ANNEX 4

Literature Review

Trevallies/ Carangoides *spp.)*

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Introduction

This literature review evaluates all seven climate hazard indicators (H1–H7) and ten biological and ecological sensitivity and adaptive capacity indicators (S1–S10) for trevallies (*Carangoides* spp.) in the SIOFA Area. SIOFA's managed trevally assemblage comprises three taxa: yellowspotted trevally (*Carangoides fulvoguttatus*), bludger (*Carangoides gymnostethus*), and unspecified *Carangoides* spp. Golden trevally (*Gnathanodon speciosus*) also appears in SIOFA catches at Saya de Malha Bank and contributes comparative biological data where relevant.

The review is structured in two parts. Part 1 works through the hazard indicators. For each hazard, the assessment first establishes what is occurring in the Indian Ocean — drawing primarily on the Indian Ocean Climate Summary (Kryc 2026 - Attachment F) — and then evaluates exposure across three dimensions: trevallies as a species (direct physiological and behavioural impacts); shallow reef and bank habitat characteristics, particularly at Saya de Malha Bank (physical and structural changes to the environment the species occupies); and food web and prey availability (indirect effects operating through the trophic pathways that sustain trevallies). The purpose is to identify which hazards are materially relevant and through what pathways.

Part 2 evaluates the biological and behavioural characteristics that determine how trevallies would respond to those hazards. Sensitivity indicators address the magnitude of likely response — how strongly a given hazard affects the species given its intrinsic biology, including physiological tolerances, life history strategies, mobility, reproductive strategies, dietary flexibility, and competitive interactions. Adaptive capacity indicators address the scope for adjustment — whether the species has the biological flexibility or ecological options to reduce adverse outcomes. Some indicators appear in both parts: thermal range and prey specificity, for example, are relevant to exposure in Part 1 and to response capacity in Part 2. They are asking different questions in each context, and the ratings should be interpreted accordingly.

A frank acknowledgement of the evidence base is necessary at the outset. None of the three named SIOFA target species has been the subject of a published population biology study from the SIOFA area or the broader southern Indian Ocean. The primary quantitative source is Grandcourt et al. (2004), which examined *C. bajad* (orangespotted trevally) and *G. speciosus* (golden trevally) in the Southern Arabian Gulf. Although *C. bajad* is distributed from Madagascar and the Comoros to the Red Sea — encompassing the western fringe of the SIOFA area — it is not itself one of the named SIOFA targets. Data from this study are applied throughout as the best available proxy, with explicit caveats where geographic and species distinctions matter. The Indian Ocean Climate Change Summary (IO Climate Summary) provides the primary reference for climate hazard characterisation across all hazard indicators.

Baseline Characterisation: Trevallies Biology, Habitat, and Food Web

Trevallies as a Species: Biological Characteristics

Carangoides species are active, schooling, open-water carnivores in the family Carangidae — approximately 140 species across 25 genera, abundant in tropical and subtropical seas worldwide (Smith-Vaniz 1984). They are medium-to-large fishes — *C. bajad* reaches approximately 55cm total length, *C. fulvoguttatus* approximately 100cm (FishBase). All are exploited using hook and line, gillnets, traps, and artisanal gear throughout their range.

In marked contrast to alfonsino and oilfish, trevallies are shallow-water species: *C. bajad* is associated with coral and rocky reefs to 50m depth; *C. fulvoguttatus* to approximately 100m (Grandcourt et al. 2004; FishBase). This positions the SIOFA trevally assemblage entirely within the surface mixed layer — the ocean stratum most directly and immediately exposed to the climate change stressors documented in the IO Climate Summary. Unlike the mesopelagic depth refuge available to alfonsino, trevallies have no vertical thermal buffer.

Life history strategy is fundamentally different from the deep-water SIOFA species. Grandcourt et al. (2004) established that C. bajad is a fast-growing fish in the Arabian Gulf: $k = 0.598\ yr^{-1}$, $L_\infty = 40.38$cm, with growth performance index Ø' = 3.13. Natural mortality $M = 1.118\ yr^{-1}$ indicates a short-lived species with rapid population turnover. Sexual maturity at approximately 24.7cm fork length, reached in roughly 1–2 years, gives population doubling times of 1.4–4.4 years (FishBase for *C. bajad*) — substantially more productive than alfonsino (6–8 years to maturity) and potentially oilfish (maturity parameters unknown; likely late-maturing based on maximum size, but undocumented). This productivity advantage is a genuine and important buffer against climate stress, though it does not eliminate vulnerability.

FishBase assigns *C.* bajad a climate vulnerability score of 90/100 (VERY HIGH) — the highest of the three SIOFA species assessed in this review — reflecting the combination of narrow thermal niche (preferred range 25.5–29.2°C), shallow habitat, and limited distributional flexibility. Reuben et al. (1992) documented population dynamics for multiple carangid species on the Indian (Kerala) coast, confirming the fast-growth, high-productivity pattern across Indian Ocean carangids broadly.

No stock assessment exists for any *Carangoides* species within SIOFA; trevallies are reported only as a combined multispecies catch category, meaning species-level catch trends, biomass, and exploitation status are entirely unknown.

Saya de Malha Bank Habitat Characteristics

Within SIOFA, trevallies are primarily associated with Saya de Malha Bank (Subarea 8) — the world's largest submerged bank, a shallow carbonate platform of approximately 40,000km² rising to depths less than 200m in the central Indian Ocean (SIOFA 2025). The Bank supports diverse reef, coralline algae, and soft-bottom habitats that serve as trevally foraging and shelter ground. EU (France), Mauritius, Thailand, and Comoros operators take Carangoides spp., snappers, emperors, and groupers as a combined catch category using set longlines, hook and line, bottom trawl, and traps (SIOFA 2025).

The shallow carbonate platform character of Saya de Malha creates a distinct and acute climate vulnerability not shared by the deeper SIOFA species. Coral reef and hard-bottom habitats are the first marine ecosystems to cross thermal thresholds under warming — the IO Climate Summary documents that thermal stress has pushed many Indian Ocean reefs past their tipping points, with continuous marine heatwave conditions projected for the East African Coastal Current region as early as the 2030s. Saya de Malha Bank, as an isolated shallow platform in the central tropical Indian Ocean with no adjacent cool-water refugia from coastal upwelling, is particularly exposed. The Bank sits within the expanding Indian Ocean Warm Pool — waters exceeding 28°C now encompassing nearly 100% of the northeast and central Indian Ocean (IO Climate Summary).

Unlike seamount habitats (alfonsino), which derive productivity from current-topography interactions and vertical flux from below, Saya de Malha Bank productivity is driven by a combination of surface warming, monsoon-driven nutrient supply, and benthic productivity from the carbonate platform itself. Changes to monsoon intensity, thermocline depth, and the Indian Ocean Walker Circulation under climate change directly threaten these productivity mechanisms.

Food Web and Trophic Ecology

Carangidae are opportunistic, active carnivores. For *C.* bajad specifically, diet consists of nekton, crustaceans, and finfish — a generalist, mixed-prey strategy typical of pelagic carangids (Blaber et al. 1990; Masuda and Allen 1993, both cited in Grandcourt et al. 2004). G. speciosus presents a contrasting strategy: a benthic feeder that uses a highly protractile mouth to root for crustaceans, molluscs, and fishes in sandy substrates (Grandcourt et al. 2004; Randall 1995). This dietary diversity within the genus creates different climate exposure pathways — the pelagic generalist is exposed to changes in pelagic prey availability, while the benthic feeder depends on the condition of sandy-substrate invertebrate communities.

