SMALL PELAGIC FISH CATCHES IN THE GULF OF CALIFORNIA ASSOCIATED WITH SEA SURFACE TEMPERATURE AND CHLOROPHYLL

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ABSTRACT

The Gulf of California supports an important fishery of small pelagic fishes. However, these species have undergone variations in both their geographic distribution and abundance over time. A GIS-based approach was used to investigate the association between weekly remote-sensed sea surface chlorophyll-a concentrations (Chl), sea surface temperature (SST) images, derived SST and Chl gradient maps, and daily fisheries catch data for Pacific sardine (*Sardinops sagax caeruleus*), thread herring (*Opisthonema libertate*), northern anchovy (*Engraulis mordax*), and Pacific mackerel (*Scomber japonicus*) from 2002–07. SST did not have a significant affect on most species, except for northern anchovy ($r^2 = 0.71$), while Chl was significant for Pacific sardine ($r^2 = 0.94$), thread herring ($r^2 = 0.90$), and Pacific mackerel ($r^2 = 0.96$). However, the SST gradient was more strongly associated with the abundance of the species studied. The Chl gradients showed similar values in relation to SST gradients with the exception of northern anchovy ($r^2 = 0.43$).

INTRODUCTION

The Gulf of California (GC) supports an important fishing industry of small pelagic fishes (Cisneros-Mata et al. 1995). This fishery is multispecific and includes eight species, although the Pacific sardine (*Sardinops sagax*) is the most dominant (about 80% of the total landings; Nevárez-Martínez et al. 2001). Small pelagic fishes have undergone considerable variations in both their distribution and abundance over time (Lluch-Belda et al. 1986; Lluch-Belda et al. 1989; Nevárez-Martínez et al. 2001) (fig. 1) influenced by variations in the ocean climate (Lluch-Belda et al. 1989; Bakun and Broad 2003; deYoung et al. 2004).

Due to the spatio-temporal nature of fisheries data, the use of spatial tools such as GIS is an essential factor in sustainable fisheries management. GIS combined with other tools such as remote sensing images can make fisheries management more efficient, since they can provide comprehensive tools, image comparison and processing functions for environmental monitoring and mapping.

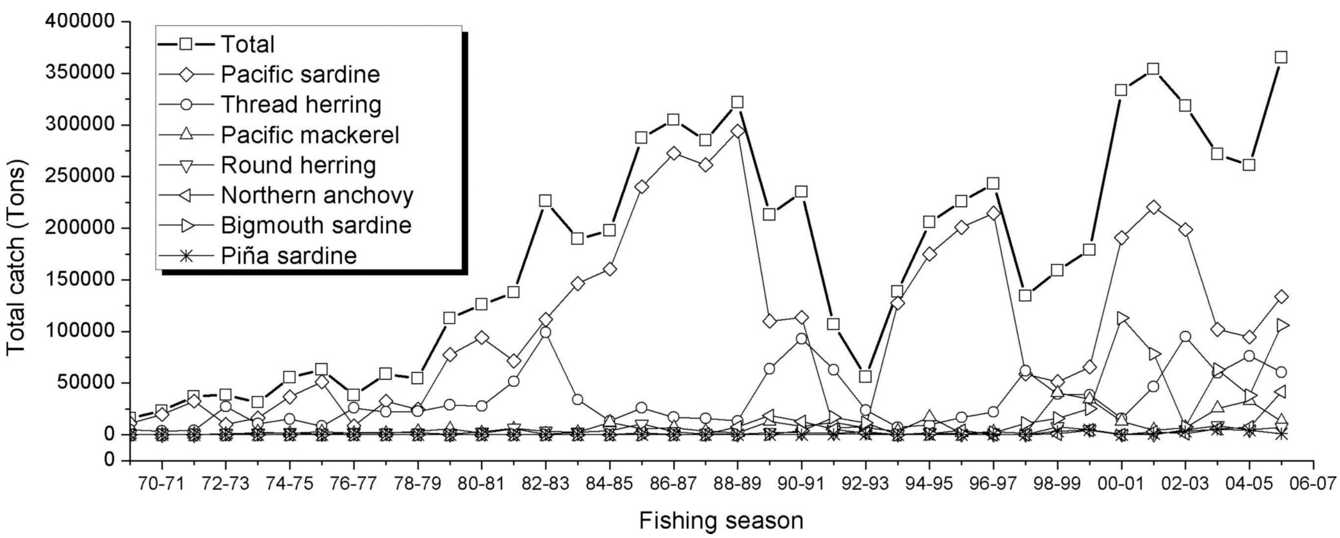

Figure 1. Total catch of Small pelagic fisheries for Pacific sardine (*Sardinops sagax*), thread herring (*Opisthonema libertate*), Pacific mackerel (*Scomber japonicus*), round herring (*Etremeus teres*), northern anchovy (*Engraulis mordax*), bigmouth sardine (*Cetengraulis mysticetus*), and piña sardine (*Oligoplites refulgens*) in the Gulf of California,1969–2006 (from Nevárez-Martínez et al. 2001).

This has been shown in other fields where spatially-related problems occur (Curtis 1999). Remote-sensed SST images and GIS tools have been widely applied to spatially relating fisheries and environmental features in the ocean (e.g., Fernández and Pingree 1996; Santos 2000). These applications have focused mainly on the Pacific sardine, northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*; Perrotta et al. 2001; Bava et al. 2002) with the use of mapping tools such as GIS (Yáñez et al. 2004). These studies showed that SST significantly affects jack mackerel distribution (Perrotta et al. 2001). Also, some SST-derived products, such as SST gradients (which detect fronts as indirect indicators of fishing-ground regions), have been used to relate oceanographic conditions and species distribution (Yáñez et al. 2004), such as for Atlantic herring (*Clupea harengus*) in the northern North Sea (Maravelias and Reid 1995), Peruvian anchovy (*Engraulis ringens*) and Pacific sardine off the coast of Chile (Castillo et al. 1996), and European pilchard (*Sardina pilchardus*) and European anchovy (*Engraulis encrasicolus*) in the northern Aegean Sea (Giannoulaki et al. 2005). These studies generally illustrated low correlation between species distribution and SST, so these species may be more directly related to plankton concentration. Other studies have looked at the associations between high plankton concentrations and fish distribution such as for Atlantic herring in the northern North Sea (Maravelias and Reid 1995) and northern anchovy in the eastern Pacific Ocean (Robinson 2004).

There are many studies relating abundance, composition, and variability of small pelagic fishes in the GC to environmental conditions (Lluch-Belda et al. 1986; Hammann et al. 1988; Lluch-Belda et al. 1991; Cisneros-Mata et al. 1996; Lluch-Cota et al. 1999; Nevárez-Martínez et al. 2001). A growing body of evidence suggests that environmental factors play a dominant role in the seasonality of small pelagic fishes; Lluch-Belda et al. 1986 observed that during an El Niño-Southern Oscillation (ENSO) event, catches of thread herring and Pacific sardine vary inversely in the Gulf of California. Recent studies on the distribution and abundance of pelagic fishes also use spatial information (Nevárez-Martínez et al. 2001; Lanz et al. 2008). For example, Nevárez-Martínez et al. 2001 analyzed the distribution and the abundance of the Pacific sardine off the Gulf of California in relation to wind patterns (upwelling) and sea surface temperature. The results showed that the highest abundance of Pacific sardine was related to moderate upwelling (13–18 m^3/s per 10 m of coastline) and sea surface temperatures of 19° to 25°C.

