

A Literature Review on the

IMPACT OF CLIMATE CHANGE ON MALDIVIAN FISHERIES 2025



MALDIVES
**Resilient
Reefs**



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Maldives Resilient Reefs is a Maldivian NGO dedicated to nurturing a future where Maldivians benefit from effectively protecting and managing the ocean. MRR focuses on (1) protection of biodiversity hotspots to safeguard our most important and vulnerable marine habitats through stronger policies, targeted protection measures, and science-led management and (2) sustainable marine resource use by supporting responsible fishing, tourism and coastal development practices that sustain livelihoods while protecting marine ecosystems. MRR is affiliated with the UK charity, Blue Marine Foundation, which works with governments, fishermen, communities and other NGOs to restore a healthy ocean forever, for everyone.

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ABBREVIATIONS

AFAD	Anchored Fish Aggregation Devices
CPUE	Catch Per Unit Effort
EEZ	Exclusive Economic Zone
FSA	Fish Spawning Aggregations
IOTC	Indian Ocean Tuna Commission
IPCC	Interdisciplinary Panel on Climate Change
MPA	Marine Protected Area
OA	Ocean Acidification
SLR	Sea Level Rise
SST	Sea Surface Temperatures

EXECUTIVE SUMMARY

Climate change is already exerting significant pressure on the Maldives' marine ecosystems and fisheries, with widespread ecological and socio-economic implications. Rising sea surface temperatures (SST), ocean acidification, and deoxygenation cause coral bleaching, reef degradation, and shifts in marine species distribution. These ongoing changes threaten the vitality of coral reefs, which serve as critical habitats, nurseries, and natural buffers against climate impacts.

Coral bleaching events, notably since 1998, have markedly reduced reef complexity and habitat availability. The loss of large, mature fish from targeted fisheries and the replacement of complex coral structures with flatter, simpler reefs compromise reef resilience and productivity. Additionally, invertebrates like lobsters and sea cucumbers are affected by ocean acidification, with larval stages particularly vulnerable, which in turn will threaten livelihoods dependent on these species.

Climate change impacts extend to the base of the food web, with declines in phytoplankton and zooplankton biomass due to warming and habitat reduction, potentially affecting baitfish populations crucial to tuna fisheries. Predatory species are forced into shallower, low-oxygen zones, with potential changes in migration, spawning behaviours, and long-term stock stability.

"Climate change is already exerting significant pressure on the Maldives' marine ecosystems and fisheries, with widespread ecological and socio-economic implications."

Socio-economically, these ecological shifts would likely increase fishing effort, operational costs, and the necessity for fishers to venture further afield—placing additional stress on small-scale local operators. Overfishing, habitat loss, and climate-induced changes threaten both subsistence and commercial fisheries, risking economic stability and food security.

Addressing these challenges requires proactive management: establishing and enforcing Marine Protected Areas, seasonal fishery closures, spawning site protections, and regulating fishing effort and gear use. While global efforts to reduce emissions are critical, targeted local actions will be vital to buffer communities against the worst climate impacts, safeguard ecosystems, and ensure sustainable fisheries into the future.

Table 1: Summary of ecological and socio-economic impacts of climate change on Maldivian fisheries with recommendations

Fishery	Potential Ecological Impacts	Potential socio-economic impacts	Recommended local mitigation
Species: Billfish, Tuna, Off- reef pelagic Gear: Trolling, Pole-and-line, Handlines, Auxiliary fishing equipment (AFADs)	High. Increase in SST, leading to decreased available oxygen will cause changes in distribution and migration patterns (both vertically and horizontally). Less oxygen impacts fish health, resulting in lower growth rates and smaller sizes. Changes in prey dynamics due to SST, storms, currents and nutrient availability could alter population distributions quickly.	Given Maldivian fishing vessels operate exclusively within the EEZ, migration of tuna species beyond the EEZ boundaries will greatly affect catch (Ministry of Fisheries and Ocean Resources, 2024). Fishers may need more resources (time, fuel, money) to locate and catch these species or reconfigure gear to target new species/depths (Ministry of Fisheries and Ocean Resources, 2024). Poorly managed (lack of regional effective management frameworks) / overfished stocks intensify the above socio-economic impacts alongside climate changes, with small-scale fishers potentially exiting the fishery altogether.	Efforts should continue with the IOTC to include climate change impacts within both scientific research and fisheries management decision-making processes (Ministry of Fisheries and Ocean Resources, 2024). Science focus on investigating potential shifts in tuna distribution patterns and identifying cooler areas that could serve as refuges for tunas amidst warming ocean temperatures (Ministry of Fisheries and Ocean Resources, 2024). Monitor species distribution for early warning signs of change. Maintaining stock health and adult spawning biomass are critical to ensure resilience against climate impacts. Therefore, effective, enforced fisheries regulations are crucial. Traditional fishing methods like pole-and- line fishing must adapt to ensure their sustainability and effectiveness (e.g., improving vessel design to make the operations more fuel efficient and investment in cutting-edge technological innovations for fishing gear, fish finding, and data analytics)