The trophic context at Saya de Malha Bank is shaped by the broader Indian Ocean food web trajectory described in the IO Climate Summary. Phytoplankton has declined 20% over the last six decades across the Indian Ocean, with surface chlorophyll showing a negative trend of −0.60% per year. Models project a cascading 40% decline in zooplankton biomass by 2100, threatening the foundational energy supply for the entire food web on which carnivorous carangids ultimately depend. The planktonic community is also shifting composition — from diatoms toward large, green mixotrophic dinoflagellates (Noctiluca scintillans blooms), a community transition that restructures prey availability for planktivores and zooplanktivores that form part of the trevally prey assemblage.

Part 1: Hazard Indicators (H1–H7)

For each of the seven climate hazard indicators, this section establishes the documented and projected change in the Indian Ocean (drawn primarily from the IO Climate Summary, Attachment F) and then evaluates exposure across three dimensions: trevallies as a species, the shallow reef and bank habitats they occupy — principally Saya de Malha Bank — and the food web that sustains them. The purpose is to identify which hazards are materially relevant to trevallies and through what pathways — the foundation on which the sensitivity assessment in Part 2 is built.

H1: Marine Heatwaves

What Information IS Available

The IO Climate Summary documents that the Indian Ocean is experiencing a fundamental thermal crisis: Marine Heat Wave (MHW) frequency has doubled since the 1980s, their duration has lengthened, and their intensity has increased. Surface warming accounts for approximately 90% of the increased upper-ocean stratification recorded in the upper 200m, and this buoyancy-driven stratification creates a self-reinforcing feedback loop that traps heat at the surface and amplifies MHW intensity. Soumya et al. (2025) documents the emergence of near-permanent marine heatwave conditions in the tropical Indian Ocean during 2023–24, with record basin mean anomalous warming of 0.88°C and severe prolonged MHW events centred in the Arabian Sea and southwestern tropical Indian Ocean —the regions encompassing the SIOFA trevally range and Saya de Malha Bank.

For a shallow-water species with a preferred temperature range of 25.5–29.2°C, the significance of MHW conditions in the tropical Indian Ocean cannot be overstated. Unlike alfonsino at 400–600m depth, which has some insulation from surface thermal anomalies, trevallies at 0–100m are fully exposed to every MHW event. Temperatures at Saya de Malha

Bank under MHW conditions will routinely and increasingly exceed the thermal optimum for Carangoides species.

The only direct evidence of MHW-equivalent thermal stress on any Carangoides species comes from Grandcourt et al. (2004), who documented that *C. bajad* in the Arabian Gulf showed maximum growth suppression during the hottest months (exceeding 35°C at peak summer), with growth oscillation amplitude C = 1.0 — the maximum possible — indicating that thermal variation drives a profound seasonal physiological response. This establishes that even within its natural range, *C. bajad* experiences growth suppression at temperature extremes. As MHWs push Saya de Malha Bank temperatures increasingly beyond current seasonal maxima, comparable and likely more severe physiological consequences are anticipated.

The IO Climate Summary documents that the East African coast is projected to face year-long continuous MHWs as early as the 2030s. Saya de Malha Bank, in the central Indian Ocean at approximately 10°S, is geographically proximate to this projection zone. Coral bleaching — a direct consequence of MHW conditions — threatens the reef habitat that supports trevally foraging. The IO Climate Summary confirms that thermal stress has pushed many Indian Ocean reefs past their tipping points and that coral reefs may be the first global ecosystem to face functional extinction due to ocean warming.

What Information IS NOT Available

No direct MHW impact studies have been conducted for *C. fulvoguttatus*, *C. gymnostethus*, or *C. bajad* at Saya de Malha Bank. Critical thermal maximum (CTmax) values — the temperature at which mortality rather than growth suppression occurs — are unknown for any SIOFA trevally species. Whether trevallies show thermal acclimation capacity (the ability to shift thermal tolerance following repeated exposure to warm events) has not been studied. The extent to which coral bleaching at Saya de Malha Bank specifically has already affected trevally habitat quality and prey availability is unmonitored. MHW recovery time for the reef assemblage at Saya de Malha and the consequences for the trevally food web are undocumented.

Synthesis and Rating Justification

RED MHW exposure for shallow-water trevallies at Saya de Malha Bank is HIGH and well-established from the IO Climate Summary and Soumya et al. (2025). Near-permanent MHW conditions are already emerging in the tropical Indian Ocean, directly overlapping trevally habitat. The species' preferred temperature range (25.5–29.2°C) places it in immediate conflict with temperatures during MHW events. Proxy evidence from Grandcourt et al. (2004) demonstrates that even temperatures within the Arabian Gulf's natural seasonal range produce maximum-amplitude growth suppression. The associated threat to reef habitat via coral bleaching is structurally well-established. Rating is RED because the hazard is severe, directionally unambiguous, and operating at or near the species' known thermal limits, with no thermal refuge available at these shallow depths. MHW impact monitoring at Saya de Malha Bank including temperature recording at trevally depth ranges, coral cover surveys, and fish community composition monitoring would be useful for the evidence base.

H2: Increased Sea Surface Temperature

What Information IS Available

The IO Climate Summary documents that the Indian Ocean Warm Pool — waters exceeding 28°C — now encompasses nearly 100% of the northeast and central Indian Ocean, driven by an average SST increase of approximately 0.7°C between 1982 and 2021. This secular warming trend is superimposed on the MHW events documented under H1, such that the baseline temperature against which extreme events are measured is itself rising. Saya de Malha Bank sits squarely within the expanding Warm Pool zone.

For *C. bajad* with a preferred temperature range of 25.5–29.2°C (FishBase), the upper end of that range is already regularly exceeded across much of the central Indian Ocean in its current state. A further 0.7°C of baseline warming — already measured — means that Warm Pool temperatures in excess of 29.2°C are not a future projection but a present reality for significant portions of the trevally range. Grandcourt et al. (2004) documented that even within the Arabian Gulf's existing seasonal temperature cycle (21–34°C mean annual range), summer temperatures suppress growth to a maximum degree. Higher baseline temperatures will extend the duration of growth suppression, intensify it, and ultimately push conditions toward thermal mortality thresholds — particularly during MHW events when daily temperatures spike above the seasonal baseline.

FishBase assigns *C. bajad* a climate vulnerability score of 90/100, the highest of the three SIOFA species, explicitly integrating the narrow thermal niche and shallow habitat exposure as primary vulnerability drivers. Indian Ocean warming is driving progressively more stratified conditions that reduce the ability of cooler deeper waters to buffer surface temperatures — removing the physical oceanographic moderating influence that currently limits peak surface temperatures at locations like Saya de Malha Bank.

What Information IS NOT Available

Specific temperature records for Saya de Malha Bank at trevally depth ranges (0–100m) are not available in the literature reviewed. Whether Saya de Malha Bank experiences SST warming at the same rate as the broader central Indian Ocean average, or whether local bathymetry creates any buffering, is undocumented. Physiological response curves (growth rate vs temperature) for the SIOFA target species across their full potential temperature range are absent. The temperature at which sustained warming produces population-level decline (rather than individual growth suppression) has not been determined for any Carangoides species.

