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Review of Long Term Macro-Fauna Movement by Multi-Decadal Warming Trends in the Northeastern Pacific

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1. Introduction

Worldwide marine ecosystems are continuously responding to changes in the physical environment at diverse spatial and temporal scales. In addition to the seasonal cycle, other natural patterns occur at the interannual scale, such as El Niño-La Niña Southern Oscillation (ENSO) with a period of about three to five years (Wang & Fiedler, 2006). When ocean conditions stay above or below the long-term average for periods of 10 to 20 years we recognize decadal fluctuations (Mantua et al., 1997), and those with periods longer than 50 years are known as regime (Lluch-Belda et al., 1989). On the ocean, marine populations respond to these variations in different ways, such as changes in their distribution and abundance. Evidence suggests that this multi-decadal scale climate variations are cyclic, which generates recurrent changes in the production level of marine ecosystems in ways that may favor one species or a group over another.

Abrupt changes between multi-decadal phases are known as regime shifts (Overland et al., 2008). The best documented regime shift in the North Pacific occurred in the mid-1970, with strong physical and biological signals, including ocean productivity (Ebbesmeyer, et al., 1991; Roemmich & McGowan, 1995), strong biomass and distribution changes in sardine and anchovy populations (Kawasaki, 1983; Lluch-Belda et al., 1989), and several other fish populations (Beamish et al., 1993; Mantua et al., 1997; Holbrook et al., 1997). These changes impacted marine food webs and ultimately affected the distribution and survival of marine top predators such as seabirds and marine mammals (Trites & Larkin, 1996; Veit et al., 1997; Trites et al., 2007). In this work we review published reports on long term macro-fauna (nekton) movements as related to multi-decadal temperature trends in the Northeastern Pacific.

2. Long term ocean surface variability on the southern California current system

The study area (Fig 1) is under the influence of the California Current System, where, several authors have observed environmental and biological multi-decadal climate signals

(Lluch-Belda et al., 1989; Ware, 1995; Mantua et al., 1997). To describe the environmental conditions on the California Current System, monthly gridded (2x2 degree) sea surface temperatures (from January 1900 to December 2010) were analyzed for the area limited by the 20-42°N latitude and 102-140°W longitude (Fig. 1). The data base is known as "Extended Reconstructed Sea Surface Temperature" and was obtained from the National Oceanic and Atmospheric Administration (NOAA) web site (http://lwf.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php).

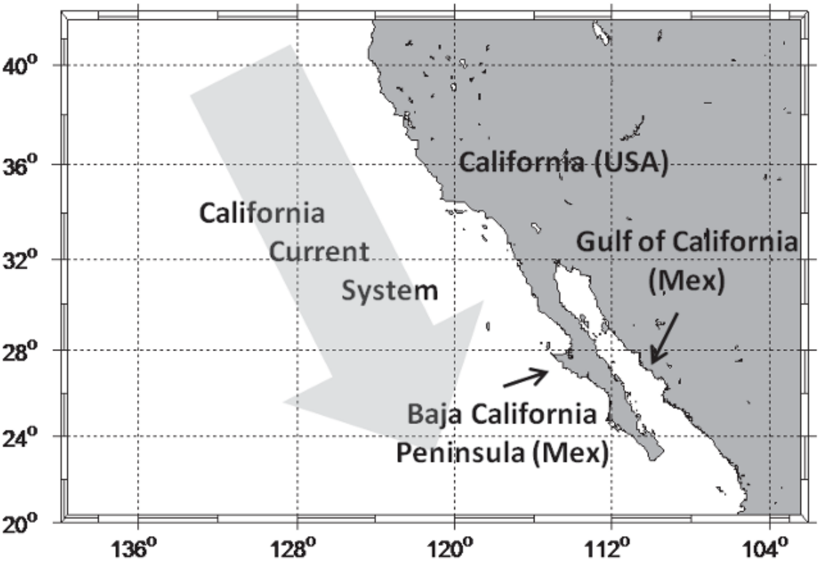


Fig. 1. Study area; USA: United States of America; Mex: Mexico.

