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INTERNAL WAVES IN THE BAY OF LA PAZ, SOUTHERN GULF OF CALIFORNIA, MEXICO

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CHLOROPHYLL-A
THERMOCLINE
BAY OF LA PAZ
GULF OF CALIFORNIA

ABSTRACT. – Internal waves in the Bay of La Paz, southern Gulf of California, Mexico, are evidenced by variations in vertical profiles of chlorophyll-*a* and temperature, which showed vertical displacements between down-up cast profiles, and by satellite images. The maximum peaks in the natural fluorescence of chlorophyll-*a* and the thermocline depth were used to compare the differences between the two profiles. The results showed that the maximum displacement in chlorophyll-*a* was 4.4 m, while the maximum displacement in the thermocline depth was 8.7 m; the elapsed mean time between down-up profiles was 11.6 min. It was possible to reproduce the structure of the internal wave along the bay. The wavelength, obtained from satellite images, in the north and south part of the bay, is 3.11 km, while in the central part it is 15.56 km. The mechanisms of generation of the internal waves observed could be in association with the currents interacting with a bathymetric sill at the connection with the gulf. This study suggests that the internal waves can manifest in the area over short distances and can be inferred by different processes, such as vertical chlorophyll-*a* and temperature profiles and by satellite images.

INTRODUCTION

Internal waves are highly energetic and ubiquitous features in the ocean caused by variations in density, which propagate at the interface between layers of different temperatures (Morozov 2018). The biological and ecological effects of internal waves have been a subject of scientific research, and to date it is well know that these features induce considerable changes in the water column including vertical transport of nutrients to the euphotic layer (Sangra *et al*. 2001), chlorophyll-*a* (CHLA) enhancement by turbulent mixing (Tweddle *et al*. 2013), aggregation of the phytoplankton community (Lennert-Cody & Franks 2002), generation of thin phytoplankton layers (Prairie *et al*. 2012), phytoplankton movement through vertical light gradient increases the average light intensity experienced by phytoplankton and augments the compensation depth (Evans *et al*. 2008) below which no net photosynthesis occurs (Lande & Yentsch 1988), and phytoplankton growth associated with the vertical displacements of the thermocline (Holligan *et al*. 1985), among others. In coastal areas, turbulent mixing by internal waves are associated with pulses of nutrients in the surface layers (Cullen *et al*. 1983). In deep waters, internal waves are also linked with anomalously high primary productivity values by increased nutrient fluxes with a significance in the trophic webs (Holligan *et al*. 1985).

Some authors have addressed studies on internal wave generation within the Gulf of California (GC), particularly in the central and northern region (Rufenach & Smith 1985, Gaxiola-Castro *et al*. 2002, Filonov *et al*. 2003, Novotryasov *et al*. 2011). These studies showed that the waves are observed mainly in summer, due to the strong seasonal pycnocline, and generated locally by the interaction of the strong tides and the differences in bathymetry as well as the coastline geometry. The periods usually are in the order of 10 min and the wavelengths rose into a range from 100 m to 2 km, with amplitudes of the order of 10 m, however, amplitudes of 100 m are present (Fu & Holt 1984). The stages of the process associated with the generation of internal waves in the GC was addressed by Paden *et al*. (1991). Gaxiola-Castro *et al*. (2002) documented the passage of these wave packets with a series of conductivity, temperature, and depth (CTD) casts, suggesting an important effect over the structure of the hydrographic properties and the phytoplankton biomass. Filonov & Lavín (2003) described the internal tides in the Northern Gulf of California with data derived from two moored arrays of temperature and current sensors.

Although there are numerous reports of internal waves within the GC, in the adjacent areas, such as the bays inside them, the information about the propagation of these features is not clear. This paper aims to characterize internal waves in the Bay of La Paz (south of GC) inferred through vertical profiles of temperature and fluorescence of CHLA. To do this, information taken on a multidisciplinary oceanographic research cruise onboard the R/V "El Puma" of the National Autonomous University of Mexico during the summer of 2004 was analyzed.

