AN ABSTRACT OF THE THESIS OF

Roberto Millán Nuñez   for the degree of Master of Science

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Title: Effects of Physical Phenomena on the Distribution of

Nutrients and Phytoplankton Productivity in a Coastal Lagoon

Abstract approved: ___ Redacted for privacy
                        David M. Nelson

Sea level, salinity, temperature, nitrate, nitrite, phosphate,
silicate, chlorophylls a, b and c, and their pheophytins, phytoplank-
ton abundance, and phytoplankton productivity time series were
generated for the mouth and three interior locations of Bahia
San Quintin, Baja California, Mexico, for ten days during summer of
1979. The samples were taken once every two hours. This was done
to describe space and time variability of these ecological properties
and to elucidate the main factors that cause this variability.
Bahia San Quintin is of considerable interest because of its develop-
ing mariculture potential, and because it is representative of a
type of coastal lagoon that is rapidly being altered by man's
activities.

Upwelling events propagate throughout the bay with a lag similar
to that of tides. In comparison with available information on
nutrients limiting growth of planktonic algae, nutrients are almost

never limiting to phytoplankton growth during the sample period. Phytoplankton cell abundances at the extremes of the lagoon are an order of magnitude lower than at the mouth. Chlorophyll concentrations at the extremes are about one third of those of the mouth. Primary productivity decreases from the mouth to the interiors in the same manner as chlorophyll does. There is not much difference in cell size between phytoplankton at the bay mouth and those at the extremes of the bay. Assimilation ratios are not significantly different throughout the bay. Primary productivity in the bay is comparable to the productivity maxima of other upwelling areas. There is no clear permanent dominance of diatoms over dinoflagellates, or vice versa, throughout the bay. The alternation of upwelling events and diurnal and semidiurnal tides were the main physical factors causing temporal variability of ecological properties throughout the bay.

Effects of Physical Phenomena on the Distribution
of Nutrients and Phytoplankton Productivity
in a Coastal Lagoon

by

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Typed by Joan A. Neuman for   Roberto Millán Nuñez

With love, respect and infinite gratitude to my parents

Alfonso Millán-Benítez

Reyna Nuñez-de-Millán

To my wonderful family. With their love, patience and
encouragement that every day bring so much meaning and joy to my
life: my wife and daughters

Yolanda Aguiñaga-de-Millán

Yolanda Millán-Aguiñaga

Yanelí Millán-Aguiñaga

Yeimmy Millán-Aguiñaga

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INTRODUCTION

During the last eight years, there has been an increased
interest in developing maricultures in the coastal lagoons of the
Baja California peninsula. The main interest has been concentrated
on oyster culture. Very successful experiments with _Crassostrea
gigas_, the Japanese oyster, and _Ostrea edulis_, the European oyster,
have been carried out in most of the coastal lagoons of the
peninsula's Pacific coast. Most of these coastal lagoons are very
much in their natural state. But, as development goes on from the
two ends of the peninsula, human activities are making an impact
upon their ecology. Some of the northern and southern lagoons are
already undergoing changes due to urban and touristic development,
besides the effect of fishing on (mainly) crustaceans and molluscs.
There is still a unique opportunity to carry on basic ecological
studies in some of these coastal lagoons before significant changes
are made by man's activities. These studies can give us the
background ecology against which the situations of the future may be
compared. Also, the studies can be designed to gain useful
information that might be applied to make rational decisions as
maricultures are developed. For example, it is important to know
the spatial and temporal ranges of important ecological variables
as temperature and salinity; the relative food availability in
different lagoons; the mechanisms that are responsible for greater
or less fertility of some lagoons with respect to others and with

respect to the open ocean; and the water exchange rate between the lagoons and the adjacent ocean (Lara-Lara, Alvarez-Borrego, and Small, 1980).

GENERAL DESCRIPTION OF SAN QUINTIN BAY

Bahia San Quintin is a coastal lagoon located between 30°24'N–30°30'N, and 115°57'W–116°01'W, on the Pacific coast of Baja California, Mexico (Fig. 1). The bay is some 300 km south of the Mexico-U.S.A. border. The bay is "Y" shaped with a single permanent entrance at the foot of the Y. It has a north-south orientation, and an area of about 41.6 km^2. The lagoon is extremely shallow, and at lower low tide $\approx$ 20% of the bottom is exposed to the air. There are narrow channels that rarely exceed 8 meters in depth. The western arm is named Bahia Falsa and the eastern arm is called specifically Bahia San Quintin (Barnard, 1962). The continental shelf is very narrow off Bahia San Quintin and the wave energy is very high on the open coast (Lankford, 1976).

The climate is arid along the coast and in the mountains. The amount of annual precipitation (5-10 cm) comes mostly in winter. The relatively cool California Current offshore of Bahia San Quintin is partly responsible for the benign climate of the region. Upwelling occurs in the open ocean immediately off the mouth of the bay during spring and summer (Dawson, 1951), a result of northwesterly winds during these seasons. The upwelling process accounts for the presence of fog off the bay in spring and summer.

Flood runoff occurs sometimes in winter, but there are no flowing streams coming into the bay. The westernmost seaward edge of the bay is a long sandspit connecting two cinder cones (Fig. 1), the southern of which marks the entrance to the bay. The south shore
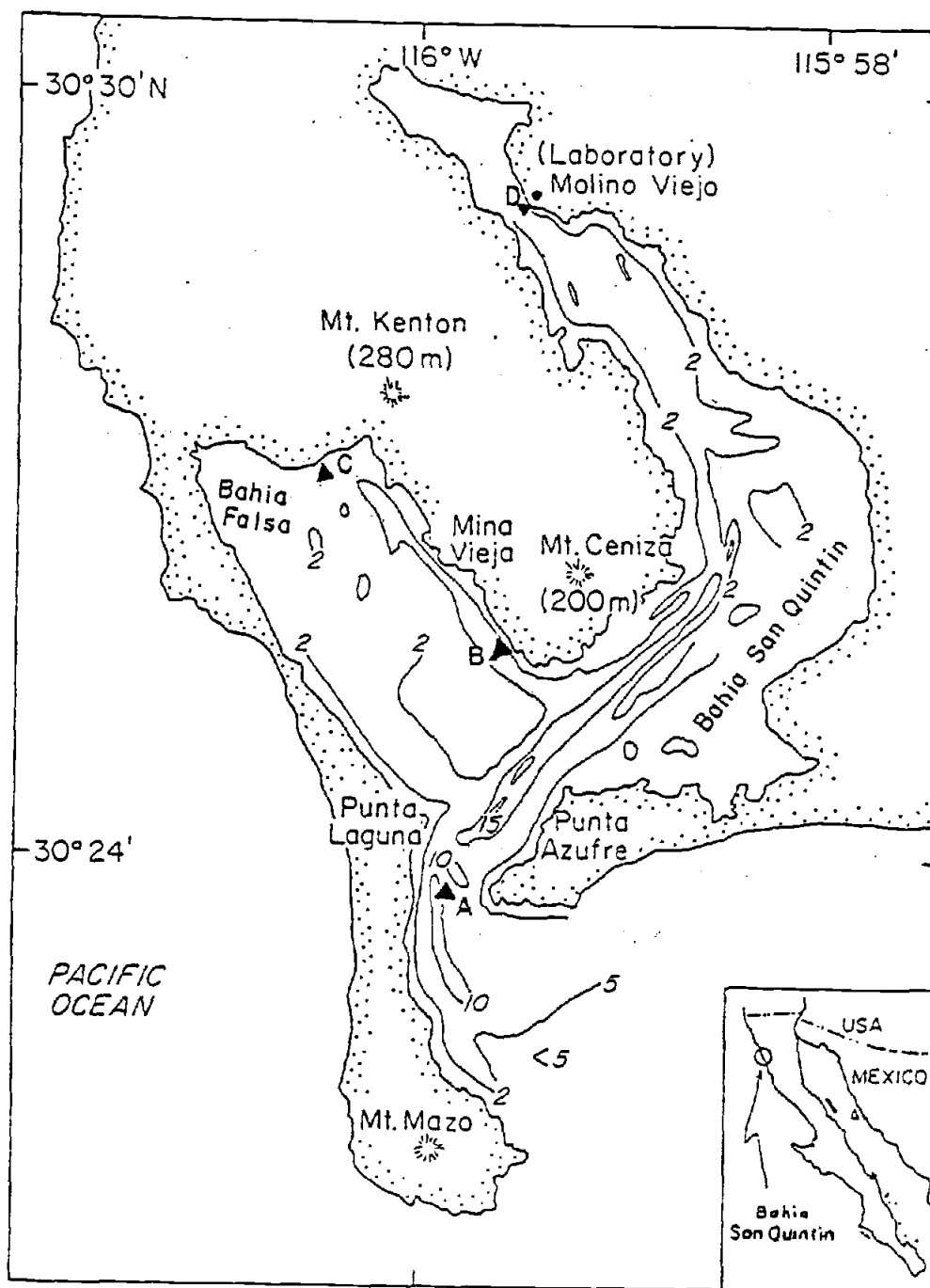
Figure 1. Bahia San Quintin. Time series anchor stations (▲). Bathymetry in meters.

on the open sea trends east and west, being formed of a sandspit
(Punta Azufre) protecting bayward marshes. The two northward
trending arms of the bay are split by two prominent cones, Mt.
Ceniza and Mt. Kenton and most of this middle peninsula is formed
of volcanic material (Barnard, 1962).

The mainly shallow mud-flat character of the bay provides for
two kinds of dominant vegetation. One is a marine flora consisting
of eelgrass, Zostera marina, which forms broad, dense strands
occupying the greater part of the muddy bottom of the lagoon. The
other is a salt marsh flora of extensive development along nearly
half of the low-lying margins of the lagoon subjected to tidal
flooding (Dawson, 1962).

GENERAL OCEANOGRAPHY

In general, all the year around, there are horizontal salinity and temperature gradients, with values increasing from the mouth to the extremes of the lagoon. Sometimes during the winter, with cold air temperatures (0-4°C), the seawater temperature gradients reverses, with values near 15°C at the mouth and near 12°C at the extremes of the bay. The lowest surface temperatures at the mouth have been recorded during summer, with values sometimes below 12°C. These low temperatures are the result of upwelling events during summer, in the adjacent oceanic area. Surface temperatures in the extremes may be higher than 23°C during summer, due to solar radiation input. Bahia San Quintin, the eastern arm, has greater salinity values than Bahia Falsa with a difference of about 1‰. This is due to the greater residence time of water in the former location. Salinity may be higher than 37‰ in the extreme of the eastern arm, and lower than 33‰ at the mouth. Average surface salinities for the whole lagoon do not change significantly from winter to summer. Tidal and solar radiation cycles cause large diel changes of the different water properties in all areas of the lagoon, so that any graph showing the spatial distribution of a seawater property is only a first approximation because sampling cannot be really synoptic (Chavez-de-Nishikawa and Alvarez-Borrego, 1974; Alvarez-Borrego, Ballesteros-Grijalva and Chee-Barragan, 1975).

Alvarez-Borrego and Chee-Barragan (1976) reported that phosphate and silicate surface values increase in general from the mouth to the extremes. These authors have suggested that the inorganic

nutrient distribution may result from high concentration of sea grasses in the lagoon bottom. The grasses act to trap the suspended material that is carried from the adjacent oceanic zone into the lagoon by the tidal currents. This trapping action causes a high deposition of organic material, which is remineralized to inorganic compounds and finally redistributed in the water by tidal currents and wind-induced turbulence. During spring and summer, in addition to the above mechanism, the system receives impulses of inorganic nutrients from the adjacent oceanic area during upwelling events. This causes nutrient concentrations at the mouth to be greater during summer than during winter. Reported ranges for phosphate for the whole bay have been 1.5 to 2.9 µM for summer and 0.7 to 2.0 µM for winter; and for silicate, 13 to 18 µM for summer and 5 to 35 µM for winter.

Alvarez-Borrego and Lopez-Alvarez (1975) reported for the mouth a phytoplankton total abundance of 485 cells ml^{-1} in July and 340 cells ml^{-1} in January, with diatoms dominating in July and dino-flagellates in January. Phytoplankton abundance decreases toward the extremes especially toward the head of the eastern arm, where values are an order of magnitude smaller than at the mouth. Lara-Lara and Alvarez-Borrego (1975) studied the surface distribution of photosynthetic pigments in Bahia San Quintin during one annual cycle. They found the lowest concentrations in winter (average chlorophyll a concentration of 1.5 mg m^{-3}), increased amounts in spring (average chlorophyll a concentration of 2.0 mg m^{-3}), and highest values in summer (average chlorophyll a concentrations of 3.0 mg m^{-3}). Highest

chlorophyll a concentrations were always found in the area between the mouth and the vertex of the "Y". Here, summer maximum values of 8.0 mg m^{-3} and winter maximum values of 3.5 mg m^{-3} were found.

Alvarez-Borrego, Lara-Lara and Acosta-Ruiz (1977) generated four 26-hr time series of salinity, temperature, oxygen, phosphate, nitrate, chlorophyll and metereological variables, once every season at the bay mouth. The variables were measured every hour. They found that chlorophyll concentration can sometimes change by an order of magnitude within an hour. Lara-Lara, Alvarez-Borrego, and Small (1980) generated an 18 day time series, also at hourly intervals, of several ecological variables for the mouth of Bahia San Quintin, during the summer of 1977. Variables were: sea level, current velocity, temperature, salinity, oxygen, inorganic phosphate, chlorophyll a, seston, phytoplankton species abundance, particulate organic carbon and nitrogen and primary productivity. They concluded that alternation of upwelling events was the main cause of variability for all properties except temperature. Semidiurnal tides were the main cause of variability for temperature. Diatoms were always the most abundant phytoplankton group. Primary productivity was always greatest at the surface, with a mean value of 27 mgC m^{-3} hr^{-1} through the sampling period. Maximum surface productivity values were obtained for the upwelling relaxation period (up to 44 mgC m^{-3} hr^{-1}). The mean surface assimilation ratio was 6.6 mgC(mgChla)$^{-1}$hr^{-1}, which indicates nutrient-rich waters.

OBJECTIVES OF THIS WORK

The objectives of this work were to study Bahia San Quintin (Fig. 1) to determine the effects of diurnal and semidiurnal tides, the alternation of spring and neap tides, the alternation of upwelling events off the bay mouth and other physical factors on the distribution of nutrients, phytoplankton abundance and phytoplankton productivity.

Ten-day time series were generated simultaneously at four strategic points (Fig. 1) for sea level, temperature, salinity, nutrients (nitrate, nitrite, phosphate and silicate), chlorophylls a, b and c and their pheophytins, phytoplankton abundance by gross taxonomic groups, and phytoplankton productivity. Sampling was done so that surface horizontal distribution of properties and their dynamics with time could be described.

DATA COLLECTION AND ANALYSIS

Time series sampling was carried out, day and night, simultaneously at four anchor stations (Fig. 1), from June 25 to July 5, 1979. Samples were collected only at the surface.

Tide height was measured at Molino Viejo (Point D, Fig. 1) by a Fisher and Porter Model 1550 digital tide gauge. In order to generate the sea level time series for the other three points (A,B and C, Fig. 1) the phase lag was taken from Monreal (1980).

Water temperatures were read off bucket thermometers every two hours. Salinity was analyzed at a shore-based laboratory (Fig. 1) with a conductivity salinometer, Beckman Model 118WA200. Salinity samples were taken every two hours at point D but only twice a day at the other points. Salinity data taken once every two hours at points A, B, and C with a conductivity meter, Kahlsico Model 188WA300, proved not to be accurate nor precise, therefore they are not included in this thesis.

