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Review

A Regional Review of Marine and Coastal Impacts of Climate Change on the ROPME Sea Area

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Abstract: The Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area (RSA) in the northern Indian Ocean, which comprises the Gulf, the Gulf of Oman and the northern Arabian Sea, already experiences naturally extreme environmental conditions and incorporates one of the world's warmest seas. There is growing evidence that climate change is already affecting the environmental conditions of the RSA, in areas including sea temperature, salinity, dissolved oxygen, pH, and sea level, which are set to continue changing over time. The cumulative impacts of these changes on coastal and marine ecosystems and dependent societies are less well documented, but are likely to be significant, especially in the context of other human stressors. This review represents the first regional synthesis of observed and predicted climate change impacts on marine and coastal ecosystems across the ROPME Sea Area and their implications for dependent societies. Climate-driven ecological changes include loss of coral reefs due to bleaching and the decline of fish populations, while socio-economic impacts include physical impacts from sea-level rise and cyclones, risk to commercial wild capture fisheries, disruption to desalination systems and loss of tourism. The compilation of this review is aimed to support the development of targeted adaptation actions and to direct future research within the RSA.

Keywords: Anthropocene; climate risk; environmental benefits; environmental change; marine heatwave; oxygen minimum zone; socio-economic factors

1. Introduction

Climate change is driving pervasive changes to oceans and coasts, including warming sea temperatures, rising sea levels, increased ocean acidity, changing storm patterns, deoxygenation and changes to atmospheric patterns and ocean circulation. This is a global challenge for marine and coastal ecosystems, often compounded by other human pressures. The evidence for, and the understanding of climate change has increased in recent decades [1,2]. Whilst globally there is necessarily a strong focus on reducing emissions, the Paris Agreement emphasises the need to simultaneously implement adaptation and resilience-building measures by identifying those risks that require the most urgent adaptation action. The scale and cross-boundary dimensions of climate change mean that impacts cannot be solely considered at the national scale, and that communities and nations need to come together to achieve the transformation required to become climate-resilient, which transcends adaptation, as it implies a fundamental shift in norms and behaviors [2].

The Regional Organization for the Protection of the Marine Environment (ROPME) is the regional seas convention established in 1982 by Bahrain, Kuwait, Iran, Iraq, Oman, Qatar, Saudi Arabia and the UAE (UAE). The ROPME Sea Area (herein referred to as RSA) is the maritime area covered by the EEZs of the ROPME Member States in the Gulf, the Sea of Oman and parts of the north-western Arabian Sea (Figure 1). The RSA is among the warmest sea regions in the world [3,4]. The RSA encompasses three distinct geographical subregions in terms of their environmental characteristics, as well as their exposure to impacts of climate change: Inner, Middle and Outer RSA. The Inner RSA (herein referred to as I-RSA) corresponds to the sea area also known as the Gulf, a shallow sea with limited exchange from the Arabian Sea through the Strait of Hormuz. The Middle and Outer RSA (herein referred to as M-RSA and O-RSA) correspond to the Gulf of Oman and the northern part of the Arabian Sea, respectively, and include much deeper oceanic zones, which are also under the influence of monsoonal weather patterns and the upwelling of the northern Indian Ocean.

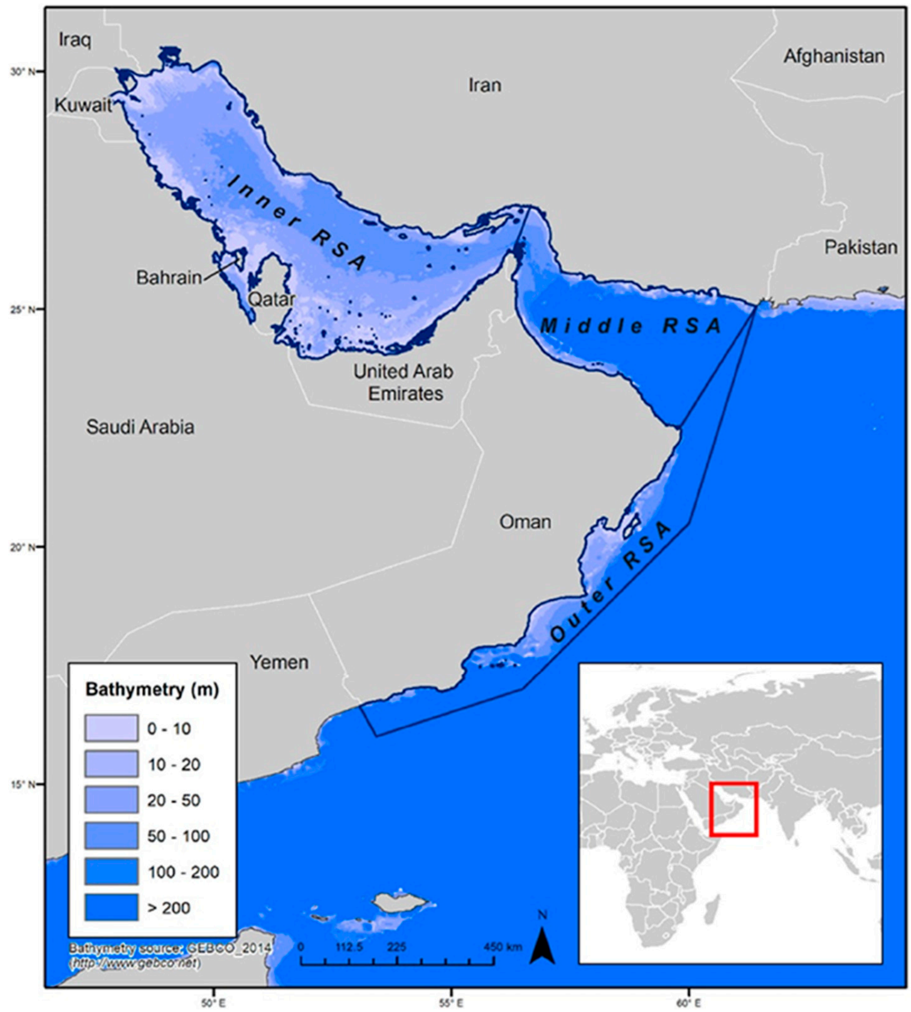

Figure 1. The ROPME Sea Area (RSA). The RSA extends for approximately 465,00 km^2, and is separated into the following three distinct subregions: The Inner RSA, also known as the Gulf, the Middle RSA, also known as the Gulf of Oman and the Outer RSA, along the northern part of the Arabian Sea [5].

Surrounded by arid and hyper-arid land regions, major urban areas are largely concentrated along the coasts, particularly in Bahrain, Kuwait, Qatar, Oman and the UAE [6,7]. The region is undergoing rapid demographic and economic development, which has led to significant pressures on the marine and coastal environment, including pollution, land use changes, habitat loss and overexploitation of natural resources [6,8–10]. These human pressures are acting along with climate change, increasing the risk of adverse impacts on ecosystems and societies [7].

Implementing targeted adaptation actions to enhance climate resilience requires an understanding of the nature and scale of climate impacts. However, there is currently a lack of integrated studies addressing the impact of climate change at the regional scale across the RSA, which will be needed to develop effective adaptation plans and actions. To support the design and implementation of targeted adaptation actions we present this regional review, aiming to compile and summarize the available information on current and projected future climate change impacts, their impacts on the marine environment and the implications for key sectors of societies and economies across the RSA.

This article is underpinned by a full review document that collates the available scientific evidence on currently observed and expected future impacts of climate change on the ROPME Sea Area [11]. It is further supported by a companion paper [12], which uses this evidence base to conduct a climate change risk assessment to identify priority ecological and societal impacts of marine climate change that could form the focus of adaptation actions.

2. Methods

Despite the mounting challenges facing its marine and coastal environment, the RSA is a data-limited region, and is frequently overlooked in global and regional climate change assessments. To develop a comprehensive evidence-base for this area, this review seeks to consolidate regional evidence on marine climate change trends and impacts on key components of the marine ecosystem of the RSA and associated societies and economies, drawing on information available from peer-reviewed scientific articles, technical reports, book chapters, monitoring datasets, Intergovernmental Panel on Climate Change (IPCC) outputs and public media. To prepare this review, the authors drew on quantitative and qualitative information at a variety of spatial scales, from detailed local research studies through to global trend analyses.

