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Report 29 I March 2023

Open Science Conference on Eastern Boundary Upwelling Systems (EBUS): Past, Present and Future & Second International Conference on the Humboldt Current System

19 – 23 September 2022
Lima, Peru and Online

The Open Science Conference on Eastern Boundary Upwelling Systems (EBUS): Past, Present and Future was held jointly with the Second International Conference on the Humboldt Current System in Lima, Peru from 19 to 23 September 2022. The conference was organised by scientists from the Instituto del Mar del Perú (IMARPE), the Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organisation (IOC-UNESCO), the Institut de Recherche pour le Développement (IRD), and the Scientific Committee on Ocean Research (SCOR) Working Group 155 (EBUS). EBUS provide valuable ecosystem services for the biosphere and for humankind. EBUS are geographically distributed and include the Canary and Benguela Current Systems in the Atlantic Ocean and the California and Humboldt Current Systems in the Pacific Ocean. EBUS provide more fish per unit area than any other part of the global ocean, thus contributing to food security and employment.

The conference had 341 on-site participants and 133 that connected remotely, and included early career scientists (i.e., undergraduate, BSc, MSc,

In this report

Attendees research profiles

Figure 1: Group photo of conference attendees. © Claudia Garcia de la Barga - Institut de Recherche pour le Développement.

PhD students, and postdocs), stakeholders, and global experts. The participants sought to review and synthesise available information on the dynamics, sensitivity, vulnerability, and resilience of EBUS and their living resources to climate variability and change with the eventual goal of predicting how they will respond in the future. There was a total of 277 talks and 175 posters distributed in 28 sessions under the umbrella of 3 thematic axis: (1) Ocean physics and associated biogeochemical processes in relation to climate variability and climate change, (2) Living resources, fisheries and adaptations to environmental variability, and (3) Socio-ecological vulnerability to climate change and extreme events. The conference also included an early career scientist event and three parallel events involving non-expert participation on ocean literacy, science to policy, and a night of videos to announce the winners of the contest “Engaging science and society in marine and coastal ecosystems within the EBUS”.

Presentations at the conference highlighted the complex interaction between physical, biogeochemical and biological processes in EBUS and their variability on scales of meters/minutes to thousands of kilometers/ centuries. EBUS are considered sentinels of anthropogenically driven climate change, the rate of which seems to be increasing. In the words of Dr. Francisco Chavez, the first keynote speaker, "EBUS are characterised by having enhanced ocean fertilization and variability, and as a result enhanced ocean acidity, anoxia and hypoxia; they display short food chains, low biodiversity; enhanced forage species and predators; and their ecosystems are susceptible to anthropogenic pressures and are poorly represented in global models”.

Presentations also noted that climate change and extreme events have become more notable, and there is now a new and urgent need to understand the sensitivity, vulnerability and resilience of EBUS to large-scale perturbations. This includes predictions of their responses to future trends, identifying societal needs and opportunities for adaptation. In near-shore regions, the anthropogenic footprint is enhanced due to multiple stressors including global warming, acidification, deoxygenation, pollution, habitat destruction, and harmful algal blooms making these regions particularly vulnerable.

Technological advances, presented at the meeting, have led to an increased capacity for observing and modelling EBUS dynamics.

Advances have also been made in the fields of molecular biology, eco-physiology, behavioral ecology and fisheries management. Together, these new knowledge and tools are leading to an improved understanding of ecosystem tipping points, and the ecosystem indicators, needed to monitor status, trends, and potential regime shifts.

Contributions from the conference will be published in Special Issues of *Deep-Sea Research II*. Full information on the event is available at https://www.ebus-lima2022.com.

The conference in numbers:

- Participants: 474 in total, 341 on-site, 133 online;
- Gender: 40.5% women, 59.5% men;
- Countries: 45.8% Peru, 13.5% Chile, 7.2% Ecuador, 7% France, 6.3% USA, 4.6% Germany, 3% South Africa, 3% Mexico, 2.1% Spain, 1.9% Portugal, 1% Senegal, 0.6% Belgium, 0.6% Canada, 0.6% China, 0.6% Colombia, 0.4% Austria, 0.4% Korea, 0.4% Switzerland, 0.2% Costa Rica, 0.2% Namibia, 0.2% Norway, 0.2% United Kingdom, 0.2% Slovenia.

