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CENSOR

Climate variability and El Niño Southern Oscillation: Implications for natural coastal resources and management

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Climate variability and El Niño Southern Oscillation: Implications for Natural Coastal Resources and Management

The CENSOR Consortium

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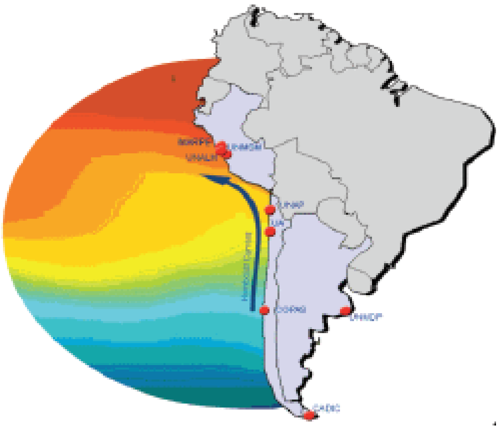

Preamble: The project "Climate variability and El Niño Southern Oscillation: Implications for Natural Coastal Resources and Management" (CENSOR) was funded within the FP6-INCO Programme of the European Commission. CENSOR targeted the study of ENSO effects on near-shore coastal environments and related socio-economics along Pacific South America. Here, we provide an overview of various scientific areas tackled within the project rather than aiming for an integrated view of the ecosystem and management problems associated with ENSO in Pacific South America alone. The compilation of past and ongoing work clearly marks the complexity of the Humboldt Current ecosystem in response to both El Niño and La Niña, which complicates management solutions. As a result, it becomes obvious that a management for sustainability of coastal areas within this upwelling system depends on locally adapted and flexible small-scale approaches; a management approach that cannot simply transfer experiences made with macro-economic management attempts. We advocate that multidisciplinary studies centered on organismal research remain the key to our increased understanding of the response to ENSO of coastal species of interest to artisanal resource users and the ecosystems within which the resources are embedded. The impact of such studies for possible mitigation of climate effects on marine ecosystems and the analysis of options for the human communities affected tends to be underrated. Herein, we present a series of compelling cases generated from across CENSOR work and incorporating the advance of the state-of-the-art from our research.

Summary

The El Niño Southern Oscillation (ENSO) significantly influences marine ecosystems and the sustained exploitation of marine resources in the coastal zone of the Humboldt Current upwelling system. Both its warm (El Niño: EN) and cold (La Niña: LN) phase have drastic implications for the ecology, socio-economy and infrastructure along most of Pacific South America. Local artisanal fisheries, which are particularly affected by EN, represent a major activity for the domestic economy of Pacific South America and in consequence a huge amount of published and unpublished studies exist aiming at identifying effects of EN and LN. However, most processes and underlying mechanisms fostering the ecology of organisms along Pacific South America have not yet been analyzed and for the marine realm most knowledge is traditionally based on rather descriptive approaches. We advocate that small-scale comparative and interdisciplinary process studies work as one possible solution forward a better understanding of the variability observed in EN/LN effects on a local scale. We propose that differences in small-scale impacts of ENSO along the coast rather than the macro-ecological and oceanographic view are essential for the sustainable management of costal ecosystems and the livelihood of the people depending on it. We summarize the conceptual approach and results from the EU-funded International Science & Technology Cooperation (INCO) project 'Climate variability and El Niño Southern Oscillation: implications for natural coastal resources and management (CENSOR)' that aims at enhancing the detection, compilation and understanding of EN and LN effects on the coastal zone and its natural resources. We promote a multidisciplinary avenue within present international funding schemes, with the intention of bridging the traditional gap between basic and applied coastal research. The long-term aim is an increased avoidance of negative effects of EN as well as a better use of beneficial effects, with the possibility of improving the livelihood of human coastal populations along Pacific South America taking differences between local socio-economic structures of the countries affected by EN into consideration. The success of such an approach however, does finally rely upon a willingness of the resource users and the various political and economic stakeholders involved to take on the message as part of sustainable management strategies.

ENSO along the western Americas

Eastern Boundary Currents play a decisive part in the budgets of both the Pacific and the Atlantic Ocean, including latitudinal heat exchange, ocean-atmosphere interactions, organism transport and genetic interchanges. They are the great motors of the circular oceanic current systems, transporting cold water into tropical and equatorial regions,and highly efficient ecosystems in which nutrients are returned to the surface layers of the ocean where they can be used by photosynthetic primary producers (Thiel et al. 2007, and references therein).

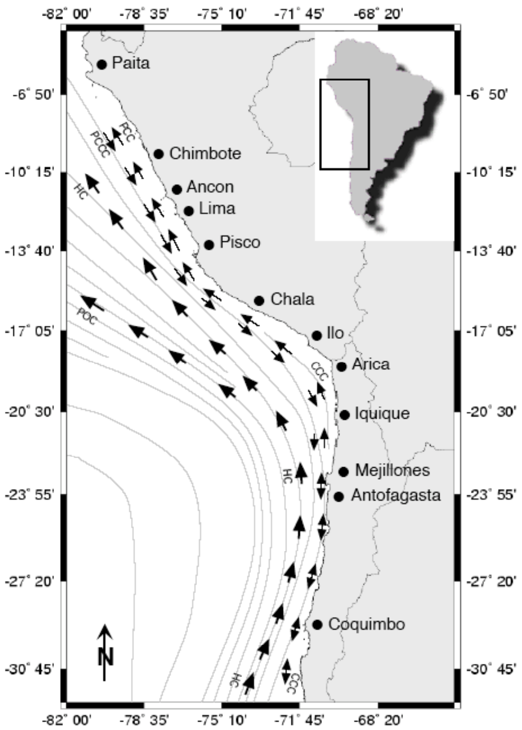

Figure 1 Scheme of the surface currents off the studied South American Pacific coast, showing the main flow of the Humboldt Current (HC), the Chile Coastal Current (CCC), the Peru Coastal Current (PCC), the Peru-Chile Counter Current (PCCC) and the Peru Oceanic Current (POC) (after Thatje et al. 2008).

In recent years monitoring of the sea surface temperature in eastern boundary currents of the Pacific Ocean (Humboldt Current off Chile and Peru, Fig. 1; California Current off USA and Mexico) has illustrated that the El Niño-Southern Oscillation (ENSO) is an interannual climate oscillation between warm phases (El Niño: EN) and enhanced cold phases (La Niña: LN) (Figs. 2, 3). These two stages of the ecosystem emerge from a background of „normal" conditions, which exhibit a large amount of meteorological and oceanographic noise. EN occurs at intervals of two to ten years (strong events every 13 - 70 years: e.g., 1925-26, 1982-83 and 1997-98) with an average return period of four years. It may last between half a year and several years in duration (Fig. 3). Thus ENSO constitutes the major intra-decadal variability in the Chilean-Peruvian coastal upwelling system. However there may also be a superposition by decadal climate oscillation, e.g. the Pacific Decadal Oscillation, and possibly also by global warming (Timmermann et al. 1999, Baumgartner and Ortlieb 2002) the effects of which may have begun to influence the development and intensity of EN and are yet far from being understood.

Some of the best data on climate impact available refer to EN as a consequence of the fact that the two strong EN events 1982-83 and 1997-98 were exceptionally well documented (e.g. Barber and Chávez 1983, Chávez et al. 1999, Tarazona et al. 2001). Both events showed major differences concerning the signals of the marine biota. These different biological responses were apparently not due to different intensity of physical changes along the equator, but were rather related to the distinct seasonal onset of EN. The 1982-83 EN event started in austral spring, just before the reproductive season and showed had much stronger effects on marine communities of the Humboldt Current, than the EN 1997-98 starting in austral autumn. For the northern hemisphere upwelling ecosystem of the

California Current the impact were reserved, according to the different reproductive periods of marine organisms (Arntz 2002).