Firstly, this review describes the observed and predicted changes in physico-chemical conditions in the marine and coastal environments of the RSA. Full details of the underpinning review are available from the ROPME Marine Climate Change Impacts Evidence Report [11]. Next, observed and predicted climate-driven changes in key groups of marine life and marine and coastal habitats are reviewed, followed by an assessment of potential impacts on ecosystem benefits provisioned to human societies. Table 1 below provides a summary of the environmental changes and their impacts on ecosystem services. Finally, those changes are discussed in the context of other human activities and environmental pressures happening in the region, and we conclude by identifying key evidence gaps and how this information can be used to support development of targeted adaptation and resilience-building actions across the RSA.

Table 1. Range of climate-driven changes covered in this review and selected key impacts for the ROPME Sea Area (RSA).

Physical and Chemical Changes	Selected Key Impacts
Temperature, salinity, and humidity	Average sea temperature increases of one degree centigrade over past 30 years, with shallow areas warming faster than deeper areas; this trend will continue. The highest ever sea temperature was recorded in Kuwait. In the I-RSA, salinity increase observed and future increases in humidity projected.
Sea level and ocean circulation	Few sea level gauges available provide sea-level rise estimates of 2.2 mm/yr in northwest I-RSA, potentially higher than in wider Indian Ocean.
pH and dissolved oxygen	Few measurements available show a decrease in pH in the O-RSA of 0.1 (shallow) to 0.2 (deep) units in recent decades. Oxygen minima in M-RSA and O-RSA, and seasonal low oxygen zones in I-RSA, projected to worsen.
Cyclones and dust storms	More intense storms and cyclones expected to occur in the O-RSA and M-RSA, may even reach the I-RSA. Apparent increase in Shamal winds and dust storms in the I-RSA this century.
Monsoon winds and upwelling	Changes anticipated in monsoon strength and timing affecting the M-RSA and O-RSA, including influence on upwelling system, but complexity makes impacts hard to predict.
Current and future impacts on biodiversity	
Phytoplankton productivity	Large-scale changes in primary productivity would have important repercussions for the marine food chain, including fisheries, but high natural variability and a lack of high-resolution data mean that projections have low confidence.
Harmful Algal Blooms (HABs)	HABs appear to be increasing across the RSA, but links to climate change are not fully established.
Jellyfish	Outbreaks of jellyfish blooms and aggregations are becoming more frequent. This has been partly attributed to warming temperatures, as well as other factors such as loss of natural predators, thermal pollution from industrial sites and eutrophication.
Fish	Up to 10% of fish species occurring in the I-RSA may become regionally extinct by the end of the century, partly due to temperature and salinity changes. Pelagic fish species such as tuna and sardines in the M-RSA and O-RSA may decline due to the expansion of the OMZ.

Table 1. *Cont.*

Physical and Chemical Changes	Selected Key Impacts
Birds	The RSA coastline and especially its wetland areas are highly vulnerable to climate change impacts as well as human activities, and potential degradation and loss of habitat has serious implications for dependent bird populations.
Marine mammals and turtles	Indirect climate change effects on food availability for some species may be important. Temperature change may affect turtle hatchlings, and flooding and erosion could damage turtle nesting areas.
Corals and coral reefs	There has been a rapid decline in the RSA's coral reefs in the last two decades; this will continue and intensify as temperatures increase, and is linked to a wide range of climatic drivers as well as other human pressures.
Saltmarshes, mudflats, sabkhas	Coastal wetlands are highly vulnerable to sea-level rise, storm and cyclone damage and increasingly arid conditions, as well as over-exploitation, coastal development and changes to drainage.
Mangroves	Changing rainfall patterns, increased evaporation and storm damage are likely to negatively affect mangroves, including the availability of sediment to keep pace with sea-level rise.
Seagrass	Seagrasses in the RSA can withstand elevated temperatures but are adversely affected by prolonged exposure. Turbidity, excess sediment loads and scouring during and following extreme weather can also damage seagrasses. However, increased carbon dioxide availability may stimulate growth.
Rocky shores and macroalgal communities	Rocky shore habitats could be negatively impacted by climate change, especially where species are already close to their thermal tolerance. Wave action and scouring from storms and cyclones could have serious impacts on their benthic communities.
Current and future impacts on economy and society	
Provision of seafood and other living resources	Warming sea temperatures, oxygen depletion and changes in salinity are likely to have significant adverse effects on fisheries in the RSA.
Provision of energy, raw materials, space and transport	Coastal industries could be physically affected by long-term sea-level rise, cyclone risk, rising temperature and salinity affecting cooling systems and desalination and mass outbreaks of HABs and jellyfish. Offshore infrastructure and shipping could be more exposed to the physical impact of wind and waves. The health and wellbeing of coastal communities could be impacted by recurrent inundation, storms and intense heat and humidity.
Provision of leisure and culture	Some areas that are currently the focus of tourism developments may become less favourable in future due to loss of climate comfort. Sea-level rise and changes in storms will affect coastal and marine habitats and accelerate beach erosion.
Provision of good environmental quality and coastal protection	The natural coastal protection afforded by mangroves, salt marshes, seagrass beds and coral reefs could be limited or lost through increased flooding and erosion. Their roles in improving water quality as well as climate mitigation through carbon storage could be negatively affected.

3. Results

The main findings of this review on the evidence of current trends and future projections of physical and chemical conditions are summarized in the following sections.

3.1. Temperature, Salinity, and Humidity

The RSA is amongst the warmest sea regions of the world, and is characterised by extreme conditions that fluctuate widely between seasons and geographical locations. In the I-RSA, temperatures range between 13–37 °C [3,13]. Sea temperature has been rising across the RSA, with a record extreme sea surface temperature (SST) event reported in July 2020 in Kuwait Bay that reached 37.6 °C [3]. Trends in the I-RSA and M-RSA show an increase in average SST of approximately 1 °C over 34 years [14], with shallow water areas showing a faster warming trend compared to deep water areas [14,15]. A recent study by Lachkar et al. [16] demonstrated that, between 1982–2010, SST has risen by 0.5–1 °C in the O-RSA and by up to 1.5 °C in the I-RSA. Data series from the O-RSA indicate a relatively slower increase of 1.2 °C over the past 50 years in the upper 30 m during the summer monsoon [17].

Salinity reaches 70 practical salinity units or PSU, the highest in the RSA, in the shallow bays of the I-RSA [18], and in parts of the I-RSA salinity has increased by 5 to 10 PSU since the 1950s, due to elevated average air temperatures and increasing evaporation coupled with a reduced input of freshwater [4,7]. The combined effect of evaporation and decreasing rainfall on the salinity of the I-RSA has been exacerbated by further reductions in riverine inputs due to the construction of dams for irrigation and power generation in surrounding countries, resulting in a sharp decline in water flows from the following three main rivers that empty into the I-RSA: Tigris, Euphrates and Karun [19]. Brine outflows from desalination plants are contributing to further increases in salinity in the I-RSA [20], particularly along the southern shores where most of the desalination capacity is located. This increased salinity of the I-RSA has not so far been observed to transfer to surface waters in the M-RSA [21], and no significant changes in salinity have yet been detected in the O-RSA either [22].

Regional modelling studies based on IPCC Representative Concentration Pathway (RCP) 8.5 ("business as usual" greenhouse gas emissions scenario) [23] projections indicate that by the end of this century, SST could increase by as much as 2.8–4.3 °C in the I-RSA, while predicted SST increases appear less pronounced—although still significant—for the M-RSA and O-RSA, at approximately 2.5 °C relative to 2005 [4,14,24]. The high increase projected for the I-RSA is the result of a combination of rapid warming of the shallow water column and the constraint of the Strait of Hormuz, which restricts water exchange with the Indian Ocean [25–27]. The current warming trend is likely to result in more frequent marine heatwaves [4], locally amplified by up to 8 °C in parts of the southern I-RSA due to thermal pollution from power and desalination plants [20,28,29]. Regional projections of salinity suggest future increases in salinity under a RCP8.5 scenario in the I-RSA by 2099, while changes appear less pronounced in the M-RSA [24]. By contrast, in the O-RSA salinity is likely to decrease slightly under the influence of long-term changes in oceanographic conditions and monsoon dynamics [24].

Regional models project increases in humidity of 10% during summer across the I-RSA [30]. Under a RCP8.5 scenario, and by the end of the 21st Century, what is known as the 35 °C "wet-bulb threshold", which represents the point at which heat and humidity become intolerable and a serious risk to human health, would become a more frequent feature [31,32].

