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Distribution and abundance of the Pacific sardine (*Sardinops sagax*) in the Gulf of California and their relation with the environment

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Abstract

In 1989–90 the small pelagic fishery of the Gulf of California began to show a very marked decline in the catch of its main component, the Pacific sardine (*Sardinops sagax*). The catch plummeted from 292,000 t in 1988–89 to 7000 t in 1991–92 and 1992–93. This caused a serious economic crisis in the local fishery fleet and industry, and resulted in the loss of 3000 jobs. In 1993–94 the fishery showed signs of recovery as the abundance of the Pacific sardine began to recover. The catch improved to 128,000 t in 1993–94 and further to 215,000 t in 1996–97. In trying to understand this great variability, we proposed the hypothesis that the distribution and the abundance of the Pacific sardine of the Gulf of California is determined by the wind patterns (upwelling) and the sea surface temperature. The results of analyzing data from 25 cruises showed the period of low relative abundance between 1990 and 1993 and one of high abundance between 1993 and 1996. The range of the sardine's distribution expanded as its abundance increased and contracted when abundances were low. The relationship between the abundances of the sardine and environmental variables proved to nonlinear and bell-shaped. The adjusted pattern explained 78.8% of the variability of the sardine abundance. The highest abundance are produced by moderate upwelling (13–18 m^3s^{-1} per 10 m of coastline) and sea surface temperatures of between 19°C and 25°C. © 2001 Published by Elsevier Science Ltd.

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Contents

1. Introduction

Large populations of small pelagic fish in the California Current System and the Gulf of California are characteristically associated with coastal upwelling areas as they are in other major ocean gyres. These species are the target of the most porductive fisheries in the world (Kawasaki, 1993; Lluch-Belda et al., 1992). In Mexico, they accounted for up to 40% of the country's total national landings (Anon, 1990), and the bulk of them caught in the Gulf of California. The fisheries provide important sources of fish products, economic activity, and employment (Cisneros-Mata, Nevárez-Martínez, & Hammann, 1995).

These small pelagic species have undergone considerable variations in both their distributions and abundances over time. Their management demands new approaches to improve understanding of the mechanisms responsible for resource availability (Lluch-Belda et al., 1995). Environmental fluctuations may cause very dynamic variations in their distribution and abundance (including expansion and contraction) over a range of timescales, from seasonal to interannual, to decadal and to geological (Shannon, Crawford, Brundrit, & Underhill, 1988; Lluch-Belda et al., 1989, 1992; Baumgartner, Soutar, & Ferreira-Bartrina, 1992; Holmgren-Urba & Baumgartner, 1993; Kawasaki, 1993).

There has been a remarkable covariance of sardine stocks and hence their fisheries off Japan, California, and South America. Landings peaked during the 1930s, but then collapses rapidly during the 1940s. Low abundances were sustained through the mid-1970s, until a new period of high abundance occurred during the 1980s. Similar oscillations have occurred in anchovy fisheries (and South African sardines) but in the opposite phase to those of the Pacific sardine stocks; maxima occurred during the 1960s, and then the stocks plummeting during the 1980s (Clark & Marr, 1955; Kondo, 1980; Radovich, 1982; Hayasi, 1983; Kawasaki, 1983; Serra, 1983; Zuta, Tsukayama, & Villanueva, 1983; Grant, 1987; Kawasaki & Omori, 1988; Lluch-Belda et al., 1989).

The small pelagic fishery in the Gulf of California (Fig. 1) is multispecific and includes eight species, although the Pacific sardine (*Sardinops sagax*) is the dominant species (about 80% of the total landings). The fishery began during the late 1960s, grew slowly during the 1970s, and

