VARIABILITY OF SARDINE CATCH AS RELATED TO ENRICHMENT, CONCENTRATION, AND RETENTION PROCESSES IN THE CENTRAL GULF OF CALIFORNIA

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ABSTRACT

The sardine (*Sardinops sagax*) fishery of the Gulf of California is among Mexico's most important fisheries, accounting for the largest catch and providing many productive jobs. During the early 1990s, this fishery collapsed to less than 3% of the production maximum. Surprisingly, after two years of very low catch the fishery recovered quickly. We propose that these large fluctuations may be explained mainly by physical processes (enrichment, retention, and concentration) governing the sardine spawning habitat. The spawning area may be influenced by processes such as tidal mixing, winter northwesterly winds, coastal upwelling, prevailing surface currents, and Ekman transport, but most of its variability is believed to be wind-forced. Therefore we attempted to relate spawning extension to wind variations. By fitting an equation that expresses spawning as a probability function of a wind-derived index, we have built a spawning-probability time series based on egg and larval survey data and then tested against an independent series of landings and biomass indices (number of recruits and adults). Results show coherent relations between the spawning-probability series and the biological and fisheries data, despite large fluctuations (collapse and recovery). Our results are encouraging and may provide a solid theoretical basis for future environment-monitoring systems for the sardine fishery in the gulf.

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INTRODUCTION

Comparative studies of fish habitat climatology have provided key clues to understanding mechanisms linking physical environment to biological populations. Bakun (1996) noted that, for most cases, three major classes of physical processes (enrichment, concentration, and retention—the "fundamental triad") must co-occur to yield favorable reproductive habitats for many types of fish, including the small pelagics.

Optimal levels of wind stress drive optimal environmental conditions for reproductive activity. Cury and Roy (1989) have demonstrated that, in regions where Ekman type upwelling occurs, one physical variable (wind intensity) can result in a spectrum of conditions affecting the survival of small pelagic larvae. Three scenarios can be identified: (1) weak winds resulting in weak upwelling activity and thus in poor food levels, (2) strong winds producing strong upwelling activity but creating unfavorably high turbulence (see Lasker and MacCall 1983), and (3) moderate winds that produce enough upwelling and nutrient supplies while the water column remains stable. These scenarios, usually dome-shaped (named optimal environmental windows after Cury and Roy 1989), have proved to operate similarly in many small pelagic grounds (e.g., Ware and Thomson 1991; Cury et al. 1995).

Because weak winds result in nutrient depletion, and because strong winds may affect both retention and concentration, the optimal environmental window for reproductive success must properly combine the elements of the fundamental triad (cf. Bakun et al. 1998).

Understanding regional triad systems should greatly benefit regional fishery management.

The Gulf of California Sardine

The history of the Gulf of California sardine (*Sardinops sagax*) fishery is mainly defined by fleet capacity and geographic distribution of landings (Lluch-Belda et al. 1986; Cisneros-Mata et al. 1995; table 1). Since the 1982–83 fishing season, it has been difficult to explain catch fluctuations solely in terms of changes in fishing capacity.

The last 14 years have seen the strongest and fastest changes in the fishery. From 1989 to 1990, a dramatic collapse caused severe economic displacement, including the loss of more than 3,000 direct jobs and about half of the fleet and processing plants. (Landings in 1991–92 were less than 3% of those in 1988–89.) Another strong change, a fast recovery, began in the 1993–94 fishing season, as shown by increasing landing levels (fig. 1).

An analysis of the fishery was done by Cisneros-Mata et al. (1995). They pointed out that a decreased recruitment index occurred several years before it became evident in the catch and catch per unit of effort (since 1986), indicating a decreased spawning biomass years before the collapse. They concluded that overfishing, in combination with climate, must have played an important role, given the high rates of exploitation during adverse environmental conditions.

