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Synchronous pattern of fluctuation in three anchovy fisheries in the Humboldt Current System

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Abstract – Interdecadal versus interannual time-scale variations of catch data of three anchovy fisheries distributed in the Humboldt Current System (HCS) were analyzed during the period 1960–2002, by using first a loess smoother. The loess residual data were considered as the interannual variation. Interdecadal changes were highly coherent for the three fisheries of anchovy distributed in the HCS, while there were differences in terms of interannual variations. The north-central Peru fishery was similar to the south Peru-northern Chile fishery in terms of the interannual component of fluctuation of these fisheries which was significantly and negatively related with El Niño-Southern Oscillations events occurring during the spring of the previous year. Interdecadal synchronous variations in the three anchovy fisheries suggest a common forcing by long-term environmental factors in the HCS, although other causes cannot be excluded. During the last 40 years, coherent changes in anchovy fisheries were observed, and this synchronous pattern is out of phase with large-amplitude sardine regimes. Long-term climate variability seems to be the main cause for interdecadal fluctuations in anchovy fisheries in the HCS, although available time series are too short to prove this link and exclude the hypothesis of nonenvironmental forcing. Large-amplitude regime shifts may be more important to consider than interannual changes since they can affect simultaneously and more dramatically the three anchovy fisheries distributed in the Humboldt Current System.

Key words: anchovy / pelagic fisheries / interannual and interdecadal variability / Southeastern Pacific / Humboldt Current

Résumé – Variations synchrones de trois pêcheries d'anchois dans le système du courant de Humboldt. Les variations des captures de trois pêcheries d'anchois du système du courant de Humboldt (HCS) ont été analysées, à l'échelle décennale au cours de la période 1960–2002, après ajustement à l'aide d'un lisseur. Ensuite, les résidus de cette relation furent considérés comme représentant les variations interannuelles, donc de fréquence plus élevée. Les variations des captures sont très cohérentes entre les trois pêcheries d'anchois du HCS, tandis que l'on observe des différences entre les variations interannuelles régionales. Les variations des captures du centre-nord du Pérou ont été similaires à celles de la pêcherie sud-Pérou/nord-Chili à l'échelle interannuelle, et les variations à cette échelle sont corrélées négativement et de façon significative avec les événements El Niño de l'Oscillation australe (ENSO) du Pacifique ayant lieu au cours du printemps austral de l'année antérieure. Les variations synchrones, à l'échelle décennale, des captures des trois pêcheries d'anchois suggèrent un forçage commun par des facteurs environnementaux du HCS à la même échelle temporelle, bien que d'autres causes ne puissent être exclues. Au cours des 40 dernières années, des variations cohérentes ont été observées et ces changements synchrones sont en opposition de phase avec des « régime de sardine ». Les variations climatiques interannuelles et interdécennales semblent être à l'origine des fluctuations des captures d'anchois dans le HCS, bien que les séries chronologiques soient trop courtes pour prouver l'existence de ces liens et exclure l'hypothèse d'un forçage nonenvironnemental. Les changements de régime de grande amplitude semblent plus importants à prendre en compte que la variabilité interannuelle car ils affectent simultanément et de façon plus intense les trois pêcheries d'anchois du HCS.

1 Introduction

In the Humboldt Current System (HCS), three main fisheries of anchovy (*Engraulis ringens*) can be identified (Fig. 1). The most productive of the anchovy fisheries is located in north-central Peru (4°–15° S), followed by the shared fishery distributed between south Peru and northern Chile (16°–27° S), and the most austral and less abundant located in the central-south area off Chile (34°–40° S). These three

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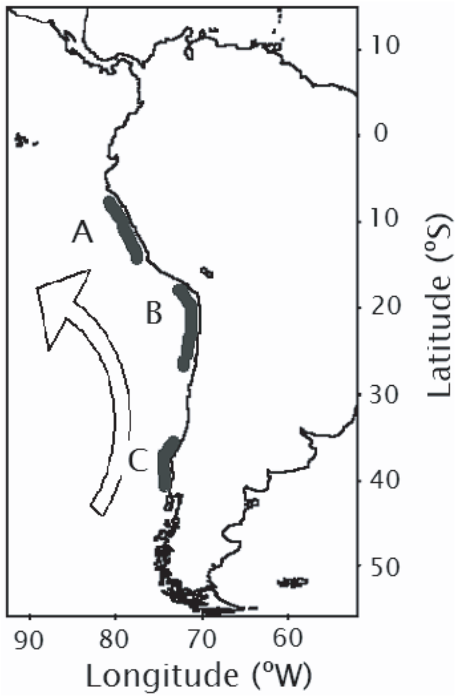