			(Ministry of Fisheries and Ocean Resources, 2024). Adoption of renewable energy solutions across both the harvesting and processing sectors (Ministry of Fisheries and Ocean Resources, 2024). Any gear reconfiguration should consider the Indian Ocean tuna stock status and the shallow-water nature of skipjack tuna.
Species: Reef fish Gear: Handlines, Drop lines, Troll lines, Jigging, Popping	Increased SST and changing habitat complexity may cause groupers to leave suboptimal spawning sites. Snapper and 'lesser' commercial species distributions/ abundances may be affected by climate change. Bleaching will continue affecting reef habitats and density of prey fish for mid-level carnivores (such as small grouper, snapper, emperor, trevally).	More dispersed populations (due to climate impacted habitat loss and SST changes) may increase fishing effort (to cover increased costs) and expenses for small-scale fishers, pushing them to exploit more exposed, dangerous fishing grounds.	Effectively manage, monitor, and enforce reef fisheries to ensure population resilience. Consider No Take Zones, spawning site closures, and minimum landing sizes. Maintain/ enforce the parrotfish ban for ecosystem (reef-algae) balance.
Species: Bait fish Gear: Night lights, Small- mesh nets	Baitfish are generally more resilient to climate change because they reproduce quickly, tolerate environmental variability, move easily to follow food, and recover faster than long-lived or habitat-dependent species.	Increased fishing in deeper waters poses bend risks for divers. Less biomass readily available.	While baitfish are more resilient to climatic changes, population needs to be maintained at healthy levels to ensure stocks can recover. Greater pressure is currently being exerted by existing methods and new technologies (e.g. submerged night lights)

	Declines may result from repetitive coral bleaching reducing habitat. Changes in sea conditions could impact planktonic foods, affecting populations.	Industrialisation and larger scale fishing may lead to stock declines and exploitation further afield, raising fuel costs.	than likely future climate impacts. Therefore, robust management is needed to ensure sustainable catch, including closed areas.
Species: Invertebrates: Lobster, Sea cucumber, others Gear: Hand collection, SCUBA for sea cucumber	Vulnerable to ocean acidification, particularly at the larval stage (especially sea cucumbers). Octopus may thrive in the short-term, but suitable spawning dens may be compromised by loss of complex reef structures due to repeated bleaching.	Many sea cucumber populations need urgent protection to remain viable. Commercial octopus catches may remain stable, unless habitat loss affects spawning.	Monitor octopus populations and habitat for decline. To ensure habitat and species health and therefore resilience to combat climate impacts, management could include habitat protection and rotating closed areas¹. Gleaning should be monitored to establish baselines to assess change responses against. Monitor/ manage sea cucumber populations to safeguard spawning potential, taking a precautionary approach to account for potential impacts of ocean acidification.

¹ This method has successfully achieved increased octopus catch per unit effort within Madagascan coastal communities (McCabe et al., 2024)

OVERVIEW

The Maldives has been inhabited by humans for over 2,000 years (Mohamed, 2005). Historically, residents have relied on marine resources: archaeological evidence suggests that money cowry (*Monetaria moneta*) attracted early settlers, and fish processing and consumption were central to local diet and economy by the early 1st millennium CE (Lister, 2016). Maldives' long-standing fisheries include a documented pole and line fishery targeting skipjack tuna (*Katsuwonus pelamis*) at least since the 9th century (Gibb H.A.R., 1953; Yadav et al., 2020). The mechanization of the tuna fleet and deployment of anchored fish aggregating devices (AFADs) during the 1970s–1980s markedly modernized the industry, however pole and line has remained the primary gear for skipjack tuna fishing throughout the history of the country (MoFMRA, 2020a). In the late 1990s and early 2000s, a specialized surface fishery for yellowfin tuna (*Thunnus albacares*) expanded to supply sashimi lucrative markets, further boosting exports. Today, these two species make up 98% of the total catch (Ministry of Fisheries and Ocean Resources, 2024). Net fishing and other forms of destructive gears are prohibited by law in the Maldives (Ministry of Fisheries Marine Resources and Agriculture, 2019). The Maldives' one-by-one tuna fishing industry is internationally recognized as one of the cleanest fisheries worldwide (Ministry of Fisheries and Ocean Resources, 2024). The sustainable nature of the pelagic tuna fishery and the strong cultural values associated with tuna is believed to have supported the reef health of the country over the past thousand years (Yadav et al., 2020).

Although tourism is the dominant economic sector, fisheries is the primary source of livelihoods in the Maldives (Hohne-Sparborth et al., 2015). In 2015, the fisheries sector employed 11% of the country's labor force, and by 2021, it contributed approximately 6% to the country's annual GDP (Maldives Bureau of Statistics, 2022; Ministry of Fisheries and Ocean Resources, 2024). Maldives also has one of the highest fish consumption rates globally, with an annual per capita fish consumption of 181kg (Hohne-Sparborth et al., 2015). Furthermore, fish and fish products make up more than 90% of the total exports (Maldives Customs Service, n.d.).

Bait fishing is integral to the tuna fishery, relying on a steady supply of small pelagic and reef associated species from shallow lagoon waters (Anderson and Saleem, 1994; Jauharee et al., 2015). However, recent reports from fishers indicate a decline in baitfish populations and insufficient catches despite the use of advanced gear including lights, SCUBA and large nets (Gillet et al., 2013; Hashim, 2025; Jauharee et al., 2015).

