


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




Elisabet V. Wehncke, José Rubén Lara-Lara,
Saúl Álvarez-Borrego, and Exequiel Ezcurra
EDITORS


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA

Elisabet V. Wehncke, José Rubén Lara-Lara,
Saúl Álvarez-Borrego, and Exequiel Ezcurra
EDITORS

UC MEXUS
The University of California
Institute for Mexico
and the United States

Conservation science in Mexico's northwest.
Ecosystem status and trends in the Gulf of California

First edition: December 2014

Instituto Nacional de Ecología y Cambio Climático (INECC-SEMARNAT)
Periférico Sur 5000. Col. Insurgentes Cuicuilco
C.P. 04530. Delegación Coyoacán, Mexico City
inecc.gob.mx

Cover photos: © Octavio Aburto-Oropeza

Editorial coordination and design: Ana Ezcurra & Amanda González Moreno

ISBN: 978-1-4951-2222-4

Printed and made in Mexico

This book is dedicated to the memory of
Laura Arriaga Cabrera, Salvador Contreras-Balderas,
and Daniel Lluch Belda, caring colleagues,
great scientists, and exceptional human beings
to whom Baja California and the Gulf of California
owe so much.

Dedicamos este libro a la memoria
Laura Arriaga Cabrera, Salvador Contreras-Balderas y
Daniel Lluch Belda, colegas comprometidos,
grandes científicos, y seres humanos excepcionales,
a quienes Baja California y el Golfo de California
tanto les deben.

PHYTOPLANKTON BIOMASS AND PRODUCTION AT THE ENTRANCE OF THE GULF OF CALIFORNIA

José Rubén Lara-Lara[1] and Saúl Álvarez-Borrego[2]

The region adjacent to the mouth of the Gulf of California is in the transitional area between temperate and warm waters of the eastern tropical Pacific off Mexico. A historical perspective of its phytoplankton biomass and productivity (PP) is given based on data from *in situ* ^{14}C experiments and estimates from semi-analytical models using chlorophyll *a* concentrations (Chl_{sat}) and photosynthetically active radiation (PAR_{sat}) from monthly composites of the satellite sensor SeaWIFS. Coastal stations have biomass and productivity values up to two times higher than those of the offshore waters. During El Niño events both Chl and PP values are reduced at the mouth region. Upwelling events, the intrusion of tropical surface waters and the El Niño events are the main sources of phytoplankton biomass and productivity variability at the region.

Keywords: entrance to the Gulf of California, chlorophyll *a*, primary production, ^{14}C method, satellite imagery.

1. INTRODUCTION

Traditionally, the Eastern Tropical Pacific Ocean off Mexico (ETPM) has been described as an area of low phytoplankton productivity (PP) as characterized by its clear waters, attributed to low chlorophyll a concentrations (Chl) (*e.g.*, Stevenson 1970). However, satellite ocean colour imagery shows that at certain times of the year (mainly spring) the entrance to the Gulf of California develops relatively high pigment concentrations, in the region off Cabo Corrientes (see Figure 1) (García-Reyes 2005, Pennington *et al.* 2006). This feature is apparent in many images (*e.g.*,

* Departamento de Ecología Marina, CICESE, Ensenada, BC, México, alvarezb@cicese.mx

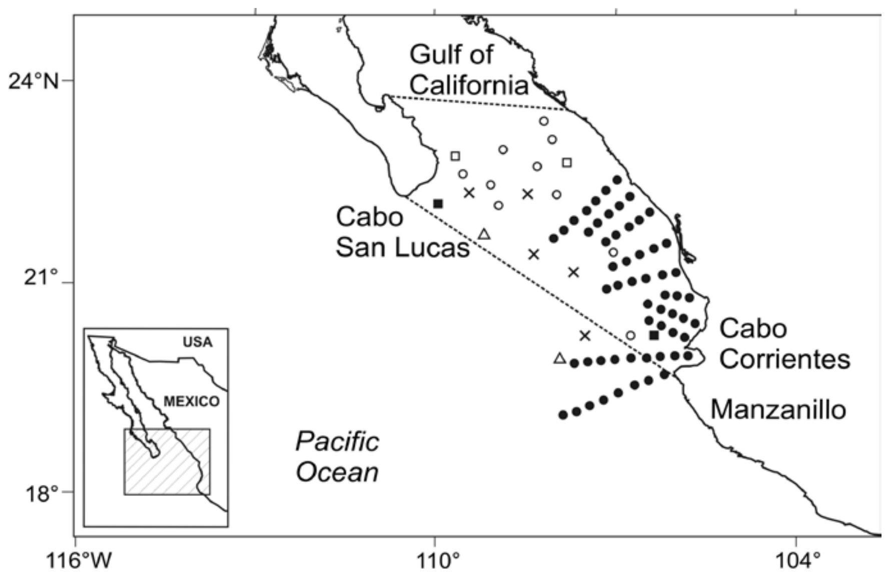

FIGURE 1. Mexican eastern tropical Pacific, showing the entrance to the Gulf of California and stations for primary productivity experiments: O Zeitzschel (1969), x Leet and Stevenson (1969), Δ Gaxiola-Castro and Álvarez-Borrego (1986), □ Valdez-Holguín and Lara-Lara (1987), ■ Lara-Lara and Bazán-Guzmán (2205), ● López-Sandoval *et al.* (2009a). The zone within the dotted lines shows the area used for remote sensing data by Santamaría-Del Ángel *et al.* (1994) and Hidalgo-González and Álvarez-Borrego (2004).

fig. 12 of Pennington *et al.* 2006, and images and field data from López-Sandoval *et al.* 2009a, b).