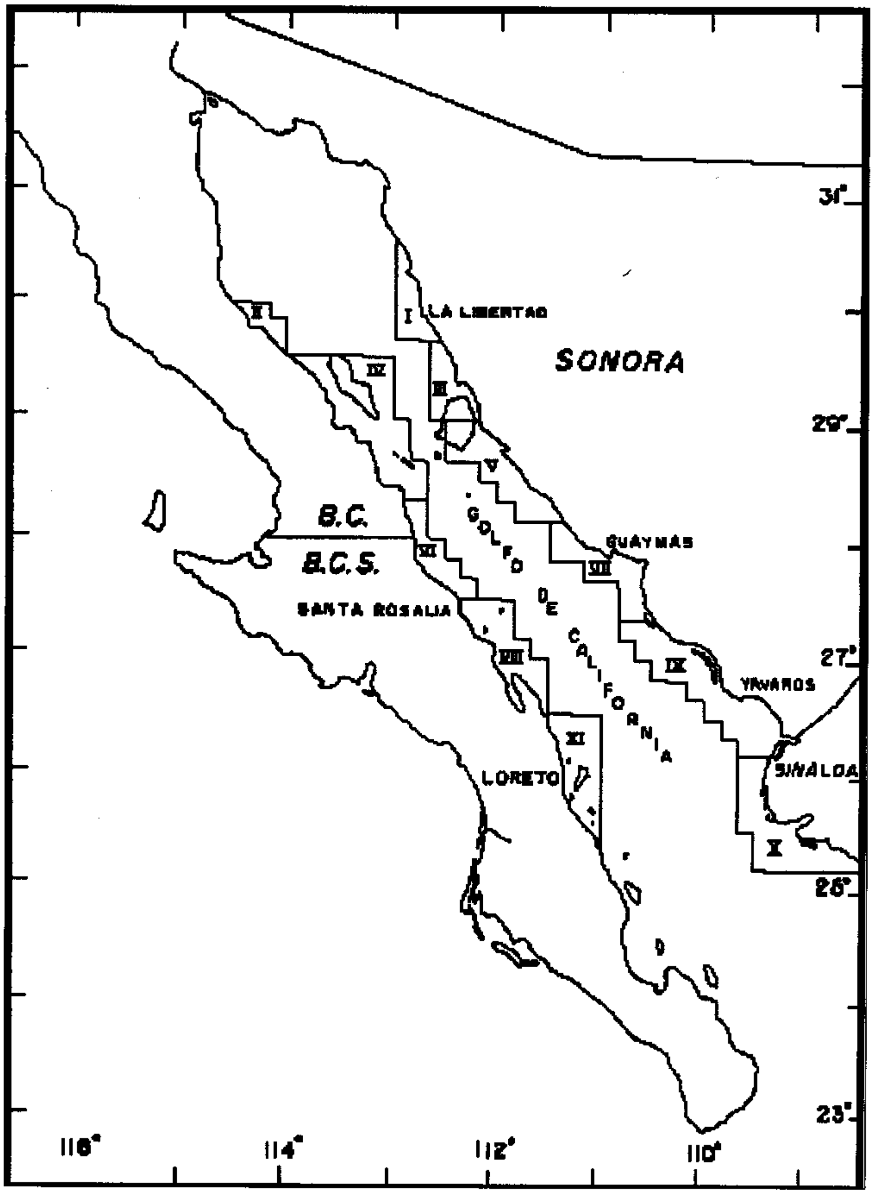

Fig. 1. Map of Gulf of California showing the principal ports for the sardine fishery.

more quickly during the 1980s; its maximum landings were during the 1988–89 season (Pedrín, Sokolov, & Molina, 1973; Pedrín & Ancheita, 1976; Molina-Valdéz, Paéz-Barrera, Magallón-Barajas, Castro, & Castro-Aguirre, 1984; Cisneros-Mata, Nevárez-Martínez, Montemayor-López, Santos-Molina, & Morales-Azpeitia, 1991; Cisneros-Mata et al., 1995). It then underwent a striking decline starting in 1989–90, driven particularly by the declines in catches of the Pacific sardine (Fig. 2). Landings plummeted from the peak of 292,000 t during 1988–89 to 7000 t during 1991–92 and 1992–93 (Cisneros-Mata et al., 1995; Nevárez-Martínez, Cisneros-Mata, Martínez-Zavala, & Santos-Molina, 1998).

This severe collapse resulted in a serious crisis for the sardine fishing industry of the state of Sonora; more than 50% of the packing plants closed and 60% of the fishing fleet was laid up between 1989–90 and 1992–93. The loss of some 3000 jobs had a major impact on the region's economy. However, in 1993–94, the abundance of Pacific sardine began to recover and once again the fishery began to grow again (Fig. 2). Landings increased, during 1993–94 they reached 128,000 t, 170,000 t during 1994–95, and more than 200,000 t during both 1995–96 and 1996–97 (Nevárez-Martínez et al., 1998).

A growing body of evidence suggests that environmental factors play a dominant role in the processes changing the abundances of the populations of small pelagic fish around the world. If such resources are to be adequately managed, it will be necessary to integrate environmental information with biological and fishery knowledge, so as to be able to forecast the population fluctuations on the basis of biological, environmental, and fishery data. The present paper attempts to examine the changes that took place in the time and area that the sardine population was present in the Gulf of California from 1990 to 1996 and its relation to environmental variability.

1.1. Working hypothesis

Catches of small pelagic fish have been variable in the Gulf of California since the onset of the fishery, mostly driven by fluctuations in the abundance of the one dominant species, the Pacific

