Toward climate-resilient fisheries in the Humboldt Current

Developing a scientific foundation for improved adaptive management

Erica Cunningham, Kristin Kleisner, Brad Parks, Sergio Palma, Samuel Amoros-Kohn, Merrick Burden

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Introduction

The Humboldt Current System (HCS) is one of the most abundant and productive marine ecosystems on the planet. This abundance stems from intense upwelling of cold, nutrient-rich water, which drives production of planktonic organisms that make up the base of the food web. As a result, the HCS is home to an array of marine life, and home to what has historically been the world's largest fishery by volume, the Peruvian anchoveta. Fisheries from the HCS also have a global reach, supporting supply chains which end in the production of goods for human sustenance, agriculture, aquaculture, pharmaceutical products, and more; making these fisheries critical for food security and economic prosperity worldwide.

One of the reasons the HCS is so productive is the predominance of coastal upwelling. The upwelling process drives cold, nutrient rich water from the deep ocean, up to the surface where it supports an immense primary production of planktonic organisms that serve as the base of the ecosystem's food chain. Areas of upwelling are directly influenced by regional wind patterns which, when they blow alongshore from the south-southwest, help to fuel this oceanographic phenomenon by pushing surface water in the offshore direction, which in turn acts to pull cold, nutrient rich water up from the deep to the surface in near shore areas (Figure 1).

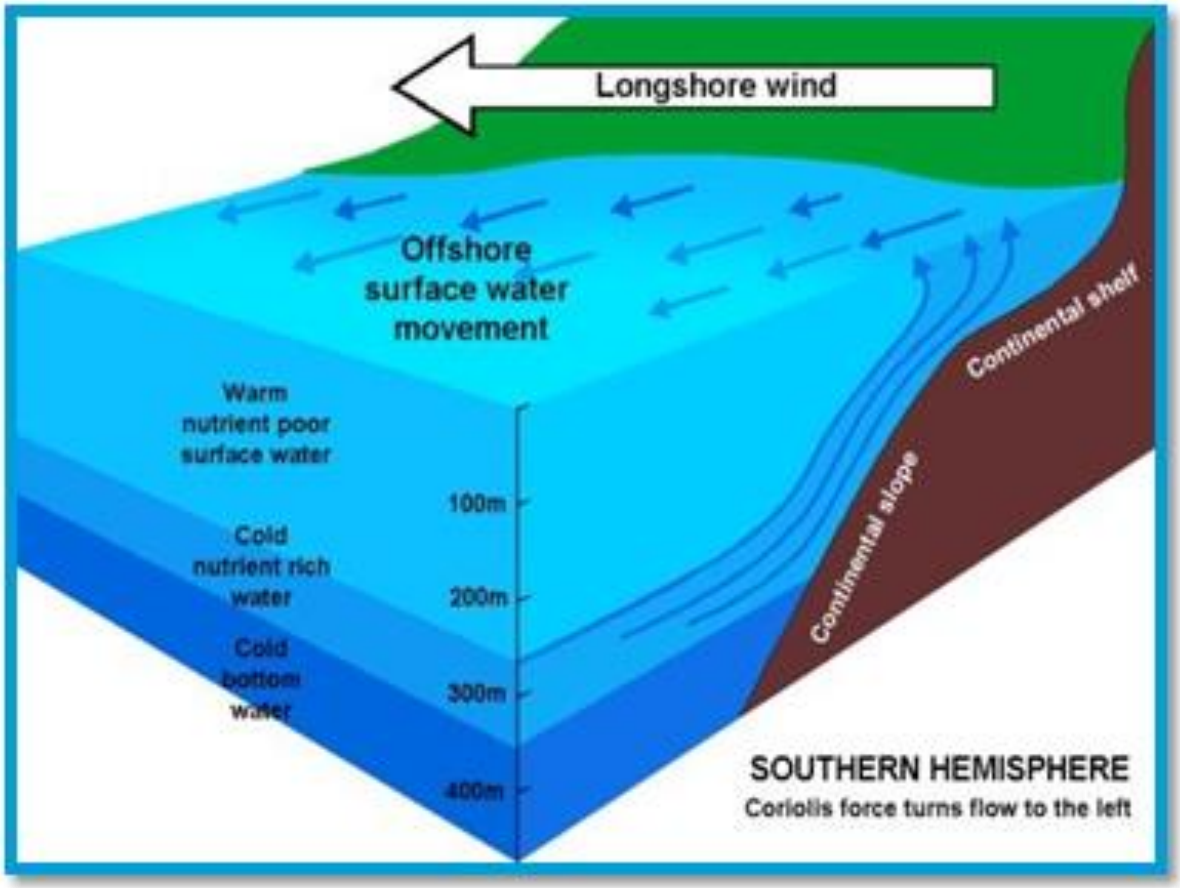

Figure 1. A depiction of upwelling patterns in the southern hemisphere where the northward longshore wind drives upwelling of cold, nutrient waters from the deep. Source: https://cmast.ncsu.edu

The HCS is also a highly variable ecosystem, subject to wide ranging oceanographic conditions that in turn drive wide swings in the productivity and abundance of marine species. These variations occur on several different timescales that range from monthly to multi-annual. One well-known phenomenon, the El Niño Southern Oscillation (ENSO), is a dominant driver of the HCS system, causing significant shifts in ecosystem productivity every few years (Figure 2). This means that the HCS system, and the fisheries that take place within it, are accustomed to a fair degree of change and variability. However, climate change is becoming an increasingly dominant force and appears to be causing more changes to ocean chemistry, fisheries productivity, species distributions, and other environmental alterations, all of which are variations outside the norm even for the highly variable HCS. Predicting these changes is difficult and therefore many of the effects of these changes have not been anticipated. Additionally, at times when such changes have been anticipated, the ability of policy makers to respond to them has been limited.

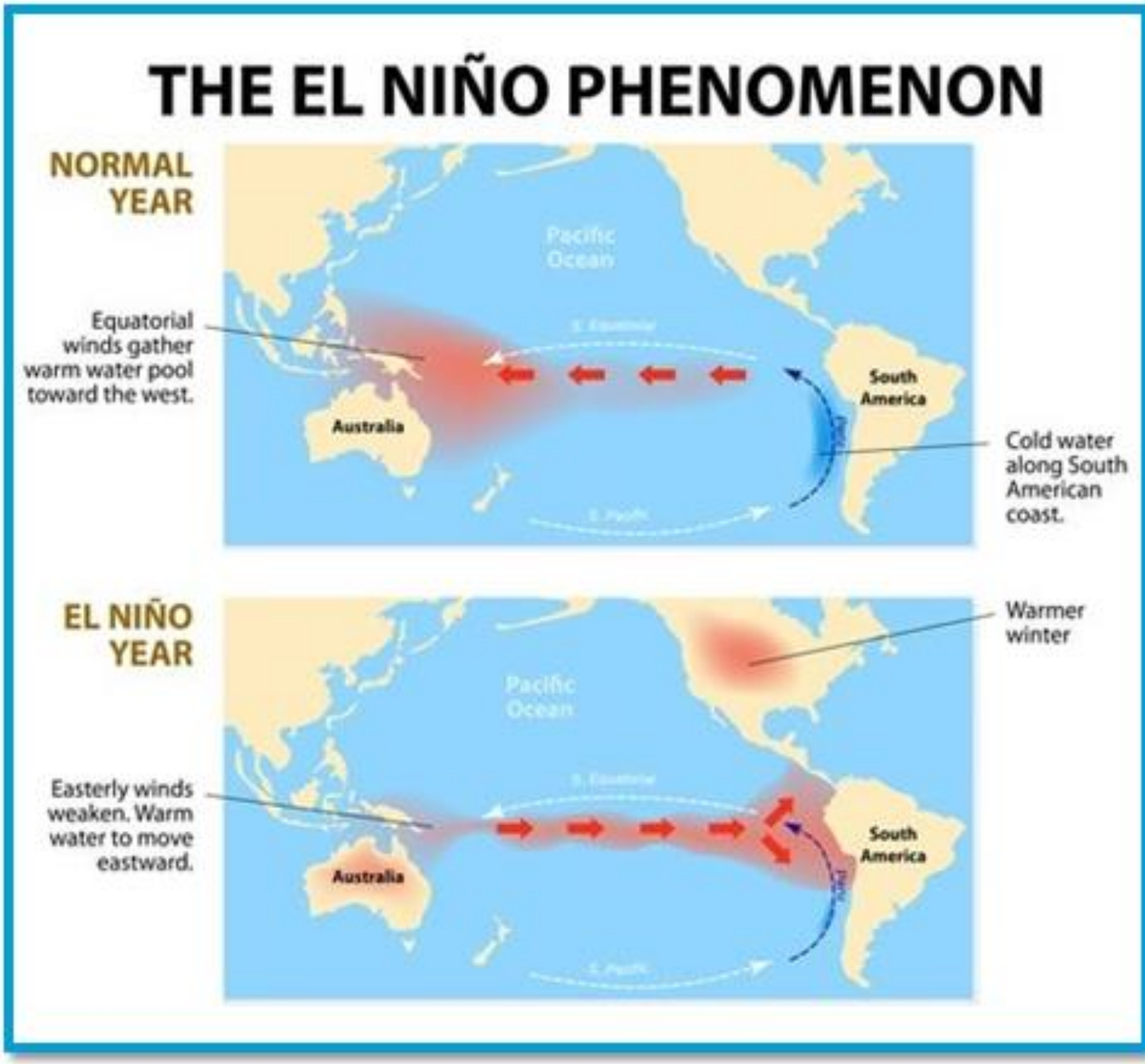

Figure 2. During La Niña ("normal years"), strong easterly trade winds push water offshore allows colder, nutrient-rich water to upwell more phytoplankton. During El Niño, easterly trade winds weaken, and warm water moves towards the coast, which suppresses upwelling and reduces chlorophyll. Source: https://elmodenafrontline.com/8260/focus/el-nino/

These atmospheric and oceanographic patterns are already being affected by climate change, and while there is still much uncertainty about what these changes mean overall for the HCS, its fisheries, and the people that rely on this ecosystem for their food and livelihood, it is accepted in the scientific community that large-scale changes will occur. The fisheries-related changes anticipated to occur to the system include:

- Variability of production: It is expected that the frequency and magnitude of already variable upwelling events will increase as a result of climate change.
- Geographic shift in relative productivity of the region: It is expected that high productivity areas of the HCS will generally shift southward, benefiting fisheries in more southern areas and potentially resulting in losses nearer to the equator.

- Warming of offshore surface water: A general warming of sea surface water may be expected offshore as a result of climate change, which may cause stocks to shift poleward, and help fuel a change in the mix of species present in any given location.
- Cooling of nearshore waters: In some southern areas, upwelling intensity is expected to increase bringing cooler water to the surface, which may counter some anticipated poleward shifts due to warming waters offshore.

The changing nature of the HCS, due to climate change and interactions with ongoing interannual variability, calls for improvements to the way in which fisheries in the system are managed. Many of the changes that will come about due to climate change are expected to be in the form of more variability of fishery opportunities (i.e., abundance, productivity, and distribution of resources) across time and space, and impacts may be felt both with more frequency and greater magnitude. The HCS, like the global ocean, is expected to experience the effects of climate change with increasing rapidity. This, combined with the underlying characteristics of the HCS, requires that fishery management systems in the region be able to adapt in a timelier manner and deal with greater uncertainty than the fishery management systems currently in place.