For the purpose of the following discussion, the entrance to the Gulf of California will be considered roughly as that between a line connecting Cape San Lucas and Cape Corrientes and a line connecting La Paz with Topolobampo (see Figure 1). This is a transitional zone that has a very complicated and dynamic oceanographic structure (Álvarez-Borrego 1983). The region adjacent to the mouth of the Gulf of California is in the transitional area between temperate and warm waters of the ETPM, and therefore it presents thermal and haline fronts. The presence of mesoscale structures such as eddies and meanders has also been reported (Torres-Orozco *et al.* 2005, Lavín *et al.* 2006, Zamudio *et al.* 2007). The region is considered one of the most productive areas for pelagic fisheries, in particular for yellowfin tuna (Stevenson 1970, Torres-Orozco *et al.* 2005).

Ship primary productivity and biomass data for the area adjacent to the mouth of the Gulf of California are very scarce and provide only single point estimates

for some locations, mainly offshore (Zeitzschel 1969, Leet and Stevenson 1969, Gaxiola-Castro and Álvarez-Borrego 1986, Valdez-Holguín and Lara-Lara 1987, Lara-Lara and Bazán-Guzmán 2005). More recently, López-Sandoval *et al.* (2009a, b) generated primary productivity data for the region off Cabo Corrientes performing 14C incubation experiments and from models based on remote sensing data. Santamaría-Del Ángel *et al.* (1994) generated satellite derived chlorophyll a (Chlsat) time series (1978-1986), and Hidalgo-González and Álvarez-Borrego (2004) generated a PP time series (1997-2002) also based on satellite data, with both data sets including information for the entrance to the Gulf.

The objective of this contribution is to review the information on the phytoplankton biomass and productivity variation at the entrance to the Gulf of California in the context of the physical environment, with emphasis on the annual and interannual variability.

2. THE PHYSICAL ENVIRONMENT

The entrance to the Gulf of California is located between 18° and 23°N, and from 105° to 110°W (see Figure 1). There are three surface waters at the entrance: Cold California Current water of low salinity (≤ 34.60), which flows southward along the west coast of Baja California; warm eastern tropical Pacific water of intermediate salinity (34.65≤ S ≥34.85), which flows into the area from the southeast; and warm highly saline (S ≥ 34.90) Gulf of California water (Roden and Groves 1959, Stevenson 1970). Winds are from the northwest during winter and spring ("winter" conditions), and from the southeast during summer and autumn ("summer" conditions), with maximum speeds during "winter". This causes a strong annual variation of phytoplankton biomass and productivity because of upwelling with "winter" conditions and very warm and oligotrophic waters with the "summer" intrusion of tropical surface waters. Upwelling conditions in this region may result at the eastern coast with alongshore winds during "winter" (Roden 1972); and also as a result of the interaction between coastal currents and the physiography, mainly at Cabo Corrientes, similar to the generation of cold-water plumes off Point Conception, California, as described by Fiedler (1984). Coastal upwelling has an important effect on the nutrient supply to the euphotic zone and hence on Chl and PP. The geostrophic currents are equatorward during "winter", including the area south from Cabo Corrientes (thus propitious to upwelling), while during "summer" they are poleward (see Figure 7 in Keesler 2006). The latter cause downwelling near the coast, and the sinking of the thermocline, with oligotrophic waters at the surface during summer and autumn.

Warsh *et al.* (1973) presented the vertical distribution of phosphate concentrations across the entrance to the Gulf. Their graphs show surface phosphate values of ~0.2 μM increasing rapidly with depth to ~2.3 μM at 100 m. Álvarez-Borrego and Giles-Guzmán (2012) reported, for the entrance region, annual mean surface values of nitrate and silicate concentrations of 0.35 ± 0.15 μM, and 2.7 ± 0.65 μM, respectively; increasing with depth to values at 100 m of 24.1 ± 0.9 μM, and 32.6 ± 1.9 μM, respectively (the numbers after ± is a standard error). Thus, high nutrient concentrations are found in very shallow waters and it takes relatively little energy to bring them up to the euphotic zone (Álvarez-Borrego *et al.* 1978).

López-Sandoval *et al.* (2009a) reported the temperature variability for the region off Cabo Corrientes, during three oceanographic cruises in May and November 2002, and June 2003. During May, mean sea surface temperature (SST) was 27.1ºC, for November it was 28.4ºC, and for June it was 27.4ºC. The SST distribution for May showed a coastal band of cool SST, suggesting upwelling. This was confirmed by the vertical distribution of potential temperature (see Figure 2a) showing the isotherms rising toward the coast and a surface mixed layer thinning in the same direction for the line of hydro-stations that cross the cool SST area. On the other hand, SST distribution for November showed evidence of coastal downwelling (see Figure 2b). During June SST was quite patchy but with the lowest SST values at the most inshore locations, which showed the presence of a very weak upwelling. The 24 and 26ºC isotherms showed an uplifting close to the coast (see Figure 2c). Thermocline near the coast (see Figure 2) was deeper during November (~80 m) than during June 2003 (50 m).

3. PHYTOPLANKTON BIOMASS

Phytoplankton biomass *in situ* ship data expressed as chlorophyll *a* concentration are very scarce for this region; however, they provide a general idea of the spatial and temporal variability. For example, Lara-Lara and Bazán-Guzmán (2005) reported the Chl size fractionated contribution at two locations during winter of 1999, the euphotic zone mean Chl values were from 0.32 to 0.95 mg m^{-3}, and the integrated concentrations varied from 16.8 to 24.9 mg Chl *a* m^{-2} (see Table 1). Nanophytoplankton (cells < 20 um) was the dominant fraction at both stations.

