The Recruitment of the Chilean Sardine (*Sardinops sagax*) and the "Optimal Environmental Window"

RODOLFO SERRA*
PHILIPPE CURY**
CLAUDE ROY**

* Instituto Fomento Pesquero
Casilla 8.V
Valparaiso
CHILE

** Sea Fisheries Research Institute
Private Bag X2
Rogge Bay 8012
Cape Town
SOUTH AFRICA

ABSTRACT

The relationships between the recruitment of Chilean and Peruvian sardine and environmental factors from 1974 to 1990 are analyzed. Recruitment indices (numbers at age 2) as well as parental biomasses are calculated using sequential population analysis. Sea surface temperature, wind mixing, and upwelling indices are used to characterize the variability of the environment in the spawning area. The analysis is performed using generalized additive models. No apparent relationship exists between recruitment and temperature. The relationship between recruitment and upwelling or wind mixing appears to be dome shaped. Switches between a sardine and an anchovy dominated ecosystem, appears also as an important contributor to recruitment variability.

RÉSUMÉ

Les relations entre le recrutement de la sardine au Chili et au Pérou et des facteurs environnementaux sont analysées de 1974 et 1990. Les indices de recrutement (nombre de poissons à l'âge de deux ans) ainsi que la biomasse parentale sont calculés en utilisant des analyses séquentielles des populations. La température de surface, le mélange dû au vent et des indices d'upwelling sont utilisés pour caractériser la variabilité de l'environnement dans la zone de ponte. L'analyse est faite en utilisant des modèles additifs généralisés. Il n'y a pas de relation apparente entre le recrutement et la température. La relation entre le recrutement et l'upwelling ou le mélange par les vents apparaît en forme de dôme. Les changements de dominance par la sardine ou l'anchois au sein de l'écosystème apparaissent importants pour expliquer les fluctuations du recrutement.

INTRODUCTION

Chilean sardine, *Sardinops sagax*, increased significantly its abundance in the Southeast Pacific since the late 1960s, becoming the most important fisheries resource in Chile in the 1980s (Serra, 1983). After 1985, sardine landings started to decline and anchovy catches increased again, suggesting a change in the dominant species within the ecosystem (Serra, 1989; Lluch-Belda *et al.*, 1992). It is well known that the most productive regions are associated with upwelling systems, such as the Benguela, the Canary, the California or the Humboldt current systems. Clupeoids are the most abundant resources in these ecosystems, suggesting a strong connection between pelagic fish population dynamics and upwelling processes.

Observed decadal changes in abundance of the sardine and of the anchovy have been related to global warming (Kawasaki, 1993; Lluch-Belda *et al.*, 1989 and 1992; Sharp, 1993). Bakun (1990) suggests that global warming results in an increase of the equatorward wind leading to an intensification of the upwelling process in eastern boundary current ecosystems. Sardine has been associated with warmer conditions in the ocean (subtropical or oceanic conditions) and anchovy with cooler conditions (coastal or upwelling conditions) (Loeb and Rojas, 1988; Serra, 1989).

The eastern margin of the Southeast Pacific is a typical upwelling system. Equatorward trade winds induce offshore Ekman transport which brings cold and nutrient-rich subsurface water to the euphotic layer, enhancing primary production. The strength of upwellings is closely related to the wind: an increase of the alongshore wind results in an intensification of the offshore transport which favors an increase of the upwelling process. Wind also generates mixing in the surface layers. Cury and Roy (1989) studied the links between recruitment variability and upwelling intensity in the major eastern boundary current ecosystems. They showed that there is a dome-shaped relationship between recruitment and upwelling intensity. There are two factors that explain the non-linearity of the curve: on the left side, the wind is weak and the limiting factor is the production of food due to low intensity of the upwelling; on the right side of the curve, the upwelling is strong and wind mixing or offshore transport are the limiting factors. Thus, there is an 'optimal environmental window' at moderate levels of upwelling, where the effects of the limiting factors are minimized.

This paper explores the links between environmental indices such as sea surface temperature, wind mixing and upwelling index, with recruitment variability of the sardine stock off southern Peru and northern Chile, i.e., which represents the 'central sardine stock' (Parrish *et al.*, 1989), located from 15°S to 25°S. This stock has sustained the main pelagic fisheries in northern Chile since the early 1970s to the late 1980s, and a smaller fishery in southern Peru.