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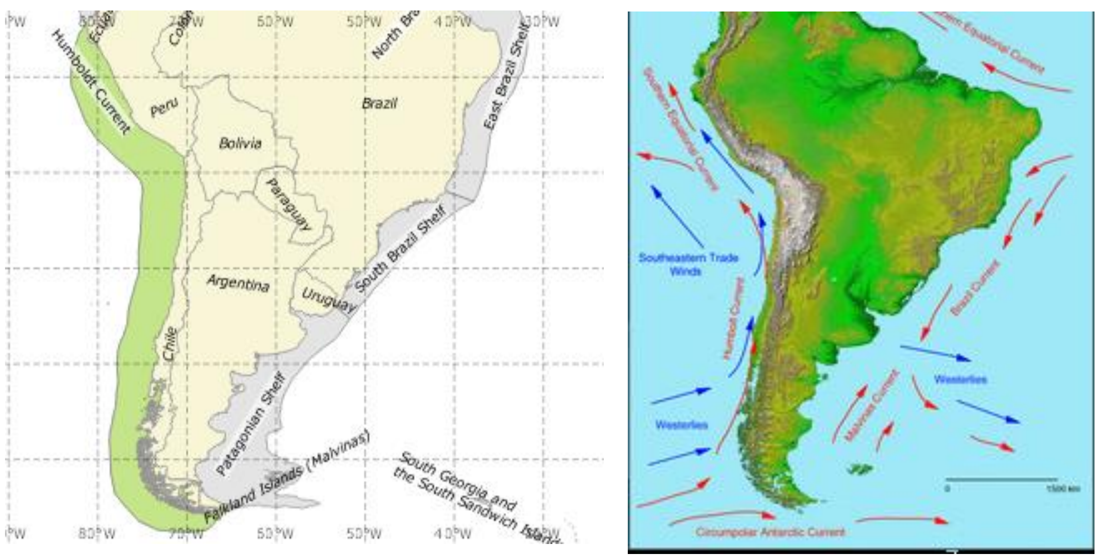

Figure 3. Map of a) the countries and b) the main currents of the Humboldt Current System. Sources: http://onesharedocean.org/LME_13_Humboldt_Current and https://ussringoffire2014.weebly.com/currents.html

It is against this backdrop that Environmental Defense Fund (EDF) and our scientific partners at Chile's Fisheries Development Institute (IFOP), Peru's Marine Research Institute (IMARPE) and Ecuador's National Fisheries Institute (INP) came together to jointly identify the impacts of climate change on fisheries in the HCS and to identify the scientific tools, analyses, and processes that would be necessary to provide timely information to fishery managers, including identifying historical physical and biogeochemical changes in the ecosystem, and anticipating further changes in the system so that management can respond and adapt quickly and effectively.

Together with help from experts in academia, multilateral institutions, and the fishery management agencies in all three countries we created a plan for the development of a scientific system with the goal of fostering better, more adaptive management and policy responses to physical oceanographic and climate change-related fishery challenges (Figure 4). The major components of this plan entail:

- *Pooling expertise and resources*: pooling the collective scientific expertise in the region to improve upon the understanding of HCS dynamics and to better recognize when change is forthcoming.
- *Establishing a common scientific information baseline*: developing a shared understanding of the HCS that can be drawn on to inform management responses. Having a common knowledge base and an understanding of the uncertainties associated with these data will be important for ensuring that all stakeholders are making fishery management decisions based on the best available information. Additionally, by establishing a common knowledge base across the Humboldt Current countries, it will be possible to identify and work to resolve gaps, and to understand changes across the entire system rather than just regionally (i.e., at national levels).
- *Developing a comprehensive coastal and ocean observing system*: building off of and integrating existing observation platforms and technologies to create a cohesive system where real-time environmental and stock information will be accessible to both fisheries scientists and managers.
- *Creating a shared data platform*: housing the data collected by the coastal and ocean observing system so that it can be accessed quickly and easily by scientists and researchers from across the Humboldt Current to enhance modeling and assessment efforts and facilitate collaboration.
- *Improving forecasting skill*: improving the ability of scientists in the region to predict forthcoming changes via climate and ecosystem modeling. Being able to predict future change and effects on fishery resources better than today will improve the ability of managers to adapt in time and accuracy.
- *Using this basis of shared knowledge and comprehensive observing system and data platform to provide early warnings of change and inform management decisions*: alerting the scientific community and fisheries managers when oceanographic or other changes are occurring that will result in a likely change in fishery opportunities or that will require a change or adjustment in management.

Overall, the aim of this effort is to create an observation, warning, and prediction system (Sistema de Alerta, Predicción y Observación – S.A.P.O) for the Humboldt Current.

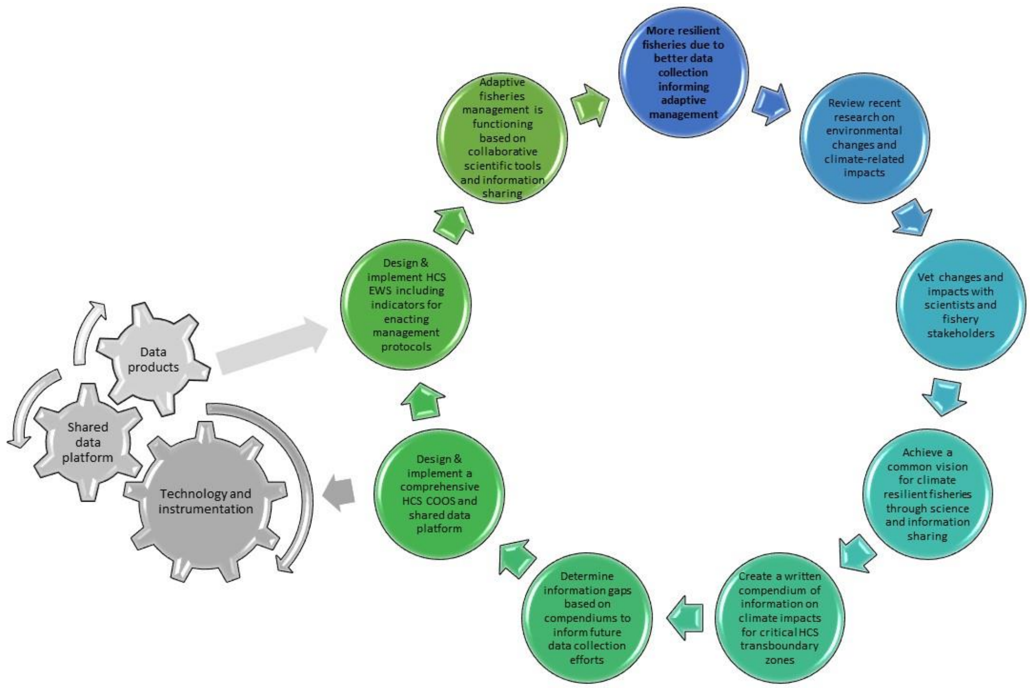

Figure 4. A roadmap for developing a scientific foundation for achieving climate-resilient fisheries.

This document is intended to provide the necessary background and context for this plan, how it was arrived at, and what the plan entails by: 1) first discussing why the HCS is important for fisheries at a local and global scale; 2) describing the anticipated climate impacts on HCS fisheries and why these impacts warrant the creation of scientific tools and processes to inform more precise and rapid adaptive management; 3) offering a shared vision for what these tools and processes are and how they can be developed; and 4) describing how these scientific products can be utilized by all three countries in the HCS to adaptively manage fisheries at a national and regional level and ensure increased resiliency in the face of climate change. In the following sections we outline this shared vision and the steps that will need to be taken to give effect to it.

A description of the Humboldt Current

The Humboldt Current System – a special Eastern Boundary Upwelling System

The HCS covers an area comprised of 55° of latitude off Peru and Chile (3°23.57′ to 58°21.02′) and extends over 200 nautical miles offshore. The dynamics of the HCS are strongly influenced by seasonal or permanent coastal upwelling. Several features distinguish the HCS from similar ecosystems associated with the Eastern Boundary Upwelling Systems of the world's oceans (EBUS: California, Canarias, Humboldt and Benguela). First, it extends closest to the equator. Second, it is the most exposed EBUS system to ENSO, the largest source of interannual climatic variability on the planet. Third, although each of the EBUS has similar levels of primary productivity, the HCS contains the most productive fisheries. Lastly, 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 altering energy and matter exchange between the atmospheric, oceanic, and continental boundaries. This leads to changes in the pressure gradients and associated alongshore and cross-shore wind fields as well as marine currents, sea surface temperature (SST) and thermal stratification. Ultimately, this modifies the intensity, spatial distribution, and frequency/duration of the coastal upwelling so important to the HCS. Global models predict a decrease in 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 in general. There is a high level of uncertainty regarding how these multiple stressors will impact the productivity and biodiversity of the HCS. While the scientific debate is ongoing with respect to the expected response of EBUS to global warming in future climate scenarios (e.g., upwelling intensification vs weakening), it is understood that physical and biogeochemical changes will likely affect the life cycles, spatial distributions and species compositions of primary and secondary producers. It is therefore imperative that the resilience of the system be improved through the application of adaptive and sustainable management approaches for fisheries of the system.

The physical background of the HCS

The HCS and the fisheries it supports sustains an abundant ecosystem full of fish, seabirds, marine mammals, and more. It also contributes to the food security and livelihoods of people in the region and supports the creation of a vast array of products for people all around the globe. Understanding the local and global importance of the HCS is critical if we wish to understand the implications of climate change on this system.

In general, the HCS can be thought of as three different sub-regions:

1. The seasonal upwelling system in central-southern Chile (~25°S – 42°S);

2. The lower productivity and rather large ‘upwelling shadow’ in northern Chile and southern Peru: ‘transboundary zone’ (~15°S – 24°S); and
3. The highly productive year-round northern Peruvian upwelling system (~5°S – 15°S).

Central-Southern Chile

Starting in the south, in the central-southern Chile sub-region, upwelling is relatively weak compared to the rest of the HCS and there is little continental shelf area in some portions of this region. Combined with lower oxygen content in the surface waters, this acts to reduce overall primary productivity. While upwelling technically occurs year-round, there is strong seasonality, with peaks in the austral spring and summer.

Northern Chile-Southern Peru

In the transboundary zone between southern Peru and northern Chile, upwelling is seasonal and strongest in the austral spring and summer as in central-southern Chile. However, the shelf in this sub-region tends to be very narrow (< 10 km in some areas), the equatorward winds are much weaker, and there is little river inflow, which contributes to localized upwelling centers that tend to be weaker than in the other regions. Surveys from aircraft between 18°S – 23°S off of Chile found that warm water pushed close inshore, to within 25 km of the coast, between the upwelling centers. Upwelled cooler water seems to be confined to the coastal zone (roughly within 60 km of the shore), which serves to concentrate species like anchovy closer to the shore in this region.

Northern Peru-Ecuador

The northern Peruvian-Ecuador sub-region is characterized by strong year-round upwelling that supports intense primary production and one of the largest fisheries in the world, the Peruvian anchovy. This region is heavily influenced by El Niño Southern Oscillation (ENSO), and has the greatest level of interannual variability of any coastal region in the world ocean (Chavez, 2008). It is in this region that we find SST anomalies greater than 10°C during the strongest El Niño (warm water) events. This magnitude of change in ocean water temperature directly affects fish distribution and productivity and therefore provides a constant challenge to fisheries managers who must adapt management to these rapid changes in species biomass. Additionally, there is an intense, shallow, and acidic oxygen minimum zone (OMZ; a portion of the water column where oxygen concentration is lower than surrounding waters) in this region that serves to concentrate fish species that are sensitive to oxygen concentrations closer to the surface.

The entire HCS is strongly affected by interactions with ocean-atmospheric dynamics acting on a variety of temporal scales ranging from intra-seasonal (e.g., coastal trapped waves), annual (e.g., Rossby waves), inter-annual (e.g., El Niño/La Niña effects), to multi-decadal (e.g., Pacific Decadal Oscillation, PDO). Spatially, the primary mechanisms for larger-scale fluctuations to local-scale conditions involve basin-scale changes in the depth of the pycnocline (layer with the most rapid change in density) and the movement of different water mass types into the local region (Montecino and Lange, 2009; Rutllant and Montecino, 2002; Pizarro and Montecinos, 2004; Ramos et al., 2006; Graco et al., 2007). It is this combination of phenomena at varying scales and localized responses to these phenomena, which make the HCS an important barometer to climate change and the overall health of the Pacific Ocean.

The importance of fisheries in the HCS

For thousands of years, indigenous populations along the eastern Pacific have utilized the marine resources of the HCS for sustenance. As time passed, local and global commerce expanded, and marine resources were an integral part of trade for the South American region. The native people made use of coastal near-shore species, salt, guano, and whales (Antezana and Bahamonde, 2002). In modern times, fishing has become a significant contributor to human sustenance, and drives both the local economy and the international commerce of the HCS nations comprising between 1.5 and 3% of GDP on average in recent years.