Species and Study Area

A variety of species of small pelagic fishes are present in the Gulf of California waters. They include Pacific sardine (*Sardinops sagax caeruleus*), northern anchovy, thread herring (*Opisthonema libertate*), Pacific mackerel, bigmouth sardine (*Cetengraulis mysticetus*) round herring (*Etremeus teres*) and Piña sardine (*Oligoplites refulgens*) (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 2001). Although all of these species are caught by commercial fisheries, Pacific sardine and northern anchovy have traditionally been the most economically important (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 2001), and therefore the main focus of scientific studies.

The study area consists of the entire Gulf of California (fig. 2). The GC's high productivity is well documented (Alvarez-Borrego 1983; Santamaría-del-Angel et al. 1994) and caused by a combination of bottom topography and a high degree of wind-induced mixing and upwelling from strong predominantly north-westerly winds particularly in the midriff islands region (Alvarez-Borrego 1983; Pegau et al. 2002). The area is becoming an important spawning area for anchovy and sardine (Lluch-Belda et al. 1991; Cisneros-Mata et al. 1996). Ocean circulation in the GC is determined mainly by the tide and winds. Residual currents in the GC are responsible for the net transport of substances (Lavin et al. 1997). Satellite measurements of sea surface temperature and ocean color have been used to study the circulation in the Gulf of California (Badan-Dangon et al. 1985; Paden et al. 1991; Lavin et al. 1997) and to provide an understanding of the biological production in the GC (Gaxiola-Castro et al. 1999). Recent studies in the GC describe the existence of small areas where biological activity is particularly high, and which have been used to regionalize the GC based on several levels of primary productivity (Santamaría-del-Ángel et al. 1994; Lluch-Cota and Arias-Aréchiga 2000). These regions, named "Biological Action Centers" (BACs), appear to be fixed in space, tied to coastal features, and tend to show little seasonal variation in productivity level. Small pelagic fish prefer these areas and commercial species aggregate in them (Lluch-Cota and Arias-Aréchiga 2000; Lluch-Belda et al. 2003a). Similar productivity patterns in the GC have been observed by Pegau et al. 2002 based on SST and Chl images from satellites that show a series of eddies with alternating directions of rotation, and suggest that the eddies are topographically locked.

Due to its high productivity, the GC supports important commercial fisheries, mainly small pelagic fishes. Small pelagic fisheries in the GC are exploited by a specialized fleet of purse-seiners, with hold capacities of between 125 and 180 t. We used the small pelagic fishery catch data from the commercial fleet for this study.

This paper describes the relationship of the commercial fishing activity in the GC and weekly remote-sensed oceanographic conditions images, particularly SST, Chl and derived SST and Chl gradients, from 2002

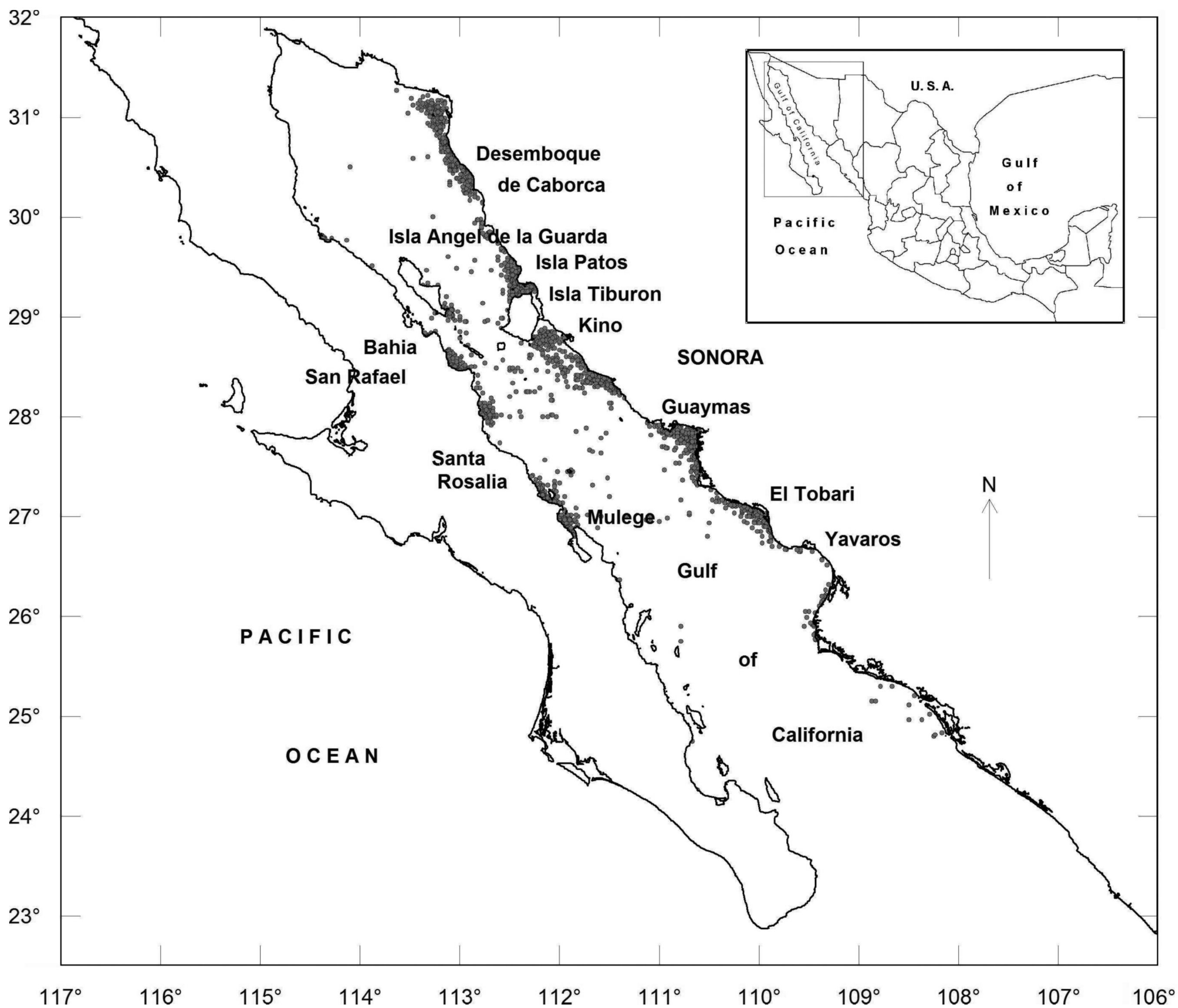

Figure 2. Location of the study area showing the catch distribution (dark grey points) of the Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), thread herring (*Opisthonema libertate*), and northern anchovy (*Engraulis mordax*) small pelagic fishery in the Gulf of California, 2002–07.

to 2007 using GIS based on the spatial distribution of fisheries data in order to get a reliable vision of the fishing grounds location especially on a small scale. This information is important to sustainable management.

