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Integrating Climate Change into Fisheries Science and Management in the SPRFMO Area

FAO DSF Project

Integrating Climate Change into Fisheries Science and Management in the SPRFMO Convention Area

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Executive Summary

Evaluating observed and projected changes in oceanographic variables

- **Climate projection models** simulate how Earth's climate system responds to various greenhouse gas scenarios; CMIP (Coupled Model Intercomparison Project) is a global initiative that standardizes these simulations to enable consistent climate analysis across models.
- Climate change is projected to cause continued **sea surface temperature** (SST) increases in the SPRFMO area, particularly in the western South Pacific, driven by weakened ocean mixing and intensified surface warming, affecting marine species' growth, reproduction, and distribution.
- **Salinity** in the SPRFMO region is expected to diverge freshening in the equatorial and tropical zones due to increased rainfall, and salinification in the subtropical southeast due to higher evaporation, affecting water density, stratification, and nutrient mixing.
- **Ocean acidification** will intensify in the SPRFMO region as the ocean absorbs more atmospheric CO_2, reducing pH and carbonate availability, which threatens calcifying organisms and alters ecosystem functioning, with lasting impacts even if emissions are curbed.
- **Ocean deoxygenation** is projected to worsen in the South Pacific, particularly in regions with existing Oxygen Minimum Zones; warmer and more stratified waters will limit oxygen mixing, compressing marine species' habitats and disrupting food webs.
- **CMIP** provides raw climate data, **ISIMIP** harmonizes and bias-corrects this data for real-world applications, and **FISHMIP** uses it to drive marine ecosystem

models, creating a reliable chain of projections for marine biomass, species distributions, and fisheries outcomes.

Action point: Integrate FishMIP outputs into ecosystem assessments to understand biomass trends, catch potential, and ecosystem vulnerability under different emissions scenarios.

Potential climate change impacts on the three main managed species in SPRFMO

- Climate change affects marine species by altering habitat suitability, food availability, and reproductive success, often causing species to shift poleward, change behavior, or experience population declines due to environmental stress.
- **Jack mackerel** is vulnerable to SST, low oxygen, and reduced productivity; its habitat is expected to shift southward and offshore, with reduced spawning success in warming waters and fragmented connectivity due to OMZ shoaling.
- **Jumbo flying squid** is sensitive to warming, productivity, and oceanographic features like eddies; its core habitat is projected to contract and move southward, affecting accessibility for coastal fishers and increasing transboundary management challenges.
- **Orange roughy**, a deep-sea species with low mobility and narrow environmental tolerance, is at risk from bottom warming and oxygen loss; suitable habitat may contract significantly, particularly on key fishing grounds like the Chatham Rise.

Action point: Promote the development and use of **Species Distribution Models (SDMs)** with key environmental variables to improve predictive capacity for these species under climate change.

Identifying socio-economic impacts of climate-induced changes in fisheries

- **Socio-economic variables** are essential in understanding climate impacts because fisheries are not only ecological systems but also economic and social ones, where communities' ability to adapt depends on income, infrastructure, and institutional strength.
- **Standardized frameworks** have been developed to characterize climate risk, although capturing fisheries adaptive capacity in depth remains a challenge.
- **Climate Risk Assessments** help evaluate risk by combining physical hazards, exposure, and vulnerability. Socio-economic parameters can be simple indicators like GDP per capita or fishery catch diversity, or more detailed public statistics on employment, nutrition, and governance capacity.

Action point: Use **FAO, ILO, and World Bank datasets** to integrate socio-economic parameters into regional climate risk assessments, identifying vulnerable countries and priority areas for support.

Integrating climate trends and environmental variability into fisheries stock assessment and management advice

- Most stock assessments and Harvest Control Rules (HCRs) do not currently account for environmental change. There are two main ways to integrate them into stock assessments: Climate-enhanced stock assessments or climate-informed HCRs.
- **Climate-enhanced stock assessments**: Link environmental drivers (e.g., SST, productivity) directly to life-history traits (growth, recruitment) while modeling species population dynamics. This would allow to continue with traditional HCR.
- **Climate-informed HCRs**: Adjust management rules based on real-time or seasonal environmental indicators
- **Management Strategy Evaluation** (MSE) with climate scenarios allows managers to test strategies under future conditions and uncertainties.
- **Spatial closures** and marine protected areas can act as climate refugia and help maintain ecosystem resilience in the high seas.
- **Better integrating small-scale fisheries** in assessments improves monitoring and equity, especially since they are often the most vulnerable and least represented.
- Promoting **international cooperation** is essential to manage shifting transboundary and straddling stocks fairly and sustainably.
- **Regular review and updating of model parameters** ensure that assessments stay relevant in a changing climate without needing major system overhauls.
- **Long-term engagement** with managers and scientists builds institutional memory and supports adaptive governance.
- **Integrating socioeconomic dimensions** into decision-making ensures that climate adaptation is socially equitable, not just ecologically effective.

Action point: Begin integrating environmental variables into SPRFMO's stock assessments through one of two methods to improve resilience and management performance.

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Abstract

This report supports the South Pacific Regional Fisheries Management Organisation (SPRFMO) in integrating climate change into fisheries science and management by reviewing current knowledge, data sources, and practical tools. It outlines expected environmental changes in the SPRFMO Convention Area, including rising sea surface temperatures, ocean acidification, decreasing oxygen levels, and shifting salinity patterns, driven by both global warming and regional climate dynamics such as ENSO and changes in ocean circulation. These environmental shifts are projected to impact key species managed by SPRFMO: jack mackerel is likely to experience habitat loss and offshore migration due to warming and low oxygen; jumbo flying squid may face shrinking habitat and increased transboundary movements; and orange roughy, due to its deep-sea habitat and biological sensitivity, may see a decline in suitable areas. The report also examines how climate change can affect fisheries-dependent communities and economies and proposes tools to assess socio-economic vulnerability and adaptive capacity using readily available data. Finally, it presents two main approaches for integrating climate change into fisheries stock assessments: climate-enhanced stock assessments and environmentally-informed harvest strategies, along with complementary actions to be considered in their management. The aim is to support anyone wishing to study these topics further by providing an entry point into the literature, a review of current practices, and guidance on where to find relevant tools and information.

Introduction

The ocean, covering 71% of the Earth's surface, plays a vital role in supporting human life by providing essential resources and ensuring global food security (Costello et al., 2020). However, growing human populations and rising demand for marine resources have significantly increased pressure on ocean ecosystems. Alongside direct human exploitation, the ocean is experiencing the compounded impacts of climate change, with approximately 93% of the excess heat from greenhouse gas emissions being absorbed by marine waters. This alters ocean temperatures, circulation, and other physical properties (Cheng et al., 2019; Oschlies, 2021), with profound effects on marine organisms' growth, reproduction, and distribution (Cheung 2018; Lotze et al. 2019). Climate change is rapidly reshaping marine ecosystems, at an even faster pace than those on land, leading to shifts in species distributions and trophic dynamics (Lenoir et al., 2020). As a result, there is growing awareness that both natural variability and climate-driven environmental changes must be considered in the assessment and management of fish populations. While tools and data now exist to assess different harvest strategies under changing environmental conditions, most fisheries management frameworks still lack meaningful integration of climate considerations (Pinsky et al., 2018; Worm et al., 2009). This gap increases the risk of management failures and stock collapses, a threat that will only grow the longer adaptation measures are postponed.

Given the urgent need for climate-responsive fisheries management, this study aims to support researchers and decision-makers working with SPRFMO fisheries by providing relevant information, guidelines and practical ideas. The goal is to help incorporate climate change into fisheries assessments and improve current management strategies, which often overlook critical environmental variables. As the SPRFMO Commission's Decision 13-2023 has elevated climate change to a permanent agenda item for the Scientific Committee and calls for urgent revision of existing Conservation and Management Measures (CMMs), the main objectives of this report are:

1) Summarize and evaluate observed and projected changes in oceanographic variables and their effects on marine ecosystems and species within the SPRFMO Convention Area.
2) Review potential climate change impacts on fisheries, focusing on the three main managed species in SPRFMO: jack mackerel, jumbo flying squid and orange roughy. Evaluate species-specific vulnerabilities and the implications for transboundary stocks.
3) Identify socio-economic impacts of climate-induced changes on fisheries, with a focus on fisheries-dependent communities and economies.
4) Identify practical methods to integrate climate trends and environmental variability into fisheries stock assessments and management advice.

1. Evaluating observed and projected changes in oceanographic variables

Climate projections are scientific estimates of how the Earth's climate might change in the future. These projections rely on complex models that simulate how the atmosphere, oceans, land, and ice interact, and how these might respond to greenhouse gas emissions, land use change, and other human activities. Because no single model can capture all the complexity of the Earth system, we compare and combine the results of many models to get more reliable predictions. This is where initiatives like CMIP come in.

The Coupled Model Intercomparison Project (CMIP) is an international initiative coordinated by the World Climate Research Program. Its purpose is to standardize climate simulations from modeling centers worldwide so that researchers can compare them directly and use them to drive impact studies. CMIP has gone through several phases with significant improvements from one to another, particularly in recent years. CMIP5 (launched in 2010) included around 50 models from more than 20 modeling centers and was widely used. More recently CMIP6 (launched in 2016) involved over 100 models from 49 modeling groups, including more detailed Earth system processes and updated greenhouse gas scenarios (Shared Socioeconomic Pathways or SSPs) and was used during the IPCC AR6 to evaluate global projections (Figure 1).

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot***	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot***		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

Figure 1: Description and relationship of scenarios and modelled pathways considered across AR6 Working Group reports.

Future projections of climate change rely on a set of emissions or concentration scenarios. These scenarios represent different pathways society might take, depending on choices about population, economic development, energy use, land use, and climate policies (Flato, 2011; Flato et al., 2013). For example, scenarios like SSP2-4.5 or SSP5-8.5 are used to drive climate models and assess how the climate system might respond to different levels of greenhouse gas emissions (Figure 2). However, the IPCC does not assign probabilities to these scenarios, none of them is considered more likely than the others. This is because there is no widely agreed scientific method to determine which future socio-economic pathway is most probable. Although some researchers have tried to estimate subjective probabilities of scenarios (Ho et al., 2019; Hausfather & Peters, 2020), the IPCC maintains a neutral position, treating all scenarios as equally plausible. As a result, the IPCC only provides probabilistic outcomes within each scenario, such as "what is the likely range of global temperatures by 2100 under SSP2-4.5." But it does not combine results from different scenarios into a single overall forecast, because there is no agreed way to weigh the scenarios by likelihood.

