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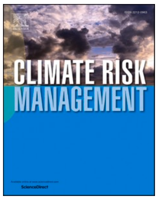

Marine climate change risks to biodiversity and society in the ROPME Sea Area

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ABSTRACT

The subtropical ROPME Sea Area (RSA), comprising the Gulf, the Gulf of Oman and the northern Arabian Sea, is a heavily exploited sea region that experiences extreme environmental conditions, and for which climate change is expected to further impact marine ecosystems and coastal communities, sectors and industries. Climate change risk assessments provide a valuable tool to inform decision-making and adaptation planning through identifying and prioritising climate risks and/or opportunities. Using the first UK Climate Change Risk Assessment as an example, a marine climate change risk assessment was undertaken for the marine and coastal environment of the RSA for the first time. Through an extensive literature review and a workshop involving regional experts, marine and coastal climate change risks were identified, scored and prioritised. A total of 45 risks were identified, which spanned two key themes: 'Risks to Biodiversity' and 'Risks to Economy and Society'. Of these, 13 were categorised as 'severe', including degradation of coral reefs and their associated ecological assemblages, shifts in the distribution of wild-capture fisheries resources, changes to phytoplankton primary productivity, impacts on coastal communities, threats to infrastructure and industries, and impacts on operations and safety in maritime transport. The diversity of risks identified and their transboundary nature highlight that climate change adaptation responses will require coordinated action and cooperation at multiple scales across the RSA. This risk assessment provides a crucial baseline for a largely overlooked

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geographic area, that can be used to underpin future decision-making and adaptation planning on climate change, and serve as a ‘blueprint’ for similar assessments for other regional shared seas.

1. Introduction

Climate change is a critical issue affecting marine and coastal environments worldwide (Doney et al., 2012; IPCC, 2019). Reducing the negative ecological and social impacts from marine climate change, and identifying any opportunities, requires anticipating future impacts and risks it may present. Examining climate risks is an integral part of decision-making and policy development processes (Jurgilevich et al., 2017; Brown, 2018). Climate change risk assessments provide an opportunity to identify and prioritise risks across biodiversity, ecosystems, industries and communities using a consistent approach to highlight the most pressing areas for adaptation interventions (Adger, Brown and Surminski, 2018). Risk assessments have been recognised as valuable tools in guiding evidence-based public policy, such as in the political global frameworks of the United Nations Framework Convention on Climate Change Paris Agreement (UNFCCC; United Nations, 2015a), the associated Warsaw International Mechanism for Loss and Damage, and the Sendai Framework for Disaster Risk Reduction (SFDRR; United Nations, 2015b; Adger, Brown and Surminski, 2018). They can also be used as evidence in countries’ UNFCCC Nationally Determined Contributions (NDC) which outline national scale actions being undertaken to address climate change issues (UNFCCC, 2016). A growing number of countries have undertaken national climate change risk assessments, adopting a range of approaches and methodologies to identify the most important environmental and societal risks within countries (European Environment Agency, 2018; MOCCAE, 2019). However, climate change risks within the marine environment can cascade beyond national boundaries, thus requiring adaptation planning and policy at a range of governance levels and geographical scales (Gupta et al., 2007; Charles, 2012; Challinor et al., 2017; Pinsky et al., 2018).

Marine ecosystems are inherently complex and dynamic systems (Hagstrom and Levin, 2017). Climate change risks within the marine environment transcend national jurisdictions as well as social and economic sectors, requiring assessments, management and adaptation actions that can acknowledge and account for these transboundary and trans-sector interlinkages (Charles, 2012; Challinor et al., 2017; Challinor et al., 2018). For example, shifting fish distributions in response to warming will have substantial implications for the governance of stocks, with potential conflicts emerging among competing interests (Pinsky et al., 2018). Similarly, climate-driven changes in run-off and hence water quality can affect human health in communities across multiple countries sharing marine waters (Baker-Austin et al., 2013; Berdalet et al., 2016). Aside from global and national frameworks, adaptation actions can also be informed by regional approaches, as is the case for some shared seas whereby marine management is coordinated at the regional scale

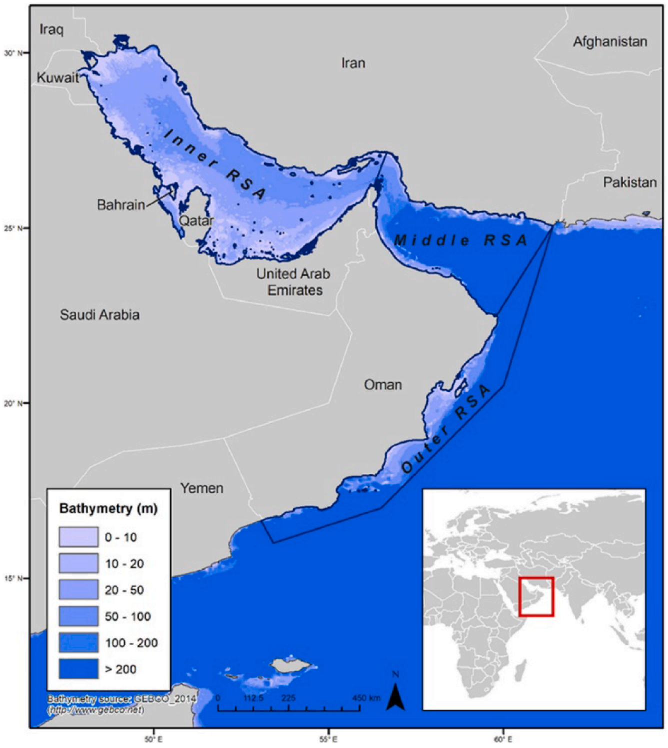


Fig. 1. The ROPME Sea Area. The RSA encompasses the territorial waters of the eight Member States of ROPME: Kingdom of Bahrain, Islamic Republic of Iran, Republic of Iraq, State of Kuwait, Sultanate of Oman, State of Qatar, Kingdom of Saudi Arabia and the United Arab Emirates.

Table 1
Physical climate drivers identified by workshop participants and a description of observed and future trends.

