20TH CENTURY VARIABILITY IN GULF OF CALIFORNIA SST

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ABSTRACT

We estimated annually-averaged sea surface temperature (SST) anomalies for four 2° × 2° quadrants in the Gulf of California, Mexico using ICOADS (International Comprehensive Ocean-Atmosphere Data Set) and ERSST (NOAA Extended Reconstructed SST) data. We compared the anomalies to large-scale environmental indices (Pacific Decadal Oscillation index, PDO; and Nino 3 index, N3). Hamming filters were used to isolate high (<10 years), decadal (10–20 years) and low (>20 years) frequencies for comparison. The relationships between the decadal-scale variations and the relative abundance of stocks being harvested by two important fisheries (penaeid shrimps and California sardine, *Sardinops sagax*) were explored. We found that sardine relative abundance coincides well with estimated SST, increasing during the cooling intervals and declining through the warming periods, as expected given the Gulf of California is the southernmost limit of its distribution. Shrimp abundance appears to increase during warming intervals with a three-year lag which remains unexplained.

INTRODUCTION

The Gulf of California has received much attention in recent years given its unique oceanographic, ecological and fisheries characteristics. While several studies on this ecosystem have been published (Lluch-Cota et al. 2007 and references therein), the low-frequency of environmental variability at time-scales longer than a year has seldom been dealt with due to the unavailability of long-term synoptic environmental data series. Widespread concern over global climate change and its impacts on marine populations and ecosystems suggests the need for reconstruction of long-term time series of environmental data.

Although the California Current system, including the west coast of the Baja California peninsula, is one of the best known marine ecosystems—mostly due to the extensive and intensive research efforts by CalCOFI over the last century—the Gulf of California has often been regarded as a separate and mostly different ecosystem (Lluch-Belda et al. 2003a). This makes it difficult to extrapolate the already reasonably well known climate variation of the west coast to the Gulf. Furthermore, the paucity of in situ data series has prevented the completion of equivalent analyses.

Recently, more complete data series have been made available, at least of sea surface temperature (SST) variations, and notably the ICOADS (International Comprehensive Ocean-Atmosphere Data Set Release 2.0) and ERSST (NOAA Extended Reconstructed SST) data. These series provide monthly averaged SST at a 2° × 2° resolution for several quadrants in the Gulf. While the ICOADS data are actual averages of in situ data, the ERSST data are the results of interpolation. The question remains whether the result of that interpolation could be biased given the close vicinity of the open-ocean SST values along the west coast. It would therefore seem to be more convenient to approach the problem using ICOADS data, but numerous gaps in the series suggest that the interpolated ERSST data should be reconstructed in order to fill such gaps, if possible.

On the other hand, it has been suggested that the Gulf ecosystem functions as the southernmost extension of the California Current system (Lluch-Belda et al. 2003b), and that much more interchange occurs between it and the west coast of the peninsula. This was particularly suggested regarding sardine (*Sardinops sagax*) populations, which appear to move regularly between the inside of the Gulf and the peninsula west coast (Félix-Uraga et al. 2005). Furthermore, large-scale interchange during certain periods, such as that of the mid-1970s (Rodríguez-Sánchez et al. 2002), emphasizes the continuity between the west coast ecosystem and that in the Gulf. This interchange would require a certain degree of coherent variation, at least.

If such is the case, during cold periods sardines would have been distributed toward their southern limits, where low temperatures, allow abundance to increase (Lluch-Belda et al. 2003b).

On the other hand, there have been attempts to relate the abundance of other fishery resources to environmental variation in the Gulf, such as for penaeid shrimp (*Penaeus* spp.) abundance (Castro-Aguirre 1976[1];

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[1] Castro-Aguirre, J. L. 1976. Efecto de la temperatura y la precipitación pluvial sobre la producción camaronera. Paper presented at the Simposio sobre biología y dinámica de poblaciones de camarones, Instituto Nacional de Pesca, Guaymas, Sonora. Centro Interdisciplinario de Ciencias Marinas, IPN. Av IPV s/n. Col Playa Palo de Sta Rita. La Paz, BCS, 23096, Mexico. jlcastro@ipn.mx.