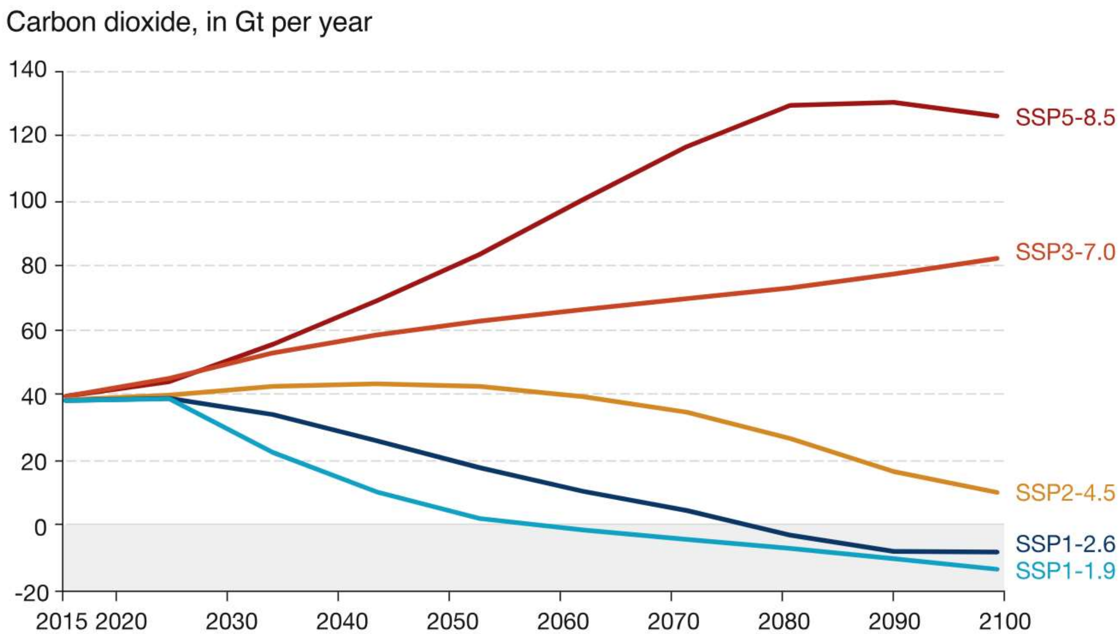

Figure 2: Projections of CO2 emissions according to IPCC scenarios
SSP = shared socio economic pathways
Note: the numbers associated with each SSP (1.9, 2.6, 4.5, 7.0 and 8.5) correspond to the radiative forcing induced by 2100 compared with the pre-industrial era, expressed in W/m2.
***Source:** IPCC,1st Working Group, 2021*

These models simulate climate variables like sea surface temperature, salinity, oxygen levels, and others critical for ocean and ecological studies. Understand how these will change is critical for the sustainability of global fisheries as they are projected to generate potential significant losses to marine biomass and therefore the fisheries sector (Cinner et al., 2022; Tittensor et al., 2021)

1.1. Sea surface temperature:

The IPCC AR6 confirms a robust and ongoing rise in global sea surface temperatures (SST), with especially rapid warming in the western Pacific Ocean, including parts of the South Pacific although eastern Pacific may show greater variability due El-Niño Southern Oscillation (ENSO) and intensified marine heatwaves.

Table 1: Projected global Sea Surface Temperature (SST) increase through different emissions scenarios (IPCC).

Scenario (SSP)	Projected SST Increase (°C)	5–95% Range
SSP1-2.6 (Low emissions)	**+0.86°C**	[0.43 – 1.47]
SSP2-4.5 (Intermediate)	**+1.51°C**	[1.02 – 2.19]
SSP3-7.0 (High)	**+2.19°C**	[1.56 – 3.30]
SSP5-8.5 (Very high)	**+2.89°C**	[2.01 – 4.07]

On the one hand, this regional intensification is driven by large-scale ocean-atmosphere interactions, notably the Walker circulation and the Indonesian Throughflow. The Walker circulation is a broad atmospheric circulation pattern over the equatorial Pacific, where changes in surface pressure and wind strength influence how warm water is distributed across the ocean. A weakening or shifting Walker circulation can lead to more stagnant or redistributed ocean currents, allowing heat to accumulate in the western Pacific (Chung et al., 2019). The Indonesian Throughflow, on the other hand, is a major ocean current system that transfers warm water from the Pacific into the Indian Ocean through the complex network of Indonesian seas (M. Feng et al., 2018). Changes in this flow can affect heat buildup and transport in the Pacific basin. Together, these systems help explain why the tropical western Pacific, including parts of the South Pacific, has warmed more than other regions. In contrast, areas like the Southern Ocean and eastern Pacific have warmed more slowly or even cooled slightly, influenced by deep ocean upwelling and circulation patterns that bring cooler water to the surface.

On the other hand, recent studies indicate that climate change is amplifying both the frequency and intensity of ENSO events. A large multi-model ensemble has shown that the amplitude of eastern Pacific ENSO events has increased by about 10% from 1901–1960 to 1961–2020, with strong eastern Pacific El Niño events now about twice as likely and strong central Pacific La Niña events about nine times as likely. El Niño events will become more frequent by 2040, regardless of near-term emissions reductions (Lopez et al., 2022). El Niño typically leads to global warming due to warmer waters in the central and eastern Pacific heating the atmosphere and suppressed upwelling limiting oceanic heat absorption, effects that contributed significantly to the record-breaking global temperatures in 2016 during the strong 2015–2016 El Niño. While La Niña generally has a cooling effect, even La Niña years are now warmer than El Niño years from decades ago due to the rising baseline of global temperatures.

The influence of large-scale circulation patterns weakened vertical mixing, and shallower mixed layers contribute to enhanced surface warming. These conditions reduce the ocean's capacity to store heat at depth, allowing surface layers to warm more rapidly. Critically, sustained increases in SST affect not only habitat suitability but also key life history traits of marine species. Elevated temperatures can lead to faster metabolic rates, which may accelerate growth and maturation, but also shorten lifespans and reduce individual body size (Poloczanska et al., 2016). Moreover, primary productivity can be disrupted when warming inhibits nutrient upwelling, leading to reduced food availability at the base of the food web (Brown et al., 2010). These effects cascade upward, potentially reducing reproductive success, shifting species distributions, and undermining the stability of predator-prey relationships. For the SPRFMO region, which supports economically and ecologically important pelagic species such as jack mackerel and squid, such changes could significantly alter population dynamics, productivity, and the broader functioning of marine ecosystems, posing urgent challenges for resource management in a warming ocean.

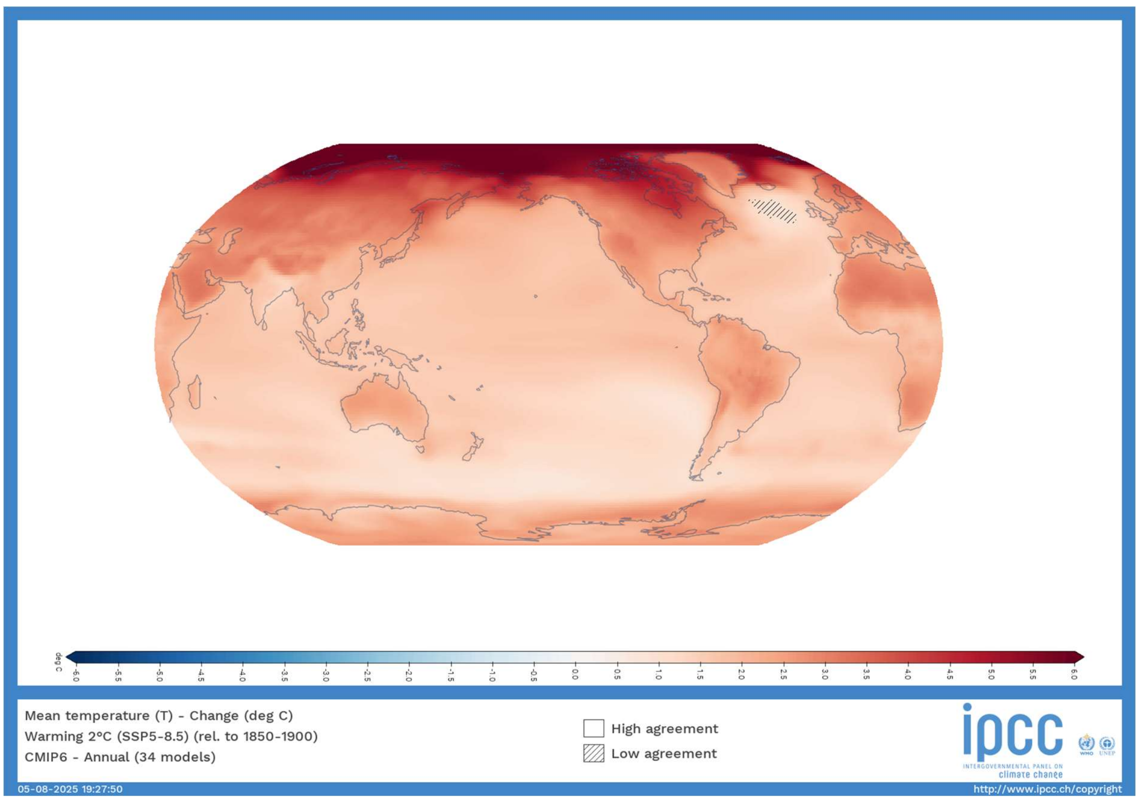

Figure 3: Temperature projections from the IPCC WGI Interactive Atlas.
Data outputs available at https://interactive-atlas.ipcc.ch/

Looking ahead, climate models project that sea surface temperatures will continue to rise globally throughout the 21st century, with the rate and extent of warming depending on future greenhouse gas emissions. These models show better agreement and regional accuracy than in past assessments but still face challenges in simulating equatorial dynamics and small-scale ocean processes. Nonetheless, the warming of sea surface, especially in the tropics, remains one of the most consistent and consequential indicators of climate change.

1.2. Salinity

Climate change is actively reshaping ocean salinity patterns across the South Pacific, including the SPRFMO region, with clear regional contrasts emerging under global warming. A key long-term trend observed globally is the intensification of the hydrological cycle—leading to saltier regions becoming saltier and fresher regions becoming fresher. However, recent high-resolution model results show that salinity changes in the South Pacific are strongly region- and time-dependent, influenced not only by evaporation and precipitation but also by ocean dynamics and their interactions with warming (Bingham et al., 2019; IPCC, 2019a). Projections reveal that sea surface waters in the western tropical Pacific and the South Pacific Convergence Zone are expected to become fresher, while the southeastern South Pacific, including parts of the subtropical gyre, will become saltier under continued climate warming (Zhi et al., 2025). These patterns reflect shifts in precipitation, surface currents, and freshwater fluxes, with enhanced rainfall in the west and increased evaporation in the southeast driving opposing salinity trends. The SPRFMO region straddles this transition zone, experiencing both freshening in the equatorial/eastern areas and salinification further south and west.

The implications for marine organisms in this region are considerable. Salinity affects seawater density, which in turn influences stratification and vertical mixing, key processes that regulate nutrient delivery to the surface and oxygen transport to deeper layers. Increased stratification can limit nutrient upwelling, reducing primary productivity and altering the base of the food web (IPCC, 2019a). At the same time, changes in salinity can impact the physiological tolerance of marine species, especially those with narrow salinity ranges or life cycles tied to specific water mass properties. For migratory species and planktonic organisms in the SPRFMO region, shifting salinity boundaries may alter habitat suitability, reproductive timing, and larval dispersal patterns. Additionally, stronger stratification may compound other stressors like deoxygenation and warming, further reducing ecosystem resilience. Understanding and monitoring salinity changes in this region is critical not only for predicting shifts in ecosystem productivity but also for managing transboundary fisheries in a changing ocean.

1.3. Ocean acidification (pH):

As the concentration of atmospheric CO_2 increases due to human activities, the ocean absorbs a significant portion, about 30% of all CO_2 emissions, helping to slow atmospheric warming but triggering ocean acidification by lowering the pH of seawater. This reduces the availability of carbonate ions (CO_3^{2-}) that are essential for marine organisms like corals, mollusks, and plankton to build calcium carbonate structures (IPCC, 2019a).