The growth of tourism and access to export markets since the 1970s have intensified exploitation of reef resources – such as reef fish, groupers, lobster, sea cucumbers, and octopus – adding additional pressure from recreational and subsistence fishing (Hashim, 2025; Maldives Customs Service, n.d.; MoFMRA, 2020b, 2020c, 2020d, 2020e). The Maldives maintains a commercial grouper fishery for export, involving lagoon cages to 'grow on' juveniles to adults. This system has been subjected to

various management restrictions to maintain a viable sustainable fishery (Wood E et al., 2011). Increasing tourism demand has further strained predator reef fish populations, especially since the 1970s (Hashim, 2025; Sattar et al., 2014). Gleaning, practiced recreationally, especially by women, involves collecting molluscs and other species and is currently unmonitored. It is a subsistence fishery though it may contribute to local income (McGowan A., 2023).



THE GLOBAL – LOCAL CONSEQUENCES OF CLIMATE CHANGE

Maldives' coral reefs have suffered major disturbances due to mass coral bleaching events, notably in 1998 and 2016, where shallow reefs lost over 70% of live coral cover (Montefalcone et al., 2018). The islands face existential threats from sea level rise (SLR), coral mortality driven by rising sea surface temperatures (SST), and ocean acidification (OA) (Moustahfid et al., 2019). These cumulative pressures diminish the reefs' ability to keep pace with SLR. Increased storm events and rising sea levels will require substantial ongoing investments for coastal protection. Healthy, growing reefs provide ecosystem services valued at approximately USD 442 million annually – about 8% of Maldives GDP (World Bank, 2024). This highlights the critical importance of reef health for national resilience. Recurrent bleaching and SLR, coupled with development needs, are already compromising these services, prompting hard engineering solutions such as seawalls, dredging, and reclamation.

Over 45 years, SST along the Indian coast have increased by 0.2-0.3°C and are projected to rise an additional 2.0-3.5°C by 2099^[2] (Vivekanandan, E., 2011; Vivekanandan, Elayaperumal et al., 2016). Globally, the Interdisciplinary Panel on Climate Change^[3] (IPCC) reports a 4°C increase in ocean temperatures between 1960 and 2010, with excess heat primarily

stored in the deep ocean (>500m depth). Elevated temperatures have led to declining ocean oxygen levels, particularly in oxygen minimum zones^[4]. Ocean acidification driven by increased CO₂ concentrations, reduce surface water pH, impairing calcification and affecting marine life, including larval stages of key species (Boco et al., 2021; Liu et al., 2023). Schematic diagram of potential climate-driven pressures to environmental characteristics of the atmosphere and oceans is provided in Annex 1.

The oceanographic changes in the Indian Ocean are known to have already started affecting its net primary productivity (Dalpadado et al., 2021). This is anticipated to disrupt current fishing patterns, leading to significant socio-economic impacts in the region (Ministry of Fisheries and Ocean Resources, 2024). A recent study conducted by the University of British Columbia (unpublished) has found that exposure to climate impacts on fisheries across the region, measured by the change in maximum catch potential (MCP), is highest for the Maldives compared to its SIDS counterparts, with a significant loss of 75% by the end of the century under the most pessimistic climate scenario (Ministry of Fisheries and Ocean Resources, 2024).

2 The range depends on emissions scenarios and regional model choices.

3 The Intergovernmental Panel on Climate Change (IPCC) is a United Nations body that assesses climate change science and provides scientific information to governments and policymakers www.ipcc.ch

4 Oxygen minimum zones are zones in the ocean (usually below 200m – 1500m), where O₂ concentrations are low (around 2mg/l) – about half of the average concentration of around 4-6 mg/l).

Projected impacts on the world's wild-capture and aquaculture fisheries include declines of 2.8–5.3% by 2050 under low-emission scenarios, rising to 7–12.1% under high-emission pathways (Barange et al., 2018). Fisheries management can

substantially mitigate the projected losses in fish stocks. Adaptive management is therefore a key tool to reduce climate impacts on fish stocks and fisheries-dependent communities in the Maldives (Barange et al., 2018).

PROJECTED IMPACT ON FISH POPULATIONS

This literature review compiles recent research on climate change impacts to global, regional and local fisheries, drawing on case studies from countries and ecosystems (mainly coral-reef countries) to project likely changes in the Maldives over the coming century.

TUNA AND OTHER LARGE PELAGIC SPECIES

Climate change is projected to reduce dissolved oxygen concentrations throughout much of the ocean due to slowed ocean ventilation and reduced surface oxygen solubility (Bopp et al., 2013; Cabré et al., 2015; Cocco et al., 2013; Frölicher et al., 2009; Keeling et al., 2010). Warmer, less oxygenated waters will disproportionately affect high performance predators (tunas, billfishes, many sharks) that require high oxygen fluxes and will also stress site specific reef species that cannot easily relocate (e.g., some reef fishes in channels and lagoons).

