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Productivity and Sustainable Management of the Humboldt Current Large Marine Ecosystem under climate change

Dimitri Gutiérrez [a,c,*], Michael Akester [b,*], Laura Naranjo [b]

[a] Dirección General de Investigaciones en Oceanografía y Cambio Climático, Instituto del Mar del Perú, IMARPE, Peru
[b] Global Environment Facility (GEF)-UNDP Humboldt Current LME Project, Chile-Peru
[c] Universidad Peruana Cayetano Heredia, Programa de Maestría en Ciencias del Mar, Lima, Peru

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ABSTRACT

The Humboldt Current Large Marine Ecosystem (HCLME) covers 95% of the southeast Pacific seaboard of which the area of influence from the Humboldt Current and associated upwelling areas in the Humboldt Current System (HCS) stretches from around 4° to 40° south. Global warming will likely affect marine circulation and land-atmosphere-ocean exchanges at the regional level, affecting the productivity and biodiversity patterns along the HCLME. The expected decrease of upwelling productivity in the HCS could be amplified by worldwide trends of oxygen depletion and lower pH. In addition, higher frequency of extreme climatic events, such as El Niño in a warmer ocean, might augment the risks for the recruitment success of anchovy and other short-lived fish resources, especially in the Northern HCLME. A range of non-climatic anthropogenic stressors also combines to reduce productivity and biomass yields. Transboundary Diagnostic Analysis (TDA) work has shown that overfishing and pollution are the main contributing factors in addition to the shared problem between Chile and Peru of high levels of fisheries bycatch and discards. An economic valuation of the HCLME and HCS has been finalized with an estimated annual delivery of around USD19.5 billion in goods and services. With many knowledge gaps this is evidently an underestimate but indicates which mitigating activities under a recently developed bi-national Strategic Action Programme (SAP) need to be prioritized. Fisheries landings are declining and demand for products is increasing. Improvement of ecosystem planning and management tools with value addition options for marine products is needed to adapt to climate change.

1. Introduction

The Humboldt Current Large Marine Ecosystem (HCLME) covers the area within 55° of latitude off Peru and Chile (3°23.57′ to 58°21.02′) and over 200 nautical miles offshore (Fig. 1). 65% of the HCLME extension corresponds to the Humboldt Current System (HCS), which is under the influence of seasonal or permanent coastal upwelling, from approximately 4 to 40° south.

Several features characterize the HCLME among similar ecosystems associated with Eastern Boundary Currents (EBCs: California, Canarias, Humboldt and Benguela). First, it extends closest to the equatorial line among the four systems. Second, it is the most exposed EBC system to the El Niño Southern Oscillation, which is the largest source of interannual climatic variability on the Earth. Third, it exhibits the highest fish productivity among the four EBC systems, notwithstanding primary

* Corresponding authors.
E-mail addresses: dgutierrez@imarpe.gob.pe (D. Gutiérrez), MichaelAkester@gmail.com (M. Akester).

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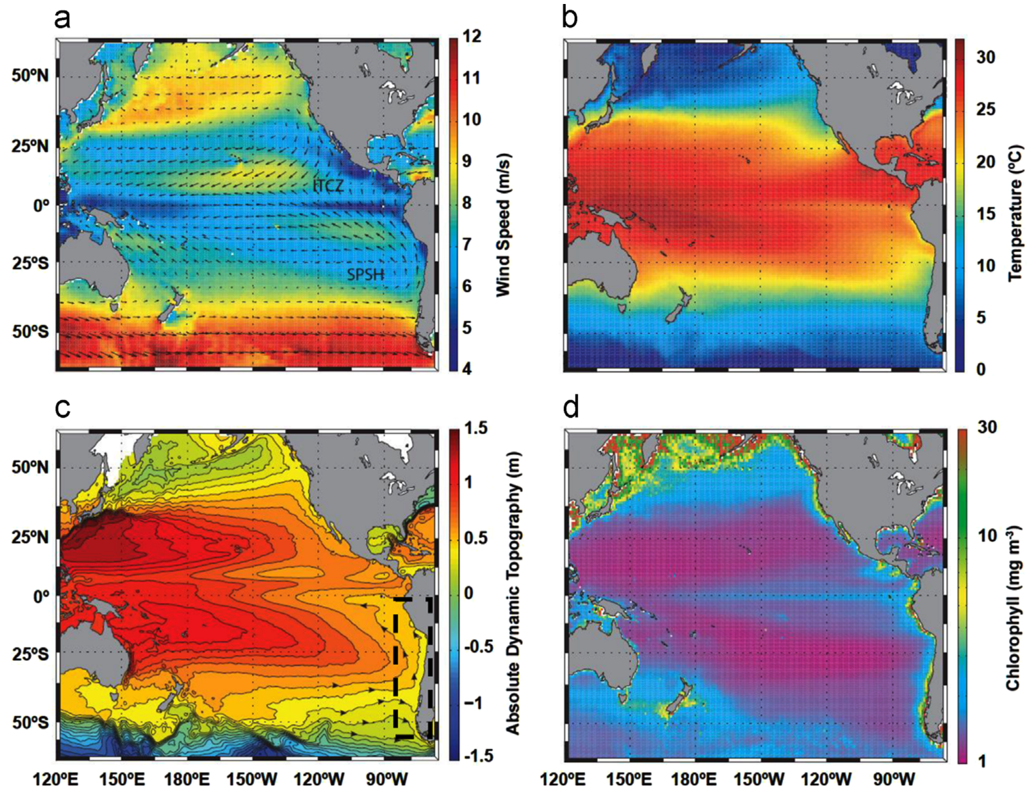

Fig. 1. The HCLME in the Pacific Ocean context. Annual mean distributions of the wind field (a); Sea surface temperature (b), dynamic topography and associated geostrophic currents (c), and surface Chlorophyll-a concentration (d). Sources: Quickscat (1999–2009), MODIS (1993–2010); AVISO (1993–2012); and Modis (2003–2010), respectively. The HCLME domain is shown in a dashed line envelope in (c).

productivity is in the same range as the primary productivity of the other systems. Fourth, it is associated with the presence of a shallow intense subsurface oxygen minimum layer that compresses the oxygenated epipelagic habitat to a few dozen meters.

Global warming is likely to alter the atmosphere–ocean–continent energy and matter exchanges, modifying the pressure gradients and alongshore and cross-shore wind fields along with marine currents, sea surface temperature (SST) and the thermal stratification, in addition to the intensity and spatio-temporal distribution of coastal upwelling. Global models predict the decrease of marine primary productivity and a significant loss of marine biodiversity, especially at the tropic and polar latitudes. On the other hand, the influx of anthropogenic CO_2 to the ocean and large-scale stratification are causing acidification and deoxygenation, which might trigger a cascade of biogeochemical and ecological changes in marine ecosystems. It is uncertain how these multiple stressors will impact on the productivity and biodiversity of the HCLME. A debate about the response of EBC upwelling ecosystems to global warming is ongoing with contradictory future scenarios (upwelling intensification vs weakening). In any case, physical and biogeochemical changes will likely affect the phenology, spatial distributions and species compositions of primary and secondary producers. Improving resiliency by reducing non-climatic hazards is the current challenge to ensure the adaptive sustainable management of this large marine ecosystem.

2. Setting the scene

The Humboldt Current (HC) or Peru Current is the large-scale offshore surface current that derives from the West Wind Drift (WWD) at around 40°S and flows northwards along the Pacific eastern seaboard as part of the Coriolis force induced South Pacific gyre (Fig. 1). The WWD also originates as a coastal poleward flow south at 45°S, the Cape Horn Current, which mixes the more saline waters with the fresher waters from the Chilean fjords. Off Central Chile the HC attains high speeds and it is relatively narrow and coastal; then it progressively moves away offshore on its northward path. Off Peru, the current mixes with eddy-like structures, until it joins the South Equatorial Current at 5–10°S (Strub et al., 1998). In general terms, the Humboldt Current System (HCS) extends up to 1000 km from the coasts of Chile and Peru, and it is composed of equatorward and poleward surface and subsurface currents (Fig. 2).

Large-scale forcing of the HCS dynamics is driven by the South Pacific Subtropical high-pressure cell (SPSH) and by the Equatorial ocean-atmosphere circulation. The SPSH-derived wind field induces the Ekman divergence nearshore and coastal

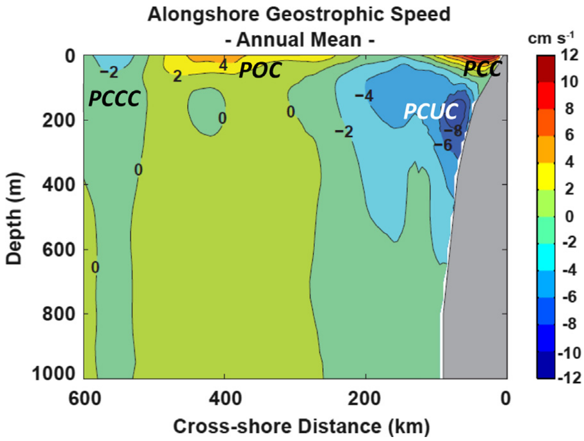

Fig. 2. Mean climatology of geostrophic currents off Peru (7–13°S), based on shipboard hydrographic measurements of IMARPE (1981–2010). PCC: Peru Coastal Current, PCUC: Peru–Chile Undercurrent; HC: Humboldt Current or Peru Current; and PCCC: Peru–Chile Countercurrent.

upwelling; the wind-stress curl permits the upward suction of the cool, oxygen-poor and nutrient-rich subsurface waters in a wider extension off the coast (Strub et al., 1998; Albert et al., 2010). On the other hand, the Walker circulation is associated with the shallowing of the thermocline in the Tropical Eastern Pacific, contributing to the geostrophic equatorward circulation and to the nutrient advection to the surface induced by the alongshore southerly winds. In addition, intra-seasonal to inter-annual (El Niño Southern Oscillation ENSO) variability of the zonal winds in the Equatorial Pacific triggers eastward Kelvin waves that, upon hitting South America, give rise to poleward coastal trapped waves that alter the cross-shore sea level slope and depth of the thermocline, which in turn modifies the coastal surface and subsurface circulation (Brink, 1982).

A key element of the circulation scheme is the Peru–Chile undercurrent (PCUC) which flows poleward and close to the continental shelf and upper slope (Strub et al., 1998). The PCUC transports the Equatorial Subsurface Waters (relatively oxygen-poor and nutrient-rich) from the north and it is the main source of coastal upwelling off most of the Peruvian coast. Along its path to southern Peru it becomes more oxygen-depleted, but off Chile the subsurface water mass properties are diluted due to the northward advection of the Intermediate Antarctic Waters (Fuenzalida et al., 2009). Recently modeling studies have proposed that the PCUC is 50% formed by a branch of the Equatorial Undercurrent and by the Tsuchiya jets, and the other 50% by the water recirculation off northern Peru (Montes et al., 2010).

3. Biogeochemistry: a system close to the edge

Lack of ventilation and low-oxygen content of source waters, long residence times of waters due to the weak to moderate winds in the Tropical South Eastern Pacific, and decay of the intense biological production in surface waters explains the existence of the oxygen minimum zone (OMZ) in the HCLME region (Pennington et al., 2006). The South Eastern Pacific OMZ accounts for 11% of the global volume of OMZ waters, and it is the fourth largest area among regional OMZs. Its upper boundary is shallower than the ones from other OMZs, attaining its shallowest depth off Central Peru, eventually reaching the euphotic layer. The OMZ gets wider (up to 1000 km), thickens (reaching 700 m depth) and gains in intensity from the equatorial line to the northern-central Peruvian coast, as oxygen is further depleted by the decomposition of sinking organic matter across the water column (Fig. 3). Further south, the OMZ shrinks gradually, from above by ventilation caused by coastal upwelling and stronger wind mixing and from below by mixing with the oxygenated Antarctic Intermediate Waters (Fuenzalida et al., 2009).

Oxygen deficiency of the subsurface waters is associated with high CO_2 contents, due to the origin of waters and circulation processes, and by the oxygen demand from the decaying organic matter in the system. Therefore low pH values characterize the subsurface waters and the upwelled waters in the surface layer. The combined stress of oxygen deficiency and corrosiveness of the bottom waters might have caused the paucity of benthic calcifying organisms in the Peruvian continental shelf and upper slope, reported by several authors (Arntz et al., 2006).

