



Climate change implications for the Arafura and Timor Seas region: assessing vulnerability of marine systems to inform management and conservation

Johanna E. Johnson^{1,2} · David J. Welch^{1,3} · Ruben van Hooidek^{4,5} · Dieter Tracey⁶ · Ganesha Chandrasa⁷ · Bianca Molinari¹ · Deti Triani⁸ · Casandra Tania⁸ · Handoko Susanto⁸

Received: 20 October 2022 / Accepted: 14 May 2023
© The Author(s) 2023

Abstract

The Arafura and Timor Seas region is shared by Indonesia, Timor Leste, Australia, and Papua New Guinea (PNG), and is at the intersection of the Pacific and Indian oceans. High coastal population densities, degraded habitats, overexploited fisheries, low profile coasts, shallow continental shelves and macro-tidal conditions mean that coastal and marine environments in the region are currently facing multiple pressures. Climate change is expected to exacerbate these pressures and have profound effects on the status and distribution of coastal and marine habitats, the fish and invertebrates they support and, therefore, dependent communities and industries. Downscaled climate change projections for 2041–2070 for air and sea temperature, ocean chemistry and rainfall were modelled to provide spatially relevant regional data for a structured semi-quantitative vulnerability assessment. Results of the assessment were spatially variable and identified shallow coral reefs as highly vulnerable, particularly in the Timor-Leste and Indonesia-Arafura sub-regions. Seagrass meadows were most vulnerable in the Gulf of Carpentaria, Indonesia-Arafura, and Timor-Leste sub-regions. Mangrove habitats were most vulnerable in Timor-Leste and Western PNG sub-regions. Drivers of vulnerability include poor habitat condition, non-climate pressures, low connectivity, and limited formal management. Marine species vulnerability was also spatially variable, with highly vulnerable and priority species identified for each sub-region, including finfish and marine invertebrates. A key driver of species vulnerability was their stock status, with many species in Timor-Leste, Western PNG and Indonesia, and several in northern Australia, overfished or potentially overfished. Limited management in some sub-regions, as well as non-climate pressures such as habitat decline, poor water quality and illegal, unregulated and unreported fishing were also key drivers. Species of conservation interest (dugong and marine turtles) were also highly vulnerable to climate change, driven by their threatened status and the fact that they are low productivity species that take years to recover from impacts. Priority species and habitats for local action were identified and current pressures that undermine condition and/or resilience, with strategic recommendations aimed at minimising climate change vulnerability.

Keywords Adaptation · Climate change · Marine ecosystems · Vulnerability · Resilience

Extended author information available on the last page of the article

1 Introduction

Climate change has been identified as a major threat to marine ecosystems (IPCC 2019, 2022), and is expected to have profound effects on the function and distribution of marine habitats and the fish and invertebrates they support (Perry and Alvarez-Filip 2019; Robinson et al. 2019). As a result, fisheries will be impacted, which will have consequences for the communities and industries that depend on them for food security and livelihoods (Bindoff et al. 2019; Cooley et al. 2022). To prepare for and respond to these impacts, it is necessary to understand potential impacts from climate change, the sources of vulnerability and identify effective and targeted adaptations.

The expected climate changes in the Arafura and Timor Seas (ATS) region include increased air and sea temperatures, ocean acidification, extreme rainfall events, changing seasonal rainfall, more intense storms, altered ocean circulation and sea-level rise. These changes are expected to have direct and indirect impacts on marine ecosystems and species in the ATS region. Understanding the nature and scale of these impacts requires an understanding of the future local climate as well as the vulnerability of species and habitats.

Vulnerability to climate change is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. Climate change vulnerability of marine habitats and fisheries has been assessed in targeted locations of Indonesia; North and South Sulawesi (RARE Indonesia 2020; Retnowati et al. 2019) and provided some local context for this study. However, these studies focused on identifying vulnerability in specific locations, and delivered localised results that could not be upscaled to the larger ATS region.

The marine environment in the ATS region supports very high diversity (Roberts et al. 2002); however, it is in significant decline, primarily due to high coastal population densities, degraded habitats, overexploited fisheries, low-lying coasts, a shallow continental shelf and macro-tidal conditions (ATSEA 2012). The Reefs at Risk project identified Indonesian reefs as having the largest area of threatened coral reefs in the ATS region, with overfishing and destructive fishing practices driving much of the threat, followed by land-based pollution and coastal development (Burke et al. 2012). The ecosystems in the ATS region have evolved to operate within a specific range of prevailing local climatic conditions — the coping range (e.g. Jones and Mearns 2005). Therefore, understanding how the climate is changing in the ATS region and the likely impacts on key habitats such as coral reefs, seagrass meadows, mangroves, and species, is important to identify targeted management under future climate change.

Within the coastal ecosystem mosaic, coral reefs, seagrass meadows, and mangroves are critical habitats for fish and invertebrate species, providing critical feeding and breeding habitat, as well as a range of goods and services, such as coastal protection and nutrient cycling. Maintaining the structural complexity of coastal ecosystems is vitally important to the continuation of these functions as well as the sustainability of fisheries. However, climate change is exacerbating existing pressures and expected to drive further declines in the ATS region.

There are documented impacts of climate change on coastal and marine habitats, for example, drought, low sea levels and marine heatwaves can cause significant mangrove dieback (Lovelock et al. 2017; Duke et al. 2021). And changes in rainfall and river flow affect species in coastal wetland and mangrove habitats, particularly recruitment success, growth and fisheries catchability (Leahy and Robins 2021). Since they provide critical habitat for different life history stages of many estuarine and reef species, any habitat changes

will have implications for the species they support. Coral reefs are susceptible to ocean warming and acidification, changing circulation, more intense storms, and changes in rainfall and terrestrial inputs from more intense rainfall. Coral reefs are particularly sensitive to thermal stress that can cause coral bleaching and changes in reef assemblages, structure and function (Hughes et al. 2018). In Indonesia, coral bleaching occurred during the 2016 summer at all major islands (Kimura et al. 2018), consistent with mass coral bleaching that occurred from 2014 to 2016 across the tropics and part of the longest and most severe global event on record (Eakin et al. 2019).

Ocean acidification can reduce coral calcification rates (Fabricius et al. 2011; Doney et al. 2020) and impact coral growth (Guo et al. 2020), with increases in temperature above 1.5 °C expected to result in net erosion of coral reefs throughout the tropics (Hoegh-Guldberg et al. 2018, 2019). Seagrass meadows are degraded through several anthropogenic impacts, including destructive aquaculture practices (e.g. intensive seaweed farming), coastal mining (e.g. sand extraction), coastal development, and poor water quality, with climate-change exacerbating these impacts (Waycott et al. 2011). The dynamics of tropical seagrasses mean that while ocean warming may limit growth, elevated CO₂ concentrations can increase thermal tolerance (Zimmerman 2021) and seagrass have some inherent resilience to future pressures (McKenzie and Yoshida 2020).

The aims of this study were to (1) document current spatially relevant climate change coastal habitats and the species they support, and (2) identify the drivers of climate change vulnerability through semi-quantitative assessments. Identifying the drivers of vulnerability provides targets for action to address these drivers for marine habitats and species, and opportunities for improving cross-jurisdictional management of large marine ecosystems (Johnson et al. 2021). The assessment approach also provides transparency to stakeholders by incorporating socio-economic survey data, allowing for potential adaptation responses for relevant fisheries stakeholder groups.

2 Methods

2.1 Study area

The Arafura and Timor Seas (ATS) region connects two major oceans, the Indian and Pacific, and is shared by Indonesia, Timor-Leste, Australia and Papua New Guinea (PNG) (Fig. 1). The ATS region covers more than 167 million ha, supporting 600 species of reef-building corals, 2500 species of marine fish, 47 species of mangroves and 13 species of seagrass (ATSEA 2023; Veron et al. 2016).

The southern Papua (Arafura Sea), Gulf of Carpentaria, and Northern Australian coasts contain the major estuaries in the region that provide habitat for mangroves and coastal wetlands, while few estuaries are found on the archipelago islands that have small rivers flowing into the ocean (Fig. 1). Seagrass meadows are present in the ATS region, with diverse and dense habitat found near Western PNG, Cape York in the Gulf of Carpentaria, and Nhulunbuy in Northern Australia (Fig. 1). Coral reefs are an important habitat in the region, with shallow fringing reefs occurring mainly around the islands of Indonesia and Timor-Leste, and the Timor Sea coast of Northern Australia (Fig. 1).

The ATS region is characterised by high connectivity between land and sea, with high islands in Timor and PNG and large catchment areas in northern Australia, resulting in large river discharges of freshwater and sediments to coastal waters. There is also

