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Doctorado en Oceanografía

Tesis

Variabilidad temporal de baja frecuencia en el Ecosistema de la Corriente Humboldt frente a Perú

Sara Regina Purca Cuicapusa

Concepción, Chile, Enero de 2005

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La Tesis Doctoral en Oceanografía *"Variabilidad temporal de baja frecuencia en el Ecosistema de la Corriente Humboldt frente a Perú"* de la Srta. Sara Regina Purca Cuicapusa, realizada en el Departamento de Oceanografía, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, ha sido aprobada por la siguiente Comisión de Evaluación:

Dr. Tarsicio Antezana
Profesor Guía
Universidad de Concepción

Tarsicio Antezana T.

Blgo. Renato Guevara-Carrasco
Miembro Comité de Tesis
Instituto del Mar del Perú

Dr. Roberto Riquelme
Miembro Comité de Tesis
Universidad de Concepción

Dr. Dante Figueroa
Miembro Comité de Tesis
Universidad de Concepción

Dante Figueroa

Dr. José Rutllant
Evaluador Externo
Universidad de Chile

Dr. Wolfgang Schneider
Director de Programa
Universidad de Concepción

Concepción, Enero de 2005.

Dedicado a las familias PURCA y CUICAPUSA,
en especial a mis padres y hermanas.

"Won't somebody please talk to me! I am a physical oceanographer who works on biological and fisheries problems. As such, I find myself straddling a gap between two distinctly separate disciplines, physical oceanography and fisheries biology, each growing out of different traditions and points of view. The communication problems go far beyond mere differences in terminology and jargon, involving completely different conceptual frameworks with which information is received and organized. What is "signal" to one group often seems to be "noise" to the other. Although I have great friends in both groups, scientifically and conceptually, I sometimes feel quite lonely".

Andrew Bakun.

Índice de Contenidos

Lista de Figuras

Figura 1. Estaciones de muestreo (n=6629) de mesozooplancton (•) realizado por el Instituto del Mar del Perú (IMARPE) desde 1964 a 2002 entre 3°S y 18°S, desde la costa hasta las 300 mn. Estación fija de la Unidad de Hidro-Química del IMARPE (❶), ubicada a 20 mn frente a Callao (12°S - 77°W) de muestreo mensual de nutrientes, oxígeno, clorofila *a*, temperatura y salinidad desde Abril 1995 a Agosto 2002. Estación fija de la Universidad Nacional Mayor de San Marcos (❷) en Ancón (11°S - 77°W) de muestreo quincenal de fitoplancton desde Enero 1995 hasta Diciembre 1999.

Figura 2. Análisis de la serie mensual de temperatura superficial del mar (TSM) frente a Perú. a. Primera componente principal de la TSM proveniente de cinco estaciones costeras peruanas, la cual se denominó Índice de Oscilación Peruano (IOP). b. Primera componente principal (PCP) del rango de frecuencia entre 3 a 6 años para el IOP, cuya señal equivale al rango de frecuencias del ciclo El Niño Oscilación Sur (ENOS). c. PCP del rango de frecuencia entre 0 a 3 años, cuya señal equivale al filtro de alta frecuencia del ciclo ENOS. d. PCP del rango de frecuencia entre 7 a 10 años, cuya señal equivale al filtro de baja frecuencia del IOP.

Figura 3. Mapa del espectro de la potencia de las “ondelettes”. El contorno negro representa el 10% del nivel de significancia. La región del cono de influencia se representó con el sombreado en la zona inferior de cada mapa. a. Filtro de ruido rojo al 5% de significancia del espectro de la potencia de las “ondelettes”. b. Varianza del espectro de la potencia de las “ondelettes”. La línea punteada representa el nivel de significancia del espectro de la potencia de las “ondelettes”. c. Filtro de ruido blanco al 10% de significancia del espectro de la potencia de las “ondelettes”. d. Varianza del espectro de la potencia de las “ondelettes”. La línea punteada representa el nivel de significancia al 10%.

Lista de Tablas

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Curriculum Vitae
Sara Regina Purca Cuicapusa
Nacida el 29 de Septiembre, 1973 Lima, Perú.
spurca@imarpe.gob.pe

1992-1998: Ingeniero Pesquero, Universidad Nacional Federico Villarreal, Lima, Perú.
1998-2005: Doctorado en Oceanografía, Universidad de Concepción, Chile.

PUBLICACIONES

Montecinos, A., S. Purca, & O. Pizarro (2003) Interannual-to-interdecadal sea surface temperature variability along the western coast of South America. Geophysical Research Letters, 30(11): 1570-1574

Ayón P., S. Purca, & R. Guevara-Carrasco (2004) Zooplankton volume trends off Peru between 1964 and 2001. ICES Journal of Marine Science, 61(4): 478-484

ÁREAS DE INVESTIGACIÓN

Principal: Oceanografía biológica
Secundaria: Oceanografía física
Otras áreas de interés: Modelos estadísticos océano y atmósfera. Pronóstico estadístico del ENOS.

FILIACIÓN ACTUAL

Centro de Investigaciones en Modelaje Oceanográfico y Biológico Pesquero (CIMOBP).
IMARPE
Esquina Gamarra y Gral. Valle S/N
Callao, PERÚ.

EXPERIENCIA DOCENTE

- 1995 Ayudante del curso de Ictiología. Universidad Nacional Federico Villarreal (UNFV). Lima, Perú.
- 1996 Ayudante del curso de Recursos Pesqueros. UNFV. Lima, Perú.
- 2003 Profesor invitado en el IMARPE. Curso: Introducción a los análisis de las series de tiempo y su aplicación para series biológicas y físicas. Callao, Perú.
- 2003 Profesor invitado en el IMARPE. Curso: Uso de ARIMA y series de Fourier en series biológicas. Callao, Perú.
- 2004 Profesor auxiliar en la UNFV, cursos: Proyecto de tesis y Tópicos especiales, Oceanografía Física (práctica) y Oceanografía Biológica (práctica). Lima, Perú.

Resumen

Variabilidad temporal de baja frecuencia en el Ecosistema de la Corriente Humboldt frente a Perú

Sara Purca
Programa de Doctorado en Oceanografía
Dr. Tarsicio Antezana J., Profesor Guía.
Universidad de Concepción, 2005.

La variabilidad temporal de baja frecuencia en el Ecosistema de la Corriente Humboldt (ECH) frente a Perú se caracteriza por cambios abruptos en la dominancia de anchoveta y sardina, así como por drásticas disminuciones en los desembarques de anchoveta durante la fase cálida del ciclo El Niño Oscilación del Sur (ENOS) (e.g. 1972-73 y 1982-1983). Sumado a estas características, estudios recientes sugieren que existen señales de largo plazo en el ECH frente a Perú (e.g. tendencia decreciente de la abundancia de aves guaneras y volúmenes de mesozooplancton). Sin embargo, las respuestas biológicas a tales señales físicas de largo plazo son crípticas o poco conocidas. En este estudio se analiza por una parte la variabilidad interanual en las variables físicas y biológicas asociadas con El Niño. Esta señal se expresó en el Índice de Oscilación Peruano (IOP), basado en las temperaturas superficiales del mar (TSM), en la variabilidad del viento del área EL NIÑO 3.4 y en el Índice de Oscilación del Sur (IOS), basado en la presión superficial del mar. Estos índices se correlacionaron significativamente, particularmente desde 1980. Los volúmenes de microplancton y los desembarques de anchoveta disminuyeron durante El Niño 1982-1983 y 1997-1998 asociados con esta variabilidad interanual. Durante El Niño 1997-1998 hubo también cambios significativos en las concentraciones de clorofila *a*, los nutrientes, la profundidad de la isoterma de 15°C, las densidades de fitoplancton y los desembarques de otras especies de peces. Los volúmenes de mesozooplancton no fueron afectados. Por otra parte, se estudió la variabilidad interdecadal en las variables físicas, el IOS y el IOP, junto con los volúmenes de microplancton y mesozooplancton y la biomasa de anchoveta. No hubo correlación en la escala interdecadal entre los índices IOS e IOP. La correlación entre microplancton y mesozooplancton fue significativa, mientras que las correlaciones entre microplancton y mesozooplancton con el IOP no fueron significativas. Comparando la variabilidad física y biológica en el ECH frente a Perú en estas dos escalas temporales, la señal en la escala interanual relacionada con El Niño fue clara y consistente tanto en las variables físicas como en las biológicas y entre los diversos índices utilizados. La señal asociada a la escala interdecadal fue aparente (a través del tratamiento estadístico) en las variables físicas y también en las variables biológicas, pero sin la coherencia esperadas entre ellas.

Palabras claves: Corriente Humboldt, series de tiempo biológicas y físicas, interanual, interdecadal, ENOS.

Abstract

Low frequency temporal variability in the Humboldt Current Ecosystem off Peru

Sara Purca
Programa de Doctorado en Oceanografía
Dr. Tarsicio Antezana J., Profesor Guía.
Universidad de Concepción, 2005.

Low frequency temporal variability in the Humboldt Current Ecosystem (ECH) off Peru is characterized by abrupt changes in dominance of anchovy and sardine, as well as drastic decreases of anchovy landings during El Niño Southern Oscillation (ENOS) (e.g. 1972-1973 and 1982-1983). In addition, recent studies suggest that long-term changes in the ECH off Peru occur (e.g. a trend of decreasing abundance of bird populations and mesozooplankton). However, the biological responses to those physical signals are cryptic or poorly known. In this study, interannual variability associated to El Nino is analyzed in the ECH. This signal was evident in the Peruvian Oscillation Index (IOP), based on the sea surface temperature (TSM), in the variability of the wind in EL NIÑO 3.4 region and in the Southern Oscillation Index (IOS), based on sea surface pressure. These indexes were significantly correlated and particularly so after 1980. Associated with this interannual signal, microplankton volume and anchovy landing decreased during El Niño 1982-1983 and 1997-1998. During El Niño 1997-1998 there were also significant changes in chlorophyll concentration, nutrients, depth of the 15°C isotherm, phytoplankton density and landing of other fish species. Mesozooplankton volumes were not affected. On the other hand, long-term interdecadal variability in physical variables, IOS and IOP was examined, along with volumes of microplankton and mesozooplankton, and anchovy biomass. There was not correlation between IOS and IOP indexes at the interdecadal scale. Correlation between volumes of microplankton and mesozooplankton was significant, while correlation between volumes of microplankton and mesozooplankton with IOP were not significant. Comparing physical and biological variability in the ECH off Peru in these two temporal scales, the signal associated to the interannual scale was clear and consistent in the physical as well as in the biological variables and between indexes. The signal associated to the interdecadal scale was apparent (through statistical procedures) in the physical variables and biological variables as well, but without the expected coherence between them.

Key words: Humboldt Current, physical and biological time series, interannual, interdecadal, ENSO.

Parte A

1. INTRODUCCIÓN

La Corriente Humboldt está comprendida entre los 4°S y *ca.* 42°S. Tal como otras corrientes de borde oriental, es ancha, somera, lenta y de dirección ecuatorial. La Corriente Humboldt es un sistema de corrientes y contracorrientes de origen Ecuatorial y Polar, superficiales y subsuperficiales, en el que surgencias costeras son características.

Debido a su importancia en la fertilización de la capa de mezcla y la alta productividad biológica resultante, gran parte de los estudios se han concentrado en describir la dinámica de la surgencia y su variabilidad geográfica, así como su variabilidad temporal en la escala de días y estaciones del año. En una dimensión temporal de más baja frecuencia, El Niño ha constituido también un foco de atención científica, no tan sólo por el impacto en las pesquerías, sino por su impacto en el clima regional y global. Sin embargo, existen otros eventos distribuidos en una escala continua de frecuencias independientemente de estas fuentes de variabilidad temporal (Haury *et al.* 1978).

La dificultad para definir la escala de tiempo más adecuada en un ecosistema (Steele 1988) radica en primer lugar en discriminar las señales en un continuo de varianza y asociarlas como causa de otras variables del ecosistema (profundidad de la capa de mezcla y productividad primaria). Las series de tiempo de variables físicas y biológicas de al menos algunas décadas adquieren un valor fundamental para enfrentar este desafío, debido a que se puede discriminar entre señales de alta frecuencia y señales de baja frecuencia en el espectro de variabilidad temporal del ecosistema.

Desde una perspectiva ecológica, es prioritario asociar la variabilidad física con la variabilidad de los componentes principales de la trama trófica (Edwards & Richardson 2004). La discriminación de señales físicas de baja frecuencia y su correlación con variables biológicas en la Corriente de Humboldt frente a la costa peruana constituye el marco de referencia fundamental de esta tesis. Esto implica reconocer que el sistema de la Corriente de Humboldt constituye un ecosistema en que las señales físicas van a tener un impacto predecible en su trama trófica en conjunto.

Los procesos físicos a escalas interanuales e interdecadal deben impactar al ecosistema en una mayor extensión espacial que los eventos a escalas diarias y estacionales (Steele 1988). Por otra parte, los impactos físicos de gran escala varían también en intensidad y cobertura geográfica y por ende la variabilidad en la cuenca del Pacífico no es necesariamente determinante en su extensión hacia el ECH.

La primera hipótesis es que señales físicas interanuales, como El Niño, generan desfases o retardos en las respuestas biológicas asociadas a su nivel trófico, de tal modo que los desfases se incrementarían desde los niveles tróficos inferiores hacia los superiores.

La segunda hipótesis es que el ciclo de vida de los organismos estaría modulado por la variabilidad física interdecadal, de tal modo que los organismos de ciclos de vida corta responderían más inmediatamente que los organismos de vida larga y por tanto estos últimos se verían más afectados por la variabilidad de gran escala.

Con el propósito de poner a prueba las hipótesis, se compiló la información disponible en la Dirección de Hidrografía del Perú y en el IMARPE para construir series de tiempo físicas, químicas y biológicas entre 1950 a 2002. La base de datos físicos estuvo constituida por velocidad del viento, TSM, concentración de oxígeno, profundidad de la isoterma de 15°C y presión superficial del mar. La base de datos biológicos estuvo conformada por volúmenes de microplancton, volúmenes de mesozooplancton, biomasas de anchoveta (*Engraulis ringens*) y sardina (*Sardinops sagax*), y desembarques de anchoveta, sardina, jurel (*Trachurus murphyi*)[1] y caballa (*Scomber japonicus*).

Se utilizaron técnicas estadísticas para el análisis de las relaciones temporales y el análisis del espectro de frecuencias de las series de tiempo (e.g. análisis de correlación cruzada, análisis de componentes principales y análisis de la transformada de "ondelettes"[2]).

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[1] Existiendo controversias sobre la especie, se ha utilizado el nombre *T. murphyi* de acuerdo al catálogo de peces de Eshmeyer (Eshmeyer 2004).

[2] No existe consenso en la traducción de "ondelette", ni el uso de "wavelet" (extensión inglesa de la original). Se sugiere buscar una traducción apropiada y consensuada entre ondeletas, onditas, ondillas, ondulaciones, etc.

Los resultados de la Tesis se han dividido en cinco capítulos, tres de los cuales corresponden a manuscritos publicados o enviados a revistas de corriente principal (Anexo 6.1). El primer capítulo se refiere a la variabilidad interanual e interdecadal de la TSM. El segundo capítulo trata sobre el cambio de frecuencia del ciclo ENOS a partir de 1979 frente a la costa peruana. El tercer capítulo se refiere a las evidencias de las respuestas sincrónicas de las variables biológicas, químicas y físicas durante El Niño 1997-1998 frente a Perú. El cuarto capítulo presenta la tendencia de variabilidad en los volúmenes de mesozooplancton entre 1964 y 2002 frente a Perú y el quinto capítulo aborda la evidencia empírica de respuestas interdecadales en las series de tiempo biológicas frente a la costa peruana.

2. MATERIALES Y MÉTODOS

2.1 Series de tiempo utilizadas para describir la variabilidad temporal oceanográfica frente a la costa peruana

Se recopiló 33 series de tiempo de las cuales 15 series de tiempo fueron físicas y 18 biológicas (Tabla 1), cuya frecuencia de muestreo y longitud de la serie de tiempo permitió realizar análisis temporales en las escalas interanual e interdecadal.

2.1.1 Series de tiempo físicas

Las series de tiempo mensuales de TSM entre 1950 a 2004 en estaciones fijas costeras de Perú y Chile fueron las series de tiempo más largas de las series estudiadas (Tabla 1).

También se utilizaron datos mensuales reconstruidos de la TSM de la base de datos global de COADS[3] (Smith & Reynolds 2003) y se compararon con las series de tiempo mensuales de TSM provenientes de estaciones fijas costeras de Perú (Anexo 6.1.1).

Los datos de velocidad y dirección del viento costero frente a Callao, Perú y del área EL NIÑO 3.4 fueron las series de tiempo más cortas (1978 a 2002) tomados de la base de datos COADS (Tabla 1).

2.1.2 Series de tiempo biológicas

Se construyeron series de tiempo biológicas mensuales de conteos de fitoplancton (1995 a 1999) provenientes de una estación fija frente a Ancón y trimestrales de volúmenes de microplancton (1979 a 2002) y mesozooplancton (1964 a 2002) provenientes de datos inéditos adquiridos en 6629 estaciones (Figura 1, Tabla 2) en cruceros de investigación que cubrieron un área de 110 000 km^2 de la costa central del Perú (Figura 1). Por otro lado, los datos provenientes de las evaluaciones pesqueras con métodos acústicos permitieron construir series de tiempo de biomasas de anchoveta y sardina con una secuencia temporal

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[3] Comprehensive Ocean-Atmosphere Data Set.

anual (1957 a 1994). Por último, se obtuvo series de desembarques anuales de anchoveta, sardina, jurel y caballa desde 1950 hasta 2002.

2.1.3 Series de tiempo de perfiles físico-químicos y biológicos

Los datos de temperatura, salinidad, concentración de oxígeno, nitritos, nitratos, fosfatos, silicatos y clorofila *a* fueron integrados en la columna de agua entre 0 y 50 m de profundidad a partir de los registros obtenidos en la estación fija ubicada a una distancia de 20 mn frente a Callao (profundidad 200 m) entre abril de 1995 y agosto de 2002 (Figura 1). Se utilizaron frascos de color ámbar de 100 ml con tapa esmerilada para el análisis de oxígeno según método de Winkler, modificado por Carrit & Carpenter (1966). Para la determinación de nutrientes se utilizó frascos de polietileno, congelando las muestras hasta el análisis en el laboratorio. Las muestras obtenidas para el análisis de clorofila *a* se filtraron a bordo y se preservaron refrigeradas hasta su análisis.

Los datos perdidos o faltantes fueron excluidos del análisis de las series de tiempo biológicas, pero para las series de tiempo físicas, los datos faltantes se interpolaron linealmente.

2.2 Métodos de análisis de las series de tiempo

2.2.1 Observación y determinación de las medidas de tendencia central y dispersión

Se utilizó gráficos de pares cartesianos; se determinó sus medidas de tendencia central y dispersión según Zhang *et al.* (1997) (Anexo 6.1.1) y se realizó interpolaciones lineales para tener una serie de tiempo continua (Anexos 6.1.2 y 6.1.3).

2.2.2 Análisis de las anomalías de las series

Se calculó las anomalías de las series de tiempo mediante la diferencia entre el dato original y el promedio total. Se simplificó las series de tiempo de TSM con el cálculo de la primera componente principal regional (Perú – Chile) mediante el análisis empírico ortogonal (Horel 1984). En el caso de las series mensuales se calculó la anomalía estandarizada multianual (diferencia entre el dato original y el promedio mensual correspondiente al ciclo anual de toda la serie de tiempo; dividido por la desviación estándar mensual correspondiente al ciclo anual de toda la serie de tiempo), de esta manera se desestacionalizó la serie de tiempo.

Se substrajo la tendencia de todas las series de tiempo y se filtró cada serie de tiempo biológica y física con promedios móviles lineales para el intervalo de 3 a 6 años y para el intervalo de 7 a 14 años que corresponden a los rangos temporales de El Niño e interdecadal respectivamente (Anexo 6.1.1). Se relacionaron linealmente las series de tiempo EL NIÑO 3.4 y EL NIÑO 1+2 y las anomalías de TSM costeras. Se elaboró mapas con los coeficientes de correlación simple entre la primera componente de las anomalías de TSM regional (Perú-Chile) y la TSM de todo el mundo, para el rango temporal de El Niño e interdecadal desde 1950 hasta 1999 (Anexo 6.1.1).

2.2.3 Análisis de frecuencia

Para determinar la frecuencia de la variabilidad temporal de las anomalías de TSM costeras de Perú y aquellas derivadas de la base de datos COADS, se utilizó la transformada de "ondelette" (Torrence & Compo 1998) y se diseñaron mapas de correlación espacial entre la primera componente principal de las potencias de las "ondelettes" para tres rangos de frecuencias: 0 a 3 años, 3 a 6 años, 7 a 10 años de los datos costeros y de los datos mundiales.

Se utilizó la sumatoria de la potencia de las "ondelettes" y los filtros de ruido rojo (valores altos de la potencia de las "ondelettes") y de ruido blanco (valores bajos de la potencia de las "ondelettes") para el análisis de la varianza total de las frecuencias (Torrence & Compo 1998).

2.2.4 Análisis de perfiles físico-químicos y biológicos

Se elaboró mapas de contornos entre 0 y 50 m de profundidad de la variabilidad de la temperatura, salinidad, concentración de oxígeno, nitratos, nitritos, silicatos, fósforo y clorofila *a* desde 1995 hasta 2002.

