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Spatial and temporal variations of phytoplankton chlorophyll *a* and suspended particulate matter in Mayagüez Bay, Puerto Rico

Fernando Gilbes[1], José M.López and Paul M.Yoshioka
Department of Marine Science, University of Puerto Rico at Mayagüez, Mayagüez, Puerto Rico 00708

[1]Present address: Department of Marine Science, University of South Florida, 140 Seventh Avenue South, St Petersburg, FL 33701, USA

Abstract. Monthly measurements of chlorophyll *a* (Chl-a), suspended particulate matter (SPM), light penetration and salinity were taken from March 1990 to February 1991. These parameters were sampled at three different transects with respect to the Añasco, Yagüez and Guanajibo river discharge in Mayagüez Bay, off the western coast of Puerto Rico. A reduction in salinities occurred at all stations from August to November, and corresponded with high precipitation and large river discharge. Maximum Chl-a values were registered at inshore stations during the rainy season. Maximum values of SPM were recorded in October and November; the minimum values were found from March to June. The spatial correlation between Chl-a and SPM was significantly positive for the entire study period, but the temporal relationship was not significant. The relationship between Chl-a and SPM may reflect the relationship between nutrients and SPM, and the physiological adaptations of phytoplankton to light intensity.

Introduction

A multitude of physical, chemical and biological processes affect marine organisms in coastal areas (Mann, 1982). These processes operate over a range of spatial and temporal scales (Lewis and Fish, 1969; Borstad, 1982; Yoshioka *et al.*, 1985; Taguchi and Laws, 1987; García and López, 1989) that must be considered in explaining variability in the structure, function and distribution of phytoplankton communities. In the tropics, this variability is highly affected by seasonal changes in rainfall (Sournia, 1969). Seasonal rainfall in tropical areas produces temporal and regional differences in river discharge, which induce fluctuations in salinity, nutrient concentrations, turbidity (i.e. penetration of light) and, therefore, biological productivity.

The heterogeneous landscape of Puerto Rican coastal waters may affect the plankton communities at different spatial and temporal scales (Margalef, 1957; Burkholder *et al.*, 1967; Cham and Seda Del Toro, 1974; García and López, 1989). Large variations in climatic (Giusti and López, 1967) and topographic (Lugo *et al.*, 1980) conditions, combined with human activities, produce changes in the amount and composition of river discharge. Intensive urban development, especially in coastal areas, accelerates soil erosion and increases the sediment load of rivers (Lugo *et al.*, 1980; Morelock *et al.*, 1983). The observed increase in fine-sediment load in rivers along the coast of Puerto Rico is probably the result of intensive cultivation of sugar cane during the past 100 years and modern urbanization. These sediments may be deposited within the coastal zone, or may remain suspended and be transported to ocean waters.

The west coast of Puerto Rico (Figure 1) represents an ideal site to study how river discharge affects the dynamics of phytoplankton communities in tropical areas. The Añasco, Yagüez and Guanajibo rivers supply terrigenous sediments derived from igneous rock environments onto the narrow insular shelf of Mayagüez and Añasco bays. The Añasco–Mayagüez basin has an average annual precipitation range of 200–250 cm (Morelock *et al.*, 1983). Seasonal fluctuations of rainfall result in maximum river discharge from September through November, and a minimum flow from February to April. Recorded values of discharge for the Añasco and Guanajibo rivers range from 0.88 to 3960 m^3 s^{-1} and 0.13 to 3620 m^3 s^{-1}, respectively (US Geological Survey, 1991). The Añasco River is the largest river on the west coast and its basin is mostly dedicated to agriculture, although it includes some virgin areas. The Yagüez basin is mainly urbanized, and highly affected by sewage discharge and other human activities. The Guanajibo basin is also dedicated to agriculture, but it is smaller than the Añasco basin and has less virgin areas. These differences in river basins along the west part of Puerto Rico could be responsible for spatial and seasonal variations in the phytoplankton dynamics of Mayagüez Bay.

In this study, we attempt to evaluate the influence of river discharge on the phytoplankton dynamics in coastal waters of western Puerto Rico. We characterize the spatial and temporal variations of phytoplankton chlorophyll *a* (Chl-a), suspended particulate matter (SPM) and light penetration in Mayagüez Bay.

Method

Field work

Monthly cruises were made between Añasco Bay and Punta Guanajibo (Figure 1) from March 1990 to February 1991. Nine stations were sampled at three inshore–offshore transects extending from the mouths of the Añasco, Yagüez and Guanajibo rivers to oceanic waters (Figure 1). At each station, samples were taken from three different depths that represented 100% (surface), 75% (0.5–5.5 m) and 50% (1.5–10.5 m) of incident light penetration, based on Secchi disk readings.

We used a peristaltic pump fitted with a plastic hose to collect duplicate 2 l samples of seawater at each depth for the analysis of SPM. For the Chl-a analysis, duplicate 1.5 ml samples were placed in test tubes and 8.5 ml 100% acetone were added. Chl-a samples were stored in the dark at 2–5°C for 24 h. Salinity was measured using a submersible multiprobe instrument (HydroLab/Model 4000). Light penetration was estimated with a Secchi disk.

