ON THE INFLUENCE OF HOT-WATER DISCHARGES ON PHYTOPLANKTON COMMUNITIES FROM A COASTAL ZONE OF THE GULF OF MEXICO

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Abstract. The influence of thermal discharges on the phytoplankton community from a coastal zone of the Gulf of Mexico was evaluated through their structure and photosynthetic behaviour focusing on responses to changes in light and temperature. Biological and physicochemical parameters were measured over a period of two years in an area with permanent hot water discharges from a thermoelectric plant. The temperature in the sampling area ranged from 23.5 to 36 °C with differences between the coldest and the hottest station from 5.3 to 9.2 °C. Photosynthetically active radiation (PAR) were reduced in the discharge area water column, due to turbulence. One hundred and one different taxa were identified with a strong predominance of Diatoms. The chlorophyll *a* concentration ranged from 0.3 to 6.1 μg L^{-1}, with highest values of the phaeophytin:chlorophyll ratio found at the hottest station. The community structure did not show significative differences among sampling stations with respect to temperature variations. However, in the algal assemblages influenced by thermal discharges, it was possible to observe alterations in the photosynthesis behaviour. Phytoplankton response to short term photosynthesis experiments was segregated according to composition and origin of microalgal assemblages. Samples with larger heterogeneous composition had more consistent oxygen production responses. Algal communities exposed to hot effluent showed different degrees of photosynthesis rate reduction, higher light requirements (>500 μE m^2 s^{-1}) and lower temperature (25 °C) to achieve Pmax than algae sampled in sites without such exposure.

Keywords: microalgal communities, photosynthesis, temperature, thermal pollution, tropical coast

1. Introduction

Temperature, light and hydrodynamics are the factors that most influence living organisms and, together with nutrient availability, constitute the basic environmental influences in the physiology of photosynthetic aquatic organisms. As primary producers, phytoplankton communities are connected to large-scale processes that make it necessary to understand how natural populations respond to local and global changes.

Most of the knowledge about the relationship between algal production and temperature is based on laboratory studies carried out on monospecific cultures or assemblages with only a few species present. There has been an exponential growth in the construction of electric power plants along coastal margins from the

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early years of the century to about the 1970's. Because these plants use sea water as a cooling agent, water heat has been considered as a potentially large-scale pollutant (Langford, 1990). This has given rise to many studies regarding the effects on organisms exposed to thermal effluents, generally at high and mid latitudes (Naylor, 1965; Hirayama and Hirano, 1970; Morris and Glover, 1974; Cushing, 1976; Goldman and Davidson, 1977; Goldman, 1977a, b; Davis and Coughlan, 1978; Bordet, 1980; Weber, 1981).

In tropical and subtropical areas thermoelectric plant construction is just beginning, yet there is a lack of information about the natural populations that could be impacted by the waters discharged by these plants and the biological processes implicated (Bienfang and Johnson, 1980; Lee, 1992; Claustre and Marty, 1995).

The results of studies on the effects of hot water discharges on phytoplankton communities vary significantly, mainly due to the different approaches, methodologies, and time scales involved. In general, they can be classified as those finding alterations in abundance, primary productivity and metabolic processes (Hamilton *et al*., 1970; Eppley *et al*., 1976; Miller and Brighouse, 1984; Tessier, 1990) and those that find no appreciable effect or even a benefit for some populations (Hirayama and Hirano, 1970; Sanders *et al*., 1981; Lee, 1992). Often, other factors such as water chlorination are cited as worse pollutants than temperature increases (Eppley *et al*., 1976; Hamilton *et al*., 1970; Jolley *et al*., 1978; Geider and Osborne, 1992).

The present study was conducted in a location where a thermoelectric power plant was discharging water with elevated temperatures into a tropical coastal region. The objective was to evaluate the response of coastal microalgae communities to changes in environmental temperature by evaluating abundance, community structure (the nature of the organisms present and their relative abundance) and community metabolism, related to the photosynthetic behaviour.

2. Methods

2.1. STUDY AREA

The study was carried out on the coast of Veracruz, Gulf of Mexico at 21°08′30″N and 97°10′30″W. Air temperature in this region ranges from approximately 18 to 34 °C, with an annual average of 22 °C. An annual mean precipitation of 1500 mm falls between May and October, with a short dry period in August. Water temperature ranges from 22 to 29 °C. As a tropical zone, mean seasonal differentiation is between dry and rainy periods (S. de Marina, 1988; SEDUE, 1992).

The Thermoelectric Plant 'Adolfo López Mateos' is located on the coastline about 9 km northeast of the port of Tuxpan, within an hydrologic complex system: one river outlet 3 km to the south and two coastal lagoons, Tampamachoco and Tamiahua, which are behind the plant and to the north, respectively (Figure 1). Coastal surface water runs from south to north. The plant has been in operation

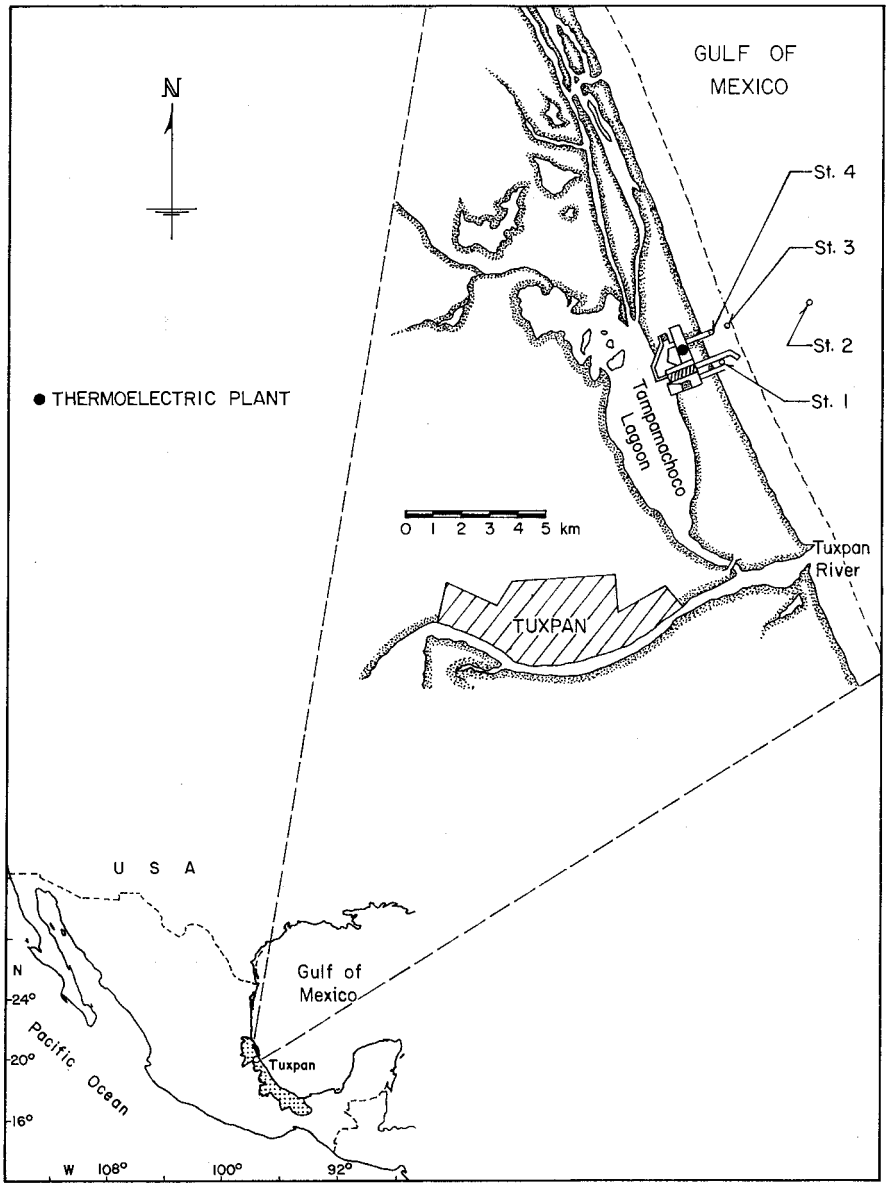

Figure 1. Location of study area and sampling stations. Station 1 is at the intake, Station 2 is 4 km offshore, Station 3 is 500 m from the exit of the discharge channel, Station 4 is at the thermoelectric plant outfall.