Key messages included the following:

1. Understanding mechanisms driving large scale changes of EBUS requires a combination of multidisciplinary (including paleo) observations and regional-scale climatic models.
2. Long systematic time-series of observations are key to understanding EBUS variability and provide input for model forecasts.
3. New multidisciplinary Upwelling Indices are being proposed.
4. Future productivity changes are projected to depend on variations in wind, currents, stratification, and source-water nutrient concentrations.
5. EBUS play a critical role in global carbon dioxide (CO_2) budgets tightly linked to Equatorial oceanic teleconnections.
6. EBUS are studied by many different scientific disciplines, but a more integrative approach is now required.
7. Chlorophyll may not be the best indicator of ecosystem productivity.
8. Remote sensing is hampered by clouds and aerosols and an *in-situ* ground truthing campaign may be needed for EBUS.
9. The application of automated optical approaches and measurements of opportunity helps to understand changing features in upwelling composition and functioning from local anthropogenic loads to global change effects.
10. Climate change may impact the distribution, migration, and diversity of zooplankton communities by altering physical processes, such as circulation, advection, as well as oxygen levels in the water column.
11. Recent variability in oceanographic conditions has led to a reassessment of previous assumptions regarding ecosystem dynamics.
12. Despite the evolution of models, the question remains on how to incorporate the variability observed in nature into fisheries models to reduce uncertainty.
13. There is a favorable international context to strengthen regional collaboration in monitoring oceanic and atmospheric conditions within the framework of the World Meteorological Organization (WMO) and Tropical Pacific Observing System (TPOS) projects. Sharing of data and information on a regional scale will be needed.
14. Promote rapprochement between science and decision makers, as well as fishermen, to strengthen their knowledge of the socio-ecological system.
15. It is important for scientists to be part of the decision-making process so that regulations utilise the best available science.

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Michael Kriegl is a marine ecologist and network scientist fascinated by the interplay between ocean and society. He uses network tools to understand the social-ecological dynamics of resource management, focusing on small-scale fisheries in Latin America. Michael is passionate about science communication and sparking curiosity in young minds (https://michaelkriegl.github.io/).

The building blocks of resilience among small-scale resource users: A network approach for understanding the role of social and natural capital in a Peruvian bay

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Abrupt changes in the marine environment, such as sudden shifts in temperature, can severely disrupt the functioning of coastal ecosystems and the associated social systems. Resource users who rely on ecosystem services provided by the ocean are particularly vulnerable to such drastic events (Marshall *et al.*, 2013). To safeguard coastal livelihoods, we need a better understanding of the factors that enhance the capacity of marine resource users to successfully cope with crises. This knowledge is gaining particular importance as sudden environmental change and other types of extreme events are expected to increase in frequency and severity as the impacts of both climate change and resource overuse intensify (Intergovernmental Panel on Climate Change, 2021).

Here, we study how artisanal fishers and small-scale aquaculture operators in Sechura Bay, northern Peru, coped with the 2017 Coastal El Niño (CEN), which heavily impacted the entire region far beyond the fisheries and aquaculture sector (Kluger *et al.*, 2019a, 2019b). This event was characterised by a substantial increase in water temperatures along the coast, accompanied by torrential rains and flooding that caused severe damage to local infrastructure. Importantly, the CEN also led to the complete die-off of economically important resources (mainly cultured scallops) as well as the proliferation of other species in Sechura Bay.

In surveys with representatives of resource user associations (n = 98), we asked about i), their

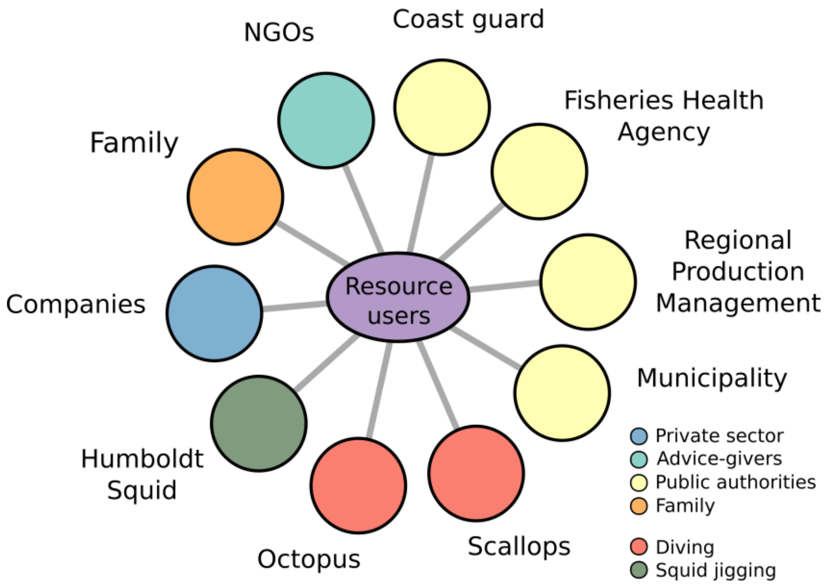

Figure 2: Representation of a social-ecological ego-network of a Peruvian small-scale resource user association indicating connections with entities from the social and ecological domain.