Based on data from the satellite sensor Coastal Zone Color Scanner (CZCS), Santamaría-Del Ángel *et al.* (1994) generated Chl_{sat} time series (1978-1986) for three locations at the entrance to the Gulf. Their Figure 2b shows a dramatic difference between the Chl_{sat} values of the location close to the tip of the Peninsula and those of the location close to mainland, with a very clear and strong effect of "winter"

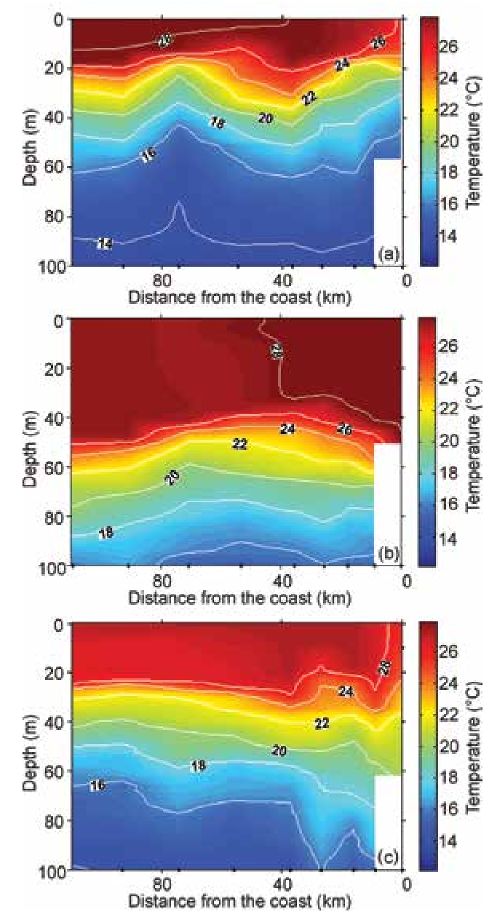

FIGURE 2. Vertical cross-section of potential temperature off Cabo Corrientes (from López-Sandoval *et al.* 2009a).

upwelling at the eastern side of the entrance (Chl_{sat} values often up to >5 mg m^{-3}), and with very low Chl_{sat} values most of the time at the western side of the entrance (very few occasions with values up to 2 mg m^{-3}). Zuria-Jordán *et al.* (1995) also used CZCS data to describe the temporal and spatial distribution of phytoplankton biomass across the entrance to the Gulf. Off Cabo Corrientes, high values occurred from January through May (5 to 8 mg m^{3}), indicating that this area experience strong seasonal upwelling. El Niño 1982-1984 had a clear effect on pigment concentration, with Chl_{sat} values <1 mg m^{3} at the whole entrance to the Gulf most of the time during September 1982–December 1984 (see Figure 2b of Santamaría-Del Ángel *et al.* 1994). A recurrent front was observed by Zuria-Jordán *et al.* (1995) off Cabo San

TABLE 1. Comparison of average range values for $PP^{14}C$ (g C m^{-2} d^{-1}), PPmod (g C m^{-2} d^{-1}), Chl (mg m^{-3}) and Chlint (mg m^{-2}) for the entrance of the Gulf of California.
Sources: 1. Zeitzschel (1969); 2.*Leet and Stevenson (1969) are mg C m^{-3} d^{-1}; 3. Gaxiola-Castro and Alvarez-Borrego (1986); 4. Lara-Lara and Bazán-Guzmán (2005); 5. Hidalgo-González and Alvarez Borrego (2004); 6. López-Sandoval *et al.* (2009a); 7. López-Sandoval *et al.* (2009b)

Sampling Date	Chla	Chlint	$PP^{14}C$	PPmod	Source
November-December			0.45-0.95		1
April-August			1.30-38.8*		2
January			0.19-1.40		3
January 1999	0.32-0.95	16.8-24.9	0.16-0.17		4
All year (1997-2002)					
- cool season	0.36-0.92			1.16-1.85	5
- warm season	0.24-0.55			0.39-0.49	5
May 2002	2.0	180	0.10-0.63		6
November 2002	0.8	155	0.11-0.30		6
June 2003	0.8	50	0.25-0.80		6
May 2002	0.47-0.60			0.55-1.50	7
November 2002	0.17-0.42			0.31-0.38	7
June 2003	0.27			0.41-0.70	7

Lucas with the strongest pigment concentration gradients at the end of spring and beginning of summer, during non-El Niño years. Based on monthly composites of the satellite sensor SeaWIFS, Hidalgo-González and Álvarez-Borrego (2004) reported Chl_{sat} for the Gulf of California, including an area from the mouth down to the northern part of Cabo Corrientes. Average Chl_{sat} values for this area during the cool season (end of November–end of June) varied from 0.36 to 0.92 mg m^{-3}, while during the warm season (July–early November) they varied from 0.24 to 0.55 mg m^{-3} (see Table 1).

