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HERRERA-CERVANTES, H.; LLUCH-COTA, S. E.; LLUCH-COTA, D. B.; GUTIÉRREZ DE VELASCO  
SANROMÁN, G.; LLUCH-BELDA, D.

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## **ENSO influence on satellite-derived chlorophyll trends in the Gulf of California**

H. HERRERA-CERVANTES

*Unidad La Paz, Centro de Investigación Científica y de Educación Superior de Ensenada,  
La Paz, Baja California Sur, México 23050*

Corresponding author; e-mail: hherrera@cicese.mx

S. E. LLUCH-COTA, D. B. LLUCH-COTA

*Centro de Investigaciones Biológicas del Noroeste P. O. Box 128,  
La Paz, Baja California Sur, México 23000*

G. GUTIÉRREZ DE VELASCO SANROMÁN

*Unidad La Paz, Centro de Investigación Científica y de Educación Superior de Ensenada,  
La Paz, Baja California Sur, México 23050*

D. LLUCH-BELDA

*Centro Interdisciplinario de Ciencias Marinas, Instituto Politécnico Nacional, P. O. Box 592,  
La Paz, Baja California Sur 23000, México*

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### **RESUMEN**

El impacto de los eventos El Niño-Oscilación del Sur (ENSO, por sus siglas en inglés) sobre la ecología del Golfo de California presenta un panorama de controversia debido a las observaciones contrastantes de campo. En este estudio se examina, a partir de imágenes de satélite derivadas del sensor Sea-viewing Wide Field-of-view Sensor (SeaWiFS), la variabilidad interanual de la concentración superficial de clorofila-a (Chl-a) en el golfo durante el periodo de septiembre de 1997, cuando iniciaron las mediciones del SeaWiFS, hasta diciembre de 2006. El grado de forzamiento climático (impacto de ENSO) sobre la Chl-a se cuantificó con base en el análisis de funciones empíricas ortogonales (FEO) y en la firma espacial del índice multivariado de El Niño (MEI) revelada por un análisis de regresión lineal simple. El patrón espacial de las FEO<sub>1</sub> (explicando el 44% de la varianza total) y los patrones espaciales de los valores de pendientes y coeficientes de correlación (R) resultaron similares, sugiriendo que los efectos de los eventos ENSO en el Golfo de California no son homogéneos, mostrando que la costa este y la zona norte fueron las más variables, afectadas y altamente correlacionadas con el MEI ( $r \approx -0.5$ ,  $P < 0.01$ ), mientras que la región de las grandes islas y la costa oeste mostraron menor variabilidad y débil correlación con el MEI, explicando la aparente contradicción respecto a los efectos de ENSO sobre la ecología del golfo. La serie de amplitudes temporales de las FEO<sub>1</sub> fue correlacionada significativamente con el MEI ( $r = -0.69$ ,  $P < 0.01$ ) mostrando aproximadamente un año de desfase entre el inicio del periodo de calentamiento sostenido, representado por el incremento de valores del MEI (1999-2004) y el decaimiento de la variabilidad interanual de la Chl-a en el Golfo de California (2000-2004). Las condiciones ENSO observadas a lo largo de las costas del golfo son representadas por un patrón de decremento/incremento

de Chl-a, mientras que un patrón opuesto se observó en la temperatura superficial del mar (TSM), reflejando el fuerte acoplamiento físico-biológico durante los eventos El Niño-La Niña.

#### ABSTRACT

ENSO impacts on the Gulf of California ecology remains a matter of controversy, because of contrasting field observations. In the present study, interannual variability is examined from fields of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) surface chlorophyll (Chl-a) from September 1997, the start of data from the SeaWiFS, until December 2006. Empirical orthogonal function (EOF) analysis and the spatial signature of the multivariate El Niño index (MEI), as revealed by a linear regression analysis (LRA), were used to quantify the degree of climate forcing (ENSO impacts) over the Gulf of California Chl-a. The spatial patterns of EOF<sub>1</sub> (that explained 44% of the total variance) and the slopes and correlation coefficients (R) values resulted similar, suggesting that the effects of ENSO events in the gulf are not homogeneous, showing that eastern coast and the northern area were the most variable, affected and closely correlated with the MEI ( $r \approx -0.5$ ,  $P < 0.01$ ), while at the Midriff Islands region and the western coast less variability and weaker correlation with the MEI were observed, explaining the apparent contradictions regarding the ecological effects of ENSO in the Gulf of California. The EOF<sub>1</sub> amplitude time series was significantly correlated to MEI ( $r = -0.69$ ,  $P < 0.01$ ) showing approximately one year lag between the 1999-2004 overall warming period onset, represented by the increase of MEI values and the decrease of the Gulf of California Chl-a interannual variability (2000-2004). ENSO conditions consisting of decreasing/increasing Chl-a patterns were observed along both coasts of the gulf, while opposite conditions were revealed in the surface sea temperature (SST) pattern, reflecting the strong physical-biological coupling during the El Niño-La Niña events.

