

RESEARCH NOTE

Bio-optical characterization of the waters of the Bay of La Paz, southern Gulf of California, during late spring 2004

Caracterización bio-óptica de la Bahía de La Paz, Golfo de California, durante fines de primavera 2004

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Abstract. Information on selected bio-optical properties and primary production values of the waters of the Bay of La Paz, southern Gulf of California, is reported during June 2004, a region characterized to have very rich biodiversity, including endemic and endangered species, with high ecological relevance. *In-situ* measurements of natural fluorescence and photosynthetically available radiation (PAR) enabled the subsequent calculation of the incident irradiance (E_0), the light extinction coefficient (k), compensation depth (Z_c) and critical depth (Z_{cl}). The results suggest the presence of light propitious conditions for phytoplankton community growth and net primary production, which are highly significant for the potential development of models of light penetration, ocean color, primary productivity, and analyses of organic carbon energy flow.

Key words: Phytoplankton, bio-optical characterization, primary production, PAR measurements, Bay of La Paz

INTRODUCTION

The Bay of La Paz is the largest basin within the Gulf of California, located on the southwestern margin of the Baja California Peninsula of Mexico (Fig. 1a). The region is known to have very rich biodiversity, including endangered and endemic species, with high ecological relevance (Silverberg *et al.* 2014). The bay interchanges water masses with the gulf through two openings, Boca Grande (wide and deep) to the north, and San Lorenzo Channel (shallow and narrow) to the south, which generates important matter and energy flows between both environments (Monreal-Gómez *et al.* 2001).

In recent years, important efforts have been made to elucidate the processes that support the high biological productivity of the region, particularly regarding the planktonic ecosystem (Cervantes-Duarte *et al.* 2005). For instance, a close relationship between the presence of a mesoscale cyclonic eddy and phytoplankton community distribution has been observed, and it has been proposed that this eddy is a quasi-permanent feature of the area, and also an interesting case study of an eddy confined within a bay of biological significance, which in turn originates a differential phytoplankton distribution, where dinoflagellates dominate its center while diatoms dominate

the periphery (Coria-Monter *et al.* 2014). The presence of this mesoscale eddy induces isopycnal uplifting (Monreal-Gómez *et al.* 2001) with an entrainment of subsurface nutrient-rich waters to the euphotic zone, which in turn promotes the primary productivity (Verdugo-Díaz *et al.* 2014). Changes in the structure of the phytoplankton functional groups has also been observed in the region as result of the seasonal variability, with a predominance of diatoms followed by dinoflagellates, the lasts to be dominant during the warm period (Verdugo-Díaz & Gárate-Lizárraga 2018).

The seasonal variability in the region is dominated by a water column stratified from June to September with a temperature of ≈ 27.5 °C, and by a well-defined mixed layer from October to May with a temperature of ≈ 18.5 °C, which in turn affect the marine phytoplankton community (Muciño-Márquez *et al.* 2018). This seasonal variability in the region is also close related with the wind field, which is mainly determined by the atmospheric shifting of the Pacific High Pressure Center and the Sonora Desert Low Pressure Center, resulting in northwesterly winds (≈ 12 m s⁻¹) during winter, and southeasterly winds (≈ 5 m s⁻¹) during summer (Monreal-Gómez *et al.* 2001).

Zooplankton functional groups respond to the relative vorticity induced by the cyclonic eddy confined to the bay, and the abundance of herbivorous zooplankton is directly correlated to the water density gradient imposed by the physical feature. An inverse correlation of carnivorous zooplankton abundance with water density was associated with negative vorticity outside the bay (Duran-Campos *et al.* 2015). More recently, Coria-Monter *et al.* (2017) reported that the physical forcing into the eddy field is the local wind, resulting in an upwelling, and promoting an increase in nutrient and chlorophyll-*a* concentrations; this cyclonic circulation shows that joint effects of baroclinity and base topography play an important role in determining horizontal mass transport patterns, owing to buoyance forces. Wind-driven upwelling occurs by means of an Ekman pumping velocity of $\approx 0.4 \text{ m d}^{-1}$ at the base of the Ekman layer, which is responsible for the increase in productivity by means of nutrient transport into the euphotic zone available for phytoplankton.

Not only cyclonic eddies represent the principal mechanism of fertilization that characterize the Bay of La Paz (Martínez-López *et al.* 2016). Recently, based on *in-situ* observations, Durán-Campos *et al.* (2019) documented the presence of a dipole structure (cyclonic-anticyclonic), which in turn originate a thermohaline front, and then an accumulation of the phytoplankton community. Additional large-scale processes, such as El Niño/La Niña and the Pacific Decadal Oscillation, were also recently associated with changes in the phytoplankton community in the region (Guevara-Guillén *et al.* 2018).

