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Wind driven nutrient and subsurface chlorophyll-*a* enhancement in the Bay of La Paz, Gulf of California

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ABSTRACT

Nutrient and chlorophyll-*a* distributions in the Bay of La Paz, Gulf of California, Mexico were analyzed during the late spring of 2004 to assess their relations to hydrography and circulation patterns. The results show the presence of both Gulf of California Water and Subtropical Subsurface Water. Water circulation was dominated by wind stress driven cyclonic circulation along f/H contours (f is planetary vorticity and H is depth), and upwelling resulting from the divergence shows a vertical velocity of ~0.4 m d^{-1}. Nutrient concentrations were higher in the center of the cyclonic pattern, where a rise in the nutricline contributed nutrients to the euphotic layer as a result of Ekman pumping. The vertical section showed the presence of a chlorophyll-*a* maximum at the thermocline shoaling to a depth of only 12 m. Along the surface, two peaks of chlorophyll-*a* were observed, one at Boca Grande and another off San Juan de la Costa, associated with upwelling and mixing derived from current interactions with abrupt topographies. The chlorophyll-*a* maximum increased from 0.8 mg m^{-3} in the external part of the cyclonic pattern to 2.0 mg m^{-3} in its center. The vertically integrated chlorophyll-*a* concentrations followed a similar pattern, rising from 10 to 20 mg m^{-2} and reaching their highest values in the center of the cyclonic circulation pattern. A schematic model was developed to describe processes that occur in late spring: the wind stress driven cyclonic structure promotes upward nutrient flux, which in turn drives an enhancement of chlorophyll-*a*. Upwelling was found to be the main mechanism of fertilization responsible for the enhancement of productivity levels by means of nutrient transport into the euphotic zone during spring. Other chlorophyll enhancement areas point to the occurrence of additional fertilization processes that may derive from interactions between cyclonic circulation patterns and the topography off of San Juan de la Costa, where phosphate mining occurs.

1. Introduction

Wind stress driven cyclonic flows are considered to be important hydrodynamic processes that may affect the productivity, abundance, and distribution of plankton in the ocean at different space and time scales (Macías et al., 2008; Lee et al., 1992). Wind-induced currents are among the strongest in the upper ocean layer; the flow within the Ekman layer is divergent from cyclonic flows that induce upward vertical motion (upwelling) while the convergent flow drives vertical motion downward (downwelling) in an anticyclonic flow. Thus, cyclonic circulation induces an upward displacement of the nutricline, which penetrates the euphotic zone and which may enhance primary production and its exportation from this input of nutrients (Lee et al., 1992). Although numerous reports have been published on the biological effects of cyclonic and anticyclonic flows in open ocean regions, such studies on coastal areas of the southern Gulf of California and particularly on areas within bays are scarce. Nevertheless, within the Bay of La Paz, a mesoscale cyclonic structure has been observed on several occasions by various researchers and has been indistinctly referred to as a cyclonic eddy (Coria-Monter et al., 2014; Durán-Campos et al., 2015), cyclonic circulation (Monreal-Gómez et al., 2001), and cyclonic gyre (García-Mirafuentes, 2010; Sánchez-Velasco et al., 2004, 2006).

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Diverse biological patterns have been found to be associated with this cyclonic structure, underscoring its biological significance. In the late spring of 1998, Monreal-Gómez et al. (2001) observed a chlorophyll maximum just above the doming thermocline and documented an enhancement of production, but this study was not conclusive in this respect. In the summers of 1997 and 1998, circulation patterns in the Bay of La Paz likely affected distributions of larval fish assemblages, which showed temporal and spatial correlations with geostrophic dynamics (Sánchez-Velasco et al., 2006).

However, to date wind driven circulation effects on nutrient and chlorophyll-*a* enhancement based on direct observations of the Bay of La Paz have not been documented.

The Bay of La Paz is located roughly 180 km NW from the mouth of the Gulf of California along the coast of the Baja California Peninsula (Fig. 1). It joins with the Gulf of California through two openings: Boca Grande and the San Lorenzo Channel, which is narrow and shallow with a depth of ~18 m. The deepest (~420 m) area of the bay is the Alfonso Basin, which is located in the northwest off of Punta Coyote. The bay is separated from the Gulf of California by a bathymetric sill found across Boca Grande (~250 m depth).

In this study, based on measurements obtained over the course of a cruise expedition carried out in the late spring of 2004, we analyzed mechanisms that induce this circulation pattern to assess coupling between nutrients and the chlorophyll-*a* distribution in the Bay of La Paz, Gulf of California, Mexico. This assessment is the first to show evidence of nutrient and subsurface chlorophyll-*a* enhancement associated with cyclonic circulation during the spring in the Bay of La Paz.

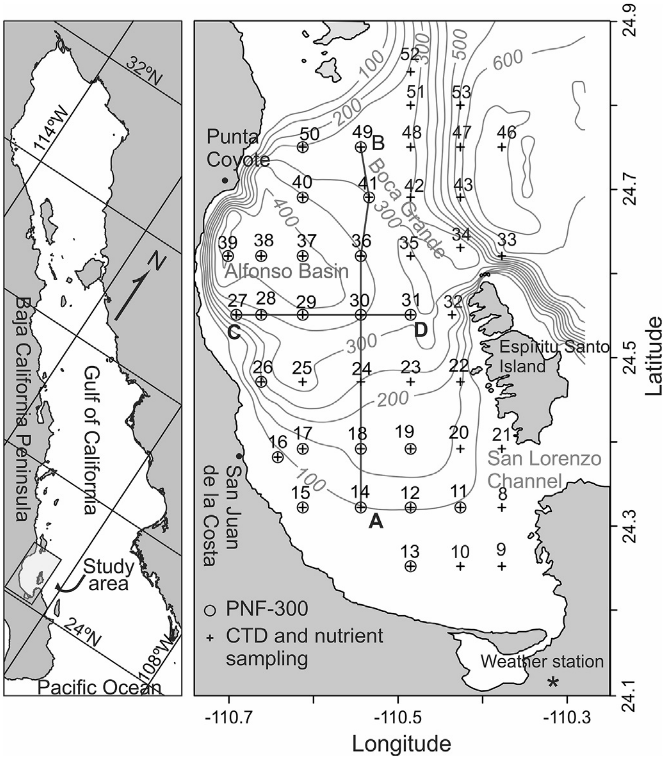

Fig. 1. Bay of La Paz hydrographic and sampling stations: ○ PNF300, + CTD and nutrients. Bathymetry (m) values are shown as thin gray lines. Along A-B and C-D transects, water mass distributions and vertical sections are analyzed, respectively.

