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Patterns of chlorophyll-a distribution linked to mesoscale structures in two contrasting areas Campeche Canyon and Bank, Southern Gulf of Mexico

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A B S T R A C T

The chlorophyll-a (Chl-a) distribution in Campeche Canyon and Campeche Bank, at the Southern Gulf of Mexico, as well as its relationship with hydrographic structure were analyzed. The results show the existence of the Gulf Common Water (GCW), the Caribbean Tropical Surface Water (CTSW) and the Caribbean Subtropical Underwater (CSUW) in the 120 m upper layer at the Campeche Canyon. While at the Campeche Bank only the Caribbean Tropical Surface Water (CTSW) was found. The 15 °C and 18.5 °C isotherms topography depict the presence of a mesoscale anticyclone-cyclone dipole. The nutrient pumping mechanism fertilizes the eutrophic zone promoted by the cyclonic eddy. Submesoscale processes in the border of an anticyclone and a cyclone results in maximum of nitrate concentration and vertically integrated Chl-a at the frontal zone. Two Chl-a vertical distribution patterns were found, a deep maximum at the base of the euphotic layer not associated to the thermocline over the Campeche Canyon and a peak associated to the thermocline related to the shallow bottom at the Campeche Bank. Oligotrophic conditions were observed in the 50 m upper layer and mesotrophic conditions were found below this layer. The differences between the Campeche Bank and Campeche Canyon are that: in the canyon, the nutrient and Chl-a peaks were linked with the cyclone, and the submesoscale processes in the border of an anticyclone and a cyclone, respectively. In the vertical the maximum Chl-a was associated to the base of the euphotic layer and dominated by coccolithophores. In the Campeche Bank the nutrient and Chl-a peaks were influenced by the shelf break in the vertical the maximum Chl-a was associated with the thermocline and the silicoflagellate was identified as the dominant species.

1. Introduction

Chlorophyll-a (Chl-a) is considered to be an indicator of the phytoplankton biomass (Boyer et al., 2009; Cullen, 2015) and due to its non-invasiveness and sensitivity, measurement of its *in situ* and *in vivo* fluorescence (the solar-stimulated in a narrow band centered at 683 nm) has become a widespread technique to evaluate photosynthetic performance (Falkowski and Kiefer, 1985; Falkowski, 1988; Kiefer et al., 1989; Chamberlin et al., 1990). Its vertical distribution is directly linked to the stratification and mixing of the water column (Ríos et al., 2016), as well as to the thickness of the euphotic layer and nutrient availability at various spatial and temporal scales (Li and Hansell, 2016). Buesseler et al. (2008) documented that these situations were generally originated due to diverse hydrodynamic processes such as internal waves, fronts, and eddies. Mesoscale eddies, often identified as cyclonic, anticyclonic, mode-water or thinnies are some of the highly energetic features of the ocean circulation supporting a variety of mechanism that create biological and biogeochemical variabilities at a wide range of temporal and spatial scales (McGillicuddy, 2015, 2016). Cyclone dome, the seasonal and main pycnoclines causes a nutrient pumping into the euphotic zone, where they are utilized by the biota, whereas, anticyclones depress the seasonal and main pycnoclines, pushing nutrient depleted water out of the well-illuminated surface layers. Mode-water eddies are composed of a lens-shaped disturbance that raises the seasonal pycnocline and lowers the main pycnocline lifting nutrients into the euphotic zone (McGillicuddy et al., 2007). Thinnies depress and dome the seasonal and main pycnoclines, respectively (McGillicuddy, 2015). The popular eddy-pumping paradigm implies that nutrient fluxes are enhanced in cyclonic and mode-water eddies, because of an upwelling inside them, leading to higher

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phytoplankton production. However, recent study by Dufois et al. (2016) challenged this paradigm considering environments in which anticyclonic eddies have elevated Chl-a compared with cyclones. Interdisciplinary studies regarding mesoscale eddies and their impact on plankton community have been addressed in different ocean environments. Recent progress in automated methods for tracking mesoscale eddies has facilitated to understand how these eddies can influence the Chl-a distribution, with emphasis in three regional subdomains like the Gulf Stream region, the South Indian Ocean and Southeast Pacific (Chelton et al., 2011; Gaube et al., 2014). Recent studies documented that nitrogen fixation in cyclonic and mode-water eddies off the Peru coast is related to the presence of cyanobacteria, and the maximum fixation occurs in the periphery and in the central parts of the eddies due to the consumption of phytoplankton (Arévalo-Martínez et al., 2016; Löscher et al., 2016). In addition, Chenillat et al. (2016) interpreted that eddies of the California Current are responsible for the transport of nitrate and plankton of nearly ~50% and 20%, respectively.

In the Southern Gulf of Mexico the vertical and horizontal structures of Chl-a have been related with the thermal and light structures (Signoret et al., 1998; Signoret et al., 2006a) as well as with the regional circulation pattern characterized by a permanent cyclonic circulation over the Campeche Bay delimited by the topography of the region (Pérez-Brunius et al., 2013). The presence of anticyclone-cyclone eddy pairs during summer, representing an interesting point of study (Salas-de-León et al., 2004). The Campeche Canyon (Fig. 1) is located