On the other hand, oxygen deficiency favors the dominance of denitrification and anammox (anaerobic ammonium oxidation) as the main biochemical processes in the water column, resulting in a significant nitrogen loss and nitrate deficiency in the HCS upwelling waters (Lam et al., 2009; Farías et al., 2015). It should be noted that up to 40% of global nitrogen loss occurs in the OMZs, particularly in the Arabian Sea, the North Eastern Pacific and South Eastern Pacific. Taking all these aspects together, the OMZ associated to the HCLME is a biogeochemical hotspot of oxygen, carbon and nitrogen cycling, enabling the existence of microbial consortia at the OMZ vertical and horizontal boundaries and at its core and interface with the sediments as well. For the larger organisms, morphological, symbiotic and metabolic features seem to be key adaptations to cope with the multiple stressors present in the habitat, which deserve more study.

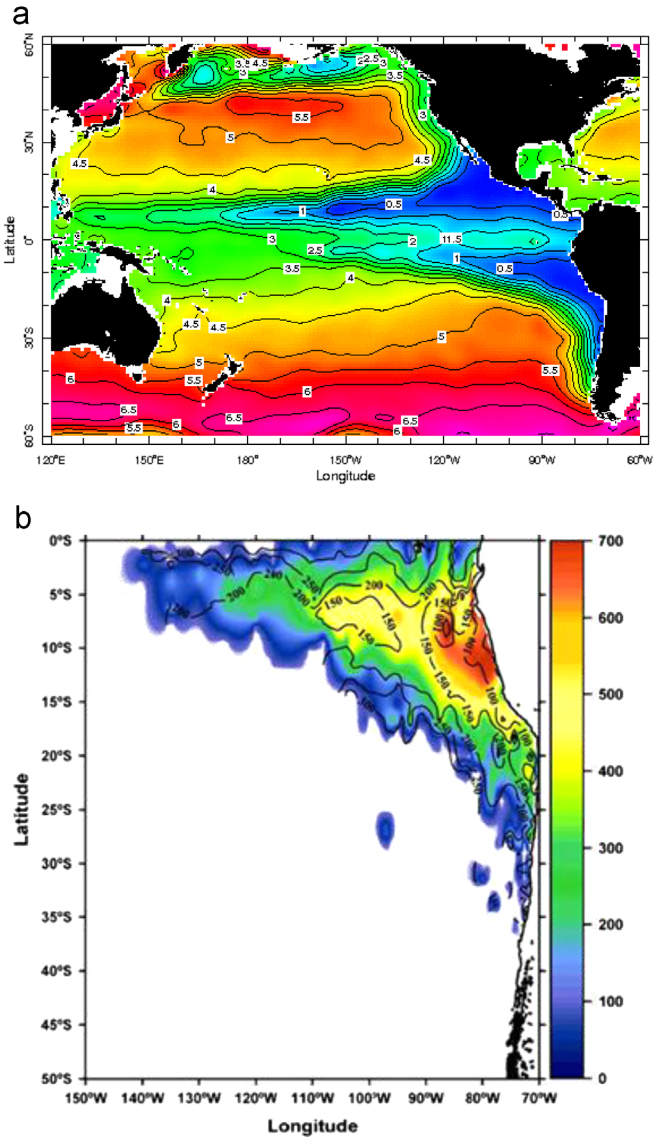

Fig. 3. a) Dissolved oxygen concentration at 200 m water depth in the Pacific Ocean depicting the distribution of the Eastern South Pacific Oxygen Minimum Zone (OMZ) that overlaps with the HCLME; b) Thickness and upper boundary (concentration ~0.5 ml L − 1) of the OMZ in the Eastern South Pacific. Colors: thickness of the OMZ; contours: depth of the upper boundary. Units are in meters (from Fuenzalida et al., 2009).

4. Primary productivity and channeling to the upper trophic levels

Fig. 4 shows the spatial and temporal changes of the primary productivity in the HCLME. At least four provinces can be described along the HCLME, based on the primary productivity of the marine coastal zone and the fjords (Table 1). The most productive area is located off the Peruvian coast, in which the offshore extension of the coastal productive belt ranges between 100 and 200 km, with an average annual primary production rate (PPR) of 1.2 kg C m^{-2} y^{-1}. Next in productivity is the area off the Central Chilean coast, where mean annual PPR is also over 1 kg C m^{-2} y^{-1}, but with a stronger seasonal change. The Northern Chilean coast presents the narrowest productive area (< 50 km), 'high nutrients low chlorophyll-a' (HNLC) condition, with annual PPR around 0.66 kg C m^{-2} y^{-1} and low seasonality (Quiñones et al., 2009). The Magellanic region, comprising neritic and fjord waters, exhibit low mean annual PPR (ca. 0.58 kg C m^{-2} y^{-1}) and wide seasonality (Montecino et al., 1998; Montecino and Pizarro, 2006; Iriarte et al., 2007; Daneri et al., 2012).

The relationship between the annual cycles of coastal productivity and physical forcing differs among the four areas (Montecino et al., 2006). In the southernmost area surface chlorophyll-a peaks in spring, following the Nutrient-Limited Spring Production Peak pattern of biological production that applies in the Westerly Winds Biome as defined by Longhurst (2007). Further north (area C), chlorophyll-a peaks in summer, when the direction of alongshore winds turn to be favorable for coastal upwelling and nutrient advection to the surface layer (Montecino et al., 2006, Farías et al., 2015). Off Peru (area

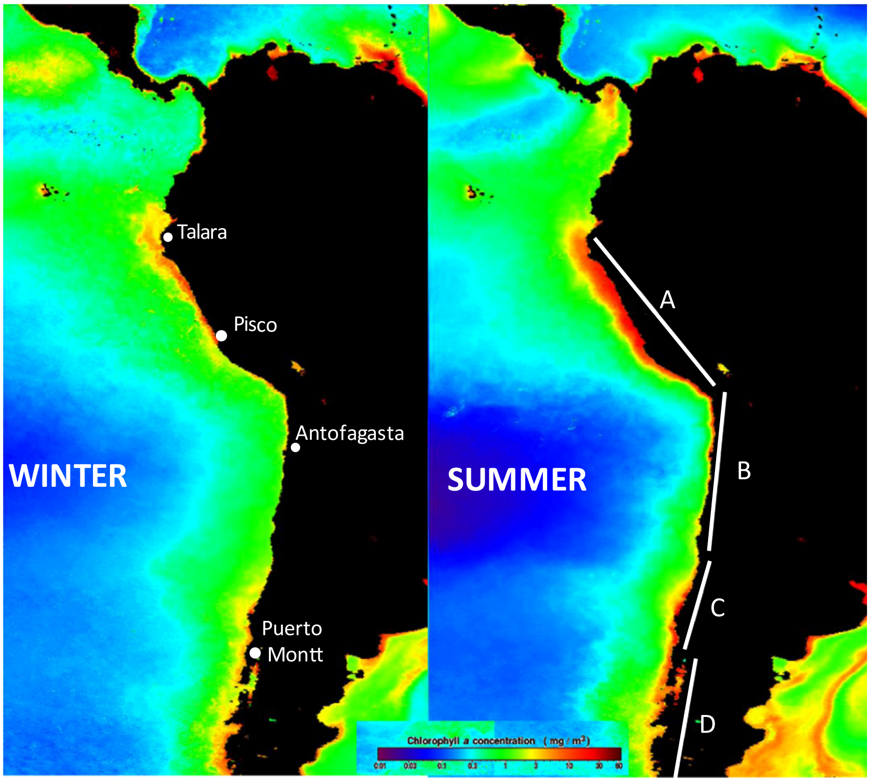

Fig. 4. Mean surface chlorophyll-a concentrations during austral summer (JFM) and winter (JJA) off Western South America (adapted from Miloslavich et al., 2011).

Table 1
Average annual primary production rates in the four areas of the coastal productive belt along the HCLME. The areas A–C belong to the Humboldt Current system, and the area D to the Magellanic Current system.

Area	Latitude	Offshore extension (km)	Primary production (gC m-2 y-1)	References
A	4–18	150	1235 ± 513, $n = 22$	Quiñones et al. (2009)
B	18–33	40	658 ± 527, $n = 43$	Quiñones et al. (2009)
C	33–42	100	1051 ± 708, $n = 17$	Quiñones et al. (2009)
D	42–55	150	574 ± 484, $n \gg 50$	Montecino et al. (1998), Montecino and Pizarro (2006), Iriarte et al. (2007), Daneri et al. (2012)

A), primary production is negatively correlated with alongshore winds intensity, which are permanently favorable to coastal upwelling and are more intense in winter (see also Fig. 5). This apparent paradox is likely explained by light limitation due to deeper wind mixing, reducing the growth performance of primary producers (Calienes et al., 1985; Echevin et al., 2008). In summer, when coastal upwelling still occurs but is less intense or frequent, upwelling relaxation is followed by windows of thermal stratification that foster phytoplankton blooms. Finally, to explain the permanent high-nutrient low-chlorophyll (HNLC) condition of area B, it has been postulated that strong and rapid offshore advection of upwelled waters here do not allow phytoplankton to take advantage of the high nutrient concentration in the coastal area (Torres, 1995).

The current knowledge confirms the predominance of the classical food web supported by chain-forming diatoms, copepods and euphausiids (Escribano and Morales, 2012, Ayón et al., 2008; Espinoza and Bertrand, 2008). Both bottom-up and wasp-waist models (Cury et al., 2000) can be used as the main mechanisms of trophic dynamics in the HCS, the latter due to the exceptional biomasses attained by euphausiids and forage small pelagic fishes. Centennial to multidecadal variations of physical forcing, primary productivity, small pelagic fish and top-predators behave roughly according the bottom-up paradigm (Gutiérrez et al., 2009; Jahncke et al., 2004), but when time-series at species level are analyzed, competition and predator-prey interactions arise as explaining processes (Muck, 1989). Studies on carbon fluxes in the pelagic realm, and on spatial structures of physical-chemical properties, plankton and forage species indicate the combination of bottom-up forcing and predator-prey interactions (Ayón et al., 2008; Bertrand et al., 2008, González et al., 2009; Grados et al., 2012).

On other hand, there is rising evidence regarding the significance of the microbial food web for channeling materials and energy up to the higher trophic levels in the region (C. Vargas et al., 2007; Quiñones et al., 2009; Molina et al., 2012). Several

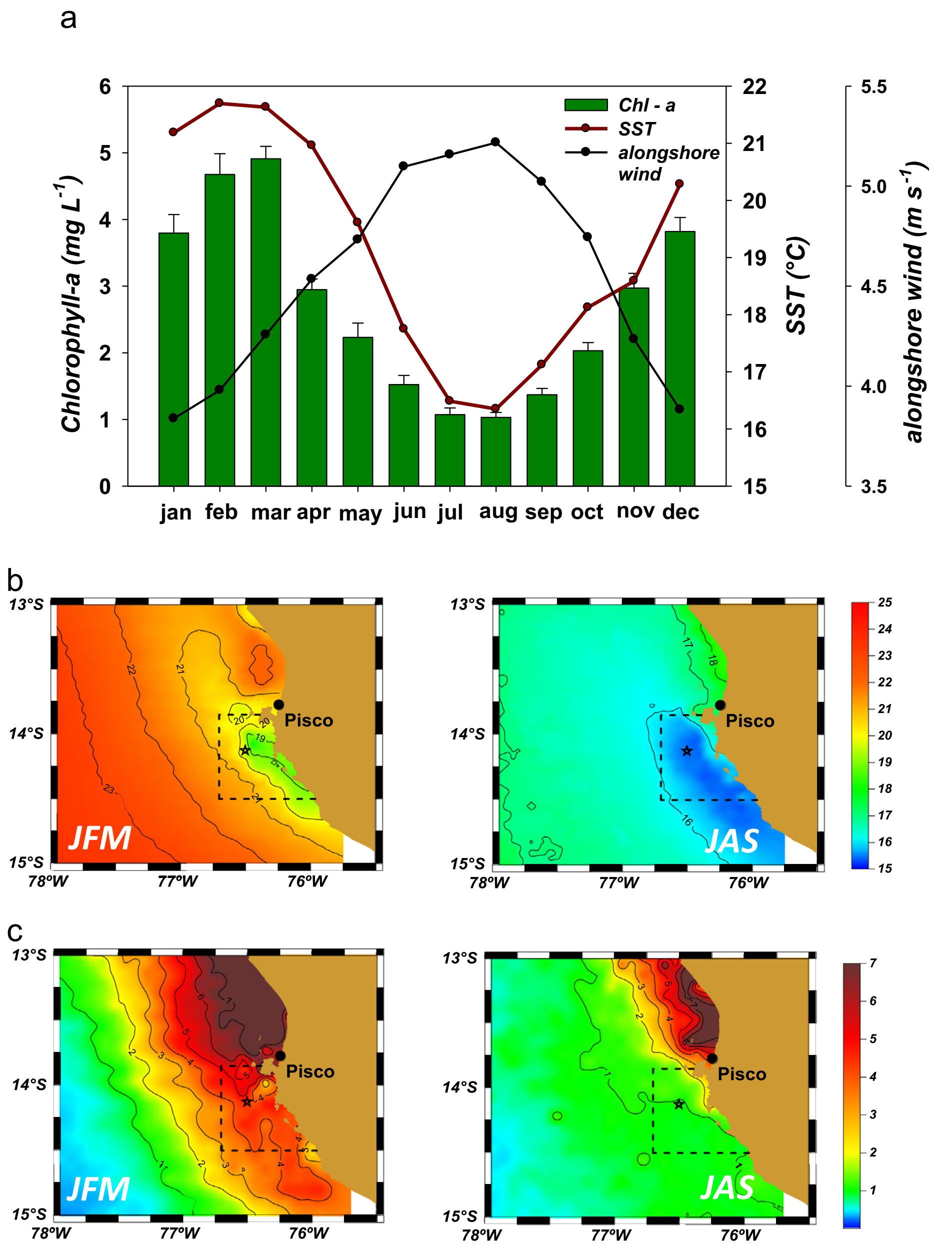

Fig. 5. Primary production, wind forcing and sea surface temperature (SST) off Pisco (14°S; Fig. 4); a) Annual cycle of surface chlorophyll-a (Chl-a), alongshore coastal-upwelling favorable winds and SST; b) SST distribution in austral summer (JFM, left) and in winter (JAS, right); c) Surface Chl-a distribution in summer and in winter. Climatologies of Chl-a and of the alongshore wind velocities in (a) are based on Sea-WiFS color data (1997–2006) and ECMWF–ERA40 reanalysis, from inside the coastal box area shown in (b) and (c). Adapted from Gutiérrez et al. (2011).