2.2.5 Análisis de tendencias temporales de volumen de mesozooplacton y biomasa de anchoveta

Se calculó el promedio de los volúmenes de mesozooplanton y biomasa de anchoveta por cada grado de latitud y longitud; posteriormente se ordenó cada serie de tiempo con un intervalo de tiempo mensual.

2.2.6 Respuestas biológicas en escalas El Niño e interdecadal

Para explorar las posibles respuestas biológicas a la variabilidad física en el ECH, se realizaron correlaciones cruzadas (Pearson) entre series físicas y biológicas disponibles. Se empleó el IOP como índice que representa la variabilidad física del área de estudio, y series de tiempo de anomalías anuales de componentes biológicos dominantes en el ecosistema (densidades promedio de volúmenes de microplancton y mesozooplancton, biomasa total de anchoveta y sardina y desembarques de anchoveta, sardina, jurel y caballa).

3. RESULTADOS

3.1 Variabilidad interanual e interdecadal de la temperatura superficial del mar frente a la costa peruana

La variabilidad interanual e interdecadal costera en el ECH se representó con las series de tiempo de TSM regional (Perú – Chile). La variabilidad interanual se obtuvo de la primera componente principal del filtro interanual (3 a 6 años) de las series de tiempo de TSM regional. Este modo interanual reflejó la señal del ciclo ENOS a lo largo de la costa, presentando un coeficiente de correlación de 0.86 y 0.94 con la señal de TSM de las regiones de EL NIÑO 3.4 (5°N - 5°S) y EL NIÑO 1+2 (0°S - 10°S), respectivamente (Figura 2a. en Anexo 6.1.1.).

La variabilidad interdecadal se obtuvo de la primera componente principal del filtro interdecadal (7 a 14 años) de las series de tiempo de TSM regional. Este modo interdecadal resultó en valores negativos durante los años 60, alcanzando valores mínimos en 1967 los cuales se revirtieron a valores positivos a mediados de los años 70, registrando valores máximos en 1983 y valores negativos en 1987-1988. Los valores negativos entraron a una fase positiva a comienzos de los años 90 (Figura 3a en Anexo 6.1.1.). Esta señal interdecadal tendió a ser más débil en las estaciones costeras ubicadas al N de los 9°S y al S de los 25°S (Figura 3b en Anexo 6.1.1.).

El patrón espacial de correlaciones entre la primera componente principal de la TSM en las estaciones fijas costeras y la primera componente de las TSM globales proveniente de datos de re-análisis COADS en escalas interanuales mostró una estructura espacial en forma de herradura en el Océano Pacífico (Figura 4a en Anexo 6.1.1.). Los valores máximos de correlación se observaron entre los 3°N y 20°S, con una mayor extensión hacia el W de los valores altos de correlación a los 7°S. En la escala interdecadal, la estructura espacial de correlación en el Océano Pacífico también presentó forma de herradura con correlaciones positivas entre los 140°W y la costa sudamericana, mientras que correlaciones altamente negativas se extendieron entre los 15°S y los 25°S en el

Pacífico Central. La señal interdecadal de la primera componente de TSM en las estaciones costeras de Perú y Chile se correlacionó negativamente con la primera componente de TSM de los giros anticiclónicos subtropicales del planeta. En el Atlántico Sur reflejan el patrón de variabilidad conocido como el dipolo del Atlántico con correlaciones positivas al S de los 25°S y negativas al N de esa latitud (Figura 4b en Anexo 6.1.1.).

3.2 Cambios de frecuencia de El Niño/La Niña entre 1950 y 2004

Se estableció un Índice de Oscilación Peruano (IOP) para la costa, mediante la primera componente de las anomalías estandarizadas de la TSM de cinco estaciones a lo largo de la costa peruana (Figura 2a).

La señal del ciclo ENOS se obtuvo de la primera componente principal de las frecuencias de potencias de las "ondelettes" entre 3 y 6 años. Este rango de frecuencias representó el mayor porcentaje (87%) de la varianza global de las potencias (Figura 2b).

La lengua fría de TSM que caracteriza el Pacífico Ecuatorial Oriental se registró en la primera componente principal de las frecuencias de la potencias de las "ondelettes" menores a 3 años del IOP (Figura 2c) lo que se evidenció en los mapas de correlaciones espaciales de frecuencias menores a 3 años y se trata más adelante. En esta señal se observó 3 eventos El Niño y 7 períodos particularmente fríos desde 1950 a 2004 en (Figura 2c, Tabla 3).

La señal interdecadal se obtuvo de la primera componente principal de las frecuencias de la potencia de las "ondelettes" de 7 a 10 años. Se observó un ciclo de 38 años, cuya máxima altura de la onda se situó en 1978 y la máxima depresión fue en 1997. Se identificó una fase fría entre 1950 y 1965 y una fase cálida entre 1966 y 1988, seguida por otra fase fría que comenzó en 1989 hasta el presente (Figura 2d).

El espectro de potencias de las "ondelettes" del IOP reveló similares intensidades durante las fases cálidas y frías del ciclo ENOS (Figuras 3 a, c). Los valores más altos del espectro de la potencia de las "ondelettes" de las anomalías de TSM se presentó después de 1980 (Figura 3a). Entre 3 y 6 años se presentaron los valores más significativos de la varianza del espectro global de las "ondelettes" (Figura 3 b). Los valores más bajos de la potencia "ondelettes" se observaron entre 1960 y 1970 (Figura 3c). Entre 2 y 10 años de frecuencia se presentaron los valores más significativos de la varianza del espectro de las “ondelettes” (Figura 3 d).

Los patrones espaciales de las correlaciones entre las primeras componentes principales de las anomalías de TSM en los tres intervalos de frecuencia de la potencia de las “ondelettes” (0 a 3, 3 a 6 y 7 a 10 años) de la costa peruana y de los datos globales (base de datos de TSM COADS) mostraron estructuras en forma de herradura en el Pacífico Oriental. En el intervalo de frecuencia 0 a 3 años, se presentó una estructura de correlaciones positivas a lo largo de la costa sudamericana, que van decreciendo desde las costas de Centro América hacia el N. El área de correlación positiva presentó la mayor extensión a lo largo del Ecuador entre los 5°N y 5°S (Figura 4a). En el intervalo de frecuencia de 3 a 6 años, las mayores correlaciones se observaron a lo largo de la costa extendiéndose en el eje de 25°S hasta los 180°W (Figura 4b). Para el intervalo de frecuencia de 7 a 10 años, el área de correlaciones altamente positivas (>0.8) cubrió prácticamente todo el Pacífico Ecuatorial hasta 160 °E (Figura 4c).

3.3 Fluctuaciones en los perfiles físico-químicos y biológicos durante El Niño 1997-1998 frente a 12°S

La temperatura de la columna de agua (0 a 50 m) en la estación fija de Callao registró valores particularmente altos durante 1997 que se extendieron hasta mediados de 1998, en tanto que la salinidad presentó sus valores más bajos durante 1997 y comienzos de 1998. La concentración de oxígeno aumentó desde los meses de primavera de 1997 hasta los meses de verano de 1998, mientras que las concentraciones de clorofila *a* revelaron sus valores más bajos durante el mismo intervalo de tiempo (Figura 5).

Durante el año 1997 y comienzos de 1998 los nitritos, fosfatos y silicatos presentaron valores altos, mientras que las concentraciones de nitratos no tuvieron una tendencia clara (Figura 6).

Se presentó una disminución de la concentración de fitoplancton desde los meses de primavera de 1997 hasta los meses de verano de 1998. La concentración de diatomeas tuvo una relación inversa y en desfase con el aumento de la concentración de dinoflagelados durante El Niño 1997-1998 (Figura 7).

3.4 Tendencias del mesozooplancton frente a la costa peruana

En la década de 1960 e inicios de la década de 1970 los volúmenes promedio de mesozooplancton presentaron valores elevados en la plataforma de Perú, los cuales disminuyeron marcadamente entre 1974 y 1990, con un débil incremento en la década de 1990 (Figura 6 en Anexo 6.1.2.).

La correlación entre el promedio de los volúmenes de mesozooplancton y el promedio anual de las TSM no fue significativa, sin embargo, se presentó una coincidencia entre los cambios de los períodos de las abundancias de mesozooplancton y biomasas de anchoveta (Figura 6 en Anexo 6.1.2.)

Los muestreos de mesozooplancton realizados en primavera presentaron valores mayores entre 1960 y 1979 que entre 1980 y 1999 (Figura 2 en Anexo 6.1.2.). Se observó un ciclo anual en las densidades promedio del mesozooplancton (con valores más altos en primavera y verano que en otoño e invierno) a lo largo del período de estudio y las densidades para la década de 1960 fueron mayores en todas las estaciones climáticas y en todas las áreas de la plataforma (Figura 4 y 5 en Anexo 6.1.2.).

3.5 Respuestas de las variables biológicas a señales físicas en las escalas de El Niño e interdecadal frente a la costa peruana

La variabilidad interanual de la TSM en el Pacífico Ecuatorial ha sido representada por los índices de las anomalías del IOS y EL NIÑO 3.4 (Figuras 1a, b en Anexo 6.1.3.); ambos son los índices de mayor aceptación del ciclo ENOS. Sin embargo, el IOP es una representación de la señal del ciclo ENOS para la región peruana (Figura 1c en Anexo 6.1.3.). En efecto, con el filtro 2-7 años del IOP se hace evidente los Niños 1957-1958, 1982-1983, 1992 y 1997-1998 y más aún que con las señales del IOS y EL NIÑO 3.4 en regiones oceánicas. El IOP, IOS y EL NIÑO 3.4 fueron coherentes entre sí (Figura 1d, e, f en Anexo 6.1.3.).

Las anomalías de TSM costeras (IOP) presentaron una señal interdecadal (filtro paso bajo mayor a 7 años) con un cambio de régimen lento durante los años 70. Un régimen frío que se extendió entre 1950 y 1965 con un máximo en el año 1958 precedió un régimen cálido entre 1966 y 1987 al que le siguió un régimen frío entre 1988 y 2002 (Figura 3b en Anexo 6.1.3.).

Una señal interanual se evidenció en el promedio de microplancton colectado en la plataforma de Perú, sin embargo fue indistinguible en la serie de tiempo del mesozooplancton colectado en la misma área. Las anomalías de los promedios mensuales de microplancton y mesozooplancton mostraron tendencias interdecadales pero incoherentes en el tiempo; en la serie de volumen de microplancton se observó un período de anomalías negativas comprendido entre 1977 a 1986 lo que precedió a un período con tendencia creciente a partir de 1987, durante este período positivo se observaron valores máximos en 1996 y 1999. La serie de volumen de mesozooplancton tuvo valores negativos entre 1975 y 1990 y los valores positivos más altos en 1964, 1966, 1967, 1972 y 1998 (Figura 3c, d en Anexo 6.1.3.).

Los promedios mensuales de la biomasa de anchoveta derivados de muestreos acústicos en toda la plataforma peruana presentaron un período de valores altos entre 1962 y 1970, mientras que entre 1971 y 1990 se registró un período de valores bajos. A partir de entonces, las biomasas tendieron a incrementarse hasta el final de la serie en 1994. La serie de biomasas promedio de sardina presentó dos períodos claramente distinguibles: entre 1957 y 1974, en el cual los valores fueron extremadamente bajos y entre 1975 y 1994 con valores que superaron el millón de toneladas (Figura 2g, h en Anexo 6.1.3.).

Las anomalías de los desembarques de anchoveta fueron negativas entre 1950 y 1959 y entre 1971 y 1991; el resto de la serie tuvo anomalías positivas. En el caso de la sardina, las anomalías de los desembarques tuvieron dos períodos negativos: entre 1950 y 1976 y entre 1998 a 2002; con un período positivo intermedio entre 1977 y 1997. Por otro lado, las anomalías de los desembarques de jurel y caballa presentaron los valores particularmente altos al final del período de estudio, en la década de 1990 (Figura 3e, f, g, h en Anexo 6.1.3).

La señal física interanual representada por el IOP estuvo correlacionada con las variables biológicas en diferentes grados de desfase. El mayor valor de correlación inversa entre el IOP y el primer nivel trófico, representado por el volumen de microplancton, se observó en fase ($r=-0.31$, $P<0.05$); el segundo nivel trófico, representado por el volumen de mesozooplancton y la biomasa de anchoveta, presentó una máxima correlación inversa con el IOP en desfase de dos años ($r=-0.23$, $P<0.05$) y un año ($r=-0.15$, $P<0.05$) respectivamente; el mayor valor de correlación directa entre el IOP y en el tercer nivel trófico, representado por los desembarques de jurel, resultó con un desfase de tres años ($r=0.15$, $P<0.05$).

4. DISCUSIÓN

Hasta finales de los años 80 se sostenía que el principal factor de variabilidad física en la costa del Perú era el ciclo ENOS (Deser & Wallace 1987). En estos últimos años se ha detectado otro modo de variabilidad en el ecosistema, asociado a la dominancia de patrones de variación interdecadal en toda la cuenca del Pacífico y a los cambios de régimen de la anchoveta y sardina (McGowan *et al.* 1998, Schwartzlose *et al.* 1999, Chavez *et al.* 2003).

Las evidencias sobre cambios de baja frecuencia en los componentes biológicos del ecosistema son relativamente recientes (Glover *et al.* 1972). En efecto, estudios de largo plazo basados en series de tiempo de abundancia de zooplancton son nuevos para la cuenca del Pacífico (Roemmich & McGowan 1995) y la evidencia paleoceanográfica de escamas depositadas en los sedimentos marinos indica que ha habido grandes fluctuaciones en la abundancia de peces pelágicos pequeños en la costa occidental de Norteamérica incluso antes del desarrollo de las pesquerías (Soutar & Issacs 1974, Baumgartner *et al.* 1992).

En este trabajo se actualizaron y construyeron nuevas series de tiempo biológicas y físicas que han tenido poca difusión (Muck 1989, Sánchez 2000), y en particular, se analizaron los cambios de baja frecuencia a partir de esas series biológicas (microplancton, mesozooplancton, biomasas y desembarques de peces) y físicas (TSM y vientos Callao-COADS) en el ECH.

Considerando la asociación de las anomalías de TSM de las costas de Perú y Chile con las de los océanos mundiales, se proponen dos señales de variación dominantes: una señal interanual y otra señal interdecadal en el ECH, las cuales presentan un patrón de correlación en forma de herradura cubriendo el Pacífico Ecuatorial. Adicionalmente, la señal interdecadal costera se correlaciona negativamente con los giros anticlónicos subtropicales (Anexos 6.1.1) lo cual corresponde a un patrón de correlación observado entre otras zonas de borde y giros subtropicales (Hare & Mantua 2000, Deser *et al.* MS.).

El ciclo ENOS en la zona costera de Perú (IOP) tuvo una escala de variación de 2 años en concordancia a la componente bianual encontrada en la señal ENOS (Rasmusson *et* *al.* 1990), pero en contraposición con la escala de variación propuesta de 3 a 7 años para el ENOS (Zhang *et al.* 1997). La diferencia entre las escalas de variación del ENOS encontrada entre las zonas costera y oceánica, explica en parte las múltiples definiciones del ciclo ENOS y acentúa el desconocimiento de los mecanismos iniciales de su génesis y evolución (McPhaden *et al.* 1998). Por ejemplo, se ha postulado que las ondas ecuatoriales oceánicas serían el mecanismo por el cual las variaciones de los vientos en el Pacífico Ecuatorial Central podrían iniciar El Niño en el Pacífico Ecuatorial Oriental (Wyrtki 1975). Aún existen controversias sobre la señal que influye más significativamente en la costa peruana. Algunos trabajos apoyan la teoría que plantea que la única señal que influiría a lo largo de la costa peruana sería el período cálido El Niño del ciclo ENOS (Fedorov & Philander 2000); otros trabajos señalan que el ciclo ENOS completo influiría en las anomalías de TSM en esta región (Larkin & Harrison 2002). Los resultados de los cambios en los parámetros físico-químicos, en la clorofila *a* y en el fitoplancton durante el evento El Niño 1997-1998 corroboran la noción del impacto determinante de la fase cálida del ciclo ENOS en el ECH (Arntz *et al.* 1985).

Los cambios de régimen lentos en el mesozooplancton y en el microplancton, en comparación con los cambios de régimen rápidos en las biomasas y desembarques de anchoveta y sardina (Anexos 6.1.3, 6.1.2), sugieren una débil correspondencia de los cambios de régimen entre las series de tiempo biológicas y las físicas frente a la costa peruana. En un contexto más global, esta inconsistencia se ve reflejada en los cambios poblacionales de sardina y anchoveta, ya que a diferencia del Pacífico Norte, donde se ha propuesto que el cambio de la intensidad del centro de baja presión de las Aleutianas condicionó un régimen de dominancia decadal de las sardinas desde finales de los años 70 hasta inicios de los años 90 (Chavez *et al.* 2003), en el ECH la señal interdecadal del IOS no se correlaciona con el IOP y el modo de variabilidad decadal del IOS tampoco se correlaciona con el régimen decadal que se observa en las biomasas de anchoveta y sardina (Figura 3 a, b, e y f en Anexo 6.1.3; Ñiquen *et al.* 1999).

El debate sobre el posible impacto de los cambios de régimen de la TSM sobre el ecosistema a lo largo de la costa W de Sudamérica, es alimentado con las nuevas evidencias que aquí se presentan en relación a que los cambios de régimen entre volúmenes de microplancton y mesozooplancton y biomasa de peces a lo largo de la costa peruana no coinciden con los cambios en la TSM (Anexos 6.1.3, 6.1.2). Se podría resumir, entonces, que en el ECH, las respuestas biológicas de escala interanual se relacionaron con las variaciones del ciclo ENOS, mientras, que las respuestas biológicas de escala interdecadal no se relacionaron con la señal interdecadal (regímenes) de las anomalías de TSM, presiones, vientos, etc.

El análisis de la relación entre las series de tiempo biológicas y las series de tiempo de la TSM permitió identificar otras inconsistencias que sugieren utilizar el concepto de cambio de régimen a la variabilidad física y biológica interdecadal observada en el ECH. Por ejemplo, la dominancia del ciclo ENOS sobre los cambios interdecadales en los regímenes de variabilidad de los componentes biológicos se puede evidenciar claramente durante los períodos cálidos 1972-1973, 1982-1983 y 1997-1998, cuando el índice de desove de la anchoveta fue nulo, las biomasas de anchoveta disminuyeron drásticamente y se observó una notoria disminución de la abundancia de aves guaneras y lobos marinos (Guzmán 2000, Ganoza *et al.* 2000, Crawford & Jahncke 1999, Goya 2000, Arias-Schreiber 2000). Los períodos fríos del ciclo ENOS también han promovido respuestas biológicas notorias; así se registró el más alto índice de desove de los huevos de anchoveta durante 1966 (Guzmán 2000) y la recuperación de las biomasas y desembarques de anchoveta en 1994 (Ñiquen *et al.* 2000).

En concordancia con las incoherencias entre la señal física interdecadal y sus respuestas biológicas, recientes trabajos concluyen que el concepto de régimen es controversial, debido a que puede haber múltiples estados de equilibrio en los ecosistemas. (Steele 2004; DeYoung *et al.* 2004). Se ha sugerido que existen evidencias sobre cambios de régimen para las especies anchoveta y sardina en el ecosistema de la Corriente de Humboldt en 1968-1970 y 1984-1986, aparentemente por un avance y predominancia de masas de agua subtropicales oceánicas, aunque estos procesos físicos aún no son claros (Alheit & Ñiquen 2004); sin embargo, estos cambios de régimen no tuvieron correspondencia con la variabilidad en las anomalías de los volúmenes de mesozooplancton y microplancton frente a la costa peruana (Anexos 6.1.3, 6.1.4).

Las relaciones observadas entre los componentes biológicos y la señal física interanual, presentaron desfases asociados a su nivel trófico por lo cual no se rechaza la primera hipótesis de esta tesis. Los mayores valores de correlación con el IOP estuvieron menos desfasados en la serie de tiempo de volúmenes de microplancton (primer nivel trófico), seguidos por las series de tiempo de volúmenes de mesozooplancton y biomasa de anchoveta (segundo nivel trófico), y la serie de tiempo de los desembarques de jurel (tercer nivel trófico).

No se observó una relación entre los componentes biológicos y la señal física interdecadal que se incrementara con la duración del ciclo de vida, por lo cual se rechaza la segunda hipótesis.

En esta Tesis no se explican las inconsistencias temporales entre series de tiempo biológicas y físicas, pero se pone en evidencia la complejidad en las señales de baja frecuencia de las series de tiempo biológicas. Evidentemente la comprensión de la variabilidad física y biológica en la Corriente de Humboldt se incrementa con este enfoque de análisis de series de tiempo, que debiera redundar en un mejor manejo de sus recursos vivos.