MATERIALS AND METHODS

Fisheries Data

We converted the commercial fishing logbook data from 2002 to 2007 in the study area with date, geographic position, total catch, and species composition to a spatial database. In order to overlay both fisheries data and satellite images and create individual point maps in a GIS environment, a georeference within a coordinate system that contains projection information was created and applied to all fishery data.

Satellite Data and Derived Maps

Global eight-day SST and Chl composites (mean) products derived from MODIS (MODerate resolution Imaging Spectroradiometer) sensor onboard the Aqua satellite from 2002 to 2007 were downloaded via the internet from http://daac.gsfc.nasa.gov/data. This data set consists of satellite measurements of global ocean color and sea surface temperature (SST) data obtained by MODIS in orbit on the Aqua (formerly EOS PM) platform. MODIS ocean color and SST products are processed and distributed by the Ocean Biology Processing Group (OBPG). MODIS Aqua processing details can be found at http://oceancolor.gsfc.nasa.gov/DOCS/MODISA_processing.html. The data were taken in L3 mapped and HDF format in 4 km ground resolution and further imported into a GIS environment. SST images corresponded to 11μ nighttime SST and Chlorophyll-a concentrations were computed using the linear (Equation 1) and logarithmic (Equation 2) scaling equations, respectively:

$$SST\_value = (Slope*l3m\_data) + Intercept), \quad (1)$$
$$Chl\_value = Base^{((Slope*l3m\_data) + Intercept)}, \quad (2)$$

where *SST_value* and *Chl_value* are the remote-sensed retrieved SST (°C) or Chl (mg/m^3) values, respectively; the *Slope* value depends on the parameter: For SST, the value is 7.1785×10^{-4} and, for Chl the value is equal to 5.81378×10^{-5}. The parameter *l3m_data* is the raw value in byte of the image, and *Intercept* value is equal to -2.0 in both equations.

Sub-maps of the weekly SST and Chl images for the study area were created for each fishing season, which represent a matrix of 228 lines and 240 columns. Additionally, SST and Chl-gradient (GSST and GChl) images were obtained from each selected weekly SST and Chl composites by applying Sobel operators in 3×3 kernels. The Sobel filter consists of two kernels that detect horizontal and vertical changes in an image. If both are applied to an image, the results can be used to approximate the magnitude of the edges in the image as follows:

$$G_{horizontal} = \begin{vmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{vmatrix}, \quad (3)$$

$$G_{vertical} = \begin{vmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{vmatrix}, \quad (4)$$

$$Magnitude_{Sobel} = \sqrt{G^2_{horizontal} + G^2_{vertical}}, \quad (5)$$

where $G_{horizontal}$ and $G_{vertical}$ are two images which, at each point, contain the horizontal (x) and vertical (y) derivative approximations. The x-coordinate increases in the "right"-direction, and the y-coordinate increases in the "down" direction. $Magnitude_{Sobel}$ is the resulting gradient approximation at each point in the image.

GIS Mapping

To explore the association of each species with remote-sensed SST and Chl, individual point maps were produced to visualize the CPUE (catch per unit of effort) values throughout the study area. These point maps were further re-sampled into a regular grid with 4 km spatial resolution to produce raster maps in order to match the spatial resolution of the fishery and satellite information.

The weekly CPUE values, in terms of tons by landing, were mapped to produce point density (mean) covers of fisheries records (point maps) by re-sampling individual records in the selected grid and by averaging the CPUE values falling in each individual cell, and further combining them with environmental (SST, Chl and gradients) maps to extract environmental values for each fishery (Pacific sardine, chub mackerel, northern anchovy and thread herring). Cells that contained no information were assigned a null attribute.

Statistical Approach

A frequency distribution analysis for each individual species was computed against each environmental parameter in order to study the associations between the fisheries data and the satellite information. A set of probabilistic distributions, both Gaussian (Equation 6) and logarithmic (Equation 7), were applied to the frequency analysis to determine the best-fit functions based on a Pearson's chi-square goodness-of-fit test (Equation 8), with a confidence level for curves of 95%. To find parameter estimates and make nonlinear curves fit parameter values for each non-linear function, an iterative process was used.

Gaussian Fit:

$$y = y_0 + \frac{A}{w\sqrt{\pi/2}} e^{-2\frac{(x - x_c)^2}{w^2}}, \quad (6)$$

Log-Normal Fit:

$$y = y_0 + \frac{A}{\sqrt{2\pi wx}} e^{-\frac{\left[\ln \frac{x}{xc}\right]^2}{2w^2}}, \quad (7)$$

where y is the output value of the probability function; y_0 is the offset of the estimated parameter; x_c is the center; w is the width of the function, and A is the area. The "best fit" nonlinear model using chi-square was computed as:

$$X^2 = \sum_{i=1}^{n} w_i * (y_i - \hat{y})^2, \quad (8)$$

where: X^2 is the chi-square parameter value; w_i is the weighted coefficient, y_i is the experimental data point