since September 1989 and discharges 7 m^3 of seawater coolant per second during normal operation.

Four sampling stations were selected (Figure 1), based on their location relative to the effluent that produces different microthermal regimes in adjacent areas:

Station 1, on the southern channel where water enters the plant; Station 2, 4 km offshore; Station 3, 500 m from the discharge channel outlet and Station 4, within the discharge channel at the northern end of the plant.

2.2. SAMPLING AND SAMPLE ANALYSIS

Six intensive sampling periods, corresponding to the different climatic conditions, were developed from March 2 to 7, June 9 to 15, December 6 to 12 in 1993, and April 13 to 17, July 20 to 28, October 23 to 28, in 1994.

Physico-chemical variables were recorded daily in vertical profiles for each sampling site. Oxygen and temperature were measured with an oxymeter (Model 58, YSI); salinity and temperature with a digital salinometer (Labcom Instruments SCT). Photosynthetically active radiation (PAR) were detected by means of a quantometer (sensors 193UW and 192 UW Li-Cor, Inc.).

Water samples for biochemical analysis and laboratory experiments were all taken at 1 m depth with a 3 L van Dorn bottle and, in some cases, a phytoplankton net (60 μm) with attached flow meter was used. Subsamples were preserved with Lugolïs solution for taxonomic identification and cell counting (Utermöhl's method) with an inverted microscope (Olympus CK2) following Navarro (1981, 1983), Round (1990) and Balech (1967, 1987). The Shannon index was calculated to make comparisons between taxa occurrence in both time and space.

Chlorophyll *a* and pheopigment concentrations were obtained with a Turner Designs fluorometer (Model 450) calibrated with concentrated algal chlorophyll (Sigma Chemical) and following the method suggested by Holm-Hansen *et al.* (1965), using Whatmann GF/F filters and 90% acetone as the solvent. The phaeophytin:chlorophyll *a* ratio was calculated for each month and station.

2.3. EXPERIMENTAL DESIGN

After the initial field studies and pilot experiments in March and June 1993, 48 laboratory experiments from December 1993 to October 1994 were conducted to follow oxygen concentration evolution. The temperature-photosynthesis response was analyzed in thirty-two of these and P-I curves obtained from the other sixteen.

Experimental samples, collected at a depth of one meter in each sample site, were always kept at room temperature in the laboratory, protected from direct light and tested the same day. Larger zooplankters were avoided by prescreening samples through a 80 μm net.

2.4. PHOTOSYNTHESIS-TEMPERATURE ANALYSIS

Incubations were carried out in BOD flasks using an average sample volume of 330 mL. Oxygen concentration was measured with continuously attached oxygen electrodes YSI (Model 58) and Orion (Model 800), calibrated at the beginning of each experimental session. The light source consisted of two slide projectors

and a frame with tungsten lamps fixed at the top of a thermal bath (Haake, with thermoregulation). In each experiment two samples were exposed to semisaturating light (between 800 and 1200 μE m^{-2} s^{-1}) and two to darkness. One bottle without organisms was exposed to the same experimental conditions, and its oxygen concentration was used as a blank to estimate variability in oxygen concentration due to physicochemical processes.

Each complete incubation lasted about two and a half hours. The temperature was increased from 20 to 40 °C at a rate of 5 °C every 10–15 min and then decreased to 20 °C similarly. The Hansatech system was used in the October experiments, following the same experimental design but time was reduced to 3 min at each temperature.

Comparison between photosynthetic production (Pmax) in samples from the entrance site and the discharge channel was made with the equation suggested by Hamilton *et al*. (1970) and Hirayama and Hirano (1970):

$$\% \text{ reduction } = \left(1 - \frac{\text{mean effluent rate}}{\text{mean intake rate}}\right) \times 100 \,. \tag{1}$$

2.5. P-I CURVES

Small volume samples (3.5 mL) were used to obtain P-I curves, following oxygen concentration evolution in a polarographic sensor system (Walker, 1990) which included stirrer, light and temperature control (Oxygen Electrode Chloroview 2, Hansatech). Incubation began with a ten minute period of darkness or until a consistent decrease in the oxygen concentration was reached. Each sample and its replicate then were exposed to increasing irradiance, 9 min for each one, with total incubation time up to one hour. Low irradiances were applied in the July experiments: 150, 270, 360, 480 and 600 μE m^{-2} s^{-1}. In the October series higher irradiances were used: 250, 600, 1100, 1850 and 2500 μE m^{-2} s^{-1}. Additional samples were tested without organisms (water filtered through Millipore membrane 0.2 μm) as a reference of water oxygen's physicochemical processes. Temperature incubation was 26 °C.

The oxygen amount generated per time and cell for each irradiance were calculated with a linear regression of experimental data. The photosynthesis versus irradiance curves that were subsequently obtained were adjusted to the exponential formulation extended by Platt *et al*. (1980) to account for photoinhibition (2). Additionally an exponential model (3) and the hyperbolic tangent function (4) (Jassby and Plat, 1976; Geider and Osborne, 1992) were applied to fit data when photoinhibition was absent:

$$P = Ps\,[1 - exp\,(-aE)]\,exp\,(-bE) \tag{2}$$

$$P = Pmax\,[1 - exp\,(\alpha E/Pmax)] \tag{3}$$

TABLE I

Characteristics of the water column at each sampling station. Average variations in temperature and oxygen concentration were calculated from measurements made at 1, 2 and 3 m

Sampling station	Location respect to the plant	Average depth	Average variability		PAR at 3 m depth percentage	
			Temperature	Oxygen		
		m	°C	mg L^{-1}	Min	Max
1	Water entrance	3.5	±0.8	±0.7	3	19
2	4 km offshore	10	±2.6	± 1	9	37
3	500 m offshore	3.5	±1.4	± 2	4	20
4	Discharge channel	2.5	±0.3	±0.3	–	–

$$P = Pmax\ tanh\ (\alpha E/Pmax) \tag{4}$$

where

Ps = maximum photosynthesis reached with presence of photoinhibition; a = α/Ps, α = initial slope; E = irradiance; β = photoinhibition (negative slope), b = β/Ps; Pmax = maximum photosynthesis recorded (Geider and Osborne, 1992). Photosynthesis is expressed in pmol O_2 $cell^{-1}$ h^{-1}, and Irradiance in μE m^{-2} s^{-1}.

