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Spatial Heterogeneity and Seasonal Patterns in a Tropical Coastal Lagoon

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ABSTRACT

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This study using multivariate statistical approaches describes the hydrology of a tropical coastal lagoon which is markedly affected by the infiltration of cold nutrient-rich groundwater discharges. Based on the results of cluster analysis, three different zones are distinguished in the lagoon. The inner zone is characterized by low salinity, high nitrate ($>$ 40 μM) and soluble reactive silica concentrations ($>$ 200 μM). This zone is strongly affected by groundwater discharges. The seaward zone is characterized by high salinity and a low concentration of nutrients. The middle zone is characterized by intermediate values of salinity and higher concentrations of soluble reactive phosphorus (3–9 μM) and ammonium (10–15 μM) than those found in the rest of the lagoon. Principal Component Analysis was applied to data collected during each season. The major components of variability in the data were associated with groundwater inputs and internal processes such as the mineralizaton of organic material. The first principal component of the variability was indicated by the salinity gradient, nitrates, and soluble reactive silicate levels, and the second by soluble reactive phosphorus and ammonium. The hydrological dynamic of the Celestun Lagoon was highly influenced by the intensity and frequency of prevailing climatic conditions coupled with biogeochemical processes.

ADDITIONAL INDEX WORDS: *Multivariate analysis, salinity, nutrients, groundwater, tropical lagoon.*

INTRODUCTION

Coastal lagoons are ecosystems with strong spatial gradients concerning the chemical characteristics of the water and of the biological populations present (PRITCHARD and SCHUBEL, 1981; GUELORGET and PERTHUISOT, 1983; KJERFVE, 1986). In temperate coastal lagoons, the changes in spatial heterogeneity follow the seasonal climatic patterns. External factors (such as rainfall, evaporation, wind, daytime) are responsible for these changes. In the North of the Gulf of Mexico, significant variations have been observed in those nutrients associated with the movement of water masses from rivers, tidal transport and frontal passages (CAFFREY and DAY, 1986). On the other hand, deviations from the concentrations of nutrients predicted by the conservative mixing of the fresh and sea water are interpreted as indicators that the system is as either a source or a sink (OFFICER, 1979; SMITH, 1984). A simple one-dimensional approach does not adequately represent changes in the relative importance of the processes affecting water column characteristics (FOURQUEAN *et al.*, 1993) in a spacial and temporal context.

COMIN *et al.* (1991) describes high variability in the chemical and biological features of coastal lagoons in Northern Spain as a result of short-term changes in water discharges. The study of a variable in a one-dimensional approach is useful to understand those factors controlling the changes found in this variable (MENENDEZ and COMIN, 1989). However, a multi-dimensional approach, considering the relationships between different variables, is necessary to obtain a satisfactory understanding of the functioning of coastal lagoons with high heterogeneity (LEGENDRE and TROUSSELLIER, 1988).

Multivariate analysis provides statistical methods to enable the study of the relationships between variables and to establish a hierarchy of the importance of their variability. Because several variables can be considered simultaneously, interpretations can be made that are not possible using univariate statistics. This approach has been recommended because one can extract, interpret,

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or reveal structures that would otherwise be overlooked or misinterpreted (BEALS, 1973; GREEN and VASCOTO, 1978).

In tropical zones, little is known about the factors which control the hydrologic heterogeneity of coastal lagoons. Celestun Lagoon is located in the South of the Gulf of Mexico. In contrast to other tropical areas where two seasons are identifiable (dry and rainy), Celestun Lagoon experiences three typical climatological seasons. These are a dry season (March–May, 0–50 mm rainfall), rainy season, (June–October > 500 mm) and "nortes" season from November to February, characterized by strong winds (> 80 km/hr), little rainfall (20–60 mm) and low air temperatures (< 22 °C) (SARH, 1989).

In this paper, multivariate analysis was applied to data concerning the water characteristics of the Celestun Lagoon in order to examine seasonal changes of spatial heterogeneity of the water masses. The relationships between external and internal factors are also discussed.