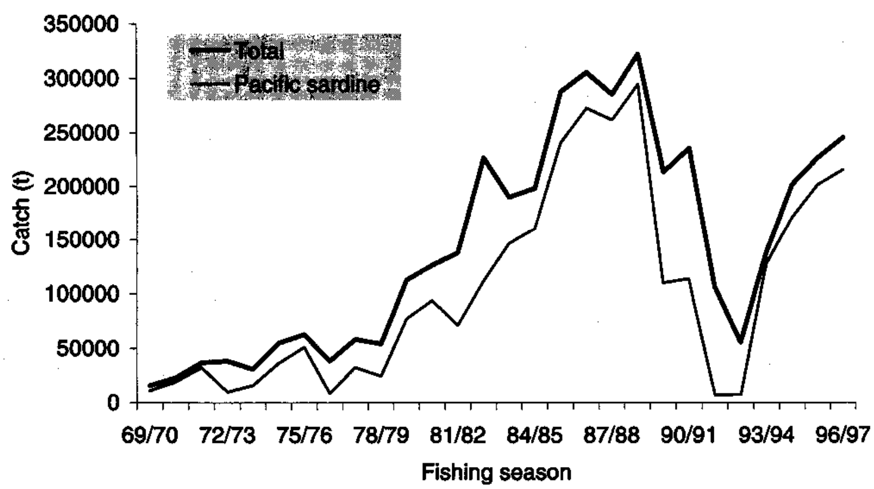

Fig. 2. Total catch of small pelagic fish and pacific sardine (metric tons) in the Gulf of California, 1969–97.

sardine (Fig. 2). Its availability to the fishery is a result of the its abundance and distribution determined by environmental conditions. For instance, during the 1972–73 and 1976–77 ENSOs, sardine availability dropped drastically along the coast of Sonora (from Guaymas to Kino). Similar reductions in availability occurred during the 1982–83 ENSO, although this was not evident in the total landings because the fishing boats were already larger and were able to compensate for the scarcity of sardine in their usual fishing grounds (the Sonora coast) by operating in the Canal de Ballenas-Salsipuedes and north of Isla Tiburon.

The interannual fluctuations in the sardine landings between 1988–89 to 1995–96 reveals that this seven-year period was dominated by high variability in the distribution and abundance of sardine, adverse environmental conditions, including the effects of the 1991–92 ENSO, could explain the drastic fall in the sardine landings between 1989 and 1993. A rapid recovery of the catches began in 1993–94 as the pelagic environment appeared to improve, with persistent negative anomalies in the sea surface temperature (SST) and favorable winds for the upwelling.

Thus, we propose that the collapse the sardine fishery suffered in 1989–90 to 1992–93 resulted both from greatly diminished abundances and a distribution shift caused by adverse environmental conditions, mostly the anomalously weak or contrary wind patterns during October–November to March–April and generally warm SST anomalies. We further suggest that the recovery of the fishery (and the population) recovery after 1993–94 resulted from environmental improvements brought about by intensive upwelling and the cooling of SST that resulting from the wind patterns favoring upwelling. In general, we pose the hypothesis that the distribution and the abundance of the Pacific sardine in the Gulf of California depends mostly on wind-induced upwelling patterns and sea surface temperature.

2. Data and methodology

It has been postulated that pelagic fish have a preference for certain ranges of environmental conditions (Mendelssohn & Cury, 1987; Cury & Roy, 1989; Cury et al., 1995). We have used time and spatial analyses to search for the relevant environmental factors that determine the changes in the abundance and distribution of sardine population.

The main information source is from a program of 25 exploratory fishing cruises undertaken by the Instituto Nacional de la Pesca (INP — CRIP Guaymas) in the Gulf of California from 1990 through 1996 (Fig. 3). A specially designed 4-layer midwater trawl with a 1″ mesh was used to sample small pelagic fish (R. Torres-Jiménez, pers. comm., Centro Regional de Investigación Pesquera de Guaymas, Guaymas, México) for periods of 30 minutes. Both sonar and video sounder were used to direct the trawl. The average percentage of tows that were successful in catching sardine and average number of fish per trawl (NPPL) were calculated for each cruise (Table 1).

Sea surface temperature (T) was routinely measured throughout the cruises and individual values were averaged for each cruise (Table 1). Upwelling activity along the continental coast was evaluated using an index based on daily records of wind at the meteorological station of Guaymas-Empalme (Lluch-Cota et al., 1999). Upwelling along the peninsular coast was estimated using the inverse of the continental coast index, corrected with the monthly pattern of Santa Rosalía's index, because of insufficient wind data to build an adequate time series. These