Fig. 1. Scheme of distribution areas of three anchovy (*Engraulis ringens*) fisheries in the Humboldt Current (schematized by the arrow) System: A: North-Central Peru fishery, B: South Peru – Northern Chile fishery, C: Central-South Chile fishery.

fisheries are supposed to correspond to three discrete stocks (Serra 1983; Alheit and Ñiquen 2004) although the issue of stock identity is still debated. In these fisheries, important fluctuations in population size have occurred during the last 50 years, including regimes of low anchovy abundance in which sardine, *Sardinops sagax,* dominate and vice versa (Serra 1983, 1989; Yáñez 1989; Lluch-Belda et al. 1992; Yáñez et al. 2001; Chavez et al. 2003; Alheit and Ñiquen 2004). Regime shifts affect the structure, dimension and dynamics of fisheries, and their causes are being intensively studied world-wide (Lluch-Belda et al. 1992; Schwartzlose et al. 1999; Hare and Mantua 2000; Miller and Schneider, 2000; McFarlane et al. 2000; Montecinos et al. 2003, Pizarro and Montecinos 2004; Steele 2004; Collie et al. 2004), but remain still poorly understood.

In this paper, we attempt to separate the interdecadal and interannual components of variability in anchovy catch data with the aim of looking for synchronous patterns of fluctuation in the three separate fisheries (see Fréon et al. 2003). Although there is empirical evidence for such synchronous patterns, this evidence has not been analyzed statistically for the HCS. Catch data may reveal coherent large-scale fluctuations in productivity because anchovy is a short-living species, recruiting at age ranging from 0.5 to 1 year (Serra 1983; Pauly et al. 1987; Yáñez 1989) and the fishery is likely to react quickly to changes in abundance. Interannual variation in catch data is expected to be dominated by interannual recruitment variability mediated through the El Niño-Southern Oscillation events. In this way, a relationship between interannual components of the variability and an El Niño index was explored.

2 Material and methods

Annual catch data of the three anchovy fisheries were obtained to construct time series covering the period from 1960 to 2002. Although catch data are available from 1950 for Peru and Northern Chile, we started the analysis from 1960 to avoid the developmental phase of the fisheries during 1950–1959 because probably the small catches during that period are not related with abundance. For the North-Central Peru fishery we used the catch inventory published by Schwartzlose et al. (1999), and updated it from the web site of IMARPE (`www.imarpe.gob.pe`) and fisheries statistics from IFOP (`www.ifop.cl`). Regarding the South Peru-Northern Chile and Central-Southern Chile fisheries, catch records for the period 1960–2002 were obtained from the "Servicio Nacional de Pesca" of Chile. We selected the annual catch to analyze components of variability because indices of abundance are not available for the three fisheries during such a long time period.

According to Spencer and Collie (1997), the simplest representation of pattern in abundance or productivity is a long-term temporal increase or decrease, which was evaluated with a linear regression of catch against year. To assess variability at an interdecadal scale, a loess smoother (Cleveland 1979) was applied to each data set using a narrow (span = 0.3) smoothing window (Spencer and Collie 1997). Different spans were tested, showing that the method is robust to this parameter. The residuals between the smoothed data and linear trend (trend removal) are defined here as the interdecadal variation. The residuals between the original and smoothed data are considered here as the interannual variation. The proportion of variance explained by the smoothed trend was evaluated with the coefficient of determination, $r^2 = 1 - [\text{Var(residuals)}/\text{Var(original data)}]$. Regression analyses were performed to identify the relationships between catches in the three fisheries at decadal and annual scales, and all residuals were standardized by resting the average of residual and then dividing them by the standard deviation. The coefficients of correlation between catch series constructed for the study of interdecadal variation are highly overestimated due to the high autocorrelation resulting from loess smoothing. Therefore, these coefficients are mainly used for comparison of the relative strength of the relationships between couples of time series.