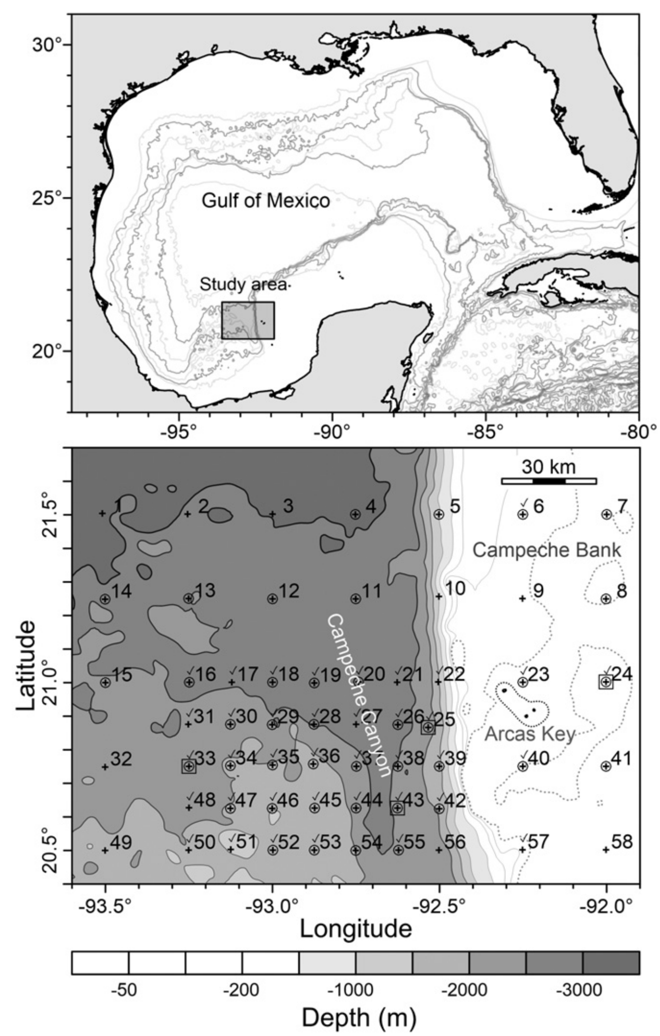

Fig. 1. Upper panel: Gulf of Mexico, and study area (small rectangle). Lower panel: sampling stations, CTD casts (+), PNF-300 casts (o), nitrate sampling (✓), phytoplankton sampling (□) and bathymetry (m).

in the Southern Gulf of Mexico, between 20° 30′–21° 36′ N and 92° 24′–93° 30′ W. The submarine canyon is an outstanding feature of the continental slope, located next to the escarpment and its origin is related to the tectonic evolution of the region (Escobar-Briones et al., 2008). The depth of the canyon ranges from 160 to 2800 m, which is a unique hydrodynamic environment with both anticyclonic and cyclonic eddies (Monreal-Gómez and Salas de León, 1997; Salas-de-León et al., 2004). Such hydrodynamic processes affect the phytoplankton biomass and sediment distribution, which originate from the occurrence of micro environments (Escobar-Briones et al., 2008). Submarine canyons, favor the downslope movement of dense shelf water (Canals et al., 2006; Bosley et al., 2004; Rennie et al., 2009; Chiou et al., 2011), moving continental shelf water onto the deep-ocean and act as regions of enhanced mixing and amplification on internal waves (Salas-Monreal et al., 2012; Santiago-Arce and Salas de León, 2012). This downslope movement can also result sub-superficial upwelling-downwelling processes (Ardhuin et al., 1999; Allen and de Madron, 2009; Aldeco et al., 2009), transportation of nutrient-rich dense water and sediments (She and Klinck, 2000), and further leads to the retention and/or resuspension of plankton and particulate matters (Palanques et al., 2005).

Submarine canyons are features of continental margins and are considered as privileged locations for the exchange of water between the coastal zone and the open ocean. The submarine canyons are significant, because they act as an agent for shelf-slope exchange of sediments; vertical motions steered by steep topography and by the formation of mesoscale eddies in their vicinity (Ardhuin et al., 1999). Mesoscale eddies are frequent in submarine canyons and studies have demonstrated that its formation and strength are directly dependent on the deep sea currents and the canyon's topography (Nof, 1983; Klink, 1996; Ardhuin et al., 1999; Salas-de-León et al., 2004; Rennie et al., 2008). At the southern Gulf of Mexico, the presence of canyon anticyclonic-cyclonic eddies has been studied and characterized by Salas-de-León et al. (2004). These authors used the 18.5 °C isotherm to characterize these eddies and stated that the formation of these eddies is derived from the canyon topography.

The Campeche Bank is a gently inclined, carbonate-dominated shelf, covering ~57,000 km^2 extending ~100–300 km from the coast to the shelf break at ~200–300 m depth (Goff et al., 2016) with an overall gradient of ~0.0002–0.001 (Logan et al., 1969). In the Campeche Bank region, cyclonic features have been identified with a life cycle that varies from 3 to 15 months (Zavala-Hidalgo et al., 2003). An important subsurface thermal gradient has been observed over the shelf break, which corresponds with a doming of low oxygen near to the base of the mixed layer. In addition, an anticyclone-cyclone dipole occurs over the region (Salas-de-León et al., 2004).

This study aimed to present the vertical and horizontal distributions of Chl-a and its relationship to the hydrography and mesoscale structures of the Campeche Canyon and Campeche Bank during June 2002. We hypothesize a vertical Chl-a distribution determined by the light supplied from the surface and nutrients supplied from the bottom and a region of high-nutrient concentration induced by mesoscale eddies that promotes a phytoplankton biomass higher than surrounding oligotrophic waters.

2. Materials and methods

Hydrographic records, Chl-a measurements and water samples for nitrate determination and phytoplankton cell quantification, were obtained during an oceanographic cruise PROMEBIO-VI carried out from 12 to 17 June 2002 on board of the R/V "Justo Sierra" of the Universidad Nacional Autónoma de México (UNAM). Using a Neil Brown III CTD, the conductivity, temperature and depth data were obtained at 58 stations, which cover both the Campeche Bank and Campeche Canyon (Fig. 1). On the basis of the CTD data, a T-S diagram was prepared to identify the water masses at the study area and in the first 120 m of the water column. The mixed layer was inferred using the maximum vertical temperature gradient at its base. Topography of the 15 °C and 18.5 °C isotherms were used to identify the circulation pattern over the area as previously described by Salas-de-León et al. (2004). The vertical sections of temperature and buoyancy frequency along transect AA' were analyzed in order to describe the hydrographic structure. The Rossby Radius of deformation (R_1) was calculated according to Chelton et al. (1998), in which R_1 is the length scale of fundamental importance in ocean dynamics, which describe the minimum length scale at geostrophic balance.