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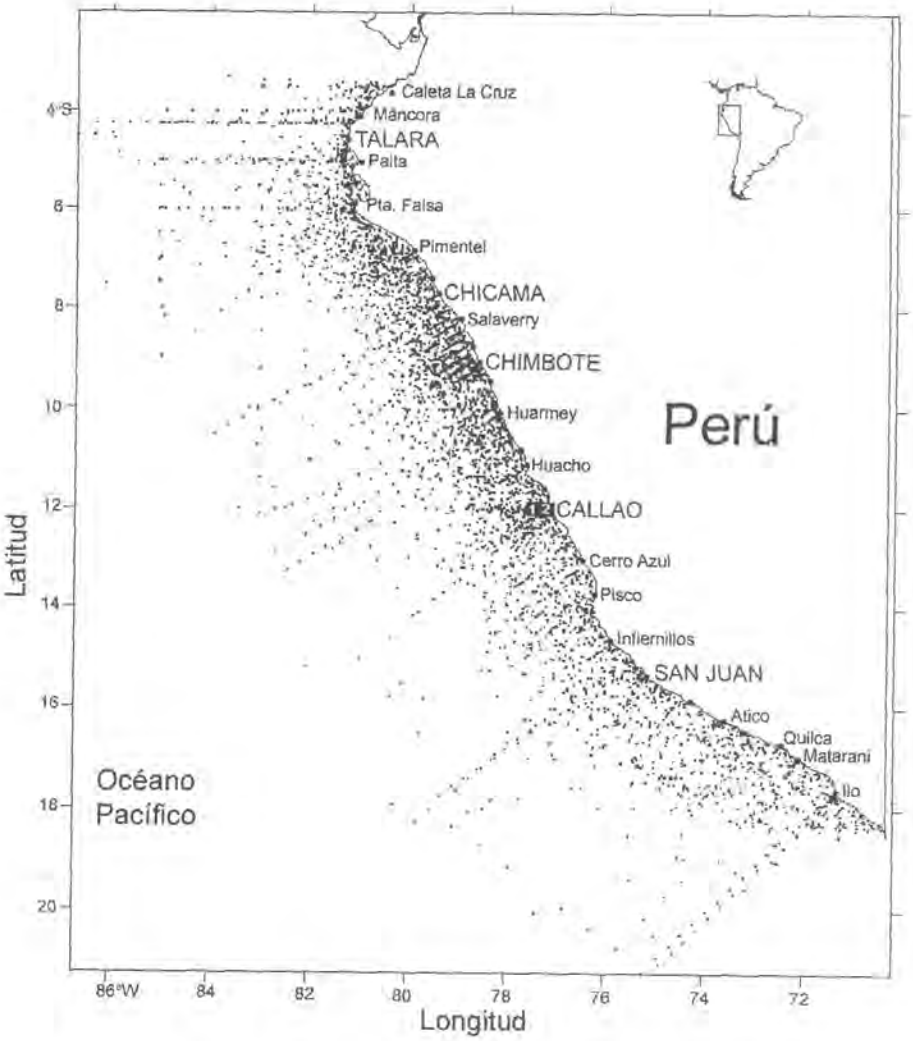


Figura 1. Estaciones de muestreo (n=6629) de mesozooplancton (•) realizado por el Instituto del Mar del Perú (IMARPE) desde 1964 a 2002 entre 3°S y 18°S, desde la costa hasta las 300 mn. Estación fija de la Unidad de Hidro-Química del IMARPE (❶), ubicada a 20 mn frente a Callao (12°S - 77°W) de muestreo mensual de nutrientes, oxígeno, clorofila *a*, temperatura y salinidad desde Abril 1995 a Agosto 2002. Estación fija de la Universidad Nacional Mayor de San Marcos (❷) en Ancón (11°S - 77°W) de muestreo quincenal de fitoplancton desde Enero 1995 hasta Diciembre 1999.

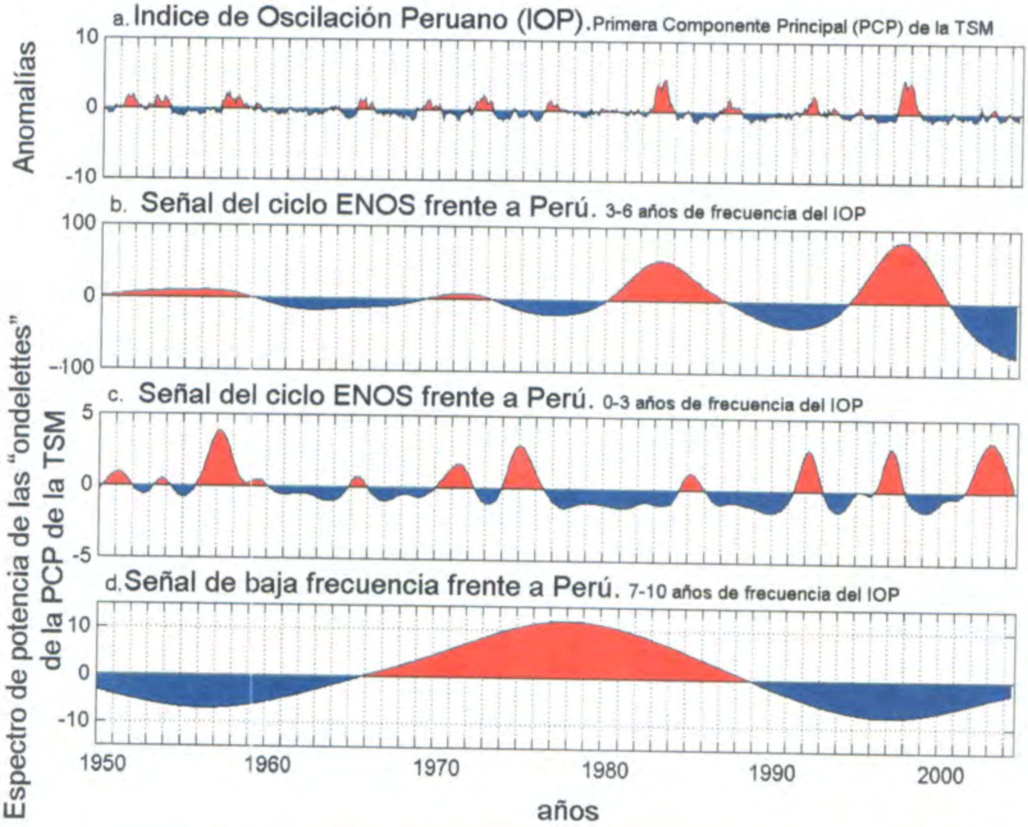


Figura 2. Análisis de la serie mensual de temperatura superficial del mar (TSM) frente a Perú. a. Primera componente principal de la TSM proveniente de cinco estaciones costeras peruanas, la cual se denominó Índice de Oscilación Peruano (IOP). b. Primera componente principal (PCP) del rango de frecuencia entre 3 a 6 años para el IOP, cuya señal equivale al rango de frecuencias del ciclo El Niño Oscilación Sur (ENOS). c. PCP del rango de frecuencia entre 0 a 3 años, cuya señal equivale al filtro de alta frecuencia del ciclo ENOS. d. PCP del rango de frecuencia entre 7 a 10 años, cuya señal equivale al filtro de baja frecuencia del IOP.

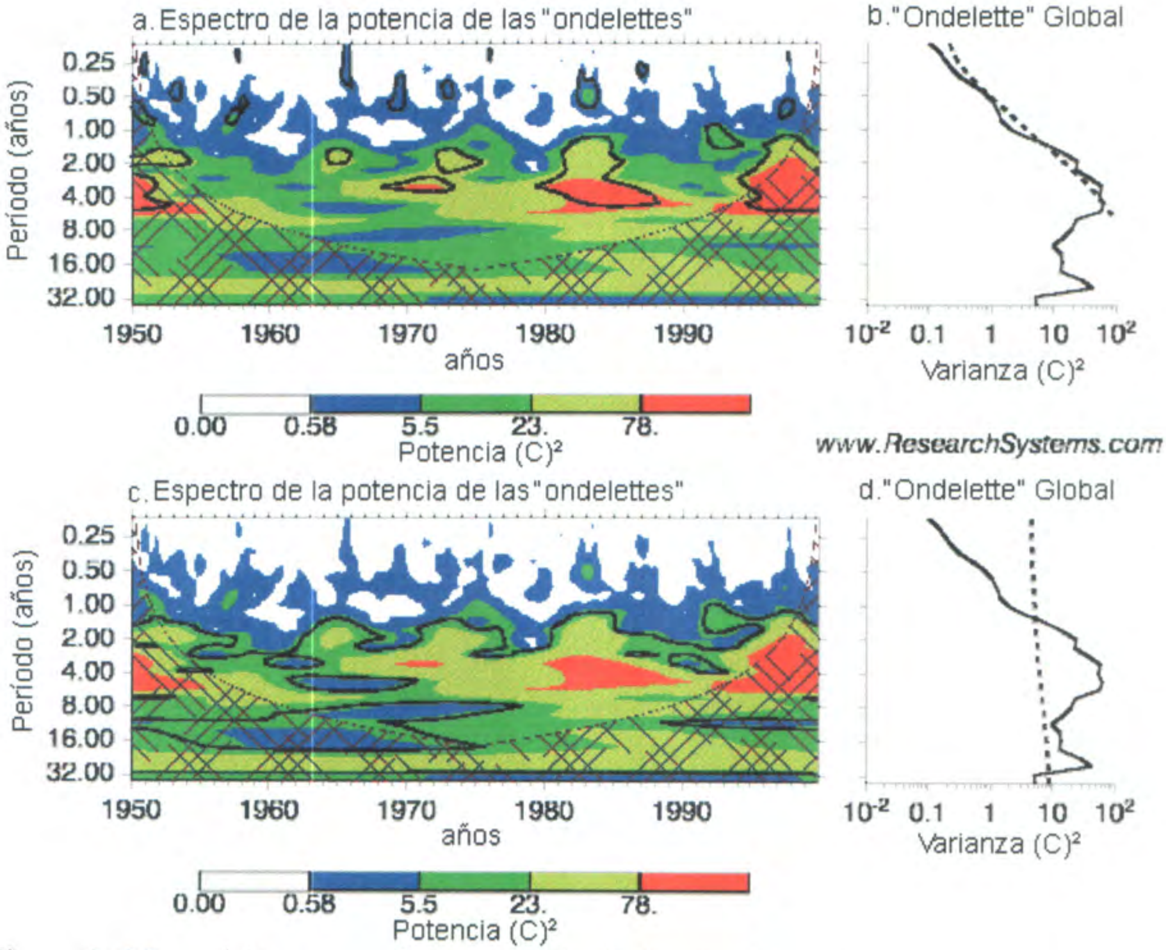
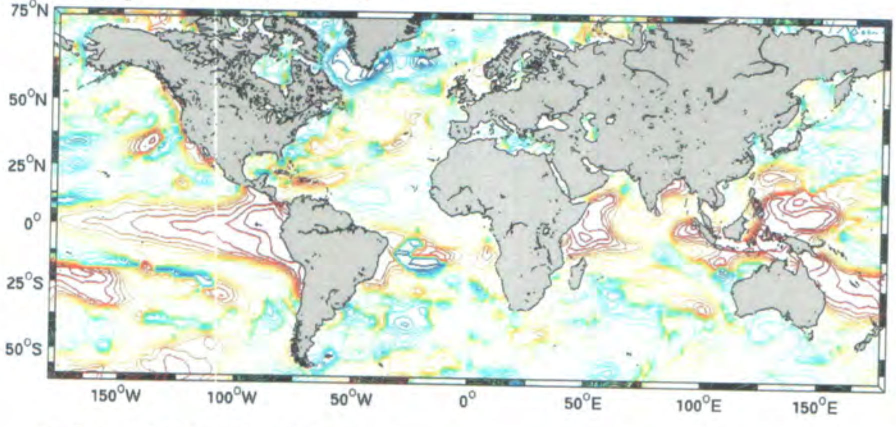
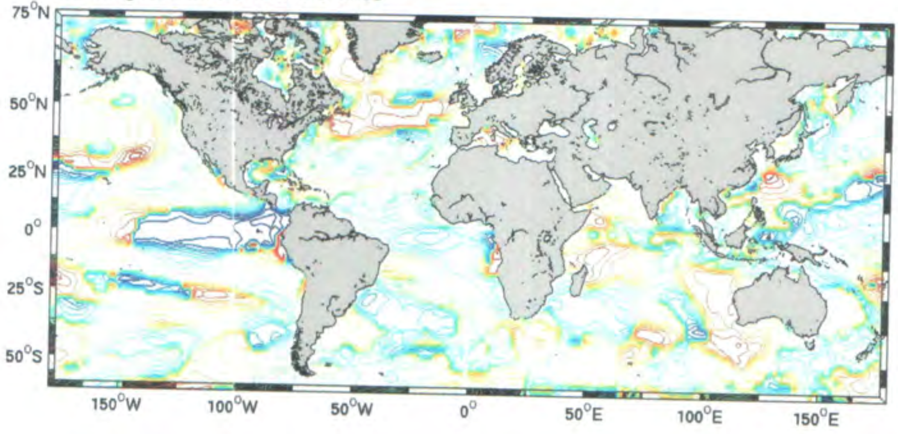


Figura 3. Mapa del espectro de la potencia de las "ondelettes". El contorno negro representa el 10% del nivel de significancia. La región del cono de influencia se representó con el sombreado en la zona inferior de cada mapa. a. Filtro de ruido rojo al 5% de significancia del espectro de la potencia de las "ondelettes". b. Varianza del espectro de la potencia de las "ondelettes". La línea punteada representa el nivel de significancia del espectro de la potencia de las "ondelettes". c. Filtro de ruido blanco al 10% de significancia del espectro de la potencia de las "ondelettes". d. Varianza del espectro de la potencia de las "ondelettes". La línea punteada representa el nivel de significancia al 10%.

a. Rango de frecuencia:0-3 años



b. Rango de frecuencia: 3-6 años



c. Rango de frecuencia: 7-10 años

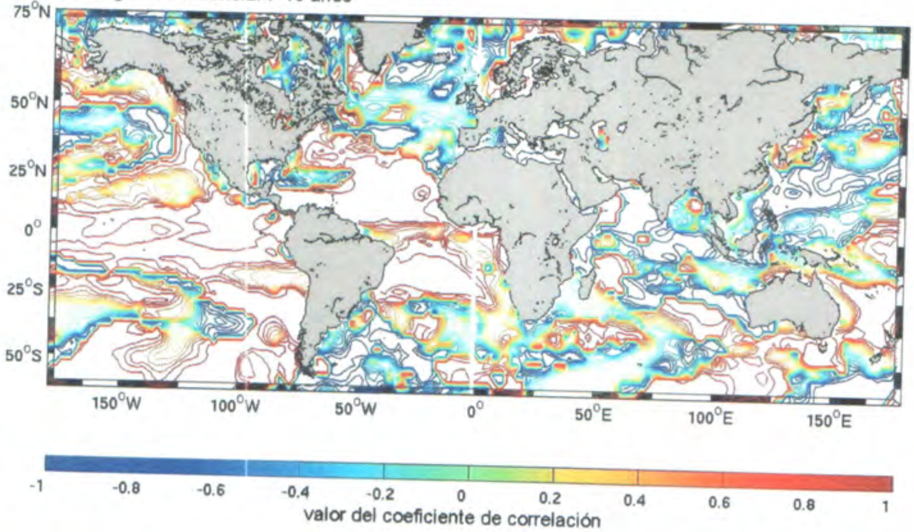


Figura 4. Mapas de correlación entre la primera componente principal de la potencia de las "ondelettes" del IOP y aquellas derivadas de la base de datos COADS.

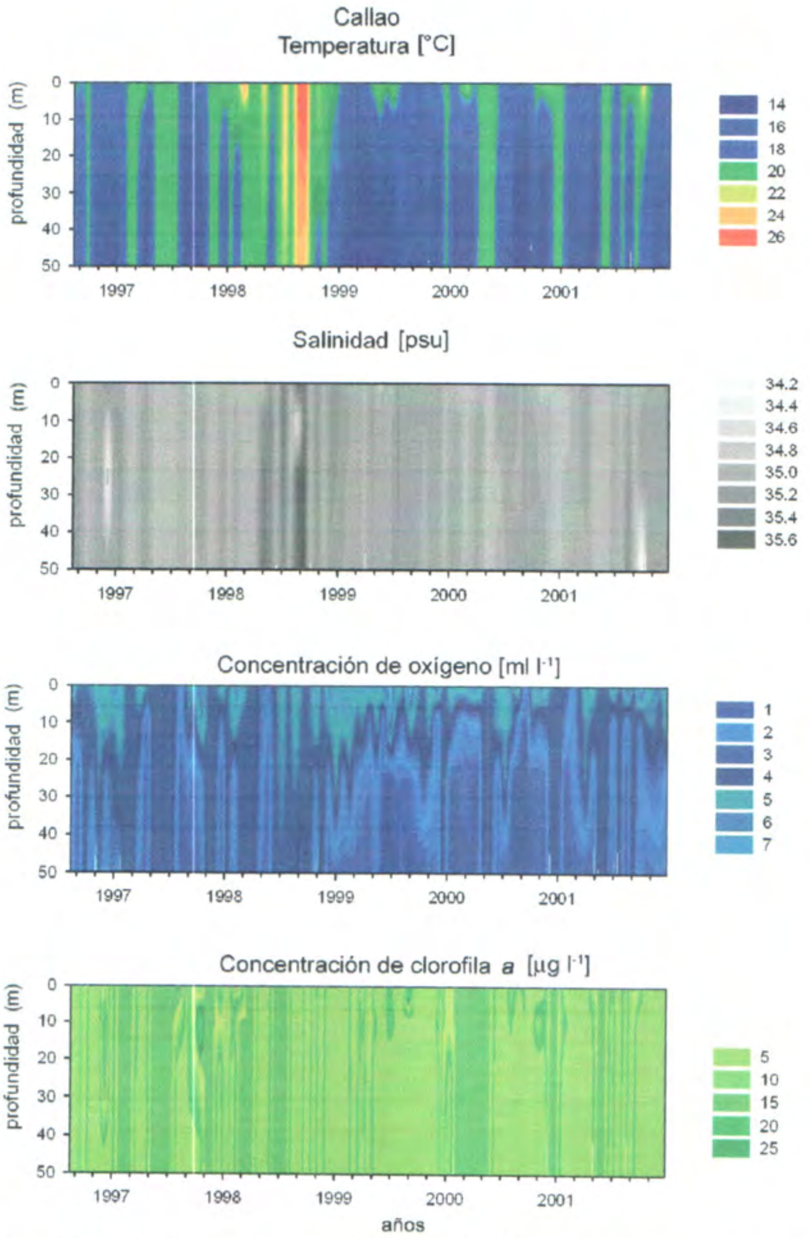


Figura 5. Variabilidad de la temperatura, salinidad, concentración de oxígeno y clorofila *a* en la columna de agua entre 1997 y 2002, frente a Callao: temperatura [°C], salinidad [ups], concentración de oxígeno [ml l^{-1}] y concentración de clorofila *a* [µg l^{-1}].

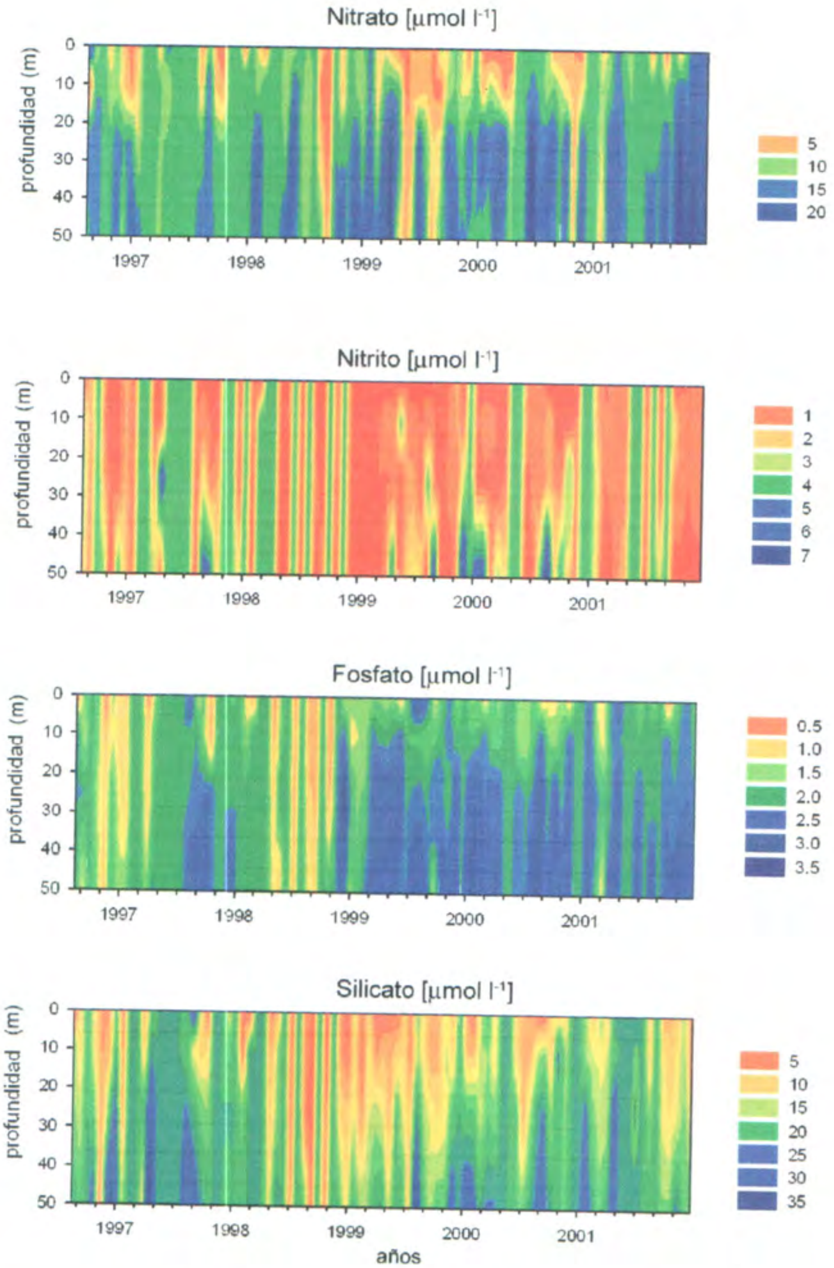
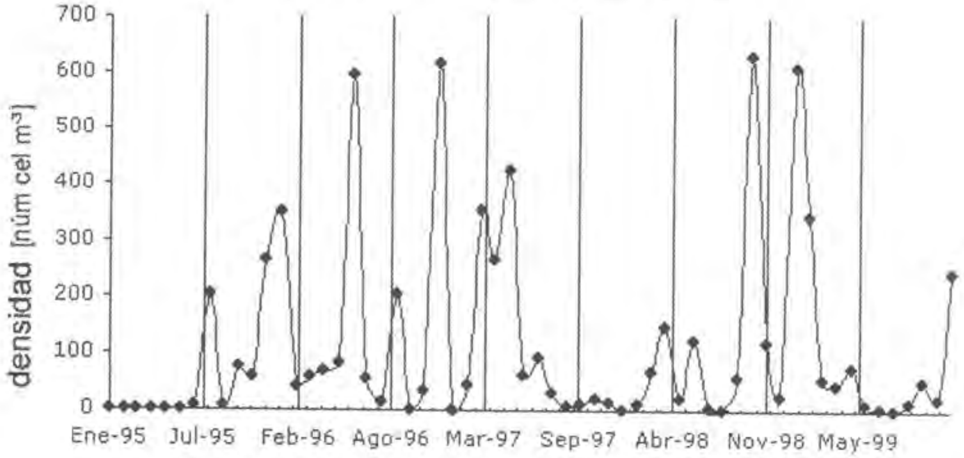
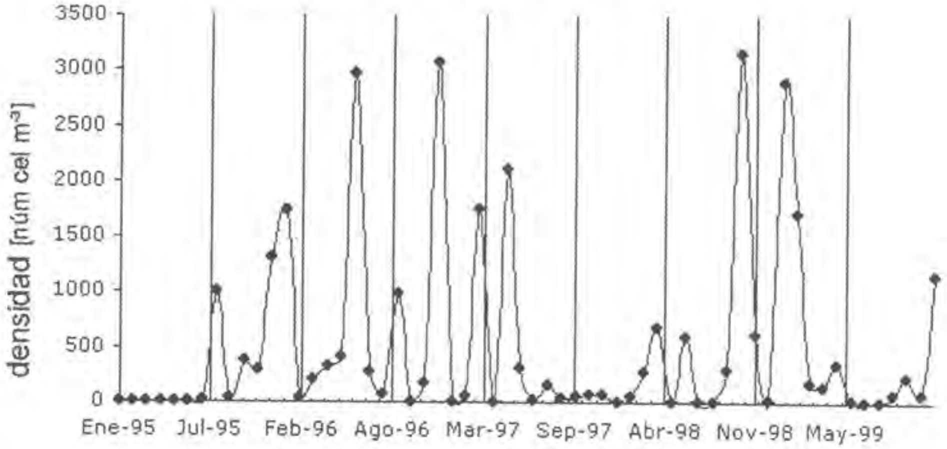