**Keywords:** Interannual variability, EOF, physical-biological coupling.

#### 1. Introduction

The Gulf of California, located between mainland México and the Baja California peninsula (Fig. 1) is a subtropical sea of complex bathymetry. A midriff islands region divides the gulf in two areas with

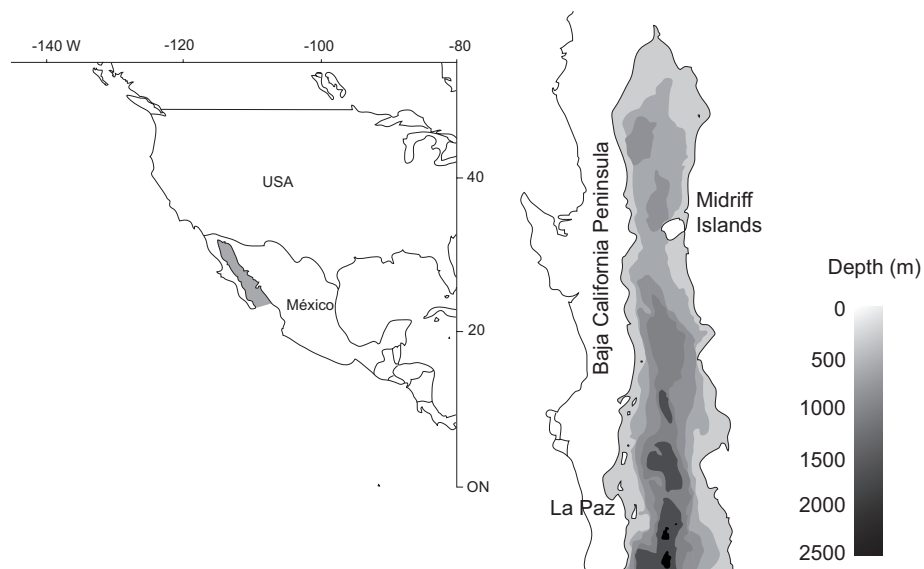


Fig. 1. Location and bathymetry of the Gulf of California.

different dynamic characteristics; the northern area, mostly shallower than 200 m deep (Reyes and Lavín, 1997) and the southern part with depths greater than 3000 m, mostly influenced by the Pacific Ocean (Marinone, 1988). Its morphology and its atmospheric conditions through the year result in this inner sea being an excellent place to study the physical-biological interactions using remote sensing (Paden *et al.*, 1991; Santamaria del Ángel and Álvarez-Borrego, 1994; Karhu *et al.*, 2004).

Tight coupling of high biological productivity and physical processes transporting nutrients to the surface layers occurs by strong tidal currents at the Midriff Island region, wind driven seasonal upwelling along the continental coast and at mesoscale structures influencing the mixed layer depth (filaments, meanders, eddies, etc.; Valdez-Olguín and Lara-Lara, 1987; Lluch-Cota, 2000).

ENSO driven interannual variability in the Gulf of California oceanography has been the topic of many studies; however, strong controversy remains, particularly regarding the ecological impacts, because of contrasting reports derived from field studies. Table I summarizes some of these published observations made during the three strongest ENSO events in the last 25 years.

In a previous work (Herrera-Cervantes *et al.*, 2007) we reported the spatial signature of ENSO in the Gulf of California sea surface temperature (SST), as related to the physical atmospheric (winds) and ocean (coastal Kelvin wave) forcing interacting with local dynamics (i.e. upwelling and tidal mixing) and the topographical characteristics of the gulf. In this work we extend that analysis to the ecological impacts based on Sea-viewing Wide Field-of-view Sensor (SeaWiFS) surface chlorophyll a data (Chl-a), a useful tool to estimate the availability of nutrients for fitoplankton growth in the upper-ocean (Behrenfeld *et al.*, 2006).