To isolate scales of variability from the SST time series, we computed the long term mean and the seasonal signal by fitting annual and semiannual harmonics to the 110-year monthly mean time series (Ripa, 2002). Then we computed SST anomalies as residuals containing sub-seasonal (meso-scale) and low frequency variability (interannual and large scales) after extracting the long term mean and seasonal signals at each grid point. To analyze the regional modes of SST anomalies over the study area (Fig. 1), an empirical orthogonal functions analysis (EOF) was conducted using SST anomalies. The EOF decomposes the variability of the anomalies in a set of *N* uncorrelated orthogonal functions; each *n*-function represents an independent "mode of variability" (Björnsson & Venegas, 1997; Venegas, 2001).

The first EOF mode of SST anomalies explains 48% of the total variance over the study area.

The spatial pattern shows a typical distribution of a global mode, where the surface temperature increase (decrease) in the whole area at the same time and according to the sign of the EOF time series, which explains up to 50% of the unseasonal SST variability off California and Baja California Peninsula (Fig. 2, upper panel). This mode shows a great interannual and multi-decadal variability in its time series (Fig. 2, lower panel). Two long warming trends and two long cooling trends are evident. Warming trends occurred between the late 1910s and the end of the 1930s, and from 1975 until the end of the 1990s, while the cooling trend occurred from the beginning of the twentieth century to the late 1910s, and between the early 1940s and 1975. The strong warming event at the end of the 1950s was not considered as a long term trend, because this was caused by the strong El Niño 1958-59 event, and a few years later the SST recovered its cooling trend until 1975. Also, our results suggested a new cooling trend beginning with the new century. The origin of these multi-decadal trends is subject to debate. In this regard, several studies and hypothesis have been developed to explain the physic mechanisms that are underlying this multi-decadal variability, but are not the matter of this work.

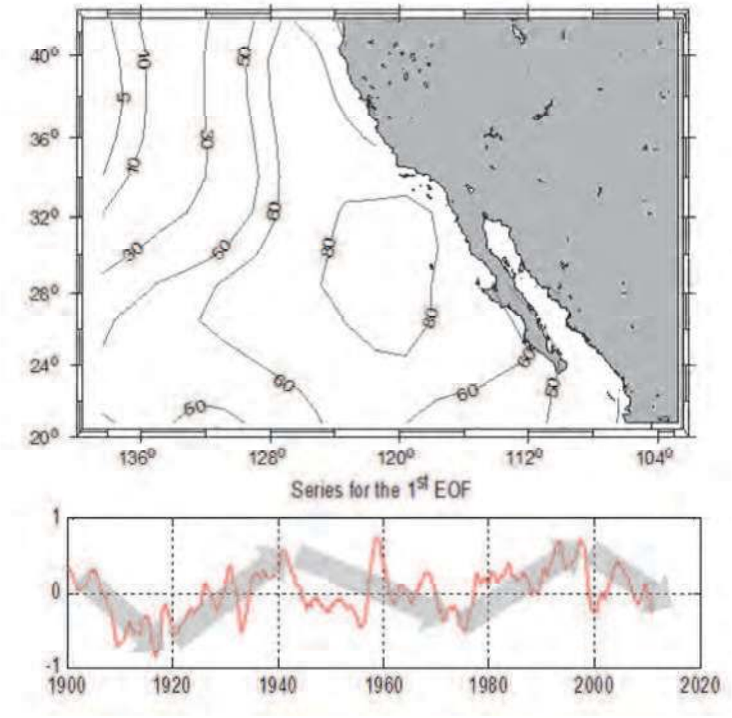


Fig. 2. Local explained variance (%) and temporal patterns of the first EOF mode of SST anomalies.

3. Long term macro-fauna movement

The California sardine (*Sardinops sagax caeruleus*) is the most abundant fish species in the northeast Pacific. It is a key component of the California Current pelagic ecosystem, being the main prey of several pelagic species such as seabirds, marine mammals, predatory fishes and squid (Bakun et al., 2010). This sardine has two core centers of distribution, one in the west coast of the Baja California Peninsula, and the other inside the Gulf of California. From these centers, schools may expand into the surrounding waters when environmental conditions are suitable. This species tends to have large interannual fluctuations in its abundance, due to strong variations in recruitment related primarily to environmental variability in their spawning areas (Lluch-Belda et al., 1986; Hammann et al., 1998). In addition to these interannual fluctuations, this group has a not yet totally understood regime shift time scale (~60 years) of global alternation between sardine and anchovy populations, due to the expansion and contraction of their populations (Fig. 3; Kawasaki, 1983; Lluch-Belda et al., 1989; Baumgartner et al., 1992; Chavez et al., 2003; Bakun et al., 2010). These can be seen in the commercial landings of California state (USA) waters (Fig. 4) and in fossil records over the last 2000 years (Baumgartner et al., 1992). Chavez et al (2003) related this regime shift to the SST variability in the northeast Pacific. This relationship is evident in the sardine landings (Fig. 4), where increases are evident during warming trends (1920-1940 & 1975-2000) and a decrease during the cooling trend (1940-1975).