TABLE 1
Periods in the Gulf of California Sardine Fishery History, with Average Annual Landings

Period	Definition	Average annual landings (t/year)
1960–70 to 1975–76	Exploration and establishment	25,354
1976–77 to 1981–82	Development and growth	51,502
1982–83 to 1988–89	Expansion and stabilization	212,377
1989–90 to 1992–93	Collapse	59,495
1993–94 to 1996–97	Recovery	175,450

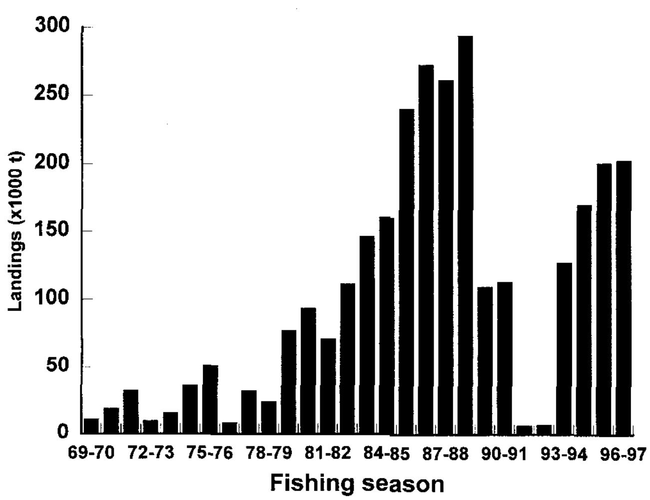

Figure 1. Gulf of California sardine landings, 1969 to 1997 (data provided by the Instituto Nacional de la Pesca, Centro Regional de Investigaciones Pesqueras CRIP-INP).

Although fishing mortality has been a major force driving the population collapse, analysis of sardine scale deposits in anaerobic sediments off the Guaymas Basin have shown large population fluctuations even in the absence of fishing activity (Holmgren-Urba and Baumgartner 1993), so natural variability must be considered. It is likely that management of the species depends on the ability to differentiate between natural variability and fishing mortality.

Previous studies of environmental forcing on the Gulf of California sardine population have been made by Sokolov (1974), Lluch-Belda et al. (1986), Nevárez-Martínez (1990), Hammann (1996), and Lluch-Cota et al. (1997).

Triad Physical Setting

Though few direct observations have been made in the Gulf of California, physical dynamics have been widely documented because the gulf combines two valuable properties: (1) It is often cloud-free, which makes it ideal for studies with satellite imagery (Badan-Dangon et al. 1985). (2) It constitutes a good-size basin for testing mesoscale and climate modeling (Ripa 1997).

Atmospheric forcing is characterized by weak summer winds blowing toward the northwest, and stronger winter winds toward the southeast (Roden 1964). Though this wind configuration is likely to produce Ekman-type upwelling along the continental margin during winter and along the peninsula during summer, only the first has been properly identified by satellite techniques (Lavín et al. 1997).

Ocean surface circulation has recently been described by Beier (1997), who used a two-layer linear model in which forcing agents (baroclinic waves, wind stress, surface heat flux) cause clockwise winter circulation and counterclockwise summer circulation. This general circulation scheme is supported by field observations (e.g., Lavín et al. 1997) and other model results (e.g., Ripa 1997).

Because both atmospheric and ocean circulation revert seasonally, strong intra-annual variability is present in almost every physical process in the gulf. An important mixing process takes place in the Canal de Ballenas area, where the bottom topography augments tidal currents year-round (Badan-Dangon et al. 1985).

We propose a theoretical model for the physical settings of the triad system in the Gulf of California (winter conditions) as a combination of six main components (fig. 2, panel 1): Strong tidal mixing (1) at the Canal de Ballenas results in an extremely dynamic water column