The Bay of La Paz is situated in the eastern portion of the Baja California peninsula; it is the biggest basin within the GC and is one of the most important ecosystems due to its high biodiversity and productivity (Durán-Campos *et al*. 2019) (Fig. 1). It connects with the GC through Boca Grande in the northern portion and San Lorenzo Channel in the southeast margin (Fig. 1). The bathymetry shows, at the central portion, a region with a maximum depth of 420 m in Alfonso Basin, which decreases gradually to the south. An important feature in the study area is the presence of a bathymetric sill along Boca Grande with ~250 m depth (Molina-Cruz *et al*. 2001). According to Lavín *et al*. (2009), the water masses interchange with the GC occurred through Boca Grande, and include the Subsurface Subtropical Water (StSsW), the Tropical Surface Water (TSW) and the Gulf of California Water (GCW). The surface and subsurface circulation pattern are dominated by the presence of a mesoscale cyclonic eddy (Monreal-Gómez *et al*. 2001), which induces a nutrient Ekman pump, rising up the nutricline with vertical velocities of ~0.4 m.d^{-1}, fertilizing the euphotic layer (Coria-Monter *et al*. 2017). Also, differential distributions of diatoms and dinoflagellates and zooplankton aggregations, have been observed during summer (Coria-Monter *et al*. 2014, Duran-Campos *et al*. 2015). The wind in the region has a seasonal component, with the northwest winds predominating during the winter, southeast winds during the summer (Monreal-Gómez *et al*. 2001) and westerly winds during the late spring (Coria-Monter *et al*. 2017).

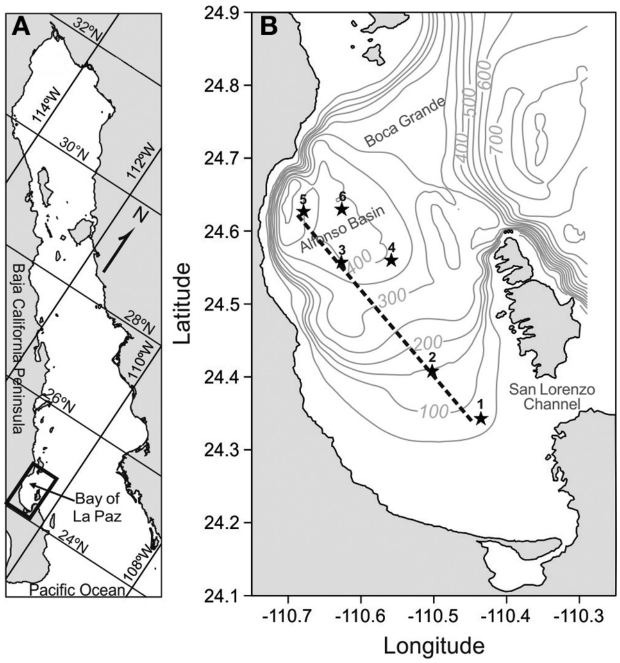

Fig. 1.- Location of Gulf of California (**A**) and Bay of La Paz (**B**) with sampling stations and transect. Bathymetry (thin gray line) is showed in meter.

MATERIALS AND METHODS

In this study, we use information gathered during the research cruise "PALEO-XII" onboard the R/V "El Puma" of the National Autonomous University of Mexico during summer 2004 (June 10 to 19) in the Bay of La Paz. Six fixed stations were selected inside the bay, representing the bathymetric gradient in the area (Fig. 1).

Natural fluorescence and temperature data were recorded with a Natural Fluorometer Profiler (PNF-300) previously calibrated by the manufacturer (Biospherical Instruments Inc.). Measurements of upwelled radiance (at 683 nm) were transformed into natural fluorescence and CHLA with the methods described by Kiefer *et al*. (1989) and Chamberlin *et al*. (1990). Under this approach, the calculation of the CHLA concentration results from two variables: 1) the incident irradiance and 2) the upwelling red radiance from the phytoplankton crop. The equipment measures the photosynthetically active radiation (PAR) into a range from 400 to 700 nm with sensors that respond equally to all wavelengths. Therefore, the CHLA concentration, expressed in MG.m^{-3}, is obtained from the incident irradiance and the natural fluorescence flux (Ff), with the expression Chl = Ff°acPAR × Φf × E_0(PAR), where °acPAR represents the chlorophyll absorption coefficient and Φf is the quantum yield of fluorescence.

