Global multi-decadal ocean climate and small-pelagic fish population

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Abstract
Ocean climate, environmental and biological conditions vary on several spatio-temporal scales. Besides climate change associated with anthropogenic activity, there is growing evidence of a natural global multi-decadal climate signal in the ocean–atmosphere–biosphere climate system. The spatio-temporal evolution of this signal is thus analyzed during the 20th century and compared to the variability of small-pelagic fish landings. It is argued that the low-frequency global ocean environment and plankton ecosystems must be modified such that small-pelagic populations vary accordingly. A small-pelagic global index or fishing ‘regime indicator series’ (RIS) (i.e. a small-pelagic abundance indicator) is used. RIS is derived from fish landings data in the four main fishing areas in the Pacific and Atlantic oceans. Global RIS changes phase (from positive to negative values) when SST multi-decadal anomalies are out-of-phase between the eastern Pacific and southern Atlantic. RIS also displays maxima during the mid-30s to early-40s and the late-70s to early-80s when the multi-decadal signal was approximately changing phases (Tourre and White 2006 Geophys. Res. Lett. 33 L06716). It is recognized that other factors may modulate fish stocks, including anthropogenic predation. Nevertheless it is proposed that variable climate and environment, and the low-frequency ‘global synchrony’ of small-pelagic landings (Schwartzlose et al 1999 S. Afr. J. Mar. Sci. 21 289–347), could be associated with the multi-decadal changes in global ocean climate conditions.

Keywords: natural climate signals, multi-decadal climate signal/oscillation, climate change, ENSO, small pelagic synchrony, managing fish stocks, global fishmeal production

1. Introduction
A penta-decadal signal (i.e. of 40- to 60-yr period band) has been observed in pelagic sardines and anchovies populations in at least three of the four major fishing and upwelling zones over the global ocean. These zones are associated with the California, Humboldt and Benguela currents (Kawasaki 1983, Lluch-Belda et al 1989, 1992, Baumgartner et al 1992, Bakun 1996, MacCall 1996, Klyashtorin 1998, Beckley and van der Lingen 1999, Schwartzlose et al 1999, Chavez et al 2003).

Moreover, in each single zone, the low-frequency signal in sardines’ abundance has been observed to fluctuate with an out-of-phase relationship with that of anchovies, thus yielding the concept of the so-called ‘global synchrony’ of small pelagic fish (Schwartzlose et al 1999, Alheit and Niquen 2004; among others).

 Independently, it has been found that global climate variability occurs on various spatio-temporal scales, including the quasi-biennial (2- to 3-yr periods, or QB), the inter-annual (3- to 7-yr periods, or ENSO), the quasi-decadal (8- to 13-yr periods, or QD), and the inter-decadal (17-to 23-yr periods, or ID) signals (White and Tourre 2003; among others). A
multi-decadal signal has also been found in other diagnostic, numerical and proxy studies of the Earth’s ocean–atmosphere–biosphere system (i.e. Schlesinger and Ramankutty 1994, Lau and Weng 1995, Minobe 1997, 2000, Mann and Park 1999, Delworth and Mann 2000, Tourre et al 1999, Venegas and Mysak 2000). Recently, there is growing evidence for global and natural multi-decadal climate variability (i.e. 40- to 80-yr periods Minobe 2000, Tourre and White 2006; or AMO in the Atlantic Ocean, following Kerr 2000, Enfield et al 2001; among others).

It has been recognized that ocean climate variability on different timescales may alter abiotic factors and migration patterns of fish populations (Fréon and Misund 1999, Roy and Reason 2001, Beaugrand et al 2003, Roy et al 2005). Other things being equal, low-frequency small-pelagic ‘global synchrony’ could then be thought of being linked to multi-decadal global ocean regime shifts as mentioned above. The latter shifts could alter/modulate regional ecosystems where the match/mismatch hypothesis applies (Cushing 1990), as well as the global fish productivity as already proposed by Lluch-Belda et al (1992). Recently Lluch-Cota et al (2003) made an attempt to associate the multi-decadal signal in sardines–anchovies’ abundance with that in the ocean–atmosphere system over the north Pacific. They observed that sardines–anchovies’ populations fluctuate along with local sea surface temperature (SST) and coupled sea level pressure (SLP) anomalies, from 1925 to 1995, with maxima (minimum) in the early-40s and mid-80s (in the 70s). Since this apparent synchronous low frequency of small-pelagic stocks variability occurs in distant regions of the Pacific and Atlantic oceans, it appears reasonable to look in detail for a common global ‘ocean climate integrator’ and basin-wide climatic coherent patterns.