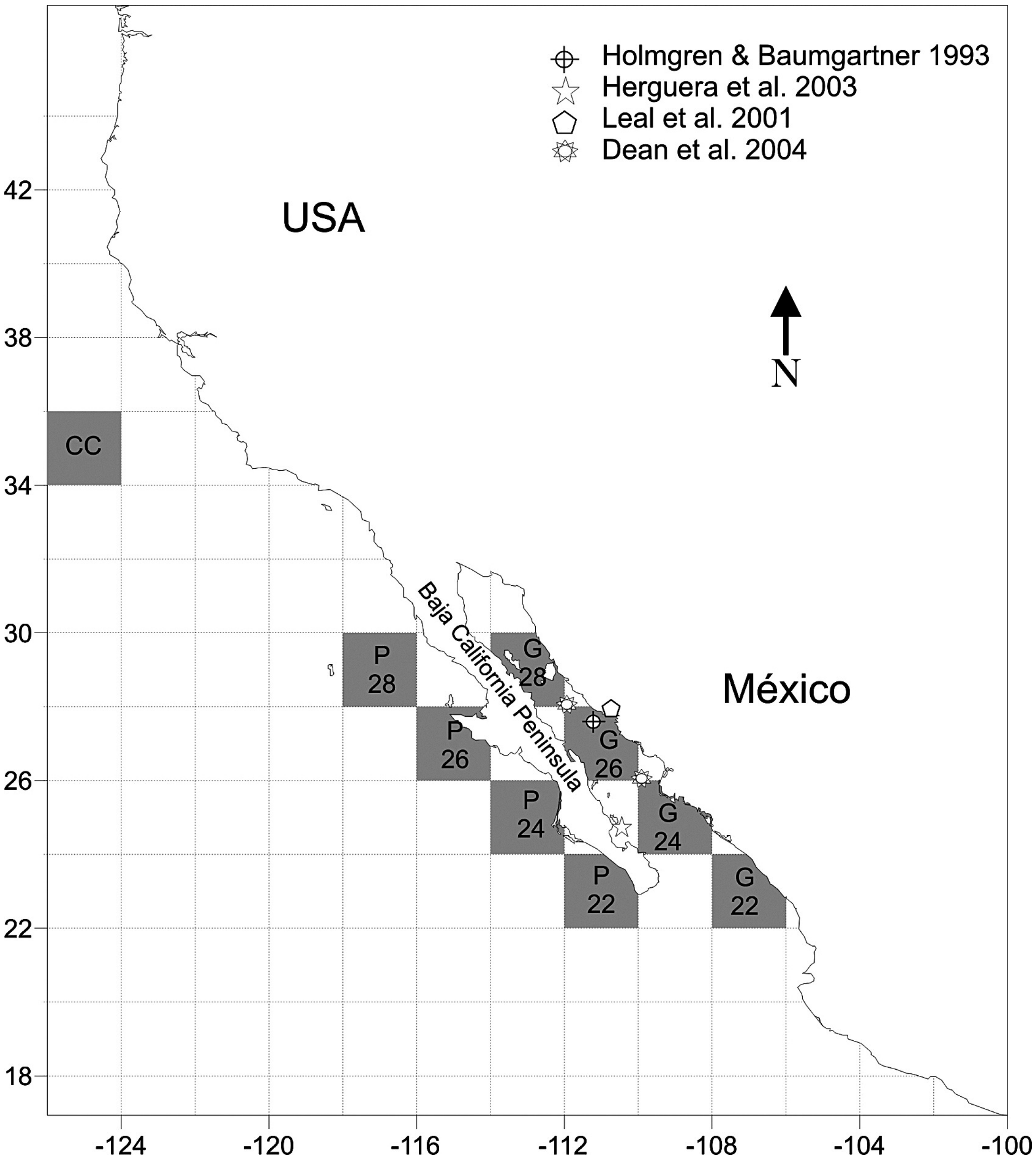

Figure 1. Areas (quadrants) for SST monthly averages, 2°x2° for the California Current (CC); coastal Pacific quadrants (PXX); Gulf of California quadrants (GXX). XX stands for the latitude of the south limit of each quadrant. Symbols refer to approximate location of sea surface temperature (SST) data, from previously published reports, as shown in the upper right box in the map and in text.

Castro-Ortiz and Lluch Belda 2007). The abundance of other fishery species, such as the giant squid (*Dosidicus gigas*), has been suspected to vary mostly due to environmental forcing (Nevárez-Martínez et al. 2000). In all cases, long-term environmental variation estimates have not been available.

In this study, we propose a reconstruction of the large-scale environmental variation in the Gulf of California, using SST anomalies at four 2° × 2° quadrants, covering most of the Gulf's surface, and compare the result to previously published series and fishery species abundance.