Climate driver	Short description of key trends
Air and sea temperature (including humidity)	Between 1982 and 2015, SST in the I-RSA and M-RSA has increased by 1 °C (Noori et al., 2019). Trends in the O-RSA suggest a similar temperature increase (Piontkovski and Al-Oufi, 2015). IPCC projections suggest that under RCP8.5 by 2099, SST could increase by 2.8–4.26 °C in the I-RSA and 2.5 °C in the M and O-RSA relative to a 2005 baseline (Hoegh-Guldberg et al., 2014). Warming is expected to be greatest during the summer season. Projections suggest mean humidity could increase by 10% by 2060 in the I-RSA (AGEDI, 2015). Annual 'hottest days' (over land) are projected to increase by an estimated 3 °C by 2050, and extreme heat wave days are also projected to increase (Almazroui et al., 2021).
Salinity	Salinity of I-RSA surface waters has increased by 0.5–1.0% (5–10 psu) over the past 60 years due to increased evaporation from rising average air temperatures (Hoegh-Guldberg et al., 2014; Vaughan et al., 2019). Trends for the M-RSA and O-RSA are less clear due to sparser monitoring data, and variation in sea surface salinity is lower due to greater mixing of waters (ROPME, 2013). Under a high-emissions scenario, an overall increase in salinity is suggested for the south of the I-RSA, although some freshening may occur along the southern coast of Iran (AGEDI, 2015). In the eastern M-RSA near the Strait of Hormuz, salinity could also increase (although at a lower rise compared to the I-RSA), whilst the O-RSA may experience declines (AGEDI, 2015).
pH	Current trends in pH are unclear, although in the O-RSA, an overall decrease in average pH of ~ 0.1 pH units in the upper 50 m and 0.2 pH units at 300 m depth between 1960 and 2000 has been observed (Piontkovski and Queste, 2016). Models suggest that pH in the RSA could decrease by approximately 0.25 units by 2050–2099 relative to the average during 1956–2005 (NOAA Climate Change Web Portal, 2020).
Dissolved Oxygen (DO)	More than 50% of the area of Oxygen Minimum Zones in the world's oceans occur in the RSA. DO concentrations within the RSA, particularly the I-RSA, are declining (Helly and Levin, 2004; Stramma et al., 2010). Areas of low oxygen concentrations are expected to become larger and more persistent over the coming century within the RSA (Bopp et al., 2013). Recent evidence suggests recurrent seasonal hypoxia events in the I-RSA are already occurring and which may form an important yet understudied threat to ecosystems such as coral reefs (Verneil et al., 2021). Global models suggest strong declines in DO in the southwestern I-RSA, and in southern areas of the M-RSA and O-RSA, of between −9 to −12 mol m^{-3} in 2050–2099 relative to the average during 1956–2005 (NOAA Climate Change Web Portal, 2020).
Changes in freshwater input	Changes in rainfall patterns are expected to occur in the future within the RSA, but will vary depending on subregion and season. Generally, declines in precipitation are expected north of the region/peninsula, and increases are expected in the south (Collins et al., 2013; Almazroui et al., 2020). Despite this broad north/south trend, downscaled projections for precipitation within the I-RSA suggest a slight increase in the north, and decreases in southern areas in 2080–2099 under RCP8.5 (AGEDI, 2015). Seasonally, IPCC projections for 2081–2100 under RCP8.5 suggest greatest increases in precipitation in autumn and summer months and spring seeing possible declines (Collins et al., 2013).
Changes in hydrodynamics	Circulation and water mass exchange within the RSA is generally controlled by a combination of heat and freshwater fluxes, river discharge, tides and winds (Al Azhar et al., 2016). By the end of century, salinity will still be a core driver of circulation within the I-RSA, but projected changes in temperature and rainfall are expected to disrupt the vertical overturning of the water column within the I-RSA, causing an increase in the inflow of less dense waters from the M-RSA (AGEDI, 2015). Currents in the surface layer of the O-RSA are predominantly driven by seasonal changes in temperatures and winds, and therefore any climate-driven changes to monsoon winds will have repercussions for these currents, in addition to upwelling of nutrient-rich cooler waters (AGEDI, 2015; ROPME, 2013).
Storms, cyclones, winds, waves and storm surges	Most cyclonic activity in the RSA occurs within the M-RSA and O-RSA regions, where on average one to two tropical cyclones make landfall each year after forming over the northern Indian Ocean (ROPME, 2013). An increase in the frequency of extremely severe cyclonic storms have been observed within the Arabian Sea (Murakami, Vecchi and Underwood, 2017). Projections for the Indian Ocean suggest that, under a high-emissions scenario, the number of tropical cyclones in the O-RSA and M-RSA may increase by the end of this century and that some cyclones may reach the I-RSA (Murakami, Sugi and Kitoh, 2013). For this assessment, increases in storm and cyclonic activity were expected to lead to rougher sea conditions, but future projections for changes in storm surges and wave activity are currently lacking for the region.
Dust storms	Dust storms appear to have increased in number across the Arabian Peninsula during summer months over the last 20–30 years (Kumar et al., 2019). In the I-RSA, desertification, changes in Shamal winds or ocean circulation patterns could all affect levels of dust deposition in the coastal and marine environment (ROPME, 2020).
Monsoon timing	Some projections for 2100 suggest a weakening in the Indian winter monsoon in the Arabian Sea, which may lead to reduced winter convective overturning in the northern Arabian Sea and affect rainfall patterns (Parvathi et al., 2017). There are also suggestions that the summer monsoon winds may strengthen which can affect upwelling and plankton productivity (Goes et al., 2005).
Sea-level rise	There are limited time series recording sea-level changes in the RSA. Within the northwest I-RSA, an average sea-level rise of 2.2 mm per year has been estimated between 1979 and 2007 (Alothman et al., 2014). In the M-RSA and O-RSA, using measurements from the wider Northern Indian Ocean, sea-level rise is estimated at 1.29 mm per year over a similar time period (Unnikrishnan and Shankar, 2007). Sea-levels are expected to rise within the RSA, but regional projections are limited. The most recent estimates from the IPCC suggest a mean global increase of 0.84 m by 2100 under a high-emissions scenario (IPCC, 2019).
Turbidity	Turbidity is not a direct climate change driver, but it is expected that this may be indirectly influenced by climate change into the future. For example, changes in storm events and hydrodynamics can influence sediment transport and could result in increased turbidity in localised areas and coastal waters. Increases in intense rainfall can increase surface run-off into coastal waters, whilst increased dust deposition in the water from dust storms may also increase turbidity.
Erosion	While not a direct climate change driver in itself, other climate change drivers may influence coastal erosion rates and therefore amplify ecological and socio-economic impacts. For example, climate driven changes in cyclones, wave patterns and sea-level rise could result in erosion of beach areas or habitats such as seagrasses.

through the United Nations Regional Seas Programmes (UNEP, 2020). Coordinating approaches at regional scales for management and adaptation to marine climate change risks therefore require risk assessments undertaken at these scales to identify commonalities and differences, as well as region-wide areas for action or intervention.