Nutrients, chlorophylls and phytoplankton samples were always taken from the same Van-Dorn bottle, sampling every two hours. Two drops of a saturated solution of $HgCl_2$ were added to each nutrient sample immediately after collection. Then samples were frozen to be transported to the laboratory. They were analyzed at O.S.U. School of Oceanography's laboratory for phosphate, silicate, nitrate and nitrite, using a Technicon II AutoAnalyzer.

Chlorophyll samples were obtained using 0.45 μm pore-sized Millipore filters. Filters were frozen to be transported to the

laboratory of Centro de Investigacion Cientifica y de Educacion Superior de Ensenada (CICESE) at Ensenada. Chlorophyll analysis was done basically by the SCOR-UNESCO (1966) method, but with some modifications. Second readings at 665, 645, and 630 nm were done after acidification, following Lorenzen (1967). A 1-to-1 volume solution of 90% acetone and dimethyl sulfoxide was used as a solvent to improve the pigment extraction (Shoaf and Lium, 1976). Spectrophoto-metric equations developed by Millán-Nuñez and Alvarez-Borrego (1978) were used to estimate concentration of chlorophylls $\underline{a}$, $\underline{b}$, and $\underline{c}$, and pheophytins $\underline{a}$, $\underline{b}$, and $\underline{c}$. The equation for chlorophyll $\underline{a}$ is exactly the same as that of Lorenzen (1967) due to the chlorophyll $\underline{b}$: pheopigment $\underline{b}$ and chlorophyll $\underline{c}$: pheopigment $\underline{c}$ ratios at 665 nm being equal to one.

Phytoplankton abundance by gross taxonomic groups was determined by the Utermohl (1958) inverted scope technique using a Carl Zeiss invertoscope D microscope.

Three times a day during daylight hours, surface ($\sim$0.5 m) carbon-14 incubations of one hour duration were done at high, intermediate, and low tide. Seawater samples for carbon-14 incubations were not taken from the same Van Dorn samplings for chlorophyll and phytoplankton. Sampling was done specifically for the incubations. The vials containing the filtered samples were transported to the O.S.U. School of Oceanography, where the radio-activity of the samples was determined in a scintillation spectrometer. Inorganic carbon-14 was purged from the vials with nitrogen gas before the radioactivity measurements. Conversion of radioactivity

to carbon productivity was done as indicated by Strickland and Parsons (1972).

STATISTICAL ANALYSIS

Sometimes it is necessary to study the relationship between two processes with possibly different scales of measurement or different variances. In this situation it is necessary to define the cross correlation function:

$$R_{12} (L) = \frac{S_{12}(L)}{S_1 S_2}$$

where S_1 and S_2 are the sample standard deviations of series 1 and 2, respectively, S_{12} is the covariance of series 1 and 2, and R is the correlation coefficient between series 1 and 2. The symbol L is the number of "lags" of a given time unit that one series must be displaced with respect to the other in order to maximize the correlation coefficient between the two series (Jenkins and Watts, 1969). In this work the time unit chosen for each lag is two hours. One application of lagged cross correlation is in the measurement of time delay between two processes.

From Platt and Denman (1975), spectral analysis of a series of data may be regarded as an analysis of variance in which the total variance of a variable or property fluctuation is partitioned into contributions arising from processes with different characteristic time scales. Thus, spectral analysis of a record of observations results in a sorting of total variance of the record into its component frequencies. The spectral analysis results presented here were computed with a fast Fourier transform algorithm. The output presents the frequency components in cycles per hour.

RESULTS

Description of time series of seawater properties

Tidal height time series showed a characteristic semidiurnal behavior and the sequence of spring and neap tides. Maximum tidal height range was about 2 m (Fig. 2). Salinity time series at point D also had a semidiurnal behavior, with high values corresponding in general with low tides, and vice versa. Salinity throughout the whole bay had a general tendency to increase with time during the sampling. Salinity increased from the bay mouth to the extremes of the bay with a mean difference of about 2.2°/₀₀ between points A and D (Fig. 2). Salinity ranges were: 33.40 to 34.57°/₀₀ for Point A; 33.84 to 34.42 °/₀₀ for Point B; 33.93 to 34.76 °/₀₀ for point C; and 34.63 to 37.69 °/₀₀ for point D.

Temperature time series showed a long wave feature at all sampling points (Fig. 3). The long wave feature for point A had a semidiurnal behavior, and at points B, C and D had a diurnal behavior mainly. High temperature values corresponded in general with low tides and vice versa. Diurnal temperature ranges were smaller in the middle of the sampling period, due to neap tides. The ranges of temperature were: 12.8 to 19.8°C for point A; 16.4 to 22.8°C for point B; 17.7 to 21.8°C for point C; and 19.2 to 25.2°C for point D.

Nitrate time series for point A showed the long wave feature very clearly, with high values at the beginning and at the end, and low values in the middle of the sampling period (Fig. 4). Nitrate

time series for points B, C and D did not show the long wave feature clearly, although values at the beginning of the sampling were in general higher than those towards the end. High nitrate values at point A at the beginning of the sampling were due to an ending upwelling event (see discussion page 48). Nitrite tended to show a similar behavior to that of nitrate (Fig. 5). The ranges of nitrate and nitrite (μM), were respectively: 0.1 to 12.5 and 0.00 to 0.42 for point A; 0.1 to 4.1 and 0.00 to 0.30 for point B; 0.03 to 4.5 and 0.07 to 0.25 for point C; and 0.2 to 2.8 and 0.01 to 0.25 for point D.

Phosphate and silicate time series for point A also showed the long wave feature with high values at the beginning and end of the sampling period, and lower values in the middle (Figs. 6 and 7). Their time series for points B, C and D did not show the long wave. Spikes in phosphate concentration appeared at point B on the sixth and ninth sampling days, but no such spikes were obvious at the other sampling points. Possibly the small phosphate spike shown at point A, on the sixth sampling day was correlated with the first spike of point B (Fig. 6). There was no clear variation tendency of phosphate from the mouth to the interiors of the bay. Silicate concentration in general increased from the bay mouth to the extremes (Fig. 7). The ranges of phosphate and silicate (μM) were, respectively: 0.5 to 2.48 and 4.9 to 23.2 for point A; 0.72 to 2.86 and 1.2 to 19.7 for point B; 0.62 to 1.59 and 6.6 to 24.5 for point C; and 0.36 to 1.93 and 10.7 to 32.8 for point D.
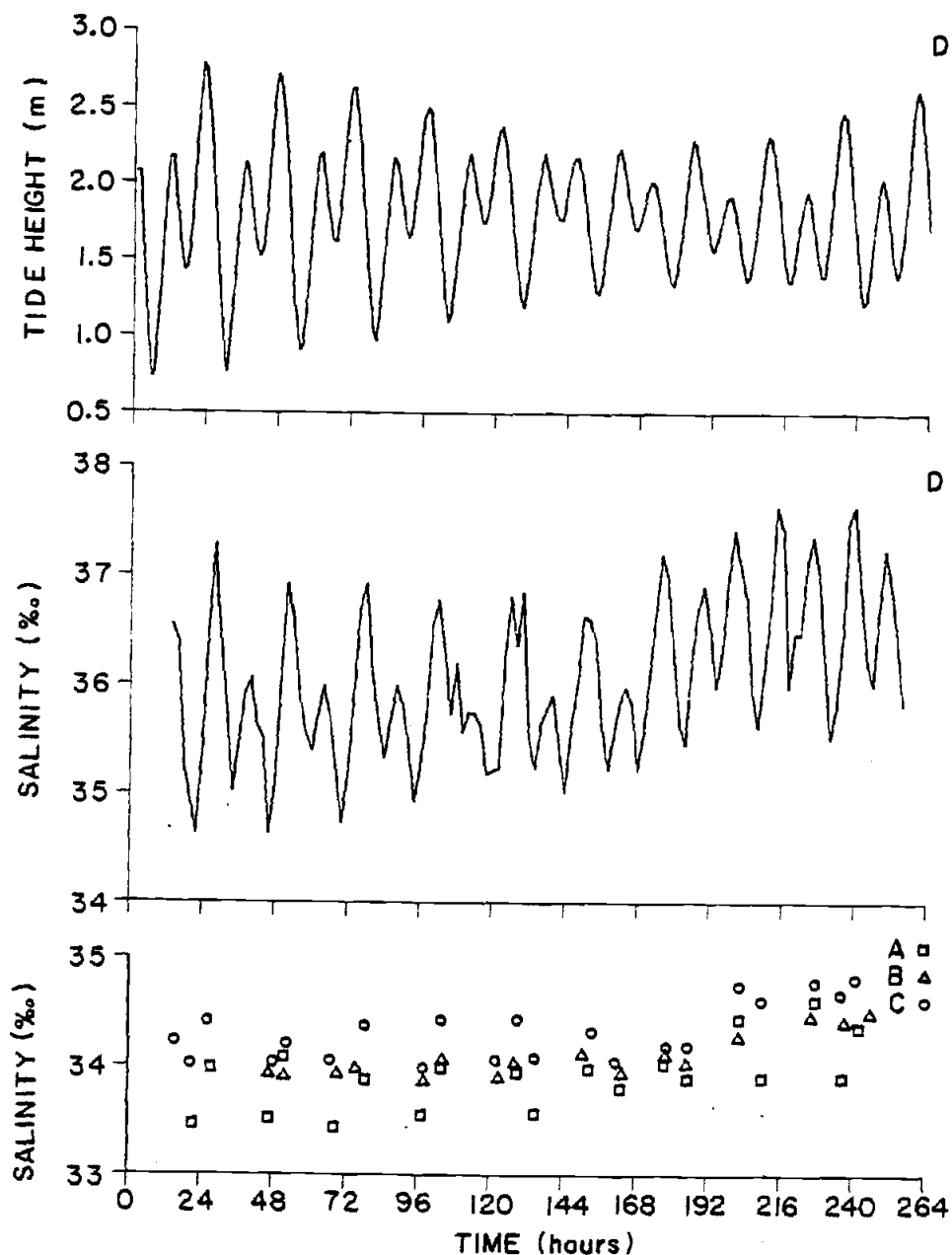
Figure 2. Tide height time series (upper) at station D. Salinity
time series (middle) at station D, this station was
sampled every two hours. Salinity time series (lower)
at stations A (□), B (△) and C (o). These stations
were sampled at times of high and low tide at station D.
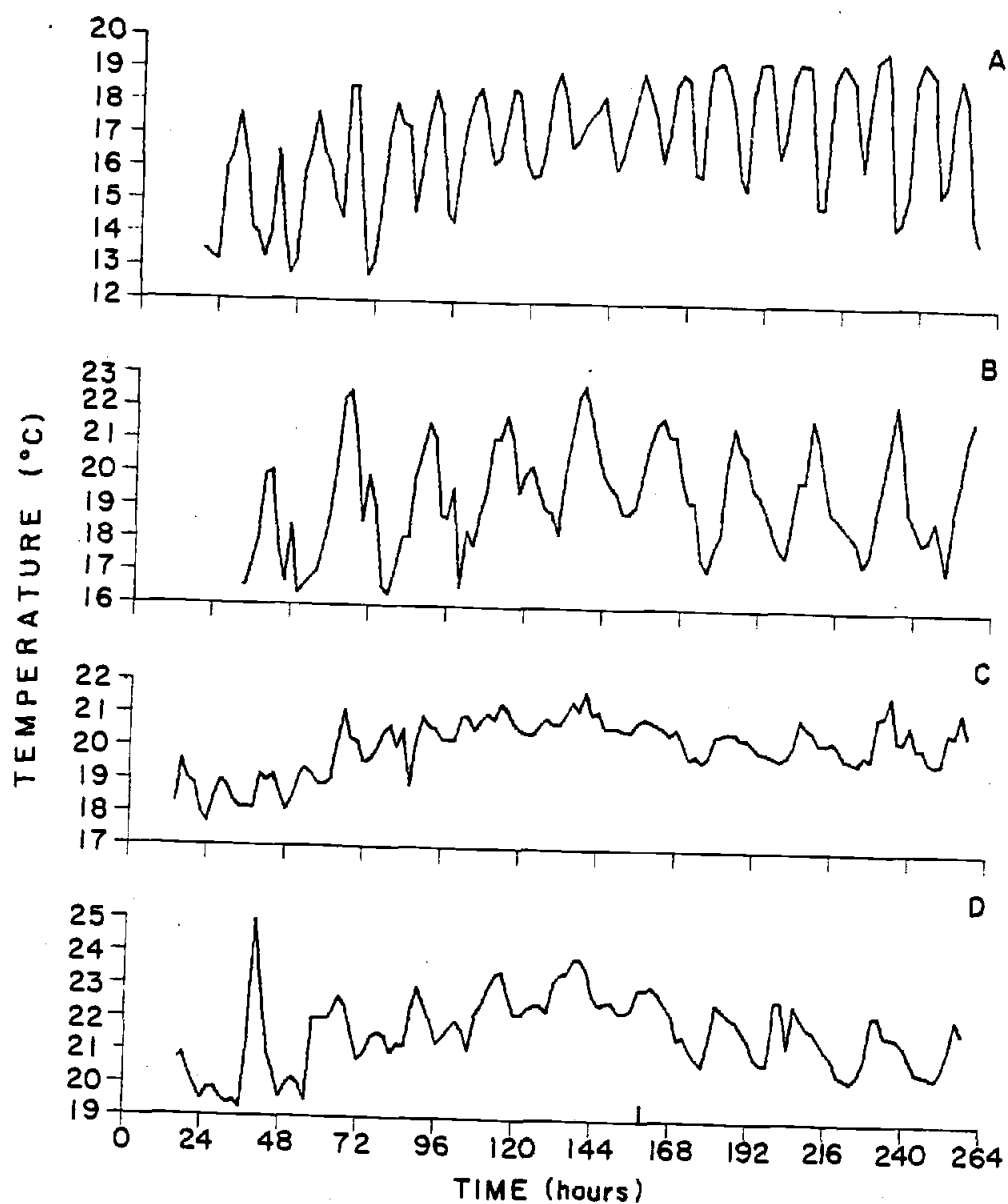
Figure 3. Temperature time series at the four sampling stations. The letters (A,B,C.D) indicate the stations. Numbers mark midnight.

Figure 4. Nitrate time series at the four sampling stations.
Numbers mark midnight.

Figure 5. Nitrite time series at the four sampling stations. Numbers mark midnight.

Figure 6.   Phosphate time series at the four sampling stations.
Numbers mark midnight.

Figure 7.   Silicate time series at the four sampling stations.
            Numbers mark midnight.

The time series at point A for chlorophyll a, b and c showed a general tendency to increase with time during sampling (Figs. 8, 9 and 10). Generally, the highest values for all three pigments at the bay mouth station were found at the end of the sampling period. Pigment time series for sampling points B, C and D showed a complicated patchiness, with no clear variation tendency. The ranges of chlorophylls a, b and c (mg m^{-3}) were respectively: 0.5 to 37.9, 0.0 to 3.8 and 0.0 to 16.1 for point A; 0.5 to 18.7, 0.0 to 1.9 and 0.0 to 12.6 for point B; 0.5 to 4.8, 0.0 to 2.7 and 0.2 to 8.7 for point C; and 0.5 to 4.9, 0.0 to 2.0 and 0.1 to 7.0 for point D. Pheopigment time series showed a very patchy distribution at all four sampling points. Pheophytin b and c often were not significantly different from zero (not illustrated). Pheophytin a concentrations had less value than their respective chlorophyll concentration (Fig. 11).