studies indicate significant values of bacterial primary and secondary production (Troncoso et al., 2003), and important biomasses of nanoplankton in coastal upwelling areas. Other studies have suggested that an important proportion of the primary production is transferred directly through heterotrophic nanoflagellate grazing (C. Vargas et al., 2007, Quiñones et al., 2009 and references therein). Off Chile, very high organic matter degradation rates have been determined in the photic zone, suggesting that the bulk of organic matter produced in the system is recycled in the upper water column (Daneri and Pantoja, 2007).

5. Current features of the main resource landings in the HCLME

The 2.5 million km^2 HCLME area currently accounts for 12% of the world's marine fish landings and includes the largest single species fishery in the world: the Peruvian anchovy. Fig. 6 presents the composition of marine fish landings for the two

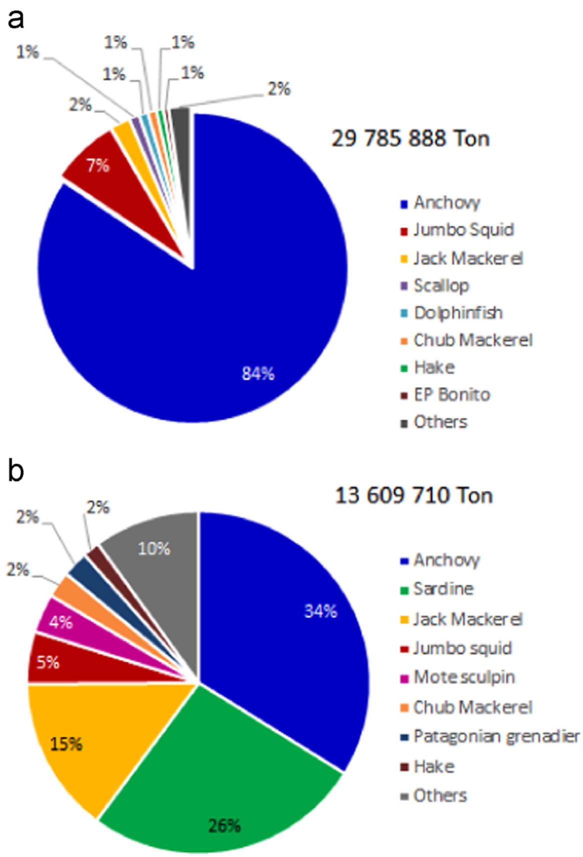

Fig. 6. Fish landings composition (top 8 species) off Peru (A) and Chile (B) for the period 2009–2013.

countries for the period 2009–2013, reflecting the dominance of anchovy catch in the total fishing activity of which 25,146,910 and 4,609,166 t of anchovy were landed during this period in Peru and Chile, respectively. Of the other three main pelagic fish resources, sardine, jack mackerel and chub mackerel, the former was nearly absent in Peruvian landings, while over 3,578,718 t of sardine were landed in Chile. In addition, Chilean landings of jack mackerel and chub mackerel reached 2,005,850 and 336,143 t, while Peruvian landings reached 611,373 and 261,303 t, respectively. It is remarkable that when the marine catches of both countries are combined, jumbo squid becomes the third HCLME fishery resource (2,806,374 t), just behind sardine but above jack mackerel.

Marine fish landings in the HCLME area have decreased from 61 million tonnes in 2004–2008 to about 43 millions of tonnes in 2009–2013. In the case of Peruvian fisheries, the period 2009–2013, compared with the previous 5-year period, exhibited a reduction of around 30% in the landings of anchovy, jack mackerel and chub mackerel, but increases in jumbo squid (9%), Peruvian scallop (234%), dolphinfish (44%), hake (29%) and Eastern Pacific bonito (121%).

Fig. 7 presents the variability of anchovy landings by stock in the HCLME (Serra et al., 2012). On average since 1999, the Northern-Central Peru stock (NCP) accounts for 75% of total catches, the Southern Peru–Northern Chile stock (SPNCh) accounts for nearly 20%, and the small stock of Central Chile (CCh) represents less than 5%. Even though strong interannual fluctuations characterize the records, negative trends are noticeable for all stocks, particularly for NCP and CCh, leading to about 50% reduction in the annual landings since 2005 and since 2007, respectively. These trends in all likelihood respond to natural changes in the availability of anchovy. Both countries have adopted individual quota systems for the industrial fishing of anchovy, in Chile since 2001 and in Peru since 2009.

6. Sensitivity to climate variability

Proxy climatic and oceanographic records show the sensitivity of the HCLME to climate variability at multiple time-scales. Millennial and centennial time-scale variability of the earth climate affects the intensity of the Walker circulation, the mean position of the Intertropical Convergence zone and the size and position of the Hadley cell. In consequence, the circulation, productivity and oxygenation patterns in the HCLME also vary with the climatic conditions (De Pol-Holz et al., 2007; Mollier-Vogel et al., 2013; Gutiérrez et al., 2009; Salvatteci et al., 2014). Studies on the sediment archives from the

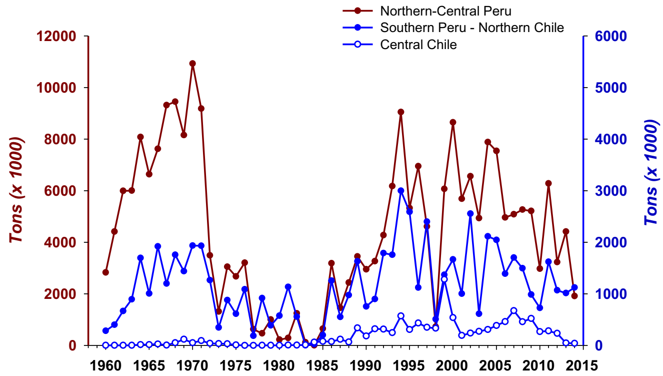

Fig. 7. Records of fish landings of the three anchovy stocks in the HCLME since the onset of industrial fishing.

continental margin suggest the occurrence of a biogeochemical regime shift towards enhanced wind stress, higher productivity and less oxygenation after the end of the Little Ice Age for Peru and northern Chile (G. Vargas et al., 2007, Sifeddine et al., 2008, Gutiérrez et al., 2009; Briceño et al., 2015). The shift was followed decades later by the installation of an enhanced upwelling, 'Anchoveta regime', which was temporarily interrupted by a bi-decadal period (ca. 1972–1993), in which the HCS pelagic system was co-dominated by sardine, anchovy and jack-mackerel, especially off Peru (G. Vargas et al., 2007; Valdés et al., 2008; Gutiérrez et al., 2009, 2011).

At supra-seasonal time-scales, the El Niño Southern Oscillation (ENSO) is the dominant mode of variability in the Pacific Ocean, resulting from the interaction between the ocean and atmosphere in the tropical Pacific. ENSO activity is itself modulated by the climate variability at longer time-scales. For instance, the current periodicity and amplitude of ENSO were established at about 4000 years BP (Carré et al., 2014). ENSO also interacts with the interdecadal-scale variability of the Pacific climate, with which it partially shares the spatial anomaly pattern over the Central and Eastern Pacific (Chavez et al., 2011). Therefore when both sources of variability are in phase, the positive anomalies are amplified leading to stronger impacts in the ecosystem. Recent studies have explored the two dominant flavors of El Niño: the Central Pacific El Niño ('El Niño Modoki') and the Eastern Pacific El Niño, also known as the canonical El Niño (Kao and Yu, 2009; Takahashi et al., 2011). While the ecological impacts of the Eastern Pacific El Niño in the HCS are well documented, little is known on the impacts of El Niño Modoki at the ecosystem level, besides the expected weaker impact on the coastal upwelling and productivity in the HCS. As well, information about the response of the Cape Horn Current system to climate variability is still scarce.

During El Niño, a deepening of the thermocline in the Tropical Eastern Pacific occurs associated to weaker trade winds and altered Walker circulation patterns. In addition, downwelling Equatorial Kelvin waves (KW) are triggered more frequently under El Niño and propagate across the Equatorial Pacific. Upon hitting the South American margin, the KWs travel as poleward coastal trapped waves along the coast, which in turn further contribute to deepen the water column structure, e.g. the vertical distribution of temperature, oxygen and nutrients (Morales et al., 1999). In contrast with the Southeasterly trade winds which follow the large-scale decrease of sea level pressure in the Southeastern Pacific, alongshore coastal winds are intensified during El Niño (Bakun et al., 2010), though the underlying mechanism is in discussion (Enfield, 1981, Bakun et al., 2010, Belmadani et al., 2014). However, the upwelled waters come from above the nutricline, so that the system becomes nutrient-limited, resulting in changes of biological communities and a decrease of coastal upwelling productivity (Barber and Chavez, 1983; Calienes et al., 1985; Escribano et al., 2004). Further offshore, the decrease of wind stress curl and the westward propagation of Rossby waves, triggered by the poleward propagation of coastal trapped KWs, amplify the thermocline deepening and primary productivity reduction (Halpern, 2002; Correa-Ramírez et al., 2012). For central-southern Chile, surface chlorophyll-a anomalies under El Niño (EN) support the view that ENSO-related variability is mostly transmitted by way of atmospheric teleconnections with the Equatorial Pacific that results in weaker coastal upwelling winds and mesoscale activity (Correa-Ramírez et al., 2012). On the other hand, the subsurface oxygenation, aided by the decreased respiration of organic matter, might reach over 200 m depth in strong El Niños (Arntz et al., 2006). This process increases the habitat for pelagic and demersal species at all trophic levels and enables the macrofaunal colonization and bioturbation of the otherwise nearly anoxic seafloor in the upper continental margin (Arntz et al., 2006; Gutiérrez et al., 2000). Fig. 8 presents interannual time-series of oceanographic parameters off Peru and the impact of El Niño from 1960 to 2008.

