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SUSTAINABILITY OF THE HUMBOLDT CURRENT LARGE MARINE ECOSYSTEM

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INTRODUCTION

Figure 1. Location of Humboldt Current LME.

The Humboldt Current Large Marine Ecosystem (HCLME) is one of the largest LMEs and one of the most productive marine ecosystems in the world. It extends along the west coast of Chile and Peru (Figure 1). The HCLME is a partially wind driven, cold water, relatively low saline flow along the eastern margin of the South Pacific Ocean, starting at around 40^{o}S with a northerly flow towards the equator. It encompasses a complex mosaic of currents, composed mainly of cold water masses with biodiversity (BD) of global importance. The relatively steady alongshore winds that blow towards the equator, drive the strong coastal upwelling from about 40^{o}S up to 4^{o}S, and it is this cold nutrient-rich water brought to the surface by the upwelling which drives the extraordinary productivity of this region (Tomczak and Godfrey, 2003). The HCLME provides about 18-20% of the total world's fish production (Bakun and Weeks 2008). Periodically, the upwelling that drives the system's productivity is disrupted by El Niño-Southern Oscillation (ENSO) events. When this occurs, fish abundance and distribution are significantly affected, often leading to stock crashes and cascading social and economic impacts (Arntz and Fahrbach 1996). These events cause regime shifts where anchovies and sardines alternate as the dominant species in the ecosystem. The HCLME is a global center for food security, marine biodiversity, the world's fishmeal production, and climate regulation.

Water masses and oceanic circulation

The HCLME has a complex water mass structure generated from the equatorial/subtropical Pacific and the Southern Ocean. A complete description can be found in Tomczak and Godfrey (2003), Chaigneau and Pizarro (2005a,b), Guillén (1983), Bernal et al. (1983),Thiel et al. (2007), and Schneider et al. (2003).

In synthesis, water masses off the coastal zone off Chile and Peru are colder than expected from the upwelling and the water is transported far offshore due to the ‘Ekman effect’ (or the combined influence of the South Pacific Anticyclone (SPA), the trade winds and the earth’s rotation – the Coriolis Effect). These cold waters make the lower layers of the atmosphere and coastal zones abnormally cold for the latitude. There is also a ‘thermal inversion’ effect impeding the formation of convection clouds. This in turn produces stable, low altitude clouds that when saturated produce drizzle and long lasting mist known as ‘camanchaca’ in northern Chile.

The SPA is a large-scale circulation of winds moving counterclockwise around a region of high atmospheric pressure in the Southern Hemisphere. This giant mass of cold, dry, oscillating air produces an eddy and is the origin of the Humboldt Current. The location of the eddy oscillates far south during January and from 25 to 35°S during June. The weakening or strengthening of the SPA is closely related to the ENSO phases and the latitudinal location of the wide Intertropical Convergence Zone (Fuenzalida et al. 2007, Ayon et al. 2008).

The HCLME facing climate change and anthropogenic activities

Unlike most of the world’s Large Marine Ecosystems that demonstrate rising sea surface temperatures (SST), the HCLME - along with the California Current LME- show a cooling trend as evidenced by interdecadal variations in the ocean environment that changed from a “warm period” to a “cold period” by the late 80s (Lluch-Belda et al. 1989, 1992, Schwartzlose et al. 1999). The primary productivity of the HCLME is generated from the nutrient rich, low salinity upwelling system and is classified as moderate to high at 200 - 300 $gCm^{-2}yr^{-1}$ (Chavez et al. 2008).

Regional impacts on biomass productivity during decadal, low frequency variation, represented by warm period (El Viejo) and cold period (La Vieja) (Chavez et al. 2003), and higher frequency variations such as El Niño and La Niña episodes, form part of natural climate variation (Schwartzlose et al. 1999). Anthropogenic forcing and short duration climatic events (e.g. Kelvin Waves) are superimposed on the natural cyclical climate variation so that marine species respond to climate variation in accordance to their plasticity and tolerance to changes in food quantity and quality plus the prevailing physical conditions (Bertrand et al. 2008).

Evidences of such climate variation can also be found in paleo-oceanographic studies of sediments in the HCLME area (Siffedine el al. 2008). Several studies have shown an intensification of the upwelling events and primary production since the second half of the 19th century - suggesting a major basin scale, climate change during this period (Vargas et al 2004). Furthermore, some upwelling systems such as the HCLME produce more acid waters because the CO_2 concentration increases as sinking organic matter from biological production is decomposed by bacteria (Fernand and Brewer 2008). These additions of CO_2 together with CO_2 of anthropogenic origin, cause the pH to decrease creating an acidic environment (Figure 2).

At smaller spatial scales, the anthropogenic activity in the coastal zones (urban, industrial, fishing) can affect the sustainability of some HCLME ecosystem niches. The most important economic activity in Peru and Chile is the mining industry. The effluent from the iron ore mine in Marcona Province (Ica, Peru, 14°S) supplies solutions rich in iron minerals and pollutants to the ocean. This can have strong consequences for the local environments because the HCLME is a coastal upwelling system with limited iron availability (Chavez et al. 2008) and iron is a limiting nutrient for phytoplankton growth. Iron leaching to the sea may induce massive blooms, eutrophication and a die-off of organisms when nutrients and/or oxygen become depleted (Figure 3).

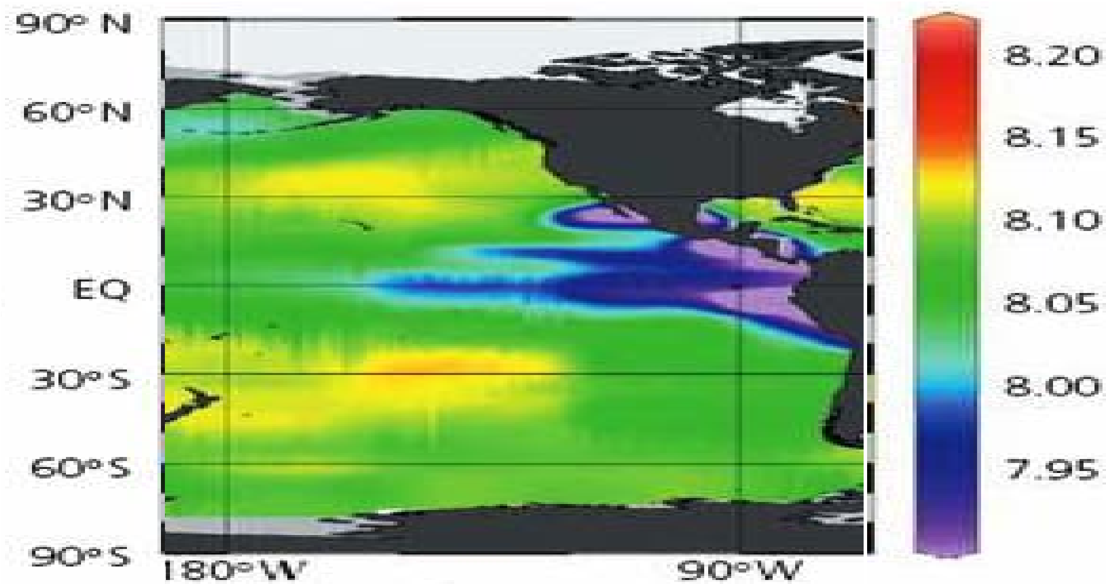

Figure 2. Chart of the Pacific Ocean according to pH. Lower values are linked to the excess CO_2 released due to respiration of organisms (e.g. micro nekton). In the case of the HCLME, there is a direct relationship between high biological productivity and relatively high acidity. Source: (www.appinsys.com/globalwarming/OceanAcidification.htm).