Laboratory work

Water samples for Chl-a were analyzed using the fluorometric technique proposed by Phinney and Yentsch (1985) using a Turner Model 111 fluorometer. Measurements of fluorescence before and after acidification were recorded. The fluorescence measurements were corrected for pheophytin *a* and converted to mg m^{-3} of Chl-a using regression curves. The fluorometer was calibrated using Chl-a from the alga *Anacystis nidulans*. Total SPM (mg l^{-1}) was measured by filtration, using Millipore HA 0.45 μm cellulose acetate membranes. Samples were heated

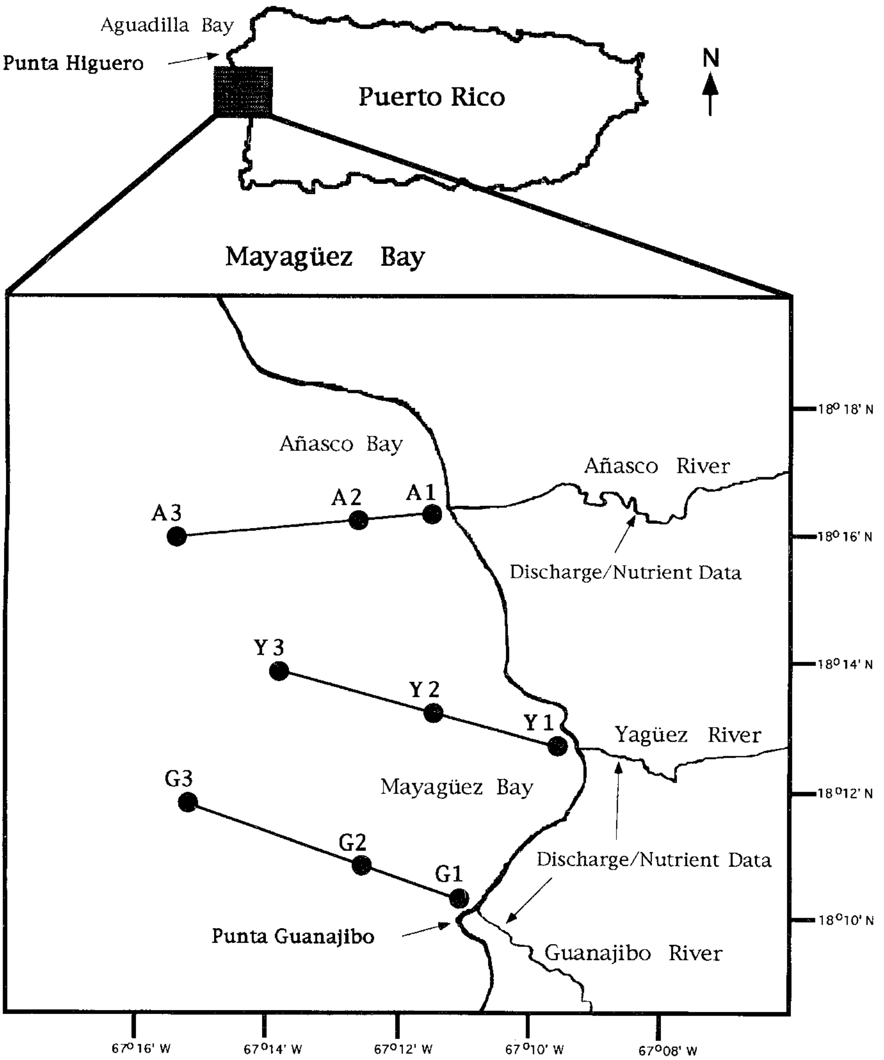

Fig. 1. Study area and sampling stations (A, Y, G = Añasco, Yagüez, Guanajibo; 1, 2, 3 = inshore, middle, offshore). The arrows indicate the location of the stations for discharge and nutrient data.

(70–80°C) for 6–8 h to reduce water content before weighing. Turbidity was obtained in relative nephelometric units using a DRT Model Turbidimeter.

Data analysis

We used a two-way analysis of variance (ANOVA) to detect monthly, station and interaction effects between phytoplankton Chl-a and SPM. The data showed low variability by depth; therefore, they were pooled for the ANOVA analyses. Temporal and spatial correlations of Chl-a and SPM were calculated following $\log_{10}$ transformation of the non-pooled data.

The spatial relationship between light penetration, turbidity and Chl-a was determined by non-parametric Kendall rank correlation coefficients (τ) because light and turbidity data were not normally distributed. We only considered surface values in this analysis to eliminate biased results due to selected depths based on light penetration.