The collapse of coastal upwelling leads to the advance of surface subtropical warm and nutrient-poor waters to the coast, leading to a size reduction of the coastal productive region (Nixon and Thomas, 2001), with its classic food-web dominated by chain-forming diatoms, large copepods, euphausiids and anchovies. In contrast, an increased relative abundance of dinoflagellates, nanoplankton, gelatinous zooplankton and warm water predatory species occurs. Tam et al. (2008) estimated that the 1997–1998 EN reduced the size and organization of energy flows of the Peruvian upwelling ecosystem, and that the reduction of diatom biomass during EN forced omnivorous planktivorous fish to switch to a more zooplankton-dominated diet, raising their trophic level. On the other hand, combined changes in water masses, and decrease of the food availability (large copepods and euphausiids) associated to lower primary production, make El Niño conditions detrimental for the

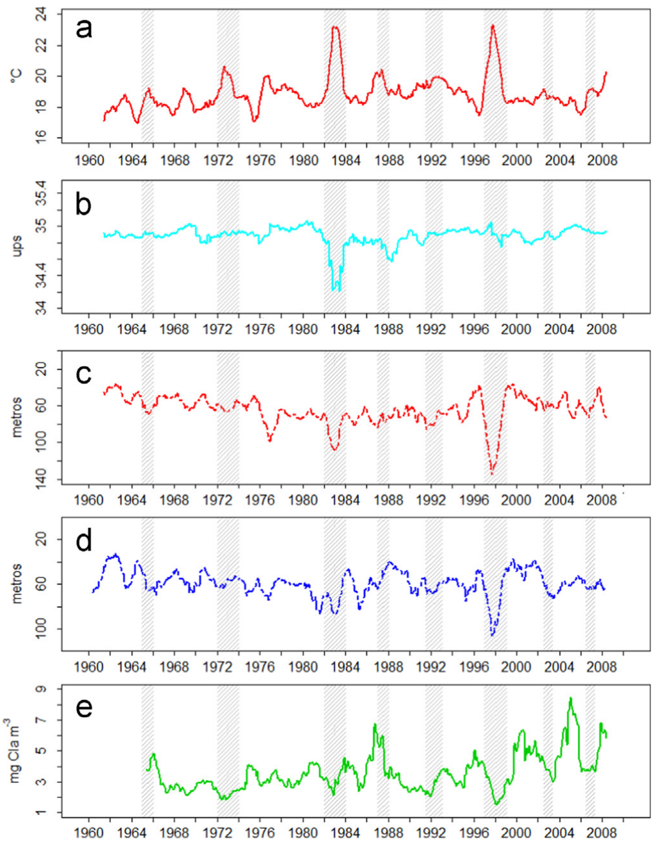

Fig. 8. (a) Interannual variability of sea surface temperature (°C); (b) surface salinity (UPS); (c) depth of the 15 °C isotherm (meters), (d) depth of the 1 ml L^{-1} iso-oxygen, taken as the base of the oxycline (meters); (e) surface chloroplyll-a content (mg Chl-a m^{-3}). The time-series correspond to monthly averages calculated from IMARPE database, (period: 1960–2008; latitude range: 3.5°S–20°S, distance to the coast: 0–100 km), at monthly resolution. Shaded rectangles correspond to El Niño events.

anchovy population (Ñiquen and Bouchon, 2004; Swartzman et al., 2008). Therefore anchovy landings drop in El Niño years (Fig. 7), but the species exhibits a large degree of resilience based on its spatial behavior (Bertrand et al., 2004), and also its high fecundity and rapid reproductive rates. An exception was the collapse of anchovy population during the 1972–1973 EN event that happened after several years of overfishing (Muck, 1989). Decadal to multidecadal oceanographic variability have longer lasting effects on the anchovy stocks, as historic biomass changes and proxy records of local biomasses have demonstrated (Bertrand et al., 2011, Gutiérrez et al., 2009).

7. Recent trends and climate change scenarios: implications for the biological productivity

As mentioned above, an exceptional pelagic fish productivity characterizes the HCLME and a major part of it is concentrated in the Peru upwelling subsystem. Despite primary productivity being within the same range of other EBUSs, the fish production (mostly anchovy) here is one order of magnitude higher. Several mechanisms have been postulated to explain this paradox: (1) a moderate alongshore wind intensity off Peru which results in strong upwelling, low turbulence and longer residence times of food and fish larvae in the coastal productive habitat (Bakun and Parrish, 1982; Bakun and Weeks, 2008); (2) a larger exposure to ENSO variability that periodically ‘resets’ the ecosystem components (Bakun and Weeks, 2008; Chavez et al., 2008); (3) the spawning timing that coincides with the peak period of both coastal retention and food availability (Brochier et al., 2013), among others. Bertrand et al. (2011) has postulated a habitat-based hypothesis including oxygen deficiency/availability, which would account for the relative compression of the epipelagic habitat, reducing predatory pressure and habitat occupation by other pelagic species such as sardine, while enabling a higher prey availability for forage fish. It is clear that most of these mechanisms are climate-driven, so that the question posed by Bakun and Weeks (2008) on what might the future hold for fisheries productivity will depend on the regional change of ocean climate and associated processes.

Global warming of sea surface and upper layer temperatures is evidenced by numerous observations (IPCC, 2013). Currently, the impact of climate change on coastal upwelling systems is under debate, with contrasting observations and model outputs among the main coastal upwelling ecosystems (Narayan et al., 2010; Sydeman et al., 2014). Previously it has been proposed that upwelling intensification occurs with anthropogenic global warming, due to the differential heating of land surface and adjacent coastal ocean, thus enhancing the land-sea pressure gradient and concomitant alongshore wind stress (Bakun, 1990; Bakun et al., 2010; Rykaczewski and Checkley, 2008).

Marine coastal sedimentary archives along the HCS help to reconstruct the history of coastal upwelling and productivity under the rising anthropogenic influence on global climate, for at least the past century. Off Pisco, within the main upwelling zone off Peru (14°S), a cooling trend of alkenone-based SSTs is accompanied by increases of carbon fluxes since the 1960′s, which prevail on interdecadal changes (Gutiérrez et al., 2011). Off Antofagasta, northern Chile (23°S), both carbon fluxes and wind-driven lithogenic input increased since the mid- 1970 s to the end of XXth century, likely forced by large-scale El Niño-like conditions driven by Pacific Decadal Oscillation (PDO) (G. Vargas et al., 2007; Caniupán et al., 2009). Off Concepcion, Central Chile (36°S), the records show a warming trend in the upwelling area for the past 70 years, consistent with decreasing fluxes of carbon and diatom fluxes. Here interdecadal variations are also evident, with warmer periods coinciding with El Niño-like PDO phases (Sánchez et al., 2012), in contrast with Antofagasta records mentioned above.

On the other hand, SST gridded analyses based on satellite and in situ observations, as well as instrumental records of SSTs exhibit significant cooling trends since at least 1979 to the mid 2000's along most of the HCLME coastal areas (Falvey and Garreaud, 2009; Gutiérrez et al., 2011). Trends calculated from piers and coastal stations SST time-series off Central to Southern Peru range between -0.2 and -0.4 °C decade^{-1} until late 2000s, on average (Fig. 9). Off northernmost Peru (≤ 5°S) a warming trend ($+0.15$ °C decade^{-1}) is observed from 1950 until late 2000s. Time-series of in situ SST measurements from the upwelling area off Concepcion exhibit no significant trend since the early 2000s (Corredor-Acosta et al., 2015).

In spite of proxy and instrumental SST records, available alongshore wind information is not conclusive to confirm a multidecadal intensification of coastal upwelling favorable winds. Most of the long-term wind information in the region is available as gridded data from a variety of sources and re-analyses, and give contradictory trends (Narayan et al., 2010; Gutiérrez et al., 2011; Belmadani et al., 2014; Aravena et al., 2014). Nevertheless the spatial resolution of current gridded wind information (≥ 50 km) does not resolve the strong gradients in coastal upwelling areas. For the latest decades, scatterometer winds exhibit a positive trend for the equatorward component off Peru and northern Chile during the 2000's (Demarcq, 2009). Off central Chile, wind data from satellites and meteorological stations show positive upwelling trends since the early 2000's (Escribano et al., 2012; Aravena et al., 2014). As an alternative driver for coastal cooling, Dewitte et al. (2012) have suggested that the increasing occurrence of Central Pacific (CP) El Niños is associated with a change of Equatorial Kelvin wave characteristics, leading to the accumulation of negative SST anomalies off Peru and northern Chile and

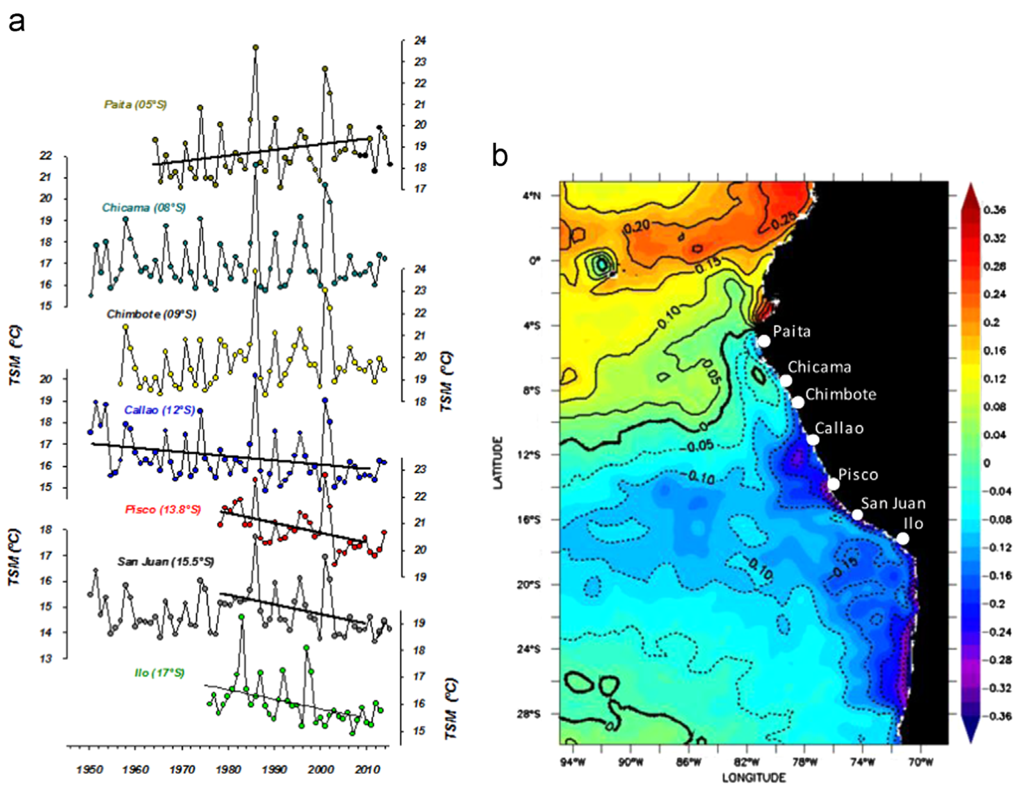

Fig. 9. (a) SST trends based on time-series of instrumental measurements in piers along the Peruvian coast; significant linear fits are over-imposed on the respective periods; for Callao, Pisco, San Juan and Ilo, SST trends until 2010 are $-0.3° \pm 0.1$ °C decade-1. (b) SST trends based on satellite records (Reynolds daily data base, 1984–2014). Units are °C decade^{-1}.

thus contributing to the observed cooling trend.

It is remarkable that the cooling trends off Peru do not hold for the latest years (Fig. 9). Data from Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature (SST) Analysis suggest an advance of the oceanic front towards the coast since 2009/2010. In parallel, sea level anomaly records off Northern Peru indicate a higher intra-annual variability that is consistent with an increasing activity of downwelling Kelvin waves during fall/winter periods (Gutiérrez et al., 2015). Further analyses are needed to explore in what extent these recent features reflect relative changes of remote- and local forcings over the Peruvian upwelling system.

Time-series of shipboard and satellite surface chlorophyll-a allow the inference of primary productivity for the last decades. Off Peru, chlorophyll-a positive trends are observed since the 1960′s, consistent with proxy records (see above) (Chavez et al., 2011; Gutiérrez et al., 2011). Satellite-based chlorophyll-a data exhibit positive trends off Peru and northern Chile, and negative trends further south (Demarcq, 2009). Given the pronounced seasonality of primary production along the coast (Echevin et al., 2008), positive trends of primary productivity might be result of stronger spring–summer upwelling, but little has been investigated on this issue (Gutiérrez et al., 2011). For Central Chile, in situ and satellite chlorophyll-a data present a negative trend with increasing Ekman transport since the early 2000s (Corredor-Acosta et al., 2015). Furthermore, Escribano et al. (2012) reported a decrease of copepod biomass off Northern and Central Chile for the same period. Increased vertical mixing and advection offshore might have been detrimental for primary productivity and copepod secondary production, respectively (Escribano et al., 2012; Corredor-Acosta et al., 2015).

Recent modeling studies give insights on the response of the HCLME coastal upwelling, productivity and anchovy production to climate change scenarios (Fig. 10). Based on outputs of an ensemble of models, Wang et al. (2015) have predicted that by the end of the 21st century the upwelling season will start earlier, end later and become more intense at high but not low latitudes in the EBUSs, resulting in a substantial reduction of the existing latitudinal variation in coastal upwelling. Regional modeling of winds, marine currents and stratification arrive to results that are consistent with strong intensification of alongshore winds off Central Chile at $2xCO_2$ and $4xCO_2$ climate change scenarios (Garreaud and Falvey, 2009; Goubanova et al., 2011, Echevin et al., 2012, Belmadani et al., 2014). In contrast, off Peru upwelling favorable winds either weaken, particularly in summer (Echevin et al., 2012, Belmadani et al., 2014) or show no significant change (Wang et al., 2015). The mechanisms involved would be the southward expansion of the Hadley cell and of the South Pacific Anticyclone position, as well as the warming of sea surface at low latitudes, likely followed by increasing upward convection that prevent the intensification of equatorward winds along the Peruvian coast (Belmadani et al., 2014). In turn, increased stratification will limit the depth of Ekman transport and hence the upward advection of nutrient-rich waters to the surface.