Figura 6. Variabilidad de nutrientes frente a Callao: nitrato [µmol l^{-1}], nitrito [µmol l^{-1}], fosfato [µmol l^{-1}] y silicato [µmol l^{-1}].

a. Fitoplancton de la Bahía de Ancón



b. Diatomeas de la Bahía Ancón



C. Dinoflagelados de la Bahía Ancón

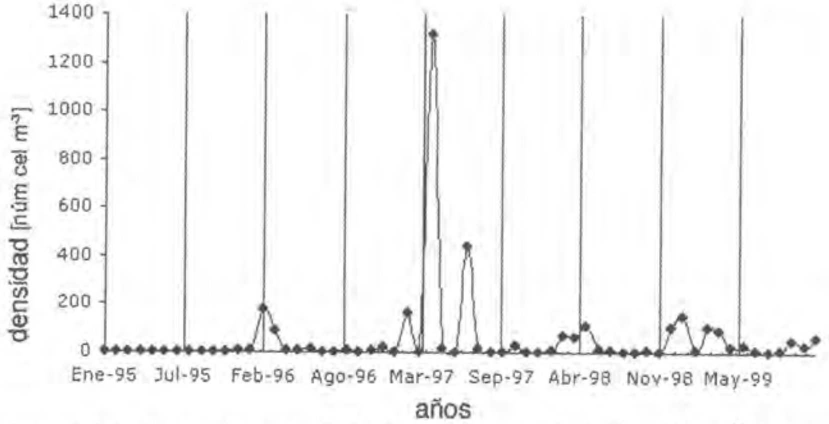


Figura 7. Promedio de la densidad de fitoplancton [núm. cél. m^{-3}] frente a Ancón, entre Enero 1995 y Diciembre 1999.

Tabla 1. Series de tiempo compiladas y sus medidas de tendencia central y dispersión. (Δt) = intervalo temporal.

Período	Variable (Δt)	Fuente	Área	Promedio (Desviación)
1978-2002	Estrés del viento a lo largo de la costa (mensual)	COADS[1]	Callao	3 m s^{-1}(±0.2)
1950-2003	Índice de Oscilación del Sur (mensual)	CPC [2]	Pacífico Sur	-0.03 (±10.06)
1950-2004	Anomalías de Temperatura Superficial del Mar (mensual)	DHN[3] IMARPE[4] DHN DHN DHN	Talara Chicama Chimbote Callao San Juan	19.3°C (±2.4°C) 17.2°C (±2.1°C) 19.9°C (±2.9°C) 16.6°C (±1.9°C) 14.9°C (±1.5°C)
1978-2003	Estrés del viento para el área EL NIÑO 3.4 (mensual)	CPC	Área EL NIÑO 3.4	8.6m s^{-1}(±2.2)
1950-2003	Temperatura superficial del mar (mensual)	CPC	Área EL NIÑO 3.4	25.8°C (±1.29°C)
1979-2002	Volumen de Microplancton (anual)	IMARPE	Área costa peruana (110000 Km^2)	0.8 ml m^{-3}(±0.4)
1964-2002	Volumen de zooplancton (trimestral)	IMARPE	Área costa peruana (110000 Km^2)	0.6 ml m^{-3}(±0.4)
1957-1994	Biomasa de anchoveta (anual)	IMARPE	Área costa peruana (110000 Km^2)	12.10 millones de toneladas (±7.03 millones de toneladas)
1957-1994	Biomasa de sardina (anual)	IMARPE	Área costa peruana (110000 Km^2)	2.1 millones de toneladas (±1.05 millones de toneladas)
1950-2002	Desembarques de anchoveta (anual)	IMARPE	Área costa peruana (110000 Km^2)	4.06 millones de toneladas (±3.52 millones de toneladas)
1950-2002	Desembarques de sardina (anual)	IMARPE	Área costa peruana (110000 Km^2)	0.84 millones de toneladas (±1.09 millones de toneladas)
1950-2002	Desembarques de jurel (anual)	IMARPE	Área costa peruana (110000 Km^2)	0.09 millones de toneladas (±0.1 millones de toneladas)
1950-2002	Desembarques de caballa (anual)	IMARPE	Área costa peruana (110000 Km^2)	0.003 millones de toneladas (±0.03 millones de toneladas)
1951-1999	Anomalías de Temperatura Superficial del Mar (mensual)	SHOA[5]	Antofagasta Iquique Caldera Valparaíso[6] Talcahuano	17.8°C (±1.9°C) 17.5°C (±2.06°C) 16.1°C (±1.7°C) 13.9°C (±1.4°C) 12.8°C (±1.39°C)

Tabla 1. Continuación.

Período	**Variable (∆t)**	**Fuente**	**Área**	**Promedio (Desviación)**
1995-2002	Temperatura columna de agua (0-100 m)	IMARPE	Callao	16.8°C (±2.4°C)[7]
1995-2002	Salinidad columna de agua (0-100 m)	IMARPE	Callao	35.9UPS (±0.7UPS)[7]
1995-2002	Oxígeno columna de agua (0-100 m)	IMARPE	Callao	2.02mol l^{-1}(±1.9 mol l^{-1})[7]
1995-2002	Fosfatos columna de agua (0-100 m)	IMARPE	Callao	1.9mol l^{-1}(±0.7 mol l^{-1})[7]
1995-2002	Nitratos columna de agua (0-100 m)	IMARPE	Callao	11.3mol l^{-1}(±6.3 mol l^{-1})[7]
1995-2002	Silicatos columna de agua (0-100 m)	IMARPE	Callao	15.9 mol l^{-1}(±8.7 mol l^{-1})[7]
1995-2002	Nitritos columna de agua (0-100 m)	IMARPE	Callao	1.3 mol l^{-1}(±1.7 mol l^{-1})[7]
1995-2002	Clorofila *a* columna de agua (0-100 m)	IMARPE	Callao	1.8 µg m^{-3}(±3.2 µg m^{-3})[7]
1995-2002	Biomasa de anchoveta, prospección acústica	IMARPE	Callao	5.4 millones de toneladas (±0.5 millones de toneladas)
1995-2002	Biomasa de sardina, prospección acústica	IMARPE	Callao	1.01 millones de toneladas (±0.1 millones de toneladas)

1. Comprehensive Ocean Atmosphere Data Set.
2. Climate Prediction Center.
3. Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú.
4. Instituto del Mar del Perú.
5. Durante el período 1974 a 1982 no presentó datos, por lo cual no fue incluido en el análisis.
6. Servicio Hidrográfico y Oceanográfico de la Armada de Chile.
7. Promedio y Desviación calculado para la capa fótica 0-50 m.

Tabla 2. Número de cruceros utilizados para el cálculo del volumen de mesozooplancton frente al Perú. Est. = número de estaciones, Vol. = volumen de mesozooplancton desplazado promedio. Datos suministrados por el IMARPE.

	Verano		Otoño		Invierno		Primavera	
Décadas	Est.	Vol. ±s.e. [ml m^{-3}]	Est.	Vol. ±s.e. [ml m^{-3}]	Est.	Vol. ±s.e. [ml m^{-3}]	Est.	Vol. ±s.e. [ml m^{-3}]
60	515	1.04 ±0.55	-	0.91 ±0.55	522	1.07 ±0.54	-	2.47 ±1.58
70	600	0.66 ±0.49	-	0.61 ±0.46	639	0.55 ±0.43	-	0.81 ±0.65
80	507	0.27 ±0.17	-	0.18 ±0.09	704	0.30 ±0.25	-	0.30 ±0.10
90	1942	0.46 ±0.25	-	0.47 ±0.26	1200	0.45 ±0.15	-	0.56 ±0.28

Tabla 3. Período El Niño frente a la costa peruana y del área EL NIÑO 3.4. Los números subrayados representan los períodos El Niño de alta frecuencia. Los números en negrita representan los años de inicio y término de la fase cálida de la señal de baja frecuencia del IOP.

El Niño	
IOP (1950-2004)	NIÑO 3.4 (1950-2004)
1951-1952	1951-1952
1953	1953
1956-1957	1957-1958
	1963-1964
1965-**1966**	1965-1966
	1968-1970
1972-1973	1972-1973
1976-1977	1976-1978
	1979-1980
1982-1983	1982-1983
1987	1986-1988
1991-1992	1991-1992
	1993
	1994-1995
1997-1998, 1997-1998	1997-1998
2002-2003	2002

Parte B

6. ANEXO

6.1 Publicaciones y Manuscritos.

6.1.1. Montecinos A, S Purca & O Pizarro (2003) Interannual to interdecadal sea surface temperature variability along the western coast of South America. Geophysical Research Letters 3(11): 1570-1573.

6.1.2. Ayón P, S Purca & R Guevara-Carrasco (2004) Zooplankton volume trends off Peru between 1964 and 2001. ICES Journal of Marine Science 61(4): 478-484.

6.1.3. Purca S, T Antezana, P Ayón, R Guevara-Carrasco, S Sánchez & R Riquelme. El Niño signal overshadows regime shifts in the pelagic ecosystem off Peru. Terminado.

6.1.1. Montecinos A, S Purca & O Pizarro (2003) Interannual-to-interdecadal sea surface temperature variability along the western coast of South America. Geophysical Research Letters 3(11): 1570-1573.

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Interannual-to-interdecadal sea surface temperature variability along the western coast of South America

A. Montecinos

Programa Regional de Oceanografía Física y Clima (PROFC), and Departamento de Oceanografía, Universidad de Concepción, Chile

S. Purca

Departamento de Oceanografía, Universidad de Concepción, Chile

O. Pizarro

DEFAO/PROFC/COPAS, Universidad de Concepción, Chile

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[1] Interannual and interdecadal regional-scale sea surface temperature (SST) variability along Peru and Chile are described based on 9 coastal stations and global SST in the period 1951–1999. ENSO-related interannual variability dominates the low-passed time series along the coast, with maximum amplitudes in the tropics decreasing southward. At tropical latitudes interdecadal variance is about one-third of the interannual variance while they are of similar amplitude in the midlatitudes (36°S). The correlation between the low frequency coastal modes and the Pacific and Atlantic SST suggests that the coastal SST variability comprises two main large-scale climate processes: the ENSO cycle at interannual timescale, and a basin-wide, perhaps even a global-scale, interdecadal oscillation. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4223 Oceanography: General: Descriptive and regional oceanography; 4522 Oceanography: Physical: El Niño. **Citation:** Montecinos, A., S. Purca, and O. Pizarro, Interannual-to-interdecadal sea surface temperature variability along the western coast of South America, *Geophys. Res. Lett.*, *30*(11), 1570, doi:10.1029/2003GL017345, 2003.

1. Introduction

[2] The El Niño-Southern Oscillation (ENSO) is the main source of interannual variability in the Pacific Ocean [e.g., *Rasmusson and Carpenter*, 1982]. ENSO-related SST anomalies exhibit largest magnitudes along the equator, decreasing over a wide, wedge-shaped region that spreads poleward along the eastern boundaries [*Enfield and Mestas-Nuñez*, 1999]. At longer periods, several studies have documented decadal-to-interdecadal variability in the Pacific Ocean, mainly in the tropics and North Pacific [e.g., *Nitta and Yamada*, 1989; *Trenberth*, 1990; *Graham*, 1994]. As in other portions of the Pacific basin [*Chavez et al.*, 2003], interdecadal variability in the eastern South Pacific was first recognized in fisheries fluctuations: in Chile [*Yañez*, 1991] and Peru [*Pauly and Tsukayama*, 1987].

[3] *Lluch-Cota et al.* [2001] documented SST variability in coastal areas of the northeastern Pacific for the period 1950–1999, finding two main modes of variability. The first mode describes the ENSO-related variability, while the second mode captures fluctuations at interdecadal timescales. Descriptions of interdecadal SST variability in the eastern South Pacific have mostly come from Pacific basin analyses which, due to the relatively poor data coverage in the Southern Hemisphere, tend to emphasize phenomenon in the North Pacific. Here we use coastal time series of SST along Peru and Chile, together with gridded reconstructed SST data, to study the low frequency variability of SST at regional-scale along the western coast of South America and its relation to basin-scale variability.

2. Data and Processing

[4] The main set of data consists on monthly coastal SST time series for 5 and 4 stations on the coasts of Peru and Chile, respectively, from 1951 to 1999 (Figure 1). Also, the extended reconstructed SST (ERSST) time series for the global domain on a 2° × 2° grid resolution for the same period are used. The ERSST employ updated COADS observations with new quality control procedures, and improved reconstruction methods [*Smith and Reynolds*, 2003]. In order to compare both sources of information, the closest grid points to the coast of Peru and Chile were extracted between 2°S and 38°S (Figure 1). Annual mean SST series were computed as the average of monthly data at each coastal station and grid point over the Pacific and Atlantic Oceans. These annual SST time series for each coastal station are depicted in Figure 1. Linear trends of the annual time series were removed to separate interdecadal timescales from very low frequency variability that could be related to other processes. Interdecadal time series were computed by smoothing the detrended-annual time series twice with a 7-year running mean. The interannual time series were computed as the difference between the detrended-annual and the interdecadal time series. After this processing the lengths of the records were reduced to 1957–1993 to remove possible end point effects of the filtering.

[5] Empirical Orthogonal Function (EOF) analysis was applied to the normalized (by the standard deviation) interannual and interdecadal time series of both data sets

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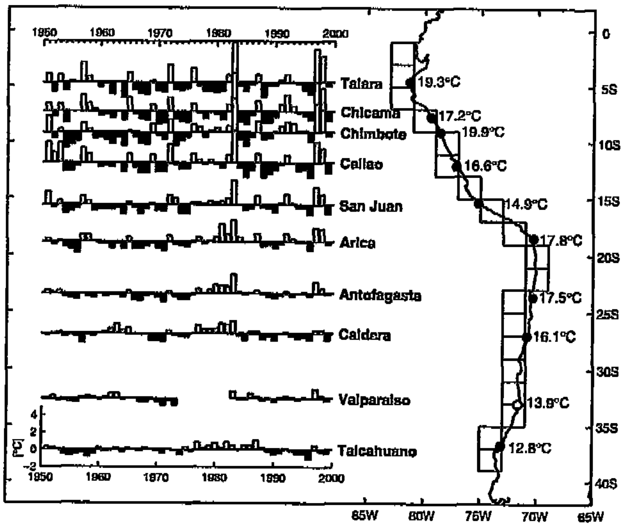

Figure 1. Location of SST coastal stations (black circles) in Peru and Chile used in the EOF analysis. Boxes represent the 2° × 2° grid points used from the extended reconstructed SST (ERSST) dataset [*Smith and Reynolds*, 2003]. Also, annual SST time series are depicted using white and black bars which indicate positive and negative deviations from the long-term mean, respectively. The figure includes the SST time series in Valparaíso (white circle) which presents a large gap between 1974 and 1982 (not included in the analysis). Long-term mean values also are shown.

to capture the main signal of SST covariability along the western coast of South America.

3. Results

[6] Coastal SST data exhibit a colder long-term mean, and a smaller positive trend in the period 1951–1999 in comparison with the ERSST data along the coasts of Peru and Chile. Specifically, Callao and Caldera present negative trends (−1.3°C and −0.2°C in 100 years, respectively). The large negative trend in Callao is in contrast with the positive trend observed at the other coastal stations near Callao and in the gridded data at this latitude. Nevertheless, low frequency fluctuations at Callao agrees well with the variability in the nearest locations (see below). It is worth noting that the colder long-term mean registered by coastal stations could be explained by coastal upwelling, which is restricted to a region near the coast. On the other hand, coastal SST time series show a smaller positive trend than ERSST data which could be related to the filtering EOF procedure described by *Smith and Reynolds* [2003] or an increasing of coastal upwelling due to a positive trend in alongshore wind stress in the eastern South Pacific [*Bakun*, 1990].

[7] The first principal component (PC1), the associated spatial pattern (presented as the correlation between PC1 and individual time series), and the standard deviation of interannual SST series for both coastal stations and ERSST data are shown in Figure 2. The PC1s are well correlated (r = 0.87), although the amplitude of the ERSST PC1 is higher due to the higher explained variance (76%) in comparison with that explained by the coastal SST PC1 (71%). Clearly, these interannual SST modes (Figure 2a) can be interpreted as the ENSO signal along the western coast of South America. In fact, the coastal SST PC1 exhibits a correlation of 0.86 and 0.94 with the annual SST time series in regions Niño 3 (5°S–5°N, 150°–90°W) and Niño 1+2 (0°–10°S, 90°–80°W), respectively. Both coastal and ERSST patterns present strong coherence -high correlation values- in tropical latitudes decaying to the south of 25°S, although the latter shows higher correlations (Figure 2b). Standard deviations show similar spatial pattern in both datasets with slightly larger values at tropical latitudes for coastal SST time series (Figure 2c). Standard deviations decrease almost linearly with latitudes from the equator to 23°S (16°S) and are constant to the south for coastal SST (ERSST) data.

[8] Figure 3 shows the PC1, spatial pattern, and standard deviation for both normalized coastal station SST and ERSST interdecadal time series. As in the interannual analysis, the amplitude of the ERSST PC1 is higher than the coastal SST PC1, consistent with a higher explained variance (90% and 66%, respectively). Both PC1 show a similar evolution (r = 0.90), although the negative values during the 1960s do not match exactly. Thus, minimum values are reached at about 1967 (1971) according to the coastal SST (ERSST) PC1. During the mid-1970s, there is a change to positive values in both SST PC1, reaching maximum values in 1983 and changing to negative ones at around 1987–1988. After a short period of negative values, both SST PC1 tend to describe the onset of a positive phase during the early 1990s. From 1957 to 1993, the interdecadal oscillation obtained by the EOF analysis has a period of 20–25 years. According to ERSST data, the interdecadal mode is highly coherent all along the coast (Figure 3b), whereas the coastal SST data show that the interdecadal signal is weaker in the equatorial region (to the north of 9°S), and decreases slightly to the south of 23°S. The standard deviation of coastal SST and ERSST data is similar at interdecadal timescale remaining around 0.2°C along the coast of Peru and Chile (Figure 3c). In comparison to the standard deviation of interannual SST

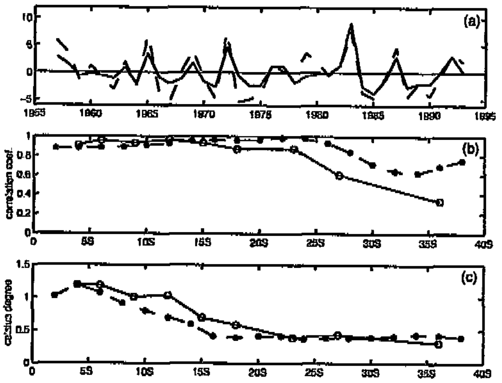

Figure 2. (a) First principal component (PC1) of normalized interannual SST time series from coastal stations (solid line) and ERSST data (dashed line). (b) Related alongshore pattern represented as the correlation between PC1 and individual time series using coastal station data (solid line and open circles) and ERSST data (dashed line and asterisks). (c) Standard deviation of interannual SST time series from coastal station data (solid line and open circles) and ERSST data (dashed line and asterisks).

data (Figure 2c), the interdecadal variability shows smaller values in tropical latitudes, but increases to midlatitudes. In fact, both time series have about the same standard deviation at 36°S (0.3°C).