## 2. Data and methods

SeaWiFS Chl-a monthly images data were derived from global level 3 standard mapped images processed and distributed by the NASA/Goddard Space Flight Center website (<http://oceancolor.gsfc.nasa.gov>). The 9 x 9 km initial grid was rotated and re-binned into 18 x 18 km pixel arrays to produce the same spatial resolution used by Herrera-Cervantes *et al.* (2007), resulting in a series of Chl-a ( $x, t$ ) matrices, where  $x$  stands for the pixels within each image and  $t$  stands for each month between September 1997 and December 2006.

We removed the annual and semiannual signals by subtracting a fitted (least squares) periodic function from each pixel time-series. The periodic function was defined as:

$$S(t) = A_0 + A_1 \cos(w_1 t - \varphi_1) + A_2 \cos(2w_2 t - \varphi_2)$$

where  $A_0$  is the annual mean,  $A_1$ ,  $w_1$  and  $\varphi_1$  are the amplitude, frequency and phase of the annual signal, and  $A_2$ ,  $w_2$  and  $\varphi_2$  are the equivalent for the semiannual signal. We computed linear trends for each pixel anomalies time series for the period 1999 to 2004, reported in the literature as a period of sustained warming trend revealed by global climatic indices (Behrenfeld *et al.*, 2006). We then mapped the slopes from each regression, to identify regions with similar trends during this period.

The spatial signature of ENSO over the Gulf of California biological productivity was revealed by applying simple linear regressions between each Chl-a ( $t$ ) anomaly time series and the inversed multivariate ENSO index (MEI), considered to represent ENSO activity (Wolter and Timlin,

Table I. Some observations on ENSO ecological impacts in the Gulf of California.

ENSO	Key observation	References
1972/73	Zooplankton biomass changes along 12 months showed no relation to the presence of an ENSO in the northern gulf, probably due to the strong local enrichment dynamics. Decreased sardine catch-per unit-effort (CPUE) and availability in the central gulf.	Farfán and Álvarez-Borrego (1992) Lluch-Belda <i>et al.</i> (1986), Nevárez <i>et al.</i> (2001)
1982/83	Decreased satellite-derived pigment concentration in some areas (including southern gulf). Phytoplankton biomasses in the southern gulf during spring of 1984 similar to previous years. Primary production remain nearly constant in the central and northern areas. Zooplankton biomass remained unchanged in the central gulf region. No harmful algal blooms (HAB) events in an area of frequent blooms (Mazatlán) during ENSO. Sardine concentrated around the midriff islands. Diatoms diminished in distribution and abundance in the central gulf. Collapse of sardine fishery. Brown pelican colonies breeding successfully in the northern gulf region. Brown pelican colonies essentially deserted during the breeding season in the southern gulf.	Santamaría del Ángel and Álvarez-Borrego (1994) Valdez-Holguín and Lara-Lara (1987) Álvarez-Borrego and Lara-Lara (1991) Jiménez-Pérez and Lara-Lara (1988), Lavaniegos-Espejo <i>et al.</i> (1989) Cortés-Altamirano and Núñez-Pasten (1992) Huato-Soberanis and Lluch-Belda (1987) Thunell (1998) Nevárez <i>et al.</i> (2001) Jaques <i>et al.</i> (1996) Jaques <i>et al.</i> (1996)
1997/98	Decreased pigment concentration from satellite. HAB events decreased. Sardine reproduction failure. Collapse of squid fishery (reallocation of abundance). Reduced reproductive success in midriff islands pelican colonies.	Karhu <i>et al.</i> (2004) Alonso-Rodríguez <i>et al.</i> (2000) Sánchez-Velasco <i>et al.</i> (2000) Lluch-Cota <i>et al.</i> (2007) Sydeman <i>et al.</i> (2001)

1993; Behrenfeld *et al.*, 2006). Monthly MEI data were obtained from the Earth System Research Laboratory at the National Oceanic and Atmospheric Administration (ESRL-NOAA) website (<http://www.cdc.noaa.gov>). In the sign-reversed MEI (InvMEI) series, positive values correspond to cold-La Niña periods, and negative values to El Niño conditions. With this setting, warming and decreasing productivity would provide positive correlation, as in Behrenfeld *et al.* (2006).