DATA AND METHODOLOGY

Data

For the purpose of reconstruction, data for monthly-averaged SST at four 2° × 2° quadrants, covering most of the Gulf of California (fig. 1), were downloaded from ICOADS (International Comprehensive Ocean-Atmosphere Data Set Release 2.0, available at http://icoads.noaa.gov/; downloaded on 09/07/2006; fig. 2) and for the same quadrants from the ERSST data set (NOAA Extended Reconstructed SST data, by NOAA

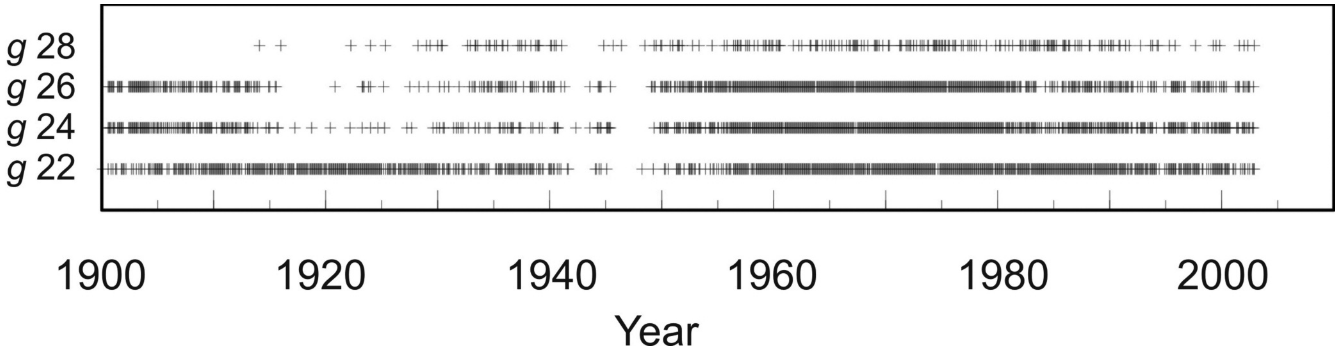

Figure 2. Temporal coverage of available ICOADS monthly sea surface temperature SST averages in the Gulf of California quadrants in Figure 1. Each cross represents one datum.

Satellite and Information Service, http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php). The 2° × 2° quadrant data were used because the coverage extends backwards well beyond the beginning of last century, while other resolutions such as 1° × 1° only go back to the mid 1900s. Figure 2 shows the temporal coverage of the ICOADS data for the quadrants chosen.

We also used annually-averaged SST anomalies for equally-sized quadrants along the western coast of the Baja California peninsula, each at the same latitude as the one inside the Gulf, plus another regarded as representative of the California Current, all previously estimated (Lluch-Belda et al. 2001, 2003a, 2005; fig. 1).

To compare them to other published series, SST data from figures in several articles were digitized: Herguera et al. 2003 presented the reconstruction of SSTs from an isotopic record preserved in the calcitic shells of the planktonic foraminifer *Globigerina bulloides* from a box core retrieved from 400 m-deep waters in the La Paz Bay Basin; Leal-Gaxiola et al. 2001 used monthly sea surface temperatures from the Guaymas tide gauge from 1979 to 1994; Lavin et al. 2003 based estimates of SST anomalies for four major areas of the Gulf (north, islands, central and south) on satellite data—eight-day averages with an approximate resolution of 18 km × 18 km, from January 1984 to December 2000; finally, Dean et al. 2004 used geochemical data (% Ti) of sediments from two box cores sampled at 0.5 cm intervals to reconstruct the PDO index. The approximate locations of each sample are shown in Figure 1, except for the Lavin et al. 2003 data, which were based on satellite data for the entire Gulf.

Large-scale environmental indices included the PDO and N3 (Pacific Decadal Oscillation Index and Nino3 index, available at http://www.cdc.noaa.gov/ClimateIndices/List/#CAR).

Sardine scale abundances in the anaerobic laminated sediments of the Gulf of California in 10 year intervals are from Holmgren-Urba and Baumgartner 1993 (location also shown in fig. 1); sardine landings data were provided by R. Félix Uraga[2]. Shrimp landings from off the Pacific coast of Mexico were taken from the work of Lluch-Belda 1977 and Magallón-Barajas 1987. Data were also obtained by digitizing figures from the management plan for the fishery (available at www.sagarpa.gob.mx/conapesca/ordenamiento/PLAN_DE_MANEJO_CAMARON_OP_agosto_.pdf) and the national fisheries chart (www.sagarpa.gob.mx/conapesca/ordenamiento/carta_nacional_pesquera/cnp.htm). It should be stressed that shrimp landings in the Gulf of California are the major component (about 80%) of the total Pacific coast landings; although it would be desirable to have the data from the Gulf, they are not available for the full time used in this study.

Methodology

To reconstruct the Gulf ICOADS environmental data series we first estimated climatologies for the ERSST (identified by *e* and the southern latitude of the quadrant, from now on) and ICOADS (*c* from now on, similarly) series for the Gulf quadrants and monthly anomalies were estimated as departures from the climatology. This procedure permits eliminating variation from the annual cycle, which is the strongest signal. Simple linear correlation was then estimated for the anomaly series (tab. 1).