METHODS

Study area

Celestun Lagoon is a long (21.2 km), narrow (0.5–2.4 km) and shallow (0.5–3 m) coastal lagoon located parallel to the coast line on the western shore of the Yucatán Peninsula (20°45'N; 90°25'W) (Figure 1). The contact with the sea is made *via* a 410 m wide entrance at the southern edge. The lagoon bottom is almost flat. A tidal channel (100 m wide, 15 km long) is the major bathymetric characteristic. The soil in the region is karstic and highly permeable and there are no rivers present. Freshwater inputs to the lagoon occur mostly through groundwater discharges (GD) *via* springs located in the northern part of the lagoon. The climate in the region is hot and semi-arid with the annual mean temperature being 26.2 °C, but varying between 24 °C in February to 35 °C in August (Figure 2). The mean annual rainfall is 747 mm.

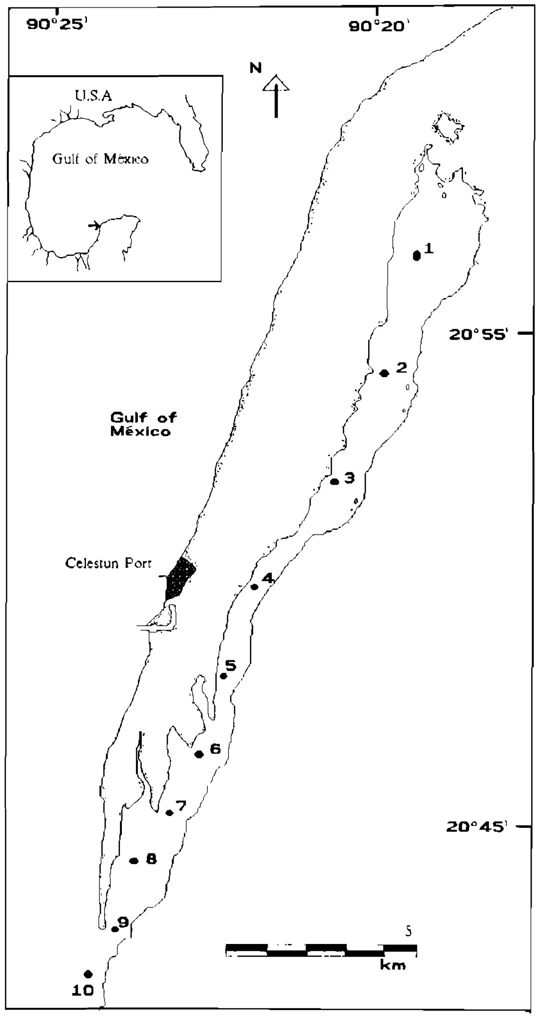

Figure 1. Location of the Celestun Lagoon, and sampling sites. Groundwater discharge (GD).

Sampling and Water Analysis

Monthly surveys were carried out for one year at ten stations located along the lagoon (and one present at groundwater discharge) (Figure 1). At each station, temperature (analogical thermometer) and pH (pH meter PHY-9401) were measured *in situ*. In order to measure salinity (induction salinometer, Khalsico RS-9) and dissolved oxygen (Winkler titration method), water samples were collected from the centre of the water column (although no stratification in the water column has been observed; CAPURRO, 1985). Water samples used for analysis of dissolved inorganic nutrients were filtered through a 0.45 μm membrane filter. The water was preserved with chloroform (2.5 ml per litre of water; HO *et al.*, 1970) and stored at 4 °C. Analyses were performed in the laboratory not more than 2 days after the collection of the samples. Soluble reactive phosphorus (SRP) corrected for arsenate/silicate interference was determined using the molybdate-

