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Southern Indian Ocean Fisheries Agreement

Accord relatif aux Pêches dans le Sud de l'Océan Indien

Assessment of SIOFA Species and Ecosystems for Vulnerability to Climate Change Impacts

Final Project Report CLI-2025-01

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1. Introduction

Under contract CLI-2025-01, SIOFA commissioned this project to assess species and ecosystems in the Agreement Area for vulnerability to climate change impacts. The four project objectives set out in the Terms of Reference are:

- Identify target species, bycatch species, and ecosystems potentially vulnerable to climate change.
- Collate information on the potential impacts of climate change on SIOFA species and ecosystems, including ocean acidification.
- Develop a process to characterise risk — the probability and magnitude of consequences — under different timescales.
- Assess species and ecosystems against that risk characterisation.

This final report presents the completed deliverables against those objectives. It documents how the project was approached, what was produced, how the annexes relate to one another, and how findings were presented to the Scientific Committee at SC11 (Fremantle, March 2026).

1.1 Climate Change in the Indian Ocean

The point of departure for this project is the oceanographic context. After the Arctic, the Indian Ocean is the fastest warming ocean on Earth. Sea surface temperatures have increased at roughly twice the global mean rate over recent decades, and the pace of change is accelerating. The rate matters: it determines how quickly species and management systems must respond and whether there is time to anticipate those changes before they can no longer be mitigated through fisheries management decisions.

Several consequences follow directly from this warming trajectory. Marine heatwaves in the Indian Ocean are becoming more frequent, more intense, and longer-lasting — events that historically occurred once a decade are approaching near-permanent conditions in parts of the tropical basin. Increased surface warming drives stronger stratification, which limits the upward flux of nutrients into sunlit surface waters, reducing primary and secondary productivity across much of the basin. That reduction propagates through the food web. At the same time, ocean acidification is advancing, and intermediate-depth oxygen minimum zones are expanding, compressing viable habitat for species that cannot simply move up or down the water column. Changes in salinity are producing an increasingly impermeable layer that further limits vertical mixing. And, significantly, the oceanographic regime governing the Indian Ocean basin — its currents, modes, and atmospheric coupling — is changing fundamentally and potentially irrevocably.

For SIOFA specifically, these trends matter because the organisation's species remit is very broad, with significant deepwater and seamount-associated components. These taxa are characterised by slow growth, late maturity, and long generational timescales — life history traits that limit the rate at which populations can respond to change. Many are also data-limited. The combination of rapid environmental change, constrained biological adaptability, and limited actionable information creates a management challenge that is not distant or theoretical: it is already underway in the Agreement Area.

1.2 Climate Risk: The Conceptual Framework

Climate risk assessments — regardless of sector or method — rest on a common conceptual architecture drawn from the IPCC risk framework. Climate risk arises from the interaction of three components:

- **Hazard:** the physical and chemical changes in the ocean environment (e.g. warming, acidification, deoxygenation, altered circulation, changes in productivity) that constitute the external forces to which species, their habitats, and food webs are exposed.
- **Exposure:** the degree to which a given species, population, or management system encounters those hazards. Exposure depends on where a species lives, where it migrates, and the spatial and temporal overlap between its distribution and the changing conditions.
- **Vulnerability:** the combination of sensitivity (how much a species or system is affected by a given level of exposure) and adaptive capacity (the ability to adjust, recover, or otherwise reduce the impact of climate-driven changes). Sensitivity is largely intrinsic — shaped by biology and ecology. Adaptive capacity reflects the flexibility of the species, the fishery, and the management system.

These three components — hazard, exposure, and vulnerability — structure the entire body of work produced under this contract. They explain why the Indian Ocean climate synthesis focuses on specific physical and chemical changes that constitute the hazard environment; why the literature reviews examine not just the biology of each species but its ecological dependencies, distributional plasticity, physiological tolerances, and population-level response capacity; and why the indicator framework is organised as it is.

1.3 Experience with Climate Risk Assessment and the RFMO Context

Climate change risk assessment is not a single method — it is a family of approaches. Successful assessments across different sectors and jurisdictions have employed diverse methodologies, from quantitative composite indicator systems through to qualitative expert-led processes. The diversity reflects the diversity of contexts: data availability, institutional capacity, time horizons, and management objectives all shape what is feasible and appropriate.

Experience developing the parallel risk assessment framework for WCPFC was instructive. Existing published climate change risk assessments tend to be multi-year endeavours involving teams of researchers, complex weighted indicator datasets, and rigid scoring systems that are difficult to replicate within routine RFMO advisory processes. The hazard component — linking specific climate variables to specific management questions — proved particularly time-consuming; it is not information that flows naturally from standard fisheries monitoring programmes.

The WCPFC experience also revealed a structural insight that applies equally to SIOFA: the specific questions that climate risk frameworks ask are not routinely answered through standard scientific advisory processes. Even with WCPFC's dedicated science capacity, answering those questions properly requires substantial new resources, new analytical approaches, or both. SIOFA's situation is more challenging in three respects: the organisation is smaller and less resourced; its species list is considerably longer; and many of SIOFA's priority species are data-poor in ways that WCPFC species are not.

None of this diminishes the importance of climate risk monitoring for SIOFA. It shapes how the project was designed and what is realistic to deliver. The aim was to provide tools and information that are genuinely useful given current constraints — not to produce a framework that looks comprehensive on paper but cannot be operated in practice.

2. Methods

The project employed desktop review methods throughout, combining comprehensive systematic literature searches with structured analytical frameworks. The integrated approach drew on several interconnected methodological elements.

2.1 Indian Ocean Climate Synthesis

The climate synthesis was developed through a systematic review of relevant Indian Ocean climate literature. The review examined observed trends and model projections across key variables directly relevant to SIOFA fisheries, including sea surface and subsurface temperature, marine heatwave frequency and intensity, ocean acidification, primary productivity, dissolved oxygen, salinity, major oceanographic circulation features, and importantly their synergies. Indian Ocean-specific literature was prioritised; where necessary, global literature was drawn upon with explicit attention to the degree to which findings are applicable to the Indian Ocean context, which differs from other major ocean basins in rate of change and underlying dynamics.

The synthesis was produced in two forms: a concise executive summary (consolidated in Annex 1) prepared for direct use by the SC, and a full technical review intended as a lasting reference document. Both are structured around the same thematic sequence: Indian Ocean overview; oceanographic regime and climate drivers; sea surface temperature changes, trends, and impacts; salinity changes; ocean acidification; marine heatwave dynamics; and synergies between climate parameters.

2.2 Species Literature Reviews

Three priority species were selected in consultation with the project reference group to represent different scenarios in terms of biology, depth range, data availability, and climate change interaction: alfonsino (*Beryx splendens*), oilfish (*Ruvettus pretiosus*), and trevallies (*Carangoides* spp.). Together they span different depth zones, habitat types, trophic positions, and data richness, ensuring that lessons drawn from the pilot assessments are transferable across a broader range of SIOFA species.

For each species, the literature review was structured around the climate risk framework indicators. The search strategy used a hierarchical approach, prioritising sources in the following order: SIOFA-specific documentation (SC papers, stock assessments, working group documents); Indian Ocean regional research; species-specific biology from any ocean basin; and, where direct evidence was unavailable, closely related species or ecologically analogous habitats as proxies. Where evidence comes from outside the Indian Ocean or from proxy taxa, this is clearly flagged. Such evidence requires careful interpretation: the Indian Ocean is warming at approximately twice the global mean rate, and physiological tolerances, growth responses, and distributional patterns established under different thermal regimes may not transfer reliably to the Indian Ocean context.

For each framework indicator, the review documents what information exists, what does not, and what a provisional rating would be based on available evidence. This structure was used because it maps directly to the questions the framework asks, facilitating both immediate use and future updating as new information becomes available.

2.3 Climate Change Risk Assessment Tool

The project adapted the Climate Change Vulnerability Assessment (CCVA) framework originally developed for WCPFC. That framework was itself derived from the IPCC AR6 risk assessment approach and was built on a systematic review of more than 500 peer-reviewed and grey literature sources and over 130 published assessments. It provides a composite indicator system covering the full spectrum of climate risk dimensions: biological sensitivity, ecological exposure, and adaptive capacity, across both species and fisheries management dimensions.

For SIOFA, the tool was reviewed and tested against the specific Indian Ocean oceanographic conditions and associated species characteristics — particularly those of deepwater and seamount-associated species, which differ substantially from the highly migratory Pacific tunas for which the original WCPFC framework was principally designed. The framework is provided as an Excel-based tool with an accompanying instructional guide (Annex 5).

2.4 Framework for Monitoring Climate Risk

The monitoring framework was developed by adapting the approach of Pinkerton et al. (2018, 2023) for CCAMLR, which provides a practical model for integrating climate risk monitoring into routine fisheries science without requiring dedicated climate assessment infrastructure. Rather than treating climate change as a separate analytical exercise, the framework asks for each biological and ecological parameter most likely to respond to climate forcing: what are the potential effects, and what monitoring approaches could detect them using data that already exist or could realistically be collected?

Crucially, the approach does not require the ability to definitively attribute observed changes to climate — a standard that is rarely achievable in practice and should not be a precondition for monitoring. Detecting that a parameter is changing is itself decision-relevant, regardless of whether the cause can be established with certainty. This makes the approach well-suited to SIOFA's situation.

The parameter set was adapted from Pinkerton et al. rather than reproduced wholesale, on two criteria: biological relevance to the climate changes documented for the Indian Ocean, and tractability given existing SIOFA monitoring capacity. A key addition was prey availability and food web linkages — a parameter not in the original CCAMLR framework but essential for SIOFA species given that the primary transmission mechanism for Indian Ocean warming is indirect, operating through declining primary productivity and food web restructuring rather than direct physiological stress alone.

2.5 Methodological Limitations and Caveats

This project was conducted within the scope and timeline of contract CLI-2025-01. Several constraints merit explicit acknowledgement.

Breadth of assessment questions: The climate risk framework addresses a broad and complex set of questions spanning species biology, ecosystem ecology, oceanographic processes, fishery operations, and institutional arrangements. Despite systematic search strategies, the scope means it is possible that relevant research was not identified. Priority was given to peer-reviewed literature and authoritative grey literature; potentially relevant material in regional technical reports, unpublished theses, or specialised databases may not have been captured.

Proxy species and cross-basin extrapolation: For numerous indicators, particularly those relating to physiological responses and climate sensitivities, the literature reviews necessarily rely on information from other ocean basins or closely related species. Whilst biological reasoning was applied to assess the validity of such extrapolations, these remain inferences rather than direct observations. The Indian Ocean's distinctive character and rate of change mean that proxy information from the Atlantic or Pacific may not always be a reliable guide.

Evolving scientific understanding: This synthesis reflects evidence available as of January 2026. New research — particularly Indian Ocean-specific studies — may emerge that materially alters conclusions. Techniques including environmental DNA, high-resolution oceanographic modelling, and improved genetic stock structure analysis may reveal patterns not apparent in the current literature.

Framework application judgements: In mapping literature findings to framework indicators, numerous professional judgements were made about how empirical observations translate into specific vulnerability dimensions. Different analysts might reasonably interpret identical evidence differently, particularly where data quality is marginal or competing hypotheses exist. The indicator ratings represent the project team's synthesis, not objective truth, and the SC is encouraged to treat them as a starting point for discussion rather than as definitive scores.

3. Results

The deliverables produced under this consultancy are a substantial, interconnected body of evidence — the Indian Ocean climate synthesis, three species literature reviews, the CCVA tool, and the monitoring framework template together constitute a significant new knowledge base. We do not expect the SC to resolve its approach to climate risk monitoring at a single meeting. The purpose of this section is to offer observations and recommendations drawn from the experience of this consultancy, and to identify the practical decisions SIOFA will need to work through in light of its priorities and institutional context. The full technical content of each deliverable is provided in the numbered annexes to this report.

3.1 Indian Ocean Climate Change Synthesis (Annex 1)

The Indian Ocean climate synthesis establishes the hazard environment — the physical and chemical changes that are occurring and are projected to occur across the Indian Ocean basin as a result of climate change. This is the context within which all SIOFA species must be viewed.

The synthesis is organised in two forms, consolidated as Annex 1. The executive summary component provides a concise, high-level account of key findings and their implications for SIOFA fisheries, suitable for direct use by the SC and Meeting of the Parties. The full technical review provides the supporting scientific detail, limitations on interpretation, and citations for independent validation. Together they constitute a lasting reference collating and synthesising a substantial body of associated literature — time-consuming work whose assembly in one place provides an enduring resource for the SC's ongoing deliberations.

The headline findings are unambiguous: the Indian Ocean is among the fastest warming ocean basins on Earth, marine heatwave frequency has doubled since the 1980s, primary and secondary productivity are declining as stratification intensifies, oxygen minimum zones are expanding particularly in the Arabian Sea, and ocean acidification is advancing. These are not projected future events — they are observed, ongoing changes with direct consequences for fish populations and the food webs that sustain them.

3.2 Species Literature Reviews (Annexes 2–4)

Three priority species were selected in consultation with the project reference group: alfonsino (Beryx splendens), oilfish (Ruvettus pretiosus), and trevallies (Carangoides spp.). Together they span different depth zones, habitat types, trophic positions, and data richness — ensuring that lessons drawn from the pilot assessments are transferable across a broader range of SIOFA species. The following section summarises the findings of the three species literature reviews; full reviews are provided at Annexes 2, 3, and 4.

3.2.1 Purpose of the Review

Climate risk to a fish species or fishery is not a single quantity — it is an integrated function of multiple interacting dimensions. The analytical framework applied in this assessment organises those dimensions into four components: hazard (the nature and magnitude of climate-driven environmental change); exposure (the degree to which the species and associated fishing operations are subject to that change); sensitivity (the intrinsic biological characteristics that determine the species' response to hazardous conditions); and adaptive capacity (the extent to which the biological population and the fishery management system can adjust to reduce adverse outcomes). An assessment that addresses only one or two of these dimensions will systematically under- or over-estimate actual risk.

Composite indicator frameworks — which decompose each of these four dimensions into specific, answerable questions — provide a structured and replicable means of making that integrated assessment, and of making explicit precisely where evidence is sufficient and where it is not. This consultancy developed a composite indicator framework climate change vulnerability assessment (CCVA) tool for application to SIOFA species (Attachment E).

The framework poses a defined set of questions which together constitute the evidence base required to form a view on species climate risk. The three literature reviews were conducted to determine how well those questions can be answered from the existing scientific literature, and to identify where evidence gaps require expert elicitation, additional data collection, or targeted research.

3.2.2 Data Availability

Source material was drawn from peer-reviewed literature, SIOFA Scientific Committee working papers and reports, and relevant grey literature from national research agencies. Indian Ocean-specific studies were prioritised; where regional data were absent, proxy evidence from Pacific, Atlantic, or Mediterranean populations was incorporated with explicit documentation of the assumptions.

The depth of the available evidence base varies substantially among the three species. Alfonsino is comparatively well-characterised, owing principally to work conducted under SIOFA processes and a body of life history literature from Pacific populations — in particular from New Caledonia, Hawaii, and the Emperor Seamount Chain — that provides a reasonable, if imperfect, proxy for Indian Ocean populations. Oilfish and trevallies are considerably less studied. For oilfish, global distribution data are robust but physiological and reproductive biology are almost entirely undescribed for any population. For trevallies, the position is more acute: virtually no peer-reviewed biological literature exists for the Carangoides species taken in the SIOFA Area, and SIOFA catch records do not resolve catches below genus level, precluding species-specific review. In all three cases, experimental studies on responses to climate-relevant stressors — thermal tolerance, dissolved oxygen thresholds, ocean acidification sensitivity — are absent from the literature.

3.2.3 Species Summaries

3.2.3.1 Alfonsino

Alfonsino *Beryx splendens*

Habitat: Deepwater seamounts, typically 400–600 m (range 25–1,300 m)

Overview

Alfonsino *Beryx splendens*

Habitat: Deepwater seamounts, typically 400–600 m (range 25–1,300 m)

Long-lived and slow-maturing, alfonsino's life history parameters — maximum age estimated at 50–70 years, maturity at approximately 6–8 years in Pacific populations — indicate low intrinsic productivity and limited capacity to recover from population perturbation. The circumglobal subtropical distribution and depth range provide some thermal buffering: mesopelagic waters attenuate surface thermal anomalies. That buffer is partial, however; climate studies demonstrate marine heatwaves penetrating to 500 m depth, placing alfonsino habitat within the thermal influence of intensifying surface warming events. A documented temperature–growth relationship in New Caledonian populations — where population-level growth metrics lag ENSO-driven SST anomalies by 7.5 months — confirms that effects operate through food web mediation rather than direct physiological stress alone.

Thermal Tolerance and Physiological Sensitivity

Experimental data on thermal tolerance thresholds (CTmax, CTmin, aerobic scope) are absent for alfonsino from any population. Broad distributional range provides circumstantial evidence for tolerance of a wide temperature envelope, but tells us nothing about the critical thermal limits needed to project vulnerability under warming scenarios. Oxygen tolerance limits are equally unmeasured — a priority gap given that alfonsino habitat overlaps with the expanding upper margin of Indian Ocean oxygen minimum zones.

Diet, Prey Availability, and Trophic Interactions

Pacific studies document a generalist diet comprising mesopelagic fish, crustaceans, and cephalopods in broadly similar proportions, suggesting moderate dietary flexibility. Whether alfonsino can actually substitute effectively if one prey category declines has not been demonstrated — dietary flexibility under prey limitation remains untested. Indian Ocean diet composition is entirely undescribed, and the assumption that Pacific prey assemblages translate to Indian Ocean seamounts is unverified. Basin-wide zooplankton biomass is projected to decline by 40% by 2100, which would contract the prey base across all three categories simultaneously — rendering dietary switching a limited response to what is effectively a system-wide problem. Competitive interactions with co-occurring mesopelagic predators (orange roughy, oreos, and other seamount-associated species documented in SIOFA catches) under reduced prey availability are unstudied.

Reproduction and Environmental Cue Dependency

As a broadcast spawner with a larval phase of approximately one year, alfonsino faces multiple sequential dependencies on oceanographic conditions: fertilisation success, temperature-dependent egg development, larval survival, and dispersal to suitable seamount settlement habitat. Serial spawning over extended seasonal periods (3–6 months documented across multiple basins) provides temporal buffering against short-term variability. The specific environmental cues governing spawning initiation in SIOFA populations, however, remain unidentified. A latitudinal gradient in spawning timing across Macaronesian populations implies photoperiod or thermal cueing, but the mechanism is unresolved. Whether spawning phenology can adjust if climate-driven shifts alter the cue environment — and over what timescale — is unknown. Larval dispersal depends on seamount-connected current systems: disruption of Indian Ocean circulation patterns could affect larval return rates to suitable settlement habitat.

Assessment Confidence and Key Limitations

Alfonsino *Beryx splendens*

Habitat: Deepwater seamounts, typically 400–600 m (range 25–1,300 m)

Pacific proxy evidence provides a partial foundation for addressing the framework questions, but critical limitations apply. Life history parameters from Pacific populations have not been validated for Indian Ocean populations. No experimental data exist for thermal tolerance, oxygen tolerance, or acidification sensitivity. Spawning biology for SIOFA populations is entirely inferred from proxy populations. Management-related indicators — addressing harvest strategy climate-responsiveness, monitoring capacity, and adaptive governance — cannot be assessed from biological literature and require engagement with fishery managers.

3.2.3.2 Trevallies

Trevallies *Carangoides spp.*

Habitat: Shallow reef and bank habitats, 0–100 m; principally Saya de Malha Bank (Subarea 8)

Overview

Trevallies represent the most significant data challenge of the three species reviewed. SIOFA catch records are reported at genus level (Carangoides spp.) without species resolution, which makes species-specific vulnerability assessment impossible and means that available biological literature — which covers individual Carangoides species from other ocean basins — cannot be reliably matched to SIOFA catch composition. The Carangoides species documented in SIOFA records, primarily from Saya de Malha Bank, occupy shallow reef and reef-associated habitats with no depth refuge from surface thermal anomalies. Trait-based vulnerability modelling (FishBase) assigns a climate vulnerability score of 90/100 — the highest of the three species reviewed — though this should be interpreted as a structured prior in the absence of direct evidence, not as an empirical measurement.

Thermal Exposure and Sensitivity

At 0–100 m depth, trevallies at Saya de Malha Bank are in full exposure to marine heatwave events — no thermal buffering of the kind available to mesopelagic species. Marine heatwave frequency has doubled since the 1980s, and near-permanent heatwave conditions were documented across the tropical Indian Ocean during 2023–24, with anomalous warming concentrated in the southwestern tropical Indian Ocean — the region encompassing Saya de Malha Bank. Growth suppression in Carangoides bajad reaches its maximum possible amplitude during peak thermal periods in the Arabian Gulf (temperatures exceeding 35°C), confirming that this genus experiences profound physiological responses to thermal extremes within its natural range. Quantitative thermal tolerance limits for the target Carangoides species remain experimentally undetermined.

Diet, Prey Availability, and Trophic Interactions

The Carangidae are broadly opportunistic carnivores. Diet data for *Carangoides bajad* indicate generalism — nekton, crustaceans, finfish — providing a moderate buffer against prey composition shifts. A contrasting vulnerability applies to *Gnathanodon speciosus*, also taken in SIOFA catches: a benthic specialist using a highly protractile jaw to exploit crustaceans, molluscs, and fishes from sandy substrates, creating specific dependency on calcifying prey groups that ocean acidification additionally compromises. No quantitative diet studies exist for *Carangoides fulvoguttatus*, *C. gymnostethus, or C. bajad* from Saya de Malha Bank. Whether any Carangoides species can sustain condition when preferred prey declines — the critical flexibility question — has not been investigated. Indian Ocean phytoplankton

Trevallies *Carangoides spp.*

Habitat: Shallow reef and bank habitats, 0–100 m; principally Saya de Malha Bank (Subarea 8)

biomass has declined 20% over six decades, and zooplankton biomass is projected to fall 40% by 2100, cascading upward through the food web. The progressive shift from nutritious diatoms toward Noctiluca scintillans blooms further degrades prey quality independently of quantity. Competitive pressure from other reef-associated and pelagic predators under these conditions is unstudied.

Reproduction and Environmental Cue Dependency

Monsoon dynamics constitute the dominant seasonal environmental signal at Saya de Malha Bank, structuring the temperature, current, nutrient, and productivity patterns presumed to govern trevally reproductive timing and feeding aggregation. Seasonal growth oscillation in *Carangoides b*ajad is temperature-entrained — consistent with monsoon-driven physiological cycles — and Indian Ocean Walker Circulation, which drives those monsoon patterns, is undergoing documented change. Yet no spawning data exist for any *Carangoides* species at Saya de Malha Bank or elsewhere in the Indian Ocean. Spawning sites, seasonal timing, environmental triggers, and larval dispersal pathways are all undescribed. The convergence of warming, altered monsoon phenology, reef structural degradation from compound thermal bleaching and acidification, and entirely uncharacterised reproductive requirements represents a compounding of hazards whose interactions cannot be assessed.

Assessment Confidence and Key Limitations

Trevallies present the most acute confidence limitation of the three species. The absence of species-level catch resolution, near-complete lack of Indian Ocean biological data, and unavailability of any experimental climate-response data mean most framework indicators can be addressed only through structured inference from taxonomically proximate populations in different oceanographic settings. Species-level catch disaggregation is an essential prerequisite for meaningful assessment progress. Very little can be confidently inferred from available literature.