1. MATERIALS AND METHODS

The data on sardine spawning stock and recruitment were produced by the working group GTE-93 of IFOP/IMARPE. They derived this information through sequential population analysis (i.e., VPA) from 1974 to 1990 (17 years). The spawning stock was expressed in tons and the recruitment in numbers at age 2.

The environmental data considered are the sea surface temperature (SST), the wind mixing (WM) and the coastal upwelling indices (CUI). Mean annual SST was calculated from data collected at the Arica coastal station located in northern Chile. Wind data from the Comprehensive Ocean-Atmosphere Data Set (Roy and Mendelssohn, this vol.) were used to estimate WM and CUI in southern Peru (14°S-18°S). Since the shared sardine stock between Peru and Chile is distributed from about 15°S to 24°S and that approximately 20% of the total spawning area is located in southern Peru (17°S-18°S), we made the

Year	Recruitment Nr.10^6	Spawning biomass (t.10^3)	Sea Surface Temperature(°C)	Coastal Upwelling Index ($m^3/s/m$)	Wind mixing (m^3/s^3)	Ecosystem Factor
1972	–	–	17.4	1.41	422	–
1973	–	–	15.3	0.97	263	–
1974	14782	2119	15.5	1.15	323	1
1975	21183	2907	15.4	1.25	372	1
1976	38782	3759	16.3	1.30	429	1
1977	40266	5593	16.8	1.19	359	1
1978	39166	6769	15.9	1.11	302	1
1979	36700	7953	17.5	1.14	310	1
1980	35520	9305	18.8	0.89	235	1
1981	25427	8924	17.1	1.11	340	1
1982	17350	8457	19.9	1.41	418	1
1983	48143	6787	17.5	1.37	394	2
1984	35346	5682	16.9	1.15	316	2
1985	19374	5883	16.1	0.98	242	2
1986	20004	4695	16.3	1.03	282	2
1987	20875	4246	17.1	1.31	384	2
1988	13299	3603	15.3	1.50	499	2
1989	9451	3094	15.8	1.24	355	2
1990	6451	2472	15.4	1.22	366	2
1991	3247	2072	16.2	–	–	2

Table 1: Sardine and environmental data used in the analysis (see text).

assumption that the environmental data are representative for northern Chile; this is also suggested by a similar general trend of both SST and CUI. The data used in the analysis are shown in Table 1.

The statistical method used in this study, is a generalized additive model (Hastie and Tibshirani, 1990), an extension of multiple linear regression, first applied to fishery science by Mendelssohn and Cury (1987). The ACE algorithm (Alternating Conditional Expectation, Breiman and Friedman, 1985) allowed Cury and Roy (1989) to explore the form of the relationship between recruitment success and environmental indices in several upwelling ecosystems. In the analysis of the relation between recruitment and environmental factors, linear statistical methods are commonly used. Because present knowledge is not sufficient to know a priori the correct form of the relationship, it is desirable to use methods which estimate the appropriate functional form. With ACE, the form of the variables is obtained by plotting the transformed values versus the original values. This approach allowed Cury and Roy (1989) to test the hypothesize that the relationship between recruitment and upwelling intensity is dome-shaped in Ekman-type upwelling, and linear in non Ekman-type upwellings. The statistical method are documented by Cury *et al.* (1995), and thus not described further in this paper.

2. RESULTS

The relationships between SST, WM (or CUI) and recruitment are shown in Figure 1. Large variations of recruitment occur without any apparent link with these environmental parameters. Using the ACE algorithm to analyze the relationship between the environmental parameters and recruitment, only a small proportion of the observed variance in recruitment can be explained. Using SST, WM and CUI for the 1972 to 1991 time period, the explained variance is: 16%, 15% and 23% respectively. When spawning biomass is added to the regression for the period 1974 to 1990, the variance explained becomes 53% with CUI. While the transformation of recruitment is linear, the shape of the transformations for WM and