A General Oceanics rosette equipped with Niskin bottles was used to obtain water samples for nitrate determinations at 38 stations at different depths (Fig. 1). The water samples were held in polypropylene containers after filtration with 0.45 and 0.22 μm (MilliporeTM type HA) nitrocellulose membranes and kept frozen until further analyses using a Skalar San Plus segmented-flow continuous auto-analyzer, in accordance with the standard methods adapted by Grasshoff et al. (1983) and the circuits suggested by Kirkwood (1994). The analytical precision of this system was 0.1 μM.

Natural fluorescence and photosynthetically available radiation (PAR) were measured at 40 stations (Fig. 1) using a PNF-300 profiler from Biospherical Instruments. The instrument is based on a measurement of the flux of natural fluorescence and can be used to estimate the instantaneous gross photosynthetic rate (Chamberlin et al., 1990). The instrument was calibrated before the oceanographic cruise by the manufacturer (Biospherical Instruments Inc.). Using the *in vivo* fluorescence data, different profiles of Chl-a (mg m^{-3}) vertical distribution and the integrated values (mg m^{-2}) were obtained by following the method described by Signoret et al. (2006a), thought the water column or to 100 m depth when the depth was deeper, in order to analyze the horizontal distribution.

To identify the most conspicuous phytoplankton organism, samples were recovered at four fixed stations, which covered the Campeche Bank and the deepest region of the Campeche Canyon (Fig. 1). The samples (4 L) were collected at different depths (5, 20, 40, 50 and 80 m) using Niskin bottles and filtered through Millipore membrane filters (0.45 μm) using a vacuum pump. Filters were immediately rinsed with distilled water to remove the salt, then air-dried and stored in plastic Petri dishes (Bollman et al., 2002). Pieces of the filters (approx. 1 cm^2) containing phytoplankton were mounted onto slides and immersion oil was added to clear the filter. Thin sections were then cover slipped and observed under a light microscope using bright field microscopy with total magnifications of ×600 and ×1200 to quantify and identify the most conspicuous species.

3. Results

Three water masses were found in the upper 120 m depth, in the Gulf of Mexico: Gulf Common Water (GCW), characterized by $22 < T < 28$ °C and $36.2 < S < 36.4$ g/kg; the Caribbean Tropical Surface Water (CTSW), characterized by $28 < T < 30$ °C and $36.4 < S < 36.8$ g/kg, and the Caribbean Subtropical Underwater (CSUW) with $22 < T < 26$ °C and $36.4 < S < 36.6$ g/kg (Fig. 2) according to Aldeco et al. (2009). The mixed layer estimated using the maximum vertical temperature gradient at its base, was ~40 m thick and had a temperature of 27 °C. A strong thermocline was present throughout at the entire study region, which was located between 38 and 45 m depth.

The 18.5 °C isotherm topography showed that this is the deepest core located at ~92.7° W and 21° N, reaching a maximum of 144 m depth. This isotherm was shallow (~122 m) at ~92.9° W and 20.85° N. These cores revealed the presence of an anticyclone-cyclone and the stretching of isolines between the two structures suggested the presence of a front. A strong gradient in the southeastern part of the study area indicates an intense southward flow along the shelf break (Fig. 3a). In the eastern part of the Campeche Canyon, at ~92.7° W and 20.8° N, the 15 °C isotherm topography (Fig. 3b) showed a shallower core, which formed a dome that reached up to 212 m depth, suggesting

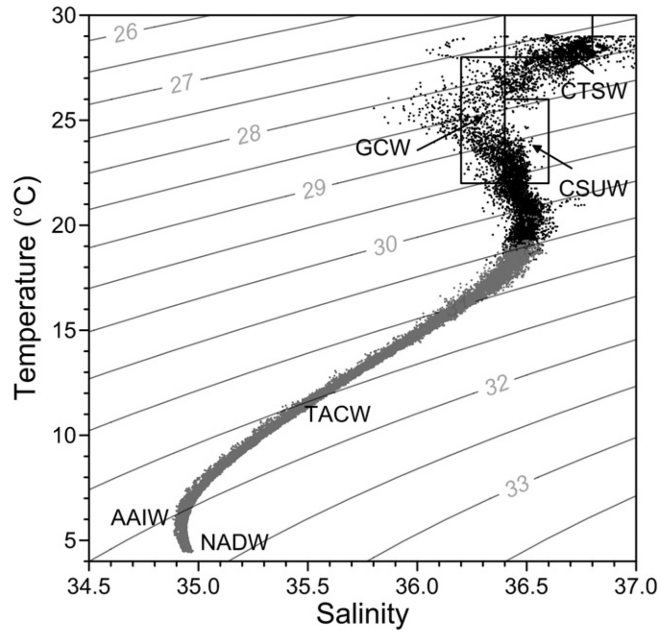

Fig. 2. Temperature-salinity (T-S) diagram: Water masses Caribbean Tropical Surface Water (CTSW), Gulf Common Water (GCW), Caribbean Subtropical Underwater (CSUW), Tropical Atlantic Central Water (TACW), Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW). The black points indicate the water in the first 120 m of the water column.

the presence of a cyclonic structure. In addition, an anticyclonic structure with a diameter of ~50 km was illustrated by the isotherm topography, which reached 234 m depth. On the other hand, the anticyclone-cyclone was evidenced by means of the vertical structures of isotherms through the transect AA', with an uplift at station 28 (cyclone) and a down lift at station 20 (anticyclone) (Fig. 3c). The buoyancy frequency along the same transect at ~40 m depth identified the pycnocline (Fig. 3d). The Rossby radius of deformation for the study area was calculated as 8 km.