3.2.3.2 Oilfish

Oilfish *Ruvettus pretiosus*

Habitat: Mesopelagic, typically 200–400 m (range 100–975 m); oceanic, associated with seamounts and topographic features

Overview

Oilfish is both the commercially most significant species in this review — averaging 13,530 tonnes per year in SIOFA catches over 2018–2022, almost entirely from the Chinese Taipei pelagic longline fleet — and simultaneously one of the least studied fish species of commercial importance. No published life history parameters exist for *Ruvettus pretiosus* from any ocean basin. Large body size (to 2 m, 63.5 kg) and deep mesopelagic habitat are strongly associated across teleost taxa with the low-productivity life history syndrome: slow growth, late maturity, low fecundity, and extended longevity. This is the syndrome of orange roughy and alfonsino — species that have proven consistently susceptible to overfishing because productivity cannot sustain removal rates that appear sustainable in the short term. The inference that

Oilfish *Ruvettus pretiosus*

Habitat: Mesopelagic, typically 200–400 m (range 100–975 m); oceanic, associated with seamounts and topographic features

oilfish follows the same pattern is logically sound, but it remains inference in the absence of measured parameters.

Thermal Exposure and Physiological Sensitivity

Typical adult occurrence at 200–400 m places oilfish squarely within the depth range where marine heatwave thermal anomalies have been documented to penetrate — to 500 m. Progressive warming and increasing stratification throughout the upper ocean add cumulative pressure. Thermal tolerance limits have not been measured. Oxygen minimum zone expansion in the Indian Ocean — particularly in the Arabian Sea — is directly relevant: intensification of OMZ boundaries may compress the habitable depth range available to oilfish and their mesopelagic prey communities.

Diet, Prey Availability, and Trophic Interactions

Evidence from the Mediterranean and equatorial Atlantic characterises oilfish as a dietary generalist, with a broad prey range encompassing cephalopods, fish, and crustaceans and documented multi-taxa switching across vertical habitat strata. Generalism provides resilience against taxon-specific prey decline. The critical limitation is that no Indian Ocean diet data exist: whether the generalist strategy documented elsewhere applies in SIOFA waters cannot be confirmed. A system-wide contraction of the mesopelagic prey community — zooplankton biomass projected to fall up to 40% by 2100 as stratification intensifies and primary productivity declines — is a different order of problem from compositional prey shifts; dietary flexibility does not compensate if all prey categories contract simultaneously. Without knowing what oilfish actually eat in SIOFA waters, the pathway through which large-scale prey community change would affect oilfish condition, growth, and reproductive success cannot be evaluated.

Reproduction and Environmental Cue Dependency

Broadcast spawning with positively buoyant, oil-rich pelagic eggs creates the standard suite of environmental dependencies: fertilisation success in open water, temperature-dependent egg development, larval survival contingent on encountering suitable prey at the right developmental stage, and dispersal back to suitable topographic habitat without parental buffering. An anomalously female-biased sex ratio (1:8.4) reported from eastern Mediterranean longline catches suggests sex-segregated habitat use or gear selectivity effects, with unresolved implications for reproductive aggregation behaviour. Beyond this, oilfish spawning biology is almost entirely undescribed globally. Spawning site characteristics, seasonal timing, environmental triggers, larval duration, dispersal pathways, and age or size at first reproduction have not been documented for any population; no reproductive data exist for Indian Ocean populations. The species' oceanodromous classification and hypothesised spawning migration imply responsiveness to seasonal environmental cues — but given that adults inhabit depths at which surface photoperiod is absent, the nature of those cues is wholly unknown. An uncharacterised reproductive biology, a warming and stratifying mesopelagic habitat, and declining prey availability for larvae together constitute a multi-pathway vulnerability that existing data cannot quantify. SIOFA's observer database contains a substantial biological dataset for oilfish that has not been formally analysed: over 21,000 weight measurements, nearly 28,000 sex determinations, and collected maturity specimens held within programme records. Formal analysis of this material would yield the first published

Oilfish *Ruvettus pretiosus*

Habitat: Mesopelagic, typically 200–400 m (range 100–975 m); oceanic, associated with seamounts and topographic features

life history estimates for Ruvettus pretiosus from any ocean basin — a high-value return on data already collected.

Assessment Confidence and Key Limitations

Assessment is constrained by the complete absence of quantitative life history data — productivity estimates, spawning parameters, thermal and oxygen tolerance limits — from any population globally. The proxy inference of low productivity from body size and habitat characteristics is scientifically defensible but insufficient to populate framework indicators. IOTC bycatch records, not yet systematically reviewed, may contain Indian Ocean biological context. Management and adaptive capacity indicators cannot be assessed from biological literature.

3.2.4 Common Evidence Gaps Across All Three Species

The three literature reviews identify a set of structural evidence deficiencies that apply, in varying degrees, to all three species. These cross-cutting gaps are documented here as they are directly relevant to the confidence level that should attach to the overall vulnerability assessment.

<u>Absence of Experimental Climate-Response Data</u>

No experimental or empirical studies on climate change responses exist for any of the three species. Thermal tolerance limits (CTmax, CTmin, aerobic scope reduction thresholds), dissolved oxygen thresholds, and ocean acidification sensitivity — including otolith development, osmoregulation, respiratory physiology, and larval survival under projected pH scenarios — have not been measured for alfonsino, trevallies, or oilfish under any conditions. Vulnerability estimates generated from FishBase trait-based modelling rest on ecological proxies — geographic range, depth, trophic level, body size — and represent structured priors rather than measurements of physiological response to projected stressors. Scores are presented in the assessment with this characterisation made explicit.

<u>Diet Flexibility and Prey Availability Under Climate Change</u>

Dietary flexibility — the capacity to maintain condition and reproductive success under altered prey community composition — is a critical sensitivity indicator in the framework and a significant evidence gap across all three species. All three appear to employ broadly generalist feeding strategies, conferring moderate buffering against taxon-specific prey decline. In no case, however, has flexibility been empirically tested under prey limitation conditions. Indian Ocean diet composition data are absent for trevallies and oilfish. For alfonsino, Indian Ocean prey community composition is uncharacterised, and available Pacific data cannot be assumed to represent Indian Ocean seamount assemblages.

Projections of a 40% decline in Indian Ocean zooplankton biomass by 2100, with concurrent shifts toward low-nutritional-value planktonic taxa, represent a system-wide reduction in prey availability rather than a compositional shift. Dietary flexibility cannot compensate for this: switching between prey categories offers no advantage if all categories are simultaneously contracting. The indirect effects of Indian Ocean productivity decline on the food web pathways sustaining all three species constitute a primary vulnerability that cannot be quantified without Indian Ocean-specific diet and prey availability data.

Competitive interactions with other predators under conditions of reduced prey availability are unstudied for all three species. Co-occurrence of alfonsino with orange roughy, oreos, and other seamount-associated species in SIOFA catches establishes that interspecific competition for mesopelagic prey resources exists; how that competitive landscape may shift under climate-driven prey reduction is assessed in no available study. For trevallies and oilfish, the competitive context is similarly undescribed.

Reproductive Biology and Environmental Cue Dependency

Reproductive biology — spanning spawning strategy, environmental triggers, phenological plasticity, and the oceanographic dependencies of early life stages — is inadequately characterised for all three species in the Indian Ocean context, and in some cases globally. All three are broadcast spawners: a shared strategy that creates inherent dependency on oceanographic conditions for fertilisation success, egg development, larval survival, and dispersal to suitable settlement habitat. Without species- and population-specific spawning data, these vulnerability pathways cannot be assessed.

For alfonsino, serial spawning over extended seasonal periods provides temporal buffering, but the environmental cues governing spawning timing in SIOFA populations have not been identified. Whether phenological plasticity exists — whether populations can shift spawning timing as climate changes the cue environment — is unknown. For trevallies, no spawning data exist for Indian Ocean populations; the monsoon-driven seasonal structure presumed to govern reproductive timing at Saya de Malha Bank is undergoing documented change, but the consequences for trevally reproduction cannot be assessed. For oilfish, spawning biology is almost entirely undescribed globally, with no Indian Ocean reproductive data of any kind.

The match-mismatch hypothesis — that climate-driven shifts in environmental phenology produce misalignment between spawning timing and the prey availability windows required for larval survival — applies to all three species but cannot be evaluated for any of them. Given the Indian Ocean Climate Summary's documentation of progressive change in seasonal oceanographic patterns across the basin, this represents a structural vulnerability pathway of real management significance.

Geographic Bias and the Limitations of Proxy Data

The biological literature for all three species is geographically biased toward non-Indian Ocean populations: Pacific and Atlantic for alfonsino, Arabian Gulf for Carangoides, Mediterranean and Atlantic for oilfish. Proxy data are used throughout the assessments where Indian Ocean data are absent, with explicit documentation of the required assumptions. The Indian Ocean, however, is not oceanographically equivalent to these basins: it warms faster, exhibits more pronounced oxygen minimum zone development, has experienced documented basin-scale productivity declines, and has a distinct seasonal forcing structure driven by the monsoon system. Life history parameters, diet composition, and reproductive biology established under different thermal regimes may diverge from Indian Ocean conditions in ways that regional data alone could detect.

Taxonomic ambiguity in catch reporting

SIOFA catch data record trevallies as *Carangoides* spp. without species resolution, rendering species-specific vulnerability assessment of the trevally component of SIOFA catches impossible. Oilfish catch records aggregate *Ruvettus pretiosus* with *Lepidocybium flavobrunneum* (escolar), two species with potentially different climate sensitivities, life histories, and habitat associations. Species-level identification in observer programmes is a prerequisite for meaningful species-specific assessment in future cycles.

3.2.5 Possible Research Directions

Individual species reviews document evidence gaps. The following table documents a selection of research or analysis that would assist in resolving these gaps.

Research Action	Species	Rationale
Experimental thermal and oxygen tolerance studies (CTmax, CTmin, aerobic scope reduction thresholds)	All species	Thermal range/tolerance is untestable for all three species without physiological data; the most fundamental gap in the assessment
Ocean acidification sensitivity studies (otolith integrity, larval development, respiratory physiology under projected pH scenarios)	All species	No experimental acidification data exist for any of the three species; a significant hazard pathway that cannot currently be assessed
Habitat suitability modelling defining quantitative depth, temperature, prey, and current requirements; climate envelope modelling identifying potential future suitable habitat and refugia	Alfonsino; oilfish	Explicitly identified in mobility, distributional range, and habitat flexibility synthesis sections; required to assess distributional vulnerability and potential climate refugia within dispersal range
Larval ecology studies: pelagic larval duration, larval depth distribution, and current-mediated dispersal pathways to settlement habitat	Alfonsino; oilfish	Identified as a high-priority gap in current change hazard assessments for both species; broadcast spawners with seamount-associated settlement have inherent vulnerability to circulation changes that cannot be evaluated without larval duration and depth data
Genetic connectivity analyses to determine population structure and infer dispersal distances across SIOFA seamounts	Alfonsino; oilfish	Middleton et al. (2024) work on alfonsino connectivity identified as a critical missing piece in mobility; low connectivity would indicate population isolation and limited capacity for climate-driven redistribution
Acoustic or satellite tagging to quantify adult movement patterns, home ranges, and spawning migration routes	Alfonsino; oilfish	Identified in mobility synthesis for alfonsino; required to determine whether adults can relocate to alternative habitat if seamounts become thermally unsuitable
Indian Ocean-specific diet composition studies and dietary flexibility experiments under prey limitation conditions	All species	Indian Ocean diet data are absent for all three species; dietary flexibility under prey limitation — a key adaptive capacity question — has not been tested for any of them
Formal analysis of SIOFA observer programme biological data for oilfish (maturity schedules, growth parameters from existing specimens)	Oilfish	Data already held within the observer database; would yield the first published life history parameters for this species from any ocean basin
Species-level disaggregation of trevally catch and effort data through	Trevallies	Prerequisite for species-specific vulnerability assessment; current genus-level reporting

Research Action	Species	Rationale
improved observer identification protocols		prevents matching biological literature to actual catch composition
Systematic review of IOTC records for oilfish and Carangoides bycatch data	All species	Not systematically searched in this review; likely to contain Indian Ocean biological context at low additional cost if not already undertaken

3.2.6 Implications for SIOFA

The literature reviews establish that the Indian Ocean climate trajectory is well-evidenced and directionally unambiguous: the basin is warming at a rate exceeding global averages, marine heatwave frequency and intensity are increasing, oxygen minimum zones are expanding, primary productivity is declining, and seasonal oceanographic patterns are changing. These are robust findings from multiple independent research programmes with converging results. The direction of risk for all three species — a warming, deoxygenating, increasingly acidic, and less productive ocean — is not in question.

What the literature reviews establish is that the species-specific biological data required to translate that climate trajectory into quantified vulnerability estimates are substantially absent. The literature reviews propose a range of amber and red ratings. This outcome reflects the actual state of the available science; it is what the framework is designed to make visible. Presenting results with this context explicit — distinguishing between indicators that are red because no data have ever been collected, indicators that are red because existing data have not been analysed, and indicators that are red because the institutional infrastructure they assess does not yet exist — will provide the Scientific Committee with a more actionable picture than aggregate scores alone.

3.3 Climate Change Risk Assessment Tool (Annex 5)

The CCRA tool (Annex 5) provides a structured framework through which biological and ecological characteristics may be evaluated systematically against climate hazards. It is provided as both a working instrument and a reference: the comprehensive indicator set maps the complete landscape of climate risk questions relevant to SIOFA fisheries, even in those cases where data to answer those questions are currently unavailable.

The tool retains the CMM-by-CMM structure of the WCPFC version, and the full indicator set extends beyond biological and ecological sensitivity to encompass fisheries management and compliance dimensions — broader than the scope of the current contract but included because that breadth is what a complete risk picture requires. For SIOFA, where individual CMMs such as the bottom fishing measure apply across multiple fisheries simultaneously, the question of how the tool is applied to specific measures, and its utility in doing so, will need to be worked through with the Meeting of the Parties.

It is important to be clear about what the tool is and what it is not. The picture of climate risk is bigger than the sum of individual indicator scores, and given resource and data constraints, a full quantitative composite assessment may not be achievable in the near term. The tool has genuine value at several levels short of comprehensive implementation:

- **As a reference and orientation tool:** the indicator system provides a structured map of the full range of climate risk questions relevant to SIOFA fisheries — a way of thinking systematically about climate risk and a comprehensive reference for what information would be needed for a mature assessment.
- **As a diagnostic instrument:** applied systematically — as in the three species reviews — it reveals where climate risk is likely to be significant and where data gaps are most acute. Both types of findings are decision-relevant.
- **For selective and strategic application:** specific indicator groups can be applied without the full system. Options include applying the tool selectively to priority CMMs, using it for periodic strategic assessments on 3–5 year cycles, or deploying it when reviewing high-risk areas or species.

3.4 Framework for Monitoring Climate Risk (Annex 6)

Annex 6 translates the findings of this consultancy into a SIOFA version of the Pinkerton et al. monitoring framework, drawing directly on the Indian Ocean climate synthesis (Annex 1) and the three species literature reviews (Annexes 2–4). The framework is organised into three columns for each parameter: (1) the parameter and its relevance; (2) the potential effects of climate variability and change on that parameter, differentiated by species; and (3) potential monitoring approaches.

What makes Annex 6 valuable is not the parameter list itself but the species-specific second column, which makes explicit how the same Indian Ocean climate drivers produce materially different effects depending on a species' depth, habitat constraint, life history strategy, and trophic position. The three pilot species have fundamentally different exposure profiles:

- *Alfonsino* lives at 400–600 m, below the surface mixed layer but within the depth range of documented marine heatwave penetration. Tightly constrained by seamount topography, its climate exposure operates principally through the food web: warming drives productivity decline, which reduces prey availability, which reduces growth with a measurable lag. The primary risk is chronic food limitation compounded by its very low productivity.
- *Oilfish* is wide-ranging and mesopelagic, spending time at the epipelagic-mesopelagic boundary. It is more directly exposed to expanding oxygen minimum zones than alfonsino. Distributional responses are more feasible because oilfish is not constrained to seamount topography — but the honest caveat is that oilfish is poorly enough studied that the monitoring framework carries substantial inference and proxy reasoning.
- *Trevallies* live in shallower, surface-influenced water with faster life histories — shorter generation times, earlier maturity — meaning temperature effects on growth and reproduction can act more directly and are potentially detectable over shorter timescales. They are also more likely to show distributional responses within management-relevant time horizons.

Column 3 — potential monitoring approaches — is the column where the honest constraint of this consultancy must be acknowledged. Testing whether growth parameters, length-weight relationships, or spatial distribution patterns show trends in existing SIOFA observer and assessment data requires access to those datasets and dedicated analytical time. Linking parameter changes to oceanographic indices from the climate synthesis requires further correlation analysis that has not been commissioned. Annex 6 therefore provides column 3 as a template specifying which data would be used, what analytical approach would be appropriate, and what the expected monitoring feasibility is. The intent is to provide the SC with a scoped, prioritised set of analyses it can decide to commission or undertake, rather than an aspirational list with no pathway to action.

4. Discussion

The deliverables produced under this consultancy — the Indian Ocean climate synthesis, three species literature reviews, the CCVA tool, and the monitoring framework — together constitute a significant new knowledge base for SIOFA. The purpose of this section is to identify what the SC needs to work through in light of these findings and SIOFA's institutional context.

4.1 The State of the Evidence

The literature reviews establish that the Indian Ocean climate trajectory is well-evidenced and directionally unambiguous: the basin is warming at a rate exceeding global averages, marine heatwave frequency and intensity are increasing, oxygen minimum zones are expanding, primary productivity is declining, and seasonal oceanographic patterns are changing. These are robust findings from multiple independent research programmes with converging results.

What the literature reviews also establish is that the species-specific biological data required to translate that climate trajectory into quantified vulnerability estimates are substantially absent. The reviews propose a range of amber and red ratings across the indicator framework. This outcome reflects the actual state of the available science; it is what the framework is designed to make visible. Presenting results with this context explicit — distinguishing between indicators that are red because no data have ever been collected, indicators that are red because existing data have not been analysed, and indicators that are red because the institutional infrastructure they assess does not yet exist — provides the SC with a more actionable picture than aggregate scores alone.

Oilfish presents the starkest case. It is the highest-catch species in this review and simultaneously the least studied fish of commercial importance in the global literature. The inference that oilfish follows the low-productivity life history syndrome of orange roughy and alfonsino is logically sound, but it remains inference. The SIOFA observer programme has already collected the data needed to resolve this — formal analysis of existing biological records would yield the first published life history parameters for this species from any ocean basin.

4.2 What SIOFA Is and Is Not Positioned to Do

SIOFA is not positioned to comprehensively monitor all of the climate risks documented in the synthesis, nor is it responsible for assessing all of the climate processes documented there. What it can do is monitor its fisheries data for the outcomes of those biological characteristics under changing conditions — tracking whether growth rates, body condition, maturity, spatial distribution, or recruitment signals are shifting in ways consistent with climate forcing.

The monitoring framework in Annex 6 specifies what to monitor, why each parameter matters differently for each species, and which data or analytical approaches would be needed. The SC's central decision from this work is whether to adopt that framework as a standing instrument and how to develop and apply it over time.

This is more than a technical deliverable. The information assembled here, and the monitoring framework proposed, represent a considered view of where SIOFA's climate risk lies and what a proportionate institutional response might reasonably comprise. The SC is well positioned to act before climate impacts become severe and before management options narrow.

4.3 Data-Poor Species

The three pilot species were selected in part because they had different levels of biological information available. Most SIOFA species are not high-information stocks. Data-poor fisheries face a compounding problem: they may receive less routine attention through the SC's scientific advisory process, they are harder to monitor because data quality is typically thinner, and yet they may face the same or greater climate risks as species with richer data. There is a real risk that climate-driven changes in these populations go undetected until they are already severe.

The SC should consider how it wants to manage this risk. One option is to use the Indian Ocean climate synthesis and general biological characteristics — life history strategy, depth range, thermal affinity — to make considered inferences about which data-poor species face the highest climate risk, and to prioritise those species for preliminary framework mapping or risk management. The full pilot methodology is not necessarily required to reach a working assessment of relative vulnerability.

4.4 Possible Approaches for the Scientific Committee

The following recommendations are drawn from the experience of this consultancy and are offered for the SC's consideration. They are not prescriptive; SIOFA's institutional context and resource constraints will shape what is achievable and in what sequence.

1. **Adopt the monitoring framework as a standing instrument.** The central recommendation is that SIOFA adopt Annex 6 as a standing instrument within its scientific programme. This does not require implementing the full framework immediately or for all species. It requires a decision to treat it as the organising structure through which climate risk information enters SC deliberation, and to develop it progressively as data and capacity allow.

   In practical terms, the SC should consider what adoption means in practice. It could mean that each time an assessment is conducted for a priority species, the relevant parameters in Annex 6 are checked — are the growth parameters, spatial distribution, or maturity data showing trends that might reflect climate influence? That means that the framework informs what biological data are collected through observer programmes and what analyses are requested from stock assessment scientists. It could mean that the SC periodically reviews the framework itself — perhaps on a 3–5 year cycle — to determine whether the parameter set remains appropriate, whether new Indian Ocean climate evidence warrants updating the potential effects column, and whether monitoring approaches that were previously aspirational have become achievable. The SC could also decide whether to complete the framework template for all species, or even those specified in Annex 1 of CMM 17-2025 species over time, using the pilot species reviews as a tested methodological model.

2. **Develop a forward work programme**. The data gap mapping in the species literature reviews provides a direct basis for prioritising monitoring investment. Rather than treating these gaps as a general observation, the SC should develop a structured work programme that identifies which gaps are most consequential for management, which are addressable within realistic resource constraints, and what sequencing of effort makes sense.

Some of the most important gaps are not fisheries-specific. They relate to basic Indian Ocean oceanography, species physiology, and food web dynamics that SIOFA cannot resolve through its own data collection alone. Leveraging existing and emerging observational programmes — Argo float networks, satellite-derived productivity estimates, Nansen cruises, national scientific oceanographic investments, and/or IOTC research outputs, among others — could be an explicit element of that work programme. In this context, the SC may wish to consider what technical and institutional partnerships would assist with monitoring or filling data gaps, including with research institutions and other bodies with Indian Ocean observational capacity. Where gaps can only be resolved through new data collection (or the analysis of existing data), the work programme should specify what is needed, who might collect it, and on what timeline — including, where relevant, requesting that CCPs implement targeted biological sampling through normal fishery operations.

3. **Consider the particular vulnerability of data-poor species.** The three pilot species were selected in part because they had different levels of biological information available. Most SIOFA species are not high-information stocks. Data-poor fisheries face a compounding problem: they may receive less routine attention through the SC's scientific advisory process, they are harder to monitor because data quality is typically thinner, and yet they may face the same or greater climate risks as species. There is a real risk that climate-driven changes in these populations go undetected until they are already severe. Many of these species are also important to SIOFA's developing CCPs where national research efforts are already challenged.

   The SC should consider how it wants to manage this risk. One option is to use the Indian Ocean climate synthesis and general biological characteristics — life history strategy, depth range, thermal affinity — to make considered inferences about which data-poor species face the highest climate risk, and to prioritise those species for preliminary framework mapping or risk management. The full pilot methodology is not necessarily required to reach a working assessment of relative vulnerability.

4. **Consider the role of predictive modelling.** The current deliverables are oriented toward detection — identifying what to monitor and how to recognise a signal when it emerges. SIOFA may wish to consider whether it also wants to invest in anticipatory capacity: predictive modelling that uses projected Indian Ocean conditions under different climate scenarios to anticipate where and when particular species are likely to experience significant parameter changes. This may be worth exploring in partnership with research institutions or through targeted project funding. The monitoring framework in Annex 6 provides a natural starting point, since it identifies the parameters for which predictive relationships would be most valuable.

5. **Consider sharing the Indian Ocean climate synthesis with IOTC.** The synthesis documents climate changes that affect the entire Indian Ocean, including pelagic and surface systems that are IOTC's primary management context. SIOFA may wish to consider whether to share the relevant elements with IOTC, both as a contribution to regional scientific knowledge and as a basis for exploring collaborative monitoring.