In order to identify vertical displacement associated with internal wave propagation, CHLA and temperature vertical profiles (down-up casts) were performed according to Kiefer *et al*. (1989). With the vertical distribution of temperature, the thermocline depth was obtained by the depth of the maximum temperature gradient (δT/δz). The CHLA peaks and the thermocline depth were used to compare the vertical displacement and infer the wave amplitude. The CHLA integrated values were calculated for each station over the displacement difference considering both profiles.

During the research cruise, several PNF-300 casts were made, and those that showed clear differences in the depths of the maximum of fluorescence and thermocline between the up- and down-casts were selected. Special care was taken to reduce the effect of the ship's motion (pitch, roll, and yaw) so as not to confuse the possible noise from surface waves (up-down in the profile by the waves) with variation in the depths of the data induced by internal waves. The surface wave amplitude during the cruise was on average lower than 1 m.

Satellite images of sea surface temperature (SST) and CHLA were obtained for the days when the cruise took place (June 14, 2004) from the Moderate Resolution Imaging Spectroradiometer (MODIS-AQUA). The spatial resolution of images was 3.5 km, were processed at Level 1 and Level 2 using SeaDAS version 7.4 (http://oceancolor.gsfc.nasa.gov) and the standard algorithm OC3/OC4 (OCx) following Hu *et al*. (2012). In order to screen bad or low-quality data when generating the images, CLDICE, HILT, LAND, and STRAYLIGHT flags/masks were applied. The use of MODIS products in the Bay of La Paz has shown that the use of these images provides relevant and representative information about the hydrographic characteristics of the water column that may be comparable with *in situ* observations (Coria-Monter *et al*. 2017; Durán-Campos *et al*. 2019).

The internal waves appear as periodic, intermittent variations in the surface optical reflectivity and are visible from satellite images (Apel *et al*. 1976). They have been observed off the North American and African east and west coasts, in the Gulf of California, the Caribbean, the Baltic, the Gulf of Mexico, and the Sulu Sea (Apel *et al*. 1975). Apel *et al*. (1976) estimate the length of the internal waves by measuring the distance between the differences in the brightness of the satellite images. In this study, we used the Apel *et al*. (1976) method to measure the lengths of the internal waves in the Bay of La Paz.

RESULTS

Table I summarizes the values of CHLA and temperature recorded for each PNF-300 cast at each station.

The CHLA records showed a wide variability between downcast and upcast profiles. In the downcast profile, station 1 showed a CHLA peak value of 0.92 mg.m^{-3} located at 11.3 m depth, while the upcast profile showed a value of 0.90 mg.m^{-3} at 7 m depth, with a difference between the two of 0.02 mg.m^{-3} in 4.3 m. The elapsed time between the two profiles was 14 minutes, and the integrated value of CHLA calculated on the displacement at this station was 0.73 mg.m^{-2} (Fig. 2A). Station 2 showed a CHLA peak value of 0.77 mg.m^{-3} at 16.7 m depth in the downcast profile, while the upcast profile showed a value of 0.72 mg.m^{-3} at 14.5 m depth, with a final difference between the two of 0.05 mg.m^{-3} in 2.2 m. The elapsed time between the two profiles was 9 minutes, and the integrated value of CHLA on the displacement was 0.65 mg.m^{-2} (Fig. 2B). In station 3, the CHLA peak in the downcast profile was 1.31 mg.m^{-3} located at 17.3 m depth, while in the upcast profile the peak was 1.18 mg.m^{-3} at 12.9 m depth, with a final difference of 0.13 mg.m^{-3} in 4.4 m. The time between the two profiles was 12 minutes, and the integrated value of CHLA on the displacement was 0.87 mg.m^{-2} (Fig. 2C). Station 4 showed a CHLA peak in the downcast profile of 2.52 mg.m^{-3} at 13.1 m depth, while the upcast profile was 2.09 mg.m^{-3} at 13.5 m depth. The difference was 0.43 mg.m^{-3} in 0.4 m. The elapsed time was 9 minutes, and the integrated value of CHLA on the displacement was 2.07 mg.m^{-2} (Fig. 2D). Station 5 showed a CHLA peak in the downcast profile of 2.36 mg.m^{-3} at 8.6 m depth, while in the upcast profile the concentration was 1.73 mg.m^{-3} at 9.1 m depth, with a final difference of 0.63 mg.m^{-3} in 0.4 m depth. The elapsed time was 13 minutes, and the integrated value of CHLA on the displacement was 1.67 mg.m^{-2} (Fig. 2E). Finally, station 6 showed a value of 0.85 mg.m^{-3} at 13 m depth in the downcast profile, while in the upcast profile the concentration was 0.87 mg.m^{-3} at 10.8 m depth. The difference was 0.02 mg.m^{-3} in 2.2 m. The elapsed time was 13 minutes, and the integrated value of CHLA on the displacement was 0.74 mg.m^{-2} (Fig. 2F).