Phytoplankton abundance time series at the four locations did not show the long wave feature of temperature and nutrients; instead, these time series showed very patchy distribution (Fig. 12). In general phytoplankton total abundance decreased from the bay mouth to the bay extremes. At the extremes, abundance was an order of magnitude less than at the bay mouth. At point B there were patches of high abundance during the first half of the sampling period. Cell abundance at point B was similar to that at points C and D during the second half of the sampling period. There was no clear, permanent dominance of diatoms over dinoflagellates, or vice versa, at any of the sampling stations except station B, where diatoms outnumbered

dinoflagellates for most of the sampling period (Fig. 13). For any given taxonomic group there was no consistent difference in cell size between stations A, B, C and D. The ranges of phytoplankton total abundance (cells ml^{-1}) were: 42 to 1815 for point A; 43 to 2580 for point B; 20 to 182 for point C; and 18 to 246 for point D.

Phytoplankton productivity time series showed a very irregular variation at point A and B (Fig. 14). There was a tendency for productivity to increase with time during sampling at point A, but not at point B. This corresponded with pigment changes through time at the two stations. Primary productivity also showed a tendency to decrease from the bay mouth to the extremes. Assimilation ratios showed irregular variation with time at all stations; however, mean values at each location were not significantly different from one another. Means and ranges of phytoplankton primary productivity ($mgC\ m^{-3}\ hr^{-1}$) were respectively: 33.4, 5.3 to 91.4 for point A; 16.5, 1.6 to 63.0 for point B; 12.5, 2.2 to 23.4 for point C; and 12.3, 1.9 to 27.4 for point D. Means and ranges of assimilation ratios [$mgC(mgChl\underline{a})^{-1}\ hr^{-1}$] were respectively: 6.4, 0.6 to 13.7 for point A; 7.8, 0.8 to 26.2 for point B; 5.4, 0.6 to 12.5 for point C; 6.0, 0.8 to 15.0 for point D.
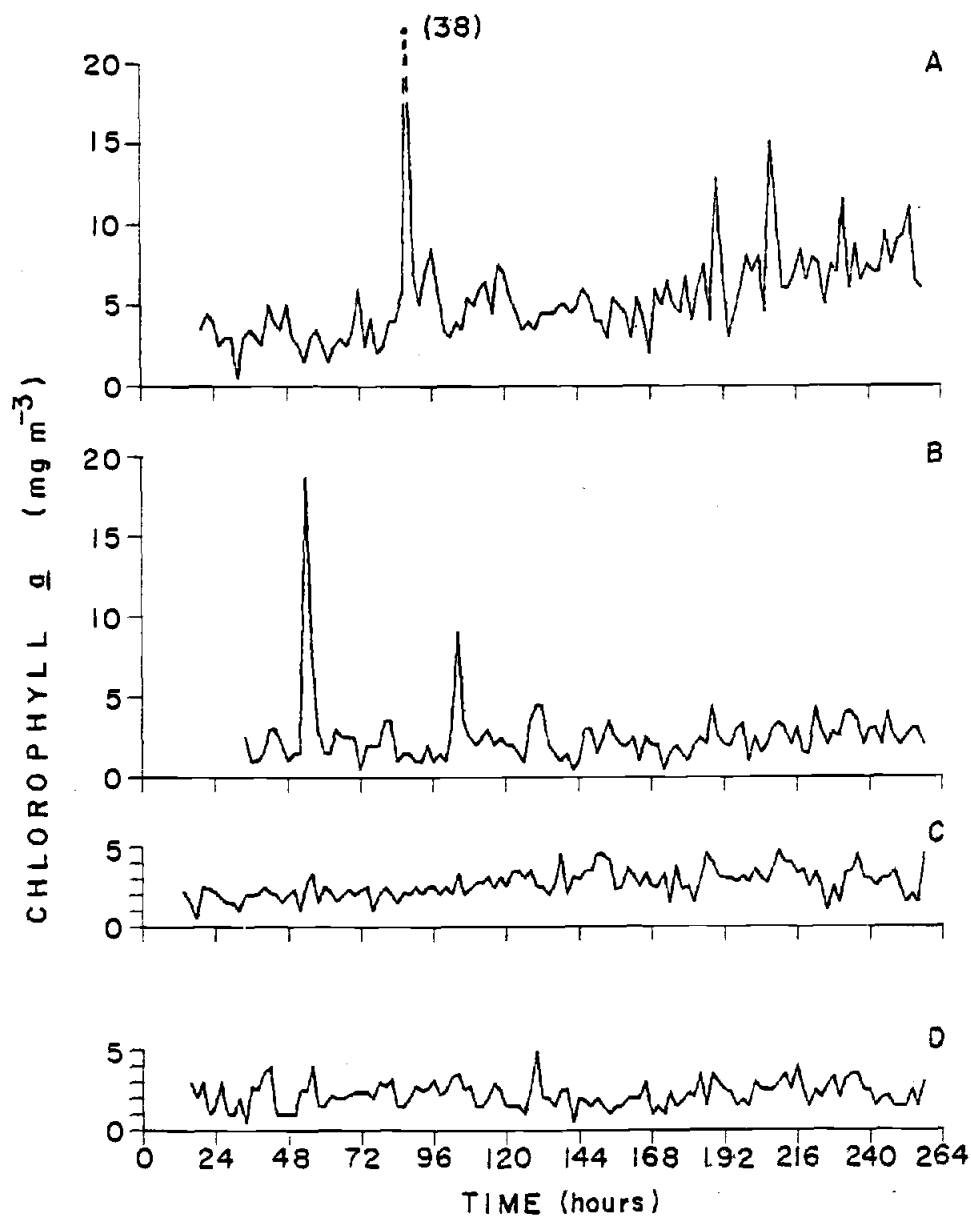
Figure 8. Chlorophyll a time series at the four sampling stations. Numbers mark midnight.
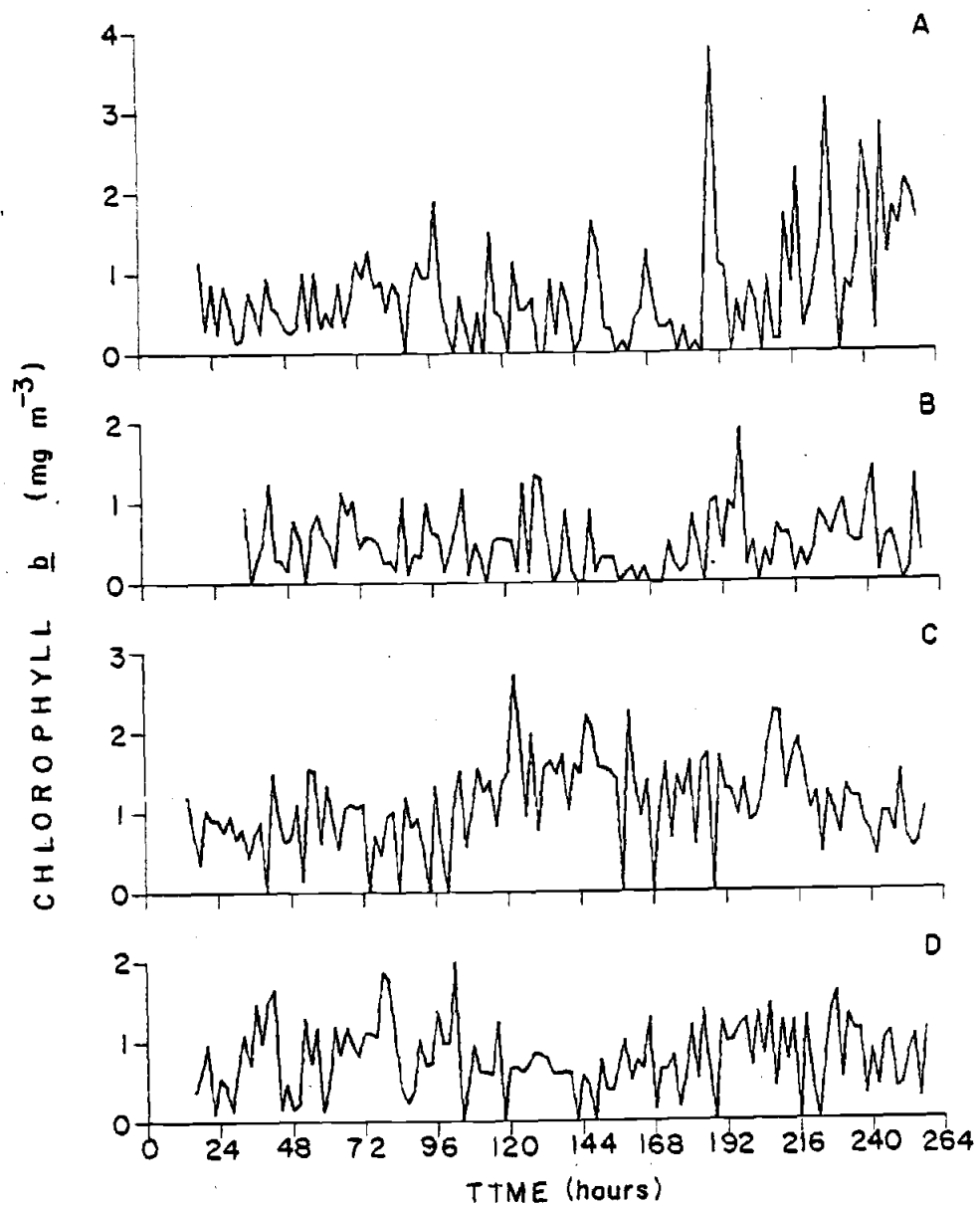
Figure 9. Chlorophyll b time series at the four sampling stations. Numbers mark midnight.