Next, the relationship between the ERSST and ICOADS series was estimated with simple linear regression (*e* as independent, *c* as dependent variables, tab. 2). Then the gaps in the *c* series were filled by reconstruction using these relationships. Later, annual anomalies were estimated as the mean of the monthly anomalies for each of the resulting series, labeled *g* from now on.

These *g* series were correlated to large-scale environmental variables (PDO for the north Pacific variation and N3 for the tropical condition) by means of multi-

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TABLE 1
Correlations between the ERSST and ICOADS monthly anomaly series for quadrants in the Gulf of California. Above and right, number of pairs; left and down, correlation coefficients. Bold numbers indicate statistical significance at $p > 0.05$

	*e*22	*e*24	*e*26	*E*28	*c*22	*c*24	*c*26	*c*28
*e*22		1236	1236	1236	894	680	666	220
*e*24	**0.93**		1236	1236	894	680	666	220
*e*26	**0.88**	**0.98**		1236	894	680	666	220
*e*28	**0.56**	**0.69**	**0.80**		894	680	666	220
*c*22	**0.48**	**0.30**	**0.25**	**0.12**		568	536	184
*c*24	**0.56**	**0.64**	**0.61**	**0.36**	**0.27**		556	163
*c*26	**0.40**	**0.47**	**0.47**	**0.36**	**0.14**	**0.53**		164
*c*28	**0.17**	**0.29**	**0.33**	**0.30**	−0.07	**0.25**	**0.26**	

TABLE 2
Linear relation equations between the ERSST and the ICOADS series. Numbers following letter indicate North latitude of the southern limit of the quadrant. *c*XX, ICOADS data; *e*XX, ERSST data

$c22 = 1.3352 + 0.94820\,e22$; $r = 0.91$
$c24 = 1.7622 + 0.93463\,e24$; $r = 0.94$
$c26 = 2.1345 + 0.92818\,e26$; $r = 0.91$
$c28 = 6.9996 + 0.61269\,e28$; $r = 0.70$

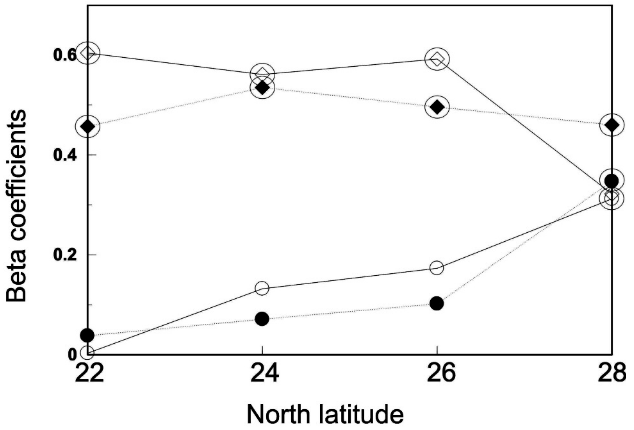

Figure 3. Multiple correlation regression coefficients of sea surface temperature anomalies on the Pacific Decadal Oscillation Index (PDO○) and NINO3 index (N3◇) for the Gulf of California (*g*, filled symbols) and coastal Pacific (*p*, hollow symbols).

TABLE 3
Correlation coefficients between the *g* series and the Herguera et al. 2003 series. Bold numbers indicate statistical significance at $p > 0.05$

	Herg An	*g*22	*g*24	*g*26	*g*28
Herg An		0.23	**0.58**	**0.57**	**0.46**
*g*22	0.23		**0.62**	**0.43**	**0.41**
*g*24	**0.58**	**0.62**		**0.77**	**0.54**
*g*26	**0.57**	**0.43**	**0.77**		**0.60**
*g*28	**0.46**	**0.41**	**0.54**	**0.60**	

TABLE 4
Linear correlations between the monthly averages of the Lavin et al. 2003 series and the Gulf of California ones. Bold numbers indicate statistical significance at $p > 0.05$

	Lavin	*g*22	*g*24	*g*26	*g*28
Lavin		**0.27**	**0.49**	**0.42**	**0.36**
*g*22	**0.27**		**0.38**	**0.16**	0.09
*g*24	**0.49**	**0.38**		**0.37**	**0.27**
*g*26	**0.42**	**0.16**	**0.37**		**0.34**
*g*28	**0.36**	0.09	**0.27**	**0.34**	

ple regression of *g* on PDO and N3. Later, the *g* series were correlated to those from Herguera et al. 2003, Lavin et al. 2003 and Leal-Gaxiola et al. 2001.

