Ecosystem approach in Chile (Islet and island)

Ecosystem approach for Chilean island systems

Storylines 39 & 40

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The EU Horizon project FutureMARES (2020-2024) was designed to develop science-based advice on viable actions and strategies to safeguard biodiversity and ecosystem functions to maximise natural capital and its delivery of services from marine and transitional ecosystems in a future climate. The program investigates effective habitat restoration, conservation strategies and sustainable harvesting at locations across a broad range of European and other marine and transitional systems. The restoration of habitat-forming species (plants or animals) and habitat conservation (e.g. marine protected areas, MPAs) represent two nature-based solutions (NBS) defined by the EU as "resource efficient actions inspired or supported by nature to simultaneously provide environmental, social and economic benefits that help to build resilience to change". A third action that will interact with these two NBS and have positive effects on marine biodiversity is nature-inclusive harvesting (NIH) such as the sustainable farming of plants and animals at the base of marine food webs and ecosystem-based management practices for traditional (artisanal) and commercial fisheries.

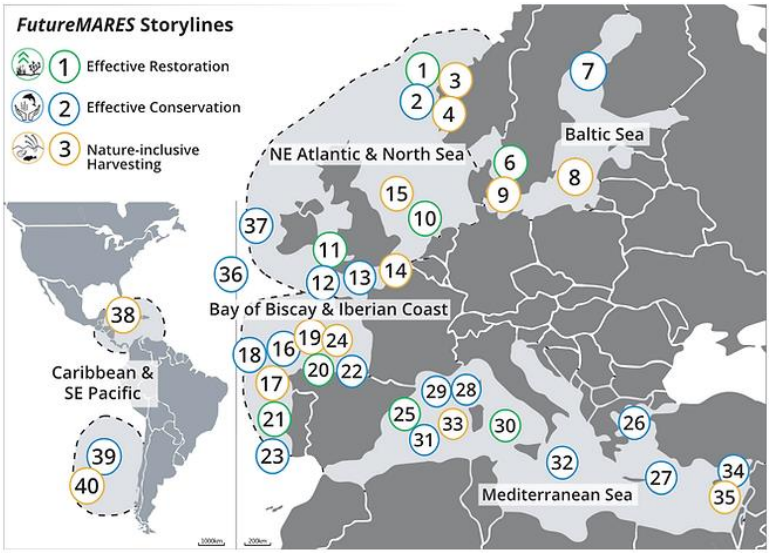

***Figure 1**: Overview of FutureMARES Storylines*

FutureMARES was designed to:

- advance the state-of-the-art forecasting capability for species of high conservation value,
- explore new and less carbon intensive aquaculture production methods,
- perform modelling analyses geared towards informing the development of climate-smart marine spatial planning approaches, and
- provide an assessment of ecosystem services based on scenarios of climate change and the implementation of NBS and NIH.

This document provides a summary of activities conducted in FutureMARES in a specific area on specific NBS and/or NIH. The activities are multi-disciplinary and include marine ecology (analyses of historical time series and experiments performed in the field and laboratory), climate change projection modelling (future physical, biogeochemical and ecological changes), economic analyses and social-ecological risk assessments. Many of these components and analyses were co-developed with local and regional stakeholders through regular engagement activities. The work presented in this Storyline document represent activities conducted by a large number of FutureMARES project partners. Broader comparisons and syntheses (across regions and/or topics) are provided in the FutureMARES deliverable reports submitted to the European Commission (www.futuremares.eu).

The South East Pacific (SEP) extending from Peru to south of Chile and from the continental coast to Easter Island is characterized by very contrasted environments with oligotrophic and biomass-poor waters in its center, and one of the most productive regions of the planet located in the coastal regions along the west coast of South America and within the extended chain of seamounts and submarine volcanoes formed by the Desventuradas and Juan Fernandez archipelagos. The SEP is currently experiencing climate stressors (warming, deoxygenation and acidification, Dewitte et al., 2021), which effects on marine biota remain largely unknown. Every 2 to 7 years, the SEP also undergoes drastic changes in its circulation associated with to multi-year climatic patterns like the El-Niño Southern Oscillation (ENSO). Typically, during the warm phase of ENSO, water temperatures along the coast of Peru and Chile can warm as much as by 6°C during a few months, while dissolved oxygen tends to increase. On the other hand during the cold phase (La Niña), the uplift of nutrient rich waters is favourable for the ecosystem functioning, while oxygen depleted waters from the oxygen minimum zone can more easily reach the euphotic layer and negatively impact organisms. The regularity of ENSO has created opportunities for organisms to adapt in anticipation of regularly changing environmental conditions (e.g. 'feedforward' effects). However, the projected increased in occurrence of ENSO variability (i.e. more intense and frequent warm events and more prolonged cold events (multi-year La Niña) in the future) may alter the ecological functions and interact with the long-term trend induced by global warming. As a first step towards bridging the gap between coupled environmental periodicities and ecosystem functioning, it appears important to better document changes in aerobic habitat induced by both ENSO and long-term changes (climate warming) in the SEP.

The underlying hypothesis is that marine organisms are highly sensitive to changes in oxygen content and temperature which control and limit the metabolic activity of marine organisms (Portner and Knust, 2007) and therefore of healthy and sustainable populations. The effects of temperature and oxygen on metabolic activity can be captured by the threshold Pcrit (minimum PO2 to sustain the life of an organism aerobically, Esbaugh et al., 2021) and by the metabolic index framework (Deustch et al., 2020), a measure of aerobic scope in oxygen-limited environment. Loss of aerobic habitat is expected as a result of decreasing oxygen content and increasing temperatures because of increasing mismatches between temperature-driven oxygen supply and demand.

In this storyline, we take advantage of the global model resources and the experimentation with a fine-tuned regional biogeochemical model (downscaling) to enhance our understanding of the impact of climate change (warming and de-oxygenation) on the marine habitat and inform the development of climate-smart marine spatial planning approaches. This case study differs from the others carried out as part of the FutureMares project in that the biases of global models are the most pronounced, and physical, biological and physiological data are sparser. It is also a region where interannual variability (e.g. ENSO and other modes) outweighs seasonal variability, leading to an interaction between changes in mean state and variability. In particular, this constrains the choice of downscaling methods and guides analyses.