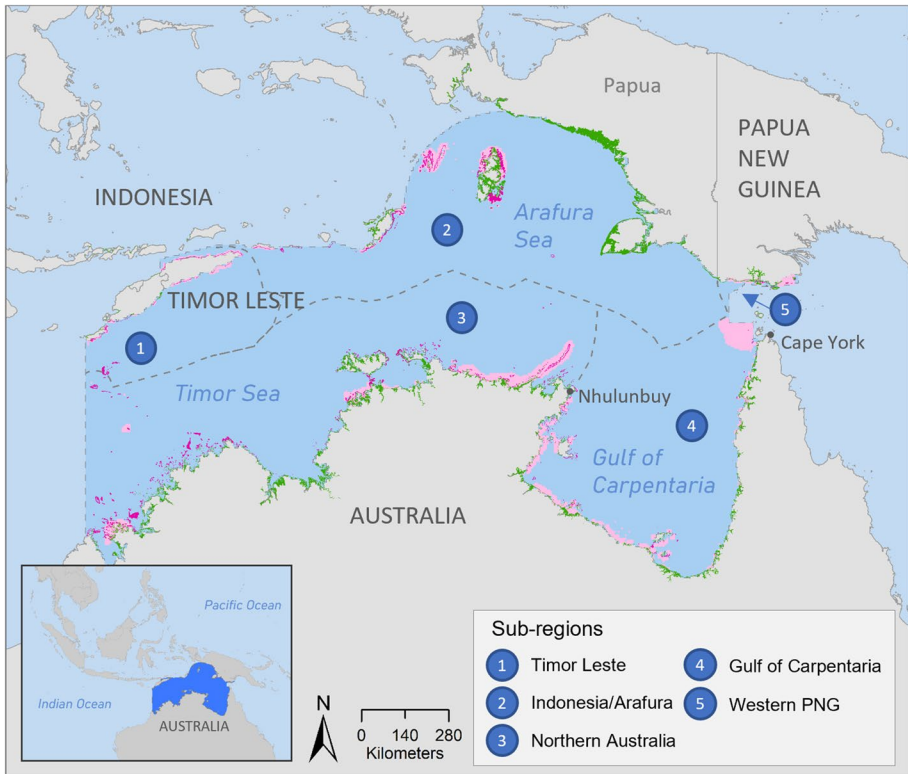


Fig. 1 Map of the Arafura and Timor Seas region and the five sub-regions assessed for vulnerability. Coastal and marine ecosystems are shown; dark pink = shallow coral reefs (<40 m depth), light pink = sea-grass, green = mangroves

strong connectivity in oceanographic and ecological processes, such as the movement of larvae, pelagic and migratory species. Therefore, species and fish stocks are shared between jurisdictions, e.g. offshore demersal snapper fisheries for *Lutjanus malabaricus*, *L. erythropterus* and *L. argentimaculatus* (Blaber et al. 2005), and globally significant populations of migratory protected species (marine turtles, dugongs, cetaceans, sawfishes, elasmobranchs) are found throughout the region (Edyvane et al. 2011). For migratory species such as marine turtles, the Arafura Sea plays an important role providing feeding and nursery grounds (Klain et al. 2007).

Fisheries in the ATS region are particularly complex and productive, with multiple stakeholders, target species and technologies. The main characteristics of the shared ATS transboundary fishery stocks are the combined pressures of climate change, unsustainable harvest, destructive fishing practices, illegal unreported and unregulated (IUU) fishing, and bycatch (ATSEA 2012). Marine pollution is also a threat to ecosystems in the region, with sources being marine debris, marine-based pollution from oil and gas, land-based runoff from rivers and coastal development (Brodie et al. 2019), and waste from vessels.

2.2 Regional climate change projections

A regional analysis of current climate change models and projections for the ATS region focused on the main climate variables that are expected to impact marine ecosystems over the next 50 years (to 2070). The climate variables applied in this study were atmospheric parameters — rainfall and air temperature — and oceanic parameters — sea surface temperature (SST) and ocean pH. Downscaled data from the Coupled Model Intercomparison Project phase 5 (CMIP-5) and CPMI-6 models were used for these projections of future change.

The analysis of the change in atmospheric parameters used an ensemble of downscaled results from the multi-model simulations of the Southeast Asia Regional Climate Downscaling/Coordinated Regional Climate Experiment – Southeast Asia (SEACLID/CORDEX-SEA) project (Supari et al. 2020; Tangang et al. 2019, 2020) within the CMIP5 framework (Taylor et al. 2012), adopted in the IPCC-AR5 report (IPCC 2014). A series of evaluations for the regional simulations were performed in the CORDEX-SEA project, to determine the best optimization in simulating past climate, as compared to observational datasets (Cruz et al. 2017; Juneng et al. 2016; Ngo-Duc et al. 2017). Utilization of regional climate models for dynamical downscaling provides added confidence, in terms of model skill representing atmospheric processes and long-term climate state (Rummukainen 2016) in a complex area such as the ATS region (Chandrasa and Montenegro 2020). Two different greenhouse gas emission scenarios were used, based on the Representative Concentration Pathway (RCP) trajectories (Meinhausen et al. 2011). The two scenarios were RCP4.5 (equivalent to moderate emissions) and RCP8.5 (equivalent to high emissions). The period used for the climate projection analysis was mid-century (2041–2070), relative to the models' historical simulations (1976–2005 baseline).

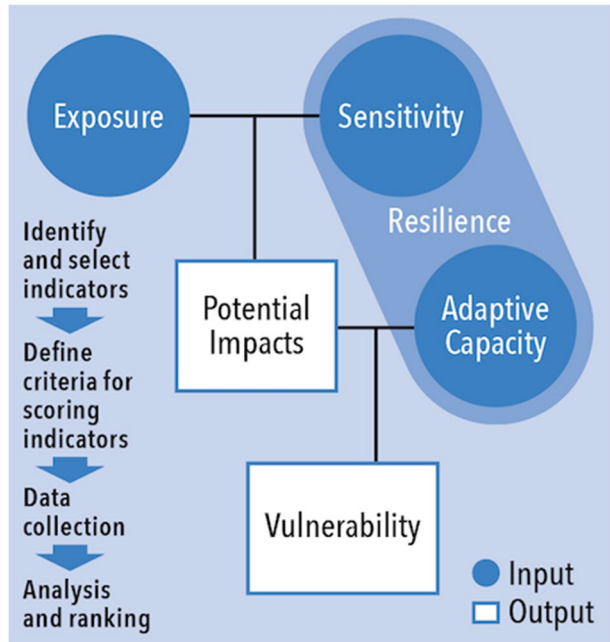
The analysis of the change in oceanic parameters used an ensemble of downscaled results from the CMIP-6 models under the new Shared Socioeconomic Pathways (SSP) scenarios SSP5-8.5 (high emissions) and SSP2-4.5 (low emissions). SST and ocean pH values were downloaded at native grid resolution,¹ for all available models in SSP5-8.5 and SSP2-4.5 (refer to van Hooijdonk et al. 2020 for lists and models used). Data were concatenated where needed to create complete time series. Where multiple runs were present, they were averaged using equal weighting. Missing data were filled in the zonal direction using NCL's Poisson grid fill function. All SST model runs were adjusted to the mean of NOAA Coral Reef Watch coraltemp_v3.1 (NOAA 2020) climatology by subtracting the mean of the first 5 years of the run from the entire period and then adding the mean of CoralTemp climatology. SST data were downscaled using the method described in van Hooijdonk et al. (2016). The ensembles were re-gridded to 5-km resolution, and the annual cycle was replaced with the CoralTemp 1985–2012 climatology.² The model delivered data at 5-km resolution up to 2070 in monthly bins to provide output maps for absolute SST and changes in SST between 2015 and 2070 using homogenised spatial data for the ATS region.

The climate change projections data were used for the regional vulnerability assessment, as a primary input for 'exposure' to assess selected species and marine habitats in the ATS region.

¹ Downloaded from <https://esgf-node.llnl.gov/on> in January 2021.

² See https://coralreefwatch.noaa.gov/product/5km/description_climatology.php for description.

Fig. 2 Vulnerability assessment framework applied for the ATS regional assessment (Johnson et al. 2016)



2.3 Regional vulnerability assessment

A structured semi-quantitative approach was applied for the vulnerability assessment, which provides a framework for determining the potential impacts of climate change on habitats and species, their relative level of vulnerability and drivers of vulnerability (Johnson et al. 2016). The vulnerability assessment applied a framework adapted from the IPCC and United Nations Framework Convention on Climate Change (UNFCCC), which includes the elements of Exposure, Sensitivity and Adaptive Capacity (Fig. 2). The vulnerability assessment focused on marine and coastal habitats and species in the ATS region important to communities, industries and governments for food security, livelihoods, traditional culture, and conservation. The vulnerability assessment was conducted for five spatial sub-regions in the ATS region — Indonesia-Arafura, Timor-Leste, western PNG, Gulf of Carpentaria, and northern Australia (see Fig. 1) to deliver results relevant to the habitats, species, and fisheries in each sub-region.

The selection of species for all sub-regions followed a similar approach to that used by Welch et al. (2014), but varied depending on available local information. For each sub-region, a range of criteria were applied, including cultural importance, importance for subsistence or recreational use, relative economic value, and conservation importance based on the IUCN Red List of Threatened Species (<https://www.iucnredlist.org>). For the Timor-Leste and Indonesia/Arafura sub-regions, the selection of species was informed by published literature (California Environmental Associates 2018; Konservasi and Nusantara 2020; López-Angarita et al. 2019) and refined through consultation with local experts including government managers, local and international scientists. For western PNG, species were selected based on published literature (Busilacchi et al. 2014) and local expert knowledge of a co-author (David Welch). For the two Australian sub-regions, the species selected were predominantly those previously assessed by Welch et al. (2014), which went through a rigorous stakeholder

consultation and expert-based selection process. To ensure that the selected species were still relevant, consultations with fisheries staff at the Northern Territory Department of Primary Industries and Resources were conducted. The species assessed were not intended to provide a definitive list for each sub-region. Rather they were representative of locally important fishery and conservation species and provide a range of likely responses to climate change so results could guide climate relevant action for these and similar species.

The assessment used indicators for exposure based on climate projections, and indicators for sensitivity and adaptive capacity based on known tolerances and responses to climate variability. Criteria were developed to analyse each indicator taking a risk-based approach using ecologically relevant triggers and relationships. The criteria used categories for scoring each indicator that are empirically based on known thresholds, where they exist. Where data were limited, expert-based thresholds were applied based on the likelihood of experiencing a change in a particular variable (exposure), quantified ecological relationships and tolerances (sensitivity), and likelihood of holding inherent resilience characteristics (adaptive capacity). A sensitivity analysis using a bootstrapping approach identified a suite of indicators that influenced species' rankings and substitutions of the high vulnerability species, which was used to interpret results and make suitable recommendations. Further details of the methods are available in the literature (Welch et al. 2014; Johnson et al. 2016; Johnson and Welch 2016), Supplementary information, and Appendix A (Tables A1, A2, A3, A4, A5).

The vulnerability assessment used existing empirical evidence, including climatologies, climate projections, ecological thresholds and responses, phenology, status and trends, demographics, modelling, and expert knowledge. Three sources of data were used for the assessment: (1) published data, (2) expert elicitation, and (3) critical data collection/modelling to fill gaps. Structured expert elicitation with 8–10 experts for each sub-region was used for several assessment indicators where there were limited data and provided data for socio-economic and governance indicators.

