Regional Organization for the Protection of the Marine Environment (ROPME)

ROPME Marine Climate Change Impacts Evidence Report

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This Report is a review of the latest scientific understanding on current and anticipated impacts of climate change on marine and coastal ecosystems, coastal communities and industry in the ROPME Sea Area, which 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

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Executive Summary

- Climate change is increasingly affecting the ROPME Sea Area (RSA), which already experiences environmental extremes and is one of the world's warmest seas.
- Increases in temperature and salinity, reduced oxygen and ocean acidification are being observed in the RSA, along with rising sea-level. The risk of cyclones in the Middle and Outer RSA could also increase. Changes in these conditions are expected to accelerate in the future.
- Climate change and other human impacts are causing extensive degradation and loss of habitats including coral reefs, mangroves, saltmarsh and seagrass leading to declines in the species and services they support (food, water quality, carbon storage, recreation and coastal protection).
- Phytoplankton, the microscopic algae that are the basis of the marine food web, could decline with negative impacts on important fish stocks.
- Coastal settlements and infrastructure are highly vulnerable to sea-level rise, flooding, erosion, storms and cyclones, and the risk of physical damage is increasing. Future changes in storm and wave conditions could affect offshore activities, including fishing, oil and gas extraction and shipping.
- Potential increases in jellyfish and harmful algae, could disrupt desalination plants and other coastal industries and affect human health.

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1. Introduction

Climate change is threatening nature and societies across the globe. The impacts of climate change are generating acute stresses upon ocean and coastal systems that are already exposed to environmental pressures caused by anthropogenic activities, thus magnifying those impacts and resulting in widespread habitat degradation, loss of biodiversity and damage to dependent societies and economies.

Climate change is increasingly impacting the Regional Organisation for the Protection of the Marine Environment (ROPME) Sea Area (RSA), which already experiences environmental extremes and contains one of the world's warmest seas. This document reviews the evidence relating to climate change impacts within the RSA. It initially focuses upon current and future changes in the physical environment, before considering implications for marine biodiversity. Social and economic impacts are then discussed by examining climate effects on existing environmental benefits that are provided by the RSA marine environment (e.g. food and energy provision), cultural benefits (e.g. recreation and tourism), and regulating benefits such as clean air and water, protection from floods and erosion.

Parts of the RSA (notably the Inner RSA) are already witnessing high temperatures and salinity, as well as large areas of oxygen depletion (hypoxia) in the Middle and Outer RSA. Relatively little is known about current pH trends within the Region. Climate change will further alter the physical environment of the RSA, with projections suggesting warming sea temperatures, increased salinity and acidification, further declines in oxygen levels, rising sea level and the potential for storm events to become more frequent and severe.

As a result of these changes, impacts on coastal and marine habitats and species in the RSA are already being observed, with further change expected. Coral reefs, for example, have suffered major declines due to elevated sea temperatures, and further bleaching events and losses are anticipated in the future. Sea temperature increases may result in a proliferation of jellyfish outbreaks, and warming has also been linked to the occurrence of harmful algal blooms (HABs). Declines in some marine mammal and fish populations are projected, most notably in the I-RSA as a result of a reduction in habitat suitability.

Sea level rise (SLR) presents a significant threat to coastal and marine habitats. Combined with coastal squeeze from urban developments, it will limit the ability of coastal habitats such as mangroves and saltmarshes to migrate further inland.

Marine climate change impacts will have major social and economic consequences. Catches of commercially important fish and shellfish species may decline due to loss of suitable habitat. Other aspects of food production, including shoreline harvesting, and fish and shellfish farms, may be affected by climate change. Increases in HABs and marine pathogens such as *Vibrio spp.* pose risks to human health, as well as marine life. The energy sector, including renewables and oil and gas, could be affected through impacts on infrastructure and operations, most notably due to increased coastal flood risk and more frequent and/or severe extreme events. Storms and high winds could lead to increased disruption of maritime traffic and other marine-based sectors. Coastal power stations and desalination plants may become less efficient due to the warming temperature of seawater used for cooling, and also due to the clogging of intake screens by congregations of jellyfish. Recreation and tourism, such as wildlife watching, sport fishing and leisure activities could be affected by declines in biodiversity, increases in HABs and jellyfish outbreaks, as well as more extreme weather events. The regulating services that habitats such as mangroves and seagrasses provide, including flood and erosion control, may be affected by SLR and changing weather patterns.

While there is sufficient evidence to provide a general overview of how climate change has, and will continue to affect the RSA, there are areas that require further research. The RSA remains relatively understudied compared with many other regions of the world, particularly around future responses of marine habitats and species to climate change, and how they interact with other human pressures. For example, current evidence indicates many marine organisms in the RSA are already very close to their upper thermal limits, making them highly vulnerable. High-resolution Regional projections are needed to understand the exact nature and scale of climate change impacts on coastal and marine environments across the RSA.

Given projections for human population growth in the RSA, with increased demands for food, freshwater, and space for coastal and marine developments, understanding how climate change interacts with these stressors will be critical to ensure a sustainable future for citizens. Finally, the vulnerability of key sectors and coastal communities to climate change impacts needs examining to identify where participatory adaptation interventions are most needed.

1.1 The ROPME Sea Area (RSA)

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 (UAE) (ROPME, 2018).

The RSA can be divided geographically and environmentally into three distinct parts (Figure 1), which vary in terms of their physical characteristics, and the diminishing influence of the Indian monsoon moving from the Outer to the Inner Sea Area.

The Outer ROPME Sea Area (O-RSA) is the northernmost part of the Indian Ocean and has a typically monsoonal climate. The summer monsoon (June to September) results in strong winds from the southwest and produces strong upwelling along the southeast coast of the Arabian Peninsula (Yemen and Oman).

The Middle ROPME Sea Area (M-RSA) is a deep 'arm' of the Indian Ocean that extends northwards and westwards for ~400 km to connect with the Inner ROPME Sea Area through the shallow (maximum depth 100m) and narrow (narrowest width 24km) Strait of Hormuz. It is affected by the O-RSA monsoons to varying degrees, but the effect diminishes with increasing distance from the Indian Ocean.

The Inner ROPME Sea Area (I-RSA) is a shallow, semi-enclosed sea with an average depth of only 35m; the maximum depth occurs near the Strait of Hormuz (100m). The bottom profile across the I-RSA is asymmetrical, with shallower slopes on the Arabian side and steeper slopes on the Iranian side. Thus, the channel with maximum depth lies along the Iranian side.

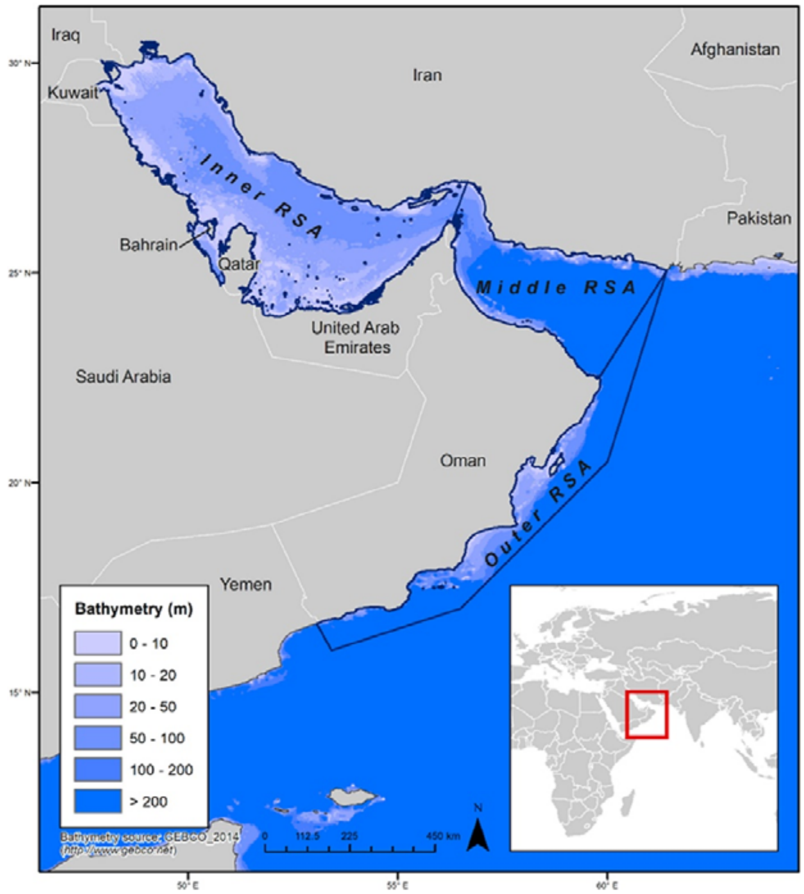

Figure 1: Geographical divisions and coverage of the ROPME Sea Area (RSA). The RSA is bounded in the south by the rhumb lines 16° 39'N, 53° 3'30'E; 16° 00'N, 53°25'E; 17°00'N, 56° 30'E; 20° 30'N; 60° 00'E; 25° 04'N; 61° 25'E, comprising three geographically and environmentally distinct parts: the Inner RSA (I-RSA), the Middle RSA (M-RSA) and the Outer RSA (O-RSA).

1.2 Purpose and scope of this report

The 2013 ROPME 'State of the Marine Environment Report' (SOMER) highlighted a need to undertake more detailed examination of climate change risks, to raise public awareness of these risks and review the capacity of the Region to respond (ROPME, 2013). The SOMER recommended that RSA Member States should agree on action plans and work with the International Community to mitigate climate change and adapt to impacts.

The work programme to develop a "Regional Marine Climate Change Adaptation and Mitigation Strategy" for the RSA was launched in 2019. This Strategy supports ROPME Member States' commitments to International agreements on climate change and biodiversity, including UNFCCC[1] (1992), UN Convention on Biological Diversity[2] (1992), and UN Sustainable Development Goals[3] (2015).

[1] https://unfccc.int/
[2] https://www.cbd.int/
[3] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

The UNFCCC requires that all signatory countries report regularly on how they are addressing climate change by publishing 'Nationally Determined Contributions' (NDCs) documents. All ROPME Member States have submitted either their Intended Nationally Determined Contributions (INDCs)[4,5] or their first NDCs to the UNFCCC[6]. These INDCs and NDCs provide an update on the ROPME Sea Area (RSA) Member States' efforts to: i) adapt to the consequences of climate change; ii) avoid further increases in greenhouse gas emissions; iii) advance towards low carbon emissions systems; and iv) achieve developmental, environmental, social and economic priorities under the framework of the United Nations Sustainable Development Goals.

The purpose of this Marine Climate Change Impacts Evidence Report is to review the latest scientific understanding on current and anticipated impacts of climate change on marine and coastal ecosystems, coastal communities and industry.

This document builds on important work already underway at national level across the Region. For example, a climate risk assessment has recently been completed in the UAE that identified adaptation measures on four priority sectors: health, energy, infrastructure, and environment (UAE National Climate Change Adaptation Programme, 2019), based on available research, stakeholder consultation, and expert inputs.

This report underpins a Marine Climate Change Risk Assessment exercise to identify the most urgent climate change issues for the Region.

1.3 Data sources and method

This report has drawn on information about climate change and climate change impacts from varied sources including, but not limited to, peer review scientific journals, scientific and technical reports, book chapters, monitoring datasets, IPCC outputs, and public media communications. Five decades worth of data and information have been compiled, organised and interpreted by applying a combination of quantitative and qualitative analyses.

The types of evidence can be categorised according to increasing geographical scale, from systematic site monitoring, local research studies, Regional studies and global trends (Table 1). Systematic monitoring and local studies provide the most accurate representation of local baseline conditions and trends, but in many cases, this level of detailed information was not readily available, or accessible. Where such data were lacking, Regional or global baseline conditions and trends were used to assess the likely implications of climate change for the Region.

The draft report was reviewed by a panel of Regional and International experts and underwent significant revision prior to being finalised.

[4] https://www4.unfccc.int/Submissions/INDC/Submission%20Pages/submissions.aspx
[5] This information was correct at the time of drafting this report
[6] https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx

Table 1: Categories of data used in this report.

Data Type	Description	Example
Site-based monitoring studies	Time-series of local data collected for monitoring status and trends of ecosystem components	Four-year time-series of pH monitoring in the Inner RSA
Local climate impact studies	Research studies conducted by ROPME States that provide information and understanding on the impact of climate change on ecosystem components	Local modelling studies on observed and projected trends in temperature, salinity and sea-level in the Inner RSA
Regional studies	Monitoring or research studies that come from outside the RSA but from the wider region, providing more locally specific information than global studies	Studies of tropical cyclones across the northern Indian Ocean.
Global studies	Studies conducted Internationally that identify trends that can be used to broadly evaluate and interpret ecosystem components	IPCC assessments based on global climate models

2. Climate change induced changes and trends in physical and chemical seawater conditions

2.1 Sea temperature

The I-RSA is one of the world's warmest seas (Hoegh-Guldberg *et al.,* 2014), but with a wide range of seasonal temperature extremes. The shallowness of the I-RSA accentuates seasonal differences in sea surface temperature (SST), with temperatures ≤13°C occurring offshore of Kuwait and Iraq in the north during February and nearing 35°C at the height of summer. The temperature difference between summer and winter is greatest (>20°C) in the north-western part and lowest (<11°C) at the Strait of Hormuz (United Nations Environment Programme - UNEP), 1994; ROPME, 2013; Vaughan *et al*., 2019).

In the M-RSA, minimum winter SSTs of around 22°C occur in February, and a maximum of 32°C in August, with water along the Arabian coast being generally warmer than along the Iranian coast (UNEP, 1994; ROPME, 2013). Moving from the M-RSA to the O-RSA, the temperature regime becomes increasingly influenced by the Indian monsoon. During the winter monsoon period, SST reduces from 26°C in November to 22–23°C in February. By contrast, with the onset of the summer monsoon, the temperature rises to ~28°C in May until upwelling dominates and temperatures in the upwelled areas drop below 22°C near the coast in August. The lower temperatures near the coast persist until the upwelling weakens in November (ROPME, 2013).

The finding of the IPCC 5th Assessment Report (AR5) was that between 1950 and 2009, annual average SST in the I-RSA increased by 0.59°C; a trend that is not statistically significant, although this may be due to the variable nature of conditions across the Region and the type of analysis used to assess the trend (Piontkovski and Claerebout, 2012; Hoegh-Guldberg *et al.,* 2014). More Regionally specific studies are now available. Noori *et al* (2019) modelled past and future trends in SST in the I-RSA and M-RSA and found an increase in the mean, minimum, and maximum trends of daily SST anomalies between 1982 and 2015, corresponding to approximately 1˚C over 34 years (Figure 2). An analysis of SST in the I-RSA by Shirvani *et al*. (2015) indicates that SST abruptly increased during the period 1990-2010. The study found that for both of the 1950–1969 and 1970–1989 periods, the warming trend was steeper in southern parts of the I-RSA compared with northern areas, while northern areas experienced a sharper increasing temperature trend during 1990–2011 as compared with southern parts (Shirvani *et al*., 2015). Several studies show that in some locations, a clearer warming signal is apparent, with shallower areas warming faster than deeper waters (Al-Rashidi *et al.,* 2009, Noori *et al*, 2019). Since 1985, seawater temperature in Kuwait Bay for example, has increased by 0.6°C per decade (Al-Rashidi *et al.,* 2009), approximately three times faster than the global average rate reported by the IPCC. This increase is thought to have been caused by a combination of climate change and local and Regional human impacts, with temperature increases greatest in the early summer, and less substantial during winter months.

Temperature data compiled following occasional expeditions on the Omani Shelf suggest an increase in temperature of 1.2°C over the past 50 years in the upper 30m layer of seawater of the O-RSA during the south-west (summer) monsoon (Piontkovski and Al-Oufi, 2015). However, long-term measurements of SST from across the Region are sorely needed in order to discern statistically significant increases that might be attributed to climate change.