Here we present a marine climate change risk assessment for the ROPME (Regional Organisation for the Protection of the Marine Environment) Sea Area (RSA), offering an important baseline assessment at a regional and system level. The RSA is a rapidly warming subtropical sea region yet is often overlooked in international climate change assessments. Given the growing pressure of climate change within the region, and the transboundary nature of such risks, there is a critical need for a marine climate change risk assessment to be undertaken to help inform regional adaptation actions and to prioritize interventions and joined-up approaches. This assessment identifies and prioritises common risks for the whole region as well as more localised risks for the specific sub-regions of the RSA. Risks considered are based on two main themes: ‘Risks to Biodiversity’ and ‘Risks to Economy and Society.’

1.1. *Study area*

The Regional Organisation for the Protection of the Marine Environment (ROPME) coordinates efforts across the sea areas of its eight member states (Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates) to protect against marine pollution and other stressors (Fig. 1). The RSA covers three distinct sub-regions: 1) The Inner RSA (I-RSA), which is a shallow, semi-enclosed sea; 2) The Middle RSA (M-RSA), a deep sea that extends for almost 400 km and connects the Indian Ocean with the I-RSA through the shallow and narrow Strait of Hormuz; and 3) The Outer RSA (O-RSA) in the northern part of the Indian Ocean (Fig. 1). The region is home to a range of internationally important (listed as vulnerable or (critically) endangered by the IUCN Red List of Threatened Species) marine and coastal species such as dugong (*Dugong dugon*), Socotra cormorant (*Phalacrocorax nigrogularis*), green turtle (*Chelonia mydas*) and hawksbill sea turtle (*Eretmochelys imbricate*), as well as a diverse range of habitats including seagrasses, coral reefs, saltmarsh and mangroves (Sheppard et al., 2010; Al-Abdulrazzak and Pauly, 2017). The RSA is heavily utilised and exploited, which generates pressures on marine and coastal ecosystem services that contribute to food, energy and water security for countries within the region (Sheppard et al., 2010; Naser, 2014; Vaughan et al., 2019). Human activities such as oil and gas extraction, desalination, coastal development, overfishing and maritime traffic are intense and widespread, with consequences for the health and status of natural marine systems (Sheppard et al., 2010; Van Lavieren and Klaus, 2013; Naser, 2014).

Climate change is also increasingly being recognised as a major stressor to the RSA and wider region (Sheppard et al., 2010; Wabnitz et al., 2018; Ben-Hasan and Christensen, 2019; Almazroui et al., 2020). Biodiversity within the RSA is likely to be sensitive to climate change effects now and in the future due to the combination of extreme environmental conditions, high sensitivity of species to

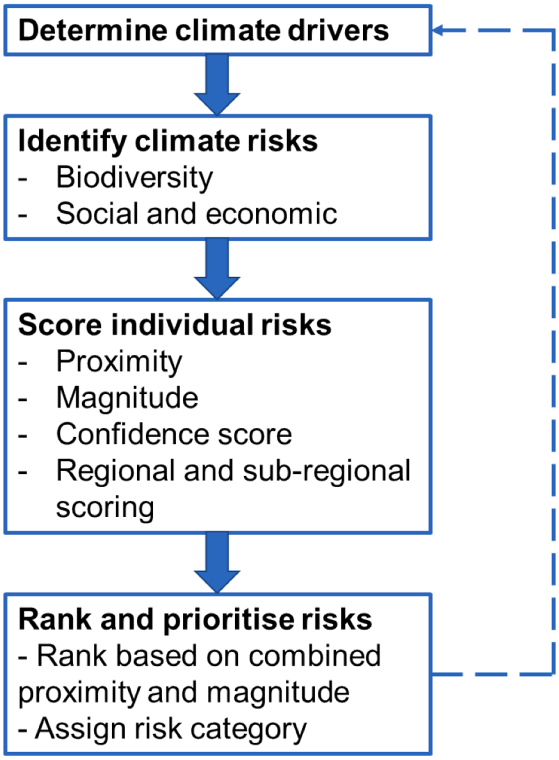


Fig. 2. A simplified risk assessment framework, informed by the 2012 UK CCRA, was used to identify and prioritise marine climate change risks within the RSA (Warren et al., 2018; CCRA, 2012). The dashed line represents the fact that this risk assessment can be updated as and when new risks emerge.

further changes beyond their physiological limits, and the range of human pressures on the marine environment (Wabnitz et al., 2018; Ben-Hasan and Christensen, 2019; Vaughan et al., 2019). Warming sea temperatures, altered salinity and decreasing pH, rising sea levels and changing cyclone activity have already been observed and are expected to continue impacting the RSA marine environment in the future (see Table 1; AGEDI, 2016; Piontkovski and Queste, 2016; Noori et al., 2019; Ben-Hasan and Christensen, 2019). Wider marine climate impacts, such as coral bleaching events reducing coral cover and expanding Oxygen Minimum Zones within the M-RSA transitioning it into a permanently suboxic state, with potential impacts on pelagic fish, have also been documented (Riegl et al., 2018; Queste et al., 2018; Saleh et al., 2021). Coastal settlements and key industries are also affected by marine climate change, with many significant coastal cities, seaports and wider infrastructure in the RSA vulnerable and at risk (Al-Saidi, 2019; Izaguirre et al., 2021; Mafi-Gholami et al., 2020; Shukla et al., 2021). The United Arab Emirates has recently undertaken the only national climate change risk assessment in the region, which while not explicitly marine focused, highlighted several marine and coastal priority risks as being important (MOCCAE, 2019). This included coral bleaching, loss of wetlands, damages to coastal infrastructure and deterioration of power facilities (MOCCAE, 2019). A risk assessment for the entire RSA is therefore urgently needed.

