measurements from mid-shelf, we used a mixing model similar to that of Minas *et al.* (1974) and applied it to the upper 30 m of each of the hydrographic sections along $21^{\circ}40'N$ occupied by the *Atlantis-II* (Codispoti *et al.*, 1976). This model assumes that salinity in the upper 30 may be treated as a conservative property over the time scale involved. It also assumes that we are dealing with two-component mixing between high salinity, low nutrient off-shore waters and low salinity, high nutrient upwelling source waters. Nutrient or dissolved oxygen deficits or excesses that result from uptake, regeneration, or oxygen exchange with

the atmosphere may be determined from this model by noting deviations from the straight salinity-nutrient or salinity-oxygen mixing lines that would result if all of the variables behaved conservatively. A fortuitous aspect of this model is that the relationships between salinity and nutrients tend to minimize the effects of varying proportions of NACW and SACW in the upwelling source waters. This is because the surface waters have the lowest nutrient contents and the highest salinities and because nutrient rich SACW is less saline than NACW. For example, when we used salinity as a guide to divide the upwelling source waters into NACW rich and SACW rich sets, we obtained similar source water-offshore surface water mixing lines for $\Delta\text{Si}/\Delta\text{S}\text{‰}$. For the NACW rich case, $\Delta\text{Si}/\Delta\text{S}\text{‰}$ was 15.1 with a standard deviation of 2.9, and for the SACW rich-offshore surface water line $\Delta\text{Si}/\Delta\text{S}\text{‰}$ was 12.8 with a standard deviation of 1.3.

Our plots indicated that nonconservative changes of nutrients and oxygen in the upwelling source waters were slight up to salinities of about 36.1‰, and that waters with salinities $\geq 36.5\text{‰}$ were offshore surface waters with little or no nutrients. Consequently, the end-points of the mixing line for each section were selected by determining an appropriate nutrient or dissolved oxygen concentration at a salinity of 36.1‰ and by assuming that the nutrient concentration at 36.5‰ was negligible and that the oxygen concentration was equal to the 100% saturation value. The average nutrient and oxygen concentrations for upwelling source waters with a salinity of 36.1‰ were considered in constructing the mixing lines, but these average values were adjusted by carefully considering the oxygen and nutrient vs. salinity relationships for each section. This procedure further reduced any possible errors arising from varying water mass composition.

We used the changes of inorganic nitrogen and oxygen that were calculated to test the validity of our model. Samples where nitrate was less than $1\text{ }\mu\text{g-atom l}^{-1}$ or ammonia was greater than $1\text{ }\mu\text{g-atom l}^{-1}$ were not included since the relationship between oxygen evolution and nitrogen consumption changes considerably during nitrogen limitation and ammonia regeneration. The results confirm those of Minas *et al.* (1978), indicating a close relationship between the uptake of inorganic nitrogen and the production of oxygen, paralleling the usual relationship of Redfield *et al.* (1963) (Fig. 10). The nonzero intercept of the linear regression line of these data points may arise from oxygen input from the atmosphere during periods when wind mixing was substantial. Additionally, the intercept may be the result of choosing mixing lines that had a tendency to give conservative estimates of uptake.

The distribution of the dissolved silicon excesses and deficits tends to confirm our earlier speculations based on the surface nutrient gradients. Within 20 km of the coast, net dissolution dominates while over the mid-shelf the greatest uptakes are recorded (Fig. 11). Since these calculations represent time integrated change of dissolved silicon content beginning with the advection of the upwelling source water onto the shelf, it is evident that considerable net uptake of dissolved silicon occurs