target species as well as ii) their interactions with other social actors (type, frequency and helpfulness), both before and during the unfolding of the CEN. Based on this information, we constructed personal networks (also called "ego-networks") for each interviewed resource user association (Figure 2), indicating their connections with entities from the ecological and social domain. Adopting a social-ecological network approach (Kluger *et al.*, 2020) complemented by qualitative information from expert interviews, we investigated how resource users drew on their natural capital (i.e. access to living marine resources (Costanza *et al.*, 1997) and social capital (i.e. relationships that facilitate access to information and other valuable resources embedded in the social fabric, Lin *et al.*, 2001) to cope with the impacts of the CEN.

We found that fishers who had a diversified catch portfolio (i.e. more target species) before the CEN were able to cope better with the disturbance than more specialised resource users. For small-scale aquaculture operators (who generally target only few species), results showed a significant positive correlation between more extensive pre-CEN social networks and more desirable recovery trajectories (Kriegl *et al.*, 2022). These results highlight two important building blocks of community resilience: Natural capital to quickly adapt fishing operations in times of crises and social capital to access relevant information and mobilise resources when needed. In other words: diversifying catch portfolios and building social relationships were associated with greater livelihood resilience towards abrupt environmental change.

Management actions aimed at strengthening resilience within coastal communities should therefore consider mechanisms to foster both, the social as well as natural capital of resource users. This is key to building and enhancing coastal livelihood resilience within vulnerable communities affected by the impacts of accelerating global change and ultimately to safeguard marine food security.

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More information on our work: https://www.youtube.com/watch?v=1bu-jiz1EI8

Carlos Escobar Medina studied fishing engineering in Peru at Universidad Nacional Federico Villareal (UNFV) from 2011 to 2015, and is currently studying for a Master's degree in marine sciences at Universidad Peruana Cayetano Heredia (UPCH), Peru. He has worked for several years on different fisheries, especially in Peruvian anchovy, horse mackerel and tuna. Also, he is working on a thesis on primary production using satellite data for the Peruvian sea.

Primary production in the Peruvian Upwelling System: An integrated model using *in-situ* data and satellite information

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The Peruvian Upwelling System is one of the most productive areas in the ocean. This productivity is influenced by a persistent upwelling current driven by trade winds alongshore, which brings rich-nutrient to the surface. In addition, it has a strong interannual variability due to the influence of the El Niño event. The productivity is usually followed by the high chlorophyll-a (Chl-a) concentration; however, this proxy does not represent the rate of carbon production by phytoplankton. The rate of productivity is known as primary production (PP). It has implications for oceanic food webs and climate change because carbon dioxide (CO_2) is taken during this process. On the Peruvian coast, there are few studies that focus on the variability of the PP due to the high specialisation techniques needed to sample it. Therefore, we propose a statistical model combining satellite data and *in-situ* observations in order to reproduce the variability of the PP in space and time (Figure 3). In order to develop this model, we used Chl-a profiles from Instituto del Mar del Perú, Lima, Peru. This data spans from 1980 to 2020 and presents 40,101 observations along the Peruvian coast. In addition, satellite data from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) were used.

The *in-situ* Chl-a data was profiled using a Gaussian distribution (Platt *et al.*, 1998). The modelled profiles (4,218) showed the highest Chl-a concentration in the water column during summer; however, there is not a significant difference between the other seasons (Figure 4). The modelled Chl-a profiles were classified using a cluster analysis to obtain the typical Chl-a profiles in the Peruvian sea. Our analysis suggests 12 typical Chl-a profiles (Figure 5), with different spatial distribution in the ocean-coastal section. Then, the random forest model was applied to predict typical Chl-a profile from satellite data (Sea Surface Temperature and Surface Chl-a) and bathymetry, the most valuable variable for the random forest resulted to be the distance from coast, followed by the bathymetry.