Results

Chlorophyll a

The monthly changes in phytoplankton Chl-a concentration at the study stations are shown in Figure 2. A two-way ANOVA showed that temporal differences in Chl-a were highly significant ($P < 0.001$). Higher Chl-a concentrations were generally found in August, September and January; lower Chl-a concentrations were recorded in different months (Figure 2). Spatial differences (between stations) of Chl-a were also highly significant ($P < 0.001$). Comparisons of ANOVA results using the least significant difference (LSD) method (Sokal and Rohlf, 1981) showed that Chl-a concentrations at inshore stations are significantly higher than those at middle and offshore stations. Among the inshore stations, the Guanajibo site (G1) was characterized by less seasonal variability than the Añasco (A1) and Yagüez (Y1) sites. Regarding differences among transects, the Añasco and Yagüez sites had higher values of Chl-a than Guanajibo River (Figure 2).

The interaction effect (month × station) was also highly significant ($P < 0.001$). The inshore stations of Añasco and Yagüez rivers showed maximum values in August, whereas the inshore station of Guanajibo presented the maximum values in October and November (Figure 2). The values for all inshore stations increased in January, but not to the same extent. Middle and offshore stations showed maximum values in September.

Suspended particulate matter

The monthly fluctuations of SPM concentration are shown in Figure 3. A two-way ANOVA showed that temporal differences in SPM concentration were highly significant ($P < 0.001$). The maximum values of SPM were recorded in October and November; the minimum values were found from March to June (Figure 3). Differences in SPM concentration were also highly significant ($P < 0.001$) among the nine stations. Comparisons of ANOVA results (LSD method) showed that SPM concentrations at inshore stations were significantly higher than those at the middle and offshore stations (Figure 3).

The interaction effect (month × station) was also highly significant ($P < 0.001$). The largest difference between stations occurred from March to July. In April, the inshore stations of Añasco and Guanajibo showed high values, but the inshore station of Yagüez showed a low value (Figure 3). From May to September, the inshore station of Yagüez showed higher values than the inshore station of Guanajibo; this latter station showed higher values from October to December. The highest values of SPM at the middle and offshore stations occurred in October, whereas

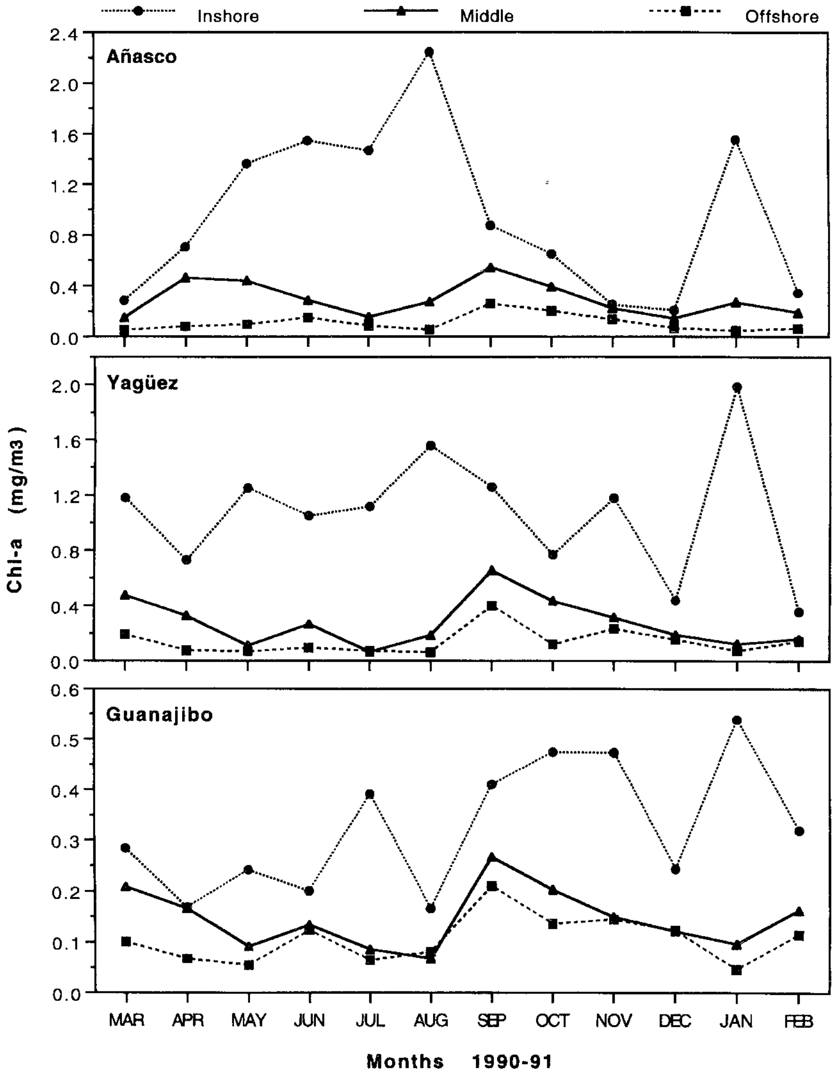

Fig. 2. Monthly variations of chlorophyll *a* in Añasco, Yagüez and Guanajibo transects from inshore to offshore stations. Note the different scales on the ordinates.

the highest values at the inshore stations occurred in different months for the different transects.