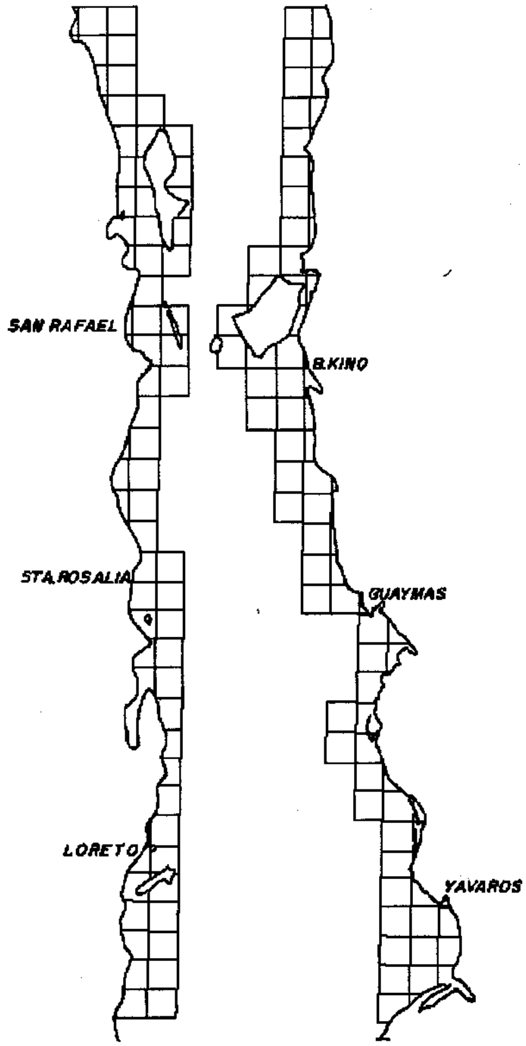

Fig. 3. Net of stations at which exploratory fishing was undertaken on board BIP XI in the Gulf of California, Mexico.

calculations are based on the seasonally inverse wind circulation and upwelling between coasts. Winter northwesterlies drive coastal upwelling on the continental side, and summer southeasterlies produce upwelling on the peninsular side (Badan-Dangon, Koblinsky, & Baumgartner, 1985). We used a proxy of upwelling (IS) as the average of the monthly value from the period of the cruise and the previous month (Table 1).

Visual inspection of scatter plots was used to determine the kind of relationship (linear or nonlinear) between relative abundance (NPPL) and environmental variables. Later, appropiate models were fitted to the data. To facilitate visual inspection of sardine time–spatial distribution

Table 1
Average percent of positive stations (PPS), average number of fish per trawl (NPPL) and sea surface temperature (*T*) estimated for each cruise, and upwelling index (IS)

Cruise date	NPPL (number per trawl)	PPS (%)	*T* (°C)	IS (m^3 s^{-1} per 10 m of shoreline)
03/90	202.80	0.14	17.81	8.72
08/90	40.01	0.22	28.15	12.35
01/91	111.44	0.13	16.84	31.70
05/91	168.00	0.09	20.44	7.00
08/91	2.33	0.10	27.85	14.30
11/91	1.89	0.26	25.88	4.00
01/92	47.17	0.09	19.78	10.88
05/92	71.64	0.30	23.78	10.00
08/92	19.44	0.26	28.09	19.09
11/92	1.01	0.06	19.39	26.78
01/93	111.75	0.19	17.77	17.48
05/93	201.70	0.51	23.51	6.40
08/93	8.22	0.32	29.29	31.41
11/93	2846.18	0.46	22.18	15.00
01/94	275.18	0.26	16.67	25.68
05/94	1304.36	0.70	21.37	16.74
09/94	66.50	0.14	29.38	8.25
11/94	482.64	0.58	17.56	22.04
01/95	1665.23	0.52	18.36	14.52
05/95	1344.06	0.60	23.55	12.36
08/95	55.50	0.56	28.84	22.63
11/95	95.88	0.42	21.02	8.74
01/96	69.72	0.26	18.03	16.06
06/96	510.83	0.46	26.66	16.77
11/96	507.61	0.58	21.26	13.01

and abundance, interpolations were made (Kriging method, isotropic linear variogram) using a commercial statistical software (SURFER V6 for Windows 95. Golden, Co, Golden Software, Inc.). Sardine distribution maps where made for all cruises.

3. Results

The two indices of sardine abundance (Fig. 4) indicate that abundances were low between 1990 and 1993, with a striking increase afterwards. The average number of individuals per trawl increased by two to three orders of magnitude, and the average number of positive stations increased 200%. The surface temperatures (*T*) showed marked seasonality, with warm temperatures in the winter of 1992 (Fig. 4b). Upwelling indices varied most markedly between 1990 (>30) and 1993 (<8); near average values occurred thereafter (Fig. 4c).

Scatter plots of abundance indices (number of sardines per trawl, NPPL), *T*, and upwelling indices (IS) are shown in Fig. 5 (a and b). Low sardine abundances corresponded to extreme