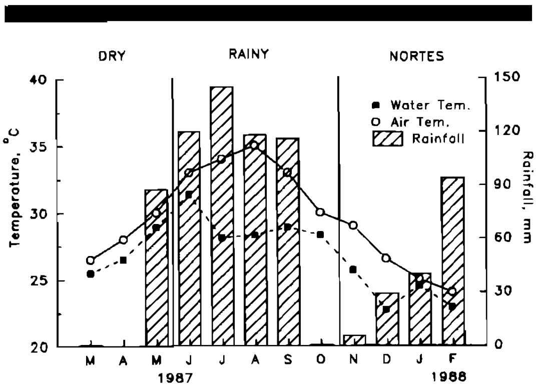

Figure 2. Monthly variation of air and water temperature, and rainfall during the study period.

Table 1. *Mean values and ±1 standard error (in parentheses), of dissolved oxygen (D.O.), salinity (S), nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+), soluble reactive phosphate (SRP) and reactive silicate (SRSi), in the lagoon, groundwater discharge (GD), and seawater (SW), during the study period.*

	D.O. mg/l	S ‰	NO_3^- μM	NO_2^- μM	NH_4^+ μM	SRP μM	SRSi μM
Lagoon	4.83	25.4	7.67	0.44	5.41	1.98	54.1
	(0.46)	(0.91)	(1.36)	(0.06)	(0.69)	(0.72)	(15.6)
GD	0.63	3.0	51.8	1.38	1.85	0.45	168
	(0.03)	(0.01)	(11.7)	(0.22)	(0.36)	(0.10)	(27.1)
SW	6.65	34.5	1.5	0.48	3.0	0.43	5.4
	(0.19)	(0.21)	(0.85)	(0.02)	(0.48)	(0.25)	(1.2)

blue method proposed by MURPHY and RILEY (1962) and as modified by STRICKLAND and PARSONS (1972). Ammonium (NH_4^+) was determined by the phenolhypochlorite method (SOLORZANO, 1969). Soluble Reactive Silica (SRSi) was determined using the molybdenum blue method with ascorbic acid acting as reductant; nitrogen in the form of nitrite (NO_2^-) was determined by using sulphanilamida in an acid solution method; and nitrate (NO_3^-) was measured as NO_2 after reduction in a Cd-Cu column (PARSONS *et al.*, 1984). Rainfall data corresponding to Celestun Port (Figure 1) were provided by SARH (1989).

Pattern Analysis

In this study, multivariate classification and ordination were employed as the main analytical tools. These pattern analysis techniques are capable of extracting meaningful information from a complex assortment of data (WILLIAMS, 1976). Furthermore, they can be used to objectively evaluate differences in water column characteristics along spatial and temporal gradients (GREEN and VASCOTTO, 1978; PEARSON and ROSENBERG, 1978).

In classification analysis, objects (for the purposes of this study the sampling sites) are placed in groups, first by similarity measure and then a grouping algorithm. The reduction in the data is derived from the formation of groups ($g < n$) out of n objects. The two most similar objects are joined into a group, and the similarities of this group compared to all other units are calculated. Repeatedly, the two closest groups are combined until only a single group remains. The results are usually expressed in a dendrogram—a two-dimensional hierarchical tree diagram representing the complex multivariate relationships among the objects (JAMES and MCCULLOCH, 1990).

The ordination analysis reduces the dimensions of a single data group by producing a small number of abstract variables which are linear combinations of the original variables. Often, most of the variations can be summarized with only a few components and the data matrix can be displayed effectively on a two- or three-dimensional graph that uses the components as axes (JAMES and MCCULLOCH, 1990). Ordination consists of plotting n points (observations) in a space of fewer than p dimensions (where p is the number of variables), in such a way that the most important features of the p-dimensional pattern are retained because only a small number of eigenvalues add up to account for most of the total variance (PIELOU, 1969). This allows the visualization of patterns of multidimensional distribution and helps to determine the major components of variation in a data set. The method is an appropriate technique when there are low levels of variation and when the changes between samples are gradual (MACKAS and SEFTON, 1984). Principal Component Analysis (PCA) transforms the original correlated variables into orthogonally rotated uncorrelated variables. All PCA's were done on the correlation matrix.