2. Materials and methods

Hydrographic data, water samples for nutrient determination and chlorophyll-*a* measurements were obtained throughout our research expedition "PALEO-XII" carried out aboard the R/V "El Puma" of UNAM from June 14 to 18 of 2004. Wind data were simultaneously obtained from five sites of the Bay of La Paz for reanalysis (NCEP, NORTH AMERICAN REGIONAL REANALISIS: NARR, https://www.esrl.noaa.gov). Wind values were also available from each hydrographic station (though not simultaneously) from the ship's anemometer. Differences between reanalysis and the ship's wind data are negligible. Therefore, the wind velocity structure in the Bay of La Paz was well represented by anemometer data from hydrographic stations. A Neil Brown CTD was used to record conductivity, temperature and pressure data from 44 hydrographic stations (Fig. 1). Water mass characteristics were identified from a T-S diagram and classified according to Lavín et al. (2009). Transect A-B (Fig. 1) was used to identify the vertical distribution of the water masses (Fig. 1).

Geostrophic velocities relative to the base were calculated from CTD data. The topography of the 20 °C isotherm, which coincides with the thermocline, was analyzed to infer circulation patterns in the bay while the topography of the 15 °C isotherm was used to confirm circulation and structural patterns. Vertical distributions of temperature, density (sigma-t), chlorophyll-*a* and nutrients were analyzed along the transect C-D (Fig. 1). Wind-induced currents are the strongest in the upper ocean layer, and when Ekman transport diverges or converges, Ekman pumping forms at the base of the Ekman layer. In regions where Ekman transport diverges, positive vertical velocity (upwelling) is generated while in cases of convergence, negative vertical velocity (downwelling) is observed, thus affecting biological production. To analyze topographical and wind effects on circulation patterns, the ratio between planetary vorticity (f) and depth (H) and vertical velocity (w_E) values were calculated. w_E was calculated following Martin and Richards (2001):

$$w_E = \frac{1}{f\rho_w}\left(\frac{\partial\tau_y}{\partial x} - \frac{\partial\tau_x}{\partial y}\right)$$

where $\vec{\tau} = (\tau_x, \tau_y)$ is wind stress $\vec{\tau} = \frac{\rho_a\, k_a}{(1+\varepsilon)^2}\left|\vec{V}_a - \vec{V}\right|(\vec{V}_a - \vec{V})$; $\varepsilon = \left(\frac{\rho_a}{\rho_w}\right)^{\frac{1}{2}}$, f is planetary vorticity, ρ_w and ρ_a are the density of water and air, respectively, $\vec{V}_a$ is wind velocity, $\vec{V}$ is the velocity current, and k_a is the drag coefficient of air over the sea determined according Kondo (1975) for wind speeds of between 2 and 8 m s^{-1} applicable for this study: $k_a = (0.87 + 0.067|\vec{V}_a|) \times 10^{-3}$. On the basis of consistency found between wind patterns derived from the reanalysis and the ship's anemometer, it was used to calculate vertical velocity values.

On the other hand, vertical velocity was estimated from wind velocity time series at 3 h intervals from the weather station at La Paz, B.C.S (Fig. 1). and from the geostrophic current ($\vec{V}$), which was taken to be constant. A General Oceanics rosette equipped with 10-L Niskin bottles was used to obtain water samples for nutrient determinations at 5, 10, 20, 30 and 50 m depths at 44 stations (Fig. 1). The water samples were stored in polypropylene containers after their filtration with 0.22-μm (MilliporeTM type HA) nitrocellulose membranes and were frozen until their analysis through a Skalar San Plus segmented-flow continuous auto-analyzer using standard nutrient methods improved by Grasshoff et al. (1983) and using circuits recommended by Kirkwood (1994). Precision levels were as follows: nitrate, 0.1 μM, soluble reactive Si (SRSi), 0.1 μM and soluble reactive P (SRP), 0.04 μM.

Fluorescence measurements were performed using a natural fluorescence profiler (PNF-300, Biospherical Instruments) at 23 stations (Fig. 1). Fluorescence signals were transformed into concentrations of chlorophyll-*a*. The instrument was calibrated by the manufacturer prior to our research expedition. The profiling radiometer used included a channel for measuring upwelled radiance at 683 nm, the peak emission wavelength for chlorophyll-*a*. Measurements of upwelled radiance at 683 nm were converted to natural fluorescence following Kiefer et al. (1989) and Chamberlin et al. (1990). Solar-stimulated or “natural” fluorescence is a passive measurement that facilitates estimates that are relatively easy to obtain and that are non-intrusive over a broad range of spatial and temporal scales (Westberry and Siegel, 2003). Potential causes of variability in the quantum yield of natural fluorescence include changes in the availability of inorganic nutrients often limited by nitrogen, changes in solar stimulation and changes in water column temperature (Falkowski and Kolber, 1995; Falkowski and Raven, 2007).

From the vertical profiles of chlorophyll-*a*, a maximum was identified at each sampling station, and the chlorophyll-*a* concentration was vertically integrated to obtain area-based measurements for each station. A satellite image of chlorophyll-*a* from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to assess the surface distribution. The image with a spatial resolution of 3.5 km (Local Area Cover) was processed from Levels 1 and 2 (http://oceancolor.gsfc.nasa.gov) using SeaDAS version 6.4 and standard algorithms.

A 3D schematic model based on observations remarking processes occurring in the Bay of La Paz was developed. The conceptual model was built to describe hydrodynamic features and their relationships to chemical-biological processes. A thermal structure with an isothermal surface (thermocline) associated with circulation was obtained from the Alfonso Basin. To analyze its effect on nutrient and chlorophyll-*a* distributions, an isosurface of nitrate and the chlorophyll-*a* maximum were considered.

3. Results

3.1. Water masses

Following the water mass classification for the Gulf of California developed by Lavín et al. (2009), the T-S diagram for this study (Fig. 2a) shows two water masses in the bay: Gulf of California Water (GCW: $S > 34.9$ psμ and $T \geq 12$ °C) and Subtropical Subsurface Water (StSsW: $34.5 < S < 34.9$ psμ and $9 \leq T \leq 18$ °C). Gray points in the T-S diagram outline records for station 30, where the two transects intersect (Fig. 2a). The vertical distribution of these water masses along transect A-B shows that GCW occupied the upper 150 m layer, and StSsW was found below it (Fig. 2b). The 34.9 psμ isohaline formed a boundary between the two water masses.

3.2. Dynamic of the bay

Wind circulation was dominated by westerly winds (~5 m s^{-1}) except at southern and northern points in the bay where northwesterly winds were observed (Fig. 3a). The geostrophic velocity at 10 m in depth shows cyclonic circulation patterns reaching values of 50 cm s^{-1} (Fig. 3b). This cyclonic circulation pattern can be viewed as a gyre. The topography of the 20 °C isotherm reached its maximum depth outside of the bay (~30 m) across Boca Grande and it shoaled in the deepest region of the bay, where it rose 4 m and formed a dome with its upper section positioned at a depth of 12 m (Fig. 3c) in agreement with cyclonic circulation patterns in the Alfonso Basin as evidenced by the geostrophic velocity. The topography of the 15 °C isotherm shows that it was located at shallower depths in inner zones of the bay, forming a dome of ~20 m thick. The isotherm was positioned at a depth of 60 m in the center of the cyclonic circulation pattern and gradually increased until reaching >80 m in depth near Boca Grande (Fig. 3d); the cyclonic circulation pattern had a ~30 km west-east extension.