Light penetration

Secchi depths increased from inshore to offshore stations (Figure 4). This spatial pattern was opposite to the Chl-a and SPM patterns. Light penetration at offshore stations showed more variability than at inshore stations. High Secchi depths were measured in May, August and January at the offshore stations (Figure 4). Middle and inshore stations showed high Secchi depths during different months.

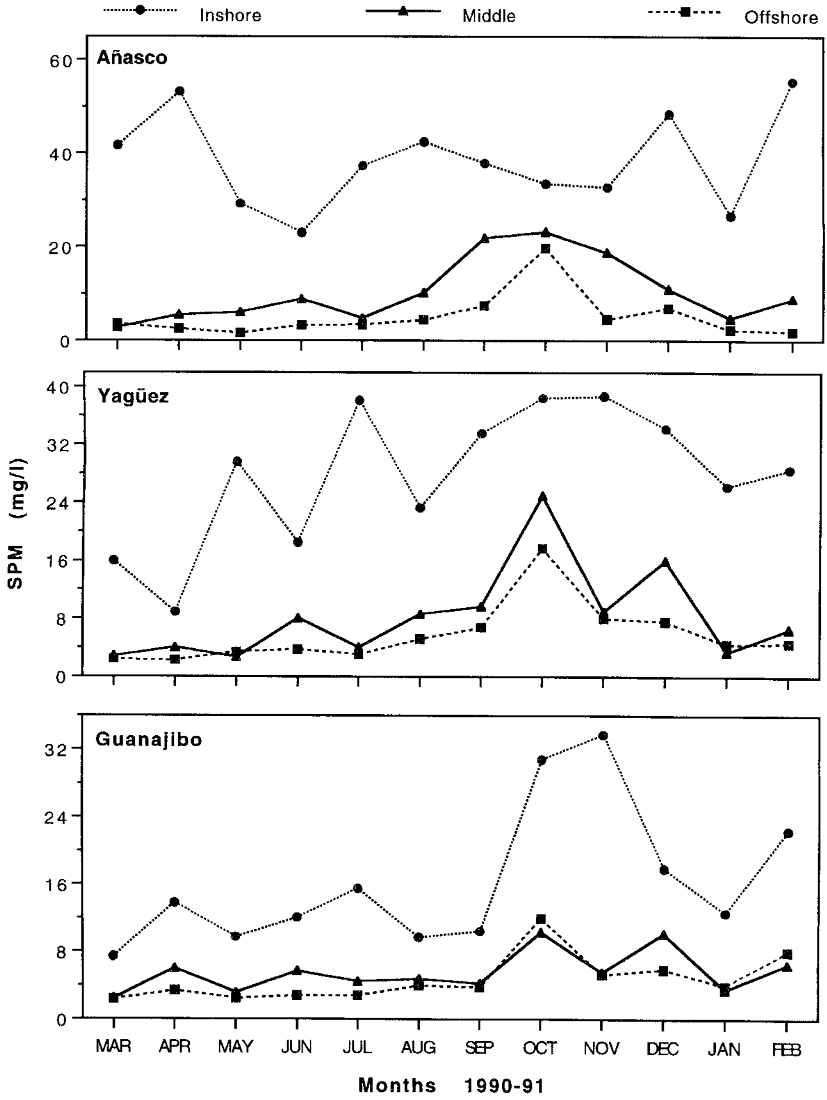

Fig. 3. Monthly variations of suspended particulate matter in Añasco, Yagüez and Guanajibo transects from inshore to offshore stations. Note the different scales on the ordinates.

Although it is difficult to identify a temporal pattern for Secchi fluctuations, low Secchi depths were found mainly in September and October. These features were most prominent at inshore stations.

Chl-a and SPM relationship

The correlation between Chl-a and SPM among stations was significantly positive for the entire study period. Lowest and highest correlations occurred during March and August, respectively (Figure 5). The principal factor underlying the