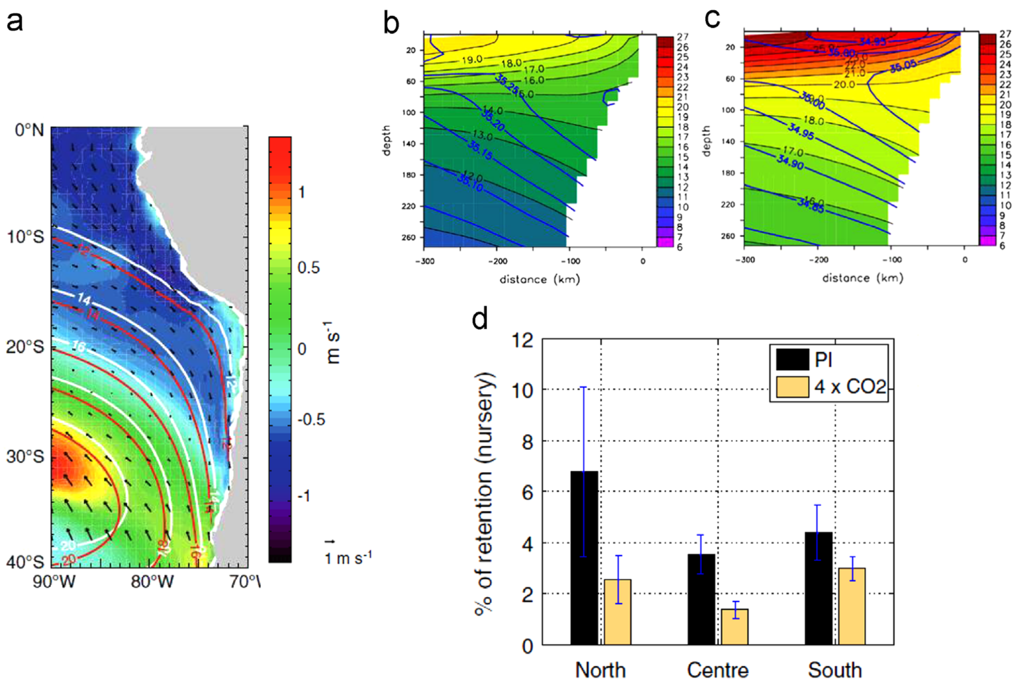

Fig. 10. Modeling climate change scenarios in the HCS. (a) Differences in surface wind intensity between the $2xCO_2$ and PI scenarios during summer (JFM) according to the global climate model LMDz, configured for the South Eastern Pacific at 0.5 × 0.5° resolution; contour lines correspond to sea level pressure distribution under PI (white) and $2xCO_2$ (red) (adapted from BelMadani et al., 2014). (b) and (c) Cross-shore vertical structure of temperature and salinity under PI and $4xCO_2$ scenarios, respectively, at 10°S (Echevin et al., 2012). (d) Anchovy larvae retention rates (% of individuals) in nursery areas, defined as where zooplankton biomass surpass a threshold value of 12.5 g m-2, in the 'Northern' (4–16°S), 'Central' (16–24°S), and 'Southern' (24–40°S) areas of the HCS under PI and $4xCO_2$ scenarios (Brochier et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Therefore off Peru, according to these models, primary productivity would decrease, at least in the main productive season. Even though retention will increase with stratification this would not compensate for lower productivity, resulting in a reduction of zooplankton abundances, i.e. less food availability for anchovy larvae (Brochier et al., 2013). For winter, the scenario is more problematic, since weaker equatorward winds (Belmadani et al., 2014) and surface warming might not necessarily reduce primary productivity in this season, which is light-limited under the present climate. For Central-Southern Chile, the predicted stronger upwelling-favorable winds may not result in larger productivity and anchovy recruitment success either (Brochier et al., 2013), which is consistent with the current behavior of productivity and zooplankton biomass with increasing upwelling there (see above). For Southern Chile, reduction of Patagonian glaciers, widening of Hadley cell and associated southward migration of westerlies and precipitation (IPCC, 2013) driven by climate change will likely impact on the productivity and biodiversity patterns, by affecting stratification and mixing.

A major uncertainty of the current projections is whether the frequency and intensity of El Niño and La Niña will vary with climate change (IPCC, 2013). While some studies indicate that Central Pacific El Niños will be more frequent with global warming (Yeh et al., 2009), other studies predict an increase of extreme El Niños in the Eastern Equatorial Pacific under climate change scenarios, driving intense atmospheric convection and heavy rainfalls in the region (Cai et al., 2014). In any case, it should be noted that the combination of SST warming and interannual SST fluctuations increase the likelihood of extreme events, due to the relationship between atmospheric convection and SST, strongly affecting the coastal circulation, biogeochemical fields and other ecosystem properties, particularly in the Northern HCLME.

Another uncertainty in regional projections is the response of the oxygen regime to global warming in the HCS. According to the last report of IPCC (2013), the current projections are still uncertain, especially concerning the evolution of O_2 in and around OMZs, because global ocean models have limitations in simulating today's O_2 distribution, as well as reproducing the measured changes in O_2 concentrations over the past 50 years. Nevertheless, retrospective studies have evidenced the large-scale expansion of the OMZs in the tropical oceans, including the Eastern Tropical Pacific (Stramma et al., 2008). At higher latitudes in the Eastern Pacific, oxygen content in the water column exhibit weak positive trends (Stramma et al., 2010), possibly driven by enhanced wind-driven ventilation (IPCC, 2013), but these response patterns are based on coarse-resolution analyses. From historic shipboard measurements of oxygen off Peru (6°–15°S, 300 Km), Bertrand et al. (2011) reported a strong interdecadal variability, associated to PDO. In particular, the late 1990's marked a transition from a deeper OMZ towards a shallower OMZ, condition that could have prevailed until the 2010's. However, more studies are needed to resolve the trends across latitudinal and onshore-offshore gradients for the entire HCLME. A shallowing of the OMZ upper boundary would amplify the negative effect of climate change on coastal retention of anchovy larvae and its recruitment (Brochier et al., 2013), not allowing the onshore advection of larvae, because of the upward compression of the oxygenated surface layer.

Finally, the role of future ocean acidification for the productivity in the region is also unknown. Currently the HCS is a natural acidic system, due to the high contents of subsurface CO_2 and strong respiration rates in the water column (IPCC, 2013); therefore marine biota in the region have likely evolved adaptations to cope with the low alkalinity. In contrast, off Southern Chile, which under the present climate exhibits pH conditions that are similar to the global average, the impacts of ocean acidification on the biodiversity and productivity patterns might be more relevant. These knowledge gaps need to be investigated in detail.

8. A transboundary diagnostic analysis of the HCLME

Peru and Chile add up to approximately 6950 km-long coastal belt, which currently is fished by close to 135,000 artisanal fisherfolk with 39,000 fishing vessels. In total, coastal fisheries support upwards of one million livelihoods in the region. As mentioned above, marine fish landings have decreased in both countries in the past decade. Even though it is early to predict if this trend will continue or not, better governance and management for the HCLME ecosystem services, from which fish production is the most important for both countries' economies and societies, are strongly needed to improve the resilience of the HCLME to the increasing climatic pressures.

The Ocean Health Index (OHI) indicators 9 and 10 (Clean Waters and Biodiversity respectively) have recorded water quality and biodiversity levels considerably below the global average in the northern sector of the HCS with a predicted tendency to improve marginally, while in the southern sector water quality is above world average and biodiversity at the global average (OHI, 2015). Threats to biodiversity come from three main areas: overfishing, pollution and coastal development attributing to between 65% and 75% of biodiversity reduction in the area (Chatwin 2007). In the southern area of the HCLME six fisheries are collapsed, eight overexploited and a further eight fully exploited (SUBPESCA, 2015). Furthermore, in the whole HCS area 76 fisheries have no management plan, biological reference points or quotas.

For the last 4-years Chile and Peru and their respective fisheries research institutions IFOP (El Instituto de Fomento Pesquero) and IMARPE (El Instituto del Mar del Perú), together with the agencies of national protected areas and the Environment Ministries, have been working on the GEF-UNDP Humboldt project to develop a Transboundary Diagnostic Analysis (TDA) followed by a Strategic Action Programme (SAP). The former registered the main issues impacting the well-being of the HCS and the latter a series of objectives and actions to mitigate the problems identified within the system.

The TDA focused on the identification of transboundary problems (TPs) and the description and analysis of environmental and socioeconomic impacts, as well as the determination of the root causes. Two main transboundary problems were identified: (i) suboptimal exploitation of fisheries resources (TP1) and (ii) anthropogenic disturbance of marine habitat (TP2).

The root causes for TP1 include: weak governance; poor or absent monitoring, control and surveillance (MCS) systems; absence of participatory processes in decision making and resource management; and perverse incentives that promote the continued participation in the sector of increased overfishing. The following environmental impacts follow the suboptimal exploitation of fisheries resources:

a) Biomass decline and changes in population structure
b) Alteration of trophic relationships within ecosystems
c) Alteration of biodiversity, environment and ecosystem resilience

The following socioeconomic impacts were identified for TP1:

a) Reduction of net income and employment opportunities
b) Decrease of fishery resource provision for food security

Regarding TP2, the HCLME environmental conditions are affected by land and marine pollutants: organic matter, solid and liquid chemical waste, microbiological compounds, hydrocarbons and heavy metals among others. These pollutants alter the productivity in coastal areas and generate social and economic impacts on human and ecosystem health. Therefore, this transboundary problem also contributes to the decline in fish biomass and productivity of the HCLME.

The following environmental impacts were identified for TP2:

a) Deterioration of water quality and that of marine sediments
b) Increased mortality at early life stages of biological resources
c) Mortality of marine species
d) Alteration of biodiversity and reduction of ecosystem resilience
e) High levels of incidental fish capture (by-catch and discards)

Table 2
Root causes and barriers of environmental and socioeconomic problems in the HCLME.

Impacts	Barrier category	Root cause
Environmental	Social	Insufficient education at all levels prevents the strengthening of environmental awareness and sensitivity.
	Environmental	Environmental variability (seasonal, annual and decadal) modifies the carrying capacity of the ecosystem and resource availability.
	Knowledge	Lack of bi-national coordination for ecosystem-based research.
		Lack of information about the economic, ecological and social values of ecosystem goods and services.
	Economic/Demographic	Increasing demand for fishery resources.
	Governance	Lack of bi-national coordination for ecosystem-based management.
		Limited capacity for monitoring, control and follow-up and limited state punitive and deterrent capabilities.
		Insufficient integration of research and knowledge for the proper management and implementation of EBM.
		Insufficient human, physical and financial resources to implement an EBM approach.
		Limited capacity for monitoring, control, surveillance and punitive deterrent capability by the state.
		Insufficient incentive policies for technological innovation aimed at cleaner production.
		Lack of strategic coastal marine spatial planning for the sustainable development of the coastal marine area under an ecosystem approach.
	Institutional	Scarce human, physical and financial resources to support the implementation of a comprehensive system for monitoring and control of fisheries with an ecosystem approach.
		Insufficient resources for the management of marine protected areas.
Socioeconomic	Social	Low awareness of the conservation and sustainable use of fisheries resources.
	Knowledge	Limited information regarding the availability, access, stability and utilization of aquatic resources.
		Lack of bi-national coordination for ecosystem-based research.
	Economic/Demographic	Increased demand for fish products for direct human consumption.
	Governance	Lack of bi-national coordination for ecosystem-based management.
		Insufficient integration of research and knowledge for the proper management and implementation of EBM.
		Insufficient ecosystem-based fisheries management.
		Insufficient policies and instruments to promote the productive development of smaller-scale fishing, as well as small scale productive activities.
		Limited capacity for monitoring, control, surveillance and punitive deterrent capability by the state.
		Limited commercial management capacity of small-scale fishermen.

Table 3
Fisheries status of key fish, shellfish and algae species in the southern HCS area of local, regional and global importance (SUBPESCA, 2015).