López-Sandoval *et al.* (2009a) reported maximum Chl values for the region off Cabo Corrientes varying from 11.3 mg m^{-3} in May 2002 to 0.8 mg m^{-3} in November 2002 and June 2003 (see Figure 3). The spatial distribution of *in situ* surface Chl for May (see Figure 3a) showed the highest concentrations in the coastal region, in correspondence with the lowest SST, with maximum subsurface values up to 11 mg m^{-3} just off Cabo Corrientes. The surface Chl distributions for November and June (see Figures 3b and 3c) were very homogeneous. During May, the mean euphotic zone Chl was 180 mg Chl m^{-2} (see Table 1). However, there was a clear gradient

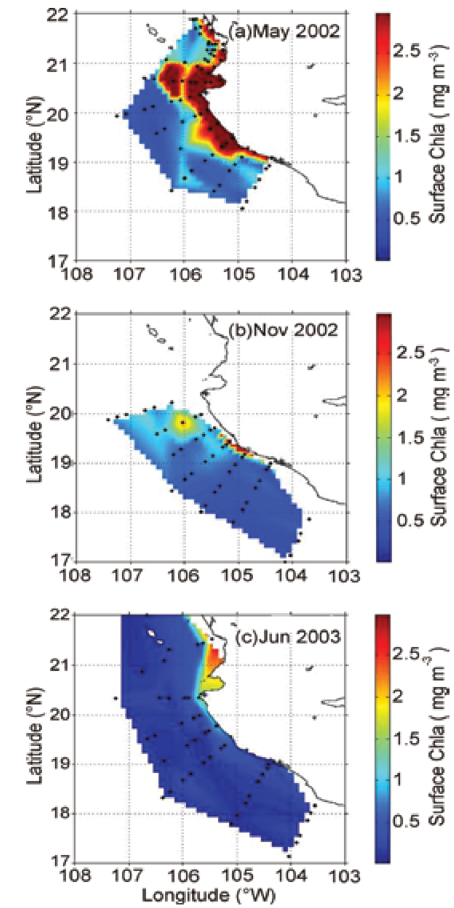

FIGURE 3. In situ surface chlorophyll *a* during (a) May 2002, (b) November 2002, and (c) June 2003 (from López-Sandoval *et al.* 2009a).

with stations close to shore (<60 km from the coast) containing higher integrated Chl (255 mg Chl m^{-2}) than those offshore (105 mg Chl m^{-2}). During November, the mean integrated Chl was 155 mg Chl m^{-2} with no clear onshore-offshore gradient (see Table 1). The lowest Chl values were found in June, with mean integrated Chl of 50 mg Chl m^{-2} (see Table 1), again with higher values onshore (72 mg Chl m^{-2}) than offshore (30 mg Chl m^{-2}).

López-Sandoval *et al.* (2009b) reported Chl_{sat} from monthly composites of the satellite sensor SeaWIFS, for May and November 2002, and June 2003, for the oceanic region off Cabo Corrientes. The May Chl_{sat} distribution showed relatively high values south of Cabo Corrientes, with highest values in the inshore zone (see

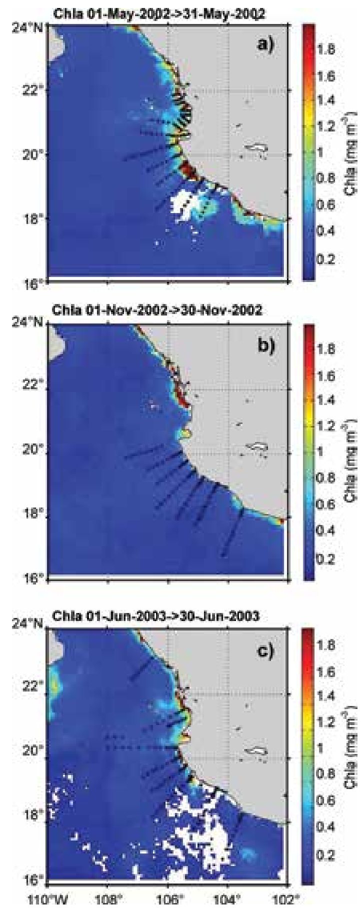

FIGURE 4. SeaWIFS monthly chlorophyll *a* (mg m^{-3}) composites for: (a) May 2002, (b) November 2002, and (c) June 2003 (from López-Sandoval *et al.* 2009b). The dots represent the hydro-stations of the three cruises of López-Sandoval *et al.* (2009a). The white areas in a and c panels indicate the presence of clouds during the whole month.

Figure 4). The June Chl_{sat} distribution also showed relatively high values in the inshore zone, but with a much smaller spatial coverage than that of the May composite (see Figure 4). The November Chl_{sat} distribution showed in general very low values, with few exceptions in the inshore zone north of Cabo Corrientes (see Figure 4). The monthly means Chl_{sat} for May were 0.60 and 0.47 mg m^{-3} for the inshore and the offshore zones, respectively; for November they were 0.42 and 0.17 mg m^{-3} for the inshore and the offshore zones, respectively; and for June they were 0.27 mg m^{-3} for both zones (see Table 1).

4. PRIMARY PRODUCTIVITY

The first reports on PP rates for the mouth of the Gulf of California were done by Zeitzschel (1969) based on half-day incubations (6h). Their integrated values ranged from 0.45 to 0.95 g C m^{-2} d^{-1} for November and December (see Table 1). Leet and Stevenson (1969) measured surface primary production for the region between Mazatlán, Cabo San Lucas and the Tres Marias islands, and their values ranged from 1.3 to 38.8 mg C m^{-3} d^{-1} for April to August (see Table 1). Gaxiola-Castro and Álvarez-Borrego (1986) reported primary productivity rates for two stations close to the entrance of the Gulf in January, ranging from 0.19 to 1.40 g C m^{-2} d^{-1} (see Table 1). Owen and Zeitzschel (1970) reported for the eastern tropical Pacific and average annual cycle from 0.13 to 0.32 g C m^{-2} d^{-1}, with maximum productivity in early spring and a secondary peak in August-September. Lara-Lara and Bazán-Guzmán (2005) reported the PP size fractionated contribution for two locations and for winter 1999; the euphotic zone mean PP values were from 0.86 to 1.65 mg C m^{-3} h^{-1}, and the euphotic zone integrated PP rates varied from 0.16 to 0.17 g C m^{-2} d^{-1} (see Table 1). Nanophytoplankton (cells < 20 um) was the dominant fraction at both stations.