Synthesis and Rating Justification

RED Sustained Indian Ocean SST increase is well-documented in the IO Climate Summary and directly relevant to a surface-dwelling species with a narrow (sub-4°C) preferred thermal range. The baseline warming of 0.7°C already documented means that current conditions at Saya de Malha Bank regularly approach or exceed the upper thermal preference for *C. bajad*. This is not a future risk scenario — it is a present condition that will intensify under all emissions trajectories. Rating is RED because the hazard is already operating on the species' thermal tolerance range and the trajectory is unambiguously upward with no available depth refuge.

H3: Ocean Acidification

What Information IS Available

The IO Climate Summary documents that the Indian Ocean basin is acidifying at 0.015 pH units per decade, with a measured decrease of 0.0675 units between 1961 and 2010 and projections of a 0.4 unit drop by 2100 under high-emission scenarios. Dissolved Inorganic Carbon (DIC) contributes 69.3% of this trend while surface temperature warming contributes approximately 13.8%. The western Arabian Sea has undergone more rapid acidification than the rest of the tropical Indian Ocean basin due to strong upwelling drawing up anthropogenic CO_2 embedded in deeper waters (IO Climate Summary)

For trevallies specifically, the primary known acidification risk pathway likely operates through habitat rather than direct physiology. Coral reefs — the primary trevally habitat at Saya de Malha Bank — are calcifying ecosystems acutely sensitive to acidification. The IO Climate Summary documents that acidification reduces coral calcification rates and increases skeletal dissolution, compounding the thermal bleaching risk from H1 and H2 to create a compound stressor on reef structural integrity. Reduced carbonate saturation also threatens foraminifera, molluscs, and crustaceans that form part of the trevally prey base, particularly for G. speciosus as a benthic invertebrate feeder.

The IO Climate Summary provides specific Indian Ocean acidification rate data confirming the basin-wide trend and its drivers. The compound nature of acidification and warming is mechanistically important for Saya de Malha Bank: both stressors simultaneously degrade reef structure, reduce carbonate availability for reef-building, and compromise the prey base.

What Information IS NOT Available

Direct acidification sensitivity studies for *C. fulvoguttatus, C. gymnostethus*, or *C. bajad* are absent from the literature. Whether trevallies show direct physiological sensitivity to acidification (otolith development, sensory function, respiratory physiology) at projected pH levels has not been studied. The specific pH trajectory at Saya de Malha Bank and the current carbonate saturation state of the Bank's reef system are undocumented in the reviewed literature. The rate at which reduced carbonate saturation is already affecting benthic invertebrate communities (and thereby *G. speciosus* prey availability) at Saya de Malha Bank is unmonitored.

Synthesis and Rating Justification

AMBER Ocean acidification is a well-documented and accelerating hazard in the Indian Ocean. The primary exposure pathway for trevallies is indirect — through reef habitat degradation and prey base impacts on calcifying organisms — rather than direct fish physiology, which is why this indicator rates AMBER rather than RED. The compound effect of acidification on top of the thermal bleaching stress (H1, H2) creates a structurally well-established threat to the Saya de Malha Bank reef ecosystem that supports trevallies. The absence of any direct acidification physiology data for the target species prevents a higher confidence rating.

H4: Salinity Changes

What Information IS Available

The IO Climate Summary documents salinity changes in the Indian Ocean as a consequence of altered evaporation-precipitation balances under warming, with regional patterns driven by monsoon variability and freshwater inputs. The Bay of Bengal is particularly affected by increased freshwater input altering salinity gradients. For the central Indian Ocean region encompassing Saya de Malha Bank, salinity changes are secondary in magnitude and ecological consequence to the temperature, MHW, and productivity changes documented under other hazard indicators.

Carangidae are euryhaline fishes capable of tolerating a range of salinities, consistent with their distribution across inshore, reef, and occasionally estuarine environments (Smith-Vaniz 1984). *C. bajad* in the Arabian Gulf experiences significant seasonal salinity variation — the Arabian Gulf is one of the world's most saline marginal seas — and this distribution indicates substantial salinity tolerance.

What Information IS NOT Available

Specific salinity tolerance ranges for any SIOFA *Carangoides* species have not been quantified. The salinity trajectory at Saya de Malha Bank specifically is not documented in the reviewed literature. Whether projected salinity changes in the central Indian Ocean will cross ecologically significant thresholds for trevallies is unknown.

Synthesis and Rating Justification

AMBER Salinity changes are a documented feature of Indian Ocean climate change (IO Climate Summary), but are less severe and less ecologically consequential for *Carangoides* species than the temperature, MHW, and productivity hazards. The euryhaline characteristics of the family, demonstrated by distribution across diverse saline environments, suggest moderate tolerance to projected salinity shifts. AMBER reflects that salinity changes are occurring and cannot be dismissed as irrelevant, but are not the primary or most urgent climate hazard for SIOFA trevallies at current best evidence. This assessment would benefit from Saya de Malha-specific salinity monitoring data.

H5: Deoxygenation (OMZ Expansion)

What Information IS Available

The IO Climate Summary documents significant deoxygenation in the Indian Ocean, driven by warming-reduced oxygen solubility and reduced vertical ventilation from enhanced stratification. The Arabian Sea hosts the world's second most intense oxygen minimum zone (OMZ), and this is expanding both vertically and horizontally. The IO Climate Summary projects that marginal sea shoaling (Persian Gulf/Red Sea) will further reduce oxygen supply to the deep OMZ and warns of potential functional anoxia in the Arabian Sea OMZ over coming decades.

For trevallies, OMZ dynamics are a secondary hazard compared to the direct thermal and MHW risks. SIOFA trevallies are shallow-water species (0–100m depth), living well above the OMZ core (typically 200–1,500m in the Indian Ocean). Direct deoxygenation of trevally habitat does not seem to be a near-term risk under current projections. That said, this assessment warrants a caveat: Carangidae are active, high-metabolic-rate predators with commensurately high oxygen demands, and should shoaling OMZ boundaries or episodic hypoxic intrusion events bring low-oxygen water into trevally depth ranges — whether at Saya de Malha Bank or elsewhere — the consequences would likely be severe. Unlike the thermal stressors in H1 and H2, which operate along a gradient that allows for some degree of behavioural thermoregulation, acute hypoxia offers little scope for adjustment. The hazard is not imminent, but it should not be dismissed.

However, OMZ expansion affects prey availability indirectly: as OMZs expand upward, the habitable vertical range for mesopelagic fish and crustaceans that form part of the trevally prey base is compressed, potentially concentrating prey at shallower depths in some scenarios, or reducing overall prey biomass in others.

The broader Indian Ocean deoxygenation context — with the Arabian Sea OMZ expanding and tropical dissolved oxygen concentrations — is also relevant to the reef ecosystem at Saya de Malha Bank through effects on benthic invertebrate communities in near-bottom waters, where dissolved oxygen reductions could affect *G. speciosus* prey availability.