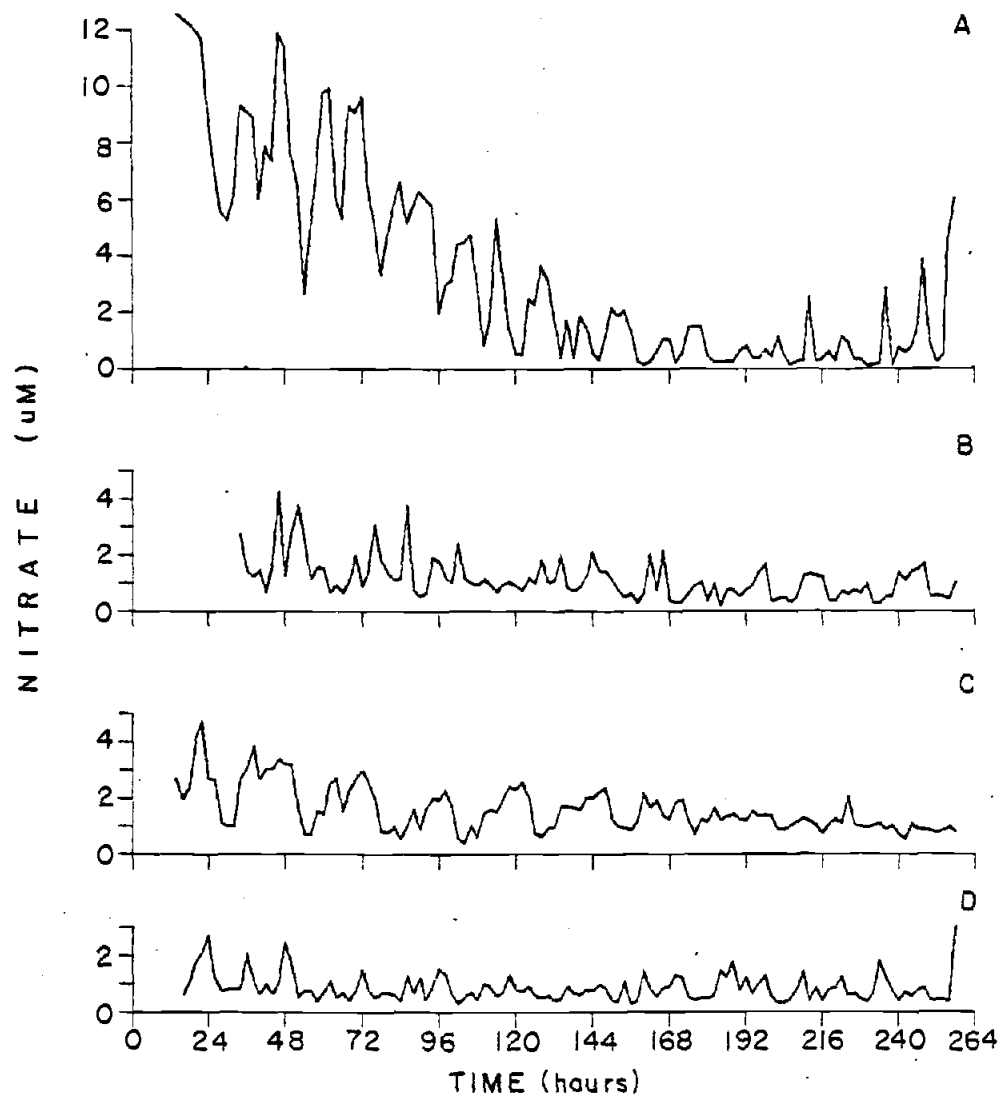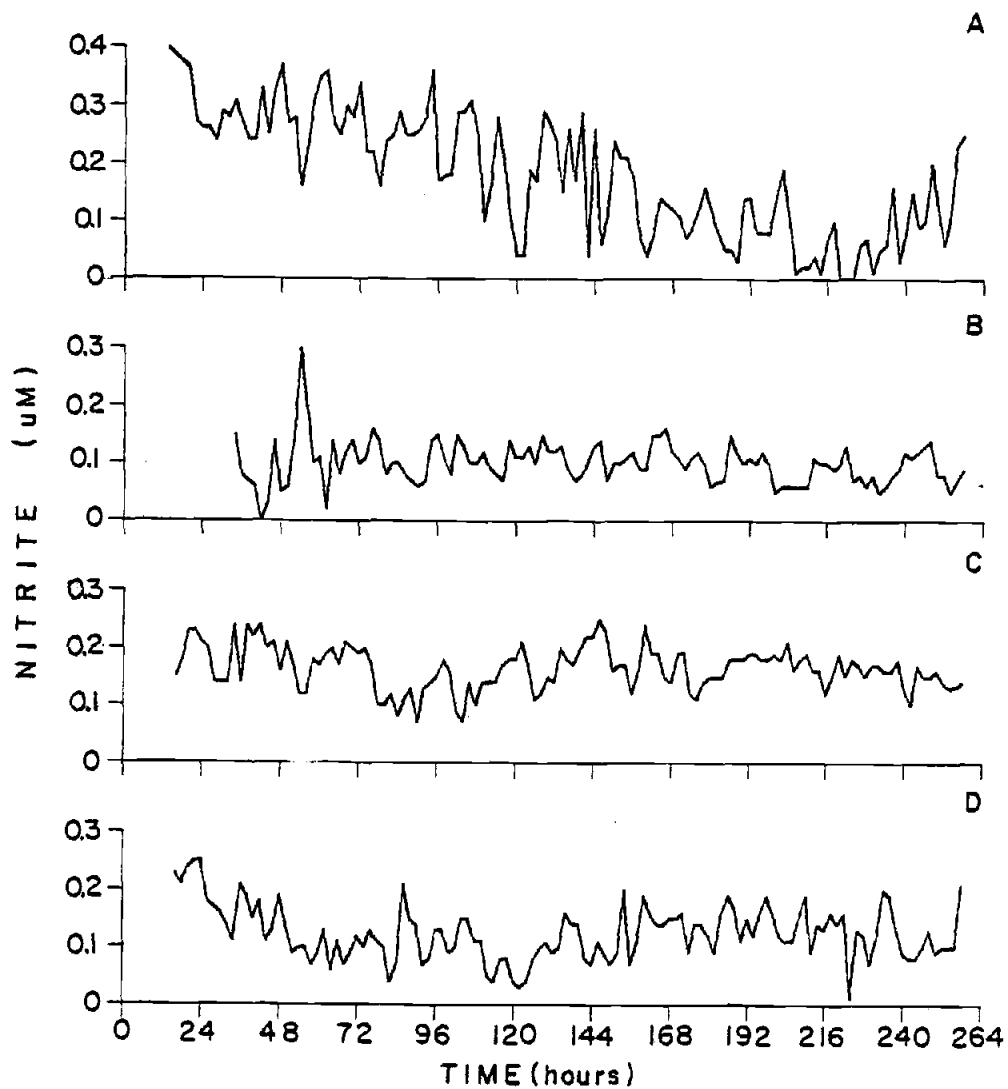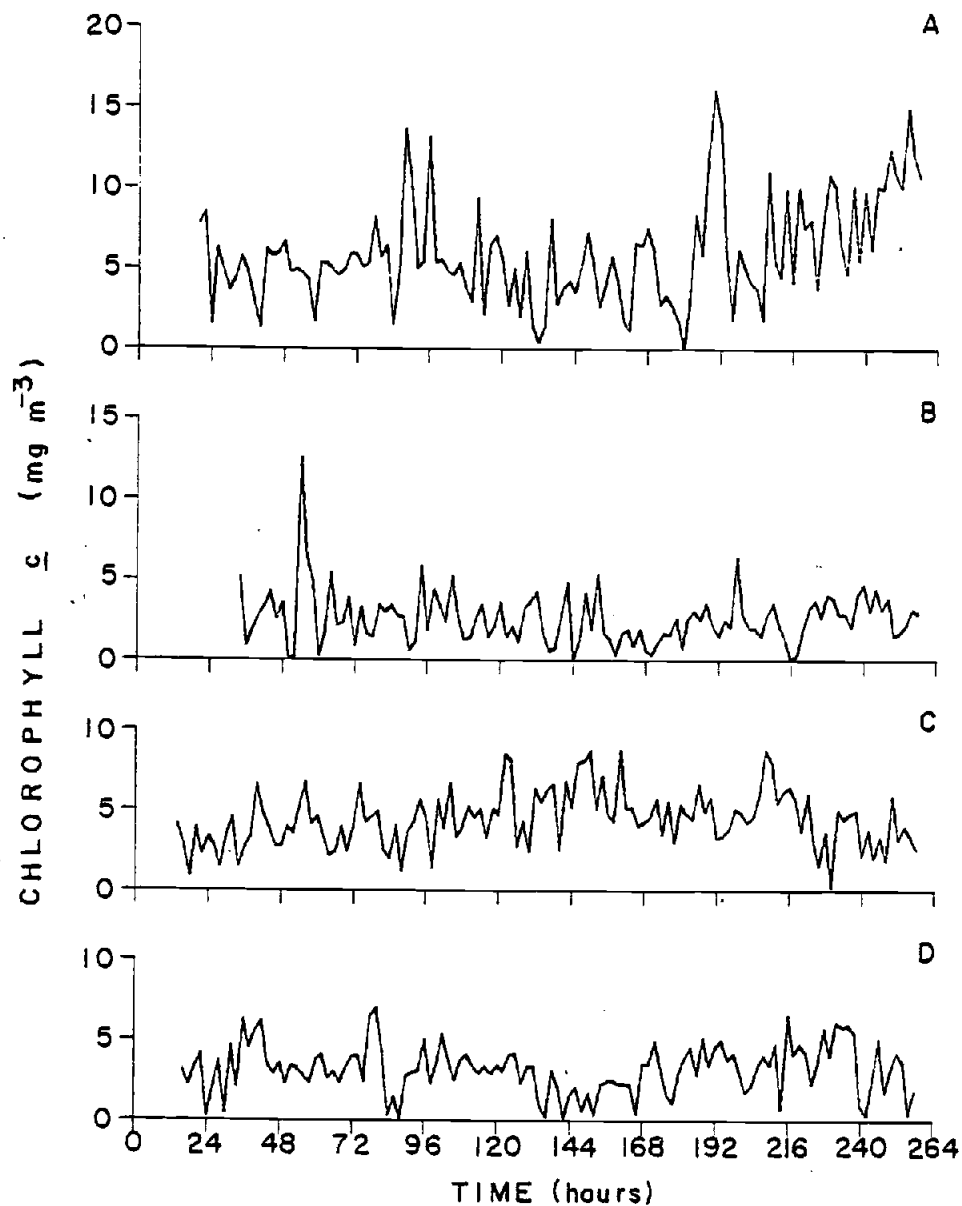
Figure 10.   Chlorophyll c time series at the four sampling stations.
Numbers mark midnight.
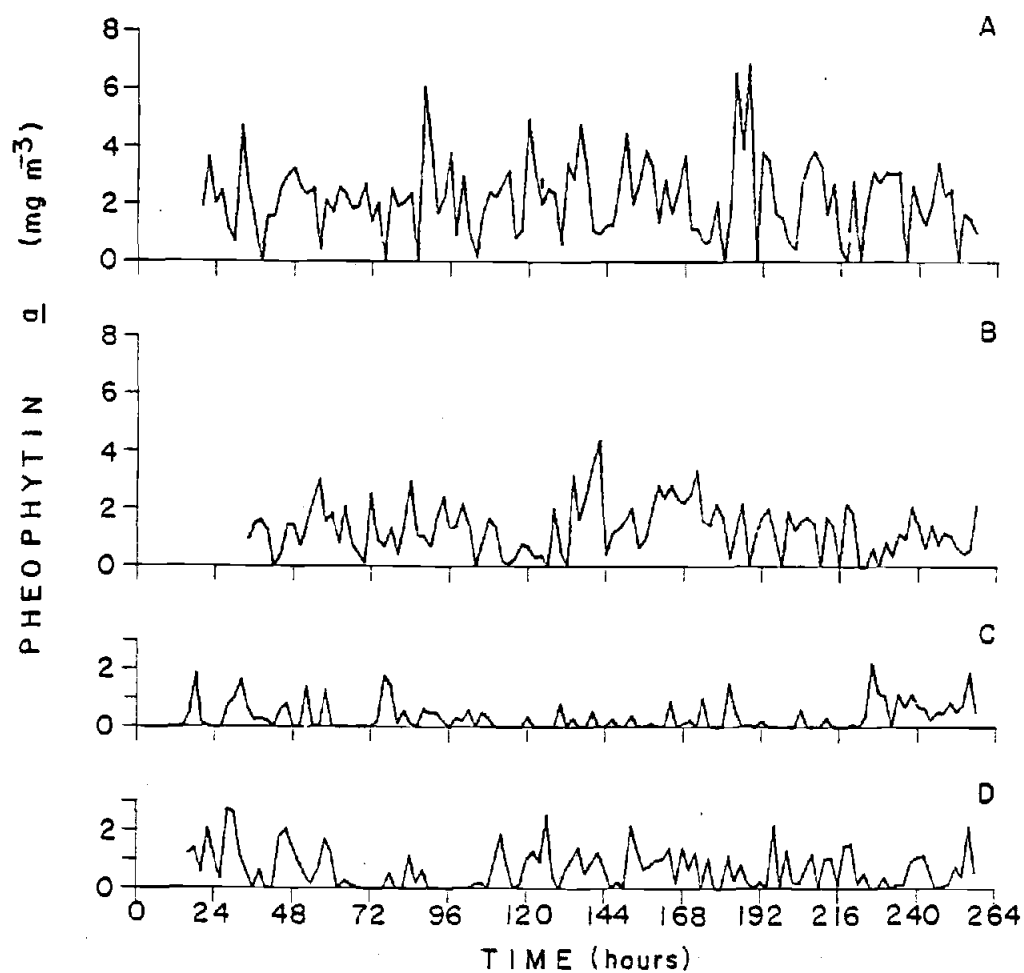
Figure 11. Pheophytin a time series at the four sampling stations.
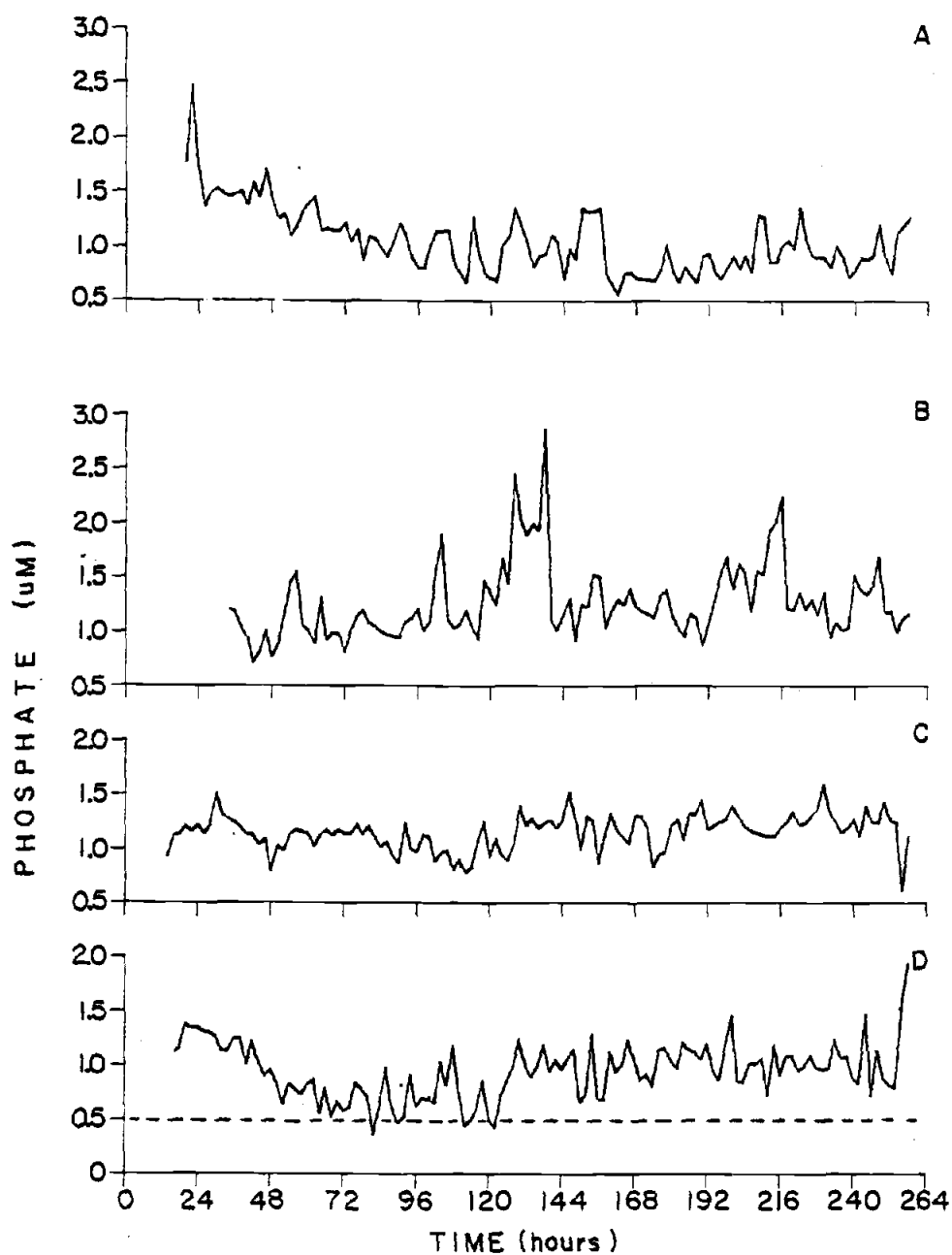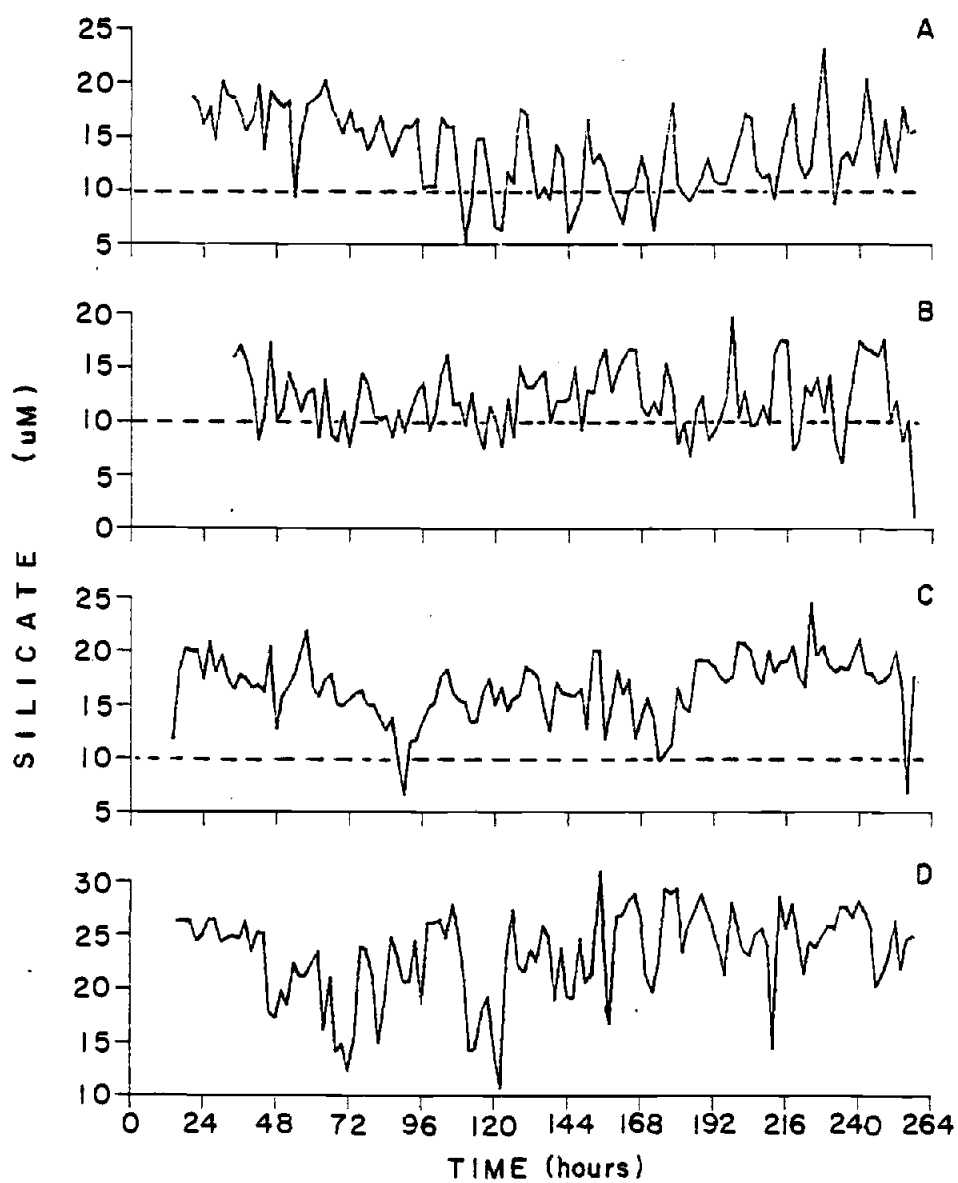Numbers mark midnight.
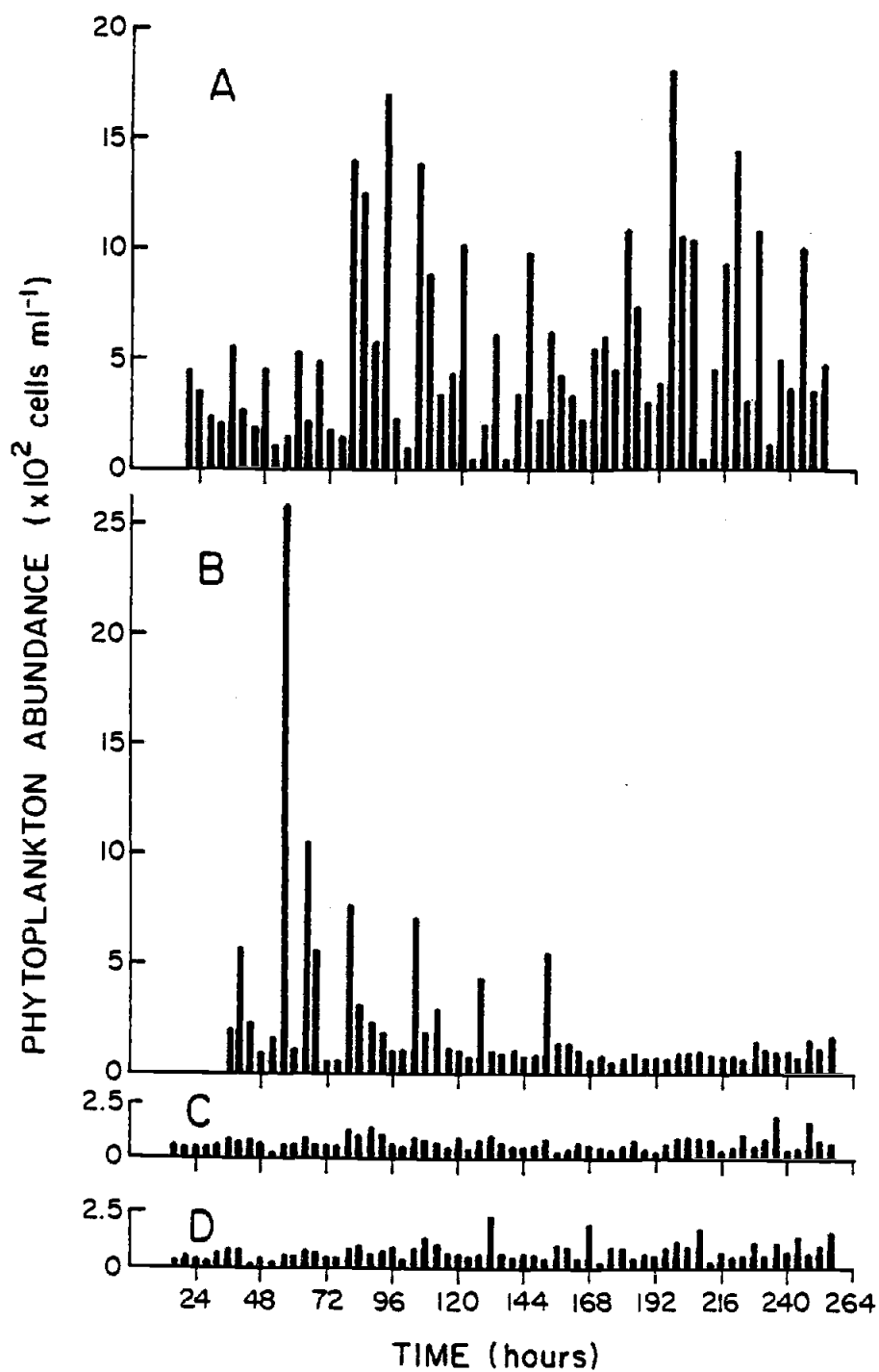
Figure 12. Phytoplankton abundance time series at the four sampling stations. Numbers mark midnight.
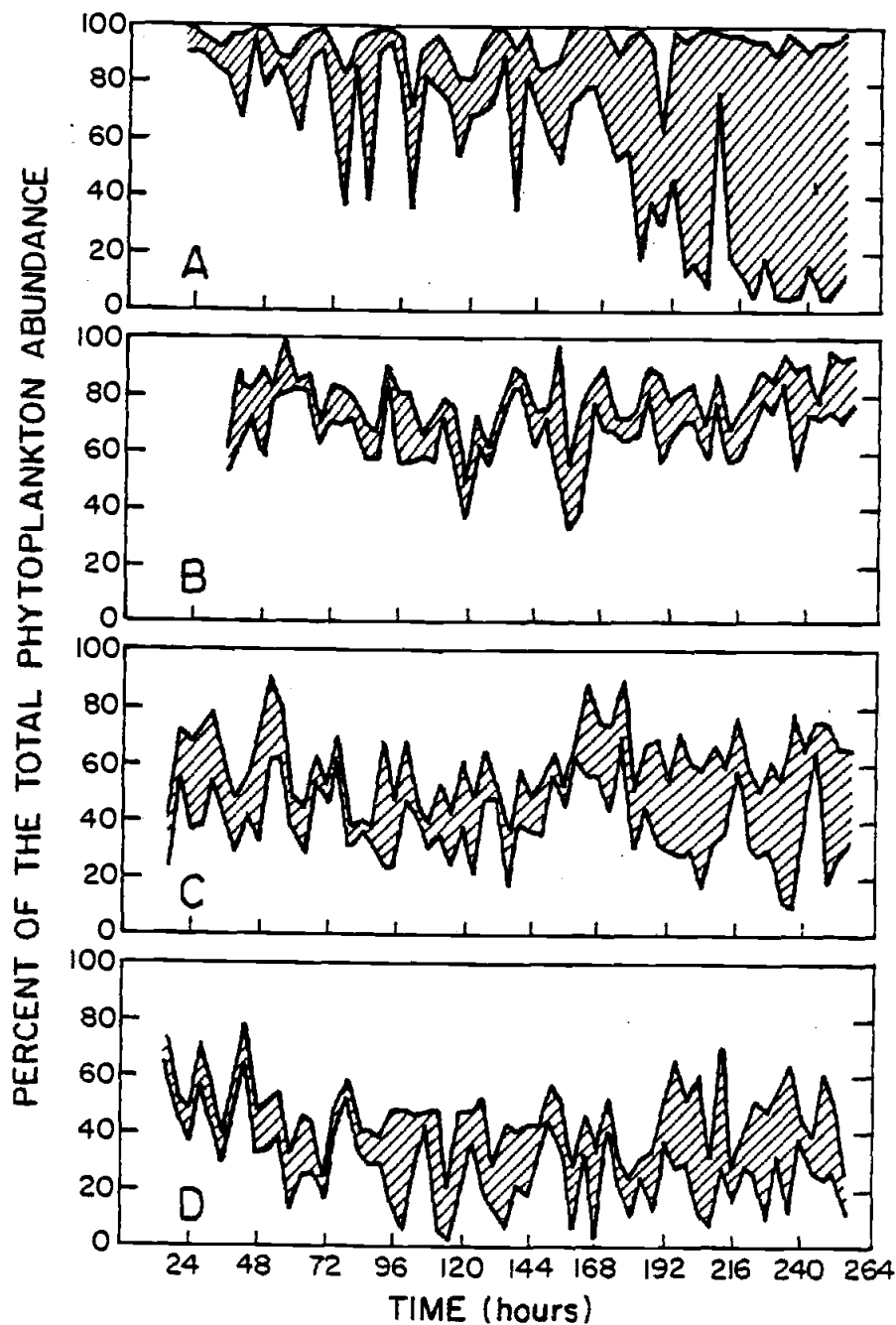
Figure 13. Percent of the total phytoplankton abundance. The dashed area corresponds to the fraction of dinoflagellates, below it the fraction of diatoms and above the fraction of microflagellates. Numbers mark midnight.
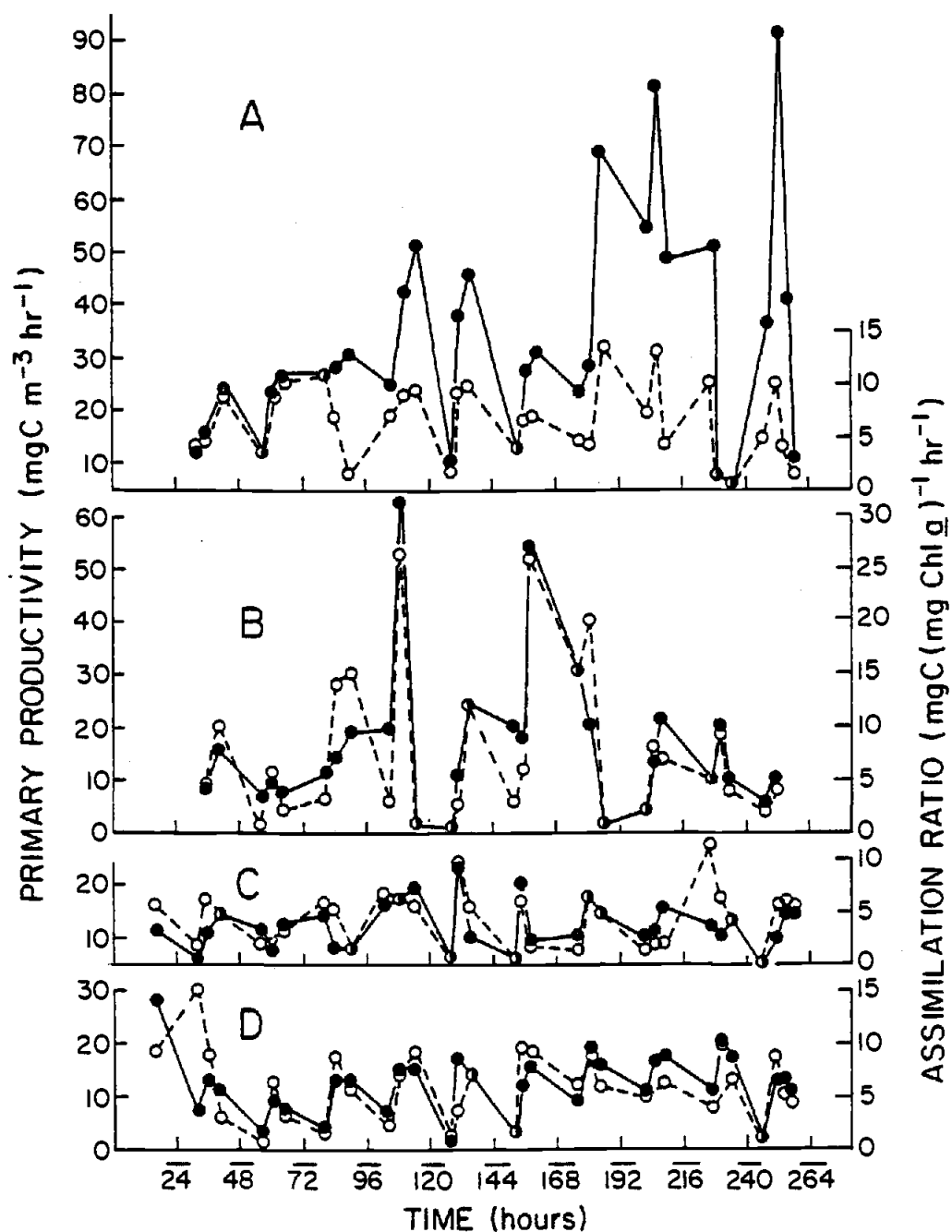
Figure 14. Phytoplankton productivity ($mgCm^{-3} hr^{-1}$) (filled circle) and assimilation ratio ($mgC(mgChl\underline{a})^{-1}hr^{-1}$) (open circle). Numbers mark midnight, the line above the numbers mark the dark period.