Chile

Chilean fisheries are comprised of industrial, artisanal, and aquaculture segments, all three contributing to important levels of national and international commerce. The artisanal fishery is comprised of over 90,000 fishermen and seaweed (kelp) farmers. Only artisanal fishermen registered with SERNAPESCA's National Registry of Artisanal Fishermen and within their respective administrative region are permitted to operate in the nearshore artisan exclusive zone (AEZ), which extends out to 5 nautical miles from shore (water column and sea bottom) and covers about 27,000 – 30,000 km^2. The offshore industrial fishery has grown from its beginnings in the 1950s to a peak in the early 1990s at over 7.5 million tons, after which it has leveled out to around 5 million tons. Both the artisanal and industrial fisheries are managed under rights-based fishery management systems that comprise of individual quotas, territorial user rights for fisheries, as well as effort controls such as seasonal closures, size limits and gear restrictions.

Despite the relatively low primary productivity, the HCS subregion off central Chile accounts for a large fraction (>30%) of total fish landings in Chile, particularly pelagic species such as anchovy (*Engraulis ringens*), pelagic horse mackerel (*Trachurus japonicus*) and sardine (*Sardinops sagax*). Additionally, the region's fjords and islands provide important and varied habitat for important commercial fisheries such as king crab (*Lithodes santolla*) and various demersal species such as southern hake (*Merluccius australis*).

In central Chile, the primary pelagic commercial fish are anchovy, jack mackerel (*Trachurus murphyi*), and sardine. Total landings of species like chub mackerel, common sardine, southern hake, and giant squid (*Dosidicus gigas*) are generally much smaller. The Chilean fjord region is an important area for trawl and longline fisheries based on gadiform fishes such as Patagonian grenadier (*Macruronus magellanicus*) and southern hake; the latter has supported annual catches of 30,000 tons in the past decade (Bustos et al., 2007). The Chilean hake (*Merluccius gayi gayi*) fishery, which is concentrated in central-south Chile, has reached maximum catches of >100,000 tons but has seen significant declines during the last decade and severe overfishing.

Peru

As of 2014, Peru was the top producer of fishmeal and the fourth largest producer by volume after China, Indonesia, and the U.S. It is thus evident that fisheries in general rank highly in terms of economic importance in the Pacific coast nation. A study for the International Labour Organization (ILO) estimated the total number of direct and indirect jobs in the Peruvian fishing sector at 142,232 in 2008, just under 1% of total employment in the country, although the actual total is most certainly much higher when including indirect labor (e.g., point of sale, distribution, etc.). Like Chile, there exists an artisanal fishery working out to 5 nm. This fishery is focused on human consumption and provides fish and seafood for much of the domestic market in Peru, it is also highly unregulated compared to the industrial fleet. The pelagic-focused industrial fleet consists of over 1200 purse seiners with capacity ranging from 30 – 120 m^3.

Presently, the primary commercial catch off northern-central Peru is taken from a single anchovy stock, with a lesser contribution from a sardine stock. Other species exploited include chub mackerel and bonito (Scombridae). In Southern Peru and Northern Chile, important commercial species include sardine, a second shared anchovy stock, jack mackerel, tuna, and swordfish (*Xiphias gladius*). Industrial demersal fisheries are actually comparatively small in the HCS (<1% of total fish landings in Peru for example). The Peruvian hake (*Merluccius gayi peruanus*) fishery has shown a significant decline in the last 15 years, attributed to overfishing, and a diminished reproductive capacity and increased population vulnerability in response to environmental stress (Ballón et al., 2008; Guevara-Carrasco and Lleonart, 2008).

Ecuador

Like its southerly neighbors, the Republic of Ecuador is a country with a long tradition in marine fisheries and aquaculture. Ecuador has 4,525 km of coastline within the eastern tropical Pacific (ETP), including the Galapagos Archipelago. Artisanal fisheries are of primary social and economic importance in Ecuador, representing a major source of employment and food production. It is estimated that the national market for fish and seafood products generated by artisanal fisheries is approximately 200 million US dollars per year. The total value of the catch of the principle large pelagic species, dolphinfish (*Coryphaena hippurus*), yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*), and swordfish, exported to the United States (fresh and frozen fish markets) from the artisanal fisheries was valued at approximately 364 million US dollars over 2008 – 2012 (US National Marine Fisheries Service, Fisheries Statistics and Economics Division).

Ecuadorian artisanal fisheries are multispecies fisheries consisting of two types of gears. The main artisanal fishery in Ecuador uses gillnets from individually operated skiffs. These gillnet fisheries (surface and bottom) are coastal and target a wide range of epipelagic, mid-water and demersal fishes, as well as shellfish and mollusks. The other artisanal fishery is a longline fishery targeting large pelagic fish species, including dolphinfish, tuna, billfish, and sharks. The traditional fishing areas, which in the 1970s was within 40 nm from the coast, expanded dramatically in the 1990s and 2000s to over 1,400 nm from the mainland coast past the Galapagos Archipelago, establishing what is now known as the “oceanic-artisanal fishery” in Ecuador.

Such spatial expansions of resource extraction, significant recent declines in stocks across the HCS nations, in addition to the decline in sardine stock as observed over the past 30 years in Peru and Chile, suggest a need for better fisheries management. The sardine-to-anchovy regime shift which has been discussed in the scientific literature is a perfect example of how the HCS can respond to stress and environmental variability (Figure 5). It also demonstrates the importance of building a management scheme to enhance the overall resilience at the ecosystem level.

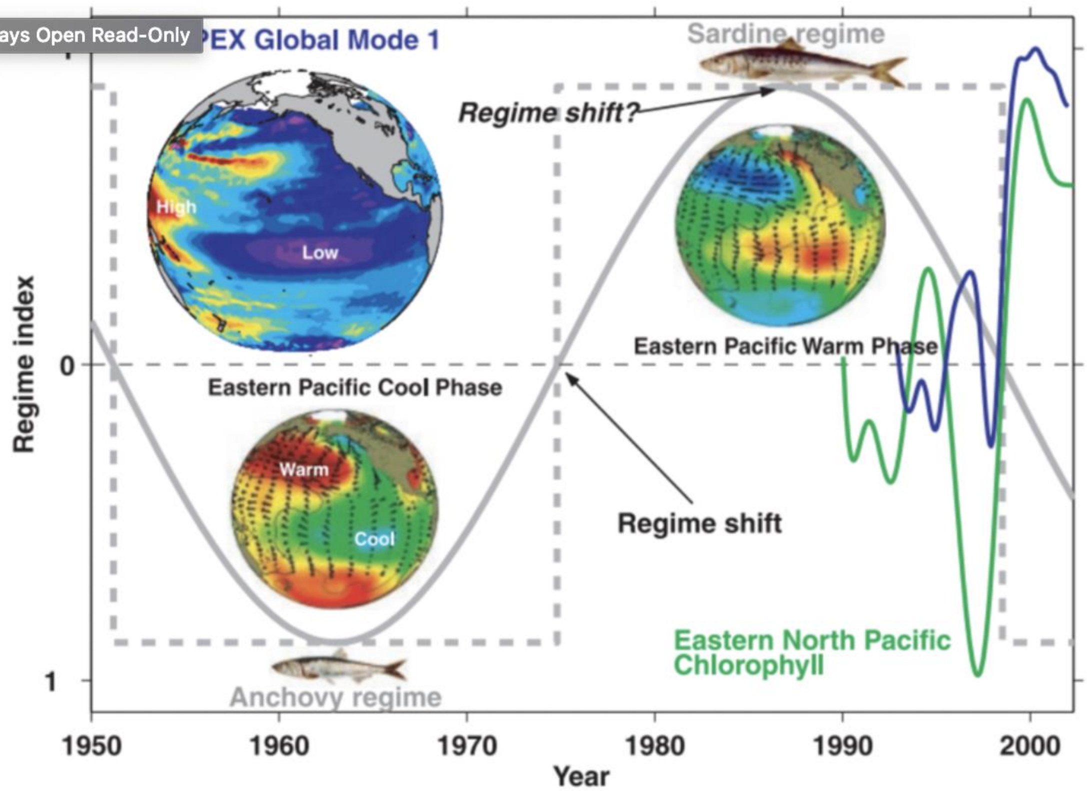

Figure 5. Hypothetical oscillation of a regime index with a period of 50 years. From the early 1950s to about 1975, the Pacific was cooler than average, and anchovies dominated. From about 1975 to the late 1990s, the Pacific was warmer, and sardines dominated. The spatial patterns of SST and atmospheric circulation anomalies are shown for each regime. The spatial pattern shows that warming and cooling are not uniform and that the eastern Pacific is out of phase with the central North and South Pacific. Source: Chavez et al., 2003.

The future of the Humboldt Current under climate change

One of the main features of the HCS is the upwelling that occurs to varying degrees in each of the three sub-regions discussed above. This upwelling and the overall dynamics of the HCS are driven by the dynamics of the Pacific Basin. In particular, climatic stress from ENSO events create ‘regimes’ with particular characteristics of wind, rain, currents, ocean temperatures and oxygen concentrations. During an El Niño event, the velocity of poleward currents increases, and the oxygen minimum zone (OMZ) and thermocline deepens, which dampens upwelling and causes a loss of nitrogen and a decrease in the export of carbon from the ocean as productivity is reduced. The opposite occurs during a La Niña event. Understanding the effects of climate change on upwelling intensity is very complicated due to the number of physical factors at play. However, there are many studies that have been carried out in the region that can be drawn on to understand these large-scale patterns.

Changes in temperature and upwelling intensity

One of the key variables examined to understand the effects of climate change is ocean temperature. While globally, ocean temperatures have been increasing, with movement of temperature ‘isotherms’ (bands of water of similar temperature) shifting towards the poles, temperatures in upwelling regions are variable due to the propensity of upwelling to drive cooler, nutrient-rich bottom waters to the surface. In the HCS, especially off of Chile, temperature records show relatively insignificant warming trends, or, in some areas, even cooling trends that may be related to several factors including increased upwelling of cold, deep waters.

Global modeling studies have indicated that upwelling intensity may shift poleward. This would mean that the central-southern Chile region could experience more upwelling and potentially cooler waters. This could be a boon in terms of fisheries yields if other factors (e.g., oxygen levels, salinity) also remain favorable. In the northern Humboldt Current, a decrease in upwelling may result in warmer waters, increased upper-ocean stratification, and a decrease in nutrient supply. Additionally, colder ocean temperatures in the southern HCS coupled with warmer temperatures on land would mean greater land-sea temperature differentials. These differentials are drivers of longshore wind intensity, which is itself a key driver of upwelling intensity.

The oxygen minimum zone

One of the interesting components of the northern HCS is the shallow and intense oxygen minimum zone (OMZ), which occurs due to lower circulation in the region as a result of the Humboldt Current veering west from the coast of Peru, and high oxygen demands from the sinking and decay of dead organic matter from primary producers. According to Graco et al. (2017), the OMZ occupies a wide swath of the water column (~ 500m), is intense with O_2 levels lower than 22.5 µmol kg^{-1}, and can be as shallow as 25–50 m, which means it intersects the euphotic zone and forces many organisms to remain near the surface where oxygen and nutrient levels are higher. In particular, the OMZ level plays a role in restricting the migration of zooplankton in the water column and is one of the reasons for the high rate of carbon exchange between the surface waters and the atmosphere. For species such as Humboldt squid that can survive in hypoxic conditions, the OMZ has less effect, and may actually serve as a refuge. Overall, the OMZ position and intensity are affected by ENSO events. During strong El Niño events, the OMZ deepens, the surface waters become more oxygenated, and the productivity of the system is reduced. Some studies have noted that there may be an increase in the intensity and potentially the frequency of ENSO events with climate change, which would mean that the northern HCS could experience an overall drop in productivity that may be compounded by a reduction in upwelling intensity.

Ocean acidification

Oceanic uptake of carbon dioxide from natural and anthropogenic sources is an important function of the oceans. However, with the high levels of anthropogenic carbon dioxide expected with climate change, the oceans are becoming more acidic, causing stress to marine life. Eastern Boundary Upwelling Systems (EBUS) are regions with naturally high CO_2 concentration meaning they are more acidic, with higher concentrations during La Niña events. The deep water brought to the surface by the upwelling process associated with EBUS is characterized by higher levels of acidity. Therefore, upwelling regions have a lesser ability to buffer against acidification because the system is likely to be nearer the acidification tolerance levels of species already. A lesser ability to buffer against acidification may significantly impact food webs. For example, if shelled organisms or other species that build structures from calcium carbonate are adversely affected by an acidic environment, this may also result in impacts on their predators. Additionally, marine species that are intolerant to low pH conditions may decrease in abundance as acidification intensifies.