What Information IS NOT Available

Dissolved oxygen measurements at trevally depth ranges at Saya de Malha Bank are not available in the reviewed literature. Whether OMZ boundaries are close enough to Saya de Malha Bank at present or in projected scenarios to directly constrain trevally habitat is undocumented. The sensitivity of *Carangoides* species to sub-optimal dissolved oxygen levels — aerobic scope reduction thresholds — has not been studied.

Synthesis and Rating Justification

AMBER Deoxygenation is a documented and accelerating hazard in the Indian Ocean, but its primary manifestation in the Indian Ocean (OMZ expansion in the Arabian Sea and deep waters) does not directly overlap the shallow trevally habitat at Saya de Malha Bank under current conditions. AMBER reflects a real but indirect and lower-urgency hazard relative to H1 and H2. The indirect pathway through prey availability compression and benthic community impacts warrants monitoring but is not an immediate primary driver of trevally vulnerability.

H6: Wind Stress Changes

What Information IS Available

The IO Climate Summary documents that the Indian Ocean Walker Circulation (IOWC) is projected to slow under greenhouse forcing. In the Arabian Sea, IOWC slowdown induces wind anomalies that inhibit the entrainment of nutrient-rich subsurface waters, reducing the upwelling productivity that drives high fish biomass in this region. Monsoon wind patterns — which drive the most important seasonal oceanographic signal in the Indian Ocean, including upwelling at the Seychelles-Chagos ridge system — are projected to change in both intensity and timing under warming scenarios.

For Saya de Malha Bank specifically, monsoon-driven seasonal productivity patterns structure the reef fish community's food web. The Bank's location in the central Indian Ocean means that monsoon dynamics drive seasonal changes in currents, temperature, and nutrient availability that are the primary environmental cues for trevally behaviour, including feeding aggregation and spawning. If monsoon timing shifts or intensifies (or weakens) irregularly, the seasonal structure that Carangoides populations depend upon for growth and reproduction may be disrupted — consistent with the temperature-entrained seasonal growth oscillations documented by Grandcourt et al. (2004) for *C. bajad*.

Reduced snow cover over the Himalayan-Tibetan plateau — documented in the IO Climate Summary as a driver of accelerated Arabian Sea stratification — has cascading effects on the monsoon system that ultimately affect the seasonal productivity of the central Indian Ocean region.

What Information IS NOT Available

The specific wind stress and monsoon dynamics at Saya de Malha Bank have not been modelled or monitored in the context of trevally ecology. How changes to monsoon intensity and timing translate into ecological consequences for the Saya de Malha reef fish community is unstudied. Whether trevallies at Saya de Malha Bank can adjust behavioural cues (spawning timing, seasonal movement) if monsoon phenology shifts is unknown.

Synthesis and Rating Justification

AMBER Wind stress changes via IOWC slowdown and monsoon variability are documented in the IO Climate Summary as drivers of productivity decline in the Indian Ocean. For shallow reef-associated trevallies, the exposure pathway is primarily indirect — through changes to seasonal productivity patterns and nutrient supply rather than direct wind stress on fish physiology. AMBER rating reflects a real hazard pathway with plausible ecological consequences for Saya de Malha Bank, but with a lower confidence mechanistic linkage to trevally population outcomes than the direct thermal hazards.

H7: Ocean Current Changes

What Information IS Available

The IO Climate Summary documents that boundary current systems in the Indian Ocean are changing under climate forcing. The weakening of trade winds and shifts in South Indian Ocean circulation are reducing larval connectivity along the East African Coastal Current system and affecting the Agulhas Current — one of the most important western boundary currents globally and a key driver of southern Indian Ocean heat distribution. These changes have documented implications for food security and species distribution in the western Indian Ocean.

Positive Indian Ocean Dipole (IOD) events — becoming more frequent and intense under warming according to the IO Climate Summary — significantly alter current patterns across the Indian Ocean basin. The IOD redistributes heat, modifies the thermocline depth across the basin, and generates current anomalies that can disrupt larval transport pathways for reef fish species. For isolated populations at Saya de Malha Bank, which likely depend on larval dispersal via Indian Ocean current systems for recruitment, intensifying IOD variability represents a specific and plausible risk to population replenishment.

The shoaling of the thermocline documented in the IO Climate Summary — linked to warming and IOWC dynamics — affects the depth structure of current systems that transport larvae and nutrients across the Indian Ocean, including the pathways that connect potential source reef populations to Saya de Malha Bank.

What Information IS NOT Available

Larval connectivity pathways for Carangoides species at Saya de Malha Bank have not been modelled or empirically documented. Whether the Bank population is self-recruiting or dependent on external larval supply from Indian Ocean source populations is unknown — a critical gap for assessing whether current changes affect population replenishment. The specific current systems transporting larvae to Saya de Malha Bank and their projected trajectories under climate scenarios have not been characterised for trevally recruitment.

Synthesis and Rating Justification

AMBER Ocean current changes are documented in the IO Climate and affect larval connectivity, seasonal productivity, and IOD-driven habitat disruption. The primary vulnerability pathway for trevallies is through larval supply disruption to the isolated Saya de Malha Bank population. AMBER rather than RED reflects that the direct current change signal is less immediately severe than the thermal hazards, but the potential disruption of larval connectivity for an isolated bank population is a genuine structural risk that warrants higher concern if stock structure analysis confirms self-recruitment limitation.

Part 2: Sensitivity and Adaptive Capacity Indicators (S1–S10)

Part 2 evaluates the biological and behavioural characteristics that determine how trevallies would respond to the hazards identified in Part 1. Sensitivity indicators address the magnitude of likely response — how strongly a given hazard affects the species given its biology. Adaptive capacity indicators address the scope for adjustment — whether the species has the life history, mobility, flexibility, or ecological options to reduce adverse outcomes. Several indicators (thermal range, prey specificity, productivity, distributional range) are assessed in both parts because exposure and response capacity are related but distinct questions: knowing that a species occupies warm, shallow reef environments tells you something about exposure; it tells you something different about whether the species can tolerate further change to those conditions.

S1;A1: Thermal Range

What Information IS Available

Thermal preference for *C. bajad* is 25.5–29.2°C (mean 28.5°C; FishBase) — a narrow tropical niche spanning less than 4°C. This is consistent with the Arabian Gulf environmental data in Grandcourt et al. (2004), where the annual mean temperature used for Pauly's mortality equation was 27.5°C and seasonal extremes spanned 21–34°C. Grandcourt et al. explicitly identified high summer temperatures as probable growth stressors, noting that the seasonal growth oscillation amplitude C = 1.0 — the maximum possible — indicates the strongest possible temperature-physiology coupling. Growth was fastest in winter (21–27°C) and most suppressed in summer (exceeding 35°C at peak), attributed to a combination of direct thermal stress and energy diversion to spawning.

The closest available family-level physiological evidence comes from Valenza-Troubat et al. (2022), who examined transcriptomic responses of silver trevally (*Pseudocaranx georgianus*) to elevated temperature. The study documented substantial but predictable plastic regulatory responses — upregulation of heat shock proteins and altered metabolic pathways — alongside clear growth differences between temperature treatments. Critically, the authors found that plastic acclimation carries a metabolic cost: resources redirected toward thermal stress management are unavailable for growth and reproduction. This is directly relevant to the SIOFA context. The Grandcourt et al. (2004) data already show that *C. bajad* suppresses growth at temperature extremes; Valenza-Troubat et al. (2022) provides a mechanistic explanation for why reproductive investment is likely to be simultaneously compromised — even in individuals that appear to be coping physiologically. For a species assemblage for which no direct thermal tolerance data exist, this family-level finding is the best available evidence that acclimation is not a cost-free buffer.