The South Pacific Ocean is a vital component of the global oceanic CO_2 sink due to its vast surface area and dynamic circulation. Cold, carbon-rich waters from the Southern Ocean flow into the South Pacific, while warm surface waters absorb atmospheric CO_2, especially in subtropical and equatorial regions. As these waters subduct (sink) beneath the surface, particularly in areas of mode water formation, they transport dissolved CO_2 into the ocean interior, effectively storing carbon for decades to centuries. However, as atmospheric CO_2 continues to rise, projections using CMIP6 models show that surface ocean pH will decline sharply, with greater reductions under high-emission pathways (e.g., a decline of over 0.44 pH units under SSP5-8.5 by 2100) (IPCC, 2021b). The Southern Ocean, which interacts closely with the South Pacific, is projected to experience widespread undersaturation of aragonite, a form of calcium carbonate vital to many marine species (Ishii et al., 2020). This process could begin as early as the 2030s, affecting waters that eventually influence the South Pacific basin.

Additionally, interannual climate variability, particularly the El Niño–Southern Oscillation (ENSO), plays a major role in modulating acidification patterns in the South Pacific (Wu et al., 2018). ENSO is a natural oscillation of ocean-atmosphere conditions in the equatorial Pacific, cycling between El Niño (warmer eastern Pacific, weaker upwelling) and La Niña (cooler eastern Pacific, stronger upwelling). These shifts impact surface temperatures, wind patterns, and CO_2 exchange between the ocean and atmosphere. For example, during El Niño events, reduced upwelling can lead to less CO_2 outgassing and potentially more CO_2 uptake, influencing short-term pH fluctuations. Even if future policies achieve negative emissions and reduce atmospheric CO_2, ocean acidification will not reverse quickly. While surface waters would begin to recover, the deep ocean will continue to acidify due to the slow turnover of ocean waters, meaning that today's emissions will leave a multi-generational legacy in ocean chemistry (Mathesius et al., 2015). This underscores the long-lasting impact of current CO_2 emissions, particularly for vulnerable marine ecosystems in regions like the South Pacific.

1.4. Ocean deoxygenation

Dissolved oxygen levels in the global ocean have been declining over recent decades, with losses concentrated in the upper 100–600 meters. This process, known as ocean deoxygenation, is driven by ocean warming, which reduces the solubility of oxygen in seawater, and by increased stratification, As the upper ocean warms, density differences increase, creating stronger layering that reduces vertical mixing that carries oxygen from the surface into deeper layers. CMIP6 models, consistent with observations, estimate a ~2% decrease in total dissolved oxygen in the upper ocean between 1970 and 2010. Of this, around 15% is due to reduced solubility from warming, while the rest is attributed to weakened ocean ventilation (IPCC, 2019b). These trends are especially concerning in regions already prone to low oxygen levels, such as the Oxygen Minimum Zones (OMZs) (Keeling et al., 2010) in the eastern tropical South Pacific, off the coasts of Peru and northern Chile (Ulloa & Pantoja, 2009). In this area, high surface productivity, combined with shallow thermoclines and sluggish intermediate circulation, leads to persistent low-oxygen conditions (Figure 4). Climate models project that OMZs in this region may expand and intensify as warming and stratification increase, further limiting oxygen renewal at Depth (Llanillo et al., 2018). Moreover, ENSO (El Niño–Southern Oscillation) events influence the thermocline depth and upwelling in the South Pacific, modulating oxygen supply from year to year. For instance, during El Niño, reduced upwelling can temporarily suppress OMZ intensity, while La Niña can exacerbate low-oxygen conditions.

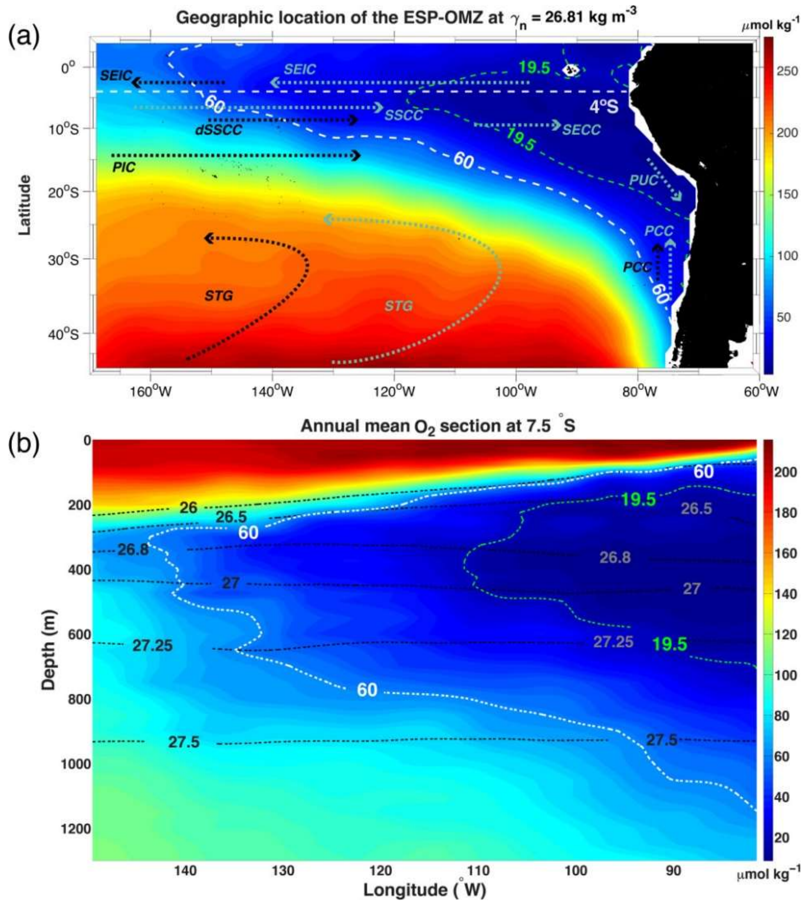

Figure 4: Map of the Eastern South Pacific-Oxygen Minimum Zone (ESP-OMZ) delimited by the oxygen contour of 60 μmol kg^{-1} (white dashed line) and its core delimited by the oxygen contour of 19.5 μmol kg^{-1} (green dashed line). The background shows the climatological mean dissolved oxygen (μmol kg^{-1}) from WOA-13 at the neutral surface of the ESP-OMZ core (γ_n = 26.81 kg m^{-3}, $z \cong$ 350 m). Source: Llanillo et. al, 2018.

The expansion of oxygen minimum zones (OMZs) in the South Pacific presents a growing threat to marine ecosystems and fisheries. As deoxygenation progresses, driven by ocean warming, increased stratification, and weakened ventilation, midwater species such as squid, pelagic fish, and zooplankton are increasingly at risk. These organisms depend on oxygen-rich zones for respiration, but as OMZs expand vertically and horizontally, they are forced into narrower layers of habitable water, a phenomenon known as habitat compression. This restriction can elevate physiological stress, disrupt feeding and reproduction, and ultimately reduce population viability. In parallel, low-oxygen conditions enhance the microbial production of nitrous oxide (N_2O), a potent greenhouse gas, particularly within persistent OMZs. This contributes to a positive climate feedback loop, reinforcing the very conditions that cause deoxygenation. Fisheries that target species near OMZ boundaries may also suffer, as fish stocks shift distribution, decline in abundance, or become less accessible. When combined with ocean warming and acidification, deoxygenation becomes part of a triple threat that undermines ecosystem resilience, elevates species mortality rates, and destabilizes marine food webs, especially in ecologically sensitive and economically important areas like the South Pacific.

1.5. Ocean circulation

Mentioned in all the above sections, ocean circulation is expected to exacerbate many of the stressors described (IPCC, 2019a). The South Pacific is influenced by complex current systems, including the South Equatorial Current, the Peru–Chile upwelling system, and interactions with the Southern Ocean. Climate-driven changes are expected to weaken vertical circulation and modify upwelling patterns, particularly in the eastern equatorial Pacific and along the subtropical gyres. These shifts are likely to reduce the delivery of nutrients to surface waters, diminishing primary production and the biomass of higher trophic levels. Moreover, interannual and decadal variability, particularly from the El Niño–Southern Oscillation (ENSO), adds additional stress and uncertainty. ENSO events influence upwelling, thermocline depth, and regional productivity. Under future warming, ENSO may become more intense or frequent, further amplifying fluctuations in temperature and oxygen, especially in the South Pacific.

1.6. Using climate projections to understand impacts on marine ecosystems

To understand how these oceanographic changes will impact marine ecosystems, the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) provides robust ensemble projections to assess how future climate change may affect fish biomass production globally (Blanchard & Novaglio, 2024). Using harmonized models and two contrasting IPCC scenarios—SSP1-2.6 (low emissions, <2 °C warming) and SSP5-8.5 (high emissions, >4 °C warming)—the study projects widespread declines in marine fish biomass, particularly under high-emission conditions. By mid-century, most countries are expected to experience declines exceeding 10%, and by 2100, losses exceed 30% in 48 countries and territories under SSP5-8.5. These include both major fishing nations (e.g., China, Peru) and climate-vulnerable island states heavily reliant on aquatic foods (e.g., Solomon Islands, Micronesia, Nauru). In contrast, under SSP1-2.6, end-of-century losses are limited to <10% or negligible change in 178 countries. While a few regions show projected biomass increases under both scenarios, confidence in these positive trends remains very low, emphasizing the global risk posed by unmitigated climate change to marine ecosystems and fisheries.

Using climate projections: CMIP, ISIMIP, FISHMIP

In order to have the best output possible for marine ecosystems, there is a chain that starts with physical Earth system models providing raw climate projections, continues with models harmonization and bias correction to represent real-world impacts, and finishes using this curated data to produce Marine Ecosystem Models. These three steps are embodied by three organisations:

1- Coupled Model Intercomparison project (CMIP)

Mentioned earlier, CMIP provides standardized outputs that capture how climate variables are likely to change under future conditions. CMIP operates in phases (e.g., CMIP5 and CMIP6), each time introducing improvements in model resolution, processes, and scenarios. CMIP data serves as the scientific foundation for climate impact studies. including global assessments like those conducted by the Intergovernmental Panel on Climate Change (IPCC). These outputs are available through the IPCC WGI interactive atlas where an extensive number of datasets, variables and scenarios are at disposal.

2- Inter-sectoral Impact Model Intercomparison Project (ISIMIP)

Building on CMIP, ISIMIP provides a critical bridge between raw climate projections and real-world impact analysis. ISIMIP curates, harmonizes, and bias-corrects CMIP outputs, making them suitable for use in various sector-specific impact models (e.g., agriculture, water, health, and ecosystems). By selecting a subset of CMIP models that represent a wide range of climate responses (temperature, precipitation, ocean conditions), ISIMIP ensures that the downstream models receive inputs that are both scientifically robust and methodologically consistent. It also integrates socio-economic pathways (SSPs) and ensures that all sectors are working with a coherent set of future assumptions. The most recent iteration of this project is ISIMIP 3a/b which can be accessed through the ISIMIP Repository online.

3- Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP)

Finally, FISHMIP is one of the sectoral applications under the ISIMIP umbrella, specifically focused on the ocean. FISHMIP uses the climate data outputs curated by ISIMIPto drive an ensemble of marine ecosystem models (MEMs). These MEMs vary in structure, scale (global or regional) and complexity but all simulate how marine species and ecosystems respond to environmental changes over time. By comparing outputs from different models under standardized climate scenarios, FISHMIP generates ensemble projections of future marine biomass, fisheries yields, species distribution, and ecosystem structure. These outputs are invaluable for understanding how climate change might impact fisheries and ocean food webs, particularly in sensitive regions like the tropical South Pacific. These outputs can also be accessed through their online repository, with available tutorials and interactive mapping.