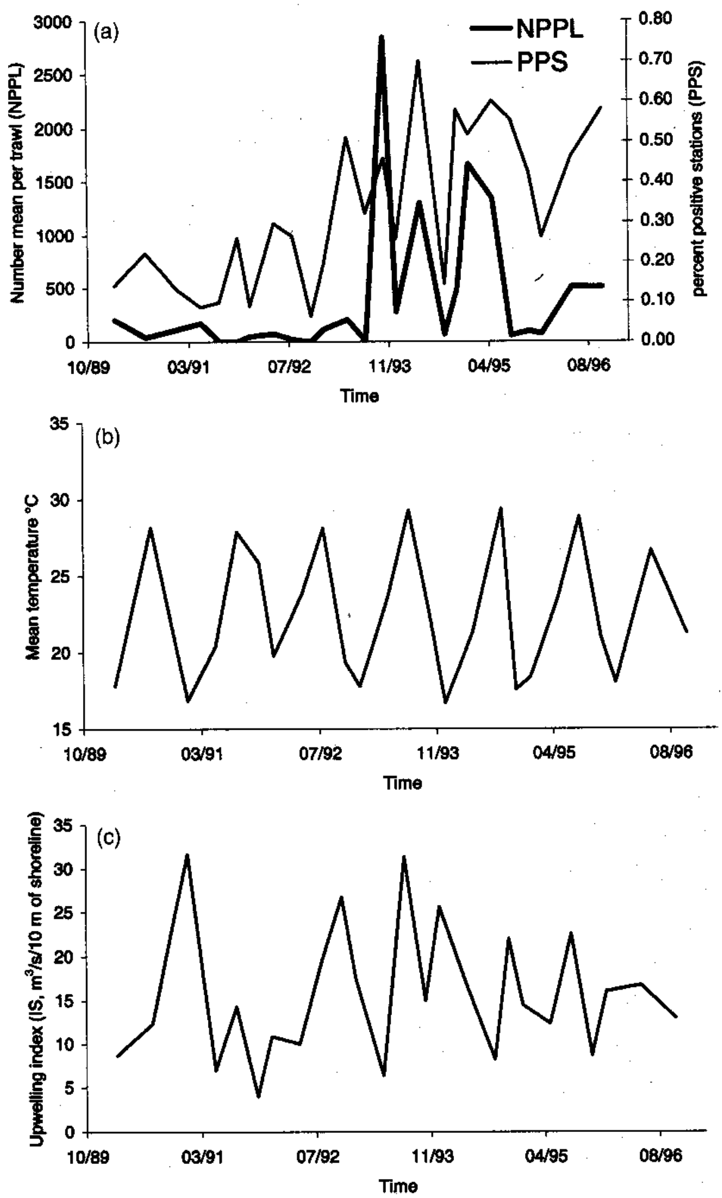

Fig. 4. Behavior of the relative abundance (a) and environmental variables (b and c).

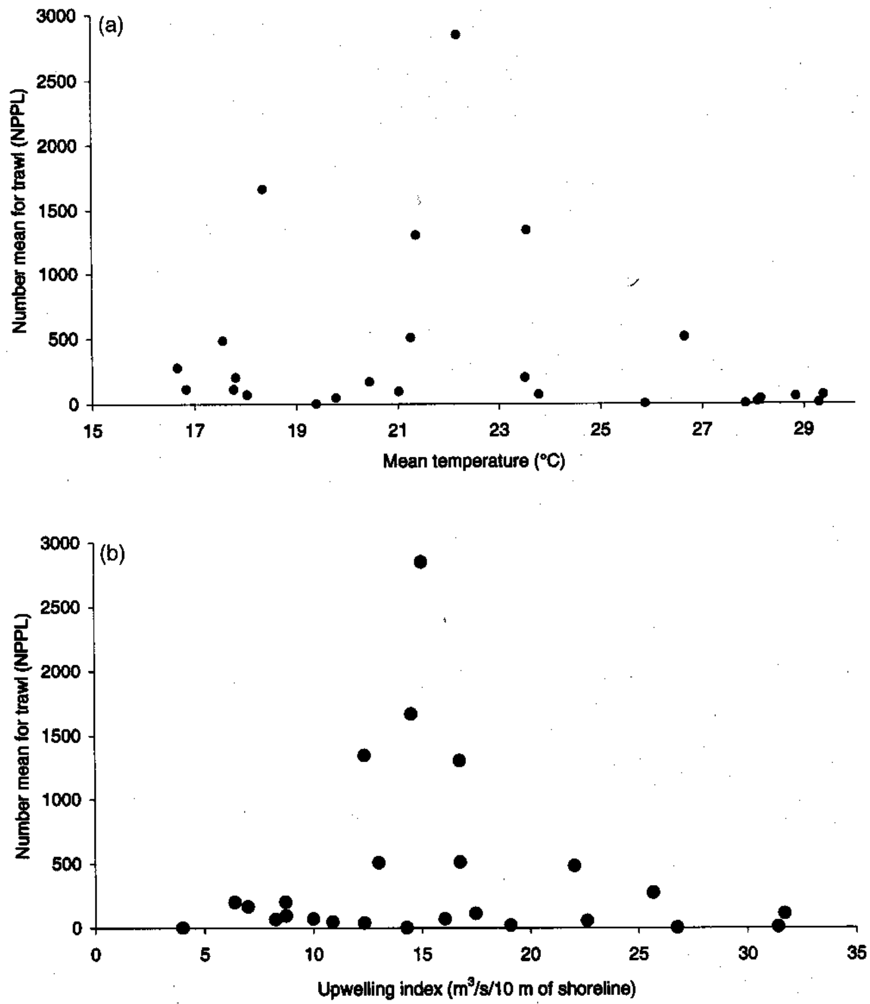

Fig. 5. Relative abundance (number mean per trawl) versus (a) sea surface temperature and (b) upwelling index.

values of both temperature and upwelling. The highest relative abundance was found for both intermediate upwelling values (12–18 m^3s^{-1} per 10 m of shoreline) and surface temperatures (18–24°C).