2. Methods

2.1. Risk assessment

The risk assessment methodology used in the present analysis was informed by the first United Kingdom (UK) Climate Change Risk Assessment (CCRA) carried out in 2012 (CCRA, 2012), which has subsequently guided a specific simplified marine climate assessment for the UK seafood industry (Garrett et al., 2015) and has been used as the model for a climate change risk assessment carried out within the United Arab Emirates (MOCCAE, 2019). Using these examples as a guide, the risk assessment reported here focused on four key steps: 1) Determining key climate drivers, 2) Identifying climate risks, 3) Scoring individual risks and 4) Ranking and prioritising risks (Fig. 2). For this assessment the United Nations Intergovernmental Panel on Climate Change (IPCC) definition of 'risk' was used, whereby risk is defined as 'the potential for adverse consequences to lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure and where the outcome is uncertain' (Oppenheimer et al., 2014). As such, risk is 'the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur' (Oppenheimer et al., 2014). The risk assessment was undertaken in November 2019, at a three-day workshop held in Muscat, Oman. Sixteen technical experts from across the RSA were invited, based on their relevant work and expertise within the region, and many of whom had been previously engaged in related work to undertake a literature review of climate change impacts in the region (Lincoln et al., 2021). These experts—co-authors of this paper—represent six of the eight ROPME member countries, and have expertise on topics including oceanography, biology and ecology, and social and economic impacts of climate change. The workshop followed the framework outlined in Fig. 2.

2.2. Determine climate drivers

Climate drivers considered to be causing change within the RSA and leading to future biodiversity and societal risks were identified through a comprehensive review of the literature and presented to workshop participants for discussion (Lincoln et al., 2021). From discussions, participants refined this list to a total of 12 key climate drivers within the region (Table 1). Subsequently, for each risk identified to ecosystems or society, the relevant drivers were selected from this list and highlighted.

2.3. Identify risks to biodiversity and society

Prior to the workshop, risks were identified and collated into a 'long-list' based on a thorough literature review undertaken together with in-region experts (Lincoln et al., 2021). This review drew on evidence from peer-reviewed scientific publications as well as wider technical and scientific reports covering impacts of climate change on the region's coastal and marine environment (Lincoln et al., 2021). Only sources in English were consulted or those in Arabic or Farsi where an English summary was available. Risks were collated

Table 2
Proximity and magnitude scoring of risks. Supplementary Table 1 provides further detail into the criteria of 'Proximity' and 'Magnitude'.

PROXIMITY (Time to consequence(s) occurring) **Score**	 **Categories**
1	Over 50 years
2	Within next 50 years
3	Within next 20 years
4	Now
MAGNITUDE of impact(s)	
Score	**Categories**
1	Low
2	Medium
3	High

by identifying the main, high-level impacts that featured in the available evidence, for example impacts to particular taxonomic groups or coastal industries. These groupings covered two overarching themes: ‘Risks to Biodiversity and Habitats’ and ‘Risks to Economy and Society’. This initial ‘long-list’ comprised 15 risks to biodiversity and habitats, and 30 risks to economy and society. At the workshop, participants discussed this initial ‘long-list’ of pre-identified risks. For each theme, some risks were added, others removed or merged based on expert judgement, evidence available, and using other risk assessment frameworks to guide thinking and discussion (e.g. CCRA, 2012; MOCCAE, 2019).

2.4. Score individual risks

Participants were assigned to one of two subgroups, based on their technical expertise and subject knowledge, to further discuss and score the risks within the two main themes. Risks were addressed sequentially before compiling a finalised prioritised list (across all topics) at the end.

Risk scores were based on their perceived ‘proximity’ and ‘magnitude’ (CCRA, 2012). Proximity indicates the time horizon after which substantial impacts are anticipated to be felt, and were allocated between 1 (50 years +) and 4 (already happening now) (Table 2). Magnitude scores were based on the perceived significance and consequences of a particular risk happening, based on an assessment of combined environmental, economic and social impacts (Supplementary Table 1), and were categorised as 1 (low impact), 2 (medium impact) or 3 (high impact). Unlike the UK CCRA (CCRA, 2012), magnitude was not scored separately for social, economic and environmental consequences. This was due to a lack of specific information and evidence for many of these aspects individually to allow detailed analysis to be undertaken.

To generate an overall score, the magnitude and proximity scores were combined using the formula:

$$\left(\frac{Magnitude}{3}\right)\left(\frac{Proximity}{4}\right)\text{x}100$$

Divisible numbers for magnitude and proximity are derived from the number of categories for each part of the risk score (see text above and Table 2). As a result, the lowest possible score is 8.3 and the highest possible score is 100.

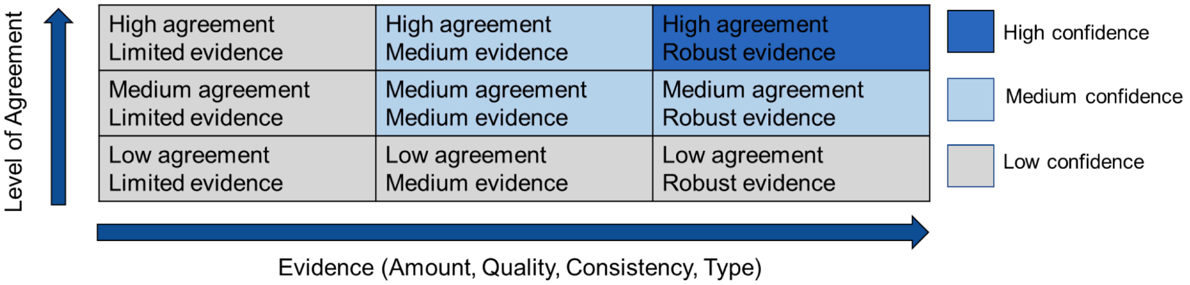
Risks were also assigned a confidence rating to reflect the level of agreement among participants and across evidence sources, as well as the level of evidence for the impacts associated with each risk. The confidence levels assigned were based on the scheme used by the IPCC (Mastrandrea et al., 2011; Fig. 3).