We first provided a robust assessment of ESM performance against observations for both mean state and interannual variability (Dewitte et al., 2023; Martinez-Villalobos et al., 2024; Concha et al., 2023; Almendra et al., 2024). We used the emergent constraint framework combined with regional modeling to reduce uncertainties in the trend in dissolved oxygen in

the SEP. We showed in particular that the SEP is more likely to experience an oxygenation in the upper limit of the oxygen minimum zone (Almendra et al., 2024). Through this we elucidated large scale dynamical understanding of physics and biogeochemistry in the SEP, including the delivery of basin scale analysis of climate and ecological pressures of temperature and oxygen (Lachkar et al., 2023; Gaymer et al., 2024). This also provided the rational for selecting the ESMs for the downscalling experiment. We then used the selected global ESM (i.e. the NCAR Community Earth System Model Large Ensemble (CESM-LE)) to describe and quantify the potentially asymmetrical impacts of changes in temperature and O2 on marine aerobic habitat at different time-scales (long-term changes and inter-annual variability) (Parouffe et al., 2023; 2024). Physiological studies were also carried out to fill in the gap in knowledge of physiological traits and adaptation capacity of one commercial species (Alvarez et al., 2023). A regional projection of the selected ESM was the carried out for the future climate (2050-2100) based on regional configuration that has been previously validated from observations (Pizarro-Koch et al., 2023). During the course of the project, several encounters with the local stakeholders and key actors of the fishery industry in the Tongoy bay, a hotspot of the scallop industry in Chile, were organized to discuss outcomes of the FutureMares project and develop socio-ecological narratives of the impact of climate change in the coastal communities, integrating storylines of possible futures in terms of changes in mean oxygen conditions and extreme events (El Niño, Chile El Niño), and exploring adaptation mechanisms for small-scale aquaculture and artisanal fishing.

Projected impacts of climate change

The SEP Ocean like any other ocean of the world will experience significant changes in its circulation with likely impact on ecosystems. What nevertheless differentiates the SEP from other regions is the presence of an extended oxygen minimum zone and a very strong connection with equatorial variability (e.g. El Niño). While the former exposes it to hypoxia, the latter makes it a highly variable environment on a variety of timescales. Understanding how these factors influence the ecosystems in a context of global warming remains a challenge. At present, the uncertainty in climate model projections lies mainly in the biogeochemical compartment of the system. In particular, despite global deoxygenation, there is still little consensus on the future of the oxygen minimum zone. The effects of warming surface waters on eddy activity in this region, and consequently on connectivity between different regions of the world, also remain poorly understood. Finally, physiological data on the region's emblematic species remains patchy, if not non-existent. In this context, we have taken advantage of regional modelling to constrain uncertainty in oxygen trends in the SEP, and have documented habitat changes on the basis of climate model projections that realistically simulate certain aspects of the region's circulation. In particular, we show that the SEP should experience oxygenation of its surface waters and upper OMZ along the coasts of Peru and Chile despite global deoxygenation of the ocean. This potentially induces habitat changes consisting of aerobic habitat extensions for hypoxia tolerant species nearing the OMZ border (~45uM) such as vertical migrators (zooplankton) and some coastal/benthic species which specially evolved to live in these conditions. This area may act as a climatic refugia for these species as suitable conditions will expand. However, it will remain closed to species with higher metabolic demand, such as pelagic species (top predators, migratory species). These species will, to the contrary, be strongly affected by the surface warming and offshore deoxygenation, and will see their habitat contract and/or shift southward (Parouffe et al., 2023). Fish species diversity of currently productive fishing areas are likely to be altered. This may result in altering fisheries ecosystems services for Chile and Peru.

The increase in extreme events such as El Niño and multiple La Niña events in the future (Cai et al., 2021; Geng et al., 2023) will also induce asymmetrical habitat changes that may superimpose to the long-term trend. Eastern Pacific El Niño will produce a strong warming of waters (of stronger magnitude than climate change) that will translate into a sharp increase of metabolic demand which ambient PO2 will hardly sustain. To the contrary, the cooling associated with La Niña supports an increase of shallow aerobic habitat, beneficial for shallow species with high metabolic demand. Deeper in the water column, El Niño will favor a downward expansion of aerobic habitat whereas the weak deoxygenation associated with La Niña weakly impacts aerobic habitat boundaries. The warming (cooling) and reoxygenation(deoxygenation) associated with EL Niño(La Niña) exert opposite effect on the metabolic activity of species evolving around the oxycline.

Overall, the impact of El Niño on aerobic habitat surpasses that of La Niña and will add up to the on-going long-term surface warming and species response to increasing warming will worsen the loss of aerobic habitat. However, the long cooling associated with La Niña slightly compensates for the climate change associated warming which could delay the negative impacts. How species will adapt to the alternation of stronger El Niño and more prolonged La Niña events remains to be investigated.

Scenarios describing future society and economy

FutureMARES developed three policy-relevant scenarios for NBS and NIH based on commonly used IPCC frameworks (Figure 5, for more details see hyperlink). These scenarios were regionalised based on stakeholder perspectives to guide activities such as model simulations and risk assessments.

(GS) Global Sustainability (SSP126) - Low challenges to mitigation and adaptation. The world shifts gradually but pervasively to a more sustainable path, emphasising inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, investments in educational and health accelerate lower birth and death rates, and the emphasis on economic growth shifts to an emphasis on human well-being.

(NE) National Enterprise (SSP385) - High challenges to mitigation and adaptation. A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to focus on domestic or regional issues. Policies shift over time to be oriented more on national and regional security. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development.