The first principal component (PC1) of the Pacific (PPC1) and the Gulf (GPC1) series were extracted. Then Hamming filters were used to isolate high (<10 years), decadal (10–20 years) and low (>20 years) frequencies to compare with formerly identified trends (Lluch-Belda et al. 2003a). The Dean et al. 2004 series was then cross-correlated to the GPC1 and the filtered frequencies.

Shrimp landings data are for all of the Pacific coast and from different sources. We used the head-off landings reported in Lluch-Belda 1977; Magallón-Barajas 1987, while from Plan de Manejo and Carta Nacional Pesquera data we used live weight; since the series overlap, the first two were scaled to heads on by multiplying by a factor obtained from their averaged difference along the overlapping years. Then, they were averaged for the common years.

RESULTS

The ICOADS series contains a reasonable amount of directly observed data, although there are numerous gaps particularly northward. Certain periods are mostly devoid of information, such as the 1940s (fig. 2). The significant correlations between the ICOADS and the ERSST anomalies (tab. 1) allow the ICOADS series to be reconstructed using the linear relationship between the two (tab. 2). The relationships show that there is some degree of smoothing in the ERSST series, as seen by slope values that are compensated by positive intercepts; the amount of smoothing increases from south to north.

The correlations between latitudinal quadrant anomalies and large-scale environmental indices (PDO and N3) for the coastal Pacific and Gulf series show similar trends (fig. 3). This may mean that the global environment is mostly forced by the atmosphere, rather than by the ocean through the Gulf mouth.

The reconstructed *g* series correlates well with those of Herguera et al. 2003 (tab. 3), which is a long series in a specific location (the La Paz Bay), and Lavin et al. 2003 (tab. 4), which is a short series of the full Gulf, but not with the Leal-Gaxiola et al. 2001 series (tab. 5), which is a short series in a very specific spot (the Guaymas Bay).