The concentration of nitrate increased with respect to depth. At 80 m, the concentrations varied from 1 to 6 μM, with a maximum at the shelf break. The high concentration (~4 μM) was located close to the center of the cyclone (C), while the lower concentration (~1 μM) was associated to the anticyclone, another peak was identified in the southwestern study area, where a cyclonic circulation was observed (Figs. 3a, 4a). At 120 m depth, the nitrate concentration was high, which varied from 2 to 13 μM and their distribution showed two notorious cores of high concentration, that at the shelf break, and another one in the northwestern part of the study area, also two cores of relatively low concentrations were observed, one of them near to the anticyclone(Fig. 4b).

Vertical profiles of Chl-a were registered over both the Campeche Canyon and Bank. Two types of vertical patterns were identified; the first was found over the deep area in the Campeche Canyon and was considered as Chl-a maximum with values ranging from 0.02 to 0.42 mg m^{-3} in a depth between 60 and 100 m. This maximum was found into the euphotic layer, associated with the depth of 1% of the incident irradiance, which is considered to be the lower limit of the euphotic zone and independent of the thermocline (Fig. 5). The second pattern was observed in the Campeche Bank region, which included a Chl-a peak with values ranging from 0.02 to 0.8 mg m^{-3}, located near the shallow region (between 50 and 60 m depth) in association with the thermocline (Fig. 6). In both cases, the values at the maximum were relatively high, which corresponds to the classification of mesotrophic condition (Koblentz-Mishke and Federnikov, 1977).

The integrated Chl-a varied from 0.10 to 0.60 mg m^{-2}, with three peaks (Fig. 7). The first located at ~93.3° W and 21.2° N reaching values

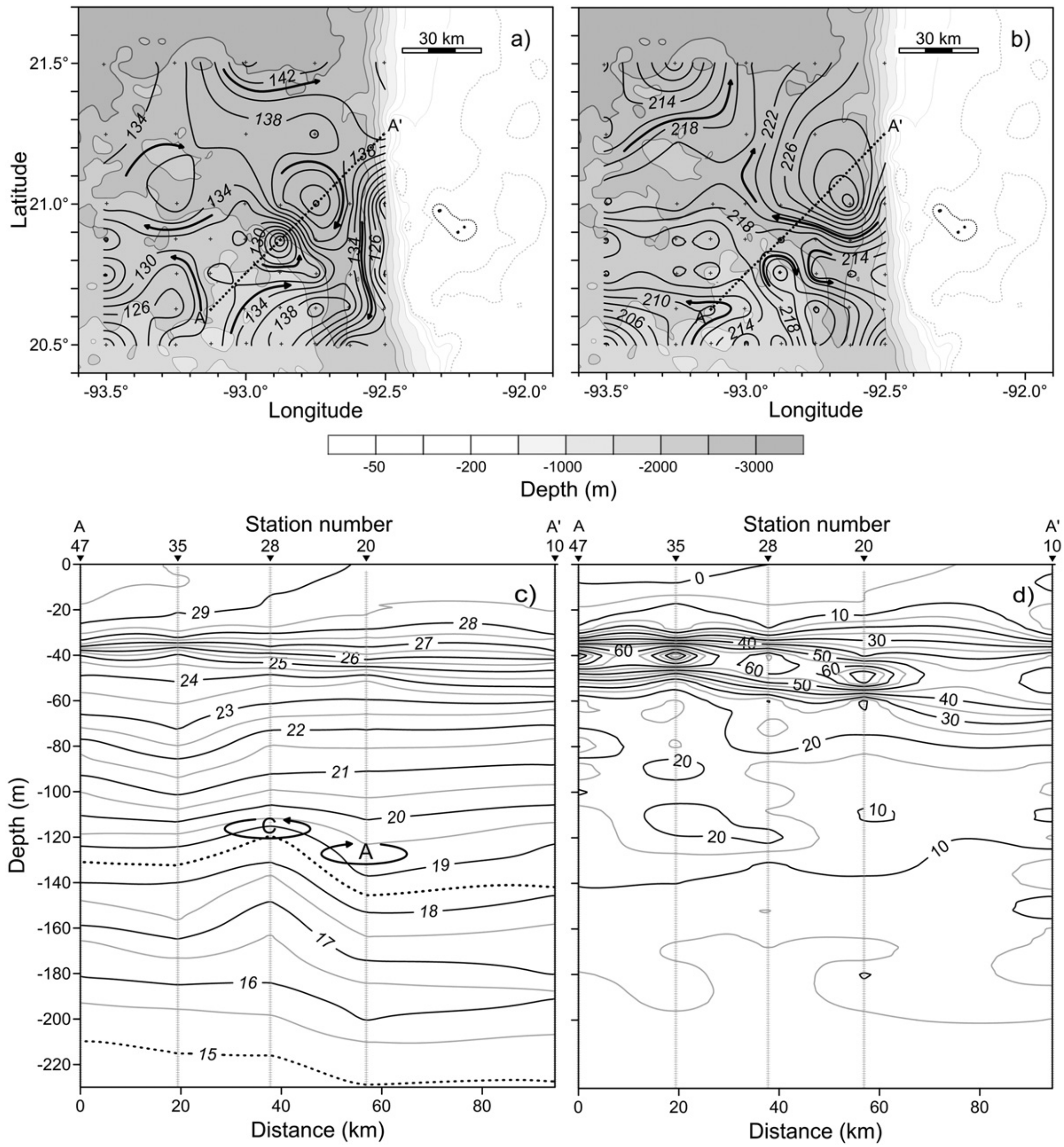

Fig. 3. Isotherm topography (m) of: a) 18.5 °C, b) 15 °C, where the arrows show the direction of the circulation. CTD cast (+), Arcas key (black dots) and bathymetry (shadow in m). The depth over the continental shelf is shallower than that of the isotherms, c) vertical section of temperature (°C). (C and A indicate the cyclone and anticyclone position), and d) buoyancy frequency ($-N^2 \times 10^{-5}\ s^{-2}$) along AA' transect.

of ~0.55 mg m^{-2}, associated with cyclonic circulation (Fig. 3b). The second was found at the boundary between the anticyclone and the cyclonic circulation in the northwestern study area as show in fig. 3b (~92.8° W and 21.25° N) with values of ~0.4 mg m^{-2}, and the third peak was associated to a cold water tongue close to the shelf break. This core (~0.6 mg m^{-2}) also recorded high nitrate concentration.