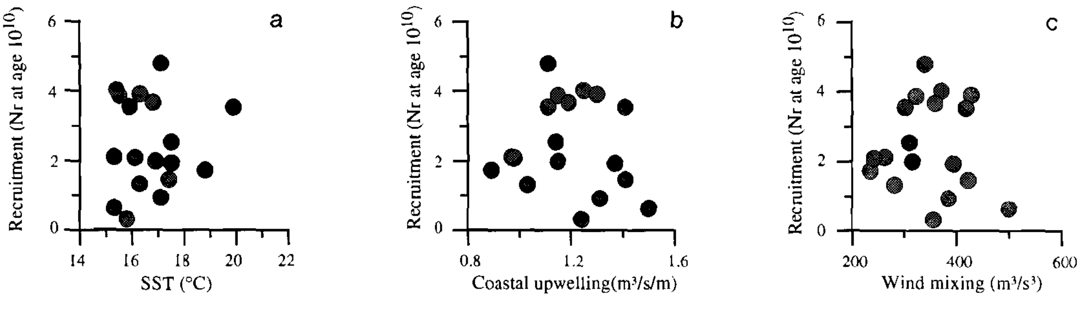

Fig. 1: Recruitment of Chilean sardine at age 2 from 1974 to 1990 vs (a) SST; (b) coastal upwelling index; and (c) wind mixing.

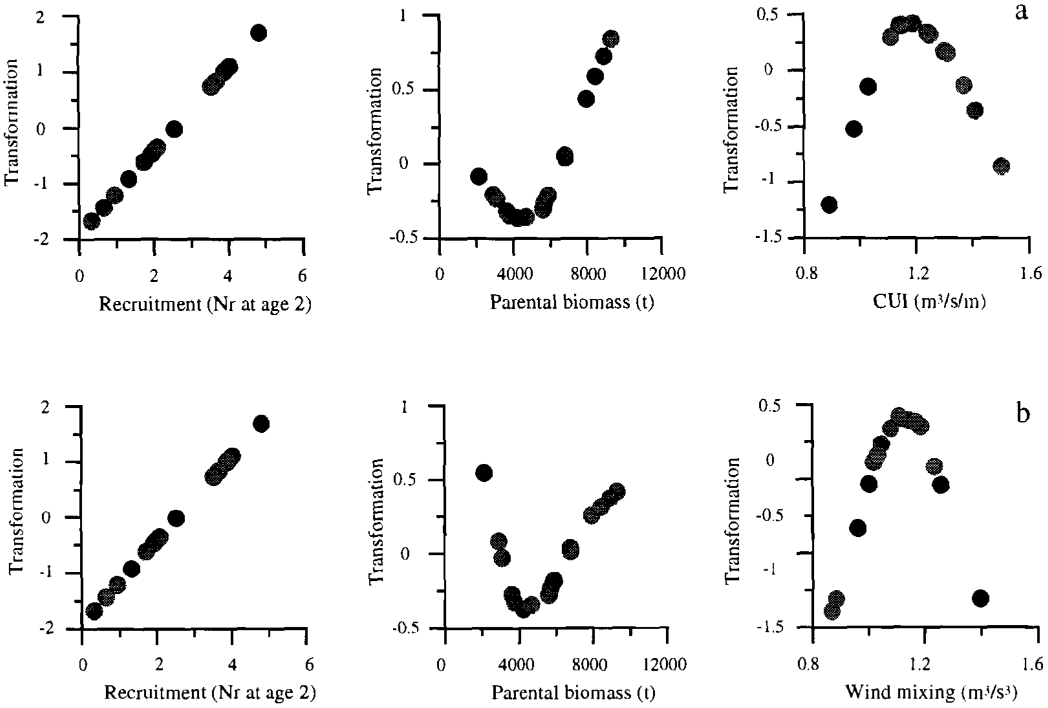

Fig. 2: Transformation from the ACE algorithm considering :
a) sardine recruitment in numbers x 10^{10} at age 2, parental biomass and coastal upwelling index (R^2=0.23);
b) sardine recruitment in numbers, parental biomass and wind mixing (R^2=0.15).

CUI is dome-shaped (Fig. 2), with a maximum of 360 m^3/ s^3 for WM and 1.1 $m^3/s/m$ for CUI. There is a V-shaped transformation for parental biomass.

The dominance from anchovy to sardine changed in the late 1960s (Serra, 1983 and 1989; Loeb and Rojas, 1988), and changed again after 1983 when anchovy again became the dominant component in the ecosystem. This last switch can be seen in the spawning stock/recruitment plot (Fig. 3) where a change in the form of the relationships suggests a change in the pelagic ecosystem, which became favorable for anchovy and unfavorable for sardine. A similar dynamics is well documented for the Californian sardine and anchovy (Skud, 1982). In order to evaluate a possible impact of fish dominance on the population, an Ecosystem Factor (EF) was introduced into the analysis; the 'sardine dominated ecosystem' is coded as 1 and the 'anchovy dominated ecosystem' as 2 (Table 1). The results given by the ACE algorithm using EF with WM or CUI, improved the percentage of explained variance to 75% and 71% respectively. The dome-shaped transformations for both WM and CUI remain unchanged (Fig. 4).