Filtered series from the Gulf and the Pacific PC1

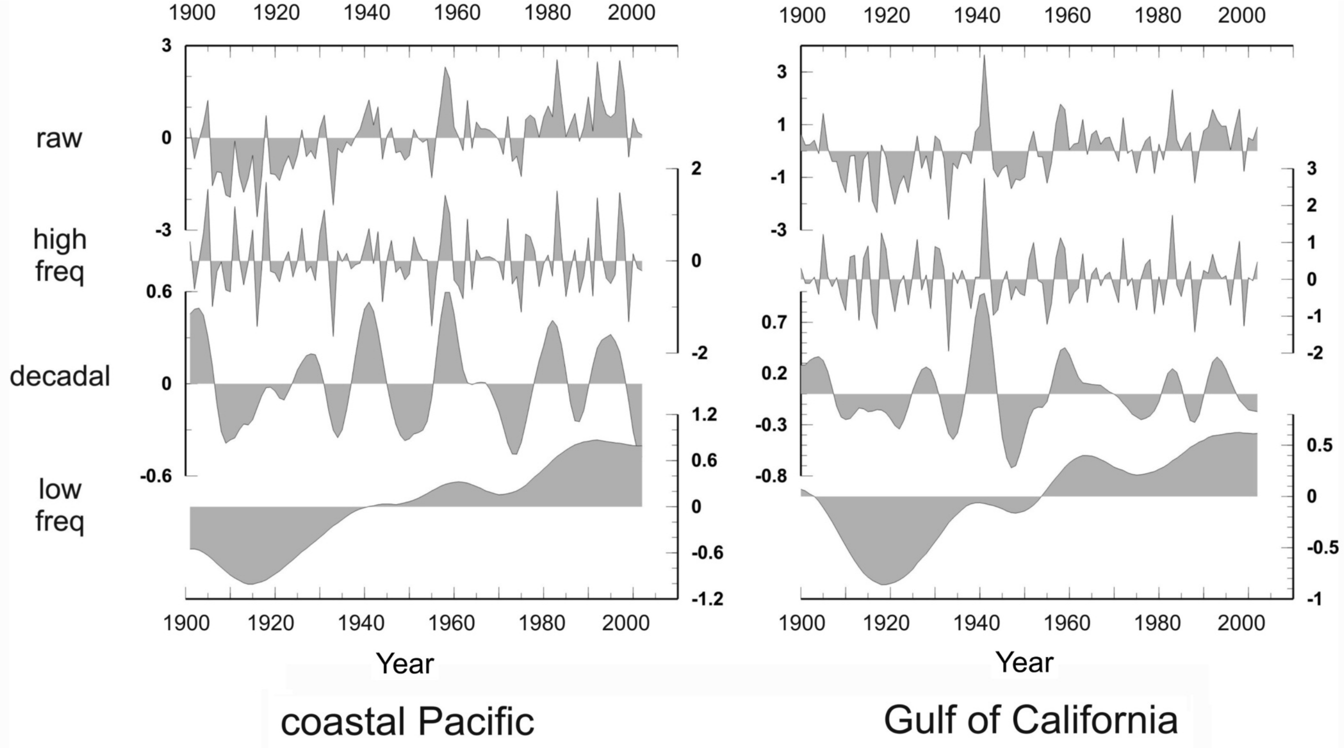

Figure 4. Raw and Hamming filtered series for the coastal Pacific (left) and Gulf of California (right) first principal component (PC1) of the sea surface temperature anomalies series.

TABLE 5
Linear correlations between the monthly anomalies at the Guaymas tide gauge (Leal et al. 2001) and the *g* series, 1979 to 1994. Bold numbers correspond to statistical significance at $p > 0.05$

	Leal	*g*22	*g*24	*g*26	*g*28
Leal		–0.12	–0.13	0.02	–0.10
*g*22	–0.12		**0.41**	**0.18**	0.03
*g*24	–0.13	**0.41**		**0.49**	**0.23**
*g*26	0.02	**0.18**	**0.49**		**0.26**
*g*28	–0.10	0.03	**0.23**	**0.26**	

(fig. 4) display mostly similar trends, although some differences are also evident; perhaps the most striking being the positive peaks of the early 1940s (stronger for the Gulf series), and the early 1960s (stronger in the Pacific series).

The Dean et al. 2004 series cross-correlates with the raw GPC1 (0.4589 with a delay of 2 years, GPC1 leading) and with the long-term trend (Hamming filtered by 30 years), also with a delay of 2 years, GPC1 leading (0.6189), both significant.

Sardine relative abundances (estimated from scales in anoxic laminated sediments and landings) are shown in Figure 5 with the Gulf decadal-filtered PC1 series, and periods of cooling and warming. The cooling period of 1940–53 corresponds well with sardine abundance increase, while the following decline corresponds with the warming period through 1960. There is also a smaller increase in abundance afterwards, coincident with the cooling period after 1960.

The landings peak during 1990 corresponds with a cooling period extending from 1987 to 1990, although it could also be confused with the increase in effort by the fishery. While the decline in abundance during the early 1990s has been blamed on overfishing, it occurred during a warming lapse, which may indicate another reason for the decline. Finally, the following dip was likely related to the impact of the 1997–98 El Niño preventing the expansion of sardine schools southward to the usual fishing areas, as proposed for previous events (Lluch-Belda et al. 1986). This was a temporary effect occurring during a cooling lapse that permitted the fishery to rebound immediately afterwards.

The shrimp landings series are shown in Figure 6, together with the 10-years smoothed GPC1. Landings are cross-correlated to the raw GPC1 with a lag of three years (0.4075, $p < 0.05$, GPC1 leading), but not to the high or decadal frequencies.

DISCUSSION

The reconstruction of the large-scale SST anomalies at the four gulf quadrants appears robust because it agrees with other records, particularly those showing major climate signals; it also avoids the smoothing effect of the