A vulnerability metric was used to quantify results so that components were systematically ranked based on their relative vulnerability to climate change. Scores were assigned for each indicator using a 3-point scale based on the specific criteria. The analysis followed the method outlined in Johnson et al. (2016) to calculate a vulnerability index using the metric (below) and the components were ranked from highest to lowest relative vulnerability.

$$V = (PI \times AC \text{ index}) + 1$$

where: V = vulnerability, PI = potential impacts (ExS), AC index = 1 – adaptive capacity

2.4 Mapping vulnerability of habitats

The habitats selected for assessment were based on their ecological, social, and economic importance, including their role as critical habitats for species and the goods and services they provide. The same habitats have been assessed in adjacent regions using the same structured vulnerability assessment framework (Bell et al. 2011; Welch et al. 2014; Johnson and Welch 2016).

Coral reef and seagrass habitat vulnerability were assessed using spatial data analysed and delivered as mapping outputs showing hotspots of vulnerability. Spatial data layers represented indicators of exposure, sensitivity and adaptive capacity (see Table A4) and were combined using map algebra. Mapping outputs were prepared using the software

Fig. 3 Projected changes in mean air temperature (°C) and rainfall for the ATS region. **(a)** Change in mean air temperature from the baseline (1976–2005) under RCP4.5 and **(b)** under RCP8.5. Projected changes in rainfall: **(c)** change in seasonal cumulative rainfall (%) during different seasons represented by 3-month periods (left to right). Rows represent the conditions under RCP4.5 (top) and RCP8.5 (bottom). Projected change in annual daily maximum rainfall (mm) under: **(d)** RCP4.5 and **(e)** RCP8.5, and the annual number of days with heavy rainfall under **(f)** RCP4.5 and **(g)** RCP8.5

Python 2.7.3 (PythonWin 2012) and *ArcGIS 10.7* (ESRI 2019). There was insufficient data at the necessary spatial resolution to conduct a spatial analysis for mangroves, therefore a semi-quantitative approach was used with locally specific indicators (see Table A5).

The input data to assess exposure, sensitivity and adaptive capacity were based on the indicators and criteria provided in Appendix A (Tables A4 and A5). The exposure and sensitivity of coral reefs and seagrass meadows were based on input layers that were normalised on a scale from 0 to 1, and included projected temperature increase, projected rainfall change, warm season temperature variability, diversity. An index of potential impacts was calculated by multiplying the normalised exposure and sensitivity layers, then re-normalising on a scale from 0 to 1. The adaptive capacity of coral reefs and seagrass meadows was based on input layers normalised on a scale from 0 to 1, and included marine-protected areas, water quality and non-climate anthropogenic threats.

Habitat vulnerability was calculated by multiplying the normalised potential impacts layer with an inverted adaptive capacity layer (1-AC), re-scaled by a ‘potential management effectiveness factor’ of 0.5 that reduces the maximum allowable management effectiveness in the model calculations, as per:

$$V = PI \times [(AC \text{ index}) \times 0.5]$$

where: V = vulnerability, PI = potential impact (ExS), AC index = 1 – adaptive capacity

The final raw vulnerability layer was then re-normalised on a scale from 0 to 1.

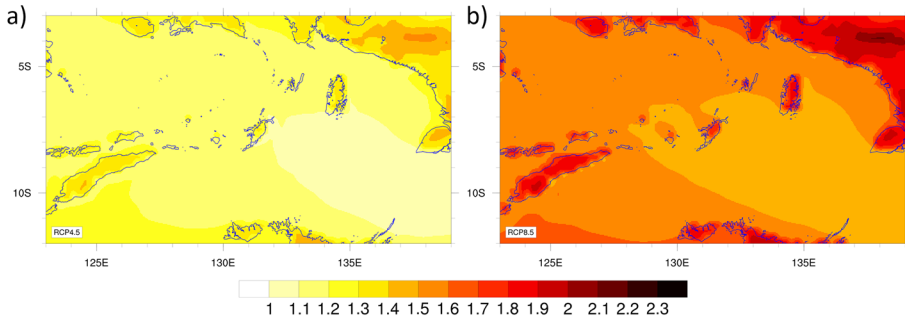
3 Results

3.1 Climate change projections

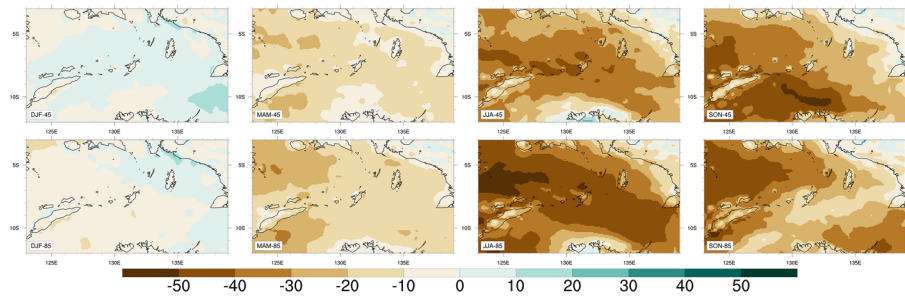
Future climate projection data by mid-century (2041–2070 period) showed a relatively uniform increase in air temperature over the ATS region under both the RCP4.5 (medium) and RCP8.5 (high) emissions scenarios (Fig. 3a–b). The mean increases over the area were +1.21 °C for RCP4.5 and +1.60 °C for RCP8.5. Air temperature increases over land and coastal areas are more significant than over offshore (open ocean) areas.

The projected change in total cumulative rainfall (in percentage) for 3-month periods in the ATS region shows generally drier conditions in the future, with varying intensity by seasons and scenarios (Fig. 3c). The most significant decrease is in the June–July–August period, which is the dry phase of the Indo-Australian monsoon season. While during the Indo-Australian monsoon wet season, some locations in the region, for example, the south-west coast of Papua and central Arafura Sea, are projected to experience an increase in rainfall (Fig. 3c). The probability of extreme rainfall events was assessed using climate indices derived from modelled daily rainfall, for example, maximum daily rainfall and the number of heavy rainfall days (Fig. 3d–g). Model results showed increased likelihood of

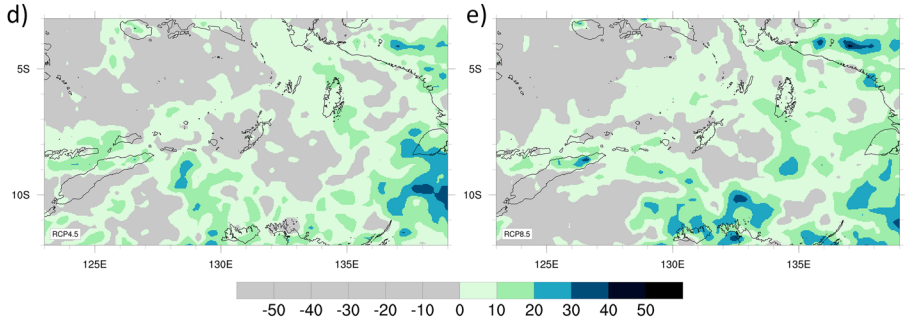
Projected Change in Mean Temperature (degC)



Projected Change in Sesasonal Rainfall (%)



Projected Change in Maximum Daily Rainfall (mm)



Projected Change in Number of Heavy Rain Days (days)

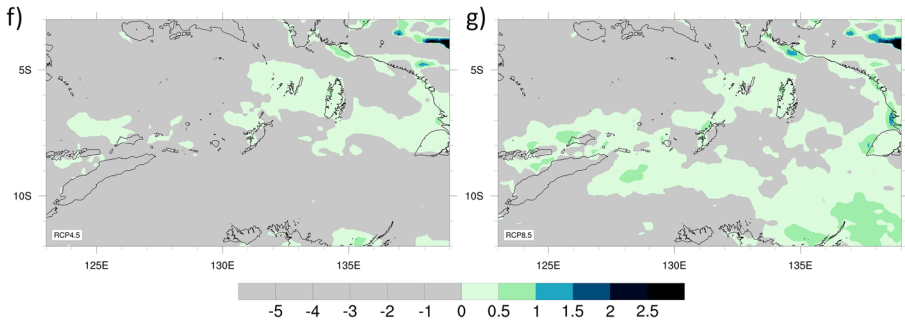


Fig. 4 Downscaled projections for (a) SST for 2070 and (b) SST differences between 2015 and 2070 under SSP2-4.5 (moderate emissions) scenario; and (c) SST for 2070 and (d) SST differences between 2015 and 2070 under SSP5-8.5 (high emissions) scenario; (e) ocean pH for 2070 and (f) ocean pH differences between 2015 to 2070 under SSP2-4.5 (moderate emissions) scenario; and (g) ocean pH for 2070 and (h) ocean pH differences between 2015 and 2070 under SSP5-8.5 (high emissions) scenario