2.6. STATISTICAL METHODS

Because the frequency distribution of the cell number, diversity index and raw experimental data did not correspond to a normal distribution, the non-parametric Kruskal-Wallis test was applied to look for differences among factors like location (sampling station) or time period. Associations between responses and sampling sites were explored also with the Mann-Whitney test, $p < 0.05$.

3. Results

3.1. VERTICAL PROFILES

Temperatures along the water column were nearly homogeneous for each sampling period in stations 1 and 4, while in stations 2 and 3 vertical differences were often found. Oxygen concentrations had slight variation within the water column of stations 1, 2 and 4 but in station 3, located in the region where the hot water discharge mixes with the Gulf water, it varied up to ±2 mg O_2 L^{-1}.

The higher photic area was found at the farthest offshore site, Station 2. In a comparable depth of three meters the maximum light penetration percentages

occurred in this station as well in April and June, the months with more incoming radiation, as in December, the month with less sunlight. General description and average variations recorded in vertical profiles of each sampling station are presented in Table I.

3.2. MEASUREMENTS TO ONE METER DEPTH

At the depth where the biological samples were taken, environmental variables behave as follows: Monthly average water temperatures and PAR are shown in Figure 2. The temperature observed throughout the study period ranged from 23.5 to 36 °C, with differences in simultaneous measurements between stations from 5.3 to 9.2 °C.

Light penetration ranged from 14 to 70% with the highest values in April (dry period), the lowest in December and the widest fluctuations in July and October (rainy season).

In Station 4 (discharge channel) vertical profiles could not be recorded beyond 1 m due to the large flow rates that produced to much drag on the PAR sensor. In this Station turbulence and re-suspension prevented a good light field.

The salinity ranged from 29 to 33‰, without significant differences among sampling stations and no seasonal patterns were identified. The lowest values of oxygen concentration (6.2 mg O_2 L^{-1}) were obtained in April at Station 4 and the highest concentration recorded (8.9 mg O_2 L^{-1}) was in July, at Station 2. In spite of its high water movement, Station 4 presented lower oxygen concentration (an average of 7.2 $\pm$1.6) than Station 1 (8.2 $\pm$0.3), Station 2 (8.2 $\pm$0.6) and Station 3 (8.1$\pm$1.5), probably due to the temperature effect in oxygen solubility.

3.3. ALGAE COMMUNITIES STRUCTURE

One hundred and one different taxa were identified: 39 belong to Pennate Diatom, 28 were Centrate Diatoms, 21 Dinoflagellates, 1 Coccolitophorid, 2 Silicoflagellates, 3 Phytoflagellates, 2 Chlorophytes and 5 Cyanophyta. Diatoms were by far most prevalent, from both bottle and net samples. In March, June, December and April they represented more than 60% of the total composition, except for Station 2 in December when a bloom of *Gymnodinium*, represented 52% of its total abundance. Pennate diatoms were clearly the most abundant of the *Bacillariophyta* throughout the study; however, an increase in Centrate diatoms was recorded in the entire area in December. *Amphora, Cymatosira, Navicula, Thalassionema, Nitzchia, Cocconeis, Stauroneis and Licmophora*, were the main genera found of Pennate diatoms, while *Skeletonema, Coscinodiscus, Ceratulina, Chaetoceros, Bacteriastrum, Guinardia and Thalassiosira* were the most common Centrate diatoms. Of the Dinoflagellates, two atecates and species of *Gymnodinium, Gonyaulax, Prorocentrum, Protoperidinium and Ceratium*, stood out. Dinoflagellates consistently represented around 10–15% of the algal assemblages in Station 2, and they

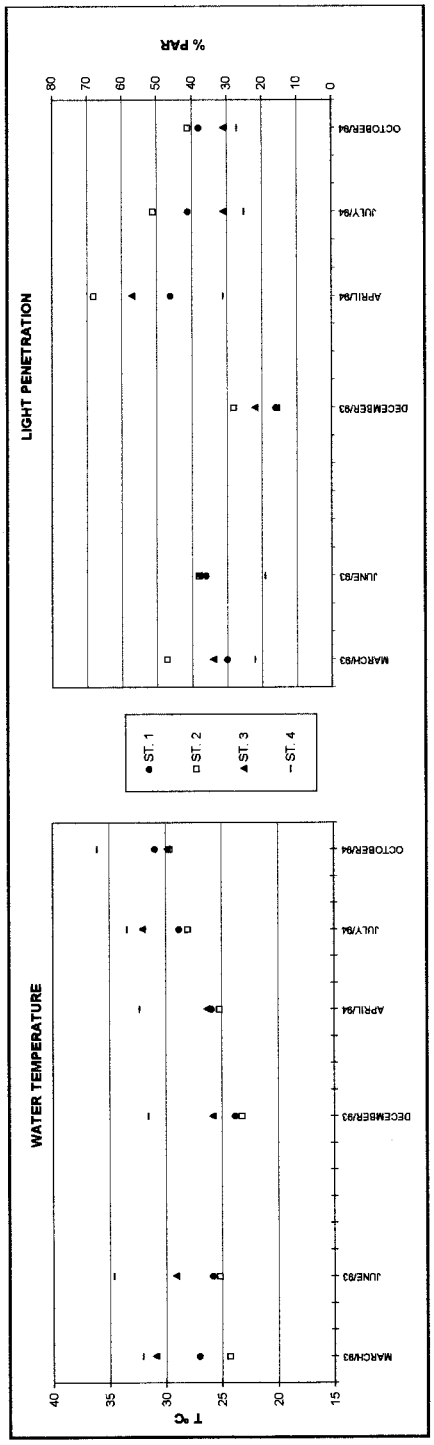

Figure 2. Monthly average of temperature and photosynthetically active radiation (PAR) at each sampling site at 1 m depth.