Although planktonic productivity in the region has been relatively well addressed, there have been major challenges in the field, particularly regarding the optical properties of the water column, which are essential for phytoplankton growth and productivity. As phytoplankton are the primary source of the marine food chain, they also control the carbon dioxide uptake by the ocean known as the biological pump and, then play a role in the global carbon cycle (Pieri *et al.* 2015). Evaluating the optical properties of the water column thus plays a key role in determine and understand variations in the fluxes of carbon and associated biogenic elements in the ocean (Platt & Sathyendranath 1988). It is also crucial for the development of models of light transmission, with the light absorption in phytoplankton cells also driving photoautotrophic production in the ocean; then, studies on the changes in these parameters, as an indicator of phytoplankton physiologic, and their relationship with the environmental variability comes to be imperative (Verdugo-Díaz *et al.* 2014). The optical properties of the water column are also essential for satellite ocean-color productivity, and exert a major effect on the whole planktonic ecosystem by controlling the biological radiation absorption and the availability of solar energy for photosynthesis (Takao *et al.* 2014).

This manuscript aims to asses and report, based on *in-situ* observations, selected bio-optical properties and primary production values of the water column of the Bay of La Paz, in the southern Gulf of California, with information gathered on a multidisciplinary research cruise during the late spring (June) of 2004. Measurements of natural fluorescence and

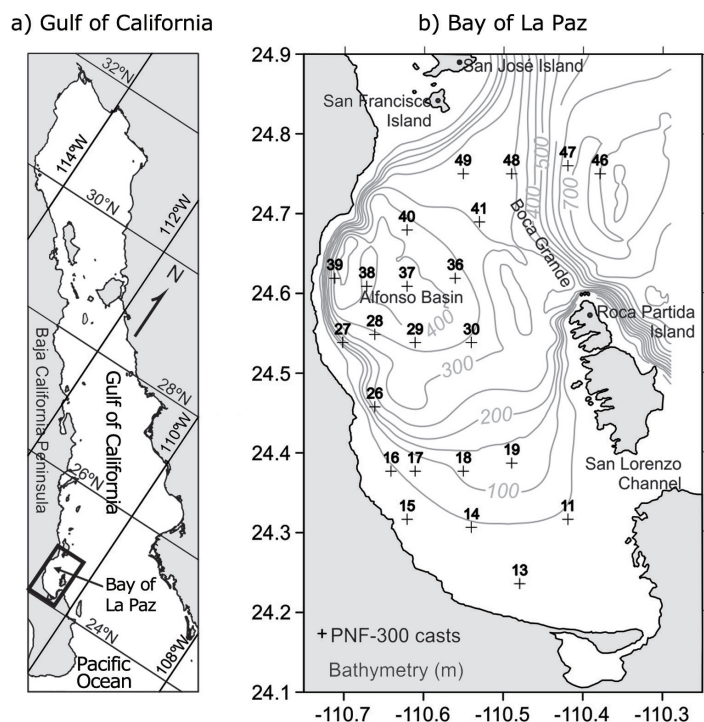


Figure 1. Study area: a) Gulf of California, the rectangle represents the sampling area; and b) Bay of La Paz, the black symbols represents the hydrographic stations / Área de estudio: a) Golfo de California, el rectángulo representa el área de muestreo; b) Bahía de La Paz, los símbolos negros representan las estaciones hidrográficas

photosynthetically available radiation (PAR), enabled the subsequent calculation of the light extinction coefficient (k), compensation depth (Z_c) and critical depth (Z_{cr}).