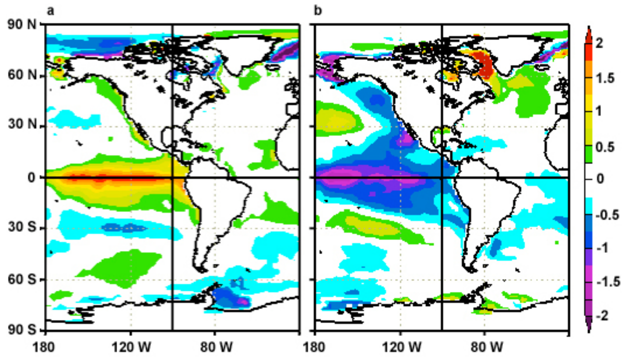

Figure 2 Winter (March to November) sea surface temperature (°C) anomaly showing (a) El Niño conditions (mean data from 1958, 1966, 1969, 1973, 1983, 1987, 1992, 1999) and (b) La Niña conditions (mean data from 1955, 1956, 1965, 1971, 1974, 1976, 1989, 1999) (NOAA-CIRES Climate Diagnostics Centre, University of Colorado at Boulder. USA).

Oceanographic changes associated with EN include Kelvin waves towards and along the coast and a rise of the near-shore sea level in the eastern Pacific connected with a deepening of the thermocline. Thus upwelling takes place only in the mixed layer without returning nutrients from the bottom water to the surface layer (Barber and Chávez 1983). Moreover, the trade wind stress driving the upwelling may be lowered. Further effects are an increment of the sea surface temperature (in extreme EN years up to 10°C) during several weeks, alterations in water circulation and subsequent changes in advection, an increase of dissolved oxygen concentration at the normally hypoxic soft bottoms, agitated sea and changes in UV radiation (Arntz and Tarazona 1990, Tarazona and Arntz 2001).

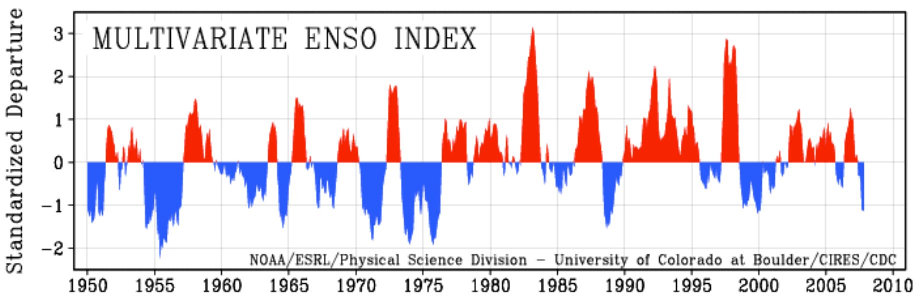

Figure 3 Multivariate ENSO Index related to warm (redey) and cold (blue) conditions (NOAA-CIRES Climate Diagnostics Center, University of Colorado at Boulder).

Arid regions of Peru and Chile receive tremendously increased rainfall during strong ENs. Such heavy precipitation causes flash floods, river inundations, erosion, mudflows, and landslides. The flood-transported sediments spill dwellings, waterworks, roads, and cropland (Glantz 1984). The significant increase of fresh water input (which changes the surface salinity), the increased sediment load and associated nutrients to the coastal system is a major boundary condition for the near-shore marine ecosystem.

These oceanographic changes have drastic effects on the marine biota. However, the affect on the ecosystem depends on the time of onset of the event, its duration and intensity, the distance from the main impact zone along the equator, and the water depth, among other factors (Arntz et al. 2006; Fischer and Thatje 2008). Moderate, strong and very strong EN events are not only of meteorological, oceanographic and biological interest, but also have major economic, infrastructural and social consequences for the countries adjacent to the Pacific coast, which may amount to billions of USD (Arntz and Fahrbach 1991). Most of these impacts are direct and negative.

However, there are also positive effects provoked by EN. Under EN conditions soft-bottom hypoxia decreases in the oxygen minimum zone (OMZ) (Kamykowski and Zentara 1990; Levin et al. 2002; Escribano et al. 2004) followed by an ecological succession to more mature stages and thus increasing diversity of benthic communities (Tarazona et al. 1988a, b, 1996; Gutiérrez et al. 2000; Peña et al. 2006; Laudien et al. 2007). Additionally, mass development of certain species with commercial value for local artisanal and/or aquaculture industry, such as the scallop *Argopecten purpuratus*, the gastropod *Thais chocolata*, and the octopus *Octopus mimus* are observed (Wolff 1987; Arntz et al. 1987; Arntz et al. 1988). Exploitable species from tropical (warmer) waters or the open ocean immigrate in the normally cool coastal waters, including the stalked barnacle *Pollicipes elegans*, various species of penaeid shrimps (Arntz et al. 1988) and many commercially exploited fish species of high value such as dolphinfish (*Coryphaena hippurus*) and scombrids (i.e. tuna) (Arntz and Fahrbach 1991; Lehodey 2001).

Each EN develops in a different way, and despite an enormous scientific effort including satellites, buoy arrays at the sea surface and to a lesser amount at depth, research vessels, merchant ships and coastal stations, its origins are still an unsolved problem. A timely prediction would be of high interest to the coastal human populations due to the socioeco-nomic significance of this climate driven phenomenon. This is even more urgent since recent results indicate that in a realistic scenario of increasing greenhouse-gas concentra-tions more frequent EN-like conditions should to be expected (e.g. Timmermann et al. 1999, IPCC 2007).

Despite all modelling attempts (e.g., Harrison and Larkin 1998, Latif et al. 1998, McPhaden 1999; Taylor et al 2008) reliable prediction is not yet possible for more than three months in advance. This also applies for biological prediction via indicator species. Spatial differences in EN effects are apparent (i.e. Laudien et al. 2007, Ashton et al. 2008) and seeming to depend on the intensity of EN, but remain little considered in current management approaches.

Reconciling multiple demands on coastal zones

The CENSOR project aims to help to reconcile the multiple demands on limited resources, in particular artisanal fishery resources, in the coastal zone of the Humboldt Current ecosystem. The most effective way to mitigate this situation is to improve the knowledge and predictive capabilities in order to allow a proper balance between the sustainable use of natural marine resources and the economic and socio-economic requirements. Marine scientists are therefore increasingly trying to understand the environmental effects of specific climatic conditions (EN/LN) on marine ecosystems with the aim to advise decision makers on the rational use of natural resources. Single research disciplines cannot provide the necessary information for integrated ecosystem management, since they are unable to cover all relevant scientific aspects for sound ecosystem management.

The value of biological approaches to EN, besides the definite confirmation of an event (including predictions by utilizing e.g. indicator species), nowadays refers rather to the accumulated long-term experience, where what kind of negative or positive effects can be expected. Both the abiotic environmental changes and the biotic effects are largely recurrent, i.e. they usually occur at the same localities, and the organisms concerned always react in very similar ways. However, in most cases an early warning of EN a few months in advance would provide the opportunity of reacting to certain well-known changes or impacts.

This knowledge, if applied in time, could potentially prevent considerable damage and allow better use of alternatives. The indicators of EN events resulting from organismal and ecosystem studies could become substantial and sustainable tools to be used in early warning/prediction systems and thus relevant to managers of environmental quality control and sustainable development, not only along Pacific South America.

The ecosystem (organismal) approach to coastal ENSO research

The CENSOR consortium identified four complementary research areas in order to enable the development of a comprehensive ecosystem management approach along the Pacific coast off South America, and which are conceptually summarized as follows:

Coastal benthic communities

The relative influence of nutrient availability ('bottom-up') vs. predation ('top-down') as the main forces controlling community structures and dynamics has been debated for a variety of habitats and is particularly important in upwelling areas (Fig. 4). The different primary producers supporting coastal food webs may be benthic microalgae (Sullivan and Moncreif 1990), macroalgae or phytoplankton (Deegan and Garritt 1997), which can be fostered by nutrient input through watersheds (Valiela et al. 1997). Studies of coastal community responses to nutrient enhancement showed inconsistent results, apparently because their trophic connections include a higher diversity of primary producers and consumers. Thus, coastal food webs may be more resilient to changes in sources of primary production or predation level (and hence harvesting). EN changes the availability of nutrients, and thus it is likely that community control (and production of commercial marine resources) changes from bottom-up to top-down controlled (Hidalgo et al. 2008). Information from recent moderate and strong EN events (e.g. 1982/83, 1987/88, 1991-93, 1997/98) as well as LN events (e.g. the strong and longer than usual 1998-2001 event) demonstrated differences in the resilience potential of coastal communities (Laudien et al. 2007, Moreno et al. 2008).

