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ANNUAL PATTERNS OF NUTRIENTS AND CHLOROPHYLL IN A SUBTROPICAL COASTAL LAGOON UNDER THE UPWELLING INFLUENCE (SW OF BAJA-CALIFORNIA PENINSULA)

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Abstract. The coastal lagoon of Bahía-Magdalena, located on the west coast of the Peninsula of Baja-California, is a subtropical ecosystem with an arid climate and very little freshwater input. During the 2005-2011 period the thermohaline properties varied between cold and warm half-yearly periods. They were influenced by the Transitional Water mass transported by the South California Current from February to July and by the Subtropical Surface Water from August to January. The nutrient concentrations increased (viz up to 16 µM of nitrate) from March to June, when the upwelling index was the highest. Similarly, the inter-annual variation of chlorophyll-*a* showed a six-monthly pattern with the highest average monthly concentrations being found in June (5 $mg \cdot m^{-3}$ *in situ* or 8 $mg \cdot m^{-3}$ based on satellite information) and the lowest in December-January. A spatial zoning was also observed in the lagoon with a shallow inner zone that is warmer and richer in chlorophyll-*a* than the deeper closed mouth area. In the Bahía-Magdalena lagoon a spatial-temporal division into two zones and two seasons was repeated year after year with only minor differences. During the first semester in the outer zone, years 2006 and 2007 were colder and nutrient rich while 2010 was warmer, according to the upwelling conditions in the Southern California Region. Hence, among the coastal lagoons that present a prevailing marine influence, the coastal system of Bahía-Magdalena corresponds to an unusual type of subtropical coastal lagoon where the nutrient input is mainly due to upwelling phenomena.

Keywords: inter-annual, intra-annual, biogeochemistry, California Current, chocked lagoon, Bahía-Magdalena, Pacific coast, Mexico.

1. - INTRODUCTION

Continental shelf waters represent 8% of the Earth's oceanic surface but it is where nearly 25% of the primary sea production occurs (Walsh, 1989) and where a variety of types of coastal systems, which determine the exchange between land and sea, are found. In these systems, coastal lagoons, making up 13% of the coastal areas worldwide, are predominant (Kjerve 1994). Coastal lagoons are inland water bodies, usually oriented parallel to the coast, separated from the sea by a barrier and connected to the ocean by one or more restricted inlets (Kjerfve and Magill 1989). In the subtropical climate region bordering, as delimited by Perillo et al. (1999), the Tropics of Cancer and Capricorn (23.5° latitude) and the temperate region (40° latitude), coastal lagoons are subject to a wide climatic diversity ranging from monsoons to desert-like conditions. In all of these climate types the availability of nutrients restricts biological richness (Salomons et al., 2005). Despite this fact, subtropical coastal lagoons have not been studied extensively from a biogeochemical viewpoint, rather it is the ecological aspects that have undergone a more in-depth examination (Kjerfve, 1994).

The wide variety of subtropical coastal lagoons have been classified according to the type of entrance channel into choked, restricted or leaky lagoons (Perillo et al., 1999), distinguished by the freshwater or marine prevailing influence (Abreu et al., 2010) or by the depth and substratum characteristics (Nichols and Boon, 1994). All the same, biological productivity in subtropical coastal lagoons is influenced by hydrodynamic processes such as water residence time (Badylak and Phlips 2004; Phlips et al., 2012), tidal mixing (Abreu et al., 2010) and water column turbidity (Caffrey et al., 2007). In addition to hydrographical factors, the type of littoral vegetation, i.e. salt marsh, mangle, seagrass and seaweed, is also relevant (Phlips et al., 2012; Badylak and Phlips 2004) as is the presence of populations of filtering macro-invertebrates, crustaceans and fishes, which may regulate phytoplankton dynamics (Badylak and Phlips 2004; Jiang et al., 2012).

A key factor in the primary production of subtropical coastal lagoons is nutrient input where the fluvial contributions may be essential (Coutinho and Mello 2011, Phlips et al., 2012). Upwelling events, rather than continental sources, are the main origin of nutrients transported to the photic layer (Hutchings et al., 1995). So, in the choked, restricted, and leaky lagoons of the arid regions found along the Pacific coast of Mexico (Gilmartin and Relevante, 1978) and southwestern Australia (Hodgkin and Lenanton, 1981), the new nutrients are principally supplied from the sea.

In Mexico there are 124 coastal lagoons (Lankford 1977) 60% of which are situated in the subtropical region and 50% on the California Peninsula and its Gulf. The lagoons located on the western shore of Baja-California Peninsula (32-23°N) from the San-Quintín lagoon (40 km^2) to the north to the Bahía-Magdalena lagoon (565 km^2) to the south are under the sea influence of the California Current. In this coastal zone the climate is dry and arid with northerly winds prevailing throughout the year. However, to the south of southern parallel 28°N south-westernly and westernly winds are common in summer and autumn (Zaitsev et al., 2010), which modifies the coastal hydrodynamic (Durazo et al., 2005; Durazo et al., 2011). The largest, deepest and southernmost lagoon of the Baja-California Peninsula, Bahia-Magdalena, is located in this area

Due to its wealth of marine resources, the ecological aspects of the aforementioned lagoon were studied extensively, as summarized in the review of Funes-Rodríguez et al. (2007). The nutrient cycle, however, received very little attention. Although the Bahía-Magdalena is the most well known system in the western Californian region, the inter- and intra-annual patterns of nutrient dynamics and, consequently chlorophyll-*a* concentrations, still need to be examined in depth. The research carried out, as little as it is, points to the local importance of coastal upwelling (Álvarez-Borrego et al., 1975) and tidal currents (Acosta-Ruiz and Lara-Lara, 1978; Guerrero-Godínez et al., 1988) in the fertilization of the lagoon. On a large scale, the seasonally high biological production in the western lagoons of the Baja-California Peninsula might be connected with the conditions in the southern boundary of the California Current System (Durazo and Baumgartner, 2002; Durazo et al., 2005).

Therefore, in relation to nutrient input and phytoplankton activity (from chlorophyll levels), in the coastal lagoon of Bahía-Magdalena it is hypothesized that, as result of a prevailing marine influence, the fertilization process inside this lagoon is mainly due to coastal upwelling. In this way, the objectives are as follows: (i) to identify and characterize the main intra-annual periods highlighting the influence of the water masses that yearly are present in Bahia-Magdalena, in particular, Sub-Arctic Water, Equatorial Subsurface Water and the mixing of both of them, the Transitional Water; and (ii) to describe the inter-annual changes in the lagoon and to explore their relationship with the California Current System. These objectives are based on forty-three sampling cruises with a bimonthly frequency and 8-day composite satellite information for Surface Sea Temperature and chlorophyll-*a*. Data were used to analyze the seasonal and inter-annual variations for a period of seven years: from 2005 to 2011.

2. - MATERIAL AND METHODS

2.1. - Study area

The Bahía-Magdalena is a subtropical lagoon located on the southwestern coast of the peninsula of Baja-California (Figure 1). Following the classification system for Mexican lagoons (Lankford, 1977), Bahía-Magdalena has a tectonic structural origin and is a choked short inlet type of coastal lagoon (Perillo *et al*., 1999). The lagoon area covers 565 km^2 with a total water volume (low-high tide) of 6.8-8.1 km^3 (Sánchez-Montante *et al.,* 2007). The lagoon is separated from the

Pacific Ocean by Margarita and Magdalena islands and sand bars that are protected from ocean swells. The inner zone occupies half of the lagoon surface and is characterized by shallow channels (<10 m in depth) surrounded by extensive mangrove areas. The deeper outer zone is connected to the ocean through a mouth 5.6 km wide and 38 m in depth. The sediment of the lagoon is relatively homogeneous with fine and very fine sands, except in the mangrove swamp area where sludge is abundant (Sanchez *et al*., 2010).