Starting with a data matrix in which all the data of the annual cycle are included, the columns represent the physical and chemical variables while the rows identify the sample stations. In order to elucidate the effects of changes in weather conditions throughout the year, three analyses were also performed using the data corresponding to each season (dry season, rainy season and "nortes" season). Since concentrations and levels of each hydrologic feature have different orders of magnitude, all data were log-transformed as $X' = (\log(x + 1))$ (NOY-MEIR, 1973).

RESULTS

General Characteristics

The annual range of water temperature was 9 °C with the highest values occurring in June (31.4 °C) and the lowest during February (22.4 °C). The maximum difference between air and water temperatures occurred during the rainy season (Figure 2) due to groundwater inputs which had lower temperatures than those found in water lagoon (Table 1).

In the Celestun Lagoon, horizontal gradient of salinity was observed throughout year. In the inner zone of the lagoon, salinity was always lower than 20‰ while in the seaward zone it was higher than 30‰ (Figure 3). The lowest salinity was observed in August after the rainfall peak. At this time, the mean salinity of the lagoon was 19.6‰ (Figure 3). During the "nortes" season, the mean salinity was <25‰ throughout the lagoon. The highest salinity was observed at the end of the dry season with mean concentrations of 30‰ occurring in May. The mean pH values follow an inverse pattern when compared to mean salinity with high values (8.3) in the inner zone during the rainy season and low values (6.8) during the dry season in the middle segment of the lagoon.

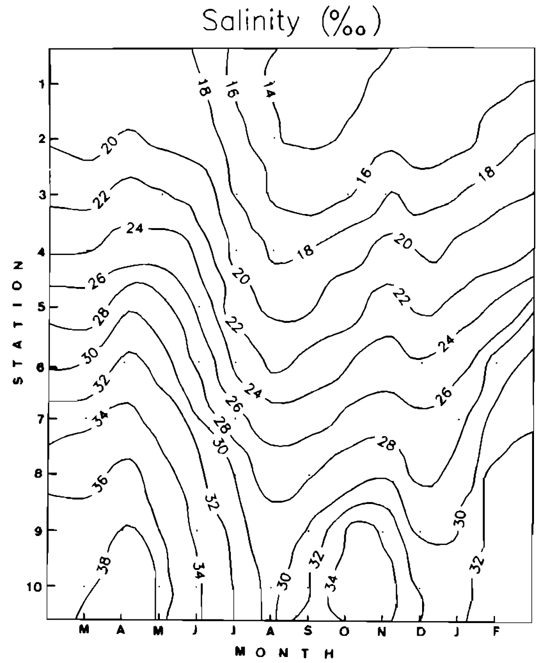

Figure 3. Space-time diagram of salinity (‰), during the study period.

The annual dissolved oxygen concentrations ranged from 2.5 mg/l in the inner zone to >8.5 mg/l in the seaward zone during the year. The highest values occurred during the "nortes" season.

The highest NO_3^- concentrations were observed in the inner stations (> 40 μM). NO_3^- values increased at all stations at the start of the rainy season. During "nortes" season, the highest concentration (10 μM) was observed in the middle of the lagoon. Nitrate concentrations decreased from the inner zone of the lagoon seawards, at all times during the annual cycle.

Ammonium concentrations in the lagoon were higher than those of the inflowing groundwater and seawater (Table 1). The highest NH_4^+ concentrations were observed in July (15 μM) and February (11 μM) in the central part of the lagoon.

The spatial and temporal distributions of soluble reactive phosphorus (SRP) differed from those of NO_3^- and NH_4^+. The SRP concentrations were higher (> 9 μM) in the inner and middle zones of the lagoon during the "nortes" season (November–February) than during the rest of the year. During the rainy season, the maximum SRP (2 μM) was observed in the central part of the lagoon at the beginning of the season. Thus, the highest concentrations of SRP were not evidently associated with groundwater discharges.