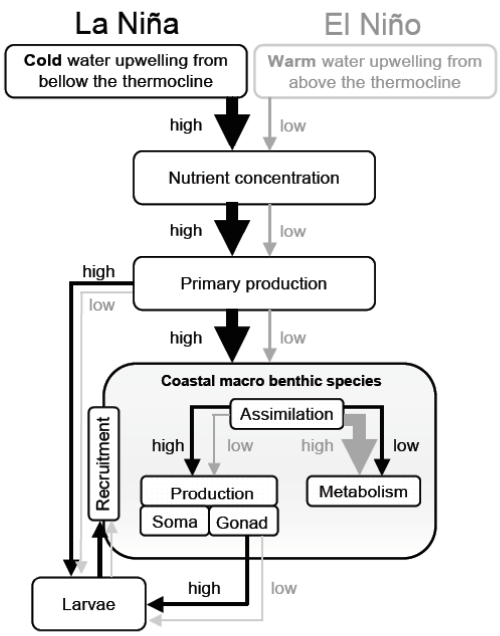

Figure 4 Owing to the high concentration of nutrients, the Humboldt Current upwelling system is the most productive marine ecosystem of the world upwelling fuels high primary and secondary production by bringing nutrient-rich water to the surface layers. Under El Niño conditions water temperature increases and the thermocline drops, which limits upwelling to the nutrient-poor surface layer. This in turn reduces primary production. Thus. Less energy can be assimilated by i.e. suspension feeding coastal macrozoobenthos. Additionally, increased temperatures impact the organisms. Even when temperatures are not lethal, more energy is necessary for metabolism under stress (Poertner 2002). This means a greater amount of energy has to be allocated to metabolic energy and less "surpluss" energy is available for reproduction and somatic growth. Temperature is often a trigger for reproduction, which in consequence might be altered during El Niño.

Larval supply to coastal communities is another major structuring force (Underwood 1997, Grosberg and Levitan 1992), which is highly affected by EN. Also, LN impacts recruitment rates by decreased water temperature and thus growth and reproductive output and/or changing larval transport (Navarrete et al. 2002).

A third driving factor is ecosystem engineering (*sensu* Jones et al. 1994), which refers to the changing of habitats by organisms. Shells and structures of macroalgae are good examples, which modify the mortality rate of many species (Gutiérrez and Iribarne 2000, Gutiérrez et al. 2003, Hidalgo et al. 2008) and provide a suitable habitat. Given that one characteristic manifestations of EN is the proliferation of local molluscs (*Argopecten purpuratus*, *Thais chocolata*; e.g., Arntz et al. 1987, Arntz et al. 1988, Wolff 1987), ecosystem-engineering effects are potentially important in EN main impact areas.

Pelagic-benthic processes and terrestrial impact

EN causes changes in oceanographic conditions (i.e. intensity of upwelling) in both space and time. Pelagic populations have to cope with these altered conditions. Therefore, the understanding of physical-biological interactions in the water column of upwelling systems provides important insight into the key processes that control production and population dynamics of pelagic species (Escribano et al. 2002, 2004). For the Humboldt Current upwelling area, two key study areas for the understanding of pelagic-benthic processes are,

(1) The mechanisms, through which the changes in the physico-chemical structure of the water column affect the coastal ecosystem (Fig. 4). The OMZ appears as prime candidate for a key mechanism, which transfers the climate signal to the ecosystem and affects the productivity and carbon flux in the near shore region; hence, the feeding conditions for shallow benthic organisms (Gutierrez et al. 2000; Escribano et al. 2004). While a general concept of the role of the OMZ has been developed recently (Escribano et al. 2004) dedicated measurements are still lacking for a more detailed understanding of the mechanism involved.

(2) The retention mechanisms that enable plankton, meroplankton, and fish larvae to successfully complete their life cycle in coastal waters. For some species regional studies have shown a complex interaction between the organisms and the hydrography (Arntz and Fahrbach 1991; Escribano et al. 2002, Criales et al. 2008). These studies need complementation by studying key fish larvae and meroplankton species.

EN/LN are associated with a regime shift in the pelagic system, from the classic diatom - large copepods - fish food chain to a microbial dominated system of bacteria - flagellates - microzooplankton - small copepods, which directly affects the feeding conditions in the pelagic and indirectly in the benthos through changes in the settling particle fluxes (Escribano et al. 2004, Noethig and Gowing 1991, Thiel et al. 2007). Nevertheless, phytoplankton biomass and production apparently do not change significantly during the ENSO cycle (Escribano et al. 2004). Studies of trophic interactions in the pelagic and the effect on the particle flux to the benthos are still lacking and are necessary for the understanding of energy flux shifts during ENSO.

It is well known, that vertical biogenic-particle fluxes (e.g., C, N) may be greatly influenced by changes in the community structure of the pelagic realm (González et al. 2000). Such changes might result from population responses (e.g., plankton distribution) to varying oceanographic conditions driven by climate variations (e.g., ENSO). However, in the coastal zone of the HCS the relationships among these processes are far from being understood, despite the fact that modern oceanography clearly accepts the idea that biogenic fluxes and their underlying mechanisms are key issues relating climate change and associated ecosystem responses.

El Niño events heavily affect the continental areas in Peru and Chile, ranging from intense droughts particularly in the high Andes to tremendously increased rainfall in arid regions. Such heavy precipitation causes flash floods, river inundations, erosion and landslides. The transport of water and sediments to the coastal system is intensified, being a major boundary condition for the coastal marine environment. Quantification of the flux of freshwater to the coastal marine system and estimation of related sediment transports are absent or locally restricted and the obvious terrestrial-marine interactions in sediment flow remain obscure. It is necessary to characterize and model the hydrological behaviour for EN/LN. This is important to quantify the average mass transport to the coastal marine system, and for defining the initial conditions for extreme events of runoff generation, erosion or landslides.

Ecophysiological constraints and aquacultural demands

Studies of coastal ecosystems in the Humboldt Current system off South America have traditionally been rather descriptive. Data acquisition on macrobenthic communities and/or the pelagic regime over time revealed changes in e.g. abundance, biomass and biotic composition related to ENSO. However, the pattern underlying ecophysiological processes, which explain diversity and biogeographic shifts (Pörtner 2001), changes in growth patterns and reproductive traits related to ENSO, remain principally undefined. One of the parameters usually indicating a changing climate is a change in temperature (Schellenhuber and Sterr 1993). Temperature changes can, directly or indirectly affect marine populations during all life stages (Urban 1994, Pörtner 2001, Heilmayer et al. 2004). Assessing the influence of changing temperature regimes as indicative of decadal-scale climate variation or change on the adult stages of key species, including invaders during EN (such as shrimp, *Xiphopenaeus riveti* see also Ashton et al. 2008) as well as such species, which suffer from mass mortality due to increased water temperatures associated to EN (e.g., *Mesodesma donacium*, *Aulacomya atra*, *Cancer* spp. *Platycanthus orbignyi*) is crucial for a better understanding of how ENSO affects species biogeography and eventual mass mortalities of key species. Assessing physiological temperature limits in commercial or ecosystem key species is particularly important if we want to understand the vulnerability of these organisms in response of variable EN intensity. This could be a key to short-term prediction of the availability of key organisms to fisheries during EN. Furthermore, it allows simple but necessary management advise as to the survival potential of natural and aquaculture stocks. Towards this goal, a profound synthesized knowledge of ecological and physiological processes is required which can only be gained by an interdisciplinary combination of ecological, physiological, genetic and modelling investigations.

From knowledge to resource management

Research to improve the understanding of coastal zones, to support the human communities living in and from this area, requires a shared interdisciplinary framework, in order to help reconciling the multiple demands on limited resources, mitigate degradation, and find equitable, innovative solutions appropriate to the social, economic, institutional and environmental contexts of developing countries (Nauen et al. 2006). This initially requires a detailed review, integration and dissemination of traditionally available datasets (published and unpublished resources, see Thatje et al. 2007) that serve as a baseline for ecosystem studies and upon which scientific gaps are identified. The traditionally descriptive data available from the coastal upwelling ecosystem off South America need augmentation by the results obtained from selected process studies, as previously outlined, which aim to integrate and explain the universality of patterns for coastal upwelling systems elsewhere. Here, it is particularly important to distinguish between patterns related to climate dependent (EN) changes in coastal ecosystems and human impacts such as overexploiting economically important fishery targets. Additionally, terrestrial fluxes of water and sediment to the coastal zone, which tremendously differ between normal and EN-conditions have an impact on the coastal marine environment.