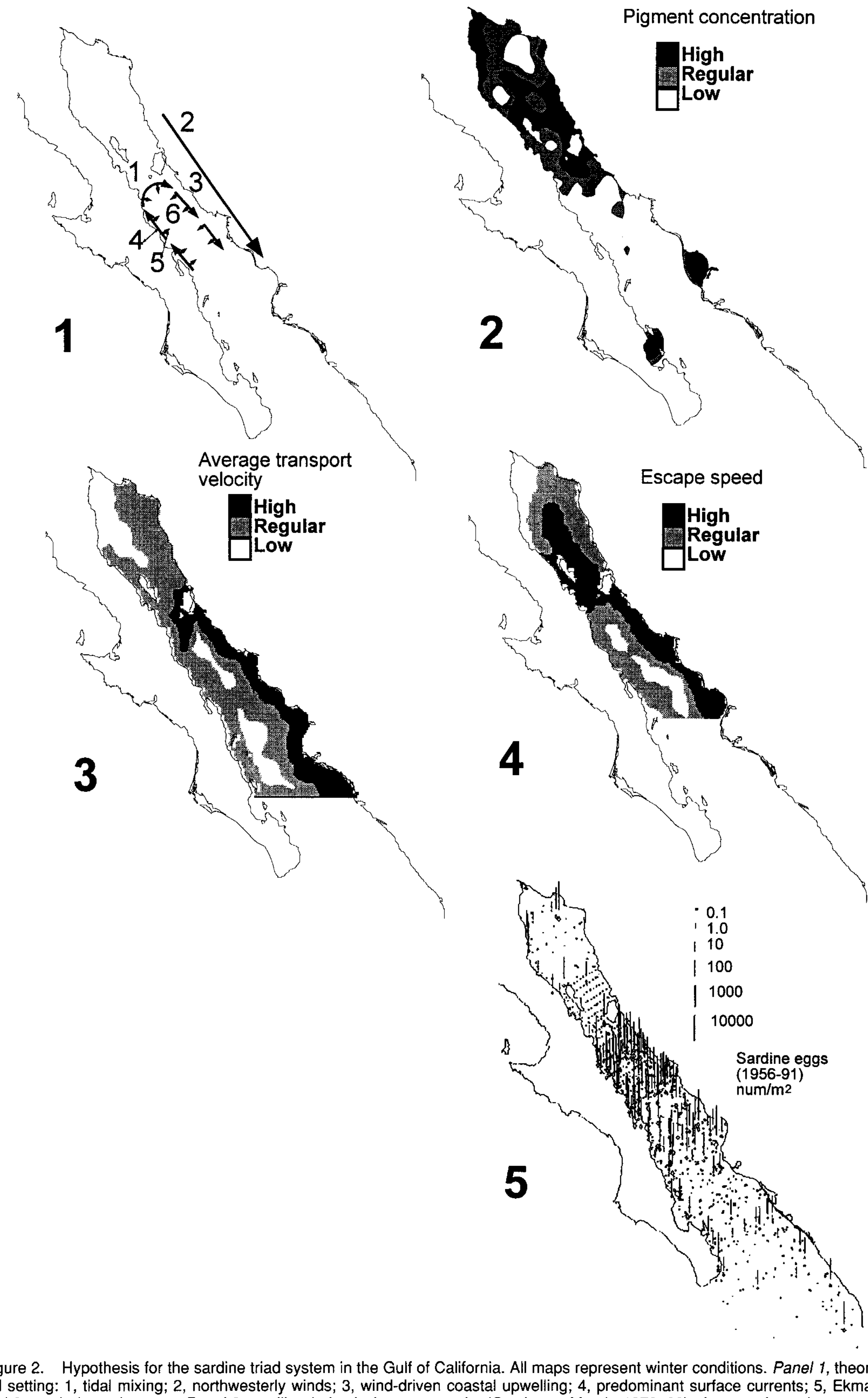

Figure 2. Hypothesis for the sardine triad system in the Gulf of California. All maps represent winter conditions. *Panel 1*, theoretical physical setting: 1, tidal mixing; 2, northwesterly winds; 3, wind-driven coastal upwelling; 4, predominant surface currents; 5, Ekman transport; and 6, weak dynamics area. *Panel 2*, satellite-derived winter-composite (October to March, 1978–86) of sea-surface pigment concentration (enrichment: data provided by Arias-Aréchiga, CIBNOR, S.C.). *Panel 3*, simulated ocean surface retention. *Panel 4*, surface circulation model results showing particle escape velocity (retention). *Panel 5*, historic abundance of sardine eggs in the Gulf of California (redrawn from Hammann et al. 1998).

inadequate for sardine reproduction (see Lasker and MacCall 1983). However, it exports nutrient-rich waters to nearby areas where more stable conditions prevail. During winter, when the wind blows south parallel to the coast (2), additional enrichment is associated with coastal upwelling along the continental margin (3). Rich water from both sources—tidal mixing and coastal upwelling—is carried along by the prevailing surface currents (4) and across the gulf by Ekman transport (5). Toward the middle area (6), the proper conditions for sardine reproduction result from high food concentration brought by surface currents and Ekman transport, as well as from water column stability and larval retention caused by weak dynamics.