Species	Fishery status	IUCN Red List	Management status - quota	Comments
Anchovy *Engraulis ringens*	In decline Full exploitation	Least concern trend unknown	Industrial yes artisanal no	Global importance for fishmeal and oil. Regional importance for trophic food web and biodiversity. Transboundary
Pilchard *Sardinops sagax*	Collapsed	Least Concern More research needed	–	Transboundary
Jack Mackerel *Trachurus murphyi*	In decline overexploited	Data deficient status unknown	South Pacific Regional Fisheries Management Organization SPRFMO	Transboundary Previously used for fishmeal but no longer
Sierra *Scomberomorus sierra*	In decline Full exploitation	Least Concern Stable	Industrial	Transboundary
South Pacific Hake *Merluccius gayi peruanus* *Merluccius gayi gayi*	In decline overexploited	Not assessed	Industrial and artisanal	Transboundary
Chub Mackerel *Scomber japonicus*	Stable	Least concern Stable	Industrial and artisanal	Transboundary
Swordfish *Xiphias gladius*	Full exploitation	Least concern Population decreasing	Industrial and artisanal. New access to fishery banned 2014 (Chile)	Transboundary
Murex snail *Concholepas concholepas*	In decline Full exploitation. Management plans	Not assessed	Artisanal	Transboundary (larval stages)
Limpet *Fissurella limbata*	Stable	Not assessed	Artisanal	Transboundary (larval stages)
Scallop *Argopecten purpuratus*	Full exploitation	Not assessed	Artisanal	Transboundary (larval stages)
Octopus *Octopus minimus*	Full exploitation	Not assessed	Artisanal	Transboundary (larval stages)
Giant squid *Dosidicus gigas*	Stable Fishmeal use banned	Data deficient trend unknown	Industrial and artisanal	Transboundary
Seaurchin *Loxechinus albus*	Stable to full exploitation	Not assessed	Industrial and artisanal	Transboundary (larval stages)
Macroalgae Many species	Full exploitation	Not assessed	Artisanal	Transboundary (spores)

General comment: main transboundary fisheries common to both countries listed.
Chile, out of 38 fisheries assessed in 2014 only 22 have biological reference points and these fall into the current categories: Collapsed 6; Overexploited 8; and Fully exploited 8.

In addition, the following socioeconomic impacts were identified:

a) Economic and employment loss and reduction of competitiveness
b) Reduction of marine-product food safety

Table 2 summarizes the underlying and root causes and associated barrier types (causal chain analysis) for the environmental and socioeconomic problems of the HCLME. Table 3 shows the status of a selection of important transboundary fisheries. Furthermore, as explained above, natural climate variability within the HCLME (e.g. ENSO or PDO) and climate change related manifestations, also affect or will affect productivity and cause alterations at all trophic levels within the HCLME.

9. The valuation of the HCLME goods and services

In order to protect the delivery of goods and services derived from the HCLME area it is obviously important to know the major threats to this LME as identified above, both natural and anthropogenic, while also being aware of the annual total economic value derived from the area. Economic valuations of ecosystem goods and services have been carried out worldwide and are summarized in Table 4. The wide variations in value reflect three factors: (1) the absence of an accepted standard LME goods and services evaluation methodology; (2) the varying importance of the range of economic activities in the different LMEs; and (3) the absence of data relating to key activities in some countries, like for example coastal tourism.

The HCLME and HCS (Chile and Peru) economic valuation amounts to USD 19,459 million and USD 14,970 million respectively (Tables 4 and 5). The Total Economic Value (TEV) work carried out in the LMEs to date should be seen as a start

Table 4
Economic valuations of Large Marine Ecosystem goods and services delivered.

Number of countries per LME	Name and LME number (#)	TEV value USD /km^2	Area in million Km^2	USD millions	Main components valued **NB The valuation process has been carried out according to regional priorities. In most cases one aspect of the valuation has been given a high priority and value e.g. coastal protection in climate change exposed areas (see http://floodlist.com/wp-content/uploads/2013/11/climate-risk-index-1993-to-.jpg)**
23	Caribbean **(12)**	**2050***	3.3	621	Fisheries, tourism, biodiversity, coastal protection
16	Guinea **(28)**	**17,223**	2.0	8611	Fisheries, tourism, waste recycling, biodiversity, blue carbon, coastal protect
9	Agulhas **(30)**	**14,297**	2.6	5499	Fisheries and aquaculture, tourism, oil and gas, regulation, bays and ports
9	Baltic **(23)**	**5278**	0.390	13,533	Fisheries, oil and gas, wind power, tourism and recreation
8	Bengal **(34)**	**64,631**	6.2**	10,424	Fisheries and aquaculture, coastline protection, storm protection, climate regulation, tourism
7	China Sea **(36)**	**6854**	3.2	2142	Fisheries and aquaculture, tourism, coastal protection, blue carbon
3	Benguela **(29)**	**3294**	1.5	2196	Fisheries, aquaculture, mining, oil and gas,
2	Humboldt **(13)**	**19,459**	2.5	7784	Fisheries and aquaculture, tourism, transport, wind power, oil and gas, climate regulation

http://lme.edc.uri.edu/ and www.humboldt.iwlearn.org and http://floodlist.com/wp-content/uploads/2013/11/climate-risk-index-1993-to-.jpg
* This value is not presented as a TEV in the Caribbean LME study as there are many knowledge gaps.
** The 6.2 million Km^2 area is 2.5 million km^2 greater than the standard Bay of Bengal LME definition of 3.7 million Km^2 as it includes the Maldives and an area beyond national jurisdiction.

point for further work including improved information sharing and data collection. In order to sustain the value of the HCLME goods and services in terms of all aspects both valued (biodiversity, quality food provision, nutrient recycling, tourism, coastal protection, carbon sequestration, climate regulation) and non-valued (oxygen production), it is important to establish what interventions will be most cost effective. Hence the need to identify leverage points (see Table 6) as apparently provisioning services make up the bulk of the value, although this may be a product of an underestimation of cultural and regulatory services due to the absence of available data.

10. Sustainable management under climate change: a challenge for adaptation

It is expected that climate change will impact on the biodiversity, habitat quality, carrying capacities and life cycles of marine ecosystems and organisms, as well as on socio-economic services, such as fish catch potential, fishing efforts and fishers incomes, increasing the vulnerability of the ecosystem and the human local communities. Other anthropic stressors, such as by-catch, discard practices and pollution can further amplify climate change impacts through effects on ecological processes, as spawning rates and distribution of nursery grounds.

A combination of replicable actions at local scale (targeting affected communities) and national policies (need to be developed for a long-term and effective enabling environment) are both required to ensure a successful adaptation process. Benefits from these adaptation measures could be distributed in the short and long-term. Of special interest are those contributing to the welfare of local communities, the preserving or restoration of key ecosystems while bringing immediate and concrete development co-benefits. Adaptation measures bringing long-term benefits, such as coastal marine zoning or

Table 5
Total Economic Value of the HCLME services 2015.

Humboldt Current Large Marine Ecosystem and Humboldt Current System Total Economic Value 2015				
Values in millions of USD	**Total Peru**	**Total: Chile**	**Total: HCLME (3–58° south)**	**Total: HCS (4–40° south)**
Total: provision services*	4115.40	6747.28	10,862.68	7,683.35
Total: cultural services**	3179.75	3268.00	6447.75	5141.50
Total: regulation services***	880.29	1268.00	2148.29	2145.60
Combined total	**8175.44**	**11,283.28**	**19,458.72**	**14,970.45**

* Food from Fisheries and Aquaculture; Salt; Guano; Fishmeal & oil; Algae; water; energy; transport.
** Tourism; Recreation; Water Sports; Archeology; Scientific Research; Sense of Place & Wellbeing.
**** Climate regulation; Waste recycling.

Table 6
Leverage points related to identified root causes.

Associated Root Cause	Intervention
Knowledge gaps	1. Develop and implement research programs and the sharing of information based on the knowledge of HCLME goods and services
	2. Improve knowledge of ecosystem variability at all scales
	3. Develop standardized procedures for the development of research activities between both countries coupled with the sharing of data
	4. Develop mechanisms for the integration of knowledge management activities in this ecosystem
Social pressures	1. Promote the formulation of an environmental education program at all levels
	2. Develop programs of scientific, technological and social outreach of the major achievements towards ecosystem-based management
	3. Progress in the development and/or implementation of a long-term multi-sectorial Action Plan for Food Safety and Security
Economic factors	1. Promote experience in marketing of marine products with strategies for economic and environmental sustainability, based on the principles of EBM
Governance aspects	1. Develop a HCLME Information System with the objective of disseminating bi-national research data and successful management experiences to allow better decision making
Institutional aspects	1. Progress towards the formulation of a Results Based Management strategy based on an approach that seeks to increase the effectiveness of decisions made in various sectors through increased interest in the delivery of tangible products
	2. Develop the foundation for an adaptive system for the management of HCLME goods and services

implementation of marine protected areas, contribute to create an enabling environment for the successful execution of adaptation measures and to the sustainability of the results.

As described above the impacts of climate change in the area are multiple and dramatic with impacts on primary productivity and fisheries composition in the region. Impacts on the small pelagic fish stocks and other associated fisheries have effects at national and international-global levels. Most of the anchovy productivity (98%) currently goes into fishmeal production providing animal protein and essential oils for livestock feed industries. While these products are important, direct human consumption (DHC) is also being promoted with value addition via the salting of fish and other preservation measures including canning, freezing and drying. The possibility of fisheries certification is also being studied as a means of improved anchovy fishery management and DHC value addition. Diversified resource use will help adjust to periods of fish scarcity while improving the nutrition of malnourished households in poor communities in the Peruvian hinterland.

A range of territorial planning tools are in use within the HCLME area as shown in Fig. 11. Within the context of ecosystem based management following the 12 IUCN principles, there is a need to promote Coastal Marine Spatial Planning (CMSP) in conjunction with Integrated Coastal Zone Management (ICZM) as a planning tool under which a range of other territorial management activities can be implemented. Legal reforms under new fisheries laws are needed to achieve this.

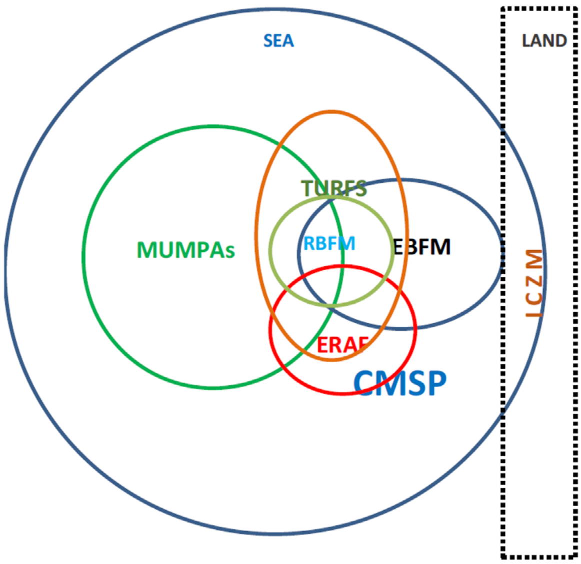

Fig. 11. Scheme showing different management instruments that are under implementation in the HCLME-GEF project: Integrated Coastal Zone Management (ICZM)-Pilot work implemented by government counterparts; Coastal Marine Spatial Planning (CMSP)-Capacity building carried out by NOAA 2014-15; Multiple Use Marine Protected Areas (MUMPAs)-12,000 km^2 MUMPA established in Juan Fernandez Islands, Chile; Ecosystem Based Fisheries Management (EBFM) - Capacity building undertaken and concepts recommended; Ecological Risk Assessments for Fisheries (ERAF)-Capacity building (CSIRO) and ERA for key fisheries completed; Territorial Use Right Fisheries (TURFs) - Experience sharing between Chile and Peru and the Americas; Rights Based Fisheries Management (RBFM) International seminar with WWF 2015. All results and reports at www.humboldt.iwlearn.org.

The GEF-UNDP HCLME project is working to monitor these changes and establish ecosystem based management while increasing multiple use of Marine Protected Areas with management plans developed in consultation with local stakeholders. In addition sustainable resource use is being promoted by value addition and the promotion of certification schemes via interventions in the region from GEF and other international programs and funding agencies.

11. Conclusions

The very large productivity of the HCLME is supported by a set of environmental factors that are highly sensitive to climate variability and climate change. Expected changes in atmosphere and ocean circulation patterns will likely affect coastal wind intensities, water mass distribution and upwelling productivity, influencing on recruitment success, biomass and spatial distribution of fishery resources. In addition, increasing extreme climatic events such as El Niño will likely increase the interannual fluctuations of fish and invertebrate resources. Ecosystem diagnostic analyses within the HCS area have shown the negative effects of overfishing and habitat destruction, which are likely contributing to the recent negative trends of fishing yields for some resources. A related causal chain analysis has identified the root causes, from both natural variation and increasingly impacts of anthropogenic origin in turn related to knowledge gaps and poor information sharing, underfunding of research, increasing demand for marine products, poor monitoring control and surveillance and insufficient incentive policies for technological innovation aimed at cleaner production, among others. Overfishing and pollution might amplify the negative impacts of climate change on the HCLME; bi-national adaptive measures need to be adopted, focusing on improving the resiliency of the ecosystem while at the same time promoting alternative profitable activities as sustainable aquaculture, value addition for fishing products, tourism and others. A bi-national Strategic Action Programme and associated National Action Plans are in the design process for implementation over the next decade.