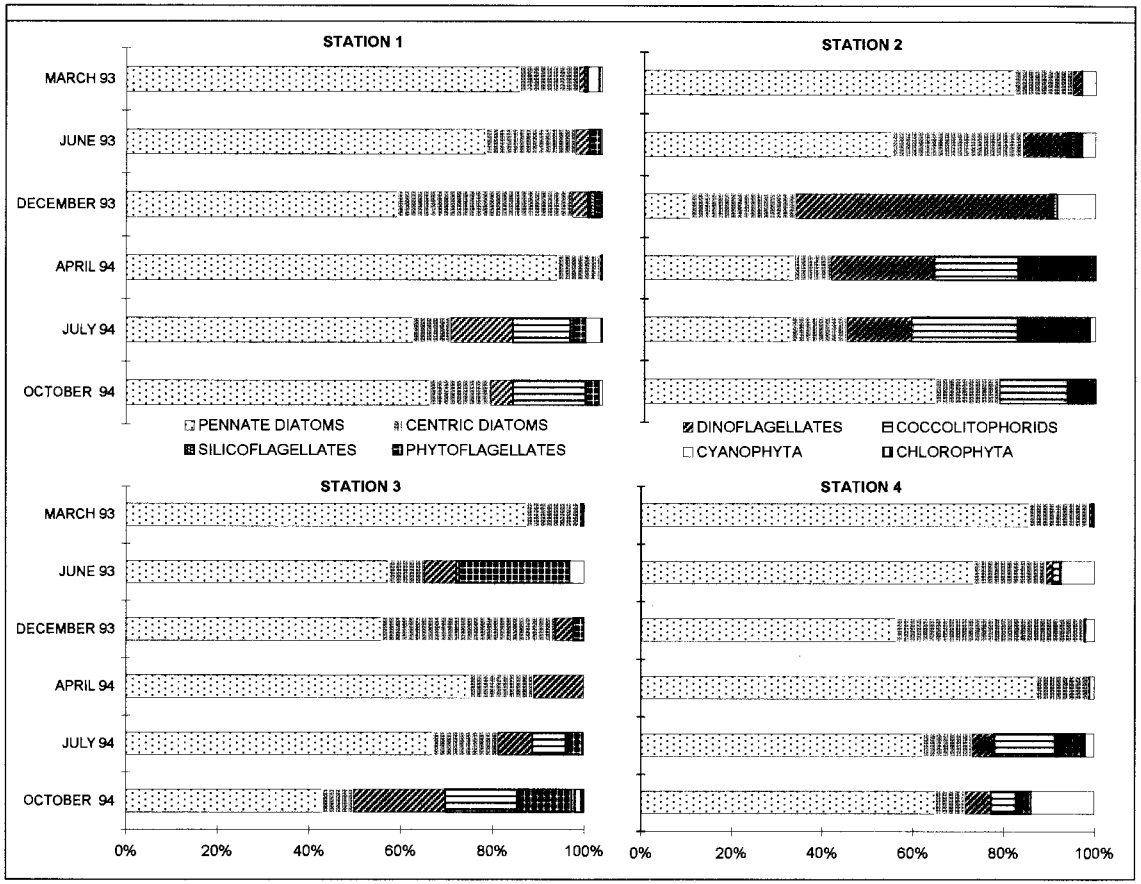

Figure 3. Community monthly composition at sampling stations and relative abundance of each group.

increased in all of the study area in the rainy season, mainly in July and October. In Station 3 dinoflagellate's abundance ranged between 4 and 15% and in Station 1 from 1.5 to 13%. The sum of all dinoflagellate's species represented $<$1.5% at the Station 4, except in July and October when they reached 6%. One species from the genus *Pyrophacus* was only recorded in this station, representing 1.2% of total abundance in July; on the contrary, one of the atecates and species of Oxytoxum, Nautiluca, Gonyaulax, Disodinium, Protoperidinium, Podolanmpas and Disodinium, which were consistently present at the other sites, were never recorded at Station 4. Coccolitophorids bloomed in July and October in all the sampling sites, but at Station 2 it began to bloom in April. Phytoflagellates had an important presence in April, July and October at Station 2. In June of 1993 they bloomed at Station 3 and were abundant again in October of 1994. In July and October they florished at Station 4 and in Station 1 they had a small but constant presence. Cyanophyta's presence was only conspicuous at Stations 2 and 4, where at the latter station they reached a maximum (14%) in the October samples. Figure 3 shows the composition by groups and the monthly variation of each station's assemblage. Table II presents the taxa (genus and some species) which represent more than 1% of relative abundance in each station at least in one of the six sampling periods. The Shannon diversity index calculated for each month and site is presented in Table III including the total number of different taxa observed.

The structure of communities did not show statistically significant differences with respect to species composition, relative abundance and diversity index (Kruskal-Wallis test, $p < 0.05$); nevertheless, cell numbers were notably lower at Stations 2 and 4.

Variability in daily algal assemblages samples can be seen in Figure 4 where cell number recorded in morning samples at 1 m depth are represented. A seasonal pattern was observed regarding algal abundance with cell number increases during the dry period. Station 2 had the lowest number of cells of the 1 m deep samples, due to its open sea location with a 9 m euphotic layer where plankton could be distributed. Station 4, in spite of its location, had the second lowest with smaller cell number. The species composition at this station is quite similar to those of Station 1. Station 3 is influenced by Station 2 during calm periods (March, April and June), by Station 4 in rainy periods and also by land breeze events (July, October and December).

Chlorophyll *a* concentrations ranged from 0.6 to 6.1 μg L^{-1} at Station 1; 0.3 to 3.3 at Station 2; 0.4 to 5.7 at Station 3 and 0.6 to 5 at Station 4. Higher values found in some samples at Stations 1, 3 and 4 are explained by their shallowness, relative enclosure conditions (Stations 1 and 4) and the microphytobenthos present in the water column due to sediment resuspension. Ratios of phaeophytin to chlorophyll *a* are presented in Figure 5, showing a higher phaeopigment concentration in Station 4. Calculation on chlorophyll a concentration per cell gave values which ranged from 0.5 to 600 ng Chl $cell^{-1}$. Nevertheless in the Figure 5 a monthly average of chlorophyll *a* concentration by cell with standard deviation is shown as

TABLE II

Incidence of algal genera which were found during the six sampling periods. A genus was included if presented more than 1% respect to its relative abundance in any period

	Occurrence (%)					Occurrence (%)			
Genus (> 1%)	St. 1	St. 2	St. 3	St. 4	Genus (> 1%)	St. 1	St. 2	St. 3	St. 4
Pennate diatoms									
Amphora	16		33	33	*Chaetoceros*	83	33	33	33
A. gracialis	83	33	50	33	*Eucampia*	16			
Cocconeis	33				*Guinardia*	16	33		
Cymatosira	67	50	83	83	*Hemiaulus*	16			
C. closterium	100	67	100	83	*Leptocilindrus*	50	16	33	33
Cymbella			16		*Lithodesmium*	16	16		
Diploneis 1	33	16		16	*Odontella*	33			
D. bombus	33			33	*Paralia*	16			
Grammatophora marina		16	16		*Podosira*				
Gyrosigma	16				*Rhizosolenia*	33	50	33	
Haslea		16		16	*Skeletonema*	83	16	83	83
Licmophora abbreviata	33	16	50	50	*Thalassiosira*	67	67	50	83
Licmophora gracile	16		33	33	**Dinoflagellates**				
Melosira triconfusa	16			16	*Atecate 1*	50	83	50	33
Navicula sp 1	33	33	67	33	*Atecate 2*	16	33	16	
Navicula sp 2	67	67	100	100	*Ceratium 1*	16	16		
Nitszchia sp.	50	50	33	67	*Ceratium 2*	16	16		
N. longissima	33	50	16	16	*Gonyaulax*	16	16		
N. paradoxa	16				*Gymnodinium*	33	83	50	16

TABLE II
(continued)

Genus (> 1%)	Occurrence (%) St. 1	St. 2	St. 3	St. 4	Genus (> 1%)	Occurrence (%) St. 1	St. 2	St. 3	St. 4
N. pungens	16	16	50	33	*Prorocentrum gracile*	16	16	33	
N. sicula	16				*Protoperidinium*	16	16		
N. sigma	16	16	50	50	*Pyrophacus*	16			
Pinnularia	16		16	16	**Prymnesiophyta**				
Plagiotropis				16	*Coccolitophorid*	33	50	50	
Pleurosigma	33		33		**Silicoflagellata**				
Raphoneis	16				*Dictyocha sp.*	16	33		
Stauroneis	33	16			**Phytoflagellata**				
Thalassionema	83	50	100	100	*Phytoflagellate 1*	50	67	50	33
Thalassiotrix		33		16	*Phytoflagellate 2*	16	16	16	
Centrate diatoms					**Cyanophyta**				
Bacteriastrum		16		16	*Cyanophyta 1*	16	33	16	50
Biddulphia				16	*Cyanophyta 2*	16	16	33	
Cerataulina	16	16	16	33	*Oscillatoria sp.*	33	16		
Climacodium	16				*Mesodiniun rubrum*	33	33		
Coscinodiscus	33	33	16	50	**Chlorophyta**				
Cyclotella	33	33	33	33	*Chlorophyta*	16	16	16	