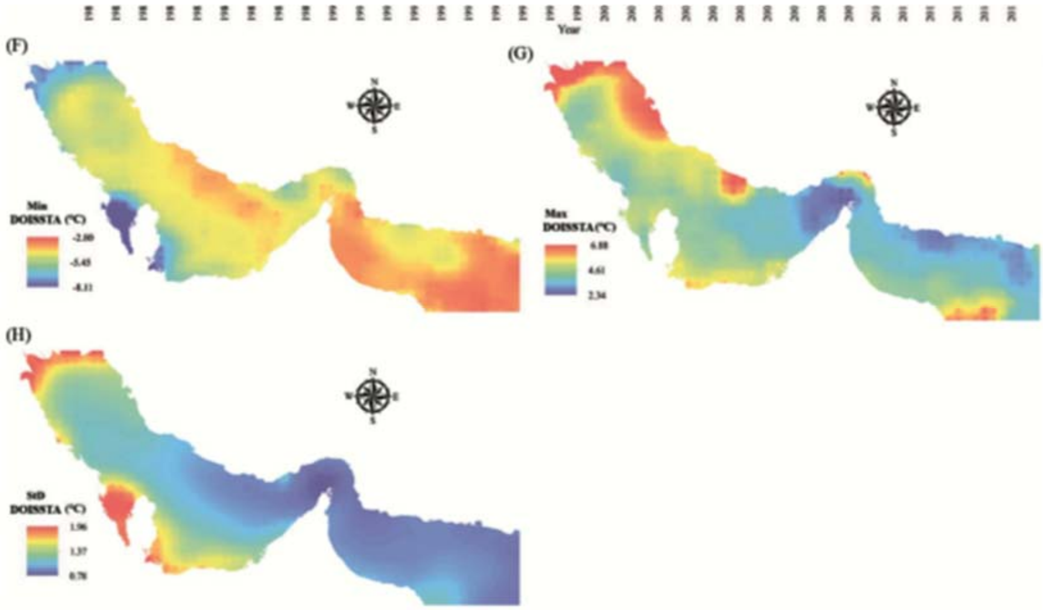

Figure 2: Historical trends in (A) mean values, (B) minimum values, (C) maximum values, and (D) standard deviation (StD) values of DOISSTA across the I-RSA and M-RSA; (E) mean annual values of daily optimum interpolation sea surface temperature (DOISST) across the I-RSA and M-RSA; and (F) spatial distribution in minimum values, (G) maximum values, and (H) standard deviation values of DOISSTA across I-RSA and M-RSA. https://doi.org/10.1371/journal.pone.0212790.g004

In one of the world's hottest recorded years, 2010, the central and southeast I-RSA was suggested to be the world's hottest sea (Riegl *et al.,* 2011). A significant positive temperature anomaly of +1 to +3°C existed over most of the North-West Indian Ocean, Red Sea and RSA, persisting into December 2010 (Riegl *et al.,* 2011). The year 2017 was also extremely hot, when an extended period of mid-summer calm winds reduced evaporative heat loss and led to dramatic warming (Burt *et al.* 2019; Paparella *et al.* 2019). The increased incidence of elevated temperatures due to climate change, and their impacts on habitats and species, is an area of increasing scientific attention and concern (Frölicher *et al.,* 2018; Oliver *et al.,* 2018; Vaughan *et al*., 2019). Marine heatwaves, defined as anomalously warm events lasting for five or more days, with temperatures warmer than the 90^{th} percentile based on a 30-year historical baseline period, are occurring increasing frequently on a global basis (Hobday *et al*., 2016). These marine heatwaves threaten the ecosystem, natural resources, and biodiversity of the I-RSA and can have devastating and long-term consequences for ecosystems, including shifts in species' ranges, local extinctions and economic impacts on seafood industries through declines in important fishery species or impacts on aquaculture (Shirvani *et al*., 2015; Frölicher *et al*., 2018; Oliver *et al.,* 2018).

The IPCC model projection for the Region (Hoegh-Guldberg *et al.,* 2014) revealed that under RCP8.5, by 2099, SST could increase by 2.8–4.26°C in the I-RSA and by approximately 2.5°C in the M-RSA and O-RSA, relative to data of 2005 (Figure 3). The higher SSTs in the I-RSA are principally due to the shallow depth that allows a rapid transfer of heat across the water column as well as the limited flush rate through the Strait of Hormuz (Reynolds, 1993; UNEP, 1994; Sadrinasab and Jochen, 2004). An increase in the incidence of marine heatwaves is projected as a consequence of this elevated warming trend (Hoegh-Guldberg *et al.,* 2014) and will have signifcant consequences for ecosystems in the Region (Fordyce *et al*., 2019). These climate change driven trends are being amplified by industrial activity, most notably along the southern coastline of I-RSA, where the effluents from desalination plants and other industrial processes cause a localised increase of the seawater temperature (and salinity, see Section 2.3) in the surrounding area by up to 7 to 8°C above ambient temperatures (Dawoud and Al Mulla, 2012).

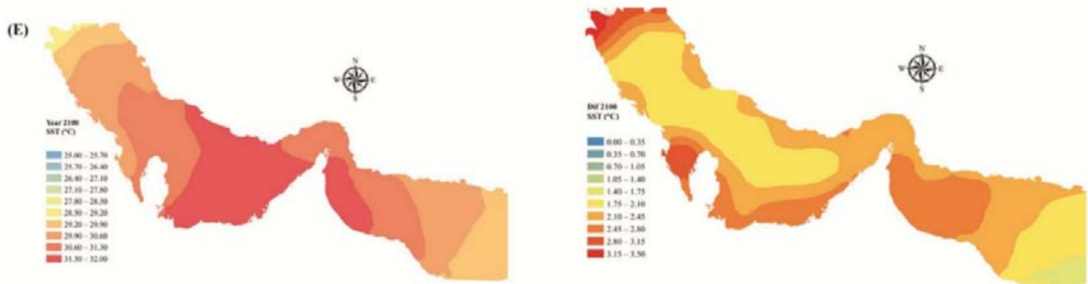

Figure 3: Spatial distribution of mean annual sea surface temperature (SST) across the I-RSA and M-RSA for the year 2100 and difference between 2100 and 2015.

A Regional study modelling trends in SST in the I- and M-RSA found that the summer season in both areas will experience the most warming (AGEDI, 2016a). Warming is projected to be greatest in the I-RSA with monthly SST increasing by up to 4.3˚C in August by the turn of the 21st Century (Figure 4). The calculation of the mean annual warming, showed that the north coast of the UAE and south coastlines of the Strait of Hormuz will experience the highest SST in the future, reaching 32˚C by 2100 and mean annual (maximum) SST across the I-RSA and M-RSA may increase from 28.5˚C (29.9) in 2015 to 30.7˚C (31.8) in 2100 (Noori *et al*., 2019). These Regional projections agree with the IPCC's global projections (Hoegh-Guldberg *et al.,* 2014).

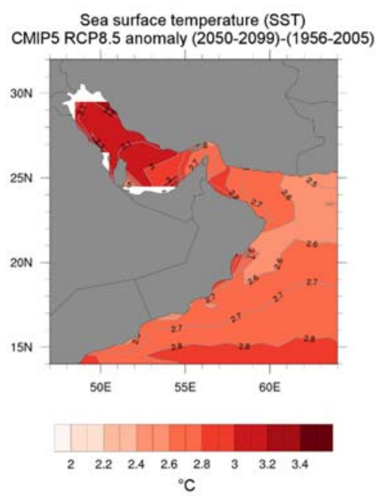

Figure 4: The projected difference in the annual average sea surface temperature (SST) in 2050–2099 under RCP8.5 compared to the historical reference period (1956–2005), calculated using CMIP5 models. White shading denotes areas where data are missing ESRL : PSD : Climate Change Web Portal _ Maps MM" 2018. From AGEDI (2016a).

The pattern of temperature increase is clearly magnified in shallow versus deep areas, as well as in southwestern versus northern areas (AGEDI, 2016a; Noori *et al*, 2019). Due to the shallow depths and seawater circulation regime in I-RSA, there is very little thermal stratification and a thermocline appears limited to the summer period when the temperature gradient in the water column is just over 3°C from the surface to the bottom.

Recently, Paparella *et al*. (2019) found that summer sea-bottom temperatures are tightly linked to Regional wind regimes, and that strong north wind events (locally known as "shamal") greatly influence the occurrence and severity of bleaching at three major coral habitats located in Abu Dhabi waters. Moreover, the study revealed that the sea-bottom temperatures were primarily controlled by latent heat flux from wind-driven surface evaporation which exceeded 300 W per square meter during shamal winds, double that of typical breeze conditions. The study is based on data observed and simulated from 2012 to 2017 and suggested that years with reported bleaching events (2012 and 2017) were characterised by low winds speeds that resulted in temperatures persisting above coral bleaching threshold temperatures for >5 weeks. The cooler intervening years (2013–2016) were characterised by summers with more frequent and/or strong shamal events, which repeatedly lowered temperatures below bleaching thresholds for days to weeks, providing corals temporary respite from thermal stress.

2.2 Humidity

In the I-RSA area, extreme humidity can be a more pressing problem than temperature. In the UAE, in extreme cases, summer temperatures can rise to near 50°C near the coast and humidity levels can reach 90%. AGEDI regional climate projections (AGEDI, 2015a) show that humidity will increase further in summer, potentially by 10% across the I-RSA.

"Wet bulb" temperature measures the combination of heat and humidity and studies have suggested a threshold "wet-bulb" temperature of 35°C, above which any length of time in these conditions would be intolerable (Sherwood and Huber, 2010). Under RCP8.5, the study found the 35°C wet-bulb threshold would be breached for a six-hour period at least once every 10–20 years by the end of the 21st Century along the I-RSA coast. Under RCP4.5, where carbon emissions are stabilised, temperatures still rise, but do not reach the 35°C threshold in any part of the Region (Pal and Eltahir, 2016).

2.3 Salinity

Patterns and drivers of seasonal variability in salinity are different between the I-RSA, M-RSA and O-RSA.

High evaporation leads to very saline waters in the I-RSA, particularly in shallow zones. This is compounded by intense seawater desalination activity (AGEDI, 2016a). The net loss of water in the I-RSA creates a Mediterranean-like circulation (Reynolds, 1993). The salinity of the I-RSA ranges widely, from 36.5PSU (practical salinity unit) at the Strait of Hormuz to more than 70PSU in shallow semi-enclosed embayments, such as Salwa Bay (southwest of Bahrain, between Qatar and Saudi Arabia). The high salinity results from a combination of high levels of evaporation, estimated at 1.5m/yr (Johns *et al.,* 2003), and a progressive decline in freshwater input in recent decades (Issa *et al.,* 2014; Mehzoud *et al*., 2016) most likely due to anthropogenic activities. Low salinity areas,are highly localised, situated at the outflows of river systems, mostly in the northern part of Shatt Al-Arab estuary. In these areas, salinity varies with the level of freshwater discharge from the Shatt Al-Arab River and other rivers along the coast of Iran (Reynolds, 1993). Salinity of surface waters in the I-RSA has increased by 0.5–1.0% (5 – 10PSU) over the past 60 years due to increased evaporation, as average air temperatures have increased with global warming (Hoegh-Guldberg *et al.,* 2014; Vaughan *et al*., 2019).

There are three very distinct water masses in the Sea of Oman (M-RSA) and O-RSA with distinct combinations of salinity and temperature: a deeper layer that does not change much over time; a surface layer (0m to ~200m) that is strongly affected by seasonal changes and also by eddies that go down several 100m deep; finally, a thin layer of water escaping from the I-RSA (higher temperature and salinity) that remains around 300m deep and circulates from Hormuz to the Indian Ocean, progressively spreading. Measurements of salinity in the surface waters of the M-RSA, from the Strait of Hormuz in the Musandam peninsula to Ra's Al Hadd at the entrance to the Sea of Oman suggest values that vary from 36.5 to 38.9PSU (ROPME, 2003) and seem little affected by the outflow from the I-RSA which rapidly sinks well below the surface. In the O-RSA (from Ra's Al Hadd to the southernmost part of the Sultanate of Oman) surface salinity varies from 35.50 to 37.70PSU (ROPME, 2003). The wider Arabian Sea, part of which forms the O-RSA, is a highly evaporative basin and temperature is assumed to control the density structure where seasonal changes and distribution of salinity values are forced by the reversing Indian monsoon system. In the O-RSA it should be noted that salinity data is sparse, and the effects of complex oceanic interactions, either remotely or through freshwater inputs from rainfall or river runoff, are little understood (Joseph and Freeland, 2005).

While salinity is projected to increase in the future under a high emission scenario (RCP8.5) in the I-RSA, changes are likely to be less pronounced in the M-RSA and O-RSA (AGEDI, 2016a). Under emission scenario RCP8.5, salinity in the eastern M-RSA, close to the Strait of Hormuz, is projected to increase; however, further away from the Strait of Hormuz no change is projected. In the O-RSA, salinity is projected to decrease slightly by 2099, most likely as a result of long-term changes in oceanographic conditions and/or monsoon dynamics. Climate change is also projected to cause further increases in salinity for the I-RSA (AGEDI, 2016a). Changes in evaporation will be exacerbated by decreases in average rainfall in some areas, combined with an increase in water demand and dam construction for irrigation and power generation in the surrounding countries (Issa *et al.,* 2014), as well as the extensive drying of the Mesopotamian marshlands in Iraq (ROPME, 2013). This loss of freshwater input has caused drastic annual reductions in the freshwater inflow from the main rivers Tigris, Euphrates and Karun (however, a few years ago the outlet of Karun river was diverted from its connection with Shatt Al-Arab River) at the northern end of the I-RSA, estimated as 0.1335km^3/yr or 0.294% for the River Tigris, which is less than the Euphrates (0.245km^3/yr or 0.961%) according to Issa *et al.* (2014).

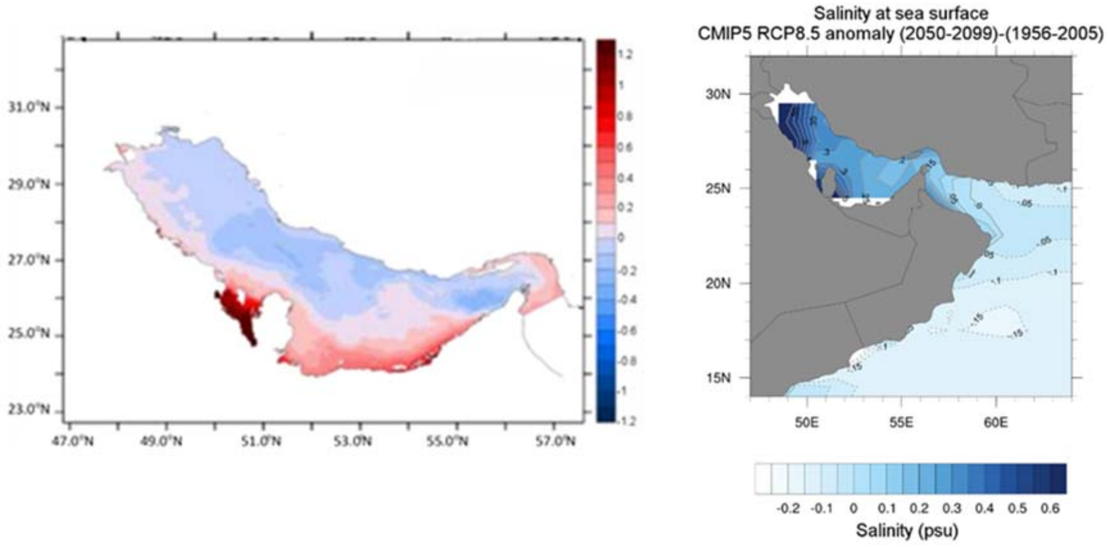

Figure 5: (Left) Salinity at 2100 for the I-RSA under RCP8.5 (AGEDI, 2016). (Right) The projected difference in the annual average sea surface salinity in 2050–2099 under RCP8.5 compared to the historical reference period (1956–2005), calculated using CMIP5 models. White denotes areas where data are missing. ESRL : PSD : Climate Change Web Portal _ Maps MM" 2018.

The combination of climate change and the increasing reliance on the I-RSA as the sink for highly saline brine discharges from desalination activity will come at an adverse environmental cost to the I-RSA (AGEDI, 2016a), at least close to the outfall areas. Hot brine from the desalination effluents is heavier than seawater and sinks to the bottom, likely causing harm to seagrasses and other benthic ecosystems on which a large range of aquatic life (e.g. dugongs) and services depend. Cumulative discharges of hot and hypersaline water from more than 55 desalination plants (Figure 6), as well as power stations, are particularly extensive along the I-RSA coast, but are assessed mainly in a local sense and not on a large-scale basis (Kim and Jeong, 2013). Studies of the areas around the outfalls have found significant increases in salinities, between 5–16PSU above the ambient conditions (Dawoud and Al Mulla, 2012; Uddin, 2014; Al-Osaimi *et al*., 2019).