[9] Figure 4 presents the correlation between coastal SST PC1 and ERSST time series for each Pacific and Atlantic Oceans grid point at interannual and interdecadal timescales. The correlation pattern for interannual periods (Figure 4a) shows the typical structure associated with ENSO [*Rasmusson and Carpenter*, 1982]. As expected, highest values are distributed along the western coast of South America, decreasing poleward in magnitude. It is interesting to note the westward projection of correlation larger than 0.9 at about 7°S, and suggested at about 3°N. At interdecadal timescale, the correlation field in the Pacific Ocean is characterized by a horseshoe pattern, though positive values are restricted to the east of 140°W in the South Pacific, and negative values to the subtropical regions (Figure 4b). As expected larger positive correlations are found in the southeastern Pacific in relation to the coastal SST PC1, with the highest values located from 15°S to 25°S, and along the equator around 110°W. Specifically, in the North Pacific the correlation pattern resembles the PDO related SST anomaly field described by *Mantua et al.* [1997]. On the other hand, *Garreaud and Battisti* [1999] presented the SST regressed on the global residual time series (GR) which represents the ENSO-like variability described by *Zhang et al.* [1997]. Their analysis reveals a similar structure to the ENSO SST pattern, but with a broader latitudinal scale. This feature is also present in the correlation pattern of Figure 4b based on coastal SST PC1, though it is focused in the eastern South Pacific. In addition, over the South Atlantic there is a dipole pattern characterized by positive (negative) values to the south (north) of 25°S. In the North Atlantic, positive correlations are restricted to the eastern coast of North America while negative values are found in the northeastern Atlantic Ocean and Mediterranean Sea.

[10] It is important to note that the ERSST is constructed with separate analysis procedures for high (interannual to shorter fluctuations) and low (decadal and longer periods) frequency variability [*Smith and Reynolds*, 2003]. In spite of the damped SST field that results from the reconstruction, the interannual variability of SST is well represented by the ERSST PC1 along the coast of Peru and Chile. However, the differences in the reconstruction SST procedure at interdecadal timescale, that tend to enhance large-scale patterns of variability, could explain the discrepancies in the coastal and ERSST alongshore structure and time evolution captured by our EOF analysis.

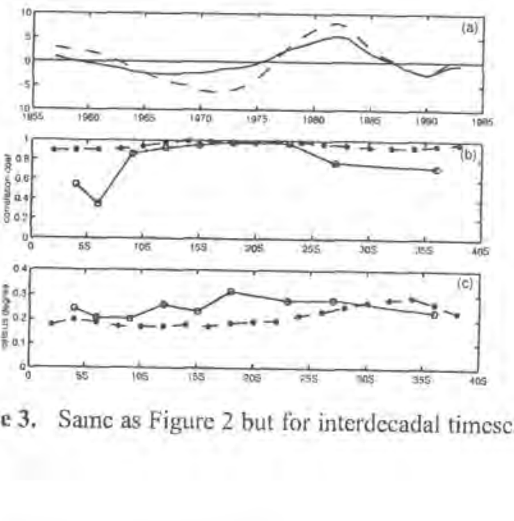

Figure 3. Same as Figure 2 but for interdecadal timescale.

(a) <PC1,SST field> interannual

(b) <PC1,SST field> interdecadal

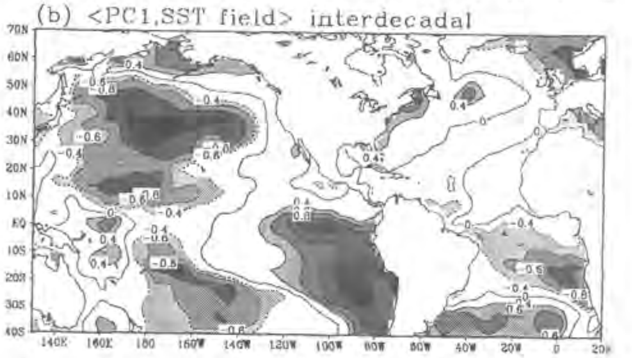

Figure 4. Spatial pattern of correlation between the coastal SST PC1 and ERSST data at (a) interannual, and (b) interdecadal timescales. Shaded and solid lines (dashed lines) represent positive (negative) correlations. Contour interval is 0.2 from values larger in magnitude than 0.4. The zero line is also depicted. In (b) correlation values larger than 0.63 are significant at 95% of confidence, using 10 effective number of degree of freedom [*Davis*, 1976].

4. Discussion and Conclusions

[11] Our main results are in some extent in agreement to those described for the western coast of North America by *Lluch-Cota et al.* [2001]. In spite of differences in methodological aspects both studies show that the ENSO-related SST variability decreases poleward from subtropical latitudes, while interdecadal variability increases from subtropics to midlatitudes. These results are suggested by the annual SST time series depicted in Figure 1.

[12] At interannual timescales correlations larger than 0.9 appear to be projected westward at subequatorial latitudes (Figure 4). This could be the result of Rossby waves which are originated in the eastern boundary of the Pacific by Kelvin waves reaching the coasts [e.g., *Philander*, 1990]. On the other hand, our results show that interdecadal SST variability along the western coast of South America is related to the North Pacific interdecadal oscillation, which suggests a basin-wide character of this variability. In this respect, *Evans et al.* [2001b] compare the coral-based SST reconstruction in Rarotonga (21°S, 160°W) [*Linsley et al.*, 2000] with the Pacific basin SST field reconstructed from

tree-ring proxy data along North and South America [*Evans et al.*, 2001a]. Both paleoproxy reconstructions produce SST patterns that extend to the North and South Pacific which, according to *Evans et al.* [2001b], suggests a tropical origin of the interdecadal variability.

[13] Different approaches have been used to analyze propagation of interdecadal features in the SST field. *Latif et al.* [1997] studied the SST in the Pacific Ocean, specifically the Global Ice Sea Surface Temperature (GISST, version 1.1) dataset [*Parker et al.*, 1995], by means of Principal Oscillation Pattern (POP) method. *Venegas et al.* [1998], used the GISST (version 2.2) and the Gridded Monthly Sea Level Pressure (GMSLP) dataset [*Allan*, 1993] to study the joint pattern in the South Atlantic using the combined Complex EOF (CCEOF), which is then projected to the entire Atlantic, Pacific and Indian Oceans. Finally, *Tourre et al.* [2001] studied the joint pattern of SST and SLP [*Kaplan et al.*, 1998] in the Pacific Ocean, by means of Multi Taper Method/Singular Value Decomposition (MTM/SVD) technique. The correlation pattern produced by coastal SST PC1 at interdecadal timescales (Figure 4b), resembles specific phases of the oscillation signals obtained by the different mentioned techniques: the (negative) real part of the decadal POP mode (Figure 10 in *Latif et al.* [1997]) with a rotation period of 13 years, the corresponding 7.5-year phase of the South Atlantic 20 year cycle (Figure 3 in *Venegas et al.* [1998]), and the 7.2-year phase of the interdecadal Pacific oscillation with a mean period of 16.7 years (Figure 2 in *Tourre et al.* [2001]). Thus, the regional-scale SST variability observed along the western coast of South America seems to be a specific phase of a basin-wide oscillation at interdecadal timescale. Moreover, the correlation pattern of Figure 4b shows a dipole pattern in both the South and North Atlantic Oceans, which are also present in the analysis by *Venegas et al.* [1998]. These authors suggest that the presence of SST signals in the Pacific and Atlantic Oceans that arise from their regional study are evidence of the global character of fluctuations at interdecadal timescale.

[14] In summary, low frequency coastal SST variability along the western coast of South America comprises two main large-scale climate processes: the ENSO cycle at interannual timescale which present large variability in the tropical Pacific Ocean, and a basin-wide Pacific, perhaps a even global-scale, interdecadal oscillation.

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A. Montecinos and O. Pizarro, Programa Regional de Oceanografía Física y Clima, Universidad de Concepción, Casilla 160-C, Concepcion-3, Chile. (amonteci@profc.udec.cl; orpa@profc.udec.cl)

S. Purca, Departamento de Oceanografía, Universidad de Concepción, Barrio Universitario, Cabina 10, Concepción, Chile. (spurca@udec.cl)

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Zooplankton volume trends off Peru between 1964 and 2001

Patricia Ayón, Sara Purca, and Renato Guevara-Carrasco

Ayón, P., Purca, S., and Guevara-Carrasco, R. 2004. Zooplankton volume trends off Peru between 1964 and 2001. – ICES Journal of Marine Science, 61: 478–484.

Zooplankton samples were collected by Hensen net (300 μm) vertical hauls from a depth of 50 m in 57 surveys along the Peruvian coast during winter and summer from 1961 to 2001. In general, the latitudinal distribution of total zooplankton volumes showed highest values within 60 nmi (111 km) of the coast. Predominantly during the 1960s, high zooplankton volumes were found between 4°S–6°S and 14°S–16°S, coinciding with narrow continental shelf areas. Strong declines of zooplankton volumes were observed in these regions in the 1990s. In the long term, zooplankton volumes off Peru were higher during "cold" decades, particularly in the 1960s, than during "warm" decades. This research supports the regime-shift previously observed in the Peruvian coastal upwelling, and is in agreement with global changes observed in lower and upper trophic levels elsewhere in the Pacific and North Atlantic basins.

Keywords: long-term changes, Peru, regime-shift, SST, upwelling ecosystem, zooplankton.

P. Ayón and R. Guevara-Carrasco: Instituto del Mar del Peru, Esquina Gamarra y Gral. Valle S/N. Chucuito Callao, Peru. S. Purca: Universidad Nacional Federico Villareal, Facultad de Oceanografía, Pesquería y Ciencias Alimentarias, Francia 726, Miraflores, Lima, Peru. Correspondence to P. Ayón: tel:/fax: +511 453 5053; e-mail: payon@imarpe.gob.pe.

Introduction

The Peruvian marine ecosystem is characterized by strong and persistent upwelling along the Peruvian coast, producing well-known biological productivity and supporting one of the largest fisheries in the world. Oceanographic and atmospheric conditions off Peru are characterized by several modes that vary on seasonal to interdecadal scales. One of the dominant modes is interannual variability due to the El Niño–Southern Oscillation cycle (ENSO), which affects ecosystem structure, reproductive strategies, and fisheries yields (Arntz and Valdivia, 1985; Bakun, 1987; Jarre-Teichmann, 1992). Interdecadal changes have also been observed and deduced from variability of sea surface temperature (SST), among other climatic variables, and linked to widely fluctuating catches of the Peruvian anchoveta (*Engraulis ringens*) and sardine (*Sardinops sagax*) (Chavez *et al.*, 2003). A multidecadal trend of increasing wind velocity off Peru as a consequence of global warming has been proposed (Bakun, 1990). Three ENSO modes have been detected in the Pacific basin, long term, interdecadal, and interannual (Enfield and Mestas-Nuñez, 2000), and it is probable that many biological and physical time-series from the Pacific basin are related with these ENSO modes.

A decline in the California Current zooplankton (Roemmich and McGowan, 1995) and in the northern part of the Subarctic Pacific (Sugimoto and Tadokoro, 1998), from the start of the 1970s onward, has been suggested. Carrasco and Lozano (1989) also showed a decline in zooplankton volumes from the mid-1960s and especially from the mid-1970s to 1987 in the Peruvian upwelling ecosystem. Changes in physical forcing, e.g. winds, thermocline, heat flux, and SST, have been proposed (Clarke and Lebedev, 1999) to explain the decline in the Californian waters, and predation upon zooplankton of pelagic fishes, such as horse mackerel (*Trachurus picturatus*) and mackerel (*Scomber japonicus*), (Carrasco and Lozano, 1989) for the Peruvian waters. However, global changes associated with an interdecadal regime-shift in the dominant small pelagic fishes in the Pacific basin (Lluch-Belda *et al.*, 1992; Schwartzlose *et al.*, 1999; Hare and Mantua, 2000; Chavez *et al.*, 2003) constitute the general framework in which we should try to understand trends in zooplankton volumes.

The current data set can be used to examine whether such changes persist off Peru. In Peruvian coastal waters, environmental factors and predation intensity may both play a crucial role in zooplankton fluctuations. Interdecadal variability of SST has been detected in this region (Montecinos *et al.*, 2003) and the main fish predators of zooplankton have also shown interdecadal changes (Csirke *et al.*, 1996; Schwartzlose *et al.*, 1999). This paper is an extension of the proposal made by Carrasco and Lozano (1989) to synthesize the temporal and spatial trends in zooplankton biomass off Peru. We focus on regime-shifts of SST during

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the 1960–1970 and 1980–1990 decades, and interdecadal fluctuations of anchoveta biomass.

Data and methods

The total area covered during the study was 9.3×10^4 km^2, from the coast to 556 km (300 nmi) offshore (Figure 1). Between 1964 and 2002, 130 seasonal surveys were carried out to assess anchoveta abundance and more than 10 000 zooplankton samples were collected by the Instituto del Mar del Peru (IMARPE). Zooplankton samples were taken with Hensen nets of 0.33-m^2 mouth area and 300-µm mesh, by vertical hauls between 50 and 0 m. The samples were fixed in 2% formaldehyde buffered with borax. The zooplankton volume (m^{-3}) was determined immediately after collection using the displacement method (Kramer *et al.*, 1972). Ichthyoplankton and large coelenterata were separated from the samples before measurement. All the data come from the database of the Zooplankton Laboratory of IMARPE; a more detailed analysis, including species composition, has been initiated. As the sampling protocol has been consistent since 1964, we observed that similar proportions of day and night samples have been collected during each cruise. For spatial analysis, the Peruvian coast has been divided into three areas: A (03°30′S–5°59′S), B (06°00′S–13°59′S), and C (14°00′S–18°20′S) according to differences in oceanographic characteristics.

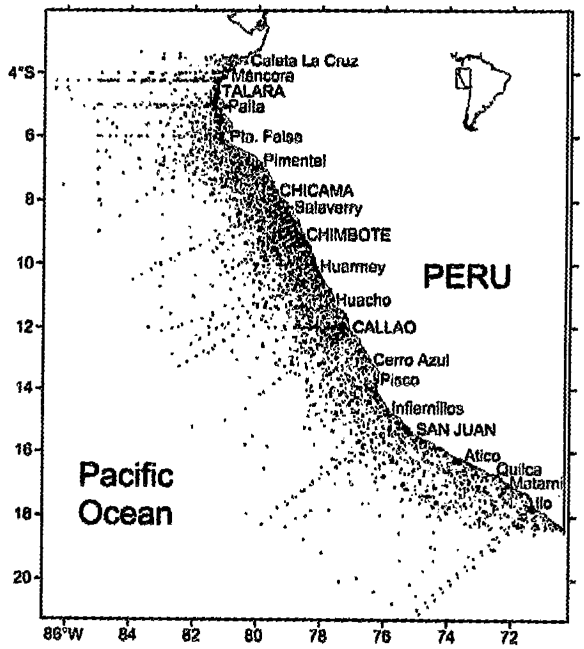

Figure 1. Study area along the Peruvian coast with a total of 6625 sampling points from summer and winter surveys from 1964 to 2002.

Monthly mean SST was measured *in situ* from 1950 to 1999 at five coastal stations along the Peruvian coast [Talara (04°34′S), Chicama (07°41′S), Chimbote (09°04′S), Callao (12°03′S), and Ilo (17°38′S)]. Data for the most recent years were not available from this source. We also show the mean annual series of SST from 1964 to 2001, from the IMARPE database. This mean annual SST was the result of averaging mean monthly SST of Paita (05°04′S), Chimbote, Callao, and Ilo coastal stations of IMARPE. The annual mean anchoveta biomass (Guevara-Carrasco, unpublished) comes from an updated version of the virtual population analysis (VPA) made by Csirke *et al.* (1996).

Statistical descriptors

The zooplankton data consist of 4 columns (seasons) and 39 rows (years). In this matrix, observations represent the mean value of each survey. The mean annual volume was obtained by averaging the rows (ZAM). Of the 39 years considered in the study, 31 have more than two surveys with complete spatial coverage, 7 years have one survey, and 1 year has no survey (1988). The surveys with incomplete spatial coverage (1979 and 1987) were discarded. These three annual mean values were replaced by a 5-year moving average of the annual series.

Time-series analysis

The survey frequency for zooplankton over the years and by season is shown in Figure 2. Monthly (PC1M) and annual (PC1A) SST data time-series were composed of the first principal component for five coastal stations. The PC1M and PC1A include most of the coastal variability during the 1950–1999 period for monthly and annual frequencies (600 and 50 observations, respectively). We analysed PC1A with a "low-pass filter" (moving average >7 years) in order to enhance "cold" and "warm" periods between 1964 and 1994.

Spatial analysis

For spatial zooplankton variation, we used 3564 and 3065 sampling points collected during summer and winter, respectively, from 1964 to 2002. Data collected during spring and autumn had large gaps and were not considered. We explored decadal spatial variation using between 5 and 13 surveys per decade. The data were plotted and interpolated with the "closed neighbour" method using Surfer v.8.0 (Figure 3). An EOF analysis was performed but it did not increase the information. Data were averaged for seasonal comparisons among decades.

Results

The mean zooplankton volume ranged from 0.03 ml m^{-3} to 5.37 ml m^{-3}. The seasonality of zooplankton volume did not show drastic changes among decades. Spring has been

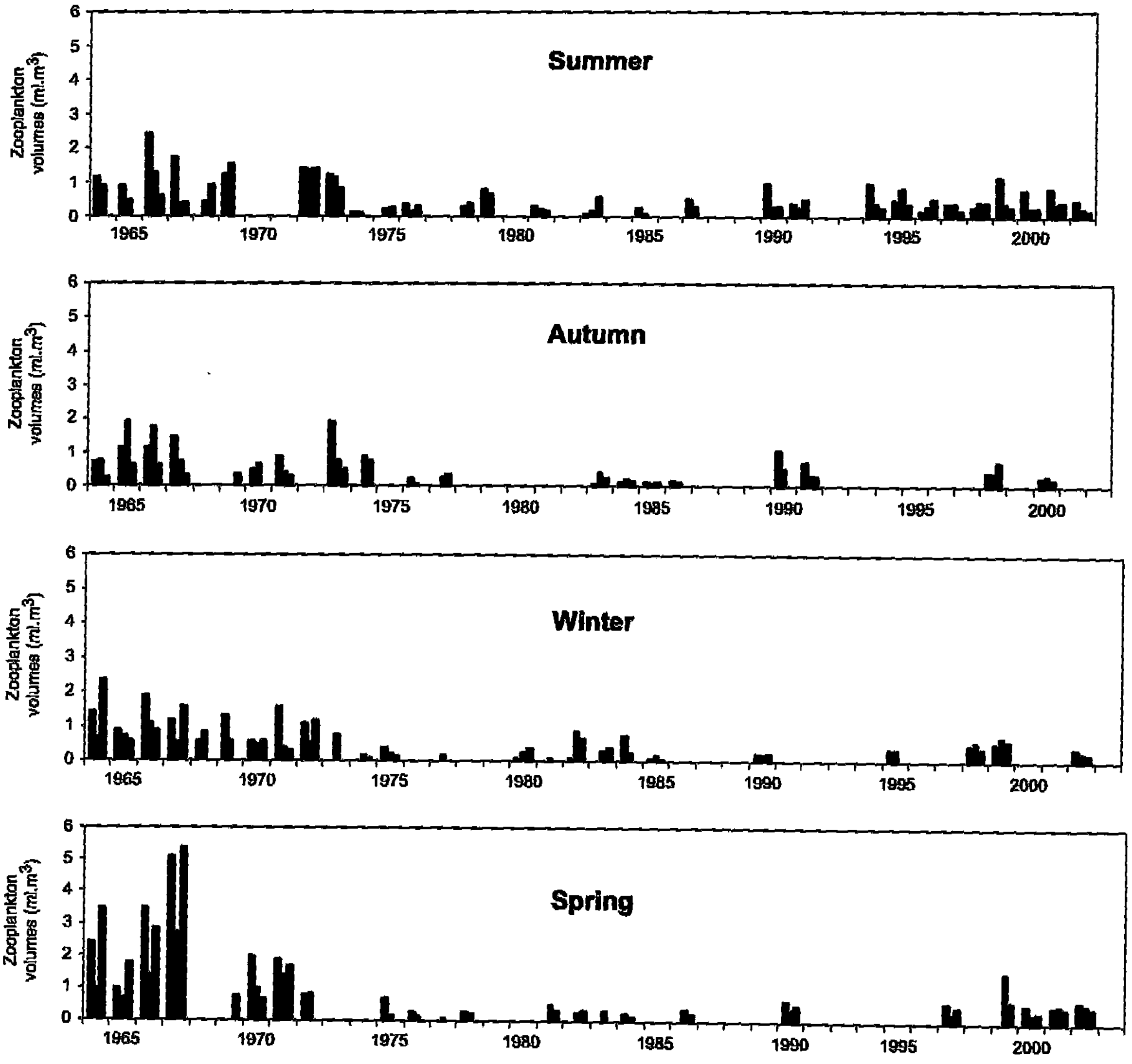

Figure 2. Zooplankton mean volumes collected during four seasons along the Peruvian coast. Each bar represents one cruise.

the season with the highest values among years in the 1960s and 1970s. A lesser contrast among seasonal volumes was observed during the 1980s and 1990s (Figure 4). The spatial distribution of zooplankton volumes showed the highest values from the coast to 60 nmi (111 km) offshore, between 04°S and 06°S and between 14°S and 16°S, coincident with narrow shelf areas and strong upwelling events (Zuta and Guillen, 1970). Important differences among areas (latitude) were detected. Although three areas had declining trends in zooplankton volumes (Figure 5), those of the northern (A) and southern (C) areas had more drastic declines between the 1960s and 1990s (65% and 70%, respectively) than the central area (B), which showed a reduction of only 55% in the same period.