Mechanisms and habitat effects

- **High current areas (e.g., atoll channels) sustain higher oxygen delivery and thus support larger semi pelagic and reef associated predators;** these areas can support larger species that would otherwise struggle to gain sufficient oxygen to function effectively (Bushnell and Jones, 1994).
- **Physiology:** Sharks, tunas and billfishes have high metabolic demands and limited low oxygen tolerance due to their aerobic scope and oxygen dependent swimming/reproductive physiology (Bernal et al., 2009; Brill and Bushnell, 2006; Brill and Chin Lai, 2016; Bushnell and Jones, 1994; Deutsch et al., 2015; Killen et al., 2016; Korsmeyer and Dewar, 2001; Stoffels, 2015; Wegner et al., 2013). Lower oxygen availability can reduce growth, maximum size, hunting performance and reproductive output (Leung et al., 2019).

Behavioural and distributional responses

- **Vertical and horizontal**

redistribution: SST and lower oxygen availability affects both yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in their migration patterns (Humphries et al., 2024). Yellowfin is predicted to spend more time in shallower more oxygen rich waters while bigeye, which normally forage deeper (below the thermocline), is predicted to increase the number and frequency of upward vertical excursions (Schaefer et al., 2009). Such shifts would likely affect their natural foraging behaviour and may increase interspecific competition for the same resources, potentially changing catch composition and fishery dynamics (Leung et al., 2019).

- **Movement away from the tropics:**

Modelling of climate effects on skipjack tuna (*Katsuwonus pelamis*) global populations suggested northward movement, and problems of prey availability (Dueri et al., 2014). The model projects deterioration of skipjack habitat in most tropical waters and an improvement of habitat at higher latitudes. The primary driver of habitat changes is ocean warming, followed by food density changes. Numerous studies have suggested potential taxonomic shifts in response to warming climates, including the migration of tuna species towards cooler areas in the Indian Ocean (Monllor-Hurtado et al., 2017). Since current observations and projections suggest the northern Indian Ocean (Monllor-Hurtado et al., 2017), particularly the Arabian Sea,

might experience faster warming compared to the southeastern Indian Ocean, it is possible that migratory fish species, including tunas, will move southward (Ministry of Fisheries and Ocean Resources, 2024). This shift is likely to result in a net loss of migratory fish within the Maldives as these species relocate from the equatorial region towards cooler southern waters. The northern region of the Maldives is more likely to experience high projected local extinction of marine species by the end of the century.

- **Stock decline:** Projections show an increase of global skipjack biomass between 2010 and 2050 followed by a marked decrease between 2050 and 2095. Spawning rates are consistent with population trends, showing that spawning depends primarily on the adult biomass. As such, it is essential that a resilient adult population is maintained to provide adequate larval supply into the adult population.

- **Movement away from thermally stressful areas:**

Recent evidence shows reef associated sharks (e.g., grey reef shark *Carcharhinus amblyrhynchos*) abandoned coral reef habitats during warming events and took up to ~16 months to return after temperatures recalibrated (Williamson et al., 2024). This may have cascading effects on the balance of the ecosystem, as their predation impact on mid-trophic and lower-trophic level species (e.g. snappers, emperors, parrotfish) is lowered during their absence.



Prey availability and trophic consequences

- Global models project declines in pelagic forage fish (prey species) biomass where nutrient supply falls (Petrik et al., 2020). Under the model, small foraging species such as anchovy and krill (and Maldivian sprat populations of bait fish such as *Spratelloides gracilis*) concentrate in shallow waters to feed on plankton, and benefit from increased shallow water oxygen concentrations. Empirical work (Koslow et al., 2011) found abundance of mesopelagic (>200m deep) prey species fell by ~63% during periods of reduced oxygen concentration within the oxygen minimum zone of the southern California Current. This likely occurred because the prey species were forced to occupy better-oxygenated shallow (and subsequently more well-lit) waters, rendering them more vulnerable to visual-orienting predators such as tunas and billfishes. Comparable shifts in the Indian Ocean/ Maldives would alter foodweb linkages and could either locally increase predation pressure on concentrated prey or reduce predator biomass if prey declines overall.

Implications for Maldivian fisheries

- Fisheries that depend on predictable vertical migrations (e.g., pole-and-line, longline and handline operations) may face altered catch rates and greater effort to locate schools.

- Catch composition and spatial distribution of target species (yellowfin, bigeye, skipjack, billfishes, and associated predators) are likely to change as species redistribute vertically and poleward, alter spawning/foraging behaviour, or decline in productivity. Since Maldives' pole and line gear is specifically designed to target surface swimming schools, the catch success rates may decline. However, since skipjack tuna exhibit a strong tendency to school in surface waters (Collette et al., 2021), any gear modifications should consider maintaining the sustainable credibility of the Maldives' tuna fisheries, while reducing by-catch. To reduce the increase in fuel costs and increase profit margins, efforts are already underway to transition the fisheries sector towards carbon neutrality (development of energy-efficient vessels and the integration of renewable energy sources across harvesting and processing operations) (Ministry of Fisheries and Ocean Resources, 2024).

Since Maldives tuna fishery depends on livebait, changes in prey distribution (e.g., baitfish/sprat concentrations) and habitat loss from coral bleaching, will affect both tuna foraging success and the availability of bait for local fisheries, with knock on effects on catch per unit effort and economic returns.