Sea surface temperature (SST) data from the El Niño 1+2 area in the equatorial Pacific (0–10° S, 90–80° W) were used as an index of the El Niño-Southern Oscillation to analyze the influence of interannual environmental changes on each anchovy fishery. These data were obtained from the NOAA data base available at `http://www.cpc.ncep.noaa.gov`. Because the interannual component of fluctuation in the catch is supposed to be correlated to recruitment, it was contrasted with the average SST anomalies in the El Niño 1 + 2 zone observed during the previous year for the period September-December. We used this time window because the main spawning season occurs between August and October (austral spring, Mendelssohn and Mendo 1987; Peña et al. 1989; Senocak et al. 1989) and the period September-December is associated with the pre-recruitment spring period. Linear regression was used

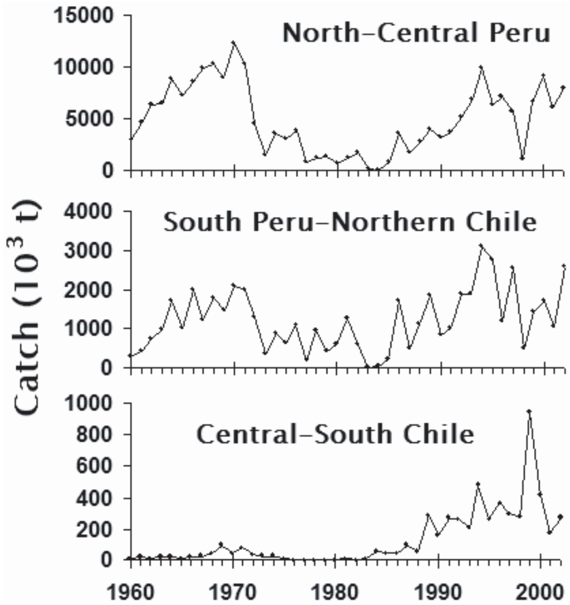

Fig. 2. Catch history in the three main anchovy fisheries in the Humboldt Current System (see Fig. 1).

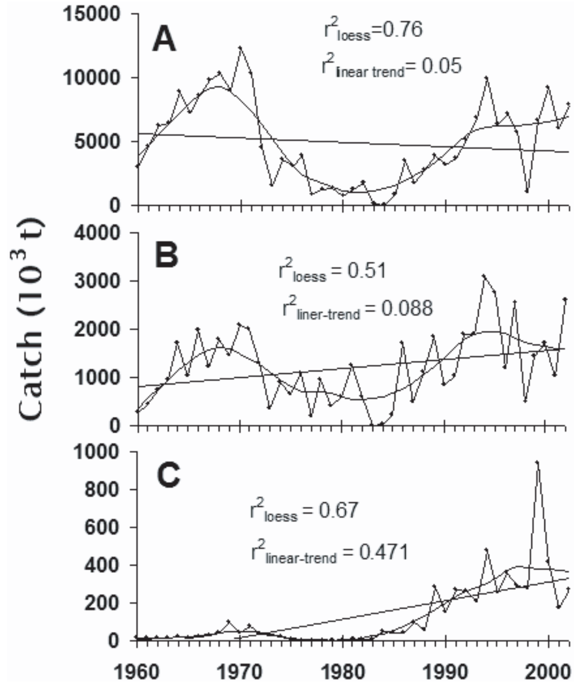

Fig. 3. Linear and loess long-term trend analysis of the catch in three anchovy fisheries in the Humboldt Current System: A: North-Central Peru fishery, B: South Peru – Northern Chile fishery, C: Central-South Chile fishery (r^2_{loess} = variance explained by loess; $r^2_{\text{linear-trend}}$ = variance explained by a linear model).

to describe the relationships between interannual residuals and SST anomalies.

3 Results

During the 1960–2002 period, there were concurrent changes in catches from the three fisheries (Fig. 2). The highest amplitude of catch variation was observed in the North-Central Peru fishery and the lowest in the central-south area off Chile. The first period of high catches occurred between 1960 and 1972. From 1973 to 1984, catches were low. Since the mid-1980s up to the mid-1990s catches from all three fisheries increased. The loess-smoothed trend explained a large proportion of the variance in catch data over time for all three fisheries ($0.51 > r^2_{\text{loess}} > 0.76$), which is indicative of significant interdecadal changes in abundance of anchovy over time (Fig. 4a). These interdecadal variations look similar in the three anchovy fisheries (Fig. 5a).