Dols (2019) has recently investigated the combined impact of climate change and increasing desalination capacity on salinity in the I-RSA using 3D modelling. This work indicated little effect on the overall salinity with the increased atmospheric and oceanic temperatures, and increased desalination activity, although at shallow and sheltered locations, salinity appears to increase by more than 1 PSU (Dols, 2019). Extreme salinities tend to become more extreme due to desalination capacity increase and climate change, while the same climate and desalination scenarios can cause salinity to decline at specific locations, and wind dominates evaporation and internal transport patterns and strongly affects the salinity distribution (Dols, 2019). There is still considerable uncertainty regarding the forcing of wind climate on future salinity distribution (Dols, 2019).

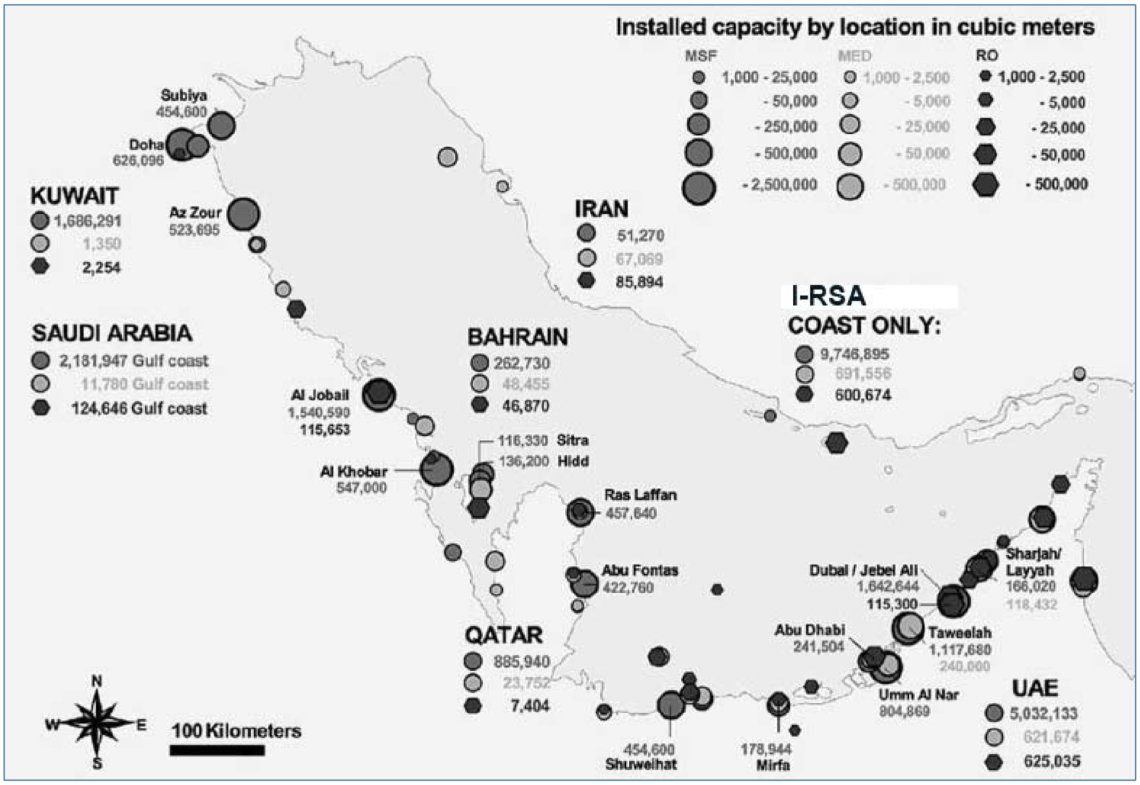

Figure 6: As of 2013, map of desalination and power plant facilities in the I-RSA showing the installed capacities for three types of desalination plants: [MSF] = Multi-Stage Flash; [RO] = Reverse Osmosis; [MED] = Multi-Effect Distillation. From Lattemann and Hoepner (2008) and Kim and Jeong (2013).

2.4 Circulation

Circulation and water mass exchange in the RSA tend to be controlled by a combination of heat flux, winds, freshwater flux and river discharge, tides, as well as the restricted exchange with the open ocean (Al Azhar *et al*., 2016). Across the RSA, stratification due to vertical gradient of both temperature and salinity is stronger in early summer in most of the RSA compared to more well-mixed water in midwinter (Reynolds, 1993). Winds are most intensive in spring to summer, when the intense shamal events propagate from the northwest to the central and southern I-RSA. During autumn the winds are weaker and less variable. Intense temperature differences between land and water result in strong breeze winds, which in turn stimulate intensive vertical mixing processes in coastal areas (Alosairi *et al*., 2011).

The overall circulation in the RSA is anticlockwise, due to Coriolis forces. The I-RSA is a shallow, semi-enclosed sea with a high evaporation rate as a result of the high temperatures experienced in the Region. This produces dense, highly saline water which sinks and causes a reverse estuarine circulation through deep waters of the Strait of Hormuz. The high salinity water is replaced by less saline surface waters that flow in from the M-RSA and move northwest up the coast of Iran in the I-RSA (Figure 7). The dense water from the I-RSA travels down the Omani coast in the M-RSA and forms a front at Ras Al Hadd where it meets the Oman Coastal Current, travelling north-eastward up the coast of Oman in the O-RSA. The front exists during summer and autumn and separates the waters of the M-RSA and

O-RSA, producing eddies which mediate the mixing during summer and autumn (Piontkovski and Claereboudt, 2012).

The currents in the surface layer of the O-RSA are dominated by the seasonal changes in temperature and winds brought about by the summer monsoon. During July-October, the monsoon reverses the wind direction and produces upwelling in the O-RSA along the south coast of Oman (Figure 7; Sheppard *et al*., 1992). The upwelling of deep waters brings cool, nutrient-rich and oxygen poor water to the surface. Occasional, irregular upwelling occurs in the M-RSA along the Iranian coast (ROPME, 2013).

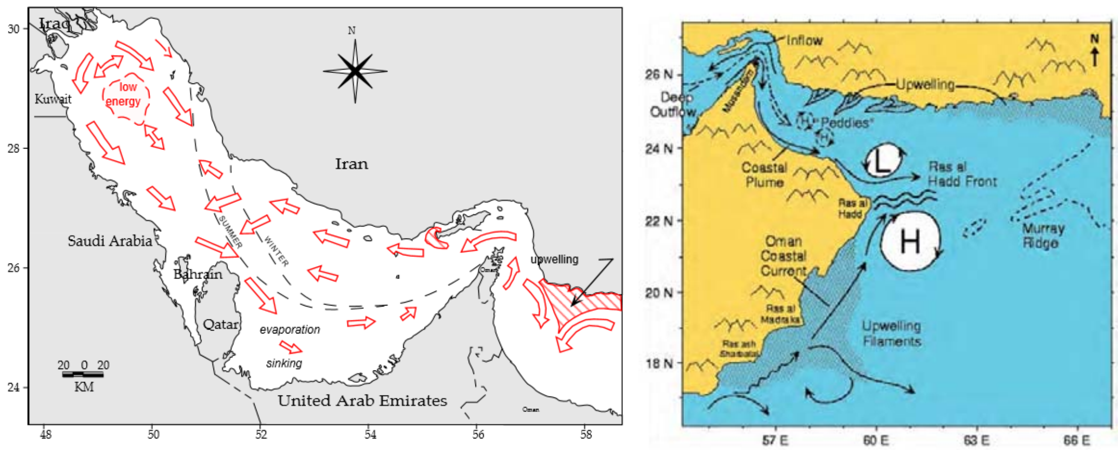

Figure 7: (Left) Circulation in the I-RSA (Meshkati and Tabibzadeh, 2016; modified from Reynolds, 1993). (Right) Schematic diagram of oceanic circulation in the M-RSA and O-RSA during the southwest monsoon. (Source: Rosenstiel School of Marine and Atmospheric Science, University of Miami).

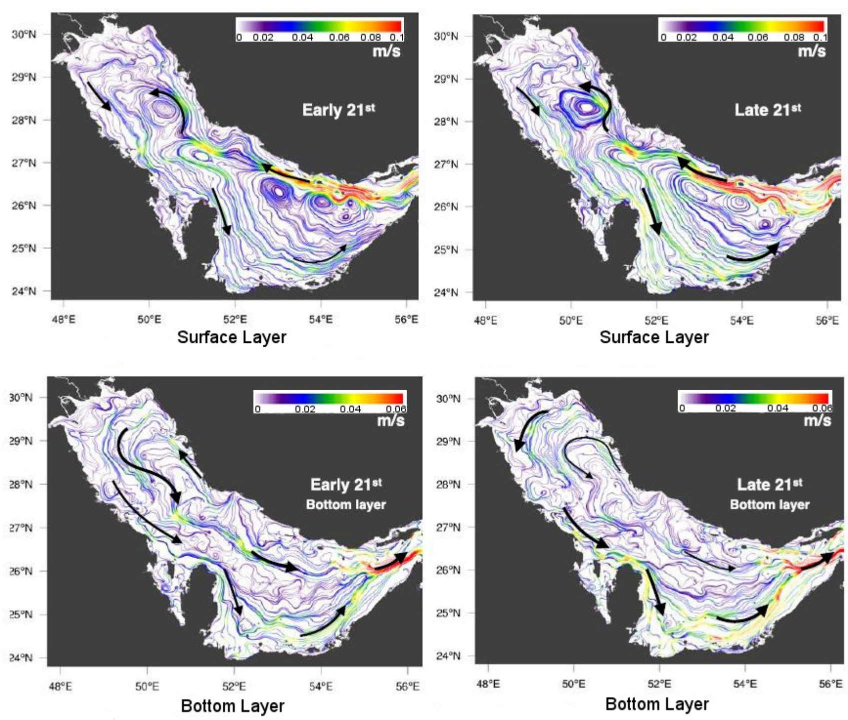

Figure 8: Residual current streamlines at surface and bottom layers during the early and late 21st Century (AGEDI, 2016a).

Future ocean currents in the I-RSA will be altered by climate change. By the end of this century, salinity is still the most important driver of the circulation of the I-RSA, however, models project that changes in sea temperatures and rainfall along the coast of Iran (a very likely climate change outcome for the area; Sandeep and Ajayamohan, 2014) will decrease the vertical overturning of the water column, causing an increasing inflow of less dense waters from the M-RSA (AGEDI, 2016a; Figure 8).

Any alterations to the monsoon winds that control the upwelling of deep nutrient-rich cooler waters in the M-RSA and O-RSA caused by climate change are likely to result in changes to water temperature, salinity, nutrients, oxygen and pH in the M-RSA and O-RSA. These changes are difficult to forecast in advance due to the significant seasonal variation and interannual variability experienced in the O-RSA (IPCC, 1990; AGEDI, 2015a).

2.5 Carbonate chemistry and pH

Approximately one-third of anthropogenically produced CO_2 has been absorbed by the oceans, or 48% of the total fossil-fuel and cement-manufacturing emissions, since the beginning of the industrial period in the late 18th Century (Sabine *et al*., 2004). When CO_2 reacts with seawater, it results in a decrease in pH through the formation of carbonic acid (H_2CO_3). When pH is low enough that waters are undersaturated with respect to calcium carbonate ($CaCO_3$), water becomes corrosive to unprotected calcium carbonate structures. Seawater pH varies with temperature, salinity, and pressure, meaning that pH decreases with depth and therefore that corrosive conditions can also occur earlier in deep waters. Since the beginning of the Industrial Revolution, the average pH of ocean surface waters has fallen by 0.1 pH units globally (Rhein *et al*., 2013; Hoegh-Guldberg *et al.,* 2014). The depth at which seawater becomes corrosive to the more soluble form of calcium carbonate (aragonite) is now 100–200 m shallower than in pre-industrial times as a result of ocean acidification (Hoegh-Guldberg *et al.,* 2014). Seawater pH is highly spatially and temporally variable, meaning that global averages may be significantly different from local conditions.

Few pH measurements exist for the RSA, however, monitoring data from the south-east subregion of the I-RSA indicates an average annual pH of 8.22, which is comparable to the global average (Pörtner *et al.,* 2014; Mezhoud *et al.,* 2016), while average nearshore seawater pH across the northern I-RSA is in the range of 8.10 to 8.55 (Saleh *et al*., 2020). There is no significant seasonal cycle in pH variation in the I-RSA (Uddin *et al.,* 2012; Mezhoud *et al.,* 2016). The semi-arid environment surrounding much of the I-RSA limits the photosynthetic removal of atmospheric CO_2 by terrestrial vegetation. A higher fraction of CO_2 is likely to be sequestered by the marine system, leading to changes in the carbonate chemistry of the seawater and ultimately acidification (Omer, 2010; Uddin, 2014). The study by Uddin (2014) in Kuwait territorial waters suggests that the hypersaline conditions in the I-RSA may be acting as a buffer to acidification, partly due to the high carbonate content of the seafloor sediments, but there are still considerable gaps in the understanding of carbonate chemistry in the marine environment, especially with regard to temporal and spatial patterns of pH variability and CO_2 sequestration (Uddin *et al.,* 2012) and preliminary results from more recent, ongoing monitoring in Qatar and Kuwait indicates that this buffering may not be happening (Ben Hamadou, personal communication). It is likely that this decrease is a result of local conditions, such as algal blooms, aerosols, dust deposition, anthropogenic waste or by organic activity via respiration or calcification (Omer, 2010). As the study period was only six years, it represents a very short time series, therefore it is not possible to derive statistically significant trends. These short-term observations may be masking long-term patterns, such as decadal oscillations in pH caused by large-scale climate forcing (Howes *et al.,* 2015; Wu *et al.,* 2018).

In the O-RSA, pH varies strongly, depending on the season. In summer, monsoonal winds drive upwelling of CO_2 rich deep water along the Omani coast. In the O-RSA, summer pH is as low as 7.93, compared to 8.05–8.09 during winter months (Omer, 2010). The pH of the M-RSA is affected to an extent by the seasonal upwelling, with a summer pH of between 8.03 in the east and 8.06 in the west (Omer, 2010). Repeated measurements from survey cruises in the O-RSA also reveal an overall decrease in average pH between 1960 and 2000. This decrease is ~0.1 pH units in the upper 50 m and 0.2 pH units at 300 m depth (Piontkovski and Queste, 2016)

The IPCC AR5 global projections (CMIP5) suggest that, by end of this century under RCP8.5, pH will decrease by 0.42 pH units globally (Pörtner, 2010). Models appear to suggest that pH in the RSA will decrease by approximately 0.25 units (Figure 9). Changes in pH and carbonate chemistry have been identified as major threats to biodiversity and ecology in the Region (Sheppard *et al.,* 2010) but currently, there are no downscaled, Regionally specific projections for future pH. The combined effect of temperature and pH changes may be amplified by the low oxygen content of water in many areas of the M-RSA and O-RSA. High productivity, alongside organic degradation, will lead to local production of CO_2 that will act to further lower pH (Melzner *et al*., 2012).

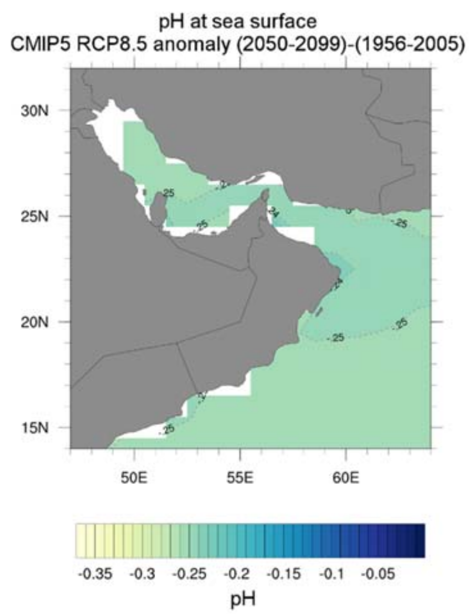

Figure 9: Projected change in average annual pH in 2050–2099, relative to the average during 1956–2005. Modelled using the CMIP5 model, under a high emissions scenario RCP8.5. White denotes areas where data are missing. ESRL : PSD : Climate Change Web Portal _ Maps MM" 2018.