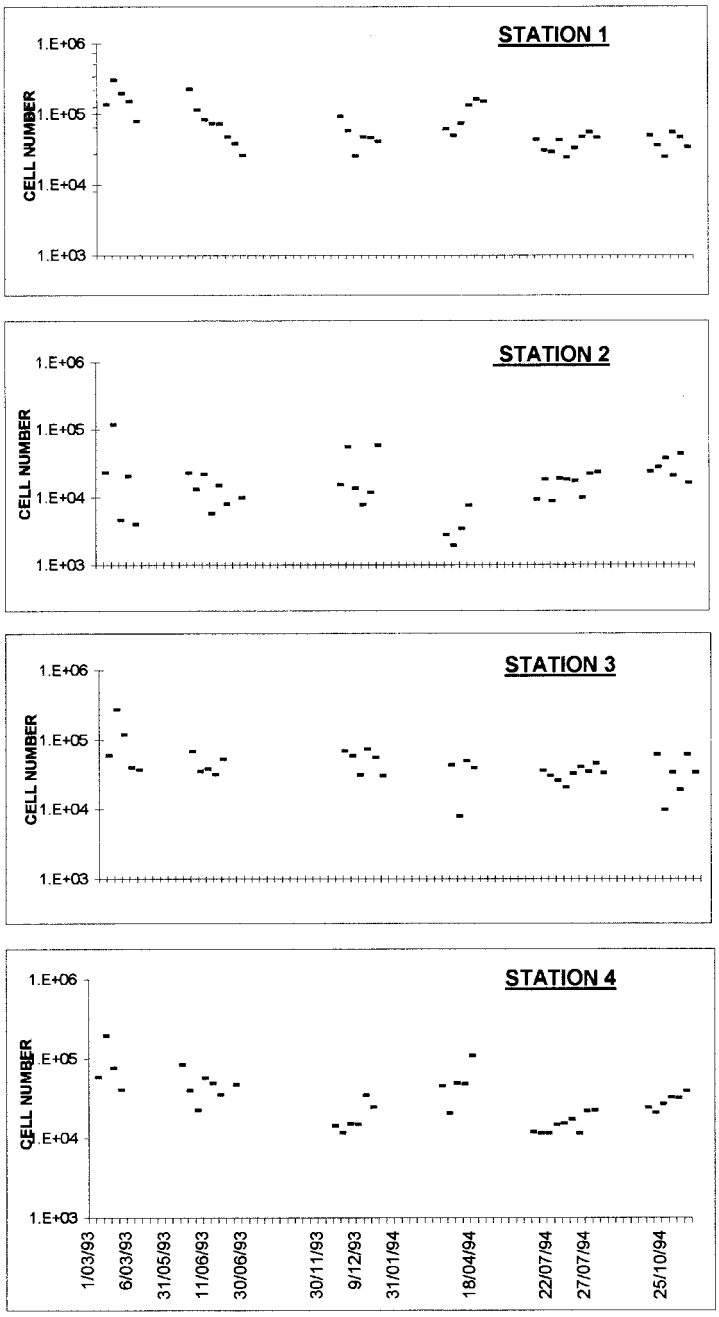

Figure 4. The daily record of cell counts shows the variability in each sampling period and site.

TABLE III

Communities' diversity expressed as the Shannon index and species number (SP) at each month and sampling station

Month/year	Index (SP)			
	Station 1	Station 2	Station 3	Station 4
March/1993	2.53 (52)	2.48 (44)	2.57 (45)	2.16 (35)
June/1993	3.71 (52)	4.07 (40)	3.88 (47)	4.07 (47)
December/1993	4.05 (50)	2.65 (26)	4.17 (48)	3.65 (32)
April/1994	3.09 (59)	3.49 (20)	3.54 (33)	3.23 (39)
July/1994	3.97 (49)	3.56 (32)	4.19 (45)	3.99 (36)
October/1994	4.20 (40)	4.03 (33)	4.02 (35)	3.70 (34)
Total	4.63 (85)	3.98 (84)	4.98 (83)	4.47 (75)

a reference. It must be noticed that higher chlorophyll contents per cell was found in dry months (December, April and October) coinciding with changes in species composition, mainly in Stations 2, 3 and 4.

3.4. PHOTOSYNTHESIS EXPERIMENTS

Experiments incubated in BOD bottles were not sufficiently sensitive for detecting oxygen concentration responses to changes in light quantity. However, responses to changes in temperature could be adequately recorded, because oxygen concentration variability was more evident. In both types of experiments respiration in light was observed, mainly in July and in Station 4.

3.5. TEMPERATURE-PHOTOSYNTHESIS EXPERIMENTS

Maximum photosynthesis and respiration rates reached each month are presented in Table IV, indicating the temperatures at the values were obtained. Exposure of algal samples from the Stations 1–3 to increasing and decreasing temperatures often showed some increment in oxygen concentration around 35–40 °C followed by a fall in production rates. Samples from Stations 2 and 3 were always able to recover production rates when the temperature decreased. Station 1 samples recuperated measurable oxygen production in April, July and October, but did not in December. Algae samples from Station 4 showed oxygen concentration decrease at temperatures from around 30 °C, except in July, when the decline began at 35 °C. Oxygen production recovered slightly only in July. Oxygen consumption in light frequently exceeded production in samples from Station 4, regardless of the magnitude of irradiance. In contrast, oxygen decrease in light at the other

TABLE IV

Experimental maximum photosynthetic production (Pmax) and their temperatures. Respiration rates were taken as the maximum negative values (Rmax) from the dark bottles and used to calculate the photosynthesis-respiration ratio (P/R)

Experiments	Station 1				Station 2				Station 3				Station 4			
Month	Pmax[a]	T (°C)	Rmax[a]	P/R	Pmax[a]	T (°C)	Rmax[a]	P/R	Pmax[a]	T (°C)	Rmax[a]	P/R	Pmax[a]	T (°C)	Rmax[a]	P/R
December	0.031	20	–0.007	4.36	3.72	25	–1.4	2.66	1.92	20	–0.09	21	0.007	25	–0.009	0.75
April	0.066	35	–0.005	13.2	0.221	35	–0.17	1.3	0.173	35	–0.02	11.5	0.054	25	–0.07	0.77
July	0.124	40	–0.21	0.59	0.102	40	–0.09	1.13	0.217	40	–0.38	0.57	0.09	35	–0.09	0.99
October	0.035	20	–0.29	0.12					0.135	40	–0.13	1.04	0.062	25	–0.02	3.65

[a] pmol O_2 $cell^{-1}$ h^{-1}.