The abundance of the phytoplankton groups varied depending on the zone. In the canyon region, the most abundant group was the coccolithophores, followed by dinoflagellates and the diatoms; silicoflagellates were not found in this region. Over the Campeche Bank, the most abundant group was the silicoflagellates, followed by dinoflagellates, coccolithophores and diatoms (Table 1).

On the basis of their abundance, the most conspicuous phytoplankton organism was identified at a species level. The results indicated differences according to the sampling zone. The dominant species in the stations that corresponded to the canyon were: three coccolithophores (*Emiliania huxleyi*, *Gephyrocapsa oceanica* and *Florisphaera profunda*), two pennate diatoms (*Nitzschia bicapitata* and *Nitzschia bifurcata*) and two dinoflagellates (*Ceratium furca* and *Oxitoxum* sp.). The taxonomic distribution over the Campeche Bank included the similar species as in the deep area, but with the addition of silicoflagellate (*Dictyocha fibula*), present in the bank.

4. Discussion

The GCW is formed inside the Gulf of Mexico *via* two mechanisms: the first involves the presence of winter storms locally called northers, which produce a cooling effect and causes a mixed surface layer (Monreal-Gómez and Salas de León, 1997). The second involves the collision of the anticyclonic eddy with the continental slope of the Northwest region of the Gulf of Mexico and becomes detached from the Loop Current (Elliot, 1982; Vidal et al., 1992; Vidal et al., 1994). The physical and ecological processes observed in this study are discussed below.

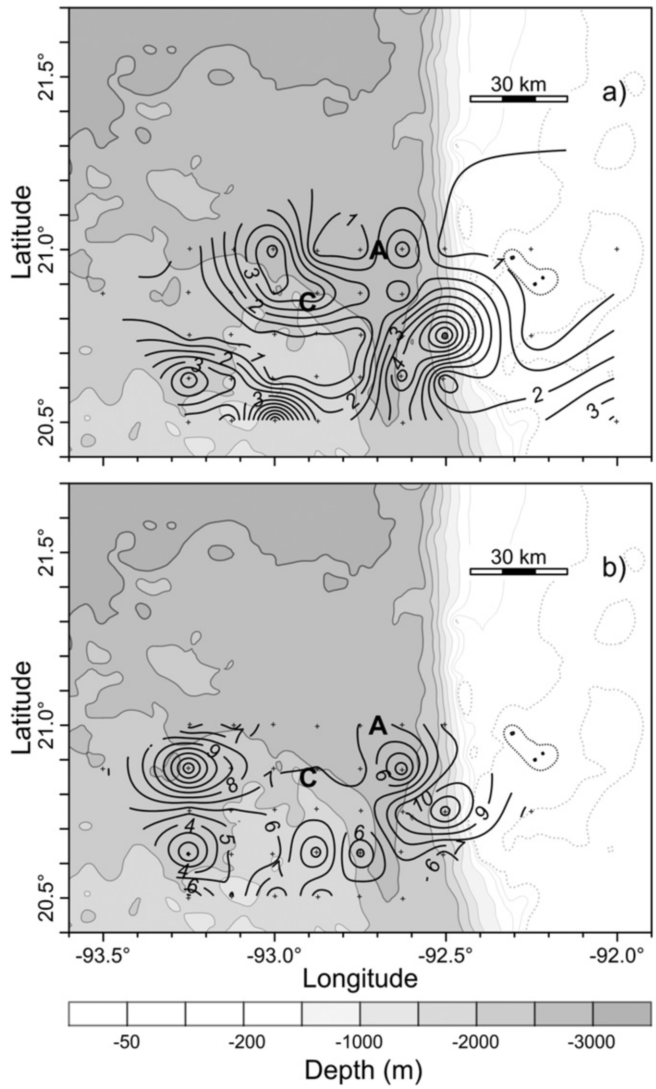

Fig. 4. Horizontal distribution of nitrate (μM) at: a) 80 m depth (contour interval = 0.5) and b) 120 m depth (contour interval = 1.0), (C and A indicate the cyclone and anticyclone position according to the 18.5 °C isotherm topography).

The CTSW (Fig. 2) originates from the Caribbean Sea reported in the central and western Gulf of Mexico was formed due to the translation of anticyclonic rings from the Loop Current to the Gulf (Elliot, 1982; Nowlin, 1972; Vidal et al., 1992). The buoyancy frequency reveals the pycnocline at ~40 m depth (Fig. 3d), which agree with the thermocline depth (Fig. 3c). The temperature section shows uplift and downlift according to cyclone-anticyclone position (Fig. 3c).

A detailed description, from hydrographic data in the vicinity of Astoria Canyon (U.S. west coast) by Hickey (1997) showed a cyclonic-anticyclonic dipole above the canyon with an important effect of the topography. In addition, a cyclonic eddy has been reported in the same canyon created by the flow turning into the canyon mouth (She and Klinck, 2000). Specific processes take place in Blanes Canyon (western Mediterranean) where a cyclonic-anticyclonic circulation has been reported (Ardhuin et al., 1999).