The offshore seawaters in Western Baja-California are under the influence of the southern boundary of the California Current; NW winds prevail during most of the year and frequent and intense upwelling events occur from April to June (Zaitsev *et al*., 2003; Cervantes-Duarte *et al.,* 2010). In Bahía-Magdalena the weather is semi-arid. Air temperature ranges from 14° C in January to 32° C in August-September (Sánchez *et al*., 2010). The average annual precipitation varies between 48 and 153 mm·yr^{-1}, collected mainly during summer (Sánchez *et al*., 2010). The lagoon does not receive river inputs and the continental freshwater sources are temporary streams. The tidal regime is semidiurnal and its range is microtidal: 0.4-2.3 m (Obeso-Nieblas *et al*., 1999). The phytoplankton consists mainly of diatoms and dinoflagellates (Garate-Lizarraga *et al.,* 2007).

The population around the lagoon numbers approximately 10,000 inhabitants concentrated in the towns of Puerto-San-Carlos and Puerto-Adolfo-López-Mateos, whose main economic activity is artisanal fishery and the processing of tuna and sardine. The first of the two ports, Puerto-San-Carlos is also used to embark phosphorite, extracted from ores of neighboring inland areas.

2.2. - Coastal cruises

Forty-three one-day sampling cruises were carried out in the lagoon of Bahía-Magdalena during the period from 2005 to 2011 with a bimonthly frequency. The water column samples were taken aboard CICIMAR-XV and CICIMAR-XXX research boats, during ebb tide conditions, in fourteen stations in Bahía-Magdalena lagoon (Fig.1). Four of the stations were located in the outer or oceanic zone (St. A-D; >10 m depth) and the remaining ten are shallows (≤10 m depth) and correspond to the inner zone (St. 0-9) which is near to the littoral channels and mangroves where the freshwater inputs should occur. Vertical profiles of temperature and salinity were obtained at each station using a CTD Sea-Bird 19-Plus. Moreover, water samples from the surface and bottom were collected, but only surface samples were taken in the shallow stations (St.4-7), using 5-L General Oceanic Niskin bottles. Subsamples for the determination of nutrient salts and chlorophyll-*a* were sampled from the bottles and refrigerated at 4° C to be processed in the port laboratory during the same day.

Air temperature in the lagoon was measured at the coastal meteorological station of San-Carlos (Fig.1). Data were provided by the Mexican “Comisión Nacional del Agua”.

2.3. - Sampling treatment and analyses

Immediately after arrival at the port water samples were filtered using a Millipore system with fiberglass Whatman GFF filters of 25 mm in diameter. The content of the filter was used to extract the chlorophyll according to the procedure of Venrick and Hayward (1984) and next to quantify the chlorophyll concentration according to the Jeffrey and Humphrey (1975) method, using a Spectronic Genesys-2 spectrophotometer. One aliquot of the filtered water was used to determine the concentrations of ammonium, which were analyzed within 6 hours of collection. Another part was stored in a freezer at -50° C for the subsequent analysis of nitrite, nitrate and phosphate. These nutrient salts were determined with the standard spectrophotometry method according to Strickland and Parsons (1972) using a Spectronic Genesys-2 device. The precision from ten replicate analyses was ±0.1 mg·m^{-3} for chlorophyll, ±0.1 μM for nitrate and ammonium, ±0.01 μM for nitrite and ±0.03 μM for phosphate.

The spatio-temporal division of lagoon in two zones and two seasons was tacked by water termohaline properties and biochemical characteristics one way ANOVA test analysis of principal components (PCA) applied to the seven years period.

2.4. - Satellite and upwelling index information

Eight-day composite data for Sea Surface Temperature (SST) and chlorophyll *a* were used to analyze seasonal and inter-annual variation during the 2005-2011 period. Data were collected in the outer zone of the lagoon from the satellite MODIS-AQUA, Level-3 with 4x4 km of spatial resolution available from ocean color home page: http:www.oceancolor.gsfc.nasa.gov/cgi/13. *In situ* data of SST and chlorophyll-*a* from the deepest stations in the outer zone of the lagoon (St. A-D) were averaged to be compared with the satellite data.

The periods of relaxation and intensification of the upwelling events were defined from the coastal upwelling index (UI) averaged every 8 days based on the data obtained daily from the Pacific Fisheries Environmental Laboratory database (http://www.pfeg.noaa.gov/pfel/about_pfel.html).

The inter-annual variability of cold and warmer events was described on the basis of the Multivariate ENSO Index (MEI) and SST anomaly for the 2005 to 2011 period.

3. – RESULTS

3.1. – Hydrographical conditions: thermohaline variables

The sea surface temperature data in the Bahía-Magdalena lagoon come from *in situ* measurements (IST) recorded during sampling cruises and from satellite measured values (SST). The results are shown in Figure 2 where the IST averaged for the four stations of the outer lagoon zone is compared with the SST grid of this outer zone on the same day of the cruise. Temperature (°C) from satellite and *in situ* are used both without distinction due to the correlation between their data was significant:

$$SST = 3.01 + 0.92 \cdot IST \quad (r = 0.94; n=43; p<0.05) \qquad (1)$$

The temperature range applied to this equation was 16-28° C and close to these limits. As observed in Fig.3, satellite estimations tend to be underestimated (overestimated) when the *in-situ* temperature is low (high). Hence, during the period exhibiting the lowest annual temperature (winter-spring), the *in-situ* values are sometimes lower than the estimates recorded by satellite, while in the other period (summer-autumn) the opposite occurs (Figure 3).

Intra-annually the temperature in the lagoon of Bahia-Magdalena, according to both IST and SST, presented a markedly seasonal pattern with peaks from August to October and minima between March and May. There were no significant changes observed between surface and bottom temperatures ($p<0.05$; Table 1) in the lagoon and in the water column, the stations nearest to the mouth were the coldest during the first half of year (Table 1). Of the two lagoon zones, the outer deeper oceanic zone had lower temperature readings throughout the year. than the inner zone, which is mainly littoral and shallow, This difference, however, was not significant during the second half of the year ($p<0.05$; Table 1).

The water temperature in the upwelling areas is usually conditioned by the wind regime which moves the surface coastal waters seaward. This is quantified by the Upwelling Index (UI), which expresses the volume of water displaced by km of coastline during a given period of time. In the coastal area of the peninsula of Baja California adjacent to the lagoon of Bahía-Magdalena, the inter-annual variation of UI generally exhibits positive values (Fig.3), i.e. it is always favourable, to greater or lesser extent, to the upwelling year-round. Intra-annually upwelling conditions tend to present two peaks; one from March to May (2000 $m^3 \cdot s^{-1} \cdot km^{-1}$; Fig.2) and another from September to November (1300 $m^3 \cdot s^{-1} \cdot km^{-1}$; Fig.2). The maximum UI during the seven-year period covered was reached in March, April and May (particularly in the years 2006, 2010 and 2011), while some values of UI, averaged over eight-days, that were close to zero or negative, occurred in January-February and July-August.