Together, the chain from **CMIP → ISIMIP → FISHMIP** provides a powerful modeling framework to forecast the future of marine ecosystems under climate change. The end products of this chain, projected changes in marine biomass, catch potential, and biodiversity, can inform climate adaptation strategies, fisheries management policies, and conservation planning. This integrated approach ensures that predictions about marine futures are grounded in the best available climate science and are directly usable by decision-makers concerned with ocean sustainability.

2. Potential climate change impacts on the three main managed species in SPRFMO

To provide the most useful and practical information, this section focuses on the three main species assessed in the SPRFMO Convention Area. It summarizes their habitat preferences, how these may change with climate impacts, and what current studies say about their distribution and environmental sensitivity. These studies also provide useful leads for anyone interested in exploring these species further.

2.1. Chilean Jack Mackerel (*Trachurus murphyi*)

The Chilean jack mackerel (*Trachurus murphyi*) is a widely distributed pelagic species in the Southeast Pacific Ocean, with a known range extending from northern Peru to southern Chile, and into the high seas managed under the South Pacific Regional Fisheries Management Organisation (SPRFMO). The species exhibits extensive seasonal migration, shifting northward during austral spring and southward in fall, with distribution patterns closely linked to sea surface temperature (SST), chlorophyll-a concentration, and dissolved oxygen levels (Z. Feng et al., 2022; Ramos et al., 2022).

The analysis on the vulnerability of *T. murphyi* to climate change, focusing on habitat suitability, thermal and oxygen tolerances, productivity dependencies, and likely responses to projected environmental shifts draws on species distribution modeling (SDM) studies as well as IPCC projections for the South Pacific Ocean.

2.1.1. Environmental Preferences and Habitat Constraints

Thermal Envelope and Habitat Suitability

Jack mackerel are thermally sensitive and occupy SST ranges generally between 12.5°C and 19.3°C, depending on season and latitude (Li et al., 2016). Habitat suitability models developed from fishery effort data and environmental satellite variables confirm that thermal range as central to predicting presence and abundance, with optimal spawning conditions centered around 13–17°C (Lang Abarzúa, 2021). When SST exceeds 20°C, particularly in northern Chile and Peru, model results show a clear reduction in habitat suitability, especially for spawning aggregations (Lang Abarzúa, 2021; Li et al., 2016)

GAM-based modeling further supports this, identifying 12–18°C as the most favorable SST range for biomass presence (Arnaud Bertrand et al., 2016). Habitat suitability degrades in warmer, stratified waters with limited food and oxygen availability, particularly during El Niño events. During such events, fish distributions shift southward or offshore, reducing access to traditional spawning or feeding (Z. Feng et al., 2022).

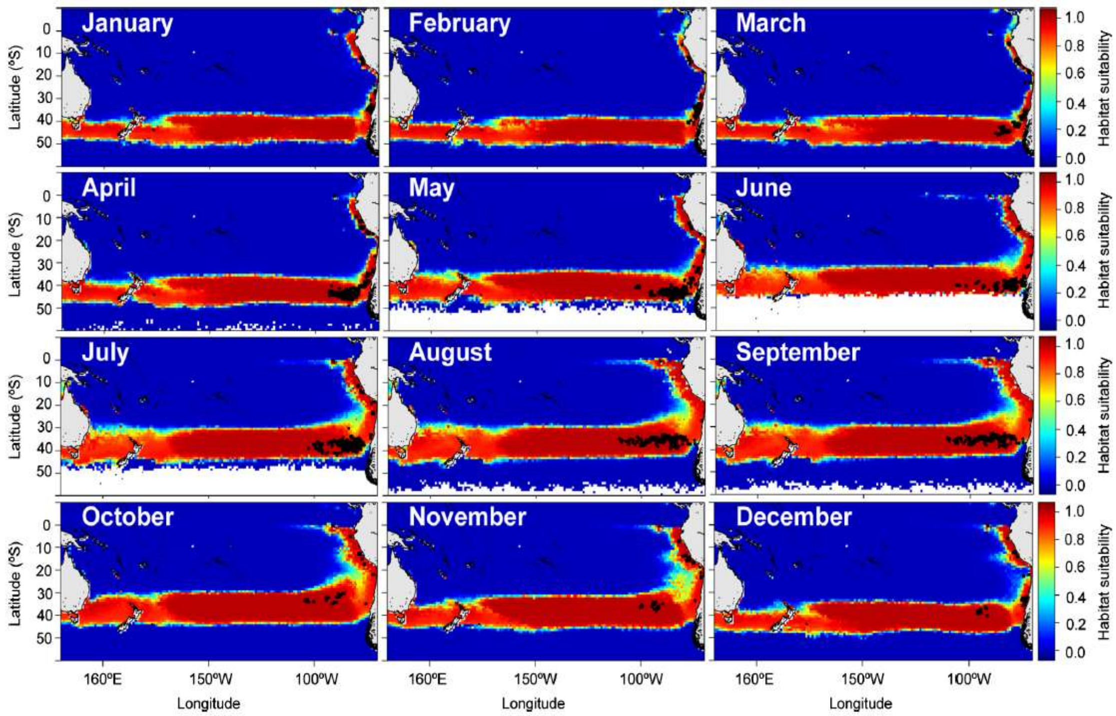

Figure 5: Climatological jack mackerel habitat probability map based on model predictions from January to December. Catch observations are superimposed as black dots.
Source: Bertrand et al., 2016

Oxygen Limitation and Vertical Habitat Compression

Jack mackerel exhibits significant sensitivity to dissolved oxygen concentrations and vertical habitat structure. Modeling studies show that the species avoids waters with oxygen levels below 2 ml/L and prefers zones where dissolved oxygen exceeds 4.4 ml/L, with the oxycline (the depth at which oxygen falls below 2 ml/L) deeper than 40 meters (Bertrand et al., 2016). The species' vertical distribution is thus constrained by the Eastern South Pacific's naturally shallow oxygen minimum zone (OMZ), especially off Peru and northern Chile.

Bertrand et al. (2016) describe "open-door" and "closed-door" connectivity scenarios based on the depth of the oxycline. In warm seasons or during El Niño events, the shoaling of the OMZ acts as a barrier to cross-ecosystem connectivity between Peruvian and Chilean populations, fragmenting what may otherwise be part of a metapopulation. Habitat compression under such conditions likely increases density-dependent interactions and fishery pressure in surface layers (Arnaud Bertrand et al., 2016).

Primary production dependence and Habitat Quality

Jack mackerel are consistently associated with moderate to high chlorophyll-a concentrations, which reflect primary production and food availability (Li et al., 2016; Langabarzua, 2021). Spawning activity has been found to increase in areas with high chlorophyll-a levels (over 0.2 mg/m^3) and decline in oligotrophic zones (Langabarzua, 2021). Biomass presence is also positively correlated with higher chlorophyll-a and stratification indicators that supported phytoplankton aggregation.

Interannual variation in productivity strongly modulates habitat availability and quality. During El Niño years, although catches may increase due to the jack mackerel’s movement towards coastal waters , spatial habitat contractions due to productivity collapse and vertical habitat compression have been documented (A. Bertrand et al., 2020). These fluctuations affect recruitment success and potentially increase larval mortality by displacing spawning activity to suboptimal areas.

2.1.2. Anticipated Climate-Induced Changes in the South Pacific

Regional Warming Trends

According to IPCC AR6 Working Group I (2021), SSTs in the eastern South Pacific are projected to increase by 1.5–2.5°C by the late 21st century under intermediate (SSP2-4.5) to high (SSP5-8.5) emission scenarios. While certain transient or localized conditions (e.g., warm Pacific Decadal Oscillation phases) may improve habitat quality in specific areas, the broader climate-induced trends suggest increasing risks and potential declines in habitat suitability, productivity, and spatial stability. These temperature increases are expected to exceed the upper threshold of jack mackerel's preferred thermal envelope in many northern parts of its current range. This will likely cause poleward and offshore displacement of both feeding and spawning areas, particularly from traditional habitats off central and northern Chile (IPCC, 2021a; Lang Abarzúa, 2021).

Jack mackerel range shifts during historical El Niño events have been observed, suggesting that climate-driven warming will mirror and intensify these temporary displacements. The retreat of spawning into cooler southern waters may pose management challenges, particularly as spawning habitats become more spatially dynamic and less predictable (Arnaud Bertrand et al., 2016).

Ocean Deoxygenation

The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC, 2019) identifies eastern boundary current systems such as the Humboldt Current as particularly vulnerable to deoxygenation. Continued OMZ shoaling will restrict the vertical habitat of jack mackerel and may further sever migratory connectivity between regional stocks (Arnaud Bertrand et al., 2016; IPCC, 2019a).As the oxycline becomes shallower, the species' habitable vertical range will be compressed closer to the surface, potentially exacerbating vulnerability to surface fisheries and predation. This physical constraint is particularly concerning for the sustainability of the fishery, as shallow OMZs are already characteristic of the core distribution range. Habitat compression may increase spatial overlap with industrial fleets, raising ecological and management pressures.

Declining Productivity and Food Availability

Global and regional projections indicate a decline in net primary productivity in the South Pacific due to enhanced stratification and weakened nutrient upwelling. In combination with warming and deoxygenation, reduced productivity will decrease prey availability, particularly in nearshore nursery and spawning habitats. Productivity is among the most important variables explaining the spatial distribution of jack mackerel. Decreases in chlorophyll-a during El Niño events led to reduced spawning success and compressed habitat suitability zones. Such outcomes are likely to become more frequent and prolonged under climate change, undermining recruitment success and long-term stock resilience.

2.1.3. Implications for Fisheries and Governance

The projected habitat shifts for Chilean jack mackerel have critical implications for regional fisheries management (Yáñez et al., 2017). As SSTs rise and oxygen and productivity conditions change, jack mackerel are likely to migrate southward and offshore, redistributing biomass from national waters (Exclusive Economic Zones, or EEZs) into shared or contested zones, including the high seas and neighboring EEZs.

Southward displacement of the population would increasingly move the stock from being largely within the EEZ of Chile into areas overlapping with the EEZs of southern Chile, Argentina, and potentially New Zealand, depending on interannual variability. The high seas west of Chile, already fished by distant-water fleets (e.g., China, Korea), will become even more ecologically important if productivity zones shift offshore. The increased presence of the stock in the high seas or boundary regions of EEZs will raise concerns regarding access, quota allocations, and monitoring responsibilities (Z. Feng et al., 2022; Ramos et al., 2022). This shift means jack mackerel will function increasingly as a straddling stock under Article 63 of UNCLOS, with implications for enforcement and data sharing. Changes in spatial availability may also intensify competition among coastal and distant-water nations and increase pressure to adopt dynamic, spatially explicit management mechanisms. Management reforms that incorporate seasonal climate forecasts, habitat modeling outputs, and flexibility in quota setting based on environmental variability might be necessary in the near future.