Nonlinear multiple regression analysis based on surface temperatures (T) and upwelling (IS) explained 78.8% of the observed relative abundance variance (NPPL). The model fitted was:

$$\text{NPPL}=(333.506{*}N(T, 22.243, 2.789)){*}(219.421{*}N(\text{IS}, 14.891, 1.476)),\ r=0.89;\ r^2=0.78\ (p \leq 0.05;\ n=25).$$

N (variable, parameter 1, parameter 2) is the mathematical expression for the normal function with mean (parameter 1) and standard deviation (parameter 2), respectively.

Calculated values by the model are shown in Fig. 6. No sardines were found when temperatures exceeded 30°C or fell below 15°C, regardless of any upwelling. Minimum sardine abundances were found when upwelling rates were either <11 m^3 s^{-1} or >18 m^3 s^{-1} per 10 m of coastline, independent of temperature. The maximum values of sardine abundance occurred when the mean SST was 22.24°C and the upwelling index of 14.89 m^3 s^{-1} per 10 m of coastline.

The time-space distribution of sardine in the Gulf of California is shown in Fig. 7. There are two clear phases. The first occurred between 1990 and early 1993 when the sardines were localised in their distribution and in low low abundance (1 to 101 sardines per trawl). The second phase was from mid-1993 to the end of 1996 characterized by the sardines being more widely distributed in areas of high-abundance of between 200 and 23,000 sardines per trawl (Fig. 8).

4. Discussion

The sardine population has fluctuated in abundance dramatically during recent decades in the Gulf of California. The evidence now seems to be sufficient evidence to show that the fluctuations have not been caused solely by the effects of fishing, but that environmental variation has also been a major causal factor.

Unfortunately, there are very few environmental data series giving adequate coverage of both spatial and temporal variation. This paucity of data limits the analyses to assessments of empirical

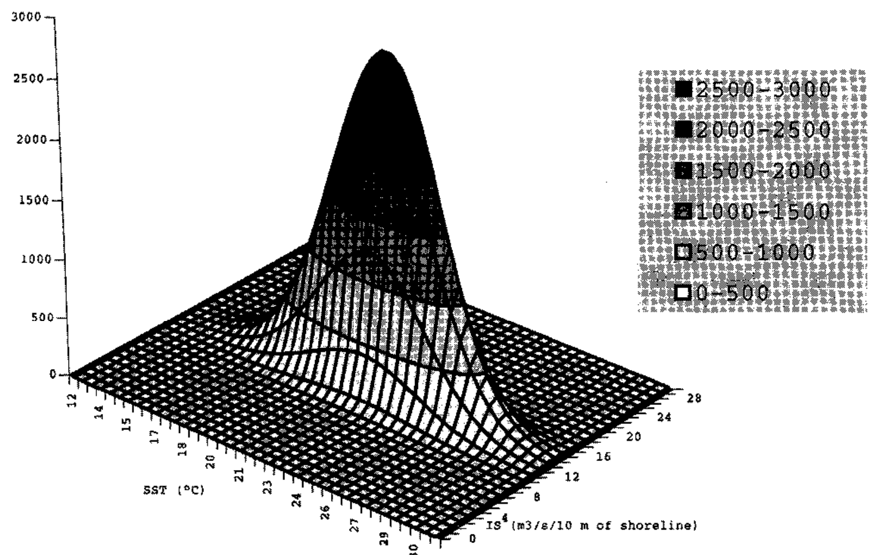

Fig. 6. Relation between the abundance of pacific sardine and the sea surface temperature and the upwelling index.