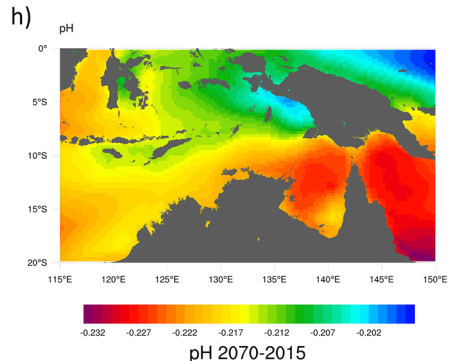
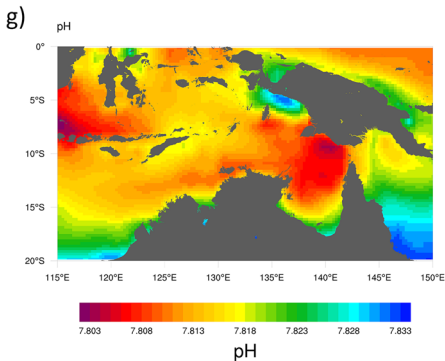
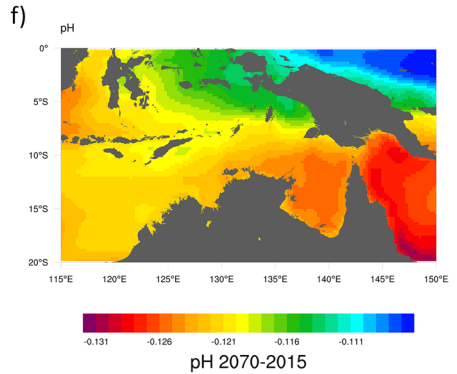
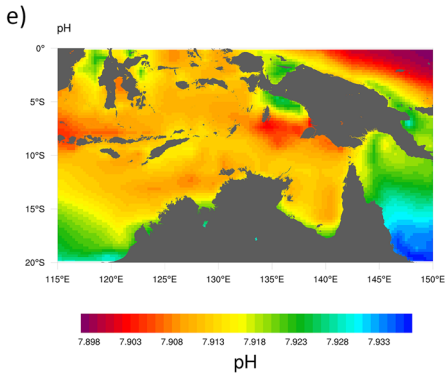
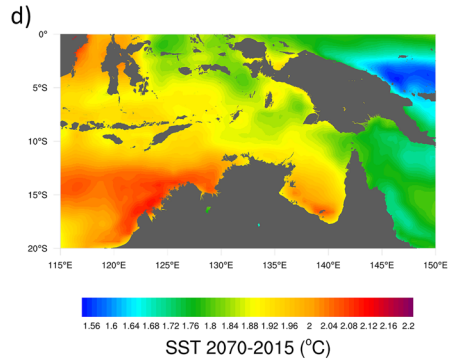
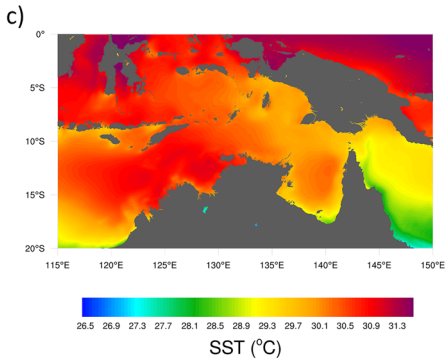
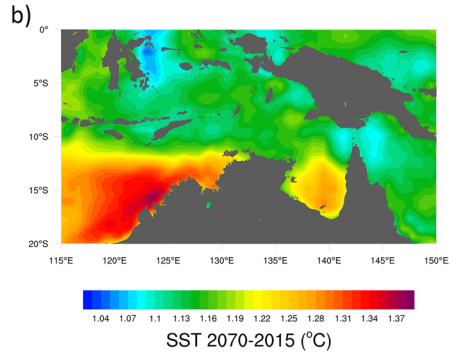
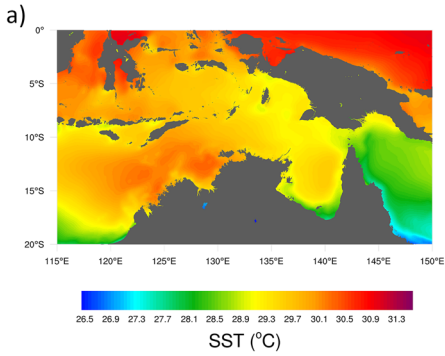
extreme rainfall events, particularly over the south-eastern part of the region. Again, the high emission scenario (RCP8.5) results in a relatively higher risk.

The modelled maps for absolute SST and changes in SST between 2015 and 2070 using homogenised spatial data for the entire ATS region show different spatial patterns under SSP2-4.5 and SSP5-8.5 scenarios (Fig. 4). Under SSP5-8.5, the absolute SST projections show similar temperatures in 2070 in northern Australia and the northern Timor Sea into the Banda Sea of 30.9 to 31.3 °C (Fig. 4c). The warming rate is greatest in northern Australia, where there is a 2.12 °C increased between 2015 and 2070, while the northern Timor Sea is warming by about 1.88 °C during the same period (Fig. 4d). Under all emissions scenarios, a net SST increase in the ATS region is projected, with the magnitude and rate of this warming proportional to the emissions scenario, i.e. the largest changes in SST are under the highest future atmospheric CO₂e concentrations (SSP5-8.5). By 2070, under SSP5-8.5, a (spatially averaged) warming of 1.72 °C is expected relative to 2015, and absolute SST will be above 29.5 °C for most of the region (as an annual average). While under SSP2-4.5, a (spatially averaged) warming of 1.13 °C is expected relative to 2015 (Fig. 4b), and absolute SST will be above 28.9 °C for most of the region (Fig. 4a).

There is a net decrease in ocean pH (acidification) under all emission scenarios, with the magnitude and rate of change proportional to the atmospheric CO₂ concentrations. Under the moderate emissions scenario (SSP2-4.5) there is an absolute pH value of 7.9 with the effects most pronounced to the east, near Papua and the Gulf of Carpentaria (Fig. 4e), and a spatially averaged decrease of 0.126–0.116 units by 2070 (Fig. 4f), relative to the 2015 observations. Under the high emissions scenario (SSP5-8.5), there is an absolute pH value of 7.8 with the effects most pronounced to the east, near Papua and the Gulf of Carpentaria (Fig. 4g), and a spatially averaged decrease of 0.227–0.212 units by 2070 relative to 2015 observations (Fig. 4h).

3.2 Habitat vulnerability

There is spatial variation in the vulnerability of habitats to climate change, with the location of habitats determining their exposure to projected climate change, and a range of ecological and social factors driving sensitivity and adaptive capacity, and ultimately vulnerability. Seagrass meadows were most vulnerable in the Gulf of Carpentaria due to a hotspot of SST increase, Indonesia-Arafura due to low connectivity and non-climate pressures, and Timor-Leste due to increases in SST, sea level rise and limited formal management (Fig. 5a). Coral reefs were most vulnerable in Timor-Leste and Indonesia-Arafura, with hotspots around Manatuto and Barique Municipality, Timor-Leste, Rote Ndao and Tual in the Arafura Sea. Poor current condition, non-climate pressures (i.e. land-based pollution), and limited formal management were key drivers of vulnerability in these sub-regions (Fig. 5b). Mangrove habitats were most vulnerable in Timor-Leste and Western PNG, with sea level rise, rainfall declines, poor current condition, low species diversity, low connectivity, limited management, and non-climate pressures being key drivers.



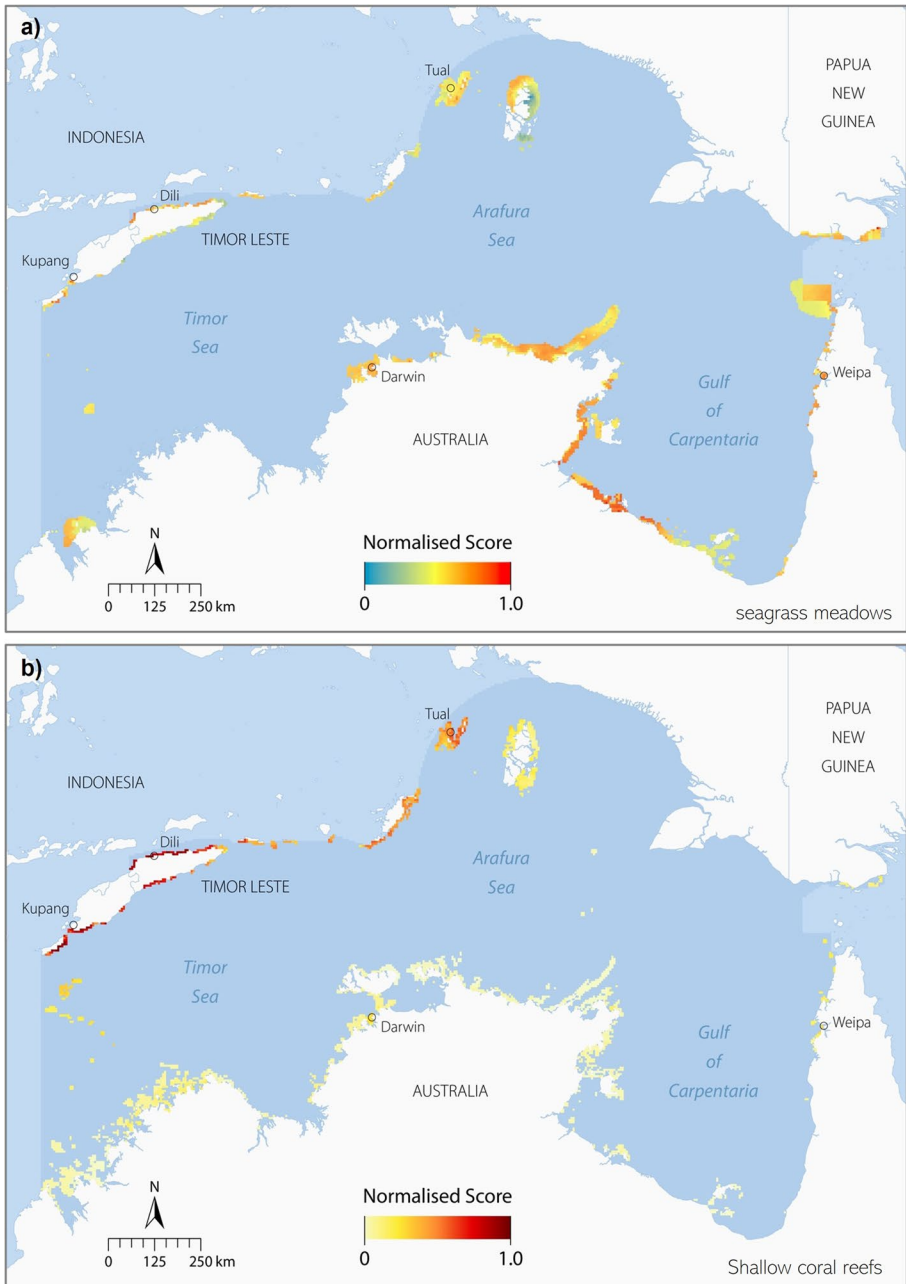


Fig. 5 Regional relative vulnerability of (a) seagrass meadows and (b) shallow coral reefs (< 40 m) in the ATS region. Colour represents normalised scores from 0 (not vulnerable) to 1.0 (very high vulnerability)

Table 1 Drivers of vulnerability for mangroves, seagrass meadows and shallow coral reefs in the ATS sub-regions and expected impacts. Sub-regions listed in order of habitat vulnerability from high to low