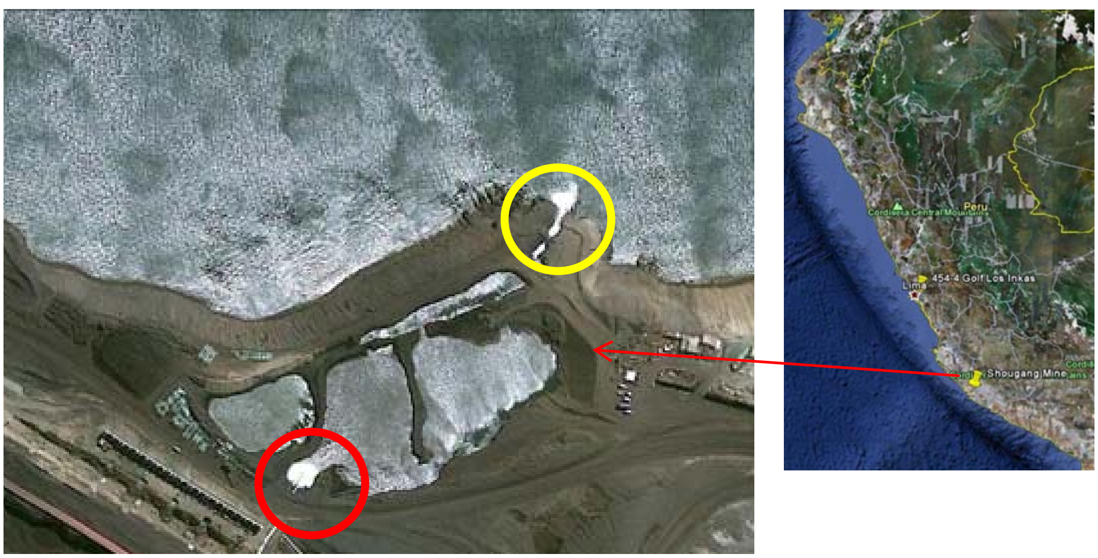

Figure 3. Water flow into a settlement lagoon (red circle) at an iron ore concentration facility on San Nicolas Bay (Marcona, Peru) and the discharge into the sea (yellow circle). The area shows a high species diversity and is close to two marine protected areas with colonies of sea lions and penguins.

CHANGING STATE OF THE HUMBOLDT

The oceanic conditions in the tropical ocean are strongly connected to the high environmental variability of the HCLME. Of the perturbations that may affect HCLME, the southern east-west climatic oscillation is the most evident source of variability. Some descriptions can be found in Shaffer et al. (1999) and Hormazábal et al. (2001). The principal variation is commonly referred as ENSO (El Niño Southern Oscillation) or the combined atmosphere/ocean coupling of physical processes. The ENSO oscillation includes La Niña (cold) and El Niño (warm) phases as well as neutral episodes.

Short and seasonal episodes of variability

One of the main features of the HCLME is the coastal upwelling (Arntz et al 2006, Thiel et al., 2007) which is the origin of a high primary, secondary and fishery productivity (Bakun and Weeks 2008) both for Chile and Peru. Nevertheless, the oceanic variability is expressed between changing limits and along different time and spatial ranges (Chavez et al. 2008, Alheit and Ñiquen 2004) from a few days to seasons, years and decades; and from small to large scales. This variability influences goods and services of the ecosystem, including fisheries and is expressed through environmental events of relative short duration such as propagation of Kelvin or Rossby waves (Dewitte et al 2008), the occurrence of other more durable events such as El Niño or La Niña, or throughout regime shifts cycles lasting decades (Thiel et al. 2007; Lluch-Belda et al. 1989 and 1992; Schwartzlose et al. 1999, Chavez et al. 2003).

To measure the changing environmental conditions of the HCLME, indicators such as Southern Oscillation Index (SOI), Oceanic Niño Index (ONI), or Pacific Decadal Oscillation (PDO) are used. SOI is based on the atmospheric pressure difference between Darwin (Australia) and Tahiti. The ENSO, although not exactly proportional to the SOI, is highly correlated with tropical sea surface temperature anomalies recorded in the El Niño Region 3 (www.cpc.ncep.noaa.gov). Fig. 4.

Interannual Variability: Kelvin and Rossby Waves

One of the main sources of variability in the HCLME comes from coastally-trapped Kelvin waves (Bertrand et al 2008) which originate in the far central Pacific (Pizarro et al. 2001, Hormazabal et al., 2001). These equatorial, large amplitude-long period waves due to variations in the wind, propagate heat eastward along the equatorial wave guide (Delcroix et al. 2000). The way they propagate depends on the wind anomalies (weakened easterlies or stronger westerlies) corresponding to two possible types: upwelling or downwelling depending on the resulting location of the thermo and oxycline when they arrive to the southeast Pacific. They continue propagating north and south as coastal trapped Kelvin waves. The longitudinal propagation of Kelvin waves can be described by variations in the vertical structure of thermal anomalies, and also analytically described by changes in the baroclinic modes (Dewitte el al. 1999) Figure 5.

There are two operational scenarios facing the propagation of Kelvin waves - the warm and the cold modes (Bertrand et al. 2008). The warm ‘downwelling’ scenario is produced when westerlies dominate the wind circulation along the surface of the tropical ocean, temperature increases and coastal upwelling decreases - at least in the northern HCLME and northern Chile. In this scenario, the thermocline is deeper and pelagic fish such as anchovy aggregate close to the coast and/or swim deeper, out of reach of top predators like marine birds. The fish also become less accessible to fishing boats.