MATERIALS AND METHODS

Information was collected during the multidisciplinary research cruise “PALEO-XII”, carried out from 14 to 18 June 2004 onboard the R/V “El Puma” of the Universidad Nacional Autónoma de México. Natural fluorescence, photosynthetically available radiation (PAR), and temperature were measured at 23 hydrographic stations (Fig. 1b), using a Profiling Natural Fluorometer (PNF-300) from Biospherical Instruments, previously calibrated by the manufacturer. This instrument measures the flux in natural fluorescence, which can then be used to estimate the instantaneous gross photosynthetic rate, while measurements of upwelling radiance ($L_u(chl)$, $nE\ m^{-2}s^{-1}str^{-1}$) are made by an optical sensor specifically over the emission spectrum of chlorophyll-*a* (Chamberlin *et al.* 1990). Based on this method, calculation of the chlorophyll concentration can be achieved via the coincident measurement of two optical variables: 1) the upwelling red radiance, which results from the fluorescence of the phytoplankton crop; and 2) the incident irradiance, which in turn drives photosynthesis. The equipment measured PAR over the spectral region from 400 to 700 nm using sensors with a flat quantum response. The chlorophyll-*a* concentration ($mg\ m^{-3}$) is thus calculated from the natural fluorescence flux (F_f) and the incident irradiance following the protocols by Chamberlin *et al.* (1990), after removing the first 5 m of the water column due to the signal contamination by the sunlight, by the expression:

$$Chl = \frac{F_f}{\phi_{ac}(PAR) * \phi_f * E_0(PAR)} \quad (1)$$

There are two important optical assumptions: 1) $\phi_{ac}(PAR)$ is the chlorophyll-specific absorption coefficient (absorption normalized to chlorophyll concentration), and 2) ϕ_f is the quantum yield of fluorescence. These values were treated here as constants, such as in the software for the PNF-300, which assigned typical values of $0.04\ m^2\ mg^{-1}$ and $0.045\ \mu E$ fluoresced per μE absorbed, respectively.

Fluorescence values were transformed to chlorophyll-*a* concentration ($mg\ m^{-3}$) using Equation 1, and were then integrated along the water column ($mg\ m^{-2}$) according to the expression:

$$Chla\ (mg \cdot m^{-2}) = \sum_{i=1}^N (Chla)_i \quad (2)$$

where $Chla\ (mg\ m^{-2})$ is the chlorophyll-*a* values vertically integrated and N is the last differential of the profile and corresponds to the depth of integration.

Based on the PNF-300 measurements obtained, the average light extinction coefficient was also estimated in the water column (k) according to Lalli & Parsons (2006) and Falkowski & Raven (2007) as:

$$k = \frac{\ln(E_0) - \ln(E_D)}{z} \quad (3)$$

where E_0 is the incident irradiance at water surface and E_D is radiation at depth z , the last defined as the limit of the euphotic zone.

The compensation depth (Z_c), defined as the depth at which gross photosynthetic carbon fixation balances phytoplankton respiratory losses over the course of one day, representing the lower boundary of the euphotic zone (Falkowski & Raven 2007), was calculated via the expression:

$$Z_c = \frac{\ln(E_0) - \ln(E_c)}{k} \quad (4)$$

where surface radiation (E_0) is measured directly by the equipment and k is calculated using Equation 3. E_c is the compensation light intensity, which varies with both the phytoplankton species and the light adaptation of any particularly species; values of E_c range between 1 and $10\ \mu mol\ m^{-2}\ s^{-1}$ (Lalli & Parsons 2006). Due to the absences of values as a baseline for the study area, in our particular case, a constant value of $5\ \mu mol\ m^{-2}\ s^{-1}$ was assigned, following the criterion of Nelson & Smith (1991) and Signoret *et al.* (2006), considering the case for waters from the Campeche Bay, Gulf of Mexico. The symbol I , which is sometimes used in older papers to denote irradiance, was not used here since it has been more recently adopted to denote radiation intensity, which is the flux of radiant energy per unit solid angle in a specified direction (Falkowski & Raven 2007).

The critical depth (Z_{cr}), defined as the depth at which the water column's integrated photosynthesis is equal to the integrated respiration, was calculated via the expression:

$$Z_{cr} = \frac{0.5\ E_0}{E_c\ k} \quad (5)$$

where E_0 is the incident irradiance at water surface [here multiplied by 0.5 based on 50% photosynthetic active radiance, according to the criterion of Salas de León *et al.* (2004) and Signoret *et al.* (2006)], E_c is the irradiance at the depth at which gross photosynthesis is equal to respiration, and k is the extinction coefficient.

Using the PNF-300 data set, values of primary production were calculated following Kiefer *et al.* (1989) and Chamberlin *et al.* (1990), and then integrated from 5 m depth to the limit of the euphotic zone according to Cervantes-Duarte *et al.* (2005). Finally, based on the vertical distribution of temperature, the mixed layer depth was estimated using the depth of maximum temperature gradient ($\delta T / \delta z$).

RESULTS AND DISCUSSION

The calculation results revealed the presence of propitious conditions for phytoplankton community growth and net primary production at the time of our observations. Table 1 summarizes the selected optical bio-properties obtained and some weather conditions recorder during the cruise.