Spectral analysis of time series

The tide variance spectrum showed most of the variance at the diurnal (freq. ∿0.041 cph) and semidiurnal (freq. ∿0.083 cph) periods (Fig. 15). The variance spectra of all other seawater properties tended to show high variance components at these two frequencies, although distinct peaks were not always obvious (Figs. 15, 16, 17, 18, 19, and 20). Salinity, temperature, nitrate, phosphate, silicate, and sometimes chlorophyll a, clearly showed a high variance component at the lowest frequency (∿0.0025 cph). These low frequency variance components might be associated with the alternation of upwelling events (Lara-Lara, Alvarez-Borrego and Small, 1980). They might also be associated with the alternation of the spring and neap tides. Variance components at high frequencies (>∿0.1 cph) are likely related to turbulence and irregular mixing conditions created by the lagoon bathymetry and the associated heating by solar radiation input.
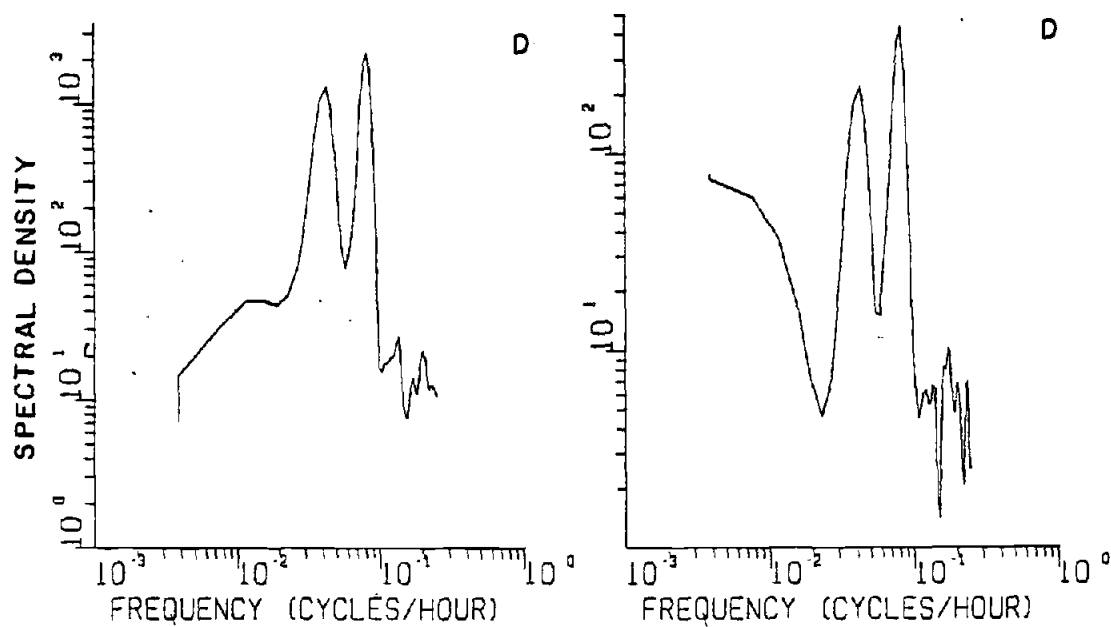
Figure 15. Spectral density of tide (left) and salinity (right) at
station D.
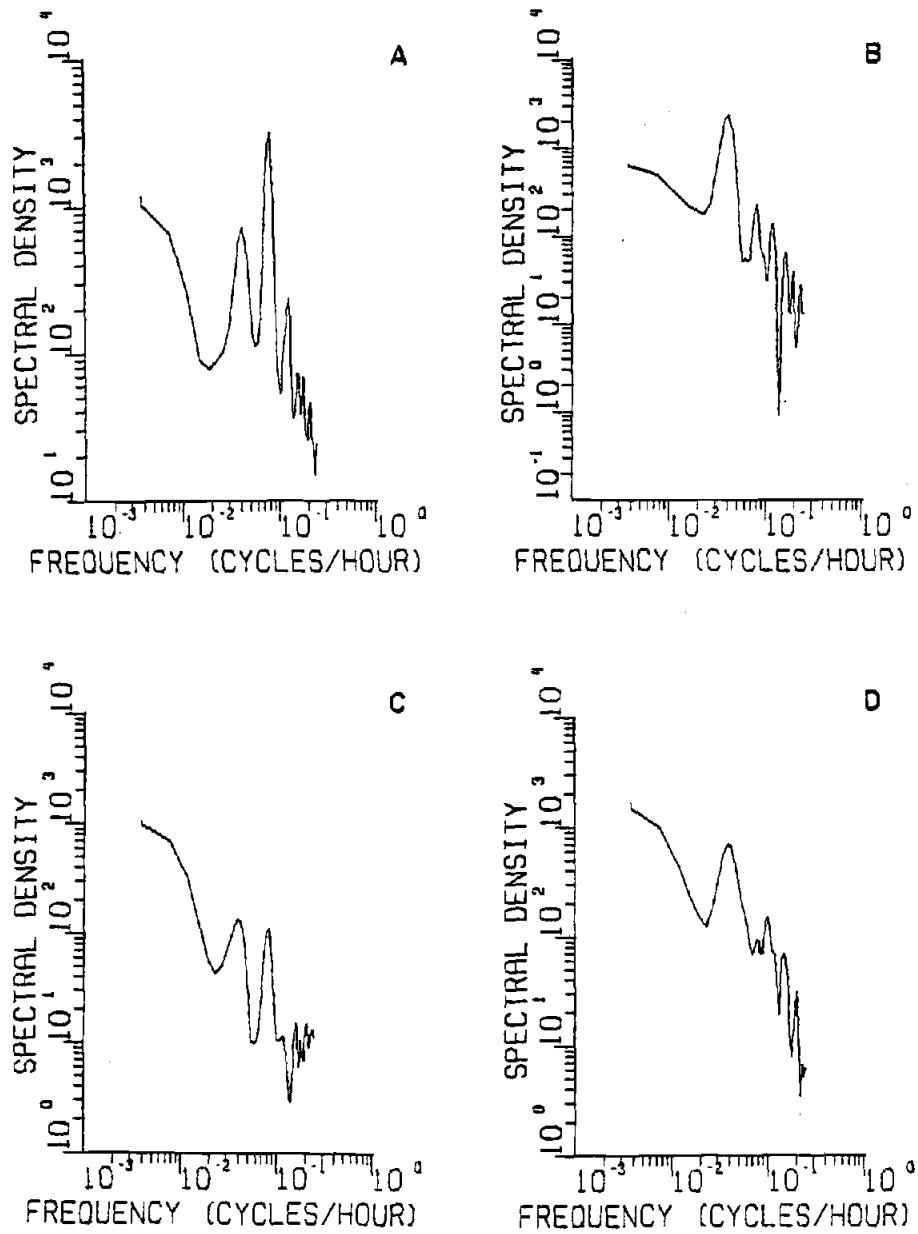
Figure 16. Spectral density of temperature at four sampling stations.
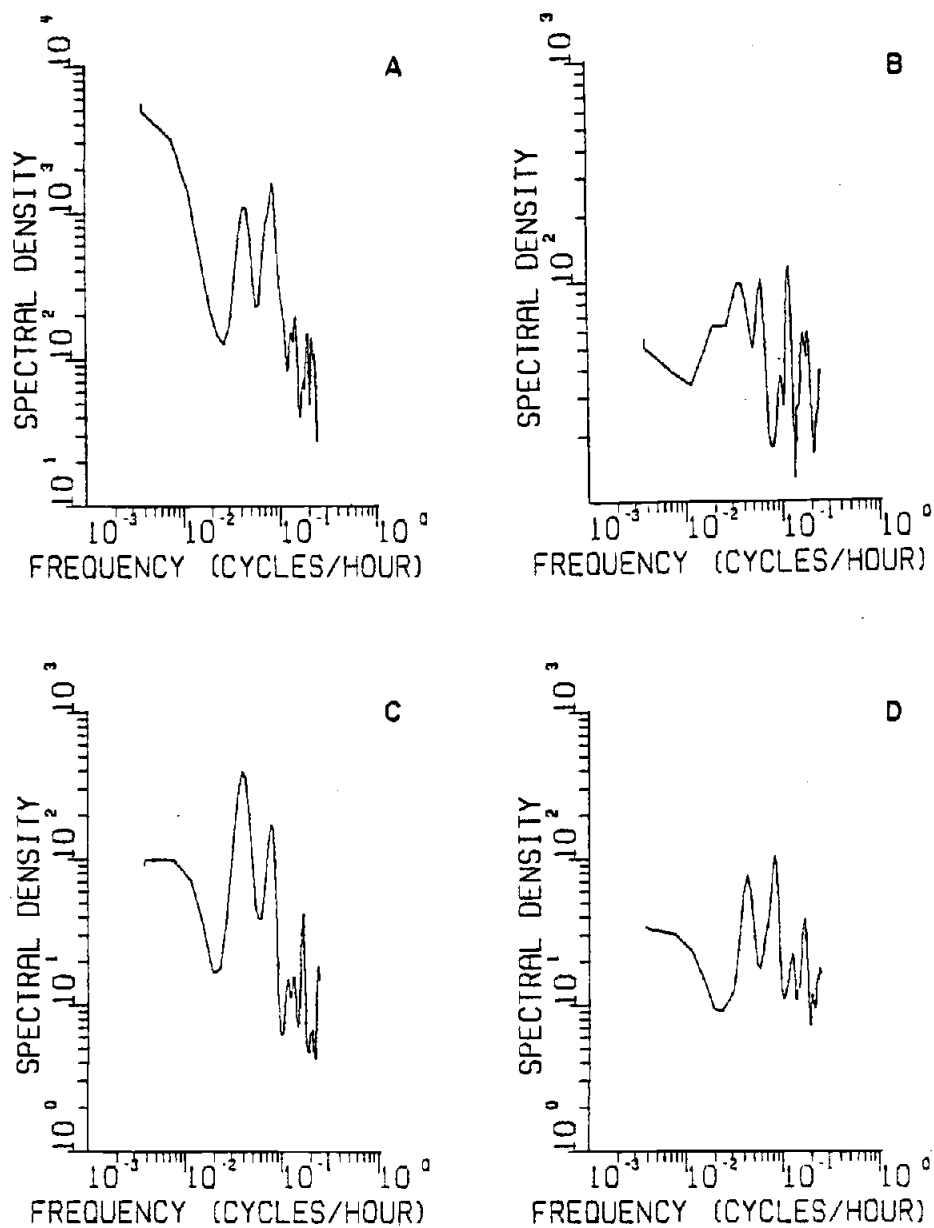
Figure 17.   Spectral density of nitrate at four sampling stations.
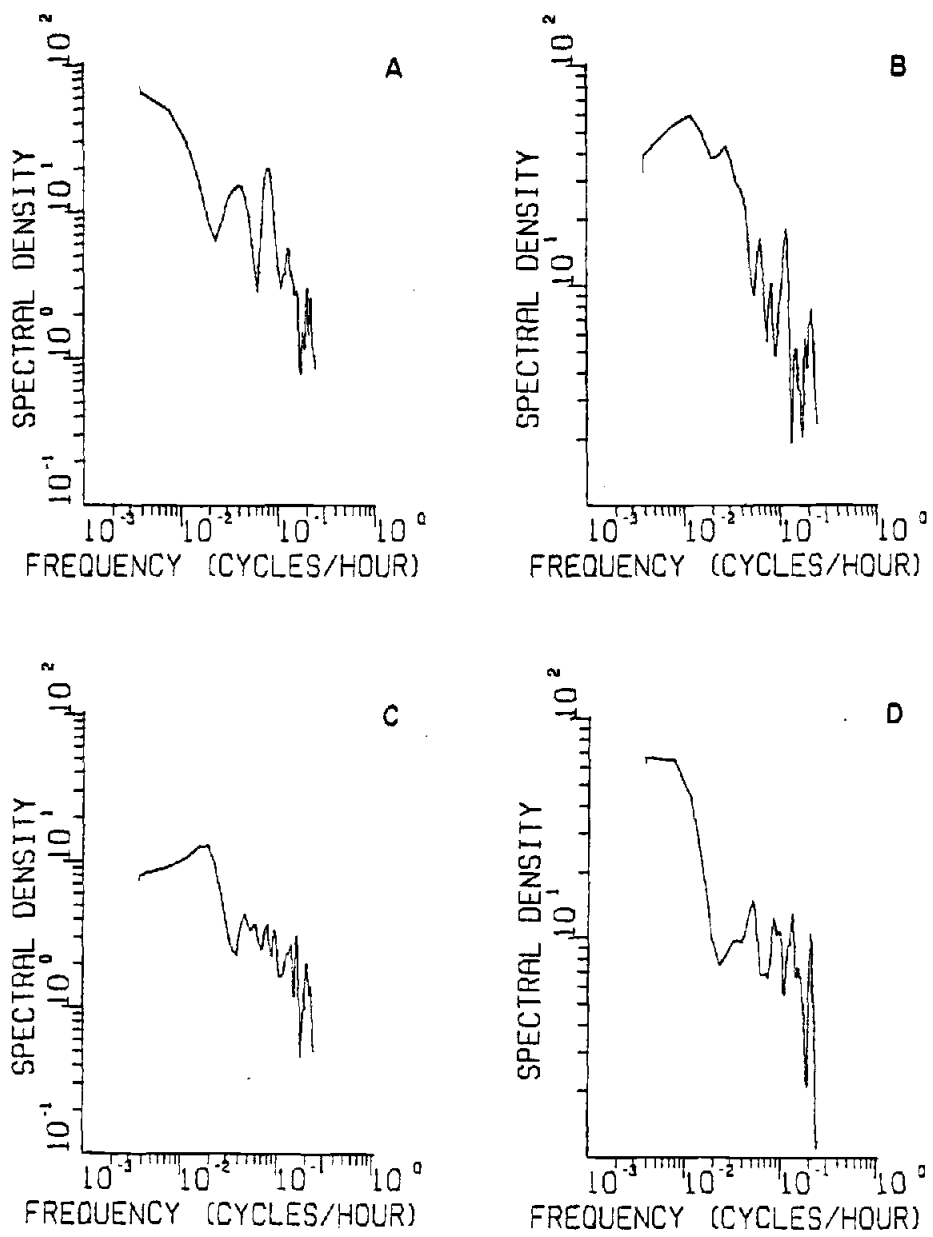
Figure 18. Spectral density of phosphate at four sampling stations.
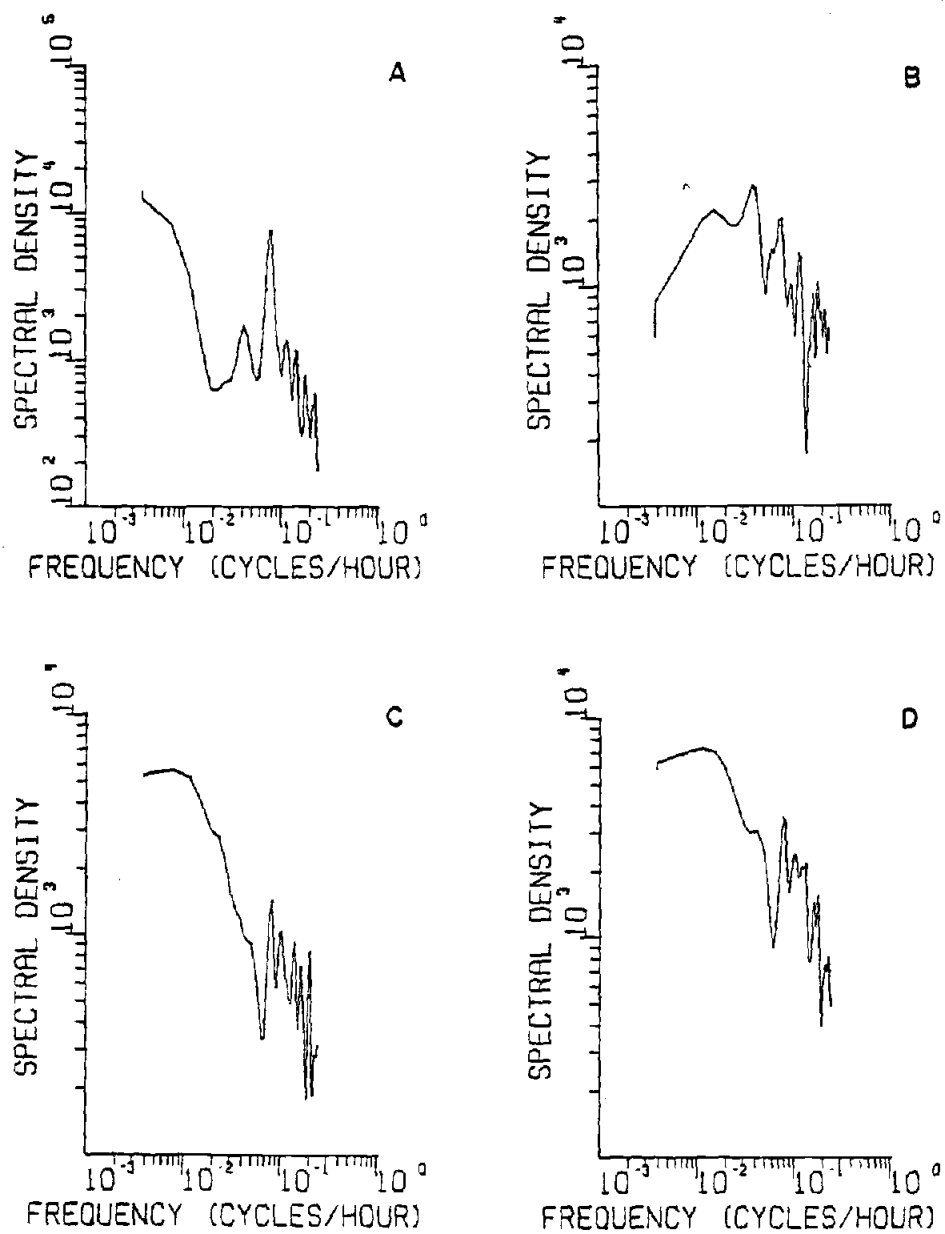
Figure 19.   Spectral density of silicate at four sampling stations.
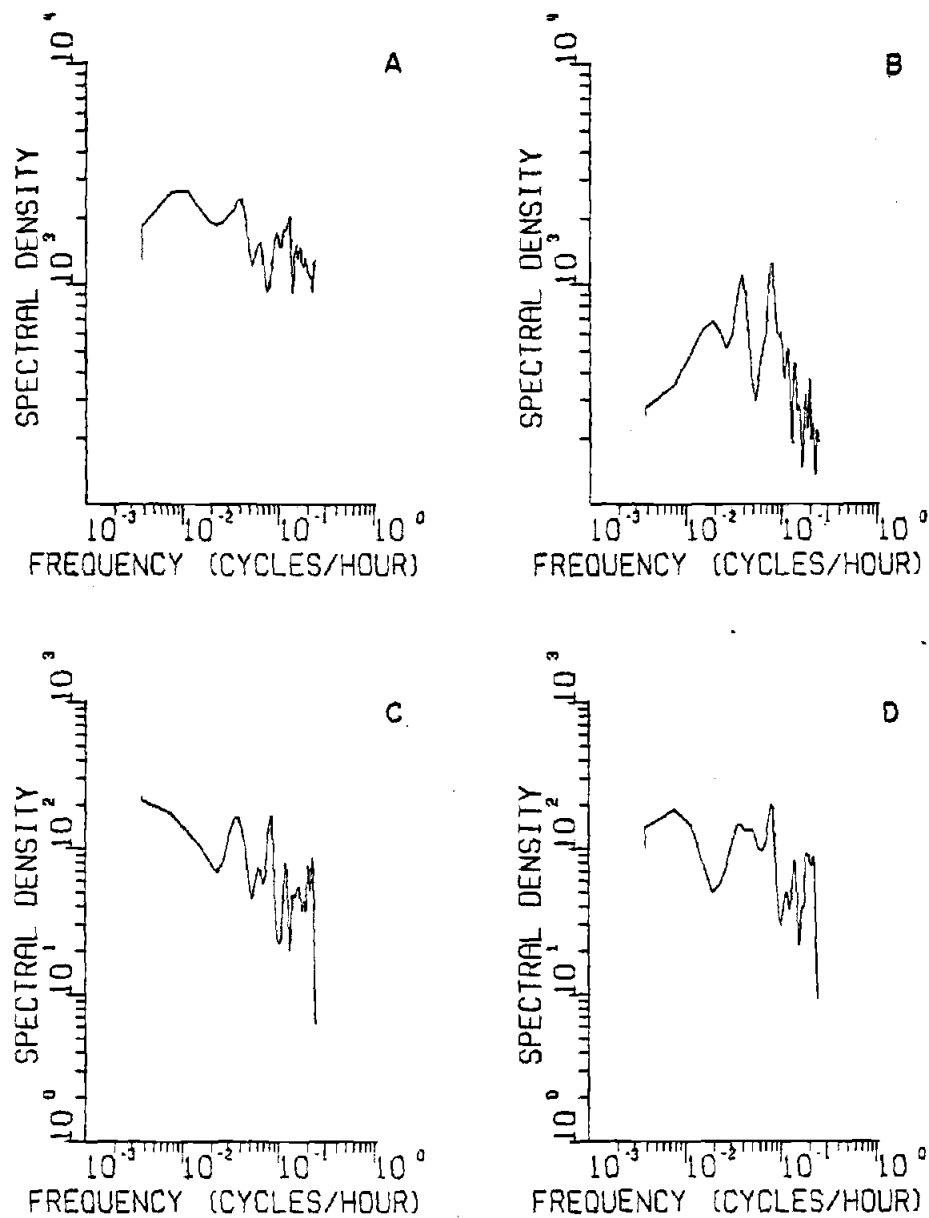
Figure 20. Spectral density of chlorophyll _a_ at four sampling
stations.
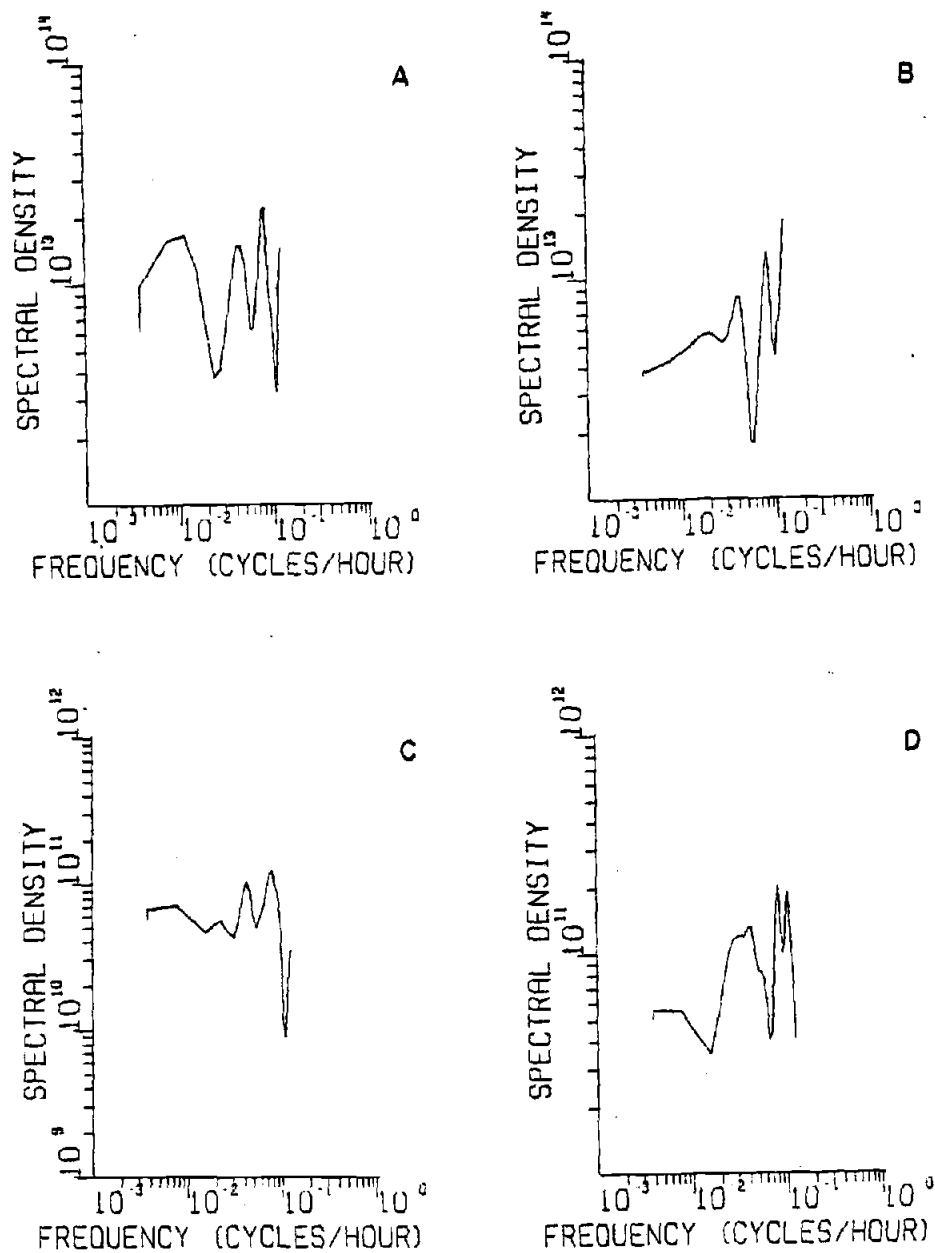
Figure 21.   Spectral density of total phytoplankton abundance at
             four sampling stations.