2.6 Dissolved oxygen

Due to the solubility effect, warmer waters contain less dissolved oxygen (DO) compared to cooler waters (Carpenter, 1966) and lead to increases in the respiration rates of marine organisms (Pauly and Kinne, 2010). Increased stratification, as a result of SST warming, adversely affects the oxygenation of deeper water masses, which also leads to a decrease in DO concentration, particularly in the benthos (Vaquer-Sunyer and Duarte, 2011).

Oxygen minimum zones (OMZs) generally refer to specific regions with midwater concentrations below 2 mg/L (hypoxia) caused by vertical stratification due to temperature differences and respiratory drawdown of oxygen. More than 50% of the area of OMZs in the world's oceans occur in the RSA (Helly and Levin, 2004; Stramma *et al.,* 2010).

Many fish and marine organisms can detect and actively avoid hypoxia, but response behaviours may make them more vulnerable to predation (Wu, 2002). Hypoxia may eliminate sensitive species, thereby causing major changes in species composition of benthic, fish and phytoplankton communities, and there is a general tendency for suspended feeders to be replaced by deposit feeders; demersal fish by pelagic fish; and macrobenthos by meiobenthos (Wu, 2002). Microflagellates and nanoplankton also tend to dominate in the phytoplankton community in hypoxic environments. Hypoxia is also often associated with increases in ammonia, hydrogen sulphide and particulate organic materials so interactions of these compounding factors make it difficult to attribute many of the observed ecological effects to hypoxia (Wu, 2002).

The OMZ that occurs in the M-RSA and O-RSA is the most intense in the world, with near-total oxygen depletion at depths from 200 to 1000 m (Piontkovski and Al-Oufi, 2015). Within the I-RSA, a permanent hypoxic water layer has also been detected in the marine zone off Qatar, caused by the interaction between temperature differences in the water column that act as a barrier to oxygen replenishment, and respiration by marine organisms, resulting in drawdown of DO (Al-Ansari *et al.,* 2015). Seasonal hypoxia also occurs in the I-RSA. An analysis of water quality data collated from Kuwait's marine waters in the I-RSA between 1983 and 2013 show that DO has a seasonal cycle ranging from mean low values of 1.43 mg/L (hypoxic) in July-October to mean high near-saturation values of 12.1mg/L around March (Devlin *et al*., 2015). This is also strongly linked to temperature, with high solubility at low temperature and vice versa.

Patches of hypoxia occurring in Kuwait Bay appear to be interrelated with fish kill events in certain bodies of water but this varies across different areas due to varying tolerances of different species to hypoxic conditions (Breitburg *et al*., 2003) as well as the ability of mobile animals to escape to oxygenated water. Mortality in fish kill events is likely due to a combination of other factors such as harmful algal blooms (Alosairi and Alsulaiman, 2019). In Bahrain the data accumulated for the period 2007–2016 on dissolved oxygen are ranged between 3.32–10.87 mg/L with an average 6.04 mg/L (Supreme Council for Environment, 2016) indicating well oxygenated surface water, however, lower levels are observed in summer due to a noticeable elevation in water temperature.

Dissolved oxygen concentrations in parts of the RSA, particularly the I-RSA, are declining (Helly and Levin, 2004; Stramma *et al.,* 2010; Hoegh-Guldberg *et al.,* 2014) and a recent study has suggested that oxygen depletion in the M-RSA has been underestimated and that the core of the M-RSA OMZ has transitioned from hypoxic to persistently suboxic, with O_2 concentrations less than 0.064 mg/L (Queste *et al.,* 2018). Goes *et al*. (2005) studied the effect of the climate change driven strengthening southwest summer monsoon winds over the RSA, which appears to be enhancing upwelling of cool, nutrient-rich deep waters and therefore leading to increased summertime phytoplankton blooms along the western and central I-RSA. Later studies show a decrease in phytoplankton production (although non-significant) and data over the last 20 years do not show any significant trends (Piontkovski and Claereboudt, 2012; Roxy *et al*., 2016). Changing productivity of the RSA could have far-reaching consequences for the OMZ due to oxygen consumption during the degradation of organic matter produced during these blooms (Goes *et al*., 2005). Furthermore, in the last two decades in the O-RSA particularly, the die-off of intense summer phytoplankton blooms has been followed by intense, long-lasting, large-scale winter blooms of *Noctiluca* and other Harmful Algal Bloom (HAB) species (see Section 3.1.1), which thrive in oxygen-poor waters and cause additional issues including fish kills and poor water quality (Goes *et al*., 2018).

Regions with low DO concentrations are expected to increase in frequency and extent over the coming century, partly in response to climate change (Hoegh-Guldberg *et al.,* 2014), with the O-RSA and M-RSA projected to undergo stronger deoxygenation than the wider Indian Ocean (Stramma, 2010; Bopp *et al*., 2013; Long *et al*., 2016). Future DO levels in the M-RSA and O-RSA will also depend on the future export and eddy stirring of water from the I-RSA as this transports more oxygenated water to the M-RSA and O-RSA, however, this transport may alter under climate change (Queste *et al.,* 2018). Global models (CMIP5) suggest strong declines in DO in the southwestern I-RSA, and in southern areas of the M-RSA and O-RSA (Figure 10).

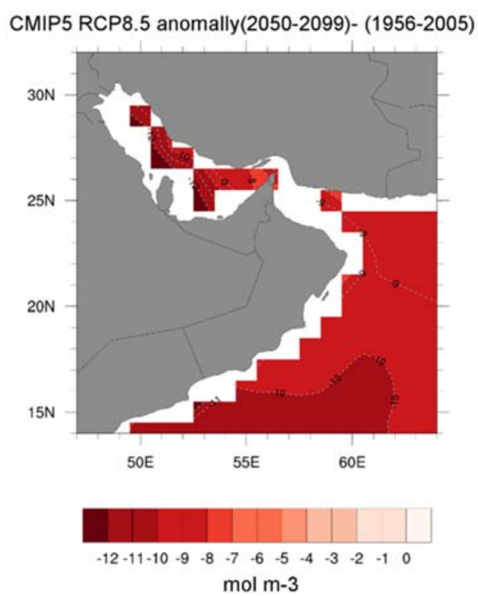

Figure 10: Projected change in average annual DO (1.E^{-3}mol/m^{3}) in 2050–2099, relative to the average during 1956–2005. Modelled using the CMIP5 model, under a high emissions scenario RCP8.5. White denotes areas where data are missing. ESRL : PSD : Climate Change Web Portal _ Maps MM" 2018.

2.7 Sea level

The observed rate of SLR varies widely between regions, depending on complex ocean dynamical processes, movements of the sea floor, and changes in gravity due to water mass redistribution from land ice, and the storage of terrestrial water masses. There are few records of Regional sea-level change across the whole RSA. To our knowledge, there are no specific studies that examine sea-level rise in the Middle and Outer RSAs, however, there are several tide gauge and satellite altimetry studies in the I-RSA (Ayhan and Alothman, 2009; Lari *et al.,* 2012; Alothman *et al*., 2014).

When considering sea-level rise in the RSA, it is important to recognise that the unique geological configuration of the I-RSA, and the narrow Hormuz passage to the Oman Sea, means that the rate of SLR may differ from the global mean (Lari *et al.,* 2012). Various studies projecting sea-level rise, Alothman *et al*. (2014), examined relative sea-level variations in the north-western part of the I-RSA using 28 years of observations from seven coastal tide gauge stations in Saudi Arabia, Bahrain, Kuwait, and Iran, covering the period 1979–2007. A relative SLR of 2.2 mm per year was estimated for the northern I-RSA. This is slightly higher than the global mean SLR over this period (2.1 mm per year over the period 1970–2015; Oppenheimer *et al*., 2019) and the earlier estimates of Ayhan and Alothman (2009) who computed the average relative SLR rate by 1.96 ± 0.21 mm per year within the west of I-RSA based on four stations spanning more than 19 years.

The best estimates available for sea-level rise in the middle and outer RSA can be gleaned from studies of sea-level in the northern Indian Ocean. Unnikrishnan and Shankar (2007) considered a wider range of tide gauge data, including stations in Aden (Yemen) and Karachi (Pakistan) at the edge of the RSA. For Aden, the trend in relative SLR was 1.21 mm per year throughout the 20th Century, compared to 0.61 mm per year in Karachi. Northern Indian Ocean records longer than 40 years yielded a range of SLR estimates between 1.06–1.75 mm per year, with an average of 1.29 mm per year for the whole Region.

Future projections of relative sea-level rise for the Region are sparse and are complicated by local land movements, however, it is very likely that the rate of global mean SLR during the 21st Century will exceed that observed during 1971–2010 for all RCP scenarios, due to increases in ocean warming and an accelerating loss of mass from glaciers and ice sheets. Future global mean sea-level rise by 2100 under RC8.5 is projected to be 0.84 m, with a likely range between 0.61 and 1.1 m (Oppenheimer *et al*., 2019). This is higher than previous IPCC estimates. Most of the coastline in the western parts of the middle and outer RSA (with the exception of Muscat and the Musandam Peninsula) is uplifting due to isostatic rebound following formation of the Oman Mountains in the late Cretaceous, so the rate of relative sea-level rise in these areas may be lower than the global average (Hoffmann *et al*., 2013; Mattern *et al*., 2018).

2.8 Storms and cyclones

On average, one to two tropical cyclones form over the northern Indian Ocean each year, with only a few of these being intense enough to be classified as “severe” (ROPME, 2013). There is marked seasonal variation, with two annual peaks in tropical cyclone genesis in months preceding and following the monsoon (April to May and October to December, respectively; Murakami *et al*., 2013). From 1979 to 2008, a total of 41 cyclonic storms formed in the northern Indian Ocean, of which 23 made landfall. Eight storms were classified as severe cyclonic storms, seven were classified as Very Severe cyclonic storms, and one super cyclonic storm was recorded in 2007. Over the period 1979 to 2008, there was an average of 4.7 cyclonic storm days over the O-RSA each year (ROPME, 2013).

In the last 12 years there have been four tropical cyclones of intensity category 3, or higher, making landfall in the RSA: Gonu (2007), Phet (2010), Ashobaa (2015) and Mekunu (2018). In June 2007, a persistent area of convection in the eastern RSA aided by warm SSTs generated Super Cyclonic Storm Gonu (Rafiq *et al*., 2015), which became the strongest storm to make landfall in the RSA to date, causing an estimated 4 billion USD in damages and 100 deaths across Oman, UAE, and Iran (ROPME, 2013). Cyclone Gonu also led to severe degradation of many coastal habitats including coral reefs as a result of wave impact (Foster *et al*., 2011; Bento *et al*., 2016). In May 2010, record heat over southern Asia helped elevate sea temperatures in the O-RSA to 2°C above normal and contributed to the formation of Tropical Cyclone Phet, the second strongest tropical cyclone ever recorded in the Region (Haggag and Badry, 2012). Cyclone Phet peaked as a Very Severe category storm, killing 44 people and causing 700 million USD in damage to Oman. Tropical cyclone Mekunu, on 21st May 2018, was the strongest storm to strike the Dhofar Governorate in Oman since 1959. The India Meteorological Department estimated 10-minute sustained winds of 177 km/h, making Mekunu an Extremely Severe Cyclonic Storm. Mekunu caused landslides and flooding, 20 fatalities and about 1.5 billion USD in damage.

Publications on the future of tropical cyclones in a warming climate suggest that the strongest storms could increase in intensity of 2–11% by 2100, but the total number of storms would fall globally by 6–34%, (Knutson *et al.,* 2010). A modelling study under a high emissions scenario (based on CMIP3 modelling under the Special Report on Emission Scenarios (SRES) A1B scenario) projects that the overall number of tropical cyclones generated at the basin scale in the Indian Ocean basin would not change significantly, but, a shift in location of storms could lead to a significant increase in the number of tropical cyclones occurring in the O-RSA by the end of this century (Figure 11; Murakami *et al.,* 2013). Recent research has documented global increases in the proportion of very intense cyclones and also of trends in the latitude of maximum intensity of tropical cyclonic storms, consistent with the model projections for future climate (Walsh *et al*., 2016). The confidence in these projections continues to increase as simulations improve in quality, but further research must be undertaken to reduce the uncertainties in the detection of trends in tropical cyclones, using continually improving observational capabilities (Walsh *et al*., 2016).

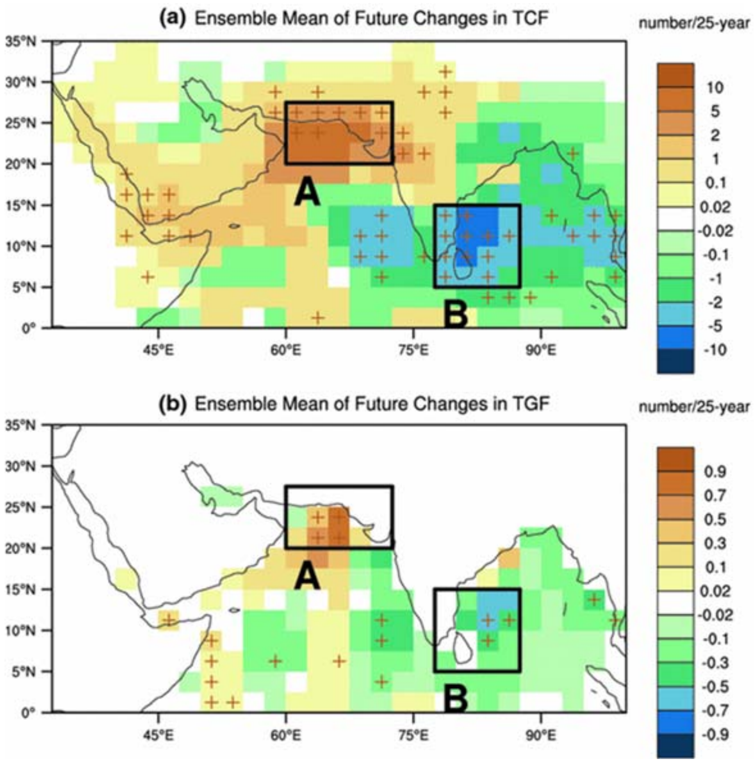

Figure 11: Average model projections of future changes in a) tropical cyclone frequency (TCF) [number/ 25 years] and b) tropical cyclone genesis frequency by the end of century. The plus symbols indicate that the differences are statistically significant (Murakami *et al*., 2013).

While the I-RSA is not affected by tropical cyclones like the O-RSA and M-RSA, due to the low humidity and high wind shear conditions typical of the I-RSA (Lin and Emanuel, 2015), the I-RSA is still under the influence of storms and storm surges generated by the shamal winds, particularly in the southern shores (El-Sabh and Murty, 1989). According to a study by Al Senafi and Anis (2015) the number of shamal events in the I-RSA, which result in abrupt changes in meteorological conditions (increased wind speeds, decrease in visibility, and reduction in humidity as well as seasonal variations in temperature and barometric pressure between winter shamals and summer shamals), has increased since 2000. These shamals also bring dust clouds to the I-RSA, which have implications for iron enrichment and have the potential to drive algal blooms (Thoppil and Hogan, 2010).

2.9 Dust storms

Significant quantities of dust derived from the Arabian Peninsula form part of the annual dust input into the Indian Ocean and the RSA in particular. In the Arabian Peninsula, dust storms and blowing dust are frequent events throughout most of the year. The major dust sources in the Arabian Peninsula include the Tigris and Euphrates River Valleys, the alluvial plain in Iraq and Kuwait, the low-lying flat lands in the east of the peninsula along the I-RSA, and the Ad Dahna and the Rub Al Khali deserts (Prakash *et al*., 2015). Shamal winds are especially important for dust accumulation, since the low-altitude dust plumes come from the south-eastern Arabian Peninsula and Somalia, while those above 3000m from northern directions (Iran, Pakistan; Rashki *et al*., 2019), meaning that the I-RSA is particularly likely to experience dust deposition.

Dust storms are a possible sensitive indicator of climate change consequences (Hamza *et al*., 2011) and play an important role in fertilising primary production by phytoplankton. Biogeochemical models, including aerosol deposition, show that without high iron inputs from dust deposition during the summer monsoon, primary production would be reduced by half (Prakash *et al*., 2015; Guieu *et al*., 2019). Despite their influence on local conditions, there are relatively few studies of trends on how the frequency of dust storms in the Region has changed and what may happen under future climate change (Prakash *et al*., 2016).