Conclusion

Chilean jack mackerel exhibit clear and multi-dimensional vulnerability to climate change in the South Pacific. Rising SST, shoaling oxygen minimum zones, and declining productivity collectively threaten the species' habitat suitability, reproductive capacity, and population structure. Observed responses during ENSO events, such as habitat contraction, spawning failure, and altered migratory behavior, offer insight into likely future impacts under long-term climate change. Management responses under SPRFMO and national frameworks would benefit from anticipating these changes. Flexible, spatially responsive, and ecosystem-informed approaches will be necessary to maintain fishery sustainability and regional cooperation in the face of environmental uncertainty.

*Table 2: Non exhaustive list of studies regarding habitat suitability and spatial distribution including environmental variables for jack mackerel (*Trachurus murphyi*)*

Author	Method	Region	DOI
Li et al., 2016	Habitat Suitability Index	Southeast Pacific	http://dx.doi.org/10.1016/j.fishres.2015.11.012
Lang Abarzúa, 2021	Maximum Entropy Modeling SDM	Southeast Pacific	https://doi.org/10.14288/1.0398724
Bertrand et al., 2016	3-D Habitat suitability model	Southeast Pacific	http://dx.doi.org/10.1016/j.pocean.2016.07.002
Feng et al., 2025	Habitat Suitability Index model	Southeast Pacific	https://doi.org/10.1007/s00343-024-4115-8
Feng et al., 2022	Habitat Suitability Index model	Southeast Pacific	https://doi.org/10.1016/j.jmarsys.2022.103758
Ramos et al., 2022	Climate Vulnerability Assessment	Northern Humboldt system	https://doi.org/10.1038/s41598-022-08818-5
Yañez et al., 2017	Artificial neural network model	Chilean coast	https://doi.org/10.1002/9781119154051.ch10
Feng et al., 2021	Habitat Suitability Index model	Southeast Pacific	https://doi.org/10.12264/JFSC2020-0533

2.2. Jumbo Flying Squid (*Dosidicus gigas*)

The jumbo flying squid (*Dosidicus gigas*) is a large, fast-growing, and short-lived cephalopod species that occupies a key ecological and economic role in the Southeast Pacific. The jumbo squid fishery spans the entire Eastern Pacific Ocean and represents the largest invertebrate fishery in the world by volume. In recent years, annual landings have exceeded one million tonnes. The species exhibits a broad geographic range, occurring from approximately 45°N to 45°S along the continental slope and extending into oceanic waters of the southeast Pacific as far west as 140°W. Vertically, *D. gigas* inhabits depths from the ocean surface down to 1200 meters (CALAMASUR, 2023).

2.2.1. Environmental Preferences and Habitat Characteristics

Temperature Sensitivity

Seasonally optimal SST ranges for *D. gigas* in the South Pacific vary between approximately 17°C and 23.0°C, depending on region and season (Yu and Chen, 2018). The species demonstrates a strong thermal preference, with maximum catch rates closely associated with these temperature bands. In years marked by strong El Niño events, such as 2015, the warming of surface waters leads to a decline in habitat suitability, as areas previously within the optimal SST range become too warm for favorable squid aggregation and feeding (Jin et al., 2024).

D. gigas has been shown to be particularly vulnerable to climate-induced habitat shifts (Z. Feng et al., 2022), with large redistributions under PDO oscillations. Projection studies simulating temperature increases have shown that both suitable and optimal habitat areas off Peru can shrink up to 50% in worst case scenarios (Figure 6), with the center of gravity of suitable habitat shifting southward by as much as 14° latitude (Yu & Chen, 2018). These results strongly indicate that climate-induced warming will cause both habitat contraction and geographic redistribution of squid populations within the region.

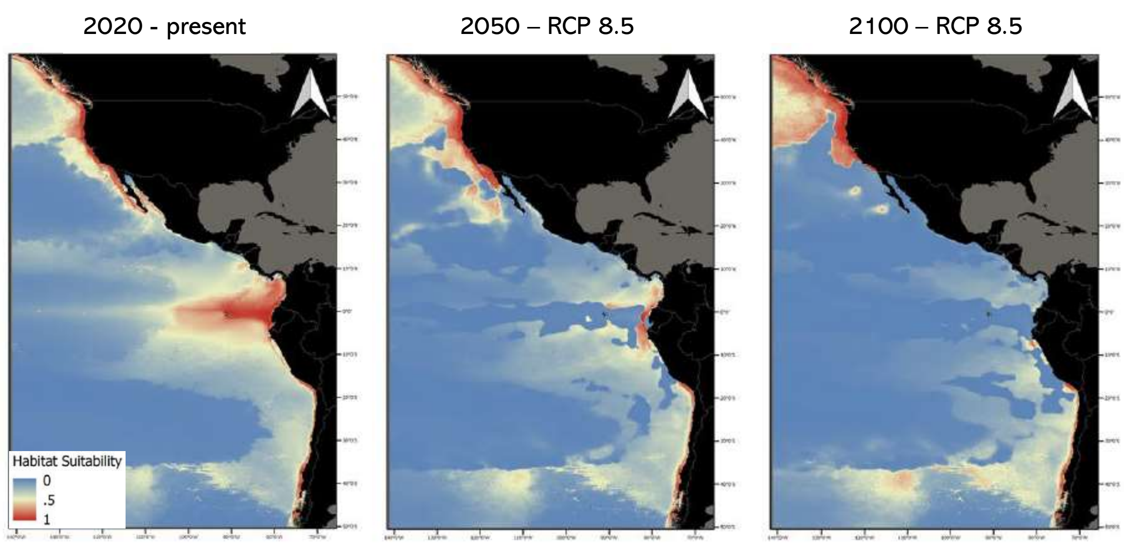

Figure 6: Map of the distribution of Dosidicus gigas in the Eastern South Pacific at the present (year 2020), year 2050 representative concentration pathways (RCP) 8.5 and year 2100 RCP 8.5.
Source: Yu et al., 2016

Oceanographic Drivers

The availability of suitable habitat is tightly coupled with moderate chlorophyll-a concentrations, an indicator of primary productivity, as well as temperature conditions at the surface and at depth (Jin et al., 2024). During El Niño years, the weakening of coastal upwelling reduces nutrient supply and primary production, leading to reduced food availability and habitat quality for *D. gigas*. In both 2015 and 2016, these conditions resulted in substantial declines in fishing effort and catch per unit effort (CPUE) across Peruvian waters (Yu et al., 2016).

Importantly, mesoscale oceanographic features such as anticyclonic eddies can act as temporary habitat refugia for squid, as they aggregate nutrients and plankton, supporting higher productivity. However, these features themselves are vulnerable to climate anomalies. In El Niño years, both the frequency and intensity of such eddies decline, compounding the habitat degradation for squid (Jin et al., 2024).

2.2.2. Climate-Induced Range Shifts

Poleward and Offshore Expansion

As SST increases and productivity declines near the equator, *D. gigas* is expected to shift poleward and into offshore waters, a pattern already observed during historical warming events and confirmed through habitat suitability modeling and species distribution models (Guerreiro et al., 2023; Xie et al., 2025). In model scenarios based on SST projections of +1°C to +4°C, the optimal habitat for jumbo flying squid off Peru moved from ~21°S to as far south as 35°S, encroaching upon southern Chilean waters and parts of the high seas (Yu & Chen, 2018).

This shift is not only latitudinal but also longitudinal. Deep learning models show that high CPUE values are increasingly located further west of the Peruvian EEZ, especially during warm season. Such redistributions elevate the importance of dynamic management approaches that can track shifting biomass beyond national boundaries.

Ecosystem and Fisheries Implications

Given its role as both predator and prey in the pelagic food web, shifts in *D. gigas* distribution could have cascading ecological effects. The displacement of squid from traditional Peruvian coastal zones may affect both dependent predators (e.g., tuna, seabirds) and artisanal fishing communities reliant on seasonal squid aggregations. On the high seas, increasing squid abundance may benefit distant-water fleets from countries, but could also lead to an increase in overlapping fishing ares and restrictive quota allocations, particularly if the squid become less accessible to traditional coastal states (CALAMASUR, 2023). These trends underscore the species' increasing role as a climate-sensitive, transboundary resource, with governance implications for SPRFMO and adjacent EEZs.

2.2.3. Management Considerations and SPRFMO Governance

Spatial Governance Challenges

As *D. gigas* becomes more prevalent in areas beyond national jurisdictions, it increasingly functions as a straddling stock. Current SPRFMO stock assessments rely heavily on high seas fishery-dependent data from Chinese vessels and often exclude EEZ fisheries data from Peru and Chile. This leads to spatial bias and underrepresentation of biologically important areas such as spawning and nursery zones. Real-time environmental data and habitat modeling tools could support dynamic effort allocation, rather than static quotas. Adaptive strategies will be critical as climate change increases the variability of squid abundance and habitat quality (Xie et al., 2025; Yu et al., 2025).

IPCC Climate Projections and Implications

The IPCC AR6 (2021) projects sustained SST warming, enhanced stratification, and deoxygenation in the Humboldt Current system. These changes align with model outcomes from, which show reduced habitat suitability and biomass under warming conditions. The Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) also notes likely declines in primary production in eastern boundary current systems, further reinforcing the outlook for habitat loss in the core range of *D. gigas*. Taken together, these projections suggest that *D. gigas* will increasingly occupy a smaller, shifting, and less predictable range, raising pressure on coastal and international management systems.

Conclusion

Jumbo flying squid in the South Pacific display a high degree of environmental sensitivity, particularly to SST, productivity, and mesoscale features like eddies. The evidence from multiple empirical and modeling studies shows that climate change is already reshaping their distribution, with clear patterns of southward and offshore movement during anomalously warm periods. Habitat suitability is expected to decline in core regions off Peru, with increased reliance on southern and high seas areas for future spawning and feeding grounds. *D. gigas* prefers cool, oxygen-rich, and moderately productive waters, with seasonal migratory behavior closely linked to sea surface temperature (SST), chlorophyll-a concentrations, oxygen levels, and mesoscale features such as eddies (Xie et al., 2025; Yu et al., 2025). As a semelparous species with a lifespan of about one year, its distribution and abundance are highly responsive to environmental variability, making it particularly vulnerable to climate change (CALAMASUR, 2023; Yu et al., 2016)

These findings carry substantial implications for ecosystem dynamics, food webs, and fisheries governance. The squid's increasing mobility across EEZ boundaries and into high seas jurisdictions will need cooperative, flexible, and ecosystem-informed management frameworks. Real-time habitat modeling and integrated datasets across

EEZs and high seas will be essential to managing *D. gigas* sustainably in a rapidly changing ocean.