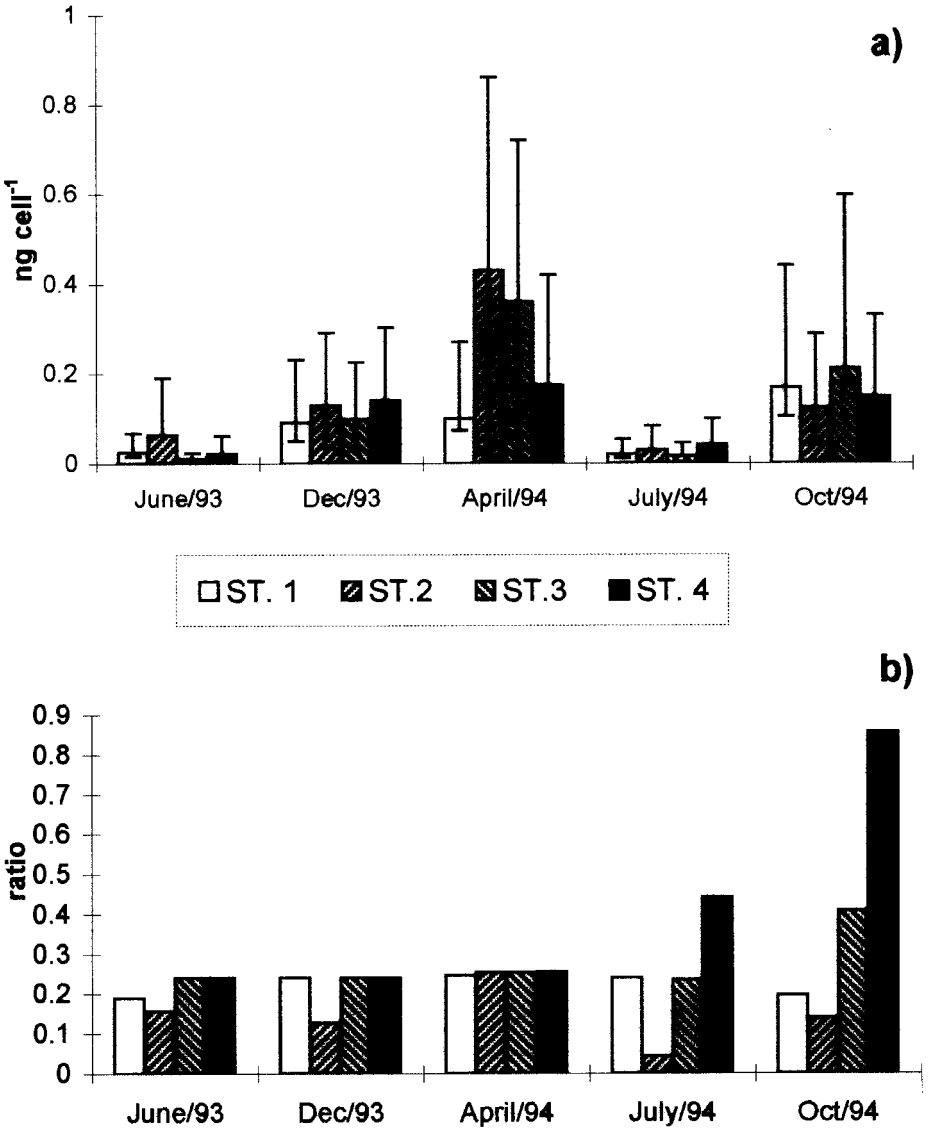

Figure 5. a) Chlorophyll a concentration by cell, monthly average showing the standard error (vertical lines) b) Phaeophytin/Chlorophyll a ratios.

stations appeared less frequently and when it occurred was at very low or very high irradiances.

Respiration was taken as an average of the highest negative values in dark bottles. For a comparison with the photosynthesis data, ratios of maximum photosynthesis values to respiration (Pmax: R) are also presented in Table IV.

When Equation (1) is applied to the Pmax reached by samples from Station 1 and Station 4, the latter present a photosynthesis reduction of 3.6, 27 and 78% in

April, July and December, and a higher net production than those from Station 1 in October. When Pmax from samples of Stations 2 and 3 are compared with values from samples in Station 4, then the percentage of reduction is even larger.

3.6. PHOTOSYNTHESIS-IRRADIANCE CURVES

P *vs* I curves for each station are plotted in Figures 6 and 7, with both observed and calculated values. Only the best fitted curve is presented indicating if it came from Equations (2), (3) or (4).

Photosynthesis irradiance curves show high saturation irradiance (Ik $>$ 200 μE m^2 s^{-1}) as might be expected in tropical environments. At Station 4, where algae are directly exposed to elevated water temperatures, samples required significantly ($p = 0.005$) more light for net oxygen production (Ik $>$500 μE m^2 s^{-1}), and its maximum photosynthesis values (Pmax) were the lowest. The July experiments did not show a net oxygen production but during the October experiments, under high irradiance conditions the algal samples from Station 4 had their highest O_2 production (Ps), mainly in the afternoon.

The initial slope (α) which describes photon harvesting efficiency, had similar and higher values in July experiments in Stations 1, 2 and 3 (0.008–0.015 pmol O_2 $cell^{-1}$ h^{-1} (μE m^{-2} s^{-1})). In October experiments α values ranged from 0.003 to 0.00004 pmol O_2 $cell^{-1}$ h^{-1} (μE m^{-2} s^{-1}) in the same stations, with highest values at Station 3. In Station 4 α ranged from 0.00021 to 0.000004 pmol O_2 $cell^{-1}$ h^{-1} (μE m^{-2} s^{-1}).

4. Discussion

The similarities between measurements at Stations 1 and 4 appear to be related to their locations close to the shoreline, the shallowness and their semi-enclosed condition. On the other hand, the differences seem coupled to their position with respect to the thermoelectric plant, i.e. water entrance and exit, respectively. Temperature affected oxygen concentration levels at Station 4 (occasionally also at Station 3) and flow dynamics increased turbidity and light distribution in the water column.

Light appears to be the determinant factor on the abundance and vertical distribution of microalgae at Station 2, which presented the lowest number of cells at 1 m deep samples and the highest euphotic layer where algae could be distributed.

Seasonal pattern is also observed regarding algal abundance with cell number increase in dry period, but overestimation of abundance in December is possible because the euphotic layer diminishes and it is easier finding cells at 1 m.

In spite of the limited census at Station 2, as was explained above, suggesting that it might not be representative of the real abundance and would require another sampling strategy, it was considered as a good reference as a free of discharge influence area. Data from Station 4 are in agreement with Langford (1990), who found