Dust events in the Middle East are becoming more frequent and intense in recent years with impacts on air quality, climate, and public health (Terradellas *et al*., 2015). Two separate studies indicate an increase in dust events in the Arabian Peninsula over the last 20–30 years (Alobaidi *et al*., 2017; Kumar *et al*., 2019). Alobaidi *et al*. (2017) only found a significant trend for the north-eastern Arabian Peninsula between 1983 and 2013, however, the direction of the shamal winds indicates that this could have caused an increase in the dust deposition in the I-RSA. Increasing desertification, as well as any changes in the strength/timing of the shamal winds or changes to circulation patterns of the I-RSA due to climate change, could all affect the levels of dust deposition in the area.

3. Current and future impacts on biodiversity

3.1 Phytoplankton productivity

The distribution and productivity of phytoplankton differs significantly between the Inner, Middle and O-RSA due to the interaction of the two main hydrodynamic systems: the freshwater outflow from the Shatt Al-Arab estuary in the north and the monsoon-induced inflow from the M-RSA and O-RSA in the southern part of the I-RSA (ROPME, 2013). Consequently, the three distinct parts of the RSA are under extremely different forcing functions and boundary conditions. The interaction between these various factors results in two large frontal zones in the central part of the I-RSA and in the southern part near the Strait of Hormuz that contribute to the significant distinction in the phytoplankton structure. The first frontal zone is located in the central part of the I-RSA and divides the area into a large northern stagnant zone and a southern down-welling zone on the Saudi Arabian coast (ROPME, 2013). Generally, phytoplankton species richness increases from Shatt Al-Arab towards the Strait of Hormuz, while phytoplankton biomass and productivity follow a reverse gradient and decreases towards the Strait (Rao and Al-Yamani, 1998; AGEDI, 2015b).

Decadal increases in annual primary productivity have been observed along the western portion of the Arabian Sea (O-RSA) that suggest enhanced wind-driven upwelling (Gregg *et al*., 2003). According to Goes *et al*. (2005), climate change may strengthen the southwest summer monsoon winds over the RSA, which will enhance upwelling of cool, nutrient-rich deep waters and therefore lead to an increase of summertime phytoplankton blooms along the western and central I-RSA. However, NOAA model simulations using historical emissions (1976 to 2005) and an RCP8.5 scenario for future projection (2006 to 2099) suggest a decline of primary organic carbon production by all types of phytoplankton across the RSA for the 1976–2099 period (CMIP5 IPCC climate model ensemble, Figure 12); apparently due to unfavourable changes in the water column in terms of currents, timing and strength of vertical mixing, nutrients and oxygen supply. A decline in primary productivity would have negative repercussions for the marine food chain, including fisheries (Al-Said *et al*., 2017, Ben-Hasan *et al*., 2018), although the magnitude of these changes is difficult to predict with confidence at present due to the significant seasonal and interannual variability typical of the RSA combined with a lack of high resolution climate models and data for this particular area (IPCC, 1990; AGEDI, 2015a).

An analysis of hydrological data and phytoplankton data from Kuwaiti waters for example, shows evidence that the salinity-related environmental changes have resulted in a coincidental decrease in species diversity and significant changes in phytoplankton community between the years 2000–2002 and 2012–2013 (Al-Said *et al*., 2017). This in turn would affect the pelagic trophodynamics as evident from a drastic decrease in the catch landings of some of the major commercial fishes in Kuwait (Al-Said *et al*., 2017). The reduction in the flow of Tigris-Euphrates Rivers in the north-western I-RSA, also appears to be correlated with declining finfish recruitment trends likely indicating a reduction in the productivity of nursery areas of finfish stocks through declines in the phytoplankton community caused by the elevated salinity (Ben-Hasan *et al*., 2018).

Dust fertilisation could be an essential factor regulating phytoplankton growth in the O-RSA (Rao and Al-Yamani, 1999), where the intensity of iron-rich dust deposition (iron being a growth-limiting micronutrient) determines phytoplankton variability in the area. By contrast, in the I-RSA, limitation by iron in the closed environment with carbonate rocks (rich in iron) and very shallow water, is very unlikely. The frequency of dust storms in the Region during the last decade has increased due to a combination of natural and man-made causes such as the drainage of marshes and military activities, as well as progressive desertification caused by climatic changes (ROPME, 2013). Increases in dust fertilisation could be a driver of the increased occurrence of phytoplankton species that are harmful, and where these blooms can affect marine species, including large-scale fish-kill events, and are potentially toxic to humans (Saburova *et al.,* 2009; Richlen *et al.,* 2010; Al-Yamani *et al.,* 2010; 2012).

The IPCC predicts that the area influenced by monsoon systems will increase globally over the 21st Century (Hsu *et al*., 2012; IPCC, 2019). While monsoon winds are likely to weaken, monsoon precipitation is likely to intensify due to an increase in atmospheric moisture. Monsoon onset dates may become earlier, or change very little, while monsoon retreat dates will likely be delayed, resulting in lengthening of the monsoon season in many regions. These changes are likely to impact the O-RSA particularly and the overall primary productivity in that area, by changing the timing, strength, and direction of winds that control the upwelling of deep nutrient-rich waters, versus the amount of sunlight available for the phytoplankton to grow.

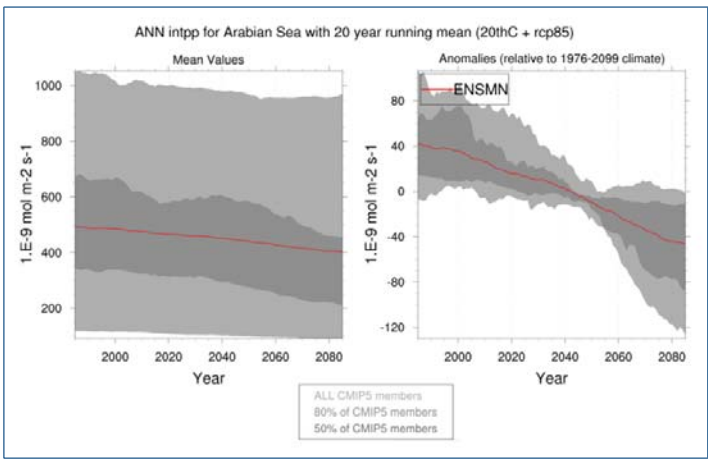

Figure 12: Time series of yearly average of primary organic carbon production in the O-RSA by all types of phytoplankton for the 1976–2099 period [7]. The simulations are forced using historical emissions (1976 to 2005) and the RCP8.5 scenario for future projection (2006 to 2099). A 20-year running mean is applied. Figures show, in colours, ENSMN ensemble mean, in light grey, the spread of all the CMIP5 models, and in medium grey, and dark grey, 80% and 50% the spread of all the CMIP5 members, respectively. Left panel shows the mean values and right panel shows the anomalies relative to the 1976–2099 climatology.

3.1.1 Harmful Algal Blooms (HABs)

The shallow, warm, stable water conditions observed in the I-RSA and M-RSA, and elevated nutrient loads in the O-RSA, can make these areas more susceptible to harmful algal blooms (HABs) (ROPME, 2013). However, the link between occurrence or proliferation of HABs in the RSA and long-term climate change has not been conclusively demonstrated, and thus confidence in any future predictions (as well as attribution of past events) is considered extremely poor.

[7] https://www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html

Harmful algal blooms in the RSA are common, and their geographical scale and persistence seem to be increasing. In 2008 a large-scale red tide (> 500 km^2) of the dinoflagellate *Cochlodinium polykrikoides* started in August 2008 near the Strait of Hormuz and remained for around 10 months. It contributed to the complete loss of the branching corals, *Pocillopora* and *Acropora* spp. (Bauman *et al*., 2010; Foster *et al*., 2011), and substantial reductions in the abundance, richness and trophic diversity of the associated coral reef fish communities, as well as direct fish kills due to hypoxia (Bauman *et al* 2010; Samimi-Namin *et al*., 2010). Although the causative agents of this *C. polykrikoides* bloom are unknown, increased coastal enrichment, natural oceanographic mechanisms, and the recent expansion of this species within ballast water discharge were suggested to be the main agents (Bauman *et al*., 2010). The potentially catastrophic impacts of HABs have led to calls for coordinated Regional monitoring as well as for action to develop protocols and technology to minimise the disruption of these bloom events (Heil *et al*., 2001; Richlen *et al*., 2010; ROPME, 2013).

Red tides have become more frequent in Omani waters in recent years but whether this is linked to climatic changes remains unproven (Al Gheilani *et al*., 2011). Although the red tides have been considered a consequence of the summer upwelling season (May to September), recent phytoplankton outbreaks have also been reported during winter (December to March; Al Gheilani *et al*., 2011). Al-Azri *et al*. (2012) demonstrated that the occurrence of algal blooms along the coast of Oman now involves an increasing number of different phytoplankton species including both toxic and non-toxic species with dominance of *Noctiluca scintillans* (Al-Azri *et al*., 2012). More broadly, consideration of the role that humans play in the transfer of HAB species is required – seeding and spreading mechanisms such as transfer of ballast water and fouling of vessels and structures (e.g. an increase in shipping activities due to two planned mega-ports at Boubyan Island, Kuwait and Al-Faw, Iraq means more ballast water discharges, in turn a higher risk of introducing more HAB species into the I-RSA), or eutrophication of coastal waters may lead to false attribution of climate change effects on the prevalence and proliferation of HABs (Wells *et al.,* 2015).

3.2 Jellyfish blooms

Globally, an increase in abundance of jellyfish has been linked to warm, high-salinity conditions (Purcell*,* 2012) and for 75% of temperate jellyfish species studied, increased abundance in warm water conditions has been reported (Purcell, 2005; Purcell *et al.,* 2007; Purcell, 2012). However, it should be noted that not all species favour warming conditions, particularly those living close to their thermal maxima (Purcell, 2005).

Jellyfish blooms are known to occur across the RSA (UNEP, 1990; ROPME, 2013). Swarming of jellyfish has been observed in the vicinity of cooling water and desalination outlets in Kuwait during July 2017 (*Kuwait News,* 2 July 2017), and large numbers of jellyfish were reported off UAE coasts during November 2018. These outbreaks and aggregations are becoming commonplace in the RSA and have been attributed to changes in water temperatures in spring and winter (*The National,* UAE November 25, 2018).

Climate change, as manifested through alterations to temperature, salinity, and currents are all likely to impact on the size and distribution of jellyfish populations, and when these large accumulations occur (Purcell, 2005; Purcell *et al.,* 2007). The persistence of jellyfish blooms and their increasingly recorded occurrence, year after year, suggests a regime shift from fish-dominated to jellyfish-dominated oceans worldwide (Boero *et al*., 2016). Global drivers, such as overfishing and climate warming, often act synergistically with more local drivers, such as the increasing availability of hard substrates suitable for polyp settlement along coastlines (Boero *et al*., 2016). Another important factor is oxygen depletion that seems to favour jellyfish blooms in various OMZs across the world; thus, if temperature does affect reproduction of the polyps, oxygen may favour the differential survival of the adult stages of jellyfish.

Future changes in the RSA are difficult to predict, due to complex life-cycles and interactions with other direct human pressures. The proliferation of artificial structures associated with coastal developments, and the exponential growth of shipping, aquaculture and other coastal industries, provides habitat for jellyfish polyps, and may play a role in the observed widespread increase in jellyfish blooms (Duarte *et al.,* 2013a). Hence, any link to long-term climate change, based on correlations, may be entirely spurious. In the RSA, jellyfish blooms are often associated with seawater warming events, which can be accentuated by the local influence of thermal effluents from power plants, as seen in Asia (Purcell *et al.*, 2007). Eutrophication (e.g. from aquaculture or agricultural runoff), could also increase jellyfish populations (Purcell, 2012).

3.3 Fish

Feary *et al.* (2010) surveyed reef fish communities at four sites within the southern I-RSA, where sea-surface temperatures were considered 'extreme' (range: 12–35°C annually), and compared them with communities at four latitudinally similar sites in the biogeographically connected Sea of Oman (M-RSA), where conditions are more moderate (range: 22–31°C annually). Although sites were relatively similar in terms of coral cover, substantial differences in the structure and composition of fish assemblages were apparent. Consequently, the authors reasoned that there is potential for substantial changes in the structure of reef-associated fish communities in the future, independent of changes in habitat, given anticipated temperature rises as well as increasing fluctuations in oceanic climate.

A range of scientific and anecdotal evidence suggests that seasonal fish kills associated with warming waters, increasing salinity and higher incidence of HABs, both inside and outside the I-RSA during the summer, may be an important factor in the observed seasonal drop in I-RSA fish numbers (Bauman *et al.,* 2010). Harmful algal blooms are responsible for mass mortalities of fish worldwide with catastrophic impacts to aquaculture and fisheries, although the link to long-term climate change is very unclear. Incidents of mortality of finfish, turtles and mammals have been reported in the RSA since 1985 in shallow marine areas of Bahrain, Qatar, Saudi Arabia, UAE and Iran, attributed to fish disease, temperature anomalies and red tides. There has been a recurrence of fish kills in Bahraini territorial waters (Tubli Bay, Nabih Salih Island, Jerdab area, Mina Salman, Sitra, Fasht al-Jaram and Durrat Marina beach) during the last 10 years attributed to high temperature rather than pollution and coinciding with the fish kills in other I-RSA sStates. Moreover, pelagic species mostly mullet (locally known as maid), gizzard shad (locally known as gawaf) and rabbit fish (locally known as safi) are also vulnerable to exceptional increase in temperature, such as those observed during the summers of 1996 and 1998 in Qatar that resulted in mass fish deaths as well as coral reef deaths (Al-Ansi *et al*., 2002). In the UAE, fish kill incidents have been regularly recorded in the waters of Abu Dhabi Emirate since 2002 as reported by the Environment of Abu Dhabi (Al Dhaheri *et al*., 2017).

Coles and Tarr (1990) and Burt *et al.* (2009) have argued that seasonal changes in fish communities may be associated with off-reef migration in winter, when fish seek refuge away from the high wave action associated with winter wind (locally known as shamal wind) substantially affecting shallow reef areas throughout the I-RSA (Coles and Tarr, 1990). However, other factors such as mortality caused by changing seasonal extremes, changes to the spawning season due to temperature anomalies and changes to distribution due to "thermal pollution" may also play a substantial part, as well as competition and predation (Ghazilou *et al*., 2016), greatly complicating any attribution to long-term climate change effects.

Wabnitz *et al*. (2018) provided an assessment of the potential impacts on, and the vulnerability of, marine biodiversity and fisheries catches in the I-RSA under climate change. Modelling outputs for 47 of the most important fish and invertebrate species suggested a high rate of local extinction (up to 35% of initial species richness) within the I-RSA by 2090 relative to 2010. Spatially, projected extinctions are highest in the southwestern part of the I-RSA, off the coast of Saudi Arabia, Qatar and the UAE (Figure 13). Fisheries-specific results suggested reduced future catch potential for several countries on the western side of the I-RSA, with projections differing only slightly among models. Qatar and the UAE were particularly affected, with more than a 26% drop in future fish catch potential.

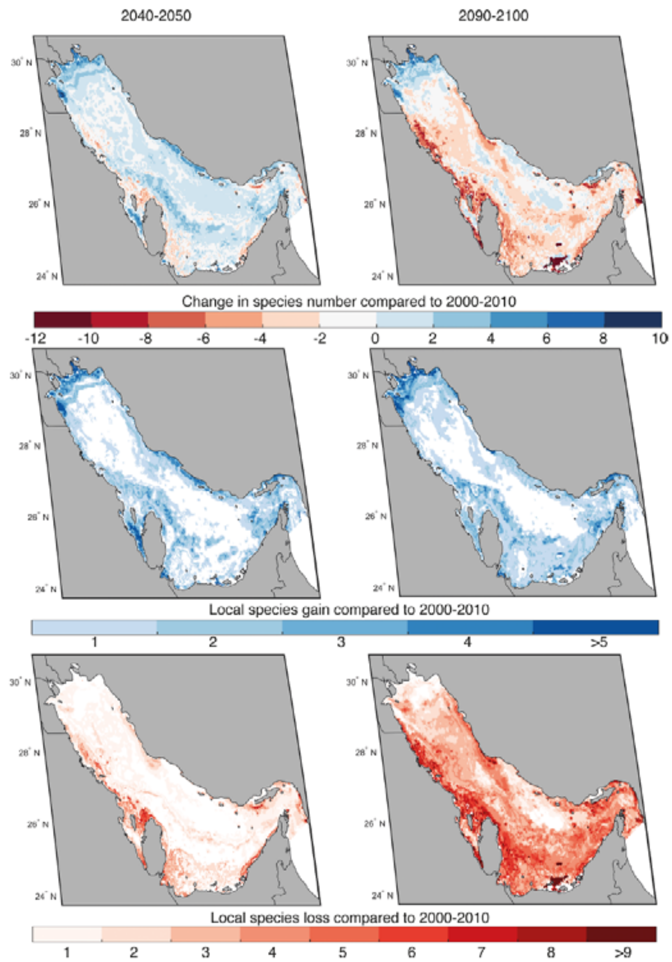

Figure 13: Projected change in species number (top), species invasion (middle) and extinction (bottom) in the I-RSA by 2050 (left) and 2090 (right) relative to 2010. Results are presented for an average of the three niche models and for the RCP 8.5 scenario. The colour bars represent number of species. From Wabnitz *et al*. 2018 [also see AGEDI 2015b].