(WM) World Markets (SSP585) - High challenges to mitigation, low challenges to adaptation.
The world increasingly believes in competitive markets, innovation and participatory societies to produce rapid technological progress and train and educate people for sustainable development. The push for economic and social development is coupled with exploiting abundant fossil fuel resources and adopting resource and energy intensive lifestyles around the world

Figure 5: The three, broad scenarios that were regionalised to guide activities in FutureMARES. © FutureMARES project.

FutureMARES research needs

Research carried out as part of FutureMARES has provided input to the various communities in Chile interested in developing adaptation measures, specifically in relation to the islands' socio-ecological systems (cf. Gaymer et al., 2024). The work has also profoundly reformed the vision of the climatic threat in the South-East Pacific associated with global ocean deoxygenation. By establishing that the most likely scenario for the region is upper water oxygenation, we are shifting the paradigm and refocusing on the other stressors (temperature and ocean acidification). Several stakeholder meetings were organized with aquaculture farmers in Tongoy Bay under the two UN Decade Programmes GOOD (https://www.ioc.unesco.org/en/global-ocean-oxygen-decade) and OARS (http://www.goa-on.org/oars/overview.php) umbrellas to inform the local communities on this paradigm shift for the region and introduce the storyline approach for risk assessment under multiple stressors.
Our work also highlights the gap that exists between the SEP and other regions of the world in terms of physiological data availability, and the urgent need to develop a data base of physiological data for as many marine species as possible, globally.

FutureMARES research (T = Task – see program structure at futuremares.eu)

- **Task 1.1** Since the physiological experiments with juvenile Lobster of the Juan Fernandez island has not been possible to organize due to delays in obtaining permits (due to COVID), we have focused on a species inhabiting the coastal region of Coquimbo: the Cojinoba (Seriolella violacea), a pelagic marine fish in the South Pacific Ocean belonging to the Centrolophidae family and an important resource for Coquimbo and Atacama fisheries in northern Chile.
- **Task 2.1** Extract hindcast and projection data from CMIP5/CMIP6 archive and a Large ensemble (CESM) and evaluate model realism for the South Eastern Pacific circulation. Production of a regional projection of climate change using the physico-biogeochemical model CROCO-BioEBUS with 1/12° resolution extending from 12°N to 40°S along the coast of Peru and Chile (and in a 1/36° configuration over central Chile). This regional model was previously tuned and validated in hindcast mode focusing on oxygen, using observational data (Pizarro-Koth et al., 2023; Almendra et al., 2024). Assessing long-term trends in situ (oxygen, phythoplankton biomass), satellite and Reanalysis data off central Chile (Bustos et al., 2024; Jacob et al., 2024).
- **Task 2.2** Reduction in uncertainties in the trend in oxygen in the South Eastern Pacific using the emergent constraint framework (Almendra et al., 2024); Evaluation

of ESMs skill in accounting for relevant climate events in the South Eastern Pacific (Dewitte et al, 2023; Martinez-Villabobos et al., 2024; Concha et al., 2024)

- **Task 2.3** Estimation of habitat changes in the South Eastern Pacific due to long-term warming and deoxygenation using the metabolic constraint (Parouffe et al., 2023; 2024)
- **Task 5.1** Estimate of the temperature and dissolved oxygen concentration on survival, metabolism and oxidative stress of post-larvae Cojinoba (Seriolella violacea) (Alvarez et al., 2023)
- **Task 5.3** Nothing done (person in charge (Laura Ramajo) left CEAZA)
- **Task 8.2** Engaging relevant stakeholders during series (5) of meetings gathering cooperatives of fisheries and public and private institutions Tongoy Bay. Engaging with Ocean Decade Actions (GOOD, OARS) and the WCRP program “My Climate Risk”. Communicating and influencing environmental governance (Rose et al., 2024).
- Training the next generation of ocean researchers in relevant issues (ocean deoxygenation and acidification) during an international summer school organized at La Serena (http://www.ceaza.cl/summerschool/)

2. Research conducted

1. Evaluating Southeast Pacific SST interannual variability in global ESM

Due to the large interannual variability in the tropical Pacific and the efficient tropical teleconnection along the west coast of South America, global ESM needs to be qualified in terms of their skill in simulation the connection between dominant climate modes in the Southeast Pacific. Dewitte et al. (2023) investigate the relationship between ENSO and the South Pacific Meridional Mode (SPMM) focusing on strong SPMM events that follows strong El Niño events. The analysis of 62 models participating to simulations of the Coupled Intercomparison Project phases 5 and 6 (CMIP5/6) indicates that very few models realistically simulate this ENSO/SPMM relationship and associated oceanic teleconnection. Concha et al. (2024) analyze how these models simulate Chile El Niño events, a long-lasting Marine Heat Waves off Central Chile, showing that despite their mean state bias, they simulate realistically their pattern and amplitude. Martinez-Villalobos et al. (2024) analyzed coastal El Niño events in global ESMs. Almendra et al. (2024) analyzed the relationship between ENSO and oxygen concentration along the coast of Peru/Chile in 19 models, showing a large dispersion even amongst the model simulating realistically ENSO pattern and variability. These analyzes provided the rational for selecting the ESM for the downscalling experiment.

2. Constraining oxygen trend along the coast of Peru and Chile (T2.1 and T2.2)

The SEP is characterized by the presence of an oxygen minimum zones (OMZs) embedded in the subsurface waters of the very productive upwelling system along the coast of Peru and Chile. These OMZs are currently diversely simulated by state-of-the-art Earth System Models (ESM) hampering a reliable projection of ocean deoxygenation on marine ecosystem services in these regions. We showed that, despite the low consensus among ESM long-term projections of oxygen levels, the sensitivity of the depth of the upper margin (oxycline) of the SEP OMZ to El Niño events in an ensemble of ESMs can be used as a predictor of its long-term trend, which establishes an emergent constraint for the SEP OMZ.

Because the oxycline along the coast of Peru and Chile deepens during El Niño events, the upper bound of the SEP OMZ is thus likely to deepen in the future climate, therefore oxygenating the SEP OMZ.