Climate-related species effects

Increasing concentrations of greenhouse gases (GHGs) have resulted in temperature increases on land and in the sea, the acidification of the ocean, and alteration of hydrology. These phenomena, in turn, affect species productivity, distribution, and seasonality in various ways, some known and others. However, a major challenge is to be able to attribute observed changes to long-term climate change rather than climate variability operating at annual or decadal scales (Checkley et al., 2017), which requires very long time series of observations spanning multiple decades. In particular, Henson et al. (2010) found that understanding the effects of long-term climate change on phytoplankton biomass requires at least 30–40 years. Species that are dependent on these lowest trophic levels (e.g., anchovy and sardine) will therefore also require time series that are as long or longer (Checkley et al., 2017).

With respect to anchovy and sardine, there is little known about how distributions of HCS stocks may shift under climate change. Yáñez et al. (2017) modeled future monthly landings of anchovy and sardine under different climate scenarios and found that anchovy and sardine landings would increase 2.8% and 19.2% by 2065, respectively. Paleo records and other evidence have indicated trends towards higher marine productivity in the Humboldt Current

System during the 20th century, with anchovy biomass up to eight times higher than 500 years ago (Gutiérrez et al., 2009; Gutiérrez et al., 2011; Salvatteci et al., 2017). This increased productivity has translated up the food chain to the top trophic levels. However, climate models have predicted a weakening of upwelling-favorable winds off Peru and northern Chile and a strengthening south of 35°S (Echevin et al., 2012; Brochier et al., 2013; Belmadani et al., 2014), which could drive a southward shift of anchovy distribution to counter the south to north pattern observed from the mid-1960s through 2009 (Gutiérrez et al., 2012).

Further up the food chain, climate change is already affecting the distribution of some species. One of the clearest examples of range expansion in the HCS is with Humboldt squid (Keyl et al., 2008), a large, abundant, and commercially important predator with a voracious and relatively unspecialized diet (Zeidberg and Robison, 2007). Since 2000, Humboldt squid have been found further north and south than its previous range (i.e., spreading poleward) and, in the southern hemisphere, have been reaching maturity at larger sizes (Keyl et al., 2008). In general, squid mature at smaller sizes in warm water (i.e., slower growth) and at larger sizes that can migrate longer distances in cooler waters. Keyl et al. (2008) hypothesize that a regime shift from warm to cool waters triggered by a shift from a strong La Niña to a strong El Niño in 1997–1998 was the catalyst for the expansion of this species (Figure 2B). It is not clear how climate change will further drive or limit the expansion of Humboldt squid, but some research has noted that this species seems to exhibit extreme plasticity in life history strategies that has allowed it to cope with and thrive during periods of extreme interannual variability with ENSO, making it a climate-adaptive species as it continues to be one of the most important predators in the HCS.

Existing management and evaluation capacity

Data collection across the Humboldt Current

Each of the HCS countries are collecting data on the physical, chemical, biological and geological oceanographic processes and conditions in their waters (Figure 6). However, these data streams are at different temporal and geographic scales and cover different habitat types and species depending on the priorities in each country. A chief goal of enhancing the climate resilience of the HCS will involve identifying where synergies and gaps exist.

In Peru, IMARPE is a specialized technical organization within the Ministry of Production (PRODUCE) with a mandate to study and evaluate the state of Peru's marine ecosystem and its valuable marine resources. In this role, IMARPE provides council to PRODUCE's decision making associated with fisheries resources and the conservation of the marine environment in general. Within IMARPE, the Directorate of Oceanographic Investigation and Climate Change (DGIOCC) is responsible for the scientific investigation of the physical, chemical, biological and geological oceanographic processes and conditions of the region with particular focus on understanding climate impacts on the marine offshore and coastal ecosystems. To accomplish this, the DGIOCC works on five overlapping project themes:

- El Niño monitoring study of the marine ecosystem off the Peruvian coast (PPR 068 El Niño);
- Integrated study of the coastal upwelling front off of Peru;
- Integrated study of the dynamics associated with physical and biogeochemical processes in the coastal ecosystem;
- Climate change impacts in the marine ecosystems off the Peruvian coast: analysis, modeling, and adaptation;
- Fisheries oceanography.

Additionally, it is important to note the collaborative scientific agreement for oceanographic studies between IMARPE and IRD, the French National Research Institute for Sustainable Development. This joint research program has the following four principle themes and associated objectives:

- Spatial ecology in a changing climate – to improve knowledge with respect to spatial ecology and investigate climate change impacts on the spatial distribution of fishery resources;
- Dynamics of species under high environmental variability – to incorporate new techniques to stock assessment modeling;
- Ecosystem modeling with an ecosystem focus for fisheries – to integrate spatial ecology and population dynamics for the configuration of ecosystem models;
- Quantitative support tools for social-ecological system management – to develop tools which integrate objectives in social, economic, and ecologic conflicts for fishery system management as well as contribute to marine spatial planning.

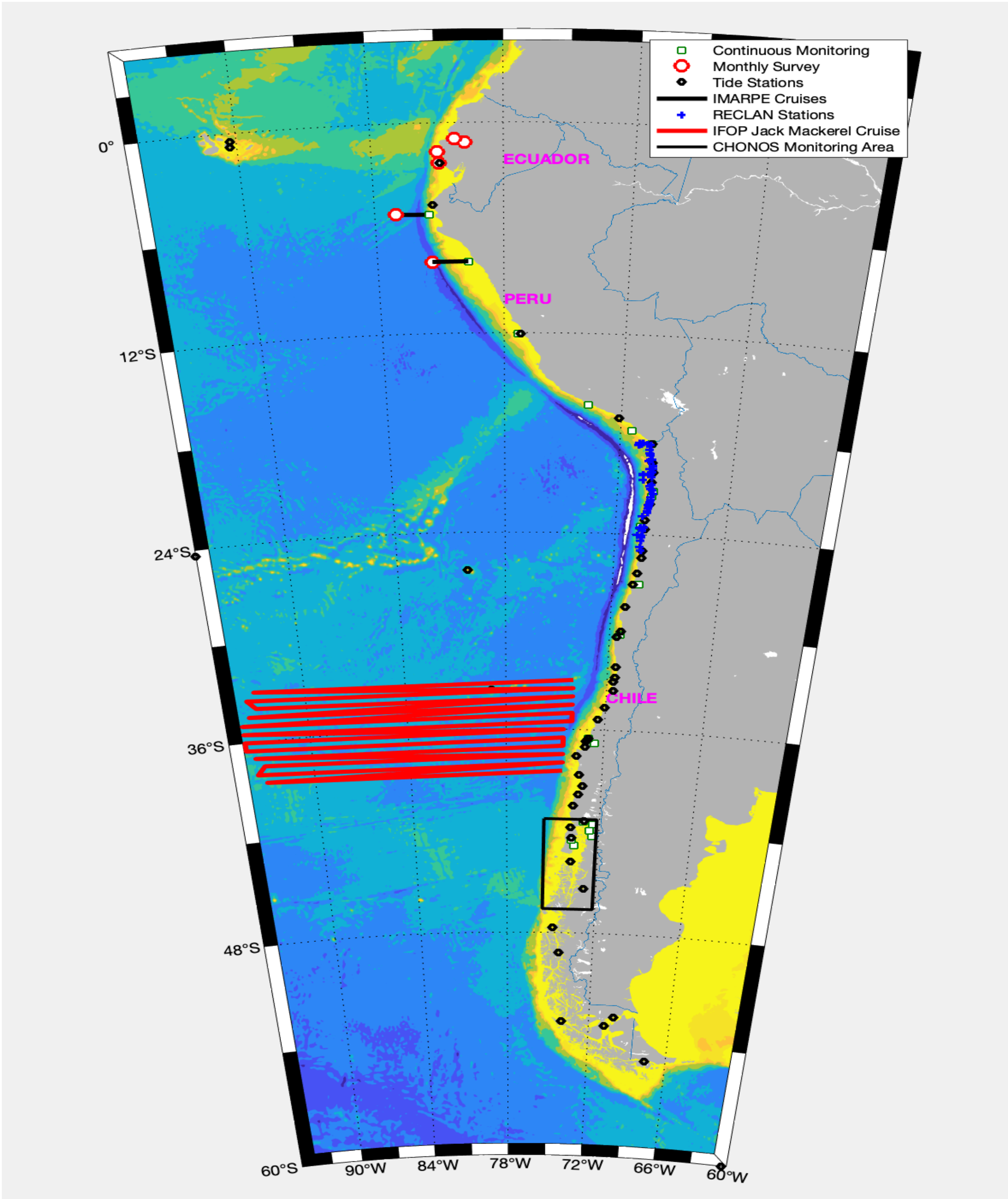

Figure 6. Select oceanographic monitoring occurring in the HCS across Ecuador, Perú and Chile. Green squares indicate continuous monitoring and includes instrumentation such as CTDs and meteorological stations (Chile). Red circles indicate monthly survey stations with black lines indicating IMARPE cruise transects at Paita and Chicama. Black diamonds depict tidal stations across the three nations (please note that the majority monitor sea surface temperature as well). Blue + symbols depict IFOP coastal RECLAN survey stations. Red lines indicate IFOP annual jack mackerel survey transects. Lastly, the black box indicates the recent IFOP initiative CHONOS for monitoring the marine environment in the Chilean Patagonia. Source: figure produced as part of this study

To meet these goals and to carry out these joint initiatives, IMARPE uses a variety of instruments to collect data:

- Coastal Monitoring Platforms provide continuous data from stations located in Paita, Chicama, Callao, Atico, and Ilo on temperature, salinity and dissolved oxygen between the surface and 100 m depth.
- Monthly Sampling Cruises in Paita and Chicama used Conductivity, Temperature, Depth, Oxygen profilers (CTDOs) to provide measurements of temperature, salinity, dissolved oxygen, nutrients, pH, Chlorophyll-a, and Niskin bottle water column samples from the surface to 500 m along transect from 5-100 nm from the coastline.
- Remote satellite data products derived from Advanced Scatterometer (SCAT), Advanced Very High Resolution Radiometer (AVHRR), Topex / Poseidon, Moderate Resolution Imaging Spectroradiometer (MODIS) - Aqua (National Aeronautics and Space Administration (NASA) / Earth Observing System (EOS) satellites and sensors which provide ocean and atmospheric monitoring and are updated daily include:
    - Atmospheric pressure at sea level (atmospheric pressure maps and associated anomalies; South Pacific Anticyclone Index)
    - Winds (wind maps at sea level; Hovmoller diagrams)
    - Sea surface temperature (maps of SST and its anomalies; Hovmoller diagrams of SST anomalies; Peruvian coastal thermal index)
    - Sea level height (maps of the average sea level and its anomalies
    - Ocean currents (maps of current velocities and direction)
    - Chlorophyll-a (maps and time series)

In Chile, IFOP is a public-private research institution charged with carrying out fisheries scientific investigation and utilizing the resulting information to provide council to the Chilean government's Undersecretariat of Fisheries and fishing industry in order to strike a balance in the sector between competitiveness and sustainability. IFOP develops advice for decision making and research projects on the evaluation of sustainable exploitation strategies, estimates the total allowable quotas of commercial interest resources, evaluates and monitors the benthic resource management areas and hydrobiological health programs, among many other aspects of oceanographic science. IFOP provides the Chilean government with the necessary information to manage and regulate the capture of resources, establish an integrated management of its fisheries, deploy a management and technical assistance model, and develop aquaculture and sustainable fishing practices.

To meet these goals and to carry out these joint initiatives, IFOP uses a variety of instruments to collect data:

- Atmospheric Weather Stations are equipped with sensors to collect atmospheric temperature, pressure, moisture, precipitation, wind speed and direction, and solar and UV radiation.
- The research vessel Abate Molina is equipped with echosounders, CTDOs, Niskin bottles, sediment traps, bongo and vertical plankton nets, and onboard workstations for biological sampling for scientific research cruises including biannual recruitment study

cruises. These instruments provide measurements of temperature, salinity, dissolved oxygen, nutrients, pH, sediment type, phytoplankton and zooplankton samples, and Niskin bottle water column samples.

These various oceanographic datasets feed into the new CHONOS oceanographic information system[1] focused on environmental observation and prediction in the Chilean Patagonia region.