Finally, following the model proposed by Demarcq *et al.* (2008), a bio-optical model will be applied, integrating predicted integrated Chl-a profiles and

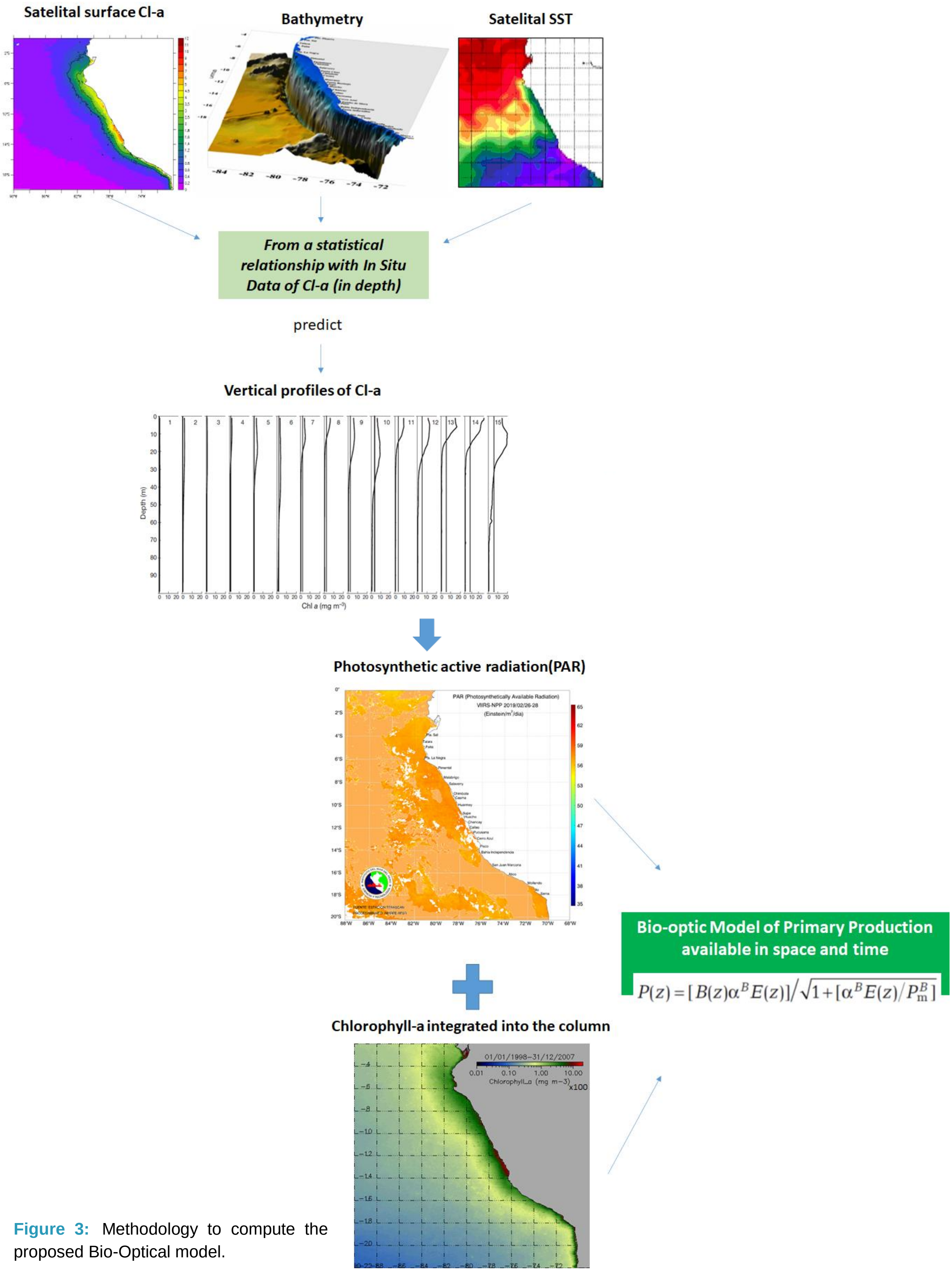

Figure 3: Methodology to compute the proposed Bio-Optical model.