Sub-region	Vulnerability drivers	Expected impacts
Mangroves		
Western PNG	Poor current condition; low species diversity; lack of management	Decline in condition and area
Timor Leste	Rainfall declines; sea-level rise; low connectivity; limited formal management	Decline in condition and area
Indonesia/Arafura	Sea-level rise; poor current condition	Decline in condition and area
Northern Australia & Gulf of Carpentaria	Sea-level rise	Stable
Seagrass meadows		
Gulf of Carpentaria	SST +; historic SST + exposure; rainfall changes; low species diversity	Decline in condition and area
Indonesia/Arafura	Rainfall increase/coastal runoff; sea-level rise; low connectivity; non-climate pressures	Decline in condition and area
Timor Leste	SST +; sea-level rise; limited formal management	Decline in area
Western PNG	Historic SST + exposure; rainfall increase/coastal runoff; low diversity; no management	Decline in condition and area
Northern Australia	SST +; historic SST + exposure	Stable
Shallow coral reefs		
Timor Leste	Projected SST +; poor current condition; limited formal management	Declining condition, diversity and area
Indonesia/Arafura	Poor current condition; non-climate pressures, particularly pollution	Decline in condition, diversity and area
Western PNG	Low diversity; lack of management	Decline in condition and area
Northern Australia	Projected SST +	Stable

The vulnerability of mangroves, seagrass meadows, and shallow coral reefs varies across sub-regions and are influenced by different drivers. The current poor condition of habitats, non-climate pressures and limited management effectiveness all influence vulnerability to varying degrees in the different sub-regions (Table 1). Ultimately, mangroves, seagrass meadows and coral reefs are expected to decline in condition and area in Western PNG, Timor-Leste and Indonesia/Arafura, and to be generally stable in Northern Australia and the Gulf of Carpentaria.

3.3 Vulnerability of species

A total of 23 species/species groups were assessed in Timor-Leste, 26 in the Indonesia/Arafura sub-region, seven in the Western PNG sub-region, 18 in the Gulf of Carpentaria sub-region, and 19 in the northern Australia sub-region (Appendix B; Tables B1, B2, B3, B4, B5). Generally, individual species were included for assessment, however in some instances, groupings of species were included where necessary. Given the overlap in species across sub-regions, a total of 51 unique species/species groups were assessed for the ATS region.

3.3.1 Indonesia/Arafura

The most vulnerable species in the Indonesia/Arafura sub-region were black teatfish (*Holothuria whitmaei*), barramundi, green and hawksbill turtles, mangrove red snapper (mangrove jack), wedgefish and mud crab (Figure B1). The least vulnerable species were mackerel scads, Indian Ocean squid, shark species, and reef and/or shoal finfish species.

Examination of the contributing elements to vulnerability found that key drivers of exposure of Indonesia/Arafura species was that many species live in shallow water or spend part of their life history in shallow water, particularly estuarine habitats. For example, the species with the highest exposure were mud crab, white banana prawn and barramundi, all estuarine species. Another key driver was that many species are dependent on specific habitats for at least part of their life cycle. These factors make these species more highly exposed to projected changes to habitat condition or area. A key driver of sensitivity in this sub-region was the short larval duration of many species or being live young bearers. Accordingly, the species that had the highest sensitivity scores were green and hawksbill turtles, dugong, mud crab and several elasmobranch species. The key drivers of sensitivity for these species were that they tend to have relatively low fecundity and high average age at maturity (i.e. species with a lower reproductive potential for replenishing their populations after impacts). Further, the gender of turtle hatchlings is strongly linked to air temperature (that drives sand and nest temperatures), which further increases their sensitivity. Mud crab was an exception, being a relatively productive species, however, it has been shown to be highly sensitive to changes in SST and rainfall and river flow, with effects on survival, growth, and recruitment.

3.3.2 Western PNG

The most vulnerable species in the Western PNG sub-region were mud crab and dugong. Green turtle, barramundi and black jewfish all had moderate vulnerability,

while whitetip reef sharks were least vulnerable (Figure B2). Overall, the seven species assessed in Western PNG generally had high exposure to climate change given their preference for shallow nearshore and/or estuarine waters, which are the dominant environments in this sub-region. Notably, there were three sensitivity or adaptive capacity indicators that were key drivers of species vulnerability in this sub-region: (i) stock status — four of the seven species were assessed as overfished while the others were ‘undefined’; (ii) non-climate pressures on stocks were very high, mainly poor water quality and IUU fishing; and (iii) poor governance, which is also linked to the influence of non-climate pressures.

3.3.3 Timor-Leste

The most vulnerable species in the Timor-Leste sub-region were green turtle, flowery cod, mangrove red snapper (mangrove jack), and octopus (Figure B3). The least vulnerable species were rabbitfish, bluefin trevally, Spanish mackerel, and fusiliers (Caesionidae).

Examination of the contributing elements to vulnerability found that key drivers of exposure was that many species spend a large part of their life history in shallow water, where they are likely to be more exposed to changes in SST and rainfall. Another key driver was the reliance of many species on coral reef habitats for all or part of their life history. There is relatively high confidence that these habitats will decline in area and condition due to the effects of climate change. For example, most species that had high-moderate exposure are coral-reef associated species, such as octopus, snappers, surgeon fish, cods, emperors and fusiliers. Another driver was that many species are dependent on specific habitats for at least part of their life cycle.

A key driver of sensitivity was that many species were either live young bearers or have a relatively short larval duration — green turtles, dugong, reef manta ray and whitetip reef sharks. These species tend to have relatively low fecundity and high average age at maturity (i.e. species with a lower reproductive potential for replenishing their populations after impacts). Furthermore, the gender of turtle hatchlings is strongly linked to air temperature (that drives sand and nest temperatures), which further increases their sensitivity. The species that had the lowest adaptive capacity were mangrove red snapper, flowery cod, green turtle, and octopus, due to their overfished status and very low replenishment potential as they are relatively long-lived, late maturing, and slow growing. Further, there was a relatively high reliance on these species for local income. Green turtles also have a low replenishment potential as egg layers. Despite octopus being a highly productive species with a rapid life cycle, this species is highly targeted for local subsistence and to a lesser extent for income, and experiences high non-climate (fishing) pressures.

3.3.4 Gulf of Carpentaria and Northern Australia sub-regions

The assessment results for the two Australian sub-regions are presented together given the overlap in the species assessed. In the Gulf of Carpentaria, the most vulnerable species were king threadfin, green turtle, dugong, barramundi, golden snapper, and mud crab (Figure B4). The least vulnerable species were blacktip reef sharks and white banana prawns. In northern Australia, the most vulnerable species were golden snapper, green turtle, black jewfish, dugong, and king threadfin (Figure B5). The least

vulnerable species were deep water snapper species, three shark species and white banana prawn.

Examination of the contributing elements to vulnerability for both sub-regions found that key drivers of exposure were species predominantly shallow water and/or nearshore distribution (e.g. golden snapper, mud crab, king threadfin, barramundi), low mobility (e.g. prawn species), and a dependency on estuarine habitats for critical parts of their life cycle (e.g. brown tiger prawn, white banana prawn, mud crab, king threadfin, barramundi, golden snapper, blue threadfin).

A key driver of sensitivity overall was a low capacity for larval dispersal, with either a relatively short larval duration or none (live/egg bearers). For example, the most sensitive species across both sub-regions were green turtle, dugong, scalloped hammerhead, and two blacktip shark species; all either lay eggs or bear live young. Other key drivers of sensitivity were late maturation (e.g. turtle, dugong, shark species, king threadfin), and the influence of environmental drivers on recruitment, survival and growth for species with populations that are known to be strongly influenced by changes in rainfall and river flow. This included king threadfin, barramundi, and mud crab.

The species with the lowest adaptive capacity across both sub-regions were king threadfin, dugong, golden snapper, black jewfish, red emperor, and mangrove jack. Key drivers of low adaptive capacity were low population replenishment potential (e.g. dugong, green turtle, golden snapper, red emperor, mangrove jack and sharks) and depleted or overfished stock status (e.g. Gulf: king threadfin; Northern Australia: golden snapper). Non-climate pressures were another driver of low adaptive capacity, especially plans for increasing water diversion in Gulf rivers using dams, further reducing river flow under a reduced rainfall future. Governance was also assessed as being relatively inflexible and non-adaptive. While current plans for new dams in the Gulf of Carpentaria region will continue to undermine adaptive capacity, fishery management reforms that are underway for the sub-region should allow for more flexible management that is responsive to the effects of climate change.

3.4 Results synthesis

The results of the vulnerability assessment were spatially variable and identified highly vulnerable habitats and species in each sub-region, vulnerability drivers, and the components that are most vulnerable across multiple sub-regions (Table 2). No species or habitats were assessed as likely to benefit from projected climate change. Habitats and species that have high vulnerability across multiple jurisdictions and extensive spatial distributions (including migratory species) provide priority targets for transboundary management.

4 Discussion and conclusions

The relative vulnerability of marine habitats and species in the ATS region to climate change was determined by assessing the current and projected state of the environment and ecological responses to projected climate change. While spatial variability in vulnerability and consistent environmental drivers were apparent, the assessment identified the current poor condition and limited effective management as consistent key drivers of high vulnerability. Non-climate pressures were also influential.