López-Sandoval *et al.* (2009a) reported the spatial and temporal variability of PP for the region off Cabo Corrientes, for May and November 2002 and June 2003. The integrated local PP values for May varied from 0.10 to 0.63 g C m^{-2} d^{-1} with a mean value of 0.36 g C m^{-2} d^{-1} (see Table 1). The onshore stations averaged 0.46 g C m^{-2} d^{-1}, while for the offshore locations the average integrated PP was 0.29 g C m^{-2} d^{-1}. For November the integrated PP values were lower, with a mean value of 0.20 g C m^{-2} d^{-1}, also with an onshore–offshore gradient, varying from 0.30 g C m^{-2} d^{-1} onshore to 0.11 g C m^{-2} d^{-1} offshore (see Table 1). In June the integrated PP mean value was 0.44 g C m^{-2} d^{-1}. During this cruise the mean PP varied from 0.51 g C m^{-2} d^{-1} close to shore to 0.25 g C m^{-2} d^{-1} offshore (see Table 1).

Hidalgo-González and Álvarez-Borrego (2004) and López-Sandoval *et al.* (2009b) calculated the integrated total (PP_{mod}) and new phytoplankton production (PP_{new}) (g C m^{-2} d^{-1}) for the mouth of the Gulf of California, and the oceanic region off Cabo Corrientes, respectively. This was done with semi-analytic models from the literature and using Chl_{sat} and photosynthetically active radiation (PAR_{sat}) from monthly composites of the satellite sensor SeaWIFS. The average PP_{mod} for the whole entrance region, as reported in Hidalgo-González and Álvarez-Borrego's (2004) time series (1997-2002), varied from year to year in the range 1.16 - 1.85 g C m^{-2} d^{-1} during the cool seasons, and in the range 0.39 - 0.49 g C m^{-2} d^{-1} during the warm seasons (see Table 1).

Meanwhile, López-Sandoval *et al.* (2009b) reported for May 2002 an average PP_{mod} for the inshore zone much larger (1.50 g C m^{-2} d^{-1}) than that for the offshore zone (0.55 g C m^{-2} d^{-1}) (see Table 1). Average PP_{mod} for both inshore and offshore zones of November 2002 were close to each other (0.38 and 0.31 g C m^{-2} d^{-1}, respectively) (see Table 1). Average PP_{mod} values for June showed a clear gradient with a higher inshore value than the one for the offshore zone, 0.70 and 0.41 g C m^{-2} d^{-1}, respectively (see Table 1).

Rigorous comparison of satellite-derived PP_{mod} values with average of results from ^{14}C incubations is difficult due to the very different time and space characteristics of these measurements (Hidalgo-González and Álvarez-Borrego 2004). Nevertheless, it is interesting to compare both kinds of data. The PP_{mod} average values from López-Sandoval *et al.* (2009b) largely overestimated (they are between double and triple) the PP_{14C} average values from López-Sandoval *et al.* (2009a) for both inshore and offshore zones. However, in agreement with the PP_{14C} results reported by López-Sandoval *et al.* (2009), PP_{mod} values were highest for May (within the relatively intense upwelling season), they were followed by those for June (during the upwelling relaxation period), and they were lowest for November when stratification was strongest. It is clear from all the PP_{14C} data reported for the region that the photosynthetic rates show that phytoplankton production is very patchy in this region of the ocean and that the PP_{mod} average values may be much more representative than instantaneous point estimates.

5. RESPONSE OF PHYTOPLANKTON BIOMASS AND PRODUCTIVITY TO COASTAL UPWELLING

Thermocline depths are very important for phytoplankton, which depends on irradiance and on the supply of nutrients to perform their two most important physiological functions: photosynthesis and growth. In regions like the eastern tropical Pacific where the thermocline is very shallow, the euphotic zone can be nutrient-enriched with a relatively low wind, increasing phytoplankton productivity (Estrada and Blasco 1985). Pennington *et al.* (2006) indicatet that in the eastern tropical Pacific the depth of the thermocline (nutricline) is controlled by three interrelated processes: a basin-scale east/west thermocline tilt, a basin-scale thermocline shoaling at the gyre margins, and local wind-driven upwelling. In our case the two first processes are not of much relevance because our whole study region is relatively close to the coast.