Inter-annually, the temperature in the outer zone of the Bahía-Magdalena lagoon showed significant differences ($p<0.05$) between the first and the second half of the year. In terms of extreme temperatures during the January-June interval of the 2005-2011 period, 2005 was the warmest year and 2008 the coldest, while during the July-December interval, the year 2008 was the warmest and 2010 the coldest (Fig.3). This annual pattern during the two seasons runs parallel to the oscillation of the air temperature (AT) in the littoral area of the lagoon (Fig.2). The monthly average maximum of AT was recorded in August (34.3^o C) and the minimum was found in January (26.5° C) while the highest SST corresponded to the months of August-October (23.4-27.2^o C) and the lowest from March to May (16.8-20.4^o C; Fig.2). If the inter-annual temperature fluctuations for the period 2005 to 2011 (Fig.3) are expressed as monthly SST anomalies, the alternation of warm and cold periods is emphasized. Hence, during the first half of 2005 the average anomalies were positive or warm ($+0.5^o$ C) but during the second half of 2005 and the first half of 2006, they were negative or cold (-1.0^o C). A similar warm-cold pattern was observed during the second half of 2006 and the first half of 2007 ($+1.5^o$ C) and the second half of 2007 and the first half of 2008 (-1.2^o C). Later there were two extended periods of time; one was warm (+1.5° C) from the second half of 2008 to the first half of 2010 and the other, cold (-2.1^o C) from the second half of 2010 to the first half of 2011.

While the temperature pattern is clear, salinity presented a complex temporal distribution with a mean value of 34.3±0.3 (Fig.3). In temporal terms, the highest salinity was observed in the year 2011 and the lowest in 2005 (34.7 and 34.1, respectively; Fig.3). Spatially, the outer lagoon zone showed a less variable mean salinity (34.2±0.2) in the first, rather than the second half of the year (34.4±0.4; Table 1). On the contrary, salinity variations in the inner zone were more obvious, reaching 35.0±0.7 in the first half and 35.1±0.8 in the second half of the year. In the water column of the lagoon, salinity did not exhibit any significant differences between the surface and the bottom ($p<0.05$; Table 1). However, salinities in the shallow inner area were significantly higher than in the mouth during both semesters ($p<0.05$; Table 1).

Temperature and salinity values together make it possible to identify the water bodies that are present in the Bahia-Magdalena lagoon during the seven-year study period. The influence of upwelled seawater that reaches the lagoon must be higher near the bottom at the mouth. Thus the salinity and temperature data in the four stations of the outer lagoon zone are shown in a TS diagram (Figure 4). The data are clustered into three groups according to their own water mass characteristics: Sub-Arctic Water (SAW), Subropical Surface Water (StSW), Equatorial Subsurface Water (ESsW), and Transitional Water (TrW) from SAW and StSW mixing, following the water mass classification of Durazo and Baumgartner (2002) for the Pacific Oceanic Region of western Baja California.

During the first yearly period until June, T-S values are largely associated with TrW while in the second yearly period until December they belong to StSW in the inner and outer lagoon zones both (Fig.4). However, in the outer zone exceptions were observed for some months between the water masses associated with semi-annual seasons, mainly due to colder water conditions. During the first semester, in April 2006 and June 2006-07-08 the seawater values of temperature and salinity in the outer lagoon zone corresponded to ESsW instead of TrW. Similarly, during the second semester the seawater in August 2007 and December 2007 and 2010 shifted from StSW to TrW. In the inner zone of lagoon the salinity increases up to 38, mainly during summer.

3.2. – Biogeochemical conditions: nutrients and chlorophyll-a distribution

Concentrations of nutrient salts in Bahia-Magdalena waters did not exceed values of 16, 1, 19 and 3 µM for nitrate, nitrite, ammonium and phosphate, respectively. Although silicate cannot be determined in the 2005-2011 period corresponding to the present study, a previous analysis (2001-03; Cervantes-Duarte, pers. comm.) indicated that its concentration did not exceed 18 µM.

Intra-annually, the mean concentrations of nitrate and phosphate in the water lagoon were higher during the first half of the year (Table 1). There is a significant seasonal (i.e. six-monthly) difference (Table 1) for the two nutrients between the inner and outer zones of lagoon. Figure 5 shows a good seasonal correlation for each semester of the seven aforementioned years between both nutrients (µM) in the outer lagoon zone:

$$\text{First semester:}\quad [\text{nitrate}] = 8.44\,[\text{phosphate}] - 3.0 \quad (r = 0.95;\ n=7) \qquad (2)$$

Second semester: [nitrate] = 1.82 [phosphate] - 0.2 $(r = 0.84; n=7)$ (3)

During the first half-yearly season, the availability of nitrate and phosphate is higher than in the second season. Intra-annually, the higher influence of upwelling during the first semester was in parallel to nutrient increase (Fig.3). Moreover, there was also observed inter-annually variations of nutrients (Fig.3), i.e. in 2006 (5.8 and 1.0 µM of nitrate and phosphate, respectively), 2007 (3.9 and 0.85 µM), 2010 (2.7 and 0.64 µM) and 2011 (2.5 and 0.68 µM).

The mean concentration of ammonium was higher during the first half of the year, but, unlike nitrate and phosphate, ammonium does not exhibit any significant differences between the external and internal areas of the lagoon or between the surface and bottom (Table 1) during this season. This spatial homogeneity does not continue on a temporal basis since there are statistically significant differences between the first and second half of the year (Table 1), associated with a greater concentration of ammonium near the littoral zone during the second season.

In the Bahia-Magdalena lagoon chlorophyll concentrations reached 17 $mg \cdot m^{-3}$ and the dissolved oxygen saturation percentage varied between 70-130%, which indicates a high biological activity associated with the availability of nutrient salts reported earlier. The mean concentrations of chlorophyll-*a* in the stations close to the mouth of the lagoon, i.e. its outer zone, were comparatively higher during the first versus the second half of the year (2.8 and 1.7 $mg \cdot m^{-3}$, respectively; Table 1). Chlorophyll-*a* ranges did not show any significant differences $(p<0.05)$ between the surface and bottom areas of the whole lagoon, but in both semesters, the concentration of Chlorophyll-*a* increased in the inner zone close to the shallow littoral zone, (2.2-3.5 $mg \cdot m^{-3}$; Table 1). The annual variation in chlorophyll showed a six-monthly pattern with its highest concentrations found at the end of the first season and the lowest at the end of the second season (Fig.2).

The chlorophyll-*a* analysis from *in situ* and satellite values, was significant. However, the values estimated from satellite measurements had a greater dynamic range with respect to the measurement *in situ* (Fig.2). The correlation between both estimates was:

Chlorophyll-a ($mg \cdot m^{-3}$): [satellite] = 1.76 [*in situ*] - 0.20 $(r = 0.74; n=42; p<0.05)$ (4)

The overestimation of chlorophyll-*a* concentrations from satellite measurements was already pointed out in the region of California Current by Kahru and Mitchell (2001). These authors indicated that the chlorophyll-*a* correlation between satellite and *in situ* data is higher offshore than near the coast. It may be associated with the inshore increase of colouring dissolved organic matter from sources different to phytoplankton.

Inter-annually, both satellite and in situ trends were similar in the lagoon. The period from 2005 to 2011 showed increases in the average concentrations of chlorophyll in 2008 (3.0 $mg \cdot m^{-3}$; Fig.3) and 2010 (2.7 $mg \cdot m^{-3}$), while 2009 (1.8 $mg \cdot m^{-3}$), 2006 and 2011 (2.0 $mg \cdot m^{-3}$) were less productive years. This inter-annual chlorophyll-*a* pattern correlates with the temperature (Fig.5) of the outer lagoon zone. There, the chlorophyll-*a* concentration increases when the water temperature decreases. This occurs during the two seasons of the year in the lagoon, although during the second season, the temperature was higher and the levels of chlorophyll-*a* lower. In both cases there was a good correlation between chlorophyll-*a* concentration (Chl-*a* in $mg \cdot m^{-3}$) and temperature (° C) in the outer lagoon zone:

First semester: [Chl-*a*] = 13.4 - 0.62·T $(r = 0.93; n=6)$ (5)
Second semester: [Chl-*a*] = 9.2 - 0.32·T $(r = 0.83; n=6)$ (6)

3.3. – Spatio-temporal zoning

The main oceanographic patterns in the subtropical lagoon of Bahía-Magdalena during the 2005-2011 period can be studied on the basis of the variables measured seasonally and averaged every year, i.e. the first (February-July) and second (August-January) semester, in each lagoon zone, i.e. inner and outer areas. Therefore, a factorial analysis may explain the response variables during those seven years, as a function of explanatory thermohaline and biogeochemical variables. This resulted in the extraction of two factors that explain 64% of the variance in the PCA of Figure 6. Factor 1 (37% of the contribution to the total variance) displayed high positive scores for nutrient salts (nitrate, ammonium and phosphate), and negative scores for temperature and oxygen saturation. Factor 2 (27% of the contribution to the total variance) loaded positively in salinity and chlorophyll-*a*, and negatively in the depth of the Secchi disk. It provided an annual season-zone division to the lagoon following the four quadrants of PCA regardless of the year. The fist quadrant comprises the inner zone and the first season; the second, the outer zone and first season; the third, the outer zone and second season; and the fourth, the inner zone and second season (Fig.6).