Table 2 Summary of relative vulnerability of marine habitats and most vulnerable species across sub-regions. Dark grey hatch = high vulnerability; grey = moderate vulnerability; light grey hatch = low vulnerability. n/a indicates habitats/species not assessed in that sub-region. Species identified in **bold** are migratory or have population structures that cross jurisdictions

Sub-region	Indonesia-Aratura	Timor Leste	Western PNG	Gulf of Carpentaria	Northern Australia
Habitats					
Coral reefs (shallow)	Dark grey hatch	Dark grey hatch	Dark grey hatch	n/a	Light grey hatch
Seagrass meadows	Dark grey hatch	Dark grey hatch	Dark grey hatch	Dark grey hatch	Light grey hatch
Mangrove forests	Light grey hatch	Dark grey hatch	Dark grey hatch	Light grey hatch	Light grey hatch
Species					
Green turtle	Dark grey hatch	Dark grey hatch	Dark grey hatch	Dark grey hatch	Dark grey hatch
Dugong	Dark grey hatch	Dark grey hatch	Dark grey hatch	Dark grey hatch	Dark grey hatch
Barramundi	Dark grey hatch	n/a	Dark grey hatch	Dark grey hatch	Light grey hatch
Mangrove red snapper	Dark grey hatch	Dark grey hatch	n/a	Light grey hatch	Light grey hatch
Mud crab	Light grey hatch	n/a	Dark grey hatch	Light grey hatch	Dark grey hatch
Black jewfish	n/a	n/a	Dark grey hatch	n/a	Dark grey hatch
King threadfin	n/a	n/a	n/a	Dark grey hatch	Dark grey hatch
Golden snapper	n/a	n/a	n/a	Dark grey hatch	Dark grey hatch
Black teatfish	Dark grey hatch	n/a	Dark grey hatch	n/a	n/a

4.1 Changes in environmental variables and impacts

The results of the climate change projections for rainfall showed increasing rainfall-related extremes. These patterns suggest an accentuation of monsoonal conditions, with the wet season getting wetter and the dry season getting drier, thus impacting seasonality. Overall, however, drier conditions are anticipated throughout most of the annual cycle and are particularly significant under the high emissions scenario. Less rainfall is expected to reduce freshwater supply and river flows leading to changes in salinity, sedimentation, nutrient delivery, and coastal water quality (Pratchett et al. 2011). Hence, changes in rainfall will impact marine ecosystems, the fish and invertebrates they support (Piccolo 2021) and ultimately the communities and industries that depend on them.

Ocean circulation in the ATS region plays an important role in influencing SST patterns. Results showed a projected increase in SST under all emissions scenarios, and of greater magnitude under the high emissions scenario. Over the past 30 years, SST in Indonesian

waters has shown an overall increasing trend, with the greatest rise (0.66 °C) occurring in the Halmahera Sea (north of the ATS region) and the smallest rise in the Timor Sea (0.36 °C) (Martono 2016). Some marine species are known to be sensitive to variations in SST, for example, increasing cool-season SST may compromise reproductive success of black teatfish (*Holothuria whitmaei*) since they spawn during winter in low latitudes, potentially resulting in a range contraction poleward (Shiell and Uthicke 2006). Other crustaceans show similar thermal sensitivities, moving into deeper water during marine heatwaves, for example, tropical rock lobster in the Torres Strait islands (Johnson and Welch 2016).

All future emission scenarios show a net decrease in ocean pH (acidification) in the ATS region, with the magnitude and rate of change proportional to atmospheric CO₂ concentrations. Ocean acidification is expected to cause reductions in coral growth, diversity, recruitment and abundance of framework building corals, driving shifts in competitive interactions between taxa as pH declines (e.g. studies in shallow CO₂ seeps in PNG; Fabricius et al. 2011).

4.2 Impacts to habitats

The results of the seagrass assessment identified low species diversity, poor connectivity, limited formal management, and non-climate pressures such as impacts from land-based runoff and poor water quality. The impact of multiple stressors from an extreme event (thermal stress, reduced light/sediment inputs due to floods) has been shown to cause ecosystem-wide loss of seagrass resilience in Western Australia (Kendrick et al. 2019), and seagrass are projected to undergo irreversible phase shifts due to marine heatwaves under > 1.5 °C warming (Cooley et al. 2022). Adaptations for local and regional management should focus on addressing sources of vulnerability, particularly in locations important for fisheries or species of conservation interest (e.g. dugong and green turtles). For example, by reducing land-based pollutant inputs through integrated catchment management of agriculture, deforestation and coastal development, and area-based management of seagrass meadows.

The results of the coral reef assessment identified poor current condition, limited or patchy formal management, and non-climate pressures such as impacts from land-based pollution, particularly sediment, nutrients, and pesticides. The range of potential impacts includes coral cover declines, increasing macroalgae, and the risk of reefs transitioning to net erosion under > 1.5 °C of warming, with adaptation options limited for most locations (Hoegh-Guldberg et al. 2018, 2019). Coral reef species' composition and diversity are also projected to change due to future interactions between climate and non-climate hazards (Kleypas 2019; Kubicek et al. 2019), resulting in simpler habitats. This will have implications for reef-dependent species, such as fish and invertebrates, as studies have detected changes in reef fish assemblages and stocks consistent with lagged impacts of habitat degradation (Richardson et al. 2018; Robinson et al. 2019; Lam et al. 2020). Adaptations that address local and regional pressures will be important for building reef resilience and maintaining diversity in the face of multiple climate hazards. However, mitigation of carbon emissions and active interventions will increasingly be required given the scale of the issue (National Academy of Sciences 2019). Therefore, adaptations can focus on addressing sources of vulnerability, such as reducing land-based pollutant inputs to coastal reefs to improve water quality (Gavio and Mancera Pineda 2015; Lam et al. 2015; Wiedenmann et al. 2013), and

directly protecting coral reef habitats, particularly from destructive fishing and coastal development. As well as restoration efforts following impacts, such as coral planting, noting however that these are only effective in small areas and will not prevent future impacts (Condie et al. 2021).

The results of the mangrove assessment identified poor current condition, low species diversity, limited formal management, and non-climate pressures such as coastal development as key drivers of vulnerability. Southeast Asia has experienced the greatest loss of mangroves globally (Friess et al. 2019) and locations where coastal development and infrastructure are extensive are particularly vulnerable since there will be physical barriers to mangrove inland migration as sea level rises. Mangroves can adapt to sea-level rise if sediment accretion keeps pace and landward barriers, such as roads, don't constrain migration (Friess et al. 2019; Friess et al. 2020). Ultimately, the success of migration depends on local topography, infrastructure barriers, and the pace of sea-level rise (Cahoon et al. 2021), which under high emissions is expected to be greater than the ability of mangroves to accrete and grow (Lovelock et al. 2017). Some important adaptations include relocation or removal of anthropogenic barriers to landward migration (e.g. weirs and roads), limiting current loss of mangroves, and urban planning that considers areas that mangroves may expand into.

4.3 Impacts to species

Identifying highly vulnerable species and the drivers of vulnerability in each sub-region informs priority species for action and management at local and regional scales. Across the ATS regions, green turtles, dugong, and barramundi were identified as the most vulnerable species, and mangrove red snapper are also a target for management given their vulnerability in some sub-regions and local livelihoods and economic importance. A consistent driver of species vulnerability was their status as overfished or depleted (many were also 'undefined'), meaning they may already be or may soon be overfished, and there is currently limited effective management. Highly vulnerable species in some sub-regions should be prioritised for action due to their conservation status. For example, while wedgefish were assessed as the sixth most vulnerable species in the Indonesia/Arafura sub-region, they have an extremely high extinction risk due to being targeted for their high-value and internationally traded 'white' fins (Kyne et al. 2020) and immediate action is warranted. Therefore, management actions that effectively and appropriately reduce and control harvest to sustainable levels and allow stocks to rebuild are urgently required for many of the species assessed as vulnerable. This may require more conservative measures for species with low replenishment potential and will need strong government will and community engagement and education.

Using the species vulnerability rankings can identify species to focus on for local action (see Tables B1, B2, B3, B4, B5). Where species identified for action are likely to be part of a stock shared by adjacent jurisdictions, cooperative inter-jurisdictional management should be explored. For example, two species that are highly vulnerable in all five sub-regions — green turtle and dugong — are likely to be part of inter-connecting populations shared across large areas of the ATS region. In addressing these species' vulnerability to climate change, the individual sub-regional assessment results can be used to identify the drivers of vulnerability, and therefore inform the most effective management actions at sub-regional and regional scales.

4.4 Key recommended actions

For many of the highly vulnerable habitats and species, there are significant fundamental issues that affect their status and resilience to future threats from climate change. Therefore, if they are to be resilient to future climate change and continue to fulfil important ecological roles and support fisheries in the ATS region, the following actions consistent with adaptations identified globally as effective solutions (Cooley et al. 2022) are recommended:

1. Primary fisheries management (sustainable harvesting aligned with an ecosystem-based approach) for stocks assessed as at risk from overfishing that effectively and appropriately controls harvest to sustainable levels and allows stocks to rebuild. Sustainable harvesting safeguards marine food resources and livelihoods, and is urgently required in the ATS region. This may necessitate more conservative measures for species with low replenishment potential, greater community awareness and education, and governance mechanisms that suit the local context, such as decentralization of fisheries management coupled with adequate resourcing (Tilley et al. 2019). Illegal, unregulated and unreported fishing can also reduce the resilience of stocks to future climate change and exacerbate climate impacts (Widjaja et al. 2020). Limiting overexploitation is the central purpose of primary fisheries management, and is expected to benefit adaptation to climate change (Free et al. 2020; Duarte et al. 2020).
2. Transboundary regional management of vulnerable species that are part of shared stocks across multiple jurisdictions requires complementary and coordinated approaches and can support climate adaptation (Pinsky et al. 2021). Holsman et al. (2019) showed that fisheries management seldom integrates across regional scales, undermining climate resilience, while transboundary cooperation between fisheries jurisdictions was shown to reduce climate change impacts (Free et al. 2020).
3. Species of conservation interest requires special attention and should be the focus of management. With large, connected ranges, wide distributions, and generally low productivity, these vulnerable species should be protected through actions that include restoration and/or protection of nesting and feeding habitats (McLeod et al. 2019), improvement of local water quality, and measures to mitigate their capture (targeted and incidental).
4. Effective mitigation measures to address multiple chronic cumulative pressures that further compromise habitat condition and fishery populations. Two key pressures are land-based pollution that drive poor water quality in coastal areas, which can lead to nutrient enrichment, macroalgal overgrowth (Gavio and Mancera Pineda 2015), impacts on coral fertilization and settlement (Lam et al. 2015), increased susceptibility of corals to thermal bleaching (Wiedenmann et al. 2013) and ecosystem-wide losses of seagrass (Kendrick et al. 2019).
5. Measures that restore and protect critical habitats, including coral reefs, estuarine and wetland areas (e.g. mangroves and seagrass). Focused biodiversity protection and co-management with local communities using area-based conservation will directly benefit habitat condition and resilience to future change, as well as the species they support (Maxwell et al. 2020; Gurney et al. 2021). Studies have detected declines in fish populations and fisheries consistent with lagged impacts of habitat disturbance (Richardson et al. 2018; Robinson et al. 2019), demonstrating the importance of restoring, conserving and protecting marine habitats. Such measures may include establishing MPAs strategically placed to protect climate refugia (Wilson et al. 2020), restoring damaged habitats