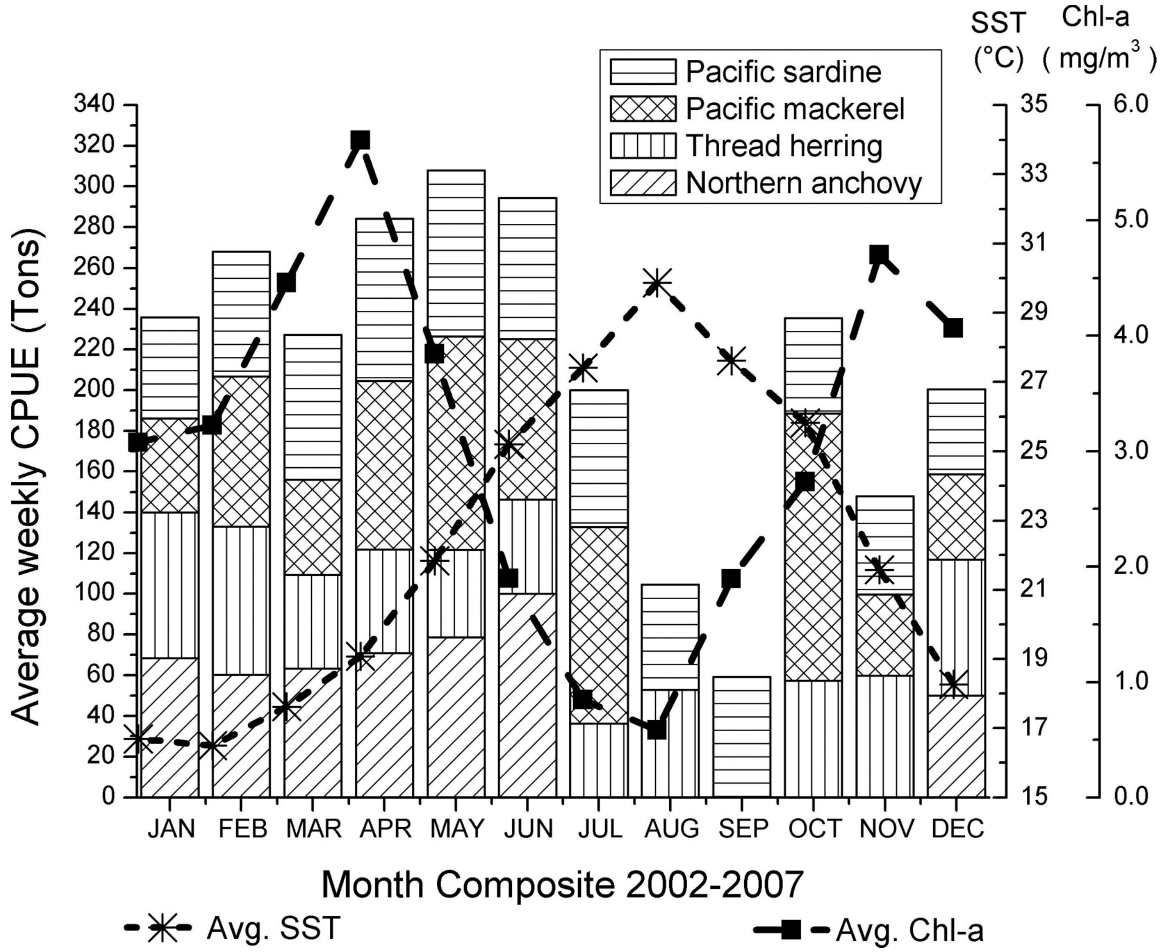

Figure 3. Mean monthly remote sensed sea surface temperature, Chlorophyll-*a* concentration and pelagic fish landings in the Gulf of California from 2002–07.

and *y* is the theoretical point. Our goal was to obtain the "best-fit" parameter values by minimizing chi-square.

RESULTS

Fisheries Data Distribution

A total of 1,842 of individual records, ranging from October 2002 to June 2007 were extracted from logbooks in the study area and matched with the environmental variables and derived maps. The spatial scatter plots (fig. 2) and the point density (not shown) maps of fishing sets show a wide distribution. The setting density map (not shown) has a range of cell values from 1 to 81, while the catch-density map has a range from 5 to 4,255.

Temporal Patterns of Satellite-Inferred SST and Chl *a*

A total of 143 weekly composites were selected from each SST and Chl image that matched the fisheries data. A comparison between monthly-averaged SST and monthly-averaged Chl concentrations (fig. 3) calculated using the satellite data for the period 2002 to 2007 had an inverse relationship. The highest monthly-averaged SST values (>25°C) were found between July and October, and the highest concentrations of Chl or blooms (>3 mg/m^3) were found during the colder months (November–May), and decreased (<1 mg/m^3) during the summer months. The observed blooms may be related to physical oceanographic features such as monsoon-causing coastal upwellings (Lavin et al. 1997; Lluch-Cota 2000; Pegau et al. 2002).

Environmental Impacts on the Abundance of Small Pelagic Fishes

For each CPUE data point, the SST, Chl concentration and derived gradient maps were extracted from the corresponding weekly composite.

Frequency analyses for the oceanographic parameters and abundances of small pelagic fishes in the GC are shown in Figure 4. Figure 4 also shows the best-fit function (Gaussian or log normal) based on a Chi-square test

TABLE 1
SST probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi²	R^2	Interval (°C)	Optimal range (°C)
Pacific sardine	1 222	LogNormal	759.91	0.700	14.5–31.6	17.0–22.0
Thread herring	348	Gauss	66.55	0.485	15.7–30.1	17.0–21.0
Pacific mackerel	143	Gauss	20.78	0.480	16.5–28.8	25.0–29.0
Northern anchovy	129	Gauss	20.00	0.710	15.7–23.1	17.0–22.0

TABLE 2
Chl probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi²	R^2	Interval (mg/m³)	Optimal range (mg/m³)
Pacific sardine	1 146	LogNormal	205.68	0.937	0.57–10.7	1.0–3.0
Thread herring	342	LogNormal	31.92	0.897	0.42–9.91	1.0–3.5
Pacific mackerel	134	LogNormal	5.526	0.959	0.45–5.60	1.0–1.5
Northern anchovy	111	Gauss	3.523	0.573	0.79–25.45	2.5–4.5

TABLE 3
Sobel SST gradient probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi²	R^2	Interval (°C/km)	Optimal range (°C/km)
Pacific sardine	1 214	LogNormal	189.76	0.969	0.32–6.51	1.0–2.5
Thread herring	352	LogNormal	32.75	0.936	0.44–4.80	1.0–3.0
Pacific mackerel	142	LogNormal	2.42	0.967	0.22–6.00	1.0–2.5
Northern anchovy	132	LogNormal	4.14	0.865	0.50–7.21	1.0–4.0

TABLE 4
Sobel Chl gradient probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi²	R^2	Interval (mg/m³/km)	Optimal range (mg/m³/km)
Pacific sardine	998	Gauss	61.34	0.955	0.36–29.32	0.5–5.0
Thread herring	318	LogNormal	5.85	0.961	0.50–34.06	2.0–6.0
Pacific mackerel	125	Gauss	2.52	0.966	0.22–14.22	0.5–2.5
Northern anchovy	92	LogNormal	3.69	0.434	1.94–67.14	3.0–17.0

with the 95% confidence limits. Table 1 through Table 4 show mean values for the variables considered in the analysis (SST, Chl, GSST [Gaussian SST], and GChl [Gaussian Chl]) for the best-fit function.

DISCUSSION

Frequency distributions of fisheries data provided a comprehensive analysis of the fishery and its relationship with environmental variables, such as SST and Chl, which can complement traditional time-series analyses in strategic management. In the GC, small pelagic fish distributions respond to a combination of biotic and abiotic factors. For Pacific sardine, Lluch-Belda et al. 1995 proposed the existence of two distribution centers: (a) the Gulf of California surrounding the Great Islands, and (b) the Pacific Ocean, Punta Eugenia west of Baja California. From these centers, populations of sardine expand and contract for feeding or spawning, following unknown environmental factors. Generally, Pacific sardine concentrate in the north-central coast of the GC (Isla Patos and south of Isla Angel de la Guarda), and thread herring along the south-central coast (Sonora and north of Sinaloa; Nevárez-Martínez et al. 2003). Figure 2 shows a wide spatial distribution of small pelagic fishes in the Gulf of California, concentrated in the Great Islands; this is similar to the findings of Lluch-Belda et al. 1995.