Soluble reactive silica (SRSi) concentrations ranged from <1 to 280 μM during the year. They followed the same spatial and temporal patterns as NO_3^-, decreasing from the inner to the seaward zone of the lagoon and increasing between the dry and rainy season. During "nortes" season, the SRSi fluctuated alternately from <10 μM to >200 μM.

Classification Analysis

The cluster analyses showed three consistent groups of stations throughout the year (Figure 4). Stations 1, 2 and 3 formed a group in the innermost zone of the lagoon; another group was formed by the stations 4, 5, 6 and 7 in the middle zone of the lagoon; while the third group was formed by stations 8, 9 and 10 located on the seaward side. The three groups of stations were grouped down to 60% of dissimilarity. The next grouping

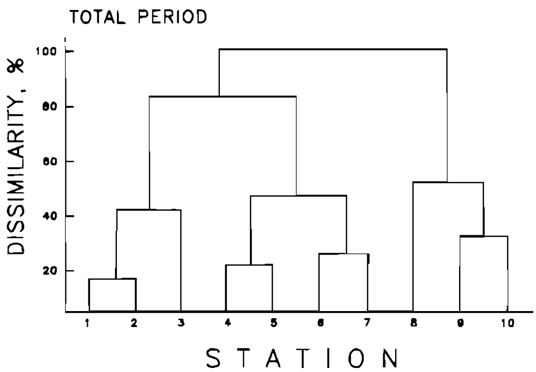

Figure 4. Dendrogram of hierarchical clustering of the sampling stations using annual data matrix.

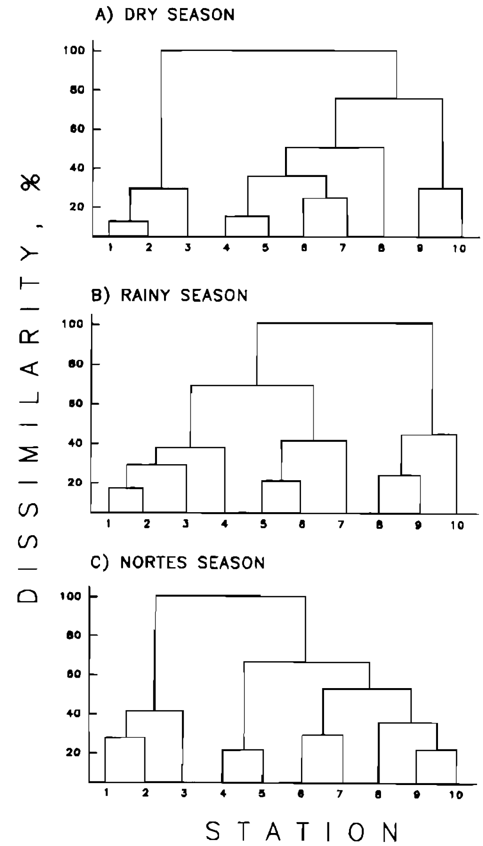

Figure 5. Dendrograms hierarchical clustering of sampling stations using the data matrix of dry season (A), rainy season (B) and "nortes" season (C).

was between the inner and middle stations at 83.3% dissimilarity level.

Cluster analysis was applied separately to the data from each season to show not only changes in dissimilarity percentages, but to demonstrate the differences in the stations that formed each group throughout the year. During the dry season, stations 4 to 8 were grouped in the middle zone (51.6% of dissimilarity) together with the sea zone stations (9 and 10) at 78.7% of dissimilarity (Figure 5A). During the rainy season, the inner zone included station 4 at 39% of dissimilarity and this was grouped with the middle zone at 69.5% dissimilarity (Figure 5B). During "nortes" season, the structure changed and the seaward zone incorporated station 6 and 7 at 57.2% of dissimilarity (Figure 5C).