BAIT FISH

Coral bleaching reduces habitat complexity and shelter, lowering recruitment and local abundance of baitfish. Respondents surveyed by Yadav et al. (2021) said declines in damselfish (*Chromis* spp.) populations were caused by repetitive coral bleaching events, reducing habitat for the species.

Historical FAO assessments indicate cardinalfish (*Apogonidae*), sprats (*Sprattellidae* spp.), damselfish (*Pomacentridae*) and fusiliers (*Caesionidae*) make up the majority of historical baitfish catch (fao.org, n.d.). These species rely on sustained zooplankton production. However, the conditions for zooplankton abundance and growth are being compromised by indirect effects of climate change such as decreased oxygen and nutrient availability (Petrik et al., 2020).

See also 'Prey availability and trophic consequences' section under *Tuna and Other Large Pelagic Species*.

REEF FISH

Shift in consumption and drivers

- Maldivians are increasingly consuming midtrophic reef fishes rather than historically dominant tuna (Yadav et al., 2021). In a survey of 100 respondents, 58% preferred reef fish; men favoured snapper, emperor, grouper and rudderfish, while women favoured tuna (yellowfin, frigate, skipjack). Fishers (56% of respondents, mostly male) reported increased reliance on reef fish partly because coral bleaching reduced *Chromis* spp. baitfish habitat and thus tuna catches.

Some respondents also linked changing fish populations to climate change and to habitat degradation and sedimentation from island development. catches.

Mechanisms and habitat effects

- Rising sea temperatures and reduced oxygen carrying capacity of oceanic waters will likely result in lower oxygen levels around coral reefs, causing stress for coral reef species (Pezner et al., 2023).
- Repetitive bleaching reduces reef three-dimensional complexity and surface area, decreasing habitat availability and lowering reef species biomass and diversity (Magel et al., 2019; Pratchett et al., 2014). Complex *Acropora* dominated shallow reefs have declined in many inner reefs and been replaced by flatter, low complexity structures after bleaching (Cowburn et al., 2019; Solandt J-L. and Hammer, 2019).
- Loss of complex habitat favours smaller, opportunistic midtrophic-groupers (such as *Cephalopholis* spp. and *Anyperodon leucogrammicus*) and reduces abundance of large, commercially targeted groupers (such as *Plectropomus* spp. and *Epinephelus fuscoguttatus*) in central Maldivian atolls (Karkarey et al., 2014; Solandt J-L. et al., 2013; Solandt, J-L. et al., 2024). Patterns in nearby Lakshadweep suggest both targeted fishing and coral bleaching driven-habitat change contribute to this shift (ncf-india.org, n.d.).

Behavioural and distributional responses

- Fish spawning aggregations (FSAs) for groupers usually occur in reef channels with strong tidal exchange; these predictable gatherings are vulnerable to shifting thermal suitability and phenology (Erisman et al., 2011; Wood E et al., 2011; Wootton and Smith, 2014).
- Models from the Caribbean predict large losses (>73%) of suitable grouper FSA habitat under high warming (high emission pathway i.e., RCP8.5) by century's end, while snapper FSAs are projected to be more tolerant (24% loss) (Gokturk et al., 2022). Maldives fish spawning migrations and timing may therefore change with thermal habitat shifts (Asch and Erisman, 2018).
- Well managed reef fisheries and effective MPAs can maintain or restore high reef fish biomass and recruitment even after bleaching events (Wismer et al., 2019). Evidence from Belize shows MPAs increased functionally important parrotfish, which help control algal turf and support reef resilience (Mumby et al., 2021; Pratchett et al., 2014).
- Increased fisher dependence on reef fish, combined with habitat loss from coral bleaching and local development impacts, threatens long term reef fish biomass and diversity and may reduce commercial reef fish yields.
- Management actions (effective MPAs, protection of FSAs, fisheries regulation to prevent overexploitation of large groupers and herbivores) can enhance recovery and maintain larval sources for damaged reefs (Mumby et al., 2021; Wismer et al., 2019).

Population level and trophic consequences

- Declines in large predatory groupers and shifts to smaller, more cryptic species alter community structure and reduce availability of historically valuable reef fish species (Cowburn et al., 2019; Solandt, Jean-Luc et al., 2013).

Implications for Maldivian fisheries and management

- Avoiding exploitation of herbivores supports reef recovery after bleaching; an expansion of herbivorous fish biomass was observed shortly after mass bleaching, likely due to increased turf algae availability (Elma et al., 2023; Muraoka et al., 2022).

INVERTEBRATES

Invertebrate vulnerability and general effects

- Invertebrates (lobsters, crabs, shrimp, molluscs, sea cucumbers) are sensitive to increased water temperature and lower pH, especially during larval development and growth; adults have limited ability to move compared with fish, increasing local vulnerability (Fernandes et al., 2017; Queirós et al., 2015).



- Impacts of increased water temperature and lower pH are often sublethal: reduced calcification rates, slower growth, decreased reproductive output and impaired larval moulting/survival (Boco et al., 2021; Mollica et al., 2018; Przeslawski et al., 2008; Zeng et al., 2020). These effects threaten tropical shrimp, lobster and crab and reduce coral calcification (Mollica et al., 2018).