5. Consideration by the Scientific Committee at SC11

Draft deliverables under contract CLI-2025-01 were presented to the 11th Meeting of the Scientific Committee (SC11, Fremantle, Australia, 23–31 March 2026) as information paper SC11-CLI2025-01. The paper presented the findings of the consultancy and invited the SC to engage with both the results and the question of how and where to apply these tools as SIOFA builds its capacity to manage climate risk.

The draft report was submitted to SC11 as an information paper rather than a working paper because the deliverables had not at that stage been through the full review process via the project advisory committee. As a consequence, the SC was not asked to provide formal scientific advice on the findings at SC11; rather, the presentation was intended to make the SC aware of the completed work and to open discussion about how the tools and findings might be applied.

A preliminary discussion was held under Agenda Item 14 (Climate Change). Members engaged with the question of next steps, including how the monitoring framework might be incorporated into existing SC workstreams. This discussion is recorded in the Report of SC11, available at:

https://siofa.org/meeting-file/meeting-documents/11th_annual_meeting_of_the_siofa_scientific_committee_sc11/SIOFA-SC11-Report.pdf

This final report, incorporating completed and reviewed deliverables, is submitted to the SIOFA Secretariat in fulfilment of contract CLI-2025-01.

6. Conclusions

The deliverables produced under contract CLI-2025-01 are complete as contractually required. Together they provide SIOFA with a substantial new knowledge base for systematic engagement with climate risk: a characterisation of the Indian Ocean hazard environment, species-level vulnerability assessments for three pilot species, a structured assessment tool, and a template monitoring framework.

The central finding — that the direction of climate risk for all three species in the Indian Ocean is unambiguous, while the species-specific biological data needed to quantify that risk are substantially absent — is not a reason to defer action. It is a reason to invest in the monitoring infrastructure that will make detection possible, and to treat the current state of knowledge as the starting point for a structured, progressive programme of climate risk management rather than a reason for waiting.

The monitoring framework provided in Annex 6 is designed to be that starting point. Adopting it as a standing instrument, embedding it in existing SC workstreams, and developing it progressively as data and analytical capacity allow represents the most proportionate and practically achievable institutional response to the climate challenge SIOFA faces. The SC is well positioned to take that step before impacts become severe and before management options narrow.

Acknowledgments

The consultants acknowledge the support and contributions of the SIOFA Secretariat for their coordination and guidance throughout the project; the SC Chairperson for facilitation of the SC11 discussion and contribution to the direction of the project; the project Advisory Panel for their guidance and review; and SIOFA Contracting Parties, Cooperating Non-Contracting Parties and Observers whose data, publications and scientific expertise inform the foundation on which this work rests. The project was funded by SIOFA, whose investment in developing the organisation's capacity to engage systematically with climate risk is gratefully acknowledged.

References

References for the Indian Ocean climate synthesis are provided in Annex 1. References for each species literature review are provided in the respective annex (Annexes 2–4). The following references pertain to the main report.

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Pinkerton, M., Dunn, A., Mormede, S. and Parker, S. (2018). Monitoring and managing the effects of environmental change on toothfish assessments. CCAMLR document WG-SAM-18/22, Hobart, Australia.

Pinkerton, M., Devine, J., Dunn, A. and Mormede, S. (2023). Monitoring the effects of environmental variability and climate change on toothfish assessments. CCAMLR document WS-CC-2023/20, Hobart, Australia.

Robertson, K. and Baird, M. (2025). WCPFC Climate Change Vulnerability Assessment Framework: Progress Report and Pathways Forward (WCPFC22-2025-17).

SIOFA (2026). Report of the 11th Meeting of the Scientific Committee (SC11), Fremantle, Australia, 23–31 March 2026. Southern Indian Ocean Fisheries Agreement Secretariat.

Appendices

1. Terms of Reference

List of Annexes

The following annexes form part of this final report. They are submitted as separate documents.

Annex	Title	Description
Annex 1	Indian Ocean Climate Change Synthesis	Consolidated climate synthesis comprising the Executive Summary and the full technical review together providing the hazard baseline for all SIOFA species assessments.
Annex 2	Alfonsino Literature Review	Detailed literature review against CCVA indicators for *Beryx splendens*.

Annex 3	Oilfish Literature Review	Detailed literature review against CCVA indicators for *Ruvettus pretiosus*.
Annex 4	Trevallies Literature Review	Detailed literature review against CCVA indicators for *Carangoides* spp.
Annex 5	Climate Change Risk Assessment Tool Package	Excel-based composite indicator tool (Attachment 5.2) and accompanying implementation guidance document (Attachment 5.1), adapted from the WCPFC CCVA framework for SIOFA application.
Annex 6	Framework for Monitoring Climate Risk	SIOFA-adapted monitoring framework translating consultancy findings into key biological and ecological parameters to track, with data sources and gaps identified (based on Pinkerton et al. 2018, 2023).

Appendix 1 — Terms of Reference for Contract CLI-2025-01

Terms of Reference (ToR)

for the provision of scientific services to SIOFA Scientific Committee

Project title: Assessment of SIOFA Species and Ecosystems for vulnerability to climate change impacts

Project Code: CLI-2025-01

Introduction

The SIOFA Scientific Committee (SC) is tasked to provide fisheries management advice to the SIOFA Meeting of the Parties (MoP). In recent years, both the SC and the MoP have agreed to have a standing agenda item at their annual meeting dealing with climate change. The SIOFA SC discussed climate change during its 9th annual meeting, in 2024 (see paragraphs 399–407 of the SC9 report). The SIOFA SC also discussed climate change at the following meeting, in 2025, when it was first added as a specific item to its agenda (see paragraphs 545–552 of the SC10 report).

The SC has also defined a list of primary, secondary and bycatch species at its 8th annual meeting, and this list is available in the annually-updated Appendix A of the Overview of SIOFA Fisheries (https://siofa.org/sites/default/files/files/SIOFA-Fisheries-Overview-2024_redacted.pdf). However, information on climate change in the Indian Ocean and its potential effects on SIOFA stocks is still scarce.

This project will assess SIOFA primary, secondary, and bycatch species and vulnerable ecosystems for levels of vulnerability to climatic change at various temporal scales, using appropriate risk characterization processes. It will identify those species and ecosystems most likely to require consideration in SC assessment processes within the next ten and twenty years.

Terms of Reference

Project Objectives

1. Identify target, bycatch, species and ecosystems potentially vulnerable to climate change.
2. Collate information on the potential impacts of climate change on SIOFA species and ecosystems, including ocean acidification.
3. Develop process to characterize risk (probability and magnitude of consequences) under different timescales.
4. Assess species and ecosystems against the risk characterization.

Relevant SIOFA information

1. SIOFA data (provided by the SIOFA Secretariat upon request)
2. SIOFA spatial data layers. Available on https://github.com/SIOFASecretariat/SIOFA_SC_Spatial_layers
3. SIOFA reporting templates. Available on https://github.com/SIOFASecretariat/SIOFA_Reporting_templates
4. SIOFA reports:

a. SIOFA SC, SC Working Group, and National Reports. Scientific Committee Meeting | SIOFA (https://siofa.org/)
b. SIOFA MoP reports. Meeting of the Parties | SIOFA (https://siofa.org/)
c. SIOFA technical and scientific reports (public reports and abstracts of restricted reports are available from https://siofa.org/, and full restricted reports will be made available by the SIOFA Secretariat to the project consultant upon request and after the approval of concerned CCPs.

Expected progress

1. Follow the project timeline as detailed in this agreement, including the submission of deliverables.
2. Collect any necessary data as early as possible, e.g. by submitting a data request to the SIOFA Secretariat or
3. Attend a kick-off meeting with the project Advisory Panel (composed by members of the SIOFA Scientific Committee and the SIOFA Secretariat) to discuss the project setup and development. Further engage, as requested, with the Advisory Panel that will assist the consultant access and interpret reports, data, and to provide advice on relevant analyses or data interpretation for the project.
4. Provide regular (i.e. every 2-3 months), proactive updates to the Project Coordinator and the Advisory Panel throughout the project, in particular informing promptly of any unforeseen delay or variation to the project.
5. Submit deliverables on time and appropriately formatted, as required. Each deliverable will be going through a SIOFA review to ensure that it meets the quality targets and the project objectives as set out in the Terms of Reference.
6. Appropriately acknowledge the project funding source (e.g. SIOFA), with appropriate corresponding logos in prominent positions, within each deliverable.
7. Take into reasonable account the outcomes of the SIOFA review or any comments made by meeting attendees, when revising the deliverables.

Expected deliverables

1. A (virtual) presentation of preliminary methods and results to the next SIOFA SC annual meeting (mid- to end-March 2026), to be confirmed depending on contract duration.
2. A Draft Report that addresses the project objectives and tasks as laid out in this contract, which will be reviewed by SIOFA. The report should follow the guidelines and format available at https://github.com/SIOFASecretariat/SIOFA_Reporting_templates . In particular, the report should include a concise (max 300 words) summary, and the report should detail the methods, the outcomes, conclusions, and recommendations.
3. A Final Report revised by considering any comments and advice from the SIOFA review or comments received during meetings, to be further reviewed by SIOFA. The Consultant is to submit this Final Report to the SIOFA Secretariat following the guidelines and format available at https://github.com/SIOFASecretariat/SIOFA_Reporting_templates.
4. Provide all the information collected to the SIOFA Secretariat (including that sourced from the Secretariat) before the final payment of the contract. Such information includes electronic data files, analysis codes, biological samples, and other relevant data if applicable.

Presentations of reports to the Scientific Committee may be given virtually and travel to the meetings is not obligatory.

Acceptance of Draft and Final Reports

1. Draft and Final Reports must be submitted to the SIOFA Secretariat (Project Coordinator).
2. Draft and Final Reports will be reviewed by SIOFA using the procedures outlined in paper MOP-09-12 (Annex B), see also

https://github.com/SIOFASecretariat/SIOFA_Reporting_templates/tree/main/SC%20reports/Review%20template%20for%20consultant%20reports.

3. Payment of contracts milestones will be subject to acceptance of the submitted reports by SIOFA.

Intellectual Property clause and confidentiality

The Consultant shall submit all the information collected to the SIOFA Secretariat (including that sourced from the Secretariat) before the final payment of the contract is made to the consultant. Such information includes electronic data files, analysis codes, biological samples, and other relevant data if applicable. Any arrangements for ownership, storage, or disposal of physical samples shall be agreed by SIOFA as a part of the contract. All Intellectual Property generated as a part of this contract shall become the property of SIOFA unless otherwise excluded in the proposal and agreed by SIOFA in the contract. The Consultant shall not release confidential data provided for conducting this study to any persons nor any organizations, other than SIOFA Secretariat. The Consultant shall delete all the confidential data upon the completion of the contract.

WORK TIMELINE AND PAYMENT SCHEDULE

The funds for this project allow for a maximum total budget of 25,000 Euro (including all costs and any travel related expenses).

The consultant shall follow the timeline described in Table 1 below.

Table 1: Timeline for payments, milestones, and report submission

Milestone	Date	Activities
Initiation of contract	30 September 2025	First instalment payment (30% of the total contract sum)
Presentation of preliminary results	18–27 March 2026	Presentation of preliminary methods and results to the SC11 meeting (virtual)
Delivery of draft report	15 April 2026	Second instalment payment (30% of the total contract sum) upon satisfactorily submission of draft report, in a format suitable for submission to SC, to the project coordinator.
Delivery of final report	1 June 2026	Submission of final report in a format suitable for submission to SC and submission of project information to the project coordinator. Final instalment payment (40% of the total contract sum) on acceptance of the final report by the advisory panel and the

Milestone	Date	Activities
		final submission of project information

Submission of applications

1. A current CV that summarises the applicant(s) relevant educational background and professional experience.
2. A brief proposal (indicatively 1-3 pages) outlining the proposed methods and analyses, including a description of how the objectives of the ToR will be achieved.
3. Any proposed exclusions to the intellectual property clause or variations to the work timeline and payment schedule.
4. The proposed consultancy price (including all consultant expenses and project related costs), noting that the available budget for this work indicated in Section 3.
5. Identification of any project risks and associated mitigation and management required to successfully complete the project.
6. A statement that identifies any perceived, potential, or actual conflicts of interest of the applicant(s), including those described in paragraph 4 of the SIOFA recruitment procedure (see Section 6), and
7. Any additional relevant information the applicant(s) wish to submit.

The applicants must have appropriate experience and knowledge of fish population dynamics, particularly of deepwater species, and knowledge of climate change models and the effects of climate change on marine fish abundance and distribution.

Applications must be submitted to the SIOFA Science Officer (Marco Milardi, marco.milardi@siofa.org, CC secretariat@siofa.org).

Only those applications received **before 12:00 PM (9:00 AM UTC) on the 15th of September 2025**, Reunion Island time, will be considered.

EVALUATION CRITERIA FOR THE SELECTION OF CANDIDATES

An evaluation panel, the SIOFA Secretariat, and the Chair and Vice-Chairs of the SIOFA Scientific Committee will select one successful applicant for this contract. The selection criteria will include the following:

1. Adequate submission of information to allow the panel to evaluate the candidate
2. Evaluation of the proposal from the candidate, including the proposed contract price
3. Ability to undertake and complete the analyses or work required in this ToR
4. The candidate’s agreement with confidentiality provisions required for the project
5. Acceptable conflict of interest statement
6. Agreement with the data submission and intellectual property terms required in this ToR, and
7. Financial and resourcing considerations.

Conflicts of interest. Paragraph 4 of SIOFA’s Recruitment Procedure

To ensure that situations relating to potential and actual conflict of interests are avoided, persons falling into the following categories may not normally be considered for SIOFA consultancy: (i). any person designated as a designated representative or alternate representative of a CCP to the Meeting of Parties (MOP) as per Rule 3.1 of the Rules of Procedure, and to the SC and any other subsidiary bodies of the MOP, as per Rule 21.3 of the Rules of Procedure; (ii). Any person fulfilling the *function of Chair or Vice-Chair of the MOP or Chair or Vice-Chair of a SIOFA subsidiary body or working group; (iii). Any person acting as a member of a delegation involved in the SIOFA decision-making process resulting in recommendations and/or approval for the SIOFA work requiring the engagement of a consultant; and (iv). Individuals who were SIOFA Secretariat staff members at the time when the recommendations and/or approval for the SIOFA works were adopted or who are members of immediate family (e.g., spouse or partner, father, mother, son, daughter, brother, or sister) of any Secretariat staff member or of the persons identified in 4 (i), (ii), and (iii).*

CONTACTS

Project Coordinator – SIOFA Science Officer (Marco Milardi, marco.milardi@siofa.org)

Administrator – SIOFA Executive Secretary (Thierry Clot, thierry.clot@siofa.org)

Annex 1 Climate Change Synthesis

Annex 1 consolidates two components: an executive summary of key findings and their implications for SIOFA fisheries, and the full technical climate synthesis; both are provided as a single annex for ease of reference.

Suggested Citation: Kryc, K (2026) Executive Summary: Climate Change Impacts on the Indian Ocean. Prepared for the Southern Indian Ocean Fisheries Agreement (SIOFA) REF CLI-2025-01

Executive Summary: Climate Change Impacts on the Indian Ocean

Introduction

Climate change is impacting the global ocean with some known and many unknown consequences for ocean life and the communities who depend on it. Due to the unique characteristics that define the Indian Ocean basin, the impacts of climate change are manifesting rapidly and acutely. Despite covering only 13% of the global ocean surface area, the Indian Ocean currently accounts for a disproportionate 25% of the total global ocean heat content increase, having absorbed 50%–70% of upper-ocean heat uptake (0–700m) over the last decade, resulting in unprecedented warming (e.g. Beal et al, 2020; Dalpadado et al., 2021; Philips et al., 2021; Dalpadado et al., 2024). As the Indian Ocean continues to warm, the basin's prevailing oceanographic regimes are rapidly changing as already evidenced by deoxygenation, acidification, stratification, and persistent marine heatwave conditions resulting in systemic ecological shifts.

The climate change summary documents (Attachments B (Executive Summary) and F (Climate Change Summary) provided to SIOFA for consideration are based on relevant, credible, peer-reviewed, scientific literature and attempt to describe a number of oceanographic parameters that are changing in response to climatic forcing; however, it should not be considered comprehensive as there are undoubtedly resources that were not included due to time and resource constraints. Note that considering each of the described parameters independently of each other risks oversimplifying a complex and interconnected oceanographic system. Where possible, the synergies between parameters are described. Despite the outsized response of the Indian Ocean to climate change, it remains understudied compared with the Pacific and Atlantic Oceans.

As biological systems and marine life are confronted with changing conditions, their life cycle tolerances will be tested and vulnerabilities exposed, which will require decision-makers and scientists to adjust accordingly, anticipate future conditions, and manage responsibly in the absence of certainty with the best available information.

The Indian Ocean: An overview

The Indian Ocean's response to global climate forcing is driven in part by its distinct geographical constraints. Unlike the Pacific or Atlantic Oceans, the Indian Ocean is blocked to the north by the Asian continent, which effectively prevents northward export of heat. This creates a unique scenario defined by intense ocean-atmosphere coupling in a confined area resulting in excess heat retention and associated changes to the Indian Ocean's physical, chemical, and biological characteristics (e.g. Bindoff et al., 2019; Sreeush et al., 2019; Abram et al., 2020a and 2020b; Roxy et al., 2020).

In addition, Indian Ocean dynamics are heavily influenced by the seasonal monsoon resulting in reversals in wind and currents that drive upwelling, mixing, and nutrient cycles and, consequently, biological productivity (e.g. Sarma and Dalabehera, 2019; Sreeush et al., 2019; Beal et al., 2020)

As noted above, the unique features that define the Indian Ocean are causing it to change rapidly across multiple oceanographic parameters simultaneously as it equilibrates to increasingly dynamic and disruptive conditions.

Indian Ocean oceanographic regime and climate-driven transformations

The Indian Ocean is dominated by four primary Indian Ocean climate modes: (1) The Indian Ocean Dipole (IOD); (2) The Indian Ocean Basin Mode (IOBM); (3) the Ningaloo Niño (NN); and (4) the Indian Ocean subtropical dipole (IOSD), which are responsible for inducing annual fluctuations of sea-surface temperatures and precipitation that, in turn, drive the basin's prevailing biogeochemistry and ecosystem signatures (e.g. Beal et al., 2020). Anthropogenic forcing is currently destabilizing these regimes. These modes are being fundamentally reconfigured (Saji et al., 1999; Phillips et al., 2021). Projections indicate a three-fold increase in the frequency of extreme positive IOD events by 2100. Simultaneously, the Indian Ocean Walker Circulation is weakening due to increased atmospheric stability, fostering a "positive IOD-like" mean state that favors deeper warming in the western basin (Sharma et al., 2025). These atmospheric shifts are coupled with a robust projected slowdown of major circulation features:

Table 1: Projected changes to Indian Ocean circulation patterns by the end of the century (modified from Stellema et al., 2019)

Circulation Feature	**Projected Reduction/Change**
Indonesian Throughflow	~26% Reduction
Agulhas Current	11% – 23% Reduction
Leeuwin Current (Surface)	2% – 11% Reduction
Leeuwin Undercurrent	15% – 17% Reduction
Deep Upwelling (at 1500m)	47% Decrease
Agulhas Current Extension	**28% Increase** (Key Exception)

This systemic deceleration of circulation provides the physical framework for intensifying surface thermal anomalies and the dramatic expansion of the Indian Ocean Warm Pool.

Dynamics of Sea Surface Temperature (SST) Change

The temporal evolution of SST in the Indian Ocean marks it as a global sink for anthropogenic heat uptake. In the last decade alone, the basin has accounted for an estimated 50%–70% of global upper-ocean heat uptake in the upper 700 meters (Phillips et al., 2021).

Historical data document a consistent warming trajectory, with SST increasing by an average of 0.7°C between 1982 and 2021 (Dalpadado et al., 2021). This has led to the expansion of the Indian Ocean Warm Pool (waters >28°C), which now maintains nearly 100% coverage across the northeast and central Indian Ocean (Kwiatkowski et al., 2020). However, this warming manifests through critical regional heterogeneities:

- **The Arabian Sea:** A dynamically driven hotspot accelerated by the slowdown of the Walker Circulation and reduced seasonal upwelling (Sharma et al., 2023).
- **The Southeastern Indian Ocean:** A radiatively driven hotspot resulting from reduced low-cloud cover and increased shortwave radiation (Sharma et al., 2023).
- **Seychelles–Chagos Thermocline Ridge:** A critical regional anomaly where thermocline dynamics further complicate the thermal map and impact localized productivity (Wang et al., 2023).

These rising average temperatures do not occur in isolation; they manifest as discrete, catastrophic thermal events that can trigger profound ecological regime shifts.

Marine Heatwave Dynamics and Impacts

Marine Heatwaves serve as harbingers of ecological collapse in the Indian Ocean. As the basin absorbs a disproportionate share of global heat, these discrete thermal anomalies are becoming more frequent, intense, and sustained.

A chronological analysis of recent major events illustrates their devastating impact to the Indian Ocean ecosystem:

- **1998:** An unprecedented basin-wide mass bleaching event, which fundamentally altered fish population age distributions (McClanahan et al., 2007a and 2007b; Graham et al., 2007).
- **2011 (Ningaloo Niño):** A regional marine heat wave off Western Australia that caused widespread ecological collapse of foundational reef species across 12° of latitude (Moore et al., 2012).
- **2016–2017:** A basin-wide mass bleaching event that pushed multiple reef systems toward functional extinction.
- **2019 Extreme IOD:** Linked to the resurgence of malaria in East Africa and extreme bushfire risks in Australia and Indonesia, demonstrating the far-reaching terrestrial impacts of marine anomalies (Hashizume et al., 2012; Wang and Cai, 2020).

Mechanistically, these extremes are often linked to the slowdown of the Walker Circulation and "positive IOD-like" patterns, which weaken vertical mixing and trap heat at the surface (Sharma et al., 2023). This extreme heat works in tandem with the accelerating chemical degradation of the basin's waters to alter the fundamental character of Indian Ocean basin ecosystems.

Ocean Acidification and pH Transitions

The Indian Ocean's role as a global carbon sink is actively degrading its own buffering capacity. The basin currently accounts for approximately one-fifth (20%) of the total global oceanic uptake of anthropogenic CO_2, leading to an increasingly corrosive environment (Beal et al., 2020).

Between 1961 and 2010, the basin recorded a pH decline of 0.0675 units (Madkaiker et al., 2023). Recent observations show an acceleration to 0.015 units per decade (Chakraborty et al., 2024). Analysis reveals that chemical factors—specifically the increase in Dissolved Inorganic Carbon (DIC)—contribute 69% to 94.5% of this acidification trend, while sea surface temperature warming contributes roughly 14% by reducing gas solubility (Chakraborty et al., 2024). Hotspots such as the Western Indian Ocean are acidifying rapidly, and this chemical stress frequently converges with acute thermal events.

This chemical shift is compounded by the physical loss of dissolved oxygen, creating a multi-stressor environment for marine biota.

Deoxygenation and Oxygen Minimum Zones (OMZs)

Dissolved oxygen serves as an effective proxy for the Indian Ocean's biogeochemical stability. Historical analysis indicates a decline in oxygen concentrations of 0.1 to 0.3 mol/kg/yr over the last five decades, driven by warming-induced solubility changes and intensified stratification (Ghosh et al., 2024).

The response of the Indian Ocean's Oxygen Minimum Zones is characterized by a non-linear "Three-Regime Response," involving the robust expansion of outer low-oxygen layers and a spatial redistribution of intermediate oxygen levels (Ditkovsky et al., 2023).