Ordenation Analysis

The Principal Component Analysis (PCA) applied to the annual data (Figure 6) showed that the first two principal components explained 60% of the total variation (Table 3). The first component (41%) was associated with high negative loadings of salinity and dissolved oxygen, and positive coefficients for NO_3 and SRSi. This inverse relationship was due to the low salinity (3–4 ‰), the dissolved oxygen (< 1 mg/l), and the high concentrations of NO_3 (40–80 μM) and SRSI (20–200 μM; Table 1) in groundwater. Thus, the first axis can be associated with the salinity gradient. The second principal component (19%) (Table 2) showed a high positive coefficient for pH and negative loading for SRP (Figure 6). This axis demonstrated the lack of correlation between SRP and salinity gradient (Table 3) and could be associated with biologically mediated processes.

The PCA's applied to data from each season showed the changes in the variance explained by each component (Table 3), and the relationship between different variables (Figure 7). For the dry season, the first two components explained 83% of the total variance. The first component (58% of total variance) was associated with high negative salinity, dissolved oxygen coefficients and positive loadings of SRSi and pH, while the second component (25%) gave high loadings to temperature and inorganic nitrogen (Figure 7A). This difference indicated the major opposing influence that the salinity gradient had on the relationships between the variables analyzed.

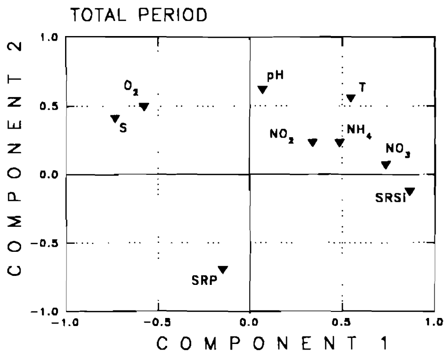

Figure 6. Projections of physico-chemical variables onto the space defined by the first and second principal components (the coordinates are the scores relative to each variable) corresponding to PCA annual. (n = 360).

For the rainy season data, the first two components explained 63% of the total variance. The first component (38%) was associated with salinity, dissolved oxygen, NO_3 and SRSi and the second component (25%) was associated with SRP, NH_4^+ and pH (Figure 7B). For the "nortes" season data, the first two principal components accumulated the same percentage (63%) of the total variance as it occurred during the rainy season. However, the first component was associated with dissolved oxygen, temperature, SRSi and SRP, and the second with nitrogen oxidized forms, dissolved oxygen and temperature (Figure 7C).

The differences in the variance associated with the first and second component were clearly lower for the data of the rainy and "nortes" seasons than during the dry season (Table 2). These differences also illustrate the relative importance of external factors (rainfall, winds, temperature) and internal processes (resuspension organic material, mineralization, primary production) during the different seasons of the year.

DISCUSSION

Based on the results of the cluster analysis, three zones can be identified in the lagoon, according to variations in physical and chemical characteristics present in a year. The inner part of the lagoon (including stations 1, 2 and 3) was characterized by low salinity and high NO_3 and SRSi. Clearly, it was strongly affected by groundwater discharges. As expected, the seaward zone of the lagoon (including stations 8, 9 and 10) is characterized by high salinity and low nutrient concentrations. The zone in the middle of the lagoon (including stations 4, 5, 6 and 7) was characterized by intermediate values of salinity as expected; however, concentrations of SRP and NH_4^+ were

Table 2. *Explained variance of the first three components from PCA analysis, during the year and in each season.*

Period	Explained Variance (%)			
	Dry	Rainy	Nortes	Year
Component I	58	38	38	41
Component II	25	25	25	19
Component III	8	12	12	15
Total	91	75	75	61