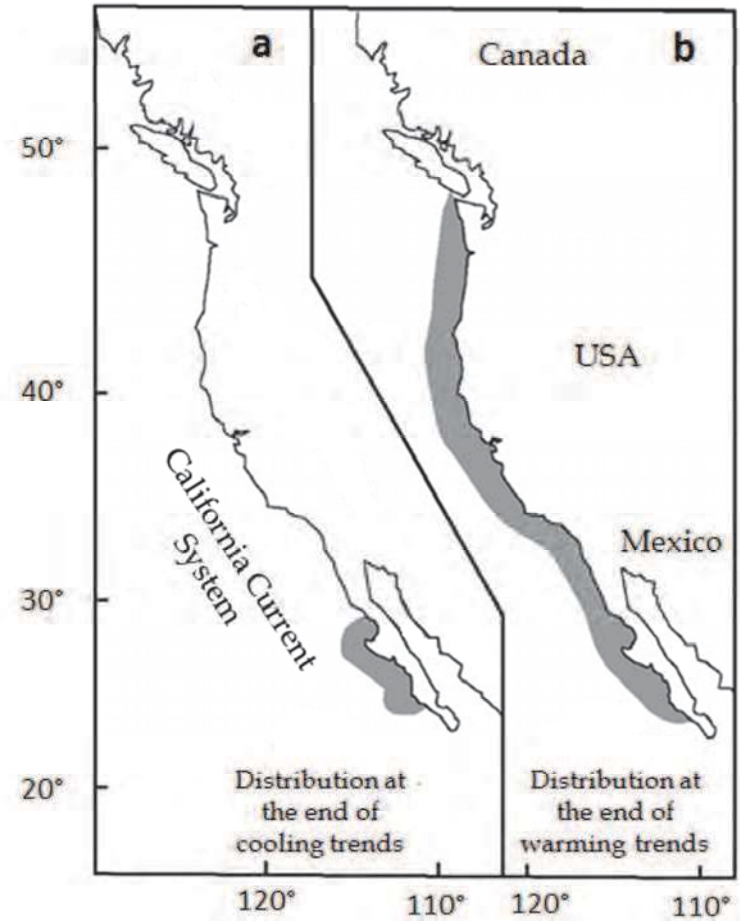


Fig. 3. Contraction (a) and expansion (b) of California sardine populations in the Northeast Pacific at the end of cooling and warming periods respectively (Bakun et al., 2010).