The Three-Regime Response of OMZs to Climate Forcing:

1. **Expansion:** A robust increase in low-oxygen volumes (< 85 μmol kg^{-1}).
2. **Contraction:** A reduction in the most intense suboxic core waters.
3. **Redistribution:** Spatial shifting of intermediate oxygen volumes

Geographically, this has resulted in the following differences between key regions of the Indian Ocean:

- **Arabian Sea OMZ:** The world's second most intense OMZ, exhibiting near-total suboxia between 200 and 1000 meters. Crucially, the Arabian Sea OMZ exhibits an eastward shift driven by the northward advection of oxygenated water and marginal sea inflows (Rixen et al., 2020; McCreary et al., 2013).
- **Bay of Bengal OMZ:** Relatively weaker, its dynamics are constrained by extreme near-surface stratification and a lack of remote organic detritus sources (Rixen et al., 2020).

Deoxygenation works in synergy with salinity shifts to restructure the water column and limit the vertical habitable range for marine life.

Salinity Changes and Stratification Dynamics

Salinity acts as a primary regulator of upper-ocean stratification, governing the distribution and storage of thermal energy. The Indian Ocean is exhibiting a spatial divergence in salinity driven by an intensifying hydrological cycle.

In the **Bay of Bengal**, massive riverine discharge and monsoonal rains create intense near-surface freshening, resulting in a persistent "Barrier Layer" that inhibits vertical mixing and nutrient entrainment (Rixen et al., 2020). Conversely, the **Arabian Sea** remains a net evaporative basin with high surface salinity, though its stratification is increasing due to thermal forcing and the shoaling of marginal sea outflows (Ditkovsky et al., 2023). Furthermore, the projected 26% reduction in the Indonesian Throughflow (ITF) will fundamentally decelerate the transport of salt and heat from the Pacific, altering the basin's buoyancy forcing (Stellema et al., 2019). These individual stressors act synergistically to transform the ocean's physical state.

Synergies Between Climate Stressors and Impacts

The nexus between climate forcing and resulting changes in the character of the Indian Ocean represents a compounding threat where interdependent stressors amplify one another. Warming accounts for 90% of the increased stratification in the upper 200 meters, creating a thermal barrier that traps heat at the surface (Dalpadado et al., 2024).

This stratification leads to significant "habitat compression." Highly migratory species are squeezed into narrower vertical layers due to the combination of surface warming and expanding deoxygenated zones. For large pelagic fish, the critical oxygen threshold of >150 μmol kg^{-1} is increasingly breached, restricting their habitable range (McCreary et al., 2013). Biogeochemical coupling further exacerbates the crisis: warming reduces gas solubility while functional anoxia triggers denitrification, releasing Nitrous Oxide (N_2O)—a potent greenhouse gas—creating a positive feedback loop (Ghosh et al., 2024).

Ecosystems, Productivity, and Biological Forecasts

The marine food web of the Indian Ocean is undergoing a forced transition, posing a threat to regional food security. Zooplankton biomass is projected to decline by 40% by 2100, a shift mechanistically linked to a 5%–10% shoaling of the mixed layer depth (Dalpadado et al., 2024; Gao et al., 2023).

A significant taxonomic shift is underway in the Arabian Sea, where traditional diatom blooms are being replaced by large, green mixotrophic *Noctiluca scintillans* blooms. This shift is mechanistically linked to reduced Himalayan-Tibetan snow cover, which intensifies monsoon winds and alters stratification (Goes et al., 2020; Hood et al., 2023).

Commercial fisheries impacts include:

- Yellowfin Tuna: Highly susceptible to habitat compression in the surface mixing layer; Western IO biomass is projected to drop 20% to 40% by 2050 (Dueri et al., 2017).
- Bigeye Tuna: Potentially more resilient due to their ability to utilize deeper, lower-oxygen waters (Marsac, 2017).
- Regional Forecasts: Fish biomass in East African waters is projected to drop by 56%–76% by 2100 (Jacobs et al., 2021).

Conclusions

The Indian Ocean is transitioning from a passive heat reservoir to a primary driver of global change. Its disproportionate heat uptake and accelerating physicochemical shifts mark it as an epicenter of ecological vulnerability. However, significant uncertainty remains due to a lack of data and observations in the basin (Phillips et al., 2021). These uncertainties are consequently amplified in model outputs.

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Section 1: Introduction/Overview of Indian Ocean Climate Dynamics

The Indian Ocean (IO) is a tropical ocean basin that serves as a sink for anthropogenic heat and carbon. Unlike the Pacific or Atlantic, the northern boundary of the IO is closed by the Asian landmass, a geographical constraint that prevents the efficient export of thermal energy and forces intense ocean-atmosphere coupling. Consequently, the basin acts as a disproportionate reservoir for global change; while it represents only 13% of the global ocean surface, it accounts for approximately 25% of the total global ocean heat content increase (Kwiatkowski et al., 2020).

The basin is currently transitioning from a passive reservoir to a primary driver of global environmental change. In the last decade alone, the Indian Ocean has accounted for an estimated 50%–70% of global upper-ocean heat uptake in the upper 700 meters (Phillips et al., 2019). This transformation is characterized by intense thermal loading—marked by the dramatic expansion of the Indian Ocean Warm Pool—and profound physicochemical shifts, including accelerating acidification and deoxygenation (Dalpadado et al., 2024; Chakraborty et al., 2024). This "capacitor effect," physically manifested through the Indian Ocean Basin Mode (IOBM), allows the basin to store massive thermal energy during Pacific El Niño events and subsequently discharge it, influencing global weather patterns and atmospheric circulation long after the initial Pacific signal has subsided (Phillips et al., 2021). From a policy perspective, the Indian Ocean has become an epicenter of ecological vulnerability, requiring a strategic shift in monitoring to manage the resulting basin-wide transformations.

Section 2: Indian Ocean Oceanography and Climate Drivers

1. The Indian Ocean Oceanographic Regime: Foundational Mechanisms and Modes

The internal variability of the IO is dictated by several fundamental oceanographic features:

- **Indian Ocean Dipole (IOD):** A primary driver of interannual variability involving a zonal sea surface temperature (SST) gradient. The positive phase (pIOD) is characterized by warmer waters and increased rainfall in the western basin, while cooler waters and easterly winds emerge in the east (Saji et al., 1999; Lu and Ren, 2020).
- **Indian Ocean Basin Mode (IOBM):** This manifests as a basin-wide warming signature, often described as the "capacitor effect." The IO warms in response to Pacific El Niño events via Kelvin and Rossby wave propagation, subsequently "discharging" this heat to influence atmospheric circulation long after the initial Pacific trigger has subsided (Phillips et al., 2021).
- **Ningaloo Niño:** A regional marine heatwave (MHW) occurring off the Western Australian coast, intrinsically linked to the intensification of the Leeuwin Current, which advects warm, tropical waters poleward (Hood et al., 2017; Beal et al., 2020).
- **Indian Ocean Subtropical Dipole (IOSD):** A regulator of thermal structures in the Southern Indian Ocean (SIO) that influences regional atmospheric pressure and moisture transport (Phillips et al., 2021).

Primary Circulation Pathways

The IO's circulation is defined by high-energy currents and meridional overturning cells:

- **Indonesian Throughflow (ITF):** The critical gateway for Pacific-to-Indian water exchange (e.g. Stellema et al., 2019).
- **Leeuwin Current:** A unique poleward-flowing eastern boundary current facilitating the southward dispersal of tropical species (e.g. Hood et al., 2017).
- **Agulhas Current:** A powerful western boundary current regulating inter-ocean exchange south of Africa (e.g. Stellema et al., 2019).
- **Cross-Equatorial and Subtropical Cells (CEC/STC):** Shallow overturning cells that facilitate tropical-subtropical exchange. The STC notably weakened by roughly 70% during the 1990s due to declining trade winds (e.g. Phillips et al., 2021).

While these natural modes have traditionally regulated the IO environment, anthropogenic forcing is in the process of disrupting established patterns, transitioning the basin from a more passive state to a primary driver of global change.

2. Anthropogenic Transformations of the Oceanographic Regime

The Indian Ocean has emerged as a primary engine of global anthropogenic heat uptake, accounting for an estimated 50%–70% of global ocean heat uptake in the upper 700 meters over the last decade (e.g. Phillips et al., 2019). This energy absorption is fundamentally altering the basin's physical structure and climate modes.

Mode Shifts and Intensification

Climate change is currently reconfiguring the behavior of IO modes:

- **IOD Extremes:** Projections indicate a three-fold increase in the frequency of extreme pIOD events by 2100, alongside a westward shift of the IOD "center of action" (Phillips et al., 2019; Saji et al., 1999).

- **Warm Pool Expansion:** The Indian Ocean Warm Pool (IOWP)—waters greater than 28°C—now covers nearly 100% of the northeast and central IO. In the south-central basin, this area has expanded by as much as 74% (Dalpadado et al., 2021; Dalpadado et al., 2024).
- **Walker Circulation Slowdown:** The Indian Ocean Walker Circulation (IOWC) is likely weakening due to increased atmospheric stability. This fosters a mean "pIOD-like" state, characterized by anomalous easterly winds and deeper warming in the western basin (Sharma et al., 2025).

Projected Circulation Deceleration

Anthropogenic forcing is expected to cause a robust slowdown of major South Indian Ocean circulation features by the late 21st century:

Circulation Feature	Projected Reduction/Change
Indonesian Throughflow (ITF)	~26% Reduction
Agulhas Current	11% – 23% Reduction
Leeuwin Current (Surface)	2% – 11% Reduction
Leeuwin Undercurrent	15% – 17% Reduction
Deep Upwelling (at 1500m)	47% Decrease
Agulhas Current Extension	**28% Increase** (Key Exception)

Source: Stellema et al., 2019

While these trends are basin-wide, their manifestation exhibits sharp regional asymmetries driven by distinct atmospheric and oceanic mechanisms.

3. Regional Asymmetries in Physical and Chemical Shifts

A "one-size-fits-all" approach to the Indian Ocean is insufficient due to the unique hydrological and atmospheric influences on its sub-basins.

Regional Differentiators:

- **Arabian Sea (AS) vs. Bay of Bengal (BoB):** The AS hosts the world's second most intense Oxygen Minimum Zone (ASOMZ), characterized by suboxic conditions between 200–1000m (Rixen et al., 2020) The ASOMZ exhibits an eastward shift driven by the northward advection of oxygenated water and Persian Gulf/Red Sea inflows (e.g. Rixen et al., 2020; McCreary et al., 2013]. In contrast, the BoB OMZ is less intense, constrained by extreme near-surface stratification and a lack of remote detritus sources (Rixen et al., 2020)
- **Southern Indian Ocean (SIO) vs. Northern Tropics:** The SIO is a nutrient-poor environment with a deep nitracline (the depth where nitrate rises sharply) often exceeding 100m. Conversely, the AS features a shallow nitracline (15–20m) driven by seasonal upwelling and convective mixing (Sarma and Dalabehera, 2019).
- **Thermal Hotspots:** Two distinct warming hotspots have emerged. The Arabian Sea warming is dynamically driven by the IOWC slowdown and reduced upwelling (Sharma et al., 2023). The Southeastern Indian Ocean (SEIO) hotspot is radiatively driven, resulting from reduced low-cloud cover and increased shortwave radiation (Sharma et al., 2023).

4. Primary Drivers of Oceanographic Change

The transformation of the Indian Ocean is driven by complex ocean-atmosphere coupling, where greenhouse gas-induced warming triggers secondary feedback loops.

Mechanistic Drivers

- **Atmospheric Forcing:** A record-breaking Interhemispheric Pressure Gradient (IHPG) between Australia and the South China Sea has been identified as a trigger for extreme events like the 2019 IOD (Lu and Ren, 2020). The slowdown of the IOWC further weakens cross-equatorial cells, reducing the upwelling of subsurface waters (Sharma et al., 2025).
- **Oceanic Dynamics:** Enhanced thermal stratification—where warming accounts for 90% of the density increase in the upper 200m—is trapping heat at the surface (Dalpadado et al., 2024). This is coupled with a shoaling of the Mixed Layer Depth (MLD**)** by 5% to 10% across much of the basin (Gao et al., 2023).
- **Terrestrial Interplay:** Reduced Himalayan-Tibetan snow cover is intensifying monsoon winds, accelerating Arabian Sea stratification, and fostering an environment conducive to massive *Noctiluca scintillans* blooms (Dalpadado et al., 2021; Hood et al. 2023)

5. Ecological Cascades and Biological Impacts

The shifting physical state of the Indian Ocean creates a dynamic interplay where physical changes translate into systemic threats to food security and biodiversity.

Synthesized Impacts

- **Trophic Collapse:** Models project a 40% decline in zooplankton biomass by 2100 (Dalpadado et al., 2024). This is mechanistically linked to the 5%–10% shoaling of the MLD, which restricts nutrient entrainment and primary production (Gao et al., 2023).
- **The Coral Crisis:** The basin is shifting toward a state of "near-perpetual" MHWs (e.g. Kwiatkowski et al., 2020). Acidification further hinders calcification, threatening the structural integrity of reefs from the Maldives to Australia (e.g. Dalpadado et al., 2021; Hollander et al., 2020).
- **Fisheries Disruptions:** Fish biomass in East Africa is projected to decrease by 56%–76% (Dalpadado et al., 2024; Jacobs et al., 2021). Yellowfin tuna are particularly vulnerable as they rely on the mixed layer, making them susceptible to habitat compression. Bigeye tuna, conversely, show greater adaptability to deeper, lower-oxygen waters (Marsac, 2017; Corbineau et al., 2008).
- **OMZ Expansion:** As OMZs expand and become functionally anoxic, they compress the habitable zones for large pelagic fish (>150 $\mu mol\ kg^{-1}$ threshold) (McCreary et al., 2013). This deoxygenation is linked to microbial shifts, including the replacement of diatoms by green mixotrophic *Noctiluca* blooms (Phillips et al., 2021; Hood et al., 2023).

Section 3: Indian Ocean Sea Surface Temperature Dynamics and Associated Ecological Transitions

1. Temporal Evolution of Sea Surface Temperatures (SST)

The Indian Ocean (IO) is in the process of transitioning to serving as a primary "clearing house" for anthropogenic heat. In the last decade, the basin has accounted for 50%–70% of total global ocean heat uptake in the upper 700 meters (e.g. Phillips et al., 2021). Most critically, the IO represents only 13% of the global ocean surface area yet accounts for a disproportionate 25% of the total global ocean heat content increase, underscoring its strategic significance in global warming dynamics (e.g. Kwiatkowski et al., 2020).

Historical data characterize a consistent and intensifying warming trajectory. Sea surface temperatures (SST) increased by an average of 0.7 °C between 1982 and 2021, while a secular warming trend of approximately 0.5 °C has been recorded since the 1950s (e.g. Kwiatkowski et al., 2020; Dalpadado et al., 2021). This thermal flux is most evident in the dramatic expansion of the Indian Ocean Warm Pool (IOWP)—waters warmer than 28 °C—which now maintains nearly 100% coverage of the northeast and central Indian Ocean (e.g. Dalpadado et al., 2021; Dalpadado et al., 2024).

Century-long projections indicate an accelerating crisis, with forecasted increases of 1.7–3.8 °C by 2100 under high-emission scenarios (e.g. Kwiatkowski et al., 2020; Dalpadado et al., 2021). However, these basin-wide averages are merely the sum of intense regional heterogeneities that define the Indian Ocean's physical and biological landscape.

2. Regional Heterogeneity and Thermal Hotspots

Uniform basin-wide averages mask critical regional vulnerabilities and localized thermal gradients. Understanding the Indian Ocean requires distinguishing "hotspots" where specific physical attributes are accelerating thermal change, creating unique, and regional environmental stressors (e.g. Dalpadado et al., 2024; Phillips et al., 2021)

Thermal manifestations diverge sharply between the Arabian Sea (AS) and the Southeastern Indian Ocean (SEIO). While heat storage in the northern IO has remained relatively constant, the Southern IO has experienced a significant increase in heat content (e.g. Dalpadado et al., 2021; Rixen et al., 2020). These regions are further distinguished by their biological baselines:

- **Arabian Sea (AS):** A high-productivity system driven by seasonal upwelling and convective mixing. It maintains a shallow nitracline (~15–20m) with high integrated nutrient levels: Nitrate at 703 ± 220 mmol m^{-2} and Phosphate at 70.5 ± 13 mmol m^{-2} (e.g. Dalpadado et al., 2024; Kwiatkowski et al., 2020; Jacobs et al., 2021).
- **South Indian Ocean (SIO):** Primarily oligotrophic with a deep nitracline (>100m) and significantly lower integrated nutrients: Nitrate at 108 ± 68 mmol m^{-2} and Phosphate at 47.0 ± 14 mmol m^{-2} (e.g. Dalpadado et al., 2024; Kwiatkowski et al., 2020; Jacobs et al., 2021).

Regional anomalies, such as the "Ningaloo Niño" off Western Australia and the dynamics of the "Seychelles–Chagos Thermocline Ridge," further complicate the thermal map (e.g. Dalpadado et al., 2024; Sharma et al., 2023; Wang et al., 2023). These regional thermal footprints are the surface manifestations of deeper atmospheric and sub-surface circulation disruptions.

3. Primary Mechanistic Drivers of Thermal Change

The thermal variability of the Indian Ocean is driven by a complex interplay between anthropogenic forcing and natural climate modes. A central driver is the greenhouse gas-induced slowdown of the Indian Ocean Walker Circulation (IWC) (e.g. Dalpadado et al., 2021; Dalpadado et al., 2024). This slowdown induces a "positive IOD-like" pattern, characterized by south-easterly wind anomalies that reduce upwelling in the western basin. This atmospheric shift facilitates stronger ocean-atmosphere coupling via the Bjerknes feedback, accelerating surface warming (e.g. Hood et al., 2017; Jacobs et al., 2021).

The basin also operates through the "Capacitor Effect," particularly in its teleconnections with the Pacific. The IO stores heat during El Niño events and subsequently "discharges" this energy, influencing atmospheric circulation and precipitation long after the original Pacific event has dissipated (e.g. Stellema et al, 2019; Sharma et al., 2023). In the SEIO, warming is amplified by a reduction in low-cloud cover, which increases the downward shortwave radiation reaching the surface (e.g. Dalpadado et al., 2024; Phillips et al., 2019; Stellema et al., 2019).

In the northern basin, monsoon reversals and terrestrial changes are paramount. Reduced snow cover over the Himalayan-Tibetan plateau has increased Arabian Sea stratification, accelerating warming faster than predicted by many global models (e.g. Stellema et al., 2019). These converging physical drivers create the environmental stressors that are currently restructuring marine biology.

4. Biological and Ecosystem Implications of Thermal Flux

The Indian Ocean is facing a thermal crisis that threatens biodiversity and the food security of rim countries. As the basin warms, the foundations of the marine food web are undergoing a forced transition (e.g. Dalpadado et al., 2024; Kwiatkowski et al., 2020; Phillips et al., 2021; Sharma et al., 2023).

Impacts on Primary Productivity and the Food Web

- **Phytoplankton and Zooplankton Decline:** Phytoplankton has declined by 20% over the last six decades, with regional surface chlorophyll showing a negative trend of −0.60% per year (e.g. Hood et al., 2017; Sharma et al., 2023). Consequently, zooplankton biomass is projected to decline by as much as 40% by 2100 (e.g. Heneghan et al., 2023; Dalpadado et al., 2024; Podder et al., 2024).
- **Species Transitions:** The reduction in snow cover over the Himalayan-Tibetan plateau has been directly linked to the emergence of *Noctiluca scintillans* blooms, as the planktonic community shifts from diatoms to large, green mixotrophic dinoflagellates (e.g. Phillips et al., 2023; Sharma et al., 2022; Poloczanska et al., 2016).

The Coral Reef Crisis Coral habitats are under threat from rising temperatures and marine heatwaves (MHWs). Following mass bleaching events in 1998 and 2016, projections suggest the East African coast will face year-long continuous MHWs as early as the 2030s (e.g. Hood et al., 2017; Dalpadado et al., 2021; Jacobs et al., 2021; Dalpadado et al., 2024).

Disruption of Commercial Fisheries Climate change is projected to cause a 90% decline in vital tuna species (e.g. Dueri et al., 2017; Hood et al., 2023; Chakraborty et al., 2024; Podder et al., 2024;). However, species exhibit varying vulnerabilities: yellowfin tuna are highly susceptible to IWC-driven surface changes as they inhabit the mixing layer, whereas bigeye tuna may adapt by utilizing deeper, lower-oxygen waters (e.g. Hood et al., 2017; Stellema et al., 2019; Hood et al., 2023). In Kenyan and Tanzanian waters, fish biomass is projected to drop by 56–76% due to "habitat compression," where warming and expanding anoxic Oxygen Minimum Zones (OMZs) restrict the vertical range of macrofauna (e.g. Roxy et al., 2016; Lu and Ren et al., 2020; Hood et al., 2023; Sharma et al., 2023).

Ocean Acidification The basin recorded a pH decrease of 0.0675 units between 1961 and 2010, with projections of a 0.4-unit drop by 2100 (e.g. Dalpadado et al., 2024; Jacobs et al., 2021). Mechanistically, Dissolved Inorganic Carbon (DIC) contributes 69.3% to this trend, while surface temperature accounts for 13.8%, severely impacting calcifying organisms like corals and foraminifers (e.g. Kwiatkowski et al., 2020; Jacobs et al., 2021; Phillips et al., 2021; Dalpadado et al., 2024). These biological assessments remain subject to the limitations of current scientific infrastructure.

Section 4: Indian Ocean Marine Heatwave Dynamics, Changes, and Impacts

1. Introduction: The Indian Ocean as a Global Heat Sink

As a result of climate change, the Indian Ocean (IO) is undergoing a fundamental transition causing it to become a sink for anthropogenic heat within the global climate system. Observations confirm that the IO now accounts for an extraordinary 50%–70% of global upper-ocean heat uptake (0–700m), a disproportionate share that marks it as a global warming epicenter (e.g. Prince et al., 2006; Kataoka et al., 2014; Sharma et al., 2022; Gao et al., 2023). In this context, the monitoring of Marine Heatwaves (MHWs)—discrete, extreme thermal anomalies—is an imperative. These events serve as harbingers of impending ecological regime shifts, signaling the rapid transformation of tropical marine systems.

2. Chronological Synthesis of Significant Thermal Anomalies

Understanding the historical timeline of MHWs is essential for identifying the "new normal," where transient anomalies are replaced by persistent thermal stress that frequently exceeds historical statistical thresholds. The following synthesis (Table 1) merges physical drivers and biological milestones to provide a standalone strategic tool for impact assessment.

Table 1: Chronological Synthesis of Significant Indian Ocean Thermal Anomalies

Year/Period	Event Name/Type	Geographic Extent	Biological/Socioeconomic Impact	Primary References
1998	Unprecedented Mass Bleaching	Basin-wide	First documented catastrophic bleaching; altered age distribution of fish populations; altered community composition.	McClanahan et al. (2007); Graham et al. (2007)
2005	Western IO Heat Stress	Western Indian Ocean	Significant thermal stress affecting Western Indian Ocean coral communities and susceptibility to extinction.	McClanahan et al. (2007)
2011	Ningaloo Niño	Western Australia	Unprecedented bleaching across 12° of latitude; widespread ecological collapse of foundational reef species.	Prince and Goodyear (2006); Moore et al. (2012); Kataoka et al. (2014)
2014–2017	Protracted Warming	Basin-wide	Multi-year thermal stress leading to large-scale, repeated bleaching and high-mortality events.	Obura et al. (2017)
2016	Basin-wide Mortality	Maldives to Australia	Unprecedented coral mortality; pushed multiple reef systems past critical tipping points toward functional extinction.	McClanahan et al. (2007); Lee et al. (2015); Beal et al. (2020); Dalpadado et al. (2021)
2019	Extreme Indian Ocean Dipole (IOD)	Basin-wide	Strongest positive IOD since 1980s; correlated with **resurgence of malaria** in East Africa and extreme **bushfire risks** in Australia/Indonesia.	Hashizume et al. (2012); Lu and Ren (2020); Wang and Cai (2020)

These increasingly frequent and sustained marine heat waves result in extreme nutrient limitation, which has the potential to disrupt food chains and the communities who depend on them for protein.