The Rossby radius of deformation for the study area was calculated as 8 km. Because the size of the cyclone-anticyclone is a multiple of R_1, we assume that their motions are quasigeostrophic (Gill, 1982; Osinkis et al., 2010). Our result of R_1 agree with those obtained in the Blanes Canyon which was of 13 km; in the Astoria Canyon, R_1 showed values range from 30 to 60 km, for weak and strong stratifications, respectively (Hickey, 1997), however this particular region is narrow and shallow in comparison with the Campeche Canyon. There are no studies linking the Rossby radius with the planktonic populations in the Gulf of Mexico; however, several authors documented that submesoscale processes strongly affect the phytoplankton distribution and abundance (Strass, 1992; Martin, 2003; Franks, 1992; Lévy et al., 2001). Eddies can enrich new biological production by the injection of nutrients into the euphotic layer (Lévy et al., 2001). In this study, we identified that the Chl-a horizontal distribution was affected by the association of anticyclone-cyclone, because the high values (0.4 mg m^{-2}) were observed at their boundaries in the northwestern part of the study area (Fig. 3b). This was because cyclonic eddy present divergent movements, and therefore, the cold and nutrient rich water goes up and fertilizes the euphotic zone, while the anticyclonic eddies are convergent and create a downwelling of warm water that is poor in nutrients (~1 μM). At the zone of the boundary between eddies, nutrient rich fronts are formed. Some studies have demonstrated that in zones in which these anticyclonic-cyclonic eddies interact and where Chl-a-rich plumes can form, there is a strong contribution of nutrients (Torner et al., 2003). Importantly, the deep maximum of Chl-a is common at canyon zones due to specific hydrodynamic (Rennie et al., 2008). In the oceanic waters of the Southern Gulf of Mexico, Signoret et al. (1998) found a deep maximum (0.3 mg m^{-3}) at the base of the euphotic layer related to the nutricline. Similar observations to those presented here were inferred during summer in the Sargasso Sea, which showed that phytoplankton are generally confined to a deep chlorophyll maximum just above the nutricline with rapidly decreasing concentrations extending into deeper, darker, but nitrate-richer waters. When these deeper waters are uplifted into the euphotic zone within a cyclonic eddy, the nitrate can be consumed by the phytoplankton already present within them (Martin and Pondaven, 2003). This could be the case for the low nitrate concentration core observed to be associated with the cyclonic circulation (Figs. 3b and 4b) due to absorption of phytoplankton in this region. This pattern has been previously documented in mesoscale cyclonic eddies in the Bay of La Paz, Gulf of California (Coria-Monter et al., 2014) as well as in the Peru coast (Arévalo-Martínez et al., 2016).

Campeche Canyon showed different trophic types of waters in the vertical plane and also in the same location, according to the classification of primary productivity water types (Koblentz-Mishke and Federnikov, 1977). At the Chl-a maximum, the conditions may be considered mesotrophic, while at the surface and low concentration areas of the vertical profile, the conditions are oligotrophic. Over the Campeche Bank, low Chl-a concentration was present throughout most of the water column, but an increase near the bottom was evident, which was associated with the thermocline.

The vertical profiles of Chl-a fluorescence and the thickness of the Chl-a maximum have been widely correlated with the availability of potential trophic sources for herbivores. At the Southern Gulf of Mexico, different types of vertical profiles have been identified: a) one deep maximum (at 95–100 m depth), which is associated with the limit of the euphotic layer; b) a homogeneous profile; c) two or more maxima; and d) the presence of a thin layer (Signoret et al., 2006b). Our results were consistent with the deep Chl-a maximum (0.4 mg m^{-3}) of Campeche Canyon and the maximum (0.6 mg m^{-3}) is associated with the bottom of Campeche Bank, which is due to the shallowness of the shelf. This abundance represents a potential food source, particularly for infauna and epifauna suspension feeders. Similar observations have been made in the Palamós Canyon (northwestern Mediterranean) where Chl-a concentration was relatively high in surface waters (Palanques et al., 2005).

The dominance of coccolithophores over the canyon region is closely correlated with the deep maximum peak of Chl-a (0.4 mg m^{-3}), evidenced by stations 25, 33 and 43 where the maximum abundance of coccolithophores were observed at 80 m depth. This group has been identified as the most predominant organism in deep maximum