*Table 3: Non exhaustive list of studies regarding habitat suitability and spatial distribution including environmental variables for jumbo flying squid (*Dosidicus gigas*)*

Author	**Method**	**Region**	**DOI**
Feng et al., 2022	Habitat Suitability Index model	Southeast Pacific	https://doi.org/10.1016/j.jmarsys.2022.103758
Ramos et al., 2022	Climate Vulnerability Assessment	Northern Humboldt system	https://doi.org/10.1038/s41598-022-08818-5
Xie et al., 2025	Neural Network Species Distribution Models	Southeast Pacific	https://doi.org/10.3390/fishes10060273
Yu et al., 2016	Habitat Suitability Index	Southeast Pacific	https://doi.org/10.1093/icesjms/fsv223
Fernandes Guerreiro et al., 2023	Species Distribution Model	Global	https://doi.org/10.1007/s00227-023-04261-w
Yu et al., 2025	Literature Review	Southeast Pacific	https://doi.org/10.1007/s11160-025-09929-8
Yu et al., 2018	Habitat Suitability Index	Southeast Pacific	https://doi.org/10.1016/j.fishres.2018.02.016
Jin et al., 2024	Habitat Suitability Index model	Southeast Pacific	https://doi.org/10.34133/ehs.0177
Feng et al., 2021	Habitat Suitability Index model	Southeast Pacific	https://doi.org /10.12264/JFSC2020-0533

2.3. Orange Roughy (*Hoplostethus atlanticus*)

Orange roughy (*Hoplostethus atlanticus*) is a deep-sea fish species found along continental slopes and seamounts at depths typically ranging from 700 to 1,500 meters, with habitat preferences tightly linked to cold, stable temperatures around 3–4 °C and complex benthic structures such as those found on the Louisville Ridge and Chatham Rise. In the South Pacific, orange roughy supports important fisheries managed under the South Pacific Regional Fisheries Management Organisation (SPRFMO), especially in areas beyond national jurisdiction. The species exhibits life-history traits that make it particularly sensitive to environmental and anthropogenic pressures, including extreme longevity (up to 130 years), late maturity (30+ years), low fecundity, and a reliance on spatially and temporally limited spawning aggregations (Brooks, 2020; Dunn & Devine, 2010; Edwards et al., 2022).

2.3.1. Environmental Preferences and Range Shifts

Orange roughy's vulnerability to climate change is strongly tied to its specialized habitat requirements. Depletion dynamics models show that the species' biomass and productivity are tightly associated with depth and latitude, and that small changes in environmental variables can drastically alter local carrying capacities (Edwards et al., 2022). This suggests a high sensitivity to bottom-water temperature increases, which are projected to occur in the South Pacific under high-emission climate scenarios (IPCC, 2023). Species distribution models using Maxent have predicted a contraction in suitable habitat under RCP 8.5 by 2100, particularly on the Chatham Rise, with increased uncertainty in northern ranges due to novel climatic conditions. These models suggest that orange roughy may face significant habitat loss in core fishing areas and limited opportunity to shift poleward due to physiological constraints and deep-sea topographic barriers (Brooks, 2020).

Moreover, joint species distribution models applied to benthic invertebrate communities in similar regions reveal that taxa dependent on stable, cold environments tend to show lower predicted abundance under changing conditions, a pattern likely relevant for orange roughy given its deep-sea associations and trophic linkages to those communities. While some models tested potential correlations between habitat-forming corals and orange roughy, results showed limited direct association, reinforcing the species' broad but environmentally constrained habitat preference (Jarvis-Child, 2024)

2.3.2. Impact on Management and Fisheries

Given orange roughy's limited ability to shift range due to depth and life-history constraints, populations may experience severe stress or collapse as bottom temperatures rise and oxygen declines. These vulnerabilities highlight the urgency for SPRFMO to incorporate climate change considerations into orange roughy stock assessments and management strategies to safeguard its long-term persistence (Cummings et al., 2021).

Furthermore, potential range shifts, even if minimal due to its life-history constraints, may lead to redistribution of biomass across jurisdictional boundaries, raising challenges for quota allocations and international fisheries governance. This possibility is underscored by broader ecological niche models, which predict significant range instability for similar deep-sea species under future emissions pathways (Brooks, 2020). Adaptive, ecosystem-based management will be necessary to reconcile changing spatial distributions with current regulatory frameworks.

Conclusion

Orange roughy in the South Pacific exhibits high vulnerability to climate change due to its deep-sea specialization, narrow thermal tolerance, and spatially fragmented stock structure. Climate projections indicate a likely contraction of suitable habitat, especially under high-emissions scenarios, with potential declines in productivity and biomass in key SPRFMO-managed areas. Given the species' ecological and economic importance, the current management framework would benefit from integrating environmental forecasting and spatially resolved modeling to remain effective. This will involve combining species distribution modeling tools, environmental covariates, and adaptive governance mechanisms to mitigate risk and ensure the long-term viability of orange roughy fisheries in a changing ocean.

2.4. Modeling species distribution and habitat

Most habitat modeling studies on jack mackerel (*Trachurus murphyi*), jumbo flying squid (*Dosidicus gigas*), and orange roughy (*Hoplostethus atlanticus*) in the South Pacific are based on Habitat Suitability Index (HSI) approaches, with far fewer studies employing Species Distribution Models (SDMs). This reliance on HSI models, while useful for visualizing habitat preferences and generally complementary to SDM, can be limiting, as they often lack formal uncertainty quantification, are not easily validated, and may perform poorly under novel climate conditions. In contrast, data-driven SDMs offer a statistically robust framework to assess climate sensitivity, quantify prediction confidence, and simulate dynamic range shifts, tools that are essential for adaptive, climate-resilient fisheries management. Expanding the use of SDMs and integrating them with mechanistic models would significantly enhance the predictive power and utility of habitat modeling in the region.

Currently, no SDMs of deep-sea fishes have been developed in the New Zealand region that explore the effect of reef-forming coral on those fishes. However, it is worth recognising research that has employed SDMs in a marine context. With respect to inference, the simplest example of a parametric SDM is a linear model (Mac Nally, 2000). In ecology, however, a generalised linear model (GLM) is commonly used since the dependent variable (e.g., encounter/non-encounter or abundance) is often non-normally distributed. For example, GLMs were utilised by Francis (2001) and Coburn et al. (2002) to 10 standardise orange roughy catch-per-unit-effort (CPUE) on the Chatham Rise and CPUE for New Zealand black oreo. GLMs for CPUE standardisation employ the same principles as more classical forms of SDMs (Hoyle et al., 2024). However, GLMs for CPUE standardisation often do not consider environmental effects on fish density and instead usually focus on covariates that influence fish catchability (e.g., net size, trawl duration).

Consequences for transboundary fish stocks

Climate-driven shifts in transboundary fish stocks are accelerating and have direct implications for SPRFMO and the management of key species such as jack mackerel, jumbo flying squid, and orange roughy. By 2030, 23% of transboundary stocks will have shifted distribution, and 85% of the world's EEZs will experience significant changes in catch proportions, averaging a 59% deviation from historical norms (Prasanta, 2022). By 2100, 45% of these stocks are projected to shift, impacting 81% of EEZs globally (Prasanta, 2022). These species, categorized as transboundary or straddling stocks, are particularly sensitive to EEZ–high seas transitions. In the South Pacific, they face a high risk of governance failure if shifting distributions are not reflected in stock assessments and quota allocations (Vogel et al., 2023; Pinsky et al., 2018).

Jack mackerel and jumbo flying squid are already managed under relatively static frameworks like SS3, which do not account for climate-driven range shifts. Orange roughy, with its deepwater distribution, is especially sensitive to changes in temperature and oxygen, emphasizing the need for dynamic, habitat-linked models. Yet most current assessments for these species rely on HSI models that lack spatial and climate responsiveness. Integrating climate-ready Species Distribution Models (SDMs) could improve predictive power and management robustness, especially when combined with adaptive allocation mechanisms and scenario planning (Vogel et al., 2023; Pinsky et al., 2018). Without such reforms, SPRFMO risks mismanaging shifting stocks, exacerbating inequities between members, and potentially triggering disputes similar to the Atlantic mackerel conflict (Pinsky et al., 2018). Proactively incorporating climate-linked stock assessments, equitable benefit-sharing frameworks, and regional cooperation is essential to safeguard long-term sustainability and avoid governance breakdowns in the region (Prasanta, 2022; Vogel et al., 2023).

*Table 4: Table 5: Non exhaustive list of studies regarding habitat suitability and spatial distribution including environmental variables for orange roughy (*Hoplostethus atlanticus*)*

Author	Method	Region	DOI
Edwards et al., 2021	Depletion dynamics model	South Pacific	https://doi.org/10.1139/cjfas-2020-0265
Sweetman et al., 2017	Expert opinion	Climate impact overview	https://doi.org/10.1525/elementa.203
Brooks, 2021	Ecological Niche Modeling (SDM)	New Zealand EEZ	https://doi.org/10.26686/wgtn.17142788.v1
Cheung, 2019	Exposure, Vulnerability and Risk of impact analysis	Vulnerability assessment	Check references
Cummings et al., 2021	Climate change impacts assessment	New Zealand EEZ	Check references
Dunn et al., 2010	Holistic stock structure assessment	Chatham Rise	Check references
Jarvis-Child, 2024	VAST Model	New Zealand EEZ	https://doi.org/10.26686/wgtn.26043319

3. Identifying socio-economic impacts of climate-induced changes in fisheries

Fisheries operate at the intersection of ecology, economy, and society, making them linked social-ecological systems (SES). Sustainable management requires understanding not only fish biology and stock status, but also fishers' behavior, their adaptive capacity, markets, community reliance, and governance structures. Neglecting the socio-economic dimensions may yield stock assessments that are biologically sound yet misaligned with human realities (Norman-López et al., 2013).

Assessing the capacity of a fishery to adapt to, or even benefit from, change is important to target the aspects that may be problematic in a crisis context, in addition to planning an adaptation strategy that plays to the strengths of each fishery. The term vulnerability can have different meanings, whether it is addressed in resilience frameworks, vulnerability assessments or community-based approaches, among others. Depending on the ecosystem, scale, perturbation or perspective, it can have extremely broad implications. Therefore, measuring it involves an equally wide range of tools and frameworks (Bukvic et al., 2020).

One of the most widely recognized and robust frameworks for assessing climate-related impacts is the IPCC AR5 Climate Risk Assessment. This framework is notable for its flexibility, having been applied across a wide range of spatial scales—including continental-level assessments. Centered on a risk-based approach, it clearly distinguishes between the physical events (hazards) and the socio-ecological services they may affect, allowing for a more targeted analysis. Risk is conceptualized as the interaction of three key components: Hazard (the potentially damaging physical events), Exposure (the elements at risk), and Vulnerability (the sensitivity and adaptive capacity of those elements). This structure makes the IPCC framework particularly suitable for comprehensive, scalable climate impact assessments (IPCC, 2014).

3.1. Vulnerabilities and adaptive capacity of fisheries

This risk is not evenly distributed. Some SPRFMO members, such as Peru, Chile, Ecuador, and the Cook Islands, rely heavily on small pelagic fisheries that are particularly sensitive to environmental fluctuations like ENSO cycles. Others, like New Zealand or the United States, have stronger governance and diversified fleets, which increases their ability to adapt. These differences reflect what Cinner et al. identify as key domains of adaptive capacity: access to assets (e.g. financial capital, technology), institutional flexibility, collective action, learning, and agency (i.e. the power to make decisions).

Countries with higher adaptive capacity, often wealthier nations with robust institutions, may be better able to absorb ecological shocks or shift fishing practices in response to changing stocks. In contrast, more vulnerable countries with limited resources and governance capacity may face substantial socio-economic disruptions. As observed in the Mediterranean, even countries with lower ecological hazard scores (i.e. targeting less climate-sensitive species) may end up with higher overall risk due to socio-economic exposure and weak institutional responses. In the SPRFMO context, this means that effective adaptation requires more than just biological stock forecasting. It also calls for investment in social resilience, such as diversifying livelihoods, improving fisheries management literacy, and enhancing institutional agility. Countries with low HDI, limited fisheries subsidies, or poor access to management tools, may be especially at risk unless supported by regional adaptation strategies

3.2. Identifying socio-economic parameters

Selecting relevant socio-economic parameters to assess fisheries' exposure and vulnerability to climate change, particularly in an international context such as the SPRFMO convention area, is both critical and challenging. The key is balancing methodological simplicity with sufficient granularity to reflect meaningful differences between countries and fleets.