3. Mechanistic Drivers: Atmospheric and Oceanographic Forcing

The generation of MHWs in the Indian Ocean is dictated by a sophisticated interplay between greenhouse gas forcing and regional climate modes. The IO's unique geography as a landlocked basin to the north creates high-sensitivity environments where heat accumulates without a northern exit, resulting in significant thermal inertia.

- **Indian Ocean Walker Circulation (IOWC) Slowdown:** Anthropogenic forcing has been shown to slow the IOWC, fostering "positive IOD-like" patterns. This weakens vertical mixing and generates anomalous easterly winds that suppress the entrainment of cooler subsurface waters (Sharma et al., 2022; Gao et al., 2023).
- **The "Capacitor Effect":** The IO acts as a thermal capacitor for Pacific El Niño events. It absorbs massive heat during the Pacific cycle and subsequently discharges this stored energy, influencing regional precipitation and atmospheric circulation long after the initial Pacific signal has dissipated (Xie et al., 2009; Stellema et al., 2019).
- **Monsoonal Wind Forcing:** The Southwest (SWM) and Northeast (NEM) monsoons are primary regulators of the Indian Ocean heat budget. Disruptions in SWM-driven upwelling off Oman and Somalia—a traditional cooling mechanism—has lead to rapid surface warming and heat accumulation.
- **The Interhemispheric Pressure Gradient (IHPG):** The extreme 2019 IOD was specifically driven by a record-breaking pressure gradient between Australia and the South China/Philippine Seas, demonstrating how remote atmospheric pressures dictate regional thermal extremes (Lu and Ren, 2020).

This slowdown in shallow meridional overturning cells—the Cross-Equatorial and Subtropical Cells—further traps heat. However, these basin-wide drivers manifest with distinct regional heterogeneities.

4. Regional Heterogeneity and Geographic Differentiators

High-resolution regional data rather than basin-wide averages for the Indian Ocean are essential, but often lacking, as sub-regional dynamics determine whether an area acts as a carbon source or sink.

- **The Arabian Sea:** Defined by "fast local warming," this region is a major CO_2 source during the SWM. Critically, marginal sea shoaling from the Persian Gulf and Red Sea is reducing oxygen supply to the deep Oxygen Minimum Zone (OMZ). This, combined with IOWC-driven wind anomalies, is intensifying deoxygenation toward functional anoxia (Lachkar et al., 2020).
- **The Bay of Bengal:** This region is characterized by high stratification and "freshening" from riverine discharge and melting Himalayan ice. This vertical stability traps heat in the near-surface layer, though data on net CO_2 flux remain sparse (Sridevi and Sarma, 2021).
- **Southeastern Indian Ocean (SEIO) & Western Australia:** Dominantly influenced by atmospheric radiative forcing (reduced low-cloud cover), this region hosts the Leeuwin Current. Mesoscale eddies here create a "wineglass shape" of carbon transport extending down to 1000m, where vertical carbon flux in eddy centers is seven times higher than at the flanks (Waite et al., 2016; Sharma et al., 2023).
- **Southern Subtropical Gyre:** A highly stratified region acting as a CO_2 sink. High stability favors the accumulation of Dissolved Organic Carbon (DOC) in the photic

zone, as DOC is produced faster than it is consumed or mixed downward (Hansell, 2009).

Regional physical forcing acts as the primary determinant for biological survivability, dictating a potential future of regional "winners and losers" based on thermal tolerance.

5. Ecological Reconfiguration and Biological Risks

Marine heatwaves are the primary engines of ecological collapse with the potential to push foundational species across physiological tipping points.

- **Foundation Species:** Enhanced stratification has caused a 20% decline in phytoplankton over six decades, which is directly linked to the projected 40% decline in zooplankton by 2100 (Lee et al., 2015; Beal et al., 2020; ; Kwiatkowski et al., 2020). Thermal stress compounded with the potential collapse of the energy hierarchy is pushing coral reefs toward being the first global ecosystem to face functional extinction (McClanahan et al., 2007; Dalpadado et al., 2021).
- **Fisheries and Food Security:** Warming is driving "habitat compression" for many tunas, forcing skipjack, yellowfin, and bigeye into narrower layers due to a shoaling thermocline. Biomass in East African waters is projected to decline by 56–76% (Prince and Goodyear, 2006; Kataoka et al., 2014). In the Bay of Bengal, the productivity decline correlates with the reduction of Hilsa Shad, a critical protein source for Bangladesh and Myanmar (Lee et al., 2015; Beal et al., 2020).
- **Microbial Shifts:** Warming favors diazotrophic cyanobacteria like *Trichodesmium*. Increased CO_2 in the water can enhance its nitrogen fixation, potentially altering the elemental ratios of organic matter and disrupting microbial nitrification (Hutchins et al., 2007; Gattuso and Hansson, 2011).

6. Physiochemical Feedback Loops: Oxygen, pH, and Stratification

MHWs function as "force multipliers" for deoxygenation and acidification, creating self-reinforcing feedback loops.

- **Stratification and Mixed Layer Depth (MLD):** Warming accounts for 90% of increased stratification, causing a 5-10% shoaling of the MLD. This traps more heat at the surface, further intensifying MHWs (Sharma et al., 2022; Gao et al., 2023).
- **Deoxygenation and "Functional Anoxia":** Warming reduces oxygen solubility and ventilation, promoting functional anoxia (<0.05 µmol/kg). While the Arabian Sea is already functionally anoxic at depth, the Bay of Bengal remains poised just above this threshold (Lachkar et al., 2019).
- **Negative Feedback Loop:** A critical feedback mechanism exists where reduced productivity—driven by nitrogen loss via denitrification—eventually reduces biological oxygen consumption at depth. This could lead to a situation where the anoxic core expands even as the total volume of hypoxic waters shrinks (Lachkar et al., 2016).
- **Acidification Dynamics:** The basin is acidifying at 0.015 units per decade. Dissolved Inorganic Carbon (DIC) contributes 70% of this trend, while warming contributes 14-16% (Chakraborty et al., 2024).
- **Deep Ocean Carbon Pools:** In the deep IO (>1000m), DOC concentrations are higher than in the Pacific. Much of this is refractory and likely >4000 years old, representing a massive but stable carbon pool (Hansell et al., 2009).

Section 5: Indian Ocean pH and acidification changes

1. Temporal Evolution of Seawater Chemistry in the Indian Ocean

The Indian Ocean's role as a global sink for anthropogenic carbon is degrading its buffering capacity and diminishing its continued ability to sequester carbon, signaling an acute shift in the basin's carbonate system attenuation.

Research reveals that the Indian Ocean is transitioning toward a more corrosive marine environment:

- **Historical pH Decline:** Between 1961 and 2010, the basin experienced a recorded pH decrease of 0.0675 units (e.g. Madkaiker et al., 2023).
- **Recent Acceleration:** From 1980 to 2019, the rate of acidification intensified significantly to 0.015 units per decade, nearly doubling the historical decadal rate (e.g. Chakraborty et al., 2024).
- **pCO_2 Accumulation:** Surface seawater partial pressure of CO_2 (pCO_2) has increased by approximately 60 μatm since 1980 (e.g. Chakraborty et al., 2024; Dalpadado et al., 2024).
- **Future Projections:** High-emission trajectories (RCP 8.5/SSP585) forecast a precipitous 0.3 to 0.4 unit pH decline by the year 2100 (e.g. Jacobs et al., 2021; Chakraborty et al., 2024; Dalpadado et al., 2024).
- **Carbon Fraction:** The Indian Ocean now accounts for roughly one-fifth (20%) of the total global oceanic uptake of anthropogenic CO_2 (e.g. Beal et al., 2020).

These temporal trends indicate an ongoing shift in seawater stoichiometry with potentially profound implications for marine life throughout the Indian Ocean.

2. Regional Heterogeneity and Spatial Vulnerabilities

Considering basin-wide averages may obscure inherent sub-basin dynamics driven by monsoon reversals, massive riverine flux, and distinct thermocline structures, among others. Below some known regional differences are detailed.

Region	Specific Chemical Trend	Primary Influencing Factors
Western Indian Ocean	Fastest-acidifying region in the basin (e.g. Madkaiker et al., 2023, Chakraborty et al., 2024).	Intense SST warming (contributing ~16% to acceleration) and rapid CO_2 uptake (e.g. Madkaiker et al., 2023).
Northern Bay of Bengal	Trends dominated by Total Alkalinity (ALK) shifts (55.6%) (e.g. Madkaiker et al., 2023).	Massive riverine runoff introducing pCO_2 rich water and high freshwater-driven stratification (e.g. Chakraborty et al., 2024).
Arabian Sea	Expanding Oxygen Minimum Zones (OMZs) and suboxia (e.g. Rixen et al., 2020; Hood et al., 2023).	Upwelling of low-pH subsurface waters; marginal sea shoaling (Persian Gulf/Red Sea outflows) altering OMZ ventilation (e.g. Ditkovsky et al., 2023).
Southern Indian Ocean	Oligotrophic state with low nutrient availability (e.g Sarma and Dalabehera, 2019).	Deeper nitracline reaching ~82m at 9°S and dropping below 100m elsewhere; stronger stratification (e.g Sarma and Dalabehera, 2019).

A unique "hotspot" is identified in the Southeastern Indian Ocean, where acidification is significantly amplified by atmospheric radiative perturbations. Reduced low-cloud cover in this region increases downward shortwave radiation, directly heating surface waters and reducing the solubility of CO_2, thereby accelerating local pH decline (e.g. Sharma et al., 2023).

3. Primary Drivers of Ocean Acidification and Chemical Flux

The chemical transformation of the Indian Ocean is a product of direct atmospheric forcing and complex internal oceanographic feedbacks. An analysis of drivers reveals that chemical factors are more impactful than physical factors:

1. **Anthropogenic CO_2 Uptake:** The primary driver, accounting for 80% to 94.5% of the net pH decline across sub-regions (e.g. Chakraborty et al., 2024).
2. **Sea Surface Temperature (SST) Warming:** A potent secondary driver, contributing between 7.0% and 14.4% to acidification trends (e.g. Chakraborty et al., 2024), while specific regional models cite a 13.8% contribution (e.g. Madkaiker et al., 2023).

Internal climate modes, specifically El Niño and the positive Indian Ocean Dipole (pIOD), serve to enhance this baseline acidification. These events foster basin-wide warming and the isopycnal shoaling of low-pH, nutrient-rich subsurface waters, particularly in the eastern basin (e.g. Chakraborty et al., 2024). Furthermore, the projected slowdown of the Indian Ocean Walker Circulation (IOWC) facilitates a "pIOD-like" state. This atmospheric shift generates easterly wind anomalies and a shoaling thermocline, which reduces the upwelling of cooler waters while enhancing near-surface stratification (e.g. Goes et al., 2020; Sharma et al., 2023). This creates a self-reinforcing cycle where heat and carbon are trapped in the surface layer, accelerating the degradation of the basin's buffering capacity.

4. Ecosystem and Biological Consequences

The Indian Ocean changing chemistry may represent a shift resulting in acute physiological stress for marine life.

Impacts on Calcifying Organisms The proliferation of H^+ ions consumes available carbonate ions ($CO_3^{\{2-\}}$), impairing the ability of calcifiers to maintain skeletal integrity (e.g. Madkaiker et al., 2023; Chakraborty et al., 2024). This mechanism threatens:

- **Corals:** Reduced calcification and increased skeletal dissolution, leading toward potential reef ecosystem extinction (e.g. Hollander et al., 2020; Ghosh et al., 2024).
- **Foraminifera and Pteropods:** These foundational micro-calcifiers face aragonite undersaturation, which can dissolve shells and disrupt the biological carbon pump (e.g. Henley et al., 2020; Madkaiker et al., 2023).

Fisheries and Habitat Compression Warming and acidification are causing significant habitat compression for commercially vital species like yellowfin and skipjack tuna. Yellowfin larvae are especially vulnerable to lethal and sub-lethal pH effects, which disrupt sensory functions and metabolic growth (e.g. Dueri et al., 2017; Chakraborty et al., 2024). Adult stocks are projected to relocate toward higher latitudes or deeper waters to maintain thermal/oxygen preferences; notably, Western Indian Ocean yellowfin biomass is forecast to drop by 20% to 40% by 2050 (e.g. Dueri et al., 2017).

Ecological State Changes There are differing views of impacts in the the Arabian Sea. While many models project a decline in Net Primary Production (NPP) (e.g. Dalpadado et al., 2024; Ghosh et al., 2024), *in situ* observations show that f-ratios and primary productivity levels remained remarkably stable between 1995 and 2015 despite rapid warming (e.g. Sarma and Dalabehera, 2019). Regardless, the planktonic community composition is shifting; winter blooms in the northern Arabian Sea are transitioning from diatoms to large, green mixotrophic dinoflagellates (*Noctiluca scintillans*) (e.g. Phillips et al., 2021; Hood et al., 2023). Simultaneously, the expansion of OMZs facilitates "functional anoxia," which triggers the production of Nitrous Oxide (N_2O)—a potent greenhouse gas—creating a positive feedback loop to the global climate system (e.g. Ditkovsky et al., 2023; Hood et al., 2023).

Section 6: Overview of Deoxygenation and Oxygen Minimum Zones (OMZs) in the Indian Ocean

1. Temporal Trends in Indian Ocean Oxygen Levels

In the context of a warming ocean basin, monitoring dissolved oxygen serves as a vital strategic proxy for the basin's biogeochemical stability. Because oxygen levels are sensitive to both physical circulation and biological consumption, they provide a sensitive metric for the disruption of vertical ventilation and the overall health of the marine ecosystem.

Synthesis of Temporal Changes

Historical analysis and Earth System Model (ESM) projections indicate a steady trajectory toward deoxygenation throughout the Indian Ocean basin:

- **Observed Secular Decline:** Over the last five decades, oxygen concentrations in the tropical open ocean have dropped by 0.1 to 0.3 μmol\kg\yr (Ghosh et al., 2024) This trend is primarily driven by warming-induced solubility changes and intensified stratification.
- **Century-Scale Projections:** Under high-emission scenarios, global oxygen levels are projected to decline by 1% to 7% by 2100 (e.g. Ghosh et al., 2024).
- **The "Three-Regime Response":** The response of IO Oxygen Minimum Zones (OMZs) to climate forcing is non-linear. Projections reveal a complex restructuring: a robust expansion of the outer layers (low-oxygen volumes < 85 μmol\kg\yr a contraction of the most intense suboxic core waters, and a spatial redistribution of intermediate oxygen volumes (85–180 μmol\kg\yr (e.g. Ditkovski et al., 2023).

These temporal shifts are characterized by significant regional heterogeneity, as the IO's unique landlocked northern boundary creates distinct regions of deoxygenation that express themselves differently to climatic forcing and advective pathways.

2. Regional Heterogeneity: Arabian Sea vs. Bay of Bengal

The Indian Ocean's geography—closed to the north by the Asian landmass—prevents the northward export of heat and restricts the ventilation typically provided by high-latitude water mass formation. This creates the conditions for two of the world's most significant OMZs, which exhibit functionally different dynamics.

Comparative Analysis of OMZs

The Arabian Sea Oxygen Minimum Zone (ASOMZ) and the Bay of Bengal Oxygen Minimum Zone (BBOMZ) are governed by distinct physical and biological drivers:

- **The ASOMZ:** Identified as the second most intense OMZ globally, it features near-total oxygen depletion (suboxia) between 200 and 1000 meters, sufficient to trigger active denitrification (Rixen et al., 2020). The upper portion of the ASOMZ is shifted eastward, away from the highly productive western upwelling zones. This shift is maintained by specific physical barriers, primarily the northward advection of oxygenated water from the Southern Hemisphere and the inflow of relatively oxygen-rich water from the Persian Gulf (e.g. Rixen et al., 2020).
- **The BBOMZ:** While significant, the BBOMZ is relatively weaker than the ASOMZ. It is functionally distinct because it lacks a remote source of organic detritus from western boundary upwelling (e.g. Rixen et al., 2020). Furthermore, high freshwater runoff from large river systems creates intense near-surface salinity stratification,

which inhibits nutrient entrainment and subsurface remineralization (e.g. Rixen et al., 2020).

- **Coastal Hypoxia Trends:** Regional dynamics create localized biological crises. During the Northeast Monsoon, the reversal of the West India Coastal Current induces strong density stratification. This prevents vertical ventilation, leading to severe hypoxia and mass fish kills on the West Indian shelf (e.g. Hood et al., 2017).

3. Primary Physical and Chemical Drivers of Change

The deoxygenation of the IO results from an interplay between atmospheric forcing and oceanic response. The implications of basin-wide warming extend beyond temperature increases to the fundamental disruption of the vertical mixing processes required to sustain subsurface life.

Mechanistic Evaluation

The primary drivers of deoxygenation and OMZ expansion are categorized below:

- **Mixed Layer Depth (MLD) Shoaling:** Warming accounts for 90% of the increased stratification in the upper 200 meters (e.g. Dalpadado et al., 2024). Crucially, the MLD in the northern tropics and southern subtropics has decreased (shoaled) by 5% to 10% since the 1980s (e.g. Gao et al., 2023). This shoaling inhibits the vertical mixing of oxygenated surface water into the interior.
- **Solubility and Buoyancy:** Rising SSTs directly reduce the solubility of oxygen. Furthermore, the rapid heating of the Persian Gulf and Red Sea increases the buoyancy of their outflows, causing them to "shoal" to shallower depths, which reduces the ventilation of the deeper layers of the northern Arabian Sea (e.g. Ditkovsky et al., 2023).
- **Monsoon Variability and Productivity Debates:** While intensified monsoon winds can enhance upwelling and biological productivity, the long-term impact on the biological pump is a subject of scientific debate. Some research indicates a decline in primary production due to nutrient depletion (e.g. Dalpadado et al., 2024) yet in situ measurements in the Arabian Sea found that mean photic zone primary production in 2015 (1238 ± 626 mgC/m^2/d) was not statistically different from 1995 values (1371 ± 132 mgC/m^2/d), suggesting a degree of stability despite rapid warming (e.g. Sarma and Dalabehera, 2019).

4. Ecological Consequences and Biological Vulnerability

The expansion of low-oxygen volumes leads to "habitat compression," a phenomenon that restricts the vertical and horizontal range of marine species. This poses a threat to regional food security and the economic viability of the Indian Ocean's blue economy.

Transformation of the Biological Environment

Shifts across trophic levels are increasingly evident:

- **Habitat Compression for Apex Predators:** Highly migratory species like tuna are restricted by oxygen and thermal thresholds. Yellowfin tuna, primarily surface-bound, are highly vulnerable, with western IO biomass projected to drop 20% to 40% by 2050 (e.g. Dueri et al., 2017). In contrast, Bigeye tuna may exhibit higher resilience by moving into deeper, lower-oxygen waters (e.g. Goes et al., 2020).
- **Nitrogen Cycle Disruption:** Suboxic conditions trigger denitrification, which converts fixed nitrogen into N_2 gas and produces Nitrous Oxide (N_2O), a potent greenhouse gas (e.g. Ghosh et al., 2024). This process can lead to silicate or iron limitation,

shifting the phytoplankton community from large diatoms to smaller, less efficient species, thereby altering the efficiency of the biological pump (e.g. Hood et al., 2016).

- **Planktonic Community Shifts:** A significant teleconnection has emerged between the terrestrial cryosphere and marine state changes. Reduced snow cover over the Himalayan-Tibetan plateau has been linked to the emergence of massive winter blooms of the green mixotrophic dinoflagellate *Noctiluca scintillans*, which is displacing traditional diatom blooms in the Arabian Sea (e.g. Ghosh et al., 2024).
- **Benthic and Reef Stress:** Marine ecosystems experience significant biodiversity loss when oxygen levels fall below the hypoxia threshold of 60 μmol\kg (e.g Ditkovski et al., 2023). Coral reefs, already compromised by marine heatwaves, find their recovery hampered by the encroachment of low-oxygen waters.

Section 7: Indian Ocean Salinity Changes

1. Strategic Context: The Role of Salinity in the Indian Ocean's Climate System

Salinity is a primary physical regulator in the Indian Ocean (IO)contributing to upper-ocean stratification and driving meridional circulation. Salinity-driven buoyancy forcing governs how this heat is distributed and stored, making the study of its spatiotemporal dynamics a priority for understanding both regional climate stability and global thermal trajectories.

2. Anthropogenic Forcing and Decadal Salinity Trends

The global hydrological cycle is intensifying under anthropogenic forcing, and the Indian Ocean exhibits a high-sensitivity response to these global signals. Observations indicate rising regional sea levels and an intensified water cycle characterized by a marked redistribution of freshwater (e.g. Beal et al., 2020). Historically, the basin has undergone a secular warming trend of ~0.5°C since the 1950s, a trend that accelerates the evaporation-precipitation cycles and alters salinity climatology (Phillips et al., 2021).

Future projections, however, are uncertain. Earth System Models (ESMs) in the CMIP6 suite show a significant lack of consensus regarding future salinity and net primary production (NPP) trends (e.g Dalpadado et al., 2024, Ghosh et al., 2024). This uncertainty is largely attributed to model physics deficiencies, including spurious convective overturning, numerical mixing, and unrealistic horizontal diffusion (e.g. Phillips et al., 2021). Despite these discrepancies, the broader trend suggests that human-induced forcing is overriding natural interannual signals, necessitating a granular analysis of regional sub-basins where these shifts manifest most aggressively.

3. Regional Heterogeneity: Spatial Divergence in Salinity Profiles

A basin-wide salinity average obscures the starkly divergent hydrological regimes of the northern Indian Ocean. The distinct hydrography of the northern sub-basins is primarily driven by the balance between terrestrial runoff, precipitation, and marginal sea inflows.

- **The Bay of Bengal (BoB):** Defined by massive freshwater input from large river systems and monsoonal rains, the BoB exhibits intense near-surface salinity stratification (e.g. Rixen et al., 2020). This results in a persistent "Barrier Layer" or halocline that inhibits vertical mixing and suppresses the entrainment of nutrient-rich deeper waters (e.g. Beal et al., 2020, Ghosh et al., 2024).
- **The Arabian Sea (AS):** Contrastingly, the AS is a net evaporative basin with high surface salinity. However, its stratification is increasingly influenced by "marginal sea shoaling" (e.g. Ditkovsky et al., 2023). As the Persian Gulf and Red Sea—key oxygen sources for the deeper Arabian Sea—warm rapidly, their outflows become more buoyant and shoal to shallower depths, reducing oxygen supply to the deeper Oxygen Minimum Zone (OMZ) (e.g. Rixen et al., 2020; Ditkovsky et al., 2023).
- **Equatorial and Southern IO:** Circulation in these regions is governed by inter-ocean exchange, specifically the Indonesian Throughflow (ITF). Projections indicate a robust 26% reduction in the ITF by the late 21st century, which will fundamentally decelerate the transport of salt and heat from the Pacific into the Indian Ocean (e.g. Stellema et al., 2019).