The ratio of planetary vorticity and depth followed a similar basin shape (Fig. 4a), whereas the vertical velocity pattern presents positive values in the center of the area of cyclonic circulation, revealing an upwelling reaching values of 0.4 m d^{-1}. Negative vertical velocities were found in the southern area of the bay and in a shallow zone in the northern area of the bay (Fig. 4b). The time series of vertical velocity for the base of the Ekman layer shows positive values for the center of the circulation pattern where clines formed a dome, revealing the presence of an upwelling. Observed wind speeds in La Paz, B.C.S. varied from 3.0 to 3.5 m s^{-1} during the survey period (shaded area) and associated Ekman pumping values ranged from 0.2 to 0.8 m d^{-1} (Fig. 4c).

Vertical distributions of temperature (Fig. 5a) and sigma-t (Fig. 5b) along the transect C-D show clines at a depth of approximately 10 m and a rise in isolines around station 30 in agreement with the positioning of the dome denoted by topographies of 20 °C and 15 °C isotherms for this region (Fig. 3).

3.3. Nutrients

The nutrient vertical distribution of the upper 50 m layer along transect C-D shows the location of the nutricline at depths of 15–20 m. At station 30, the nitrate and SRP isolines showed a strong uplift in this area (Fig. 5d and e) while SRSi doming was weaker (Fig. 5f). This uplift confirms that the supply of nutrients to the upper layer was driven by cyclonic circulation at this time, which in the case of SRP was quite intensive, as its vertical distribution shows a core of high concentrations (~2 μM) extending to the euphotic layer (Fig. 5e). The transport of these nutrients from subsurface water to the upper layer was sustained by their vertical pattern, which particularly for nitrate and SRSi concentrations shows an increase with depth (Fig. 5d and f).

Nutrient distributions at a depth of 10 m also followed interesting patterns along the bay. Nitrate concentrations reached a maximum at station 30 (>7 μM), forming a dome in the center of the cyclonic circulation pattern (Fig. 6a). The SRP concentration rose from 0.2 to 0.8 μM at this station and formed a dome similar to that described above (Fig. 6b). SRSi exhibited a more variable range of values at this depth of 2–16 μM and showing two peaks: one (~8 μM) at the center of the cyclonic circulation pattern and another (~16 μM) close to the coastlines of San Juan de La Costa areas, which support phosphate mining activities (Fig. 6c). Overall, with the exception of those of this last peak, horizontal nutrient distributions at 10 m show relatively maximum concentrations within the dome described in the previous section.

Nutrient concentrations at a depth of 20 m were higher than they were at 10 m, as is expected when nutrients are vertically transported upwards. Nitrate concentrations varied from 2 to 16 μM with the highest concentration forming a dome closely following the shape of the circulation pattern (Fig. 6d). SRP levels rose from 0.4 to 1.8 μM, reaching their highest concentrations in the central part of the cyclonic circulation area and forming a dome (Fig. 6e) reflecting the topography of the 20 °C isotherm. Another high concentration core formed further south in the shallower half of the bay. SRSi levels varied from 4 to 18 μM, also showing their highest concentrations at two peaks: one in the northern Alfonso Basin (14 μM) and another in the southern region (18 μM) (Fig. 6f). Overall, the horizontal distribution of nutrients at 20 m showed higher concentrations at Alfonso Basin in conjunction with the cold water dome, indicating that cyclonic circulation drives nutrient flux

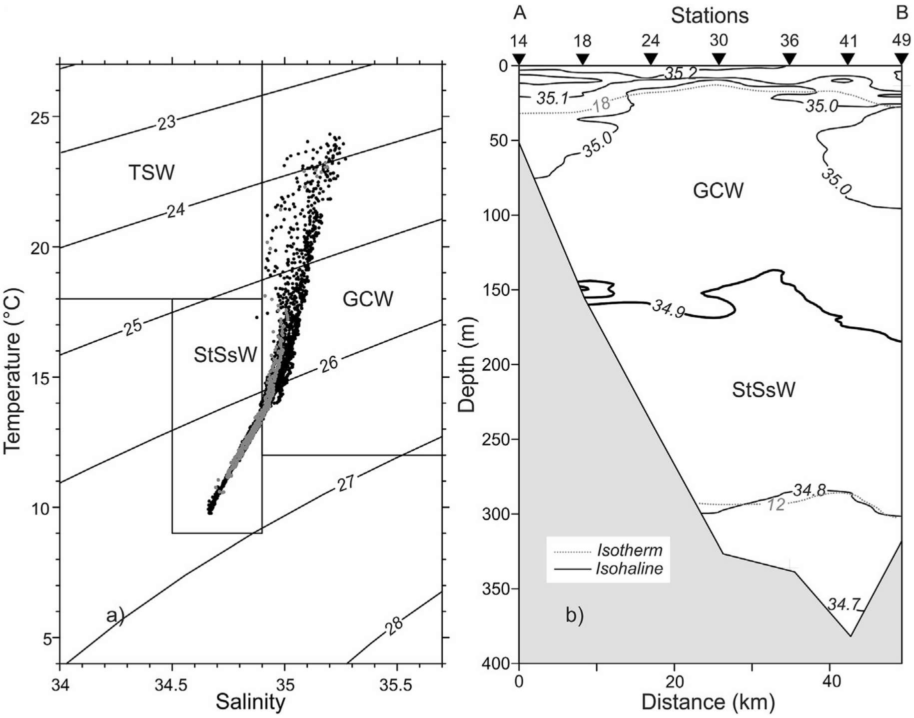

Fig. 2. a) T-S diagram and water masses within the Bay of La Paz (Gulf of California Water: GCW, Subtropical Subsurface Water; StSsW). Samples drawn from station 30 are shown as gray points and b) for the vertical distribution of water masses along transect A-B, the 34.9 psμ isohaline forms the boundary between the water masses.

upward in this area.

3.4. Chlorophyll-a distribution

Effects of cyclonic circulation on the vertical distribution of chlorophyll-*a* were analyzed along the transect C-D that crosses it (Fig. 5c). The highest concentration (2.1 mg m^{-3}) was found to be associated with the pycnocline and nutricline, forming a subsurface chlorophyll-*a* maximum at the center of the cyclonic circulation pattern at 15 m in depth (Fig. 5c). Horizontally, the magnitude of the chlorophyll-*a* maximum decreased from 2.1 mg m^{-3} in the central region of the cyclonic circulation to 0.8 mg m^{-3} in its periphery (Fig. 7b), closely following the shape of the cyclonic flow (Fig. 3) consistent with upward nutrient flux induced by the upwelling. Higher concentrations (>1.2 mg m^{-3}, Fig. 7b) at the chlorophyll-*a* maximum extended from the central core towards Boca Grande and to southern shallower sections of the bay. Vertically integrated chlorophyll-*a* concentrations followed a very similar concentrically shaped pattern ranging from 10 to 20 mg m^{-2} with the highest concentrations observed in the center of the cyclonic circulation area (Fig. 7c).