Analyses of fishing data time series for the fishing seasons 2002 to 2007 (fig. 3) suggest that the highly seasonal nature of the fishery is associated with seasonal changes in temperature and chlorophyll. The normalized data structure from Figure 3 in the form of CPUE anomalies compared to average monthly composites

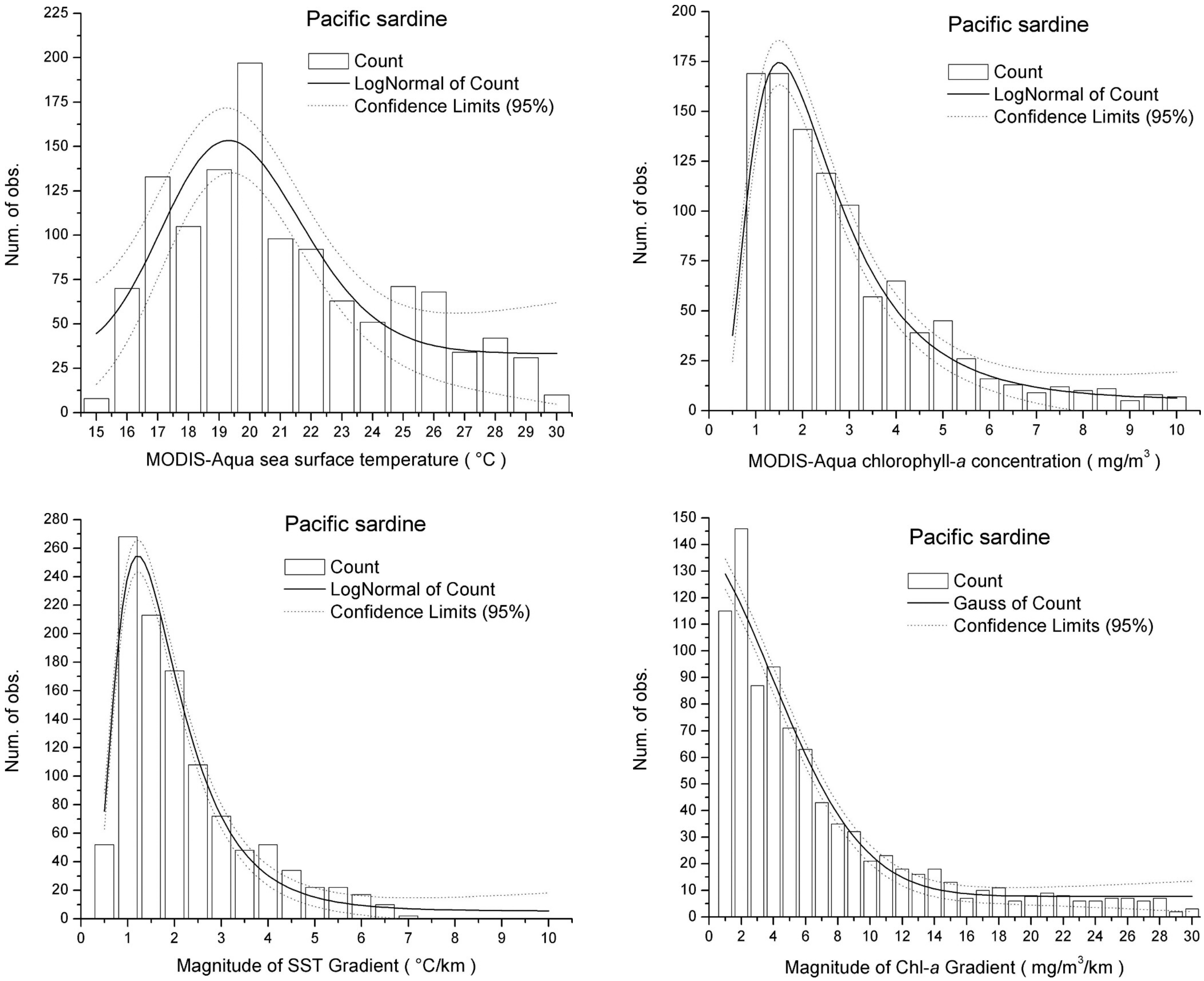

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for Pacific sardine (*Sardinops sagax)* for the period 2002–07.

(fig. 5) supports this relationship as do alternating patterns of fisheries-associated environmental parameters. This is reflected in an increase in anchovy abundance when the SST increases and the Chl decreases. Although most catches are made at the end of spring (May), fishes are abundant during the cold season, especially in spring (April–May) and early summer (June). Small pelagic fishes are present during part of the summer, decreasing in abundance towards the end of August and September, except for Pacific sardine, which become the most prominent fish. Incorporating this temporal information can provide insight on the presence/absence of certain species due to environmental features and be used in management. Although the seasonal CPUE presents a common trend over the years, there are fluctuations in the fishing season from year to year. These fluctuations were not analyzed in this study.

In the GC, the spatial distribution of oceanographic conditions varies considerably (Lavín et al. 1997; Gaxiola-Castro et al. 1999; Pegau et al. 2002). The most notable differences are at the central-upper part of the GC which has the lowest SST values and the highest Chl values (Gaxiola-Castro et al. 1999; Pegau et al. 2002). SST is much cooler at the Large Islands and the "Ballenas-Salsipuedes" channel (Isla Angel de la Guarda in fig. 2; Nevárez-Martínez et al. 2001). This suggests that cooler SSTs in the area present unfavorable conditions for Pacific sardine and basically for all species (fig. 5). The distribution of Chl in the GC is characterized by higher levels of nutrient enrichment in shallower waters close to the coastline (Gaxiola-Castro et al. 1999; Pegau et al. 2002). Previous studies have documented the productivity of these areas, where oceanographic processes such as wind stress cause nutrient enrichment of surface waters