Mechanisms and habitat effects

- Ocean acidification and warming impair invertebrate larval survival and development.
- Reduced larval survival, slower growth and lower reproductive success hinder population replenishment, especially where overfishing of adults lowers local spawning biomass (González-Durán et al., 2021; Liu et al., 2023).
- Experimental water pH reductions caused large declines in larval survival of sea cucumbers (~50% reduction with a 0.5 pH drop in lab trial and are thought to reduce growth rates (González-Durán et al., 2021). Laboratory work on *Holothuria spinifera* showed better larval development, growth and survival at higher (less acidified) pH. Yuan et al. (2015) reported pH effects on post fertilization success and larval growth for *Apostichopus japonicus* across pH 7.42–8.04.
- Observed Maldives seawater pH declines from *Porites* corals in (1979–2015 weighted average) was 0.02–0.04 units per decade, implying harmful pH thresholds for some sea cucumbers could be approached within ~10 years (González-Durán et al., 2021; Liu et al., 2023).
- Slipper lobster (*Thenus australiensis*) larvae exhibited reduced moult survival under elevated CO₂ (Boco et al., 2021).
- Octopus (Common reef octopus, *Octopus cyanea*, and other regional species) may increase growth and reproductive output with warmer SSTs, but habitat loss from reef degradation could negate these benefits (Arreguín-Sánchez, 2019; McCabe et al., 2024; Willer et al., 2023).
- Repetitive coral bleaching reduces reef complexity and cryptic shelter used by many reef invertebrates, lowering refuge and recruitment habitat (Graham, 2014).

Behavioural and distributional responses

- Some invertebrate species may shift distribution to cooler/deeper waters as temperatures rise (example: northward shift of American lobster (*Homarus americanus*) in the Gulf of Maine over 40 years) (Waller et al., 2017).

Implications for Maldivian fisheries and management

- Combined stressors (ocean warming and acidification) plus adult overfishing reduces recovery potential and raise local extinction risk, particularly for invertebrate species with short larval duration and limited adult movement.



- Sea cucumber larvae have short planktonic durations (~10 days), localized overfishing therefore limits recovery because larval from distant populations are unlikely to reach depleted atolls (Marxan Conservation Solutions, n.d.).
- Management should consider reduced adult harvesting, protection of spawning aggregations, and measures to maintain reef complexity to support shelter and recruitment—especially given probable low larval connectivity between atolls.
- Octopus respond rapidly to protection: fishery closures of only a few months can lead to considerable biodiversity increases (McCabe et al., 2024).



Table 2: Summary of primary and secondary climate impacts on key ecosystem species/ groups.

Species/group	Species group name (level in food chain)	Primary climate change impacts	Secondary climate change impacts
	Copepods and other plankton (secondary producers)	Temperature stress, variation in depth distribution	Great variation with temperature change.
	Anchovy, sprat, glassfish (planktivores)	Climate impacts on prey (zooplankton) distribution and concentrations	Stochastic population changes ⁵ due to plankton changes.
	Chromis/damselfish/ butterflyfish (planktivores)	Climate impacts on prey (zooplankton) distribution and concentrations	Stochastic population changes due to plankton changes.
	Parrotfish (herbivores)	Potentially more food (ephemeral algae)	Less habitat for shelter
	Lobster (scavengers)	Lower larval survival	Less habitat
	Grouper (mid predators)	Less habitat, less prey	Less habitat for shelter, less food.
	Tuna (mid and apex predators)	Distributional changes, lower oxygen.	Less food locally, more energy to source food.
	Dolphins (apex predators)	Less prey	Less food locally, need more energy to source food.
	Sharks (apex predators)	Distributional changes, lower oxygen.	Less food locally, need more energy to source food.

⁵ Stochastic population changes are random fluctuations in a population's size that occur due to chance events, as opposed to predictable, deterministic factors.



SOCIO-ECONOMIC CONSEQUENCES

Distributional change, assessment and fishery impacts

- Shifts in tuna and billfish distributions will complicate stock assessments and undermine CPUE based abundance indices. Standardization methods will need to be adapted to prevent compromised stock assessment data which would prevent effective management of the stocks and may result in overexploitation and stock collapse.
- As target species move or decline in local abundance, fishers must expend more time, fuel and money to locate catches or reconfigure gear, increasing operational costs (Corporate Maldives, 2025).
- Small scale, coastal fisheries and those in developing countries are especially vulnerable to range shifts; fishers may need to change target species or exit the fishery (Macusi et al., 2021). For example, changes in fish aggregations will impact small-scale fishers who only fish within atolls using small outboard-powered vessels so are unable to relocate to other areas to fish.

Operational and safety consequences

- Declines in locally available groupers will result in fishers having to fish deeper (>100 m) in outer reef sites, increasing danger, fuel costs and risk of overfishing. Mesophotic reefs that once supplied larvae to shallow reefs may be further depleted due to this increased fishing pressure.