The satellite images reveal a pattern corresponding with in situ chlorophyll-*a* measurements obtained at the surface (Fig. 7a), allowing for the comparison of chlorophyll-*a* patterns on a broader scale. Average surface concentrations within the bay were (~0.55 mg m^{-3}) roughly two to three times higher than those outside of the bay (0.1–0.2 mg m^{-3}) (Fig. 7a). The highest chlorophyll-*a* surface values were found close to the littoral margins and likely due to vertical mixing in these shallow areas. Two cores of higher values also extended across the bay, with one located off of Boca Grande and the other located off of San Juan de la Costa, where the bay becomes shallower. At both points, interactions between cyclonic circulation and the topography of the bay may play a key role in euphotic layer fertilization. Off of San Juan de la Costa, interactions with the continental slope and base may promote vertical mixing. North of Boca Grande, a frontal area has formed (Figs. 3a and 7a). In both cases, the two plumes of higher values in the chlorophyll-*a* maximum (1.0 mg m^{-3}, Fig. 7a) are evidence of fertilization occurring in these two areas.

Based on our observations, a schematic model is proposed as a means to illustrate processes that occur in the bay (Fig. 8). A dome is formed by the 20 °C isotherm entraining a nutrient uplift, which is followed by subsurface chlorophyll-*a* enhancement across the Alfonso Basin. Divergent flows associated with cyclonic circulation transport nutrient-rich water upward in the core, creating an enhanced chlorophyll-*a* region in the central region characterized by the formation of a subsurface chlorophyll-*a* maximum. Secondary chlorophyll-*a* enhanced areas are also found off of Boca Grande and San Juan de la Costa, where interactions between cyclonic circulation and topographical features likely play a key role.

4. Discussion

Water-mass distributions in the Gulf of California change throughout the year (Obeso-Nieblas et al., 2004). California Current Water (CCW), Gulf of California Water (GCW), Subtropical Subsurface Water (StSsW), and Tropical Surface Water (TSW) (Fernández-Barajas et al., 1994; Lavín et al., 2009) occupy the mouth of the Gulf of California. Regional wind patterns influence water mass distributions. In the late spring, southeasterly winds cause TSW to enter the Gulf of California and Bay of La Paz. TSW enters the bay as it penetrates through Boca Grande and the San Lorenzo Channel (Monreal-Gómez et al., 2001). However, TSW was not found in this study. In the winter, northwesterly winds restrict the water mass to the mouth of the Gulf of California. The presence of StSsW in the Bay of La Paz is described as follows: winds from the south cause the water mass to penetrate the Gulf of California, causing the water mass to enter the bay through Boca Grande. Overall, the presence of GCW in the bay may be attributed to one of two

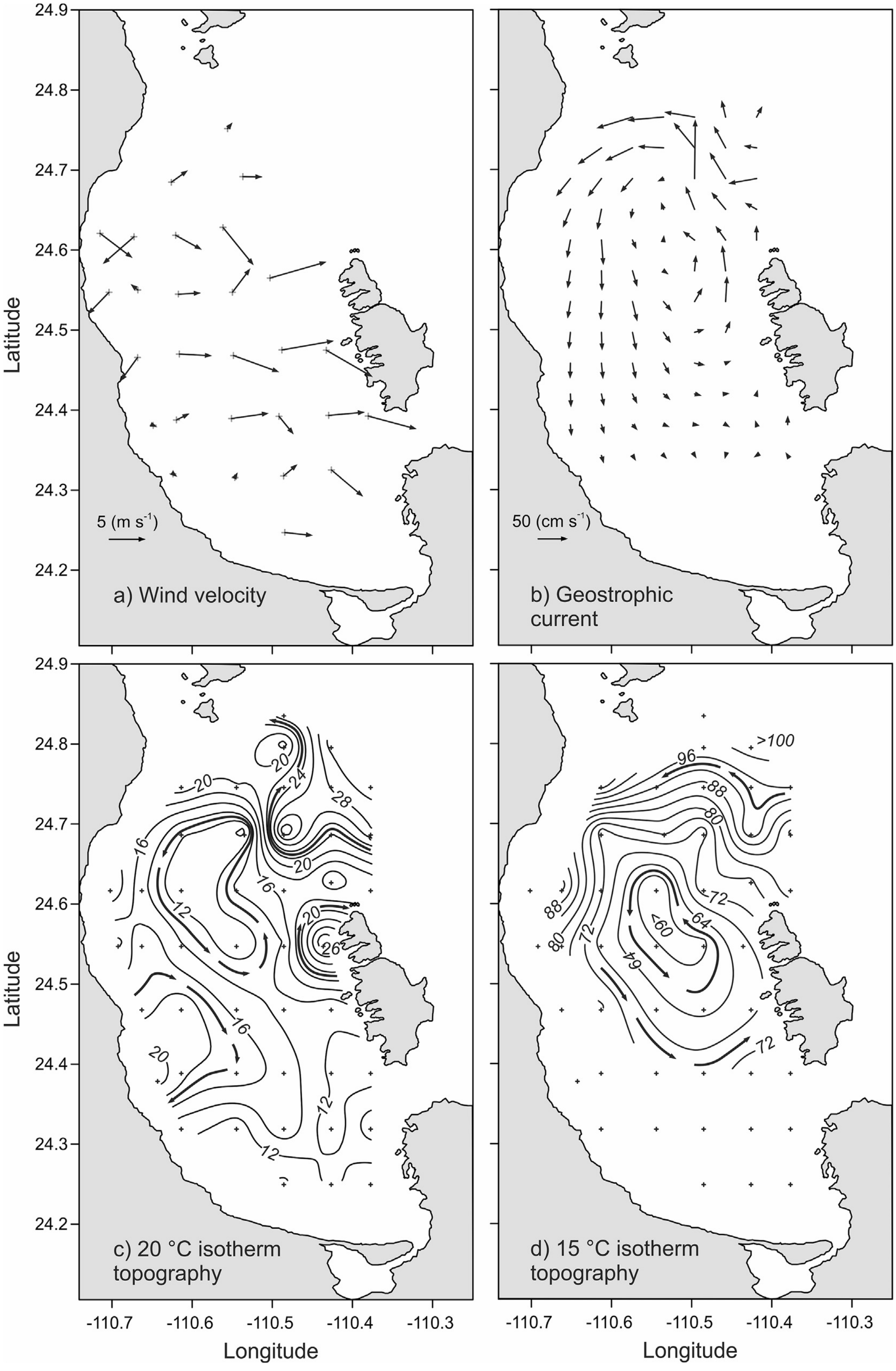

Fig. 3. a) Wind velocity (m s^{-1}), b) geostrophic velocity (cm s^{-1}). Topography (m) of the c) 20 °C and d) 15 °C isotherms. The circulation pattern is marked with arrows.