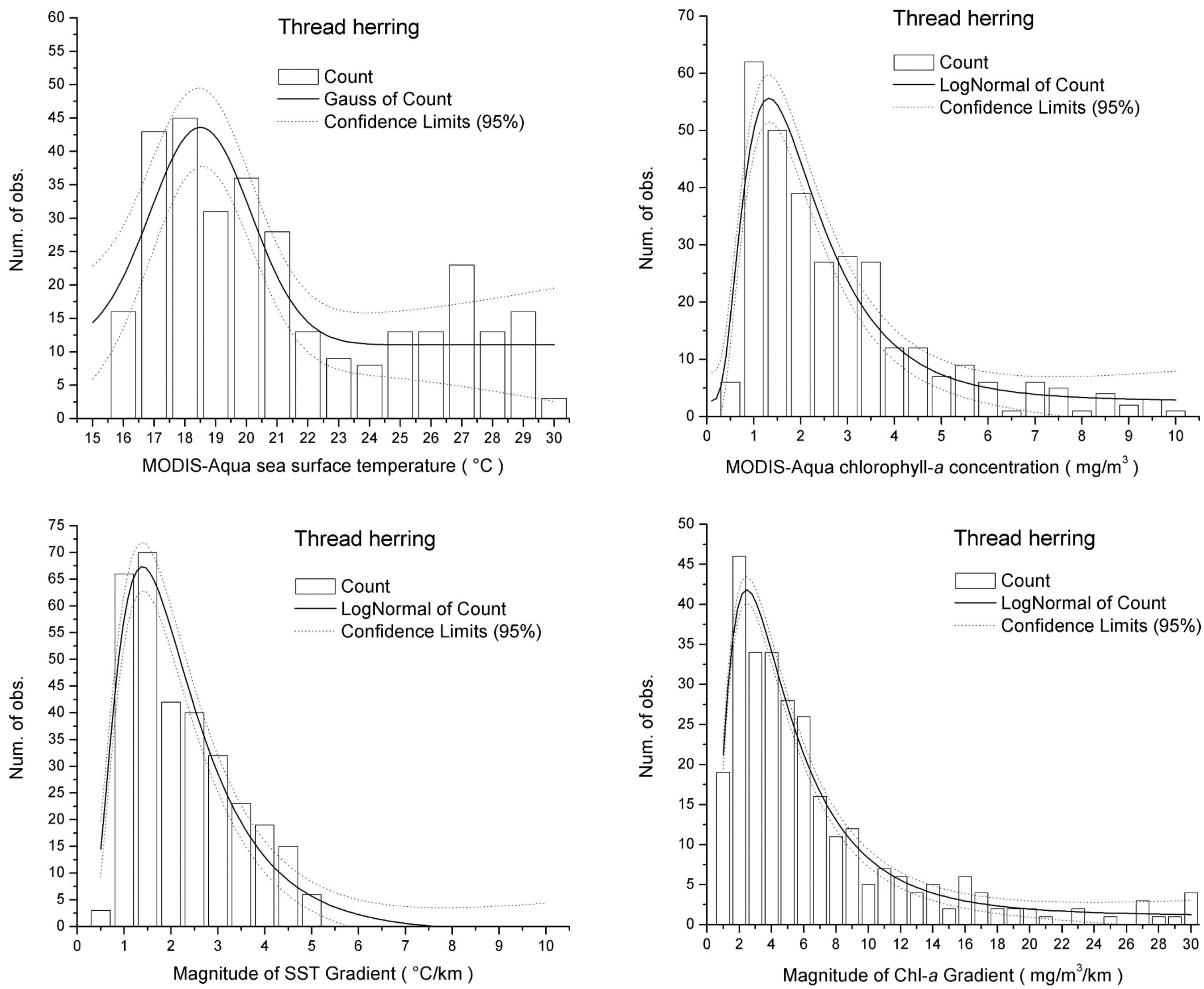

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for thread herring (*Opisthonema libertate*) for the period 2002–07.

(Santamaria-del-Angel et al. 1994; Lluch-Belda et al. 1995; Cury et al. 2000; Bakun and Broad 2003). It is likely that small pelagic fishes select these areas due to the higher concentration of food associated with these productive waters (Fréon et al. 2005, and Brown et al. 2006). On the other hand, cooler SST can be indicative of nutrient-enrichment processes, such as wind mixing, upwelling and river-run off, which are associated with favorable conditions for small pelagic fishes.

Gradient maps (GSST and GChl) derived from spatial components (horizontal and vertical differences among neighboring pixels) had a better fit with catch distribution than the single parameters of SST and Chl. The relationship between the magnitude of the SST or Chl-concentration gradient and fish presence was generally significant (tabs. 3 and 4), with a strong negative effect at steeper gradients. This was especially the case for chub mackerel presence and Chl concentration (fig. 4). The relationship between Chl concentration and fish presence was generally high with considerable uncertainty where Chl concentration was high due to a low number of values (fig 4). SST was generally the least important variable. The relationship between SST and fish presence varied considerably, especially for mackerel, which had the largest range and variation in preferences (fig. 4). However, Figure 4 and Table 1 illustrate that mackerel prefer warmer waters (25.0°–29.0°C) than do the rest of the species.

Environmental Preferences of Small Pelagic Fish

Several authors have investigated the relationship between small pelagic fishes (e.g., Pacific sardine) and SST and the upwelling index in the GC (Lluch-Cota 2000; Nevárez-Martínez et al. 2003) and found that the rela-

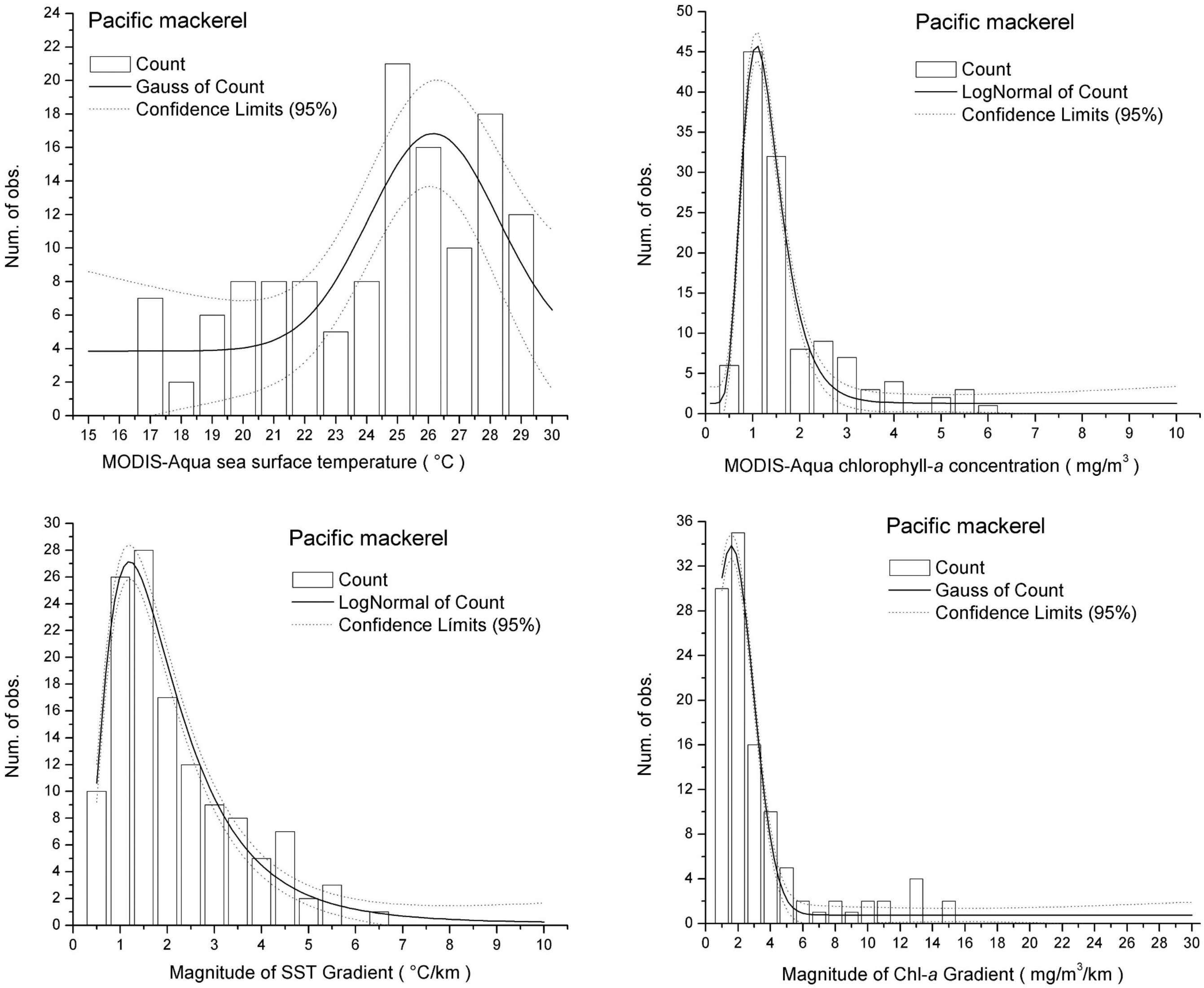

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for Pacific mackerel (*Scomber japonicus*) for the period 2002–07.