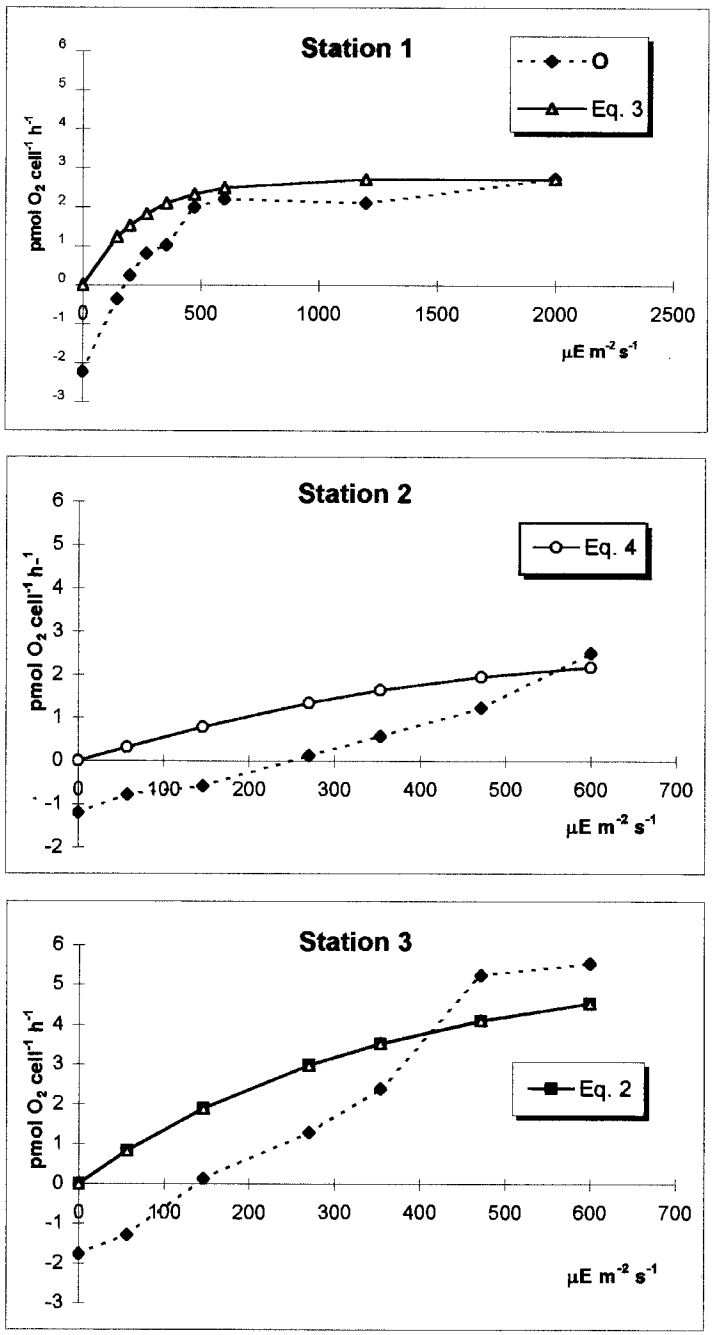

Figure 6. Irradiance-Photosynthesis curves corresponding to July experiments. Values from experiments (O- dashed lines) and data adjustment to one of the models (Equation (2), (3) or (4)) described in the text.

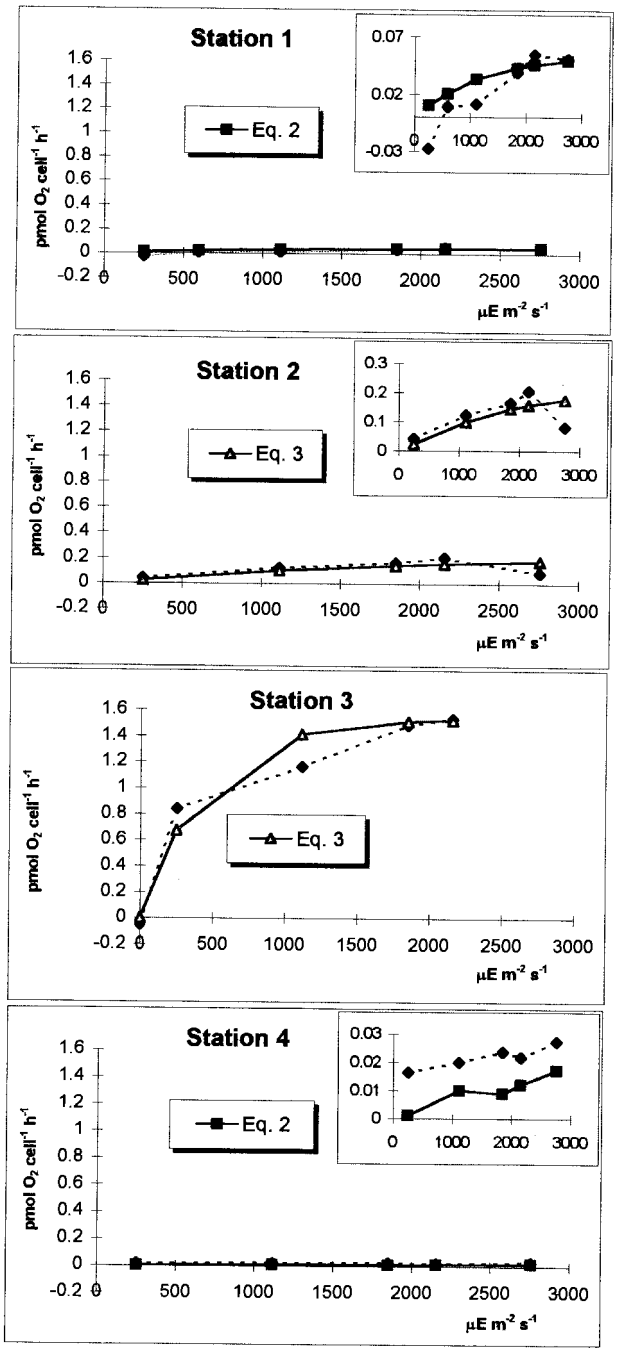

Figure 7. Similar to Figure 6, but for October experiments and with a magnified view (inside boxes) showing the fitting between observed and adjusted data.

cell number and diversity reduction in receiving waters, suggesting mechanical damage of cells associated with environmental factors such as reduction of light penetration, high temperature and periodic presence of some chemicals. Langford (1990) reported lethal effects for many tropical algae with temperatures between 32 and 35 °C. The higher phaeophytin values found could be related to this effect.

Regarding the chlorophyll content by cell, Prézelin *et al*. (1986) observed a depth-dependent pattern where pigment concentration was enhanced with depth. The low light field in Station 4 could be playing the same role i.e., that could be the reason it did not indicate a chlorophyll concentration proportional to cell number, coinciding with García and Purdie's (1992) observation that cell chlorophyll content increased towards low growth irradiances.

The decline in photosynthesis in short term exposures from 35 °C observed in this study is in agreement with Hirayama and Hirano (1970). Li and Morris (1982) and Davison (1991) found that algae growth at low temperatures resulted in higher maximum photosynthetic abilities. In our study, production rates of algae from colder stations (2 and 3) were higher than those from hotter sampling sites, showing also a better tolerance to thermal change. Morris and Glover (1974) observed that the decline in photosynthesis ability was marked in algae during growth at higher temperatures.

Respiration could be influenced by bacterial activity in both darkness and changing temperature experiments, then the measured values are only indicators. Photosynthesis-respiration ratios obtained in this study were higher than those found by García and Purdie (1992) and Humphrey (1979) but coincided with the trends pointed out by Eppley (1972) regarding the genera composition of samples. This author also observed that photoinhibition is higher at elevated temperatures which could be related with the respiration in light conditions recorded in this study.

The irradiance-photosynthesis curves suggest that communities from environments exposed to higher temperatures (>30 °C) required more photons for their net oxygen production. Kana and Glibert (1987) found light harvesting efficiencies (α) decrease in algae with lower growth irradiances, which coincide with results in this study. Nevertheless Pmax values obtained were not small. They were lower than presented by García and Purdie, much higher than those from Franks and Marra (1994) and within the ranges found by Humphrey (1979) and Lewitus and Kana (1994).

The results from light and temperature experiments are complementary in behaviour and trends, but differences in volume and accuracy of methods make detailed comparisons difficult.

Species composition also plays a role. Predominance of some groups such as Pennate Diatoms or Coccolitophorids in experimental samples showed little photosynthetic response relative to more heterogeneous samples from the same station and month. It coincides with Humphrey (1979) who recorded the most pronounced peaks in photosynthetic rates in Centric Diatoms, whereas Pennate gave flatter curves.