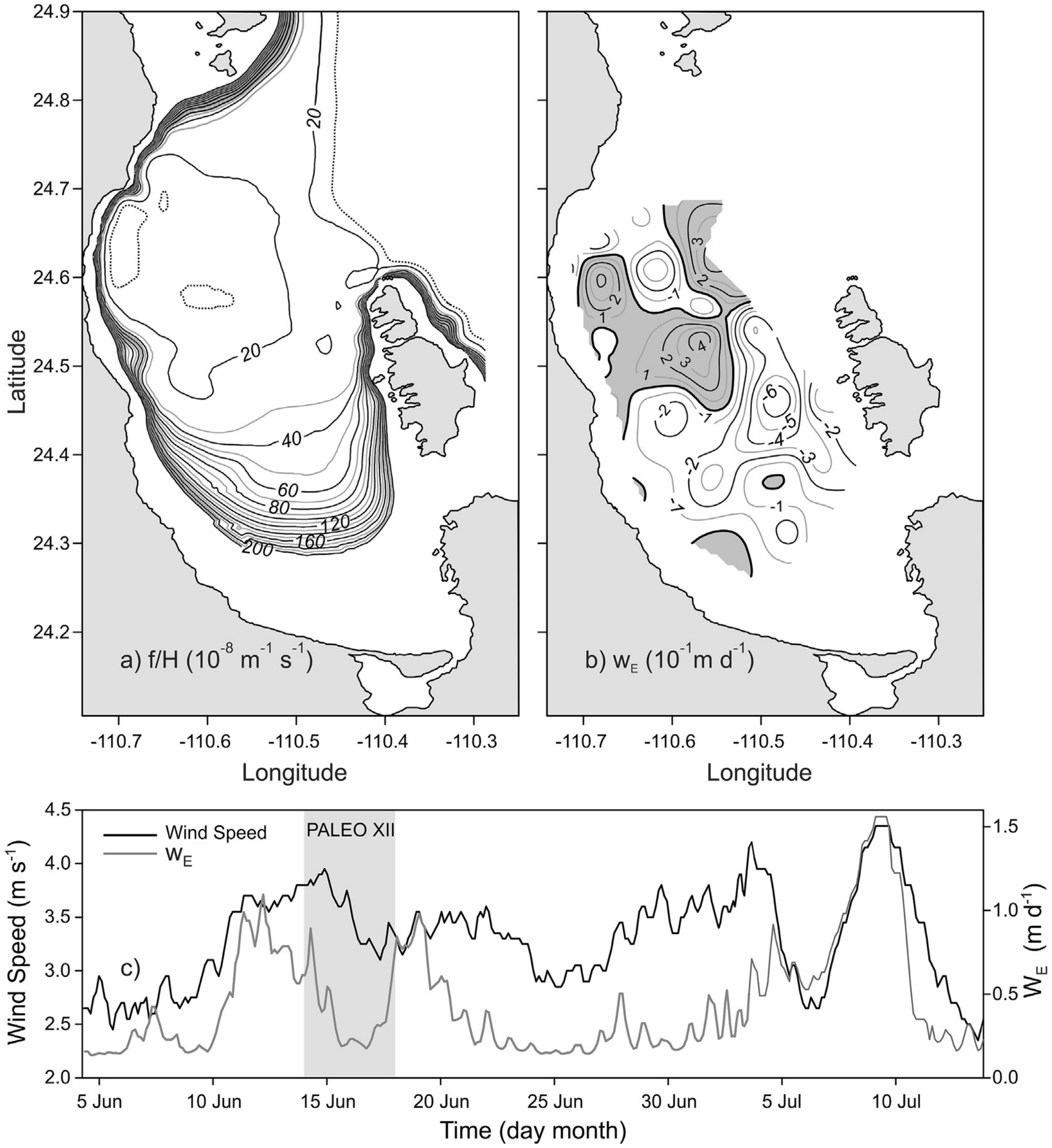

Fig. 4. a) Contours of f/H values (10^{-8} m^{-1} s^{-1}), b) vertical velocity (10^{-1} m d^{-1}), and c) wind speed (m s^{-1}) time series collected every 3 h from the weather station at La Paz, B.C.S. and vertical velocity (m d^{-1}).

mechanisms: 1) GCW is locally formed within the bay through the modification of TSW due to high evaporation levels characteristic of the region or 2) it penetrates through Boca Grande (Monreal-Gómez et al., 2001). As evaporation levels are low in the late spring, the second mechanism is more plausible at this time. The presence of GCW and StSsW within the bay agrees with distributions observed by Obeso-Nieblas et al. (2004) for the late spring and summer.

Earlier studies have postulated potential mechanisms of a cyclonic structure within the Bay of La Paz (Monreal-Gómez et al., 2001; Sánchez-Velasco et al., 2004, 2006). Several studies have proposed that the main mechanisms generating this cyclonic structure are local winds and that circulation patterns are influenced not only by the base topography of the basin but also by exchanges with the Gulf of California through Boca Grande. This cyclonic structure has been observed in the bay in the winter (García-Mirafuentes, 2010), late spring (Monreal-Gómez et al., 2001), and summer (Sánchez-Velasco et al., 2004), when different wind patterns are present. We postulate that the mechanism of generation should involve effects of both wind and base topography, which may regulate the positioning and extension of the cyclonic structure into the Alfonso Basin, the deepest section of the Bay of La Paz (Fig. 1). Our results confirm the presence of cyclonic circulation as a form of wind stress-driven circulation. The flow is oriented along (f/H) contours. According to the density distribution and geostrophic velocity field, the study area includes a baroclinic bay of variable depth. Joint effects of baroclinity and base topography are central in the determination of horizontal mass transport patterns. This effect drives the conversion of potential energy (associated with depth) to/from kinetic energies. Two forms of kinetic energy are considered: kinetic energy associated with horizontal mass transport and that associated with vertical shearing from buoyancy forces described by Holland (1977). These kinetic energies are referred to as external and internal modes, respectively. The flow along (f/H) contours may relate to the momentum forcing. Thus, in this case, the cyclonic structure is forced