If causal connections underlying the proposed association can be further highlighted, then decision-makers may be able to better assess competing influences between natural fluctuations on different timescales (including the possible ‘modulating’ effect of the multi-decadal signal on higher frequency signals such as ENSO), anthropogenic predation and climate change. This might lead in the long term and in the context of climate change to improved sustainability of fish population, fishmeal production and mitigate socio-economical impacts (IRI 2002, Bakun and Broad 2002).

2. Data and method

In this paper global SST and sea level pressure (SLP) independent data sets (the GISST-SLP datasets from Folland and Powell (1994)), from 50°S to 60°N and for the 20th century winters, are analyzed to isolate key climate signals including the multi-decadal signal discussed later. Prior to the analyses the time series of SST and SLP on 2° lat. × 2° long. gridded fields are detrended and standardized. The data has been then submitted to the joint multi-taper method/singular value decomposition (MTM/SVD) technique, i.e. a frequency-domain approach optimal at isolating band-limited and spatially coherent joint signals, from a slowly varying background (Mann and Park 1999). In short, the chosen time–frequency bandwidth parameter is based upon three tapers, which allow for reasonable frequency resolution and sufficient degrees of freedom. The fractional variance explained by the lead eigenvectors, as a function of given frequencies, is obtained from a multivariate spectrum where dominant peaks (within significant frequency bands) can be identified. The significance levels are obtained from Monte Carlo testing, using a non-parametric bootstrap approach (Efron 1990, Mann and Park 1999; see also figure 1 in Tourre and White 2006). To obtain joint spatial evolution of significant SLP and SST associated with the significant multi-decadal climate signal (∼30–60-yr periods) time sequences

Figure 1. Standing mode of the ‘multi-decadal climate signal’ obtained from a global joint sea level pressure–sea surface temperature or SLP-SST MTM/SVD analysis. SLP anomalies in hPa are displayed at intervals of 0.05 per contour. Hatched areas are for negative anomalies. Dashed rectangles in the tropical band delineate regions where anomalies have the same sign. An alternation in signs is conspicuous which resembles that of seasonal signatures of Walker cells.
of monthly anomalies are band-passed using a recursive filter (Kaylor 1977), with a period admittance window with half-power points at 30- and 60-yr (periods' cutoff for the filter). While the band-pass filtering is similar to running first a low-pass filter and then a high-pass filter, the technique here allows us also to eliminate possible ‘contamination’ in the SST analysis from the low-frequency Gleisberg cycle (Lohman et al 2004). Prior to band-pass filtering we apply maximum entropy spectral analysis (Andersen 1974) to minimize loss of data at the ends of each time series (i.e. extending the series by 1/2 of the band), which also preserves the integrity of the frequency response function of the filter, and allows over half of the variance of the signal at end points to be faithfully represented (White 2000). Since the filtered response function of Kaylor’s filter is flat, with steep sides and negligible lobes, it eliminates potential phase shifts (this is equivalent to running a double-filtering technique ending up with symmetric low-pass and high-pass filters). The significant multi-decadal signal is thus effectively ‘isolated’. Evolution of SST and SLP multi-decadal anomalies are subsequently obtained and globally mapped every 5 yr (see figures 2 and 4). The slanted lines in figure 4 are obtained by following centers with maximum SST anomalies (positive and negative), for each single winter.

To further investigate the potential relationships between global multi-decadal ocean climate fluctuations, global small-pelagic fish population, additional and specific analyses of fish landings (including a small-pelagic abundance indicator) and SST anomalies, are presented in the four regions of the oceans where fishing industries are very active, i.e. the northwest and northeast Pacific, the southeast Pacific and southeast Atlantic oceans. It is important to note that statistical significance of the latter results derives not only from one long time sequence in one upwelling zone, but from shorter time sequences in four geographically and entirely distinct upwelling zones, thus representing four independent realizations.