The long-term trend of annual mean zooplankton volume, from 1964 to 2001, indicated three different periods of abundance: highest from 1964 to 1973, lowest from 1974 to 1989 (although the recovery seems to start in 1985), and an intermediate level from 1990 to the present (Figure 6). For comparison, the annual time-series of anchoveta mean biomass is shown. From 1964 to 1983 a significant match between two series can be observed with a high linear correlation ($r^2 = 0.58$; $p < 0.01$; ANOVA test); however from 1984 to 2001 there was no significant correlation.

The trend of smoothed PC1A of SST showed alternating "cold" and "warm" periods (Figure 7). Two clear changes of phase (cold—warm—cold) have occurred in the environmental characteristics of the Peruvian upwelling ecosystem, as indicated by SST analysis. One change occurred in the mid-1970s and the other by mid-1980s. It is also possible to postulate a third change of phase at the start of the 1990s (cold—warm), but this is still uncertain because of recent

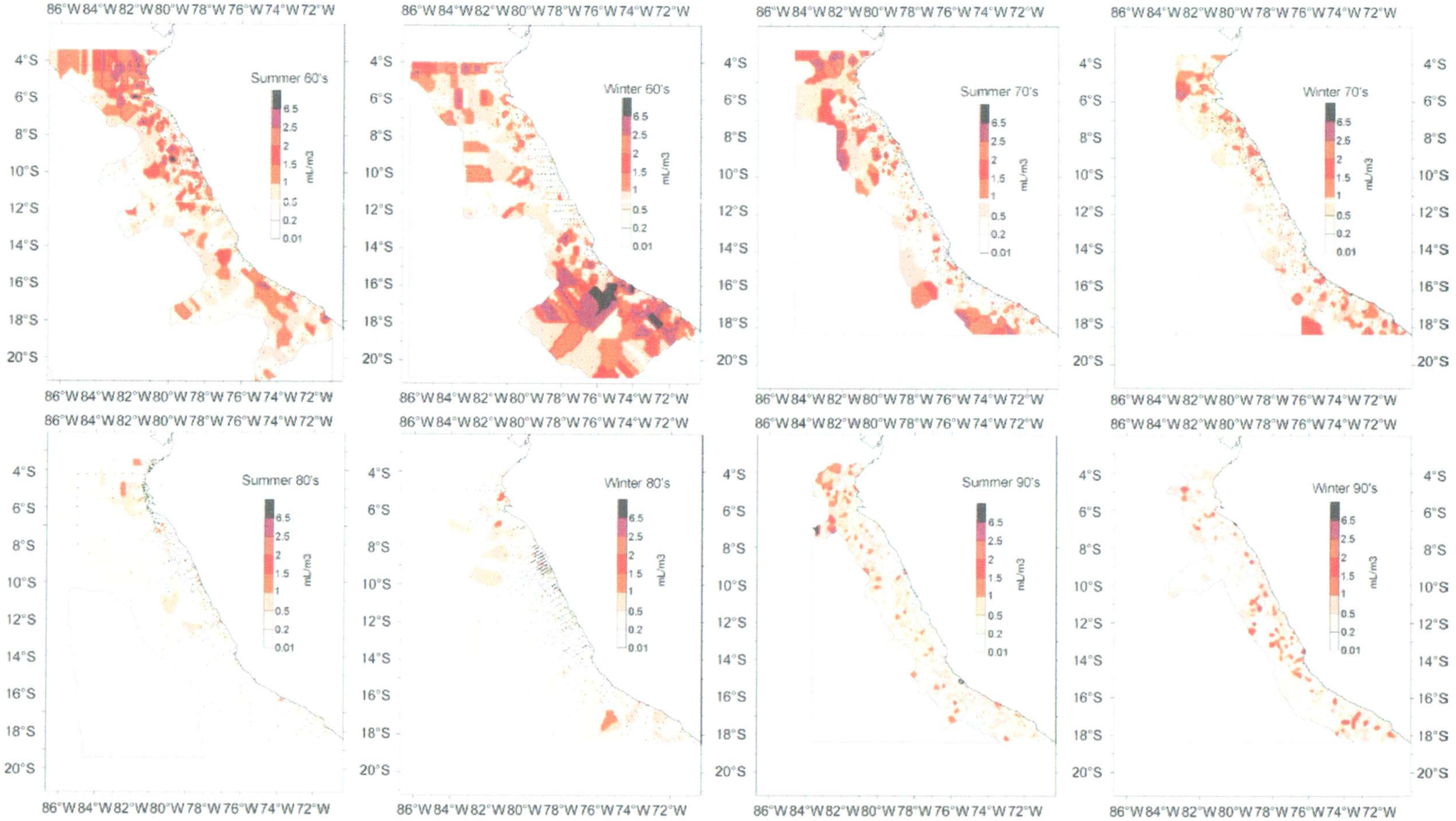

Figure 3. Spatial variability of zooplankton volumes, by decade and season, from 1962 to 2002. Contours were made by the closed neighbour method of interpolation. Sampling points are shown.

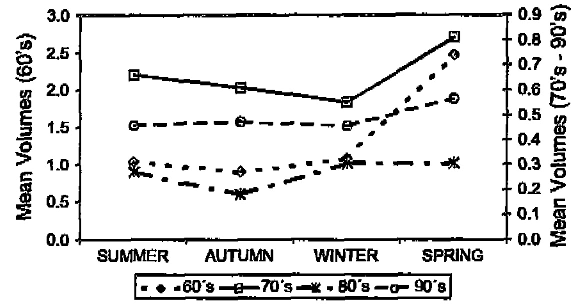

Figure 4. Mean seasonal zooplankton volumes for four decades for four seasons. Spring has always shown the highest values even during periods of less contrast during the 1980s and 1990s. Note that the scale of the ordinate in the 1960s differs from that of the 1970–1990s.

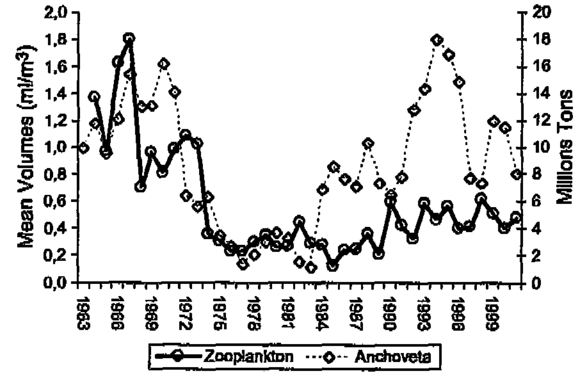

Figure 6. Mean annual zooplankton volumes and Peruvian anchoveta biomass from 1963 to 2001. Zooplankton values of 1979, 1988, and 1989 were interpolated with a 5-year moving average.

alternations of cold years (1995–1996) and warm years (1997–1998). No significant correlation between mean zooplankton volumes and annual mean SST was detected. However, there was a coincidence between changes of phase of SST and changes in periods of abundance of zooplankton volumes and anchoveta biomass (Figures 6 and 7).

Discussion

This paper is a contribution to the knowledge of long-term zooplankton dynamics in the Pacific basin. Trends observed in different components of the Peruvian ecosystem are in general agreement with changes observed over the entire basin (Chavez *et al.* 2003). Zooplankton represents one of the key elements of the marine ecosystem. This updated time-series of biomass in the Peruvian upwelling ecosystem has been made possible following active rescue of archival samples. Although "volume" (ml m^{-3}) is not the best measure of biomass, it is the only one available at the moment in such long time-series. We recognize that the data are sparse in some periods. However, the quantity and quality of the data are probably the best available in the southeast Pacific, taking into account that all these samplings were part of surveys for the assessment of Peruvian anchoveta abundance and not specifically directed to the assessment of zooplankton.

It is clear that SST does not explain the changes observed in zooplankton volumes by itself, but can be a good indicator of what is happening with other oceanographic and atmospheric variables. For this reason, even when the correlation between biological variables and SST was not significant, its usefulness for interpreting observed changes is very important. According to an interannual analysis of ENSO indices (Trenberth and Stepaniak, 2001), the SST near the international date line has a different trend with respect to the SST along the coast of the Americas in the tropics. At the same scale, Montecinos *et al.* (2003) found a highly significant positive correlation between the SST of the American coast and that of the central Pacific. However, on an interdecadal scale the SST of the Peruvian coast and the

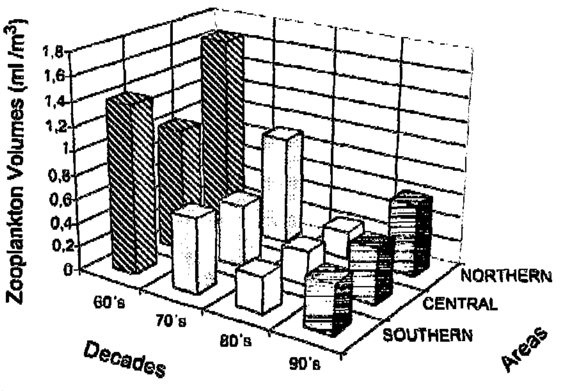

Figure 5. Mean spatial pattern of zooplankton volumes among decades indicates a dramatic decline in northern and southern areas.

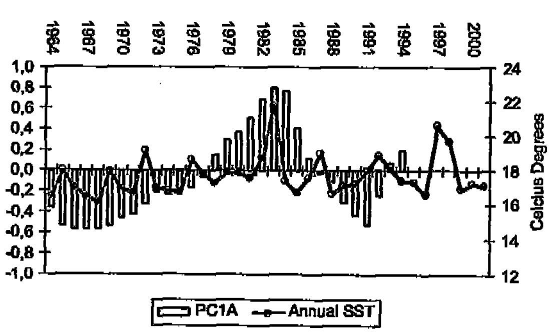

Figure 7. Trend of smoothed first principal component of sea surface temperature (SST) from five coastal stations from 1964 to 1994, to observe "cold" and "warm" regimes. Mean annual SST is also shown (compare with Figure 6).

PDO was highly significantly negatively correlated (−0.65, $p < 0.05$); thus, according to these authors, the Peruvian system has cold and warm regimes, slightly out of phase with the total signal for the Pacific basin. The change of phase between these regimes (Figure 7) resulted in a notable agreement with those observed in biological variables (Figure 6).

The relationship between zooplankton and the anchoveta series is quite interesting. Even when a predator–prey relationship is known to exist, the ability of anchoveta to switch from phytoplankton to zooplankton under adverse environmental conditions (Rojas de Mendiola, 1989), and *vice versa*, precludes the establishment of an inverse correlation between zooplankton and anchoveta. In general, both series presented show three approximately congruent periods of different abundance: higher, lower, and intermediate. While it is clear that a good match exists between the two series from 1964 to 1983, they have some differences from 1984 to the present. Csirke *et al.* (1996) postulated three levels of carrying capacity for anchoveta or what could now be called "regimes": the highest occurred in the 1960s until the collapse in 1972, the lower regime occurred from 1973 to 1983, and an intermediate level occurred from 1984 to 1994, now updated by this work to 2001 (Figure 6). During the recent period, anchoveta had 5 years (1992–1996) of high abundance that were similar to those of the 1960s, but after that it seems to have stayed at the "intermediate" level. Zooplankton also had three periods of different abundances, but the period of "intermediate" abundances started later (1990) than that of anchoveta (1984), and the zooplankton volumes have increased from the mid-1980s to the present at a lower rate than those of anchoveta.

At the moment, we do not have a sound explanation for these observations, but we should consider that the Peruvian anchoveta is only one species while the zooplankton is a complex of interacting species with a taxonomic composition that probably changes through time. Considering the type of net used to collect samples, the data of this study represent only changes of some in the taxonomic groups of the total zooplankton community. Different taxa can respond to environmental changes in different ways. For example, Nakata and Hidaka (2003) report that trends in biomass of large species of copepods respond better to global climate variables, while biomass of small species of copepods respond better to local climate variables.

Sánchez (2000) showed trends in total plankton volumes, collected with a phytoplankton net, in relation to distance from the coast from 1976 to 1999. Samples collected within the first 30 nmi of the coast corresponded mainly to phytoplankton, while samples taken beyond 30 nmi offshore contained more microzooplankton (S. Sánchez, pers. comm.). According to this study, plankton volumes decreased from 1976 to 1986 and increased from 1988 to 1999, both inside and outside 30 nmi offshore. This trend also showed two periods of different abundance, in similar ways to those of the anchoveta and zooplankton. If plankton volumes from the inshore represent a reasonable index of phytoplankton abundance, then the same observed trends in the series of three components could have important consequences for the understanding of the functioning of the Peruvian upwelling ecosystem.

Considering the spatial distribution of zooplankton over the decades studied, a strong decrease in zooplankton total volume in both northern and southern areas was also observed in the 1990s. These facts could be explained by the changing dynamics of water masses off the Peruvian coast. In fact, one of the authors of this paper observed a slightly different trend between SST at 5°S and 12°S. Also, different spatial patterns of water masses prevailing over periods of time have been observed (O. Moron, pers. comm.). From the mid-1970s to the mid-1980s, a strong prevalence of oceanic warm and high salinity waters inside the first 60 nmi offshore has been reported, influencing a significant part of the coast. This observation agrees with the period of low zooplankton abundance, anchoveta, and the high abundance of sardine, jack mackerel, and mackerel. Also, the recovery of anchoveta coincides with the years 1984 and 1985, when cold upwelled water prevailed along the coast. These dynamics probably explain the slight change in the seasonality of zooplankton volumes among decades. The changes of local dynamics of water masses are definitely related to changes over the whole Pacific basin, especially in the southern hemisphere (Clarke and Lebedev, 1999).

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El Niño signal overshadows regime shifts in the Humboldt Current Ecosystem off Peru

Purca S[1,2], T Antezana[1], P Ayón[2], R Guevara-Carrasco[2], S Sánchez[2] & R Riquelme[3].

1. Departamento de Oceanografía. Universidad de Concepción. Concepción-CHILE.
2. Instituto del Mar del Perú. IMARPE. Callao-PERU. spurca@imarpe.gob.pe
3. Departamento de Ingeniería Matemática. Universidad de Concepción. Concepción-CHILE.

Summary

Overimposed to seasonal and meteorological scales events, interannual and interdecadal scales impact primary production, fish production and community structure to a much larger extent. Effects of planetary or global scale events vary in intensity and geographic coverage. To what extent the Humboldt Current is affected by these global event is uncertain and is the focus of this work. What are the physical forcing and how are their signals depicted in the region and how do they correlate with biological components are specific goals of this study, under the assumption that the strongest and more immediate impact of physical forcing will occur at the primary producers level, and will be mitigated or significantly deviated in organism of longer life span and more complex behavior.

Rich and wide time series of physical data (namely wind stress, pressure, sea surface temperature and sea subsurface temperature) and biological factors (namely microplankton, mesozooplankton and anchovy biomasses) collected along the coast of Peru from 1950 to

present days. These are the first time examined together, in order to establish the effect of ENSO and other lower frequency events. Raw data are analyzed by classical floating average techniques and wavelets. Pressure and wind regime were expected to show the clearest signals of ENSO and interdecadal cycles. However, no clear pattern in either pressure or wind time series appeared. SST anomalies at 5 equally spaced locations along the Peruvian coast showed coherent ENSO signals alternating with cooler periods, yet no long-term events appeared in this time series. Clear ENSO signals appeared in 1957-58, 1972-73, 1982-83, 1986-87,1997-98.

The microplankton biomass time series showed the most extreme negative anomalies in 1982, 1992 and 1997 somewhat coinciding with ENSO events and a clear interdecadal trend of negative anomalies during the 70's, preceding a 10 yr period of positive anomalies starting in 1987.

The mesozooplankton biomass time series showed an opposite trend with a 10 yr period of positive anomalies from the beginning of the series until 1973, followed by a period of *ca.* 25 yr of negative anomalies to 1990, and a period of mild recovery of positive anomalies to the present.

The anchovy biomass showed a period of high levels until 1970 and a crash down afterward, with a slow recovery from 1983 onward till 1991, and a rapid increase to reach maximum values in 1993. After El Nino 1997-98, anchovy biomass abruptly decreased again.

Landing of other main pelagic fish resources are depicted (in the absence of biomass data) to show inconsistent changes with ENSO or regime shifts.

Overall, ENSO physical signals are coherent along the coast of Peru and equally depicted in microplankton. Mesozooplankton and anchovy biomass, showed interdecadal trends

instead, but uncorrelated in time with each other, except for the ENSO 1972-73 when both mesozooplankton and anchovy biomasses began a long term decrease. In concordance with other shifts in biological time series that were also uncorrelated with in time with physical forcing in the Central Pacific basin. Biological responses may overshadow the immediate physical forcing in this highly perturbed ecosystem.

INTRODUCTION

Global climate changes in diversity and community structure indicate that ecosystems are affected by events in a wide range of scales and that those of lower frequencies may be more devastating than high frequency ones (Steele, 1985), however there is no agreement on which is the priority scale to focus research (Longhurst, 1995).

For basin-wide events affecting Large Marine Ecosystems, like El Nino Southern Oscillation (ENSO) and regime shifts, the intensity and geographical coverage of these events vary significantly (Trenberth, 1997; Trenberth and Hurrel 1994; Trenberth and Stepaniak, 2001). The onset, duration and end are poorly predicted (Cane, 1992).

While agreements exist for the identification and prediction of ENSO (Kerr, 1998), since understanding of immediate physical forcing is validated by long term series of atmospheric pressure and SST (Smith, 2000), poor understanding exist of the mechanistic effect upon biological components, community structure and its functioning to explain abrupt changes in major resources. Many studies have recorded specific changes in the distribution and population dynamic of species, but very few studies has approached comprehensively both physical forcing and impact upon biological components (McGowan *et al.*, 1998).

Longer term than ENSO cycle have been claimed to be associated with low frequency changes in main fishing resources (Lluch-Belda *et al.* 1989), or to cause them (Csirke *et al.*, 1996). Consequently regime shifts have been identified and indexes have been estimated in the North Pacific (Hare and Mantua, 2000), North Atlantic (Aebischer *et al.*, 1990) and in the Humboldt Current (Bakun, 1990, Chavez *et al.*, 2003).

The Humboldt Current extends in a wide (ca. 200 nmi) and long belt (ca. 6000 km) of the Eastern South Pacific between southern Chile to North of Peru and Galapagos, and although having upwelling as a common feature throughout it, latitudinal changes are expected to occur, despite being infrequently identified from the view point of oceanography (Hill *et al.,* 1998) and biogeography (Vega, 1989; Antezana, 1978). Yet not only differences in the signals are expected between the Pacific basin and the Humboldt Current as a whole, but also within its latitudinal range.

The study area, a delimited but significant region of the Humboldt Current which is the site of the largest fishery of the world, where ENSO impacts fisheries widely (Arntz and Valdivia 1985, Barber and Chavez, 1983) and where interdecadal changes have been suggested to occur (Chavez *et al.* 2003, Bakun, 1990) causing species succession (Walsh 1981, Barber and Chavez 1983, Ochoa *et al.* 1987, Jarre-Teichmann 1998, Bohle-Carbonell 1989, Muck 1989, Chavez *et al.* 1989, Arrieta 1992, Tarazona *et al.* 1999, Ñiquen *et al.* 1999). But, time matching of biological data series with physical data series are not accurate enough to explain changes in the biological components or predict them.

Therefore, beside exploring to what extent the basin-wide interannual and interdecadal signals pervade in the Humboldt Current, the main aim of this study was to establish links between low frequency physical forcing and responses of main biological components, under the hypothesis that impacts through the food-chain should be expressed in progressively longer time gaps and rather complex deviations, as associated with length of life spans and diversity of behaviors of organisms involved (e.g. phytoplankton, zooplankton, anchovy and carnivorous fish).

Although basic such question is: time series are usually restrictive in length and spectrum of data to approach it. New and robust data banks were available to be examined by classical methods for discrimination among time scale events.

MATERIAL AND METHODS

The study area is restricted to a 60 nmi. wide belt extending from 3°S to 18°S along the northern half of the Humboldt Current , which extends along the coast of Chile and Peru from ca. 40°S to 3°S. Although well described as a wide and slow current, the Humboldt Current is rather a system of equatorward surface current and poleward undercurrents (Antezana, 1978, Bernal *et al.* 1982, Strub *et al.,* 1998). Although sharing the common feature of coastal upwelling, (which brings cold and nutrient rich waters to the photic zone enhancing its production) along the entire latitudinal range, this northern sector has a much stronger influence of warm equatorial waters than the most southern sector, which is mainly affected by subantarctic and by central Pacific waters including their corresponding biota (Brinton, 1962; Antezana, 1978 and 1981). The study area has been the typical focus of ENSO impact (Arntz and Valdivia 1985), and eventually of interdecadal changes (Barber and Chavez, 1983; Bakun, 1990; Schwartzlose *et al.,* 1999).