To mitigate potential issues surrounding subjectivity of scoring, the following actions were undertaken: 1) Identifying other sources of evidence (e.g. scientific articles, reports, policy documents) that might not have been captured before the workshop, but which could be used to help inform risk scoring; 2) Cross checking with the other sub-group to ensure consistency of scoring across the two risk themes; 3) Assigning a confidence score to each risk to provide further insight into the level of evidence and consensus; and 4) ‘Sense checking’ in a plenary setting and further refining a final condensed risk list to decide whether risk scoring across themes was reflective of both the evidence base and expert judgments.

Acknowledging that this is a regional risk assessment, there were instances whereby identified risks were more relevant or salient for particular sub-regions. As such, scoring was also conducted on each sub-region (Inner, Middle and Outer RSA) when evidence was available, as well as for the whole RSA in these cases.

2.5. Rank and prioritise risks

After individually scoring risks, risks from both themes were combined and ranked highest to lowest based on their overall scores to identify the most important priority risks to the RSA system overall. A risk categorisation was developed by the authors to provide a more intuitive and simplified scoring of risks alongside the numerical scores that emerged. Due to the limited variation of different overall risk scores (due to the small number of categories for proximity and magnitude restricting the amount of resulting numerical outcomes), three categories were developed. Risks were categorised as ‘Severe’ (score from 67 to 100), ‘Moderate’ (score from 25 to 50) and ‘Low’ (score from 8 to 17). Scores listed as ‘Severe’ were typified by a proximity of occurring ‘now’ and magnitude of ‘medium’



High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Fig. 3. IPCC matrix used for qualitative scoring of confidence associated with each risk.
Adapted from Mastrandrea et al. 2011

or ‘high’, highlighting that these risks require action urgently due to the immediate timeframe in which they are occurring and/or their large magnitude of potential impact. Most ‘Moderate’ risks were expected to occur within the next 20 years and had ’medium’/’low’ potential magnitude of impact. Those listed as ‘Low’ had a proximity of within the next 50 years and magnitude of ‘low’. The reported confidence scores provided alongside these risk scores and categorisations provided further information regarding the current available evidence on which scores were based. A similar exercise was also undertaken for the two risk themes (‘Risks to Biodiversity’ and ‘Risks to Economy and Society’) separately.

3. Results

A total of 45 marine and coastal risks were identified across the two themes, comprising 23 biodiversity risks and 22 social and economic risks (Table 3, Supplementary Table 2). Of these 45 risks, 13 were scored as ‘Severe’ in the risk assessment (Table 3, Supplementary Table 2). Eight risks were scored as ‘Low’, the majority of which were in the ‘Risks to Society’ theme, and which often had low confidence scores associated with them.

Table 3
Identified and prioritised marine climate change risks for the RSA. Scores are reflective for the overall region. Further descriptions of risks and the associated identified drivers can be found in Supplementary Table 2.

Risk	Proximity	Magnitude	Risk score	Risk category	Confidence level
Changes in coral reef associated communities	4	3	100	Severe	High
Increased incidence of harmful algal blooms (HABs) and nuisance species	4	3	100	Severe	Medium
Impacts on coastal communities	3	3	75	Severe	High
Changes in wild-capture fisheries resources	3	3	75	Severe	High
Flooding impacts on coastal industries and infrastructure	3	3	75	Severe	High
Impacts on desalination plants	3	3	75	Severe	High
Non-flooding related impacts on coastal industries and infrastructure	3	3	75	Severe	Medium
Impacts on operations, safety and movement of goods in the maritime transport sector	3	3	75	Severe	Medium
Changes to phytoplankton primary production	4	2	67	Severe	High
Changes in coral species (cover, distribution and health)	4	2	67	Severe	High
Change in jellyfish/gelatinous plankton outbreaks	4	2	67	Severe	Medium
Changes in benthic invertebrates (abundance and distribution)	4	2	67	Severe	Medium
Changes in pelagic fish (abundance and distribution)	4	2	67	Severe	Low
Changes in dugong (abundance and distribution)	3	2	50	Moderate	Medium
Changes in demersal fish (abundance and distribution)	3	2	50	Moderate	Low
Changes in sea turtles (abundance, distribution and nesting sites)	3	2	50	Moderate	High
Changes in seabirds (abundance, distribution and nesting sites)	3	2	50	Moderate	Low
Changes in waterbirds (abundance, distribution, nesting sites, feeding and overwintering sites)	3	2	50	Moderate	Medium
Changes in mangrove forests	3	2	50	Moderate	Low
Changes to rocky shores	3	2	50	Moderate	Medium
Changes to deep sea habitats (greater than 200 m)	3	2	50	Moderate	Medium
Impacts on fishing communities, infrastructure and operations	3	2	50	Moderate	High
Impacts on oil and gas offshore industries infrastructure and operations	2	3	50	Moderate	Low
Impacts on the provision of natural coastal protection	3	2	50	Moderate	Medium
Changes in aquaculture resources, infrastructure and supply chain	2	2	33	Moderate	Low
Impacts on coastal tourism infrastructure, resorts and facilities	2	2	33	Moderate	High
Impacts on pearl oysters	2	2	33	Moderate	Low
Impacts on human health from the marine environment	2	2	33	Moderate	Low
Changes to non-gelatinous zooplankton	4	1	33	Moderate	Low
Changes to microbial communities	4	1	33	Moderate	Low
Changes in saltmarshes, mudflats and Sabkhas	2	2	33	Moderate	Low
Changes to macroalgal beds	2	2	33	Moderate	Low
Changes in seagrass meadows	3	1	25	Moderate	Low
Changes to sandy beaches	3	1	25	Moderate	Low
Impacts on coastal and marine recreational activities	3	1	25	Moderate	High
Impacts on cultural heritage and historic sites	3	1	25	Moderate	Low
Impacts on the provision of natural climate regulation services	3	1	25	Moderate	Low
Changes in cetaceans (abundance and distribution)	2	1	17	Low	Medium
Spread of Alien Invasive Species (AIS)	2	1	17	Low	Medium
Impacts to onshore, nearshore and offshore marine renewable energy (wind, waves, tides)	2	1	17	Low	Low
Impacts on freshwater availability and quality from groundwater sources	2	1	17	Low	Low
Impacts on aggregate extraction operations	2	1	17	Low	Low
Impacts on the provision of natural waste breakdown and detoxification	2	1	17	Low	Low
Loss of education and research value from the marine environment	1	1	8	Low	Low
Loss of future use value of genetic and biological resources	1	1	8	Low	Low

3.1. Risks to biodiversity

A wide range of biodiversity risks were identified, for both key species and habitats in the RSA, impacting all trophic levels and many important coastal and marine habitats (Table 3, Supplementary Table 2).