Similarly, the temperature records showed variations coherent with the CHLA profiles. In this case, we used the thermocline depth to identify the vertical displacements. In station 1, the thermocline depth was observed at 10.9 m in the downcast profile, while in the upcast profile it was observed at 6.9 m depth, representing a difference of 4 m between the two profiles (Fig. 3A). In station 2, the thermocline depth in the downcast profile was observed at 9 m, while in the upcast profile it was at 7.6 m depth with a difference of 1.4 m (Fig. 3B). Station 3 showed the thermocline at 16 m in the downcast profile and in the

Table I. – Values of CHLA and temperature recorded by the PNF-300 and differences between down-cast and up-cast profiles.

Date, Time (CDT)	Stations			Concentration of CHLA (mg.m^{-3}) and its depth (m) at peak						Thermocline depth (m)			
	St	Lat	Long	Down	Depth	Up	Depth	Difference (mg.m^{-3}.m^{-1})	Integrated values of CHLA (mg.m^{-2}) at displacement	Down	Up	Difference (m)	Time (min)
Jun 14 08:26	1	24.32	–110.42	0.92	11.3	0.90	7.0	0.02 / 4.3	0.73	10.9	6.9	4.0	14
Jun 14 19:19	2	24.39	–110.50	0.77	16.7	0.72	14.5	0.05 / 2.2	0.65	9.0	7.6	1.4	9
Jun 15 14:00	3	24.55	–110.61	1.31	17.3	1.18	12.9	0.13 / 4.4	0.87	16.0	7.3	8.7	12
Jun 15 15:59	4	24.55	–110.55	2.52	13.1	2.09	13.5	0.43 / 0.4	2.07	11.8	10.6	1.2	9
Jun 16 12:03	5	24.61	–110.67	2.36	8.6	1.73	9.1	0.63 / 0.4	1.67	8.4	8.1	0.4	13
Jun 16 10:24	6	24.62	–110.62	0.85	13.0	0.87	10.8	0.02 / 2.2	0.74	7.1	9.2	2.1	13