Food Security issues

- Maldives has one of the highest fish consumption rates globally, with an annual per capita fish consumption of 181kg (Hohne-Sparborth et al., 2015). Maldivians are increasingly consuming mid-trophic reef fishes rather than historically dominant tuna (Yadav et al., 2021). Increased harvest of mid-trophic reef fishes can accelerate reef ecological decline, creating a food security trap. Lower, less predictable fish landings can drive domestic fish price hikes with greater reliance on imported proteins and exposing households to global price shocks. Additionally, reduced access to fresh tuna/reef fish may lower omega-3 and micronutrient intake, raising health risks.

Cultural and social impacts

- As more people exit the tuna fishery, there is a risk of the loss of community cohesion tied to fishing. This will also exacerbate youth outmigration from fishing communities seeking alternative work.

Policy, governance and transboundary issues

- Fish movements across management boundaries create economic, geopolitical and regulatory barriers to adaptation. Where species cross jurisdictions, constrained access and conflicting rules can hinder effective responses.



Longline debate and bycatch concerns

- Reopening longline fisheries (periodically opened/closed; consultation in Aug 2024) risks increasing effort on shifting pelagic stocks and exacerbating climate-driven impacts. Longlining is associated with bycatch of seabirds, cetaceans, turtles and sharks, and could further stress vulnerable, range-shifting populations.

Regional macroimpacts and recommendations

- World Bank (2024): medium-term climate impacts (from ~2050) threaten coral reefs, fish stocks, land and infrastructure. Ocean heating could lead to widespread loss of living coral and fish stocks. It is recommended to maintain resilient populations and habitats by reducing reef fishing pressure and limiting reef adjacent coastal development.
- **FAO observations and recommendations for the Indian Ocean (Moustahfid H. et al., 2018):**
 1. Climate change is resulting in warmer habitats with declining productivity.
 2. Human impacts (island development, sedimentation) compound reef decline from repeated bleaching, reducing fish habitat.
 3. Significant distributional changes of large pelagics likely.
 4. Spatial allocation of effort should account for migratory characteristics of tuna fisheries.
 5. Awareness, monitoring and information provision are critical, ignorance hampers management.

6. Develop and implement fishery specific adaptive management plans with awareness programmes.
7. Implement effective MPAs with local enforcement and outreach.
8. Apply code of conduct for responsible fisheries and voluntary guidelines for small-scale fisheries.
9. Adopt a sustainable, inclusive blue economy approach to reduce pressure on marine ecosystems.

An Example summary of impacts and management recommendations from increased CO₂ and sea temperatures for worldwide fisheries (Dell'Apa et al., 2018) is presented in Annex 2.



CONCLUSION

Climate change is a global issue requiring coordinated efforts to reduce emissions, but localised management can boost resilience, protecting both livelihoods and ecosystems. Maldivian reefs are experiencing daily impacts from climate change, affecting livelihoods and national security. Marine ecosystems struggle to recover and adapt to frequent coral bleaching, and the ocean's nature is changing on a macro scale, leading to less diverse reef structures and biology.

The effects of ocean acidification, while less visible than bleaching, likely impact critical life stages of fish and invertebrates – especially larvae. The Maldives is unlikely to revert to the ecological health of the early 1990s, requiring precautionary fisheries management and habitat protection to ensure resource sustainability.

Healthy coastal ecosystems, such as seagrass, coral reefs and mangroves, are crucial for climate resilience, buffering shorelines from harsh weather, and trapping sediment. Strict management of development, especially in highly populated atolls, is essential to safeguard communities and their resources.



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ANNEX 1

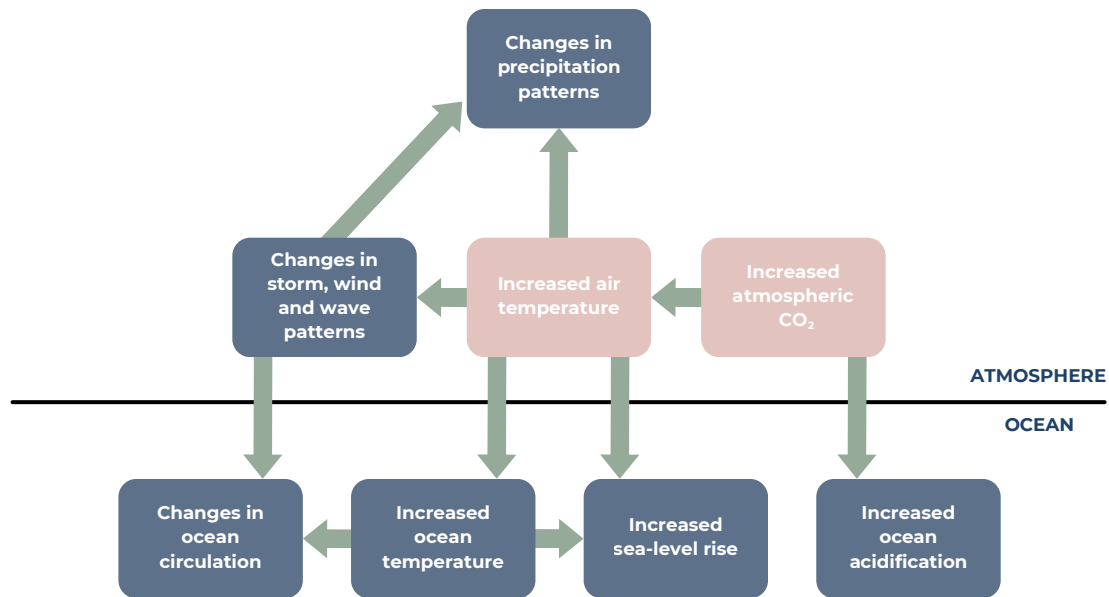


Figure 1: Schematic diagram of potential climate-driven pressures to environmental characteristics of the atmosphere and oceans, reproduced from Dell'Apa et al. (2018)