Sub-Basin Comparative Dynamics

Dimension	Bay of Bengal (BoB)	Arabian Sea (AS)
Primary Freshwater Source	River runoff (Ganges-Brahmaputra) and monsoons (e.g. Rixen et al., 2020)	Dominated by evaporation; limited runoff (e.g. Chakraborty et al., 2024)
Stratification Driver	Buoyancy forcing from riverine freshwater plumes (e.g.Ghosh et al., 2024)	Thermal forcing and shoaling marginal sea outflows (e.g. Ditkovsky et al., 2023)
Model Representation Bias	Systematically underestimates oxygen levels (e.g. Ditkovsky et al., 2023)	Systematically overestimates oxygen levels (e.g. Ditkovsky et al., 2023)
Model Skill Issues	Poor representation of large river runoff (e.g. Dalpadado et al., 2024)	Fails to resolve marginal sea dynamics (e.g. Ditkovsky et al., 2023)

4. Primary Drivers of Salinity Transformation

The transformation of IO salinity is dictated by the interplay between atmospheric forcing, terrestrial flux, and ocean-atmosphere coupling.

- **Hydrological Cycle and Aerosol Forcing:** Increased greenhouse gases and aerosol emissions over Asia have disrupted monsoonal cycles (e.g. Ghosh et al., 2024). Notably, the reduction in snow cover over the Himalayan-Tibetan plateau is accelerating the stratification of the Arabian Sea at a rate exceeding global model projections (e.g. Ghosh et al., 2024).
- **The "Capacitor Effect":** The IO does not merely respond to external forcing; it acts as a capacitor for El Niño events. It warms in response to El Niño and subsequently "discharges" this heat, modulating precipitation and atmospheric circulation long after the initial Pacific event has dissipated (e.g. Phillips et al., 2021).
- **Climate Modes:** Interannual salinity shifts are driven by the Indian Ocean Dipole (IOD). Positive IOD events trigger anomalous easterly winds and enhanced upwelling in the east, while extreme events (e.g., those in 2019) can create record-breaking pressure gradients that fundamentally shift surface salinity and thermocline depth (e.g. Lu and Ren, 2020; Fereday et al., 2025).

5. Trophic Cascades and Habitat Compression

Salinity-induced stratification acts as a physical gatekeeper for the "biological pump," regulating nutrient availability and ecosystem health.

- **Nutrient and Oxygen Inhibition:** Excess freshwater in the BoB creates a stable halocline that starves the surface layers of nutrients and inhibits the ventilation of deeper waters (e.g. Beal et al., 2020). In the Arabian Sea, the expansion and intensification of functional anoxia in the OMZs trigger denitrification, leading to the loss of essential fixed nitrogen (e.g. Rixen et al., 2020; Phillips et al., 2021).
- **Primary Productivity Decline:** A critical distinction must be made between historical and projected productivity losses. Satellite and model data confirm an alarming 20% decrease in phytoplankton has already occurred over the last six decades (e.g Dueri et al., 2017). Future projections forecast a further 20% reduction in net primary productivity by 2100 as stratification intensifies (e.g. Beal et al., 2020; Dalpadado et al., 2024).
- **Community Composition Shifts:** Biogeochemical imbalances are triggering a taxonomic shift in phytoplankton community structure. There is a documented transition in northern Arabian Sea winter blooms from diatoms to large, green mixotrophic dinoflagellates (*Noctiluca scintillans*), signaling an ecosystem in crisis (e.g. Phillips et al., 2021).

- **Habitat Compression:** The combination of deoxygenation and warming is compressing habitable zones for large pelagic species. For instance, skipjack tuna face significant habitat disruption as surface waters exceed their 29-30°C limits, while declining oxygen levels in the eastern basin limit the vertical movement of yellowfin and bigeye tuna (e.g. Stellema et al., 2019; Wang et al., 2023).

Section 8: Climate Change Dynamics in the Indian Ocean: A Synthesis of Interdependent Stressors[1]

1. Thermal Forcing and the Escalation of Surface Stressors

The Indian Ocean (IO) has emerged as a preeminent global warming hotspot, exhibiting some of the most rapid surface warming rates of any tropical basin. Sea Surface Temperature (SST) acts as the primary catalyst for a cascade of physical and chemical shifts, serving as the strategic driver of an escalating thermal crisis. This forcing is not merely a surface phenomenon; it dictates the pace of heat uptake and the redistribution of energy across the basin, fundamentally altering the vertical structure and biogeochemistry of the water column.

The Warming-Heatwave-Stratification Nexus

The intensification of Marine Heatwaves is inextricably linked to an average SST increase of approximately 0.7 °C observed between 1982 and 2021. This secular warming trend is further evidenced by the dramatic expansion of the Indian Ocean Warm Pool (IOWP)—waters exceeding 28 °C—which now encompasses nearly 100% of the northeast and central Indian Ocean. Surface warming accounts for approximately 90% of the increased upper-ocean stratification recorded in the upper 200 meters. This buoyancy-driven process increases the density gradient, creating a potent thermal barrier that inhibits vertical mixing and dictates isopycnal shoaling across the northern basin.

The Feedback Loop

The synergy between warming and stratification creates a self-reinforcing feedback loop that traps anthropogenic heat at the surface, thereby amplifying the intensity and duration of MHWs. This mechanism limits the vertical exchange of heat and nutrients, leading to a 300% increase in compound MHW and low-chlorophyll events in specific provinces. By restricting the upward flux of cooler, nutrient-rich waters, this thermal nexus sets the stage for the progressive nutrient depletion and subsequent biogeochemical imbalances observed in the water column.

2. Biogeochemical Interdependencies: Acidification and Deoxygenation

The Indian Ocean's biogeochemical landscape is uniquely shaped by its landlocked northern boundary and the seasonal reversals of the monsoon. These geographic constraints, combined with rapid thermal forcing, create a volatile environment for the manifestation of acidification and deoxygenation.

Drivers of Ocean Acidification (IOA)

Ocean acidification in the basin is driven primarily by the uptake of anthropogenic CO_2, increasing Dissolved Inorganic Carbon (DIC) which accounts for 69.3% of the observed pH decline. However, the Warming-Acidification Link is significant; SST increases contribute between 13.8% and 14.4% of the acidification trend by reducing gas solubility and altering carbonate chemistry. Regional variability is pronounced: in the Northern Bay of Bengal, Total Alkalinity (ALK) acts as a unique regulatory factor, dominating the trend at 55.6%. Overall, the basin has experienced a mean pH decrease of 0.0675 units since 1961, with high-emission projections suggesting a further 0.4-unit decline by 2100.

[1] This section is a synthesis of the previous section and the references therein.

The Dynamics of Deoxygenation and Nutrient Regimes

Warming-induced stratification directly reduces vertical ventilation, driving the expansion of Oxygen Minimum Zones (OMZs) in the Arabian Sea and Bay of Bengal. This is exacerbated by marginal sea shoaling, where rapid heating of the Persian Gulf and Red Sea increases outflow buoyancy, causing these oxygenated waters to shoal at shallower depths and bypassing the deeper OMZ cores. Furthermore, a stark disparity exists in nutrient architecture: the Arabian Sea maintains a shallow nitracline (15–20m) and high integrated nitrate (703±220 mmol m^2), whereas the South Indian Ocean (SIO) exhibits a deep nitracline (>100m) and significantly lower nutrient concentrations (108±68 mmol m^2).

Biological Impacts and Feedbacks

These shifts are restructuring the marine food web. In the Arabian Sea, a critical shift has been observed from diatoms to large, green mixotrophic dinoflagellates (*Noctiluca scintillans*), likely fueled by changing oxygen and silicate levels. Functional anoxia triggers denitrification—converting fixed nitrogen into N_2 and N_2O gas—removing essential nutrients while creating a positive greenhouse gas feedback loop. Furthermore, acidification poses a potential threat to fish larvae by disrupting growth and sensory functions, such as hearing and orientation.

3. Atmospheric-Oceanic Coupling: Walker Circulation and Climate Modes

The Indian Ocean Walker Circulation (IOWC) and the Indian Ocean Dipole (IOD) regulate basin-wide environmental variability and are highly sensitive to anthropogenic forcing.

Circulation Slowdown and Interhemispheric Drivers

Greenhouse forcing leads to a robust slowdown of the IWC, fostering a "positive IOD-like" pattern characterized by anomalous easterly winds and stronger warming in the western basin. The extreme 2019 positive IOD, which reached a peak intensity of 2°C, was uniquely triggered by a record-breaking Interhemispheric Pressure Gradient (IHPG) between Australia and the South China Sea. Concurrently, the Southern Hemisphere exhibits a significant circulation slowdown, including a 26% reduction in the Indonesian Throughflow (ITF) and an 11–23% weakening of the Agulhas Current.

The Capacitor Effect and Habitat Compression

The Indian Ocean acts as a climate "capacitor," storing and subsequently discharging heat in response to El Niño, influencing global precipitation patterns. Structurally, the IOD is shifting westward, manifesting an "ENSO-like" variability characterized by a shallower eastern thermocline. This leads to severe "habitat compression" for migratory species.

4. Summary of Key Interdependencies:

Climate Effect	Influenced/Driven By	Impact on Other Effects
Sea Surface Temperature (SST)	Anthropogenic CO_2, IWC slowdown	Increases stratification; drives MHW expansion; accelerates acidification (14%).
Ocean Stratification	Surface warming, IHPG-driven wind anomalies	Traps surface heat; reduces vertical oxygen supply; induces isopycnal shoaling.
Ocean Acidification	Anthropogenic CO_2 (DIC), SST warming, ALK (in BoB)	Reduces calcification; compromises yellowfin larval sensory functions; reduces sink efficiency.

Deoxygenation (OMZ Expansion)	Stratification, Marginal Sea Shoaling, IOD modes	Causes habitat compression; triggers denitrification-driven N_2O feedback loops.
Walker Circulation (IWC)	Greenhouse forcing, atmospheric stability	Drives "positive IOD-like" pattern; alters moisture transport; reshapes SST gradients.
Indian Ocean Dipole (IOD)	Interhemispheric Pressure Gradient, IWC, ENSO	Modulates carbon/oxygen variability; drives species-specific habitat compression.
Thermocline Shoaling	IOD shifts, atmospheric forcing, IWC slowdown	Restricts vertical movement of tuna; temporarily increases surface nutrient access.
Boundary Current Slowdown	Weakening trade winds, SIO circulation shifts	Reduces larval connectivity (e.g., Agulhas/NEMC); impacts East African food security.

Section 9: Data and Observational Gaps and Methodological Limitations in Indian Ocean Climate Research

1. Strategic Overview of the "Indian Ocean Data Void"

Acknowledging scientific uncertainty in the Indian Ocean (IO) is a strategic necessity for global climate risk management. Although the basin represents only 13% of the global ocean surface area, it has emerged as a disproportionate global heat sink, accounting for an estimated 50%–70% of global upper-ocean heat uptake in the last decade (e.g. Phillips et al., 2019; Phillips et al., 2021). This role as a primary regulator of global climate stability means that the current data limitations directly undermine the accuracy of global climate modeling and regional adaptation strategies. Without a robust data framework, the transition of the basin to a primary driver of global change cannot be fully quantified.

The core of this scientific challenge lies in two primary barriers: the "Signal-to-Noise" problem and the "Heat Flux Dilemma." The brevity of high-quality *in situ* records—with many comprehensive datasets, such as the Argo float record, only beginning around 2005—makes it technically difficult to distinguish long-term anthropogenic trends from natural decadal and interannual variability, such as the Indian Ocean Dipole (IOD) or El Niño-Southern Oscillation (ENSO) (e.g. Phillips et al., 2021; Dalpadado et al., 2024). Furthermore, the lack of consensus on net heat flux creates high levels of uncertainty in long-term forecasting. These foundational uncertainties propagate through exisiting predictive systems, leading to deficiencies in the Earth System Models (ESMs) currently used to project future climate states.

2. Synthesis of Modeling Deficiencies and CMIP6 Inconsistencies

The scientific community relies heavily on Earth System Models to anticipate the impacts of climate change; however, the strategic risks associated with known model biases in the IO are substantial. Current modeling frameworks frequently struggle to replicate the complex ocean-atmosphere coupling unique to this landlocked tropical basin. These inconsistencies create a "predictability gap" that limits the utility of model outputs.

Evaluated Shortcomings of CMIP6 Models:

- **IOD Amplitude Bias:** Models suffer from excessive amplitude bias in the Indian Ocean Dipole, which distorts interannual variability projections and seasonal forecasting (e.g. Phillips et al., 2021).
- **Net Primary Production (NPP) Inconsistencies:** There is a lack of consensus among CMIP6 models regarding future NPP trends, leaving the future of the marine food web and regional food security highly uncertain (e.g. Henley et al., 2020; Chakraborty et al., 2024).
- **Failure to Resolve Mesoscale Features:** Models consistently fail to resolve critical mesoscale eddies—particularly in the Agulhas system—and struggle with the complex river runoff dynamics in the Bay of Bengal, leading to significant biases in salinity and carbon cycling simulations (e.g. Stellema et al., 2019; Beal et al., 2020; Gao et al., 2023).

These deficiencies lead to uncertainties that threaten the validity of regional sea-level rise projections and warming intensity estimates, which are critical for coastal infrastructure planning and the management of heat-sensitive fisheries.

3. Critical Gaps in Observational and Biogeochemical Data

To move toward reliable climate forecasting, model outputs must be ground-truthed with physical observations. However, the Indian Ocean remains the most under-sampled and poorly observed of the major basins (e.g. Jacobs et al., 2021; Phillips et al., 2021). This data scarcity is not merely a logistical hurdle but a fundamental limitation on the ability to track the basin's shifting chemistry and the expansion of Oxygen Minimum Zones (e.g. Lachkar et al., 2020).

- **Global pCO2 Contribution:** The Indian Ocean accounts for only 2.8% of global quality-controlled pCO_2 data (e.g. Dalpadado et al., 2021; Chakraborty et al., 2024; Ghosh et al., 2024).
- **Observational Baseline:** High-quality *in situ* records for many parameters only date back to approximately 2005 (e.g. Phillips et al., 2021; Dalpadado et al., 2024).

Key Observational Gaps:

1. **Lack of Biological Time-Series:** There is a critical absence of long-term biological data for lower trophic levels, specifically zooplankton, preventing accurate modeling of trophic shifts and projected biomass declines (e.g. Dalpadado et al., 2024).
2. **Inorganic Carbon Records:** Scarcity in inorganic carbon data hinders the tracking of ocean acidification and the basin's capacity to continue serving as a carbon sink (e.g. Chakraborty et al., 2024).
3. **Unmonitored Boundary Currents:** Major current systems, including the Oman Coastal Current and the East Madagascar Current, are poorly monitored, hindering the understanding of regional nutrient transport and species connectivity (e.g.Chakraborty et al., 2024).

The lack of ground-truth data in high-productivity upwelling zones, such as those off the coasts of Somalia, Oman, and Java, prevents scientists from accurately tracking the biological carbon pump (e.g. Beal et al., 2020). Without these data, the effectiveness of carbon sequestration through biological activity remains speculative. This gap in physical monitoring is mirrored by environmental factors that limit the efficacy of remote sensing technologies.

4. Remote Sensing Validation and the "Winter Predictability Barrier"

Satellite oceanography is a vital tool for basin-wide monitoring, but its accuracy in the Indian Ocean is frequently hindered by regional environmental factors. The reliance on remote sensing without sufficient regional validation introduces significant margins of error into the understanding of primary production and sea surface temperature (SST) dynamics.

A major methodological hurdle is the "Winter Predictability Barrier," which specifically impacts eastern equatorial SST forecasts. Predictability skill drops significantly around December, creating a seasonal blind spot for understanding interannual transitions (e.g. McCreary et al., 2013; Phillips et al., 2021). Furthermore, persistent monsoon cloud cover often hampers the collection of satellite-derived ocean color data, which is the primary metric for measuring chlorophyll and phytoplankton biomass (e.g. Beal et al., 2020).

Satellite Validation Discrepancies

Data Type	Limitation Factor	Impact on Accuracy
Primary Production	Lack of ground-truthing in the Arabian Sea	Underestimation of production by 35% to 58% (Sarma and Dalabehera, 2019).
Ocean Color	Persistent monsoon cloud cover	Significant data gaps and lack of seasonal certainty in phytoplankton tracking (Beal et al., 2020).
Eastern Equatorial SST	Winter Predictability Barrier	Sharp decline in forecast skill during the December period (McCreary et al., 2013).

Southern Hemisphere	Unverified satellite models	Unverified satellite ocean color data leading to lack of model certainty (Beal et al., 2020).

5. The Biological "Black Box": Physiological and Mechanistic Shortcomings

Current marine biological research in the Indian Ocean is often forced to rely on correlative studies—linking environmental variables like temperature to species distribution—rather than a true mechanistic understanding of species' survival. This reliance on "Black Box" correlations is a significant weakness. Without understanding underlying physiological mechanisms, long-term forecasting for commercially vital species, such as tuna, remains fundamentally unreliable (e.g. Dueri et al., 2017). Correlative models may show where a species *is*, but they cannot predict how it will adapt when multiple stressors, such as warming and acidification, occur simultaneously.

Specific Physiological Data Gaps:

- **Metabolic Response to Multiple Stressors:** There is a profound lack of understanding regarding how species respond to the synergy of rapid warming and declining pH. This is particularly critical for fish larvae, which may suffer sensory and metabolic disruption (e.g. Dueri et al., 2017; Chakraborty et al., 2024).
- **Stability of Primary Productivity:** Despite rapid warming, *in situ* observations show that f-ratios and primary productivity in the western Indian Ocean remained remarkably stable between 1995 and 2015, a finding that contradicts many model-based projections of decline (e.g. Sarma and Dalabehera, 2019). This discrepancy highlights a major gap in our understanding of the stability of the biological pump under thermal stress.

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Annex 2 Species Literature Reviews – Alfonsino

Annex provided separately

Annex 3 Species Literature Reviews – Oilfish

Annex provided separately

Annex 4 Species Literature Reviews – Trevallies

Annex provided separately

Annex 5 – Climate Change Risk Assessment Tool Guidance Material

Climate Change Risk Assessment (CCRA) Tool

Guidance and procedural information

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About this document

Version

Element	Detail
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Responsible	[Approval party]
Next review	DD/MM/YY

Purpose

This document provides a comprehensive overview of the Climate Change Risk Assessment (CCRA) Tool developed for the Southern Indian Ocean Fisheries Agreement (SIOFA) to assess the level of climate risk associated with relevant Conservation Management Measures (CMMs) and associated species. In addition to outlining guidance for how to understand, interpret and operate the CCRA Tool, a comprehensive methodology (procedure) is provided to support the establishment, operation and refinement of CCRAs to ensure the CCRA Tool is effectively implemented and maintained by SIOFA.

Structure

This document is presented in three parts:

Part One – Introduction

Part Two: CCRA Tool design

Part Three: Assessment methodology

Contents

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Glossary

Acronym	Definition
AIS	Automatic Identification System
CCRA	Climate change risk assessment
CMM	Conservation Management Measure
EBSA	Ecologically and Biologically Significant Areas
GIS	Geographic Information System
IMMA	Important Marine Mammal Areas
IPCC	International Panel on Climate Change
IPCC AR6	IPCC Annual Report 6
LEK	Local ecological knowledge
MCS	Monitoring, Control and Surveillance
RCP	Representative concentration pathways
SAR	Search and rescue
SIOFA	Southern Indian Ocean Fisheries Agreement
SST	Sea Surface Temperature
VME	Vulnerable Marine Ecosystem
VMS	Vessel Monitoring System

Part one: Introduction

Context

Origin of the SIOFA CCRA Tool

The SIOFA Climate Change Risk Assessment (CCRA) Tool has been developed under contract CLI-2025-01. The tool provides a structured framework, adapted from the WCPFC's Climate Change Vulnerability Assessment Framework.

CCRAs are increasingly valuable tools for informing management planning—not only by identifying biological and ecological risks, but also by identifying institutional and governance vulnerabilities, and an institution's capacity to cope with or adapt to these changes.

The CCRA Tool is intended to assist SIOFA to anticipate, monitor, prevent and mitigate potential threats, especially when scientific information is uncertain or inadequate. CCRAs can highlight where existing management structures, decision-making processes, or technical planning processes could improve to respond to shifting species distributions or increased resource uncertainty.

This CCRA Tool is intended to be a diagnostic tool to identify the level of climate risk associated with individual species of importance or wider CMM design, to improve understanding and inform management decision making.

Benefits of having a CCRA Tool

Climate change is impacting global oceans, which has direct implications for international management bodies, particularly in the case of SIOFA noting the rate of observed changes to the Indian Ocean basin. Climate-driven changes—such as ocean warming, monsoonal variations, species distributions, and altered productivity—are likely to create challenges to the effectiveness of species under current CMM settings. For example:

- Shifting species distributions may impact the assumptions underpinning certain CMMs as well as alter fishing operations and fleet dynamics, impacting enforcement
- Changes in productivity could require adjustments to catch limits and reference points
- Altered seasonality – including monsoonal variations[2] – may affect the timing and effectiveness of temporal closures and gear restrictions
- Disrupted food webs could undermine current bycatch mitigation strategies, and
- Economic and environmental instability may increase pressure on compliance and enforcement systems.

The SIOFA Meeting of the Parties aspires to take a proactive approach by undertaking standardized CCRAs of its CMMs and associated species. This will support adaptive management through improved understanding of climate risk, identification of associated limitations, and strategic adjustments required to strengthen CMM design and overarching governance structures.

[2] Climate change has notably weakened the large-scale Indian Ocean monsoon circulation while increasing atmospheric moisture, leading to more variable monsoons characterised by weaker mean rainfall but more frequent and intense extreme rain events.

Purpose

CCRAs focus specifically on identifying risks arising from climate-related drivers—such as changing ocean temperatures, acidification, and sea-level rise—because these stressors are largely external to the control of fisheries management and may require distinct, long-term adaptation strategies. Separating climate risks from other pressures, such as fishing mortality, enables SIOFA to develop targeted, forward-looking policies that complement existing management measures rather than conflate different sources of risk.

The primary purpose of this CCRA Tool is to:

- **Inform Decision-Making:** Provide evidence and analysis to SIOFA and its subsidiary bodies to inform the development, review, and adaptation of climate-resilient CMMs
- **Identify and Prioritize Risks:** Systematically identify and prioritize climate change risks to the effectiveness of existing or proposed management measures, and their capacity to ensure the long-term conservation of target stocks, non-target species, associated and dependent species, and the broader marine ecosystem, as well as the human communities that are reliant on them
- **Identify Data Needs:** Highlight critical data gaps and uncertainties to guide future research, monitoring, and data collection efforts
- **Document Risks:** Maintain scientific evidence of climate change risks to SIOFA-managed species and fisheries, and
- **Risk Prioritization:** Identify which CMMs are most vulnerable to climate change risks

Role within SIOFA

The CCRA Tool functions as one of several tools within the SIOFAs broader fisheries management toolbox. For example, it complements:

- **Stock Assessments** – Evaluate the current status of fish stocks
- **Ecosystem Indicators** – Monitor the health and dynamics of marine ecosystems
- **Compliance Monitoring** – Assess the effectiveness of management measures and ensure compliance, and
- **Technical Implementation** – Considering practical and enforceable management approaches.

Together, these tools support adaptive, science-based decision-making in response to environmental and management challenges.

Part Two: CCRA Tool Design

Principles

The CCRA Tool draws on the IPCC AR6[3] approach to understanding climate risk, emphasizing the roles of hazards, exposure, sensitivity, and adaptive capacity as key components. In line with IPCC AR6, it also reflects a shift toward holistic assessments, moving beyond purely biophysical vulnerability to consider the broader social and governance context within which SIOFA operates. The SIOFA CCRA Tool is a systematic evaluation tool that examines how climate change may affect the performance and effectiveness of new or existing management settings for individual species and wider CMMs.