A practical and replicable approach is to use standardized indicators that are readily accessible and internationally comparable as did (Payne et al., 2021) in the context of European Union (Figure 7):

- **Exposure:** diversity of catch through diversity indexes of catch composition (Shannon, Simpson). Fleets or coastal regions have lower exposure (higher resilience) if they catch a wide range of different fish species, rather than concentrating on a specific resource.
- **Vulnerability:** the resilience of the region and its ability to mitigate the hazard via adaptation. The metric was based on the gross-domestic product per capita of the region. This approach has the advantage of being possible to do at the scale of the fleet (through net profit margin instead of GDP), simple and with information accessible for most countries.

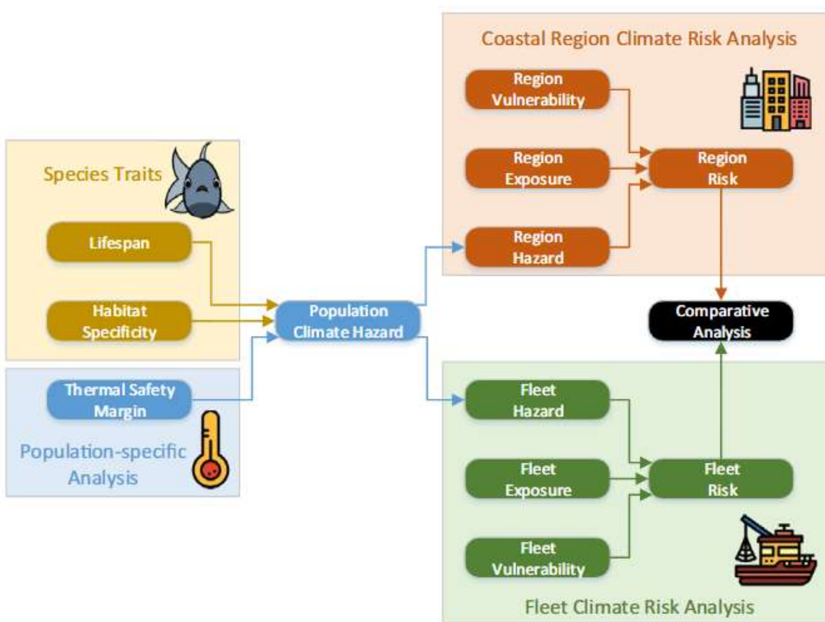

Figure 7: Schematic diagram illustrating the approach used by Payne et al., 2021, to estimate climate risk in European fishery-dependent coastal regions and fishing fleets integrating socioeconomic factors. Species traits and population specific analyses of the Thermal Safety Margin are combined to give a population-specific climate hazard. This hazard then forms the basis for the region- and fleet-level CRAs, based on the combination of hazard, exposure, and vulnerability.

To explore socio-economic parameters in greater depth, macro-indicators of fisheries dependence and adaptive capacity can be used as done in (Pita et al., 2021), made possible by the extensive datasets provided by organisations such as FishStat, FAO, ILO, WorldBank and HDR and others. These indicators help assess both exposure, through economic and nutritional reliance on fisheries, and vulnerability, understood as the system's resilience and adaptive capacity (Figure 8):

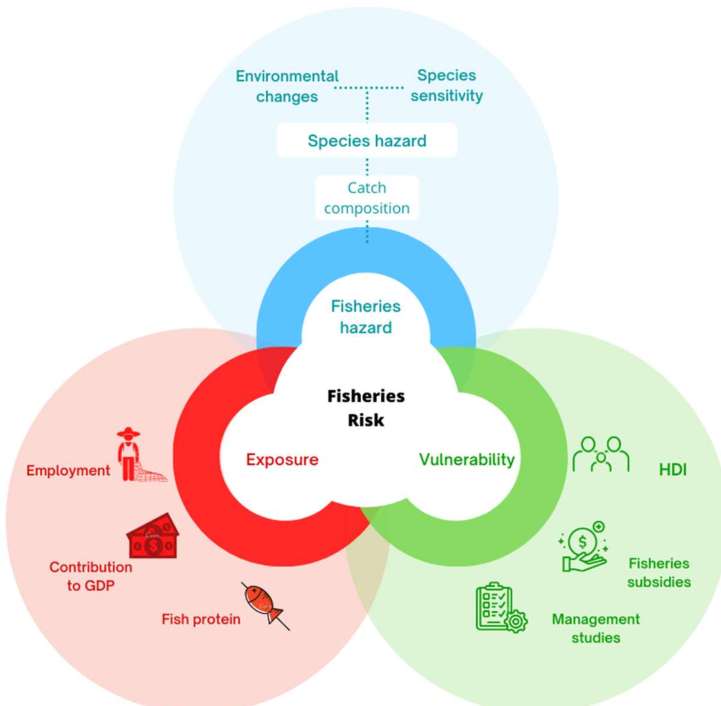

Figure 8: Conceptual schematic drawing of the CRA framework applied by Pita et al., 2021, including socio-economic parameters to a climate change fisheries risk assessment. First, fisheries hazard was determined through species hazard due to climate change. Second, fisheries risk was obtained based on hazard, exposure and vulnerability.

- **Employment Dependence**: The *percentage of national labor force in fisheries* can be calculated using FishStat data on the number of fishers per country (FAO, 2025c) and ILO figures on total workforce (ILO, 2025). High percentages suggest greater socio-economic exposure.
- **Nutritional Dependence**: The *percentage of fish protein in national dietary intake* reflects nutritional reliance on fisheries. This metric, accessible through FAO nutrition databases, signals vulnerability in the face of declining fish availability (FAO, 2025b).
- **Economic Dependence**: While the *contribution of fisheries to GDP* is not directly reported, it can be estimated using FishStatJ fisheries production values (FAO, 2025a) relative to national GDP figures from the World Bank DataBank(WBG, 2025).

- **Human Development Index (HDI)** can offer a robust and multi-dimensional proxy. It encapsulates health, education, and income, three key enablers of institutional and individual resilience (UNDP, 2025). This indicator can be very useful to assess adaptation, as it encompasses several domains of adaptive capacity. Countries with higher HDI are generally more capable of mobilizing resources, engaging in proactive planning, and fostering innovation.

Other elements of vulnerability, such as governance robustness and institutional flexibility, are harder to quantify. In the absence of direct metrics, proxies like the scale of fisheries subsidies, presence of fisheries risk assessments, and policy responsiveness may provide insight, though these require qualitative interpretation or further data collection.

3.3. Accounting for socio-economic impacts of climate change

Socio-economic parameters are essential to Climate Change projections to ensure they are not only ecologically sound but also socially and economically relevant. In the SPRFMO context, where member countries differ significantly in governance capacity, fleet structure, and fisheries dependence, such integration becomes even more critical. Macro-indicators, such as employment in fisheries, nutritional dependence, and fisheries' contribution to GDP, offer a practical and standardized means to capture economic exposure and vulnerability. However, capturing social resilience and adaptive capacity remains a challenge. Local customs, cultural attachment to fishing, and the flexibility of fishers to shift practices are deeply context-specific and difficult to quantify at an international scale. Moreover, disparities in data availability between countries introduce potential biases that must be recognized and mitigated. Nevertheless, the incorporation of multidisciplinary approaches will be essential for resilient and adaptive fisheries in the face of climate change.

As an international organisation, SPRFMO is uniquely positioned to coordinate collaborative Climate Risk Assessments by leveraging the collective data and expertise of its member countries. While individual nations hold the most detailed and context-specific socio-economic data, SPRFMO can provide the structure and standardization necessary to harmonize this information across the region. This is particularly valuable given the disparities between members. A coordinated assessment would not only enable a more accurate understanding of regional risks but also help identify specific gaps and priority areas for support. By pooling knowledge and resources, SPRFMO can facilitate targeted adaptation strategies, and guide capacity-building efforts where they are most needed in the coming years

4. Integrating climate trends and environmental variability into fisheries stock assessment and management advice

Integrating climate change into SPRFMO's fisheries management is essential given the region's unique vulnerability to Pacific climate oscillations, including ENSO events (El Niño/La Niña), the Pacific Decadal Oscillation (PDO), and dynamic ocean currents like the South Pacific Convergence Zone. The SPRFMO Commission's Decision 13-2023 has elevated climate change to a permanent agenda item for the Scientific Committee and calls for urgent revision of existing Conservation and Management Measures (CMMs), harvest strategies, and data collection to account for the projected impacts of warming, acidification, and ecosystem shifts in the Convention Area (SPRFMO, 2024).

Integrating climate change into fisheries management is therefore a critical challenge, and steps on how to do it are beginning to be clear, whether it is through multidisciplinary actions, improved data gathering and impact knowledge, or directly integrated in stock assessments.

4.1. Climate Change through stock assessments

This report has shown that environmental and climate factors are expected to influence the dynamics of fished populations, affecting the ability to achieve both conservation and harvest objectives. Despite this, very few stock assessments currently used to set harvest allocations, including those for SPRFMO-assessed species, account for environmental effects or link changes in population parameters over time to environmental variables. As a result, there is growing interest among managers and stakeholders in methods that can quantify how environmental change may affect the outcomes of applying current or alternative harvest control rules, particularly in terms of stock status and catch levels. An increasing number of studies aim to meet this need by providing climate-informed advice. Generally, there are two ways to respond: one is to develop "climate-aware" harvest control rules that adjust target exploitation rates or reference points based on environmental conditions (Collie et al., 2021; Wildermuth et al., 2023). The other is to continue using conventional harvest control rules but base management advice on projections from climate-enhanced stock assessments, which are informed by Earth System Models and account for potential long-term trends in biological and fishery parameters driven by environmental change (Punt et al., 2024).

4.1.1. Climate enhanced stock assessments

Integrating climate change can be done directly at the modeling level for stock assessments. It is possible to account for climate scenarios through Earth System

Models and climate models presented by CMIP6 and ISIMIP as shown in the first part of the report. As environmental variables are linked to the species' life-history traits, their projections can be used to model environmental effects on population dynamics. Although they are few, this is already being done in some stock assessments such as the CEATTLE multi-species stock assessment that merges environmental effects into both growth and trophic interactions (Holsman et al., 2022). Another example is the peruvian anchoveta (*Engraulis ringens*) stock assessment led by IMARPE (IMARPE, 2020). In this case, the stock assessment is based on environmental scenarios that drive growth and mortality parameters based on the likelihood of oceanographic anomalies. The objective is to be able to adapt quickly to ENSO events that can have drastic implications on the Anchoveta's habitat, and by consequence its fisheries.

A proposed best-practice framework for climate-enhanced stock assessments is detailed in (Punt et al., 2024), following a structured, modular approach for integrating climate change into stock projections without needing to alter formal harvest control rules (HCRs). The objective of this method is to:

- Link environmental variables to life-history traits (recruitment and growth)
- Project these under climate scenarios
- Quantify model, process and parameter uncertainty

With this framework, changes to formal HCRs are not required and still allows for climate informed management advice making it more flexible and actionable under existing governance systems.