Additionally, as far back as the early 2000s, IMARPE and IFOP have been hosting annual Joint Evaluation Workshops focused on enhancing the scientific understanding of relevant pelagic resources (anchovy, sardine, and horse mackerel). This is a key example of a shared data and knowledge program.

In Ecuador, the Instituto Nacional de Pesca (INP) is the agency responsible for realizing scientific and technological investigations of aquatic resources, based on the understanding of the environment and its inhabitants. The focus of the agency's research is to evaluate the aquatic resource potential, diversify production, further develop the fishing industry, and achieve an optimal and rational resource utilization level. One important regional program is ERFEN (Regional Study of the El Niño Phenomenon), which is a multidisciplinary effort in the fields of meteorology, oceanography, marine and fisheries biology, and socioeconomics with the fundamental goal of predicting oceanic-atmospheric changes. This prediction ideally would occur with sufficient anticipation to allow for the establishment of adaptation or emergency policies for industrial fishing performance such as quota shifts, marketing decisions and adaptive management of aquatic resources.

To meet these goals and to carry out these joint initiatives, INP uses a variety of instruments to collect data as part of the Regional Study of the El Niño Phenomenon in the Southeast Pacific (ERFEN):

- Oceanographic buoys and ARGOS profiling floats provide continuous data for SST, profiles of temperature, salinity, and dissolved oxygen, the depth of the mixing layer and isotherm, and nutrient profiles.
- Monthly Sampling Cruises in Puerto Lopez and Salinas provide samples of phytoplankton, zooplankton, and ichthyoplankton.

The necessity for an improved adaptive management system for the HCS

Currently, each country is conducting management and evaluation of their fisheries resources to a large degree at the country scale. In order to better respond to the effects of climate change, it will be necessary to consider and be able to respond to changes that occur at the scale of the HCS. This necessitates the ability to anticipate physical and biological climate-related changes, recognize when these changes are occurring, and identify appropriate responses to these changes. Such an approach will need to anticipate changes with more accuracy, foresight, and swiftness.

[1] https://www.ifop.cl/en/ifop-y-subpesca-lanzan-sitio-chonos-que-entrega-informacion-oceanografica/

With this in mind, in 2018, EDF hosted a workshop in Washington D.C. to discuss the impact of climate change on the HCS with IFOP, IMARPE and INP, and other stakeholders from the affected countries. The objective of the meeting was to develop strategies for building resilience over the next ten to thirty years in the shared fisheries of the HCS. A primary goal was the ability to manage stocks sustainably across the HCS, taking into account climate change and other environmental variability, based on information collected across the region from a shared observational data system and common knowledge base. This resulted in the identification of the need for an improved scientific and monitoring system, emphasizing a shared knowledge base, a more holistic and synoptic observation and data collection system, a more refined understanding of how physical and biological changes in the HCS will affect fisheries and the need for more responsive and adaptive management.

The components of such a plan include:

- Prediction and early warning of physical system level changes,
- What these changes mean for the biological resources in the HCS, and
- Implications for fisheries and fisheries management.

Realizing these components necessitates a coastal and ocean observing and data collection system that is synoptic in time and space across the HCS.

Improved data collection, dissemination, and utilization for better management

Data can be used to inform better management at several different scales from shorter-term tactical planning and response to longer-term strategic considerations of goals and objectives. A key part of the shared vision in the HCS is to design and implement a comprehensive coastal ocean observing system (COOS) and shared data platform (Figure 7). We describe what such a COOS entails, including the type of technology and instrumentation that is needed, and how the data can be housed in a central repository or data platform. Ideally, this data platform would increase the accessibility of the data for multiple stakeholders, which would speed up the rate at which new data products and analyses can be implemented and ultimately used to build a predictive early warning system (EWS) for the HCS to facilitate better, more adaptive management (Figure 1).

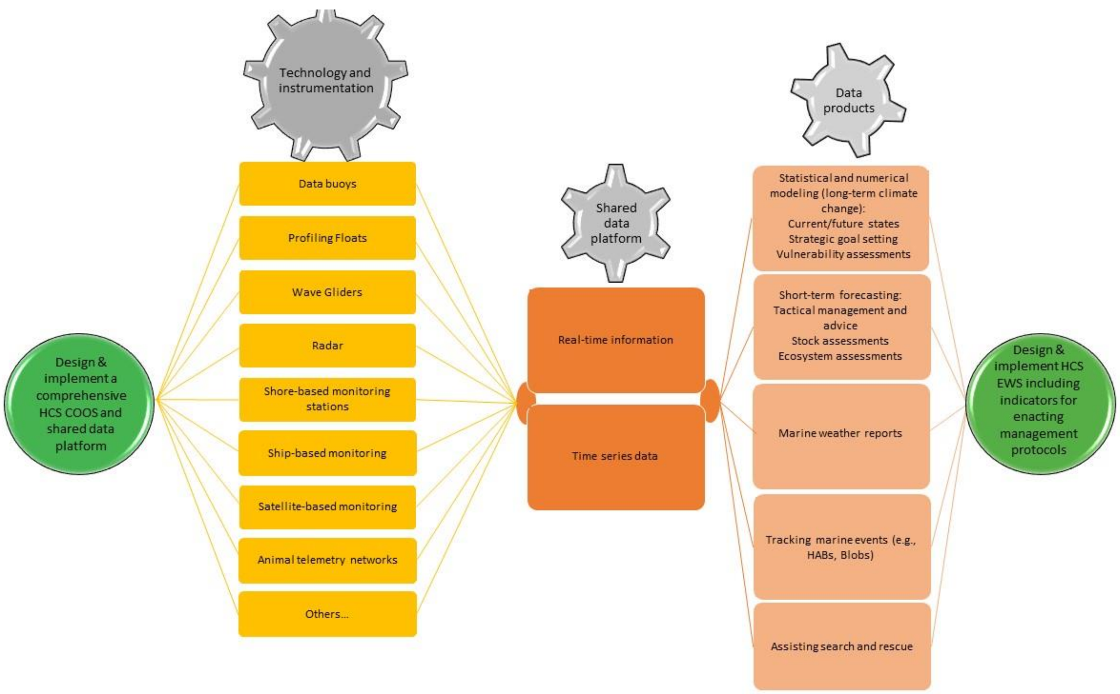

Figure 7. Components of a comprehensive coastal and ocean observing system (COOS) that can feed into a predictive EWS for the Humboldt Current System (HCS). For example, ocean observations from various instruments can be combined and used to provide data that can inform models, provide weather reports, track marine events, assist search and rescue efforts, or inform EWS.

What is a coastal ocean observing system?

Coastal ocean observing systems (COOS) are critical tools that help inform on the state of the coastal ocean worldwide and how changes in marine and atmospheric systems impact society. These systems integrate networks of information gathered by various people and organizations and allow different stakeholders to utilize the data, share advances, improve research capabilities, and provide decision-makers with access to information and scientific interpretations. Such a data system would speed up the rate at which data can be used and make data available to more users, which would improve the ability of researchers to develop analytical products and novel tools (e.g., ecosystem-based assessments, early warning indicators, forecasting models that link physical changes with biological outcomes) that can ultimately help fisheries managers more proactively and efficiently manage resources in the face of change.

Data, observations, and models typically integrated into COOS come from a variety of platforms, including:

- **Data buoys:** moored buoys and offshore platforms are anchored to the ocean floor with a floating surface structure to gather information on temperatures, winds, waves, currents, salinity, chlorophyll a levels, and other oceanographic data. Data can be collected at the surface and along the mooring rope to obtain water column profiles. Surface drifters are unattached and can collect data at the surface and provide information on currents. These instruments relay information in real-time.
- **Profiling floats:** cylinder-shaped submersible robot equipped with specific physical and/or biogeochemical sensors. Used as an autonomous platform to sample oceanographic data. The Argo (http://www.argo.net/) program is an international initiative that deploys and maintains an array of approximately 3000 profiling floats scattered across the global ocean that provide measurements of sea temperature and salinity. Most Argo floats take measurement profiles every 10 days, allowing the floats to work for 2–4 years and undertake investigations on monthly-seasonal to inter-annual timescales.
- **Gliders:** autonomous underwater vehicles (AUVs) that can operate at the water surface or at depth and that are equipped with various sensors to measure oceanographic properties such as temperature, winds, waves, currents, salinity, and chlorophyll a levels. They may also be equipped with acoustic sampling data to collect information on fish population densities. Gliders transmit data every few hours and can be programmed to sample in different areas. They are deployed for routine observing missions, but also for continuous monitoring of events such as harmful algal blooms (HABs) or oil spills.
- **Radar:** land-based High Frequency radar (HFR) provide real-time data on the speed and direction of surface currents over large areas, which can be incorporated into global ocean models. This information can also be useful in tracking oil or other hazardous materials such as harmful algal blooms, and for assisting with search and rescue operations at sea. Currently about 400 HFR operate in 36 countries around the world and the international community is working to share best practices on data management

and integration of these data into models and support services. In addition to HFR, X-band and microwave radars are also being utilized to assess tides, waves and ocean surface currents.

- **Shore-based monitoring stations:** these platforms are located on beaches, piers and offshore platforms and measure information such as air and surface water temperature, barometric pressure, wind speed, direction and intensity, and rainfall in real-time that can be used to inform on changes in weather and longer-term climate change patterns and events.
- **Ship-based monitoring:** research and fishing vessels are used to collect physical, chemical and biological data on ocean conditions along a cruise route or fishing trajectory. Ships are equipped with sensors to collect this information, or scientists or fishermen can deploy instruments to gather data. If data are collected on a fishing vessel, this is called fishery dependent data and must be corrected or standardized to account for specific targeting of particular species or ocean conditions. This is in contrast to research vessels, which typically employ stratified random sampling designs to minimize bias due to uneven sampling of conditions, events, or species.
- **Satellite-based monitoring:** Earth observing satellites orbit the Earth at an altitude of 500 – >20,000 miles and collect images that can be used to measure SST, ocean color, and sea surface height and identify ocean fronts, polar ice distributions, HABs, oil spills, and weather events like hurricanes.
- **Animal telemetry networks:** acoustic and satellite telemetry tags are attached to animals to assess distributions, track migrations and understand their behaviors. The tags can also collect oceanographic data within the water column, which can complement data from AUVs and buoys. The data can be relayed in real-time or periodically depending on the type of hardware used. The data gathered can be used to inform stock assessments and inform on the status of protected species, define essential habitat, and be used for evaluations of anthropogenic disturbances.

Shared data platform: structure and dissemination of data

All of the data collected from the systems above, as well as other monitoring platforms, should ideally be made available to researchers so that they can be used to inform various models and analyses. Having a centralized data platform can help to integrate data from multiple sources and allows users to download historical and real-time data in a useful format. Data can be provided via websites, smartphone apps and via radio reports for use at sea. When possible, raw data can be compiled and processed into more useful information or indices which provide insight regarding overall environmental conditions or fishery status.

In the HCS, each country is collecting data on the physical and biological system, as noted above, but at different spatial and temporal scales and with different geographic scopes. These data are made available to different stakeholders with varying degrees of specificity.

Establishment of data standards
One important component of a shared observational platform is the development of standards or protocols for data collection, post-processing, and analysis. For data collection, this may include sampling methods, a selection of approved instrumentation for particular scientific applications and field guidelines for instruments during data acquisition. In post-processing, standard operating procedures (SOPs) may be developed to automate or guide manual procedures to assure data quality for downstream use. Lastly, data analysis may incorporate protocols such as standards utilized in laboratory analyses or guidelines for statistical procedures to assure consistency in data products for end users.

For many instruments and data types, standards or protocols have been established in existing COOS networks and may be utilized here. One such example is the Global Oceans Ship-based Hydrographic Investigations Program (GO-SHIP), which provides manuals and guides for various oceanographic instruments including preparation pre-cruise, data acquisition, and post-processing. One such example pertains to CTD (a sensor that collects information on conductivity, temperature, and pressure of seawater) and oxygen measurements collected by Sea-Bird software and hardware (https://www.go-ship.org/Manual/McTaggart_et_al_CTD.pdf). Whether such existing manuals and/or standards are included, or rather new ones created, it is important that agreement amongst participating country agencies (INP, IMARPE, and IFOP) be established and upheld throughout the process.