For species, many of the risks identified focused on changes in distributions and abundance, habitat suitability, and the availability of food supply. Such risks can have wider consequences for the ecosystem, for example changing distributions of pelagic fish may affect the predator–prey dynamics of dependent cetaceans (whales and dolphins) or seabirds. For key habitats, risks often focused on the loss of or damage to sites from extreme events and changes in structure, function and productivity. The most frequently assigned climate drivers across the biodiversity risks were changes in: temperature (listed 23 times), hydrodynamics (21), storms and cyclones (18), salinity (16) and pH (14) (Supplementary Table 2).

A total of seven 'severe' risks to biodiversity were identified for the overall RSA region. Two focused on coral reefs, including the risk to coral species themselves through impacts on health, cover and distribution, as well as the wider changes in reef associated communities including fish and invertebrates, such as abundance or distribution. This risk was expected to be particularly important for the I-RSA and O-RSA, where the majority of coral reef habitats are currently found (Maghsoudlou et al., 2008) and there have been extensive investigations into the effects of climate change on reefs and corals (e.g. Coles and Riegl, 2013; Riegl et al., 2018; Burt et al., 2019). Changes to phytoplankton primary production was listed as a severe risk, with decreases in phytoplankton species diversity and community composition already observed within the region and wider Arabian Sea in recent decades, although there is seasonal variability in these trends (Piontkovski and Claereboudt, 2012; Al-Said et al., 2017). These changes have potential major repercussions for marine foodwebs and ecosystems due to the important role of primary production in underpinning these systems (Brown et al., 2010; Shurin et al., 2006).

Increases in Harmful Algal Blooms (HABs) and jellyfish outbreaks were listed as severe risks, with potential for significant cascading effects on both the wider ecosystem as well as for society. Such impacts are already being observed within the RSA (Richlen et al., 2010; Al Gheilani et al., 2011; Gholami, Mortazavi and Karbassi, 2019; The Express Tribune, 2020) and hence these risks were assigned a high proximity score. Alterations to abundance and distribution of benthic invertebrates such as shrimp, oysters, sea cucumbers and abalone, in addition to biofouling organisms, was also highlighted as a severe risk due to a range of climate drivers including ocean acidification, temperature increases and changing storminess. Little is known about climate impacts on benthic organisms in this region, but they scored highly because some species (such as abalone) are known to be adapted to the cooler conditions of the O-RSA that exist as a result of upwelling (de Waal et al. 2016). There have also been occasional catastrophic die offs of bivalves (e.g. razor clam) and other shellfish associated with harmful algal bloom events (Al Gheilani et al. 2011, Saeedi et al. 2011). Finally, changes in pelagic fish abundance and distribution were also identified as a severe risk, with changing hydrodynamics and declining levels of dissolved oxygen driving this risk, due to their sensitivity to hypoxic conditions (Stramma et al., 2012; Piontkovski and Al-Oufi, 2015).

Due to the unique characteristics and differences in species and habitat distributions across the three sub-regions within the RSA, some differences emerged regarding the ranking of biodiversity risks (Supplementary Table 3). Within the I-RSA, changes in dugong abundance and distribution were highlighted as a severe risk due to its international conservation importance (Preen, 2004; Wabnitz et al., 2018). Risk ratings for the M-RSA broadly reflected those for the overall RSA, although risks to coral reefs scored lower as they are less widespread in this sub-region (Maghsoudlou et al., 2008). Within the O-RSA, several risks were highlighted as being 'severe' yet they were not categorised as such within the overall RSA risk assessment. These centred on risks to turtle abundance, distribution and nesting sites from, among other drivers, coastal erosion and beach instability affecting populations along the coast of Oman. Changes to deep sea habitats, only present within the O-RSA, were also considered 'severe' primarily due to already expanding oxygen depletion zones in this area (Stramma et al., 2010; Bopp et al., 2013; Piontkovski and Al-Oufi, 2015).

3.2. Risks to Economy and society

Risks identified within the social and economic theme extended across many different sub-sectors of the regional marine and coastal economy (e.g., fisheries, transport, desalination, oil and gas etc.) i.e., 'the blue economy' (Table 3, Supplementary Table 2). Some risks focused on the vulnerability of industries and their infrastructure and operations to flood and storm damages, disrupting their services and operating efficiency. Other risks focused on regulating and provisioning services provided by the marine environment, including fisheries resources, freshwater availability (through desalination plants), climate regulation, waste breakdown, and coastal protection. Cultural and wellbeing services, including potential threats to human health, recreation and tourism were also considered to be at risk from climate change. Climate drivers assigned most frequently across these risks were changes in: storms and cyclones (21), temperature (18), sea-level rise (16), and freshwater input (16) (Table 3, Supplementary Table 2). Compared to biodiversity risks, there was limited sub-regional scoring of risks due to a lack of evidence at these finer scales to provide reliable scoring, as well as wide-scale occurrence or relevance of activities and industries (Supplementary Table 4).

Six 'severe' risks were identified over the whole of the RSA. The first encompassed risks to coastal communities themselves, including impacts to property, businesses and people's wellbeing. Flooding and erosion from sea-level rise will likely lead to displacement, damage or loss of belongings, housing, and amenities, compounded by effects from short-term extreme weather events. Given the large population and urban developments along the coastal region of the RSA, many millions of citizens are likely to be exposed to such risks in the near future (Alsahli and Al Hasem, 2016; Mafi-Gholami et al., 2020). A further two 'severe' risks focused specifically upon flooding and non-flooding impacts on major coastal industries and infrastructure, such as seaports, marinas, power plants, roads, railways, sewage treatment plants and nearshore oil and gas refineries and terminals. Flooding impacts are related to longer-term inundation from sea-level rise, resulting in damage to and loss of sites or facilities, with possible effects on operating efficiency and disruption at these sites. Non-flooding impacts included physical damage associated with severe storm and cyclones, and increasing temperatures affecting cooling efficiency and energy demands. Desalination plants were identified as comprising a separate 'severe' risk from other coastal infrastructure and industry due to their significance for water security in the region (Nair and Kumar, 2013; Tahir, Baloch and Ali, 2020). Climate driven changes will affect both water availability and quality, for example associated with cyclones damaging site infrastructure, HABs and alterations in salinity affecting water quality, and jellyfish blocking intake filters and operating efficiency (Anderson et al., 2017; Nair and Kumar, 2013).