4.1.2. Climate integration through Harvest Control Rules

Harvest Control Rules (HCRs) are pre-agreed guidelines used in fisheries management to help decide how much fishing is allowed based on the status of the fish stock following the stock assessment. The management of SPRFMO fisheries is guided by agreed-upon harvest control rules, reference points, fishery assessment procedures, and risk criteria. These measures, designed to support the long-term sustainability of the fishery, depend on a solid understanding of the population dynamics of both target and associated species, as well as the biological processes that influence those dynamics. Harvest control rules (HCRs) can be misleading if they fail to account for environmental changes that affect fish population dynamics. These rules are typically based on historical data and assumptions about stock productivity, growth, and recruitment under relatively stable conditions. However, shifts in ocean temperature, currents, oxygen levels, and ecosystem structure, driven by climate change or other environmental factors, can alter the productivity and distribution of fish stocks.

Studies have shown that relatively simple ways of integrating environmental drivers into HCRs can drastically improve their performance over future horizons. The parameter that plays a main role in this is productivity, which can be strongly influenced by environmental drivers, in particular sea surface temperatures. One example is the U.S. Pacific sardine fishery that has been managed with harvest levels determined with respect to the sea surface temperature (SST) in the southern portion of the California Current ecosystem for over two decades (PFMC, 1998). Pacific sardine productivity is strongly influenced by SST and Current HCRs explicitly link biomass thresholds to temperature indices, making it one of the few “climate-aware” HCRs in use. A study by (Wildermuth et al., 2023), focused on this particular stock, evaluated alternative climate-driven HCRs to highlight what methods were the most robust and reliable.

In addition, If we understand the underlying processes where climate change affects productivity, (Collie et al., 2021) argues that fisheries can be managed effectively without relying on climate forecast and predictions. Per-capita recruitment (termed “productivity”) is the most important variable influencing reference points and stock status, more so than growth or maturity. What is needed is frequent updating of stock assessments and use of adaptive HCRs that respond to observed changes in productivity and biomass. Climate-aware fisheries management is feasible now, using existing data and tools.

4.2. Perspectives for fisheries management

In addition to climate-enhanced stock assessments and harvest control rules, integrating climate change into fisheries management also requires strengthening the governance, social, and systemic aspects of fisheries systems. These are critical for enabling adaptive and inclusive responses to climate-driven changes in marine ecosystems. These topics were recently discussed at a workshop during the One Ocean Science Congress 2025 in Nice where the following themes were highlighted:

1) Support long-term engagement:

Integration of climate science into fisheries requires ongoing collaboration with managers to build trust, capacity, and institutional memory. Long-term engagement helps identify what tools and strategies are effective in practice and which are not, ensuring lessons learned are translated into policy. Adaptive co-management systems, those that evolve through learning, are better suited to respond to nonlinear, climate-driven ecological shifts.

2) Promote international cooperation for transboundary and migratory stocks:

Climate change is causing distributional shifts in fish stocks, many of which cross EEZ boundaries or span international waters. SPRFMO’s convention area includes several transboundary species whose spatial dynamics are sensitive to ENSO and PDO variability. Shared stock agreements and coordinated monitoring are essential to prevent overexploitation and promote equitable resource sharing under shifting baselines. In addition, international cooperation ensures that we have the most reliable and complete data available. Effective management in this context depends on shared surveillance systems, synchronized quota-setting processes, and transparent data exchange among coastal states and distant-water fishing nations. Climate-resilient management requires explicit recognition that transboundary species must be governed collectively.

3) Acknowledge that uncertainty is the primary barrier:

There is a common misconception that fisheries managers are reluctant to adopt new approaches. In reality, what often holds back action is uncertainty about the reliability of forecasts, the validity of model outputs, or the magnitude of future change. Fortunately, progress is constantly being made in this area. Climate and Earth System Models (ESMs) are increasingly aligned, with CMIP6 and ISIMIP platforms providing more consistent and comparable projections. This growing model convergence helps reduce uncertainty and enhances confidence in scenario-based planning. In turn, it enables managers to make precautionary but proactive decisions, such as adapting harvest strategies or initiating temporary closures based on robust climate indicators, even in the absence of perfect foresight.

4) Integrating Socioeconomic Dimensions into Management:

As mentioned earlier, climate change does not act on ecosystems in isolation; it interacts with market forces, governance structures, and social dynamics to shape outcomes. Effective fisheries management must therefore move beyond ecological forecasting to also include socioeconomic variables. While most ecological models are time-based, many social responses to climate change are not driven by time but by thresholds, values, and institutions. Interdisciplinary research can close this gap by modeling social tipping points, institutional flexibility, and equity outcomes. This allows us to identify the most vulnerable regions and communities, understand the sources of risk, and focus our efforts efficiently and effectively. For example, setting restrictive catch quotas to protect a declining stock might unintentionally undermine the adaptive capacity of small-scale fishers who rely on diversified harvest strategies to buffer against shocks. This highlights the need for integrated approaches that examine trade-offs between conservation goals and community well-being. Bioeconomic modeling, participatory governance, and policy instruments that support equitable outcomes all have a role to play in ensuring that adaptation is socially just as well as ecologically sound.

5) Improving monitoring and inclusion of small-scale fisheries:

Small-scale fisheries are vital to food security and livelihoods across the Pacific, yet they remain severely under-monitored and under-represented in data systems. These fisheries are also highly vulnerable to climate change due to their dependence on seasonal resources and limited access to adaptive tools. Strengthening data collection in these sectors, through community-based monitoring, mobile data platforms, and co-managed research initiatives, will help fill critical knowledge gaps and enhance the ability to respond to rapid environmental shifts. Better representation of small-scale fisheries in assessments and management processes is not only a question of equity, but also a prerequisite for climate-resilient governance.

6) Regular review and updating of model parameters:

Stock assessment models are often built on a set of fixed parameters that remain unchanged for many years. In a rapidly changing climate, this can make the models less accurate and responsive to actual trends. A simple but impactful step would be to institute regular (e.g., biennial) reviews of key model parameters considering new environmental data and scientific evidence. This does not require structural changes to models but can significantly improve their alignment with reality. Updating parameters regularly is a low-cost, high-reward strategy that brings greater flexibility to the modeling and decision-making process.

7) MSE with climate scenarios:

Management Strategy Evaluation (MSE) is one of the most powerful tools available to fisheries managers for testing how alternative management strategies perform under uncertainty. In the context of climate change, its value becomes even more critical. By incorporating environmental and climate scenarios into MSE frameworks, managers can simulate how harvest strategies, stock dynamics, and ecosystem responses may unfold under different future conditions such as warming temperatures, changes in primary productivity, or shifts in recruitment patterns due to ENSO or PDO variability. Rather than relying on static assumptions, MSE allows for decision-making embedding climate variability and projections that explicitly test the robustness of HCRs, allocation policies, and spatial closures. This means managers can better anticipate failures, avoid unintended outcomes, and choose policies that remain effective even when future conditions deviate from historical norms. In regions like the SPRFMO Convention Area, where climate variability is high and species are sensitive to oceanographic shifts, MSE with climate scenarios can guide the development of adaptive, precautionary rules that support both sustainability and long-term resilience.

8) Closed areas for climate and fisheries resilience:

As mentioned by the SPRFMO 12th scientific committee (SPRFMO, 2024), Closed areas such as marine protected areas (MPAs), spatial closures, and other area-based management tools can play a vital role in enhancing the resilience of marine ecosystems in the face of climate change. These zones can act as ecological refugia, providing safe havens for vulnerable species and habitats from fishing pressure and other anthropogenic disturbances, allowing populations to recover and adapt to changing environmental conditions. In the high seas, where governance is often fragmented and ecological baselines are shifting, closed areas offer one of the few tools available to slow the global decline in biodiversity and ecosystem function. Well-designed closures can also safeguard habitats with long-term ecological importance, including seamounts, cold-water coral gardens, and 'blue carbon' ecosystems like seagrasses, which contribute to carbon sequestration and climate mitigation. As climate impacts intensify, the strategic placement of protected areas can support connectivity and migration pathways, fostering adaptive capacity in marine populations. Within this context, SPRFMO must be prepared to engage proactively with the emerging governance framework under the UNCLOS Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement). Set to enter into force in late 2025 or early 2026, the BBNJ Agreement mandates the creation of area-based management tools, including high seas MPAs, and outlines a process for environmental impact assessments for activities in areas beyond national jurisdiction.

5. Conclusion

The South Pacific is experiencing rapid and unprecedented oceanographic change, driven by global climate dynamics that are altering the foundation of marine ecosystems. As warming, deoxygenation, acidification, and shifts in ocean circulation reshape the physical environment, these transformations are already cascading through food webs and affecting the distribution, productivity, and behavior of key species. In this context, effective fisheries management under the SPRFMO Convention must evolve to become climate-informed, responsive, and equitable. This report lays out a roadmap to support such a transformation—one that weaves together climate science, species vulnerability, socio-economic resilience, and adaptive management into a coherent strategy.

A critical first step is building a solid understanding of how the ocean is changing and what these changes mean for marine life. Outputs from the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) provide readily available projections of biomass, productivity, and ecosystem structure under different emissions scenarios. These ensemble projections should be used as the scientific foundation for anticipating climate-driven risks across the SPRFMO Convention Area. By integrating these outputs into regional assessments, managers can better predict where and when ecosystem disruptions are likely to occur, enabling early responses rather than reactive crisis management.

Understanding the implications of these changes for managed species, namely jack mackerel, jumbo flying squid, and orange roughy, requires a shift in assessment approaches. Species Distribution Models (SDMs) complemented with Habitat Suitability indexes offer a robust and climate-responsive tool that needs to be encouraged. They allow managers to quantify how key environmental variables such as sea surface temperature, oxygen concentration, and primary productivity influence species ranges, spawning grounds, and migration patterns. Promoting the use of SDMs within SPRFMO will enhance predictive power and ensure that management advice reflects the environmental realities these species face. These models are particularly urgent for highly mobile and climate-sensitive species like jack mackerel and jumbo squid, whose ranges are already shifting into new jurisdictions.

However, species responses do not occur in isolation. They interact with human systems, economies, communities, and institutions that rely on fisheries for income, food security, and identity. As stocks shift and productivity declines, countries with limited governance capacity, low income, or high dependence on fisheries are likely to be hit hardest. Fortunately, socio-economic data from international organisations such as the FAO, ILO, and World Bank are widely available and can be used to assess fisheries dependence and resilience across SPRFMO member states. Integrating these socio-economic dimensions alongside biological data will enable more balanced and just adaptation strategies, those that do not simply protect biomass, but also the people who depend on it.

To turn these insights into policy, environmental change must be directly integrated into stock assessments and decision frameworks. There are two complementary ways to do this. First, climate-enhanced stock assessments can explicitly incorporate environmental drivers into population models, linking, for example, recruitment or growth rates to sea temperature or productivity. This is already being implemented in cases like the Peruvian anchoveta and the CEATTLE multi-species model. Second, existing harvest control rules (HCRs) can be adapted to become environmentally informed, by adjusting exploitation rates based on real-time or seasonal indicators such as SST. Both approaches provide flexible, science-based options for integrating climate uncertainty without requiring complete structural overhauls. Importantly, this enables managers to make informed, adaptive decisions using data and tools that already exist.

This report confirms that climate change is no longer a future threat, it is a present-day reality reshaping the marine environment and the fisheries it supports. SPRFMO is at a critical juncture: adaptation is no longer optional but essential. With coordinated action, inclusive governance, and the integration of the best available science, SPRFMO can transition from a reactive to a proactive institution, one capable of safeguarding both marine ecosystems and the livelihoods they support in a rapidly changing ocean.

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