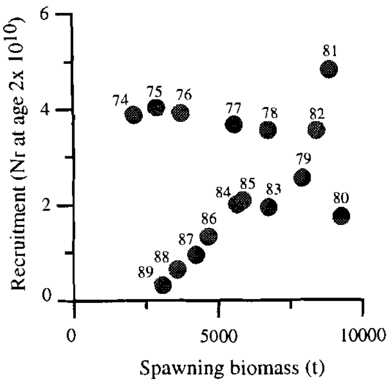

Fig. 3: Sardine spawning stock-recruitment plot. The numbers above the data points correspond to the years at recruitment of age-group 2 fish.

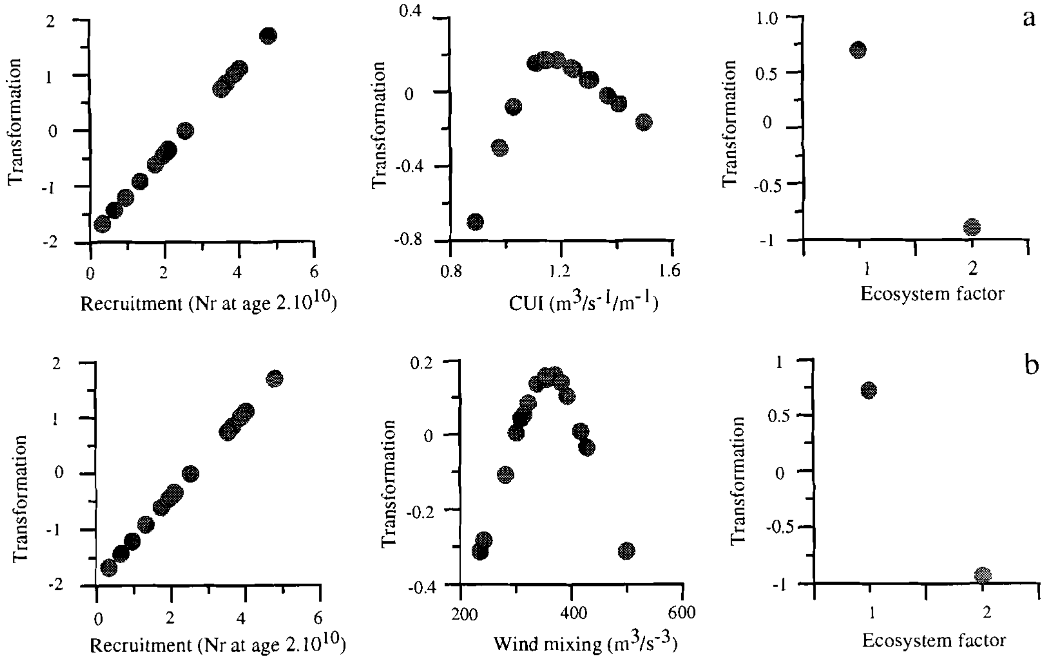

Fig. 4: Transformation from the ACE algorithm considering:
a) recruitment in numbers, Coastal Upwelling Index and the Ecosystem Factor (R^2=0.71)
b) recruitment in numbers, Wind Mixing and the Ecosystem Factor (R^2=0.75).

DISCUSSION

The dome-shaped pattern between recruitment and CUI or WM is consistent with Cury and Roy's (1989) findings and other results obtained in different upwelling systems (Roy *et al.*, 1992; Cury *et al.*, 1995). Following Cury and Roy (op. cit.), the dome-shaped relationship between recruitment and the environment results from the positive effect of upwelling on larval food and the counteracting effect of wind mixing or offshore transport on larval mortality (Lasker, 1975; Peterman and Bradford, 1987, Parrish *et al.*, 1981). However, in this study, CUI and WM are both derived from wind speed observations collected by ships of opportunity. CUI and WM are positively correlated and they give almost identical results. Using these variables, it remains impossible to separate the effect of the upwelling process from the effect of wind mixing on recruitment.