3.2. Sea Level and Ocean Circulation

Drawing on the limited availability of sea level height data from tide gauge measurements and satellite data from within the I-RSA, a relative sea-level rise of 2.1–2.2 mm per year has been estimated for the northern shores over the period 1970–2015, a figure slightly higher than the global mean sea-level rise, likely as a result of subsidence [33–36]. No information was found for the M-RSA or O-RSA, with the nearest sea-level rise estimates being from the northern Indian Ocean, where Unnikrishnan and Shankar [37] estimate an average of 1.3 mm of sea-level rise per year for this wider region based on 40 year-long records. Future projections of regional relative sea-level rise for the RSA are also constrained by this lack of tidal gauge time-series data and by the complexity of isostatic land movements. Sections of the coastline along the western shores of the M-RSA and O-RSA are rising due to isostatic rebound, and therefore for these areas the relative sea-level rise may be lower than the estimated global average [38,39]. Recent estimates of end-of-century future global mean sea-level rise under RCP8.5 give a likely range of 0.6–1.1 m, with a median value of 0.8 m [36].

It is expected that climate change will have a profound impact on the hydrodynamics of the I-RSA. By the end of the century, while salinity will continue to drive circulation, the vertical overturning in the water column will be attenuated due to increasing SST and rainfall along the coast of Iran, which is likely to intensify the flow of less saline waters into the I-RSA from the M-RSA through the Strait of Hormuz [24,40].

3.3. pH and Dissolved Oxygen

Whilst there are no long-term datasets to confidently assess trends of seawater pH across the RSA, data available from monitoring studies in the southern I-RSA show average annual pH values of 8.22, comparable to global average values [41,42]. The I-RSA is an area of active carbonate deposition, with the exception of the coastal waters of Iran [43]. Nearshore pH across the northern I-RSA ranges from 8.10–8.55 [44]. No seasonal trends of pH changes have been detected in the I-RSA [41,45].

In the O-RSA, repeated measurements from survey cruises indicate a decreasing trend in average pH for the period 1960–2000, equivalent to 0.10 pH units in the 0–50 m depth water layer and 0.20 pH units at 3000 m depth [46]. IPCC CMIP5 AR5 global model projections suggest that pH could decrease by approximately 0.25 units in the RSA this century, compared to a projected decrease of 0.42 units globally, however there is limited confidence in those estimates in the absence of downscaled regional projections [47].

Oxygen Minimum Zones (OMZs) are extensive and permanent features of the RSA [48,49]. The OMZ found across the M-RSA and O-RSA is the most intense in the world, with oxygen levels nearly depleted between 200–1000 m depth [17]. The latest observations indicate that at its most intense point, the concentration of oxygen in the M-RSA OMZ is less than 0.06 mg/L [50]. Dissolved oxygen also appears to be declining in I-RSA waters [4,48,49]. Near Qatar, for example, a permanent layer of hypoxia is caused by the interaction between thermal stratification and respiration [51]. Seasonal deoxygenation has also been detected in Kuwaiti waters, caused by elevated SST and intense stratification [8]. In the northern I-RSA, a seasonal hypoxic layer has been documented, which develops during summer and autumn and extends for more than 50,000 km^2 from the sea floor up to 50 m depth [52]. The oxygen levels in this hypoxic layer are lower than any previous open water measurements elsewhere in the I-RSA (26 µmol/kg, or 0.83 mg/L), and are also associated with low pH values, reflecting similar conditions to those predicted under end-of-century ocean acidification conditions [52].

In the O-RSA, an intensification of suboxic conditions has been linked to greater vertical stratification due to SST warming, which restricts ventilation of the intermediate ocean layer, while strengthening of the summer monsoon wind causes the thermocline depth to rise in the northern Arabian Sea, depleting oxygen in the upper 200 m. Elsewhere in the Arabian Sea, meanwhile, intense summer monsoon winds have the opposite effect of deepening the thermocline and increasing oxygenation [16]. OMZs are expected to expand and intensify during this century, partly in response to climate change [4], and the O-RSA and M-RSA are projected to experience intense deoxygenation, more so than other parts of the Indian Ocean [49,53–56]. At present, future projections of dissolved oxygen levels in the RSA are lacking in confidence due to the complexity of related changes to hydrodynamic circulation through the Strait of Hormuz and the exchange of water with the I-RSA [50].

3.4. Cyclones and Dust Storms

Since 2007, the following six tropical cyclones reaching category 3 or higher have made landfall in the RSA: Gonu (2007), Phet (2010), Ashobaa (2015), Mekunu (2018), Kyarr (2019) and Shaheen (2021). Super cyclonic storm Gonu, the strongest storm recorded to have reached the RSA, was generated by a persistent area of convection aided by warmer than average SSTs [57]. Cyclone Gonu caused an estimated $4 billion USD in damages and 100 deaths across Oman, the UAE, and Iran [13]. It also led to severe degradation of many coastal habitats, including areas of coral reef, due to wave impact [58,59]. Cyclone Phet, the second strongest cyclone after cyclone Gonu, was formed following a record heatwave over southern Asia that raised SSTs in the O-RSA by 2 °C above normal [60]. One modelling study suggests that more tropical cyclones could reach the O-RSA and M-RSA by the end of this century under RCP8.5 as storm tracks shift, even if the total number of tropical cyclones formed within the Indian Ocean does not change significantly [61].

Cyclones rarely reach the I-RSA due to its typical conditions of low humidity and high wind shear, but this subregion is still exposed to damage from wind and surges generated by Shamal events, which are strong north westerly winds that blow over the I-RSA and bordering land areas, mostly in summer but sometimes also in winter, particularly along the southern shores [62,63]. The number of Shamal events resulting in abrupt unseasonal changes to meteorological conditions appears to have increased since 2000, and given their importance in driving seasonal changes across the I-RSA there is a need for further regional projections of Shamal winds under future climate scenarios [64]. Desertification coupled with changes in strength, timing and direction of Shamals could intensify the amount of dust deposited on the sea surface, which could then lead to iron fertilization and more algal bloom occurrences in the I-RSA [65–68]. Across the Middle East, dust storms appear to be occurring more frequently, and are also larger and more intense, raising concerns in terms of air quality and public health [65,69,70].

3.5. Monsoon Winds and Upwelling

The oceanography of the O-RSA, and to some extent the M-RSA, is dictated by the seasonal monsoon-driven upwelling of cool, nutrient-rich waters [13,71]. Any changes to the trajectory, timing and strength of the monsoon winds that control the upwelling in the M-RSA and O-RSA caused by climate change are likely to affect water conditions in in terms of temperature, salinity, nutrients, oxygen and pH. Goes et al. [72] have suggested that climate change is strengthening the southwest monsoon winds that predominate in summer, which enhance upwelling conditions and favour the onset of intense phytoplankton blooms in western and central areas of the M-RSA and O-RSA. Strong summer monsoon winds also contribute to lowering oxygen levels in the upper ocean, as seen above [54]. In contrast, later studies predict either a slight decline or no significant trends in phytoplankton production [73,74]. It is difficult to detect a climate signal in observed changes in monsoon winds, due to high natural variability in timing and strength [30,75]. However, any monsoon-driven intensification and expansion of algal blooms could further aggravate the OMZ due to oxygen consumption as the algae degrade, sink and decompose [72].

Monsoon forcing also determines the strength of the Shamal winds, which are particularly important in controlling SST in the I-RSA. Stronger Shamals maintain mixing in the water column and keep sea temperatures below lethal thresholds for most marine fauna, but weak Shamals allow summer SSTs to rise, resulting in coral bleaching and mass mortality events of fish, turtles and other marine life [64,76].

3.6. Ecological Impacts on Coastal and Marine Ecosystems

3.6.1. Primary Productivity

There is great natural variability in the composition, distribution and productivity of phytoplankton across seasons and between the subregions of the RSA. Within the I-RSA, there is also a marked gradient in terms of phytoplankton communities from those influenced by the freshwater outflow from the Shatt Al-Arab estuary in the north to those nearer the Strait of Hormuz [13,77–81]. In the O-RSA, primary productivity is governed mainly by the strength and timing of the upwelling, and some projections of primary productivity show increases at a decadal scale, linked to an enhanced upwelling from stronger wind activity [13,82]. In the I-RSA, on the other hand, iron fertilization through dust deposition is likely a regulating factor for phytoplankton growth and composition [13,80]. Large-scale, long-term changes in phytoplankton community structure and in primary productivity in the RSA would have cascade effects throughout the entire marine food web, but natural variability and a lack of high-resolution data mean that future projections carry considerable uncertainty, and more research is needed to better understand current and future changes [30,74,78,79,81,83,84].