Following coral bleaching events – associated with temporarily elevated seawater temperatures, reef fish assemblages have been observed to change. As the coral dies and the calcareous frame is gradually overgrown by algae, there is a drop in the total number of fish species observed, and at the same time herbivorous fish appear to proliferate and come to dominate over assemblages of fish that feed on invertebrates (Riegl, 2002). Local scale studies, such as in Bahrain, demonstrate that extensive overfishing on herbivorous fish only serves to entrench algal dominance over the coral on the reefs, and inhibits their potential for recovery (Morgan, 2006; Grandcourt, 2012; Burt *et al*., 2013).

The most recent International Union for Conservation of Nature (IUCN) report on the status of sharks and rays in the RSA indicates that 78 out of 153 species occurring in the Region are included within one of the three threatened categories ranked by: critically endangered, endangered or vulnerable (Jabado *et al*., 2017). The report attributes the elevated risk to these species to a combination of overfishing and habitat degradation as well as to the effect of climate change (Jabado *et al*., 2017). In a recent effort to evaluate the Regional conservation status of fish species based on IUCN Red List criteria, Buchanan *et al*. (2019) examined the extinction risk for all known marine bony fishes of the I-RSA and found that about 8.2% of the 471 marine bony fishes examined are under threat of Regional extinction, which is at least twice the proportion of other regions where such assessments have been undertaken. The highest concentration of threatened species occurs in the nearshore areas of the western I-RSA from Kuwait to the UAE and around several offshore islands. The distribution of threatened species seems to coincide most closely with coastal areas with high human activity (and hence overfishing or habitat degradation), exposure to extreme temperature events and anticipated climatic change. Offshore, deep-water habitats may provide refuge for some species (Burt, 2015; Burt *et al*., 2017). However, long-distance migrations across areas with little protection and limited availability of suitable habitats such as coral assemblages and seagrasses at such depths means that successful immigration to these areas is highly unlikely for many species.

3.4 Marine mammals and turtles

There are a range of marine mammal and turtle species present in the RSA, most of which are included in the 2019 IUCN Red List of Threatened Species as being at various levels of risk of extinction.

Marine turtle species include loggerhead, leatherback, hawksbill, green and olive ridley turtles. The habitats and life-cycles of the marine turtles in the RSA, are potentially vulnerable to climate change impacts, such as temperature change and SLR, but there is limited direct scientific evidence of climate change impacts on these species in the Region specifically. In the case of marine turtles, changes in ambient temperature can impact the sex ratio and fitness of hatchlings (e.g. Fuller *et al*., 2013) at nesting beaches. Rising sea levels and storms can cause severe damage to nesting grounds, and changes to food resources (seagrass) will compromise their overall fitness and resilience and ultimately survival.

According to model projections and based on estimates of future temperature relative to these species' current environmental niches, green and hawksbill turtles may experience a severe loss of habitat suitability, particularly around the southwestern parts of the I-RSA, and near the Strait of Hormuz (AGEDI, 2015b; Wabnitz *et al.,* 2018). The projected changes are similar for both species, with more substantial habitat loss for green turtles along the coast. These areas have been shown to be important for post-nesting green turtles, providing essential foraging grounds (Pilcher *et al.,* 2014). However, the migratory nature of marine turtles, and their ability to move considerable distances in short periods of time, should increase their resilience to climate change (AGEDI, 2015b; Wabnitz *et al.,* 2018). A recent study in the I-RSA showed that, when water temperatures were elevated, hawksbills travelling between nesting and foraging grounds undertook summer migration loops generally moving in a north-easterly direction toward deeper water, and had trajectories that were significantly inversely correlated with temperature (Pilcher *et al*., 2014). These summer migration loops of hawksbills in the I-RSA may be a thermoregulatory response to avoid elevated sea surface temperatures and potentially physiology-threatening conditions (Wabnitz *et al.,* 2018). Continued increases in temperature may force turtles to extend such migrations and spend more time in deeper cooler waters, increasing their overall energy demand (Wabnitz *et al.,* 2018). As cold-blooded animals, turtles will experience higher metabolic costs with increasing summer average temperatures, while at the same time they face the degradation of their habitats and food source (i.e. seagrasses). The status of the seagrass beds, the main source of food for green turtles, has not been considered in the expected changes of distribution pointed out by these models. In the context of the I-RSA, this may mean that marine turtles may spend less time in the Region in the future (AGEDI, 2015b).

Marine mammal records in the RSA include 24 species of toothed whales, dolphins, and porpoises (Odontoceti) as well as baleen whales (Mysticeti), and one species of sirenian (dugong). There are considerable gaps in the knowledge of marine mammal abundance and distribution, with the widescale reporting of by-catches, strandings, and other sources of mortality completely missing in the Region, which makes it particularly difficult to assess current or future impacts of climate change. For Indo-Pacific dolphins (Indo-Pacific humpback dolphin and Indo-Pacific bottlenose dolphin), projections indicate large declines in habitat suitability, particularly around the southwestern parts of the I-RSA. For Indo-Pacific bottlenose dolphin, however, the environmental niche models suggest a relative refuge in the northern part of the RSA (AGEDI, 2015b). In the case of dolphins and dugongs, changes in their environment other than sea temperature, such as alterations to the distribution and abundance of food are likely to be more significant in determining their vulnerability to climate change – particularly in the case of dugongs the impact of climate change and other human pressures on seagrass meadows, their exclusive source of grazing, can be critical (AGEDI, 2015b; Wabnitz *et al*. 2018).

The I-RSA is currently a major area where dugong are found, second only to Northern Australia (Preen*,* 2004). The most important habitats for dugongs, occur around Murawah Island (UAE); between Qatar and Bahrain; and between Qatar and the UAE (Preen, 2004). The range of dugong is broadly coincident with the distribution of seagrasses, although individual animals are able to move into different home ranges, travelling hundreds of kilometres in a few days (Marsh and Rathbun, 1990; Sheppard *et al*., 2006). A major factor controlling the movement of dugong is temperature. Dugongs have been sighted, grouped in large aggregations, during winter in the southern I-RSA, possibly seeking thermal springs (Preen, 2004). Projections are inconclusive for this species, with some models showing that the I-RSA would become less hospitable to dugong, particularly around the southwestern area, while other models predicted no overall loss of habitat suitability (AGEDI, 2015b). Projections suggest that dugong distribution may decline around the UAE and Qatar in response to declines in *H. ovalis* seagrass species. However, whilst these projections provide useful insights, confidence in projections is low because the models do not capture important ecological characteristics such as food availability, migratory behaviour, complex life histories and preference for particular habitats (AGEDI, 2015b; Wabnitz *et al.,* 2018). This is also true for projections of other marine mammals (i.e. cetaceans) that are fish predators. If we observe a decrease in fish abundance, particularly small pelagic species, this could affect the distribution of dolphins etc.

Al-Abdulrazzak and Pauly (2017) revealed that dugongs were once found more widely in the I-RSA than thought. Based on papers dating back to the 1800s, it was found that dugongs once inhabited the seas off Kuwait and Iran (Figure 14), however dugongs off Iran are now considered "vagrant". By reconstructing past distributions, the study concluded that the dugong range in the I-RSA has shrunk by about 26%, falling from a distribution within an area of 41,236km^2 to 30,606km^2. This reflects the reality that seagrass beds with which dugong are associated have also declined substantially, due to a number of climatic and non-climatic factors, causing higher than expected losses in the size and number of dugong herds (Al-Abdulrazzak and Pauly, 2017).

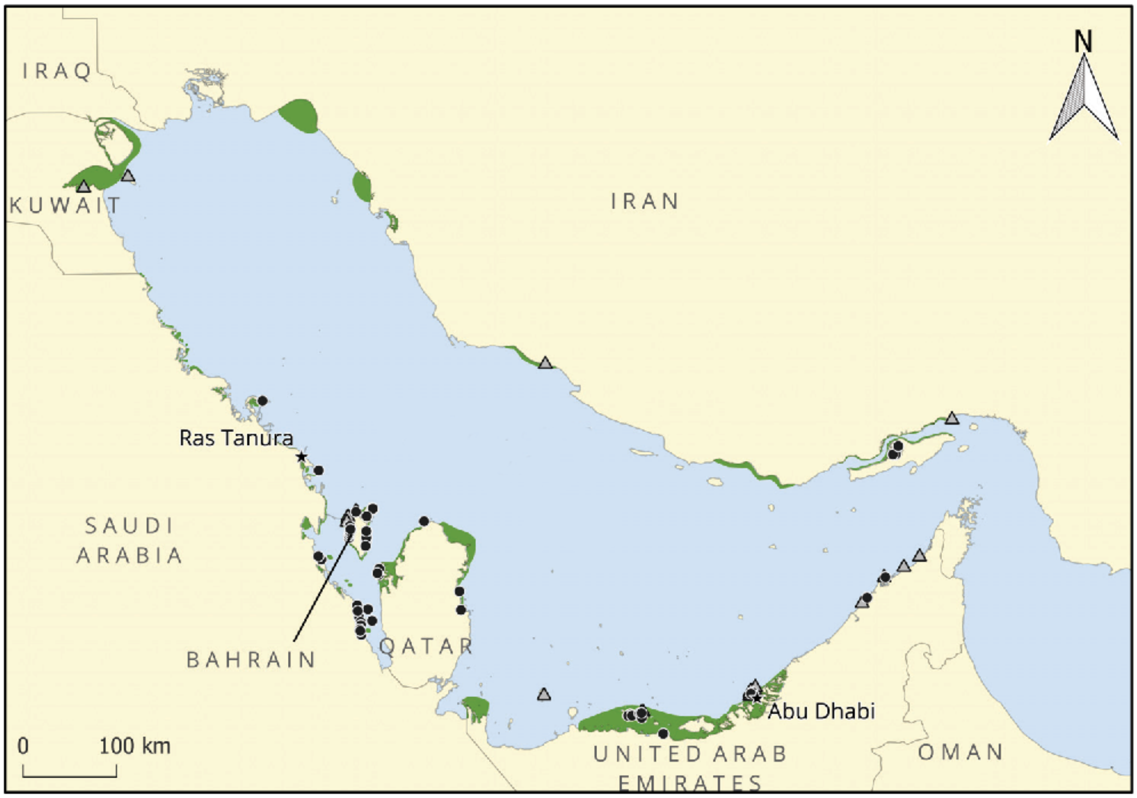

Figure 14: Dugong distribution in the I-RSA according to Al-Abdulrazzak and Pauly (2017).

Climate change is of concern to these species (AGEDI, 2015b), partly because they are under threat already, due to other human stressors such as over-exploitation (of the animal themselves or their food), accidental bycatch, shoreline developments, dredging, and oil drilling. The latter are likely to represent a more imminent and dangerous threat than climate change. On the other hand, marine mammals generally have broader tolerance to changes in temperature and salinity (Wabnitz *et al.,* 2018) compared to other (e.g. ectothermic) marine species. The cumulative effect of anthropogenic stressors could compromise their resilience and heighten vulnerability to future climate change (Baldwin *et al*., 1999; Naser, 2014; Wabnitz *et al.,* 2018).

3.5 Birds

The RSA is particularly important for wintering waders, passage migrants and breeding seabirds (especially the highly vulnerable Socotra cormorant). Intertidal coastal areas in the RSA support several million overwintering waders, making this a globally important Region for such species (Zwarts *et al*., 1991; ROPME, 2013). Sixty-five species have been identified in Kuwait alone (ROPME, 2013) and surveys undertaken in Saudi Arabia in 1991 recorded 21 wader species represented by nearly 30,000 individuals in winter (Zwarts *et al.,* 1991). These Internationally important populations of breeding seabirds and wintering shorebirds depend on freshwater and salt marshes, mangroves, coral islands and intertidal mudflats (Al-Obaid *et al*., 2017). Waterfowl are also regular users of the coastal area, particularly the mudflats of UAE where they congregate in their millions, and 65 species have been identified in Kuwait alone (ROPME, 2013). Mudflats, which are extensive particularly along the shores of the I-RSA, have been found to support greater wader feeding densities than rocky or sandy coastal areas (Zwarts *et al.,* 1991; ROPME, 2013) and clearly play an essential role in the life-cycle of these bird species.

The I-RSA is an important rest and feeding area for birds, mostly waders, that migrate from overwintering grounds further south to the northern breeding grounds and in spring these migrating birds surpass the numbers of resident wintering birds (Zwarts *et al.,* 1991). Offshore islands also provide nesting grounds for numerous colonies of terns: Bridled tern, Lesser crested tern, White-cheeked tern and Swift tern, as well as Socotra cormorant. The most common of the terns is the Lesser crested tern, with an estimated 25,000 pairs nesting on five of the Saudi Arabian coral islands in 1991, suggesting that the I-RSA hosts a large part of the world's breeding population of Lesser crested tern (Zwarts *et al.,* 1991). Greater flamingo are found throughout the RSA with resident populations in Iran (ROPME, 2013). Of all the seabirds found in the RSA, the majority are currently listed in the IUCN Red List as species of Least Concern, some as Near Threatened and one, the Socotra cormorant, as Vulnerable. In most cases, their global populations are currently decreasing.

As the RSA is a water-stressed Region, its wetlands are highly vulnerable to SLR and alterations to hydrological regimes driven by climate change, as well as human activities associated with sustained human population growth, habitat degradation, water abstraction and coastal development, with serious implications for the bird populations that depend on them (Al-Obaid *et al*., 2017).

There are large knowledge gaps with regard to the potential effect of climate change on seabird populations within the RSA specifically, however, scientific evidence from elsewhere suggests that climate change can be one of the main causes of seabirds decline worldwide. For example, an exhaustive review of seabird populations trends in Europe concluded that observed declines at the end of the last century were primarily related to the effect of climate warming on food supply (Daunt *et al*., 2017). In addition, there is growing evidence that short-term and extreme weather conditions such as coastal flooding and storms, which according to climate models are likely to become more severe and/or frequent, are having an important effect on long-term populations of seabirds (Daunt *et al*., 2017). Warmer winters and changes in the availability of fish prey can result in poor breeding success, reduced survival and overall population declines (MCCIP, 2017). Analysis of Black-faced spoonbill (*Platalea minor*) populations in Asia revealed that temperature fluctuations are capable of reducing population growth rates by half, suggesting that environmental variability could be a major driver in the dynamics of some bird populations (Pickett *et al*., 2015). In addition, loss of suitable low-lying coastal zones due to coastal erosion or inundation for example, and the presence of artificial coastal defences, can result in “coastal squeeze”, thereby restricting the space available for nesting seabirds with a potential negative impact on long-term populations sizes.

3.6 Corals and coral reefs

The composition and distribution of coral assemblages, their condition and the level of disturbance they experience differ markedly across the RSA. Typically, the healthiest corals occur in offshore shoals and as part of fringing reefs (Riegl and Purkis, 2012; Naser, 2014). Reports from ReefBase[8] of studies published in 2000 indicated that coral communities in the RSA still remained in relatively good condition (at least up to that point in time), despite the extreme conditions of temperature and salinity experienced, due in part to the mitigating effects of upwelling that cools summer seawater temperatures in the O-RSA and M-RSA, but also because corals in the Region may be pre-adapted to relatively harsh environmental conditions.