Upwelling in this region has previously been reported to occur from March through June, in response to the predominant north-westerly winds (Roden 1972, Garcia-Reyes 2005, Torres-Orozco *et al.* 2005). However, López-Sandoval *et al.* (2009a) used the upwelling index and indicated that during 2002-2003 it started in January in the region off Cabo Corrientes, upwelling was relatively intense in March-May, relaxing in June, and there was no upwelling from July through December. Their May 2002 Chl_{sat} composite showed strong upwelling south from Cabo Corrientes, with high Chl_{sat} values near the coast. They showed also that local upwelling causes periods of enhanced chlorophyll and primary productivity in the inshore area, relative to the offshore area. Their data showed that both PP and Chl were two-fold higher in the coastal stations than in the oceanic region. The highest mean PP rates were registered for the coastal region during the spring cruises (May 2002 and June 2003; 465 and 512 mg C m^{-2} d^{-1}, respectively), and they argue that this was due to coastal upwelling. They showed that for the May 2002 cruise there were low-SST and high-Chl waters in the coastal stations, and the vertical distribution of isotherms for this cruise (see Figure 2a) also showed uplifting of the thermocline toward the coast. It is very likely that the spatial patterns of PP for the region off Cabo Corrientes are, in general, a response to the supply of nutrients from below the thermocline. Unfortunately no nutrient data are available for this region. On the other hand, during late autumn (November 2002 cruise) the lowest Chl (<0.2 mg Chl m^{-3}), PP (<200 mg C m^{-2} d^{-1}), and assimilation ratios were registered. This was probably due to the absence of upwelling, coupled with a deeper mixed layer and a strong thermocline (López-Sandoval *et al.* 2009b). Santa María-Del-Ángel *et al.* (1999) and Hidalgo-González and Álvarez-Borrego (2004) reported that the strong warm season depletion of primary production at the entrance to the Gulf was because of the invasion of equatorial surface waters (ESW). This warm surface water, up to >30 °C, causes very strong water-column stratification, greatly decreasing the effect of upwelling on the phytoplankton biomass and primary production. The vertical salinity distribution reported by López-Sandoval (2007) clearly show the low surface values inshore indicating the presence of the Surface Equatorial Water Mass, with warm and low nutrient waters. Water column stratification acts as a barrier to nutrient inputs from below the mixed layer (Mann and Lazier 1991). Therefore, López-Sandoval *et al.* (2009a, b) confirm the report by Pennington *et al.* (2006) that during spring the enrichment of the Cabo Corrientes region is mainly due to upwelling events.

6. RESPONSE OF PHYTOPLANKTON BIOMASS AND PRODUCTIVITY TO EL NIÑO EVENTS

Santamaría-Del Ángel *et al.* (1994) reported a dramatic suppression of Chl_{sat} at the entrance to the Gulf during El Niño 1982-1983, with values down to ~20% of those for non-El Niño years, but with a relatively small impact in the central and northern Gulf. This was very consistent with Mee *et al.* 's (1985) Chl (1979-1983) time series obtained for a location at the mouth of the Gulf, 30 km from the eastern coast, which showed that Chl values for winter dropped from ~10 mg m^{-3} in 1981-82 to <2 mg m^{-3} in 1983.

Hidalgo-González and Álvarez-Borrego (2004) also reported the effect of El Niño event in the entrance to the Gulf region. Their Chl_{sat} time series (1997-2002) show a clear interannual variation, with lower values in 1997-1998 than during the other "winters". During the other cool seasons there was no clear south to north gradient of integrated PP. During the warm season Chl_{sat} average values for the whole Gulf were similar to those for the entrance region during the cool season and with El Niño event (with the exception of the big islands region). The summer intrusion of the ESW into the Gulf of California produces every year an effect on primary production stronger than that of an El Niño event with winter conditions (González-Hidalgo and Álvarez-Borrego 2004).

7. CARBON FLUXES

New primary production (PP_{new}) is the fraction of PP supported by the input of nitrate from outside the euphotic zone (Dugdale and Goering 1967), mainly from below the thermocline by vertical eddy diffusion (Eppley 1992). It is an estimate of oceanic particle flux in the global carbon cycle. The description of the temporal and spatial variability of PP_{new} may give us an idea of the variability of the flux of organic matter out of the surface layer. For example, Hidalgo-González and Álvarez-Borrego (2004) reported from their time series (1997-2002) a range of PP_{new} values from 0.38 to 0.48 g C m^{-2} d^{-1} during the cool season and from 0.25 to 0.31 g C m^{-2} d^{-1} during the warm season; and for the Cabo Corrientes region López-Sandoval *et al.* (2009b) reported that PP_{new} varied from 0.03 to 0.60 g C m^{-2} d^{-1}. Although organic particle flux has not been measured in our region of interest, and data needs to be generated on this issue for a clear understanding of its benthic ecological dynamics, in any case the PP_{new} seasonality in the region shows that this flux of organic matter is much lower during summer and autumn than during the upwelling season.

8. CONCLUDING REMARKS

With *in situ* and satellite data, López-Sandoval *et al.* (2009b) identified three periods for the phytoplankton dynamics in the region off Cabo Corrientes: first the intense upwelling period (spring), which presented relatively high phytoplankton biomass and production rates; second the upwelling relaxation period (late spring-early summer), when the maxima PP were measured; and third the summer-autumn period, with a deep mixed layer capping a strong thermocline and with minimum Chl and PP. These environmental periods were more evident in the coastal locations (<60 km from the coast). In general, phytoplankton biomass and production rates in the coastal locations were up to two times those of the offshore stations.

It is clear that the region at the entrance to the Gulf, mainly that off Cabo Corrientes, exhibits significant seasonality (hydrography, phytoplankton biomass and productivity rates). This agrees with the comment of Pennington *et al.* (2006) that seasonal cycles are weak over much of the open-ocean eastern tropical Pacific, but that several eutrophic coastal areas do exhibit substantial seasonality. Undoubtedly, this is a response to the physical and chemical environmental variability of the region caused by upwelling that enhances the rates of nutrient supply to maintain high levels of primary production, above those of oligotrophic waters in tropical regions (López-Sandoval *et al.* 2009b).