3.6.2. Harmful Algal Blooms (HABs)

HABs are a common feature in the RSA, and they are becoming larger in scale and more persistent [85]. At their peak, HAB events are reported to reach 100s of km^2 and persist for several months, causing extensive loss of coral and fish communities [59,86–89]. Within the I-RSA, particularly along the southern coast, HABs often appear associated with hypoxic conditions, higher than average SST events and fish kills [3,90]. In the M-RSA and O-RSA, HABs seem enhanced by the summer upwelling season, although winter algal blooms have also been reported [91] and often involve assemblages of toxic and non-toxic phytoplankton species [92] The link between HABs and climate change in the RSA is not fully clear [91]. Other factors such as transport via ballast water, fouling by vessels and man-made structures and eutrophication of coastal waters may also contribute to the onset and spread of HABs [93]. On the other hand, it is also recognized that there is an enhanced risk of the introduction of invasive species via ballast water under climate warming conditions [94].

3.6.3. Jellyfish

Reports of large-scale jellyfish blooms are on the increase globally and appear to be linked to warming conditions [95–97], as well as constituting an indirect effect of the declining population numbers of their natural predators, including turtles, seabirds and sharks [98,99]. In the RSA, jellyfish outbreaks are becoming regular events, often following warming SST, and in some coastal locations jellyfish appear to aggregate around thermal discharge plumes from power plants, as also seen in Asia [95]. Eutrophication could also be a contributing factor to the proliferation of jellyfish [97].

3.6.4. Fish

The changes in conditions anticipated for the RSA have the potential to cause substantial alterations in the structure of fish communities, particularly reef-associated fish [100–102]. Coral bleaching in the I-RSA has led to a decline in the total abundance and variety of species of reef fish, although the number of fish that feed on benthic invertebrates was observed to increase [103]. Declines in the total number of fish species in favour of herbivorous fish have also been observed following coral bleaching events [100,104–106]. Other observed declines in fish numbers in the I-RSA have been attributed to warming waters, increasing salinity, low oxygen and HABs [86,102,107,108]. However, other drivers of changes in fish species abundance and diversity have also been suggested, such as shifts in competition and predation interactions between species [109,110], which can distort any underlying climate change effects.

In addition to direct impacts on species richness and abundance, environmental conditions in the I-RSA are known to cause shifts in diet and behavior, impair growth rates leading to smaller size at maturity and inhibit the diversity and productivity of fishes [101,111–113], suggesting that future climate change may result in related changes to fish communities in the M-RSA and O-RSA where conditions are currently more benign.

Around 8% of known species of bony fish in the RSA are under threat of disappearing from the region, two times higher compared to the Mediterranean Sea, the northeast Atlantic and the Gulf of Mexico, where such assessments have also been undertaken [114]. Vulnerability assessments indicate that some fish species as well as invertebrates are likely to disappear altogether [114,115] particularly in southwestern coastal areas of the I-RSA, due to the combined effects of climate change, overfishing and habitat degradation. A large proportion of shark and ray species found in the RSA are also endangered due to similar cumulative pressures [114,116].

3.6.5. Birds

The low-lying coastal wetlands of the RSA provide rest and feeding habitats for internationally important populations of wintering waders, passage migrants and breeding seabirds [13,117,118]. Many small inhabited islands provide ground for nesting colonies of terns as well as Socotra cormorants, and there are resident populations of greater flamingoes in Iran [13,118]. Most seabirds in the RSA are cited as species of Least Concern in the IUCN Red List, but there are a few classed as Near Threatened, and the Socotra cormorant is classed as Vulnerable. Large knowledge gaps remain regarding the impact of climate change on the seabirds of the RSA, but recent studies highlight that climate change is driving seabird decline globally, mostly through changes in food resources [119,120]. The RSA coastline and especially its wetland areas are highly vulnerable to climate change impacts as well as human activities, and potential degradation and loss of habitat could have catastrophic implications for dependent bird populations [117].

3.6.6. Marine Mammals and Turtles

The marine turtle species of the RSA include loggerhead, hawksbill, green and olive ridley turtles, listed by the IUCN Red List as Near Threatened, Critically Endangered, Endangered and Vulnerable, respectively [121]. Changes in the temperature of the sand during turtle nesting season can affect the sex ratio as well as the fitness of turtle hatchlings [122,123], and sea-level rise and storms can damage both their nesting beaches and the seagrass meadows where they feed [124]. Model projections estimate a severe loss of habitat suitability [77,115], and in the I-RSA in particular hawksbill and green turtle numbers may decline through loss of habitat suitability in the southwest and towards the Strait of Hormuz [77,115,125], though these projections carry some uncertainty, and the status of their seagrass feeding grounds, which could be a determining factor, is not being taken into consideration [77].

In the case of dugongs, noting that the I-RSA has the second-largest world population outside Northern Australia, projections of future population dynamics for the RSA are as yet inconclusive, as they are based solely on changes to habitat conditions driven by salinity and temperature, and it is expected that other factors such as the extent and condition of seagrass meadows will strongly determine the future distribution of this species [77,115,126]. As for cetaceans, much is yet unknown in terms their diversity and distribution in the RSA, although recent studies have confirmed a high diversity of species [127]. The number of Indo-Pacific humpback dolphin and bottlenose dolphin in the I-RSA are expected to decline due to loss of suitable habitat [77], though it should be noted that this projections are based on habitat suitability as determined by temperature and salinity alone, but do not take other factors into account such as prey distribution. Marine mammals have higher tolerance and adaptive capacity to environmental changes then turtles, so whilst climate change remains a threat [77,115], in the RSA the concerning risks to these species are still from pressures from other human activities such as pollution, bycatch and habitat degradation. These pressures are causing direct mortality and population declines, as well as heightening vulnerability to future climate change for these species [115,128–133], and should therefore be targeted as a priority.

3.6.7. Corals and Coral Reefs

Coral communities vary widely across the RSA. The corals of the I-RSA are less diverse and typically dominated by stress-tolerant poritids and merulinids, compared to those in the M-RSA [7,10,58,100,134]. In the O-RSA, the extent of coral is much more limited by the cooling influence of the seasonal upwelling and by cyclone disturbance [135–137].

To some extent, the coral species of the I-RSA can tolerate extreme thermal conditions [134,138,139], and some coping mechanisms found in corals of the I-RSA and M-RSA include upregulating the expression of heat stress-related genes [140] and hosting heat-tolerant algae [141–145]. Despite these adaptations, SST anomalies in the I-RSA have caused mass mortality events, as well as transforming the hard structure of reefs, through bleaching and the stunting of the growth of some species [76,146–149]. Since the 1990s, recurrent SST anomalies have caused severe coral bleaching [7,76,134,150]. Entire reefs of staghorn coral have died off and turned to mobile rubble, which impedes new recruitment [7,64,76,137,151,152], and the supply of larval settlers and subsequent recruitment of juveniles following bleaching events has been demonstrated to be impaired and under-representative of more sensitive coral taxa [100,153].

Relative "refugia" exist in offshore shoals and fringing reefs where deeper, cooler surrounding waters buffer the extreme conditions [43,150,154,155], but elsewhere in the I-RSA corals reefs exhibit varying degrees of stress, physiological impairment, disease and mortality [7,58,134,152,156–159]. Shamal winds can also provide some temporary respite by maintaining water temperature below bleaching thresholds during summer [64], but during calm periods marine heat waves can develop, as has been occurring with increasing frequency [76]. Under future climate change, with severe bleaching events reoccurring more often, the conditions for I-RSA corals will deteriorate further [151,160,161]. Areas of coral around Qatar and Bahrain have been declared essentially extinct following combined chronic damage by bleaching and the effects of coastal development [136,162,163]. Coral diseases are another cause of significant coral loss in the last decade [88,106,134,156,157,159], and a link between climate warming and disease is now confirmed, with studies reporting disease outbreaks directly following thermal anomalies and bleaching events [134,157,159,164]. Ocean acidification remains an additional threat to the future of reefs, though there is a need to better understand the physiological responses of corals to acidification [44,165,166].