The CCRA Framework is underpinned by the following principles:

- **Practical**: Designed to be implemented during normal meeting cycles and within existing resource constraints. It can be used by SIOFA efficiently and independently, without requiring ongoing reliance on external support or funding.
- **Integrated into Existing Processes**: CCRAs can be conducted using established SIOFA procedures and meetings, and, where appropriate, in line with normal CMM / species review processes.
- **Responsive to Management Needs**: The framework is tailored to meet the specific information needs of SIOFA managers and decision-makers, offering clear, actionable insights to support climate-resilient fisheries management.
- **Adaptive and Iterative**: Built to evolve, the framework can be updated as new scientific knowledge, socio-economic data, and insights into climate change impacts become available. This aligns with adaptive management principles, which are essential for managing uncertainty in fisheries.
- **Focused**: While recognizing that other stressors may compound climate risk, the CCRA tool is specifically focused on identifying and addressing risks directly attributable to climate change, rather than unrelated pressures such as overfishing.
- **User-friendly:** Designed so that it is easy to navigate, operate and understand without necessarily having an in-depth scientific or technical background.

Key definitions

To ensure consistency and clarity across all CCRAs, the following concepts, aligned with IPCC AR6 terminology, are used:

- **Climate Risk:** The potential for adverse consequences of climate change, resulting from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems.
- **Hazard:** The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In the context of climate change, this refers to climate stressors (e.g., ocean warming, acidification, sea-level rise, changes in ocean currents, extreme weather events).
- **Exposure:** The presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by climate hazards.

[3] Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. AR6. Geneva, Switzerland.

- **Vulnerability:** The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. This includes the propensity of *management measures or strategies* to be adversely affected by climate change impacts.
- **Sensitivity:** The degree to which a system or species is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in productivity in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damage caused by an increase in the frequency of storm events).
- **Adaptive Capacity:** The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. This includes the ability to implement effective *and flexible* management measures, adjust fishing practices, or develop new technologies *to respond to climate-driven changes*.

Conceptual approach

IPCC IR6

In line with the IPCC AR6 approach, the SIOFA CCRA Tool assesses the level of Climate Risk associated with CMMs or individual species. Climate Risk is defined as a function of Hazard, Exposure and Vulnerability, where Vulnerability is determined as a function of Sensitivity and Adaptive Capacity (see Figure 1 below).

Simply:

Climate Risk = combined output of Hazard, Exposure and Vulnerability

Where:

Vulnerability = combined output of Sensitivity and Adaptive Capacity.

Rapid assessment

In line with best practices, the CCRA Tool represents a pragmatic rapid assessment tool that:

- enables rapid identification of where attention is required where climate risk is determined 'high' and what elements drive it
- offers a high degree of flexibility with the ability to add or remove indicators
- enables efficient determination of where information gaps exist, and
- can be readily updated or modified on a regular basis without requiring extensive technical expertise and investment.

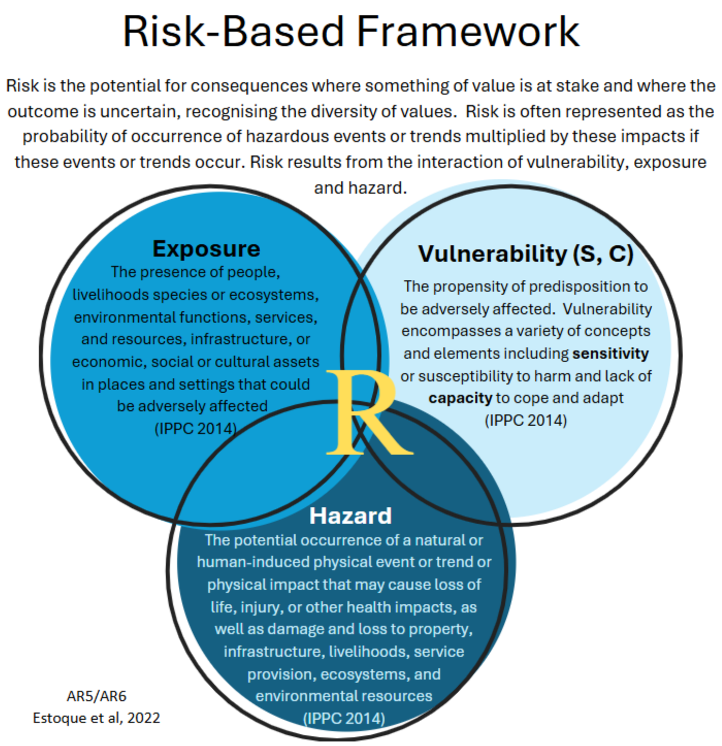

Figure 1. *V ENN diagram by Estoque et al (2022) of the climate risk-based approach defined in the IPCC AR6.*[4]

Key design features

Software platform

The CCRA Tool has been designed in Microsoft Excel, recognising that it is a globally accessible and well-known software platform, that can be easily modified and updated over time, and that readily enables automated outputs and long-term reliability without it being dependent on other external software or operating systems.

Structure

The CCRA Tool is made up of a total of eight tabs. The first tab is a 'guidance and information' tab to aid users in understanding the structure and functionality of the workbook in the case they do not have access to this document. The remaining tabs are numbered and are split into two category types (working tabs and results tabs), which are described in Table 1 below.

Tab design

Each working tab follows the same design to ensure consistency in scoring and understanding while navigating through the scoring process. An exception to this is the '1. Start' tab which provides the starting point from which to identify the CMM that is to be scored. In all cases, a user-friendly design approach ensures that any delegate or CCP can readily access the framework and operate it.

Colour coding is used on the four main working tabs (2.-5.) to ensure users can easily navigate between tabs.

Table 2. *Summary overview of the seven working and results tabs that make up the SIOFA CCRA Tool*

[4] Estoque RC, Ishtiaque A, Parajuli J, Athukorala D, Rabby YW, Ooba M. Has the IPCC's revised vulnerability concept been well adopted? Ambio. 2023 Feb;52(2):376-389. doi: 10.1007/s13280-022-01806-z. Epub 2022 Nov 21. PMID: 36414854; PMCID: PMC9755408.

Type	Tab	Description
Working tab	1. Start	The start tab is the starting point from which the relevant CMM is selected. Once selected, embedded functionality in working tabs 2. - 5. automatically updates
	2. Hazard	The hazard tab provides a series of indicators to identify and determine the level of application of individual climate change hazards relevant to the CMM
	3. Exposure	The exposure tab provides a set of indicators to determine the level of exposure a particular CMM faces when facing an identified climate change hazard
	4. Sensitivity	A set of indicators to determine the level of harm faced by a particular CMM when it is exposed to a climate change hazard
	5. Adaptive capacity	A set of indicators to measure the adaptive capacity of a CMM to lower its sensitivity in the face of exposure to a climate change hazard
Result tab	6. Climate risk	An automated results tab that shows the climate risk associated with the CMM via a combination of Hazard, Exposure and Vulnerability (noting vulnerability is a combination of Sensitivity & Adaptive Capacity)
	7. Indicator summary	A summary overview of the different scores for individual indicators under each of the components of climate risk

Working tabs

Four working tabs are provided to score Hazard (Tab 2.), Exposure (Tab 3.) and Vulnerability (as a function of Sensitivity (Tab 4.) and Adaptive Capacity (Tab 5.)). Within each working tab, a set of indicators are provided to generate a score for that component of Climate Risk. To ensure consistency in scoring, each indicator is framed as a question, with indicator reference point information provided to guide the scorer in selecting an appropriate score for the indicator. An example of the design is provided below in Figure 2. In addition, several further sections are provided to record the supporting rationale used to justify the determination of the score, to record commentary, and to identify any planned activities / developments / requirements to aid future assessments.

Result tabs

The two result tabs (6. and 7.) are fully automated output sheets that are protected to ensure the longevity of the implemented code required to generate the climate risk scores. Tab 6 provides an overview of all the generated scores including individual theme scores for each climate risk component (Tabs 2.-5.), as well as an overall Climate Risk rating. Graphics are also automated to help users identify visually how each score has been influenced by individual indicator scores and their respective indicator themes. Tab 7 provides a comprehensive automated list of each indicator by scoring category to aid in the easy identification of indicators requiring immediate or further attention (see Figure 3).

Auto-indicator selection

Several design features are included in each of the working tabs (2.-5.), including drop-down options to ensure consistent scoring and an ability to turn off auto-indicator selection based on the type of CMM being scored. The auto-indicator selection applies to MCS & Data Management based CMMs in which all biological and ecological indicators are automatically set to N/A. Importantly, the auto-indicator selection is able to be toggled off using an in-built button in each tab labelled “Turn off auto-indicator selection function” (see Figure 2).

Sensitivity

CMM-02 **Working tab**

☑ Turn off auto-indicator selection function

Theme	Ind. Ref #	Committee	Criteria	Question	Indicator reference information Low sensitivity	Medium sensitivity	High Sensitivity
Biological and ecological	S1		Thermal range	What is the temperature tolerance of the focus species? (when unknown the breadth of distribution can be used as a proxy for temperature range)	Temperature tolerance is broad, with the ability to function normally under a broad range of temperatures	Temperature tolerance is considered mid-range, with the focus species able to function normally under medium temperature changes for short durations (e.g., heatwaves)	Temperature tolerance is considered very narrow, with small temperature changes causing significant difficulties for normal functionality
	S2		Mobility	What is the ability of the focus species to move to a new location if the current location changes and is no longer favourable for growth and / or survival?	The focus species has high mobility, able to travel significant distances to new locations	Mobility of the focus species is considered moderate, with the species able to change locations but not to the level observed under 'low sensitivity'	Mobility of the focus species is low, with limited ability to actively move to change to more favorable conditions
	S3		Productivity	What is the productivity of the species?	The focus species has high productivity, with an ability of the population to rapidly recover after a negative impact	Moderate productivity, with the population able to recover after a negative impact over a longer period of time	Low productivity, with negative events to the population causing sustained impact over long periods of time
	S4		Distribution	What is the distributional range of the species?	The focus species has a high distributional range, covering large areas of the ocean and able to adjust to a range of habitats found in coastal and open-ocean environments	Moderate distributional range with the species found across a wide range of areas in the ocean but limited in their ability to adjust and occupy different habits (e.g., restricted to specific coastal environments)	Low distributional range with the species confined to specific / localised areas and habitat requirements
	S5			What is the level of influence of environmental cues on the distribution of the species?	Environmental cues such as seasonality have minor influences on the distribution of the focus species	Environmental cues have some influence on the distribution of the species	Environmental cues have very high levels of influence on the distribution of the species
	S6		Reproduction	How dependent is reproductive success on specific or complex environmental conditions / triggers?	The focus species is a broadcast spawner, with environmental conditions having a limited influence on spawning events	The focus species spawns (broadcast / aggregate) when conditions are favourable and with environmental conditions playing a role in these events to a moderate degree	The focus species is an aggregate spawner, with the formation and gathering of aggregations heavily dependent on seasonality and environmental conditions
	S7			How sensitive is the spawning cycle and duration to changes in seasonal cues and temperature changes?	The focus species is a year-round spawner or spawns over relatively long periods of time when conditions are favourable	The focus species spawns at several different times throughout the year when environmental conditions are favourable	The focus species spawns once annually and for short durations, heavily reliant on seasonal cues and temperature changes
	S8			What is the age at maturity of the species?	The focus species matures rapidly (<1 year) during its lifecycle	The focus species matures relatively quickly (1-2 years)	The focus species matures over longer time periods (+5 years)

Figure 2. *Snapshot of indicator scoring system for 'Sensitivity'*

Climate risk (Results)

CMM-02 Working tab

Result summary

Risk rating	High

Hazard

Score	High	Medium	Low	Unknown
Biological and ecological				
Number	2	3	2	0
Ratio	0.28571429	0.42857	0.28571	
Rating	Medium			
Operations and infrastructure				
Number	1	0	0	0
Ratio	1	0	0	
Rating	High			
Overall				
Number	3	3	2	0
Ratio	0.375	0.375	0.25	
Hazard rating	High			

Exposure

Score	High	Medium	Low	Unknown
Biological and ecological				
Number	2	1	0	0
Ratio	0.666666667	0.333333333	0	
Rating	High			
Operations and infrastructure				
Number	1	1	2	0
Ratio	0.25	0.25	0.5	
Rating	Low			
Socio-economic				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Management				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Overall				
Number	3	2	2	0
Ratio	0.428571429	0.285714286	0.285714286	
Exposure rating	High			

Vulnerability

Sensitivity

Score	High	Medium	Low	Unknown
Biological and ecological				
Number	3	2	2	0
Ratio	0.42857143	0.28571429	0.28571	
Rating	High			
Management				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Information				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Socio-economic				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Overall				
Number	3	2	2	0
Ratio	0.42857143	0.28571429	0.28571	
Sensitivity rating	High			

Adaptive capacity

Score	High	Medium	Low	Unknown
Biological and ecological				
Number	2	2	2	0
Ratio	0.33333	0.33333	0.33333	
Rating	Medium			
Management				
Number	1	0	0	0
Ratio	1	0	0	
Rating	High			
Information				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Socio-economic				
Number	0	0	0	0
Ratio	#DIV/0!	#DIV/0!	#DIV/0!	
Rating	Low			
Overall				
Number	3	2	2	0
Ratio	0.42857	0.28571	0.28571	
Adaptive capacity rating	Medium			

Vulnerability rating	High

Indicator summary (Result)

CMM-02 Working tab

Hazard

Number	High	Medium	Low	Unknown
1	H2	H1	H3	H9
2	H7	H4	H6	
3	H8	H5		
4				

Exposure

Number	High	Medium	Low	Unknown
1	E1	E3	E4	E8
2	E2	E6	E5	
3	E7			
4				

Sensitivity

Number	High	Medium	Low	Unknown
1	S2	S1	S4	S9
2	S3	S5	S6	
3	S7			
4				

Adaptive capacity

Number	High	Medium	Low	Unknown
1	A1	A3	A2	A8
2	A6	A5	A4	
3	A7			
4				

Figure 3. *Snapshots of Result tabs 6. and 7.*

Indicators

The specific indicators for each climate risk component are designed taking into consideration the most commonly identified fisheries specific climate risk indicators found in global literature. A total of 82 indicators make up the scoring framework. These are split by climate risk component as set out in Table 2 below.

Table 3. *Number of indicators by climate risk component*

Climate risk component	Number of indicators
Hazard	12
Exposure	17
Sensitivity	29
Adaptive capacity	24

The indicators per climate risk component are also grouped by theme for easy reference. These include:

- Biological and ecological
- Operations and infrastructure
- Management
- Information
- Socio-economic.

The themes are not consistently applied for each climate risk component noting that in some cases they are not applicable e.g., a climate change hazard does not exist for the theme 'Information'.

A full list of the CCRA Tool indicators per climate risk component is attached as Annex A.

Indicator scoring

Five scoring options are built in as drop-down selection options for each indicator in working tabs (2.-5.). These are set out in table Table 3.

Table 4. *Scoring options*

Score	Description
High	The user determines either a high, medium or low score using the indicator reference information to guide determination[5]
Medium	
Low	
Unknown	In the case there is no information, or a high uncertainty associated with available information, 'Unknown' can be selected. The 'Unknown' score enables the quick identification of information gaps. It does not influence the overall scoring.
N/A	In the case the indicator does not apply to the CMM, N/A is able to be selected

The scoring methodology used to generate scores based on the individual indicator responses is discussed in detail in the Section 8 below.

[5] Note, for adaptive capacity the reverse colour coding applies e.g., Low adaptive capacity = red background with red text.

Responsible SIOFA bodies

To help increase efficiency in scoring, each working tab (2. -5.) also has a 'Committee' column which enables users to select which indicators individual SIOFA bodies are responsible for reviewing or providing the necessary information to generate an indicator score. Available options are provided as a drop-down list, with one, two, or all SIOFA bodies able to be selected as required.

Future-proofing

The entire workbook has been designed in a manner that allows for the ready addition, deletion or modification of indicators as required over time, without impacting in-built automated functionality. In addition, all automated functionalities have been manually coded into the workbook to avoid the use of macros, to ensure longevity and functionality as software updates occur over time.

Indicator timeframe

A timeframe of 5-years has been set as the default timeframe for assessing the indicators in working tabs 2. – 5. This timeframe was selected as the most reasonable starting point for CMM / species review noting that the accuracy of best available scientific information diminishes over longer timeframes, the rate at which systems change and considering the process / operational timeframes at which the SIOFA MOP operates. The timeframe of the framework can be manually updated to longer time-periods as required by adjusting the relevant questions accompanying individual indicators throughout the framework.

Scoring method

Ratio-based approach

The scoring methodology of Hazard, Exposure, Sensitivity and Adaptive Capacity was purposefully designed to avoid weighting individual indicators. This approach was identified as the most suitable for the CCRA Tool, to avoid consistent review and updates to the weighting arrangement in the event indicators are added or removed or become less or more significant over time.

A counting methodology has been used that automatically sums up the number of times a specific score has been selected for an indicator and then generates a ratio from the total number of indicators that have been scored. This approach also ensures that indicators that are not applicable and are scored accordingly are not used in the development of the overall score for each climate risk component.

Additionally, this approach assists each component resulting in a 'truer' score, because of the ratio-based approach which also helps to remedy differences that could otherwise be caused by having different numbers of indicators per component. These automated counting and ratio functions are 'hidden' as a default within the framework but can be made visible by 'unhiding' the columns found at the end of each scoring table.

Component results

To generate an overall rating for each climate risk component, including Hazard, Exposure, Sensitivity and Adaptive Capacity, a series of thresholds were identified that would generate either a High, Medium or Low final rating (see Table 4 below).

Table 5. *Thresholds used to determine overall component score*

Scenario	High	Moderate	Low	Result

1	>0.5			High
2	>=0.3		<0.3	High
3	>=0.3		>=0.3	Medium
4	<=0.29		<0.3	Medium
5	<0.3		<0.5	Medium
6	<0.3		>=0.5	Low

The thresholds and associated results can be updated by accessing the applicable code for each result cell in Tab 6 and adjusting the thresholds within the code accordingly.

Unknown score

As noted earlier in Section 7.1.1, an indicator score of 'unknown' identifies specific information gaps but does not affect the overall scoring of each component, noting in some instances there may be very little information available, but that does not necessarily equate to the focus topic being vulnerable.

Vulnerability

Noting that Vulnerability is a function of Sensitivity and Adaptive Capacity, a Vulnerability final rating was developed by combining the Sensitivity final rating with the Adaptive Capacity final rating. This was done using a combination matrix that reflects that when Sensitivity is high and Adaptive capacity is low, Vulnerability is High and vice versa (see Table 5. Below).

Table 6. *Vulnerability matrix (Sensitivity and Adaptive capacity)*

		Sensitivity		
		High	Medium	Low
Adaptive capacity	High	Medium	Low	Low
	Medium	High	Medium	Low
	Low	High	High	Medium

Climate risk

The final climate risk score is determined based on the combination of the Hazard, Exposure and Vulnerability final ratings (see Table 6 above below).

Table 7. *Climate risk result based on combinations of final ratings for Hazard, Exposure and Vulnerability*

Hazard	Exposure	Vulnerability	Climate risk result
High	High	High	High
High	High	Medium	High
High	High	Low	Medium
High	Medium	High	High
High	Medium	Medium	High
High	Medium	Low	Low
High	Low	High	Medium
High	Low	Medium	Medium
High	Low	Low	Low
Medium	High	High	High
Medium	High	Medium	High
Medium	High	Low	Low
Medium	Medium	High	High
Medium	Medium	Medium	Medium
Medium	Medium	Low	Low
Medium	Low	High	Medium
Medium	Low	Medium	Medium
Medium	Low	Low	Low
Low	High	High	High
Low	High	Medium	Medium
Low	High	Low	Low
Low	Medium	High	High
Low	Medium	Medium	Medium
Low	Medium	Low	Low
Low	Low	High	Medium
Low	Low	Medium	Low
Low	Low	Low	Low

Part Three: Assessment methodology

Objective

The key objective for each CCRA is to determine:

- Whether a CMM or specific species has a low, medium or high risk to climate change impacts
- How vulnerable the CMM or specific species is and what drives that vulnerability (sensitivity vs. adaptive capacity)
- Whether and why current management approaches may become less effective
- Information gaps that need to be filled
- When critical adaptation requirements may be needed
- Whether SIOFA can cope with the identified level of risk, meaning
    - Institutional capacity: Does SIOFA have the legal authority, technical expertise, and financial resources to implement necessary adaptations?
    - Operational flexibility: Can existing processes be modified quickly enough to respond to climate-driven changes?
    - Management effectiveness: Will current tools and measures remain effective, or do they need fundamental redesign?

Scope

The scope for each CCRA must be explicitly defined, including:

- The specific CMM or species
- The accompanying spatial focus of the CMM or species:
    - Single Site/Area: e.g., a specific area or a designated fishing area
    - Network of Sites: e.g., a series of areas across the SIOFA Area
    - Range of Sites: e.g., the entire SIOFA Agremeent Area or specific sub-regions
- Timeframe
    - As a default, the CCRA Tool has a timeframe of five years, however this can be readily updated as required to longer timeframes as required.

Scoring

Using the best available information, the CCRA Tool should be worked through systematically from Tabs 1. – 5., scoring individual indicators to generate the climate risk result. Responsible SIOFA bodies (SC or CC) should be identified for each indicator to ensure the required level of technical input and expertise required to effectively score each indicator is involved.

For each indicator scored, relevant reference information and supporting rationale for why the score was chosen must be recorded as justification, and to enable effective tracking of how information is changing over time in relation to individual indicators.

Where discussions or different views are expressed in relation to the scoring of an individual indicator, these should be captured in the comments section provided for each indicator. Likewise, if the information does not exist at a particular point in time, this should be clearly recorded to justify a score of “unknown” for the indicator.

Lastly, if future activities or planned actions are known that relate to the indicator are known, these should also be recorded to ensure effective tracking of progress towards strengthening the indicator score over time.

Data requirements

Data Credibility

Because CCRAs rely on available data, their accuracy is only as strong as the information they are based on. Highlighting data gaps is crucial to improving future assessments. All CCRAs must be based on:

- Verified or verifiable data
- Peer-reviewed scientific literature
- Quality-controlled observational data
- Validated model outputs
- Expert knowledge from recognized specialists, and
- Indigenous and local knowledge where appropriate.

Indigenous and local ecological knowledge (LEK) should be viewed as a primary information source together with other knowledge categories, particularly where there is low confidence or limited / no availability of other information types. In these cases, indigenous and LEK will play a fundamental role in ensuring effective overall scoring.

Core Data Categories

Climate Data

Data that provides the environmental context for assessing how changing ocean conditions may affect fisheries management effectiveness. This could include historical observations of ocean temperature, chemistry, currents, monsoon patterns, extreme events, future projections from IPCC-validated climate models and scenarios and key variables such as sea surface temperature, ocean acidification, current patterns, and productivity levels.

Ecological Data

This data provides the biological context for understanding how species and ecosystems may respond to climate-driven environmental changes. This could include species information on distribution patterns, life history parameters, and thermal tolerances and ecosystem structure, including food web dynamics, habitat mapping, and bycatch records.

Fisheries Data

Biological and operational data that provides the information to monitor, manage and assess fishery resources. It could include catch and effort data, biological data on species size, sex, age and reproductive status, and independent observer (human or electronic monitoring) data

Management Performance Data

Management performance data refers to the information used to evaluate the effectiveness, accountability, and outcomes of fisheries management systems. It includes records and analyses of how CMMs or management settings have performed over time, outcomes from monitoring, enforcement, and compliance processes, assessments of whether management objectives (such as stock sustainability, bycatch reduction, or ecosystem protection) have been achieved, performance metrics as well as evaluations of the resources, staffing, infrastructure, and governance systems in place to support implementation and enforcement of management measures.