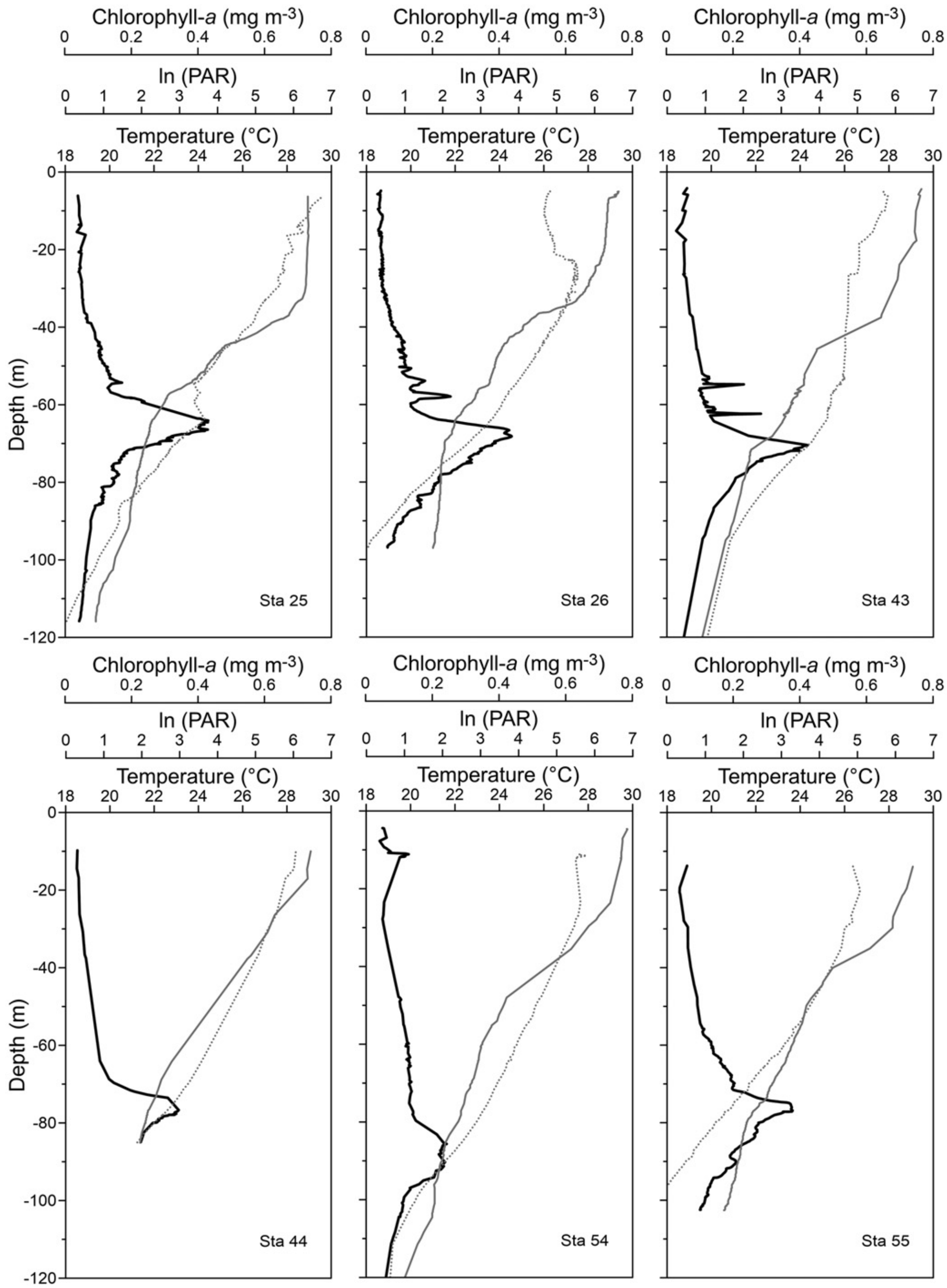

Fig. 5. Vertical distribution of chlorophyll-a (mg m^{-3}) (black solid line), irradiance (PAR) (gray dotted line), and temperature (°C) (gray solid line) in Campeche Canyon.

(Signoret et al., 2006a). To explain the formation of this deep maximum, several mechanisms have been proposed: a) high cell density by adaptation to the depths related with nutricline; b) accumulation by physical processes; and c) adaptation to low levels of irradiance (Cullen, 1982). In our case, the three mechanisms could play a fundamental role in the distribution patterns.

Although there are no Soluble Reactive Si measurements, the dominance of silicoflagellates in the Campeche Bank suggest that they are abundant and the Chl-a maximum at the bottom also suggests a mixing mechanism that could ensure the availability of nutrients. On the other hand, in the shelf break the topography of the 18.5 °C isotherm had a similar pattern to that described for summer 1999 by Salas-de-León et al. (2004). These authors documented an upwelling of cooler midwater induced by topographic effect, which could be the mechanism that fertilizes and support the silicoflagellates abundance and the high Chl-a integrated over the Campeche Bank.

5. Summary and conclusions

On the basis of our results, we infer that different trophic conditions in the vertical distribution of Chl-a could have substantial effects on the fluxes of energy and matter in the ecosystem, and represent different trophic or bioenergetic potential layers with a high significance for the pelagic food web.

In June 2002, at the Campeche Canyon, three water masses were found in the upper layer of 120 m: The Gulf Common Water (GCW), the Caribbean Tropical Surface Water (CTSW) and Caribbean Subtropical Underwater (CSUW). Also, below the three typical water masses;