The importance of "Grey Literature" in ENSO research

The ENSO phenomenon has received a great increase of interest since the severe EN in 1981/82, which is indicated by a steep increase in the number of publications of the following years (Fig. 5). This pattern is coherent in "organism and ecosystem, and "climate change and physical environmental studies", with a decline in publication activity during the early 1990ies following the first peak of publications in 1985/86, which coincided with the 1987/88 EN event (Thatje et al. 2007).

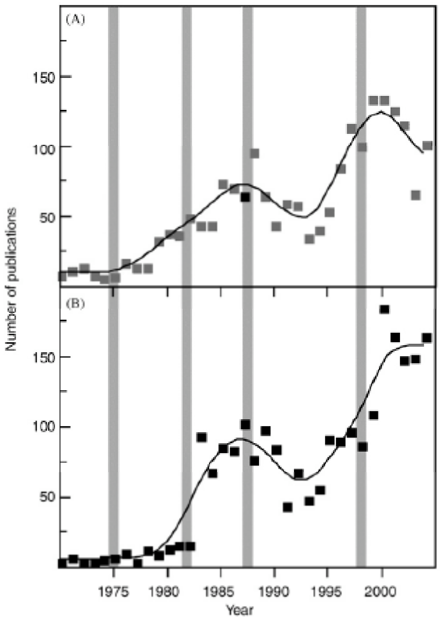

Figure 5 The contribution of Grey Literature (NON-ISI) to ENSO literature of **A)** Organisms and ecosystems and **B)** Climate change and physical studies. Trend lines are fitted with JMPv 5.1 and present a "smoothing spline fit (lamba=10)". Grey bars indicate major El Niño events.

"Grey Literature" contributed a high and constant share to organism and ecosystem studies focussing on the regional scale in the past 25 years (>60% of all; more than 66% of "Grey Literature" is written in Spanish), with a recent decline since the year 2000. This points at another problem in disseminating the knowledge gained in "Grey Literature" at international scale - the language barrier - a large, but manageable challenge to databases, which needs more and specific attention. Whereas the language barrier might be manageable in database management in a longer perspective, it is striking at present that primary ISI journals rarely cite articles written in Spanish, which mostly represent "Grey Literature". Although this observation may need further analyses, it might either be the citation policy in high-profile journals that discourage the citation of "Grey Literature", or a language barrier problem. The latter would not explain why Hispanic authors publish increasingly in English without making massive reference to publications in Spanish. From empirical experience we suggest that it may be a mixture of several factors with the positive element of creating a vast intellectual space with English effectively as the universal *lingua franca* in the sciences, but with a shrinking space for scientific expression in other languages and a potentially growing gap between scientists and other citizens, especially those unfamiliar with English. Our quantitative analyses on the importance of “Grey Literature” do not reflect quality of scientific work. It is likely that peer-reviewed ISI journals, on average, achieve a higher and more reliable scientific standard. However, “Grey Literature” represents data and information that still is very valuable in a comprehensive and long-term view, indeed, in some cases it may be the only source.

In the past, EN events have been the predominant driving factors in fostering research on impacts of the same (Fig. 5). It is striking, however, that the appearance of EN, which is of catastrophic proportions for the countries off Pacific South America and the coastal communities living there (e.g. Arntz and Fahrbach 1996), is not reflected in a coherent increase in socio-economic studies. It seems that ENSO knowledge in the natural sciences is not matched by equivalent study on the interaction between ENSO, ecosystems and society. Investigating such linkages appears by far more challenging and urgent than we had previously believed. The INCO-Programme’s emphasis on integrated approaches will be useful here by ‘forcing’ the different disciplines and stakeholders to engage and cooperate actively.

The recent decline in “Grey Literature” since the year 2000 might be the result of increased pressure on scientists in South American countries to publish in ISI journals, as the economy of these countries is growing and higher education has become more and more an issue to catch up with the international community. This holds true as national, and especially international, funds are more readily allocated to scientists with a good publishing record in peer-reviewed journals and institutes are assessed against their ISI-article contributions. Nevertheless, it should be noted that the declining publication trend coincides with a general decrease in publications in the field, which could be the result of decreasing overall funding.

The use of PANGAEA in archiving data from (Grey) Literature

Within the CENSOR project, we use the information system PANGAEA — Publishing Network for Geoscientific and Environmental Data (http://www.PANGAEA.de or via www.CENSOR.name) for archiving data related to ENSO research. Data are made available at the World Data Center for Marine Environmental Sciences (WDC-MARE) using PANGAEA as its central data library [16-19]. Belonging to the ICSU system of World Data Centres, an international exchange of data on a long-term basis is ensured to assist scientists in working with comprehensive data collections. PANGAEA was originally developed to archive climate data coming from geology and glaciology, but has subsequently been made available to a wide range of biological and environmental data. Within the INCO-CENSOR project, the consortium is improving this platform for the use of biological data by complementing data archiving forms that allow the storage and use of a great variety of biological and oceanographic data, which required different formats of storage within the database. Besides we are developing new tools to integrate socio-economic datasets, whenever available. Information on how to provide and use PANGAEA is given on the web portal.

Once data are provided to PANGAEA, the data set receives an identification number, the Digital Objective Identifier (DOI, http://www.idf.org). The DOI gives ownership to the originator(s) of the data. Authors, institutions, and funding sources are also considered. CENSOR uses PANGAEA to store newly emerging data from ongoing research. In this case, the DOI is used to cite raw data in later publications, which allows the international scientific community to refer to the original data. Most importantly, the user elsewhere in the world can be made aware that such data do exist and can be used. In this context, the electronic availability of data via the worldwide web (www) is fundamental for the dissemination and accessibility of information.

The use of old and long-term datasets considerably reduces time for analysis, cuts research costs and, most importantly, increases the immediate evidence for trends and regime shifts in the environment (Taylor et al. 2008). Recent significant insight into climate change and anthropogenic impacts on the environment based on long-term (old) data are i.e. regime shifts in the marine trophic food web based on the over-exploitation effects of unsustainable fisheries (Pauly 2001, Froese et al. 2004), the importance of fisheries discards in the conservation of endangered seabirds (Votier et al. 2004) or long-term impact of climate change.

Applications

The use of database information is key to assessing long term trends and/or to distinguish anthropogenic effects of exploitation from i.e. climate change. Multivariate models are one option to make use of the ENSO PANGAEA data platform and to integrate data from various resources and to evaluate the overall effect of environmental (abiotic and biotic) conditions on community composition, species diversity and resource biomass (Taylor et al. 2008, Fischer et al. submitted). Only the integrated analysis will allow for decisive understanding of coastal, ecosystem underlying processes in upwelling regions and will help to understand the response of communities to EN. This will enable direct advice to fisheries, politics, and ecosystem management/restoration and aid to socio-economic stability in coastal upwelling zones.

Coastal (artisanal) fisheries – lessons from Chile and Peru

International trades have largely affected local fishing practice by setting the scene for economic demands, competition, and product value. The Chilean management approach of coastal natural marine resources is based on the "management area" (Spanish: area de manejo) approach, which gives the local fishermen syndicate the right to manage a management area assigned to them (Castilla 1996). The number of fishermen responsible for a management area strongly varies and can reach 150 individuals in larger syndicates; this is also true for the size of the management area, which in a few cases may reach up to 150ha. Fishermen possess management rights for their management area but do not obtain any legislative or property rights from the government. The community has to pay monthly concession rights to the government; legal measures, however, such as control of illegal fisheries, is generally not enforced by the government. In consequence, syndicates are largely unable to protect their stocks from illegal fisheries, which is a major concern. Private company security controls are installed for some of the larger management areas, but cost implications involved prevent large-scale fisheries control along the coast and many smaller communities are thus unable to protect their stocks.