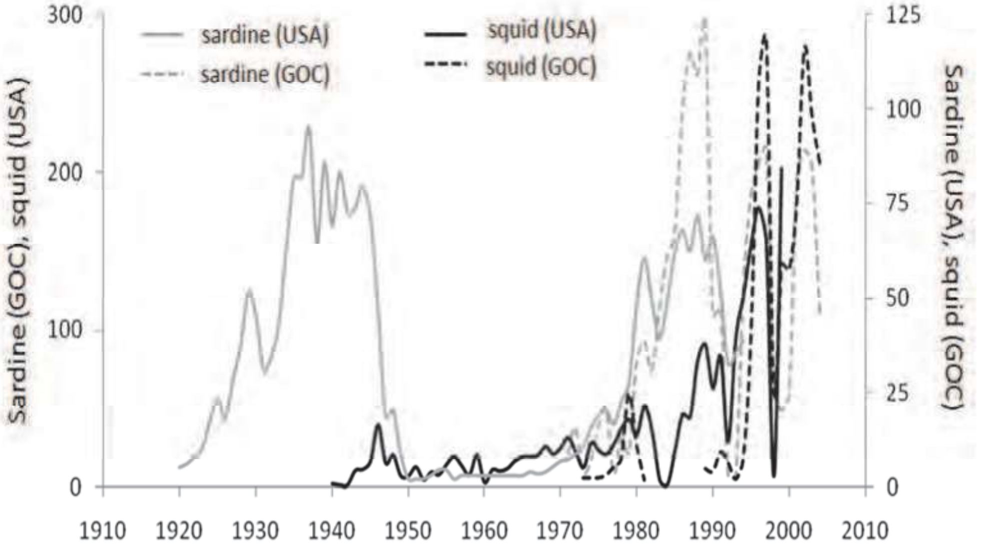
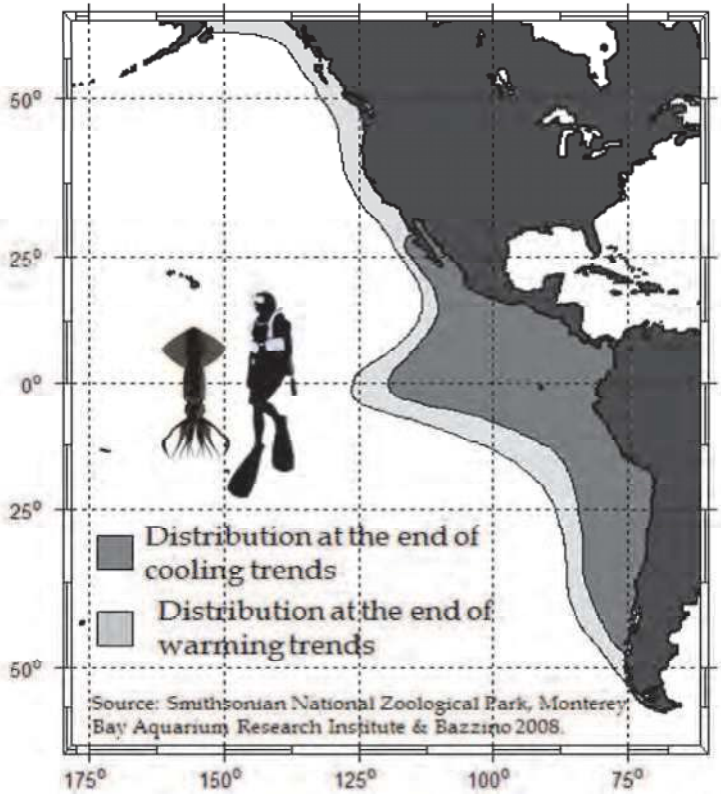


Fig. 4. California sardine landings at California waters (USA; thousands of tons) from FAO (1997), and for Gulf of California waters (GOC; thousands of tons) from SAGARPA; jumbo squid landings at California waters (USA; millions of pounds) from NOAA web page (http://www.pfeg.noaa.gov/research/climatemarine/cmffish/cmffishery.html), and Gulf of California (GOC; thousands of tons) from SAGARPA.

The Jumbo squid (*Dosidicus gigas*) is a large ommastrephid (up to 50 kg mass and overall length of 2.5 m) endemic to the Eastern Tropical Pacific. This squid is an important component of the marine food web that prey on small pelagic and mesopelagic fishes, crustaceans and squids (Markaida & Sosa-Nishizaki, 2003; Armendáriz-Villegas, 2005; Field et al., 2007); being an energy transfer from the mesopelagic food web to higher trophic level species as tunas, billfish, sharks, and marine mammals (Galván-Magaña et al., 2006; Field et al., 2007). The jumbo squid maintain the largest squid fishery in the world, which operates off the coasts of Peru, Chile and Central America, and in the Gulf of California (Morales-Bojórquez et al., 2001; Waluda & Rodhouse 2006). Recent scientific publications, anecdotal observations and fisheries landings pointed out a range expansion of jumbo squid throughout the California Current and southern Chile over the past decade (Fig. 4 & 5; Cosgrove, 2005; Chong et al., 2005; Wing, 2006; Zeidberg & Robinson, 2007). This sustained range expansion has generated hypotheses related to changes in climate-linked oceanographic conditions and reduction in their competing top predators (Zeidberg & Robinson, 2007; Waters et al., 2008). However, the coincidence of the recent poleward range expansions in both hemispheres, and the reports of the increases in the abundance off the west coasts of North and South America in the late 30s (Rodhouse, 2008), (just at the end of the 1910-1940 warming trend), suggests a physically-induced forcing mechanism. This may be related with long term warming trends and the poleward expansion of their primary habitat (Bazzino, 2008).