Socio-economic data

Socio-economic data refers to available information on the importance of specific species or fisheries to fisheries dependent local communities (e.g., employment, income, cultural significant fisheries), market data trends (e.g., the relative importance of the species or fisheries to overall annual economic stability), and governance and institutional capacity information.

A tool to effectively track the availability of data sets is attached as Annex B. This should be used to effectively trace available sources of information while undertaking a CCRA.

Data Sources and Tools

The following data sources and tools should be utilized when acquiring best available information to inform a CCRA:

- SIOFA Data Holdings: Utilize existing SIOFA data catalogue, including those from the SC, CC and the compliance monitoring scheme
- Academic Literature and Scientific Reports: Incorporate findings from peer-reviewed publications and relevant scientific assessments
- Databases including the World Bank, International Monetary Fund, identifying and including relevant socio-economic assessments
- Traditional and LEK: Integrate local and traditional expert knowledge where available and appropriate, as a valuable source of information for understanding ecosystem dynamics and historical changes, and
- Defined Tools and Software: Specify the analytical tools, models, and software platforms to be used for data processing, analysis, and visualization to ensure consistency and reproducibility across CCRAs such as AIS, GIS, VMS.

Roles and responsibilities

Each year at its annual meeting, the MOP can decide which CMMs or species will undergo a CCRA. The selected review will be led by a CCP, or a group of CCPs, which will coordinate the assessment and compile relevant data and analysis.

The review process will follow established pathways for technical input and oversight. Specifically, it will be submitted to the SC for scientific review and the CC for consideration of implementation and compliance implications.

Based on the outcomes of these subsidiary body discussions, the findings and any recommendations will be submitted to the MOP for consideration and decision-making. All CCRAs will utilise the approach outlined in the CCRA Tool and report the findings using the CCRA Report format (Annex C).

A detailed process breakdown is provided in Table 7 below.

Table 8. *CCRA procedure.*

Step	Responsible
Step 1: Establish a CCRA review process	MOP

• Confirm a CCP(s) to undertake the CCRA • Select a CMM or species to be assessed • Determine why the assessment is required • Determine what will be assessed and at what scale (scope) • Determine what time horizon is to be used (5 years is default)	

Step 2: Use the CCRA Framework to assess the CMM or species.
Determine:
• Whether a CMM or species is at a low, medium or high risk to climate change impacts
• The components driving the climate risk and individual indicators that require further attention
• Whether and why certain management approaches may become less effective
• Where adaptation is required to reduce vulnerability
• Whether SIOFA can cope with identified risks in the absence of action, or through strengthening adaptive management, taking into consideration:
  ○ Institutional capacity: Does SIOFA have the legal authority, technical expertise, and financial resources to implement necessary adaptations?
  ○ Operational flexibility: Can existing processes be modified quickly enough to respond to climate-driven changes?
  ○ Management effectiveness: Will current tools and measures remain effective, or do they need fundamental redesign?
• How results can be used to inform management proposals and decision-making.
	CCP reviewer

Step 3: Consultation and validation of findings with expert input	SC & CC
Step 4: Present findings to the MOP using the report template (Annex C)	CCP reviewer
Step 5: Consider CCRA and determine appropriate actions or decisions in accordance with recommendations	SIOFA MOP
Step 6: On MOP approval, the CCRA is uploaded on the SIOFA website and used to inform the development of proposals with required management actions	SIOFA Secretariat

Review and continuous improvement

Regular Review Cycle

The CCRA Tool and this document should be reviewed on both a regular basis (annually) and comprehensively reviewed on a longer-term basis (5-years).

Annual reviews should focus on updating individual indicators, refining methods in response to new climate and biological information, validating results against observations, and incorporating feedback from CCPs and subsidiary bodies to ensure the tool remains responsive and relevant.

Every five years, a comprehensive review should be conducted to evaluate the overall effectiveness of the tool in supporting decision making, to compare alternative assessment approaches (including against new IPCC definitions / approaches), assess institutional capacity, and to set strategic priorities for the next five-year cycle.

Adaptive Framework Development

The framework is designed to support continuous improvement. This includes ongoing development of assessment methods, integration of emerging data sources, efforts to reduce uncertainty, and streamlining of processes to improve efficiency. Over time, the framework may also expand to incorporate newly identified approaches to measuring socioeconomic and other ecosystem dimensions, to allow for region-specific application, be adapted as broader multilateral thinking develops, and to align more closely with other ocean sectors to support cross-sectoral climate adaptation planning.

Annexes

Annex A: Indicator list by climate risk component

Hazard indicators

Theme	Indicator reference	Criteria	Description	Question
Biological and ecological	**H1**	Marine heatwaves	Marine heatwaves have the potential to significantly affect species distribution and survival if they have narrow thermal tolerances and limited mobility, adaptability to new habitats / areas	How applicable is the hazard to the focus topic of the CMM?
	H2	Increased sea surface temperature (SST)	Stock displacement, increased mortality, reduced productivity, reduced prey availability a species is dependent on	
	H3	Ocean acidification	Can cause harm to exposed systems in acidifying zones by impairing calcification, disrupting food webs and weakening species resilience	
	H4	Salinity	Salinity fluctuations can severely impact fish biology, affecting both health and homeostasis. Deviations from optimal salinity can cause mortality, reduced growth and impaired immune function	
	H5	Deoxygenation	Tropical pelagic species live near or above oxygen minimum zones. Changes in hypoxic or suboxic zones can affect species physiology, habitat availability and ecosystem function	
	H6	Wind stress	Changes in wind strength or direction can disrupt ecological or physical systems e.g., upwelling, larval dispersal and can contribute to other hazard e.g., intensification of tropical cyclones	

Theme	Indicator reference	Criteria	Description	Question
	H7	Current change	Changes in strength, direction, timing or vertical structure can disrupt larval dispersal, nutrient delivery, primary productivity; alter species migration routes; affect heat distribution, oxygen levels and acidification patters, destabalize or shift climate systems	How applicable is the hazard to the focus topic of the CMM?
Operations & infrastructure	**H8**	Storms	Wind damage, storm surge, port infrastructure damage, loss of life or injury, damage to vessel infrastructure, loss of fishing days	
	H9	Cyclones	Wind damage, storm surge, port infrastructure damage	
	H10	Precipitation extremes	Flooding, port infrastructure damage, reduction in port access and service	
	H11	Sea level rise	Flooding, port infrastructure damage, reduction in port access and service	
	H12	Wave height	Changes in wave heigh, frequency or intensity can result in disruption to marine operations, infrastructure damage, wave-driven over wash and saline instruction and stress to intertidal ecosystems	

Exposure indicators

Theme	Indicator reference	Criteria	Question
Biological and ecological	**E1**	Habitat	How frequently does the habitat of the focus species experience the identified hazards?
	E2	Food web	How frequently is the food web of the focus species exposed to the identified hazards? (considering predator and prey relationships)
	E3	Species population	How frequently does the focus species population experience the identified hazards?
	E4	Fishing fleet	How exposed are the relevant fleets to the identified hazards?

Theme	Indicator reference	Criteria	Question
Operations and infrastructure	E5	At sea operations	How frequently do operations face inadequate weather information for decision-making?
	E6		What percentage of operations cannot financially survive a major weather event?
	E7		How often must operations relocate fishing grounds due to climate-driven species shifts?
	E8	At sea operators	How often are crew and observers exposed to dangerous working conditions or hazardous deck conditions due to weather and identified hazard events
	E9		What is the crew's proximity to SAR services during extreme weather events?
	E10		How often do crew experience dangerous heat stress conditions while working at-sea?
	E11		How frequently do crew face reduced navigating conditions that increase the risk of collision or incidents
	E12	Port infrastructure	How frequently are port facilities affected by the identified hazards (e.g., storm surge/flooding)?
Socio-economic	E13	Economies	What percentage of SIDS/Territory income is affected by the identified hazards?
	E14	Livelihoods	What is the level of exposure to community livelihoods of SIOFA CCPs from the identified hazards?
Management	E15	Spatial boundaries	Do the identified hazards affect any fixed geographic boundaries used to manage the fisheries or set by the CMM?
	E16	Scientific assumptions	Are the identified hazards factored into the temporal and spatial assumptions used to define management settings?
	E17	Information	How often does the SIOFA receive updated scientific information on these hazards?

Sensitivity indicators

Theme	Indicator reference	Criteria	Question
Biological and ecological	**S1**	Thermal range	What is the temperature tolerance of the focus species? (when unknown the breadth of distribution can be used as a proxy for temperature range)
	S2	Mobility	What is the ability of the focus species to move to a new location if the current location changes and is no longer favourable for growth and / or survival?
	S3	Productivity	What is the productivity of the species?
	S4	Distribution	What is the distributional range of the species?
	S5		What is the level of influence of environmental cues on the distribution of the species?
	S6	Reproduction	How dependent is reproductive success on specific or complex environmental conditions / triggers?
	S7		How sensitive is the spawning cycle and duration to changes in seasonal cues and temperature changes?
	S8		What is the age at maturity of the species?
	S9	Prey	What is the prey specificity of the focus species?
	S10	Competition	What is the level of competition that the focus species has with other species for the same habitat requirements / prey and diet requirements?
Management	**S11**	Health status	What is the current health status of the focus species population?
	S12		What is the projected health status of the focus species population in 5 years' time based on current environmental conditions?
	S13		What is the variability of the focus species' abundance / CPUE indexes?
	S14	Harvest strategy	Is there a harvest strategy or equivalent best practice management measure implemented for the species?
	S15		How does the harvest strategy account for increased uncertainty due to climate change?

Theme	Indicator reference	Criteria	Question
	S16		How quickly can the harvest strategy adjust to new information about stock status or environmental conditions?
	S17	Non-compliance	What is the level of non-compliance across the fishery / fisheries that the focus species is associated?
	S18	IUU	What is the level of serious IUU fishing activity across the fishery / fisheries that the focus species is associated?
	S19	Observer coverage	What is the level of observer coverage (human and / or EM) across the fishery/ies that the focus species is associated with?
	S20	Fishing effort	What is the level of collective fishing effort associated with the focus species?
	S21	Resource and governance	What is the level of resource available to comprehensively assess the health status and distribution of the focus species regularly?
	S22		What is the current capacity of SIOFA CCPs to respond and implement required changes?
	S23		What is the level of confidence to make informed decisions associated with current available information on the focus species?
Information	**S24**	Information availability	What is the level of availability of climate change information associated with the focus species?
	S25	Awareness	What is the level of climate change knowledge and environmental awareness among SIOFA CCPs reliant on the focus species?
Socio-economic	**S26**	Economic Dependence	What is the relative economic importance of the focus species to SIOFA CCP?
	S27		What is the livelihood reliance of SIOFA CCPs on the focus species?
	S28	Food dependence	What is the relative dependency of CCPs on the focus species for food security?
	S29	Cultural importance	What is the level of cultural / social significance of the focus species to the SIOFA CCPs?

Adaptive capacity indicators

Theme	Indicator reference	Criteria	Question
Biological and ecological	A1	Thermal range	What is the ability of the focus species to adapt to increased temperatures?
	A2	Productivity	What is the likelihood of the focus species to maintain or improve its productivity in response to increased temperatures and different environmental conditions?
	A3	Distribution	What is the ability for the focus species to change its distributional patterns?
	A4	Reproduction	What is the likelihood of the focus species being able to adapt to successfully spawn under differing environmental conditions and changes in seasonal / temperature cues?
	A5	Prey	What is the likelihood of the focus species being able to change its prey and diet if required in response to environmental changes?
	A6	Competition	What is the ability of the focus species to adapt to reduce its level of competition with other species for habitat requirements / prey and diet requirements?
Management	A7	Health status	Under the current management settings, what is the likelihood of the focus species being able to maintain its current health status or rebuild its health status in response to environmental change (SST, ocean acidification, dissolved oxygen, salinity)
	A8	Species diversification	What is the level of flexibility to change the focus species (if it is a target species) to another target to reduce the impact of fishing?
	A9	Fishing gear	What is the level of flexibility to modify gear requirements or implement gear restrictions for fishing gear identified as creating a higher risk to the focus species compared to others?
	A10	Fishing effort	What is the likelihood of fishing effort associated with the focus species of being significantly affected because of not being able to operate at sea due to increased storm events etc.?
	A11	Observer coverage (human and / or EM)	What is the likelihood of monitoring levels being consistently sufficient for the fisheries associated with the focus species over the next 5 years?

Theme	Indicator reference	Criteria	Question
	A12	Research and technology	What is the level of investment (current and planned) in research and technology of direct relevance to the focus species to improve understanding?
	A13	Agile decision making	How easily is the management framework / management settings for the focus topic able to be readily adapted?
	A14	CCP capacity	What is the likelihood of SIOFA CCPs having the required capacity to readily respond to required changes over the next 5 years?
	A15		What is the capability of the fleet to change its distribution (fishing grounds)?
	A16	Resource and governance	Is the level of resource currently required (and likely to be required in future) to effectively assess the status of the focus species likely to be sustainable?
	A17		Is there likely to be appropriate resource and capacity for the SIOFA secretariat to effectively manage the sustainability of the focus species?
Information	**A18**	Information sharing and cooperation	What is the level of certainty / likelihood of improved cooperation and information sharing between CCPs and internationally, to improve efficiencies and understanding associated with the focus species over the next five years?
	A19	Contribution	What is the level of contribution (currently and in future) with social, environmental and fishery organizations on the climate change issues facing the focus species?
	A20	Traditional knowledge	What is the level of engagement (currently and in future) by CCPs with their nationals? (including traditional knowledge holders and local communities) on the climate change issues facing the focus species and to fill information gaps where possible?
Socio-economic	**A21**	Diversification	What is the relative ability for SIOFA CCPs to diversify their economic interests in response to required changes to reduce risk to the focus species?
	A22		What is the relative ability for SIOFA CCPs to diversify livelihood reliance away from the focus species if required?
	A23	Port resilience	What is the relative ability of the ports of SIOFA CCPs being able to maintain function over the next five years as climate changes become more observed e.g. sea-level rise

Theme	Indicator reference	Criteria	Question
	A24	Food security	What is the relative ability for SIOFA CCPs to ensure food security should the focus species require changes to current food supply associated with the fisheries?

Annex B: Data Set Tracker

Category	Does SIOFA have this data?	Source
Climate Data		
Historical and projected oceanographic data (e.g., sea surface temperature, ocean heat content, pH, oxygen levels, current patterns).	☐ Yes ☐ Partial ☐ No	
Climate model outputs (e.g., IPCC Representative Concentration Pathways - RCPs).	☐ Yes ☐ Partial ☐ No	
Extreme event frequency and intensity projections.	☐ Yes ☐ Partial ☐ No	
Ecological Data		
Species distribution data (historical and current).	☐ Yes ☐ Partial ☐ No	
Life history parameters (e.g., growth rates, reproductive cycles, thermal tolerances).	☐ Yes ☐ Partial ☐ No	
Stock assessment data (biomass, fishing mortality, recruitment).	☐ Yes ☐ Partial ☐ No	
Ecosystem structure and function data (e.g., food web dynamics, habitat mapping, EBSA locations, IMMA locations).	☐ Yes ☐ Partial ☐ No	
Bycatch and associated species data.	☐ Yes ☐ Partial ☐ No	
Fisheries Data		
Catch and effort data (by species, gear, area, time)	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Vessel monitoring system (VMS) data.	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Observer data (including bycatch and VME encounters).	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Fleet characteristics and fishing capacity.	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Management Effectiveness Data		
Historical CMM performance and compliance rates under varying environmental conditions.	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives

Category	Does SIOFA have this data?	Source
Responsiveness of management decisions to scientific advice and environmental shifts.	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Implementation rates of management measures	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Fleet information (number/age of vessels, fleet movements)	☐ Yes ☐ Partial ☐ No	SIOFA Data Archives
Socio-economic Data		
Fisheries-dependent community data (e.g., employment, income, cultural significance of fisheries).	☐ Yes ☐ Partial ☐ No	
Market data (e.g., prices, trade flows).	☐ Yes ☐ Partial ☐ No	
Governance and institutional capacity data	☐ Yes ☐ Partial ☐ No	

Annex C: CCRA Report Format

Executive Summary

- Key findings and management implications
- Vulnerability [rankings]
- Uncertainties and limitations
- Priority actions

Introduction

- Assessment objectives and scope
- CMMs (incl species and regions covered)
- Climate scenarios considered

Methods

- Data sources and quality assessment
- Indicator selection and metrics
- Analysis approaches and tools
- Validation procedures

Results

- Climate risk [Hazard, Exposure and Vulnerability outcomes]
- Spatial and temporal patterns
- Sensitivity analysis results

Discussion

- Interpretation of results
- Comparison with other studies
- Management implications
- Data Gaps, Uncertainties, and Limitations

Conclusions

- Summary of key findings
- Priority actions for management
- Future assessment needs
- Research recommendations
- Management Implications and Recommendations (Specific actions/triggers for CMMs, Harvest Strategies, etc.)

Appendices

- Supporting data, model outputs, and information of the assessment
- References

Annex 6 Framework for Monitoring Risk

SOUTHERN INDIAN OCEAN FISHERIES AGREEMENT **Assessment of SIOFA Species and Ecosystems for Vulnerability to Climate Change Impacts** Annex 5: Framework for Monitoring Risk | CLI-2025-01 | DRAFT	Adapted from ***Pinkerton et al.*** 2018, 2023

High priority — existing data platform	**Monitoring aspiration —** data development needed	**New addition —** not in Pinkerton	Lower priority

Overview

This framework identifies the biological and ecological parameters that SIOFA can monitor within its existing mandate to detect the outcomes of climate change on priority species. Where the climate change vulnerability assessment indicators (Attachments E, G, H, and I) characterise what makes a species sensitive — its life history traits, thermal tolerance, habitat dependence, dietary flexibility — this framework asks what those characteristics mean for parameters that can actually be tracked through fisheries data over time: whether growth is changing, whether maturity is shifting, whether spatial distribution is moving. The reference materials underpinning this table — the Indian Ocean climate summary (Attachment F) and the species literature reviews (Attachments G, H, and I) — provide the biological, behavioural, and climate linkages that connect each parameter to specific hazards; the table translates those linkages into a monitoring programme.

> **Note:** *Column 2 (potential effects) will be species-specific — the climate exposure profile differs materially between alfonsino, oilfish, and trevallies, and a generic cross-species description would misrepresent the actual risks. Column 3 (monitoring approaches) identifies existing SIOFA data streams or specifies what new data collection would be required. Neither column is complete at this stage.*

Parameter / process	Priority	Rationale for inclusion	Potential effects of climate variability/change (col. 2)	Potential monitoring approaches (col. 3)
BIOLOGICAL PRODUCTIVITY PARAMETERS				
Growth rate *Von Bertalanffy: L∞, k,* t_0*; age-length relationship*	**High priority — existing data platform**	Most tractable entry point. Biological sampling (otoliths, length, weight) already occurs in the alfonsino fishery. Temperature-growth linkage via food web pathway established for alfonsino (Lehodey & Grandperrin 1996; 7.5-month lag to ENSO). Observer data provide a platform across all three species.	*— to complete, by species —*	*— to complete —*
Length-weight relationship and body condition *W/*L^n *condition index; residuals from observed L-W*	**High priority — existing data platform**	Practical proxy for food availability and physiological stress. Length and weight sampling from observer data available for alfonsino. Changes in length-weight residuals over time reflect integrated environmental condition without requiring new collection.	*— to complete, by species —*	*— to complete —*
Age at maturity and reproductive parameters a_{50}*; GSI; spawning seasonality and site fidelity*	**High priority — existing data platform**	Critical for alfonsino given unresolved longevity uncertainty (10–25 vs 50–70 years), which fundamentally affects productivity assessment. For trevallies in surface-influenced water, warming-driven shifts in maturity timing are	*— to complete, by species —*	*— to complete —*

Parameter / process	Priority	Rationale for inclusion	Potential effects of climate variability/change (col. 2)	Potential monitoring approaches (col. 3)
		biologically plausible and fast-acting. Observer-based sampling programme already endorsed by SC.		
Natural mortality *M (inferred); assessment model residuals; condition-based inference*	**High priority — existing data platform**	Direct measurement not feasible. Inference from assessment model diagnostics (for alfonsino) and length-weight residuals is practical. M is highly sensitive to the longevity uncertainty for alfonsino; monitoring body condition provides an indirect signal of stress-related mortality change.	*— to complete, by species —*	*— to complete —*
Mean recruitment *Mean year class strength (YCS)*	**Monitoring aspiration — data development needed**	Theoretically essential but no time-series data exist for any of the three species. Alfonsino stock assessment treats recruitment as constant — an assumption, not a measured signal. Included so SIOFA knows what data development to prioritise; cannot be implemented immediately. Direct monitoring not currently feasible, but length frequency data offer a practical proxy — cohort signals may be trackable without ageing if growth parameters are known and sampling is	*— to complete, by species —*	*— to complete —*

Parameter / process	Priority	Rationale for inclusion	Potential effects of climate variability/change (col. 2)	Potential monitoring approaches (col. 3)
		consistent. Tractability is highly species-specific (see col. 3)		
Recruitment variability *σR; interannual variability; environmental drivers*	**Monitoring aspiration — data development needed**	Dependent on recruitment time-series development above. Climate-driven changes to larval dispersal and prey availability during early life stages are biologically plausible for all three species but cannot be assessed without adequate monitoring. Signals the research investment needed.	*— to complete, by species —*	*— to complete —*
DISTRIBUTION, HABITAT, AND POPULATION STRUCTURE				
Spatial distribution and depth profile *Latitudinal and depth range; CPUE vs. oceanographic indices*	**High priority — existing data platform**	CPUE and logbook data provide an existing monitoring platform. Shifts in fishing effort or catch distribution may signal distributional responses. Species differ substantially: alfonsino is constrained by seamount topography; oilfish and trevallies less so and more capable of active redistribution.	*— to complete, by species —*	*— to complete —*

Parameter / process	Priority	Rationale for inclusion	Potential effects of climate variability/change (col. 2)	Potential monitoring approaches (col. 3)
Stock structure and connectivity *Genetic diversity; population units; seamount connectivity*	High priority — existing data platform	Climate-driven changes in ocean circulation may alter larval dispersal and connectivity between seamount populations — particularly relevant for alfonsino. Middleton et al. (2024) has initiated genetic stock structure work across SIOFA seamounts. Should be incorporated into regular SC reporting as analysis develops.	*— to complete, by species —*	*— to complete —*
Sex ratio *Male:female ratio; age/sex structure in catch*	Lower priority	Observer sex ratio data may exist for alfonsino. Temperature-dependent sex determination not documented for these species. Included for completeness. If data exist, trends should be checked periodically; not a primary monitoring focus.	*— to complete, by species —*	*— to complete —*
ECOSYSTEM AND FOOD WEB LINKAGES · New addition — not in Pinkerton et al. (2018, 2023)				
Prey availability and food web linkages *Primary productivity indices; mesopelagic prey biomass; CPUE vs. NPP*	New addition to Pinkerton framework	Added because the primary transmission mechanism for Indian Ocean warming to SIOFA deepwater species is **indirect** — through declining primary productivity and food web restructuring — rather than direct physiology. Alfonsino's temperature-	*— to complete, by species —*	*— to complete —*

Parameter / process	Priority	Rationale for inclusion	Potential effects of climate variability/change (col. 2)	Potential monitoring approaches (col. 3)
		growth response operates through food web pathways with a 7.5-month lag (Lehodey & Grandperrin 1996). Satellite-derived NPP and chlorophyll indices allow monitoring without new fisheries data collection. Not in Pinkerton because CCAMLR has more developed food web monitoring infrastructure.		

CLI-2025-01 · Attachment D (draft) · Adapted from Pinkerton, Dunn, Mormede & Parker (2018) and Pinkerton, Devine, Dunn & Mormede (2023) · February 2026