Catch records from Japan, California, Humboldt and Benguela sardine and anchovy fisheries systems have been introduced by fishery scientists involved in SCORWG98 (1998) with the homepage housed by CIBNOR, and first released by Schwartzlose et al (1999), where data quality is discussed. To further highlight the global ‘synchronicity’ between small-pelagic fish population from the above regions and ocean climate, the variation of small-pelagic landings is integrated into a single index, the so-called ‘regime indicator series’ composite index or RIS (see also FAO 1997, Lluch-Cota et al. 2003, and Chavez et al. 2003). It is recalled that RIS is obtained from standardized individual annual catch time series (i.e. annual catch anomalies divided by their respective standard deviations), and by taking into account ‘positive’ Pacific (Atlantic) sardine (anchovy) landings and ‘negative’ Pacific (Atlantic) sardine (anchovy) landings. Values of RIS are then obtained from the sum:

\[ RIS = (JS + CalS + HS + BA) - (JA + CalA + HA + BS) \]

where JS, JA, CalS, CalA, HS, HA, BS and BA are standardized annual catch of sardines (S) and anchovies (A) for Japan, California, Humboldt, and Benguela fisheries’ systems, respectively.

![Figure 2. Time evolutions of the band-passed multi-decadal climate signal. SLP anomalies are displayed every five years for simplicity. The colored scales at the bottom are for SLP anomalies in hPa. Red and blue ovals (i.e. during 1925, 1950 and 1975) are to identify periods when the patterns resemble that displayed in figure 1. Bold Hs and Ls represent maximum/minimum SLP anomalies during those periods.](image)
anchovy (sardine) catches of the other systems. The RIS index can then be considered as a global representation of small-pelagic abundance and is superimposed onto the evolution of SST multi-decadal variability from 1925 until 1994 for easy comparison (figure 4).

3. Results

From the four fishing regions mentioned above, standardized time series of anchovy and sardine landings (good proxies or indicators of their populations) have been individually re-analyzed (not shown). While low-frequency variability is shown with sardine landings in the northwest Pacific off Japan, the northeast and the southeast Pacific rises and falls are more or less in unison during the mid-30s and early-40s and during the 80s. In addition, during periods of low sardine landings (or abundance) the anchovy population seems to dominate. Interestingly enough southeast Atlantic landings (as mentioned above) display an inverse relationship to the southeast Pacific landings, i.e. periods of high sardine abundance in the southeast Pacific are periods of low sardine abundance in the southeast Atlantic and vice versa.

Hereafter the possible links between global ocean climate variability and regional small-pelagic abundance are investigated by examining first and in detail the spatio-temporal evolution of global ocean climate associated with the multi-decadal climate signal. In figure 1, the multi-decadal SLP global anomalies (also identified by Tourre and White (2006)) are displayed. Tropical and coherent regions with alternating signs for SLP anomalies are conspicuous, and must be associated with the surface signatures of zonal Walker cells. The southern oscillation index (SOI) is thus seen as being directly modulated by the multi-decadal signal. This in turn is going to modulate ENSO signals as well. The global spatial evolution of SLP anomalies are displayed in figure 2, data for every 5 yr are shown for clarity. Spatial patterns which correspond to that of the standing mode displayed in figure 1, are striking during the mid-20s, 50s and mid-70s. The SOI is thus modulated accordingly (see bold Hs and Ls, for maximum SLP highs and lows), i.e. enhanced (reduced) from the mid-20s until mid-30s, and from the mid-60s until mid-70s (from the mid-40s until mid-50s, and from the mid-80s until mid-90s). From the slow evolution of SLP anomalous patterns and gradients in the Pacific, contemporaneous periods with increased/decreased mid-latitudes westerlies and simultaneous decreased/increased ageostrophic and tropical easterlies in the central/eastern Pacific must follow.