Data products: Utilization of data
Observed data, housed in a data platform as described above, can be drawn on for multiple purposes. These data can inform both shorter-term tactical management as well as longer-term goal setting and strategic planning. One way that this can be done is through the use of statistical and numerical models, which are powerful tools that can be used to forecast ocean conditions, assess ecosystem states, and provide information for planning on short and longer-term time horizons. Observed data can be incorporated into computer models and used to forecast changes in ocean conditions, circulation patterns, flooding, the movement of harmful algae, fish larvae or pollutants through the ecosystem and more. These data can also be utilized to inform stock assessment models and to develop early warning indicators. The highly variable nature of the HCS combined with the effects of climate change means that we will need better early warning capabilities. One means of achieving this is through the development of an EWS or Sistema de Alerta, Predicción y Observación (SAPO).

An EWS is a set of protocols in place that help decision-makers, businesses and private individuals prepare for and respond to a hazard. Its purpose is to anticipate what is going to happen and to allow for more rapid adaptive management and better long-term strategic planning. With respect to fisheries and climate change, such a system would provide an alert when unfavorable conditions for the health, distribution, or productivity of the stock are likely to arise due to climatic forcing and allow for the sustainable and efficient use of resources contingent on the current conditions. To be able to make decisions in advance of a climatic event, an EWS needs to be based on sound science that incorporates historical and current physical and biological data and observations and that develops indicators, models, and other analytical tools to identify people and resources exposed to the risk. Such decision-making should also incorporate systems thinking on short and long timescales that account for all relevant ecological, environmental and social risk factors.

EWSs are especially important in regions of extreme change that are experiencing strong forcing. For example, Australia is currently experiencing climate-related impacts due to atmospheric forcing associated with the Indian monsoon cycle. Impacts associated with this forcing can provide global-scale indicators of climate change. Similarly, fluctuations in the HCS, which is driven to a large degree by ENSO variability, may provide early indications of climate-related impacts on the world's oceans.

According to the European Climate Adaptation Platform, Climate-ADAPT, effective EWSs must contain four interacting elements: 1) risk knowledge, 2) monitoring and warning services, 3) effective dissemination and communication of risks and timelines, and 4) response capability (https://climate-adapt.eea.europa.eu/). These elements should operate at the system scale so that observations of conditions are made synoptically in time and space and responses take into account the needs and risks of all stakeholders. Overall, implementing an effective EWS will require resources and capacity. Each system will have more or less of the necessary components, but in general there are some clear needs:

- *Reliable data*: unreliable or inconsistent monitoring, budget restrictions, and limited capacity to process and analyze data will hamper the use of information in EWS. The COOS described above would provide reliable data on the right scale and scope to identify and respond to system-level changes.

- *Credible data*: high uncertainty around monitoring data that is used in models or indicators leads stakeholders to doubt and sometimes challenge findings and makes it challenging to build consensus around an adaptive management approach or protocol. Having an HCS-wide COOS and EWS would facilitate collaboration and buy-in from stakeholders across the region.

- *Clear protocols for response*: once the data are collected, analyzed and validated, it is necessary to create a response matrix or decision tree that defines how to act given a particular outcome. These protocols should clearly articulate responses for all stakeholders so that actions are coordinated and as effective as possible across the HCS.

- *Effective information distribution systems*: being able to communicate the information and decision criteria and responses is critical for ensuring buy-in and making sure that all parties are aware of a potential change in the system and how and when to act. A networked data collection and dissemination system for the HCS would allow more rapid development of analysis and techniques that would improve management responses and capacity.

Examples of early warning systems in practice

Early warning systems are used frequently with natural disasters such as hurricanes or typhoons, floods, and heat waves on land to provide information on the scale and intensity of the event so that decision-makers and emergency services can prepare and issue guidance to communities. As climate change is stimulating more frequent and intense weather events, these EWSs are being refined and enhanced along each of the four elements described above with the overall goal of being able to better forecast extreme events and provide effective and rapid guidance on responses.

In the marine environment, marine heatwaves are considered by many to be indicators for longer-term changes like marine species distribution changes and changes in fish abundance. However, despite the range of physical, biological and social outcomes involved with marine heatwaves, these phenomena are not measured in a systematic way like hurricanes, which are classified as to their size and intensity. Researchers have noted that there is a need for a naming and measurement system for marine heat waves and other climatological phenomena, which will allow for a better understanding of how these events are unfolding over time and for comparison of events around the world. Hobday et al. (2018) recently developed a definition and classification system which allowed for comparison of marine heatwaves around the world. Their analysis revealed a long-term increase in the occurrence of all marine heatwave categories (Figure 8).

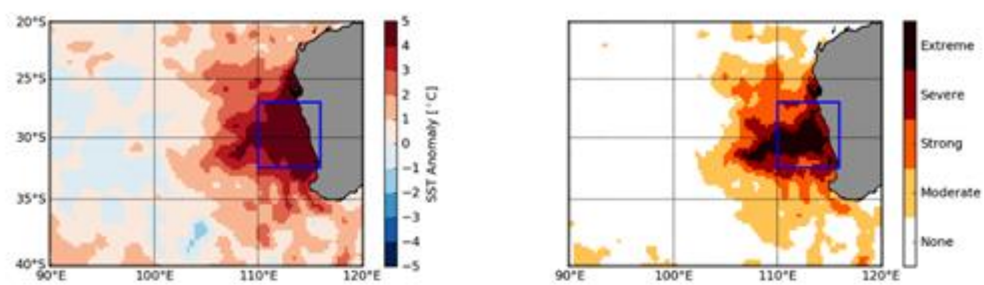

Figure 8. The Western Australia 2011 Marine Heatwave was more than 4.5°C hotter than average (left) and classified as a Category IV at the center (right) Source: Hobday et al., 2018.

Other examples of EWSs in marine systems exist for the prediction of heat stress to inform the management of coral reef systems. For example, since 2012, each week NOAA's Coral Reef Watch calculates the probability of heat stress capable of causing a mass coral bleaching event over a 4-month time horizon. This information is used by marine resource managers, scientists, and decision makers around the world to help make management decisions to protect and monitor coral reefs.

Examples and use of observed marine data systems in the HCS

With respect to fisheries in the HCS, managers want to be able to manage stocks across the region, accounting for climate change and environmental variability, and utilizing relevant data and information. In order to do this, environmental observations are needed across the region, assessments and management decisions for stocks distributed across jurisdictional borders should be conducted or determined jointly when possible and using common data and information.

Chile

The Chilean Socio-Environmental Observatory of the Ocean (OSO) is a proposed system of automated, publicly available data on the state and trends of ocean and human related activities, with emphasis on fishing and aquaculture. This system is being designed as a tool to generate high quality, timely, and clear information to support private and public decisions regarding the use and conservation of ocean resources. The objective of OSO is to contribute to minimizing the asymmetry of information in decision-making, a crucial condition for promoting the sustainable development of the country.

As a first stage, the implementation of OSO will be at a pilot level in the Valparaíso Region, given its geopolitical importance, number of public institutions, and its position in Chile as a focal point for marine research, marine resources and related economic activities. However, the plan is to expand this program across Chile in an effort to provide enhanced transparency of information regarding climate change impacts on the marine environment, so that these impacts may be considered by both the public and private sector.

In addition to OSO, Chile's role as the Presidency of the 25th session of the Conference of the Parties (COP25), which took place in early December 2020 in Madrid, Spain, resulted in this COP being called the "Blue COP" for its focus on the importance of the ocean in climate change policies, adaptation and mitigation strategies. It also included the launching of a Platform for Science Based Ocean Solutions (PSBOS). PSBOS aims to promote the necessity of addressing ocean and climate issues together and incorporating those commitments into countries' nationally determined contributions (NDCs). Furthermore, Chile's Oceans Table (or "mesa de oceanos") also committed to developing an integrated system of ocean observing (SIOOC – sistema integrado de observación del océano Chileno) for its territorial waters. The SIOOC will provide quality control, standardization, and publicly accessible data for the study, monitoring, management and surveillance of the ocean and its resources, including fisheries. This effort will capitalize and synthesize current ocean observing systems in Chile under one system based on existing experience and current gaps, following the timeline below:

- First, consolidate existing systems into a network that has management commensurate with available human resources and financing. This should include the participation of multiple sectors of the economy, including private and civil society.
- Second, incorporate new equipment and infrastructure (primary and secondary) into the system, with an analysis of the enabling capacities and the technological transfer

necessary to increase the type, number, and coverage of observations, in addition to strengthening capacities.

- Third, incorporate other international networks, especially in the areas of the SIOOC.

The universities and state services participating in this initiative have committed to providing their existing knowledge and infrastructure to launch the SIOOC. In turn, the Chilean government is expected to take this initiative and form an international commitment in an effort to achieve greater marine protection and conservation of resources at an ecosystem level.

Peru

The long-term oceanographic observational program off Peru consists of two networks of coastal multidisciplinary (in place from 1960 to present) and ocean-meteorological (in place from 2000 to present) stations at nine selected sites along the Peruvian coast. These two networks are under IMARPE and the Directorate of Hydrography and Navigation (DHN), respectively. Long-term, ship-based observations mainly consist of (i) three multidisciplinary cross-shore sections (1992 to present) at 5°S, 7°S and 12°S, (ii) regularly scheduled research fishery assessment cruises covering the entire Peruvian coast (1960 to present), (iii) some dedicated surveys and (iv) an annual oceanographic cruise (1998 to present). The latter is part of the Southeastern Joint Oceanographic Research Survey, a regional initiative coordinated by the South Pacific Permanent Commission (CPPS). Fixed moorings (1999-2009) and new available technologies such as autonomous underwater vehicles (gliders) were also deployed for short periods. Thus, a complete set of physical, biogeochemical, paleo-oceanography, biological and fishery hydroacoustic data has been collected by IMARPE at different spatio-temporal scales. These data are, for instance, currently used to prevent societal and economic impacts of extreme events such as ENSO events, a priority task for the Peruvian Government.

A plan for a shared observational platform, prediction and early warning system in the HCS

Given the particular variability of the HCS combined with the uncertainty of climate-related effects, there is a need to develop a sophisticated ocean and coastal observing system, data platform, and novel analytical tools to help facilitate better and more adaptive management responses. In the HCS, the timing is ripe to pool expertise and resources across the region to achieve advancements in observation, prediction, and early warning capabilities regarding physical ocean dynamics and climate impacts on fisheries. This enhanced technical capacity will improve our ability to understand the ecosystem-level, climate-related impacts on fisheries, and ultimately improve our ability to respond to them. Ultimately, a common vision for how to establish a shared platform for an HCS coastal and ocean observing system and an HCS-wide prediction and EWS will allow each country to conduct improved adaptive fisheries management in a coordinated, or at least complementary, manner to neighboring countries (Figure 9). In this section we outline steps in a road map to an improved system.

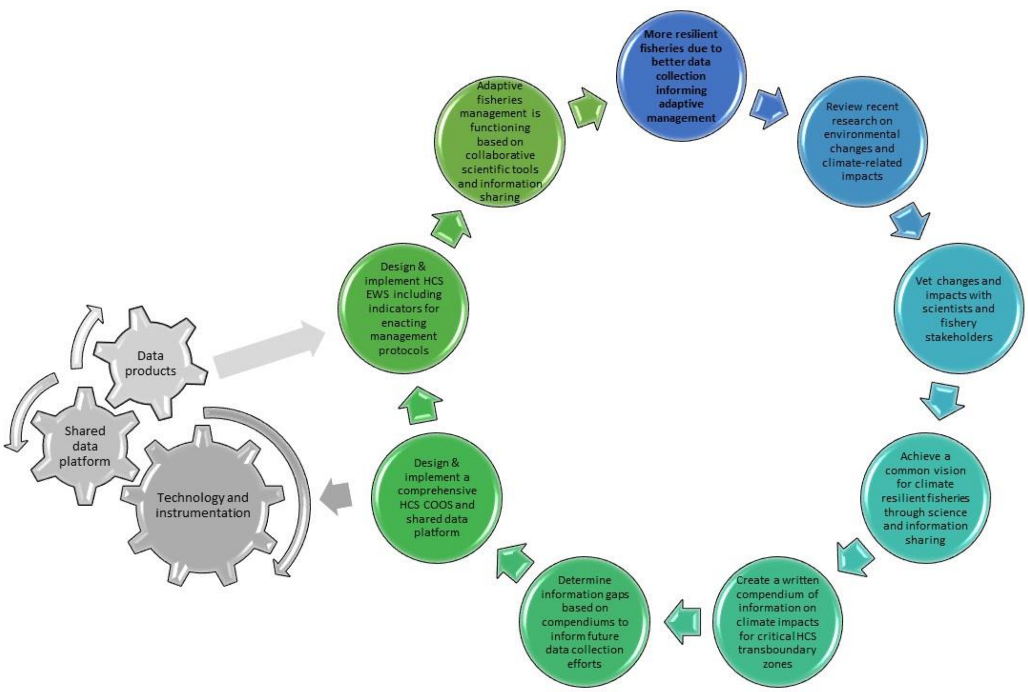

Figure 9. A roadmap for developing a scientific foundation for achieving climate-resilient fisheries.