A strong pattern of interannual variation was observed only in the North-Central Peru and South Peru-Northern Chile fisheries, the Central-South Chile fishery displaying a high interannual variability only during the last decade (Fig. 4b). Only these first two fisheries show significant relationships between their interannual residuals ($r^2 = 0.471$, $p < 0.05$, $F = 36.51$, $\mathrm{d}f = 41$). There was no significant relationship between interannual residuals of Central-South Chile and North-Central Peru fisheries ($r^2 = 0.045$, $p = 0.171$, $F = 1.94$, $\mathrm{d}f = 41$) nor between the South Peru-Northern Chile and Central-South Chile fisheries ($r^2 = 0.004$, $p = 0.704$, $F = 0.146$, $\mathrm{d}f = 41$; Fig. 5b).

A significant and negative relationship was observed between the interannual variability and the El Niño-Southern Oscillation (ENSO) for the North-Central Peru and South Peru-Northern Chile anchovy fisheries. The SST anomalies in the El Niño 1+2 region, during the austral spring (September-December) of the previous year, had negative effects on North-Central Peru ($p < 0.05$, $F = 15.38$, $\mathrm{d}f = 41$) and South Peru-Northern Chile ($p < 0.05$, $F = 8.84$, $\mathrm{d}f = 41$). However, in the case of the Central-South Chile anchovy fishery, the interannual component of fluctuation was not related with ENSO variability (Fig. 6, $p > 0.05$, $F = 0.14$, $\mathrm{d}f = 41$). It must be mentioned that the relationship for the two northerly anchovy fisheries was rather weak and only strengthened because of the occurrence of three El Niño events of great magnitude (leverage effect).

4 Discussion

The catch series of the three fisheries display large and synchronous interdecadal changes. Interannual variations are synchronous only between the two northern fisheries. Only those two fisheries display a significant relationship with interannal variation of the SST anomalies in the El Niño 1+2 region during the austral spring of the previous year. These three main results and their implications are now discussed in sequence, although they are largely related.

4.1 Interdecadal variability

Regional synchronies in fish populations might be easier to explain than remote synchronies because consistent low-frequency environmental change is more often observed at

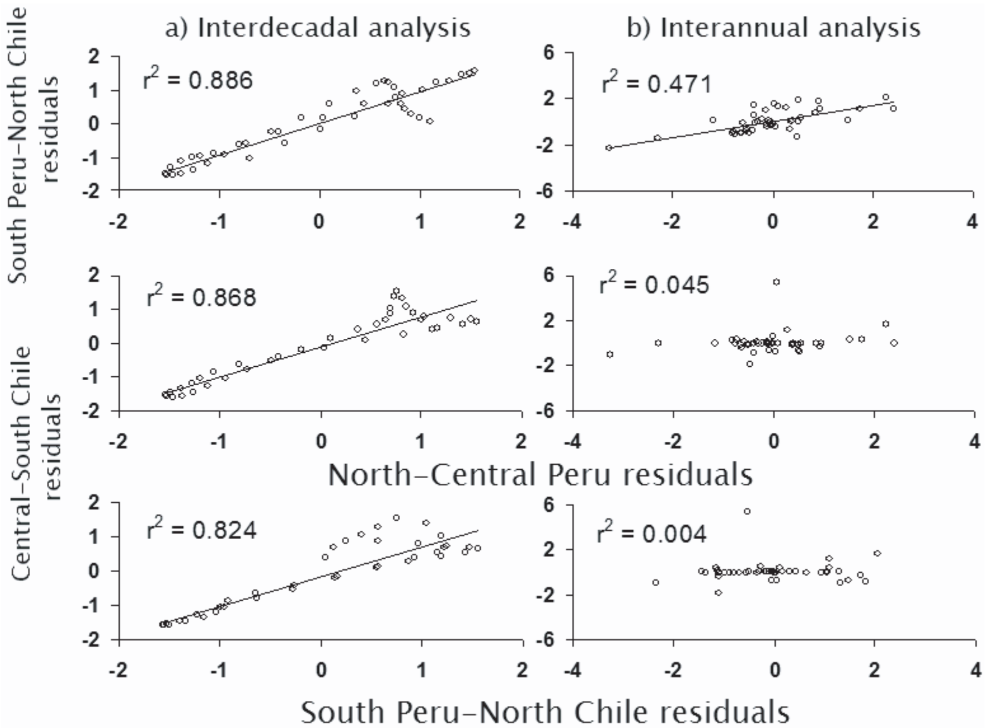

Fig. 5. Relationships between interdecadal and interannual components of the variability in the catches for three anchovy fisheries in the Humboldt Current.