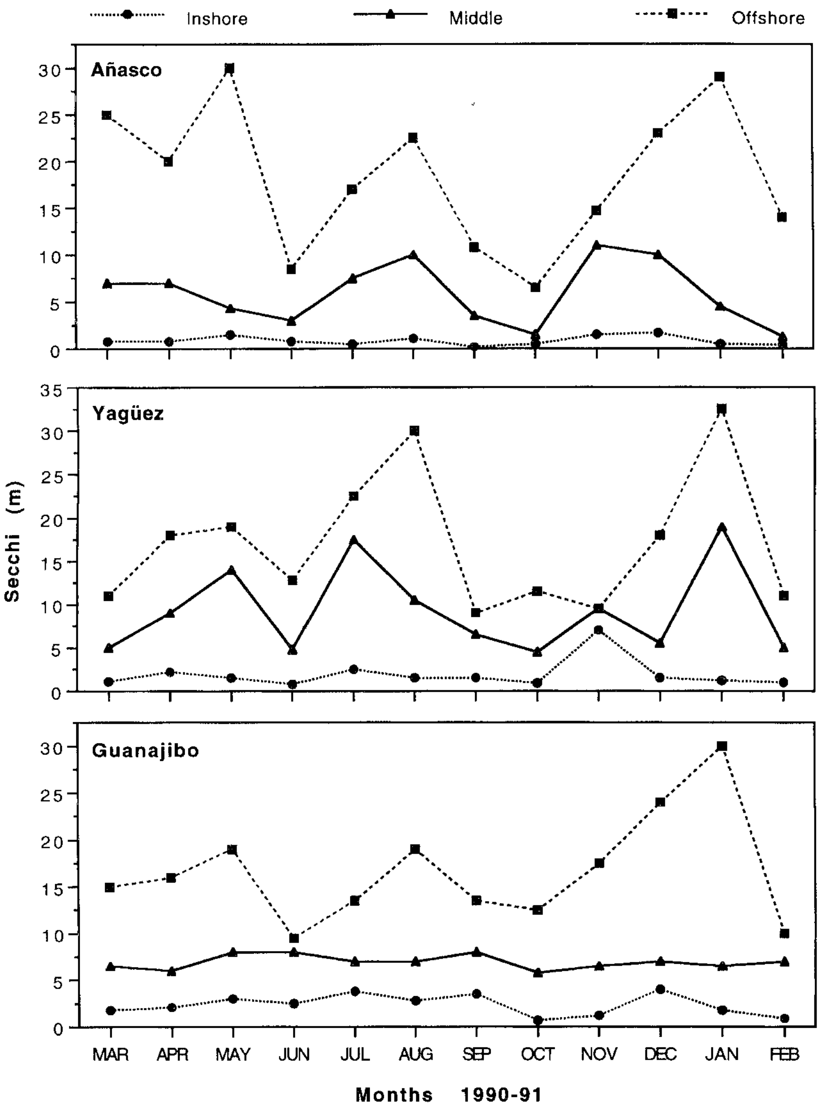

Fig. 4. Monthly variations of Secchi disk measurements in Añasco, Yagüez and Guanajibo transects from inshore to offshore stations. Note the different scales on the ordinates.

positive correlation between Chl-a and SPM was an inshore–offshore decrease in both parameters (Figures 2 and 3).

The correlation within stations between Chl-a and SPM through time was not significant ($r < 0.57$; $n = 12$). Although the temporal fluctuations for each parameter did not present a clear temporal trend during the study period, the higher values of both parameters were registered from August to December in most stations. This suggests that different processes (physical and biological) are affecting the temporal relationship between Chl-a and SPM.

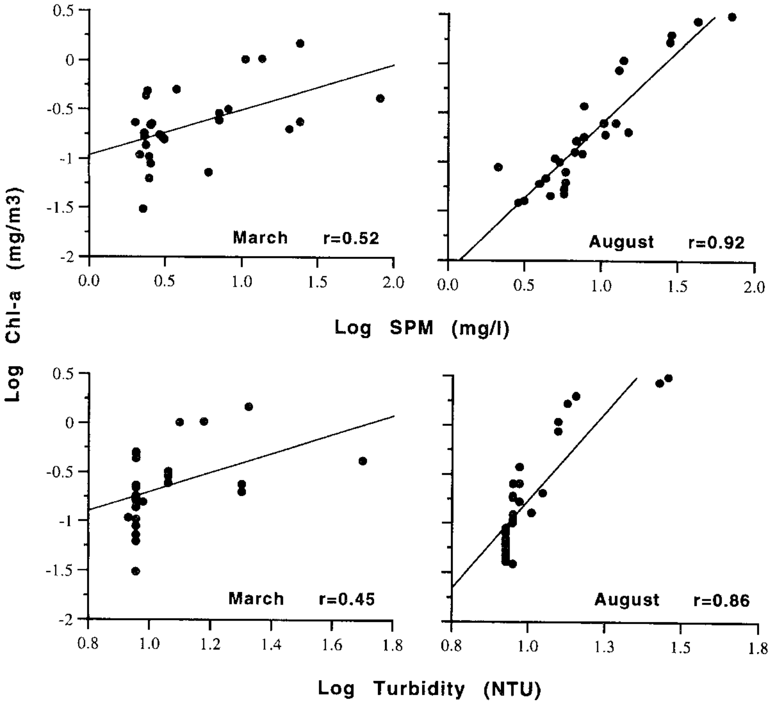

Fig. 5. Relationship between chlorophyll *a*, suspended particulate matter and turbidity during March and August. The data ($n = 27$) were transformed to $\log_{10}$ and the correlation coefficient (r) was calculated.

Relationship with light penetration

Light penetration in the water column was highly affected by suspended particles, which changed the water turbidity. As a consequence, the lowest and highest correlation coefficients between Chl-a and turbidity also occurred during March and August, respectively (Figure 5). A high correlation between SPM and turbidity occurred throughout the whole year ($r > 0.78$; $n = 27$).

The inverse relationship between turbidity (using surface values only) and Secchi depths was significant ($P < 0.01$), except for December ($\tau = -0.51$). The expected high negative correlation among stations confirmed that turbidity has an inverse effect on the penetration of light. The correlation coefficients of Chl-a versus Secchi depths were significantly negative ($P < 0.01$) as well, except for October ($\tau = -0.50$) and November ($\tau = -0.48$).