Cross correlation among variables at the same sampling point.

Table I shows the cross correlation coefficients and the number of lags needed to maximize the correlation coefficients (lag unit equal to two hours) between nitrate, nitrite, silicate, phosphate, chlorophyll a, chlorophyll b, chlorophyll c, pheophytin a, temperature and tidal heights, all at point A. The highest cross correlation coefficients were: NO_3-NO_2(0.78 with zero lags), NO_3-PO_4(0.76 with zero lags), $T^{\circ}C$-tide (-0.71 with zero lags).

Table II shows the cross correlation coefficients for point B. The highest cross correlation coefficients were: NO_3-$T^{\circ}C$(-0.41 with zero lags), NO_2-Chl$a$(0.51 with zero lags), Chl$a$-Chl$c$(0.68 with zero lags).

Table III shows the cross correlation coefficients for point C. The highest cross correlation coefficients were: NO_3-NO_2(0.66 with zero lags), NO_3-tide (0.53 with zero lags), SiO_2-PO_4(0.60 with zero lags), Chl$a$-Chl$c$ (0.61 with zero lags).

Table IV shows the cross correlation coefficients for point D. The highest cross correlation coefficients were: NO_2-PO_4(0.65 with zero lags), SiO_2-PO_4(0.73 with zero lags), and $S^{\circ}/_{\circ\circ}$ - tide(-0.80 with zero lags).

Cross correlation coefficients higher than 0.20 and 0.26 were statistically significant at the 95% and 99% confidence levels, respectively. However, such low coefficients indicated that only a small fraction of the variability of the dependent variable could be accounted for by linear relationship with the independent variable.

	NO_3	NO_2	SiO_2	PO_4	Chla	Chlb	Chlc	Pheoa	T°C	Tide
NO_3		0.78++ (0)	0.60++ (0)	0.76++ (0)	-0.31++ (5)	-0.16 (4)	-0.16 (2)	-0.137 (-4)	-0.63++ (0)	0.24+ (0)
NO_2			0.55++ (0)	0.58++ (0)	-0.30++ (1)	-0.30++ (3)	-0.25+ (3)	-0.10 (0)	-0.39++ (2)	0.13 (2)
SiO_2				0.66++ (0)	-0.12 (1)	0.25+ (0)	0.12 (0)	-0.13 (0)	-0.59++ (3)	-0.26++ (0)
PO_4					-0.32++ (5)	-0.13 (2)	-0.17 (1)	-0.16 (-5)	-0.41++ (1)	0.10 (-4)
Chla						0.33++ (5)	0.49++ (0)	0.17 (0)	0.27+ (-4)	-0.24+ (-4)
Chlb							0.59++ (0)	-0.11 (0)	0.22+ (0)	0.23+ (-3)
Chlc								0.21+ (0)	0.15 (-6)	-0.20+ (6)
Pheoa									0.19 (-3)	0.23+ (0)
T°C										-0.71++ (0)

Table I. Cross correlation coefficients and numbers of lags (in parentheses) needed to maximize the correlation coefficients at station A. The time series of the variables in the column at the left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to two hours. ++ = significance at 99% confidence level. + = significance at 95% confidence level.

	NO$_3$	NO$_2$	SiO$_2$	PO$_4$	Chl<u>a</u>	Chl<u>b</u>	Chl<u>c</u>	Pheo<u>a</u>	T°C	Tide
NO$_3$		0.41++ (0)	0.36++ (0)	-0.21+ (-1)	0.26++ (1)	0.13 (0)	0.27++ (4)	0.35++ (4)	-0.41++ (0)	-0.21+ (2)
NO$_2$			0.42++ (0)	0.29++ (0)	0.51++ (0)	-0.17 (-5)	0.34++ (0)	0.45++ (0)	-0.23+ (0)	0.37++ (-4)
SiO$_2$				0.44++ (0)	0.11 (0)	-0.27++ (4)	-0.18 (2)	0.19 (4)	-0.22+ (0)	-0.28++ (1)
PO$_4$					0.20+ (0)	0.17 (1)	-0.14 (2)	0.15 (2)	0.41++ (5)	-0.29++ (0)
Chl<u>a</u>						0.11 (0)	0.68++ (0)	0.31++ (0)	-0.23++ (-2)	-0.37++ (-1)
Chl<u>b</u>							0.27++ (0)	-0.38++ (0)	-0.13 (0)	-0.08 (-1)
Chl<u>c</u>								0.29++ (0)	-0.24+ (1)	-0.22+ (-1)
Pheo<u>a</u>									-0.09 (3)	-0.10 (1)
T°C										0.35++ (0)

Table II. Cross correlation coefficients and numbers of lags (in parentheses) needed to maximize the correlation coefficients at station B. The time series of the variables in the column at the left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to two hours. ++ = significance at 99% confidence level. + = significance at 95% confidence level.

	NO$_3$	NO$_2$	SiO$_2$	PO$_4$	Chl$\underline{a}$	Chl$\underline{b}$	Chl$\underline{c}$	Pheo$\underline{a}$	T°C	Tide
NO$_3$		0.66++ (0)	0.09 (3)	-0.15 (1)	-0.38++ (-2)	-0.17 (-2)	-0.24+ (-2)	-0.18 (0)	-0.50++ (0)	0.53++ (0)
NO$_2$			0.30++ (0)	0.36++ (0)	0.11 (2)	0.16 (2)	0.16 (1)	-0.21+ (-1)	-0.35++ (5)	0.29++ (1)
SiO$_2$				0.60++ (0)	0.18 (-1)	0.23+ (-4)	-0.12 (3)	0.17 (1)	-0.27++ (-2)	-0.14 (0)
PO$_4$					0.18 (2)	0.22+ (-4)	0.09 (1)	0.16 (1)	-0.08 (-3)	-0.17 (-1)
Chl$\underline{a}$						0.56++ (0)	0.61++ (0)	-0.52++ (0)	0.46++ (-2)	-0.21 (2)
Chl$\underline{b}$							0.60++ (0)	-0.38++ (0)	0.29++ (-1)	0.08 (0)
Chl$\underline{c}$								-0.37++ (0)	0.29++ (-2)	0.20+ (2)
Pheo$\underline{a}$									-0.21+ (-2)	0.33++ (3)
T°C										0.33++ (3)

Table III. Cross correlation coefficients and numbers of lags (in parentheses) needed to maximize the correlation coefficients at station C. The time series of the variables in the column at the left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to two hours. ++ = significance at 99% confidence level. + = significance at 95% confidence level.

	NO_3	NO_2	SiO_2	PO_4	Chl<u>a</u>	Chl<u>b</u>	Chl<u>c</u>	Pheo<u>a</u>	T°C	S‰	Tide
NO_3		0.39++ (0)	-0.16 (-1)	0.22+ (0)	-0.24+ (0)	0.13 (3)	0.12 (0)	0.28++ (-1)	-0.27++ (0)	-0.59++ (0)	0.60++ (0)
NO_2			0.51++ (0)	0.65++ (0)	0.16 (0)	-0.20 (1)	0.09 (0)	0.31++ (-1)	-0.55++ (4)	0.34++ (-4)	-0.30++ (-4)
SiO_2				0.73++ (0)	0.20+ (1)	-0.13 (3)	0.15 (1)	0.14 (4)	-0.27++ (-3)	0.45++ (1)	-0.31++ (0)
PO_4					0.13 (4)	-0.13 (0)	0.07 (1)	0.31++ (2)	-0.25+ (0)	0.20+ (1)	-0.11 (-2)
Chl<u>a</u>						0.41++ (0)	0.43++ (0)	-0.59++ (0)	-0.25+ (-4)	0.27++ (1)	0.23+ (3)
Chl<u>b</u>							0.38++ (0).	-0.43++ (0)	-0.19 (-3)	0.11 (0)	-0.13 (0)
Chl<u>c</u>								-0.25+ (0)	-0.27++ (-4)	0.25+ (4)	-0.10 (4)
Pheo<u>a</u>									-0.21+ (1)	0.10 (-2)	-0.13 (3)
T°C										-0.25+ (3)	0.33++ (3)
S‰											-0.80++ (0)

Table IV. Cross correlation coefficients and numbers of lags (in parentheses) needed to maximize the correlation coefficients at station D. The time series of the variables in the column at the left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to two hours. ++ = significance at 99% confidence level. + = significance at 95% confidence level.

Three examples were chosen to show the variation of cross correlation coefficients with lagged units from -12 to +12 units: first, strong variation from positive to negative cross correlation coefficients (Fig. 22a), second, high positive cross correlation coefficients at all lagged periods (Fig. 22b) and third, low cross correlation coefficients at all lagged periods (Fig. 22c).

Temperature vs tide cross correlation coefficient variation (Fig. 22a) is obviously due to the typical inverse relation between the two variables. We can see the high negative cross correlation coefficient every six and twelve lags [corresponding to 12 hours (semidiurnal) and 24 hours (diurnal) component of tidal cycles]. High positive cross correlation coefficients lagged every three and nine lags (corresponding to 6 and 18 hours, respectively).

Figure 22b shows the cross correlation coefficient between nitrate and phosphate. The cross correlation coefficient is always positive, regardless of the lag period, and also shows the periodicities every six lags (12 hours).