Step 1: Review recent research on environmental changes and climate-related impacts

EDF, with assistance from regional partners, compiled information from the published literature on ecosystem changes from modeling studies and other analyses to gain a better understanding of how the HCS has changed over time. This review also included information from studies that have examined potential future changes on the physical and biogeochemical components of the ecosystem, noting, when possible, where studies provided conflicting or supporting data as well as levels of certainty in these predictions.

Step 2: Vet changes and impacts with scientists and fishery stakeholders

The information compiled in Step 1 was synthesized in a report that was provided to regional collaborators for review prior to a meeting that was convened at the EDF offices in Washington D.C. in June 2018. The vetted information was used to build consensus at the meeting on the types of changes that have been occurring in the HCS and to focus on the primary challenges. Additionally, the information was helpful in structuring discussions around the types of approaches and management interventions that would be needed to deal with these changes.

Step 3: Achieve a common vision for climate resilient fisheries through science and information sharing

As a result of the conversations described in Step 2, at the meeting, the group developed a collaborative vision for increasing climate-adaptive management and ensuring climate resilient fisheries. This plan was detailed on a five- and ten-year timeline (see Appendix 3: timeline for ten-year vision).

The overall goal of the ten-year vision for the HCS is to reach formalized and trans-nationally agreed upon protocols for dealing with stock shifts and productivity changes that may occur as a result of climate changes or other environmental changes that are in accordance with the legal frameworks for fishery management in each country. By 2030, the group envisions that Chile would have established guidelines for ecosystem-based management, would be using the precautionary principle across all commercially fished species, and that fisheries management interventions would be implemented through participatory fishery management plans. Over this same timeframe, the goal is for Peru to develop a better understanding of the dynamics of the upwelling system in the Humboldt Current and the anticipated effects of climate change, and to develop and use best practices for ecosystem-based fisheries management. Similarly, the goal for Ecuador is to have an increased understanding of upwelling effects and physical and biological changes in the system that are likely to occur under climate change, and to incorporate this knowledge into fishery management regulations. As a united HCS region, all three countries will ideally be collaborating on scientific advances, and policymakers in fisheries management should be utilizing this science in decision making. Lastly, each of the three HCS countries will aim to have the capacity and tools installed for climate-ready adaptive management.

The five-year vision for the HCS involves first identifying priority needs and filling essential gaps to reach the 2030 goals stated above as well as building momentum to achieve the ten-year vision. These priorities include:

- Detailing the ‘state-of-knowledge’ on physical and biological changes and data collection in the HCS and identifying knowledge gaps.
- Determining how each country collects direct and remotely observed data, including geographic and temporal scope and frequency, instrumentation and technology used, and how data are archived and maintained.
- Identification of how these individual and/or country-wide systems can be linked to create an ocean observing system for the HCS, including a shared data platform.
- Determination of how these observed data can be used to inform a prediction and EWS for the HCS.

These last two priorities are longer-term goals, but the aim is that progress is made within the next five years to begin to build a framework for realizing these initiatives.

Ideally, the scientific collaboration around climate impacts on fisheries will be aligned with the GEF-UNDP Strategic Action Program for key fisheries such as Chile and Peru’s transboundary anchoveta stock, as well as other regional programs for the key sub-regions in the HCS. In addition, over the coming five years fishery science institutes from each country in the HCS will continue to work together to attract funding sources for advancing regional observation and information sharing, and will have created a set of scientific volumes as a compendium of the scientific knowledge and advancement on climate change impact on fisheries in the Humboldt Current. Within five years, a scientific capacity building strategy at the regional level will be implemented to achieve the long-term vision.

Step 4: Create a written compendium of information on climate impacts for critical HCS transboundary zones

In order to prepare for the climate change impacts in the HCS and the high levels of uncertainty that are inherent in this dynamic system, it is essential for public and private fishery stakeholders across the Humboldt to collaborate and to pool their expertise and resources. Recent collaborative efforts between IMARPE, IFOP and INP, and facilitated by EDF, have resulted in the organization of a compendium of baseline information collected by each country’s scientific institutions. These volumes will provide fishery scientists and decision makers organized and categorized ‘state-of-knowledge’ information to help understand what is known, and identify areas where more information is needed (gap identification) about various sub-regions of the HCS that will be most impacted by climate change. A particular focus will be on the two transboundary zones (i.e., between northern Peru and southern Ecuador, and southern Peru and northern Chile).

In May 2019, a workshop involving the three institutions and hosted by EDF was convened as a follow-up to the meeting in June 2018. The group developed an outline for the first volume of information on southern Peru and northern Chile. Appendix 1 presents this annotated outline, which discusses the scientific content that each of the nine chapters will cover and indicates the topical leaders from each institution.

Step 5: Determine information gaps based on compendiums to inform future data collection efforts

The plan is for the chapters in the first volume to be drafted by the topical leaders over 2020 and 2021. When this information is compiled, an assessment will be made to determine where information is needed, and a plan will be developed to determine how to best collect these data. A meeting planned for May 2020 will focus on data needed at the HCS-scale to inform a system wide coastal ocean observing system and shared observational data platform for the HCS. EDF is currently seeking funding to help with the scoping and planning that will be needed for such a system.

Step 6: Design and implement a comprehensive HCS COOS and shared data platform

Learning from examples from around the world such as the global ocean observing system program (GOOS, https://www.goosocean.org/), other regional coastal ocean observing systems (COOS), and the OSO and SIOOC programs in Chile, the fisheries science institutes of the three countries of the HCS have committed to building a cohesive platform for ocean observation, including a shared platform for hosting data from this observing network, for the purpose of ensuring climate resilient fisheries management. This platform will be able to digitally pool data and expertise from each country's fisheries dependent, independent and oceanographic monitoring systems in order to have a shared database upon which researchers and other stakeholders can conduct collaborative analyses. The idea is that more synergistic research could be conducted, such as what is currently the case for the shared anchovy fishery in Peru and Chile, where scientists from IMARPE and IFOP jointly conduct the assessment on an annual basis, using oceanographic data, to help each country's management agency make informed decisions regarding fishing quotas. The goal of developing an HCS COOS would be both to improve the shared anchoveta assessment process and to spur further international collaboration.

Additionally, the vision for the shared platform for observation is to go beyond the current data collection efforts in each country by more efficiently using research vessels and other observation equipment (e.g., radars, CTDs, buoys, etc.) to build a more comprehensive picture of system-level changes in the physical environment and effects on the biological system. This new data collection for the Humboldt could be greatly aided by applying innovative technologies, such as smart boats, gliders, or radar networks, some of which can provide data in real time to the platform.

Step 7: Design and implement HCS EWS including indicators for enacting management protocols

Based on the volumes of information and the shared observational data platform, the science institutes of the three countries in the HCS, will collaboratively design a prediction and EWS for fisheries management. This system will hinge upon the ability of each country to pool their expertise and resources and work collaboratively to create a set of indicators that can help trigger warnings and provide response guidelines for fishery management protocols in each country. The advantage of working at an ecosystem scale across the HCS is that other countries' expertise with a given fishery (especially those that may be entering new jurisdictional waters) or environmental variables such as increased upwelling or temperature changes could help inform another country's response or future response depending on climate change trends. Ensuring that HCS countries have coordinated, if not complementary, responses to climate impacts on fisheries can help promote better ecosystem based management of fisheries, uphold the precautionary principle, and provide the tools for both rapid and long-term adaptive approach towards management that ultimately creates more resilience in the system.

Steps 6 and 7 are envisioned as the core of a plan for the development of a regional scientific and governance framework that includes development of the following three areas (Figure 10):

1) *Technology and instrumentation:* Implementation of technology for a shared (real time) observational data platform;
2) *Shared data platform:* Communication with the scientific community, decision makers, and stakeholders regarding regime shifts and climate shocks occurring or about to occur; and
3) *Data products:* Implementation of the components of a comprehensive system to include observations, predictions, and early warning signals.

This innovative system will provide fishery managers with the information and tools they need to make adaptive management decisions in both the short- and long-term depending on the impacts of climate change on fisheries' productivity, abundance, and movement patterns.

Figure 10. Key areas where capacity building is needed in order to develop a regional scientific and governance framework in the HCS.

Step 8: Adaptive fisheries management is functioning based on collaborative scientific tools and information sharing

The steps above will ideally lead to the development of better overall understanding of system-level changes through the collection of better, more temporally and spatially synoptic data across the HCS, the pooling of knowledge and expertise, and the development of collaborative scientific tools such as models and indicators that can help spur management that is adaptive and responsive to changes in the fisheries.

Step 9: More resilient fisheries due to better data collection informing adaptive management

The goal is to continue to improve fisheries management through the ongoing collection of data across the region, through the development of new tools and analyses, and through the assessment of more species and components of the ecosystem. In this way the steps above are envisioned as a feedback loop, spurring continual improvements in the overall process.

Future directions for adaptive management in the HCS

The management of Peruvian anchovy by Peru, which includes near real-time data on stock dynamics from the commercial fishing vessels is touted as an example of the effective use of environmental data in stock assessments and successful management of an extremely dynamic and variable fishery. Additionally, the joint assessment by Peru and Chile of the shared stock of Peruvian anchoveta is a good example of international collaboration in the region. However, there are few other examples of this type of collaboration for other stocks in the region and climate change is affecting both the variability of the physical system and the abundance, productivity, and distribution of species in the HCS. Therefore, the fishery management systems within the HCS will need to evolve and become more adaptive. Ultimately, the challenges that climate change will bring to fisheries management in the HCS will demand that management systems become better equipped to identify and anticipate the scope, scale, and frequency of environmental change and the corresponding effects on fisheries, including the necessary and appropriate responses.

Inherent in fisheries management is an assumption that conditions and responses exist within a certain tolerance level while varying around some average state. Therefore, management approaches are often set up to respond to some degree of environmental change. However, long-term directional change poses a different challenge that often invalidates the traditional assumptions of stationarity (e.g., a mean and variance that does not change with time). As a result, current management systems are unable to adjust appropriately in the face of a fundamental re-shuffling of the ecological regime. This is especially true as such change is often fraught with uncertainty (e.g., is a species shift a permanent or a pulse event?), and political pressures that stem from the socioeconomic impacts of these changes can make identifying and implementing appropriate solutions challenging. However, in the face of climate change, failure to adapt to such fundamental ecological change can exacerbate climate effects and erode the overall success of the fishery management system.

It is against this backdrop that the fishery management systems in the HCS will need to evolve. This may involve adapting at higher order fundamental and strategic levels (i.e., overall goal setting and long-term expectations of fisheries), as well as shorter term tactical levels (e.g., setting harvest control rules and regulating access to fisheries), as opposed to current frameworks which tend to focus intently on tactical adaptation and revisit strategic considerations infrequently. In other words, the temporal scale of climate change will dictate a greater emphasis on long-term, strategic goal setting with more frequent evaluation than managers, stakeholders and scientists are generally accustomed to. In doing so, it will challenge all of us to re-define what success looks like and how we get there.