Discussion

Temporal and spatial changes in Chl-a and SPM

Previous research in the Caribbean region shows that rainfall and river run-off affect inshore areas, producing temporal and spatial changes in the dynamics of coastal waters and phytoplankton standing crops (Burkholder *et al.*, 1967, 1972; Hargreaves *et al.*, 1970; Sander and Steven, 1973; García and López, 1989). In western Puerto Rico, the seasonal patterns of rainfall and river discharge produce a wet season from August to November and a dry season beginning in January or February (Lowman *et al.*, 1966; Rickher *et al.*, 1970; Morelock *et al.*, 1983; and personal observations, 1991). We found that low salinities were a consequence of the high input of fresh water during the wet season (Figure 6). A reduction in salinities was detected from August to November for all stations, and October showed the lowest values (31–33‰).

The seasonal rainfall and river discharge (Figure 6) also affected the monthly variations in Chl-a and SPM in the inner regions of Mayagüez Bay (Figures 2 and 3). The inshore stations of Añasco and Yagüez rivers registered low values of Chl-a from September to November, after a peak in August (Figure 2). In these months, the total precipitation in the western region of Puerto Rico was high, resulting in increased river discharge. In contrast, monthly records of Chl-a at the Guanajibo inshore station were different from those of the inshore stations of the two other rivers (Figure 2). This may suggest that the discharge of these rivers differs in nutrients, suspended sediments, freshwater run-off and other components that may affect the dynamics of coastal phytoplankton. Many authors have shown these differences in other locations and suggested various causal mechanisms (Cloern *et al.*, 1983, 1989; Harding *et al.*, 1986; LeBlond *et al.*, 1986; Powell *et al.*, 1989).

Nutrient concentration is one of the most important and variable components of coastal areas. Its transport by river run-off has been well documented around the world (Meybeck, 1982). Consequently, the spatial and temporal response of coastal phytoplankton will be highly affected by the amount and composition of nutrient supply by rainfall run-off and river discharges (Mann, 1982). In the Caribbean region, some variations in standing crop and production of coastal phytoplankton are attributed to run-off of nutrients (Hargreaves *et al.*, 1970; Burkholder *et al.*, 1972; Sander and Steven, 1973). In a coastal lagoon at western Puerto Rico, nutrient inputs from rainfall run-off affect the seasonal pattern of phytoplankton (García and López, 1989). In Aguadilla Bay, close to the current study site (Figure 1), Santiago (1988) registered monthly correlations between rainfall, inorganic nitrogen, Chl-a concentration and zooplankton abundance. She found that maximum NO_2/NO_3 concentrations occur during large rainfall events in May and October. She also showed a positive correlation of monthly mean concentrations of Chl-a and the corresponding NO_2/NO_3 concentrations.

We found high concentrations of nitrogen (measured as total $NO_2 + NO_3$) for Añasco and Yagüez rivers during the wet season (Figure 7). In Añasco River, the peak value was registered during October, which was also the peak of rainfall and river discharge in western Puerto Rico (Figure 6). Although the Añasco River had a higher discharge than the Yagüez River during September and October, the nitrogen concentration for these two rivers was similar. The seasonal variations in nitrogen concentration for Guanajibo River were quite different from those for the other two rivers. For most cases, the peak occurred at the beginning of the dry season, although the range of values was not so different.

These nutrient data, however, were taken at stations far away from the estuarine zone (see Figure 1 for locations); the final amount reaching the coast should be higher because additional input of nutrients will take place along the basin before