A combination of stressors from climate change and other human activities has caused the loss of an estimated 70% of live reef cover in the I-RSA [7,9,13,58,132,134,152,162,167–170]. Some studies suggest the possibility of using "assisted migration" to transplant corals from the I-RSA into surrounding areas [151], or to cross-breed corals from the I-RSA with those from the Indian Ocean to enhance thermal tolerance of coral offspring [171]. So far, research indicates that the future of I-RSA corals is highly uncertain due to the increasing cumulative stressors [61,104,105,134,162]. By 2050, virtually all corals in the I-RSA will be at a critical level of risk [134,167], which threatens the sustainability of many vital ecosystem benefits that RSA societies receive from reefs, from fisheries to coastal protection to tourism [134].

3.6.8. Salt Marshes, Mudflats, Sabkhas

Coastal wetlands, intertidal mudflats and sabkhas or salt pans are common in the low-lying coastlines of the I-RSA, and they are globally important habitats and sanctuaries of biodiversity, used by millions of resident and migrant birds as well as other wildlife every year [7,117,150,172–175]. Salt marshes, together with mangrove forests and seagrass beds, are blue carbon sinks, and play a valuable role in absorbing and storing CO_2 [174,176,177]. They also provide important ecological goods and services, including coastal erosion control and space for agriculture and farming [117,174].

These coastal wetlands are exposed to sea-level rise, storm and cyclone damage and arid conditions, as well as coastal development activities resulting in deforestation, changes in sedimentation rates and drainage of freshwater inputs [13,117,176,178–181]. The long-term future of the coastal wetlands of the RSA, the biodiversity they support and the sustainability of their ecological services are at risk as climate change impacts intensify [117], though these impacts are not yet well understood at a regional or local scale.

3.6.9. Mangroves

Coastal mangrove forests are found in all RSA Member States, with the sole exception of Iraq, and they are dominated by grey mangroves (*Avicennia marina*), with small stands of red mangroves (*Rhizophora mucronata*) also occurring in the coast of Iran [10,174,181,182].

It is difficult to assess the risk of current and future climate change to the RSA mangroves due to a scarcity of data [181,183]. Sea-level rise, storm damage, warming temperatures and changes in precipitation are all likely to impact mangroves in the future [179–181,183–185] due to effects on forest health and productivity, photosynthesis, respiration, recruitment, biomass allocation, inundation periods, sediment input, accretion rates and ground-water levels [178]. It is estimated that approximately 96% of all the RSA coastal wetlands, including mangroves, will be at risk by the end of this century from a combination of sea-level rise and subsidence, compounded with the negative effects of pollution and coastal squeeze [33,181,186–188]. Mangroves also play a vital role in mitigating climate change by absorbing and storing substantial amounts of CO_2 on an annual basis [176]. The destruction or disturbance of mangrove habitats results in the release of carbon back into the atmosphere, and the loss of this climate mitigation service in the future [176].

Mangrove breeding and re-plantation projects have contributed to increasing mangrove coverage in some areas [183,189–191]. Mangrove trees in the I-RSA are often stunted compared to those in the M-RSA and O-RSA, likely as a response to the colder winter temperatures and more extreme environment generally [174,192–194]. The extent of mangroves, the only evergreen forests in the RSA, has increased in some areas of the UAE and Saudi Arabia particularly thanks to conservation and re-plantation projects, although mangrove cover across the wider RSA remains fragmented and scattered [7,150,181,183,189]. Research on the RSA mangroves has grown exponentially in recent years [191], with studies focusing on the adaptive potential of regional mangroves for informing potential climate change responses globally [195,196].

3.6.10. Seagrasses

Seagrass meadows are common, particularly in shallow sandy and muddy subtidal sediments in the northeastern, southern and southwestern I-RSA [7,150,197], and there may exist meadows below 15 m depth that have not been fully mapped [197–199]. Seagrasses in the I-RSA are dominated by *Halodule uninervis*, *Halophila stipulacea* and *Halophila ovalis*, opportunistic species that tolerate extreme salinity and temperature conditions [150,197,200]. Seagrasses are a critical habitat for a number of threatened macrofauna, including sea turtles and dugongs, and serve as nursery grounds for many commercial finfish and shellfish species. They are therefore vital for the sustainability of artisanal fisheries, including pearl oyster fisheries [7,126,150,197]. Seagrass meadows contribute to the maintenance of good water quality by filtering particles and stabilizing coastal sediments and protect against erosion from wave action [201]. Like mangroves, seagrasses are another important carbon sink habitat, and given their large extent across the RSA they represent the largest stock of blue carbon in the region, more so than mangroves and salt marshes [176,201–204].

Storms and strong wave action can damage seagrasses causing sand scouring and leaf loss, and turbidity and poor water quality conditions following storm events can have lasting negative effects on seagrass growth [205–207]. Excess sediment loading can smother entire seagrass meadows, or overtake the growth of new shoots, resulting in burial [150,197,208,209]. However, seagrasses may be able to keep up with rising mean sea levels by colonizing new areas of sediment, and by accreting new sediment and maintaining their optimal depth [205,206]. Seagrasses are carbon-limited and consequently seagrass productivity is expected to be stimulated under conditions of higher CO_2. Some studies go as far as suggesting the potential for seagrasses to buffer local pH levels in coastal zones, thus creating relative "refugia" from ocean acidification for coral reefs and other calcifying marine organisms [210]. Overall, however, the extent of seagrass meadows continues to decline in the RSA due to climate change but also to pollution, eutrophication and coastal developments.

3.6.11. Rocky Shore and Macroalgal Communities

The RSA also hosts a variety of other marine habitats, although these are less well-known. These include rocky shores along the M-RSA and O-RSA inhabited by macrobenthic communities that in some locations (e.g., in Iran and Saudi Arabia) may already be experiencing conditions close to their thermal limits, and are therefore very vulnerable to further extremes [211]. Storms and cyclones can also have adverse effects on these rocky shores, as strong waves and sand can scour large stretches of coast following the passage of cyclones. These stretches of rocky shoreline are less well studied than other parts of the region, but some long-term studies show evidence of a decline in the condition of their benthic communities [58,212]. Also unique are the underwater forests of macroalgae found along the coast of Oman, which are dominated by species associated with cooler upwelling conditions [213,214]. In the future, warming SST and the potential changes to the intensity and frequency of upwelling could put these unique habitats at risk – along with the associated commercial fisheries – of endemic abalone (*Haliotis mariae*) [135,215].

3.7. Impacts on Society and Economy

The ROPME member states rely on their coastal and marine environments for many vital goods and services, including food, water, transport and recreation. In the next sections, we review climate change risks to ecosystem benefits generated by the RSA. These benefits, including goods, services and intangible welfare gains, are summarized in Table 1, and are presented in the following sections grouped according to ecosystem service type, including the following: provision of living resources, materials and energy; space and transport; leisure and culture; recreation and wellbeing; and, finally, provision of good environmental quality and coastal protection [216,217].

3.7.1. Provision of Seafood and Other Living Resources

Marine Wild Capture Fisheries

Fishing still represents a significant proportion of national economies across the RSA, and is key for the region's food security. For some of the ROPME member states, marine fish resources are second to oil and gas production in their economic importance [218,219]. As well as finfish, shellfish including shrimps and to a lesser extent crabs and molluscs also constitute an important part of the catches of fisheries in the RSA. Despite their importance, studies report serious problems with the conservation of fish stocks and fisheries, particularly in the I-RSA [218]. The size, distribution and species composition of fish catches and the landing value of commercial species are changing due to climate but also to overfishing. Better landing records and more data on population dynamics and environmental tolerances of species are needed in order to understand the impact of climate change on the commercial fisheries within the RSA [219], and to manage stocks sustainably.

Climate change is likely to push many commercial fish species to the limit of their physiological tolerance in the I-RSA, given the extreme environmental conditions already being experienced [115,220–222]. Climate change can also impact fisheries through changing oceanographic conditions, increasing occurrence of HABs and the effects of increased storm and cyclone activity disrupting fishing operations and damaging coastal infrastructure [13,223–227]. Declines in commercial catches and changing species composition are projected for most RSA countries [114,115], although detailed regional climate projections at the species level are not yet available.

Climate change is likely to impact all aspects of recreational fisheries, including not only the distribution and abundance of target species, but also the participation and motivation of fishers as they will need to gradually transform the way they fish, the places where they fish from, and the equipment they use [228], which may result in the activity becoming no longer enjoyable or competitive. Recreational fishing in the RSA typically targets mackerel and cobia. Pearl diving festivals are also popular and are an important tradition in parts of the RSA. All these activities will be exposed to similar climate change impacts as those affecting commercial fisheries. Whilst modern fisheries may be able to adapt and target novel species in future decades, some of the more traditional fisheries may be permanently lost. Other impacts can manifest over much shorter periods of time, for example, loss of fishing spots due to erosion or storms, and these will be more difficult to overcome [228].