4. - DISCUSSION

Thermohaline and biogeochemical variables were able to identify an inner zone that is associated with depths lower than 20 m in the subtropical lagoon of Bahía-Magdalena. This shallow zone occupies approximately 80% of the lagoon area and it is characterized by a homogeneous vertical distribution of salinity and temperature. Salinity increased near the littoral, where there are intertidal channels, and during summer. According to the explanation given by Zaitsev et al. (2010) it has to do with the main physical processes affecting the thermohaline structure, such as tidal transport and surface heat in Bahia-Magdalena. Moreover, this vertical homogeneity may be extended to the nutrients and chlorophyll in the water column of the shallow lagoon zone. This inner pattern is due to the absence of freshwater contributions towards the lagoon, which is located in a semi-arid climate region. This fact makes a key difference between Bahia-Magdalena and other subtropical lagoons where the fluvial contributions fertilize the inner areas and give rise to a vertical stratification in salinity and nutrients (Caffrey et al., 2007; Murrell et al., 2007; Phlips et al., 2012). So, in the subtropical lagoons with estuarine zones the nutrient inputs are mainly connected with the rainfall season (Eyre 2000; Lehrter 2008; Abreu et al., 2010) and chlorophyll concentration increased up to four times the observed during the dry season (Phlips et al., 2012). On a local level in Bahia-Magdalena, the presence of a mangle forest in the littoral zone (Acosta Velázquez and Ruiz-Luna, 2007) and the phosphorite ores from neighboring areas that are loaded at San-Carlos port increased the ammonium and phosphate concentrations in the shore waters.

Consequently, in keeping with the typology of Abreu et al. (2010), Bahia-Magdalena can be classified among the coastal lagoons which have a prevailing marine influence, such as was emphasized by the salinities higher than 35 in the inner lagoon zone, showing the very scarce continental freshwater inputs during all the year (Fig.4). It is in the outer zone of the lagoon where the influence of the sea can be clearly identified. This outer zone is characterized by its situation close to the sea-mouth of the lagoon and depths greater than 20 m. Temperature-salinity diagrams show the influence of upwelling events within the lagoon (Fig.4). The incoming seawater corresponds to the typical water mass classification off the western coast of Baja California (Durazo and Baumgartner 2002). Therefore, the three main groups of the Pacific Oceanic Region of western Baja California (Durazo and Baumgartner, 2002) have been observed in the lagoon: TrW in the California Current (CCW), and to a lesser extent ESsW, prevailing during the February-July season, while StSW was mainly associated with the August-January season (Fig.4). The boundary between the seawater transported by CCW, i.e. TrW and SAW, and the saltier and warmer StSW, i.e. the temperate-tropical transition (Lluch-Belda et al., 2003), moves northward during late summer and fall. Then, tropical and subtropical waters are observed farther to the north (Durazo, 2009). In this annual period, the coastal lagoon of Bahía-Magdalena was under the domain of StSW while the influence of the CCW coincided in time with the intensification of the California Current (Schwartzlose and Reid 1972), associated with the coastal upwelling induced by the prevailing north-westerly wind in the period from March to June.

Bahía-Magdalena belongs to the type of marine-domain coastal lagoon, but unlike the most of these subtropical types, Bahia-Magdalena is different because it is situated in a perennial upwelling region. However, upwelling is not a temporally continuous or spatially uniform process;

rather it displays periods of more favourable conditions. Along the entire coast of the peninsula of California, the upwelling intensity changes in accordance with local wind conditions and bottom topography (Zaitsev et al., 2003). There is an intensification of the spring upwelling activity towards the middle latitudes. Average UI magnitudes for the Magdalena Bay latitude (24^o N) were three times lower than for the Ensenada location (31^o N) for the period from April through June. Moreover, the duration of upwelling events is also shorter in Bahía-Magdalena, 4-5 days (Zaitsev et al., 2003; Durazo et al., 2010) than in the north-eastern zone, i.e. two weeks at Point Conception (34.5°N; Wilkerson et al., 2006). There is a very little scientific knowledge on subtropical coastal-upwelling lagoons although at 30^o N on the Californian Peninsula there is another similar coastal system, the Bahía-de-San-Quintín (42 km^2 and 20 m in depth at its mouth). In this subtropical lagoon influenced by the California Current System, upwelling events and tides are the main causes of variability in the lagoon's hydrographical properties (Millan-Nuñez et al., 1982; Alvarez-Borrego, 2004).

The temporal pattern in the Bahia-Magdalena lagoon shows the nutrient dependence of upwelling events (Fig.3). So, among the coastal lagoons presenting a prevailing maritime influence (Abreu et al., 2010), this coastal system corresponds to an unusual type of subtropical coastal lagoon where its water is under fertilization by upwelling phenomena. This Bahia-Magdalena pattern was also observed in temperate ria systems (Evans and Prego, 2003) with seasonal upwelling (Fraga, 1981; Prego and Bao, 1997). During spring-summer in the Western and Middle Galician Rias of the Iberian Peninsula the fluvial contributions are very low; hence nutrient input as result of upwelling events is the main reason for the fertilization of the ria (Prego, 2002; Varela et al., 2008). In both systems, the subsurface nutrient-rich water upwells: The Eastern North Atlantic Central water mass in the case of the rias (up to 12 μM of nitrate; Prego et al., 1999) and the Sub-Arctic water mass in the California Current in the case of Bahia-Magdalena, which is below 100 m depth and upwells to the surface (Zaitsev *et al*., 2003; Durazo 2009; Durazo *et al*., 2010). Under upwelling conditions in the western shelf of the Baja-California region, Pennington and Chávez (2000) indicated nitrate concentrations of 7-20 μM in the Bay of Monterey, from May to June and Ribas-Ribas et al. (2011) measured up to 12 μM of nitrate in the Bay of San-Quintín. Moreover, during the period of high upwelling intensity (March-June) nitrate concentrations increased up to 15 μM in the Bahía-Magdalena lagoon. The phytoplankton pattern in this lagoon (Gárate-Lizarraga et al., 2007) and the chlorophyll-*a* concentrations (Fig.2), both of which increased to reach maximum values in June, allow for a high exploitation of marine resources (fishes, mollusks and crustaceans; Funes-Rodríguez et al., 2007) in the Bahía-Magdalena lagoon. It is mainly supported by nutrient inputs from upwelling in the February-July period.

The spatial (inner and outer areas) and temporal (February-July and August-January semesters) duality of the subtropical lagoon of Bahía-Magdalena during the 2005-2011 period is repeated year to year. The PCA grouping (Fig.6) shows how the intra-annual pattern is recurrent according to the pattern described in the previous section. The oceanographic parameters in the outer lagoon zone during the 2005-2011 period (M points in the Fig.6) varied between cold and warm half-yearly periods in association with the California Current water and Subtropical Surface Water alternation off the Baja-California region (Goericke *et al*., 2007; Bjorkstedt *et al*., 2010).