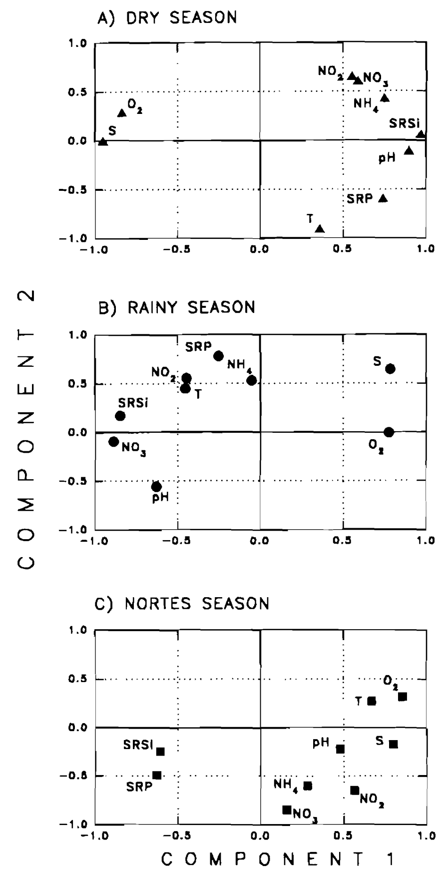

Figure 7. Projections physico-chemical variables onto the space defined by the first and second principal components (the coordinates are the scores relative to each variable) corresponding to PCA of (A) dry season (n = 90), (B) rainy season (n = 150) and (C) "nortes" season (n = 120).

Table 3. *Annual correlation matrix of physical and chemical variables. The data are log-transformed ($X' = \log(x + 1)$). Significance level: $P = 0.01^*$, $P = 0.001^{**}$.*

	T	S	OXI	NO_3	NO_2	NH_4^+	SRP	SRSi	pH
T	1	0.01	0.26	0.30**	0.10	0.42**	0.41	0.45**	0.04
S		1	0.50**	0.29	0.05	0.09	0.08	0.49**	0.67**
OXI			1	0.43**	0.13	0.10	0.20	0.68**	0.34*
NO_3				1	0.54**	0.26	0.01	0.41**	0.14
NO_2					1	0.40**	0.06	0.28	0.12
NH_4^+						1	0.11	0.36**	0.01
SRP							1	0.11	0.09
SRSi								1	0.21
pH									1

higher than in the rest of the lagoon as a consequence of non-conservative behaviour of these compounds probably due to biological processes.

These zonations represent a typical pattern found in coastal lagoons with one inlet for water exchange with the sea and freshwater discharges occurring at the landward end (KJERFVE, 1986; GUELORGET and PERTHUISOT, 1992). The salinity gradient is relatively stable from the freshwater input zone to the seaward zone. The differences between the grouping of stations of different seasons reflect the changes of this spatial pattern during the year, due to changes in the relative magnitude of the freshwater inflows versus those of the seawater and biogeochemical processes.

Thus, during the dry season the middle zone includes five stations (4 to 8) with low dissimilarity values suggesting little movement of water as shown by the strong salinity gradient (Figure 3) and the extension of the water characteristics in the central part of the lagoon to a larger area than during the "nortes" and rainy seasons.

The high salinities and NH_4^+ concentrations were favoured by increased air temperatures (a seasonal correlation), very low freshwater inflows and the seawater influence (Figure 3), as shown by the group formed between the middle and seaward stations (Figure 5A). During the rainy season, station 4 is grouped with stations 1, 2 and 3 (Figure 5B). This is due to the freshwater inputs during this season which extend their influence further down the lagoon. During the "nortes" season, the seaward group incorporated stations 4 and 5 with a group formed by stations 6 to 10 during the dry and rainy seasons. This clustering represented a greater inflow of seawater into the lagoon and an increase in the mineralization processes, as shown by the salinity gradient (Figure 3) and the high inorganic nitrogen concentrations (50 μM)

The distinct station assemblages between seasons indicates a strong relationship between external factors (temperature, freshwater *versus* saltwater inflows and atmospheric fronts and storms) and internal biogeochemical processes (primary production, mineralization). These interactions favored the spatial heterogeneity within the lagoon during the rainy season and, therefore, the primary production as shown by the high oxygen concentrations and the non-conservative behaviour of the nutrients. However, during the dry and "nortes" seasons, the interactions favour mineralization processes as shown by the O_2 (2 mg/l), NH_4^+ (20 μM) and SRP (9 μM) levels.