The non-seasonal Chl-a anomalies matrix was also analyzed by means of EOF analysis (Storch and Zwiers, 1999) to obtain the dominant mode of Chl-a non-seasonal variability. We mapped the EOF loadings to visualize the spatial structure of the variability (first mode), and compared the time-dependent EOF to the InvMEI. Additionally, we built time plots (Hovmöller diagrams) of Chl-a and SST anomalies based on time series data for pixels within the ~50 km closest to the east and west coasts of the Gulf of California. between September 1997 and December 2006 (SST

data downloaded from the NOAA/NASA AVHRR Ocean Pathfinder sea-surface temperature data website at <http://podaac.jpl.nasa.gov>).

### 3. Results

Figure 2 (left panel) shows the spatial pattern of the EOF<sub>1</sub> loadings for pigments concentration. EOF<sub>1</sub> accounted for 44% of the variance, and no other mode could be resolved because their sampling errors are large enough to prevent neighboring eigenvalues from being statistically different (North *et al.*, 1982), so we can consider Chl-a interannual variability in the Gulf of California represented by a single, dominant mode. The surface plot of the EOF<sub>1</sub> loadings shows that variability is higher along the east coast and the northern area as compared to the west coast and the midriff islands region. Slope values (central panel) and  $R$  values obtained by means of the simple Lineal Regression Analysis (LRA) (right panel) bear a resemblance to that of the EOF<sub>1</sub>, indicating a strong statistical relationship between the InvMEI ( $t$ ) and the individual Chl-a ( $t$ ) series in areas of steeper slopes and higher  $R$  values ( $> 0.4$ ).

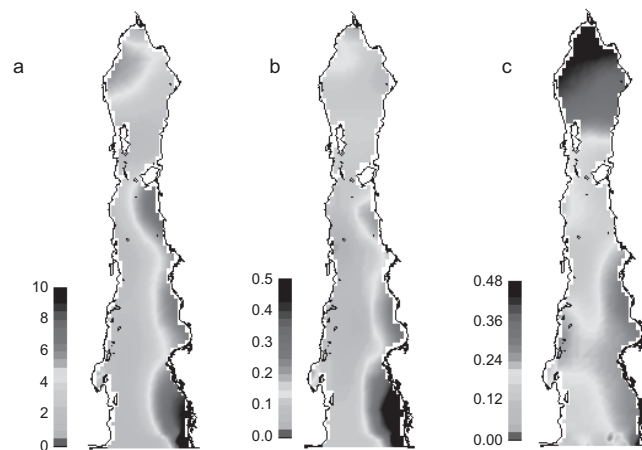


Fig. 2. Spatial patterns of the EOF<sub>1</sub> a) from SeaWiFS Chl-a concentrations anomalies, slope values b) and correlation coefficients c) from the linear regression between the Chl-a anomalies (mg m<sup>-3</sup>) and the sign-reversed MEI (InvMEI) as the independent variable.

Figure 3 shows how the EOF<sub>1</sub> amplitude and the InvMEI index time series are related during this time period, indicating that the Chl-a interannual variability was forced by ENSO-related events (e.g., the signals of the 1997-1998 El Niño and 1999-2000 La Niña). The two series are highly correlated ( $R \approx 0.7$ ,  $P < 0.01$ ), and EOF<sub>1</sub> trend (regression line) shows a direct relationship, with an approximately one year lag, with respect to the sustained warming period associated with ENSO, as shown by MEI variability (starting in 1999, Behrenfeld *et al.*, 2006).

Figure 4 shows the time series (bars) the InvMEI, as compared to the evolution of Chl-a and SST coastal anomalies signals plotted in two Hovmöller diagrams, along the entire Gulf of