tionships between small pelagic fishes and SST were typically weaker and less significant than those between small pelagic fishes and Chl concentration. This suggests that Chl is an indicator of conditions favoring most small pelagic fishes. Chl concentration is a measure of the standing stock of phytoplankton in surface waters; therefore higher concentrations are likely to be associated with productive feeding grounds for planktivorous fish, such as small pelagic fishes. SST is likely to be less correlated with fish abundance than Chl. However, in the GC a time lag of 1–2 weeks may produce stronger relationships with fish abundance (Bakun and Broad 2003). For example, enrichment events indicated by high Chl and low SST may be more associated with the presence of certain small pelagic fish after sufficient time has passed for both zooplankton abundance to rise and fish to locate the area.

Identifying parameter preferences for small pelagic fish requires considering a variety of data issues. Among them are the highly dynamic nature of fisheries data on varying temporal and spatial scales which means that the use of satellite remote-sensing data must take into account this variability. This involves a variety of spatial ground resolution (e.g., 4 km vs 9 km), and temporal data composites (e.g., daily, weekly, monthly composites). In this study, this spatio-temporal uncertainty was not validated with in situ information. Therefore, the preferences analysis presented in this study does not accurately predict the areas where fish will be present. Instead it serves as a tool for identifying areas where environmental conditions are suitable or unsuitable for fish. Another aspect is that the environmental conditions which have been shown to influence fish distribution vary spatially and temporally and long time series of fishing data should be consid-

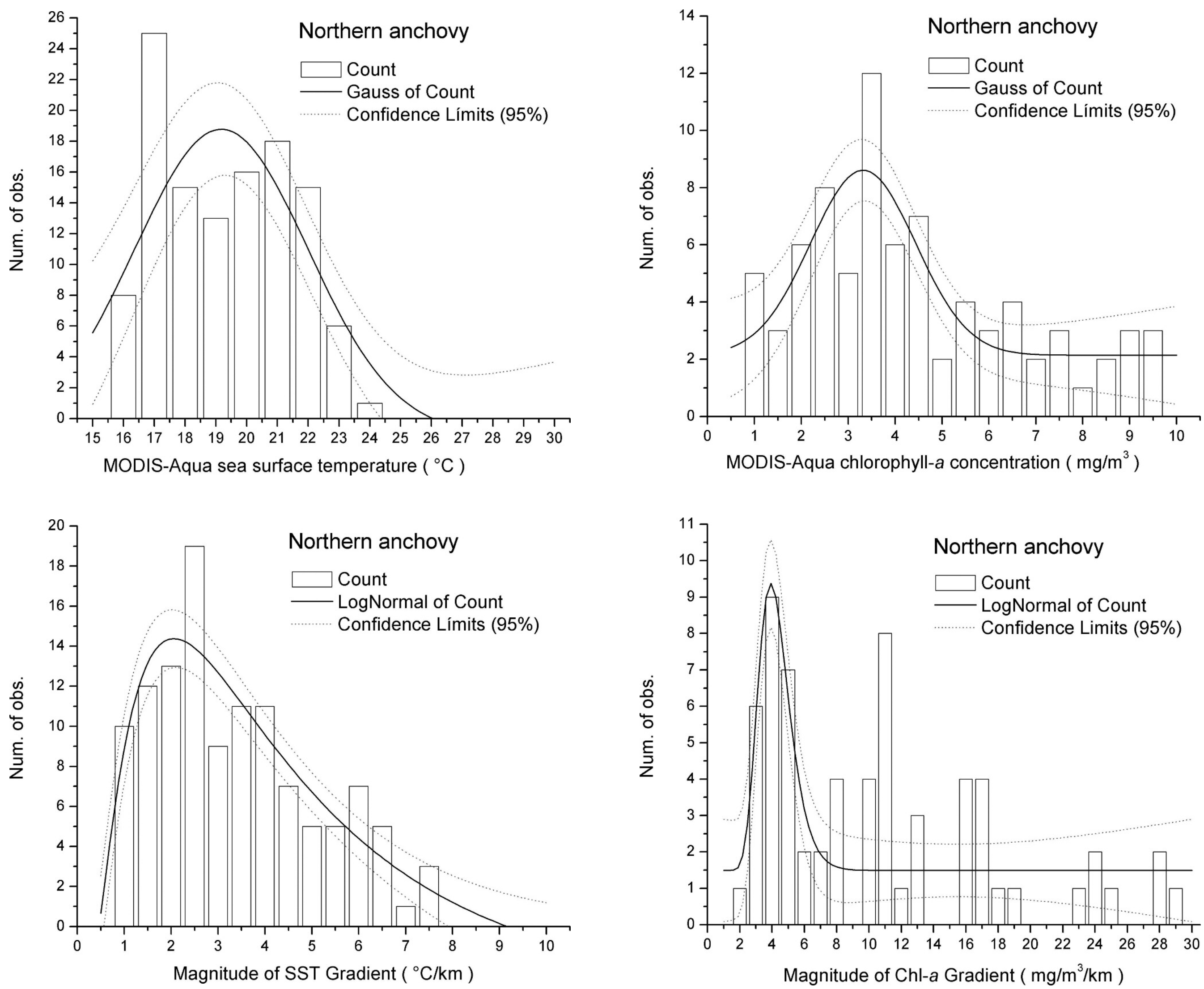

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for northern anchovy (*Engraulis mordax*) for the period 2002–07.

ered. Among this environmental variability, large interannual variations, such as El Niño/Southern Oscillation, reflect substantial temporal changes in the distribution and abundance of small pelagic fishes in the GC (Lluch Belda et al. 1995). This has considerable implications for the fishery and can alter the catchability of fish and the migration or replacement of other opportunistic or well-adapted fishes, such as mackerel (Fréon et al. 2005). Among the small pelagic fishes, the relative abundance of a single species signifies its dominance in the ecosystem and its ability to use resources. In some cases, different species may compete for the same biological niche. For example, the rise in the population of one small pelagic fish may be associated with a decline in the population of another, as for northern anchovy and South American pilchard (Christy 1997). Sardine population changes, however, are seemingly related to environmental variability (Nevárez-Martínez et al. 2003), whereas the spatial pattern of abundance for another competitor (e.g., northern anchovy) appears to be inversely related to sardine population abundance (Rodríguez-Sánchez et al. 2002; Lluch-Belda et al. 2003b). According to the literature, thread herring is relatively more frequent in the southern part of the GC—especially the ports of Guaymas and Yavaros—when Pacific sardine are scarce, such as occurred from 1990 to 1993 and during the 1997–98 fishing season; both were El Niño periods (Anonymous 2001).