In this trend some minor differences can be noticed. During the first semester in the outer lagoon zone, 2006 and 2007 are the furthest on the X-axis of Fig.6, which implies that they are the coldest (17.2, and 17.9^o C, respectively) and most nutrient abundant years (9.8 and 6.1 μM-NO_3, respectively) of the seven years period. The meteorological conditions of these two years presented an increase in the upwelling tailwinds of the southern California Current region (Peterson et al., 2006; Goericke et al., 2007). On the contrary, upwelling intensities were low the years 2010 and 2011 and there were low differences between chlorophyll-*a* concentrations between their first and second semester seasons (Fig.3 and equations 5 and 6). Both semesters were close together in the inner lagoon zone (Fig.6), which indicates that no significant differences occurred throughout these years. Moreover, in 2010-11 the points corresponding to the outer zone and the first semester were closest to the X-origin (Fig.6), i.e. a year with low upwelling intensities. During 2005 and 2010 unusually cold waters were recorded in the south California region, resulting from intense upwelling (Peterson et al., 2006), but there was no information on the Bahía-Magdalena coast. However, in spring 2010, warm conditions were observed together with an increase in gelatinous zooplankton (Bjorkstedt et al., 2010). Lastly, 2009 was an unusual year with regard to the position of the outer points close to the end of the negative ordinate axis (Fig.6); 2009 was an atypical year. During 2009, the negative Pacific Decadal Oscillation index of 2007-08 returned to normal (McClatchie et al., 2009).

In the world, different temporal trends were observed as result of the climate forcing on the upwelling variability. So, in the California Current region (32-40°N) an increase in the seasonal upwelling was pointed out by Schwing and Mendelssohn (1998), similarly to those reported for the coastal upwelling areas off North-West Africa and Peru (Bakun 2001; Narayan et al. 2010). The time series of seven years (2005-2011) obtained in the Bahía-Magdalena lagoon show an ambiguous trend, in accordance with the 24-27°N result from the latitudinal model developed by Bakun (1990). However, Kahru et al. (2012) detected a decrease in the chlorophyll concentration in the Southern Baja-California zone; they attributed it to a reduction in the upwelling intensity. It can be speculate that the upwelling decrease in the Bahía-Magdalena lagoon should modify the chlorophyll levels during the boundary months between the two seasons; so, the warm pattern will prevail over the cold and the lagoon could become biologically less productive. Longer time series in Bahía-Magdalena lagoon are necessaries for researching the impact of climate on oceanographic changes.

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Figure Captions

Figure 1. Location, bathymetry and sampling stations in the subtropical coastal lagoon of Bahía-Magdalena. Letters A-D correspond to the four stations located in the outer lagoon zone while the ten stations numbered 0-9 are within the inner lagoon zone.

Figure 2. Monthly average values during the period 2005-2011: (A) upwelling index (UI); (B) air temperature and sea surface temperature; and (C) surface chlorophyll-*a*. The grey circles correspond to satellite records and the triangles to *in situ* measurements. Dashed lines and bars represent one standard deviation of the seven year period.

Figure 3. Seven year record of the temporary variation of the surface values of temperature, chlorophyll-*a*, salinity, nitrate, phosphate and upwelling index (UI) in the outer zone of Bahía-Magdalena lagoon. The squares show the monthly average of the four outer stations, and the line corresponds to satellite and 8-day averaged UI data.

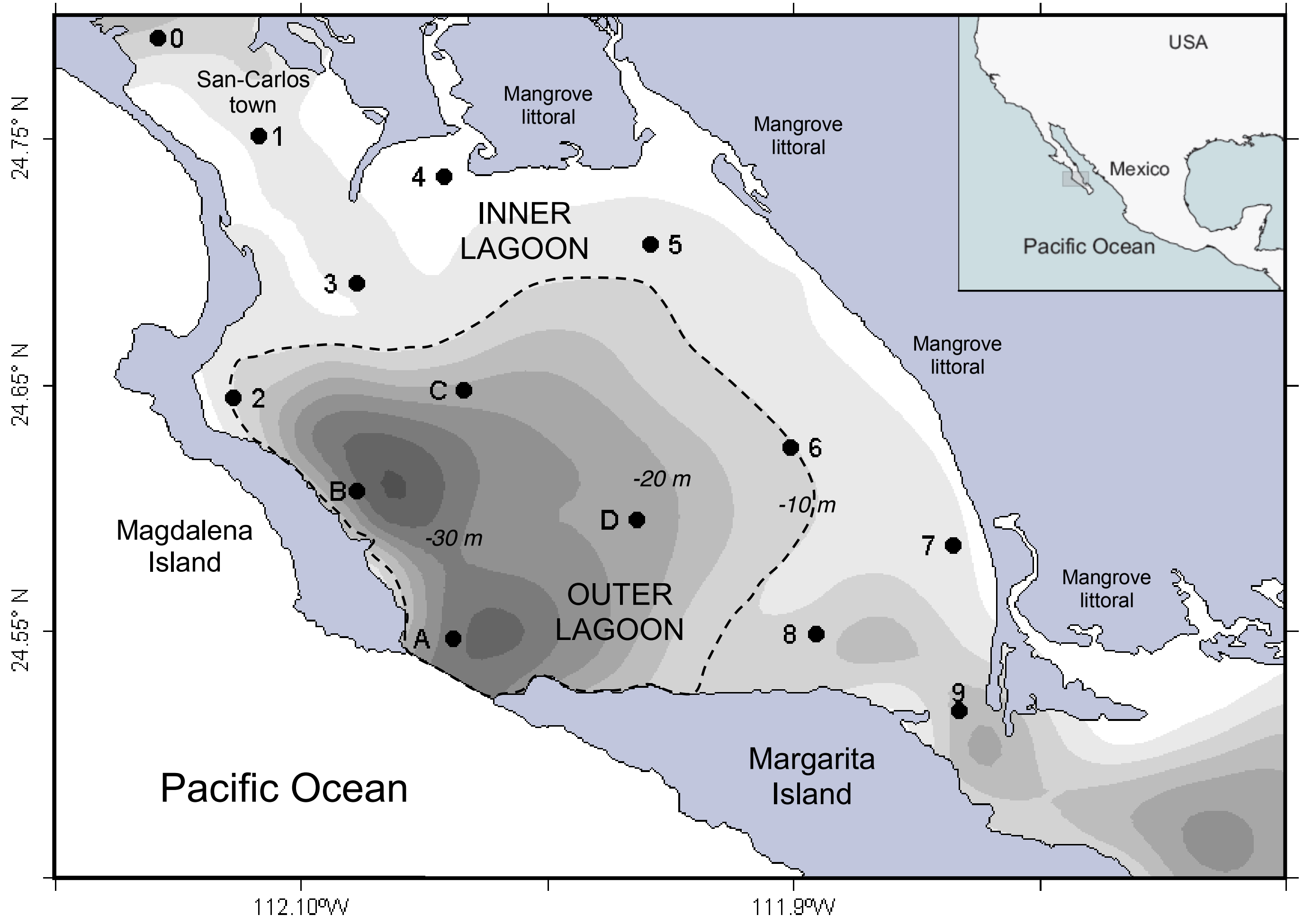
Figure 4. Temperature-Salinity diagram showing the lagoon bottom data of the outer (Stations A-D) and the inner (Stations 0-9) zone. Shaded and empty symbols correspond to the first and second semester of the year, respectively. TSW is the acronym for Tropical Surface Water; StSW, Subtropical Surface Water; TrW, Transitional Water; SAW, Subarctic Water; and ESsW, Equatorial Subsurface Water (Durazo and Baumgartner, 2002).