Source: Smithsonian National Zoological Park, Monterey Bay Aquarium Research Institute & Bazzino 2008.

Fig. 5. Jumbo squid expansion during multi-decadal environmental trends.

The sperm whale *(Physeter macrocephalus)* is the largest odontocete, or toothed whale. This predator can be found in all world oceans in deeper waters, feeding largely on epi- and mesopelagic squid species (Whitehead, 2003). Groups of females and immatures are distributed on tropical and temperate waters, while solitary males are distributed on polar waters and only go to lower latitudes to breed. In the California Current System, Barlow & Forney (2007) showed that the abundance of sperm whales is temporally variable, and the two most recent estimates (2001 and 2005) were markedly higher than the estimates for 1991−96. Related to this increased in whales abundance, Jaquet et al. (2003) noted that few sightings of sperm whales were reported during the 1980s along the Baja California Peninsula; then their abundance appeared to increase since 1992. Actually these whales occur into the Gulf of California year-round and the high proportion of mature females and first-year calves suggests that this area is an important breeding and feeding ground for the sperm whale (Jaquet et al., 2003). As sperm whales are known to forage on jumbo squid, these authors coincided that the increased in the presence of sperm whale in both regions could be related with the expansion of jumbo squid in the California Current System and in the Gulf of California during the past two decades. Concurrently, a decrease in sperm whale abundance in the Galapagos Islands since the early 1990s has been observed (Whitehead et al., 1997), as well as animals from Galapagos have been spotted inside the Gulf (Jaquet et al., 2003), suggesting a northward shift in their distribution.

The Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) is an average-sized oceanic dolphin (from 2 to 2.5 m) found in temperate waters of the North Pacific Ocean, feeding on small pelagic and mesopelagic fish and squid. In the eastern Pacific, large groups of this species are frequently seen in the California Current System (Leatherwood et al., 1984; Stacey & Baird, 1990; Keiper et al., 2005). The southern boundary of the distribution of Pacific white-sided dolphins is the Gulf of California, where the species has been observed only in its southwest area during the winter and spring (Aurioles et al., 1989). During the last 3 decades, Salvadeo et al. (2010) documented a decline in the presence of this dolphin species in the southwest Gulf of California, just during the end of the last warming trend in the California Current System (Fig. 2). Considering that the thermal environment is physiologically important to animals, the authors listed three evidences consistent with a poleward shift in their range: 1) The occurrence of this dolphin has decreased by approximately 1 order of magnitude per decade since the 1980s, (Table 1); 2) their monthly contraction to cooler months of the year (Fig. 6); and 3) the occurrence of this dolphin has increased on the west coast of Canada from 1984 to 1998 (Morton, 2000).

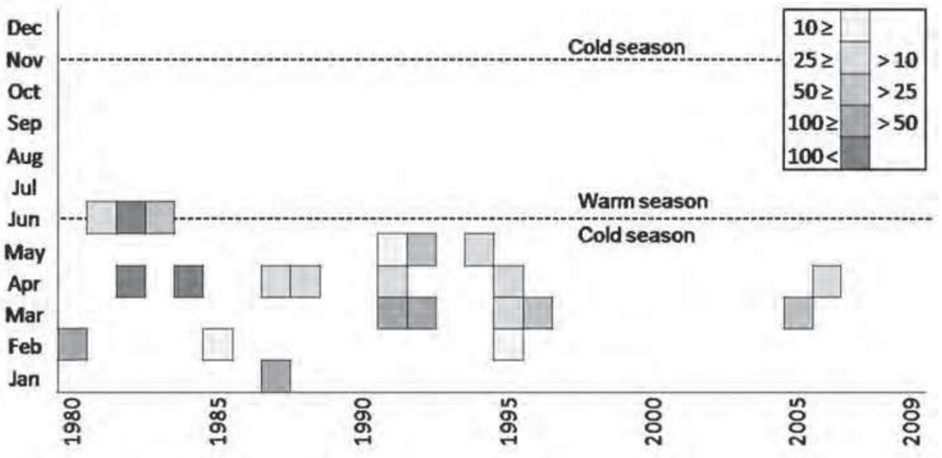


Fig. 6. Historical numbers of animals per month of Pacific white-sided dolphin from the southwest Gulf of California (Salvadeo et al. 2010).