The "winter" PP_{14C} and PP_{mod} values for the entrance to the Gulf of California were of similar magnitudes as the values reported for other productive regions of the Mexican Pacific coast. For example, Álvarez-Borrego and Lara-Lara (1991) reported 26 PP_{14C} data for "winter" conditions of the central Gulf of California with an average of 1.43 g C m^{-2} d^{-1}, they reported 12 values for the big islands region of the Gulf with an average of 2.1 g C m^{-2} d^{-1} , and they reported four values for the northern Gulf with an average of 1.1 g C m^{-2} d^{-1},compared to the May value of 1.50 g C m^{-2} d^{-1} for the inshore zone off Cabo Corrientes. Also, the spring inshore PP_{mod} rates are comparable to the satellite-derived values reported by Hidalgo-González and Álvarez-Borrego (2004) for the upwelling season of the Gulf of California (1.16 - 1.91 g C m^{-2} d^{-1}). The PP rates were also comparable to those reported for other regions in the Pacific such as the Gulf of Tehuantepec (Robles-Jarero and Lara-Lara 1993, Fiedler 1994, Lara-Lara and Bazán-Guzmán 2005, Fiedler and Talley 2006, López-Calderón *et al.* 2006, Pennington *et al.* 2006), and the California Current System (Aguirre-Hernández *et al.* 2004, Martínez-Gaxiola *et al.* 2007).

The high PP values observed for the coastal locations off Cabo Corrientes shows that this is an area of high fertility during spring. We conclude that upwelling events, the intrusion of southern eastern tropical Pacific surface waters and El Niño events are the main sources of phytoplankton biomass and production variability at the entrance to the Gulf of California.

ACKNOWLEDGEMENTS

This research was partially supported by CONACYT under the project: Flujos de Carbono: Fuentes y sumideros en los márgenes continentales del Pacífico Mexicano (SEP-2004-C01-45813/A-1). It was also supported by CICESE. J.M. Domínguez and F. Ponce did the art graphics.

REFERENCES

Aguirre-Hernández, E., G. Gaxiola-Castro, S. Nájera-Martínez, T. Baumgartner, M. Kahru, and G.B. Mitchell. 2004. Phytoplankton absorption, photosynthetic parameters, and primary production off Baja California: summer and autumn 1998. *Deep-Sea Research II* 51: 799–816.

Álvarez-Borrego, S. 1983. Gulf of California. In: B.H. Ketchum (ed.), *Estuaries and Enclosed Seas*. Amsterdam: Elsevier, pp. 427–449.

Álvarez-Borrego, S., and J.R. Lara-Lara. 1991. The physical environment and primary productivity of the Gulf of California. In: J.P. Dauphin and B. Simoneit (eds.), *The Gulf and peninsular province of the Californias*. Tulsa: American Association of Petroleum Geologists, pp. 555–567.

Álvarez-Borrego, S., and A.D. Giles-Guzmán. 2012. Opal in the Gulf of California sediments as a tool to estimate the vertical component of water exchange between the Gulf and the Pacific. *Botánica Marina* 2: 161–168.

Álvarez-Borrego, S., J.A. Rivera, G. Gaxiola Castro, M.J. Acosta Ruiz, and R. Schwartzlose. 1978. Nutrientes en el Golfo de California. *Ciencias Marinas* 5: 53–71.

Dugdale, R.C., and J.J. Goering. 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnology & Oceanography* 12: 196–206.

Eppley, R.W. 1992. Towards understanding the roles of phytoplankton in biogeochemical cycles: Personal notes. In: P.G. Falkowski and A.D. Woodhead (eds.), *Primary productivity and biogeochemical cycles in the sea*, New York: Plenum, pp. 1–7.

Estrada, M., and D. Blasco. 1985. Phytoplankton assemblages in coastal upwelling areas. *Simposio internacional sobre las áreas de afloramiento más importantes del Oeste Africano (Cabo Blanco y Benguela)*. Barcelona: Instituto de Investigaciones Pesqueras, pp. 379–402.

Fiedler, P.C. 1984. Satellite observations of the 1982-1983 El Niño along the US Pacific coast. *Science* 224: 1251–1254.

Fiedler, P.C. 1994. Seasonal and interannual variability of coastal zone color scanner phytoplankton pigments and winds in the eastern tropical Pacific. *Journal of Geophysical Research* 99: 18,371–18,384.

Fiedler, P.C., and L.D. Talley. 2006. Hidrography of the eastern tropical Pacific: a review. *Progress in Oceanography* 69: 143–180.

García-Reyes, M. 2005. Procesos físicos que controlan la variabilidad estacional de la temperatura superficial del mar y de la concentración de clorofila en la entrada al Golfo de California. M.Sc. Thesis, Universidad Nacional Autónoma de México, Mexico City.

Gaxiola-Castro, G., and S. Álvarez-Borrego. 1986. Primary productivity of the Mexican Pacific. Ciencias Marinas 12: 26–33.

Hidalgo-González, R.M., and S. Álvarez-Borrego. 2004. Total and new production in the Gulf of California estimated from ocean color data from the satellite sensor SeaWIFS. *Deep-Sea Research II* 51: 739–752.

Kessler, W.S. 2006. The circulation of the eastern tropical Pacific: A review. *Progress in Oceanography* 69: 181–217.

Lara-Lara, J.R., and C. Bazán-Guzmán. 2005. Distribution of chlorophyll and primary production by size classes along the Mexican Pacific coast. *Ciencias Marinas* 31: 11–21.

Lavín, M.F., E. Beier, J. Goméz-Valdés, V.M. Godínez, and J. García. 2006. On the summer poleward coastal current off SW México. *Geophysical Research Letters* 33: L02601, doi:02610.01029/02005glo24686.

Leet, W.S., and M.R. Stevenson. 1969. *Oceanographic observations from the Mazatlán project: October-August 1967. Data Report 3*. InterAmerican Tropical Tuna Commission, La Jolla.