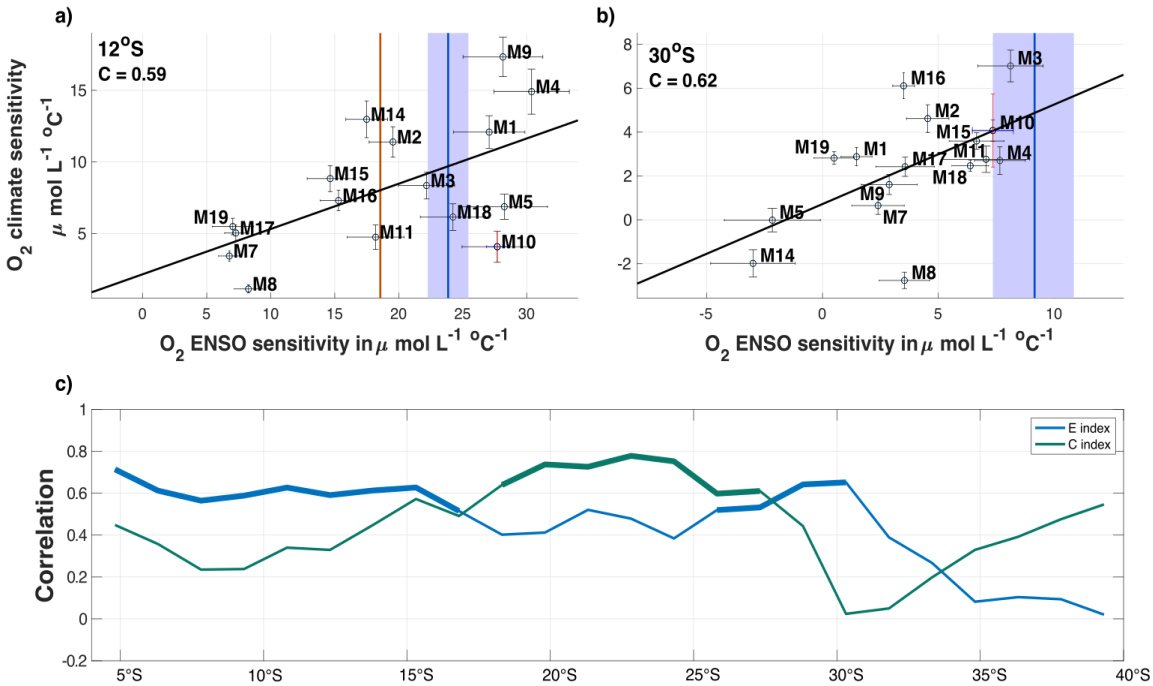

Figure 1: Relationship between the sensitivity of Dissolved Oxygen (DO) to ENSO and to global warming (emergent constraint): The long-term (2015-2100) sensitivity of DO to SST warming in the Eastern equatorial Pacific (average over the E mode region) against the interannual sensitivity (1920-2014) of DO to the E index at (a) 12°S and (b) 30°S for the 18 ESMs (Mi dots, where i=1,..,19). The straight line (black) in a) and b) corresponds to the linear fit to the Mi points. Pearson correlation value is indicated in the top left corner in each panel. The horizontal and vertical black segments on the point labels provide an estimate of the errors. The size of the black segment represents ± the standard deviation amongst 1000 estimates of the ENSO and climate sensitivities using a bootstrap method for which 80 years are chosen randomly. The coloured segments on the point corresponding to CESM-LENS (M10) correspond to the errors associated with natural variability estimated as ± the standard deviation of the ENSO and climate sensitivities amongst the 34 members. The vertical line in blue with purple shading indicates the value of ENSO sensitivity of the regional biogeochemical model simulation. The shading stands for the 25% and 75% percentiles of the distribution of DO ENSO sensitivity obtained from a bootstrap method applied to the regional model data (1958-2008). 1000 values of the DO ENSO sensitivity were estimated based on 40 years of the simulation selected randomly amongst the 51 years. The red vertical line indicates an estimate of the observed value at 12°S. The value is estimated from Figure 6a of Graco et al. (2017) taking the value at 100m as an estimate of the mean between 25m and 200m like for the models. This value is further divided by 0.29°C that corresponds to the norm of the observed E mode pattern. c) Correlation amongst the models between the DO ENSO sensitivity and the DO climate sensitivity as a function of latitude between 5°S-39°S for the E index (blue) and the C index (green). DO is averaged in a region corresponding to the upper oxycline: a) i.e. (25m-200m; 82°W-77°W), b) (25m-200m; 75°W-72°W), and c) 25m-200m in a coastal fringe of 3° in longitudinal extent. The thicker portions of the curves indicate where the correlations are significant at the 95% level based on a student's t-test. (After Almendra et al. (2024))

Based on this result, we have further documented habitat changes based on a model that simulates a positive trend in oxygen within the upper OMZ as well as that can simulate realistically extreme ENSO events (i.e. The NCAR CESM Large Ensemble, cf. Dewitte et al. (2023)), adopting a storyline approach framework.

3. Regional impacts on aerobic habitat for an ensemble of species representing the SEP (T2.3)

The SEP with its much contrasted environment hosts an important variety of species uniquely adapted to various levels of O2 content (i.e. hypoxia tolerance) and with unique

degrees of sensitivity to temperature. In this context, we investigated future marine habitat change in the SEP (horizon 2100) applying climate velocity to the metabolic index (CVΦ) that encapsulate the effect of both temperature and oxygen on the metabolism of a given species. Due to the scarcity of data to estimate physiological and ecological traits of species inhabiting the SEP (see Deutsch et al., 2020), we worked with a model species corresponding to the mean of traits of 71 documented species of the global ocean. We showed that CVΦ is weakly dependent on physiological traits composing Φ, which conveys to this metrics some value for inferring the projected mean displacement and potential changes in viability of metabolic habitat in this region. Based on sensitivity experiments to physiological traits and natural variability, we propose a general method for inferring broad areas of climate change exposure regardless of species-specific Φ. We show in particular that for the model used here, the upper OMZ region can be considered a "safe" area for species with ecophysiotypes close to that of our model species (Parouffe et al., 2023).