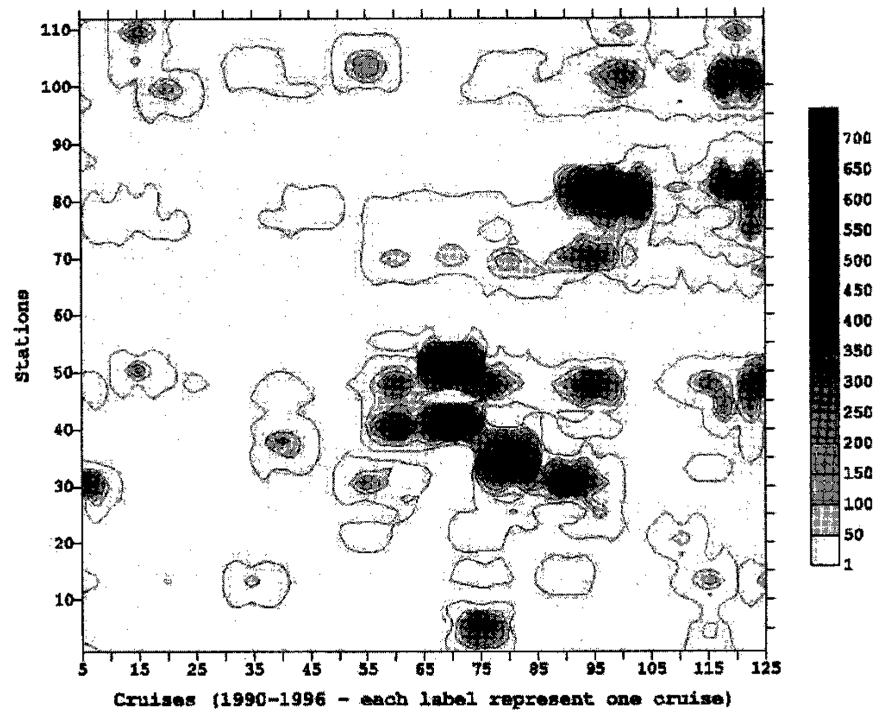

Fig. 7. Spatial (vertical axis) and time (horizontal axis) distribution of the pacific sardine in the Gulf of California, México. Stations 0–60 are mostly those at the eastern coast, while from 60 to 112 are mostly distributed along the peninsular coast (see Fig. 4). Each mark at the horizontal axis represents a cruise, from winter 1990 through autumn 1996.

correlations that may be indicative of causal relationships, but fall far short of rigorous proof. It is only the accumulated evidence that adds some weight to the proposed hypotheses.

In this particular case, coincident time series of sea surface temperature and winds are available when the sardine population underwent a sharp change in abundance, probably induced by short term ENSOs and one of longer duration. Their description and comparison has added sufficiently to our understanding of the parallels between the environmental and the population variations to permit us to propose a cause-effect relationship.

A relationship between sardine availability and temperature has been proposed by a number of authors (Ahlstrom, 1965; Tibby, 1937; Hammann, Baumgartner, & Badan-Dangon, 1988; Lluch-Belda, Magallon, & Schwartzlose, 1986; Lluch-Belda, Lluch-Cota, Hernandez-Vazquez, Salinas-Zavala, & Schwartzlose, 1991). Although most attention has been focused to the cold side of the sardine's distribution, there is also information on its warm limits. It is well known that ENSOs result in the advection of warmer water into the Gulf of California, and that sardines restrict their distribution to the areas around the larger islands where the water stays cooler during these episodes (Huato-Soberanis & Lluch-Belda, 1987).

The effects of upwelling on sardine availability have also been described. The sardines are

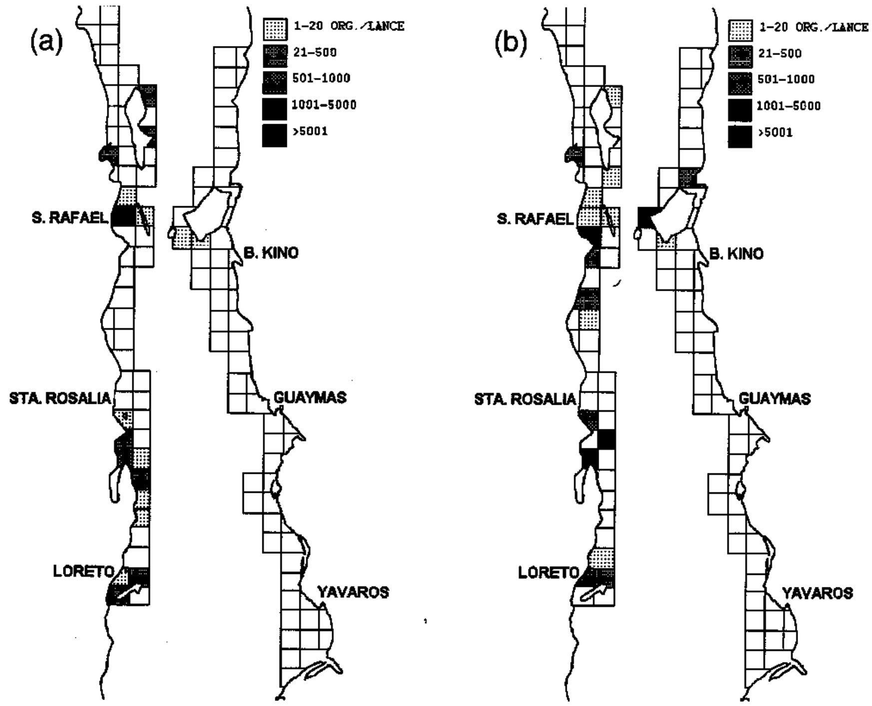

Fig. 8. Distribution of the pacific sardine in the Gulf of California, during the spring 1995 and spring 1996.

restricted to areas of nutrient-enriched waters and thus to the more productive areas (Bakun, 1996), thus making it evident that they require a minimum amount of upwelling, but there other papers have shown that too much upwelling also restricts their abundance and distribution (Ahlstrom, 1954; Lasker & MacCall, 1983; Cury & Roy, 1989; Lluch-Belda et al., 1991).