The 'severe' risk covering operations, safety and movement of goods in the maritime transport sector focused on safety at sea, navigation and disruption of shipping, largely due to changes in storm and cyclone activity and sea conditions. The Strait of Hormuz has been highlighted as an area of particular concern due to it being a recognised maritime chokepoint within the region, with both regional and global implications (Guzansky, Lindenstrauss and Schachter, 2011). Changes in wild capture fisheries resources through changes in abundance and shifting distributions, including projected declines in fisheries catches, also pose a 'severe' risk with implications for wider food security as well as the livelihoods of both commercial and artisanal fishers (Wabnitz et al., 2018; Pinnegar et al., 2020). This risk covered impacts on both fish and shellfish, with key drivers being changes in hydrodynamics, changes in temperatures and depleting oxygen levels.

4. Discussion

This work provides the first marine climate change risk assessment for the RSA, highlighting a range of significant challenges that climate change presents for ecosystems and communities. This region has been largely overlooked in climate change assessments such as those of the IPCC, often being considered alongside the wider Asian continent and therefore being under-studied (Ben-Hasan and Christensen, 2019).

The risks identified threaten several important species and habitats, some of which are already at their physiological limits or stressed by other anthropogenic pressures such as coastal development or pollution (Sheppard et al., 2010; Naser, 2014; Vaughan et al., 2019). Indeed, many of the biodiversity risks are now already occurring or starting to emerge, such as coral bleaching, HABs and associated mass fish kills (Glibert et al., 2002; Al-Azri et al., 2012; Coles and Riegl, 2013; Burt et al., 2019; Vaughan et al., 2019). Documented evidence for some socio-economic risks is less apparent or at least not in the public domain (Al-Saidi, 2019; Mafi-Gholami et al., 2020; Lincoln et al., 2021), yet coastal communities and important economic sectors are expected to be especially adversely affected through changes to key resources, damages to infrastructure, impacts on operations and efficiency, as well as more widely through impacts on human health and wellbeing (Izaguirre et al., 2021; Mafi-Gholami et al., 2020; Narita et al., 2010; Wabnitz et al., 2018). Importantly, many of the identified risks are shared throughout the region, yet differences in levels of exposure to climate drivers and adaptive capacity will influence the exact vulnerability of different sub-regions to risks and when these risks will emerge (AGEDI, 2016; Alsahli and Al Hasem, 2016; Mafi-Gholami et al., 2020). For example, increasing temperatures, changing salinity patterns and declining pH are likely to be key drivers of change within the I-RSA, whereas cyclones, declining dissolved oxygen and altered hydrodynamics are particularly important for the O-RSA (Murakami, Sugi and Kitoh, 2013; AGEDI, 2015; Piontkovski and Al-Oufi, 2015).

Species, habitats, human communities and sectors will also differ in their adaptive capacity. For species and habitats, their adaptive capacity will be influenced by, for example, physiological tolerances, species life history traits, and habitat connectivity and diversity and which can differ by RSA sub-region (Whitney et al., 2017). Some industries may already have some resilience 'built in', such as desalination plants having alternative water supply options in times of stress (Tahir, Baloch and Ali, 2020), but much greater emphasis and research is needed on preparing coastal communities, sectors and industries for future impacts in the region (Al-Saidi, 2019). Given sufficient financial resources, industries and nations of the RSA might well be able to adapt, as wealthier communities are often considered to have higher adaptive capacity, however not all threats can be tackled by further financial investments and oil revenues are generally expected to decline throughout the region in the long-term (Kabbani and Ben Mimoune, 2021). Further vulnerability assessments of biodiversity and society at sub regional and national scales are therefore critical to understand who and what will be most severely impacted by the risks identified and the impact pathways or trajectories such risks may take. The nature of this risk assessment has meant that no opportunities were identified in this process, but some may potentially arise, such as waters becoming too hot for establishment of certain non-native species and pathogens (Clarke et al., 2020). Therefore, while this initial risk assessment provides an important first step, we anticipate that this assessment should be updated and revised in the future to reflect new evidence, new risks that emerge or changing rankings of risks, and lessons learnt from this initial process.

Despite using a framework that has been used in other risk assessments contexts (Garrett et al., 2015; MOCCAE, 2019), undertaking this assessment for the RSA presented a number of challenges. Importantly, as highlighted by others, several significant knowledge gaps exist which in some instances limited confidence scoring of risks and/or sub-regional scoring (Feary et al., 2013; Ben-Hasan and Christensen, 2019). These included a lack of detailed regional future climate projections, how different habitats and species would be affected, and the social and economic impacts of climate change in the region. A lack of regional or sub-regional evidence also challenged scoring the 'magnitude' of impacts, particularly regarding social and economic risks or risks that were more 'intangible' in nature, such as (loss of) future education or genetic use values. This led assessments of magnitude to be based on subjective assessment and group discussion, and as such future risk assessment processes would need to consider more deeply how to better assess 'magnitude' at these large scales. Engaging multiple stakeholders, for example industry representatives, resource managers and affected communities, to incorporate other perspectives and identify additional evidence sources could help to address some of these challenges. While a regionally focused risk assessment enabled identification of transboundary risks to aid decision-making at these scales, it also highlighted difficulties for when risks were not as relevant to all sub-regions. For instance, particular species such as dugongs and Socotra cormorant were not present in all sub-regions but have international significance (Muzaffar et al., 2017; Al-Abdulrazzak and Pauly, 2017). Balancing prioritisation of risks between regional versus global importance, or between sub-regional and regional risks, has no easy solution and depends often on value judgement and priorities. However, presenting results additionally at a sub-regional scale allowed these differences to be highlighted (Supplementary Table 3,4), and providing time within the workshop to enable discussion of this issue was particularly valuable. Through highlighting the challenges encountered in this process, we emphasise the need for future risk assessments in this region and more broadly to consider these particular issues and additionally to evaluate and discuss other challenges that might arise, to enable assessments to improve each time.