Figure 15 shows the historic distribution of corals in the RSA, and that they are known to have existed throughout the RSA in most shallow coastal areas (typically down to 10–15 m depth), with greatest coral diversity above 10m, Pilcher *et al*., 2000) and surrounding offshore islands (Maghsoudlou *et al*., 2008; Wilkinson, 2008; Coles and Riegl, 2013). Even though corals in the I-RSA are adapted to a harsh physical environment, living within these extreme conditions can lead to physiological stress, resulting in restricted growth and development, patchy distributions and an overall lower diversity of coral species compared to the wider Indian Ocean (Wilson *et al*., 2002; Wilkinson*,* 2008; Sheppard *et al.,* 2010; Vaughan *et al*., 2019). More recent studies show that some of the coral areas featured in Figure 15 have been lost or degraded since the study by Maghsoudlou *et al*. (2008) due to the combined effect of climatic and other human pressures (Burt *et al*., 2013; 2014; 2019).

Corals in the I-RSA are known to be genetically adapted to extreme conditions (Howells *et al*., 2016; Kirk *et al*., 2018; Smith *et al*., 2017). Changes have been observed in the formation of the reef in the I-RSA, due to mass mortality during high SST anomalies, where major frame builders Acropora and Porites are replaced by faviid-dominated communities (Riegl *et al*., 2011). In addition, the cover extent and calcification rates of several coral species has declined as their growth is stunted by bleaching episodes driven by climate warming (Goreau and Macfarlane, 1990; Cooper *et al*., 2008; Lough, 2008; De'ath *et al*., 2009; Cantin *et al*., 2010; Carilli *et al*., 2010; Carricart-Ganivet *et al*., 2012; Coles and Riegl, 2013; De'ath *et al*., 2013; Tanzil *et al*., 2013; Vajed-Samiei *et al*., 2013; Howells *et al*., 2018; Kourandeh *et al*., 2018). Research suggests that some species are able to sustain fecundity rate and gamete size to adapt to thermal stresses, to an extent, but coral reproduction appears to become impaired beyond their thermal thresholds, which is a concern for future corals in the I-RSA as SST increments are set to become increasingly extreme (IPCC, 2007; Baird and Maynard, 2008; Strong *et al*., 2008; Bauman *et al*., 2011; Albright and Mason, 2013; Bauman, 2013; Fabricius *et al*., 2017).

Another coping strategy of corals to deal with high SSTs is to accommodate populations of thermally tolerant algal symbionts (Baker *et al*., 2004; Van Oppen and Lough, 2009; LaJeunesse *et al*., 2010; Silverstein *et al*., 2015), either by hosting new symbionts after a bleaching event or by shuffling already present symbionts (Buddemeier and Fautin, 1993; Rowan *et al*., 1997; Baker *et al*., 2004; Berkelmans and van Oppen, 2006). This has been reported in corals collected from the I-RSA (Baker *et al*., 2004; Ghavam Mostafavi *et al*., 2007; Shahhosseiny *et al*., 2011; Hume *et al*., 2015; Varasteh *et al*., 2017; Oladi *et al*., 2019) and from the M-RSA (Oladi *et al*., 2019). The association between corals and Symbiodinium (Zooxanthellae) algal symbionts is highly sensitive to thermal perturbations and can break down under temperatures as little as 1°C above the average summer maxima, resulting in bleaching (Hume *et al*., 2015).

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[8] ReefBase: A Global Information System for Coral Reefs: http://www.reefbase.org/global_database/default.aspx?section=s1&region=51&country=IRN&dbid=38

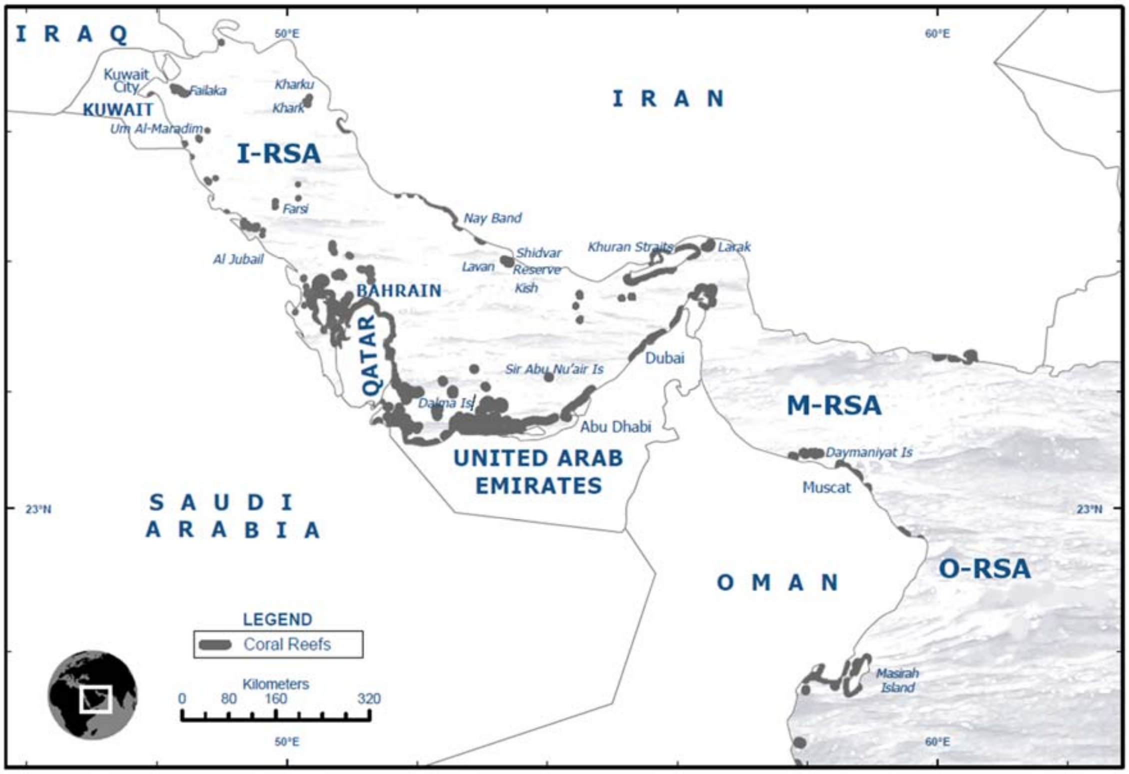

Figure 15: Historic distribution of coral reefs in the RSA according to Maghsoudlou *et al*. (2008).

In the I-RSA, coral reefs are typically less diverse and are characterised by stress-tolerant poritid and faviid coral species (Sheppard *et al.,* 2010; Bento *et al.,* 2016; Vaughan *et al*., 2019). Up to 28 coral species have been previously recorded in the I-RSA (Owfi *et al*., 2004). Within the M-RSA, there is a greater diversity of coral species, which are more stress-sensitive due to the area experiencing relatively less extreme water conditions on average, although they still experience major disturbances, compared to the I-RSA (Sheppard *et al.,* 2010; Bento *et al.,* 2016; Vaughan *et al*., 2019).

In the O-RSA coral growth is relatively limited, constrained by cooler temperatures on average, due to cold monsoon-driven upwelling in summer. According to Rezai *et al*. (2004) coral cover in the O-RSA is typically 30–40% at depths of 4–12 m and has not changed significantly, in spite of the impact of crown-of-thorns starfish outbreaks and periodic recruitment failures. Unlike the I-RSA and M-RSA, coastal industrial development in coral rich areas in O-RSA does not generally involve large-scale land reclamation or dredging. Fishing, however, remains the major human threat to coral communities in the O-RSA (Rezai *et al*., 2004). A century ago, reefs were healthy, structurally simple, dominated by Acropora (staghorn) corals to about 4–5 m depth, then by massive corals (Porites and Faviids) from 5m to about 10m. In the mid-1990's corals remained in similar condition in most areas but much of the coastal areas suffered losses due to coastal development and oil and gas exploration.

Severe SST anomalies have resulted in recurrent coral bleaching events throughout the Region in 1996, 1998, 2002, 2010, 2011, 2012 and 2017 (Wilkinson*,* 2008; Coles and Riegl, 2013; Burt *et al.,* 2019; Vaughan *et al*., 2019). This has in turn resulted in the loss of entire shallow water staghorn (Acropora) zones, killed in many areas and reduced to rubble in less than a decade, the mobile rubble likely impeding new recruitment (Rezai *et al*., 2004; Paparella *et al*., 2019). Some deeper sites are showing signs of recovery where there is significant recruitment of more tolerant and adaptable species that previously made up a minor components of the reefs. This suggests that, in the long term, there could be a shift in the species that dominate the I-RSA and M-RSA reefs (Rezai *et al*., 2004). Levels of estimated reef destruction ranged widely within the Region, from a low of 1% in Oman to a high of 97% in Bahrain (Rezai *et al*., 2004). Rezai *et al*. (2004) predicted that by 2014 the shallow staghorn coral reefs would be unlikely to recover due to unfavourable sea temperatures, while deeper reefs would increase their cover, probably with a shift in the dominant species. A later review by Maghsoudlou *et al*. (2008) suggested that SST anomalies in 2002, the impact of Cyclone Gonu in 2007 and a subsequent bleaching event in the northern I-RSA later in the same year, added to the direct damage by coastal engineering activities, and caused severe and widespread losses resulting in the complete disappearance of corals in some areas. For example, Bahrain is in severe danger of losing all its coral reef resources, and most coral communities off Qatar are essentially extinct, with the exception of a few offshore reefs (Maghsoudlou *et al*., 2008; Burt *et al*., 2013; Burt *et al*., 2016). In the I-RSA, corals are currently experiencing extremes of high SST that for other tropical regions are not projected to occur until the end of century (Naser, 2014; Burt *et al.,* 2019; Vaughan *et al*., 2019).

Except for some hot spots of coral abundance and diversity around offshore islands, most of the coral reefs throughout the Region have exhibited varying degrees of stress, damage and mortality during recent bleaching episodes (Riegl, 2003; Burt *et al.,* 2008; Wilkinson *et al.,* 2008; Burt *et al.,* 2011; Riegl *et al.,* 2012a; Coles and Riegl, 2013; Bento *et al.,* 2016; Vaughan *et al*., 2019). These impacts are likely to become more acute if bleaching events become more frequent and severe, as is expected with climate change (Burt *et al.,* 2011; Coles and Riegl, 2013; Wong *et al.,* 2014; Paparella *et al*., 2019). A recent study by Paparella *et al*. (2019) at three coral sites near Abu Dhabi shows that summer sea-bottom temperatures are tightly linked to Regional wind regimes, and that strong north shamal wind events control the occurrence and severity of bleaching. Years with reported bleaching events (2012 and 2017) were characterised by low wind speeds that resulted in temperatures persisting above coral bleaching threshold for >5 weeks. In the cooler intervening years (2013–2016), the summers had more frequent and/or strong shamal events, which repeatedly cooled temperatures below bleaching thresholds for days to weeks, providing corals temporary respite from thermal stress (Paparella *et al*. 2019).

Corals in the M-RSA are particularly exposed to the impact of tropical cyclones. A survey of live hard and soft coral along the Muscat Oman shoreline before and after Cyclone Gonu revealed significant destruction that corresponded spatially with physical damage from the cyclone in June 2007 (Coles *et al*., 2015). The greatest mortality and structural damage were experienced at wave-exposed locations and on stands of Acropora and Pocillopora, which are typically less resistant to physical disturbance (Coles *et al*., 2015). Massive Porites, Platygyra and Faviia species were also affected in the most exposed locations by wave breakage or wave-related sand abrasion. In areas of intermediate exposure, branching and tabular corals were more impacted than massive forms, but these fast-growing species were noted to recover within one year, particularly at island locations (Taylor, 2010). In sheltered, shallow areas with low flushing rates, associated freshwater runoff caused significant mortality of massive Porites colonies (Maghsoudlou, 2008). Similar results were found for impacts to coral communities from Cyclone Gonu further north in the M-RSA off Fujairah and Dibba, in the UAE (Foster *et al*., 2008) followed by indications of some recovery within one year (Coles *et al*., 2015). Projected changes in tropical cyclone activity under climate change may pose further threats to the persistence of coral species in areas directedly affected by cyclones, notably in the O-RSA (Murakami *et al.,* 2013).

Coral diseases can take a significant toll on corals of the I-RSA and M-RSA and have caused coral losses in the last decade (Riegl *et al*., 2012). The Arabian Yellow band disease seems to be unique to the I-RSA and M-RSA, but other diseases have also been described some of which are as yet uncharacterised, for example Black band disease, White syndrome, Pink spots and Pink line disease and ciliate infections (Riegl 2002; Samimi-Namin *et al*., 2010). A link between climate warming and disease, where thermal anomalies and bleaching events are followed by outbreaks of disease has been confirmed in UAE waters after the 2010 bleaching event (Riegl and Purkis personal observation, in Riegl *et al*., 2012b). The prevalence of coral diseases has been found to correlate with ocean heat and coral disease outbreaks in the aftermath of bleaching events have been widely reported elsewhere (Brandt and McManus, 2009). In the O-RSA, disease may also pose a further threat under climate change, as ocean warming may lead to more frequent disease outbreaks, impacting coral structure and dynamics (Riegl *et al.,* 2012b).

Coral reefs were one of the first ecosystems to be recognised as being vulnerable to ocean acidification. Ocean acidification (OA) threatens coral reef futures by reducing the concentration of carbonate ions that corals need to construct their skeletons. However, quantitative predictions of reef futures under OA are confounded by contradictory responses of often closely related corals to OA in experiments and field observations (Chan and Connolly, 2013). The skeletal growth of corals consists of two distinct processes: extension (upward growth) and densification (lateral thickening). Mollica *et al*. (2018) demonstrated that skeletal density in corals is directly sensitive to changes in seawater carbonate ion concentration and thus, to OA, whereas extension is not. Unfortunately, there have been very few studies focused on responses of corals to OA in the RSA specifically. However, a recent paper by Saleh *et al*. (2020) characterised the temporal and spatial variability of seawater carbonate chemistry on the nearshore waters of the Iranian side of the I-RSA, adjacent to coral patches and rocky intertidal shores. In the case of coral patches, all measurements and sub-samplings were performed on water samples taken from a depth of 1m above corals. pCO_2 at Hengam coral reefs located in the western part of the Strait of Hormuz was measured to be in the range of 378 ± 32 to 473 ± 25µatm with an annual average of 430µatm which is significantly higher than the corresponding atmospheric values (about 400–410ppm at the time of the study by Saleh *et al*., 2020).

Climate change is happening against a wider backdrop of coral decline across the Region, and other anthropogenic pressures stressing these systems. It is estimated that almost 70% of original reef cover in the I-RSA has already been lost (Burt *et al*., 2014; Sheppard, 2016; Vaughan *et al*., 2019) and that remaining is threatened by local human activities (Burke *et al.,* 2011; Naser, 2011; Burt, 2014; Vaughan *et al*., 2019), which can also aggravate the risk of diseases, as well as outbreaks of crown-of-thorns starfish (ROPME, 2013). Human pressures include coastal development, introduction of brine from desalinisation plants, sediment runoff from dredging and reclamation, pollution, eutrophication and sewage discharges, recreational boating and anchoring and overfishing including ornamental, recreational and commercial fishes (Wilkinson *et al.,* 2008; ROPME, 2013; Bento *et al.,* 2016; Petersen *et al*., 2018).

By 2030, almost 90% of corals within the I-RSA are projected to be under high threat from the combined effects of climate change (warming, ocean acidification) and local stressors, and by 2050 virtually all reefs will be under critical threat (Burke *et al.,* 2011).

3.7 Saltmarshes, mudflats and sabkhas

Saltmarshes and mudflats in the RSA are highly bio-productive intertidal environments that provide a sanctuary for biodiversity offering habitat, food and resting areas for a wide range of organisms. The huge numbers of migrating waders and waterfowl that reside or visit these habitats in their millions every year make these habitats a globally important resource (Lutz, 2011; Al-Obaid *et al.,* 2017). Mudflats are also favourable areas for mangrove growth and colonisation by algal and cyanobacterial mats (Naser, 2014; Al-Obaid *et al.,* 2017; Vaughan *et al*., 2019).

Saltmarshes, together with other vegetated coastal ecosystems (mainly mangrove forests and seagrass beds) play a valuable role in sequestering carbon dioxide, termed “blue carbon” (McLeod *et al*., 2011; Lutz, 2011). Carbon burial rates per year for saltmarsh in the western I-RSA have been estimated at 81 ± 20 Mg C_{org}/ha and 8 ± 4 g C_{org}/m^2 respectively (Cusack *et al*., 2018). In addition, these wetlands provide important societal services generated from coastal protection, mineral extraction, agriculture and grazing (Lutz, 2011; Al-Obaid *et al.,* 2017).