METHODS

Sources and Preparation of Data

An area from the southern limit of Isla Tiburón south to Bahía Concepción and all across the gulf was selected as representative of the central gulf.

As an indirect indicator of the wind-forcing component relevant to the oceanographic processes in that area, we considered a monthly coastal upwelling index as derived from daily wind records at the Empalme (Sonora) Meteorological Station (Servicio Meteorológico Nacional). This index ($CUI_{Empalme}$), computed by Lluch-Cota (pers. comm.), represents the only long and continuous time series of wind-driven ocean processes inside the gulf.

We considered results from 24 sardine egg and larvae sampling cruises covering the central gulf (carried out by the Instituto Nacional de la Pesca from 1971 to 1987) as published by Nevárez-Martínez (1990). For each cruise, we evaluated the relation between the corresponding monthly value of the $CUI_{Empalme}$ and the estimated proportion of positive stations. Data are shown in table 2.

Spawning Probability Function

Attempts to express biological success as a function of one or a few easily measured environmental variables have been based on linear statistical methods, although nonlinearity is often recognized.

We have defined an equation to express spawning probability as a function of one measured variable (CUI) by combining simple ecological concepts with the hypothetical triad system dynamics in the Gulf of California:

1. Enrichment and stability limit spawning.
2. Nonlinearity in the relation between CUI and spawning success results from the interaction of two mutually exclusive processes: enrichment and stability.

TABLE 2
Base Data for the Spawning Probability Function

Cruise[a]	Total sampled stations	Positive stations	Proportion (positive/total)	Associated $CUI_{Empalme}$
AA7101	17	7	0.41	124.3
AA7204	24	12	0.5	57.3
AH7206	30	0	0	0.7
AA7302	25	4	0.16	8.8
AA7305	22	9	0.41	13
AA7308	16	3	0.19	−14.7
AA7402	12	7	0.58	97.9
AA7403	8	6	0.75	37.7
AA7405	9	9	1	56.9
AA7501	18	5	0.28	51.1
AA7503	13	6	0.46	99
AA7504	15	8	0.53	71.3
AA7601	18	7	0.39	57.9
AH7605	18	6	0.33	3.3
AA7605	17	0	0	3.3
AH7703	19	1	0.05	171.8
AA7708	16	5	0.31	−24.4
AA7802	24	10	0.42	8.8
AA7810	22	0	0	120.3
AA8103	18	15	0.83	89.7
PU8403	24	13	0.54	56.4
PU8611	135	58	0.43	153.4
AA8701	20	19	0.95	77.7
PU8711	22	19	0.86	138.2

Note: All data come from the central Gulf of California.
[a]Cruises as named by CRIP-INP.

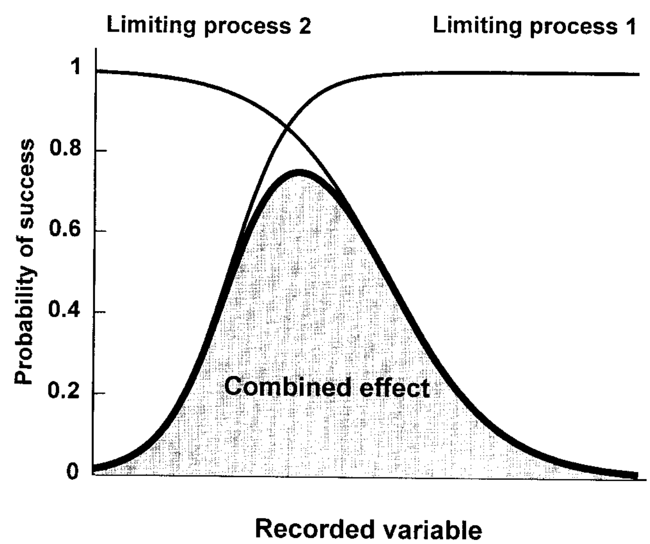

Figure 3. Theoretical approach for the spawning probability function.