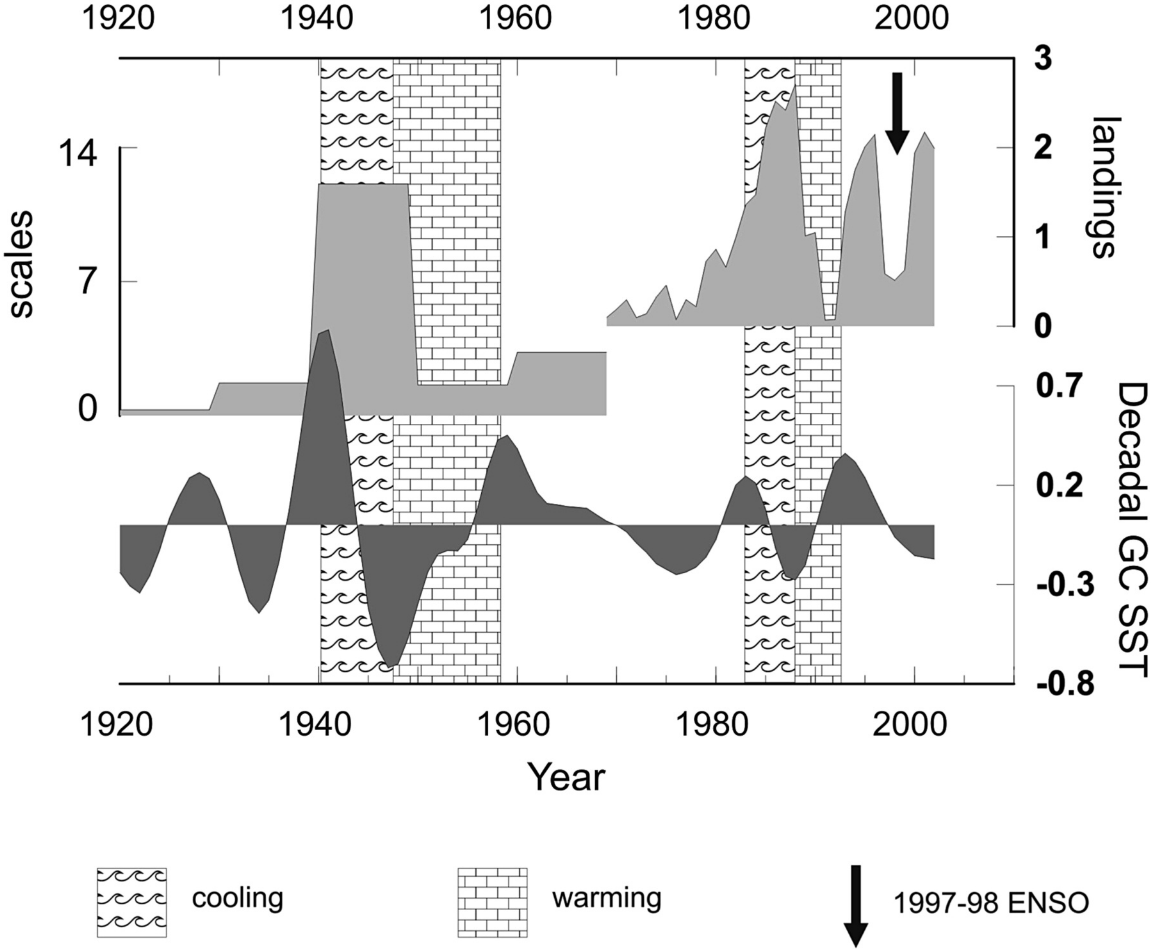

Figure 5. Comparison between the decadal filtered of the first principal component of the sea surface temperature anomalies at the Gulf of California and sardine relative abundance indices: scales in anoxic varved sediments and landings.

ERSST interpolation process. Published large-scale series vary similarly to the reconstructed data, as do proxies derived from sediment deposition data. No correlation was found with the data from Leal-Gaxiola et al. 2001, which corresponds to SST data at a very specific spot and thus largely depends on local conditions. The similarity of the relationships between the coastal Pacific and Gulf latitudinal quadrants and the large-scale environmental indices (PDO and N3) suggests that a great part of the latitudinal variability is being forced by the atmosphere, which may be because oceanic isolation between the two areas increases from south to north.

Interannual, decadal, and longer frequency trends are similar at both coasts, although some differences exist. The most relevant appears to be the relative importance of the early 1940s peak event, which is much more pronounced in the Gulf. That year has also been described as a regime shift in the North Pacific Ocean (Lluch-Belda et al. 2003a).

We found that the relative abundance of sardines covaries with the cooling and warming states of the environment which agrees with previous findings (Lluch-Belda et al. 2003b). Since the sardine population in the Gulf is at the southernmost limit of its distribution, its relative abundance is expected to be higher during cooling periods and vice versa, as was observed (fig. 5). The period of high abundance—denoted by the number of scales in anoxic varved sediments—also coincides with the cooling period right after the early 1940s, while the decline in abundance coincides with the warming lapse between the late 1940s and the early 1960s. However, sardine scales were reported in 10-year blocks (Holmgren-Urba and Baumgartner 1993) and a more reliable indicator of correlation is the coincidence of population growth from 1981 to 1988 and from 1992 to 1996, while it declined during 1989 to 1992. Further declines coincided with the strong 1997–98 ENSO, similar to what occurred during previous events (Lluch-Belda et al. 1986).

Since at least the mid 1950s, several authors have suggested a relationship between tropical shrimp abundance and rainfall (Chapa 1966; Chapa and Soto López 1969; Castro-Aguirre 1976[1]; Sepúlveda-Medina 1991; etc.).