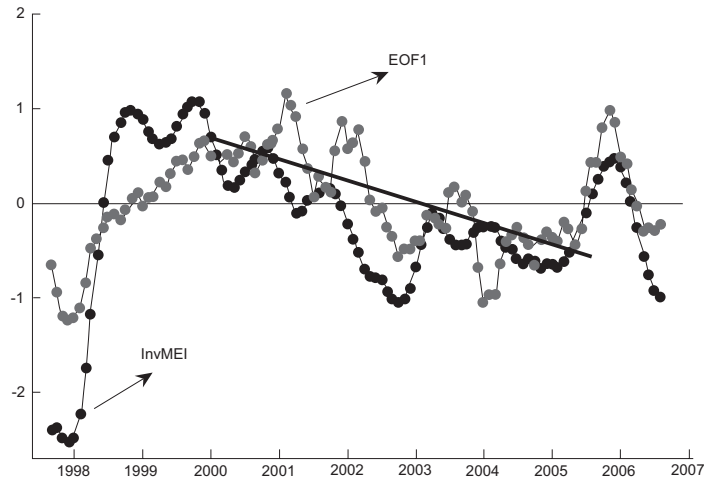


Fig. 3. Time-series of the temporal evolution of the EOF<sub>1</sub> (gray circles) and the InvMEI (black circles), both series are highly correlated ( $R = 0.69$ ) and both were smoothed by a five-term running mean. Trend lines are least-squares fits to pre-2000 and post-2000.

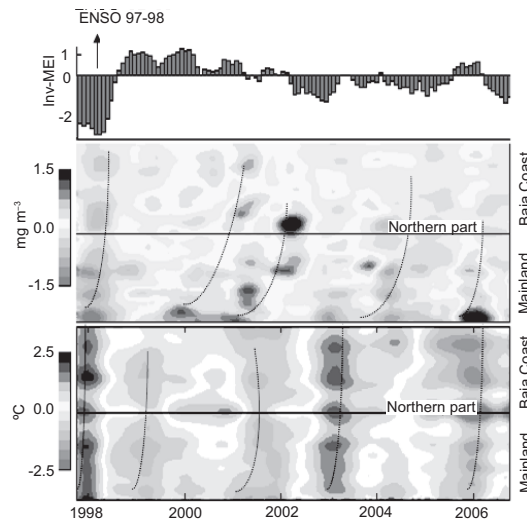


Fig. 4. Temporal evolution of the MEI index. El Niño (La Niña) episodes are indicated by orange (blue) bars respectively as reported by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (CPC-NCEP-NOAA). Hovmöller diagrams of monthly averaged coastal Chl-a anomalies (central panel) and monthly averaged coastal SST anomalies (low panel), from September 1997 to December 2006, covering both coasts of the Gulf of California. Solid lines indicate the northernmost portion of the gulf coast and dotted lines indicate the signals propagation associated to ENSO events.

California coast, from the mainland at the mouth of the gulf (in the bottom of the diagrams) to the southern tip of the peninsula (at the top). Warm (cold) ENSO events are associated with negative (positive) chlorophyll anomalies ( $\pm 1.2 \text{ mg m}^{-3}$ ) along both coasts of the gulf ( $\sim 2000 \text{ km}$ ). Higher concentrations occurred during the peak of the 1999–2000 La Niña conditions along both coasts, but were stronger along the mainland (Fig. 3; central panel). We draw the dotted curves to suggest signal propagation associated to ENSO events. Anomaly signals at the mouth and along the mainland coast are strong and seemingly bypassing the midriff islands region, with a considerable attenuation on their way northward, resulting in a weak signal propagating southward along the west coast of

the peninsula. The lower panel shows the temporal evolution of the SST coastal anomalies inside the Gulf of California. The positive (negative) SST anomalies appeared associated to warm (cold) ENSO events and contrary to Chl-a, SST coastal anomaly signals did not present a clear delay or attenuation along both coasts of the gulf (dotted curves).

Both Hovmöller diagrams reveal the anticipated inverse relationship of increasing SST coupled to decreasing Chl-a, emphasizing the eminent role of climate variability over the Gulf of California upper-ocean chlorophyll concentration and SST; surface warming associated to an increase in MEI results in a decrease in Chl-a and vice versa.

#### 4. Discussion

Our results show that interannual variability of the chlorophyll pigment concentration in the Gulf of California is dominated by the ENSO influence, at least during the 1997 to 2006 period. In a previous paper (Herrera-Cervantes *et al.*, 2007), based on 21 years of monthly composites of SST satellite images, we suggested that the Gulf of California plays a significant role in the poleward propagation of ENSO-related coastal waves. We argued that the physical processes that cause this pattern are associated to the disruption of the wind-driven upwelling corridor along the east coast of the gulf, together with the propagation of ENSO-related coastal waves being smoothed by bottom friction.