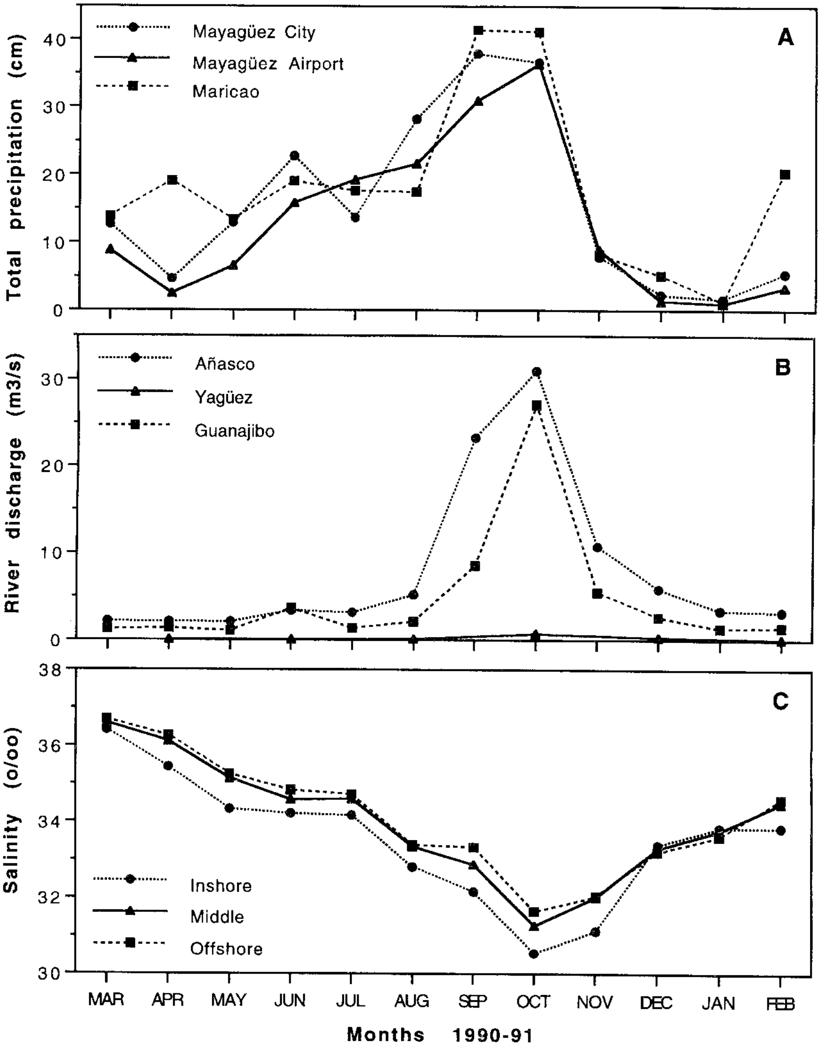

Fig. 6. Monthly variations of total precipitation in the western region of Puerto Rico (**A**), river discharge of Añasco, Yagüez and Guanajibo rivers (**B**), and pooled data of salinity from inshore to offshore stations (**C**).

the water mass from the rivers gets into the bay. A complete and detailed study of nutrient concentration at Mayagüez Bay is necessary for better understanding.

The inshore–offshore changes in phytoplankton Chl-a are not only related to the impact of local river run-off; other regional events, such as the discharge of the Amazon and Orinoco rivers, may also be contributing to the overall pattern (Ryther *et al.*, 1967; Hulburt and Corwin, 1969; Kidd and Sander, 1979; Müller-Karger *et al.*, 1989; Müller-Karger and Aparicio Castro, 1994). The Chl-a peak at the middle and offshore stations was registered in September, 1 month later than at the inshore stations. These results suggest that middle and offshore stations might respond to regional events, like the Orinoco River discharge, which reaches

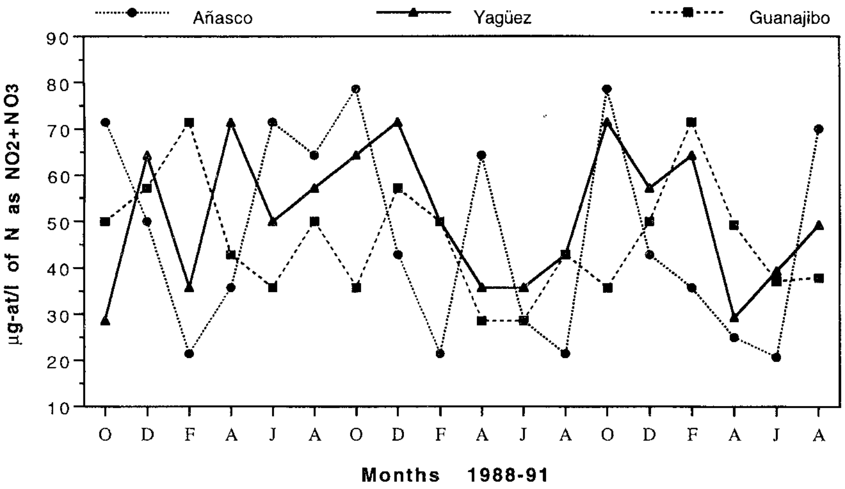

Fig. 7. Bimonthly variations of nitrogen concentration as total nitrate + nitrite in the studied rivers from October 1988 to August 1991. Figure 1 shows the station location of these data.

the vicinity of Puerto Rico during September or October (Müller-Karger *et al.*, 1989). This possibility also requires more investigation.

The SPM measurements at the inshore station off the Añasco River were different from those of the other two rivers. Yagüez and Guanajibo rivers showed SPM peaks between October and December, whereas the Añasco's peak occurred during May and June. Rainfall events (e.g. coastal versus mountainous rains) may lead to different responses in discharge of rivers along the west coast of Puerto Rico (Giusti and López, 1967; Lugo *et al.*, 1980; and personal observations, 1991). The Añasco River has the largest basin on the west coast, and drained more material than the Yagüez and Guanajibo rivers during the wet season, with a maximum peak of river discharge in October (Figure 6).

Temporal and spatial relationship of Chl-a and SPM

Statistical analysis of the relationship between Chl-a and SPM showed that the responses of these parameters were different in time and space. A significant positive relationship was observed spatially, but not temporally. The relationships presented in this study can be explained considering three important factors: (i) the relationship between nutrients and SPM in river run-off; (ii) the physiological adaptations of phytoplankton to light intensity (hence, SPM concentration); (iii) the possible bias introduced by the method used to measure SPM.