Period	Effort	Sightings	Animals	Mean	Min.	Max.	SD	Sightings/hrs	Animals/hrs
1980s	252	10	647	65	2	200	67	0.039	2.56
1990s	1659	16	316	20	1	45	12	0.010	0.19
2000s	1986	2	50	25	20	30	7	0.001	0.03

Table 1. Pacific white-sided dolphin: accumulated historical data from the southwest Gulf of California for the last 3 decades. Effort (h); sightings: number of occasions when the species was observed; mean, minimum (min.), maximum (max.), and SD for group size; sightings h–1 and animals h–1: abundance relative to effort; 1980s: 1978–1988; 1990s: 1989–1999; 2000s: 2000–2009 (Salvadeo et al., 2010).

The gray whale (*Eschrictius robustus*) is a medium sized baleen whale reach 14 m in length and weigh of 45 metric tons. Some pods of gray whales breed every boreal winter at three lagoons along the Baja California Peninsula. At the end of the breeding season, the whales migrate to the feeding grounds in the Bering and Chukchi Seas, where they feed on benthic fauna (Rice & Wolman, 1971). The population of gray whales seems to have reached carrying capacity, with population size fluctuating between 20,000 and 22,000 animals (Rugh et al., 2008). As the Pacific white-sided dolphin, the evidences pointed out a possible poleward shift of the gray whale distribution related to the last warming SST trend. These evidences are: 1) there is an apparent long term tendency in the use of breeding lagoons, increasing at the northern lagoon and decreasing at the southern lagoon (Urbán et al., 2003a); 2) the decrease in the numbers of whales at the breeding lagoons during the last years, also observed from shore-based surveys at Piedras Blancas during the northbound migration (Urbán et al., 2010); 3) an increase in calf sightings at California (USA) correlating with warmer sea surface temperature anomalies (Shelden et al., 2004); 4) a range expansion into Arctic waters (Moore and Huntington, 2008); 5) during warming El Niño years the whales tend to use northern areas more intensively than in normal years (Gardner & Chávez-Rosales, 2000; Urbán et al., 2003b); 6) the unusual sighting of a gray whale in the Mediterranean Sea, it is another possible effect of their expansion to the north, which allows them to cross the Arctic to the Atlantic (Scheinin et al., 2011); and 7) in spite of having an increasing population of gray whales in the eastern Pacific, the observations of individuals inside the Gulf of California has been consistently declining (Salvadeo et al., 2011).

4. Conclusions

Two well defined long term climate warming trends were observed in the SST anomalies, these appear to be part of cyclical changes that include cooling trends over the study area (Fig 2). Changes in the SST are indicators of more complex ocean processes related to alterations in oceanic and atmospheric circulations, which ultimately affect the enrichment of superficial waters. The biological responses to those ocean processes are complex and not well understood.

There are evidences which indicate that distribution shifts related to long term ocean warming had occurred for some species, including poleward shifts (gray whale and Pacific white-sided dolphin), range expansions (California sardine and jumbo squid) and redistribution (sperm whale). The distributions of most species are defined by interactions between available environmental conditions and the ecological niches that they occupy on the ecosystem (Macleod, 2009). For gray whales and Pacific white-sided dolphins the cause of their range shift is apparently driven by the importance of thermal environment for the species. This poleward shift caused by thermal niche was also recorded in stranding records of dolphin species in the north-eastern Atlantic Ocean (Macleod et al., 2005). For the sperm whale it seems to be related with a trophic link, because their redistribution appears to be coupled with the range expansion of their primary prey, the jumbo squid. Multi-decadal range shift related with trophic interactions was also observed in the north-eastern Atlantic Ocean, from the subpolar gyre variability via plankton, to marine top predators (Hátún et al., 2009)

For the California sardine and the jumbo squid, their range expansions appear to be related with the extension of suitable habitat for their reproduction and recruitment. These range shifts seems to be cyclical, where their populations retract to subtropical areas during cooling trends and expand to temperate areas during warming trends. For cetacean species, this cycle was not observed yet, possibly due to the lack of information, so maybe this could also happen. These recurrent populations' changes also were observed on small pelagic fish and squids in other world oceans current systems (Fig. 7), and show the links between multi-decadal global ocean climate variability and regional fish and squid populations (Lluch-Belda et al., 1989; Schwartzlose et al., 1999; Sakurai et al., 2000; Tourre et al., 2007). These synchronous population shifts are consequence of cyclic changes on the environment that affect the production level of marine ecosystems in ways that may favor one species or group of species over another, affecting the marine food web structure and function.