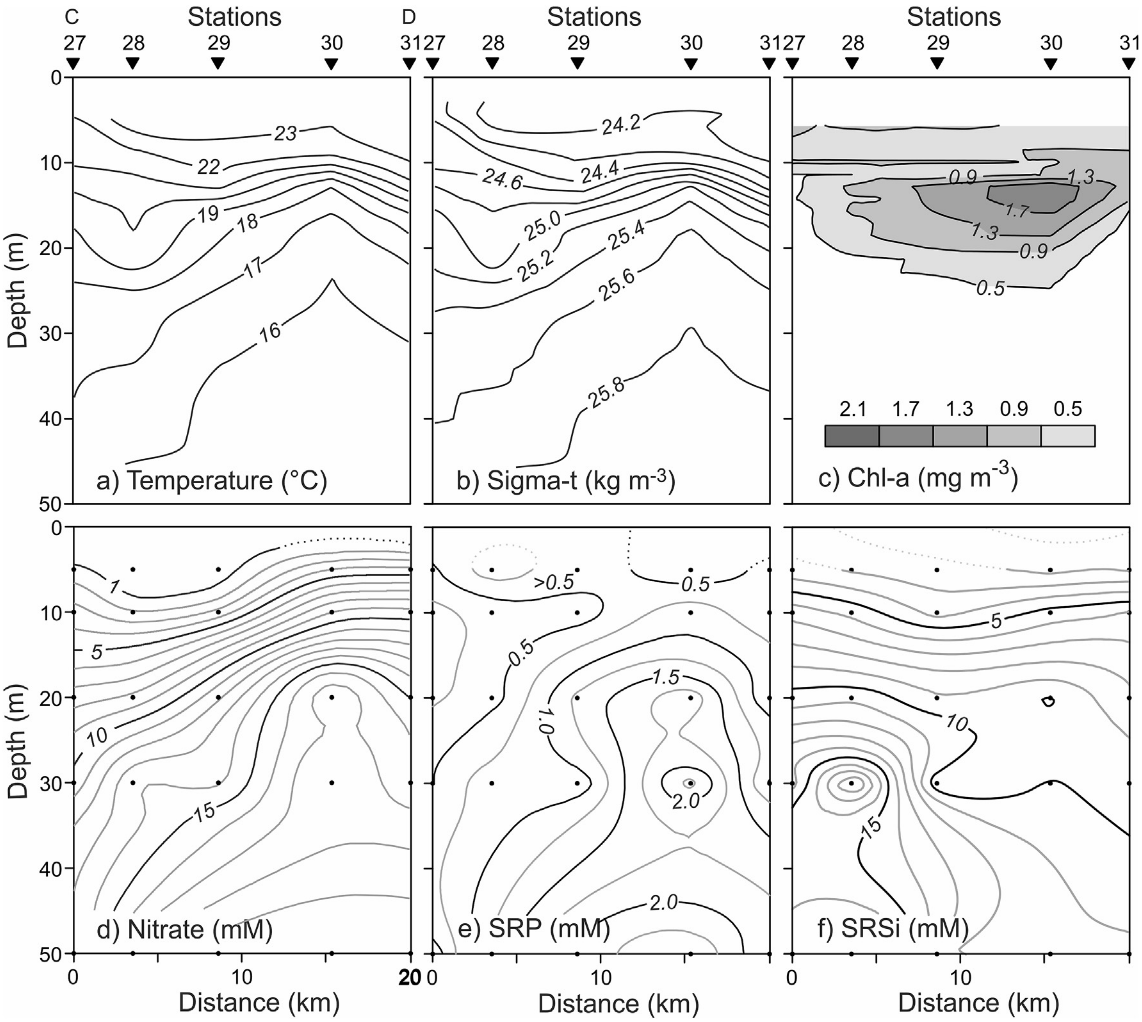

Fig. 5. Vertical distributions in the upper 50 m layer along transect C-D for: a) temperature (°C), b) sigma-t (kg m^{-3}), c) chlorophyll-*a* (mg m^{-3}), d) nitrate (μM), e) SRP (μM), f) SRSi (μM).

by the local wind field interacting with the topography, resulting an upwelling that promotes the enhancement of nutrients and chlorophyll-*a* (Fig. 4).

Diverse processes may also play a role in the regulation of euphotic zone fertility levels along the coastal region and within the bay. Monreal-Gómez et al. (2001) studied the effects of different water masses on trophic states and found that GCW within the bay confers low concentrations of chlorophyll-*a* (0.04–0.50 mg m^{-3}). However, these reported values are low relative to those of this study and with values for the southern region of the Gulf of California, for which a mean value of 0.71 mg m^{-3} has been reported for the spring season (Valdez-Holguín et al., 1995), denoting the importance of other fertilization processes at this time of the year. Coastal upwelling has been observed within the Gulf of California mainly in the autumn (Signoret and Santoyo, 1980) and in the winter around the Espíritu Santo island (Zaytsev et al., 1998). If upwelling events also occur during the spring, they could be maintaining higher chlorophyll levels observed outside of the bay during this time of the year (Valdez-Holguín et al., 1995, Fig. 7a).

However, within the bay, we observed much higher chlorophyll-*a* concentrations and particularly in the Alfonso Basin, where vertically integrated chlorophyll-*a* values reached 20 mg m^{-2}. Spatial patterns of nutrient and chlorophyll concentrations clearly point to cyclonic circulation as the main fertilizing mechanism operating within the bay at this time. Divergent movements caused by cyclonic circulation promote the uplift of subsurface water rich in nutrients and of the deep chlorophyll maximum, spurring the fertilization of the upper layer. The consequent increase in phytoplankton biomass drives the enhancement of maximum chlorophyll-*a* concentrations within the area of cyclonic circulation as observed within the thin subsurface layer (~10 m). Although fluorescence profiling is a very powerful tool used to detect chlorophyll patterns such as those that we have found, the estimation of chlorophyll-*a* from natural fluorescence is made complicated by the fact that the signal is not a simple linear function of chlorophyll concentrations (Westberry and Siegel, 2003), and so its estimations can vary due to changes in quantum yields of natural fluorescence. Both nutrient availability and light intensity can affect this relationship, causing deviations mainly in the upper layer and in areas where cells are nutrient-replete (Falkowski and Kolber, 1995; Falkowski and Raven, 2007). Nevertheless, although this must be considered when examining absolute chlorophyll-*a* values, the concentration variations observed are so distinct that potential variations involved when assuming a constant relationship do not likely vitiate the patterns observed in terms of their relations to cyclonic circulation.