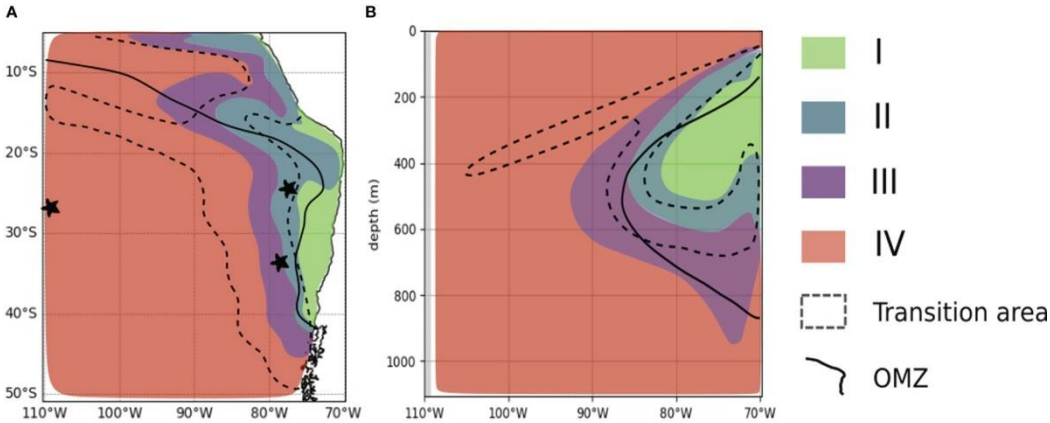

Figure 2: Areas of climate change exposure. Areas of climate exposure in the SEP at 200m (A) and the vertical representation at 26°S (B) derived from the climate velocities. We defined areas of climate exposure based on the components of the climate velocities of Φ using the model species. Areas I and II designate "safe" areas based on positive trends in Φ. Areas III and IV designate "at risk" areas based on negative trends in Φ. Areas II and III are areas of slow velocities (|CV|< 1 km.yr-1) where the spatial gradient controls the magnitude of CVΦ over the temporal trends. The transition area (dashed envelope) is the area most subjected to uncertainty in the sign and magnitude of the velocity due to high uncertainty in the sign of oxygen trends and the effect of E0. The black and solid contour represents the OMZ limit at 45 mmol.m-3. Note that the OMZ contour also coincides with Φ = 1. (After Parouffe et al. (2023))

As to ENSO timescales, shorter but more intense changes are expected compared to long-term trends, in particular under Eastern Pacific El Niño events, during which upper ocean temperatures increase, theoretically negatively affecting metabolic activity of most species. Less intense but longer La Niña events also affect aerobic habitat with symmetrical effect to that of warm El Niños. These episodic changes can superimpose to the long-term trend, which we assessed from the NCAR CESM Large ensemble.