Figure 3 shows the theoretical integration of these two concepts. We combined two sigmoid curves, each representing a limiting factor. These processes are mutually exclusive, inversely related, and controlled by the same external physical forcing (wind); thus one has a positive relation to the probability of success and the other a negative relation. Total probability is estimated by simply computing the arithmetic product. Because the response variable is given as a probability, the maximum possible value of individual curves (commonly called K) takes the value 1. This combination of curves is then expressed as

$$P_{spw} = [1/(1 + ae^{-b \cdot CUI})] \cdot [1/(1/(1 + ce^{d \cdot CUI})]$$

where P_{spw} is the final spawning probability; CUI is the associated upwelling index value; and a and b are the parameters for the first sigmoid curve, c and d for the second.

After fitting the model with our data (shown in table 2), we applied the resulting function to a winter $CUI_{Empalme}$ (built by averaging consecutive months of a typical sardine spawning season, October–March) and computed a spawning probability time series for the period 1978–96. We then filtered this series with a 3-year moving average to eliminate the highest frequency, and compared it with the number of recruits and adults (as published by Cisneros-Mata et al. 1995) and landings (as provided by the Instituto Nacional de la Pesca).

RESULTS

The curve representing spawning probability as a function of $CUI_{Empalme}$ is shown in figure 4, together with the original data (as presented in table 2). The spawning-probability time series was built by applying that function to the winter $CUI_{Empalme}$ data. The resulting series (fig. 5) shows a peak during the period 1981–82 through 1983–84 and then a persistent decline until the 1990–91 fishing season. Since then a fast upward trend can be seen. Published data series (number of recruits and number of adults) show peak values in 1985–86, and then downward trends (more recent data are not available). Landings peaked around the 1988–89 fishing season and dramatically declined through 1992–93. Since then, they have shown a persistent upward trend.

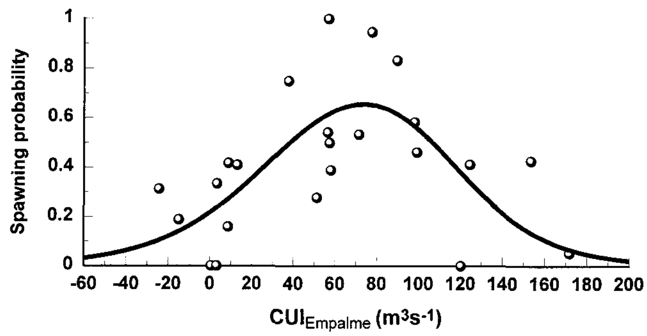

Figure 4. Spawning probability as a function of the $CIU_{Empalme}$ (circles) and fitted model (line).

DISCUSSION

Enrichment concentration and retention processes co-occur during a certain part of the year in the central Gulf of California. Panels 2 through 5 of figure 2 show