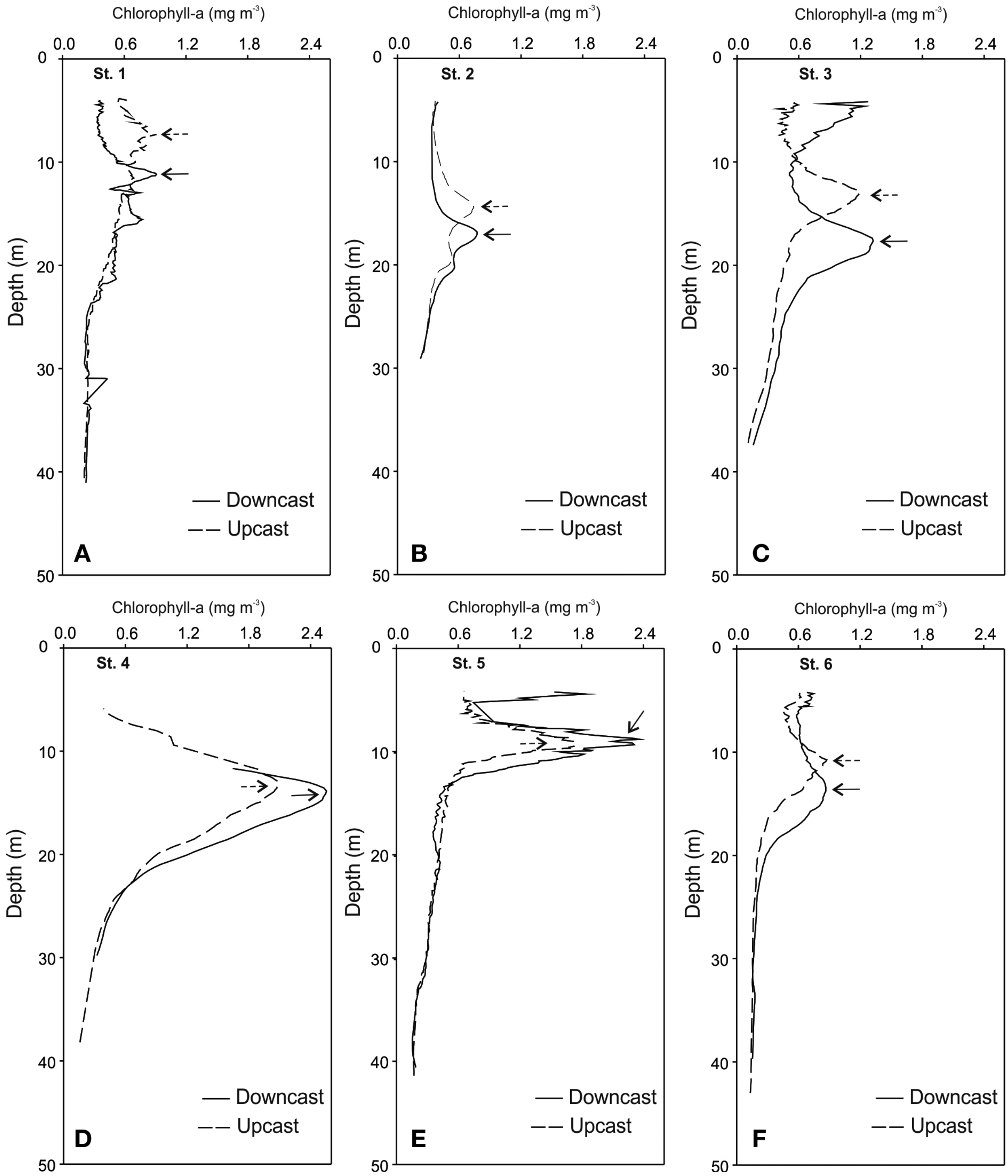

Fig. 2. – Chlorophyll-*a* (mg m^{-3}) vertical distribution in the downcast (solid line) and upcast profiles (dash line). The arrow indicates the maximum of CHLA.

upcast profile it was at 7.3 m depth, with a difference of 8.7 m between the two profiles (Fig. 3C). In station 4, the thermocline depth was 11.8 m, while in the upcast it was 10.6 m depth, with a final difference of 1.2 m (Fig. 3D). In station 5, the downcast profile showed the thermocline depth at 8.4 m, while the upcast profile showed it at 8.1 m depth (Fig. 3E). Finally, station 6 showed the thermocline depth in the downcast profile at 7.1 m, while in the upcast profile it was 9.2 m with a difference of 2.1 m (Fig. 3F).

The satellite image from the internal wave atlas and its propagation (Jackson 2004) clearly shows internal wave packets in the Bay of La Paz (Fig. 4). From this image, we can see that the wave length in the north and south part of the bay is 3.11 km, while in the central part it is 15.56 km. While the MODIS satellite images of June 14, 2004, when the research cruise took place (Fig. 5) showed the pres-