While challenging, undertaking a regional marine and coastal risk assessment provided a valuable opportunity to use a consistent methodology to identify and assess cross-cutting, transboundary risks across countries. Although not all risks are relevant to all sub-regions and countries, the interconnected nature of marine ecosystems means that regional assessments are vital for informing and developing coordinated responses and shared visions for how to manage climate change risks. This risk assessment complements other efforts within the region, such as the national climate risk assessment undertaken in the UAE which highlighted several marine focused risks (MOCCAE, 2019), although additional national risk assessments are also required from the seven other RSA countries. Importantly, a regional approach allows broader risks to be considered that aren't necessarily captured within national assessments or adaptation planning, and highlight where interlinkages between risks may arise. ROPME was established in 1979 as a result of Article XVI of the Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution. ROPME provides a unique coordinating role regionally for strengthening scientific monitoring of risks and facilitating knowledge exchange to aid the development of a shared adaptation strategy that seeks to address transboundary climate risks for the RSA. While this region has been noted for limited transboundary coordination and cooperation on these or wider marine issues in the past (Van Lavieren and Klaus, 2013; Al-Saidi, 2019; Ben-Hasan and Christensen, 2019), ROPME has already undertaken similar coordination work on issues of pollution in the marine environment (ROPME, 2013). For example, the Marine Emergency Mutual Aid Centre aims to facilitate cooperation and information exchange among RSA countries regarding oil and other harmful substances from polluting marine emergencies (MEMAC, 2014). Consequently, this risk assessment, combined with a planned adaptation strategy, are expected to form the basis of a wider marine climate change strategy across the RSA. With climate change continuing to rise up the political agenda and UNFCCC requiring nations to demonstrate climate actions, many countries in the RSA have referenced or outlined marine and/or coastal focused plans and ambitions within their NDCs, which are expected to be re-updated every five years as per the Paris Agreement (United Nations, 2015a). Therefore such risk assessments play a valuable part in helping countries to fulfil these international NDC obligations by highlighting priority areas for future adaptation planning.

The results from this assessment indicate that significant adaptation interventions throughout the region will be required to tackle climate risks, depending not only on coordinated, regional efforts to account for the transboundary nature of risks, but also upon sub-regional, national and local level responses and action. Addressing biodiversity risks will require adaptation actions that consider climate drivers alongside wider anthropogenic pressures that are driving biodiversity loss, such as coastal development, pollution and overexploitation (Sale et al., 2011; Naser, 2014; Vaughan et al., 2019). Reducing these wider pressures could help to increase the resilience of species and habitats to climate change, and approaches could include actively restoring coastal habitats such as mangrove forests and seagrass beds, increasing the effectiveness of the region's existing Marine Protected Area network, and improving fisheries management and/or compliance (Van Lavieren and Klaus, 2013; Naser, 2014; Abelson et al., 2016; Duarte et al., 2020; Gaines et al., 2018). Identifying approaches that can deliver multiple benefits will also be valuable to support reducing risks to both biodiversity and society, such as Nature Based Solutions (Chausson et al., 2020) or ecosystem-based interventions. For example, protecting and restoring coastal mangroves and coral reefs can improve coastal protection for low-lying communities vulnerable to sea-level rise and storm surge events while also conserving species and habitats (World Bank, 2016). Adaptation actions that are more holistic in their approach to account for multiple stressors, the complexities of direct and indirect impact pathways, the interlinkages between risks, and their often wide temporal and spatial scales will be particularly valuable (Burt et al., 2017).

Some sectors and industries may already have policies, systems or plans to build resilience and cope with short-term impacts or shocks that climate change may present (Tahir, Baloch and Ali, 2020). For example, desalination plants implement additional measures to ensure continued water supply when impacted by algal blooms or natural disasters (Tahir, Baloch and Ali, 2020), and efforts are underway in some countries to diversify coastal livelihoods away from vulnerable fisheries into aquaculture (Pinnegar et al., 2020). Yet, given the severity of threats the RSA faces, the importance of the marine environment for the region, and the differences which may exist among and across communities and sectors regarding their vulnerability and adaptive capacity to climate risks, further adaptation action is critical (Al-Saidi, 2019; Salimi and Al-Ghamdi, 2020; Vaughan et al., 2019). Development of adaptation actions, particularly at a regional and system-orientated scale also provides the opportunity to integrate wider goals outlined within the global frameworks of the UN Sustainable Development Goals and the Sendai Disaster Framework, which have natural synergies to climate adaptation goals that seek to reduce vulnerability and increase resilience (UNCCS, 2017).

5. Conclusions

The RSA is home to some of the world's hottest seas (e.g. I-RSA), experiencing extreme conditions that make it a unique ecosystem, but which is often overlooked among international assessments regarding climate impacts and adaptation (Hoegh-Guldberg et al., 2014; Ben-Hasan and Christensen, 2019). This new assessment exposes the range of risks climate change poses to the region's biodiversity, societies and economies. Such results are crucial for informing adaptation planning within the RSA to enhance resilience and reduce vulnerability, and highlight that adaptation will require action at all scales, from individual businesses and communities to national government and wider regional cooperation.

Importantly, lessons can be learned from this region. The conditions that species and habitats tolerate in the RSA, particularly the I-RSA, has meant they are adapted to environmental extremes that are not frequently experienced in other parts of the World (Coles and Riegl, 2013; Burt et al., 2014). Understanding how organisms have adapted to these conditions, such as coral reefs, could hold important insights for global conservation and climate adaptation efforts (Burt et al., 2014). The RSA is also a prime example of a heavily utilised, shared sea area that is increasingly impacted by climate change (Vaughan et al., 2019). Many seas globally are shared by nations, which will need to work together and develop regional coordinated responses to address climate change challenges.

As this work demonstrates, undertaking a regionally focused marine climate change risk assessment was critical for identifying transboundary issues and informing adaptation approaches at a relevant scale. We hope that this risk assessment can provide a 'blueprint' for similar simplified or rapid risk assessment exercises that could be undertaken in other under-studied sea regions throughout the world. Indeed, while the Regional Seas Programmes (UNEP, 2020) encourage coordinated actions and planning for shared seas, to our knowledge, few if any of these programmes have undertaken specific climate change risk assessments for their marine resources. Ultimately, regional, coordinated responses will be critical to address climate risks and reduce their threat to marine systems, and those reliant on them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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