Building adaptive fishery management systems to meet this challenge will require some key considerations and adjustments to the system, including:

- *Working to understand future change*: Increasing the understanding of how an ecosystem will change with climate change, and what this means for the future possibilities for the socioeconomic prospects of a fishery
- *Recognizing uncertainties regarding future conditions*: Forecasts of future ecological states will inherently come with much uncertainty. Some of the sources of this uncertainty may be identifiable, but many may not. Therefore, there will be impacts that catch managers and stakeholders by surprise and there will need to be flexibility built into the system to allow for adaptation to these events
- *Socializing future possibilities:* Ensuring that stakeholders and managers are aware of what the future will bring, what may be possible, and what may not be possible in a climate-changed future
- *Re-evaluating fishery goals in the face of climate change*: The goals and expectations for a fishery may need to change in accordance with potential possibilities from a fishery given future ecological states
- *Anticipating sources of social conflict:* Changes in harvest opportunities may create winners and losers in terms of fishery access, which can trigger social resistance to policies that are otherwise sustainable. Dealing with these by making sure key stakeholders and affected parties have a seat at the table will be imperative.
- *Making decisions within appropriate timeframes:* Uncertainty is often used to delay or defer decisions. However, inaction can result in adverse consequences for fisheries. For example, a failure to reduce fishing effort on a stock in advance of a forecasted environmental shock can lead to overfishing. Decisions should be made using the best available information, estimates of uncertainty, following the precautionary principle, and with an understanding that those decisions can and should be reconsidered in the face of new information.

While there is certainly latitude to implement adaptive management in different ways in order to address climate change, the following steps below are provided to help provide a vision for what such a system may incorporate. More detail is included in Appendix 2.

Strategic considerations

- Make an assessment to determine potential ecosystem states given anticipated climate effects, including measures of overall abundance and productivity, changes in species' distributions, and evaluating changes in the mix of species that may be found in a system.
- Socialize this assessment with stakeholders and managers and help establish a collective understanding of what may be possible or not.
- Explicitly consider whether existing fisheries goals are still relevant, or whether the range of future potential states necessitates re-considering goals and establishing new ones.
- After goals that are relevant to climate change are established, assess the vulnerability and status of the ecological and socio-economic dimensions of the fishery system in relation to those goals.

- Knowing that management and scientific resources are limited, identify priorities for management efforts given the vulnerabilities and fishery status.

Tactical considerations

- When priorities have been established, identify indicators and reference points that will work to help identify how the fishery is doing relative to goals and management priorities.
- Following the establishment of indicators and reference points, identify suitable tactical management measures. These include rules that specify allowable catch levels, often referred to as Harvest Control Rules, and catch control tools that maintain adherence to rules and reference points such as fishing quotas and spatial management measures.
- Finally, collect information on performance in relation to multiple aspects of the management system, including performance of the tactical management measures, performance of the harvest control rule, the response of the fishery resources to the management system, and others.

While these steps can be separated into strategic and tactical decisions, there is, of course, feedback between them, especially as the climate is changing. Large, strategic goals help to determine the scope and type of tactical activity, but information collected through more tactical management activity (e.g., from fishery dependent data) can be used to help inform and re-evaluate both tactical and strategic goals. Overall, with respect to climate change, it is likely that broad, strategic adaptations will need to occur with some frequency as the ecological system changes. In other words, climate change will demand that adaptive systems become even more adaptive in terms of their ability to respond to the rate of change, their ability to adjust goals and priorities of management, and the ability to quickly respond to unforeseen events.

The creation of a scientific foundation and the associated tools, such as a comprehensive and shared ocean observation platform and a HCS-wide prediction and EWS (known as SAPO in Spanish), is the first step towards being able to evolve fisheries management at both the strategic and tactical levels in the HCS. Following the shared vision set forth in this roadmap (refer to Figure 4) will allow for the fisheries science institutes and management agencies in each country to work together to achieve a consensus on how they each can set management goals at a national level that will be complementary to HCS-wide goals for resilient fisheries in the face of climate change. The scientific tools that are outlined above starting with a shared data platform that will feed into a COOS that is HCS-wide will provide the information necessary to predict environmental changes and make tactical decisions accordingly using agreed upon early warning indicators developed by all three countries. Therefore, this prediction and EWS will allow fishery management agencies to enact adaptive management at various geographic and time scales in the HCS. Most importantly, given the dynamism and uncertainty around climate change impacts on HCS fisheries, adaptive management at both strategic and tactical levels will require an ongoing iterative process to ensure that the indicators and management measures that are taken by all three countries individually and together under international frameworks are ensuring sustainable and resilient outcomes.

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Appendix 1

Physical, Chemical, and Biological Oceanography and Marine Geology of the Humboldt Current System (Humboldt Current System)

1. Physical Factors Affecting the Humboldt Current System
    1.1. General description of the marine geology
    1.2. Atmospheric forcing and climate on the basin and regional scales
        1.2.1. ENSO
        1.2.2. APS, winds
    1.3. Circulation and Water masses
    1.4. Fertility and Productivity
    1.5.OMZ / Oxycline
    1.6. Trends and variability of the regional oceanographic conditions

2. Pelagic Resource Distribution Patterns in the Humboldt Current System
    2.1. Peruvian anchovy (*Engraulis ringens*)
    2.2. Pacific sardine (*Sardinops sagax sagax*)
    2.3. Jack mackerel (*Trachurus symmetricus*)
    2.4. Giant squid (*Dosidicus gigas*)
    2.5. Red squat lobster (*Pleuroncodes monodon*)
    2.6. Other species

3. Biology of the Principal Species Present in the Humboldt Current System
    3.1. Demography
    3.2. Reproduction
    3.3. Growth
    3.4. Feeding

4. Ecological Communities of the Humboldt Current System
    4.1. Communities of phytoplankton and zooplankton/ichthyoplankton
    4.2. Ecological interactions
    4.3. Top predators
    4.4. Ecosystemic models

5. Principal Fisheries in the Humboldt Current System
    5.1. Fleet and landings
    5.2. Catch Per Unit Effort (CPUE)
    5.3. Fishing effort
    5.4. Description of other fisheries (demersals and others)

6. Population Evaluations of the Principal Fishing Stocks Present in the Humboldt Current System

6.1. Peruvian anchovy
6.2. Pacific sardine
6.3. Jack mackerel

7. Associated Socio-Economic Aspects at All Scales
   7.1. Social aspects
   7.2. Economic aspects
   7.3. Socio-ecologic modeling

8. Institutional Aspects and Governance
   8.1. Legal framework
   8.2. Fishing resource management
   8.3. Regional integration aspects

9. Regional Climate Change Scenarios

10. Perspectives and Future Challenges for Investigation and Management with an Ecosystem Focus under the Theme of Climate Change

Appendix 2: General steps to adaptive, sustainable fisheries management in a climate-change context

A2.1. Conduct Ecosystem Assessments to Identify the State of an Ecosystem and Key Drivers Affecting its Future Status

- Evaluate the current health and resilience of a system
  - Is the system nearing a tipping point? Has it been altered substantially from a prior state?
  - Identify how influential different drivers/impacts are on the current state of a fishery (e.g., illegal fishing; pollution; etc.). It is often helpful to rank such drivers in terms of importance for driving unwanted system change
    - This allows for prioritization of interventions – if fishing (or something else non-climate-driven) is the most important threat facing a system, then implementing sustainable fisheries management can be highest priority. If another driver appears more important, efforts should be prioritized in the direction of that driver.

A2.2. Understand what's possible in a fishery through Climate Impacts and Vulnerability Assessments

- Apply tools like scenario modeling to understand what climate impacts are likely to be in your system
  - Will target stocks' ranges shift; will they shift out of a jurisdiction?
  - Will new stocks shift into a jurisdiction?
  - Will target stock productivities decline or become more variable?
    - In data-limited settings, use what is known regarding climate effects in different ecological contexts and on species categories (e.g. pelagic, demersal, reef associated, etc.)
    - This knowledge can be used to help classify stocks as high, medium, or low "vulnerability" or "resilience" to climate change and to identify risks to a fishery
  - Identify measurable indicators of expected ecosystem change in order to anticipate when climate-driven impacts are occurring
    - These indicators are intended to help understand when predicted changes are unfolding, assisting managers and stakeholders in understanding when to transition from long term goals to more short-term tactics. These indicators can include things like: temperature changes; habitat changes; biomass of grazers; nutrient input; appearance of stocks in new places; primary productivity; upwelling changes; ocean currents; dissolved oxygen; carbonate chemistry; basin-scale climate indices; and the abundances, distributions, and recruitment of species across multiple trophic levels, among others.

A2.3. Socialize the Range of Future Fishery States and Risks

- Communicate potential future fishery states with stakeholders and policy makers.

    - Identify how values, needs, and wants to align or are in conflict with likely future states
    - Identify what is possible to achieve and the desired outcomes that may not be possible

A2.4. Set Forward-looking Goals and Objectives

- Utilize the input gained in steps 1 and 2 to set goals for a fishery, based on climate-updated understanding of what will be possible and the needs and wants of affected stakeholders
    - Set long term and intermediate goals that reflect the transition of a fishery as climate change takes hold. Set short term objectives which help to achieve them.

A2.5. Prioritize stocks for assessment and management

- PSA
- Simple stock health assessment
- Climate vulnerability and climate adaptability attributes
- Identify management buckets/complexes if it is a multispecies fishery
- Prioritize stocks (including any emerging stocks; and keeping climate-driven changes in mind) for short- and long-term assessment and management

A2.6. Select Performance Indicators, identify Reference Points, and develop Harvest Control Rules

- Select PIs that can tell you how close you are to your climate-updated system goals.
    - These stock-level PIs should be *in addition to* the ecosystem-level PIs identified previously.
    - Identify appropriate RPs for each PI, based on climate-updated system
    - Develop adaptive HCRs to trigger management action based on PI relationships to RPs.
        - This should be done via participatory process and should include climate-related goals and expectations

A2.7. Conduct detailed assessments of prioritized stocks and interpret results

- Include – to the extent possible – climate considerations within assessments. Techniques for doing so may include:
    - Replace assumptions about abundance-productivity relationships with ecosystem metrics
    - After identifying a climate shift, use data only from the recent regime for stock assessments
    - Examine variation in ecosystem metrics as proxy for variation in productivity, rather than assuming productivity is constant throughout time

A2.8. Design and implement Adaptive Harvest Control Measures/ Plans

- Set a schedule for reviewing results of monitoring (including indicators of climate-driven changes)/redoing assessments, revising goals and objectives, and related plans
- Include adaptive and experimental fishing programs on emerging stocks

A2.9. Concurrently collect more data

- As part of the data collection effort, strive to improve the ability to separate effects of climate from the effects of fishing. This may include:
    - Using or establishing long time series to capture multiple cycles
    - Comparing across many independent populations
    - Collecting data on species distributions - fishing tends to reduce the breadth of a population’s distribution, while climate shifts a population’s spatial distribution in one direction
    - Detecting changes in species composition
    - Implementing spatially explicit assessment models to avoid complications from shifting distributions

Appendix 3: 10-year plan

2018	• Discuss plan with other climate projects (e.g., GEF Humboldt I) and with partners (i.e., scientific and management agencies)
2019	• Define gaps and analyze needs for 2025 and 2030 goals • Achieve synergy with other GEF Projects/ Other Regional Programs • Identify funding sources for advancing on regional observation & information & prediction early warning sharing
2020	• Complete annotated outline for two scientific volumes • Development of working groups and content for two scientific volumes • Design workshop for observation, prediction and EWS • Synergize with GEF Humboldt II
2021	• Complete two scientific volumes for HC regions • Presentation of scientific volumes in IMARPE Climate Change Congress for Humboldt Current • Design workshop for observation, prediction and EWS - development of early warning indicators
2022	• Each country commits to working on filling gaps in coastal and ocean observing, and shared data platform based on reality of their respective country • Complete capacity-building strategy to support each country's ability to implement data collection for observing and shared data platform • Begin communication strategy: ▪ Communication technology in place for real time sharing ▪ Scientific community ▪ Decision makers ▪ Stakeholder • For regime shifts & changes, each country has the ability to create protocols & actions to be taken
2023	• Identify regional management framework for reaching 2028 goals (scientific & governance) based on prediction and early warning indicators

2024	• Socialize regional management framework
2025	• Formalize regime shift protocols based on regional management framework for proactive EBM & precautionary approach • Gain support from stakeholders
2026	• Chile implements EBM & precautionary approach • Peru has a better knowledge of upwelling and develops best criteria for adaptive management with ecosystem focus • Ecuador has knowledge of how HC upwelling contributes to fisheries for goal management
2027	• Implement adaptive management at regional HC level • Science being used by decision makers
2028 to 2030	• Three HC countries have capacity installed for adaptation in fisheries sector to confront climate change using prediction and early warning indicators • Comprehensive system for observing the ocean by the three HC countries (tech. tools) is in place and functional