This 1000 km long study area has been subdivided into 3 latitudinal sectors for research and resource management purposes (Zuta and Guillén 1970).

Data were gathered from several institutions data banks and data reports, and selected to cover the coastal 60 nmi wide belt only, in order to diminish the variance accounted for by the influence of more oceanic processes. Such a belt coincides to a great extent with the area of stronger influence of upwelling, and the offshore distribution of endemic zooplankton species (Antezana, 1981).

Several data series were examined for the last 50 yr. They varied in length (Table 1) being SST the longest (1950-2002), and microplankton the shortest (1976-2002).

Alongshore wind stress estimated from monthly wind velocities and directions data from Direccion de Hidrografia y Navegacion (DHN) were restricted to the Callao coastal land-based station, located at 12°S, which is near to the middle of the study area. Monthly Sea Surface Temperature (SST) data from DHN and Instituto del Mar del Peru (IMARPE) came from 5 rather equally spaced land-based stations: Chicama (8°S), Chimbote (9°S), Huacho (11°S), Callao (12°S), Ilo (18°S).

Additional SST data were gathered for the El Nino 3.4 area (5°N-5°S and 170-120°W) from Comprehensive Ocean-Atmosphere Data Set (COADS) for comparisons with those of the more coastal study area.

Microplankton data (averaged from a total of 130 seasonal cruises and selected for the study area) belonged from net-phytoplankton sample analyses at IMARPE. Samples were taken with a standard net 75 μm mesh size, towed at the surface at 0.5 m/s during 5 min. Samples after fixation in 2% formaldehyde were homogenized, and 1/16 th aliquots were sorted out to count phytoplankton species under an Uthermohl Microscope (Uthermohl, 1958). Parallel to counting, qualitative analyses of species composition were done under a high power inversed microscope (Calienes, 1992)

Mesozooplankton data (averaged for the study area from the same seasonal cruises) came from sample analyses done at IMARPE. Samples were taken with Hensen net 0.33 m^2 mouth area and 300 μm mesh, vertically hauled between 50 m and 0 m. The samples were fixed in 2% formaldehyde buffered with borax. Mesozooplankton volume (after ichtyoplankton and large jelly-fish were sorted out) was determined by volume displacement, immediately after collection (Kramer *et al.*, 1972). The number of day and night samples in each cruise according to the same sampling protocol since 1964 was closely balanced. Anchovy biomass data (yearly averaged for the 3°-12°S latitudinal range and 60 nmi offshore region) were estimated with Virtual Population Analyses and acoustic surveys from IMARPE seasonal cruises (Csirke *et al.*, 1996).

Annual landing of sardine, mackerel and jack mackerel originated from IMARPE data banks.

Data processing:

Physical and biological data were linearly examined, interpolated and transformed in anomalies (Matlab, 2003). Two types of anomalies were used. The standardized anomalies were calculated for monthly physical data, and simple anomalies were calculated for annual and quarterly biological data. For the former analysis, the anomalies were calculated with respect to the overall series mean, the mean were subtracted from the original data. The based used to calculate the standardized anomalies, which were standardized by dividing them by climatological standard deviations. The based period for physical data series was 1950-1999, while the based period for the biological data series was the total length of the time series. In order to explore the temporal responses for energy flow through trophic levels, we used ecological time series such as: microplankton volume since 1978, mesoplankton volume since 1964, biomass of anchovy since 1957 and biomass of sardine since 1972.

Alongshore wind stress

Alongshore wind stress was used both in the correlation analysis with other physical data series and biological data series. For the correlation with the biological data series, quarterly anomalies of alongshore wind stress were calculated by anomalies.

Time series of anomalies alongshore wind stress were filtered with running mean every less than or equal to 2, 2-7 yr and greater than or equal to 7 yr.

Peruvian Oscillation Index (POI)

In order to represent the pooled variance of the 5 SST monthly series of standardized anomalies along the coast, the first principal component by empirical orthogonal analysis (PC1) (Zhang *et al.* 1997) was computed in order to obtain the Peruvian Oscillation Index (POI) as proposed earlier (Purca *et al* MS). The POI series was filtered with a wavelet power spectrum (WPS). The PC1 of the WPS was computed in three range: greater than or equal to 7 yr, between 2 and 7 yr, and less than or equal to 2 yr range according to Zhang *et al.* (1997).

The SOI, El Niño 3.4 area, POI and alongshore wind stress were analyzed with the wavelet transform. The Morlet wavelet was used and the transformation was performed in Fourier space using the method described by Torrence and Compo (1998).

Monthly POI values were quarterly averaged to compare them with the biological quarterly data for the based period 1964-1999.

Microplankton

Anomalies quarterly of volume of microplankton were calculated by substracting the original data from the overall time series mean and were linearly interpolated to fill data gaps (Matlab, 2003).

Anomalies for microplankton, mesozooplankton and anchovy biomass were calculated by subtracting the original data from the overall time series mean. After that, each time series were interpolated every 3 months (Matlab, 2003). The microplankton and mesozooplankton time series were filtered with a moving average every 2, 2-7 and 7 yr range according to the method described by Mestas-Nunez and Enfield (2001).

Mesozooplankton

The mesozooplankton data was arranged in a matrix of 4 columns (seasons) and 39 rows (years), where observations represented the value of each survey. The mean annual mesozooplankton volume was obtained from averaging the rows. Of the 39 yr, 31 yr had more than 2 surveys per year with complete spatial coverage, 7 yr had 1 survey and 1 yr had no survey (in 1988). Surveys with incomplete spatial coverage (1979 and 1987) were discarded.

Fish biomass and landing

Annual anchovy, sardine, mackerel and jack mackerel biomass and landings data were linearly interpolated to obtain a quarterly data series to compare with other data series. (Matlab, 2003). The cross correlation and coefficient correlation of Pearson were used for compare between physical and biological data.

RESULTS

As an initial step to test for consistency of the data with basin-wide signals in the Pacific, time series of SOI, El Niño 3.4 area, and POI were used as frameworks (Figure 1 a, b and c). Time series of SST anomalies at 5 stations along the coast of Peru consistently depicted El Niño signals in 1957, 1972, 1976, 1982, 1986, 1992 and 1997 and among these, the strongest and more extended ones were for the 1982-83 and 1997-98 ENSO events.

For the SOI and POI time series, ENSO signals for the years 1972-1973, 1982-1983 and 1997-1998 were more conspicuous than for the periods 1953, 1957-1958, 1965, 1968-69, 1972-73, 1976-77, 1982-83, 1986-87 and 1991-1992, (Figure 1 d, e f). This time series expectedly depicted the ENSO events and particularly those of 1982-83 and 1997-98 within a background of low and long negative field.

In order to identify the dominant frequency for ENSO off Peru, the PC1 of the global wavelet spectrum for POI indicated that El Niño was in 2-7 yr frequency. Nevertheless, the El Niño 3.4 area and SOI had similar patterns in frequencies after the 80s for ENSO cycle in the Tropical Pacific (Figure 1 d and e).

The PC1 of the variance for 2-7 yr scale-average POI time series showed an increasing trend with major bell-shaped maxima centered in 1983 and 1997 (Figure 1 f).

Data were high passed filtered less than or equal to 2 yr range represented the ENSO signal in highest frequencies. That pattern was consistent for tropical and coastal area during: 1965, 1972-1973, 1982-1983, 1997-1998.(Figure 2 a, b, and c).

The along-shore wind stress data series off Callao from 1950 to 1997 (COADS) did not show negative anomalies for the 1982 and 1997, as in the El Nino 3 region, but only weaker variation within those periods. The shortness of the data series did not allow to use a >7 yr filter to seek for regime interdecadal changes (Figure 2 d).

When physical data were low pass filtered (greater than 7 yr) a negative anomalies regime extending between 1963 and 1987 was followed by a positive anomalies regime extending until 2001 for SOI, in other hands, positive anomalies regime extending between 1966 and 1989, this period was following by a negative anomalies regime extending until 2004 in the POI time series. (Figure 3 a. and b.). The regime shift seems to begin in the mid 60s and late 80s.

Yet, we double-checked for consistency of regime shifts given by the oceanic Pacific signal (SOI) by dividing the Peruvian data sets into the cold regime data, ending in 1966 and the warm regime ending, in 1989. We tested in particular for differences in the slope, y intercept and variance of the regression between time and anomalies. No significant differences were established between our data sets when 1975 is chosen as the time for the regime shift.

Therefore, we further examined our data under the assumption that the most consistent signal within latitudinal sectors off Peru and between the Peruvian region and the Central Southern Pacific was the ENSO signal.

Microplankton smaller than 75 µm, mainly net phytoplankton collected during the period 1975- 2002 showed two regimes in the data series (Figure 2 e). The low biomass microplankton regime extended between 1977 and 1987, and was followed by a high biomass regime, with an abrupt shift centered in 1987 (Figure 2 a). Both regimes show conspicuous negative anomalies during El Nino events e.g. 1982,1992 and 1997. It should be noticed, that a positive anomaly occurred during the low biomass regime, which coincided with a warm anomalies in period 1966 to 1989 (Figure 3 b and c).

Mesozooplankton was expected to have a coherent trend with microplankton biomass, however zooplankton biomass did not vary accordingly. Contrary to expectations, no coherent interannual changes associated with ENSO were detected. Instead, data showed two regimes at an interdecadal scale: a high biomass initial regime lasting until 1972-1973 and a low biomass regime from 1974 to present days, with a short and abrupt transition period or regime shift in 1973-1974 (Figure 2 g. and h.). It seems that after El Nino 1972-1973 the zooplankton biomass did not recover, until a slight long-term recovery detected after 1990 to these days (Figure 3 d).

Anchovy biomass showed two peaks: in 1969 and in 1991-94, followed by an intermediate decreasing-recovering period of ca 20 yrs (1970-1990). Biomass from the beginning of our time series started rather high in 1962, and increased step wisely until 1969, reaching a record of 16 million tons. In 1970, two years before ENSO 1972-73, anchovy biomass started to decline abruptly to crash in one year to a level of ca. 7 million ton. It remained at that level during ENSO 1972-1973 and continues to decrease step wisely afterward until 1982, when it experienced a sudden recovery to a higher level, which remained until 1989. Afterwards, it increased abruptly until the second maximum record of 10 million tons in 1993. From then onward the anchovy biomass has been decreasing again (Figure 2 g). Sardine biomass time series showed increase values during 76 to 94 periods.

Sardine, mackerel and jack mackerel and hake time series of landing for the same area showed an opposite trend with regard to anchovy, such as 4 yr after the anchovy crashed in

1970-1971, the sardine and jack mackerel landing increased and began decreasing again by 1992, when the anchovy begin to recover (Figure 3 f g and h .).

In order to examine deterministic effects of physical forcing on some biological components of the ecosystem, physical and biological time series were cross-correlated. A weak relation between physical and biological time series was observed between high pass filter of POI and anchovy and sardine biomasses. Whereas time series of microplankton volume and POI high pass filter had timing during El Niño events: 1982-1983, 1992, 1997-1998 (Figure 2 c,e).

DISCUSSION

The wide range of scales of variation affected the Pacific basin (Ghil, 2002). ENSO may be so abrupt and unexpected that can produce catastrophic consequences not only in the ecosystem but also in the economy of large regions of the planet. Despite of efforts, mechanistic understanding of their effects through the food chain and their forecasting is poor. El Niño 1997-1998 was one of the most devastating world-wide phenomenons and was poorly predicted in its onset and intensity (Larkin and Harrison, 2002). Furthermore, less abrupt and even less understood are lower frequency events such as interdecadal changes and regime shifts occurring throughout the world (e.g. NAO, PDO; Hare and Mantua 2000). As changes are subtler in the physical forcing, identification of long term trends or cycles and their shifts are highly dependent on the existence of long time series of data. Although much shorter than time series for the North Atlantic, North Pacific and Tropical Pacific allowed the identifications of cold and warm trends (Sugimoto and Takodoro 1998), high and low levels of zooplankton (Roemmich and McGowan 1995) and main shifts in 1975 and 1987 (Hare and Mantua 2000), the data series of this study from a marginal area of the Pacific like the Humboldt Current attempted to identify ENSO signals and regime changes and match them to these large ocean-basin trends. ENSO signal and ENSO-like signal were consistent and coherent between both regions, but regime shifts were inconsistent among the data time series and ocean-wide trends (Figure 2, 3 a, b, c).

The region under study has a well-known productivity and high fish catch, yet is poorly known with regard to large-scale changes and impacts. Most studies have examined fish landings, guano bird stocks and SST time series (Jahncke *et al.* 2001, Jahncke *et al.* 2004) to identify and described El Niño impact (Arntz and Valdivia, 1985), but just a few studies have examined similar data sets to identify interdecadal trends and regime shifts (Muck 1989) and essentially to match data to formerly described trends of the large Pacific basin (Chavez *et al.* 2003). Studies about the ecology of the upwelling system off Peru found three dominant features in its community structure: short length food chain (Walsh 1981), high biomass of small pelagic fish (Cury et al. 2000) and the season dominant temporal pattern on the transfer energy into the Peruvian food web (Jarre-Teichmann and Pauly 1993).

The focus of our work was to examine the impact of physical forcing on biological components under the hypothesis that physical forcing does not have a deterministic impact on the ecosystem but it is mitigated or deviated through the complex food chain. In other words, while changes in wind stress, could be well correlated to nutrient and primary production (Chavez *et al.* 1989) and primary production to herbivorous fish production and guano birds (Jahncke *et al.* 2004), changes in phytoplankton production may be either unfavorable to some herbivorous and favorable to other herbivorous zooplankters or fish, that they should not necessarily produce immediate and straight effects up in the food chain.

We gathered the most robust data source, which have been systematically collected by the same institutions in a very conservative way, yet it has been improved in frequency and number of parameters in recent decades.

Basically our data showed coherence among most parameters when dealing with identification of ENSO events, but incoherent with regard to interdecadal scales. ENSO events were particularly clear in SST along the coast of Peru, in the POI and barely noticeable for mesozooplankton. On the other hand, interdecadal or "regime shifts" were undetected in most data series, or were synchronized. In other words, while offshore conditions in the South Pacific (2400 nmi from the Peruvian coast) conspicuously showed both several ENSO events and a regime shift centered in 1975, which lasted ca 3 yrs between a cold period of 10 yrs and a warm period of ca 20 yrs interrupted by a short warm period in 1987 (Nitta and Yamada 1989, Trenberth and Hurrel 1994), nothing like that could be detected in our 12 time series.

Long-term changes were obvious in microplankton, mesozooplankton and anchovy biomass, yet they were not synchronous nor they had similar trends or lasted the same periods. On the contrary, there were two regimes in microplankton biomass, with an abrupt recovery after ENSO 1986-1987, two phases in mesozooplankton with abrupt crashes in 1969 and after ENSO 1972-73, and a cycle of a high biomass, a crash in 1970 and the years after 1972-73, and a slow recovery until 1993 to a high biomass regime, which lasted until 1996 and a final decrease which continued after ENSO 1978-1998.

Lack of coherence between wind patterns off Peru (at 5 stations along the coast or within the near 60 nmi off the coast) and the El Nino 3 region was evident at the ENSO scale and at the regime scale. However these deviations in wind stress should not surprise much, since the local effects of coastal topography and continental climatic regimes can generated overwhelming deviations in coastal winds (Figueroa and Moffat 2000). Furthermore, deviation in the wind pattern may occur between ENSO events, as shown earlier for 1982-83 and 1997-98 (Fedorov and Philander 2000). At the regime scale of change, shifts were described in 1975 and 1987 in the El Niño 3 region (Nitta and Yamada 1990; Hare and Mantua 2000) without evidences in our data series.

Regime shifts in the Oceanic South Pacific centered in 1966, 1980, 1985 and 1992, only barely coincided with former results (Folland *et al.* 1999) but no such breaks could be identified in our study. At a much larger latitudinal range, (five coastal stations of Peru and four located on Chile) regime shifts of the Humboldt Current could be matched with Pacific ocean-wide regime shifts (Montecinos *et al.* 2003).

A further evaluation of average variance of wavelet power spectra indicated that most variance occurred within the 3-6 yr range. Clearly and contrary to commonly understood, the ENSO events signals (variances) were more mitigated for El Nino 3 than for the El Niño 1 +2 region data set, which suggests that the northern and more oceanic area are much more affected by ENSO than the coastal area. By deduction, one could expect that other long term and less abrupt changes than El Niño could as well be mitigated off the Peruvian coast. (Trenberth 1997).

Intermittent ENSO signals were not clear or rarely seen simultaneously in biological components. A recent study suggests that the zooplankton time series along Peruvian coast presented a long trend (Ayón *et al.* 2004). Although ENSO events could be identified by low microplankton biomasses in 1982, 1992 and 1997, the major feature of the microplankton series is an interdecadal trend of low biomass between 1978 and 1987 followed by a period of high biomasses afterward, with an abrupt shift centered in 1987. This shift is definitely consistent with North Pacific and Bering Sea physical and biological time series including phytoplankton (Hare and Mantua, 2000; Sugimoto and Tadokoro 1998).

It is well known that high biological production is associated with low temperature and high nutrient up-welled waters, and El Niño warm periods are associated with periods of low production (Ryan *et al.* 2002). Yet correlations between physical forcing and higher trophic changes (usually fish landing) are black box derived conclusions since data are difficult to obtain. The microplankton time series are presented a positive correlation with SOI time series during change phases in 1987 for Peruvian coast.

Mesozooplankton biomass was expected to have a coherent trend with microplankton or at least to show immediate effect to ENSO signals, as suggested previously as consequence of an increase of predator zooplankters replacing herbivore copepods (Per. Comm. P. Ayón). However, mesozooplankton biomass did not vary according to ENSO signal. An interdecadal trend of uneven but persistent high biomasses appeared between 1964 and 1973 followed by a long phase of low biomasses thereafter. This regime shift centered in 1973 right after ENSO 72-73 was abrupt and impressively similar to the trend of zooplankton off California (Roemmich and McGowan 1995) where a steady decreasing trend of zooplankton biomass since 1951 consistent with warming waters during that period was observed, but there was not a regime shift in either zooplankton or temperature.

The time series for anchovy, which was based on biomass rather than fish landing as most other studies (Schwartzlose *et al.* 1999, Chavez *et al.* 2003), showed as in microplankton and mesozooplankton no instantaneous effects of intermittent ENSO events except for ENSO 1982-83 and 1997-98. It should be emphasized that the well-referred anchovy crash at the time of El Niño 1972 started (according to anchovy biomass), with a sudden decrease 2 yrs earlier, in 1969, which lasted to 1971, to continue with a steady but gentle decrease until 1976. A steady and slow recovery begun by 1983, reaching a maximum biomass level in 1993.Then, a rapid decrease begins again in 1994 to nowadays. Therefore, it is not possible to match a regime shift initiated after the El Niño 1972 to natural ecosystemic processes. Instead, the decrease in landings and biomasses of anchovy has been associated with ENSO 1972-73 (Csirke *et al.* 1996) without plausible causal effect arguments according to the literature. Such a decrease and slow recovery was nevertheless associated not only with ENSO 1972-73, but also to overfishing during the previous 3 years (despite scientist warnings) and during 1975. The final recovery of the anchovy population to about 9.2 mill tons despite the impact of ENSO 1982-83, occurred while the fishery was basically inactive for a 36 months and further conservative management was applied (Csirke *et al.* 1996).

Therefore the large-scale change in anchovy biomass may be seen as strongly influenced by human rather than by large scale physical forcing. Yet, the ecosystem may be crucially affected by the drastic decrease of the anchovy biomass, so that changes in energy flow and community structure may expected and eventually triggered and lasting much longer than the appearance and disappearance of the original physical forcing (Alheit and Bernal 1993, Alheit and Ñiquen 2004).

Nevertheless, such explanations seems still simplistic as there are other major components such as euphausiids, copepods, jelly fish etc., which also may affect or be affected by large changes in the anchovy biomass. Other components such as phytoplankton may also change accordingly, and consequently basic biological processes such as primary production, regeneration of organic matter, etc will do too (Walsh 1981).

Microplankton biomass change (low to high values) in 1987 appears positively associated with the anchovy decline and recovery (and sardine in the opposite trend) (Figure 2 e,g,f). In the other hand, the relationship between egg standing stock and anchoveta parent stock, suggesting a strong effect of parental cannibalism (Santander 1987). The egg pelagic spatial distribution off Peru between 1964 and 1986 was analyzed with data from 81 egg and larval survey. These studies were conducted with emphasis on the interrelationships between sardine eggs, laval of mackerel and horse mackerel, SST and Anomaly SST, turbulence and anchoveta biomass. A significant negative correlation was found between anchoveta biomass and sardine egg, while a significant positive correlation was found to occur between SST and the abundance of mackerel and horse mackerel larvae (Muck et al. 1987). Relationship between sardine larval and warm water in northen of Peru was observed during 1972. Two features lead an increased in sardine population biomass: warming of waters and decline of anchovy population. However, the competition between anchovies and sardines during 1976-1982 or 1983 has not been clear (Zuzunaga 1985). It is well known that sardine feeds upon a smaller part of the plankton size spectrum than the anchovy (Espinosa and Blaskovic 2000) and after 1972-1973 sardine biomass have localized in the oceanic area, them the sardine biomass were found along the coast during 1982-1983, but there were a small and young species in the total sardine landings (Zuzunaga, 1985). It can be then argued that microplankton growth could have been limited by sardine predation pressure. Sardine as well, could be out-competing anchovy larvae and recruitment rates and therefore explaining slow anchovy population recovery. Predator control of small pelagic or euphausiids over microplankton, or changes in food competition and switching diets of sardine, anchovy or euphausiids are to be investigated (Santander and Zuzunaga 1984). The reason for the pattern of sardine–anchovy alternation has been a puzzle. Anchovies and sardines do not seem to directly compete. Each one is able to filter a quite different particle size range, they tend to occupy differing spatial distributions (Ñiquen and Bouchon 1991; Bakun 2004), they have very different degrees of migrating capacity, sardines being strong migratory and anchovies much less so.