López-Calderón, J., H. Manzo-Monroy, E. Santamaría del Ángel, R. Castro, A. González-Silvera, and R. Millán-Núñez. 2006. Variabilidad de mesoescala del Pacífico tropical mexicano mediante datos de los sensores TOPEX y SeaWIFS. *Ciencias Marinas* 32: 539–549.

López-Sandoval, D.C. 2007. Variabilidad de la productividad primaria en la región de Cabo Corrientes, México. M.Sc. Thesis, Centro de Investigación Científica y de Educación Superior de Ensenada, BC, Ensenada.

López-Sandoval, D.C., J.R. Lara-Lara, M.F. Lavín, S. Álvarez-Borrego, and G. Gaxiola-Castro. 2009a. Primary productivity in the Eastern Tropical Pacific off Cabo Corrientes, Mexico. *Ciencias Marinas* 35: 169–182.

López-Sandoval, D.C., J.R. Lara-Lara, and S. Álvarez-Borrego. 2009b. Primary production by remote sensing in the region off Cabo Corrientes, Mexico. *Hidrobiológica* 19: 185–192.

Mann, K.H., and J.R.N. Lazier. 1991. *Dynamics of Marine Ecosystems: biological-physical interactions in the oceans.* Blackwell Scientific Publications, Boston.

Martínez-Gaxiola, M.D., R. Sosa-Ávalos, and G. Gaxiola-Castro. 2007. Producción de carbono orgánico en los mares mexicanos (1998-2005). In: B. Hernández de la Torre and G. Gaxiola Castro (eds.), *Carbono en ecosistemas acuáticos de México*. INE-CICESE, Mexico City, pp. 251–266.

Mee, L.D., A. Ramírez-Flores, F. Flores-Verdugo, and F. González-Farías. 1985. Coastal upwelling and fertility of the southern Gulf of California: impact of the 1982-1983 ENSO event. *Tropical Ocean and Atmosphere Newsletters* 31: 9–10.

Owen, R.W., and B. Zeitzschel. 1970. Phytoplankton production seasonal change in the oceanic eastern tropical Pacific. *Marine Biology* 7: 32–36.

Pennington, T.J., K.L. Mahoney, V.S. Kuwahara, D.D. Kolber, R. Calienes, F.P. Chávez. 2006. Primary production in the eastern tropical Pacific: A review. *Progress in Oceanography* 69: 285–317.

Robles-Jarero, *E.g.*, and J.R. Lara-Lara. 1993. Phytoplankton biomass and primary productivity by size classes in the Gulf of Tehuantepec, Mexico. *Journal of Plankton Research* 15: 1341–1359.

Roden, G. 1972. Termohaline structure and baroclinic flow across the Gulf of California entrance and in the Revillagigedo Islands region. *Journal of Physical Oceanography* 2: 177–183.

Roden, G.I., and G.W. Groves. 1959. Recent oceanographic investigations in the Gulf of California. *J. Mar*. Res. 18: 10–35.

Santamaría-Del Ángel, E.M., S. Álvarez-Borrego, and F.E. Muller Karger. 1994. Gulf of California biogeografic regions based on coastal zone color scanner imagery. *J. Geophys. Res*. 99: 7411–7421.

Santamaría-Del Ángel, E.M., S. Álvarez-Borrego, R. Millán-Núñez, and F.E. Muller Karger. 1999. Sobre el efecto débil de las surgencias de verano en la biomasa fitoplanctónica del Golfo de California. *Revista de la Sociedad Mexicana de Historia Natural* 49: 207–212.

Stevenson, M.R. 1970. On the physical and biological oceanography near the entrance to the Gulf of California, October 1966–August 1967. *Inter-Am. Trop. Tuna Comm. Bull.* 4: 389–504.

Torres-Orozco, E., A. Trasviña, A. Muhlia-Melo, S. Ortega-García. 2005. Dinámica de mesoescala y capturas de atún aleta amarilla en el Pacífico Mexicano. *Ciencias Marinas* 31: 671–683.

Valdez-Holguín, J.E., and R. Lara-Lara. 1987. Primary productivity of the Gulf of California of El Niño 1982-1983 event. *Ciencias Marinas* 13: 34–50.

Warsh, C.E., K.L. Warsh, and R.C. Staley. 1973. Nutrients and water masses at the mouth of the Gulf of California. *Deep-Sea Research* 20: 561–570.

Zamudio, L., H.E. Hurlburt, J.E. Metzger, C.E. Tilburg. 2007. Tropical wave-induced oceanic eddies at Cabo Corrientes and the Maria Islands, Mexico. *Journal of Geophysical Research* 112(C05048), doi:10.1029/2006jc004018.

Zeitzschel, B. 1969. Primary productivity in the Gulf of California. *Marine Biology* 3, 201–207.

Zuria-Jordan, I.L., S. Álvarez-Borrego, E. Santamaría del Ángel, and F.E. Müller-Karger. 1995. Satellite-derived estimates of phytoplankton biomass off southern Baja California. *Ciencias Marinas* 21: 265–280.

[1] División de Oceanología, CICESE, Ensenada, BC, México, rlara@cicese.mx

[2] Departamento de Ecología Marina, CICESE, Ensenada, BC, México, alvarezb@cicese.mx

Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

Elisabet V. Wehncke

UC MEXUS
The University of California Institute for Mexico and the United States

SEMARNAT
SECRETARÍA DE MEDIO AMBIENTE Y RECURSOS NATURALES

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

ISBN 978-1-4951-2222-4
90000>