The self-regulated management approach has given great independence to local fishermen in the exploitation of 'their' resources and yielded some sustainability in income (Castilla and Fernandez 1998). However, in Chile everyone who wants to work as a fisherman can subscribe to a register for free and without any necessary training/education background, with the result that within the last 15 years the number of registered fishermen that are not part of a management area community has risen from about 1,500 to 15,000 individuals (Subsecretaría de Pesca, Chile, pers. Communication). Such a development gives rise to concern regarding the effectiveness of the management area approach, mainly the lack of governmental enforcement and effectively no control on fishing licenses. Due to this development, the situation outside management areas has become critical (Castilla and Fernandez 1998; Fernandez 2005)for many artisanal resources such as the gastropod *Concholepas concholepas* ("loco").

The lack or only sporadic control of illegal fisheries in the near-shore environment resulted in many management area communities increasing investments in security by means of credits, which are often encouraged by cash crop enterprises and cause financial dependencies.

In theory, the "area de manejo" approach could develop a powerful tool against overexploitation of many coastal resources; however, local fishermen communities will require more socio-economic and political support in order to cope with the challenges involved that derive from the ecological needs of sustainability and the economic demands on coastal marine resources and human populations. Current management concepts have widely ignored the fact that the resilience potential and time of recovery of marine communities slows down with increasing latitude because of lower temperatures. Marine resources with a wide latitudinal distribution range, such as many shellfish organisms off Pacific South America, are likely to mature later and at a smaller size, and grow slower with increased latitude (Urban 1994). This does indeed complicate management of size at maturity, legal fishing size, and fishing quota, to mention just a few, and current fishing regulations tend to apply universal rules along the Chilean coast.

The situation of the Peruvian artisanal fisheries remains by far more obscure and largely depends on self-organisation of syndicates. Lack of enforcement in the control of illegal fisheries is certainly a problem. The major difference to Chile, however, is the principal lack of management areas that develop some degree of self-awareness and responsibility although some local fishermen communities exist that demonstrate clear awareness of the problem, but with no legislative support. Furthermore, Peruvian artisanal fleets tend to move to where the targeted stocks are (Arntz and Fahrbach 1991), which causes migratory behaviour and aggregations of artisanal fishing boats in certain areas along the coast. Under these circumstances, and without assigned fishing rights and control, a sustainable management is rather difficult and puts the targeted stocks at risk.

CENSOR studied livelihoods of fishermen and how they responded to El Niño events in two sites in the North (Sechura) and South (Pisco) of Peru. Livelihood assets exhibit mixed patterns with Pisco possessing a stronger livelihood platform in terms of assets but lower incomes than in Sechura. This finding highlights the fact that income is not an accurate measure of resilient livelihoods and needs to be contextualized. Seasonal migration is a livelihood option practiced by fishermen in both sites depending on seasonality, the *de facto* open access facilitating fishermen mobility – a substantial difference to fishing practice in Chile. Fishermen are largely dependent on marine resources for their livelihoods, occupational pluralism being low at both sites. El Niño events engender negative livelihood outcomes in the North of Peru, where floods have a significant impact on households and the collapse of the scallop fishery considerably decreases incomes. Conversely, in Pisco the increase in scallop landings provides an economic "bonanza" for fishermen. An array of coping strategies can be observed in both sites, mainly prey-switching and migration. However, in Sechura, leaving the fisheries sector is also a favored strategy. Additionally, the damages of the devastating floods in the North poses considerable strain on livelihoods and disaster risk reduction initiatives in these communities are needed. CENSOR compiled one of the few empirical studies exploring fishermen livelihoods in Peru and further research is warranted as well as the incorporation of the findings into ecological and biological studies looking at the dynamics of the artisanal fisheries, especially in the context of El Niño.

Chile – fisheries shifting South – shellfish example

Brachyuran crab catches in Chile (composed of 8 species), steeply increased from ~ 1 000 t annually in the early 1980s to 6 000 – 7 000 t in recent years, which was partly driven by changes in market structure from domestic consumption to international export of processed crab meat. However, the catches did not increase for all species. Decreasing landings of *C. setosus* and *H. plana* occurring at least since 1991 throughout the country were masked and overcompensated by the rapidly developing *C. edwardsii* fishery in Chiles southernmost regions (X-XII) nowadays contributing ~85% of the countries landings. Prior to 1991 Chilean statistics did not report crab landings to the species level, but it seems reasonable to conclude that formerly higher crab landings in Central- to Northern Chile were mainly composed of *C. setosus*, *H. plana* and *C. porteri*. For the period from

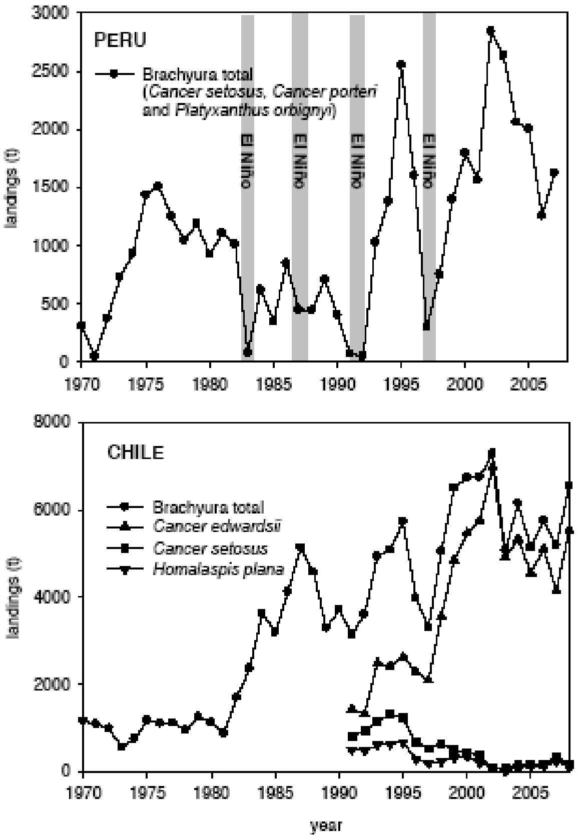

Figure 6 Temporal development of brachyuran crab landings in Peru and Chile (1970-2008, Fischer et al. under review, and sources referenced therein). In Peru landings of *Cancer setosus*, *Cancer porteri*, and *Platyxanthus orbygnii* are reported together. In Chile landings of 8 brachyuran crab species are reported to the species level since 1991 (*C. edwardsii*, *C. setosus*, and *H. plana* contribute to 95% of the landings). The major El Niño periods are indicated.

1970-1983 *C. edwardsii* contributed to no more than 1/3 of Chiles brachyuran landings (CORFO-IFOP, 1984).

The historical higher importance *C. setosus* and *H. plana* over *C. edwardsii* is reflected in the ammount of published scientific work. The population dynamics, reproductive parameters, feeding ecology, and the trophic role in the ecosystem of *C. setosus* (syn. *C. polyodon*) have been studied primarily in the II, IV and VIII regions (Gutiérrez and Zúñiga, 1976; Veaz, 1981; Wolff and Soto, 1992; Wolff and Cerda, 1992; Jesse, 2001; León and Stotz, 2004).

For *H. plana,* feeding ecology, recruitment pattern and development of catch per unit effort were studied in Central Chile (V region) (Morales and Antezana, 1983; Fernández and Castilla, 1997, 2000) and clutch-size, sex-ratio and the reproductive period in the X region (Steffen, 1975; Retamal and Quintana, 1980; Carvacho et al., 1995). The size of first massive maturity of *C. edwardsii* in the X region was recently assessed based on the presence of egg-masses as 103 mm CW for females (confidence intervals 88 – 129 mm CW) and for males based on allometry in chelae-growth as 118 mm CW (Pardo et al., 2009). These findings well support the minimum landing size of 120 mm CW, which if enforced, would allow at least for one reproduction in both sexes. However, owing to the uncontrolled fisheries development, nowadays roughly 80% of the *C. edwardsii* caught in the X region are below 120 mm CW (Pool et al., 1998; Olguín et al., 2006). Throughout most of Chile hooka-diving represent the main crab capture technique, while the fishery on *C. edwardsii* in the sparsely populated Chilean South (regions X-XII) is to 90% based on trapping (Olguín et al., 2006). In the remote XI region fishermen construct temporal living sites in the regions of crab-trapping and the crabs are transported by larger vessels to the landing sites further north for processing of crab meat (Olguín et al., 2006). In the XI region most of the *C. edwardsii* caught are still larger 120 mm CW and the size composition has not changed in the past years, which is explained by the processor demanding crabs of preferably >130 mm CW or with large chelae (Olguín et al., 2006). However, ongoing overexploitation in the X region, is likely to lead to an increase in fishing pressure in the more southerly regions.