Figure 5. Relationships of (A) chlorophyll-*a* vs temperature and (B) nitrate vs phosphate. Surface *in situ* data of the outer lagoon zone were semester averaged for each year of the 2005-2011 period; empty and shaded symbols correspond to the first and second semester, respectively.

Figure 6. Principal Component Analysis (PCA) applied to the *in situ* surface data of salinity, temperature, nitrate, phosphate chlorophyll-*a* and depth of the Secchi disk. They were temporary-spatially averaged by lagoon zone and semester of the period 2005-2011. Letter M and L, correspond to the outer and inner lagoon zones, respectively; the following number represents the first (1) or second (2) semesters of the year and the number after the media bar shows the last two digits of the years 2005-2011.

Table I. Mean values and standard deviation. The significant differences ($p<0.05$) between zones in each layer and season (1st and 2nd semesters) were calculated applying the Kruskal-Wallis One Way Analysis of Variance on ranks. Results are showed according to the upper-index "a, b, c, d".

Layer	Zone-semester	Temperature (°C)	Salinity	Nitrate (μM)	Ammonium (μM)	Phosphate (μM)	Oxygen (% saturation)	Chlorophyll-*a* ($mg \cdot m^{-3}$)
Surface	^{a}Outer-1	18.0 ± 1.9^{bcd}	34.3 ± 0.3^{cd}	5.0 ± 5.2^{bcd}	3.7 ± 3.0^{bd}	0.94 ± 0.52^{bd}	100 ± 16	2.7 ± 1.9^{b}
	^{b}Outer-2	23.2 ± 2.5^{ac}	34.4 ± 0.4^{cd}	0.9 ± 1.0^{a}	1.4 ± 2.0^{ac}	0.54 ± 0.22^{acd}	98 ± 15	1.7 ± 1.4^{acd}
	^{c}Inner-1	19.8 ± 1.8^{abd}	35.0 ± 0.7^{ab}	2.4 ± 3.6^{a}	3.3 ± 2.8^{bd}	0.84 ± 0.38^{abc}	96 ± 21	2.8 ± 2.5^{b}
	^{d}Inner-2	24.0 ± 2.7^{ac}	35.1 ± 0.8^{ab}	1.1 ± 1.7^{a}	1.4 ± 2.4^{ac}	0.70 ± 0.25^{ab}	93 ± 15	3.1 ± 2.4^{b}
Bottom	^{a}Outer-1	15.3 ± 1.9^{bcd}	34.4 ± 0.2^{cd}	12.2 ± 5.2^{bcd}	2.2 ± 1.2	2.08 ± 0.71^{bd}	67 ± 16^{c}	2.7 ± 2.1^{b}
	^{b}Outer-2	19.6 ± 3.2^{ad}	34.4 ± 0.3^{cd}	6.4 ± 6.2^{a}	2.5 ± 2.1	0.92 ± 0.42^{a}	81 ± 14^{c}	0.9 ± 0.4^{ad}
	^{c}Inner-1	19.2 ± 2.0^{ad}	35.3 ± 0.8^{ab}	6.4 ± 5.8^{a}	3.7 ± 2.5	1.46 ± 0.82^{d}	99 ± 13^{abd}	3.5 ± 2.0^{d}
	^{d}Inner-2	22.7 ± 2.9^{acd}	35.5 ± 1.1^{ab}	2.8 ± 3.2^{a}	2.5 ± 2.6	0.94 ± 0.34^{ac}	79 ± 11^{c}	2.2 ± 1.9^{bc}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San-Carlos town
1
Mangrove littoral
Mangrove littoral
4
INNER LAGOON
5
3
Mangrove littoral
2
C
6
-20 m
-10 m
B
D
Magdalena Island
-30 m
7
OUTER LAGOON
Mangrove littoral
A
8
9
Margarita Island
Pacific Ocean
USA
Mexico
Pacific Ocean
24.75° N
24.65° N
24.55° N
112.10ºW
111.9ºW

Figure 1

Figure(s)