the Basin scale than at the planetary one (Fréon et al. 2003; Stenseth et al. 2003). The interdecadal fluctuation in the three anchovy fisheries may be related with large-scale climate variability occurring in the Pacific (e.g. Beamish 1995; Hare and Mantua 2000; Bakun and Broad 2002) called "El Viejo" and "La Vieja" Events by Chavez et al. (2003). During the last 40 years, coherent changes in anchovy fisheries have been observed, and this synchronous pattern is out of phase with large-amplitude sardine regimes on oceanic scales (Lluch-Belda et al. 1989, 1992; Chavez et al. 2003). During the second period of low anchovy catches, from the mid 1970s to the 1980s, sardine became more abundant in the HCS (Serra 1989; Chavez et al. 2003; Alheit and Ñiquen 2004). The turning points of the initial change from a regime of anchovy to one of sardine and back to anchovy are far from clear, probably due to sardine recruiting at more advanced age than anchovy (Yáñez 1989; Schwartzlose et al. 1999). However, there is evidence in ichthyoplankton data supporting that the sardine recruitment increased from the early 1970s (Loeb and Rojas 988), and started to decrease again from about 1988–1990.

Alheit and Ñiquen (2004) summarized the changes observed in the biota during 1968–71, including changes in zooplankton and predators. Recently, Ayón et al. (2004) confirmed large changes in zooplankton volume off Peru from 1964 to 2001, and found higher zooplankton volume during "cold" decades, particularly in the 1960s, than during "warm" decades. Although there is little published data on faunistic changes in plankton in the Humboldt ecosystem, the hypothesis of sardine being favored by longer food chains with smaller plankton particles than anchovy is gaining ground in several upwelling ecosystems (Chavez et al. 2002; van der Lingen et al. 2006). All these results are supporting the regime shift observed in the Peruvian coastal upwelling, from an anchovy-dominated system before mid-1970s to another in which the system was dominated by sardine (*Sardinops sagax*) until mid-1980s. Unfortunately, most recruitment time series of anchovy and sardine are short to allow powerful hypothesis testing at the interdecadal scale.

Factors other than synchronous changes in abundance could also explain synchronous changes in catches. Synchronous changes in fishing effort (Yáñez et al. 2001) unrelated to changes in abundance are the most obvious candidate and may explain most of the simultaneous positive trend in landings that occurred at the start of these three industrial fisheries in the 1950s (not shown and not used) and 1960s. But subsequently, the interdecadal changes in anchovy catches match quite well with the abundance estimates derived from Virtual Population Analysis (Pauly et al. 1987). During the more recent period, Bertrand et al. (2004) showed that, despite interannual discrepancies, hydroacoustic biomass estimates are closely related with the magnitude of the interdecadal variation in catch of the Peruvian anchovy. In addition, for the South Peru-Northern Chile fishery, Braun et al. (2004) show that the changes in the spawning stock biomass, estimated by Daily Egg Production Method, are correlated with annual landings in the 1992–2003 period.

4.2 Interannual variability

The catches from the North-Central Peru and South Peru-Northern Chile fisheries have similar interannual trends, but

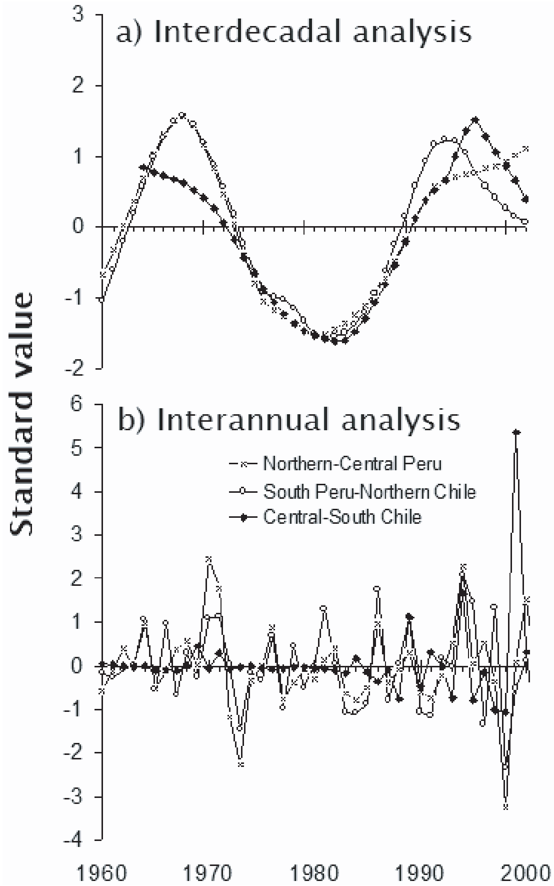

Fig. 4. Interdecadal (a) and interannual (b) residuals (standardized values) for three anchovy fisheries in the Humboldt Current System. In Fig. 4a the first four data-points for Central-South Chile anchovy stock were deleted because the values predicted by the linear trend were negative for those years, resulting in very high positive residuals (see Fig. 3).