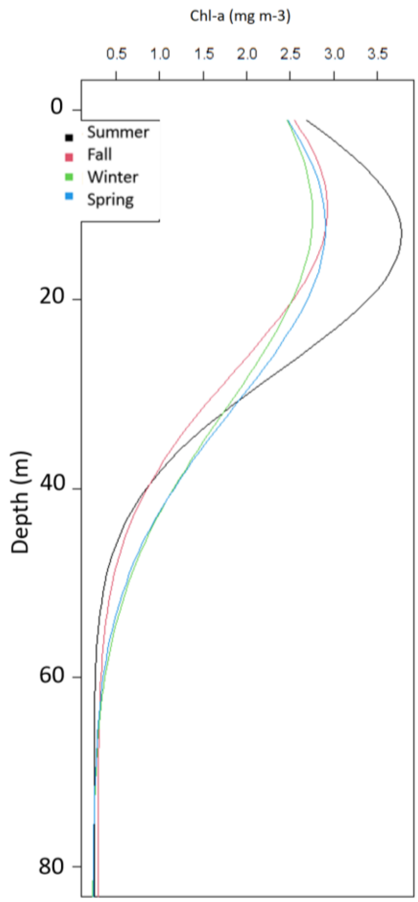

Figure 4: Seasonal profiles of modelled chlorophyll-a (Chl-a) obtained from Gaussian distribution applied to *in-situ* data from Instituto del Mar del Perú Lima, Peru.

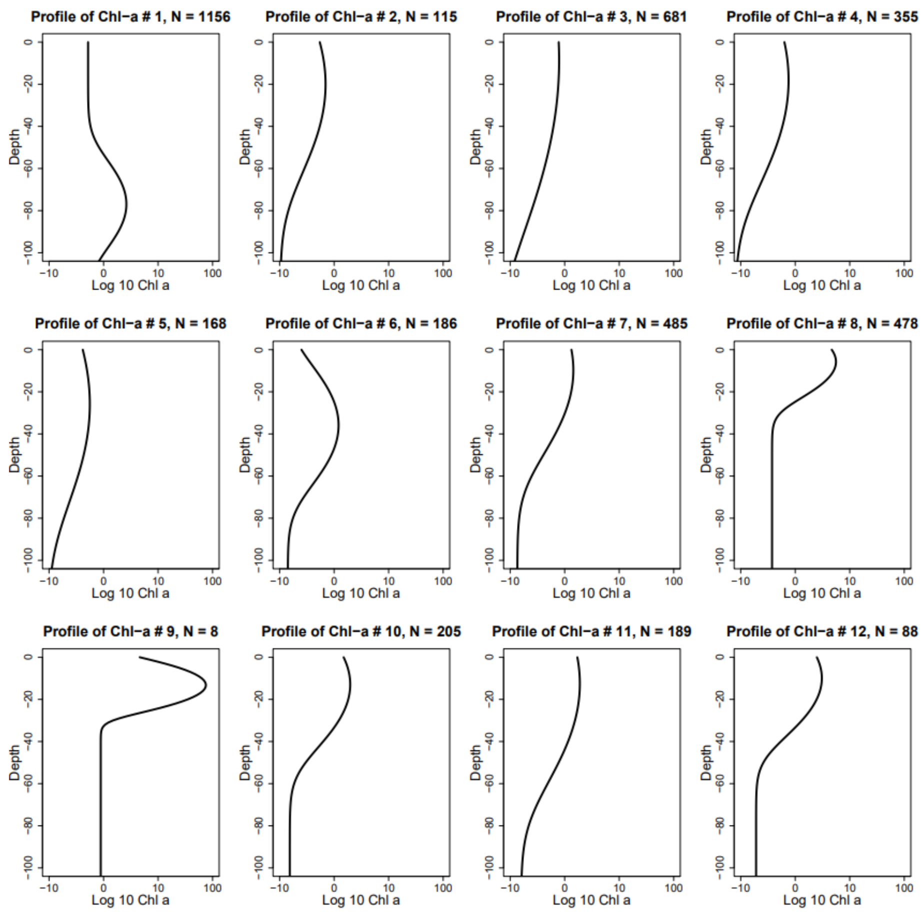

Figure 5: Typical Chl-a profiles of the Peruvian Sea. The Chl-a is in logarithm scale. N represents the numbers of profiles.

Photosynthetically Active Radiation (PAR) from MODIS to obtain PP in the Peruvian sea during satellite periods (September 1997 to present). Our study represents an improvement of estimation PP based on satellite data, and it allows us to evaluate the recent trends of the PP on Peruvian coasts.