Growth and population dynamics have not been studied in *C. edwardsii*, but other commercial *Cancer* crabs showed a considerable reduction in growth rate and higher size of first maturity with lower temperature. North of ~42 °S, the Humboldt Current reduces the latitudinal temperature gradient. South of this biogeographic boundary, temperature and other abiotic parameters show pronounced changes (Brattström and Johanssen, 1983, Fischer et al. under review), which probably lower the growth-rate and resistance to exploitation of *C. edwardsii* in the XI region.

Latitudinal variation in life – history traits: the Cancer setosus *as a model organism for management*

Within the distributional range of *C. setosus* the mean annual sea surface temperature ranges from 10 to 20 °C, which has implications for this crabs reproductive biology and early life history traits. In Ancud (43°S) oviposition occurs annually in late winter, and thus follows the typical seasonal reproductive pattern of *Cancer* crabs (Shields, 1991), while slightly warmer winter temperatures in Concepcíon allow for continuous reproduction leading to the output of more than 3 annual egg-masses (Fischer and Thatje, 2008).

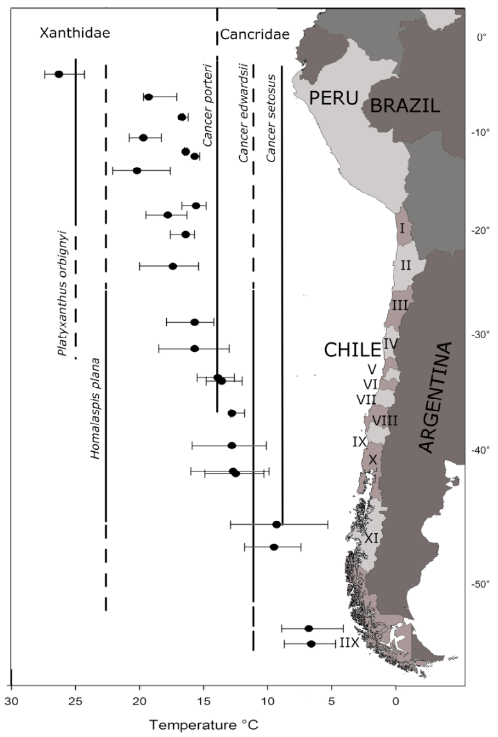

Figure 7 Distributional ranges of *Cancer edwardsii*, *C. setosus, C. porteri (Cancridae)* and of the Xanthidae *Homalaspis plana*, and *Platyxanthus orbinyi* along the coast of Peru and Chile (hatched lines: reported maxium range, uninterrupted line: range of regular fisheries captures). The long-term mean SST (1996-2006) is shown for various coastal locations. The seasonal temperature oscillation is indicated by the “error bars”: the left hand side being the mean SST in January (autral-summer) and the right hand side the mean SST in July (austral-winter). The administrative regions of Chile are indicated (I-XII) as in 2007.

At increasingly higher temperatures ovigerous females are still observed year-round, but the annual number of egg-masses produced decreases towards Northern Peru (~2 in Coquimbo (29°S) and ~1 in Casma (9°S)), which was attributed to the higher metabolic costs of life at warmer temperatures (Fischer and Thatje, 2008). In La Herradura Bay in Coquimbo, the growth efficiency of mature female *C. setosus* was lowered by ~50% compared to males due to the energetic investment in two annual ovipositions (Wolff and Cerda, 1992). Up to now it remains speculative how temperature dependent differences in annual clutch-number affect female growth, fecundity, and size at maturity. Furthermore, females showed temperature dependent plasticity in egg-energy provision. Eggs produced in Puerto Montt (43°S) at ~11°C were 32% higher in dry-mass, carbon, nitrogen and fatty acids compared to eggs produced in conditions representative of the species upper thermal range [(~19°C) in Antofagasta (23°S)]. When reared in aquaria under higher pre-oviposition temperatures females from Puerto Montt (43°S) proceeded with the production of smaller eggs demonstrating a pronounced physiological plasticity in response to environmental settings (Fischer et al., 2009). Higher energetic investment in the single egg under lower temperatures is discussed as adaptive maternal response, providing the hatching larvae with more energy needed for its prolonged development under cold conditions. Furthermore, eggs incubated at 12°C required almost twice as much fatty-acid based energy for embryo differentiation until larval hatching compared to eggs incubated at 19°C (-1.1 and -0.6 µg fatty acids per eggs, respectively). Higher energetic investment under lower temperatures might also represent an energetic requirement for the reduced metabolic efficiency of low-temperature egg-development (Fischer et al., under review b). The duration of egg-development decreased from 65 days at 12.5 °C to 23 days at 22°C. Above temperatures of 22°C, which may be reached throughout Peru under moderate El Niño conditions, eggs failed to attach to the female abdomen at oviposition or they died a few days later. Changes in temperature conditions, latitudinal throughout the crabs >40° latitudinal range and in the course of ENSO, showed effects on life-history traits, which may translate into recruitment and later life history.

Current knowledge into management: the present study provides clear evidence that very often the available information is not sufficiently implemented in management approaches. CENSOR research into brachyuran crabs will allow for better management of this important fisheries resource. Key implementations have to be 1) enforcement of minimum size (more important than prohibition to land ovigerous crabs) 2) traps with escape vents for crabs smaller 120 mm, 3) closed areas to maintain the genetic diversity, and the consideration that 4) the capture of smaller specimens is economically devastating because of their exponentially lower meat yield for processing and implied long-term effects on specimen size (for details see Fischer et al. under review).

Environmental variability and the Jumbo Squid Fishery – from data to modeling and management

A “traditional” surplus-production-model was unable to explain observed CPUE of the Peruvian squid *(Dosidicus gigas*) fishery. A non-linear, unimodal connection of the model-parameters carrying capacity and catch coefficient to SST-anomalies of the Niño 1+2 box (Fig. 8. lower panel) raised the models predicting power although it still was not able to explain peaks (Fig. 8 upper panel). These peaks are attributed to migration between inside

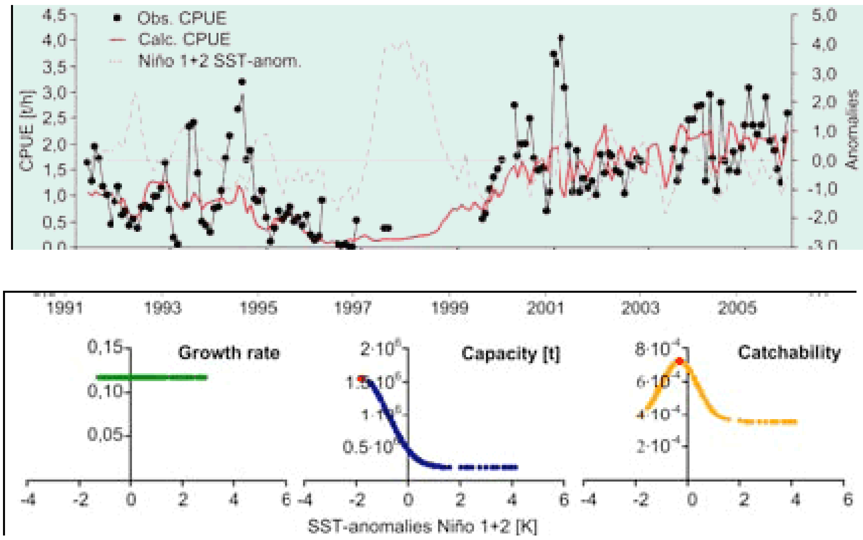

Figure 8 Upper panel: SPM incorporating the SST-anomalies to carrying capacity and catch coefficient; lower panel: parameter values independence of SST-anomalies.