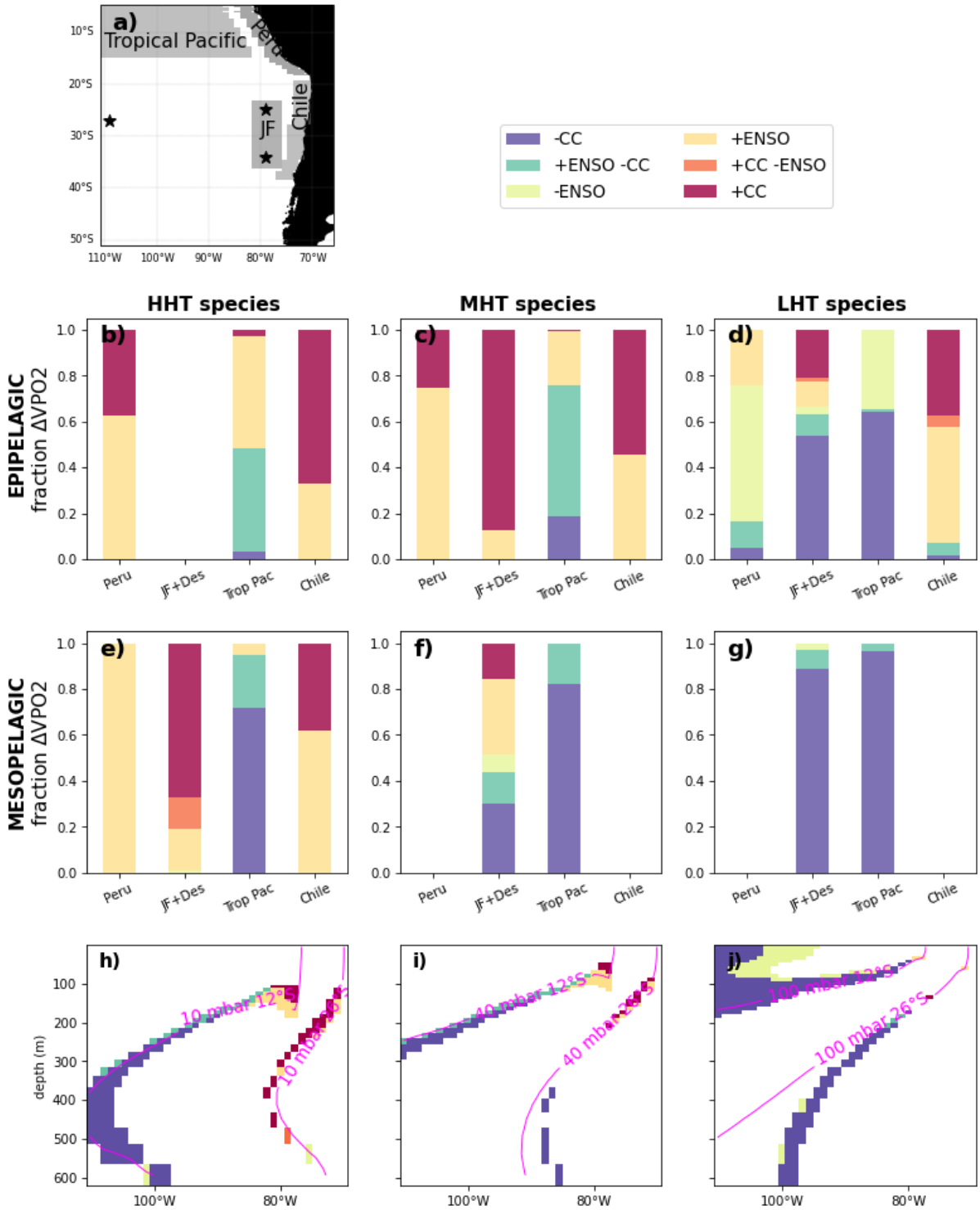

Figure 3: **Average fraction of ΔVPO2crit due to El Niño and climate change in the SEP in the END_RCP period (2050-2100) in the epipelagic and mesopelagic layers**. Fractions of ΔVPO2crit were calculated within several key regions of the SEP (see panel a) for the definition of the region). In each cell, we identify if CC or El Nino produce a gain or loss within that cell, leading to 6 different combinations of gain/loss due to El Nino and/or CC. A "+"("-") sign means that ENSO or CC cause a gain (loss) of VPO2crit within the cell. The fraction is estimated by normalising (i.e. dividing) ΔVPO2crit by the sum ΔVPO2crit for the 6 combinations. Hence fractions vary between 0 and 1 and allow comparing the regions. In h), i) and j), spatial patterns of ΔVPO2crit along vertical sections at 12°S and 26°S (After Parouffe et al. (2024)).

Results indicate a marked asymmetry between warm El Niño and La Niña where warm El Niño yields an overall gain in habitat that is twice as large as the loss in habitat during La Niña. In the future, the effect of the long-term trends is two-fold: First, it reduces the habitat gain during El Niño (except for MHT species). Second, it overshadows the effect of El Niño

events in the mesopelagic layer and in the open-ocean, whereas along the coasts, long-term trend and El Nino have a positive effect on habitat (gain) through both increasing VPO2crit.

4. Regional dynamical downscaling of the future climate

Based on WP2 analyses, one member of the CESM Large ensemble representative of the mean was selected for dynamical downscaling, using the physico-biogeochemical model CROCO-BioEBUS with 1/12° resolution extending from 12°N to 40°S along the coast of Peru and Chile (and in a 1/36° configuration over central Chile). This RCOM was tuned and validated in hindcast mode focusing on oxygen, using observational data from WP1 (Pizarro-Koth et al., 2023; Almendra et al., 2024). To avoid inheriting strong bias in the mean equatorial circulation from the ESM, we applied a delta change approach, adding to boundary conditions of an hindcast run the ESM-derived changes in a seasonal cycles between the present day (historical) and future (RCP8.5) climates. Projections were produced for the 2050-2100 period (time-slice). The RCOM simulated a warming trend significantly weaker than that of the global model below the mixed-layer; this was attributed to its greater skill in simulating the shoreward sloping thermocline (coastal upwelling) along the coast of Peru and Chile.

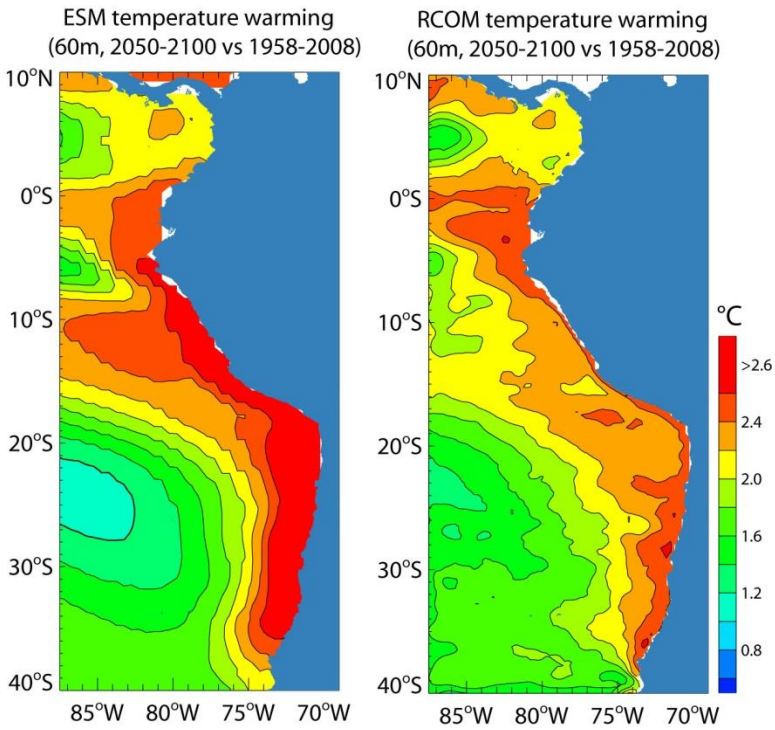

Figure 4: Change in mean temperature at 60m between the future (2050-20100) and present (1958-2008) climates in the (left) global ESM (CESM1) and the (right) regional model (CROCO-BioEBUS, 1/12°).

5. Estimating physiological traits of the Cojinoba (*Seriolella violacea*), an important fish species for artisanal fishermen in northern Chile.

Experiments to determine hypoxia tolerance and temperature sensitivity of the fish species Cojinoba have been carried out at the Fish Culture Laboratory at Universidad Catolica del Norte in Coquimbo, Chile. These experiments allow determining of relevant blood biochemical parameters, Routine metabolic rate (RMR), maximum metabolic rate (MMR) and its temperature sensitivity. This data may be used to infer exposure to future climates on the

Chilean and Peruvian coasts. This study may be replicated on the fish species yellowtail (*Seriola lalandi*), a migrating fish present across the entire south Pacific, with likely contrasting hypoxia tolerance (Alvarez et al., 2023).