Contextualised against the IO Climate Summary, this narrow preferred temperature range is alarming. The Indian Ocean Warm Pool (>28°C) now encompasses nearly 100% of the northeast and central Indian Ocean, and MHW conditions in 2023–24 produced record basin mean anomalous warming of 0.88°C (Soumya et al. 2025). For a species with an upper thermal preference boundary of 29.2°C, near-permanent conditions at or above this threshold represent the transition from a suboptimal environment to one approaching physiological stress territory. FishBase assigns *C. bajad* a climate vulnerability score of 90/100 (VERY HIGH), the highest of the three SIOFA species, explicitly integrating this narrow thermal niche as the primary vulnerability driver.

What Information IS NOT Available

No thermal tolerance experiments — critical thermal maximum (CTmax), aerobic scope measurements, or metabolic rate responses to temperature — have been conducted for *C. bajad, C. fulvoguttatus,* or *C. gymnostethus*. The precise upper thermal limit at which mortality rather than growth suppression occurs is unknown. Growth suppression at 35°C documented in the Arabian Gulf (Grandcourt et al. 2004) is an indirect signal of thermal stress but not a mechanistic physiological threshold measurement. No thermal niche information is available specifically for the SIOFA target species, and no Indian Ocean thermal habitat modelling has been conducted for Carangoides.

Synthesis and Rating Justification

AMBER Thermal preference quantified for *C. bajad* (25.5–29.2°C; Grandcourt et al. 2004; FishBase); maximum-amplitude seasonal growth suppression above ~30°C documented. FishBase climate vulnerability score (90/100) provides an integrated signal. AMBER rather than GREEN reflects that the physiological data derive from a proxy species in a geographically distinct location, and mechanistic thermal tolerance thresholds remain unknown for all three SIOFA target species. The hazard context (H1, H2) combined with this narrow thermal range creates a HIGH vulnerability signal overall. The metabolic cost of thermal acclimation documented by Valenza-Troubat et al. (2022) also bears on S3 (Productivity) and S6 (Reproductive Strategy), where the consequences of energy reallocation under chronic warming are assessed.

S2;A3: Mobility (Ability to Move to New Locations)

What Information IS Available

Carangidae are pelagic, open-water fish with well-developed swimming musculature, documented as active predators capable of sustained directional movement. Carangoides species form schools and range across reef and coastal environments. *C. bajad* is characterised as a coastal species associated with reefs to 50m (Grandcourt et al. 2004; Al-Abdessalaam 1995) suggesting site association, but not the extreme seamount fidelity documented for alfonsino.

The wide Indo-Pacific distributions of all three SIOFA target species — *C. bajad* from Madagascar to Japan, *C. fulvoguttatus* and *C. gymnostethus* broadly across the Indo-Pacific (FishBase) — demonstrates high historical dispersal capacity, most likely achieved through larval transport during an extended larval/early juvenile period. Recruitment to the fishery at 4–6 months age (Grandcourt et al. 2004 for *C. bajad*) implies an extended larval phase with potential for oceanographic dispersal to isolated bank environments such as Saya de Malha.

What Information IS NOT Available

No tagging or acoustic tracking studies have been conducted for any Carangoides species in the SIOFA area. Adult home range, site fidelity to Saya de Malha Bank, and seasonal migration patterns are entirely undocumented. Larval dispersal distances and settlement cues are unknown. Whether the Saya de Malha Bank population is self-recruiting or depends on external larval supply is a critical unknown — an isolated, self-recruiting population has no immigration buffer against local climate impacts, while a well-connected population may be replenished from unaffected source areas.

Synthesis and Rating Justification

Rating: AMBER General mobility of the Carangidae is high and wide geographic distribution indicates historical dispersal capacity. However, the complete absence of direct movement or connectivity data for SIOFA Carangoides populations — combined with the geographic isolation of Saya de Malha Bank in the central Indian Ocean — prevents a GREEN rating. Even a mobile genus may have constrained recolonisation capacity if the bank population is self-recruiting and depleted by combined climate and fishing pressure.

S3;A2: Productivity

What Information IS Available

Trevallies represent a fundamentally different life history strategy from the deep-water SIOFA species, and this is one of the most important findings of this assessment. Grandcourt et al. (2004) established that *C. bajad* is a fast-growing fish: $k = 0.598\ yr^{-1}$, $L_\infty = 40.38$cm, growth performance index $Ø' = 3.13$. Natural mortality $M = 1.118\ yr^{-1}$ is high, consistent with a short-lived, fast-turnover life history. Sexual maturity at approximately 24.7cm fork length (roughly 1–2 years), with population doubling times of 1.4–4.4 years (FishBase), represents a substantially higher productivity than alfonsino (6–8 years to maturity, potentially 50–70 year lifespan).

Reuben et al. (1992) documented population dynamics for multiple carangid species on the Indian (Kerala) coast, including *Decapterus russelli* and *Atropus atropus*, confirming the fast-growth, high-productivity pattern across Indian Ocean carangids broadly. For *G. speciosus* (also present at Saya de Malha), Grandcourt et al. (2004) documented $k = 0.514\ yr^{-1}$ and maturity at approximately 32.5cm (~2–3 years) — slightly lower productivity given larger body size ($L_\infty = 72.33$cm), but still substantially higher than the deep-water SIOFA species.

Temperature response of growth is directly documented for *C. bajad*: Grandcourt et al. (2004) showed maximum growth oscillation amplitude C = 1.0, with winter growth substantially exceeding summer, demonstrating that production is already being modulated by seasonal thermal variation. Under projected warming from the IO Climate Summary — particularly the expanding Warm Pool and increasing MHW frequency — summer growth suppression periods will lengthen and intensify. While the fast life history potentially provides more recovery capacity than deep-water species, sustained growth suppression during extended MHW periods could reduce annual production substantially.

What Information IS NOT Available

Growth parameters and maturity data for *C. fulvoguttatus* and *C. gymnostethus* specifically are absent from the accessible literature. Both are larger-bodied than *C.* bajad — *C. fulvoguttatus* reaching ~100cm — and larger maximum size generally correlates with slower growth and later maturity, reducing the productivity advantage. Fecundity data for any SIOFA Carangoides species are absent. The quantitative effect of sustained elevated temperature on annual production (rather than seasonal growth suppression) has not been modelled for any target species.

Synthesis and Rating Justification

AMBER Fast life history clearly established for *C. bajad* from Arabian Gulf data and corroborated broadly by Reuben et al. (1992) for Indian Ocean carangids. This is a resilience advantage: trevallies can potentially recover from climate-driven mortality events faster than the other SIOFA species reviewed. AMBER rather than GREEN reflects that: the two primary SIOFA target species lack direct data; both are larger-bodied than the proxy species (suggesting somewhat lower productivity); and the IO Climate Summary documents conditions that will extend growth suppression periods in the tropical Indian Ocean. The productivity advantage is real but not unlimited.