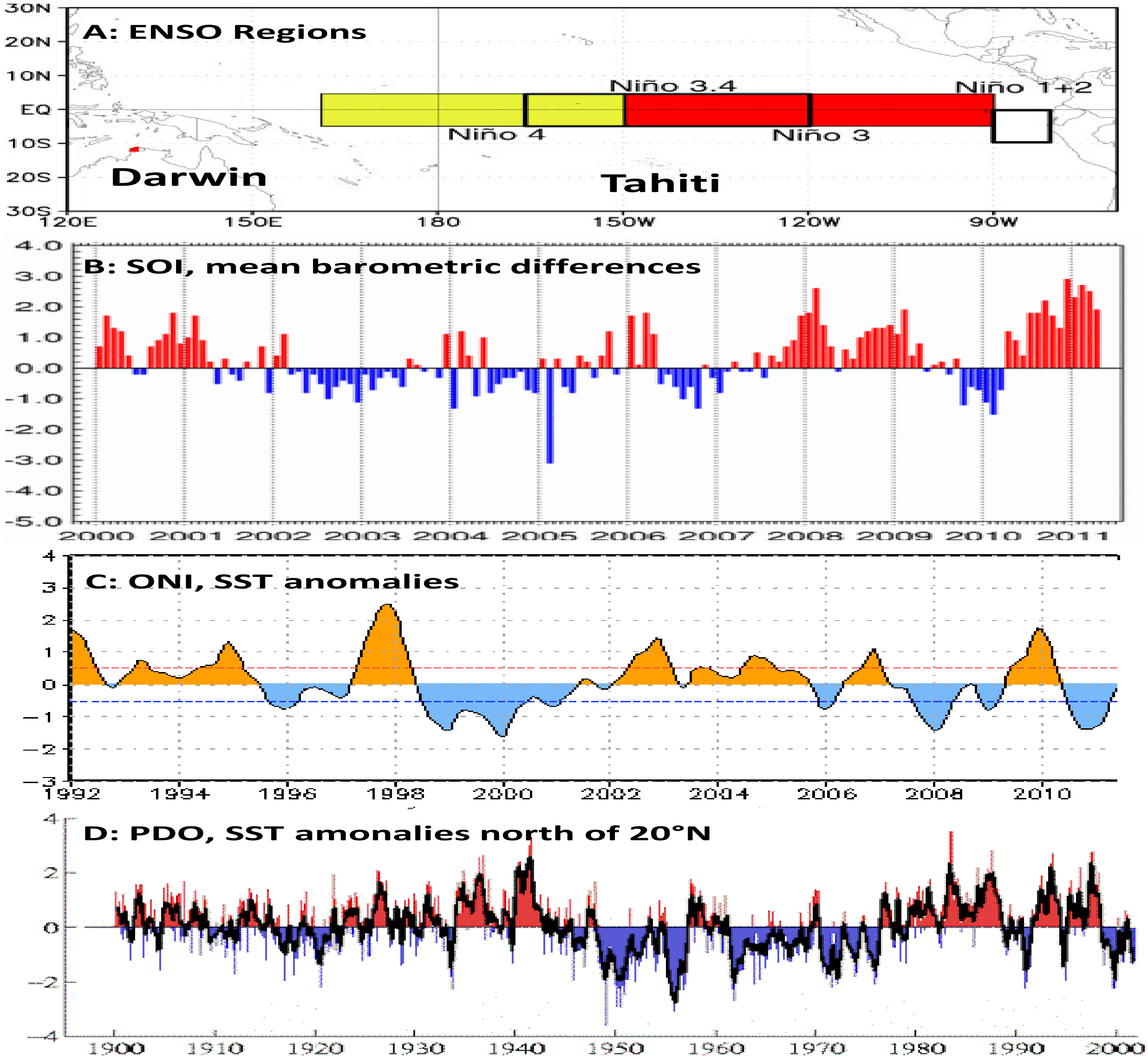

Figure 4. Some indexes used in calculating variability affecting the HCLME. A: ENSO regions and Darwin-Tahiti stations in monitoring the equatorial tropical Pacific for the phases of the ENSO cycle (El Niño, La Niña, Neutral). The tropical Pacific ocean has been divided into four Regions:Niño 1+2, Niño 3, Niño 4 and Niño 3.4. B: the SOI for 2000 to 2011, negative (blue) values are related to warm El Niño-like conditions in the tropical ocean, then positive values are a proxy of La Niña-like events. C: the ONI is based on SST departures from average in the Niño 3.4 region, and is a principal measure for monitoring, assessing, and predicting ENSO. El Niño is characterized by a positive ONI greater than or equal to +0.5°C during three consecutive months. La Niña is characterized by a negative ONI less than or equal to -0.5°C. D: PDO describe an oscillation in northern Pacific sea surface temperatures. When the PDO is in its positive phase (e.g. from 1977 to 1995), there are prevailing warm conditions in the HCLME (positive phase), then the negative phase is related to prevailing cold conditions in the southeast Pacific.

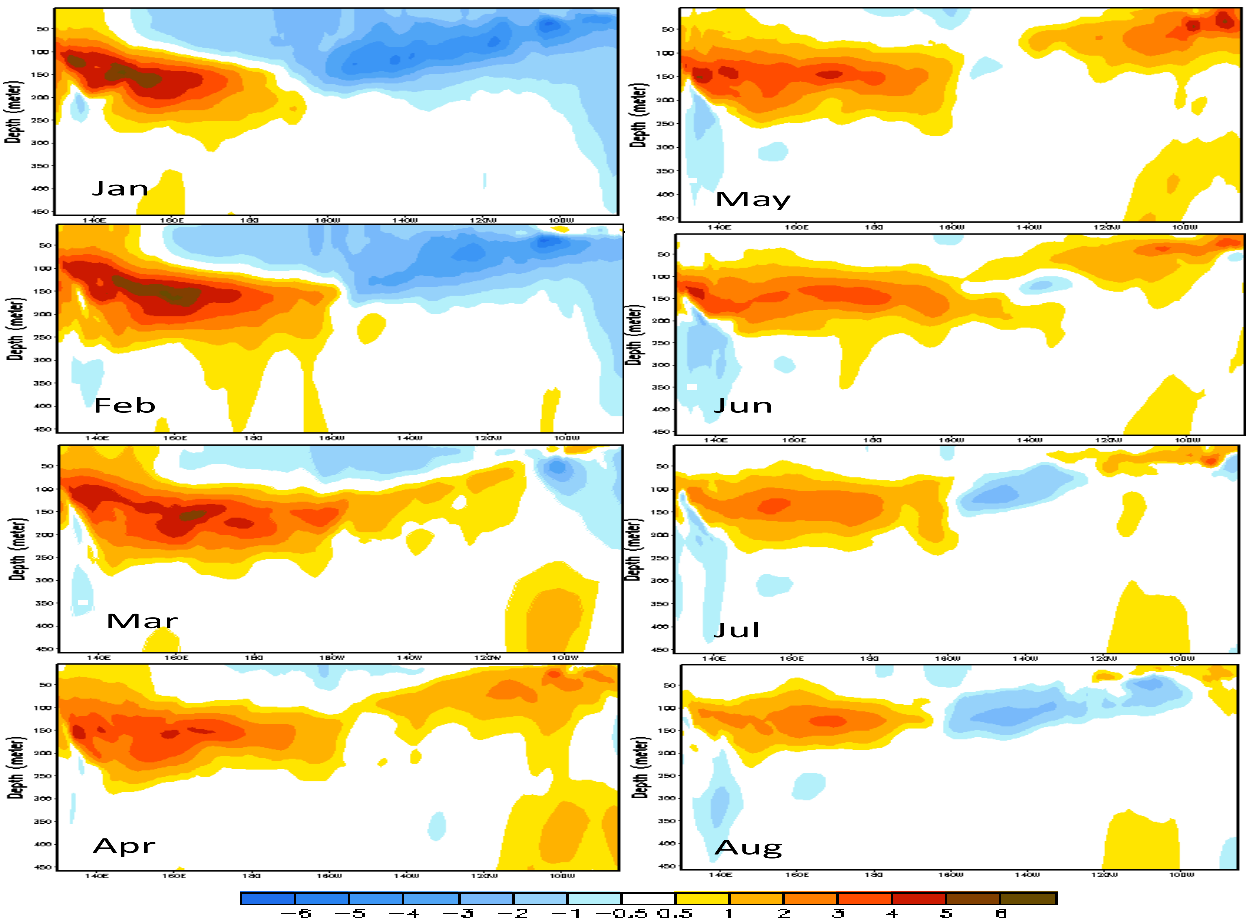

Figure 5. Thermal anomalies by months (°C) measured along the tropical ocean (X-axis) and depth (Y-axis) since January to August 2011. Red colors correspond to positive (warmer) thermal anomalies and blue colors indicate negative anomalies. Since January 2011, a set of Kelvin waves were observed developing from west to east, which are presented here as thermal progression anomalies, from left to right for each month in the figure. During April, a downwelling-type Kelvin wave reached northern Peru, dispersing and deepening anchovy and affecting the Peruvian northern fishery. During August normal conditions were restored. Images taken from NOAA-NCEP (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_update/wkxzteq.shtml).

The cold ‘upwelling’ scenario is produced when Kelvin waves propagate with dominating easterlies in the tropical wind circulation, the temperature decreases and coastal upwelling increases toward open ocean in the northern HCLME. In this scenario, the thermocline becomes shallower and anchovy distributes wider and closer to surface, available to predation and fishing. During this scenario, the area explored by fishing vessels, the duration of trips and catches are higher though sinuosity of trips decreases (Figure 6).