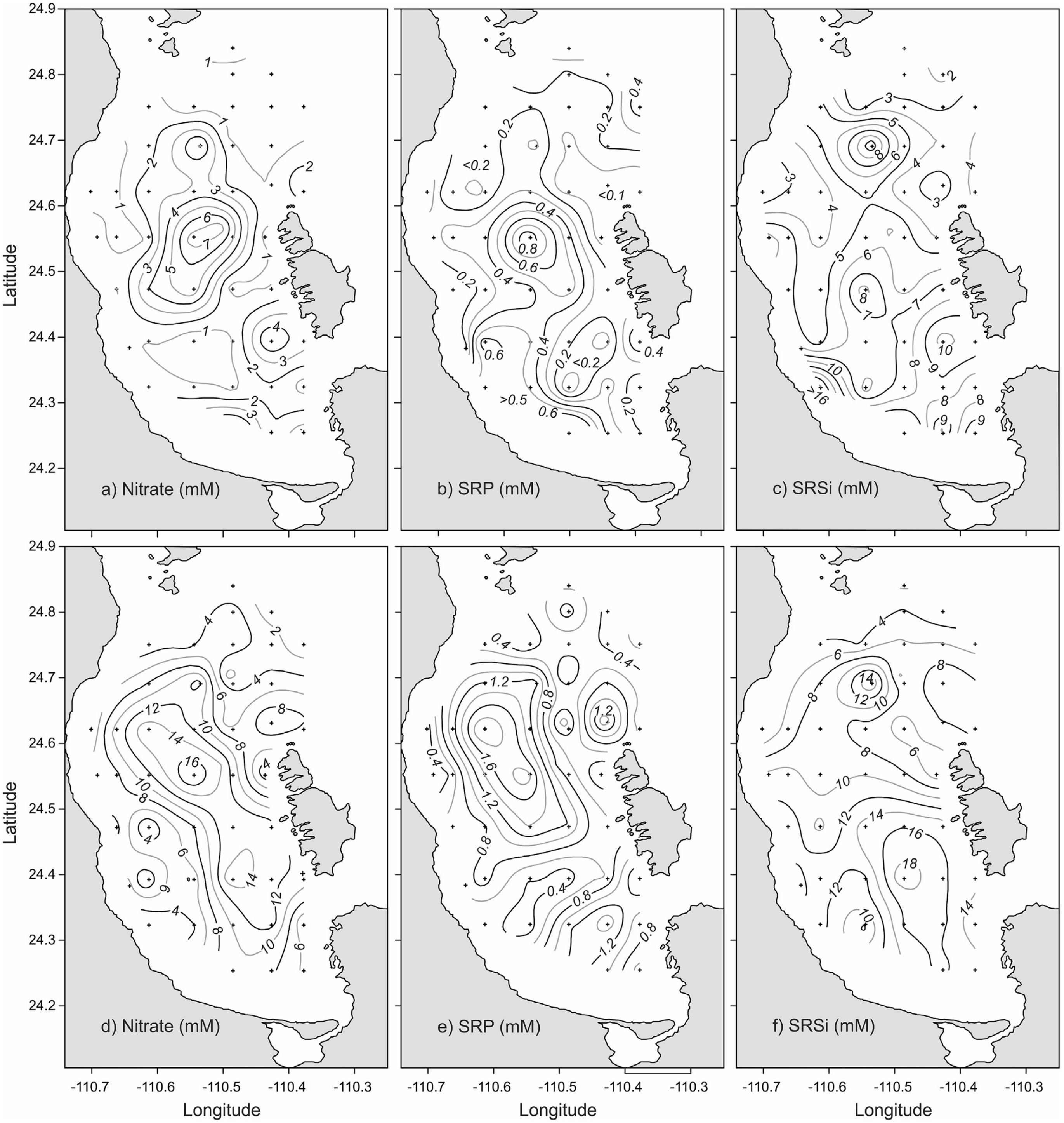

Fig. 6. Horizontal distributions of nutrients (μM) at 10 m: a) nitrate, b) SRP, c) SRSi and at 20 m: d) nitrate, e) SRP, f) SRSi.

Hydrodynamic processes, nutrient and chlorophyll-*a* distributions, and enhanced levels of productivity observed in this study area cannot be explained by eddy/wind interactions proposed by McGillicuddy et al. (2007), as local winds traveling across the cyclonic flow should generate a downwelling and our results show the presence of positive vertical velocity (upwelling) in its central region. Our results show that during the late spring of 2004, the Bay of La Paz was characterized by strong nutricline uplifting and by the enhancement of chlorophyll-*a* induced by cyclonic circulation in contrast with chlorophyll-*a* patterns inferred for the summer of 2009 in a cyclonic eddy reported by Coria-Monter et al. (2014). In some areas such as the Alboran Sea, a cyclonic gyre induces changes in the distribution of biogeochemical variables and mainly in terms of maximum nutrient and chlorophyll concentrations (Macías et al., 2008). In the Strait of Florida, fluid trapped in a cold cyclonic gyre generates lateral fluxes of physical, chemical, and biological