The results of our analysis of some of the environmental variables and the relative abundance of the Pacific sardine for the period 1990–1996, suggest that the high fluctuations in the sardine abundance were results of a switch from low to high upwelling intensity. Low upwelling intensity resulted in high SST's in the central area of the Gulf of California and a reduction in the primary production in the main areas of breeding, growth and spawn of the sardine. Thunell (1998a,b) showed that diatoms, the dominant group in the basin of Guaymas, and one of the main components of the diet of the Pacific sardine (López-Martínez, 1991; López-Martínez, Nevárez-Martínez, Molina-Ocampo, & Manrique-Colchado, 1999), diminished in abundance from 1990 to mid-1993 (the period in which there was an ENSO influence). But between 1994 and 1996 the abundance of the diatoms doubled, confirming that productivity is depressed during ENSO years and is significantly higher in non-ENSO years (Thunell, 1998b). Thus decline (1990–1993) and recovery (1994–1996) of the sardine abundances appear to a reflection of the upwelling activity and the associated changes in SST influencing primary productivity and the quality of that productivity. These abiotic factors, in turn reflect interannual changes in the prevailing climatic and hydrographic conditions in the Gulf whose variation is predominantly caused by ENSO events

(Lavín, Beier, & Badan, 1997; Ripa & Marinone, 1989; Robles & Marinone, 1987; Baumgartner & Christensen, 1985; Thunell, 1998b) that have repercussions on the meteorology and oceanography of the whole globe (Philander, 1990). It is not surprising is that the Gulf of California is strongly affected by its close proximity to the equatorial zone, where ENSO has its origin (Baumgartner & Christensen, 1985).

Our data on the spatial-temporal distributions of the pacific sardine, show that when the population declined, the area they occupied also declined, and as their abundance increased, so the area of their distributional range expanded. Similar results have been reported previously (Noto & Yasuda, 1999; Schwartzlose et al., 1999; Bailey, Maravelias, & Simmonds, 1998; Ottersen, Michalsen, & Nakken, 1998; Atkinson, Rose, Murphy, & Bishop, 1997; Kawasaki, 1993; Kawasaki & Omori, 1995; Lluch-Belda et al., 1989, 1991). In general, all these reports agree that the variations in the geographical distribution depend on the size of the stock and, to a lesser degree variations in the SST. The suggests that there is a direct relationship in the pacific sardine in the Gulf of California, between their areal distribution and the population's size, which are determined by the prevailing climatic conditions in the Gulf.

It is important to stress that during a periods of low abundance and adverse conditions along the continental coastal area, the region occupied by the sardine is near the bigger islands (Angel of the Guarda — Tiburón) where temperatures are relatively cooler than in the rest of the Gulf throughout the year. There the local bottom topography increases the tidal currents (Badan-Dangon et al., 1985), and creates a region of high of biological activity throughout the whole year (a Center of Biological Activity (BAC), Lluch-Belda, personal communication, CICIMAR — La Paz, B.C.S.). During summer the range of the pacific sardine is restricted to this region (Molina-Valdéz et al., 1984; Lluch-Belda et al., 1986; Cisneros-Mata et al., 1991; Hammann et al., 1988; Hammann, Nevárez-Martínez, & Green-Ruiz, 1998; Nevárez-Martínez, 1990) and then normally it expands its range during the spawning season at the end of autumn and winter. However, when conditions are adverse, such as during 1990–1992 and probably at earlier times, the migration pattern at the southern end of its distributional range change and the smaller population is restricted to the area of the bigger islands (BAC). These adverse conditions limit the southward expansion of adults and pre-adult juveniles. Reproductive activity also appears to be adversely affected because almost none of the plankton samples collected during the 1990–92 research cruises contained any sardine eggs or larvae (Yanira Green Ruiz, personal communication, CRIP — Mazatlán, Sinaloa, Mexico). These findings are being confirmed by the analyses of current research and in the distribution of the catches during recent fishing seasons near Guaymas, Sonora and the region of the bigger islands. We propose that the BAC is a key refuge area for the pacific sardine when extremely adverse conditions occur in the Gulf of California. One additional aspect that has important implications for the population and the fishery, is that sardine probably undertakes vertical migrations (Laevastu & Hela, 1970), since trawls towed at depths of 200 m, have captured large, mature sardines (J. L. Castro-Aguirre, personal communication, CICIMAR-IPN, La Paz, B.C.S.). These supports the conclusion that during the summer (or during an ENSO) mature sardines can extend their depth range below 100 m (D. Molina-Valdéz and M.A. Cisneros-Mata, personal communication, CRIP of Guaymas, Sonora, Mexico) where temperatures are lower and the availability of food poses no problem, because it is an area of high productivity thoughout the year (Alvarez-Borrego, Guthrie, Culberson, & Park, 1978; Alvarez-Borrego & Lara-Lara, 1991).

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