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References

Albert, A., Echevin, V., Lévy, M., Aumont, O., 2010. Impact of nearshore wind stress curl on coastal circulation and primary productivity in the Peru upwelling system. J. Geophys. Res. 115, C12033, http://dx.doi.org/10.1029/2010JC006569.

Aravena, G., Broitman, B., Stenseth, N.C., 2014. Twelve years of change in coastal upwelling along the central-northern coast of Chile: spatially heterogeneous responses to climatic variability. PLoS ONE 9 (2), e90276, http://dx.doi.org/10.1371/journal.pone.0090276.

Arntz, W., Gallardo, V.A., Gutiérrez, D., Isla, E., Levin, L.A., Mendo, J., Neira, C., Rowe, G.T., Tarazona, J., Wolff, M., 2006. El Niño and similar perturbation effects on the benthos of the Humboldt California, Benguela Current upwelling Ecosystems. Adv. Geosci. 6, 243–265.

Ayón, P., Swartzman, G., Bertrand, A., Gutiérrez, M., Bertrand, S., 2008. Zooplankton and forage fish species off Peru: large-scale bottom-up forcing and local-scale depletion. Prog. Oceanogr. 79, 208–214.

Bakun, A., Parrish, R., 1982. Turbulence, transport, and fish in California and Peru currents. CalCOFI Rep. 23, 99–112.

Bakun, A., 1990. Global climate change and intensification of coastal ocean upwelling. Science 247, 198.

Bakun, A., Weeks, S.J., 2008. The marine ecosystem off Peru: what are the secrets of its fishery productivity and what might its future hold? Prog. Oceanoogr. 79, 290–299.

Bakun, A., Field, D., Redondo-Rodriguez, A., Weeks, S.J., 2010. Greenhouse gas, upwelling favourable winds, and the future of upwelling systems. Glob. Chang. Biol. 16, 1213–1228, http://dx.doi.org/10.1111/j.1365-2486.2009.02094.x.

Barber, R.T., Chavez, F.P., 1983. Biological consequences of El Niño. Science 222, 1203–1210.

Belmadani, A., Echevin, V., Codron, F., Takahashi, K., Junquas, C., 2014. What dynamics drive future wind scenarios for coastal upwelling off Peru and Chile? Clim. Dyn. 43, 1893–1914, http://dx.doi.org/10.1007/s00382-013-2015-2.

Bertrand, A., Segura, M., Gutiérrez, M., Vásquez, L., 2004. From small-scale habitat loopholes to decadal cycles: a habitat-based hypothesis explaining fluctuation in pelagic fish populations off Peru. Fish Fish 5, 296–316.

Bertrand, A., Gerlotto, F., Bertrand, S., Gutiérrez, M., Alza, L., Chipollini, A., Díaz, E., Espinoza, P., Ledesma, L., Quesquén, R., Peraltilla, S., Chavez, F., 2008. Schooling behaviour and environmental forcing in relation to anchoveta distribution: an analysis across multiple spatial scales. Prog. Oceanogr. 79, 264–277.

Bertrand, A., Chaigneau, A., Peraltilla, S., Ledesma, J., Graco, M., Monetti, F., Chavez, F., 2011. Oxygen: a fundamental property regulating pelagic ecosystem structure in the Coastal Southeastern Tropical Pacific. PLoS ONE 6 (12), e29558, http://dx.doi.org/10.1371/journal.pone.0029558.

Briceño, F., Sifeddine, A., Caquineau, S., Cardich, J., Salvatteci, R., Gutierrez, D., Ortlieb, L., Velazco, F., Boucher, H., Machado, C., 2015. Terrigeneous material supply to the Peruvian central continental shelf (Pisco 14°S) during the last 1100 yr: paleoclimatic implications. Clim. Discuss. 11, 3211–3239, http://dx.doi.org/10.5194/cpd-11-3211-2015.

Brink, K.H., 1982. A comparison of long coastal trapped wave theory with observations off Peru. J. Phys. Oceanogr. 12, 897–913.

Brochier, T., Echevin, V., Tam, J., Chaigneau, A., Goubanova, K., Bertrand, A., 2013. Climate change scenarios experiments predict a future reduction in small pelagic fish recruitment in the Humboldt Current system. Glob. Chang. Biol. 9, 1841–1853, http://dx.doi.org/10.1111/gcb.12184.

Cai, W.J., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M., Wu, L.X., England, M.H., Wang, G.J.,

Guilyardi, E., Jin, F.F., 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. Nat. Clim. Chang. 4, 111–116.
Calienes, R., Guillén, O., Lostanau, N., 1985. Variabilidad espacio-temporal de clorofila, producción primaria y nutrientes frentes a la costa Perúana. Bol. Inst. Mar. Perú Callao 10, 1–44.
Caniupán, M., Villaseñor, T., Pantoja, S., Lange, C., Vargas, G., Muñoz, P., Salamanca, M., 2009. Sedimentos laminados de la Bahía Mejillones como registro de cambios temporales en la productividad fitoplanctónica de los últimos ~200 años. Rev. Chil. Hist. Nat. 82, 83–96.
Carré, M., Sachs, J., Purca, S., Schauer, A.J., Braconnot, P., Falcon, R.A., Julien, M., Lavallee, D., 2014. Holocene history of ENSO variance and asymmetry in the Eastern tropical Pacific. Science 345, 1045–1048.
Chatwin, A., 2007. Priorities for Coastal and Marine Conservation in South America. The Nature Conservancy, Arlington, Virginia, USA.
Chavez, F.P., Messié, M., Pennington, J.T., 2011. Marine Primary Production in Relation to Climate Variability and Change. Annu. Rev. Mar. Sci. 3, 227–260.
Chavez, F.P., Bertrand, A., Guevara-Carrasco, R., Soler, P., Csirke, J., 2008. The northern Humboldt Current System: brief history, present status and a view towards the future. (editorial). Prog. Oceanogr. 79, 95–105.
Corredor-Acosta, A., Morales, C.E., Hormazabal, S., Andrade, I., Correa-Ramírez, M.A., 2000. Phytoplankton phenology in the coastal upwelling region off central southern Chile (35°S–38°S): Timespace variability, coupling to environmental factors, and sources of uncertainty in the estimates. J .Geophys. Res. Oceanogr. 120.813–831120, http://dx.doi.org/10.1002/2014JC010330.
Correa-Ramírez, M., Hormazabal, S., Morales, C., 2012. Spatial patterns of annual and interannual surface chlorophyll-a variability in the Peru–Chile Current System. Prog. Oceanogr. 92–95, 8–17.
Cury, P., Bakun, A., Crawford, R.J.M., Jarre, A., Quiñones, R.A., Shannon, L.J., Verheye, H.M., 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES J. Mar. Sci. 57, 603–618.
Daneri, G., Pantoja, S., 2007. Mineralization of organic matter: the importance of pelagic bacterioplankton in the Humboldt Current system off Chile. COPAS Newsl. 13, 1.
Daneri, G., Montero, P., Lizarraga, L., Torres, R., Iriarte, J.L., Jacob, B., Gonzalez, H., Tapia, F.J., 2012. Primary productivity and heterotrophic activity in an enclosed marine area of central Patagonia (Puyuhuapi channel; 44°S, 73°W). Biogeosci. Discuss. 9, 5929–5968.
Demarcq, H., 2009. Trends in primary production, sea surface temperature and wind in upwelling systems (1998–2007). Prog. Oceanogr. 83, 376–385, http://dx.doi.org/10.1016/j.pocean.2009.07.022.
De Pol-Holz, R., Ulloa, O., Lamy, F., Dezileau, L., Sabatier, P., Hebbeln, D., 2007. Late Quaternary variability of sedimentary nitrogen isotopes in the eastern South Pacific Ocean. Paleoceanography 22, PA2207, http://dx.doi.org/10.1029/2006PA001308.
Echevin, V., Aumont, O., Ledesma, J., Flores, G., 2008. The seasonal cycle of surface chlorophyll in the Peru upwelling system: a modelling study. Prog. Oceanogr. 79, 167–176.
Echevin, V., Goubanova, K., Belmadani, A., Dewitte, B., 2012. Sensitivity of the Humboldt Current system to global warming: a downscaling experiment of the IPSL-CM4 model. Clim. Dyn. 38, 761–774.
Enfield, D.B., 1981. Thermally-driven wind variability in the planetary boundary layer above Lima Peru. J. Geophys. Res. 86 (C3), 2005–2016, http://dx.doi.org/10.1029/JC086iC03p02005.
Escribano, R., Daneri, G., Farías, L., Gallardo, V.A., González, H., Gutiérrez, D., Lange, C.B., Morales, C., Pizarro, O., Ulloa, O., Braun, M., 2004. Biological and chemical consequences of the 1997–1998 El Niño in the Chilean coastal upwelling system: a synthesis. Deep Sea Res. II 51 (20–21), 2389–2411.
Escribano, R., Morales, C., 2012. Spatial and temporal scales of variability in the coastal upwelling and coastal transition zones off central-southern Chile (35–40°S). Prog. Oceanogr. 92–95, 1–7.
Escribano, R., Hidalgo, P., Fuentes, M., Donoso, K., 2012. Zooplankton time series in the coastal zone off Chile: variation in upwelling and responses of the copepod community. Prog. Oceanogr. 97–100, 174–186.
Dewitte, B., Vazquez-Cuervo, J., Goubanova, K., Illig, S., Takahashi, K., Cambon, G., Purca, S., Correa, D., Gutierrez, D., Sifeddine, A., Ortlieb, L., 2012. Change in El Niño flavours over 1958-2008: implications for the long-term trend of the upwelling off Peru. Deep Sea Res. II 77–80, 143–156.
Espinoza, P., Bertrand, A., 2008. Revisiting Peruvian anchovy (*Engraulis ringens*) tropho-dynamics provides a new vision of the Humboldt Current system. Prog. Oceanogr. 79, 215–227.
Falvey, M., Garreaud, R.D., 2009. Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of south tropical South America (1979–2006). J. Geophys. Res. 114, D04102, http://dx.doi.org/10.1029/2008JD010519.
Farías, L., Besoain, V., García-Loyola, S., 2015. Presence of nitrous oxide hotspots in the coastal upwelling area off central Chile: an analysis of temporal variability based on ten years of a biogeochemical time series. Environ. Res. Lett. 10http://dx.doi.org/10.1088/1748-9326/10/4/044017.
Fuenzalida, R., Schneider, W., Garces, J., Bravo, L., Lange, C., 2009. Vertical and horizontal extension of the oxygen minimum zone in the eastern South Pacific Ocean. Deep-Sea Res. II 56, 992–1003, http://dx.doi.org/10.1016/j.dsr2.2008.11.001.
Garreaud, R., Falvey, M., 2009. The coastal winds off western subtropical South America in future climate scenarios. Int. J. Climatol. 29, 543–554, http://dx.doi.org/10.1002/joc.1716.
Grados, D., Fablet, R., Ballón, M., Bez, N., Castillo, R., Lezama-Ochoa, A., Bertrand, A., 2012. Multiscale characterization of spatial relationships among oxycline depth, macrozooplankton, and forage fish off Peru using geostatistics, principal coordinates of neighbour matrices (PCNMs), and wavelets. Can. J. Fish Aquat. Sci. 69, 740–754.
González, H., Daneri, G.-, Iriarte, J.L., Yannicelli, B., Menschel, E., Barría, C., Pantoja, S., Lizárraga, L., 2009. Carbon fluxes within the epipelagic zone of the Humboldt Current System off Chile: the significance of euphausiids and diatoms as key functional groups for the biological pump. Prog. Oceanogr. 83, 217–227.
Goubanova, K., Echevin, V., Dewitte, B., Codron, F., Takahashi, K., Terray, P., Vrac, M., 2011. Statistical downscaling of sea-surface wind over the Peru–Chile upwelling region: diagnosing the impact of climate change from the IPSL-CM4 model. Clim. Dyn. 36, 1365–1378.
Gutiérrez, D., Gallardo, V.A., Mayor, S., Neira, C., Vásquez, C., Sellanes, J., Rivas, M., Soto, A., Carrasco, F., Baltazar, M., 2000. Effects of dissolved oxygen and fresh organic matter on the bioturbation potential of macrofauna in sublittoral sediments off central Chile, during the 1997-98 El Niño. Mar. Ecol. Prog. Ser. 202, 81–99.
Gutiérrez, D., Sifeddine, A., Field, D., Ortlieb, L., Vargas, G., Chávez, F., Velazco, F., Ferreira, V., Tapia, P., Salvatteci, R., Boucher, H., Morales, M., Valdés, J., Reyss, J.-L., Campusano, A., Boussafir, M., Mandeng-Yogo, M., García, M., Baumgartner, T., 2009. Rapid reorganization in ocean biogeochemistry off Peru towards the end of the Little Ice Age. Biogeosciences 6, 835–848.
Gutiérrez, D., Bouloubassi, I., Sifeddine, A., Purca, S., Goubanova, K., Graco, M., Field, D., Méjanelle, L., Velazco, F., Lorre, A., Salvatteci, R., Quispe, D., Vargas, G., Dewitte, B., Ortlieb, L., 2011. Coastal cooling and increased productivity in the main upwelling cell off Peru since the mid-twentieth century. Geophys. Res. Lett. 38. L07603-1–L07603-6.
Gutiérrez, D., Tam, J., Romero, C. Espinoza, D., Quispe, C., Echevin. V., F. Chavez, 2015. Recent trends in the Peruvian Coastal Upwelling Ecosystem and climate change scenarios: challenges for adaptation. International Conference "Marine and human systems: Addressing multiple scales and multiple stressors (IMBIZO IV)", 27-30 October 2015, Trieste, Italy.
Halpern, D., 2002. Offshore Ekman Transport and Ekman Pumping off Peru during the 1997-98 El Niño. Geophys. Res. Lett. 29 (5). 10.1029/2001GL014097.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1535.
Iriarte, J.L., González, H., Liu, K.K., Rivas, C., Valenzuela, C., 2007. Spatial and temporal variability of chlorophyll and primary productivity in surface waters of southern Chile (41.5–43°S). Estuar. Coast. Shelf Sci. 74, 471–480.
Jahncke, J., Checkley, D., Hunt Jr., G.L., 2004. Trends in carbon flux to seabirds in the Peruvian upwelling system: effects of wind and fisheries on population regulation. Fish Oceanogr. 3 (13), 208–223.