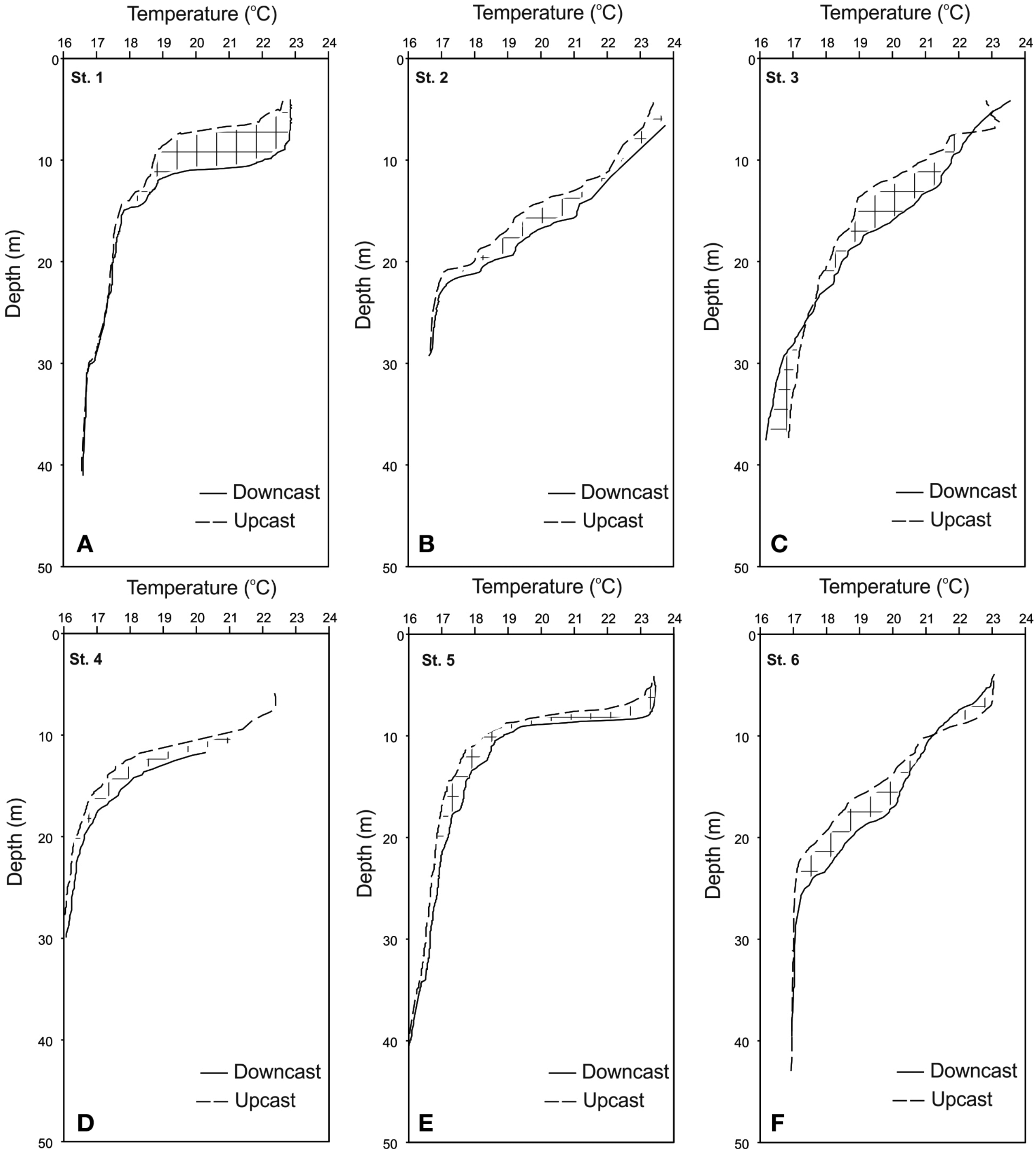

Fig. 3. – Temperature (°C) vertical distribution in the downcast (solid line) and upcast profiles (dash line).

ence of two cold cores, one in the north and another in the south of the bay, in the central part, a band of warm water was observed. In the case of CHLA, it is not as evident as for the temperature, although if it is possible to perceive a band of higher CHLA concentration, it would be slightly displaced to the right of the line that joins the sampling stations analyzed in this study.

As discussed earlier, the wavelength, obtained from satellite images following the Apel *et al*. (1976) method, in the north and south part of the bay is 3.11 km, while at the central part it is 15.56 km.