The values of k have a significant effect on phytoplankton crop growth. In this study, k -values averaged 0.110. Since k -values varies according to the wavelengths of light, values ranging from 0.035 to 0.140 m^{-1} have been reported by Lalli & Parsons (2006), in agreement with our observations. Similar observations were reported by Salas de León *et al.* (2004) who found mean values of k of 0.05 for waters of the southern Gulf of Mexico. According to Falwowski & Raven (2007), values of k could be potentially affected by the amount of chlorophyll contained in living phytoplankton and in plant debris or the dissolved and particulate matter along water column.

Our observations revealed mean values of 452 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the incident irradiance (E_0); although values $>1,000 \mu\text{mol m}^{-2} \text{s}^{-1}$ on a sunny day have been reported in the literature (Kirk 2011), it is important to bear in mind that these depend on the time of the day that measurements are made, due to the sun's angle, and on the season as well as the latitude, so the values presented here are in agreement with those reported in regions at $\sim 20^\circ\text{N}$ of latitude. For

example, Salas de León *et al.* (2004) and Coria-Monter *et al.* (2019) reported values for the southern Gulf of Mexico ranging from 84.6 to 1061 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

In our study, Z_{cr} varied from 4.8 to 27.7 m; there are very few *in-situ* observations and consequent calculation of Z_{cr} into the Bay of La Paz in the literature, and these are limited to the work of Cervantes-Duarte *et al.* (2005), who found values ranging from 41 to 80 m, which seems higher than those reported in our study; however, they used a constant value of 35 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for their Z_{cr} calculation, while 5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was used as a constant value, following the criterion of Signoret *et al.* (2006) for regions located approximately at the same latitude, which set the differences in the values. The depth of mixed layers found in this study is in the same order of magnitude by those reported by Cervantes-Duarte *et al.* (2005) who found, using the maximum temperature gradient, mean values of 35 m.

The chlorophyll- a values observed along water column at the time of our observations ranged from 0.7 to 2 mg m^{-3} in agreement with those reported for the southern Gulf of California region, particularly the Bay of La Paz. Indeed, Coria-Monter *et al.* (2014) reported maximum values of 1.8 mg m^{-3} during August, while Verdugo-Díaz *et al.* (2014) showed values of 2.51 mg m^{-3} during May in the Alfonso Basin. Gaxiola-Castro *et al.* (1999) reported a maximum of 2.75 mg m^{-3} in regions in the middle of the Gulf of

Table 1. Bio-optical properties of the waters of the Bay of La Paz, southern Gulf of California, during June 2004 with some weather conditions / Propiedades bio-ópticas en la Bahía de La Paz, durante junio de 2004 con algunas variables climáticas