(landings reported) and outside (unknown catches) the Peruvian EEZ of parts of the stock. The findings emphasize the importance of the incorporation of environmental variability for the evaluation of marine resources.

Trophic modeling (Ecopath with Ecosim)

Resource dynamics of the larger coastal upwelling system (4°-16°S; 110km offshore extension) and the nearshore benthic system (Independence and Sechura Bays) were explored. Results show that the dynamics of the larger system are better explained by a relatively fewer number of external drivers (Fig. 9), indicating a greater importance of trophic effects. Conversely the dynamics of the bay systems are better explained by environmental-mediation. Industrial fisheries of the larger coastal upwelling ecosystem are more important to resources dynamics, whereas dynamics of the artisanal fisheries of the bay systems are more likely to be in response to changing resource abundances.

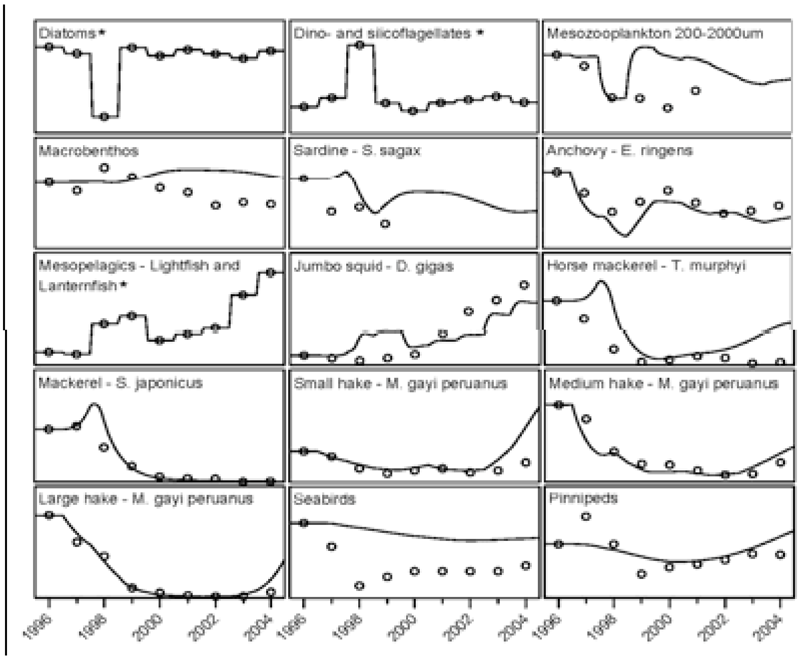

Figure 9 Time-series trends of biomass changes from the data sets (dots) and Ecosim simulations (lines) in the coastal upwelling ecosystem. Yearly data points represent “biological years” (i.e. July-June of following year). Asterisks (*) indicate artificially-forced functional group "drivers"(Diatoms, Dino – and silicoflagellates and Mesopelagics)."

Agent-based model (ABM) of the Peruvian scallop fishery

The ABM was used to understand the fluctuations of catch and fleet in the scallop extraction sites Sechura and Pisco. Scallop dynamics were modeled using environmental variables and an endogenous factor, the size of the spawning stock. Fleet dynamics were modeled using simple rules of entry and exit, derived from interviews. Entry was defined as a function of CPUE and fishery exit was forced when catch was below a profitable threshold. The model could qualitatively reproduce the most important dynamics in catches, while the simulation of effort dynamics was much poorer highlighting the need for more complex rules of entry and exit. Two stages of the ABM simulation of the scallop fishery of Pisco and Sechura had been identified. During the normal year (2000), scallop density is medium in Pisco, and similar in Sechura, where due to the size of the bay, total biomass is somewhat greater and the fleet size is accordingly larger. During the El Niño Pisco shows extreme high densities of scallops sustaining a large fleet, while the stock in Sechura collapses, and in consequence the fishing fleet is reduced.

Scallop fishery dynamics: role of institutions and migration

The conceptual model of the scallop fishery was constructed based on secondary data and interviews. Eight balancing (negative) feedback loops were identified by a causal loop diagram, which tends to have a stabilizing effect on the system (Fig. 10). They reveal that markets, constant scallop biomass and controlled entry to the fishery are keys to stability. Migration, enabled by the open access nature of the fishery, is identified as an important endogenous process as opposed to exogenous environmental and economic variables that play an important role but are beyond the control of Peruvian institutions.

Conclusions:

A multi-method and multiple case study approach allow the identification of key drivers in the Peruvian marine social ecological system. With El Niño being a recurrent phenomenon, expected to increase in frequency due to global climate change, adaptive management strategies for the artisanal sector that take into account climate variability and focus on issues such as migration of species and fishermen as well as property rights regimes are imperative. For the industrial sector the control of fishing effort is the key to enhance the resilience of the larger coastal upwelling system.

Results from Bahía independencia, Bahia Sechura and the Pelagic HCS – a case study

In the following specific results of the modelling of the 3 systems of the HCS: Bahía Independencia, Bahia Sechura and the Pelagic HCS are summarised:

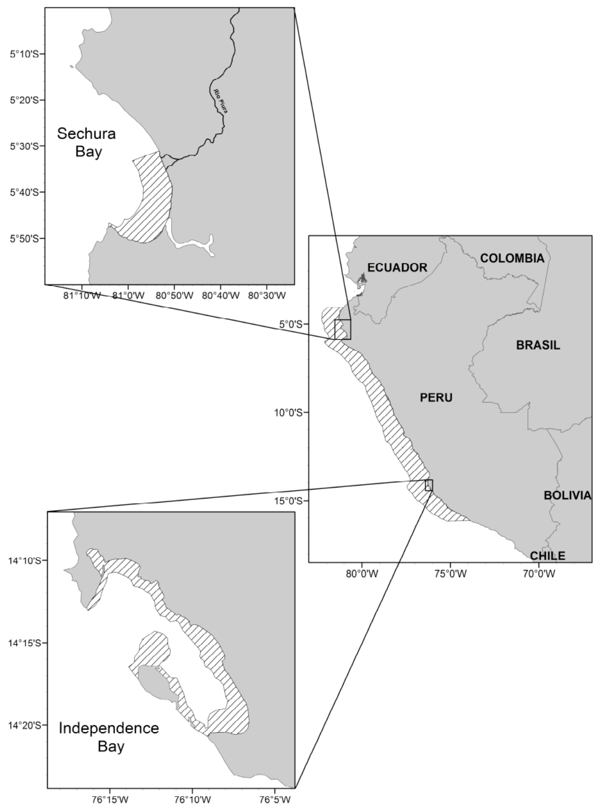

Figure 10 Modelled subsystems of the Northern Humboldt Current Ecosystem. Sechura Bay (upper), coastal upwelling ecosystem (middle), Independence Bay (lower). The model areas considered are hatched.

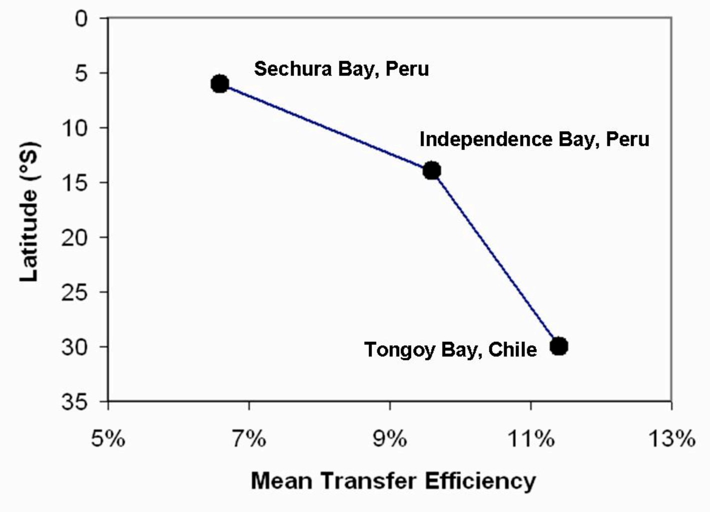

Figure 11 Mean transfer efficiency of trophic levels II-IV as calculated from three trophic models of South American bay systems (trophic models from Ortiz and Wolff, 2002; Taylor et al. 2008). Increased ENSO-related environmental variability at lower latitudes of the Humboldt Current ecosystem may act to "reset" the organization and development of higher trophic connections as reflected by lower values in transfer efficiency. This hypothesis is supported by the observed latitudinal trend of increasing transfer efficiencies at higher latitudes.