DISCUSSION

Internal waves play an important role in the dynamics of the oceanic thermocline, and the use of commercial fluorometers, widely available and easily operational, has been useful in order to summarize the relationship

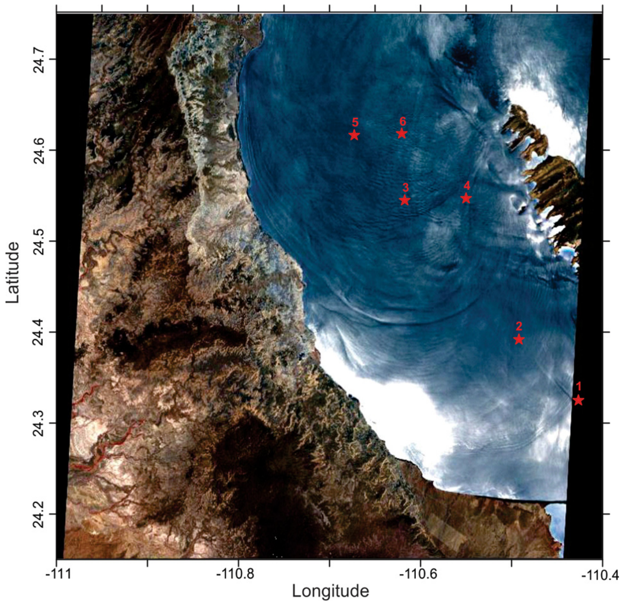

Fig. 4. – Internal wave propagation during summer in the Bay of La Paz (modified from Jackson (2004), http://www.inernalwaveatlas.com).

between fluorescence and internal waves in coastal areas (Lennert-Cody & Franks 1999, 2002). Internal waves have important ecological relevance because they play a fundamental role in vertical and horizontal mixing. The generation of internal waves varies considerably from one location to another as regards the function of the bottom slope and the stratification of the water column. In the GC, the presence of large islands enhances the tidal flow by squeezing it, reducing the channel cross-section and propagating packets of internal waves that originated over the sills between the islands like the one between San Lorenzo and San Esteban islands in the GC (Gaxiola-Castro *et al*. 2002).

Internal waves and mixing have been associated with topographic features over the continental shelf (Dewey *et al*. 2005) and sills (Inall *et al*. 2005, Xing & Davies 2006). The existence of sills in the presence of high tidal energy, together with the year-round strong stratification that characterizes the GC and adjacent areas, such as the Bay of La Paz, results in appropriate conditions for the generation of internal waves (Filonov & Lavín 2003). Salas-Monreal *et al*. (2012) show that zooplankton patches moved downward at the GC continental slope and then upward, exhibiting wave patterns. In the particular case of the Bay of La Paz, the presence of the sill along the Boca Grande could be closely related to the generation of internal waves, and the strong summer stratification suggests an ideal scenario for internal wave propagation. The presence of internal waves has been reported by satellite images inside the Bay of La Paz in the summer of 2001 by Jackson (2004), which showed propagation through the Boca Grande extending along the bay. The stations analyzed here were overlaid in Fig. 4 in agreement with displacements observed both in the CHLA and the thermocline depth, associated with the propagation of internal waves. The figure shows that internal waves can manifest during summer in small-enclosed basins over short distances. Striking examples of internal wave propagation associated with other bathymetric sill regions and stratified water columns have been evidenced using satellite imagery (Vázquez *et al*. 2008, Vázquez *et al*. 2009).

The largest chlorophyll variations between the upcast and downcast were observed for stations 4 and 5 (Fig. 2), where the vertical displacements suggests that the phytoplankton located around the thermocline, probably in the presence of adequate nutrients for growth, were advected vertically and exposed to a different level of irradiance near the surface, resulting in a change in the fluorescence values, which implies a purely physiological response to rapid changes in illumination. When phyto-