Figure 22c shows the variation in cross correlation coefficients between silicate and chlorophyll a. It describes the independence of these two variables, with low cross correlation coefficients at all lag periods.
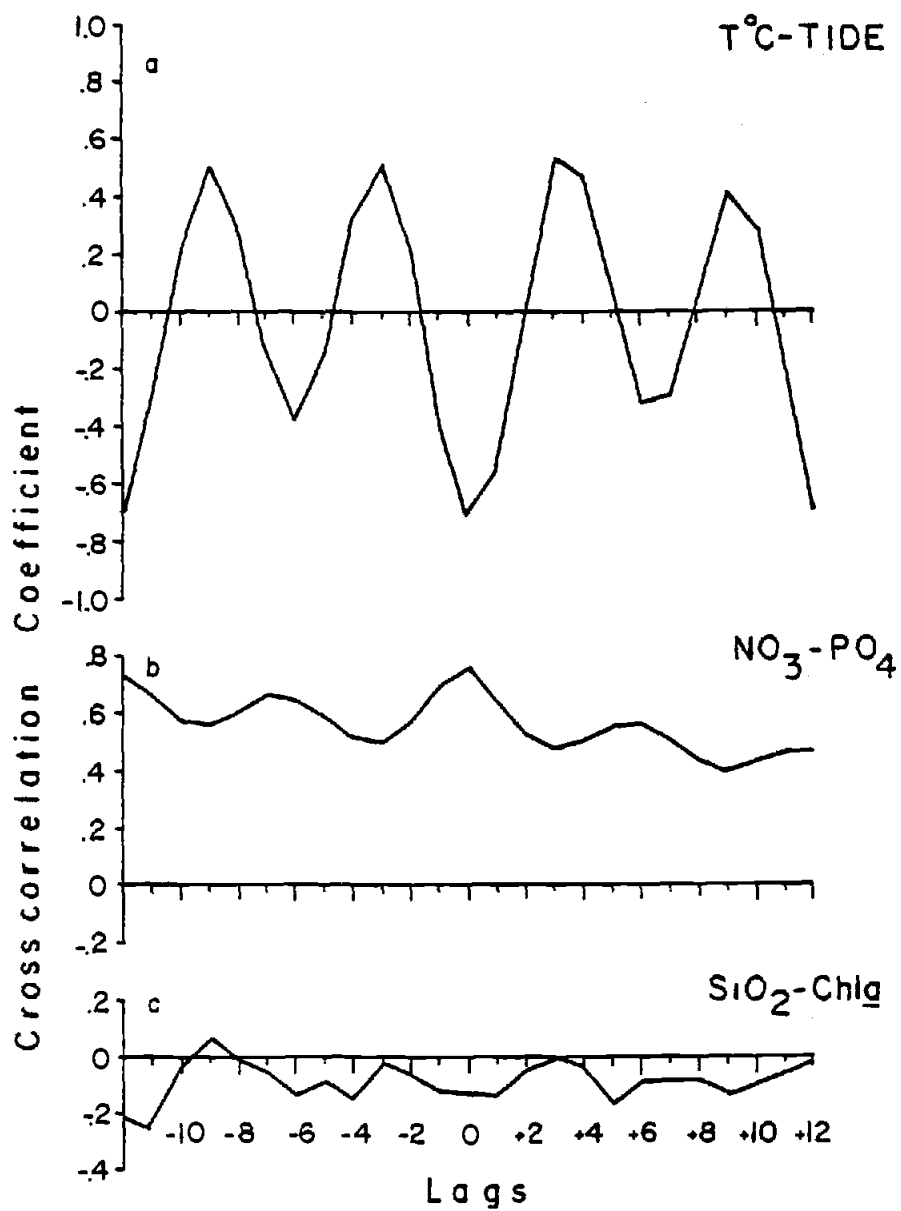
Figure 22. Variation of cross correlation coefficients with lagged units.

DISCUSSION

The generation of time series to study the variability of
seawater properties is a relatively old technique. Legendre
(1908) explained the oxygen, temperature, salinity and density
variations in the coastal zone of Concarneau, France in terms of
tidal and solar radiation cycles by generating time series as long
as 22 days. He concluded that photosynthesis was the most important
variation factor for the oxygen concentration, and aereation by
wind-induced turbulence was secondary.

Alvarez-Borrego and Alvarez-Borrego (in prep.) generated one
year hourly temperature time series for the same four locations as
this work, from May 1979 to May 1980. Their time series for the
Bahia San Quintin mouth shows the alternation of upwelling events
in the adjacent oceanic area, from May to September. Lara-Lara,
Alvarez-Borrego and Small (1980) clearly showed that summer seawater
temperatures near 12°C at the Bahia San Quintin mouth are the product
of upwelling, because dissolved oxygen percent saturation was found
to be as low as 60% and this is characteristic of the upwelling water.
Alvarez-Borrego and Alvarez-Borrego's temperature time series indicates
that sampling for the work reported here started at the beginning of
an upwelling relaxation period, and ended when the strongest upwelling
event of the year was about to begin. Also, sampling for my study
started at spring tides, continued through neap tides, and ended at
the beginning of the following spring tides (Fig. 2).

Minimum temperatures during the upwelling event previous to my sampling were about 12°C, while they were about 11°C for the one after my sampling (Alvarez-Borrego and Alvarez-Borrego, in prep.). Upwelling previous to my sampling was weaker than the first upwelling detected by Lara-Lara, Alvarez-Borrego and Small (1980). Their minimum temperatures were below 12°C, compared with a minimum temperature of 12.8°C in my sampling. They measured phosphate values up to 4.4 µM, compared with a maximum of 2.5 µM in my case. Within the lagoon, the effects of the alternation of upwelling events and those of spring and neap tides on the variation of seawater properties are not easy to separate, because their periods are similar.

Lara-Lara, Alvarez-Borrego and Small (1980) concluded that variability at the mouth of Bahia San Quintin was mainly caused by three factors during summer: upwelling events, the tidal cycles, and the solar radiation cycle. During winter, upwelling is two orders of magnitude weaker than during summer (Bakun, 1973); thus, tidal and solar radiation cycles should be the two most important variation factors in winter. Spectral analyses of salinity, temperature, nitrate, phosphate, silicate, chlorophyll a and total phytoplankton abundance time series (Figs. 15, 16, 17, 18, 19, 20 and 21), from points A, B, C and D, show that the same main factors that cause variability of seawater properties at the bay mouth do it also throughout the bay. However, in general semidiurnal tides have greater effect on the variability of properties at the bay mouth than at the other three sampling points.

The bay region between points A and B is very much affected by conditions in the oceanic region adjacent to the bay mouth. The greater residence times in the extremes cause different conditions to develop at points C and D. Salinity and temperature are higher at points C and D due to solar radiation input and evaporation. The temperature long wave feature of points C and D (Fig. 3) may be due to alternation of spring and neap tides, to the alternation of upwelling events that make their impact in the whole bay, or both. If this long wave feature were mainly due to the alternation of spring and neap tides, it would mean that spring tides were bringing colder water from the mouth region to points C and D while, during neap tides the water was moving in and out, near points C and D, without much exchange with the oceanic region, the net effect being to warm the water relative to the spring tides. The salinity time series at point D shows that this is not what happened (Fig. 2). If it were, salinity values at the spring tide would be lower than those for neap tides. But they are not lower, they are indeed higher. Thus, the temperature long wave feature for points C and D (Fig. 3) must be due mainly to the alternation of upwelling events. Upwelling is propagated throughout the bay. My time series are too short to estimate the lag of this propagation between the mouth and points C and D. Alvarez-Borrego and Alvarez-Borrego (in prep.) found that the upwelling lag, measured by temperature change, is practically that of the tide.

Lara-Lara, Alvarez-Borrego and Small (1980) calculated mean fluctuation fluxes of seawater properties between Bahia San Quintin and the adjacent oceanic area. A fluctuation flux is the flux that results from variability of a particular sea water property with time. If the water entering the bay on the incoming tide is higher in (for example) nitrate concentration than the water leaving the bay on the ebb tide, this phase relationship between nitrate concentration and tide will result in a net flux of nitrate into the bay. Their mean fluctuation fluxes were not significantly different from zero in most cases. From their results, they inferred that possibly much of the water that goes out from the lagoon during ebb flow comes back into the lagoon during flood flow. This phenomenon can happen if there are relatively weak net horizontal currents in the adjacent ocean. During spring tides, up to 80% of the bay water may go out. When an upwelling event occurs, water leaving the bay on ebb tide mixes to a certain extent with the newly upwelled water. Then, the flood flow brings water with changed properties into the bay. Ultimately a dynamic equilibrium is reached unless properties outside the bay change again before equilibrium is established. Upwelled water has lower temperature, chlorophyll concentration, oxygen, phytoplankton abundance, primary productivity and higher inorganic nutrient concentrations and salinity (Lara-Lara, Alvarez-Borrego and Small, 1980). During the relaxation of upwelling, greater water residence time in the bay allows for an increase in chlorophyll concentration and productivity, and increased consumption of inorganic nutrients.

Lara-Lara, Alvarez-Borrego and Small (1980) reported rates of phytoplankton primary productivity in Bahia San Quintin mouth about 2 to 3 times greater than average rates in the Gulf of California (Zeitzchel, 1969), in the upwelling areas off the west coast of Baja California (SIO, data report, 1969), and off Oregon (Curl and Small, 1965). Productivity in Bahia San Quintin mouth during summer is similar to the highest productivity found by Small and Menzies (in press) in narrow bands of the nearshore Oregon upwelling system. Productivity rates at Bahia San Quintin mouth, may be more comparable than rates averaged over broad upwelling zones. Similar high rates have been reported by Beers, Stevenson, Eppley and Brooks (1971), and Barber, Dugdale, MacIsaac, and Smith (1971) for the Peru upwelling zone and by Huntsman and Barber (1977) and Smith, Barber and Huntsman (1977) for the Northwest Africa upwelling zone. My results for phytoplankton primary productivity and assimilation ratio for the bay mouth are very similar to those found by Lara-Lara, Alvarez-Borrego and Small (1980). Surface primary productivity decreases from the bay mouth to the two extremes, along with chlorophyll concentration (Figs. 8 and 14). Mean assimilation ratios are not significantly different at the four sampling points. At the extremes, while both primary productivity and chlorophyll a are about one third of the values at the bay mouth, total phytoplankton cell abundance is only about one tenth (Figs. 8, 12, and 14).

This indicates that chlorophyll content per cell at the extremes is about three times that at the mouth. The higher chlorophyll per

cell may be due to turbidity being greater, and light penetration less at the extremes than at the bay mouth.

There is not much difference in cell size between phytoplankton at the bay mouth and those at the extremes of the bay for any given taxonomic group. Beardall and Morris (1976) did experiments with Phaeodactylum tricornutum in order to determine the rate of photosynthesis and adaptation at different light intensities. They concluded that phytoplankton can be adapted to low light intensity, and this adaptation consists of an increased chlorophyll content per cell, and decreased rate of light-saturated photosynthesis per unit chlorophyll.

It could be that the phytoplankton at the extremes of the bay are adapted to low light intensity. Water at the extremes is more turbid [secchi disk reading about a half (1.5 m) of that of the bay mouth], resulting in less light penetration, and causing the phytoplankton cells to increase their chlorophyll content. At the extremes we found ten times lower phytoplankton abundance, three times lower productivity, three times lower total chlorophyll, three times higher chlorophyll per cell, higher turbidity (shallower secchi disk depth), shallow bottom depth (2 m vs 9 m) than the bay mouth. Therefore, light limitation, probably resulting from absorption of light by resuspended bottom sediments, is probably the most important factor causing phytoplankton abundance and productivity to be much lower at the extremes than the bay mouth. Since, as it was described above, seawater for carbon-14 incubations and phytoplankton abundance analyses were not taken from the same sampling, results of these two

sets of measurements might not be directly comparable. At location B, phytoplankton abundance was low the last five days of the sampling period, while primary productivity was high the seventh and eighth sampling days (Figs. 12 and 14). A possible explanation for these latter higher values is that they corresponded to patches of high chlorophyll concentrations.

Comparison of measured nutrient concentrations (Figs. 4, 5, 6 and 7) with numerous reported studies of the kinetics of nutrients limited growth of planktonic algae (Paasche, 1975; Conway, 1977; fineko, 1974; Eppley et al., 1969) indicates that nutrient concentrations were almost never low enough to limit phytoplankton growth during the sampling period, at any of the four locations of the bay. At the mouth, during the relaxation of upwelling (Figs. 4, 5, 6 and 7), the effect of nutrient uptake by the phytoplankton is clear. All inorganic nutrients were in high concentration at the beginning of the upwelling relaxation period and decreased until the eighth or ninth sampling day. At the end of the sampling period all nutrient concentrations were starting to increase again, as a result of the following upwelling event. Inside the bay mixing by tidal currents and winds, stirring up the sediments, may be of great importance for nutrient concentrations and distributions. Uptake of phosphate and nitrogen compounds by seagrasses may also be of importance in the spatial distribution of nutrients, but its effects cannot be estimated with the present data. Horizontal gradients of nutrients within the bay are highly variable. Sometimes nutrient concentrations are higher at the mouth than at the extremes. Such is the case

for nitrate, nitrite and phosphate during an upwelling event
(Figs. 4, 5 and 6). And sometimes the situation reverses, such as
during the relaxation period. In general, the spatial distribution
of nutrients is very patchy, as is the case for chlorophylls and
phytoplankton abundance. In general, silicate concentration
increases from the mouth to the extremes even during an upwelling
event (Fig. 7). At the extremes, dissolution of exoskeletons,
mainly of diatoms, may be the main source of dissolved silicate.
The phosphate spike detected at point B the sixth sampling day, and
the more moderate spike detected the ninth sampling day, did not
have a clear correspondence with the other nutrient values in the
same point, or with similar phosphate spikes on the other three
sampling points (Figs. 4, 5, 6 and 7). At point A there are small
phosphate spikes lagging those at point B by about one day (Fig. 6).
Lara-Lara, Alvarez-Borrego and Small (1980) detected a phosphate
spike at the Bahia San Quintin mouth, which was correlated, to a
certain extent, with an inorganic seston spike. They explained
these spikes in terms of stirring of sediments by wind-induced
turbulence. Point B, being at the base of the "Y" may have greater
turbulence caused by tidal currents during ebb flow. If this is
coupled with relatively strong winds, it may cause a greater stirring
effect in the sediments. If wind-induced turbulence alone were the
cause of these spikes, they would have been detected at all four
sampling points, (or at least in a similar fashion at points B and
C). The fact that the other nutrients did not show similar spikes
indicates different remineralization processes for them. Nitrogen

from the sediments probably are mostly in reduced forms. It is not explainable why there are no silicate spikes in correspondence with phosphate spikes. Silicate has high values, but with no clear effect from turbulence.

Lara-Lara, Alvarez-Borrego and Small (1980) found that diatoms were the most abundant group at the bay mouth, followed by dino-flagellates and microflagellates. They also found dinoflagellates and microflagellates were in greater abundance than diatoms toward the bay extremes. My results show that diatoms were not always more abundant than dinoflagellates at the mouth (Fig. 13). Also, diatoms were often more abundant than dinoflagellates at points B, C and D. Thus, there is no clear, permanent pattern for these phytoplankton groups throughout Bahia San Quintin. More detailed studies are needed to explain the shifting of phytoplankton groups in the bay.

For time series generated at fixed points, if the number of lags is different from zero, cross correlation coefficients do not neces-sarily have a proper physical meaning. For example, if, in order to find the maximum cross correlation coefficient, the chlorophyll time series is lagged one time unit with respect to the temperature time series, a relationship is established between variables of possibly different water bodies. For the bay mouth, with maximum current speeds, the water body with the chlorophyll concentrarion may be more than a mile removed from the water body in which the temperature was measured. When using time series analysis to find cause-effect relationships for ecological variables under natural non-controlled

conditions, a more proper sampling design is needed. Ideally the sampling platform should move with the seawater. This is not easy in a coastal lagoon, with bathymetric limitations

CONCLUSIONS

1. In general the variability of seawater properties at the bay mouth was influenced more by semidiurnal processes than those at the extremes of the bay; these were in general dominated by diurnal variation.

2. At low frequencies the effect of upwelling events on the distribution of seawater properties was stronger than the effect of spring and neap tidal cycles throughout the bay.

3. Comparison of nutrient concentrations in the bay with the available information on the kinetics of nutrients limited growth of planktonic algae indicates that nutrient concentrations were almost never low enough to limit phytoplankton growth during the sampling period, at the four locations in the bay.

4. At the extremes of the bay, turbidity and light penetration appears to be the most important limiting factors for phytoplankton abundance, and phytoplankton productivity.

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