Therefore, we agree with Bakun and Broad 2003 that ENSO in this region produces an effective impact in the ecosystem, some of which could be followed through the trophic levels to anchovy and sardine, yet the outcome of this impact is unpredictable due to biological complexities of the trophic food web even as shaped by keystone herbivores (recently named wasp-waist structured), which propagate both bottom up and top down control (including man as a top predator). This complexity and the still no deterministic outcome at the intermediate level are due to the fact that not only anchovy, but sardine, euphausiids, copepods etc. may be sharing or widely overlapping role of channeling primary production to upper trophic levels. Their complexity given by differential migratory behavior, ingestion rates, reproductive rates, life spans and there different relative abundance may affect drastically the outcome of the energy transfer. Their relative abundance as they are prey for others (including man), will induce changes in the community structure which by far will become independent or strongly mitigating the original or real time physical forcing (Haury *et al.* 1978) in these highly perturbed ecosystems.

The hypothesis that greater changes in shelf trophodynamics have occurred within the 6-10°S area than in the 15°S region seems to reflect the impact of both overfishing by man and alteration of larval survival by nature off Peru. The decline of anchovy grazing pressure has apparently led to increases in plankton biomass, increased stocks of sardine and hake, increased carbon loading and sulphate reduction at the "downstream" sea bed, and a decline in oxygen and nitrate content of water column (Walsh 1981).

The examination of data series have provided with evidences of interannual and interdecadal basin-wide processes of major significance as they focus to understand not only population and community structure but also energy flow and carbon budgets and their association with climatic changes. Evidences are consistent to identifying ENSO, but less consistent to identify interdecadal changes and the timing of regime shifts (Table 2), yet most of them coincide in the period 1988-1989 and 1997-1998.

Most of previous results about regimen shift in the Humboldt Current did not match with our data, which can be attributed to the new data source used in our study and data analysis interpretation but also to either imprecise matching in former data series, where one to several years differences were ignored when attempting to match the main regime shift of 1988-1989 (Bakun and Broad 2003).

Based on such informative basis, a cold environment perturbed by strong and weak short warm events and no immediate response in microplankton and only dragged responses in zooplankton and anchovy were detected. No large scale changes could be associated with large scale physical forcing in the area although the effect of 1972-73 and 1987 events seems significant for microplankton, mesozooplankton and fish biomass. We could clearly identify El Niño events in wind stress and, SST but no interdecadal shifts were identified in physical forcing. Instead and opposite to these data series, ENSO events were detected only for microplankton. Only for major ENSO events, mesozooplankton and anchovy data series responded. Large scale changes were observed as follows: 2 out of phase periods in microplankton (1978 and 1987) and in mesozooplankton (1968 and 1990) and 3 phases in anchovy (1960, 1972 and 1992). It seems organisms of larger life span mitigate impacts of the El Niño events.

We found no support to match interdecadal physical forcing in the Humboldt Current to regime shifts described for other regions of the world, which could have explained natural alternating anchovy and sardine populations. These alternating anchovy-sardine regimes have been observed in other ecosystems of the world (Lluch-Belda *et al.* 1989, Schwartzlose *et al.* 1999), but these other ecosystems of the world have commons features: overfishing, the coastal upwelling, was one of the world's most "studied", "advised" and "managed" coastal resource, societal conflicts and anchovy, sardine, mackerel and horse mackerel resource.

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FIGURES

Figure 1. a., b., c., SOI (Southern Index Oscillation), NIÑO 3.4 (5°N-5°S, 170°W-120°W) and POI (Peruvian Index Oscillation) represent monthly time series, and d., e., f., panels show filter 2-7 yr for these time series. The wavelet power spectrum has been use for frequency filter.

Figure 2. Filter less than or equal 2 yr for time series: a. SOI, b. NIÑO 3.4 and c. POI. d. alongshore wind stress along Peruvian coast, e. Biomass of anchovy and f. Biomass of sardine.

Figure 3. Filter greater than or equal 2 yr for time series: a. SOI low-pass filter, b. POI low-filter, c. volume of microplankton. d. Volume of mesozooplankton. Anomaly landings pelagic species of Peru. e. Anchovy. f. Sardine. g. horse mackerel. h. mackerel.

TABLES

Table 1. The Peruvian time series recompiled by author since 1999 were: SST, winds and landings along Peruvian coast, P Ayón recompiled and actualized the zooplankton volume time series since 1987, and R Guevara recompiled and actualized biomass anchovy time series.

Table 2. The initial year change for interdecadal and interannual periods on physical and biological time series along Peruvian coast.

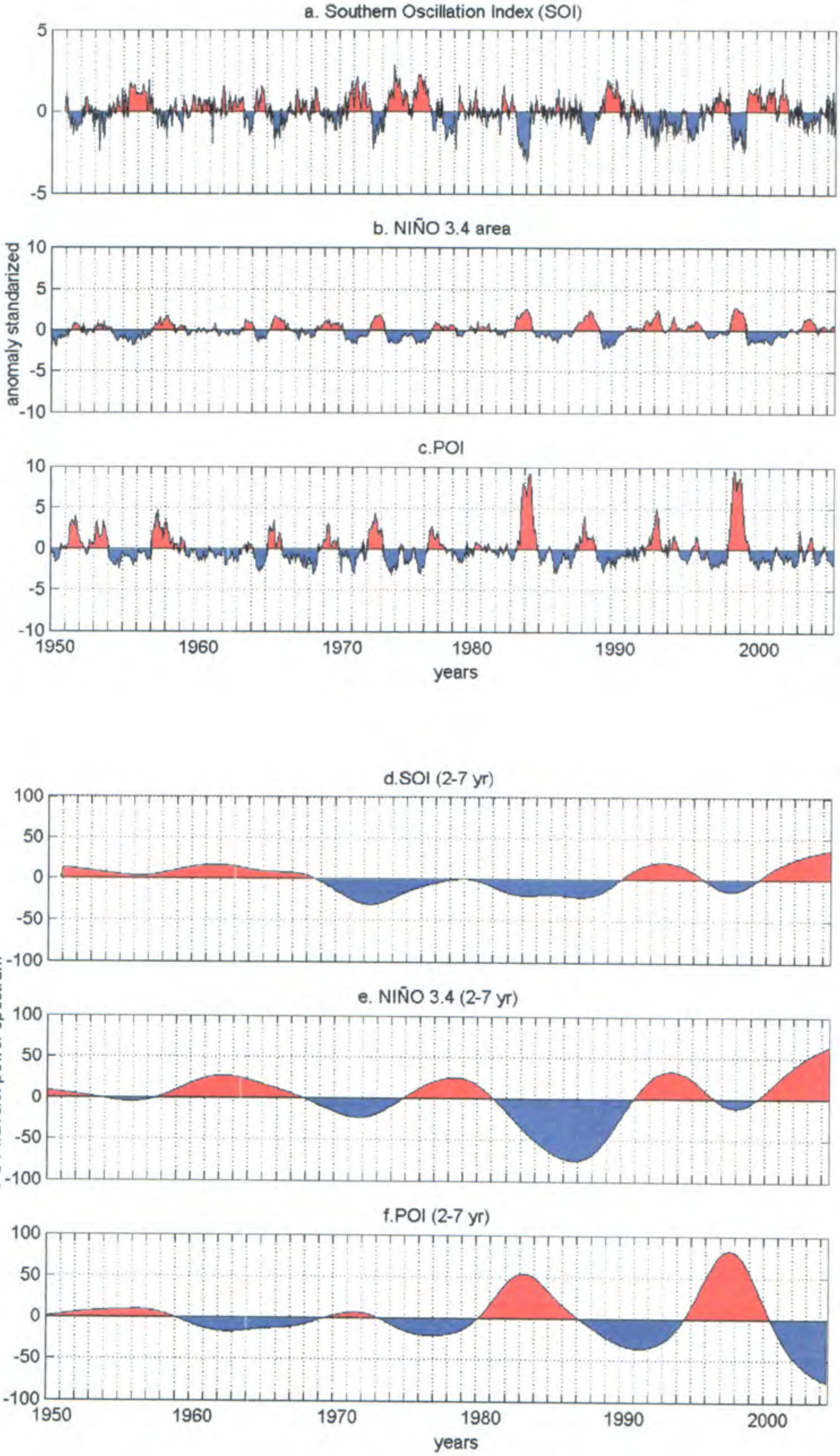
a. Southern Oscillation Index (SOI)
5
0
-5
b. NIÑO 3.4 area
anomaly standarized
10
5
0
-5
-10
c.POI
10
5
0
-5
-10
1950
1960
1970
1980
1990
2000
years
d.SOI (2-7 yr)
100
50
0
-50
-100
PC1 wavelet power spectrum
e. NIÑO 3.4 (2-7 yr)
100
50
0
-50
-100
f.POI (2-7 yr)
100
50
0
-50
-100
1950
1960
1970
1980
1990
2000
years

FIGURE 1

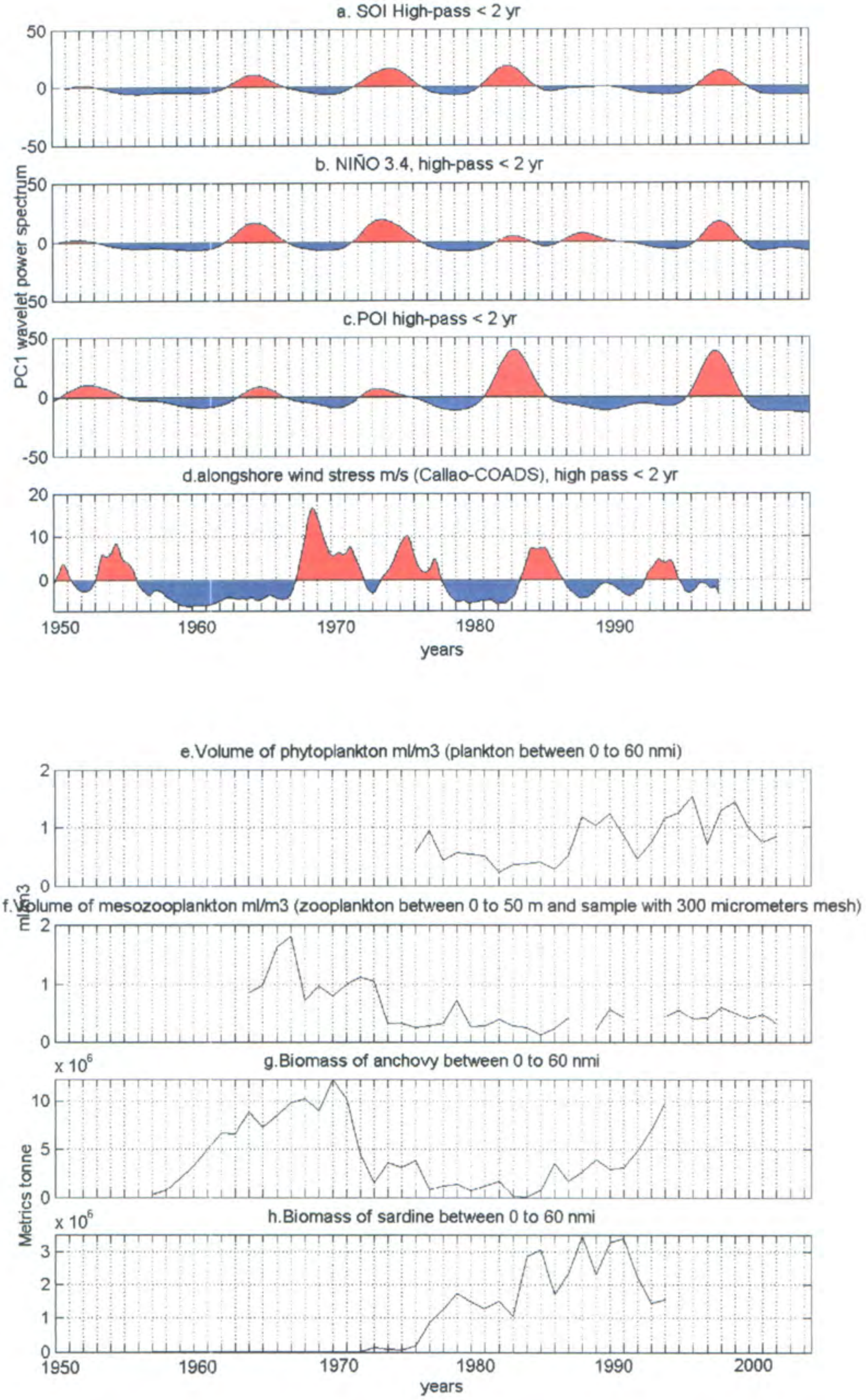
a. SOI High-pass < 2 yr
50
0
-50
b. NIÑO 3.4, high-pass < 2 yr
50
0
-50
c.POI high-pass < 2 yr
50
0
-50
PC1 wavelet power spectrum
d.alongshore wind stress m/s (Callao-COADS), high pass < 2 yr
20
10
0
1950
1960
1970
1980
1990
years
e.Volume of phytoplankton ml/m3 (plankton between 0 to 60 nmi)
2
1
0
f.Volume of mesozooplankton ml/m3 (zooplankton between 0 to 50 m and sample with 300 micrometers mesh)
ml/m3
2
1
0
x 10^6
g.Biomass of anchovy between 0 to 60 nmi
10
5
0
Metrics tonne
x 10^6
h.Biomass of sardine between 0 to 60 nmi
3
2
1
0
1950
1960
1970
1980
1990
2000
years

FIGURE 2

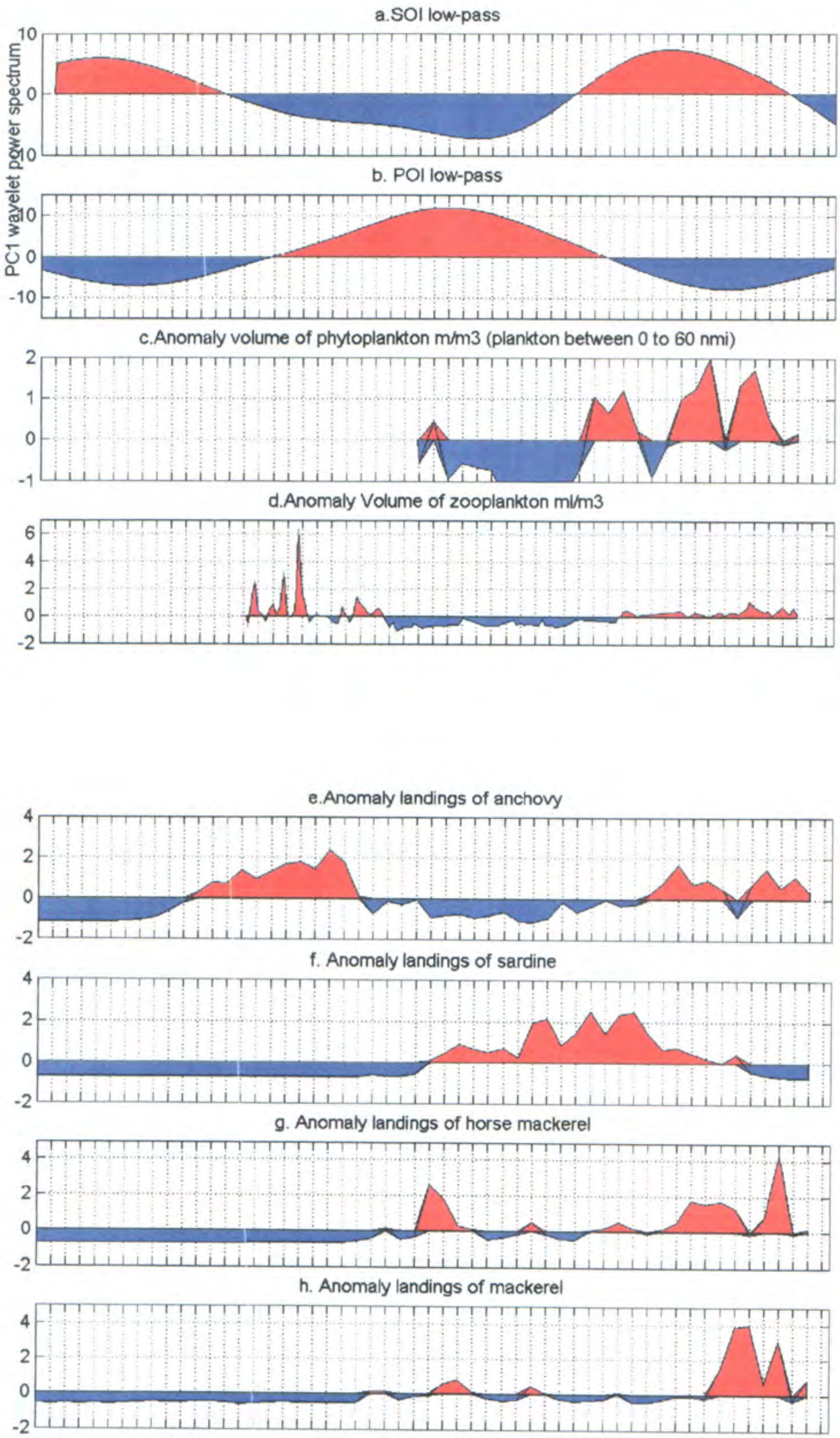
a.SOI low-pass
PC1 wavelet power spectrum
10
0
-10
b. POI low-pass
10
0
-10
c.Anomaly volume of phytoplankton m/m3 (plankton between 0 to 60 nmi)
2
1
0
-1
d.Anomaly Volume of zooplankton ml/m3
6
4
2
0
-2
e.Anomaly landings of anchovy
4
2
0
-2
f. Anomaly landings of sardine
4
2
0
-2
g. Anomaly landings of horse mackerel
4
2
0
-2
h. Anomaly landings of mackerel
4
2
0
-2
1950
1960
1970
1980
1990
2000
years

FIGURE 3

Period	Variable (∆t)	Origin	Area	mean (std)
1978-2002	Alongshore wind stress along Peruvian coast (monthly)	COADS[1]	Callao	3 m*s^{-1}(±0.2)
1950-2003	Southern Index Oscillation (monthly)	CPC [2]	South Pacific	-0.03 (±10.06)
1950-1999	Anomaly sea surface temperature (monthly)	DHN[3] IMARPE[4] DHN DHN DHN	Chicama Chimbote Huacho Callao Ilo	17.2°C (±2.4°C) 19.9°C (±2.1°C) 17.3°C (±2.9°C) 16.6°C (±1.9°C) 14.9°C (±1.5°C)
1978-2003	Alongshore wind stress NIÑO3 area(monthly)	CPC	NIÑO3.4 area	8.6m*s^{-1}(±2.2)
1950-2003	Sea surface temperature (monthly)	CPC	NIÑO3.4 area	25.8°C (±1.29°C)
1979-2002	Volume of Microplankton (annual)	IMARPE	Peruvian area (110000 Km)	0.8 ml*m^{-3}(±0.4)
1964-2002	Volume of zooplankton (quarterly)	IMARPE	Peruvian area (110000 Km)	0.6 ml*m^{-3}(±0.4)
1967-1998	Biomass of anchovy (annual)	IMARPE	Peruvian area (110000 Km)	12.10 million tons (±7.03 million tons)
1950-2002	Landings of anchovy (annual)	IMARPE	Peruvian area (110000 Km)	4.06 million tons (±3.52 million tons)
1950-2002	Landings of sardine (annual)	IMARPE	Peruvian area (110000 Km)	0.84 million tons (±1.09 million tons)
1950-2002	Landings of jack mackerel (annual)	IMARPE	Peruvian area (110000 Km)	0.09 million tons (±0.1 million tons)
1950-2002	Landings of mackerel (annual)	IMARPE	Peruvian area (110000 Km)	0.003 million tons (±0.03 million tons)

1. Comprehensive Ocean Atmosphere Data Set.
2. Climate Prediction Center.
3. Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú (DHN).
4. Instituto del Mar del Perú (IMARPE).

TABLE 1

Periodo Based	**Variable (Anomaly quarterly time series)**	**Interdecadal**	**Interannual**
1978-2002	Alongshore wind stress along Peruvian coast	1986 1990	1978, 1985 1988, 1993
1950-2003	Southern Index Oscillation	1975 1986	1953, 1957-1958 1965-1966 1968-70 1972-73 1977-78 1982-83 1986-87 1991-1996 1997-98
1950-1999	POI	1978 1987	1957, 1972, 1976, 1982, 1986, 1992 and 1997
1978-2003	Alongshore wind stress NiÑO3 area	1978 1982 1992	1982 1997
1979-2002	Volume of microplankton	1987	1982 1992 1997
1964-2002	Volume of mesozooplankton	1973-1974 1990	1964, 1966 1967, 1968 1972, 1990
1967-1998	Biomass of anchovy	1970 1989	-
1950-2002	Landings of anchovy	1970-1972 1992	1961, 1991 1996
1950-2002	Landings of sardine	1976	1994
1950-2002	Landings of jack mackerel	1976 1994	1976, 1991 1997
1950-2002	Landings of mackerel	1976 1994	1976

TABLE 2