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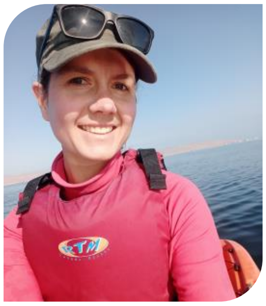

Fanny Rioual started her PhD in 2022 at the Laboratory of Environmental Marine Sciences (LEMAR) in France and at the Instituto del Mar del Perú (IMARPE) in Peru, to investigate the dynamics of hypoxia and hydrogen sulphide in shallow coastal bays in Peru, and its effects on the Peruvian scallop physiology.

Hydrogen sulphide dynamics in EBUS shallow coastal ecosystems: The case study of Paracas Bay, Peru

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The Peruvian coastal upwelling system is characterised by high primary production, which makes it one of the most productive marine ecosystems in the world (Chavez and Messié, 2009). The decomposition of this large amount of organic matter leads to an extensive shallow oxygen minimum zone. It has been shown that in anoxic conditions, the degradation of organic matter by sulphate-reducing anaerobic bacteria leads to the formation of hydrogen sulphide (H_2S) gas, toxic for the organisms (Jørgensen, 1982). Sulphide outbreaks have been reported along the Peruvian coast, mainly off Callao and Pisco (Ohde, 2018), and are manifested by milky turquoise surface plumes, resulting from the oxidation of H_2S into colloidal sulphur (S^0) (Weeks *et al.*, 2004). In the area of Pisco, Paracas Bay is a small shallow semi-enclosed bay located within the influence of one of the most active upwelling zones of the Peruvian coast. It is the birthplace of Peruvian scallop (*Argopecten purpuratus*) aquaculture in the country; however, mass mortalities have affected this activity over the last decades, with economic consequences for local producers (Aguirre-Velarde *et al.*, 2019). This area is known to present chronic and severe hypoxia conditions (Aguirre-Velarde *et al.*, 2019). Additionally, sulphidic events are regularly observed in Paracas Bay and a previous work focused on sulphide production in the sediments of the bay (Rafael and Elvis, 2016). Nevertheless, hypoxia-related sulphide dynamics remains poorly understood in this area.

In order to understand the dynamics of oxygen conditions and its relation with the occurrence of H_2S in the bay, a high frequency monitoring was conducted in Paracas Bay from 9 March to 4 April 2022, during austral summer, at a 10 m-deep station located in the centre of the bay. Dissolved oxygen at 20 cm above the bottom was registered every 15 minutes, and H_2S concentration in the water was measured using Diffusive Gradients in Thin films (DGT) sensors, which are low-cost, passive samplers that provide time-integrated H_2S measurements (Teasdale *et al.*, 1999).

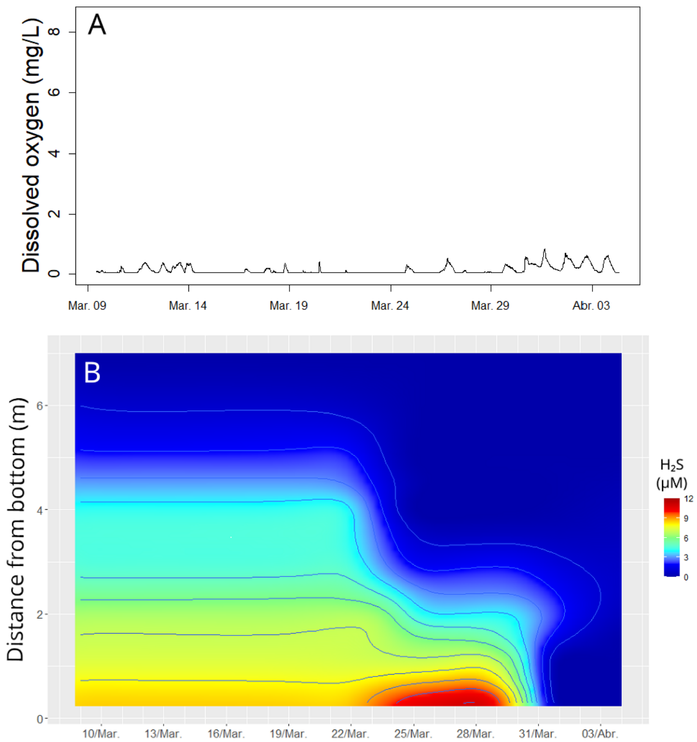

Figure 6: A) dissolved oxygen concentration at 20 cm above the bottom, B) H_2S concentration in the water column at the monitoring site.