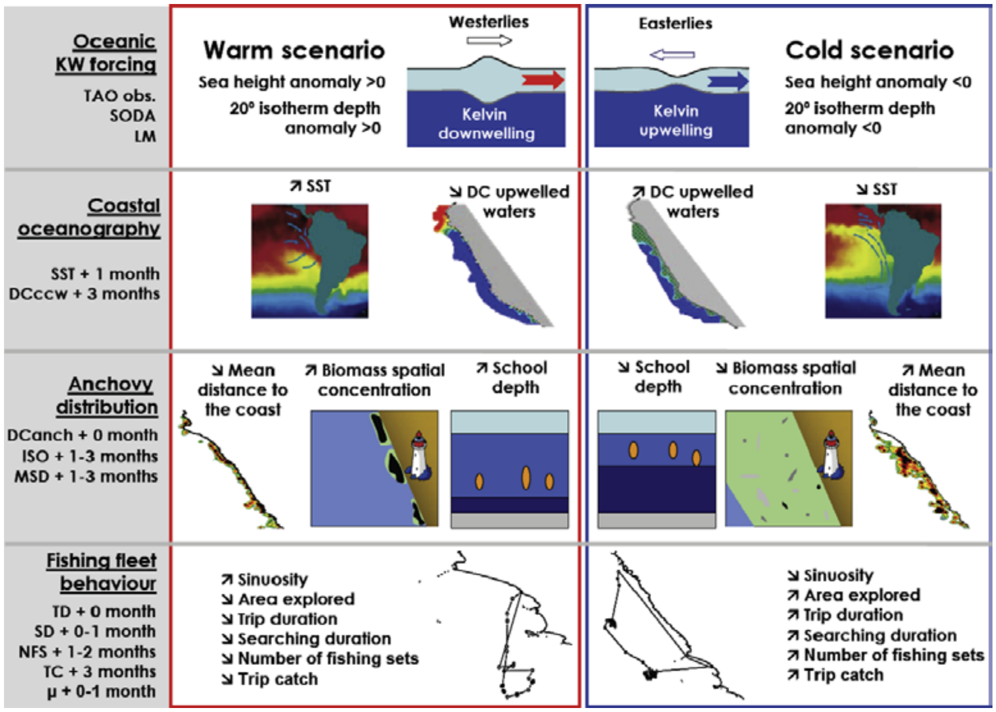

Figure 6. Bertrand et al. (2008) conceptual description about the way Kelvin waves can affect fisheries off Peru and Chile. Accordingly, two propagation scenarios are proposed. Measurements used were (i) sea surface temperature, mean distance to the coast of the cold coastal waters (DCccw); (ii) anchovy distribution: mean distance to the coast (DCanch), index of anchoveta spatial distribution (ISO), mean depth of the schools (MSD); (iii) fishing fleet behavior: mean travel duration (TD), mean searching duration (SD), mean number of fishing sets (NFS), mean trip catch (TC), synthetic index of fishing trip trajectories (l).Kelvin wave activity in the equatorial Pacific was observed through the depth of the 20°C isotherm as measured by the Tropical Atmosphere Ocean TAO/TRITON moorings (http://www.pmel.noaa.gov/tao/data_deliv/deliv.html). Used output came from the Simple Ocean Data Assimilation re-analysis of ocean climate variability (SODA).

Rossby wave formation is due to a restoring force propagating westward after Kelvin waves reach the south Pacific coasts, although part of it also propagates north and south as trapped coastal Kelvin waves (Steward 2007). In other words, as the Kelvin wave moves along the coast, it creates Rossby waves, which move west across the Pacific with a velocity dependent on the latitude (Rossby 1936). Equatorial Kelvin waves travel three times faster than the fastest equatorial Rossby waves (Dewitte et al. 2008). The way trapped Kelvin and Rossby waves generate baroclinic instabilities is possibly associated with temporal eddy activity, related to the intensification of the upwelling thermal front at inter annual scales (Chaigneau et al. 2008). Two types of eddies have been identified: anticyclonic eddies, which tend to propagate northwestward and cyclonic vortices, which migrate southwestward (Chaigneau and Pizarro 2005b).

The Niño and La Niña events

The interannual variability of the HCLME is explained by warm-cold, alternated cycles corresponding to what are now known as El Niño and La Niña events, respectively. The expression ‘El Niño’ was annotated for the first time by Alexander von Humboldt in 1802 (Nuñez and Petersen 2002) as cited by fishermen of the northern Peru to describe the intrusion of warm waters in late December (Christmas) when the birth of Jesus (Niño) is celebrated.

Specifically, the El Niño event is the warm phase of ENSO, or periodic warming of ocean waters in the eastern tropical Pacific. These conditions develop along the HCLME and also affect weather patterns around the world. El Niño events occur roughly every two to seven years and last from 12 to 18 months. The NOAA Climate Prediction Center's (CPC) definition for El Niño is the positive sea surface temperature departure from normal (for the 1971-2000 base period), averaged over three months, greater than or equal in magnitude to 0.5°C in the 3.4 Region. However an El Niño declared for the 3.4 Region does not necessarily have noticeable effects in the HCLME, as happened for the El Niño in 2010 along the Peruvian and north Chilean coasts.

Another way for describing an El Niño event is by a succession of Kelvin waves arriving in the HCLME area from north to south. These anomalies are caused by perturbations in the pressure fields along the equatorial Pacific as well as the weakening of trade winds. The signals are the changing sea surface level and the deepening of thermo, nutri and oxycline. Also, the upwelling is reduced or cancelled, resulting in increased environmental stress. This causes dramatic changes in the vertical distribution of low trophic level species and in turn affects top predators populations such as sea lions and seabirds.

The two decades (1980s and 1990s) featured five El Niño events (1982/83, 1986/87, 1991-1993, 1994/95, and 1997/98) alternating with three La Niña episodes (1984/85, 1988/89, 1995/96). During that period, the two strongest El Niño events during the 20th century were produced: 1982/83 and 1997/98. Nevertheless, there are decades where the alternation is relatively less pronounced (Arntz et al. 2006).

Seasonality and inter annual variability of zooplankton assemblages

Physical and biological processes are the main causes of variation in plankton biomass and composition in the HCLME (Ayon et al. 2004, Thiel et al. 2007). Those factors can occur on different time and spatial scales, including the short life cycle of zooplankton, diurnal interactions, or the length of time of inshore-offshore displacements and advection of water masses.

According to Santander and Flores (1983) and Bernal et al. (1983), anchovies and other species spawn more intensely on a seasonal basis, which suggests that favorable pelagic conditions might also be seasonal. The success of spawning is related to the moderated trade wind and upwelling intensity, which produces rich nutrients and maximum phyto and zooplankton production in the northern HCLME (Bakun and Nelson 1991) during winter months. Off Chile, the alternating periods of upwelling and relaxation support the best phytoplankton blooms (Echevin et al. 2004, Thiel et al. 2007). The same pattern is behind successful recruitment of Peruvian pelagic fish stocks (Walsh et al. 1980). It is the ''optimal environmental window" (Cury and Roy 1989) or ''optimal stability window" (Gargett 1997).

These are interannual and intraseasonal processes influenced in smaller temporal scales by the so called "vertical turbulence" (Franks 1992) which concentrate organisms otherwise dispersed horizontally, though able to maintain their depth, such as zooplankton and fish larvae (Genin et al. 2005). However, interannual and intraseasonal adverse physical–chemical processes can also be generated - leading to steep temperature gradients, low oxygen, and high ammonia concentrations. These episodes are mostly related to weak wind or to strong wind episodes. Minimum zooplankton abundance from 1970 to 1976 in the northern HCLME coincided with long periods with strong La Niña (cool) conditions, when upwelling intensity was maximal (Ayon et al. 2008) (Figure 7).