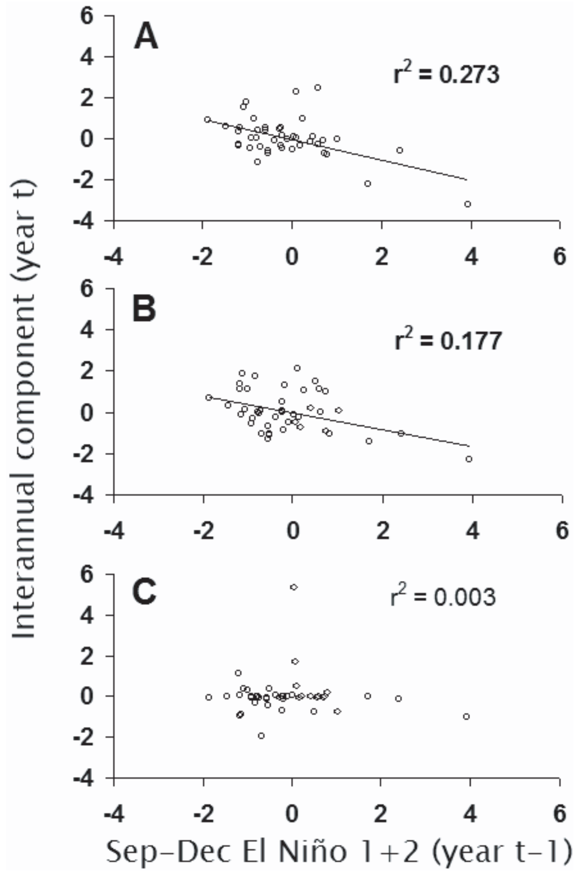

Fig. 6. Interannual variation (standardized value) of three anchovy fisheries in the Humboldt Current System and sea surface temperature anomalies during the austral spring of the previous year (1960–2002) in the El Niño 1+2 regions of the Equatorial Pacific. A: Northern-Central Peru fishery, B: South Peru – Northern Chile fishery, C: Central-South Chile fishery.

the central-south Chile fishery of anchovy has a different pattern. The North-Central Peru and South Peru-Northern Chile fisheries are closer and likely to be subjected to more similar interannual environmental conditions than the Central-South Chile fishery. In addition, the two northerly fisheries may have a higher probability of mixing than the Central-South anchovy. Indeed, according to Ñiquen and Bouchon (2004) the North-Central Peru stock becomes asymmetrically distributed towards the southern Peruvian coast under El Niño conditions. Synchronous catches at the interannual scale can also result from synchronous changes in accessibility related to changes in the spatial distribution of the fisheries. ENSO events are known to impact on both abundance and accessibility of the resource (Bertrand et al. 2004), for example, by modification of the vertical distribution owing to changes in the thermocline and/or oxycline depth, as observed in tuna (Green 1967; Maury et al. 2001; Prince and Goodyear 2006).

4.3 Link with interannual variability of the environment

Significant and negative relationships were found between the interannual residuals of the two northerly anchovy fisheries and interannual changes in the El Niño-Southern Oscillation index represented by sea surface temperature anomalies observed during the austral spring of the previous year in the El Niño 1+2 region of the Equatorial Pacific. We think this relationship could be associated with the impact of positive anomalies on reproductive process and subsequent recruitment. Usually populations at the limit of a species range exhibit differential response to environmental factors and are more prone to density-independent factors than those at the centre of the distribution (Wooster and Bailey 1989; Myers 1998). In addition, interannual abundance variation of anchovy in the North-Central Peru and South Peru-Northern Chile may be explained by stronger ENSO effects in the central Pacific than further south (see Blanco et al. 2002 and references cited there; Ñiquen and Bouchon 2004).

As far as fisheries management is concerned, progresses in research may possibly allow in the future understanding interannual variability in recruitment for each anchovy stock in relation with ENSO, but regime shifts, at the interdecadal scale, may be more important to consider since they are of larger amplitude and can affect simultaneously the three anchovy fisheries located in the Humboldt Current System.

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