St	Lat°N	Lon°W	Time GMT-7	Z (m)	k	E_0	Zc (m)	Z_{cr} (m)	EL (m)	ML (m)	IChl (mg m ⁻²)	ChlMAX (mg m ⁻³)	DMC (m)	IPP (g C m ⁻² d ⁻¹)	TChla MAX (°C)	WS (m s ⁻¹)	Dir (°)
11	24.32	110.42	08:25	67	0.15	133	3	7.0	35	7	2	0.9	7.3	0.79	19.54	5.7	310
13	24.24	110.48	11:43	27	0.13	420	11.2	5.0	27	10	6.6	1.1	9.8	2.45	20.01	3.9	276
14	24.31	110.54	12:53	54	0.12	225	5.8	9.2	46	7	3.7	1.1	8.5	1.28	20.37	0.8	150
15	24.32	110.62	14:43	33	0.10	61	16.1	6.7	33	5	3.3	0.7	10	0.52	20.31	0.3	306
16	24.38	110.64	15:51	33	0.08	28	10.6	19.3	33	29	3.2	0.7	11.4	0.22	20.95	0.6	293
17	24.38	110.61	17:05	70	0.18	291	3.3	6.1	44	15	5.0	1.0	5.3	1.23	21.72	2.0	244
18	24.38	110.55	17:50	157	0.15	22	13.6	15.0	29	7	3.5	1.4	13.2	0.32	20.48	5.2	262
19	24.39	110.49	19:19	215	0.17	14	9.2	11.6	24	21	2.2	0.7	14	0.09	19.68	3.2	321
26	24.46	110.66	07:51	42	0.24	56	2.8	4.8	27	14	1.8	0.7	5	0.58	21.99	4.1	036
27	24.54	110.70	10:16	62	0.16	247	4.3	6.8	47	13	3.1	1.0	8	0.82	21.20	4.2	044
28	24.55	110.66	11:47	101	0.16	363	4.3	6.8	52	6	3.1	1.1	13	0.78	20.53	1.3	330
29	24.54	110.61	14:00	330	0.16	517	4.3	6.7	50	7	2.0	1.0	13	0.97	18.80	3.1	267
30	24.54	110.54	15:59	330	0.19	70	3.4	6.0	37	6	4.0	2.0	13	0.88	17.56	4.1	217
36	24.62	110.56	07:49	345	0.20	89	4.0	6.0	33	10	4.4	1.1	12	0.41	18.88	6.7	321
37	24.61	110.62	10:24	404	0.15	380	4.4	7.2	55	8	2.4	1.7	9	1.60	18.85	4.1	299
38	24.61	110.67	12:03	220	0.14	359	33.3	27.7	55	9	1.1	0.9	11	0.68	20.78	5.7	049
39	24.62	110.71	14:56	34	0.13	248	7.4	15.0	34	6	4.0	0.8	5	1.51	22.68	5.5	306
40	24.68	110.62	15:26	405	0.12	31	20.4	21.0	47	9	1.8	1.0	11	0.17	20.15	2.8	234
41	24.69	110.53	18:11	390	0.30	13	5.2	6.6	33	7	3.0	1.0	5	0.26	22.05	2.7	271
46	24.75	110.38	07:54	835	0.17	28	2.5	6.5	27	12	3.0	0.7	26	0.02	22.13	1.8	328
47	24.76	110.42	11:03	750	0.13	37	5.6	9.1	50	39	4.1	0.8	11	0.18	23.29	1.4	172
48	24.75	110.49	13:53	170	0.16	484	3.8	6.7	52	22	1.4	0.9	5	1.17	23.18	0.4	317
49	24.75	110.55	16:54	318	0.13	30	17.5	18.1	42	20	2.4	0.9	16	0.14	22.27	1.1	220

St= number of station; Lat= Latitude (°N); Lon=Longitude (°W); Time=GMT-7, Greenwich Mean Time-7; Z= total depth (m); k= Average extinction coefficient; E_0 = Incident irradiance, ($\mu\text{mol m}^{-2} \text{s}^{-1}$); Zc= Compensation depth, (m); Z_{cr} = Critical depth, (m); EL= Euphotic layer thickness, (m); ML= Mixed layer, (m); Chl (mg m^{-2})= integrated chlorophyll- a values; ChlMAX (mg m^{-3})= chlorophyll- a maximum values; DCM= deep chlorophyll- a maximum, (m); IPP= Integrated Primary Production ($\text{g C m}^{-2} \text{d}^{-1}$); TChlaMAX=Temperature at ChlaMAX (°C); WS= Wind speed (m s^{-1}); Dir= wind direction (°)

California. Similar values have been also reported for the water of the southern Gulf of Mexico by Durán-Campos *et al.* (2017), using PNF-300, who found mean values of 0.8 mg m^{-3} . The chlorophyll-*a* vertical distribution in three representative stations along the bay (stations # 15, 30 and 40), showed the maximum values close related with the thermocline and the peaks into the euphotic zone (Fig. 2).

The values of the chlorophyll-*a* vertically integrated in our study rose to range from 1.1 to 6.6 mg m^{-2} , in agreement with those reported by Martínez-López *et al.* (2001) who found values of $\sim 10 \text{ mg m}^{-2}$ in the summer.

The integrated primary production values, obtained from the PNF-300 data set, were in a range from 0.02 to $2.45 \text{ g C m}^{-2} \text{ d}^{-1}$, in agreement with those reported by Cervantes-Duarte *et al.* (2005) who showed maximum values of $2.26 \text{ g C m}^{-2} \text{ d}^{-1}$ into Bay of La Paz during June.

It is also clear from Table 1 that, in all stations, the chlorophyll-*a* maximum are into the euphotic layer, showing properly conditions for photosynthesis, and thus the production of phytoplankton. Statistical analyses were performed in order to test the significance levels. For

example, a significance correlation ($R = 0.61$, $P = 0.0001$) was found between temperature and the chlorophyll-*a* levels, while the significance between the mixed layer and the integrated primary production values was $R = 0.33$, $P = 0.0001$.