S4; A3: Distributional Range and Habitat Flexibility

What Information IS Available

All three SIOFA target species are Indo-Pacific wide in distribution: *C. bajad* from Madagascar to Japan*; C. fulvoguttatus* and *C. gymnostethus* broadly across the Indo-Pacific (FishBase; Smith-Vaniz 1984). This broad historical range is consistent with ecological plasticity and high dispersal capacity. Within SIOFA, the trevally assemblage is primarily associated with Saya de Malha Bank (Subarea 8), the world's largest submerged bank at <200m depth (SIOFA 2025).

The habitat flexibility dimension of this indicator is more constrained than the broad distribution suggests. Unlike alfonsino, which — in principle — can shift depth or seamount location within a continuous mesopelagic habitat zone, trevallies depend on the availability of shallow reef and bank ecosystems. Saya de Malha Bank is an isolated geographic feature in the central Indian Ocean. Redistribution to alternative shallow-bank habitats would require crossing hundreds of kilometres of unsuitable open ocean — a barrier that adult fish are unlikely to traverse even for a mobile genus. The IO Climate Summary documents that reef ecosystems are facing functional extinction under warming trajectories, threatening the habitat foundation that makes Saya de Malha Bank suitable for trevallies regardless of the species' intrinsic mobility.

What Information IS NOT Available

Stock structure within the SIOFA area is completely undocumented for *Carangoides* spp. Whether the Saya de Malha Bank population is genetically isolated from reef populations in Mauritius, Madagascar, or the wider Indian Ocean is unknown. No habitat suitability modelling under climate change scenarios has been conducted for any SIOFA trevally species. Whether alternative shallow-bank habitats within the region could support Carangoides populations if Saya de Malha Bank conditions deteriorate has not been assessed.

Synthesis and Rating Justification

AMBER Wide distributional range demonstrates historical habitat flexibility across the genus. However, within the SIOFA context, trevallies are functionally tied to the shallow reef and bank environment of Saya de Malha — a habitat that is itself highly climate-sensitive. The isolation of the Bank creates a redistribution constraint that the broad species range does not resolve. Rating is AMBER because wide historical range provides some confidence in intrinsic adaptability, but Saya de Malha dependency and unknown stock connectivity prevent a GREEN assessment. The reef habitat loss trajectory documented in the IO Climate Summary adds further urgency. Habitat suitability modelling under projected warming for Saya de Malha Bank would provide useful information.

S5;A3: Environmental Cues Influencing Distribution

What Information IS Available

The most direct evidence of environmental cue dependency comes from the seasonal growth oscillations documented by Grandcourt et al. (2004). *C. bajad* showed maximum-amplitude seasonal growth oscillations (C = 1.0) synchronised with the Arabian Gulf annual temperature cycle — growth fastest in winter, suppressed in summer. This demonstrates that temperature cues structure physiology throughout the year, consistent with temperature-entrained distribution and behaviour documented across Carangidae.

The Indian Ocean monsoon cycle drives pronounced seasonal changes in upwelling, temperature, and productivity that function as master environmental cues for fish distribution across the Indian Ocean. The IO Climate Summary documents that the timing of seasonal oceanographic events is already shifting under warming — monsoon dynamics and IOD-related current patterns are changing in both timing and intensity. IOWC slowdown generates wind anomalies that alter the seasonal structure of nutrient entrainment and phytoplankton productivity. To the extent that Carangoides at Saya de Malha Bank are seasonally distributed in response to productivity-linked prey availability, these shifting cues may be a direct behavioural disruption pathway.

What Information IS NOT Available

No direct study of the environmental cues guiding trevally distribution or movement at Saya de Malha Bank exists. Whether temperature, prey distribution, current patterns, or photoperiod dominate as distribution cues in the SIOFA context is unknown. Whether the species exhibits phenotypic plasticity in its environmental cue responses — the ability to adjust behavioural responses to track shifting seasonal patterns — is undocumented.

Synthesis and Rating Justification

AMBER Temperature-coupled seasonal physiology is well-documented for *C. bajad* in the Arabian Gulf (Grandcourt et al. 2004), establishing that Indian Ocean Carangoides are sensitive to environmental cue timing. The IO Climate Summary documents that seasonal oceanographic signals are already shifting in the Indian Ocean. AMBER reflects that cue sensitivity is established by proxy, not directly for the SIOFA species and location, and that the consequences of disruption have not been characterised.

S6;A4: Reproductive Environmental Dependency and Spawning Strategy

What Information IS Available

Carangoides species are broadcast spawners — they release eggs and sperm freely into the water column for external fertilisation, with no parental investment, nest construction, or post-spawning care of any kind. This is the universal reproductive strategy across the Carangidae (Smith-Vaniz 1984) and represents one of the most environmentally exposed reproductive modes in marine fish: every stage from gamete release through fertilisation, embryonic development, hatching, and larval survival is entirely dependent on ambient oceanographic conditions, with no mechanism available to buffer offspring from environmental extremes.

Grandcourt et al. (2004) provides the only quantitative reproductive data for *Carangoides* in the Indian Ocean region. *C. bajad* in the Southern Arabian Gulf showed bimodal seasonal spawning: gonadosomatic index (GSI) peaked in females during May and August, with corresponding male peaks in July. Batch spawning was confirmed over an extended season, consistent with the serial broadcast spawning strategy typical of carangids. Critically, peak reproductive investment coincided precisely with the highest water temperatures of the Arabian Gulf annual cycle — northern summer months when growth suppression (C = 1.0; maximum amplitude) was simultaneously at its greatest. This is not a coincidental alignment: tropical carangids appear to spawn into the warmest period of the year, meaning that reproductive physiology is already operating under the most thermally stressful ambient conditions the species encounters naturally.

For *Gnathanodon speciosus* (also recorded in SIOFA catches at Saya de Malha Bank), spawning peaked in April–May — earlier in the seasonal cycle, during the northern pre-summer warm period — with GSI patterns likewise temperature-coupled (Grandcourt et al. 2004). Both species showed near-unity sex ratios (*C. bajad* 1:1.01; *G. speciosus* 1:1.1), indicating no sex-specific differential mortality that would skew spawning stock composition.

The thermal sensitivity of broadcast-spawned early life stages is well-established across marine teleosts. Díaz-Gil et al. (2016) — using *Sparus aurata* and *Argyrosomus regius* as model broadcast-spawning species — demonstrated that the odds of successful hatching under elevated temperature were only 0.39 times those under control conditions (i.e., approximately 2.6 times more likely to hatch at control temperatures than under warming), with effects independent of pCO_2. Larval survival and foraging behaviour were additionally impaired. While this study is from Atlantic species in controlled conditions, it establishes a mechanistic basis for thermal impairment of hatching success in broadcast-spawning marine fish that is directly applicable to the trevally context: broadcast-spawned eggs have zero capacity for behavioural thermoregulation, meaning that every degree of warming during the spawning season translates directly into increased developmental failure risk.

At the carangid level, Valenza-Troubat et al. (2022) examined transcriptomic responses of the silver trevally (*Pseudocaranx georgianus*) to elevated temperature, finding substantial but predictable plastic regulatory responses — upregulation of heat shock proteins, altered metabolic pathways — alongside clear growth differences between temperature treatments. The authors noted that while plastic regulatory responses occur, they carry metabolic costs that reduce energy available for growth and reproduction. This suggests that even where *Carangoides* species can acclimate physiologically to elevated temperatures, reproductive investment is likely to be compromised as metabolic resources are redirected toward thermal stress management.