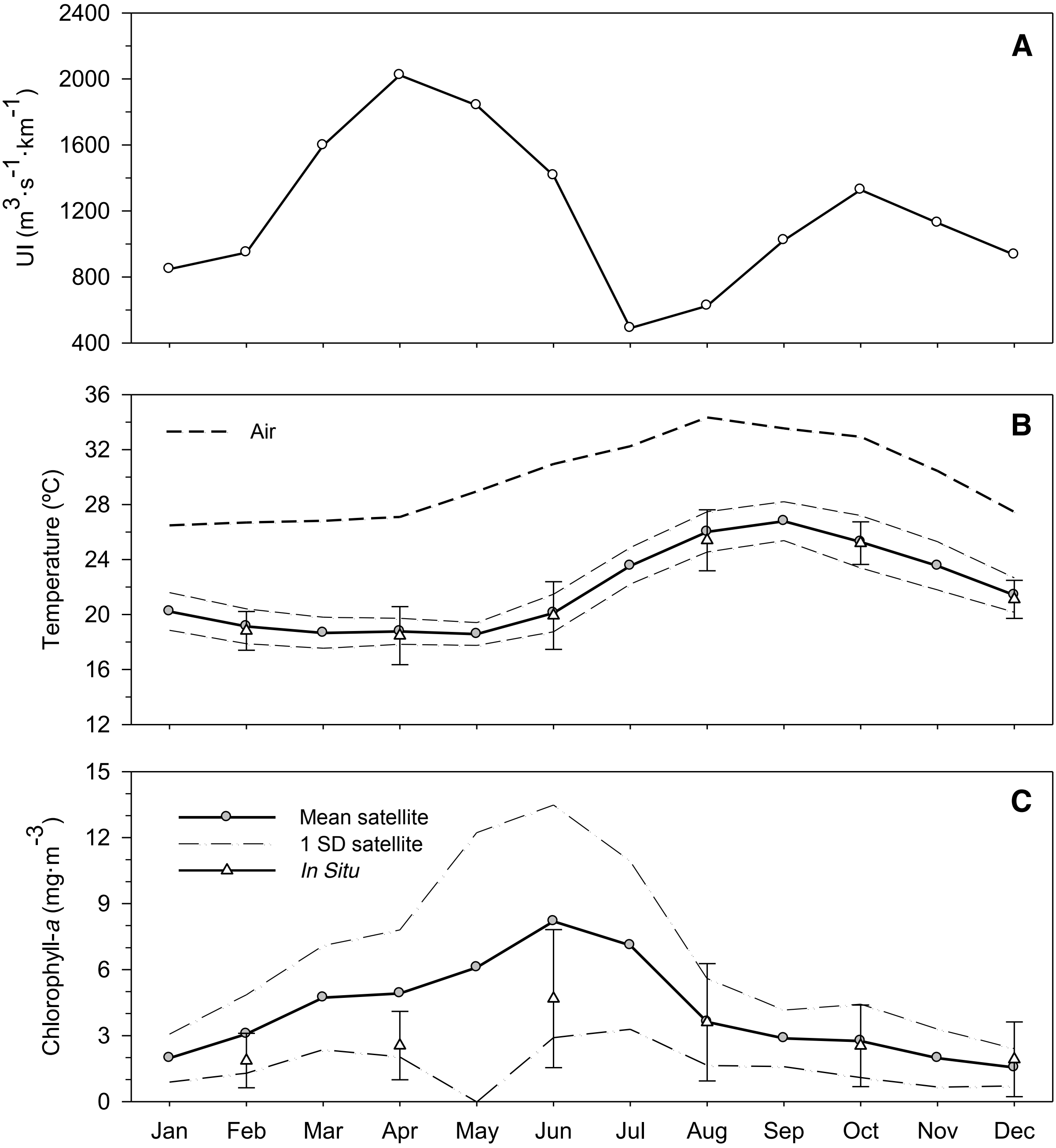
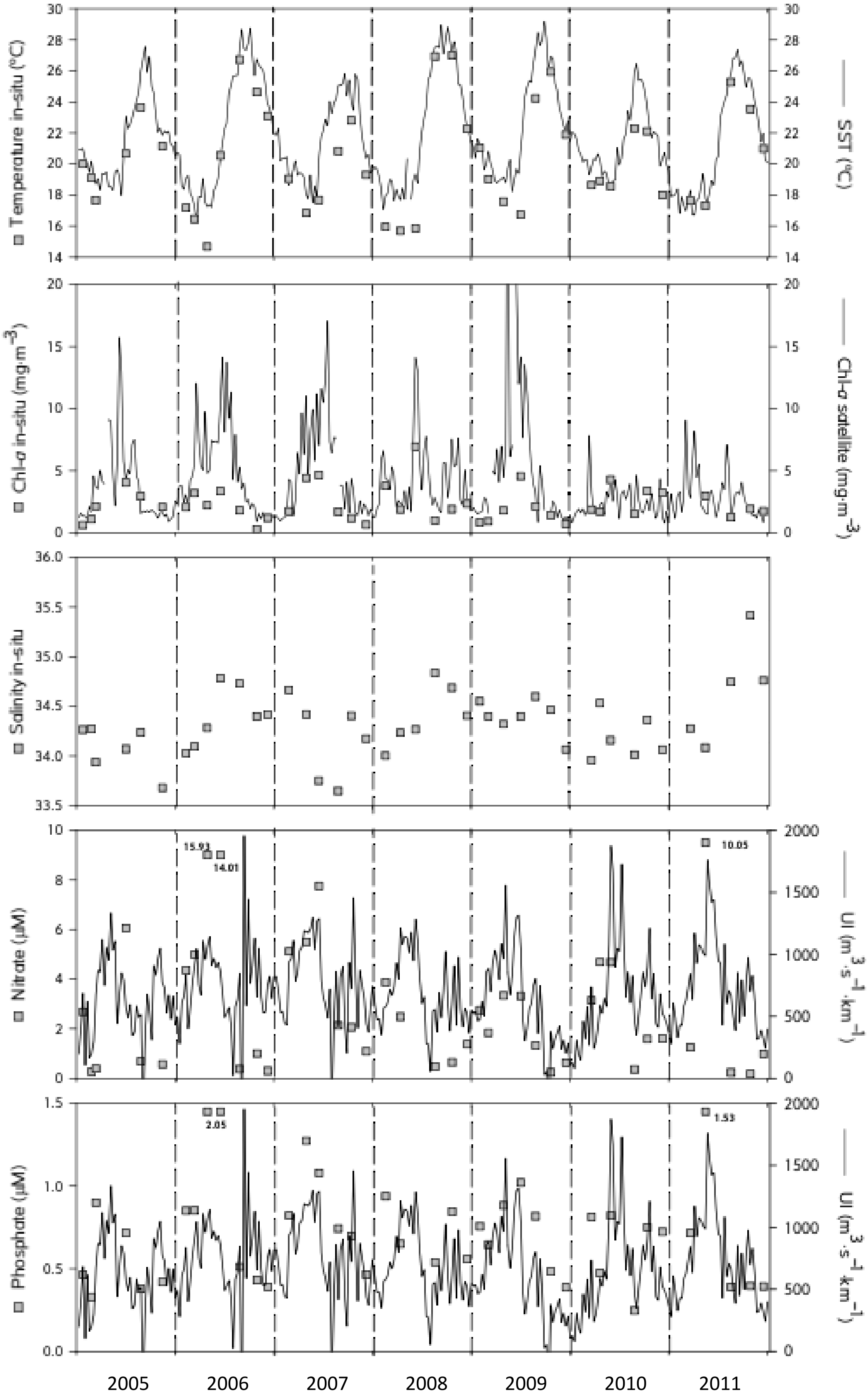


Figure 2



Temperature in-situ (°C)
SST (°C)
30
28
26
24
22
20
18
16
14
Chl-a in-situ (mg·m^{-3})
Chl-a satellite (mg·m^{-3})
20
15
10
5
0
Salinity in-situ
36.0
35.5
35.0
34.5
34.0
33.5
Nitrate (µM)
UI (m^3·s^{-1}·km^{-1})
10
8
6
4
2
0
2000
1500
1000
500
0
15.93
14.01
10.05
Phosphate (µM)
1.5
1.0
0.5
0.0
2.05
1.53
2005
2006
2007
2008
2009
2010
2011