To our knowledge, very few *in-situ* measurements of the optical properties of the water column in the Bay of La Paz have been reported, and the information available is limited to the works of Reyes-Salinas *et al.* (2003), Cervantes-Duarte *et al.* (2005) and Verdugo-Díaz *et al.* (2014), who showed a significant spatial and seasonal variability in the photosynthetic parameters and the primary production levels in the region, with the existence of two seasons in the primary production cycle: one of high primary production values from March to August; another one of low primary production values from September to February. Gaxiola-Castro *et al.* (1999) reported a strong seasonal and interannual variability in the photosynthetic parameters along the Gulf of California, related to the presence of hydrodynamic processes (such as fronts), which in turn modify the thermohaline structure of the water column.

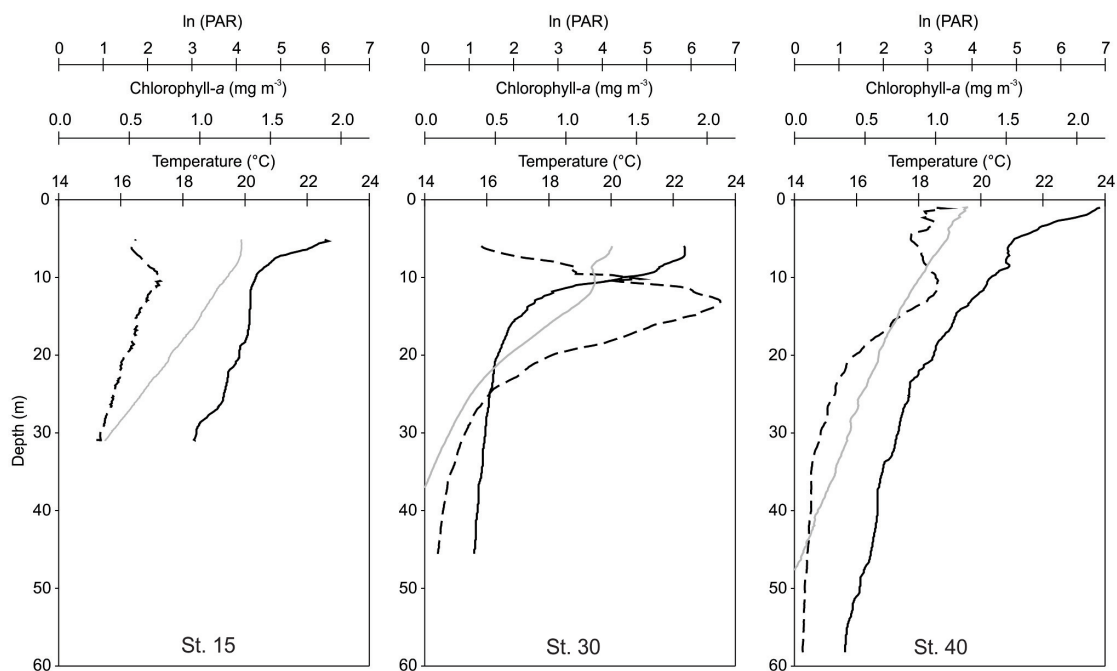


Figure 2. Vertical profiles of temperature (°C) (solid black line), chlorophyll-*a* (mg m^{-3}) (black medium dash line) and PAR (solid gray line) in three stations (# 15, 30 and 40) along the Bay of La Paz / Perfiles verticales de temperatura (°C) (línea continua negra), clorofila-*a* (mg m^{-3}) (línea punteada negra) y PAR (línea continua gris) en tres estaciones (# 15, 30 y 40) a lo largo de la Bahía de La Paz

The results reported here are highly significant for the bio-optical properties of Bay of La Paz, regarding the potential development of models of light penetration, ocean color and primary productivity in the region. The data could also be used to examine the interannual variability of heterotrophic processes such as the energy flow from autotrophs to heterotrophs, as well as for future analyses of organic carbon energy flow. Many more detailed *in-situ* observations regarding the optical properties of the water column in the Bay of La Paz are required to establish the possible seasonal variation in these parameters, which are linked not only to circulation patterns but also to the nutrient concentrations available to phytoplankton. The region is known to be subject to a wide seasonal variability, and due to its location near the connection to the open Pacific Ocean, the site is a sensitive record of regional variations in the gulf and the larger scale climate circulation of the subtropical Pacific Ocean. One of the major sources of interannual and monthly variability in the southern gulf, and consequently the Bay of La Paz, has been connected to the El Niño/Southern Oscillation (ENSO) (Pérez-Cruz 2013), which in turn modifies the hydrographic conditions of the water column, as already discussed.

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