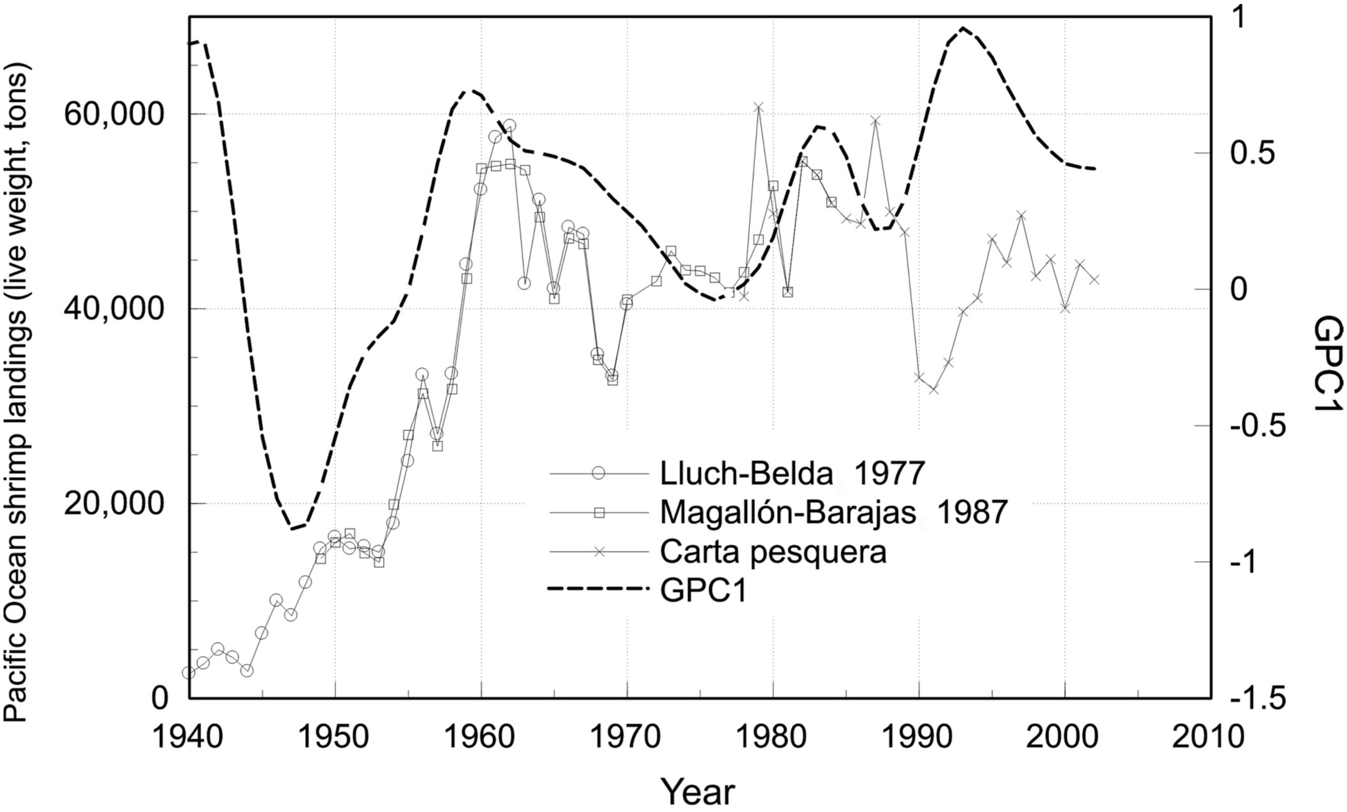

Figure 6. Comparison between the decadal filtered first principal component of the sea surface temperature anomalies (GPC1) at the Gulf of California, shrimp relative abundance indices and number of boats in the fishery. Inset denotes the reference for each shrimp abundance series. The Lluch-Belda 1977 and Magallón-Barajas 1987 series were transformed to live weight.

Both Castro-Aguirre and Sepúlveda-Medina noted a lag of two-three years between rain and shrimp abundance.

The data presented here (fig. 6) indicate a correlation between landings and the 10-year smoothed SST, although there is a clear lag. Increasing trends were similar during ~1950 to ~1960, ~1975 to ~1985 and ~1991 to ~1997; and were significantly correlated with a lag of three years, with SST leading. A major discrepancy in the relationship is the increasing landings trend between ~1970 to ~1975, when SSTs were decreasing; however, the fleet grew explosively from 762 to 1192 (56%) during those years.

Most of the reported correlation, however, is in the ~1950 to ~1960 trends; there is no significant correlation if only years after 1955 are considered. Catch per unit of effort (CPUE), estimated from yearly landings per boat, are poor estimators. There is no available information to estimate catch per standard fishing days, as done in the past (Lluch-Belda 1977).

There is also a coincidence in the lag between SST and shrimp abundance and between SST and Ti% in the Dean et al. 2004 series; Ti concentration is an indicator of increased rainfall. Why rainfall should be higher three years before the maximum SST is not yet understood.

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