- (McLeod et al. 2019), prohibiting damaging practices, and minimising upstream pressures, e.g. land-based pollution.
6. Diversifying to alternative species as a local food source to reduce community dependence on vulnerable species, thereby increasing resilience to possible future impacts on stocks (Robinson et al. 2020). These alternative species should be acceptable to communities, currently underutilised, and have high replenishment potential.
 7. Assessing potential land-use change implications on downstream marine environments is important to avoid future impacts and has been particularly highlighted in some sub-regions. Activities in catchments drive impacts on coastal and marine environments, through direct impacts of land-based pollutants, such as sediment and nutrients on habitats (UNEP 2017), and indirect impacts of land-use changes that can transfer livelihood pressure to marine resources or change the connectivity between land and sea, e.g. dams.
 8. A localised co-management approach should be undertaken to prioritise adaptation actions based on ecological, economic, and cultural values, and to inform local area-based measures that consider the dual goals of ecological protection and sustainable use (Gurney et al. 2021).

Although regional assessments can offer insight into the potential impacts of climate change on habitats and species, local actions should be based on information to effectively address the drivers of vulnerability through management at the local level. This means adopting a localised approach that considers the habitats, species, and target fisheries that are important at the local scale to select appropriate adaptations (Johnson et al. 2022). At the same time, complementary regional approaches to management can minimise the drivers of vulnerability through coordinated multi-jurisdictional efforts.

Considering that many marine and coastal resources in the ATS region are highly vulnerable to climate change, an urgent call to action is needed. The compromised condition and resilience of these resources, due to existing pressures such as overfishing, land-based pollution, coastal development, and limited management, underscore the importance of addressing these drivers. While global action is needed to reduce greenhouse gas emissions, taking local and regional action can support the resilience of marine ecosystems and provide time for mitigation. For instance, addressing current pressures and promoting adaptation can help to minimise short-term impacts. However, long-term sustainability of marine ecosystems in the ATS region ultimately requires global climate change mitigation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-023-03554-9>.

Acknowledgements The authors thank the partners from the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) in Indonesia, and the University of Miami, Florida, USA. for supporting this project. They also thank the ATSEA-2 national coordination unit in each ATS country for their assistance, local stakeholders who provided input, and scientific experts who reviewed the assessment.

Author contribution Johanna Johnson coordinated the team and led habitat analyses with spatial analysis support from Dieter Tracey. David Welch led species analyses and contributed to project concept development and write-up. Ruben van Hooidonk conducted downscaled climate projections for ocean temperature and pH, Ganesha Chandrasa conducted downscaled climate projections for air temperature and rainfall. Ruben and Ganesha contributed to write-up of downscaling projection methods and results. Bianca Molinari and Deti Triani contributed to technical write-up, and developed figures. Casandra Tania and Handoko Susanto provided project oversight and contributed to conceptual thinking and write-up.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions This work was supported by the Global Environment Facility (GEF). Author Dr van Hooidonk has received research

support from the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program.

Data availability The datasets generated during and/or analysed during the current study are available in the PEMSEA repository.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- ATSEA [Arafura and Timor Seas Ecosystem Action] program (2023) Draft transboundary diagnostic analysis: Arafura and Timor Seas Region. Bali, Indonesia.
- ATSEA (2012) Transboundary diagnostic analysis: Arafura and Timor Seas Region. Indonesia.
- Bell J, Johnson J, Hobday A (2011) Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community, Noumea, New Caledonia
- Bindoff NL, Cheung WWL, Kairo JG et al (2019) Changing ocean, marine ecosystems, and dependent communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner H-O et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 447–587.
- Blaber SJM, Dichmont CM, Buckworth RC et al (2005) Shared stocks of snappers (Lutjanidae) in Australia and Indonesia: integrating biology, population dynamics and socio-economics to examine management scenarios. *Rev Fish Biol Fisheries* 15(1):111–127
- Brodie J, Johnson JE, Waterhouse J, Erdmann S (2019) Wastewater pollution and coral reefs: supporting science. United Nations Environment Programme, Nairobi, Kenya
- Burke L, Reyter K, Spalding M, Perry A (2012) Reefs at risk revisited in the coral triangle.
- Busilacchi S, Butler J, Skewes T et al (2014) 2014 Characterization of the traditional fisheries in the Treaty communities of Torres Strait (Papua New Guinea). CSIRO, AFMA
- Cahoon DR, McKee KL, Morris JT (2021) How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Est Coasts* 44:883–898
- California Environmental Associates (2018) Trends in marine resources and fisheries management in Indonesia: 2018 review. Prepared with the support of the David and Lucile Packard Foundation. 146
- Chandrasa GT, Montenegro A (2020) Evaluation of regional climate model simulated rainfall over Indonesia and its application for downscaling future climate projections. *Int J Climatol* 40(4):2026–2047
- Condie SA, Anthony KR, Babcock RC et al (2021) Large-scale interventions may delay decline of the Great Barrier Reef. *Roy Soc Open Sci* 8(4):201296
- Cooley S, Schoeman D, Bopp L et al (2022) Oceans and coastal ecosystems and their services. In: *Climate Change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Pörtner H-O et al. (Eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 379–550.
- Cruz FT, Narisma GT, Dado JB et al (2017) Sensitivity of temperature to physical parameterization schemes of RegCM4 over the CORDEX-southeast Asia region. *Int J Climatology* 37(15):5139–5153
- Doney SC, Busch DS, Cooley SR, Kroeker KJ (2020) The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annu Rev Environ Resour* 45:83–112
- Duarte CM, Agusti S, Barbier E et al (2020) Rebuilding marine life. *Nature* 580(7801):39–51. <https://doi.org/10.1038/s41586-020-2146-7>


- Duke NC, Hutley LB, Mackenzie JR, Burrows D (2021) Processes and factors driving change in mangrove forests: an evaluation based on the mass dieback event in Australia's Gulf of Carpentaria. In: Ecosystem collapse and climate change [Canadell JG and Jackson RB (Eds.)]. Springer International Publishing, Cham, 221–264.
- Eakin CM, Sweatman HPA, Brainard RE (2019) The 2014–2017 global-scale coral bleaching event: insights and impacts. *Coral Reefs* 38(4):539–545. <https://doi.org/10.1007/s00338-019-01844-2>
- Edyvane K, do Guterres MO, Widodo Pranowo W, Wasson R (2011) Biophysical profile of the Arafura and Timor Seas.
- ESRI (2019) ArcGIS: Release 10.7.1. Environmental Systems Research Institute (ESRI).
- Fabricius K, Langdon C, Uthicke S et al (2011) Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nat Clim Chang* 1:165–169
- Free CM, Mangin T, Molinos JG et al (2020) Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLoS One* 15(3):e0224347
- Friess DA et al (2019) The state of the world's mangrove forests: past, present, and future. *Annu Rev Environ Resour* 44:89–115
- Friess DA et al (2020) Mangroves give cause for conservation optimism, for now. *Curr Biol* 30(4):R153–R154
- Gavio B, Mancera Pineda JE (2015) Blooms of ephemeral green algae in San Andres Island, International Biosphere Reserve Seaflower. *Southwest Caribb Acta Biol* 20(2):259–262
- Guo W, Bokade R, Cohen AL, Mollica NR, Leung M, Brainard RE (2020) Ocean acidification has impacted coral growth on Great Barrier Reef. *Geophys Res Lett* 47(19):e2019GL086761
- Gurney GG, Darling ES, Ahmadi GN et al (2021) Biodiversity needs every tool in the box: use OECMs. *Nature* 595(7869):646–649
- Hoegh-Guldberg O, Kennedy EV, Beyer HL, McClennen C, Possingham HP (2018) Securing a long-term future for coral reefs. *Trends Ecol Evol* 33(12):936–944
- Hoegh-Guldberg O, Jacob D, Taylor M, et al (2019) The human imperative of stabilizing global climate change at 1.5 C. *Science* 365(6459).
- Holsman K, Hazen EL, Haynie A et al (2019) Towards climate resiliency in fisheries management. *ICES J Mar Sci* 76(5):1368–1378
- Hughes TP, Kerry JT, Baird AH et al (2018) Global warming transforms coral reef assemblages. *Nature* 556(7702):492–496
- IPCC (2014) Climate Change 2013: the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change.
- IPCC (2019) IPCC special report on the ocean and cryosphere in a changing climate [Pörtner H-O et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 755pp.
- IPCC [Intergovernmental Panel on Climate Change] (2022) Climate Change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner H-O et al. (eds.)]. Cambridge University Press, Cambridge University Press, Cambridge, UK and New York, USA, 3056pp.
- Johnson JE, Welch DJ (2010) Climate change implications for Torres Strait fisheries: assessing vulnerability to inform adaptation. *Rev Fish Sci* 18(1):106–124
- Johnson JE, Welch DJ (2016) Marine fisheries management in a changing climate: a review of vulnerability. *Clim Change* 135(3–4):611–624
- Johnson JE, Welch DJ, Maynard JA et al (2016) Assessing and reducing vulnerability to climate change: moving from theory to practical decision-support. *Mar Policy* 74:220–229
- Johnson JE, Welch DJ, van Hooidonk R, Tracey D (2021) Assessing the vulnerability of the Arafura & Timor seas marine region to climate change. Report to Arafura and Timor Seas Ecosystem Action Phase II, Bali, Indonesia
- Johnson JE, Welch DJ, Tracey D et al (2022) Guide for facilitators: incorporating regional climate change results into local action planning. C2O Consulting, Prepared for Arafura & Timor Seas Ecosystem Action Phase II. Bali, Indonesia.
- Jones RN, Mearns LO (2005) Assessing future climate risks. In book: Adaptation policy frameworks for climate change: developing strategies, policies and measures, 119–144. Cambridge University Press.
- Juneng L, Tangang F, Chung JX et al (2016) Sensitivity of Southeast Asia rainfall simulations to cumulus and air–sea flux parameterizations RegCM4. *Clim Res* 69(1):59–77
- Kendrick GA, Nowicki RJ, Olsen YS et al (2019) A systematic review of how multiple stressors from an extreme event drove ecosystem-wide loss of resilience in iconic seagrass community. *Front Mar Sci* 6:455
- Kimura T, Tun K, Chou LM (2018) Status of coral reefs in East Asian Seas Region. Ministry of Environment Japan and Japan Wildlife Research Center, Tokyo, Japan, p 58