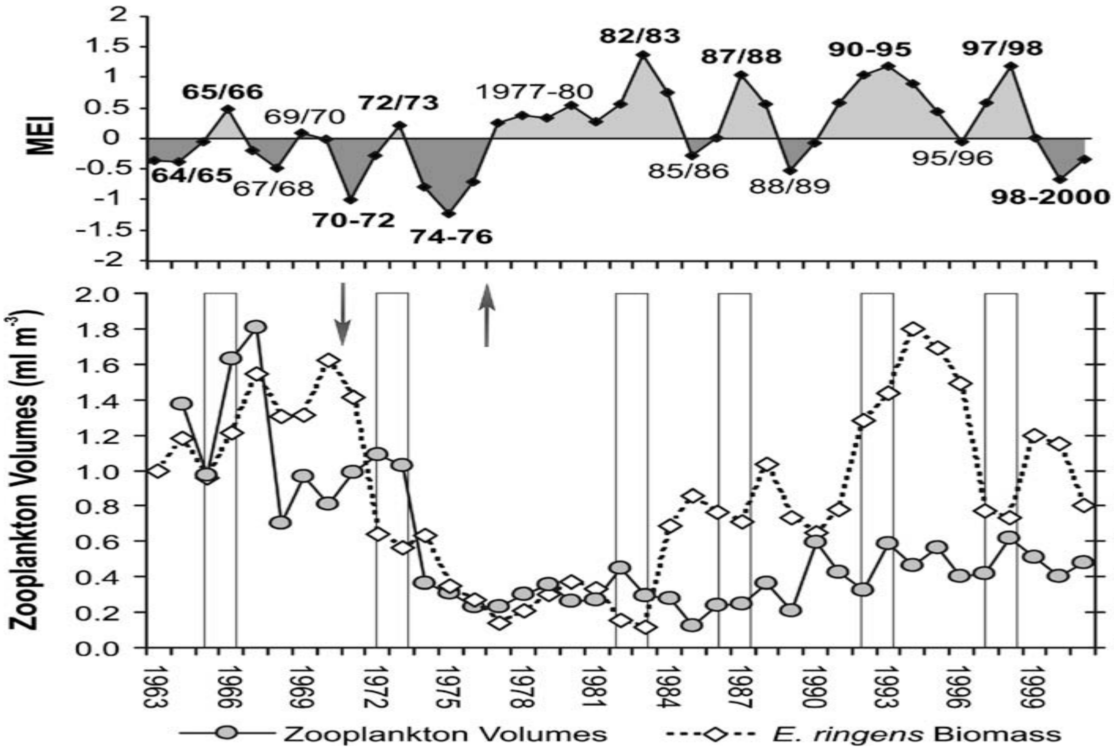

Figure 7. Mean annual tropical Pacific Multivariate ENSO Index (MEI), zooplankton volumes, and biomass of Peruvian anchoveta (*Engraulis ringens*) from 1963 to 2001. Above: the MEI time series shown is the annual average calculated from the original bimonthly MEI series (Wolter and Timlin, 1998). El Niño periods are highlighted above zero and La Niña periods are shown below zero. Source: http://www.cdc.noaa.gov. Below: average zooplankton volumes from more than 10,000 samples taken from the Peruvian coast to 300 nautical miles offshore. Values of 1979 and 1988 were interpolated with a 5-year moving average [according to Ayón et al. (2004), modified]. Strong El Niño events are shown as vertical bars. Arrows indicate global sea surface temperature regime shifts in 1970–1971 and 1976–1977 (Yasunaka and Hanawa, 2005). Source: Ayon et al. 2008.

New zooplankton research findings

The HCLME is producing enough macrozooplankton to sustain more forage fish populations per unit area than any other region in the world, although the paucity of information hampers research on this topic (Ballon et al. 2011). Nevertheless, the development of new acoustic methods for high resolution detection of the upper limit of the Minimum Oxygen Zone (MOZ) has opened new and yet unsuspected possibilities for ecological ocean research (Bertrand et al. 2010). The concept is simple – oxygen is essential for supporting life (Chin and Yeston 2011). Furthermore, a bi-frequency acoustic method has been developed for automated classification of crustacean macrozooplankton, fish, and other marine organisms. Euphausiid numbers and net sampling patterns revealed that past calculations of macrozooplankton biomass might have been underestimated by two to five times from previous estimations (Ballon et al. 2011). The total macrozooplankton biomass was calculated to be 105 g m^{-2} for a complete sampling survey in the summer of 2005, off Peru. This finding about a key trophic component of the ecosystem is consistent with the observations that forage fish consume mainly macrozooplankton (Espinoza and Bertrand 2008) and supports the hypotheses surrounding high fish production in the HCLME (Bakun and Broad 2003). Finally, these methodological developments allow scientists to revisit digitally recorded acoustic surveys for both Chile and Peru, carried out in the early

2000s - in order to extract high-resolution information on zooplankton to relate it to the physically driven primary producers and the biologically driven tertiary consumers.

DECADAL CHANGES AND REGIME SHIFTS

Beside interannual variability, there is evidence that large amplitude, low frequency variability occurs in many ecosystems of the world's oceans and is associated with "warming" and "cooling" periods (Bakun and Broad 2001). Descriptions of such interdecadal variation for the HCLME have been reported by Montecinos et al. (2003) and Montecinos and Pizarro (2005). Interdecadal variations in fish stocks - driven by the low frequency variability – are evident in large marine ecosystems including the California Current, Kuroshio Current, Benguela Current and the Humboldt Current, where alternating dominance between anchovies and sardines has been observed. The sediment records also support this phenomenon (Kawasaki 1983, Schwarztlose et al. 1999, Lluch-Belda et al. 1989 and 1992, Kawasaki et al. 1991, Serra 1991, Chavez et al. 2003, Gutierrez et al. 2007).

In this section we will focus on biomass yield as indicators of the biomass variability typically found in eastern margin of oceans, represented in the Humboldt Current ecosystem by *Engraulis ringens, Sardinops sagax, Trachurus murphyi, Scomber japonicus and Merluccius gayi*. *Strangomera bentincki*, a small and short living, endemic pelagic fish, distributed off south central Chile, is also included.

The catch biomass indicates the dominance of anchovy in the system (Figure 8). It also shows the succession of species: anchovy replaced by sardine and jack mackerel from the early 1970s to the 1990s and earlier. The recovery of the anchovy since the mid-1980s is also evident. There is also a synchronic shift in abundance of the different stocks of anchovy from north to south in the HCLME (Cubillos et al. 2007). By extension, a similar process occurs in sardine stocks.

Variations of biomass occur in both time and space as demonstrated by the spatial redistribution of maximum biomass yield for the different stocks. Figure 9 demonstrates that the major concentration of anchovy production is in northern Peru i.e. in the northern part of the HCLME; and to a lesser extent off south-central Chile, i.e. in the southern segment of the HCLME. In the latter, if the biomass yield of the common sardine is considered, the production is still much less compared with the stock in north central Peru. For sardine, the stocks in north central Peru and in southern Peru/northern Chile are a similar size, while production in central Chile is much less. However, the largest concentrations of jack mackerel are found off south central Chile. These results suggest that associated with the interdecadal change and sequential change in species dominance, the areas of main fish production might change. For example, the overall fish production in north central Peru is less when sardine is dominant versus anchovy. South Peru and northern Chile have increased fish production when sardine is dominant and south central Chile has increased fish production when jack mackerel is dominant.

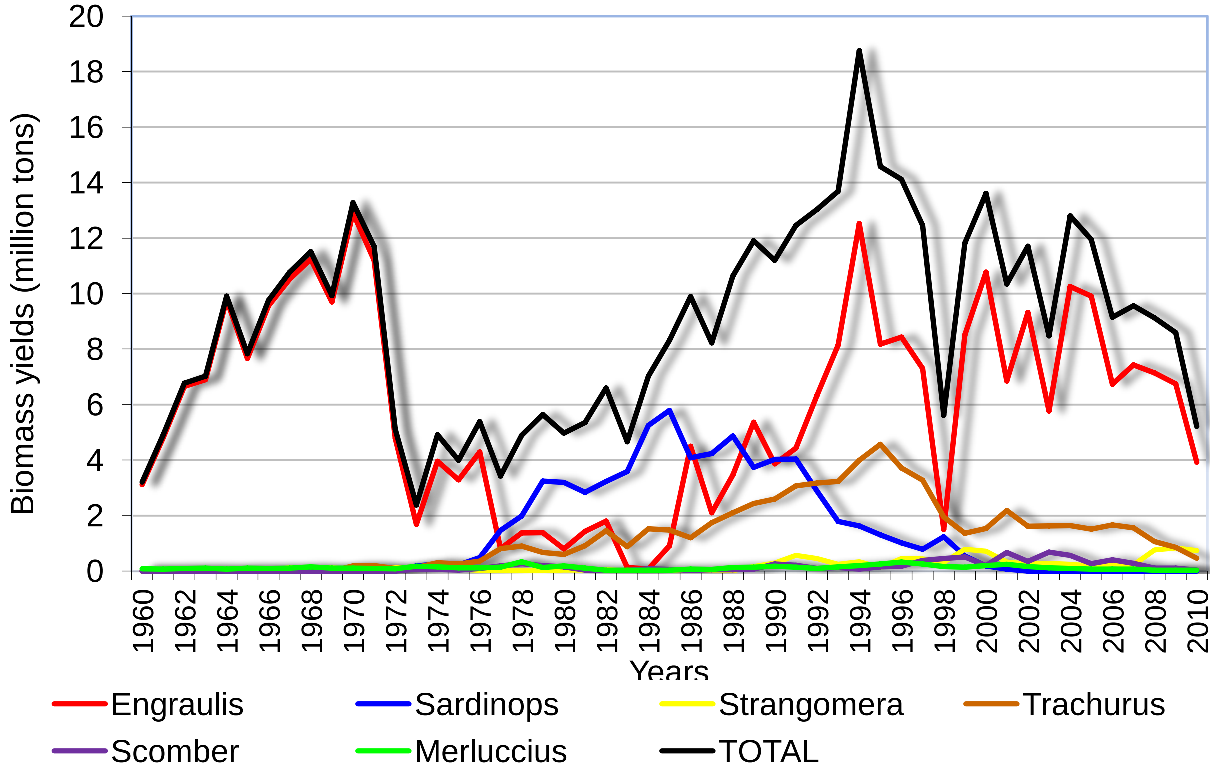

Figure 8. Biomass yield of key fish species in the HCLME during the past 50 years – in hundreds of thousands of tons (10^6) and millions of tons (10^7). The HCLME is comprised of mainly small pelagic fish species (anchovy - *Engraulis*, jack mackerel - *Trachurus*, mackerel – *Scomber*, and sardines - *Sardinops*), as well as demersal species like hake (*Merluccius*).