Over the Atlantic Ocean, patterns of SLP anomalies display an overall slow meridional evolution from the northern Atlantic into the southern Atlantic. This evolution must also modulate the meridional Hadley’s circulations there. It can also be seen that SLP anomalies for almost the entire Atlantic basin are alternatively positive (early-40s and mid-80s) or negative (mid-60s), prior to strengthening (weakening) of the St Helena anticyclone in the southern Atlantic, 5 to 10 yr later (see bold Hs and Ls, for maximum SLP highs and lows).

In figures 3(a)–(d), indices of SST anomalies are constructed for the four investigated regions, and are compared to sardine landings. It can be seen that in the three regions where coastal upwelling regimes dominate (i.e. northeast Pacific, southeast Pacific and southeast Atlantic, figure 3 (b)–(d)) SST anomalies are in phase with the sardine landings. The opposite relationship holds true for the northwest Pacific, offshore of Japan (figure 3(a)). The time difference between maxima of SST anomalies in the northwest and northeast Pacific is approximately 5 to 10 yr, indicative of a slow eastward propagation of the multi-decadal climate signal (see black curved arrows between figures 3(a) and (b); see also slanted lines in figure 4).

More information about the thermal multi-decadal variability in the Pacific and Atlantic oceans is obtained by examining the spatial evolution of SST anomalies on the same timescale, displayed in figure 4. As mentioned above, in the northern Pacific there is a conspicuous overall eastward evolution of SST anomalies, along the Kuroshio–Oyashio extension (KOE) and the sub-arctic frontal zone (SAFZ), with approximately a 25-yr alternation in polarity. In the southeast Pacific the main SST anomalies intensify locally from approximately 10–15 yr and switch polarity also every ~25-yr. In the south Atlantic, the main SST anomalies evolve mostly counterclockwise from the South African coastline, following the anticyclonic gyre there. Finally, the anticyclonic evolution and timing of SST anomalies in both basins lead to surface thermal conditions of the same polarity along the Americas’ coastlines, which last for approximately 10–15 yr. The surface conditions must then reflect subsurface thermal conditions throughout mechanical wind action linked to the SLP anomalous patterns and gradients as described above. Another result from figure 4 is the conspicuous synchrony in sardine landings in the northeast Pacific, and southeast Pacific, while the ‘Benguela sardines’ in the southeast Atlantic ‘behave like anchovies’ (and vice versa). This is indicative of opposite environmental conditions which could be linked to the multi-decadal climate signal as suggested here.

4. Conclusion and discussion

Besides direct ocean thermal effects on the environment, ecosystems and fish stocks, results presented here outline the fact that the spatial extension of the sardines’ habitat is a non-negligible factor contributing to their landings. Indeed, sardine population tends to spawn during optimal environmental conditions and to occupy the maximum available habitat (Lluch-Belda et al 1992). Geographic extension of a spawning habitat is associated with abundance levels for the following years. For example, the main difference between the northwest Pacific/offshore Japanese system and the coastal upwelling systems is that sardine stocks increase oceanward during years of extended intrusion of nutrient-rich Oyashio–Kuroshio currents, so that larger spawning areas are not confined to the coastline (Sugimoto et al 2001). Sardines are also more zooplankton feeders than anchovies. This latter remark could explain the out-of-phase relationship between sardine landings and SST anomalies in regions where strong vertical mixing occurs, with enhanced productivity. Moreover, biological linkage mechanisms between the small-pelagic fish
species, the dominant food source, reproduction and climate variability have already been discussed (Bakun 1996). It has been argued that the spawning reproductive mode provides a means of exploring environmental conditions associated with low-frequency climate variability (Bakun 2001). The results presented here corroborate previous findings from Schwartzlose et al (1999). The low-frequency variability of small-pelagic and associated adaptation and/or abundance are somewhat independent of human predation, as evidenced by paleo-records of fish scales deposited in the ocean floor of the northeast Pacific. The latter records show that these fluctuations also occurred at periods prior to human exploitation (Baumgartner et al 1992, Bakun 1996, Beckley and van der Lingen 1999, Diffenbaugh et al 2003). Moreover the AMO multi-decadal phase changes have been observed to occur 16 times since the 16th century, using tree-ring records (Gray et al 2004). Another striking feature is the alternation between sardine and anchovy abundance or the so-called ‘regime change’ or ‘habitat switching’ (see Kawasaki 1983, Lluch-Belda et al 1992, Bakun 1996, Schwartzlose et al 1999, Kuroda 1991), which is further evidenced here. These alternations can also be due to a switch between near-shore and offshore favorable ecosystems/habitats for feeding and reproduction (i.e. spawning extension and phytoplankton/zooplankton availability like offshore of Japan, following Wada and Kashiwai (1989)).