Aquaculture

Aquaculture is a rapidly growing sector in the RSA, with major investments progressing in almost all ROPME states. Aquaculture is at risk from a range of impacts resulting from climate change, depending on the type of operation [226]. Temperature and salinity changes, declining oxygen levels and ocean acidification can impact the physiological performance of culture species. Climate change-driven impacts resulting from HABs and jellyfish and marine pathogen outbreaks are also substantial threats capable of causing significant economic losses [95,229]. Aquaculture facilities are also vulnerable to physical damage from sea-level rise, coastal erosion, and storms, with facilities in the O-RSA and M-RSA at a higher risk from cyclones. Conversely, large-scale intensive aquaculture facilities have the potential to cause major water quality issues through uncontrolled excess nutrient discharges [230].

Bait Fishing

Bait fishing involves harvesting seafood for use in bottom fishing, jigging, trolling and rod fishing. Traditional bait species such as cephalopods (squid, cuttlefish) are well suited to warming conditions, and are in fact replacing other traditional fisheries in other seas [231,232]. The factors behind their increasing abundance are not yet well understood, however [231,232], nor is how this could be applied to the case of the RSA.

Pearl Oyster Farming

Most wild pearl oyster beds have been badly degraded due to overexploitation and poor water quality, although there are currently some plans to recuperate oyster pearl farming in the I-RSA [233]. The risk of climate change to pearl oysters is not yet overly clear, but it has been suggested that warming seas could stimulate calcification in pearl oysters, therefore counteracting the impact of ocean acidification [183,234]. Where climate change impacts may lead to poor water quality, however, those are likely to be detrimental for oysters.

3.7.2. Provision of Energy and Raw Materials

Fossil Oil and Gas

The fast-growing economies of some of the RSA member states are largely based on their oil and gas resources and associated extraction and export, which accounts for a third of global production [185]. Rising temperatures, changes in precipitation, sea-level rise and extreme weather create risks to offshore oil and gas activities and assets [235]. However, the overall effect is likely to be modest in proportion, as most of the production is land based. Sea-level rise and extreme weather can undermine the integrity and operation of offshore superstructures and cause scour and displacement of submerged pipes. Extreme events can cause significant disruption to oil and gas extraction, maintenance and transport activities [121,236], and heavy rainfall and coastal flooding can overwhelm drainage systems of facilities onshore. These impacts will increase the cost of maintaining infrastructure and the risk of environmental spills. Safety policies may need to adapt to the increased likelihood of extreme weather conditions.

Power Generation Plants

Coastal power plants in the RSA are major contributors to energy supply in the region. These coastal facilities are exposed to direct physical impact from cyclones, to long-term flooding from sea-level rise and to inundation from storm surges [237], although more research is needed to quantify the risk to local facilities. In the case of gas-fired plants, their efficiency and power output is also dependent on air and sea temperature, with reported loss of power output of 0.1–0.8% for every 1 degree increase, depending on the technology [28,113,238], meaning that efficiency of power stations may decline as temperatures raise. Warming conditions will also increase the risk of equipment failure if design thresholds are exceeded [235]. In the case of liquefied natural gas production and gas-fired thermal power installations, sustained extreme high-temperature conditions can interfere with cooling and cause significant loss of output and efficiency over time [86,235,239,239].

Exposed overhead transmission lines, transformers, switchgear and cables are also vulnerable to extreme heat. Higher temperatures de-rate the carrying capacity of overhead lines and transformers and curtail their lifetime depending on equipment and peak load.

By comparison, it is projected that rising summer air temperatures in the United States will reduce transmission capacity by up to 6% by 2050, relative to the years 1990–2010 [240]. Mitigation measures are possible, and include the burying of cables and the use of insulation coatings [241].

Nuclear energy is a growing sector in the region [239,242–244]. As with fossil fuel-based power plants, rising temperatures are likely to have an impact on the efficiency of cooling systems of nuclear plants. A 1 °C increase in temperature could potentially reduce nuclear outputs by 25 billion kilowatt-hours of power [245]. A 1.5 °C increase in seawater temperature, which could be seen in the I-RSA by the 2040s, would lead to a 0.5% loss of nuclear power. Combined with the thermal footprint of cooling water outflows this could also result in greater local increases in SST and therefore higher power shortfalls, eventually leading to loss of revenue [244]. In turn, the impact of thermal pollution around power plants will exacerbate the impact of climate change in the local marine environment. Like other critical coastal infrastructure, nuclear plants are also exposed to coastal erosion, sea-level rise and coastal flooding, as well as intake blockages from jellyfish mass outbreaks [95,246]. Climate-proof engineering is being incorporated into nuclear plant developments [247], and more favourable thermo-aquatic conditions could be considered for future nuclear energy plans by selecting alternate sites to ensure higher plant efficiency [244].

Water and Desalination Plants

Desalination is essential for water security in the RSA [29,244,248–251]. Seawater desalination plants are located on the shoreline and are exposed to similar impacts as coastal power stations. In addition, depending on the technology, desalination plants are exposed to changes in coastal water conditions, with some of the larger installations in the I-RSA drawing water at a rate of more than 120 million m^3 per day [20]. The efficiency and stability of their systems can be limited by increasing water temperature and salinity, as well as mass jellyfish and algal blooms [246]. The desalination sector across the RSA already experiences disruption and damages from mass jellyfish ingress and HABs, which are likely to become more frequent and severe in the future [95,246,252]. Toxic HABs near desalination plants have forced cessation of operations for days due to serious human health concerns [248,252]. The desalination industry has some built-in resilience to be able to cope with current environmental risks to water supply and quality, but future climate change will further challenge the region's water security [253].

Sea-level rise may also result in saltwater intrusions and contamination of groundwater reserves in coastal areas, increasing the demand on desalination plants and leading to greater exposure to climate risks for the desalination sector.

Renewable Energy

RSA member states have committed to deploying substantial resources into renewable technology to meet their energy demands over the next decade, using a combination of photovoltaic solar, solar thermal, wind and geothermal energy, as well as waste-to-energy systems [254]. The RSA has great potential regarding solar photovoltaic energy [255], but offshore marine renewable energy is also being explored [256]. The potential output increase from renewable energy sources will depend on specific designs that can cope with the extreme conditions of the RSA [257]. Solar energy technology can be affected by dust, humidity and high temperatures, which are set to worsen under future climate change [255]. Extreme high temperatures can degrade photovoltaic efficiency by up to 25% [258], and although future projections of atmospheric dust in the RSA are not available, levels of dust particles are expected to increase with warming air temperatures and desertification. With regards to wind and wave energy developments at sea, they are undergoing a rapid expansion in many regions of the world, including the RSA, though further research to downscale climate models is needed to better understand the potential impacts of climate change on these [256].

Marine Aggregates and Sand Mining

In the RSA, sand and gravel for construction are mined mainly from coastal areas and from the seabed, and demand is expected to continue to rise with the expansion of urban developments [259]. There are concerns about the environmental impact of these activities [260], but the aggregates industry does not appear at risk from climate change particularly. Coastal erosion and sea-level rise are likely to contribute to a rise in the demand for materials for construction and repairs, while erosion processes are expected to replenish sand and gravel resources on the seabed.

Wetland Resources

Wetlands are some of the most biodiverse environments in the RSA. They provide a wide range of resources such as grazing for livestock, traditional remedies, soil, silt and clay for construction and salt for industrial use. However, rising temperatures and salinity, sea-level rise, erosion, coastal flooding and changing rain patterns, as well as pollution, drainage and urban encroachment threaten these habitats across the RSA [181]. Although salt marshes and other intertidal and coastal habitats are typically resilient to the effects of storms and floods, for example, and are in fact important coastal buffering systems against extreme weather, their fragmentation and decline from combined stressors is undermining their adaptive capacity and accelerating their degradation and loss, together with the important goods and services they provide.