These variations of fish production in time and space can have strong consequences on the fishing activities and performance. The shift from anchovy to sardine had a strong impact on the Peruvian and Chilean fishing industry. The dramatic drop in anchovy abundance in the seventies created a nationalization process of the fishmeal industry in Peru. This coincided with a dramatic decrease in the fishing fleet and closure of processing plants, strongly affecting employment. The change to a sardine and jack mackerel dominated system favored the further development of the Chilean industry in north and south central Chile and included large investments in processing plants and fishing fleets. In same sense, the return to an anchovy dominated system favored the Peruvian industry and had a negative impact on Chile, leading to the closure of fishing plants and loss of employment.

Population status of guano sea birds and pinnipeds

The nutrient-rich upwelling fuels zooplankton and fish production over the HCLME, which also supports higher trophic levels, including large populations of seabirds and marine mammals. Pelagic fisheries, typically concentrated near main upwelling centers, remove an important proportion of the fish production, which affects trophic interactions in the HCLME (Thiel et al. 2007).

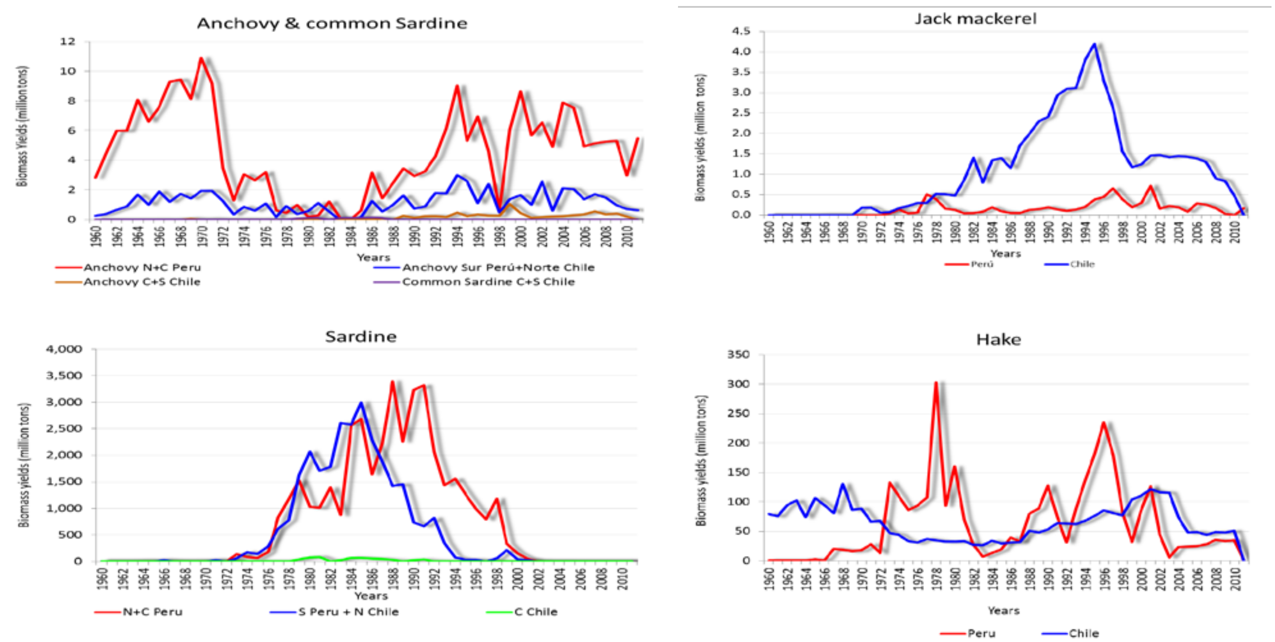

Figure 9. Yield biomass variations by different stocks. NC: north-central; SPNCH: south Peru-north Chile; CS: central south; C: central.

Furness and Monaghan (1987) determined that guano-producing birds of the HCLME have advantageous, biological features (more weight, for example) than similar species of other ecosystems due to their superior capacity for adaptation to a highly variable environment. The guano sea birds feed on a variety of coastal species, and some of them are specialized for eating anchovies. Nevertheless, the main species of guano-producing birds, the guanay (*Phalacrocorax bougainvillii*), the booby (*Sula variegata*) and the pelican (*Pelecanus thagus*) exhibit lower abundances than expected since the El Niño of 1964-1965 (Chavez et al. 2008). Despite the fact that anchovies have maintained high abundance levels since El Niño 1992, the bird populations have not followed the same trend in the northern HCLME. The combined effect of the El Niño events and the fishing activity (Goya 2000) may be hampering the recovery of guano-producing birds despite the high anchovy biomass observed in the HCLME after El Niño of 1997-98 (Taylor et al. 2008) (Figure 10).

Goya and Valverde (2006) presented complementary hypotheses for this discrepancy: (1) young birds with less strength and capacity to locate their prey represent an increase in the natural mortality rate versus an “old” population with declining reproductive capacity; (2) the El Niño events have increased in frequency since El Niño of 1957, altering the adaptive response, which would explain why there is now a lower reproductive proportion. Furthermore, sea birds take advantage of the presence of fishing vessels to feed, though often the effect became negative in the short term due to the fact the birds abandon nests to follow actively the vessels when local fish schools are depleted (S. Bertrand, pers. comm.).

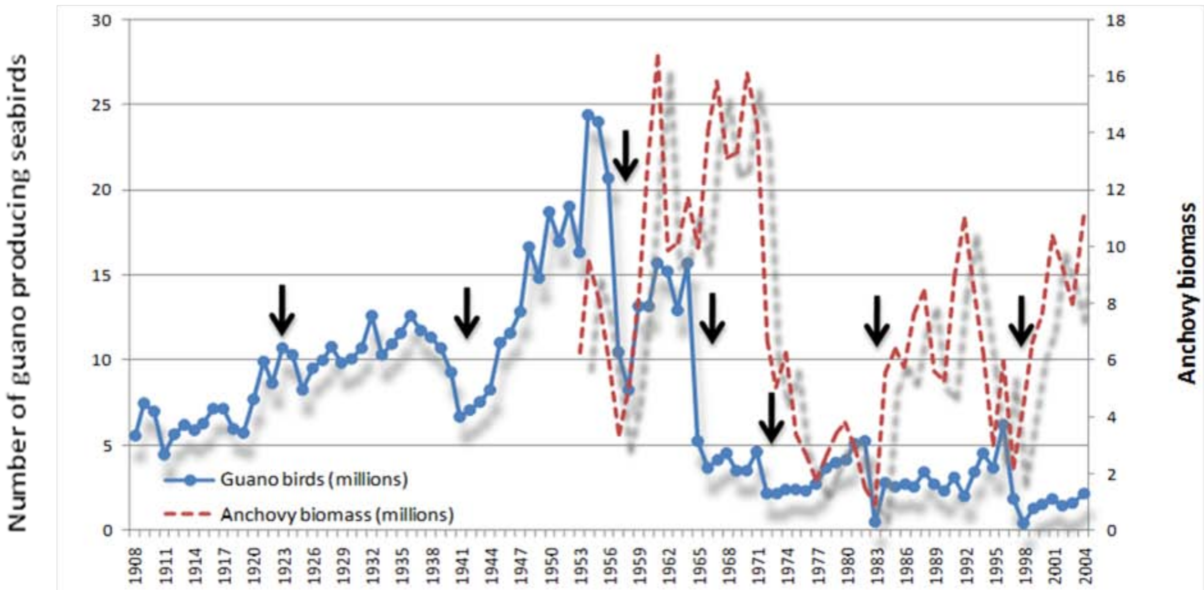

Figure 10. Abundance of birds (blue line) between 1908 and 2004 in comparison with the anchovy biomass between 1955 and 2004 (red dotted line). It can be observed that each El Niño event (the principal events are indicated by arrows) has had a negative effect on the abundance of birds. Since the 1950s, the frequency of these types of events has increased, resulting in a continuous decline in the abundance of these animals. During El Niño of 1997-1998, the number of surviving birds was very small, although they have displayed a sustained recovery. The total abundance of these populations is unknown, but they may be greater than shown, since current estimates are based on censuses restricted only to accessible areas Taylor et al. (2008).