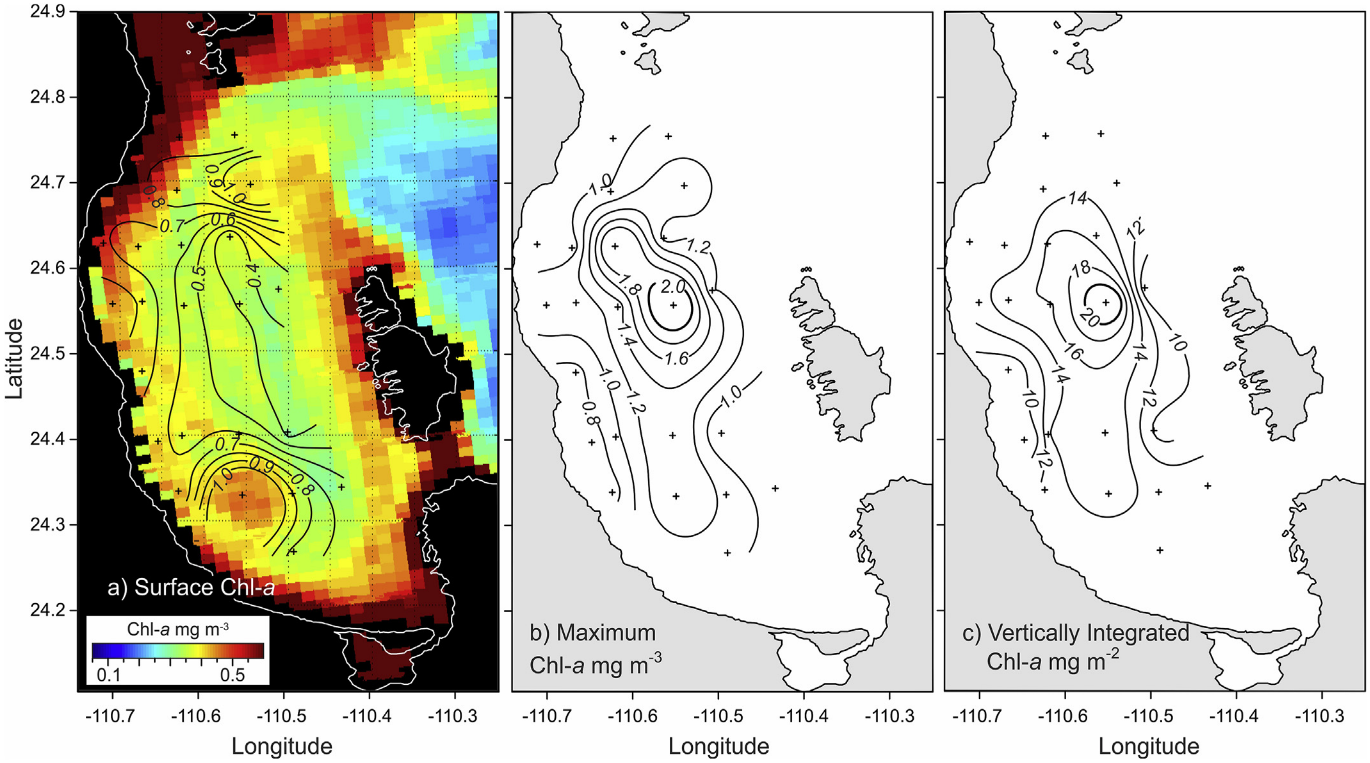

Fig. 7. Horizontal distribution of chlorophyll-*a*: a) satellite image (MODIS-AQUA Local Area Cover; 14 June 2004) and in situ chlorophyll-*a* measurement isolines superimposed (mg m^{-3}), b) chlorophyll-*a* maximum concentration (mg m^{-3}), c) vertically integrated chlorophyll-*a* (mg m^{-2}).

properties; the gyre traps remineralized nutrients, thus sustaining relatively high chlorophyll concentrations and phytoplankton organisms over a period of several months (Lee et al., 1992). In our particular case, regarding major components of the phytoplankton community, a maximum abundance of diatoms (genus *Chaetoceros* and *Thalassiosira*) has been found during the spring season in the Alfonso Basin (Acevedo-Acosta, 2015).

Our results complement those described above, indicating that wind stress-driven cyclonic circulation promotes nutrient and chlorophyll-*a* enhancement. In the bay, two chlorophyll-*a* peaks were observed (with one located at the main entrance to the bay near Boca Grande where an abrupt decrease in depth is observed), and the mixing mechanism of chlorophyll-*a* enhancement is comparable to that found in shallow seamounts as described by Trasviña-Castro et al. (2003). Uda and Ishino (1958), who theorize that topographically induced upwelling enhances primary production and consumer biomass over seamounts, predict that when currents encounter seamounts, some of the water is upwelled and flows above the summit. In areas surrounding Boca Grande, the topography of the 20 °C isotherm (Fig. 3c) shows a small anticyclone (Taylor column) attributed joint effects of the contraction of streamlines and to changes in potential vorticity (Genin, 2004). The second is located off of San Juan de la Costa where phosphate mining activities take place and where upwelling mechanisms are frequently generated when ambient currents impinge on abrupt topographies, enhancing local biological production (Genin, 2004). Further south across base shoals positioned along the path of cyclonic circulation, mixing likely plays a central role.

Satellite color images also reveal spatial variability in surface chlorophyll distributions in the Bay of La Paz during the late spring of 2004, with a peak located at the center of the area of cyclonic circulation in contrast to low concentrations found in the summer of 2009, when a mesoscale cyclonic eddy dominated circulation in the bay and when chlorophyll distribution was associated with planktonic populations (Coria-Monter et al., 2014).

5. Conclusions

Our observations show that the examined cyclonic structure was forced by the local wind field, resulting an upwelling and promoting the enhancement of nutrient and chlorophyll-*a* levels. This cyclonic circulation pattern along f/H contours shows that joint effects of baroclinity and base topography play an important role to determining horizontal mass transport patterns owing to buoyance forces. Wind driven upwelling occurs by means of an Ekman pumping velocity of ~0.4 m d^{-1} at the base of the Ekman layer, which is responsible for the enhancement of productivity by means of nutrient transport into the euphotic zone. The highest concentrations of nutrients and chlorophyll-*a* found in the Bay of La Paz during the late spring were promoted by the local wind field and by flow interactions with the topography that supported enhanced nutrient levels, and upwelling was found to be the main mechanism of fertilization. Secondary chlorophyll-*a* enhancement areas point to the presence of additional fertilization processes that may derive from interactions cyclonic circulation and the topography, and such upwelling mechanisms are frequently generated when ambient currents impinge on abrupt topographic features, enhancing local biological production.

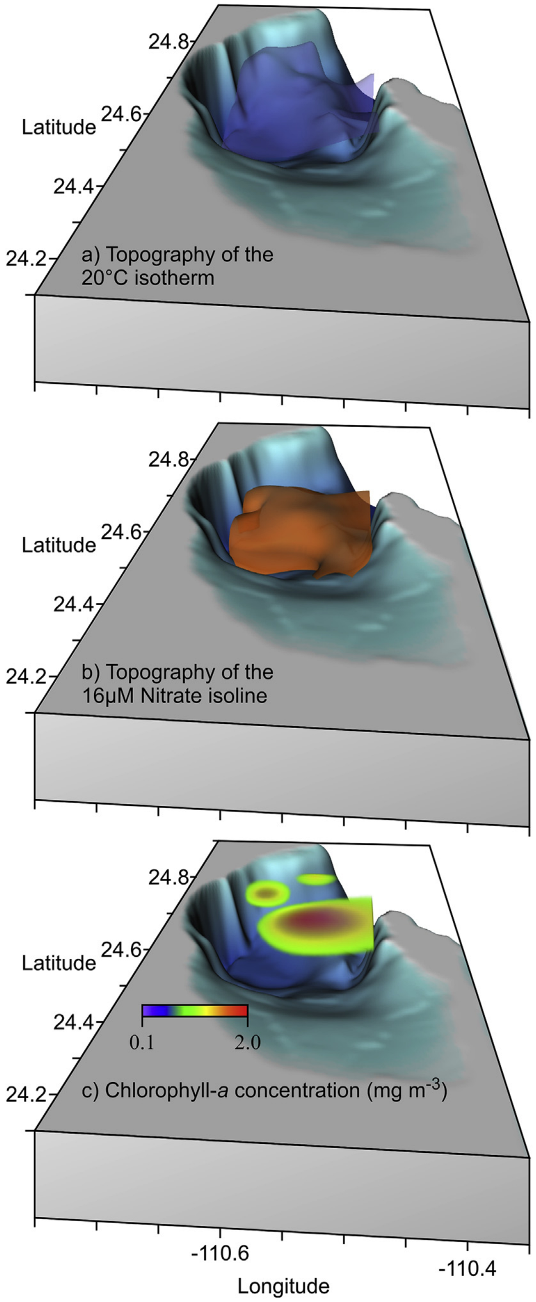

Fig. 8. Schematic model of processes in the Bay of La Paz during the late spring of 2004. a) Topography of the 20 °C isotherm showing doming at the eddy core, b) topography of the 16 µM nitrate contour, revealing nutrient pumping in the eddy, and c) chlorophyll-*a* concentrations (mg m^{-3}) in the eddy core exhibiting subsurface chlorophyll-*a* maximum enhancement at ~20 m and secondary chlorophyll-*a* enhanced areas close to Boca Grande and San Juan de la Costa.

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