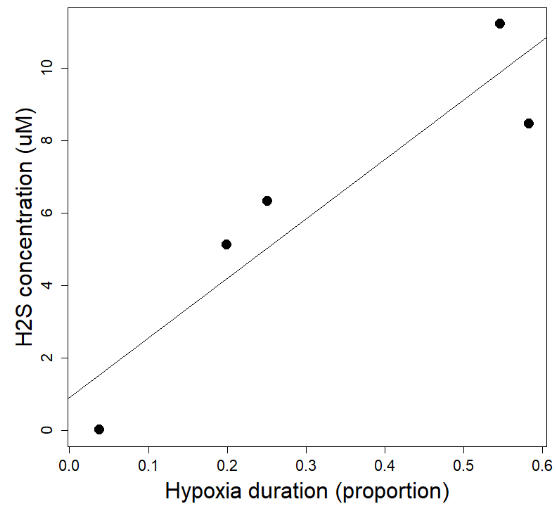

Figure 7: Relation between severe hypoxia ($\leqslant$ 0.05 mg L^{-1} O_2) duration (as a proportion of the total period of monitoring) in the bottom layer and H_2S concentration.

Furthermore, other oceanographic variables, such as temperature, light irradiance, and currents were measured.

The preliminary results of this study show that during the monitoring period, hypoxia (dissolved oxygen concentration < 1 mg L^{-1} O_2) and anoxia conditions occurred daily in the bottom water layer of the monitoring site (Figure 6). H_2S concentrations gradients were detected between 20 cm and 5 m, decreasing from the bottom towards the surface (with concentrations ranging from 2.22 to 11.21 µM). The comparison between the duration of severe hypoxia (dissolved oxygen concentration $\leqslant$ 0.05 mg L^{-1} O_2) conditions and H_2S concentrations, showed that H_2S concentration is positively correlated to hypoxia duration in the bottom water layer (Figure 7). This suggests a local emission of H_2S in the bay, diffusing out from the sediment.

This study illustrates the first record of sulphide concentrations in the water column in Paracas Bay. It provides a first understanding of the link between oxygen conditions at the bottom of the bay, and sulphide plume occurrences. Nevertheless, to fully understand the dynamics of sulphide emissions, and be able to provide adaptation strategies for Peruvian scallop aquaculture, these results have to be discussed in relation to the variability of the oceanographic environment in the bay, such as primary production and circulation patterns.

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Jennifer Veitch heads up the Sustainable Ocean Modelling Initiative: A South African Approach (SOMISANA) initiative whose vision is for a critical mass of South African numerical ocean modelling experts who provide accurate information about the changing state of the ocean for enhanced societal impact. Her research expertise spans the Benguela System from its northern to southernmost boundary.

The Benguela System: A short review of what we think we know and what we need to fill the gaps

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The Benguela upwelling system (BUS) on the west coast of Africa is one of the World's four major Eastern Boundary Upwelling Systems (EBUS) and has sustained a thriving marine ecosystem that has supported the livelihoods of coastal communities for thousands of years. It is the only EBUS that interacts with tropical waters at both its northern and southern boundaries that are both associated with intense frontal systems: the Angola Benguela Frontal Zone (ABFZ) in the north and the alongshore-oriented Benguela Jet in the south (Figure 8). Remote drivers of change in the Benguela system penetrate these boundaries in the form of tropical Atlantic anomalies in the north and Agulhas Current interactions in the south. The former resulting in warm anomalies off Angola and Namibia and the latter in not only producing a region of intense turbulence in the Cape Basin region, but also modulating shelf-scale dynamics that are critical to the functioning of the southern Benguela ecosystem.

The BUS can be clearly divided into distinctly separate northern and southern regimes (Veitch *et al.*, 2010) at about 27°S based on: a distinct narrowing of the continental shelf (that is broader in the south), the large-scale depth-integrated current-field (weakly cyclonic in the north and driven by the wind-stress curl and meandering and north-westward in the south and partly driven by the passage of Agulhas Rings), the seasonality of coastal upwelling (strongly seasonal in the south, less so in the north with peak upwelling occurring during austral summer/spring in the south).