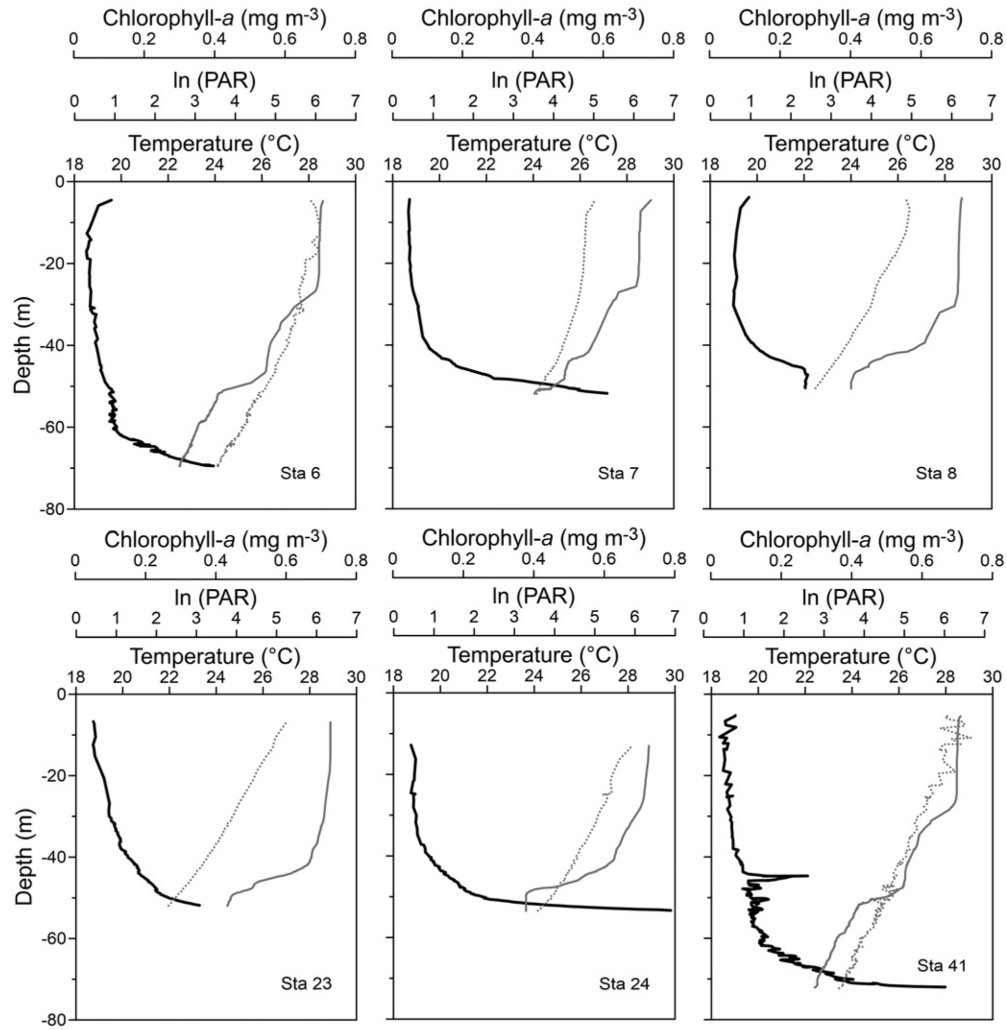

Fig. 6. Vertical distribution of chlorophyll-a (mg m^{-3}) (black solid line), irradiance (PAR) (gray dotted line), and temperature (°C) (gray solid line), over the Campeche Bank.

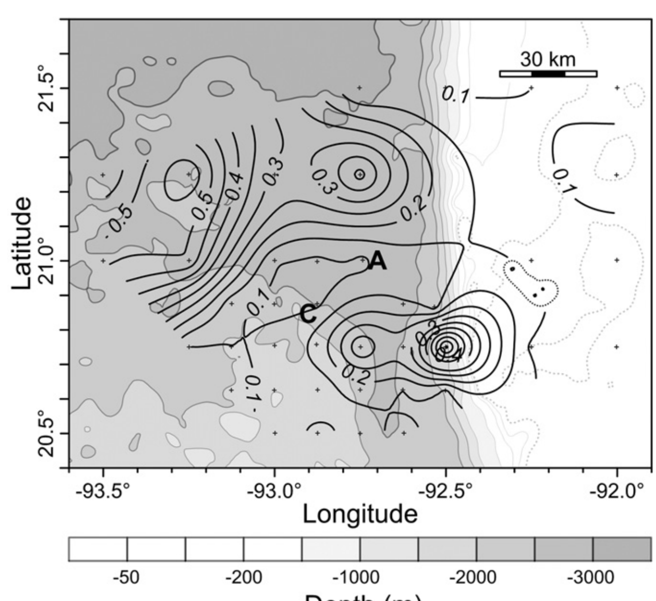

Fig. 7. Horizontal distribution of integrated chlorophyll-a (mg m^{-2}) (C and A indicate the cyclone and anticyclone position according to the 18.5 °C isotherm topography).

Tropical Atlantic Central Water (TACW), Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW) were found. While at the Campeche Bank only the Caribbean Tropical Surface Water (CTSW) was found. Because the size of the eddy is multiple of R_1, the motion was quasigeostrophic.

Campeche Canyon showed different trophic types of waters in the vertical plane and in the same location, at the Chl-a maximum, the conditions may be considered as mesotrophic, while at the surface with low concentration areas of the vertical profile, the conditions are oligotrophic. In the upper layer the nutrient pumping mechanism fertilizes the euphotic zone promoted by the cyclonic eddy. Eddy-induced uplifting caused by the cyclone promotes a high biological production; the divergent dynamic of the cyclonic eddy is combined with the converging characteristics of the anticyclone resulting in a high concentration of nitrate and integrated Chl-a in the border of an anticyclone and a cyclone.

Two patterns of Chl-a vertical distribution were found: a) a deep maximum peak; and b) a peak associated with the bottom and the thermocline. Dominant phytoplankton species are represented by coccolithophores (*Emiliania huxleyi*, *Gephyrocapsa oceanica* and *Florisphaera profunda*), pennate diatoms (*Nitzschia bicapitata* and *Nitzschia bifurcata*) and dinoflagellates (*Ceratium furca* and *Oxitoxum* sp.). The taxonomic composition over the Campeche Bank included the same species as in the deep area, but with the addition of silicoflagellate (*Dictyocha fibula*).

Table 1
Phytoplankton abundance per group and station recorded from different sampling stations.

Station	Zone	Depth (m)	Coccolithophores abundance (cells L^{-1})	Dinoflagellates abundance (cells L^{-1})	Diatoms abundance (cells L^{-1})	Silicoflagellates abundance (cells L^{-1})
24	Campeche Bank	5	2000	2500	598	1700
		20	1598	2000	280	2000
		40	900	1600	100	2700
		50	500	900	59	2780
	Average		1250	1750	259	2295
25	Campeche Canyon	5	3020	220	1220	–
		20	1580	1900	280	–
		40	2000	2900	360	–
		80	4500	3600	30	–
	Average		2775	2155	473	–
33	Campeche Canyon	5	2860	1000	2220	–
		20	1240	1600	760	–
		40	1470	2800	760	–
		60	2620	2600	320	–
		80	3160	2300	90	–
	Average		2270	2060	830	–
43	Campeche Canyon	5	2328	1600	400	–
		20	2080	1980	520	–
		40	1700	2000	600	–
		60	2440	2500	300	–
	Average		2137	2020	455	–

The differences between the Campeche Bank and Campeche Canyon are that: in the canyon, the nutrient and Chl-a peaks were linked with the cyclone, and the submesoscale processes in the border of an anticyclone and a cyclone, respectively. In the vertical the maximum Chl-a was associated to the base of the euphotic layer and dominated by coccolithophores. In the Campeche Bank the nutrient and Chl-a peaks were influenced by the shelf break, in the vertical the maximum Chl-a was associated with the thermocline and the silicoflagellate was identified as the dominant species.

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