4.1. The multi-decadal climate signal

The global and coherent joint evolution of multi-decadal SLP and SST fluctuations as displayed in this paper can then be summarized as follows.

- In the Pacific and during the mid-30s until the 50s and mid-70s until late-80s, the multi-decadal climate signal contributed to the intensification of the Aleutian Low and the atmospheric circulation in mid-latitudes (see also Beamish and Bouillon 1993, Klyashtorin 1998).
Figure 4. The smoothed (5-yr moving average) regime indicator series (RIS) computed as the difference between the sum of standardized annual landings series of sardines (anchovies for the southeast Atlantic) minus the sum of standardized annual landings series of anchovies (sardines for the southeast Atlantic) is displayed as a thick black line arbitrarily displayed for easy comparison (standardized RIS values are on the top axis). The spatial evolution of SST ‘multi-decadal’ anomalies (°C, bottom colored scale) is displayed in the background. Blue (red) rectangles are meant to highlight periods when out-of-phase relationships exist between the southeast Pacific and southeast Atlantic oceans. Blue (red) lines highlight the main eastward evolution of negative (positive) SST anomalies in the Pacific Ocean. When the coastal southerly winds are getting weaker (stronger), the weaker (stronger) coastal upwelling and depressed (surfacing) thermocline depth must follow accordingly in the southeast Atlantic Benguela area.

Contemporaneously, the Walker circulation and the SOI were weaker. SLP anomalous gradients were associated with stronger westerlies in the mid-latitudes.

- Negative SST anomalies were found during the same periods in the northwest and north Pacific where strong vertical mixing due to wind increase must have occurred, with additional supply of nutrients (Chavez et al 2003). In contrast, positive SST anomalies were simultaneously found in the northeast Pacific with possibly reduced coastal upwelling and depressed thermocline depth there.
- SST anomalies in the northeast and southeast Pacific evolved ‘in-phase’ for approximately 10–15 yr (for example, positive SST anomalies for the 1940–1955 period).
- In the southern Atlantic, positive (negative) SST anomalies develop rapidly, indicative of fast weakening (strengthening) of the subtropical anticyclone and southeasterly trades. When the coastal southerly winds are getting weaker (stronger), the weaken (strengthen) coastal upwelling and depressed (surfacing) thermocline depth must follow accordingly in the southeast Atlantic Benguela area.

Interestingly enough, the periods mentioned above in the first point are also the periods when in-phase relationships exist between the Aleutian and the Icelandic Lows (i.e. global atmospheric linkage), through fluctuations of the Arctic SLP anomalies (Venegas and Mysak 2000). These periods correspond also to maximum sea-ice concentration in the Greenland Sea with stronger northeasterly winds and a stronger East Greenland Current, contributing to the modulation of the meridional thermohaline circulation in the Atlantic Ocean (Delworth and Mann 2000, Venegas and Mysak 2000).

From the above, periods are found with similar phasing of SST anomalies in the northeastern Pacific, southeastern Pacific and southwest Atlantic, and out-of-phase relationships offshore of Japan and in the Benguela–Namibian regions. Corresponding thermal conditions must then be associated with the synchrony of small-pelagic landings. Here there is additional evidence that the patterns of alternation seem to correspond to the multi-decadal changes in ocean thermal oceanic conditions (which include upwelling regimes and associated boundary currents). It is nevertheless recognized that the signal can be blurred since the temperature range for sardine reproduction is much larger than that for anchovies (13–25°C compared to 11.5–16.5°C). Thus sardines have a much larger migratory capacity and can thrive in a colder environment with a lush phytoplankton biomass (Tomosada and Odate 1995). For example, during warm years in normally upwelled areas, sardine distribution expands poleward, as opposed to anchovies which tend to remain in more restricted geographical areas. Finally, local meandering structures of weaker boundary currents, which might also modulate concentration and retention of nutrients, and zooplankton abundance on smaller spatial scales (Parrish et al 1981, Carrasco and Lozano 1989, Bakun 1996), could not be evaluated here. In any case a better understanding of actual trophic pathways and linkages with regime shifts requires further investigation (Steele 2004).
4.2. Multi-decadal ocean climate and fish population