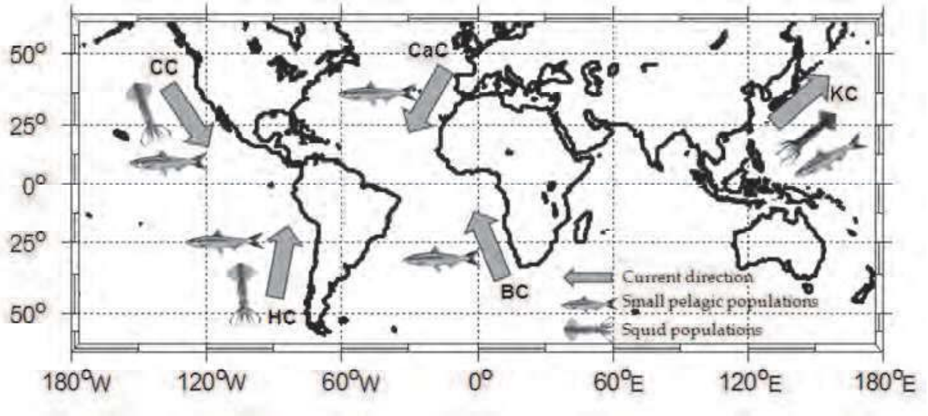


Fig. 7. Oceans current systems, where distribution shift were recorded on small pelagic fish and squid populations; ocean currents: California (CC), Canary (CaC), Kuroshio (KC), Humboldt (HC) and Benguela (BC); source: Lluch-Belda et al., 1989; Schwartzlose et al., 1999; Sakurai et al., 2000; Tourre et al., 2007, Bazzino 2008.

In conclusion, there are evidences that distribution shift occurred for some species due to long term ocean warming. Future scientific studies need to focus on understand the mechanisms of these long term cyclic variations and their effects on marine fauna, and incorporate this knowledge into the management and conservation approaches of the living marine resources.

Finally, the first EOF mode of SST anomalies showed a cooling trend for the last 10 years (Fig. 2). If the observed trends during the past are replicated, we should expect the beginning of a new ecological cycle, forced by climate tendencies that will restrict the distribution of California sardine to the west coast of the Baja California peninsula; and will move the jumbo squid range southward, forcing lower squid population levels at the west coast of the Baja Peninsula and the Gulf of California; related with this, a subsequent movement of sperm whales to other areas of the Pacific would occur, and the return of white-sided dolphins and gray whales as seasonal visitors of the Gulf of California.

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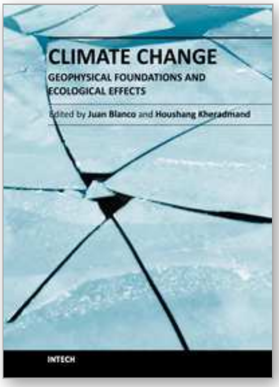

Climate Change - Geophysical Foundations and Ecological Effects
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This book offers an interdisciplinary view of the biophysical issues related to climate change. Climate change is a phenomenon by which the long-term averages of weather events (i.e. temperature, precipitation, wind speed, etc.) that define the climate of a region are not constant but change over time. There have been a series of past periods of climatic change, registered in historical or paleoecological records. In the first section of this book, a series of state-of-the-art research projects explore the biophysical causes for climate change and the techniques currently being used and developed for its detection in several regions of the world. The second section of the book explores the effects that have been reported already on the flora and fauna in different ecosystems around the globe. Among them, the ecosystems and landscapes in arctic and alpine regions are expected to be among the most affected by the change in climate, as they will suffer the more intense changes. The final section of this book explores in detail those issues.

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