A comparison of community energetics of different subsystems of the northern Humboldt Ecosystem (Peru) was calculated using steady-state trophic models. Result had demonstrated that the overall larger coastal upwelling system is more efficient – with a larger proportion of energy flows consumed and respired. The near-shore benthic systems are characterized by intense primary production; a large part of which remains unutilized and contributes to high flows to detritus and, ultimately, to the export. During an El Niño event, primary production is reduced and contributes to decreased total flows in both subsystems.

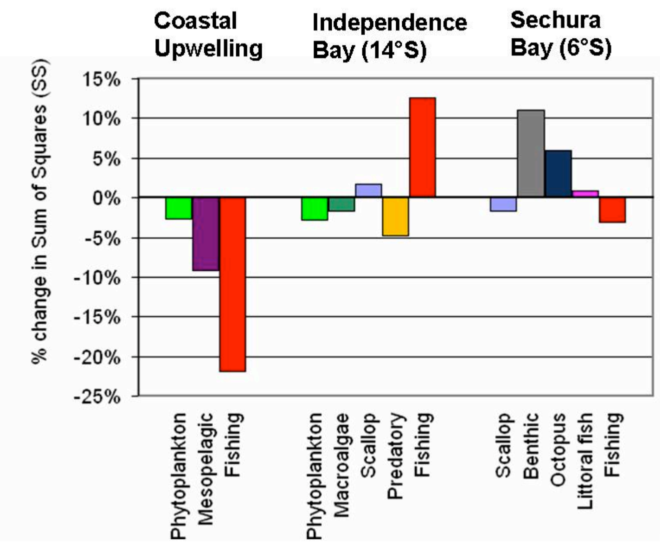

Figure 12 Simulated versus observed (Catch per unit effort) relative biomass changes. All simulations consider changes in fishing effort (fishing and diving),

This increases the efficiency of the nearshore system, but it remains less efficient when compared to the larger upwelling system. The upwelling of waters near the coast fuels high primary production and flows of detrital material to the seafloor. As the upwelling cell moves offshore during El Niño, the utilization of primary production is nearly complete, resulting in high energy cycling.

There are a few key messages that can be derived from the above examples of modeling approaches:

(1) El Niño greatly reduces systems size in terms of flows, more so in the open upwelling then the nearshore bay systems:
(2) Detritus production is greatly reduced during El Niño conditions and transfer efficiency is increased in the lower part of the food web;
(3) Fishery is a main system driver for the pelagic system, but not for the near-shore bay systems, where environmental changes drive proliferations/mass mortalities of key fishery targets causing adaptive behaviour by the fishery.

Modelling approaches are largely dependent upon good and comprehensive data sets over time that in the CENSOR case, have been compiled within Pangaea (www.pangaea.de). The examples given here support the view that open-access databases are key to designing ecosystem based management approaches.

Suggestions on the Management derived from CENSOR-Workshops

As a result of scientific work and a series of workshops with stakeholders and fishermen, the following suggestions regarding the required actions for a sustainable management of the Peruvian scallop (*Argopecten purpuratus*) in Northern Peru (Sechura and Isla Lobos de Tierra) were put forward,

Measures suggested

- ❖ Do not allow the collection of seed scallops from the natural banks, but allow seed collection by the use of suspended collectors
- ❖ Leave a minimum adult stock of specimens above the minimum landing size (>65mm) (30%)
- ❖ Divide the scallop banks into (1) stocking areas for bottom cultures, (2) protected areas, (3) areas for commercial harvest
- ❖ Do not allow incremention of the stocking areas at Isla Lobo de Tierra and Bahía Sechura and reduce the present stocking areas to 25 ha.
- ❖ Request the declaration of the origin of the landings for stocking areas and for scallop commercialization for the Island Lobos de Tierra and for Bahia Sechura

Furthermore, applied research to optimise management approaches is needed to

- Determine the connectivity between the scallops banks of Lobos de Tierra and Bahia Sechura
- Determine the economically most profitable harvest size
- Calculate the carrying capacity for Sechura Bay
- Implement a pilot project with the local fishermen of larval collection in Lobos de Tierra
- Evaluate the impact of predator control during the „limpieza del corral“
- Elaborate a plan for an MPA at Isla Lobos de Tierra

In order to enforce and manage/verify the measurements, the following monitoring approach was summarised,

- Conduct monitoring of environmental conditions (physical and biochemical)
- Use small mesh bags for sample collection to avoid the loss of small juveniles
- Conduct monthly population sampling at fixed stations within Sechura Bay and Lobos de Tierra

Summary Conclusions

The successful implementation of ecosystem management plans requires the perceptions and willingness by each participatory group to hear and integrate the messages brought forward by the different stakeholders involved in this process (Nauen et al. 2006). Mitigating the effects of climate oscillation events, such as EN, on coastal ecosystems, are especially challenging because of their unpredictability in strength and small-scale variability in impact. As outlined here, efforts in bringing together the traditionally controversial socio-economic approaches and natural scientific analyses are essential if we are to enhance the management impact of marine ecosystems in general; a concept, which does not only apply to the Humboldt Current system alone. Differences in traditional fisheries, as briefly outlined for Chile and Peru, furthermore complicate the development and application of management tools.

Organism biology holds one key to small-scale management advice, as a stepping-stone to more flexile and user-oriented, large-scale management approaches. This bottom-up approach is certainly different from large-scale top-down management concepts currently in place for most of the ocean (i.e. ITQs). Small-scale management is also needed to protect traditionally more sustainable artisanal fisheries from industrial-scale operations, which are by far more destructive and part of a globally driven economy. Strengthening artisanal fisheries will not only enable a more sustainable use of local natural resources, but also support the livelihood of coastal communities by fostering local economy, and social stability of the regions concerned.

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CENSOR: Who we are

The CENSOR project was funded through the Framework Programme-6 INCO-STREP (Integrated Cooperation, Scientific Targeted Research Programme) programme of the European Commission and for the period of four years (2004-2008), with the aim of strengthening relationships and the exchange and development of academic expertise between Europe and targeted Developing Countries. One if not the most important objective of the Call is the advance of sustainability in coastal regions by reconciling the multiple demands on coastal areas including both marine and terrestrial environments. The CENSOR Consortium comprises more than 60 scientists and students from 14 institutions of three South American (Peru, Chile, Argentina) and four European (Germany, France, United Kingdom, Spain) countries and specialists from other countries associated with CENSOR in the course of the project. Prior to CENSOR, many of us had already developed academic links often based on rather focused bilateral projects between European and South American countries, based on the nature of academia mostly with limited scope beyond one's academic area of specialisation. Such cooperation in some cases had previously resulted in academic contact going back many years if not decades, but was often constrained by limited resources and logistics. The CENSOR project, for the first time in many years, provided the platform of an umbrella project for various small-scale activities between South America and Europe in the ENSO context. By bringing together a whole range of expertise ranging from i.e. ecology, physiology, hydrography, oceanography, and ecosystem to socio-economic work, the project raised the foundation for something more substantial, indeed a reconciliation of current knowledge available in the ENSO context and by including state-of-the-art research approaches that lead ENSO-research into the 21st century. However, CENSOR is not only a multidisciplinary research platform, but also a stepping-stone for a new generation of ENSO researchers encompassing all areas of research within CENSOR who may develop and take on this initiative as part of their future careers. Such long-term investment is crucial for reaching sustainability of any natural resource that is much more than research and management recommendation alone – but with a sense for sustainability encompassing a range of stakeholders, ranging from the formation of future researchers, the trust-building between different stakeholder communities and involvement of local and international decision makers. Only long-term commitment to this philosophy can guarantee a significant shift in socio-economic activities toward sustainability. Despite the fact that such approach covers a time scale that goes well beyond that of any current funding scheme, we herein advocate the CENSOR approach as a case for future commitment by funding bodies and stakeholders for supporting the search for sustainability in an increasingly overexploited world.

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