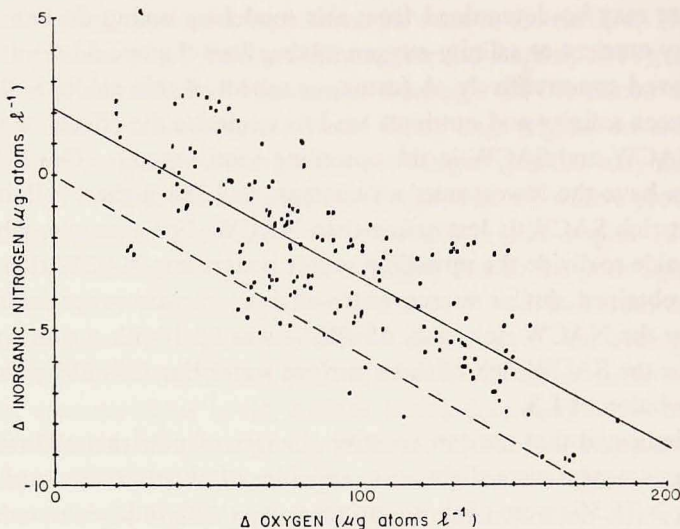


Figure 10. Inorganic nitrogen consumption vs. oxygen evolution along 21°40'N. Solid line is the linear regression of the data [Δ inorganic nitrogen $\mu\text{g-atoms l}^{-1} = (2.11 - 0.054 \Delta\text{oxygen}) \mu\text{g-atoms l}^{-1}$, $r = 0.77$]. Dotted line is the relationship of Redfield *et al.* (1963) (Δ inorganic nitrogen $\mu\text{g-atoms l}^{-1} = -0.058 \Delta\text{oxygen} \mu\text{g-atoms l}^{-1}$).

over the shelf in the upper 30 m. According to this analysis, almost 80% of the change in dissolved silicon concentration between the coast and the shelf break is explained by biological uptake. Beyond the shelf break, the dissolved silicon deficit decreases due to a combination of factors. As the proportion of low dissolved silicon offshore water becomes greater, the potential dissolved silicon concentration and deficit become smaller, ultimately approaching zero. Additionally, biological uptake may have been inhibited due to the deep mixed layers frequently found over the slope. The same trend is also seen in the inorganic nitrogen deficit.

The nutrient concentrations in the offshore flow should exhibit the cumulative effect of uptake, regeneration, and mixing, since the water has entered the study area. Considering that the average dissolved silicon deficit for the upper 30 m at the shelf break was about $1.3 \mu\text{g-atoms l}^{-1}$ and that the average residence time of the surface water over the shelf may be on the order of five to six days, the net uptake rate had an average value of about $0.24 \mu\text{g-atoms l}^{-1}\text{d}^{-1}$. Since this figure includes dissolution at depth and in the photic zone, the upper layer uptake rate may have been considerably greater. The net inorganic nitrogen uptake calculated in the same manner is $0.63 \mu\text{g-atoms l}^{-1}\text{d}^{-1}$, very similar to the average gross uptake rate of $0.87 \mu\text{g-atoms l}^{-1}\text{d}^{-1}$ actually measured by R. C. Dugdale and J. J. MacIsaac (personal communication) for the upper 20 m. Their measurements do not include regeneration and therefore should be somewhat higher than ours.

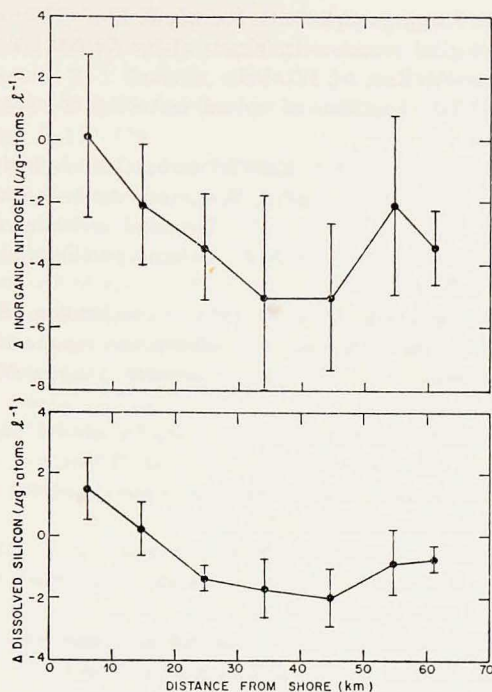


Figure 11. Average inorganic nitrogen and dissolved silicon excesses and deficits along 21°40'N. Depth ≤ 30 m and bars indicate ± 1 s.d.

We suggest that the measurements of Nelson and Goering are representative of the particular water sampled, but not of overall conditions during JOINT-I. We feel that our analysis of the routinely collected data shows how these abundant results can aid in choosing the collection sites for powerful but difficult techniques, such as the methods of Nelson and Goering (1977).

Acknowledgments. We thank D. Cromoga, D. Doyle, A. Hafferty, and S. Patterson for their technical assistance. We are also grateful for the cooperation extended by the master and crew of the R. V. *Atlantis-II* during the JOINT-I experiment. We wish to thank J. J. MacIsaac, and Drs. J. J. Anderson, R. C. Dugdale, J. J. Goering, and D. M. Nelson for their helpful discussions and for permitting us to use some of their data.

Financial support was provided by the Office for the International Decade of Ocean Exploration under National Science Foundation grants OCE76-04825 and OCE77-27128. This paper is Contribution 1055 of the Department of Oceanography, University of Washington.

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