The statistical approach in this study did not reflect such changes in fish distribution, which leads to another challenge. The catchability of fish is particularly important in the Gulf of California because the fishing industry is regulated by effort and gear restrictions, not quotas. Fishing is not required to cease once a certain

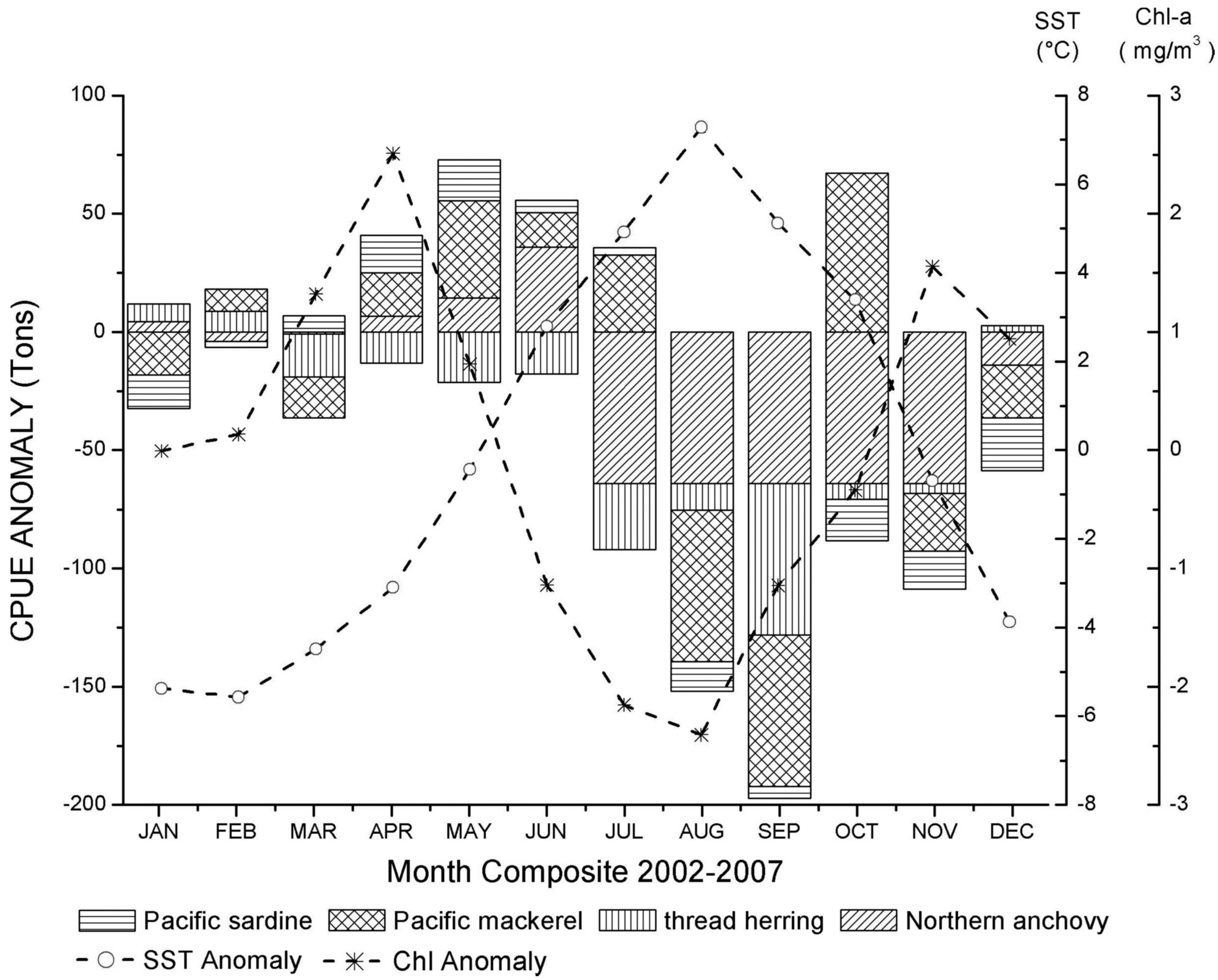

Figure 5. Normalized values of average monthly composites of catch and remote-sensed SST during 2002–07 in the Gulf of California.

amount of fish are landed. Therefore, an increase in the catchability of a stock will alter the perceived relationship between environment and fish. Increasing commercial landings may give the false impression that fish are becoming more abundant (based on number of observations or landings), when they are actually only becoming more available to fishing. Over short time scales, environmental variability can change fish distributions with considerable fishery implications (Fréon et al. 2005). For example, rapid horizontal and vertical migrations can be induced, altering the distribution of fish and therefore their availability to fishing. While many of these shifts in distribution may be relatively local and temporary, they have been observed to persist for several months and over large areas, greatly influencing the exploitation of populations (Bertrand et al. 2004).

Frequency analyses illustrated fish presence and its relationship with environmental conditions through GIS maps. In this study, these relationships were not defined as habitat with a predicted probability of presence above a specific threshold value. The relationships between the environmental factors and the small pelagic fishes are likely to result from differences in the species composition of the pelagic community. Thus, these relationships vary with species, independent of abundance, and analyses should be performed on an individual basis. Therefore, grouping all fish together is likely to obscure some relationships, particularly those of less abundant species.

CONCLUSIONS

In this study, we explored the association between small pelagic fishes with sea surface temperature and chlorophyll-*a* concentrations in the GC. For most pelagic species studied here, fish abundance was more closely related to Chl than SST distribution. Moreover, gradient maps describe more efficiently these preferences than the raw parameters. Small pelagic fishes seem to prefer oceanic waters with relatively low gradients over more productive waters (e.g., instantaneous upwelling event which produces higher primary productivity). Pacific sardine was an ideal species to describe such associations, because it is caught in a wide SST range (14.5°–31.6°C) and is found most often in waters at 17.0° to 22.0°C. Pacific sardine are found in waters with Chl concentrations ranging from 0.57 to 10.7 mg/m^3 but they prefer 1.0 to 3.0 mg/m^3. However, anchovy showed an anomalous preference for respect to SST and Chl even in the gradient maps.

ACKNOWLEDGEMENTS

We appreciate the fishing company PROPEGUAY S.A. DE C.V. for supplying us with valuable fisheries data. This research was supported by INP-CRIP and CIBNOR Guaymas. The corresponding author thanks CONACYT (85931) and CIBNOR for the support of this research.

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