The seasonal changes in external and internal factors that can affect the relationships between physical and chemical variables were observed in the differences between the results of the PCA performed separately with data from each season (Figure 7). The major components of variability in the data were associated with groundwater inputs and internal processes in the lagoon. The first component was indicated by the salinity gradient NO_3 and SRSi levels, and the second by SRP and NH_4^+ concentrations. These patterns indicated a dynamic and heterogeneous pattern of nutrients in the different zones of the lagoon during different times of the year. As the climate changed significantly throughout the year, one would expect greater annual fluctuations in the lagoon when the data of the year were analysed together rather than separately according to season. However, the results show that the processes contributing to the variability of the data for each season and each group of stations are buffered in the PCA analysis of the data taken throughout the year. This means that the differences between data of different seasons (Figure 5 and 7) hide when the annual database was analysed. This pattern can be extracted through the analysis of all variables working on the same way as multivariate approach does.

The results obtained from the differences between the 3 seasons and 3 groups should reveal spatial and seasonal patterns. The differences between seasons and groups were due to the coupling of the intensity and frequency of external factors such as rainfall, winds, frontal systems, and biogeochemical processes such as primary production, mineralization, conservative and nonconservative behaviour of the nutrients, fertilization and bioturbation. If these patterns are to be repeated year-after-year a microsuccession process should be inferred.

During the dry season, the strong salinity gradient, seawater inflow and high water temperatures explained the high loadings of salinity and SRSi. However, the association with inorganic nitrogen suggests remineralization and denitrification processes (FLINT and KAMYKOWSKI, 1984; BOWDEN, 1986; KEMP *et al.*, 1990). During the rainy season, the low salt and high NO_3 and SRSi concentrations of the groundwater have a strong influence on the lagoon contributing to the meaning of the first principal component of the PCA. However, the SRP and NH_4^+ changes were not associated with freshwater inputs, so, other processes such as primary production, plant and animal recycling were thought to be responsible for their concentrations (TEAGUE, 1983; WARD and TWILLEY, 1986; FOURQUREAN *et al.*, 1993). An interesting feature is the change in loading sign from the dry to rainy season. During "nortes" season, the high loadings of dissolved oxygen, temperature, SRP and SRSi (Figure 7C) could be explained by the influence of the strong cold winds that mix the water column and resuspend organic material from the sediments supporting remineralization processes. This phenomenon was observed by CAFFREY and DAY (1986) in Louisiana.

SRP and SRSi concentrations show important changes during the "nortes" season due to resuspension of sediments, inflow and outflow of seawater in short time periods, and biological activity, *e.g.*, bird colonies. In temperate and subtropical coastal zones, nutrient regimes with large assemblages of birds differ significantly from those lacking such colonies (POWEL *et al.*, 1991; BILDSTEIN *et al.*, 1992). In Celestun, this most probably occurs during the "nortes" season (November–February) when the concentrations of SRP reach the maximum ($> 9\ \mu M$) and bird populations reach densities of 5,000 individuals/km^2 in the inner zone (BARRIOS-ESPINO, 1988). The changes of SRSi concentrations were due to GD inputs and high amounts of silica removed from the water along the lagoon, particularly in the middle and seaward stations, probably as a consequence of high particulate matter in these zones, which suggests abiological removal by adsortion onto suspended sediments (LISS and SPENCER, 1970; BIENG *et al.*, 1985).

Multivariate statistics approach applied to hydrological variables of Celestun Lagoon show that seasonal changes of the spatial patterns of physical and chemical variables are controlled by climatic changes and internal biogeochemical processes. This is in contrast to other coastal aquatic ecosystems with groundwater inputs where external factors are the major causes of variability (D'ELIA *et al.*, 1981; JOHANNES and HEARN, 1985).

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