These physiological parameters are key to understanding the environmental/ecological niche of these fish species, for resource management, in particular in a context of a collapse in the landings of Cojinoba. Understanding the precise role of the environment, its evolution and impact on species under climate change, may support relevant designs of effective Marine Protected Areas and effective resource management.

Loss-of-equilibrium (LOE) experiments revealed that *S. violacea* juveniles were significantly more tolerant to hypoxia than *S. lalandi*. Similarly to Messina-Henríquez et al. (2022), cojinoba juveniles started to loss balance as a sign of hypoxic stress at an oxygen concentration of 3 mg O_2/L (35% O_2 saturation). In contrast, the first signs of hypoxia stress behavior of *S. lalandi*, such as loss of balance and intense gasping on the surface, were observed from 6 mg O_2 /L (85% O_2 saturation). Fish that exhibited fast gasping at the surface, intense opercular movement and increased swimming frequency leading to the loss of balance were classified as non-tolerant. The hypoxia simulation for *S. lalandi* ended at 3 mg O_2 /L (35% O_2 saturation) because the juveniles presented high sensitivity (erratic swimming, heavy gasping on the surface) after this oxygen concentration, which can result in their death. Finally, after LOEhyp, 114 *S. lalandi* juveniles were classified as hypoxia-tolerant (55.6%), 77 fish as non-tolerant (37.6%) (Figure 4A), while 14 *S. lalandi* juveniles died at the end of the trial (6.8%). In the case of *S. violacea*, LOEhyp experiments ended at 1 mg O_2/L and resulted in the classification of 415 juvenile fish as hypoxia-tolerant (83.7%) and 81 fish as non-tolerant (16.3%) (Figure 4A). No mortality was observed among cojinoba juveniles.

To further understand the potential reasons behind the enhanced hypoxia-tolerant in *S. violacea* compare to *S. lalandi*, we conducted an analysis of their energy metabolism. Our findings revealed noteworthy disparities in these metabolic indicators between the two fish species. Firstly, the *S. lalandi* juveniles exhibited significantly higher blood glucose levels (197.5 ± 100.2 mg/dL, on average ± SD) compared to *S. violacea* (74.7 ± 35.5 mg/dL, on average) in spite of their hypoxic tolerance ($p<0.001$, Kruskal-Wallis)(Figure 4A). This elevation in blood glucose suggests a potentially heightened glucose utilization and availability for energy production for growth performance. Furthermore, we observed marked differences in triglycerides levels between the two fish species with an average ± SD of 101.3 ± 62.0 mg/dL for *S. lalandi* compared to an average of 386.3 ± 282.8 mg/dL for *S. violacea* ($p<0.001$, Kruskal-Wallis)(Figure 4B). The *S. violacea* juveniles displayed substantially higher triglyceride levels, indicating a potential deviation in lipid metabolism as energy production compared to *S. lalandi* juveniles. This distinction in triglyceride metabolism suggests a shift towards alternative energy sources or a more efficient utilization of lipids by *S. violacea* during hypoxia-environments. Supporting said assumption, our analysis revealed significantly higher basal lactate levels in *S. lalandi* (63.2 ± 33.2 mg/dL, on average ± SD) compared to *S. violacea* (6.6 ± 3.0 mg/dL, on average ± SD) ($p<0.001$, Kruskal-Wallis) (Figure 4C) (Alvarez et al, 2023). Therefore, the results suggest that *S. violacea* likely exhibits a higher anaerobic metabolism threshold in response to hypoxic environments, which aligns with our previous findings in the same fish species (Alvarez et al., 2023).

The oxygen consumption measurements of juvenile individuals from both fish species enabled us to compare crucial metabolic traits. The results showed a higher MMR for *S. lalandi* than for *S. violacea* juveniles (Figures 4 D and F), which could be associated with differences in their vertical distribution and migration behavior (Vergani et al., 2008). *S. violacea* is found near the coasts of Northern Chile and Peru, where upwelling events of oxygen-poor waters occur frequently near the coast (Allen et al., 2021; Messina-Henríquez et al., 2022). In contrast, yellowtail kingfish is a highly migratory pelagic fish with reported

movements of up to 2,960 km, linked to food availability and favorable environmental conditions (Kerwath et al., 2021). Previous studies have provided evidence that *S. lalandi* is an active fish species, exhibiting a significant cardiac capacity. Therefore, given life history of the two species analyzed, the more frequent exposure of palm ruff to hypoxic-like condition could explain their higher tolerance to hypoxia and the reason for the higher locomotor activity observed in yellowtail kingfish compared to palm ruff juveniles (Alvarez et al., 2023). Additionally, our results demonstrated that tolerance to hypoxia within individuals of the same species is associated with a lower metabolic rate and reduced locomotor activity (Figures 5D and F). This suggests that the strategy of remaining stationary rather than engaging in active escape behaviors allows them to minimize reliance on aerobic metabolism, contributing to their ability to cope with low oxygen environments (Alvarez et al., 2023).