3.7.3. Provision of Space and Transport

Maritime Transport

International maritime transport across the RSA is critical to the region, and the Strait of Hormuz is a strategic waterway of global importance, with an estimated 40% of the world's oil supplies passing through it daily [261]. All vessels as well as the infrastructure supporting navigation including around ports and terminals are exposed to climate change impacts, particularly to damage by storms and cyclones [262]. Extreme weather events could disrupt navigation and intensify the risk of collision and pollution events. Adverse climatic conditions can also interfere with supply chains and port and traffic control facilities, with knock-on effects on shipping activities [263,264]. Seaports and sea links are important transport hubs in the RSA. New seaports currently under planning and development will be factoring in changes in mean water levels and storm surge as part of their engineering design, but accurate projections in terms of future extreme sea levels and the likelihood and ranges of other climatic factors are not yet available [263]. The scale of damage and disruption from future climate change impacts on critical maritime transport infrastructure could be significant, but it is difficult to predict and quantify without downscaled, regional models.

Wind-wave energy is expected to increase during this century, particularly in the O-RSA and M-RSA, though further research is needed to understand potential changes in wave intensity and direction [265]. Changes in mean sea level increase the destructive power of storm surges, and waves are likely to inflict significant damages to infrastructure and cargo, increase construction and maintenance costs, cut off coastal road and railway links and lead to the relocation of people and businesses [263].

Adverse wind and wave conditions make harbor conditions particularly difficult for large freight vessels [263,266]. The level of exposure of seaports will be determined by local characteristics, including the presence of natural buffering systems such as wetlands, reefs [267,268] and land reclamation schemes. Coastal protection structures may become obsolete, resulting in overtopping, flooding, damage to cargo areas and disruption to road transport within port areas as well as off-site [263,269–272]. This represents a significant threat to the economy of some areas where large ports are linked to important industrial sites [273]. Smaller harbors and sport marinas are also exposed to climate change, and although this would be on a lesser scale compared to the larger international port terminals, damage and disruption from extreme weather can badly affect those communities whose livelihoods depend directly on them. In addition, climate change combined with other human stressors such as pollution and eutrophication is set to exacerbate the risk to environments around marinas [274].

Prolonged higher-than-average as well as extreme temperatures may result in higher costs and loss of competitiveness for ports as it will undermine the integrity and safety of infrastructure, equipment and cargo; reduce assets lifetime; elevate cooling costs and raise health risk concerns [263,264,275].

Coastal Cities and Infrastructure

The RSA coastline supports major urban centers and a wide range of industries vulnerable to the physical risks of inundation, coastal erosion, storms and cyclones. Cyclone risk is greatest in the O-RSA and M-RSA, where the number of intense cyclones making landfall is projected to increase [61]. Cyclones can cause major damage due to high winds, flooding from heavy rainfall and coastal inundation. Increases in cyclones may cause direct loss of life and significant economic costs with national impact.

Over the 21st Century, many of the RSA's low-lying coastal areas, particularly in Bahrain, Kuwait, Qatar and the UAE, could retreat landward, exposing large cities and strategic infrastructure in these areas to long-term inundation from the sea [6,259,276–279]. Without adaptation actions the percentage of GDP lost to direct climate change impacts by the end of this century could be considerable for RSA member states [280]. According to a study of 136 port cities by Nicholls et al. [281], by 2070, the exposure of population and assets in large cities is likely to expose over 150 million people to extreme events unless adaptive measures are adopted, with Dubai ranked in 23rd place in terms of asset vulnerability to current climate change scenarios of extreme wind and water levels, and in 24th place in terms of asset vulnerability to future climate change scenarios. Kuwait City is the other RSA port city included in this study, ranking 84th and 82nd in terms of asset vulnerability to extreme wind and water levels under current and future climate change scenarios, respectively [281].

In Iraq, the estuary of Shatt Al-Arab and surrounding cities are highly vulnerable to sea-level rise [282]. The only two Iraqi seaports, Umm Qasr and Al-Faw, are lifeline hubs for the country's trade including oil as well as goods. The ports and access channels are exposed to sea-level rise and shifting sediments during extreme storms which often obstruct navigation channels requiring dredging [282].

The risks of inundation of coastal lagoons and stagnation of water in reclaimed land areas could also increase. Combined with high humidity levels this may give rise to public health issues, including mosquito infestations and the spread of harmful molds and fungi. Further research is needed, and flood risk maps would be useful to mitigate and prepare for these impacts, considering current and future land use of the RSA coastline [279].

Sea bridges and causeways are often utilised in shallow areas of the RSA, as road links between nearshore islands – natural or man-made – and the mainland. These structures are exposed to the impact of wind and waves during extreme weather events and need to be closed to traffic as they become unsafe during those conditions. Tropical cyclones and surges caused by the seasonal Shamal winds in the I-RSA cause extensive structural damage to seaports and surrounding areas every year, generating significant costs, which will likely rise in future as the risk of extreme weather intensifies [263]. More extreme events will also put pressure on emergency response services to deal with the impact of coastal flooding and wave damage on the structural integrity of buildings and equipment [263,283].

Waste and Sanitation

In the RSA, outfall pipes from sewage treatment facilities often discharge a mixture of treated and untreated wastewater onto coastal areas [8]. In some shallow bays of the I-RSA, where evaporation rates far exceed freshwater inputs, this can restrict the diffusion and dilution of effluents, resulting in a heightened risk of coastal pollution incidents, which is set to increase further under future climate conditions [8,71]. Sanitation services and solid waste and wastewater treatment facilities are vulnerable to changes in temperature, rainfall, sea level and extreme weather [8,284]. In Abu Dhabi, for example, most solid waste is disposed of in coastal landfill sites that are highly exposed to flooding and erosion, increasing the risk of environmental pollution from contaminated gas and leachate [285–287]. Under warmer temperatures, some microorganisms, including pathogens, may become more prevalent, leading to increasingly costly treatments [284] as well as public health emergencies.

3.7.4. Provision of Leisure and Culture

Tourism, Recreation, and Wellbeing

Tourism is expanding rapidly in the RSA [170,288]. The enjoyment of tourists is influenced by their experience of temperature and humidity levels, as well as rain and wind conditions and the duration of sunlight [289]. Prevalent local weather and environmental conditions are one of the main criteria used by tourists to choose their destination, and they also determine the duration of the peak tourist season [290]. The value of beach amenities in Abu Dhabi is estimated to be 8–14 million USD per hectare [291]. The UAE could see a 55% reduction in tourism by the end of this century, mainly due to persistent high temperatures and the flooding risks presented to many coastal heritage and tourist resources due to rising sea levels [292]. Over the next few decades a general decline is expected in what is termed "tourist comfort climate index" across the RSA [259,290,293].

Rising sea levels and coastal erosion will put coastal resorts at risk of losing visual appeal and spoiling the experience of visitors, while worsening impacts from HABs and jellyfish outbreaks present a direct risk to human health. It has been estimated that the degradation of reefs and the loss of marine biodiversity may result in a loss of revenue of up to 10% per year for tour operators and marine recreation companies [259]. Further research is needed to understand and adapt to the potential impacts of climate change on the tourist sector, given its strategic importance for the economic diversification of the RSA.

Environmental wellbeing services are equally important for both residents and visitors in the RSA and depend on safe and pleasing visual aspects. Extreme weather, nuisance HABs and jellyfish outbreaks all contribute to spoiling the experience of the sea and create public health hazards, dissuading visitors [170,288,294]. Further research is required to further understand and predict the impacts of climate change at a local scale on the coastline of the RSA [250]. Coastal protection measures such as hard defenses and re-alignment may further degrade the aspect of these destinations. Options to diversify into a more climate-smart, alternative eco-tourism industry are being explored [250,259].

Wildlife Watching

Marine wildlife watching activities in the RSA are becoming increasingly popular. Some of the best-known of these include, for example, snorkeling and scuba diving on the coral reefs of Iran's Kish Island, and, in the UEA, dolphin watching around Hengam Island, visiting the hawksbill turtle rookeries in Abu Dhabi's Saadiyat Island, watching flamingoes in the wetlands of Umm Al Quwain and snorkeling and scuba diving in the reefs surrounding Fujairah. Climate change is likely to cause widespread decline in these habitats, so that whilst the impacts on charismatic species such as turtles, dugongs and dolphins are difficult to predict, loss of habitat suitability is likely to cause population distribution shifts [77] that could result in population declines locally. Adding to the worsening climatic conditions, many visitors are likely to be dissuaded from popular nature spots in the future.