Contextualised against the IO Climate Summary and Soumya et al. (2025), the projection of near-permanent marine heatwave conditions in the tropical Indian Ocean — already manifested as a record basin-mean anomalous warming of 0.88°C during 2023–24 — means that the summer spawning period for Indian Ocean *Carangoides* will increasingly coincide not merely with seasonal warm temperatures but with MHW-amplified thermal extremes that extend well beyond the conditions under which the Arabian Gulf proxy data were collected. Eggs broadcast into surface waters during MHW events at Saya de Malha Bank will experience temperatures that have, in recent years, exceeded the species' thermal preference ceiling (29.2°C) by significant and growing margins.

What Information IS NOT Available

No reproductive data whatsoever are available for *C. fulvoguttatus* or *C. g*ymnostethus from the Indian Ocean or from Saya de Malha Bank. Thermal tolerance thresholds for fertilisation success, egg development, hatching, and larval survival are unknown for all three SIOFA target species. Whether spawning occurs at Saya de Malha Bank or whether the bank population is dependent on larvae transported from elsewhere (with implications for which water temperatures eggs actually experience at the time of spawning) is entirely undocumented. The duration of the spawning season and whether it has shifted phenologically under recent Indian Ocean warming — a change that would already be detectable if monitoring existed — is unknown. Whether the metabolic cost of thermal stress responses documented in *Pseudocaranx georgianus* (Valenza-Troubat et al. 2022) reduces fecundity or egg quality in Carangoides at warm temperatures has not been investigated.

Synthesis and Rating Justification

RED. Broadcast spawning strategy confirmed for the *Carangidae* (Smith-Vaniz 1984); seasonal spawning synchronised with peak thermal stress established for *C. bajad* and *G. speciosus* in the Arabian Gulf (Grandcourt et al. 2004); thermal impairment of hatching success demonstrated for broadcast-spawning marine teleosts (Díaz-Gil et al. 2016); metabolic costs of thermal acclimation in a carangid confirmed (Valenza-Troubat et al. 2022). The combination of broadcast spawning — the reproductive mode most exposed to environmental conditions — with spawning peaks timed to coincide with maximum thermal stress, and the documented emergence of near-permanent MHW conditions in the tropical Indian Ocean (Soumya et al. 2025; IO Climate Summary), creates a structurally coherent and serious vulnerability to reproductive failure. All evidence derives from proxy species and locations; no direct evidence of reproductive impairment exists for the SIOFA target species or at Saya de Malha Bank, and this caveat is noted. However, the structural case for high vulnerability is sufficiently well-established from family-level physiology and Indian Ocean climate projections that a RED rating is warranted. Critical research priorities are identification of spawning grounds and seasons for *C. fulvoguttatus* and *C. gymnostethus* at Saya de Malha Bank, and larval connectivity analysis to determine whether the Bank population is self-recruiting or dependent on external supply.

S7;A4: Spawning Cycle Sensitivity to Seasonal and Temperature Cues

What Information IS Available

The seasonal growth oscillation amplitude documented by Grandcourt et al. (2004) — C = 1.0, the maximum possible under the Hoenig and Hanumara seasonal growth model — establishes that *C. bajad* physiology is coupled to the annual temperature cycle with the strongest detectable signal. Maximum-amplitude oscillations indicate that seasonal temperature drives year-round physiological state as comprehensively as it does in any studied fish population. The bimodal spawning peaks documented in the same study — June and September for *C. bajad*, April–May for *G. speciosus* — are consistent with temperature-entrained reproductive cycles in which rising or threshold temperatures trigger gonadal recrudescence and spawning behaviour.

Valenza-Troubat et al. (2022) provides molecular evidence of the mechanisms underlying this thermal coupling in a carangid. Transcriptomic analysis of silver trevally (*Pseudocaranx georgianus*) exposed to two temperature treatments revealed predictable and substantial changes in gene expression profiles, including genes involved in the somatotropic axis (growth hormone, somatostatin), lipid metabolism, and heat shock response. The authors noted that while plastic regulatory responses occurred, they involved fundamental reconfiguration of physiological priorities — the kind of reprogramming that, if temperature cues shift, would alter the timing and intensity of reproductive investment alongside somatic growth. This provides a plausible molecular mechanism by which shifting temperature cues in the Indian Ocean could alter spawning timing in *Carangoides* species.

The IO Climate Summary documents that the seasonal oceanographic cycle of the Indian Ocean is already changing under warming. The Indian Ocean Walker Circulation (IOWC) slowdown is generating wind anomalies that alter the timing and intensity of monsoon-driven nutrient entrainment. Positive Indian Ocean Dipole (IOD) events — becoming more frequent and extreme under warming — restructure the seasonal temperature and current patterns that function as the dominant environmental cues for reef fish across the Indian Ocean. The IO Climate Summary documents a 300% increase in compound marine heatwave and low-chlorophyll events in specific Indian Ocean provinces — a signal that the synchrony between temperature and productivity cues, which reef fish spawning timing presumably evolved to exploit, is breaking down. The IO Climate Summary documents accelerating stratification and monsoon-linked wind anomalies in the Arabian Sea region, with implications for the seasonal structure of the entire western Indian Ocean system.

Critically, the consequence of spawning cue disruption for a broadcast spawner is more severe than for a species with parental care or demersal eggs. If spawning timing shifts relative to the peak larval food availability window — the classic match-mismatch mechanism (Cushing 1990) — larvae are broadcast into waters where prey fields are inadequate for first-feeding, producing recruitment failure even when adult spawning behaviour and gamete quality are unimpaired. For an isolated bank population at Saya de

Malha, where there is no nearby source population to buffer a failed recruitment year with immigration, even a single severe mismatch event could produce detectable cohort failure — though this would only be visible with the monitoring infrastructure that currently does not exist at the Bank.

What Information IS NOT Available

No time-series data on spawning timing, larval abundance, or juvenile recruitment exist for any *Carangoides* species at Saya de Malha Bank, making it impossible to detect whether phenological shifts are already occurring. Whether the species exhibits genuine plasticity in spawning phenology — the capacity to shift reproductive timing to track changing environmental cues — or is physiologically locked to a fixed seasonal window is unknown. The transcriptomic evidence from Valenza-Troubat et al. (2022) demonstrates capacity for plastic gene expression responses to temperature, but whether this translates into phenological plasticity in spawning timing (rather than merely altered physiology within a fixed timing window) has not been established for any *Carangoides* species. The specific environmental cues that trigger spawning at Saya de Malha Bank — temperature threshold, photoperiod, monsoon-linked productivity pulse, or a combination — are entirely uncharacterised, meaning that the sensitivity of the spawning cycle to shifts in any specific cue cannot be assessed.