- Klain S, Eberdong J, Kitalong A et al (2007) Linking Micronesia and Southeast Asia: Palau sea turtle satellite tracking and flipper tag returns. *Mar Turtle Newsl* 9–11
- Kleypas J (2019) Climate change and tropical marine ecosystems: a review with an emphasis on coral reefs. *UNED Res J* 11(1):24–35
- Konservasi Y, Nusantara A (2020) Snapper fishery profile in Aru district and surrounding areas, Indonesia Fisheries Management area WPP 718. Report prepared for Accelerating EAFM implementation and progress fisheries improvement project red snapper fisheries, UNDP/ENV-ATSEA/84306/029/2019, 70pp.
- Kubicek A, Breckling B, Hoegh-Guldberg O, Reuter H (2019) Climate change drives trait-shifts in coral reef communities. *Sci Rep* 9(1):1–10
- Kyne PM, Jabado RW, Rigby CL et al (2020) The thin edge of the wedge: extremely high extinction risk in wedgfishes and giant guitarfishes. *Aquat Conserv Mar Freshwat Ecosyst* 30(7):1337–1361
- Lam EK Y, Chui AP Y, Kwok CK et al (2015) High levels of inorganic nutrients affect fertilization kinetics, early development and settlement of the scleractinian coral *Platygyra acuta*. *Coral Reefs* 34(3):837–848
- Lam VWY, Sumaila UR, Allison EH et al (2020) Climate change, tropical fisheries and prospects for sustainable development. *Nat Rev Earth Environ* 1(9):440–454. <https://doi.org/10.1038/s43017-020-0071-9>
- Leahy S, Robins J (2021) River flows affect the growth of a tropical finfish in the wet-dry rivers of Northern Australia, with implications for water resource development. *Hydrobiologia* 848
- López-Angarita J, Hunnam KJ, Pereira M et al (2019) Fisheries and aquaculture of Timor-Leste: current knowledge and opportunities. Penang, Malaysia: WorldFish. Program Report: 2019–15
- Lovelock C, Feller I, Reef R, Hickey S, Ball M (2017) Mangrove dieback during fluctuating sea levels. *Sci Rep* 7
- Martono M (2016) Seasonal and inter annual variation sea surface temperature in Indonesian waters. *Forum Geografia* 30(2):120–129
- Maxwell SL, Cazalis V, Dudley N et al (2020) Area-based conservation in the twenty-first century. *Nature* 586(7828):217–227
- McKenzie LJ, Yoshida RL (2020) Over a decade monitoring Fiji’s seagrass condition demonstrates resilience to anthropogenic pressures and extreme climate events. *Mar Pollut Bull* 160:111636
- McLeod E, Anthony KR, Mumby PJ et al (2019) The future of resilience-based management in coral reef ecosystems. *J Environ Manag* 233:291–301
- Meinhausen M, Smith SJ, Calvin K et al (2011) The RCP greenhouse gas concentrations and extensions from 1765–2300. *Clim Change* 109(1–2):213–241
- National Academy of Sciences (2019) A research review of interventions to increase persistence and resilience of coral reefs. National Academies Press, Washington, D.C., p 258
- Ngo-Duc T, Tangang FT, Santisirisomboon J et al (2017) Performance evaluation of RegCM4 simulating extreme rainfall and temperature indices over the CORDEX-Southeast Asia region. *Int J Climatol* 37(3):1634–1647
- NOAA (2020) NOAA Coral Reef Watch Version 3.1 Thermal History (1985–2019) (Version 3.1.0, Experimental, Released October 9, 2020). College Park, Maryland, USA: NOAA Coral Reef Watch, https://coralreefwatch.noaa.gov/product/thermal_history/index.php.
- Perry CT, Alvarez-Filip L (2019) Changing geo-ecological functions of coral reefs in the Anthropocene. *Funct Ecol* 33(6):976–988
- Piccolo MC (2021) Chapter 12: effects of rainfall extreme events on coastal marine ecosystems. 261–285.
- Pinsky ML, Fenichel E, Fogarty M et al (2021) Fish and fisheries in hot water: what is happening and how we adapt? *Popul Ecol* 63(1):17–26
- Pratchett MS, Bay LK, Gehrke PC (2011) Contribution of climate change to degradation and loss of critical fish habitats in Australian marine and freshwater environments. *Mar Freshwat Res* 62(9):1062–1081
- PythonWin (2012) Python IDE and GUI framework for Windows. Copyright 1994–2008 Mark Hammond. Python Copyright 2001–2012 Python Software Foundation.
- RARE Indonesia (2020) Climate change vulnerability assessment: South Sulawesi, Indonesia.
- Retnowati E, Yusri S, Idris, Widodo MPS, Fakhurrozi (2019) Vulnerability analysis to climate change in Lembeh Island, North Sulawesi. *IOP Conference Series Earth Env Sci* 363(1):12011
- Richardson LE, Graham NA, Pratchett MS et al (2018) Mass coral bleaching causes biotic homogenization of reef fish assemblages. *Glob Change Biol* 24(7):3117–3129
- Roberts C, McClean C, Veron J et al (2002) Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science* 295:1280–1284
- Robinson JPW, Wilson SK, Jennings S, Graham NAJ (2019) Thermal stress induces persistently altered coral reef fish assemblages. *Glob Change Biol* 25(8):2739–2750

- Robinson JPW, Robinson J, Gerry C et al (2020) Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. *Sci Adv* 6(8):eaz0587
- Rummukainen M (2016) Added value in regional climate modeling. *Wiley Interdisc Rev Clim Change* 7(1):145–159
- Shiell GR, Uthicke S (2006) Reproduction of commercial sea cucumber *Holothuria whitmaei* in the Indian and Pacific Ocean regions of Australia. *Mar Biol* 148(5):973–986
- Supari FT, Juneng L, Cruz F et al (2020) Multi-model projections of precipitation extremes southeast Asia based on CORDEX-southeast Asia simulations. *Env Res* 184:109350
- Tangang F, Santisirisonboon J, Juneng L et al (2019) Projected future changes in mean precipitation Thailand based on multi-model regional climate simulations CORDEX southeast Asia. *Int J Climatol* 39(14):5413–5436
- Tangang F, Chung JX, Juneng L et al (2020) Projected future changes in rainfall southeast Asia based on CORDEX–SEA multi-model simulations. *Cli Dynamic* 55(5–6):1247–1267
- Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93(4):485–498
- Tilley A, Hunnam KJ, Mills DJ et al (2019) Evaluating the fit of co-management for small-scale fisheries governance in Timor-Leste. *Front Mar Sci* 6:392
- UNEP (2017) Wastewater pollution and coral reefs: science-to-policy brief. Johnson, J.E., Brodie, J., Waterhouse, J. (Authors). United Nations Environment Programme, Nairobi, Kenya.
- van Hooidonk R, Maynard J, Tamelander J et al (2016) Local-scale projections coral reef futures and implications of the Paris Agreement. *Sci Rep* 6(1):39666
- van Hooidonk R, Maynard J, Grimsditch G et al (2020) Projections of future coral bleaching conditions using IPCC CMIP6 models: climate policy implications, management applications, regional seas summaries. United Nations Environment Programme, Nairobi, Kenya
- Veron JEN, Stafford-Smith MG, Turak E, DeVantier LM (2016) Corals of the world.
- Waycott M, McKenzie L, Mellors J et al (2011) Vulnerability of mangroves, seagrasses, intertidal flats in the tropical Pacific to climate change. In: *Vulnerability of Fisheries and Aquaculture in the Pacific to Climate Change*.
- Welch DJ, Saunders T, Robins J et al (2014) Implications of climate change on fisheries resources Northern Australia. Part 1: vulnerability assessment and adaptation options.
- Widjaja S, Long T, Wirajuda H (2020) Illegal, unreported and unregulated fishing and associated drivers.
- Wiedenmann J, D'Angelo C, Smith E et al (2013) Nutrient enrichment can increase the susceptibility of reef corals to bleaching. *Nat Clim Chang* 3:160–164
- Wilson KL, Tittensor DP, Worm B, Lotze HK (2020) Incorporating climate change adaptation into marine protected area planning. *Glob Change Biol* 26(6):3251–3267
- Zimmerman RC (2021) Scaling up: predicting impacts of climate change on seagrass ecosystems. *Estuaries Coasts* 44(2):558–576

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Johanna E. Johnson^{1,2}  · David J. Welch^{1,3} · Ruben van Hooidonk^{4,5} · Dieter Tracey⁶ · Ganesha Chandrasa⁷ · Bianca Molinari¹ · Deti Triani⁸ · Casandra Tania⁸ · Handoko Susanto⁸

✉ Johanna E. Johnson
j.johnson@c2o.net.au

¹ C₂O Pacific, Port Vila, Vanuatu

² College of Science & Engineering, James Cook University, Cairns, Australia

³ C₂O Fisheries, Cairns, Australia

⁴ Cooperative Institute Marine and Atmospheric Studies, Rosenstiel School of Marine Atmospheric Science, University of Miami, Miami, FL, USA

- ⁵ Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL, USA
- ⁶ Science Graphics, Cairns, Australia
- ⁷ Center for Climate Change Information, Agency Meteorology Climatology and Geophysics (BMKG), Jakarta, Indonesia
- ⁸ ATSEA-2 Team, Bali, Indonesia and Dili, Timor-Leste