History and Heritage

Ancient forts and seaports and valuable archaeological sites, as well as historic freshwater wells and springs, are found along the RSA coastline and are highly valued as part of the regions' identity [295]. Some of these sites, such as Tarout Island in Saudi Arabia and the Qal'at al-Bahrain fort in Bahrain, are of universally recognized outstanding value [223,296]. Depending on the location, the integrity of some of these sites will be under threat due to the increasing risk of erosion, flooding and sea-level rise. Buried historic evidence could be compromised through changes in soil consistency and chemistry, for example, from long-term changes in rainfall patterns [297], which would also affect the quantity and quality of water in ancient wells. Historic and heritage sites are typically engrained in their surrounding environment, meaning that changes to the landscape and prevailing conditions can have negative and potentially irreversible consequences [298].

3.7.5. Provision of Good Environmental Quality and Coastal Protection

Water Quality

Coastal mangrove forests contribute to good water quality conditions by filtering and retaining suspended sediments and other solids as well as nutrients and pollutants from land runoff [176]. Like mangroves, seagrass meadows also trap particles and accrete sediments, keeping the water clear [299]. A combination of impacts from human activities and climate change is causing a rapid decline of these habitats. As these impacts intensify in future decades, important ecosystem services such as the regulation of coastal water quality could be lost.

Flood and Erosion Protection

Coastal mangroves, salt marshes and other wetland areas, together with seagrass meadows and reefs, provide effective protection against coastal flooding and erosion [300,301]. Global estimates suggest that if coastal mangroves were lost, the risk of inundation from the sea would rise by a third during 1-in-10-year events, and by 16% during 1-in-100-year events [302]. An example of the importance of preserving natural protection systems was highlighted in a modelling study of coastal vulnerability, showing that 4–32% of the UAE coast is exposed to sea-level rise in terms of population and coastal assets [303].

Carbon Storage by Coastal and Marine Habitats

Mangrove forests, coastal salt marshes and seagrass meadows represent the three main blue carbon habitats globally [177]. In the I-RSA, microbial mats and coastal sabkhas are also considered to be active sinks of CO_2, particularly along the western coastline [66,204]. Recent studies have attempted to measure the total carbon stock for these habitats in the UAE, which ranges from 2.2–109.3 Mg C per hectare for seagrass, to 18.6–242.4 for microbial mats, to 77.4–514.5 for mature mangrove, to 51.3–182.3 for planted mangrove, to 31.4–205.0 for salt marsh and to 51.0–120.5 for coastal sabkha. The combination of hot and dry conditions restricts the extent of some of these habitats and the amount of carbon they are able to store within their sediments compared to other regions [204]. Studies on the mangrove *Avicennia marina* have shown small increments of photosynthesis in response to higher CO_2 concentrations [304]. Whilst these results might suggest a positive effect under future high emission scenarios, the large-scale decline of these blue carbon habitats is putting this important carbon mitigation service at risk, and potentially releasing additional carbon to the atmosphere.

4. Discussion

The RSA already experiences naturally extreme environmental conditions and incorporates one of the world's warmest seas. This review highlights the growing evidence supporting the claim that climate change is already affecting the RSA and that these changes will accelerate in the future with significant consequences for the region's natural ecosystems and biodiversity, as well as for its societies and economies. Adaptation and resilience-building plans and actions are urgently required across the region to protect both the marine environment and associated livelihoods from the adverse impacts of marine climate change. However, long-term data on key environmental parameters, habitats and species, and high-resolution climate models for the RSA, are currently lacking, which makes it difficult to identify trends and limits confidence in future projections for the region. Equally lacking are studies on climate change impacts on the many crucial environmental benefits derived from the RSA, and the key marine sectors of societies and economies that depend on them. This review seeks to contribute to the development of a greater understanding of the impacts of climate change, to guide further research and support the development of prioritized and targeted climate-smart plans and actions across the RSA.

The RSA hosts a rich marine and coastal biodiversity, including many species of global conservation importance. All components of the marine ecosystem are likely to experience direct or indirect impacts of climate change. Furthermore, climate impacts can be exacerbated by other human pressures such as over-exploitation, pollution and habitat degradation, which in many instances are the current main threats and therefore require urgent attention and action. Whilst species and habitats in the RSA have adapted to the extreme ranges of environmental conditions that are typical from the region, the rapidity of changes expected over future decades may exceed the tolerance limits of marine life and its adaptive capacity. The RSA remains a poorly studied region overall and more targeted, coordinated research is needed to better understand physiological responses to the changing marine environment and the climate vulnerability of habitats and species in the RSA [218]. Notwithstanding this need for further detail and refinement, available evidence points to the urgent need for action.

There are marked differences in environmental conditions, habitats and species across the I-RSA, M-RSA and O-RSA, as well as varying exposure to climate drivers across the RSA. It is therefore important to evaluate the impact of climate change at the sub-regional scale, as priority adaptation needs will vary across the RSA. Future changes in phytoplankton productivity provide an example of geographic variability in responses to different climate drivers operating across sub-regions of the RSA. For example, progressive hyper-salination is driving a decline in finfish populations in the northern I-RSA [84], while in the O-RSA conditions are boosting phytoplankton growth and primary production [80,227,305–307], which could results in increases in fish populations.

In addition to spatial variability, there is also a high degree of uncertainty and inconsistency between regional climate projections due to high seasonal variability and lack of high-resolution, long-term data [30,74]. For example, primary production of plankton appears to be increasing in decadal scales along the west of the O-RSA, linked to strengthening summer monsoon winds and upwelling [72,82]. On the other hand, model simulations by NOAA [308] suggest that over the period 1976–2099 primary production in the O-RSA will decline because of de-coupling between hydrodynamic circulation and the supply of nutrients and oxygen in the water column. Improving confidence in these predictions will enable more focused adaptation actions to be implemented.

The RSA is a heavily exploited marine region that is witnessing a very rapid expansion of coastal development that also carries a multitude of additional human pressures [168,309]. These pressures can undermine the resilience of natural systems to climate impacts and can also exacerbate climate impacts. For example, the development of desalination capacity generates thermal pollution into the coastal environment that compounds with the heating effect from climate change. Simulation studies suggest that salinity changes from brine discharges can be significant but vary spatially and seasonally [310]. By 2050, the effect of climate change in conjunction with thermal pollution may cause the temperature of 75% of the coastal areas less than 20 m deep to increase by more than 2 °C [20]. This indicates the need to consider climate change in conjunction with trends in other anthropogenic drivers affecting the RSA.

The impact of climate change added to other human pressures also makes it difficult to understand the driving factors behind the changes observed in the marine environment, as well as to manage and adapt to these changes. For example, reports of HAB outbreaks are on the increase and appear to be linked to climate change [85]. It has also been suggested that jellyfish aggregations are driven by changes in temperature, salinity, dissolved oxygen and currents [95,96], though jellyfish life cycles are complex, and populations also appear to respond to other direct human pressures such as overfishing, eutrophication, coastal developments and thermal pollution from outlet discharges around desalination and coastal power plants [97,311,312]. Understanding the drivers of HABs and jellyfish blooms is important, so that potential local factors such as eutrophication or overfishing can be better managed and even mitigated. However, where driving factors are linked to climate change, other adaptation actions should be explored and implemented. Finally, there may be a need to apply a precautionary principle, and so whilst it is important to understand these dimensions, they should be tackled through careful, adaptive actions. Management efforts are needed to reduce the cumulative effects of the various stressors affecting these vulnerable habitats and species if there is to be any hope of maintaining the function of these important and undervalued marine ecosystems of the RSA [7].

5. Conclusions

This review provides a synthesis of available information on climate change impacts in the RSA, which to the best of our knowledge has not been attempted before at the regional level. The compilation of this review is intended to support the development of targeted adaptation actions and to direct future research within the RSA.

Strategic, targeted and coordinated research is needed to provide greater confidence in predictions of climate change and its ecological and socio-economic impacts. Addressing these evidence gaps would benefit from the co-operation of all the ROPME member states. Specific evidence gaps include the following: (i) lack of downscaled regional projections of temperature, salinity and storminess; (ii) understanding of ecological responses and thresholds for key species, communities and habitats to changing environmental conditions; (iii) understanding of cumulative impacts of climate change and human pressures; and (iv) understanding of the impact of climate change on the environmental goods and services of the RSA.

To take the next step towards designing targeted adaptation actions, this evidence review was used as the basis for a regional marine climate change risk assessment [12], which uses the evidence base presented in this review to identify the priority ecological and societal impacts which could form the focus of targeted adaptation actions.

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