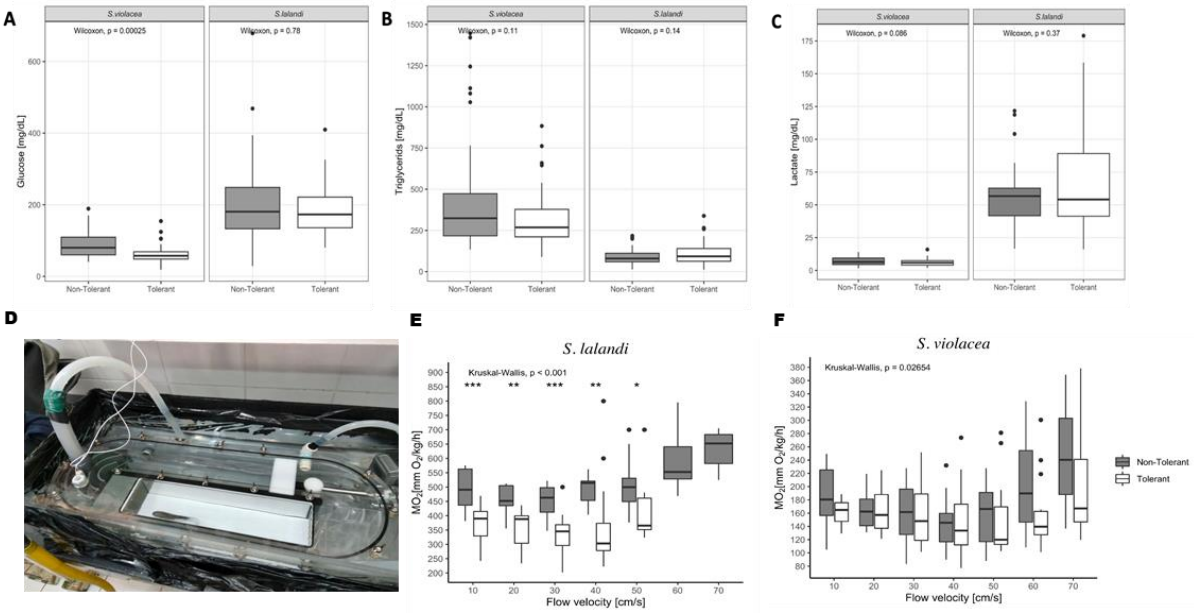

Figure 5: Blood biochemical parameters and Aerobic metabolic rate of tolerant and non-tolerant juveniles of *S. violacea* and *S. lalandi*. (A,B,C) Levels of glucose, triglyceride and lactate from *S. violacea* and *S. lalandi* classified as tolerant and non-tolerant to hypoxia. (D) Swimming Tunnel Equipment Integrated with Respirometry used for Precise Oxygen Consumption Analysis in juveniles from marine fish. (E, F) Relationships between of MO_2 and water flow velocity of hypoxia-tolerant and non-tolerant juvenile yellowtail (Seriola lalandi) (after Alvarez et al. (2023)).

6. **Outreach and engagement with the aquaculture industry in Tongoy bay** (contribution to WP8)

LEGOS/IRD and CEAZA have organized several encounters (3) with local stakeholders during the course of the project, which objective was to disseminate FutureMares products and elaborate a narrative of possible futures of the aquaculture industry in a hot spot of the scallop production in Chile, the Tongoy Bay.

A first meeting with 8 stakeholders partners (see Table below) took place on 22nd of April, during which FutureMares objectives were presented and discussions on how to organize the collaboration took place. Besides clear interest from stakeholders in the project outcomes, there was also concerns on how to collaborate towards the enhancement of the coastal observing system (e.g. participation of fisheries to Argo float development, sharing of existing data (from logbooks, fish landings, etc.).

Organisation	Sector
Ostimar S.A (https://www.ostimar.cl/index.php/en/)	Cultivation, processing and commercialization of oyster
Sociedad Nacional de Pesca (Sonapesca, https://www.sonapesca.cl/)	Fishery federation (Coquimbo region)
Asociación de Industriales y Armadores Pesqueros de Coquimbo (AIP) (http://aipcoquimbo.cl/)	Fishery association (Coquimbo region)
Masmar (https://www.masmar.cl)	Regional development program funded by Ministry of the economy and tourism development (Chile)
Cooperativa M31	aquaculture cooperative (in Tongoy)
IFOP (National Fishery Institute of Chile)	Fishery (governmental)
TASA (https://www.tasa.com.pe)	Industrial fishery
IOC (Intergovernmental Oceanographic Commission of UNESCO)	International scientific organization

Table: list of stakeholders linked to FutureMares.

This first meeting allowed establishing a good communication with the stakeholders during the course of the project, which in particular contributed to the successful deployment of 22 Argo floats in the South Eastern Pacific during the course of the project, as well as the incorporation of relevant data (e.g. landings) in the CEAZA quarterly bulletin (http://ceazamar.cl/boletines-ceazamar/).
The second stakeholder event took place in the framework of the GOOD-OARS-CLAP-COPAS summer. It was organized in Tongoy on the 10th of November 2023 and gathered 88 participants, including 5 fisheries, 3 cooperatives of fisheries, 5 “caletas” (fishing coves) and 13 public and private institutions (see Figure 6).

Figure 6: Stakeholder engagement meeting on the 10th of November 2023 in Tongoy Bay, Chile: Visit on site of the sea scallop aquaculture farms in Tongoy Bay and afternoon dialogues with local policy makers, aquaculture farmers and scientists.

The attendees were introduced to modeling and observational activities in the Tongoy sector in the framework of the FutureMares project, and storylines of possible futures were presented in terms of the change in mean oxygen conditions and extreme events (El Niño). This event, organized in collaboration with the Instituto Milenio SECOS, CEAZA (CLAP) and Universidad Santo Tomas, was focusing on outreach, but was designed so as to lay the foundations of a series of encounters with the fishery and aquaculture community of the Tongoy Bay to better assess needs and vulnerability in the socio-ecological system of the Tongoy/Guanaqueros bays sector. These encounters took place over four days in August 2024 (21, 22 and 28,) and aimed at better targeting risk perception by the local communities and developing a narrative that integrates the socio-ecological narratives into the physical storyline (Almendra et al., 2024). These workshops were co-organized by FutureMares, "My Climate Risk" of the WCRP (https://www.wcrp-climate.org/my-climate-risk, collaboration with Ted Shepherd (University of Reading)) and with OARS Outcome 3 (collaboration with José Martin Hernandez Ayon (Universidad Autonoma de Baja California, Mexico) and Isensee, Kirsten (Intergovernmental Oceanographic Commission, France)). OARS Outcome 3 aims at enhancing synergies between several actions of the ocean decade in relation with the co-design and implementation of observation strategies related to ocean acidification and its impacts on marine life and sustainability of marine ecosystems. A preparatory meeting to these encounters took place in Coquimbo on the 17-18 of July, 2024, followed by a meeting with stakeholders of Tongoy Bay on the 19th of July, 2024.

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