Although the results concerning algal community structure did not reach significant differences associated with the variation of water temperature, the bulk photosynthesis experiments indicate alteration in the behaviour of those algal assemblages directly inundated by thermal discharges.

5. Summary

The structure and photosynthetic behaviour of algal assemblages were analysed with respect to the influence of a thermoelectric plant coastal effluent. Different physicochemical conditions were identified among areas with diverse influence to hot water discharges. In general, the structure of the algal community did not show statistically significant differences among the sampling sites, even though cell number, diversity index and chlorophyll concentration were always lower in the outfall than in the water intake station, in addition to the occurrence of some genera.

The results from experiments testing photosynthetic responses to temperature and light intensities showed that the algae from the station receiving hot water presented lower photosynthetic capacity and light harvesting efficiency. This algae also showed lesser tolerance to thermal changes and higher light requirements to reach net oxygen production.

More experimental data and integrated research on natural microalgal populations, mainly on tropical coasts, are necessary to assess alteration in the efficiency and behaviour of these primary producers with respect to human-influenced environmental changes.

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References

Balech, E.: 1967, Microplankton of the Gulf of Mexico and Caribbean Sea. Proj. 382; Ref. 67–10T, Texas A&M. Res. Found. College Station, pp. 144.

Balech, E.: 1987, Los Dinoflagelados del Atlántico Sudoccidental. *Inst. Oceanogr. Esp.* Ed. Publ. Espec. No. 1. Madrid, España.

Bienfang, P. and Johnson, W.: 1980, *Environmental Pollution* (Series A) **22**, 165.

Bordet, F.: 1980, *Cahiers du Laboratoire d' Hydrobiologie de Montereau* **10**, 33 (Trans).

Claustre H. and Marty, J. C.: 1995, *Deep-Sea Res*. I **42**(8), 1475.

Cushing, D. H.: 1976, *Geogr. J.* **142**, 216.

Davis, M. H. and Coughlan, J.: 1978, 'Response of Entrained Plankton to Low-Level Clorination at a Coastal Power Station', in Jolley, R. L., Gorchev, H. and Hamilton, D. H. (eds.), *Water Chlorination: Environmental Impacts and Health Effects*, Ann Arbor Science, pp. 369–376.

Davison, I. R.: 1991, *J. Phycol.* **27**, 2.
Eppley, R. W., Renger, E. H. and Williams, P. M.: 1976, *Estuar. Coastl Mar. Sci*. **4**, 147.
Eppley, R. W.: 1972, *Fisher Bull.* **70**, 1063.
Franks, P. J. S. and Marra, J.: 1994, *Mar. Ecol. Prog. Ser.* **111**, 143.
García, V. M. T. and Purdie, D. A.: 1992, *J. Plankton Res.* **14**(9), 1251.
Geider, R. J. and Osborne, B. A.: 1992, *Algal Photosynthesis*, Chapmand Hall, New York, pp. 250.
Goldman, J. C. and Davidson, J. A.: 1977, *Environ. Sci. Technol*. **11**, 908.
Goldman, J. C.: 1977a, *J. Exp. Mar. Biol. Ecol*. **27**, 161.
Goldman, J. C.: 1977b, *Limnol. Oceanogr.* **22**, 932.
Hamilton, D. H., Flemer, D. A., Keefe, C. W. and Mihursky, J. A.: 1970, *Science* **169**(3441), 197.
Hirayama, K. and Hirano, R.: 1970a, *Mar. Biol.* **7**, 205.
Holm-Hansen, O., Lorenzen, C. J., Holmes, R. N. and Strickland, J. D. H.: 1965, *J. Cons. Perm. Int. Explor. Mer.* **30**, 3.
Humphrey, G. F.: 1979, *J. Exp. Mar. Biol. Ecol.* **40**, 63.
Jolley, R. L., Gorcheu, H. and Hamilton, D. H.: 1978c, *Water Chlorination: Environmental Impacts and Health Effects*, 2. Ann Arbor Science, Michigan.
Kana, T. M. and Glibert, P. M.: 1987, *Deep-Sea Res.* **34**(4), 497.
Langford, T. E. L.: 1990, *Ecological Effects of Thermal Discharges*, Elsevier Applied, Science London, pp. 468.
Lee Chen, Y.-L.: 1992, *Bulletin of Plankton of Japan* **39**, 25.
Lewitus, A. J. and Kana, T. M.: 1994, *Limnol. Oceanogr.* **39**(1), 182.
Li, K. W. W. and Morris, I.: 1982, *J. Exp. Mar. Biol. Ecol.* **58**, 135.
Miller, D. S. and Brighouse, B. A.: 1984, *Thermal Discharges: A Guide to Power and Process Plant Cooling-Water Discharges into Rivers, Lakes and Seas*, British Hydromechanics Research Association, London.
Morris, I. and Glover H. E.: 1974, *Mar. Biol.* **24**, 147.
Navarro, J. N.: 1981a, *Bot. Mar.* **24**, 427.
Navarro, J. N.: 1981b, *Bot. Mar.* **24**, 615.
Navarro, J. N.: 1983, *Bot. Mar.* **61**, 1.
Naylor, E.: 1965b, 'Effects of Heated Effluents Upon Marine and Estuarine Organisms', in Russell, F. S. and Yonge, M. (eds.) *Advances in Marine Biology*, 3, New York Academic Press, London, pp. 63–103.
Platt, T., Gallegos, C. L. and Harrison, W. G.: 1980, *J. Mar. Res.* **38**, 687.
Prézelin, B. B., Putt, M. and Glover, H. E.: 1986, *Mar. Biol.* **91**, 205.
Round, F. E., Crawford, R. M. and Mann, D. G.: 1990, *The Diatoms. Biology and Morphology of the Genera*, Cambridge University Press, 747 pp.
Sanders, J. G., Ryther, J. H. and Batchelder, J. H.: 1981, *J. Ex. Mar. Biol. Ecol.* **49**, 81.
Secretaría de Marina: 1988, Física y Química del Océano, Dir. General de Oceanografia Naval INV. Ocean, F. Q. Informe Técnico, México, **4**, 1.
SEDUE: 1992, Comisión Nacional del Agua. Gerencia Estatal en Veracruz Subgerencia de Admon. Del Agua, No. BOD.734.2.2, México, pp. 18–25.
Tessier, C.: 1990, 'Suivi environnemental des rejets thermiques dans le fleuve Saint-Laurent a Gentilly de 1980 a 1989', *Collection Environnement et Geologie* **11**, 562. Messier, Legendre et Delisle (eds.), Québec, Canada.
Treguer, P. and Le Corre, P.: 1975, Manuel dïanalyse des sels nutritifs dans lï eau de mer. Laboratoire d' Oceanologie Chimique, Universite de Bretagne Occidentale. Brest, France, pp. 110.
Walker, D.: 1990, *The Use of the Oxygen Electrode and Fluorescence Probes in Simple Measurements of Photosynthesis*, Robert Hill Institute, The University of Sheffield, U.K., pp. 1–203.
Weber, C. I.: 1981, *Evaluation of the Effects of Effluents on Aquatic Life in Receiving Water: An Overview*, American Society for Testing and Materials, IAEA (a). U.S.A., pp. 3–13.