Figure 3

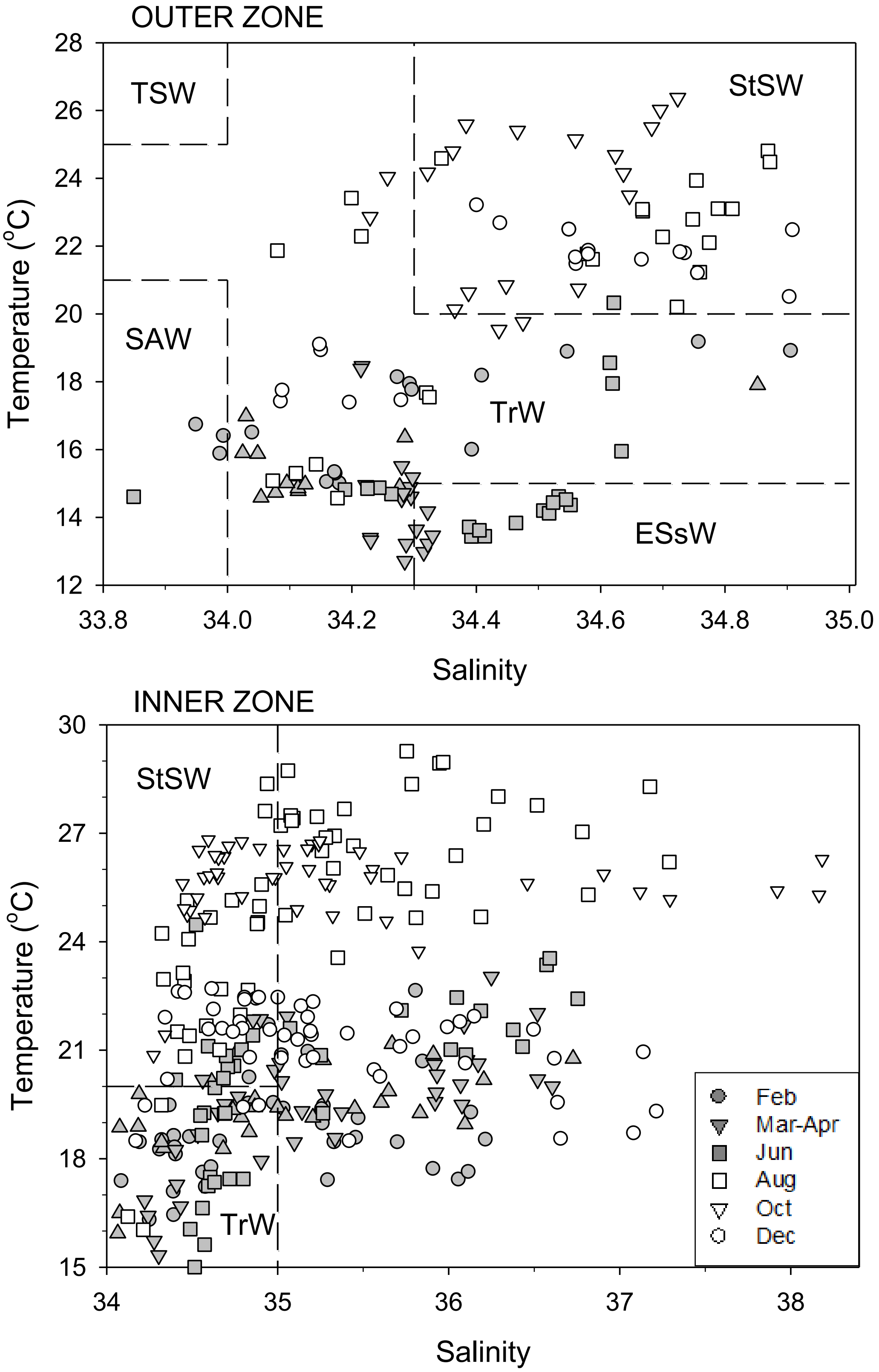

OUTER ZONE
28
26
24
22
20
18
16
14
12
Temperature (°C)
TSW
SAW
StSW
TrW
ESsW
33.8
34.0
34.2
34.4
34.6
34.8
35.0
Salinity
INNER ZONE
30
27
24
21
18
15
Temperature (°C)
StSW
TrW
34
35
36
37
38
Salinity
Feb
Mar-Apr
Jun
Aug
Oct
Dec

Fig.4

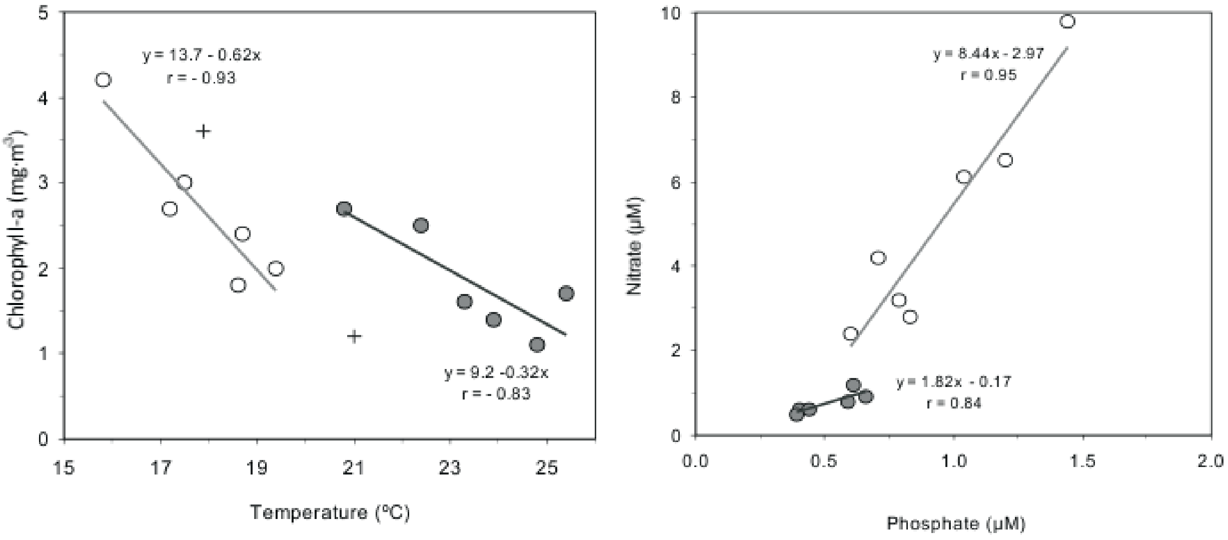

5
4
3
2
1
0
Chlorophyll-a (mg·m^{-3})
y = 13.7 - 0.62x
r = - 0.93
y = 9.2 -0.32x
r = - 0.83
15
17
19
21
23
25
Temperature (ºC)
10
8
6
4
2
0
Nitrate (µM)
y = 8.44x - 2.97
r = 0.95
y = 1.82x - 0.17
r = 0.84
0.0
0.5
1.0
1.5
2.0
Phosphate (µM)

Figure 5

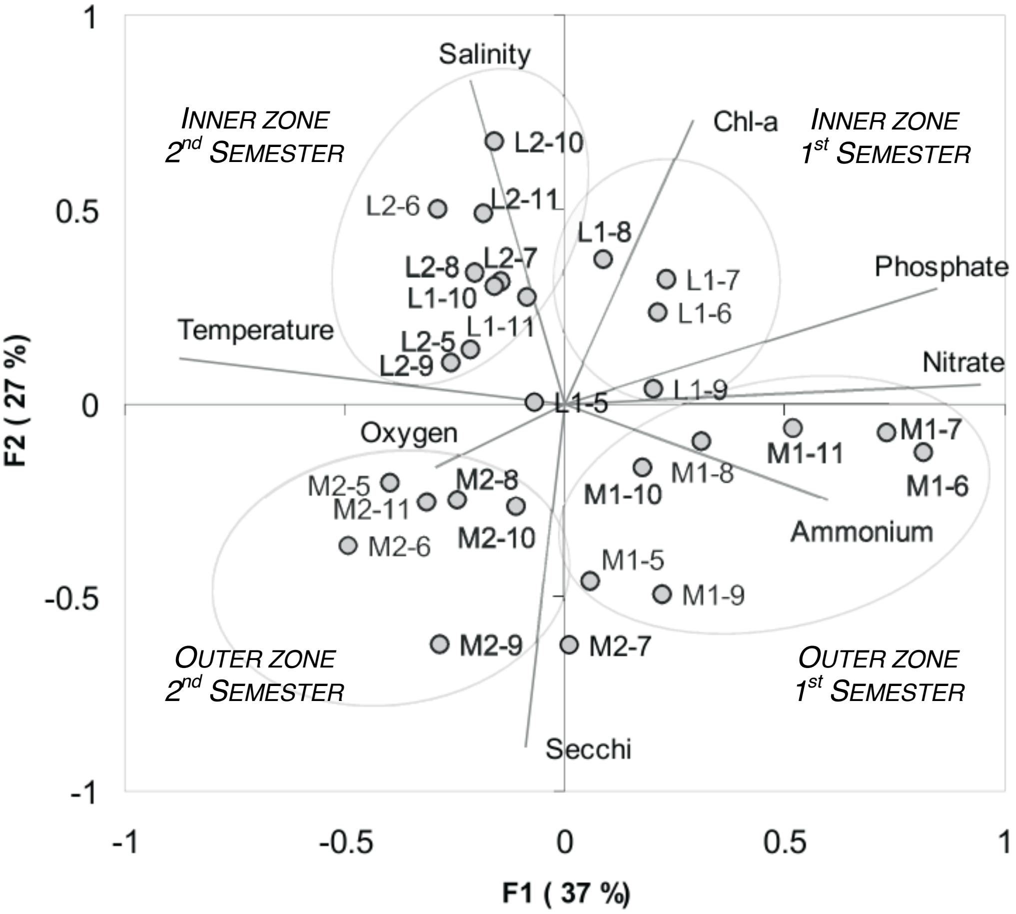

Salinity
Chl-a
INNER ZONE 2nd SEMESTER
INNER ZONE 1st SEMESTER
L2-10
L2-6
L2-11
L1-8
L2-8
L2-7
L1-10
L1-7
L1-6
Phosphate
Temperature
L1-11
L2-5
L2-9
Nitrate
L1-9
L1-5
Oxygen
M1-7
M1-11
M1-6
M1-8
M2-5
M2-8
M2-11
M1-10
M2-10
Ammonium
M2-6
M1-5
M1-9
M2-9
M2-7
OUTER ZONE 2nd SEMESTER
OUTER ZONE 1st SEMESTER
Secchi
1
0.5
0
-0.5
-1
F2 (27 %)
-1
-0.5
0
0.5
1
F1 (37 %)

Figure 7