To further discuss the global synchronicity between ocean climate and small-pelagic fish population, the RIS index is superimposed onto the evolution of SST anomalies from 1925 until 1994 (figure 4). The global synchrony of the world’s largest fish stocks fluctuate with a striking ‘coordination’ and a coherent evolution with the ocean–atmosphere climate system on a low-frequency timescale. It can be seen, for example, that RIS maxima occur after warm conditions in the northeast Pacific and cold conditions in the northwest Pacific and vice versa. The out-of-phase relationship of SST anomalies in the southeast Pacific and Atlantic occur after RIS maxima (1945–1955, 1990–1994) or minima (1970–1975). Maxima during the mid-30s to early-40s and the late-70s to early-80s occur when the multi-decadal is approximately changing phases (see Tourre and White (2006), their figure 2, top). Finally, global RIS is changing phases (from positive to negative values, see large grey dots in figure 4) when SST multi-decadal anomalies are out-of-phase between the eastern Pacific and southern Atlantic.

Landings data (or catch) have been used here as proxies for biomass, since no biomass data is available for most of the period under investigation. It is acknowledged that illegal landings data do exist (Hansen et al 2006), a potential drawback at local levels, and it is recognized that sardine fisheries from the mid-20s to the mid-30s were not under full exploitation, while there was a larger demand for tinned sardines and fishmeal in Japan and California. The latter remark could have contributed to the apparent maximum of the RIS time series from 1930 to the mid-40s and the following drop of the RIS index from the late-40s until the late-60s. The RIS shape could then reflect a likely combined effect of climate variability and societal strong fishing pressure (that could explain the short-lived maximum during the mid-80s?). The global market void for fishmeal was then filled by the new development and rise of the Peruvian anchovetas and the Benguelan sardine fisheries.

In this paper evidence is proposed for plausible relationships between global multi-decadal ocean climate fluctuations and small-pelagic fish population. The small-pelagic fisheries are the most voluminous source of marine biomass for fishmeal production used as animal feed, but their management has been extremely difficult. As proposed by Beamish et al (2004) the existence of ecosystems with low-frequency alternative states induces severe management consequences. It has been shown that integrated management, when based on a purely ecosystem-based strategy, may lead to serious problems (Eisenack et al 2006). Nevertheless, from the results presented here, combining the surveillance of ecosystems with monitoring of climate variability at different timescales, could lead to an improvement of economic planning capabilities though adaptive management options (Kuroda 1991). It is believed that this new relationship between SLP, SST (and sub-surface thermal content) and biological joint fluctuations could be used for improving fish stock management worldwide. For example, knowing the phasing of the global multi-decadal climate signal, and the way it could modulate higher-frequency climate signals such as ENSO, and the role of associated off-shore meso-scale eddies (Logerwell and Smith 2001), should allow local decision-makers to add additional and comprehensive information. This also could contribute to the optimization of fishmeal global production. Slow rise, decrease and alternations of small-pelagic populations could possibly be predicted at shorter time scales, while timely adequate management decisions for immediate action could be undertaken (Alheit and Hagen 2001). Fishing pressure could be increased when stocks are on the ascending limb and reduced when stocks decline again. This could even lead to an increase in stock productivity and yields (Kuroda 1991). A better understanding of the physical mechanisms associated with the global multi-decadal climate signal and its relationships with higher-frequency climate events seem crucial for sustainable development. The next objective includes understanding the variability of other fish populations/landings, such as yellowfin tuna, Spanish hake, European herring and Icelandic cod, among others (Alheit and Hagen 1997, Agostini et al 1999).

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