EOF analysis of monthly SeaWiFS Chl-a anomalies dataset yields a single dominant mode (EOF<sub>1</sub>), showing a spatial pattern very similar to that of the SST reported in Herrera-Cervantes *et al.* (2007). This pattern can be grossly described as highest variability along the east coast (the upwelling corridor) and the midriff islands region (where tidal mixing occurs), and lower values along the peninsular side. A similar pattern was also observed for the slope values and the relation with MEI (regression coefficients), strongly suggesting that interannual variability of temperature and pigment concentration are controlled by the same ENSO-related forcing.

We argue here that this spatial pattern explains the apparent contradictions regarding the ecological effects of El Niño in the Gulf of California (see Table I). For example, the pattern is consistent with the report on brown pelican colonies successfully breeding in the northern Gulf of California, but not in the southern gulf region during the 1992-93 El Niño (Jaques *et al.*, 1996). Similarly, Valdez-Holguín and Lara-Lara (1991) report that during 1982-1983 ENSO there was no decrease in the primary production rate in the southern gulf, but rather an increase caused by diminished predation pressure, while Kahru *et al.* (2004) reported that during the 1997-1998 El Niño period, primary productivity decreased in the southern part of the gulf, but the changes in the central and northern parts were less evident. We suggest that a reanalysis of the physical and biological evidence, with considerations for the ENSO spatial signature shown here, and accessing the original observations from each field survey is needed for a more consistent and reliable description of the ENSO effects on the Gulf of California marine ecosystem.

During El Niño conditions, coastal trapped waves transmit ENSO signals along both coasts over a period of weeks (Beier, 1997; Herrera-Cervantes *et al.*, 2007), deepening the thermocline (nutricline) and reducing the effects of wind-driven coastal upwelling (Lluch-Cota *et al.*, 2007). The Chl-a anomaly evolutive diagram (Fig. 4; central panel) showed that not all the signals associated to El Niño-La Niña events are transmitted to the peninsular coast, as shown for the weak 2002-2004 El Niño. Comparison of Chl-a and SST signals (dotted curves) observed along both coasts of the Gulf of California

reveals the anticipated inverse relationship of increasing temperatures coupled to decreasing pigment concentration. Time-longitude contours of these variables suggest that Chl-a anomaly coastal signals associated with ENSO events showed propagation, delay (lag) and attenuation, while SST warm/cold anomalies travel across the basin without any significant delay or attenuation.

From our analysis we also found an interesting significant positive correlation between the EOF<sub>1</sub> time series and InvMEI ( $r = 0.69$ ,  $P < 0.01$ ; Fig. 3). Behrenfeld *et al.* (2006) related the global ocean trends of satellite ocean color measurement with MEI during this sustained warming period, and concluded that the Chl-a and net primary productivity of the intertropical global ocean responds directly to MEI variations; in other words, productivity decreases with global warming, except for some upwelling dominated systems where the opposite occurs, apparently related to increased winds driven by land-ocean temperature gradients (Bakun, 1990; Demarcq, 2008; Lluch-Cota *et al.*, 2008). In the Gulf of California we found a decreasing trend, indicating a behavior similar to that of most of the intertropical band, even when wind driven coastal upwelling appears to follow the other upwelling systems trends (Lluch-Cota, 2000).

## 5. Conclusions

The temporal and spatial resolution of the SeaWiFS-chl-a and AVHRR Ocean Pathfinder-SST satellite data over the Gulf of California allowed us to obtain a basin-wide view of the biophysical coupling during ENSO events. The nearly identical spatial signature of Chl-a and SST interannual variability in the Gulf of California suggests that the processes which create these pattern are the same on the interannual timescale.

We propose that the spatial patterns of the variability (different geographical impacts of ENSO within the Gulf of California) explain the apparent contradictory field observations in the ecological impacts. We suggest that a reanalysis of the physical and biological evidence, with considerations for ENSO spatial signature shown here, would allow for better understanding of the ENSO effects on the Gulf of California marine ecosystem.

Finally, we identify a positive relation between the productivity trends within the Gulf and InvMEI during a period considered as sustained warming (1999 to 2006), similar to what has been observed for most of the intertropical world ocean, and different to recent observations in upwelling areas. Because of ongoing research on the topic, we expect better understanding of this observation in the near future.

## Acknowledgments

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