The southern boundary is characterised by the Benguela Jet, that is situated between the 300-500 m isobaths and is sustained by an intense alongshore-oriented temperature front that arises from the highly variable offshore warming associated with Agulhas influx juxtaposed against the highly seasonal nearshore cooling associated with the upwelling regime (Veitch *et al.*, 2017). The importance of the jet lies in its role in transporting fish eggs and larvae from their spawning ground on the Agulhas Bank to their nursery area in St Helena Bay (Ragoasha *et al.*, 2019). Furthermore, model results show that the intensification of the jet by the influx of Agulhas waters contributes to retention on the southern Benguela shelf to about 30°S, that has implications for the local generation of low oxygen water (LOW).

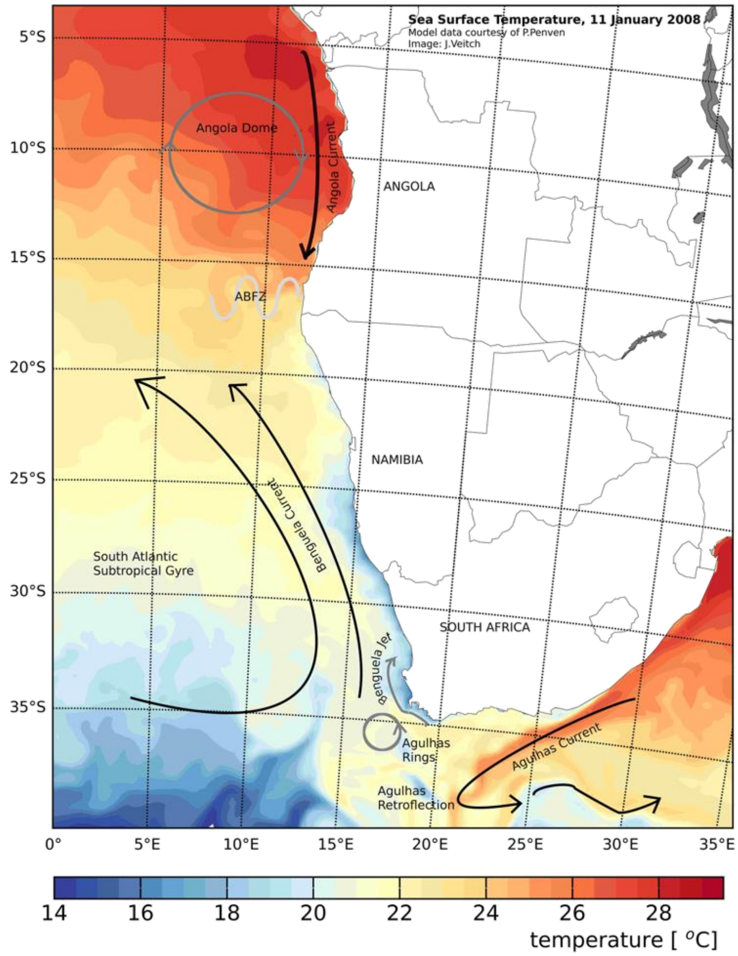

Figure 8: Schematic of the Benguela System with model-derived sea surface temperatures (courtesy of Pierirck Penven) capturing the cold coastal waters and the intense frontal features at the northern and southern boundaries of the system.

The coastal upwelling regime and dynamics on the shelf in general is closely tied to both, the nearshore wind field as well as to topographical and coastline characteristics, which are distinctly different in the northern and southern parts of the system. Despite the relatively straightforward dynamics of coastal upwelling, both global and regional models struggle to capture the nearshore temperatures sufficiently: a warm bias is common in coupled climate models, while a cool bias is common in regional uncoupled models. The latter is almost certainly related to the poor representation of the wind drop-off in the atmospheric forcing product used, while the former is thought to be related to a number of factors including the underestimation of the stratocumulus clouds, errors in the winds and lack of offshore transport by ocean eddies as a result of too-low horizontal grid resolution (Richter, 2015). A further troubling aspect of modelling EBUSs is that satellite-derived sea surface temperatures that are routinely used for model evaluations are notoriously unreliable near the coast particularly in the vicinity of extreme frontal systems, such as coastal upwelling regions (Carr *et al.*, in preparation).

In order to support good governance and adaptable management of the Benguela ecosystem as well as the resilience of coastal communities in a world of increasing uncertainty, it is essential that we continually improve our understanding of these dynamics, particularly at the boundaries of the system through which change penetrates. These boundaries include: the northern and southern boundaries, the ocean-atmosphere interface, exchanges between the open ocean and the continental shelf and the mixed layer as the transition between the surface and deep ocean. To do this we need: improved and sustained observations, optimised models and satellite processing techniques, open data policies and improved strategies for societal and stakeholder engagement.

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