Kao, H.Y., Yu, J.Y., 2009. Contrasting eastern-Pacific and central-Pacific types of El Niño. J. Clim. 22, 615–632.
Lam, P., Lavik, G., Jensen, M., van de Vossenberg, J., Schmid, M., Woebken, D., Gutierrez, D., Amann, R., Jetten, M., Kuypers, M., 2009. Revising the nitrogen cycle in the Peruvian oxygen minimum zone. Proc. Nat. Acad. Sci. 106, 4752–4757.
Longhurst, A.R., 2007. Ecological geography of the sea, 2nd. Edition Academic Press542.
Miloslavich, P., Klein, E., Díaz, J.M., Hernández, C.E., Bigatti, G., et al. 2011. Marine Biodiversity in the Atlantic and Pacific Coasts of South America: Knowledge and Gaps. PLoS ONE 6(1): e14631. http://dx.doi.org/10.1371/journal.pone.0014631.
Molina, V., Morales, C.E., Farías, L., Cornejo, M., Graco, M., Eissler, Y., Cuevas, L.A., 2012. Potential contribution of planktonic components to ammonium cycling in the coastal area off central-southern Chile during non-upwelling conditions. Prog. Oceanogr. 92–95, 43–49.
Mollier-Vogel, E., Leduc, G., Böschen, T., Martinez, P., Schneider, R., 2013. Rainfall response to orbital and millennial forcing in northern Peru over the last 18 ka. Quat. Sci. Rev. 76, 29–38.
Montecino, V., Pizarrio, G., Quiroz, D., 1998. Primary production off the Chilean coast. In: Hollowary, G., Muller, P., Henderson, D. (Eds.), Proceedings of the Aha Huliko'a Hawaiian Winter Workshop: 69-76. Biotic impact of extratropical climate variability in the Pacific, School of Ocean and Earth Science and Technology (SOEST) Special Publication. University of Hawaii at Manoa, Honolulu, USA.
Montecino, V., Strub, T., Chavez, F., Thomas, A., Tarazona, J., Baumgartner, T., 2006. Bio-physical interactions off Western South-America. In: Robinson, A.R., Brink, K.H. (Eds.), The Sea. The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses, Vol. 14. , Harvard Press, USA, pp. 329–390.
Montecino, V., Pizarro, G., 2006. Productividad primaria, biomasa y tamaño del fitoplancton en canales y fiordos australes: patrones primavera-verano. In: Silva, N., Palma, S. (Eds.), Avances en el conocimiento oceanográfico de las aguas interiores chilenas, Puerto Montt a cabo de Hornos., Comité Oceanográfico Nacional-Pontificia Universidad Católica de Valparaíso, Valparaíso, pp. 93–97.
Montes, I., Colas, F., Capet, X., Schneider, W., 2010. On the Pathways of the Equatorial Subsurface Currents in the Eastern Equatorial Pacific and their contributions to the Peru–Chile Undercurrent. J. Geophys. Res. 115, C09003, http://dx.doi.org/10.1029/2009JC005710.
Morales, C.E., Hormazabal, S.E., Blanco, J.L., 1999. Interannual variability in the mesoscale distribution of the depth of the upper boundary of the oxygen minimum layer off northern Chile (18–241S): implications for the pelagic system and biogeochemical cycling. J. Mar. Res. 57, 909–932.
Muck, P., 1989. Major trends in the upwelling system off Peru and their implications for management, p. 386-403. In: D. Pauly, P. Muck, J. Mendo and I. Tsukayama (eds.). The Peruvian upwelling ecosystem: dynamics and interactions. ICLARM Conference Proceedings 18, 438 p. Instituto del Mar del Perú (IMARPE), Callao, Perú; Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), GMBH, Eschborn, Federal Republic of Germany; and International Center for living Aquatic Resources Management (ICLARM), Manila, Philippines.
Narayan, N., Paul, A., Mulitza, S., Schulz, M., 2010. Trends in coastal upwelling intensity during the late 20th century. Oceanogr. Sci. 6, 815–823, http://dx.doi.org/10.5194/os-6-815-2010.
Nixon, S., Thomas, A., 2001. On the size of the Peru upwelling ecosystem. Deep-Sea Res. I 48, 2521–2528.
Ñiquen, M., Bouchon, M., 2004. Impact of El Niño events on pelagic fisheries in Peruvian waters. Deep-Sea Res. II 51, 563–574.
OHI, 2015. http://www.oceanhealthindex.org/region-scores/annual-scores-and-rankings.
Quiñones, R.M.H., Gutiérrez, G., Daneri, D., Gutiérrez Aguilar, H., González, Chavez, F., 2009. Pelagic carbon fluxes in the Humboldt Current System. In: Liu, K.-K., Atkinson, L., Quiñones, R., Talaue-McManus, L. (Eds.), Carbon and Nutrient Fluxes in Continental Margins: a Global Synthesis, Springer-Verlag, Weinheim, pp. 44–64. Chapter 2.3. Series: Global Change-The IGBP Series.
Rykaczewski, R., Checkley, D.M., 2008. Influence of ocean winds on the pelagic ecosystem in upwelling regions. PNAS 105, 1965–1970.
Salvatteci, R., Gutiérrez, D., Field, D., Sifeddine, A., Ortlieb, L., Bouloubassi, I., Boussafir, M., Boucher, H., Cetin, F., 2014. The response of the Peruvian Upwelling Ecosystem to centennial-scale global change during the last two millennia. Climate 10, 715–773.
Sánchez, G.E., Lange, C., González, H., Vargas, G., Muñoz, P., Cisternas, C., Pantoja, S., 2012. Siliceous microorganisms in the upwelling center off Concepción, Chile (36°S): preservation in surface sediments and downcore fluctuations during the past 150 years. Prog. Oceanogr. 92–95, 50–65.
Serra, R., Akester, M., Bouchón, M., Gutiérrez, M., 2012. Sustainability of the Humboldt Current Large Marine Ecosystem. In: Sherman, K., McGovern, G., Frontline observations on climate change and sustainability of Large Marine Ecosystems. Vol. 17, pp. 112–134.
Sifeddine, A., Gutierrez, D., Ortlieb, L., Boucher, H., Velazco, F., Field, D., Vargas, G., Boussafir, M., Salvatteci, R., Ferreira, V., García, M., Valdes, J., Caquineau, S., Mandeng Yogo, M., Cetin, F., Solis, J., Soler, P., Baumgartner, T., 2008. Laminated sediments from the central Peruvian continental slope: a 500 year record of upwelling system productivity, terrestrial runoff and redox conditions. Prog. Oceanogr. 79, 190–197.
SUBPESCA, 2015. Estado de situación de las principales pesquerías chilenas-2014. ⟨http://www.subpesca.cl/prensa/601/articles-87256_recurso_1.pdf⟩.
Stramma, L., Johnson, G.C., Sprintall, J., Mohrholz, V., 2008. Expanding oxygen minimum zones in the tropical oceans. Science 320, 655–658.
Stramma, L., Schmidtko, S., Levin, L.A., Johnson, G.C., 2010. Ocean oxygen minima expansions and their biological impacts. Deep-Sea Res. I 57, 587–595.
Sydeman, W.J., García-Reyes, m, Schoeman, W.S., Rykaczewski, R., Thompson, S.A., Black, B.A., Bograd, S.J., 2014. Climate change and wind intensification in coastal upwelling ecosystems. Science, 345; 77–80.
Swartzman, G., Bertrand, A., Gutiérrez, M., Bertrand, S., Vasquez, L., 2008. The relationship of anchovy and sardine to water masses in the Peruvian Humboldt Current System from 1983 to 2005. Prog. Ocean. 79, 228–237.
Takahashi, K., Montecinos, A., Goubanova, K., Dewitte, B., 2011. ENSO regimes: Reinterpreting the canonical and Modoki El Niño. Geophys. Res. Lett. 38, L10704, http://dx.doi.org/10.1029/2011GL047364.
Tam, J., Taylor, M., Blaskovic, V., Espinoza, P., Ballón, M., Díaz, E., Wosnitza-Mendo, C., Argüelles, J., Purca, S., Ayón, P., Quipuzcoa, L., Gutierrez, D., Goya, E., Ochoa, N., Wolff, M., 2008. Trophic modeling of the Northern Humboldt Current Ecosystem, Part I: comparing trophic linkages under La Niña and El Niño conditions. Prog. Oceanogr. 79, 352–365.
Torres, R., 1995. Condiciones oceanográficas y baja concentración de clorofila frente a Coquimbo-Chile (Lat. 30°S) durante 1992–1994 (M.Sc. thesis). Universidad de Concepcion, Chile123.
Troncoso, V.A., Daneri, G., Cuevas, L.A., Jacob, B., Montero, P., 2003. Bacterial carbon flow in the Humboldt Current System off Chile. Mar. Ecol. Prog. Ser. 250, 1–12.
Strub, P.T., Mesías, J.M., Montecino, V., Rutllant, J., 1998. Coastal ocean circulation off western South America. In: Robinson, A.R., Brink, K.H. (Eds.), The Global Coastal Ocean: Regional Studies and Syntheses. The Sea, 11. , John Wiley & Sons, New York, pp. 237–313.
Pennington, J.T., Mahoney, K.L., Kuwahara, V.S., Kolber, D., Calienes, R., Chavez, F.P., 2006. Primary production in the eastern tropical Pacific: a review. Prog. Oceanogr. 69, 285–317.
Valdés, J.L., Ortlieb, D., Gutiérrez, L., Marinovic, G., Vargas, Sifeddine, A., 2008. A 250 years–sedimentary record of sardine and anchovy scale deposition in Mejillones Bay, 23°S, Northern Chile. Prog. Oceanogr. 79, 198–207.
Vargas, C.A., Martínez, R.A., Cuevas, L.A., Pavez, M.A., Cartes, C., González, H.E., Escribano, R., Daneri, G., 2007. The relative importance of microbial and classical food webs in a highly productive coastal upwelling area. Limnol. Oceanogr. 52, 1495–1510.
Vargas, G., Pantoja, S., Rutllant, J., Lange, C., Ortlieb, L., 2007. Enhancement of coastal upwelling and interdecadal ENSO-like variability in the Peru-Chile Current since late 19th century. Geophys. Res. Lett. 34, L13607, http://dx.doi.org/10.1029/2006GL028812.
Wang, D., Gouhier, T.C., Menge, B.A., Ganguly, A.R., 2015. Intensification and spatial homogenization of coastal upwelling under climate change. Nature 518, 390–394.
Yeh, S.W., Kug, J.S., Dewitte, B., Kwon, M.H., Kirtman, B.P., Jin, F.F., 2009. El Niño in a changing climate. Nature 461, 511–514.