Changes in nutrient concentration due to river discharge and their effects upon phytoplankton dynamics have been discussed previously. We suggest that the positive spatial correlation between Chl-a and SPM is based on the relationship between SPM and nutrients. High values of SPM may indicate a high concentration of nutrients in the environment, supporting in turn optimum conditions for phytoplankton growth.

A physiological adaptation approach may also help to explain the spatial correlations of phytoplankton Chl-a to SPM and light penetration. We observed that SPM directly affected the turbidity of water. This agrees with other studies (Hard-

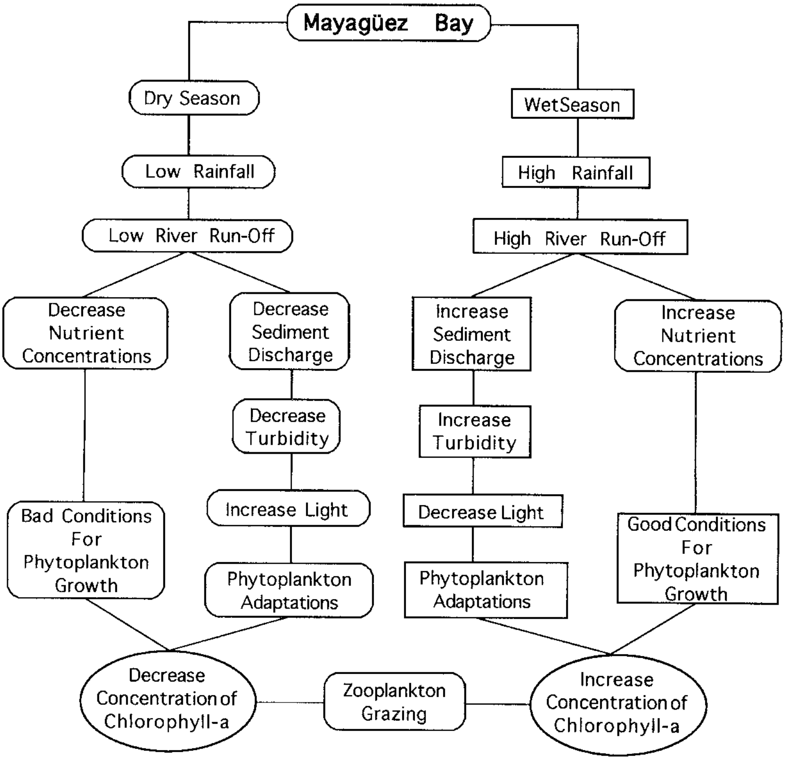

Fig. 8. Proposed dynamic of chlorophyll *a* and suspended particulate matter in Mayagüez Bay.

ing *et al.*, 1986; LeBlond *et al.*, 1986; Cloern *et al.*, 1989) that establish how suspended particles affect the optical properties of seawater. Changes in water properties due to SPM can be producing physiological responses of phytoplankton to light regimes in the water column (Falkowski, 1983, 1984; Kirk, 1994). It is generally found among unicellular and multicellular algae that the content of their photosynthetic pigments increases from 2- to 5-fold as light intensity decreases (Kirk, 1994). This adaptation permits the organism to capture the available light more efficiently. Our study presents evidence indicating that high concentrations of SPM increase the water turbidity and decrease the light intensity. These changes in the optical properties of seawater may induce phytoplankton to increase its content of Chl-a (up to 5-fold) to enhance light-trapping mechanisms, especially at inshore areas.

The measurements of light penetration using a Secchi disk could introduce errors in the interpretation of our results. Some studies showed the serious complications of the Chl-a–Secchi disk relationship due to a high chlorophyll concentration (Carlson, 1980; Lorenzen, 1980). Our study area is characterized by low algal concentration (3 mg m^{-3} of Chl-a), and the self-shading of light by phytoplankton cells appears to be less significant than suspended sediment (Smith, 1982). Consequently, it is expected that the negative correlations between turbidity, Secchi and Chl-a were largely controlled by light-absorbing properties, other than those of shading by phytoplankton cells.

Nevertheless, phytoplankton cells may be contributing to SPM measurements. The selected method of SPM measurements retains organic and inorganic suspended particles ($> 0.56\ \mu m$), and may be introducing some error in the correlation analysis of Chl-a and SPM. However, an estimate of phytoplankton biomass (based on Chl-a measurements) revealed that the dry weight contribution of phytoplankton cells was $< 1\%$ of the total registered SPM measurements. Thus, the introduced error should be relatively small.

In conclusion, the spatial and temporal changes of Chl-a and SPM in Mayagüez Bay are determined by different events, summarized in Figure 8. We conclude that the differences in discharge of the rivers are affecting the dynamics of phytoplankton Chl-a, suspended sediments and penetration of light in Mayagüez Bay, Puerto Rico. In future studies, these parameters and the implication of many other parameters directly or indirectly affected by discharge of the rivers must be investigated in more detail.

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