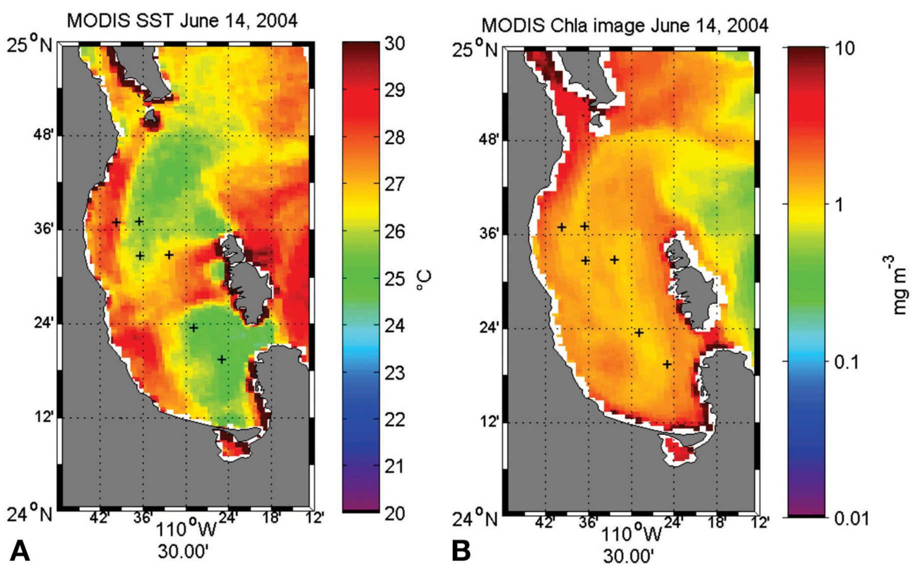

Fig. 5. – MODIS sea surface temperature and Chlorophyll-*a* from June 14, 2004.

plankton adapted to low light is suddenly exposed to high light, the fluorescence yield can decrease rapidly via non-photochemical quenching, giving an apparent decrease in biomass (Lennert-Cody & Franks 2002). According to Falkowski (1981), phytoplankton at different depths are acclimated to specific irradiance regimes and have different physiological characteristics. Under this approach, when vertical transport occurs, this will force a change in phytoplankton cells.

The vertical displacement (in meters) in the CHLA peaks between the two profiles rose in a range from 2.3 to 4.4 m, which was consistent with the thermocline depth displacement, which rose in a range from 2.9 to 8.7 m; this information could be associated with the amplitude of the waves and the mean elapsed time between the two profiles (11.6 minutes) suggests the period.

Short period internal waves have been commonly detected through measurements of temperature fluctuations in the seasonal thermocline. Although those fluctuations are not always due to internal waves, our results suggest that the displacement in thermocline depth could be closely related to the propagation of internal waves inside the bay. Those displacements cannot be associated with the drift of the ship. Due to the amplitude and period of internal waves varying with season, the seasonal variability in the Bay of La Paz suggests an ideal scenario for internal wave propagation, thus an important modification in the phytoplankton structure community is expected.

However, additional hydrodynamic processes could potentially impact the phytoplankton structure, such as the presence of mesoscale cyclonic eddies, which have been reported inside the bay as quasi-permanent features in the central portion of the bay, inducing important changes in the hydrographic properties of the water column, particularly in the temperature regime inside the bay (Coria-Monter *et al*. 2014, 2017). To date, it is well recognized that the formation and maintenance of peaks of CHLA are closely related to physical processes associated in turn with vertical mixing and upwelling by eddies. It is well known that mesoscale eddies are closely related with advection of nutrients to the euphotic layers, doming up the nutricline, and injecting waters with high concentration, particularly nitrate (McGillicuddy *et al*. 2016). Therefore, the presence of the mesoscale cyclonic eddy reported in the central portion of the Bay of La Paz could potentially impact the vertical distribution of CHLA due to the nutrient pumping associated with it, considering that temporal and seasonal evolution of this feature could induce differences in hydrographic properties modifying the phytoplankton community structure, in terms of vertical migrations by the phytoplankton for nutrient acquisition.

In summary, during summer 2004, important vertical displacements in CHLA concentration and thermocline depth suggested propagation of short-period internal waves inside the Bay of La Paz with an amplitude of 8 m, wavelengths between 11 and 15 km, and a period of 11 minutes. This formation could be closely related to the presence of the bathymetric sill located over Boca Grande, and the strong summer stratification suggests an ideal scenario for propagation. In addition, the bathymetric sill across the Boca Grande suggests that the local perturbations observed could be significant in biogeochemical fluxes inside the bay.

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