Potential climate-driven pressures (dark blue boxes) to environmental characteristics of the atmosphere and oceans related to the primary climate-dependent drivers of rising atmospheric carbon dioxide (CO₂) and associated increase in air temperature (light blue boxes). Arrows indicate existing links between climate pressures (e.g., “increased ocean temperature” have impacts on “changes in storm and wind patterns”). This diagram and its framework and terminology are based on the driver-pressure-state- impact-response (DPSIR) approach in the Gulf of Mexico but would be equally applicable to the Maldives.

ANNEX 2

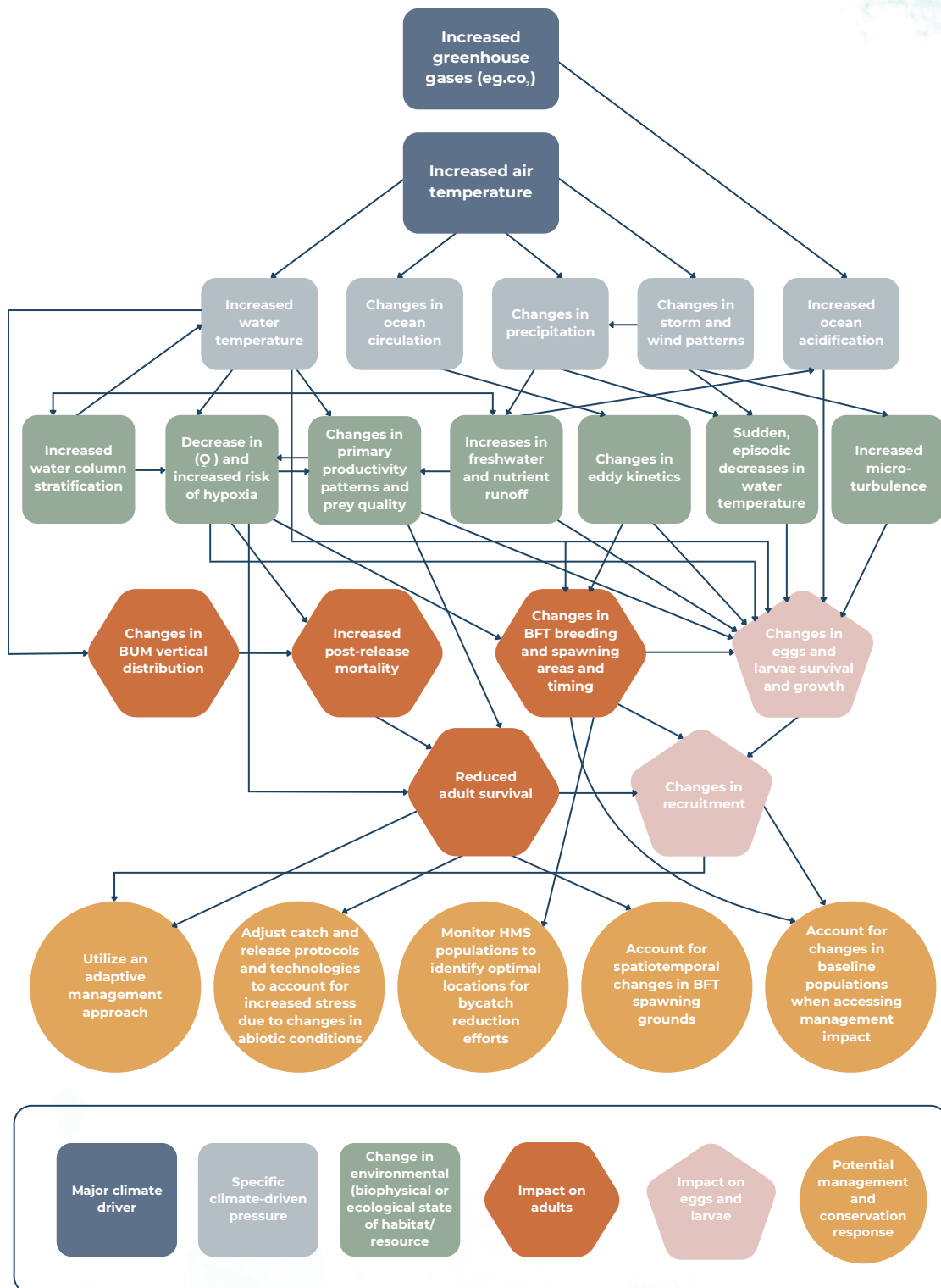


Figure 2: Example summary of impacts and management recommendations from increased CO₂ and sea temperatures for worldwide fisheries, after Dell’Apa et al. (2018) focused on Mexican pelagic fisheries.

Impacts (orange) and management recommendations (yellow)



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