Other hypotheses that attempt to explain the dwindling bird population are: (1) the number of small-scale fishermen has increased by 243% since 1997 (Escudero 1997) in the Moquegua-Tacna region (Estrella et al. 2006), bringing an increased human presence in nesting zones; (2) the use of illegal practices such as manipulation of explosives was acknowledged by small-scale fishermen in a survey carried out by IMARPE (2009) that illustrates how unawareness of the law led to the illegal practices; (3) the inaccessibility of the nesting zones limits the collection of scientific information on the distribution and abundance of sea birds; (4) the decreased water transparency, a consequence of higher plankton productivity since El Niño of 1997-1998, affects the birds' ability to fish; and (5) the lesser abundance of species such as dolphins and skipjack (*Sarda chilensis*) which would normally force anchovy close to surface, where birds can easily feed (Taylor et al. 2008).

Sea lions seem to have recovered their numbers after El Niño of 1997-98, at least in the northern HCLME. However, because sea lion censuses are most difficult to perform, trophic models and simulations have been used to determine the relative abundance of this species. Based on an ecotrophic model (Ecopath with Ecosim–EwE-), Taylor et al. (2008) proposed a possible "bottom-up" relationship between the anchovy and its main coastal predators (sea birds and mammals) wherein the anchovy may regulate the abundance of its predators by modifying its distribution. For instance, migrating or swimming at deeper depths for prolonged periods, as occurs during El Niño events, will limit the distribution of sea birds and mammals. Also, in the HCLME, the location of the oxycline is relatively shallow (Siffedine et al. 2008). This restricts the distribution of fish and enables predation by sea birds and mammals.

However, the sinking of the oxycline, which is characteristic of the El Niño events or periods of Kelvin wave propagation, also increases the depth of the distribution of pelagic species. If these periods last long enough, the mortality between top predators can increase dramatically (Arntz and Fahrbach 1996).

Another factor to be considered is the illegal catching and use of sea lion meat by small-scale fishermen (IMARPE 2009) as a way to protect their fishing gear from attacks by sea lions. In some locations, sea lions are also victims of poaching by fishermen. The magnitude of illegal hunting and catching of sea lions is unknown though suspected to be high (Figure 11).

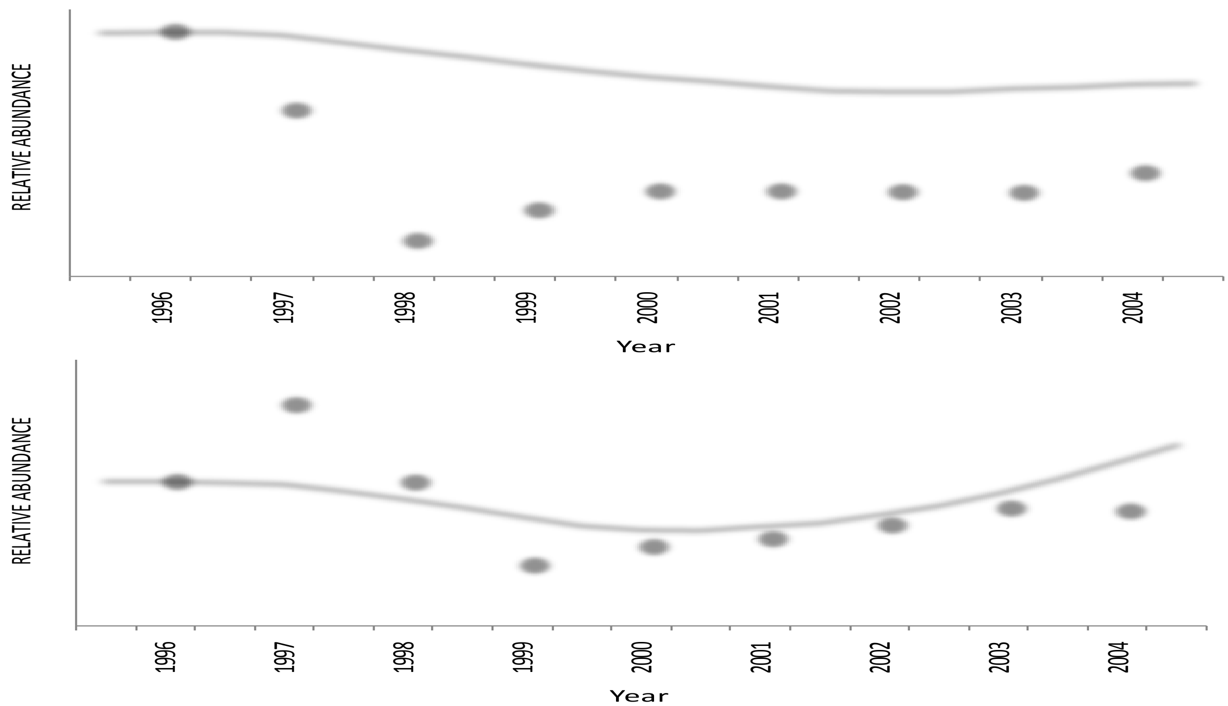

Figure 11. Time series (1996-2004) of relative abundance of birds (top) and sea lions (pinnipeds, bottom). According to the model used (continuous line) by Taylor et al (2008), the relative abundance of seabirds might be declining, while sea lions are increasing. However, the direct assessments made (circles) show that the abundance of both birds and sea lions has been on the rise since 1998. Source Taylor et al (2008).

REGIONAL COOPERATION: THE KEY TO SUCCESS

The limited understanding of the causes of variability of the HCLME (affecting the fish resources), threats to biodiversity, and the multiple uses of the ecosystem services, represent a challenge for Chile and Peru. The ecosystem they share and the complexity of the problems and issues are formidable. In addition to the importance of the fisheries, the Humboldt Current LME has globally significant biodiversity and has been designated a WWF Global 200 Ecoregion. Particularly visible and valuable are the very large colonies of seabirds and marine mammals. Sea mammals, sharks, sword fish and seabirds are top predators in the trophic chain of the HCLME. But climate variability has also an important effect on biodiversity, particularly strong El Niño events and interdecadal variation.

Barriers exist that make managing with an ecosystem approach a considerable challenge. Understanding the functioning of the HCLME requires a holistic approach. There is a need to harmonize research activities within institutions. Therefore, Peru and Chile have committed to collaborate and have asked the Global Environment Facility (GEF) to support sustainable uses in the HCLME and help form a resilient LME that can maintain biological diversity together and ecosystem services for current and future generations despite changing climatic and social pressures.

Some of these barriers are:

- The government institutions responsible for managing coastal and marine systems are fragmented and tend to be organized along political, rather than ecological, boundaries and the linkages between conservation and economic and sometimes social interests are often not appreciated.
- Deficient information and planning frameworks for consensus building and collaborative action.
- Weak institutional frameworks and capacities for ecosystem-based management for effectively incorporating scientific understanding into the decision-making process and management tools.
- Limited knowledge of management options for protecting living marine resources and their habitats.
- Incomplete coverage and representations of Marine Protected Areas (MPA) in both countries.

There is clearly a need to share expertise, to build capacity and to develop a collaborative approach to ensure the sustainability of the HCLME.