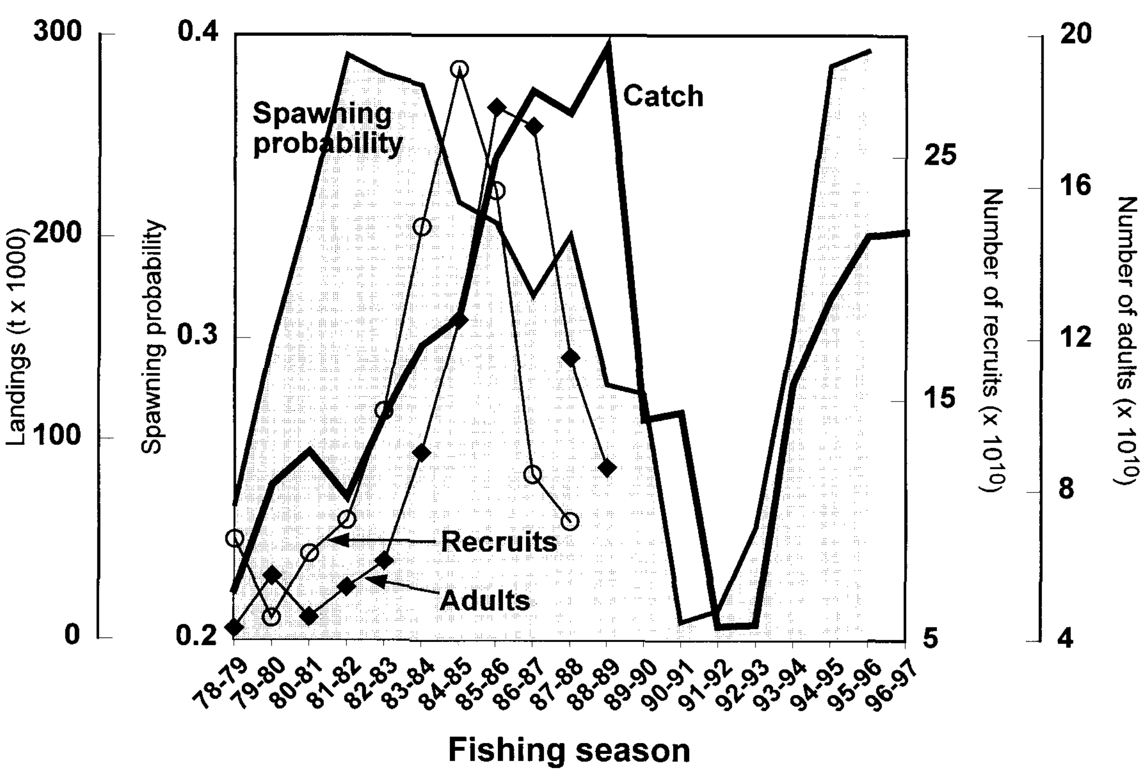

Figure 5. Time series of spawning probability as estimated from the spawning probability function (shaded curve), number of recruits (open circles), and number of adults (dark diamonds) digitalized from Cisneros-Mata et al. (1995). Landings of Gulf of California sardine (bold line) provided by CRIP-Guaymas-INP.

some real data and numerical model results. Enrichment is illustrated by a satellite-derived winter-composite pigment concentration (October–March; 1978–86). Retention and concentration are shown by outputs from a POM (Princeton ocean model; Blumberg and Mellor 1987) adapted to the gulf by Pares-Sierra and simulating surface ocean conditions after a month of winter winds and tidal forcing. Concentration is given as current residuals (i.e., transport without tidal influence). Retention is represented by a first escape index (the average residence time of a particle in a given). Finally, historically integrated sardine egg abundance (as modified from Hammann et al. 1998) demonstrates the importance of the central gulf as a spawning ground.

We believe the coherent, parallel behavior between the sardine series and the spawning probability series (i.e., an index of the extent of spawning as computed from wind data) strongly supports the existence of a wind-forced triad system governing the sardine spawning habitat and therefore large fluctuations of the population. If we look at the first part of the series (1978–86), coherent relations can be established between the probability series—based on egg and larval survey data—and the independent series of population dynamics. The environmentally favorable conditions, as reflected by the spawning probability estimated from the $CUI_{Empalme}$, are followed by the number of recruits with a delay of one year. The adult members and the landings series are also consistently delayed. Thereafter, from 1987 through 1996, spawning probability still led the sardine landing series, but the delay does not correspond to that observed during the previous period. Although we are not certain how the number of recruits and adults behaved during this second period, we can state that, at least to some extent, this difference is because the landings before the collapse consisted mainly of 2- to 3-year-old fish, whereas the recovery was based mainly on very young (1-year-old) fish (Nevárez-Martínez, pers. comm.). In any event, this second period is still more encouraging because it behaves coherently during a period of large, dramatic changes in the population (collapse and recovery). More important, the probability function was constructed only from data prior to this period, and thus the spawning probability series is predictive.

CAVEATS AND FURTHER RESEARCH

Though the physical setting of the model was formulated from observations and results from many authors, knowledge gaps must be filled and complete understanding reached by combining results from numerical models, retrospective analyses, and field observations. Besides testing the proposed hypothesis, we should improve our modeling capabilities. If it is true that the wind signal is a good predictor of tendencies in the fishery, it may also be true that more quantitative and valuable results could be obtained if we also consider other key environmental signals. Numerical modeling and field observations could indicate the concentration and retention processes in the spawning ground; the importance of coastal upwelling as a rich water source in relation to total food availability; changes in the size and quality of the spawning ground; and turbulence. Furthermore, quantification of the relative importance of temperature as a limiting factor, and its incorporation into the model should be relevant.

Implementing environmental monitoring systems for fishery forecasting represents a further step, and the main goal for this type of research. Such work requires high-quality data. Fortunately, remote sensing can now be combined with sophisticated field sensors to measure many physical properties of the ocean. However, a solid theoretical basis is needed before any advance can be made.

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