The results obtained with SST are against the general belief that 'warm' environmental conditions favor the abundance of sardines. Recruitment variability appears to be related to the upwelling process, but in a non-linear fashion. The environment is an important contributor to recruitment variability but it is not the only such factor. The switch from a sardine to an anchovy-dominated ecosystem, as it occurred after 1983, appears to be an important contributor to recruitment variability. A consequence of the changes within the biological components of the ecosystem is that different levels of abundance can be reached for a given value of the upwelling intensity depending on the dominant species within the ecosystem, so it does not explain the long term change in abundance of the sardine (Skud, 1982).

REFERENCES CITED

Bakun A. 1990. Global climatic change and intensification of coastal ocean upwelling. *Science*, 247: 198-201.

Breiman L. and J.H. Friedman. 1985. Estimating optimal transformations for multiple regression and correlation. *J. Am. Stat. Assoc.*, 80(391): 580-619.

Cury P. and C. Roy. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Can. J. Fish. Aquat. Sci.*, 46: 670-680.

Cury P., C. Roy, R. Mendelssohn, A. Bakun, D.M. Husby and R.H. Parrish. 1995. Moderate is better: exploring nonlinear climatic effect on Californian anchovy. *In*: R.J. Beamish (ed.). Climate and northern fish populations. *Can. Spe. Pub. Fish. Aquat. Sci.*, 121: p 417-424.

Hastie T. and R. Tibshirani. 1990. *Generalized additive models*. Chapman and Hall, London.

Kawasaki, T. 1993. Recovery and collapse of the far eastern sardine. *Fish. Oceanogr.*, 2(3/4): 244-253.

Lasker R. 1975. Field criteria for survival of anchovy larvae: the relation between onshore chlorophyll maximum layers and successful first feeding. *Fish. Bull.*, 73: 453-462.

Lluch-Belda, D., R.J.M. Crawford, T. Kawasaki, A.D. MacCall, R. H. Parrish, R. A. Schwartzlose and P. E. Smith. 1989. Worldwide fluctuations of sardine and anchovy stocks: the regime problem. *S. Afr. J. Mar. Sci.*, 8:195-205.

Lluch-Belda D., R.A. Schwartzlose, R. Serra, R. Parrish, T. Kawasaki, D. Hedgecock and R.J.M. Crawford. 1992. Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. *Fish. Oceanogr.*, 1(4): 339-347.

Loeb V. and O. Rojas. 1988. Interannual variation of ichthyoplankton composition and abundance off northern Chile, 1963-83. *Fish. Bull.*, 88(1): 1-24.

Mendelssohn R. and P. Cury. 1987. Fluctuations of a fortnightly abundance index of the Ivoirian coastal pelagic species and associated environmental conditions. *Can. J. Fish. Aquat. Sci.*, 44: 408-428.

Parrish R.H., C.S. Nelson and A. Bakun. 1981. Transport mechanism and reproductive success of fishes in the California Current. *Biol. Oceanogr.*, 1(2): 175-203.

Parrish R.H., R. Serra and S. Grant. 1989. The monotypic sardines, *Sardina* and *Sardinops*: their taxonomy, distribution, stock structure and zoogeography. *Can. J. Fish. Aquat. Sci.*, 46: 2019-2036.

Peterman M.R. and M.J. Bradford. 1987. Wind speed and mortality rate of a marine fish, the northern anchovy (*Engraulis mordax*). *Science*, 235: 354-356.

Roy C., P. Cury and S. Kifani. 1992. Pelagic fish recruitment success and reproductive strategy in upwelling areas: environmental compromises. *S. Afr. J. Mar. Sci.*, 12: 135-146.

Serra R. 1983. Changes in the abundance of pelagic resources along the Chilean coast. *FAO Fish. Rep.*, 291 (2): 255-284.

Serra R. 1989. Long-term variability of the Chilean sardine. *In*: T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi (eds.). *Long-term variability of pelagic fish populations and their environment*. Pergamon Press, Oxford, 165-172.

Sharp, G. 1993. Fisheries, El Niño-southern oscillation index and upper-ocean temperature records: an eastern Pacific example. *Oceanography*, 6(1):13-22.

Skud, B. 1982. Dominance in fishes: the relation between environment and abundance. *Science*, 216 (9): 144-149.