Changing habitat for pelagic fish: the LMEs synchrony

The combined pelagic fishery of Peru and Chile produces over 15% of the world's marine capture landings (FAO 2010). Pelagic fish species play an important ecological role by transferring energy from lower to higher trophic levels. They are characterized by interannual variations in their abundance due to their dependence on environmentally-driven variables (Barange et al. 2009). Furthermore, there is evidence of multi-decadal, alternating productivity cycles among species such as anchovy and sardine (Schwartzlose et al. 1999, Lluch-Belda et al. 1989). These so called 'regime shifts' are possibly linked to oceanic forcing and large-scale climate trends operating at basin scale (Chavez et al. 2003, Alheit and Ñiquen 2004). An investigation led by the Global Ocean Ecosystem Dynamics (GLOBEC) highlighted the need for clarifying the existence of out-of-phase production cycles among LMEs due to their important consequences (De Oliveira 2006). If this synchrony can be confirmed, cooperative management procedures might be more efficient if local managers observe signals from other ecosystems and use specific ecological models to account for these changes.

As an example, Barange et al. (2009) investigated and produced the first comparative study on the relationships between the expansion and contraction of habitats - in the context of climate change, stock biomass, distribution area, mean density, and the synchrony and asynchrony of sardine and anchovy populations off California, Peru, South Africa and Japan. Their results indicated that when biomass of the two species increased, they increase their distribution area and density between certain limits. This was consistent with the basin model (MacCall 1990). Regarding synchrony, they found that differences in the use of space provides opportunities for diverging population paths for both species, though the ecological process explaining the observed out-of-phase fluctuations (see Figure 12) can be far more complex than a simple replacement. A different approach explains synchrony by the fact that sardine populations, in different LMEs, grow in small pockets, while anchovy grows in synchrony with other similar species. The study concluded that (1) if anchovy and sardine are equivalent species in different LMEs demonstrating synchrony/asynchrony then their habitat selection mechanisms should also be similar, and (2) whatever causes one species to decline must act positively on the second species (Figure 12).

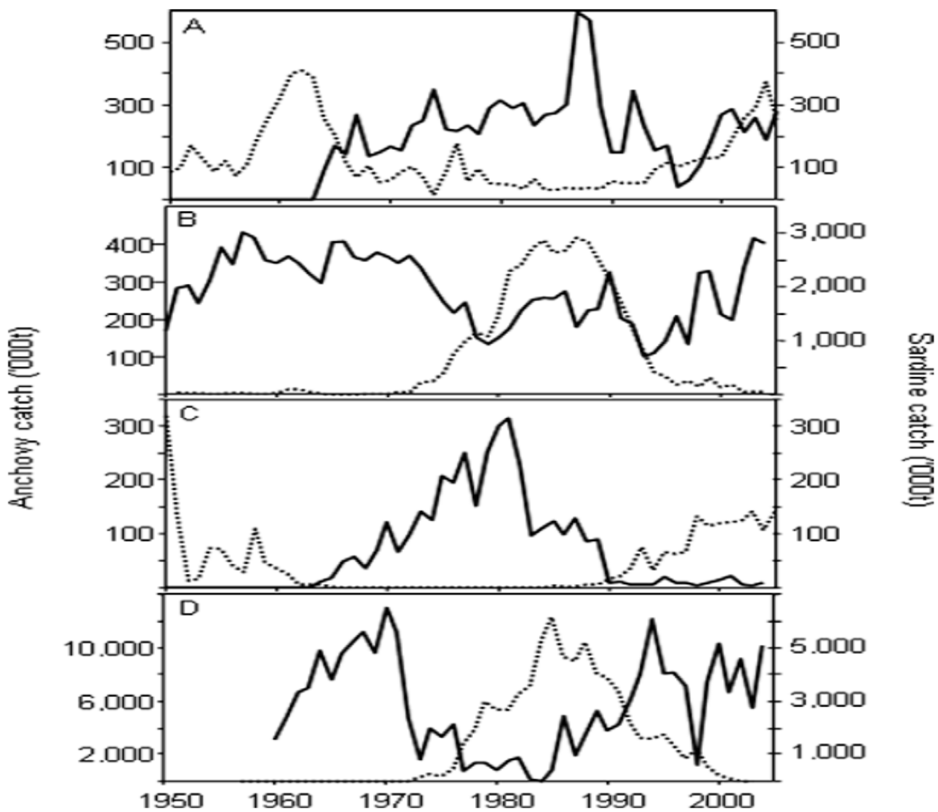

Figure 12. Landings of anchovy (solid line) and sardine (dotted line) in the Benguela Current (South Africa, A), Kuroshio Current (Japan, B), California Current (USA, C) and Humboldt Current (Peru, D). The anchovy populations appeared in synchronic phase between the Benguela Current and California Current LMEs, and out of phase with Humboldt Current and Kuroshio Current LMEs. Similarly sardine populations are in phase between Kuroshio Current and Humboldt LMEs and out of phase regarding California and Benguela LMEs (Barange et al. 2009).

TRANSBOUNDARY CONSIDERATIONS

Cooperation regarding transboundary considerations is being developed following principles established by national Peru-Chile legislation and current international laws:

- Sustainable development, as it is stated by the World Summit on Sustainable Development and the Johannesburg declaration (2001) on Sustainable Development.
- The Ecosystem-based Approach (EBA) and Code of Conduct for Responsible Fisheries as defined by FAO (1992), and the Precautionary Approach of the Rio Declaration on Development and Environment (1995).

Chile and Peru shall also promote:

- An adaptive management approach to reflect the highly variable HCLME environment.
- The use of safe, modern and clean technologies and methods.

- The approval of legal instruments to support sustainable development with special consideration of climate change challenges.
- The active participation of all stakeholders by adhering to the principles of shared responsibility, liability and commitment regarding the ecosystem services.
- Transparency in the management, monitoring, scientific and technological research, and the exchange of experiences.

TOWARDS A SUSTAINABLE FUTURE

Ecosystem Based Management (EBM) seeks to restore and sustain the health, productivity, resilience, and biological diversity of coastal and marine systems and promote the quality of life for humans who depend on them. Chile and Peru are just starting to develop the project "Towards ecosystem management of the Humboldt Current Large Marine Ecosystem" with the support of GEF and UNDP. The project will put in place a governance framework for the identification and prioritization of actions needed to preserve and maintain ecosystem services of importance for the HCLME.

The success of any management action will clearly be dependent on understanding the underlying ecosystem processes and the linkages between the Humboldt Current LME and the larger ocean-atmosphere environment. However, the sources of much of the significant variability and change in the Humboldt ecosystem lie outside the system. Regional human impact on the ecosystem includes fishing, pollution, oil production, guano, and coastal exploitation.

Unlike fixed boundary ecosystems such as the Baltic or the Black Sea, where corrective management can largely ignore external forcing, in an open ecosystem such as the HCLME, sustainable integrated management has to take the external forcing into account, and that means looking beyond the narrow confines of the various fronts. The approach to a highly variable LME like the Humboldt will be very different from one for a closed or semi-closed system. The HCLME does not function in isolation, but rather as part of the global ocean system and the synchronic, sequential changes in anchovy and sardine populations and ENSO events are clear indicators of this.

Within the next decade, it is likely that the first signs of global environmental change will become more apparent, and governments which choose to ignore this probability do so at their peril. To move forward, management requires good advice based on good science, and accordingly the regional research structures will need to be strengthened, not undermined. Access to international expertise and collaboration with other players in the Pacific is essential, particularly in terms of modeling and improving predictability.

In order to address the main transboundary problems and barriers to policy development - regional networking, capacity development and training are high priority activities. Collaboration in surveys, monitoring, and assessments are likewise seen as very important. From an LME research and management perspective, system boundaries cannot ignore regional, political and economic realities, or the interdependence of countries. However, the success of any management action will clearly be dependent on the proper understanding of the underlying ecosystem processes and the linkages between the Humboldt Current LME and other similar LMEs such as the California Current, Benguela Current and Canary Current.

Sustainable integrated management of the Humboldt Current LME requires a collective and proactive approach by Peru and Chile, not a reactive response to problems. Apart from the joint actions which the two countries are committed to, visionary thinking and innovative management on the part of the governments will be required. Management depends on good advice based on good science, and accordingly the regional research structures will need to be strengthened and demonstrate to the rest of the world how a fragile and variable large marine ecosystem can be managed sustainably.

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