Synthesis and Rating Justification

AMBER. Temperature-entrained physiology and seasonal spawning established for *C. bajad* and *G. speciosus* in the Arabian Gulf (Grandcourt et al. 2004); molecular evidence of temperature-driven physiological reprogramming in a carangid (Valenza-Troubat et al. 2022); well-documented disruption of the seasonal oceanographic cue structure of the Indian Ocean under warming, including IOD intensification and monsoon-linked wind anomalies (IO Climate Summary; Roxy et al. 2020). The risk pathway — seasonal cue disruption leading to match-mismatch between broadcast-spawned larvae and optimal prey availability or current transport windows — is ecologically coherent and mechanistically plausible. AMBER rather than RED reflects that all evidence derives from proxy species and locations, no time-series data exist to confirm disruption is already occurring at Saya de Malha Bank, and the degree of phenological plasticity in the SIOFA assemblage is entirely unknown. The consequence of cue disruption for an isolated bank population dependent on broadcast spawning and without an immigration buffer makes this a priority monitoring gap. Critical research needs are multi-year larval abundance and juvenile recruitment monitoring at Saya de Malha Bank, characterisation of the specific environmental spawning cues for SIOFA *Carangoides* spp., and larval connectivity modelling under current and IOD-altered circulation scenarios.

S8;A4: Age at Maturity

What Information IS Available

Size at first sexual maturity for *C. bajad* females: Lm = 24.7cm fork length, corresponding to approximately 1–2 years of age given the growth parameters (Grandcourt et al. 2004). *G. speciosus* matures at approximately 32.5cm (~2–3 years). Both represent substantially earlier maturity than alfonsino (6–8 years) and provide a meaningful resilience buffer. However, Grandcourt et al. (2004) documented a critical complication: the mean size at first capture (L50 = 14.8cm for *C. bajad*; 13.5cm for *G. speciosus*) was substantially below Lm in both cases, resulting in juvenile retention rates of 39.3% and 70.7% respectively. For *G.*

speciosus, the exploitation rate (E = 0.511) exceeded FMSY — the species was growth-overfished in the Arabian Gulf despite its relatively fast life history.

No stock assessment exists for any Carangoides species within SIOFA. SIOFA (2025) reports trevallies only as part of a combined multispecies catch category — species-level catch trends, biomass, and exploitation status are unknown. The Arabian Gulf data showing growth overfishing of *G. speciosus* demonstrates that fast life histories do not prevent overexploitation when gear selectivity captures pre-mature fish at high rates, and that species-level assessment within mixed-fishery management is essential.

What Information IS NOT Available

Maturity data for *C. fulvoguttatus* and *C. gymnostethus* from the SIOFA area are absent. Current stock status at Saya de Malha Bank is unknown — no stock assessment exists, quantitative assessment may not be possible. Whether the pre-maturity exploitation pattern documented in the Arabian Gulf (Grandcourt et al. 2004) characterises the Saya de Malha fishery is undocumented but critical to assess. Without stock status, the population health dimension of this indicator cannot be evaluated.

Synthesis and Rating Justification

AMBER Age at maturity is relatively early (~1–2 years for *C. bajad*) and is a resilience advantage. However, the Arabian Gulf data simultaneously demonstrate that fast life histories do not prevent growth overfishing when gear selectivity is poorly matched to maturity. Without a stock assessment, the current population health status — a critical framing condition for any climate vulnerability rating — cannot be determined. AMBER reflects the inherent resilience advantage balanced against the complete absence of SIOFA stock status data.

S9;A5: Prey Specificity and Dietary Flexibility

What Information IS Available

Carangidae are broadly opportunistic, active carnivores. For *C. bajad*, diet consists of nekton, crustaceans, and finfish (Blaber et al. 1990; Masuda and Allen 1993, both cited in Grandcourt et al. 2004) — a generalist, mixed-prey strategy. *G. speciosus* presents a contrasting strategy as a benthic feeder using a highly protractile mouth to root for crustaceans, molluscs, and fishes in sandy substrates (Grandcourt et al. 2004; Randall 1995). Dietary generalism in *C. bajad* provides a moderate buffer against climate-driven prey composition shifts.

The IO Climate Summary documents, however, that the prey base itself is undergoing structural decline across the Indian Ocean: phytoplankton has declined 20% over six decades, zooplankton biomass is projected to decline 40% by 2100, and planktonic community composition is shifting from nutritious diatoms toward Noctiluca scintillans blooms that provide poor energetic value to higher trophic levels. These changes cascade upward to reduce the abundance and quality of the invertebrates and small fish that trevallies consume. The benthic prey base of *G. speciosus* — crustaceans and molluscs — includes calcifying organisms additionally impacted by acidification (H3).

What Information IS NOT Available

Quantitative diet composition studies for *C. fulvoguttatus*, *C. gymnostethus*, or *C. bajad* at Saya de Malha Bank are absent from the literature. Dietary flexibility under prey limitation — whether trevallies switch effectively when preferred items decline or show foraging conservatism — has not been tested. The rate at which prey composition at Saya de Malha Bank is already shifting under Indian Ocean warming is unmonitored.

Synthesis and Rating Justification

AMBER Generalist carnivore diet documented for *C. bajad*; *G. speciosus* shows benthic specialisation (Grandcourt et al. 2004). The generalist feeding of the primary target species provides a moderate resilience buffer against prey composition shifts. AMBER rather than GREEN because the IO Climate Summary documents severe and progressive decline in the Indian Ocean prey base across trophic levels, and *G. speciosus* benthic specialisation creates a specific dependency on calcifying invertebrates under additional acidification pressure. Dietary flexibility under prey limitation at Saya de Malha Bank is entirely uncharacterised.

S10;A10: Competition for Habitat and Resources

What Information IS Available

Trevallies at Saya de Malha Bank form part of a diverse multispecies assemblage — snappers, emperors, groupers, and other reef-associated predators — all caught together in the same mixed fishery (SIOFA 2025). Competitive interactions within this assemblage for prey and space are structurally plausible. The IO Climate Summary documents that warming is driving distribution shifts across trophic levels in the Indian Ocean, with habitat compression and community restructuring already underway. Coral bleaching — documented as accelerating across the Indian Ocean (IO Climate Summary) — degrades structural complexity of reef habitats, simultaneously reducing carrying capacity for all reef-associated species and intensifying competition for the remaining functional habitat.

The IO Climate Summary documents that fish biomass in East Africa is projected to decline by 56–76% due to habitat compression from warming and OMZ expansion — a regional signal of the severity of competitive pressure changes as available habitat for reef carnivores contracts. While this projection is for East African waters rather than Saya de Malha Bank specifically, it illustrates the scale and direction of competitive pressure intensification under warming.

What Information IS NOT Available

No direct studies of competitive interactions involving Carangoides species at Saya de Malha Bank have been identified. Baseline reef fish community composition and current competitive structure at the Bank are undocumented in the reviewed literature. Whether reef degradation through bleaching is already affecting trevally habitat quality and competitive dynamics at Saya de Malha is unmonitored.

Synthesis and Rating Justification

RED The competitive dynamics and habitat condition at Saya de Malha Bank under climate change are essentially uncharacterised for Carangoides. RED reflects that reef habitat degradation — a well-documented and accelerating consequence of Indian

Ocean warming (IO Climate Summary) — creates a structurally well-established mechanism for habitat and prey loss that cannot be evaluated or quantified for this species at this location given the current evidence base. The absence of any baseline reef community monitoring at Saya de Malha Bank is itself the critical gap that drives the RED rating: we cannot assess competitive vulnerability without knowing the competitive context.

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