In terms of distribution, marshes and mudflats are more extensive along the low-lying coastline of the I-RSA, with tidal mudflats most commonly found in low energy environments well flushed by the tide, often adjacent to mangrove forests and sabkhas (salt flats) along the coast of the UAE, Kuwait and Saudi Arabia (Lutz, 2011; ROPME, 2013; Vaughan *et al*., 2019). These salt flats form through sea inundation followed by progressive sedimentation until the sabkha is only flooded after rainstorms, when it reaches an elevation of about 1 m or more above sea-level (Al-Farraj, 2005). There are extensive and well-studied coastal sabkhas along the southern shoreline of the I-RSA. For example, field-based observations have been made on a regular basis in the Abu Dhabi sabkha since the year 2000 (Wilson *et al*., 2013; Lokier *et al*., 2018).

Despite their ecological values and societal services, the long-term permanence of Saudi Arabia’s wetlands faces strong challenges resulting from human activities associated with sustained population growth, habitat degradation, and coastal development, as well as climate change (Al-Obaid *et al.,* 2017). Changes in precipitation and temperature regimes are expected to seriously impact wetland ecosystem services including provision of fisheries, recreational activities, and wildlife habitats (Al-Obaid *et al*., 2017).

Intertidal mudflats and saltmarshes across RSA are under increasing pressure from the combined effects of rising sea-level, over-exploitation, coastal development and drainage (Al-Obaid *et al.,* 2017). Their loss will not just affect the habitats they support, including mangroves, but also reduce the function they play in preventing coastal erosion and climate regulation (ROPME, 2013). The destruction or disturbance of these habitats could result in the remineralisation of a fraction of the stored carbon, giving rise to significant carbon emissions, while also making the ecosystems incapable of acting as carbon sinks in the future (Cusack *et al*., 2018). The intertidal mudflats and saltmarshes in the RSA are especially vulnerable to climate change driven SLR, increasingly arid conditions with very limited rainfall, reduction in permanent fresh water and an increasing human population (Cusack *et al*., 2018). The long-term permanence of these coastal wetlands faces strong challenges as the rate of environmental changes accelerates (Al-Obaid *et al.,* 2017).

3.8 Mangroves

Mangroves are the only evergreen forests in the RSA and are found along the shores of all RSA Member States with the exception of Iraq, as shown in Figure 16 (Naser, 2014; Ward *et al.*, 2016; Vaughan *et al*., 2019). A recent study mapped 165 km^2 of fragmented and scattered mangroves in the Region, with the most substantial coverage recorded for the UAE, where plantation projects have contributed to increasing forest cover (Almahasheer, 2018). Similarly, change detection analysis was conducted on mangrove forests along the Saudi Arabian coast of the I-RSA, and this suggested an overall increase in mangrove coverage the northern Tarut Bay and Tarut Island, by 0.21 km^2 from 2000 to 2010 and by 1.4 km^2 from 2010 to 2018. The increase was primarily due to mitigation strategies such as mangrove breeding and re-plantation projects (Li *et al*., 2019).

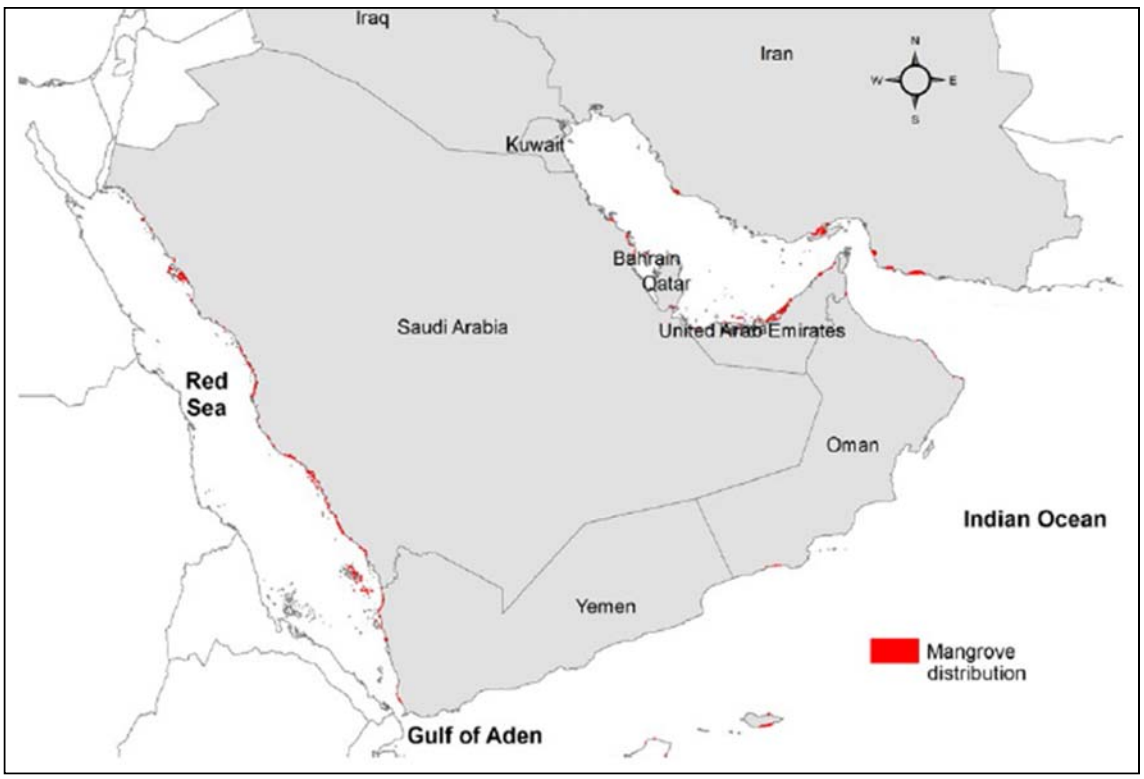

Figure 16: Distribution of mangroves in the RSA and Red Sea (Ward *et al*., 2016, data derived from Giri *et al*., 2011).

These mangrove forests are some of the most northerly in the world and are predominantly dominated by the native species, *Avicennia marina*, as this species is best adapted to cope with the hypersaline conditions they experience (Dodd *et al.,* 1999; Lutz, 2011), although *Rhizophora mucronata* or red mangrove is also found in some areas, often introduced (Ward *et al.,* 2016). *Avicennia marina* covers ca. 130 km^2 across the Region, three-quarters of which are in Iran (Van Lavieren *et al*., 2011) and with the largest single area of mangrove coverage (38 km^2) found in Abu Dhabi, UAE (Dodd *et al.,* 1999). *Rhizophora mucronata* is known to occur on the Iranian side on the

Strait of Hormuz, but only occupies an area of 0.2 km^2 (Sheppard *et al*., 2010). *Avicennia marina* varies from 2–6m in height in the M-RSA and up to 10m in the O-RSA (Fouda and Al-Muharrami, 1996; Lutz, 2011), whereas in the I-RSA mangrove trees are poorly developed and often stunted (1–2 m), at least along the western shores (Price *et al*., 1993; Kauffman and Crooks, 2015).

Climate change is likely to have a substantial impact on mangrove ecosystems, through processes including SLR, increased storm damage, increased temperature, and changes in precipitation (Ellison, 2015; Ward *et al.,* 2016) (Table 2).

Table 2: Exposure components of climate change impacts on mangroves, processes affected, and sensitivity outcomes, adapted from Ellison (2015).

Exposure components	**Processes affected**	**Sensitivity components**
Rising sea level	Forest health Forest productivity Recruitment Inundation period Accretion rates	Forest mortality, dieback from the seaward edge, migration landward, depending on sediment inputs, topography and lack of barriers
Increased waves, wind, and extreme storms	Forest productivity Recruitment Accretion rates	Forests damaged or spatial area changed, surface elevation change, erosion or excess sedimentation
Increased air and sea temperatures	Respiration Photosynthesis Forest productivity	Reduced productivity at low latitudes and increased winter productivity at high latitudes
Enhanced carbon dioxide	Photosynthesis Respiration Biomass allocation	Increased productivity, subject to limiting factors of salinity, humidity, nutrients. Soil elevation increase
Increased rainfall and freshwater availability	Sediment inputs Ground water Salinity Productivity	Increased accretion and maintenance of surface elevation, increased ground water, diversity, productivity and recruitment
Reduced freshwater availability	Sediment inputs Ground water Salinity Photosynthesis Forest productivity	Reduced ground water, diversity, photosynthesis, productivity, and accretion Mangrove migration landward, species changes

A lack of information on climate change impacts on mangroves within the RSA, compared to other regions of the world, makes it difficult to confidently make predictions (Ward *et al.,* 2016). High spatial resolution remote sensing imagery is increasingly being used to map the extent and changes to mangrove forests, but it can be challenging to detect changes in certain areas where submerged mangroves can be confused with salt marshes and macroalgae (Li *et al*., 2019). Some estimates of 2.2 mm per year of SLR in the RSA and 0.7 mm subsidence per year (Alothman *et al*., 2014), coupled with the constrained location of many mangrove forests whose landward migration is being limited by coastal development (so-called 'coastal squeeze'), suggest that up to 96% of the RSA coastal wetlands including mangroves could be at risk by the end of the 21st Century (Blankespoor *et al.,* 2014; Ward *et al.,* 2016).

Projected increases in surface air temperature by the end of the century could constrain mangrove growth rates, due to moisture limitation and temperatures exceeding their maximum tolerance limit

(Lelieveld *et al.,* 2012; Ward *et al.,* 2016). At the same time, particularly in the O-RSA and M-RSA, a predicted decrease in precipitation, and increased evaporation and salinity levels of seawater are likely to further impact mangrove forests as well as affecting accretion of fluvial and runoff sediment supply, which is important for maintaining surface elevation and counteracting SLR (Clough, 2013, Ranasinghe *et al.,* 2013, Kostopoulou *et al.,* 2014). Intense storms and cyclones can significantly impact mangrove productivity and health and could become an increasing problem due to projected changes in extreme weather events (IPCC, 2013). Taking all these climate change pressures together, and the effects of coastal development and other stressors including heavy metal pollution, the remaining mangrove forests in the RSA are at substantial risk (Ward *et al.,* 2016; Al-Kahtany *et al*., 2018; Almahasheer, 2019).

Mangroves play a vital role in mitigating climate change, storing a significantly high amount of carbon per square meter compared to tropical forests and other vegetated ecosystems (McLeod *et al.,* 2011). Emissions resulting from mangrove losses make up nearly one-fifth of global emissions from deforestation, resulting in economic damages of some 6–42 billion USD annually (UNEP, 2015). In a recent study of organic carbon sequestration and storage in vegetated coastal habitats of the I-RSA, it was shown that mangroves (along with seagrass and saltmarshes) are acting as active CO_2 sinks, burying substantial amounts of carbon on an annual basis (Cusack *et al.,* 2018). The destruction or disturbance of these habitats could result in the remineralisation of some of the carbon stored within these systems and give rise to significant CO_2 emissions, while also making the ecosystems incapable of acting as carbon sinks in the future (Cusack *et al.,* 2018).

A national report to the UNFCCC prepared by Bahrain (General Commission for the Protection of Marine Resources, Environment & Wildlife, 2005), suggested that mangrove areas are already under high stress due to land reclamation activities. In the event of SLR, major areas of mangrove would be inundated and, in theory, this could lead to a gradual retreat to areas inland. However, in view of land reclamation and associated commercial land development pressures, it is unlikely that there will be suitable areas to accommodate the gradual landward retreat of mangrove forests. The total area of mangrove plantations affected, though not directly quantified in the SLR vulnerability assessment, is expected to be quite high. Coastal salt marshes in the main islands will be among the hardest hit due to rising sea levels in terms of the extent of impact. Home to unique and sensitive ecosystems, the total area that would be affected by a 1 m rise in sea level is about 32 km^2 equivalent to ~ 55% of all submersed habitats and 5% of the total land area of the main islands.

3.9 Seagrass

Seagrasses are present along the shores of most RSA countries with the exception of Iraq, and their presence is limited in Kuwait. They are most common in the vast shallow subtidal areas that dominate much of the south and southwestern I-RSA (Erftemeijer and Shuail, 2012; Vaughan *et al*., 2019) (see Figure 17). In 2012, 70% of the seagrass habitat in the I-RSA was mapped, yielding an estimated area of around 7,000 km^2 (Erftemeijer and Shuail, 2012), however this may be an underestimate as the survey did not include seagrasses that exist below 14 m depth. The largest areas of seagrass are typically associated with sandy and muddy substrates in nearshore and shallow waters off the coasts of UAE and between Bahrain and Qatar (Erftemeijer and Shuail, 2012; Naser, 2014; Vaughan *et al*., 2019). Three species occur in the I-RSA, the most abundant being *Halodule uninervis* (90% abundance) followed by *Halophila stipulacea* and *Halophila ovalis*, and *Syringodium isoetifolium* can also be found along the coasts of Oman (Wilson, 2000). All these species are known to be opportunistic, and tolerant of the extreme salinity and temperature conditions encountered in this area, particularly in the I-RSA (Erftemeijer and Shuail, 2012; Naser, 2014). Most seagrass populations in the RSA do not appear to be restricted by high salinities and can be found thriving in hypersaline coastal lagoons at salinity levels exceeding 62PSU (Erftemeijer and Shuail, 2012). Records show that seagrass plants grow as deep as 22 m, although the maximum depth penetration of seagrasses has not yet been thoroughly assessed (Vousden, 1986; Phillips, 2003; Erftemeijer and Shuail, 2012).

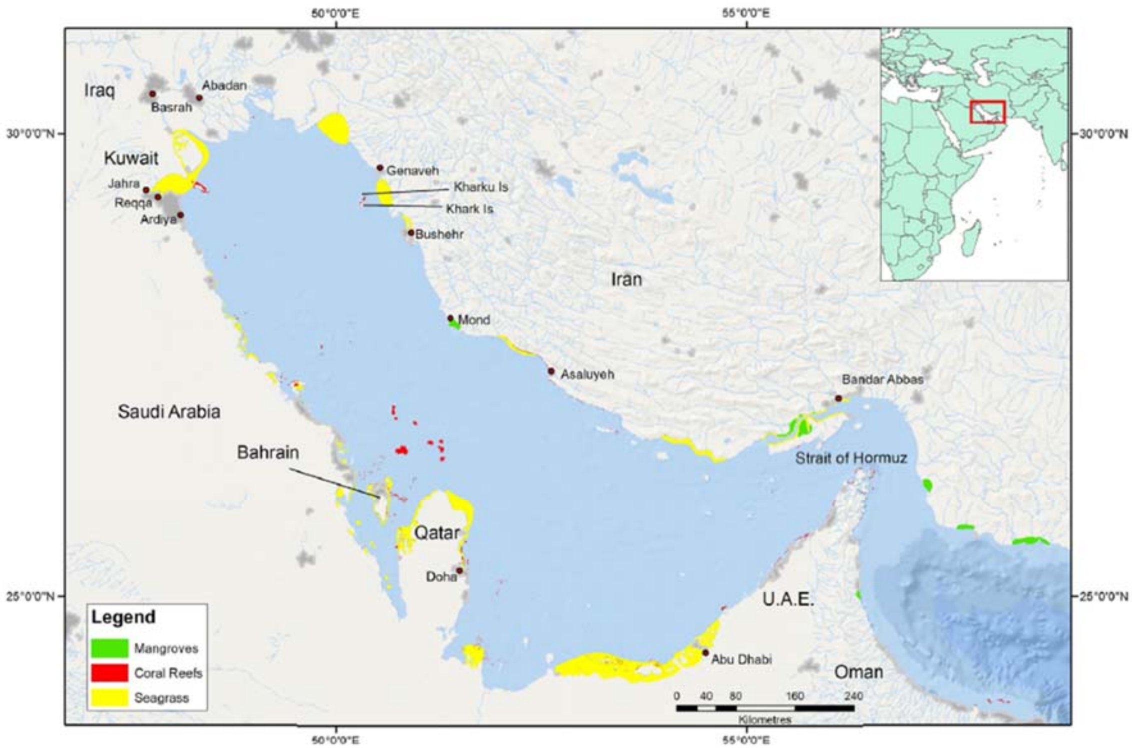

Figure 17: Distribution of seagrass beds in the I-RSA according to Vaughan *et al*. (2019).

In the I-RSA, seagrasses are critical for the sustainability of important artisanal fisheries as they are nursery grounds for fish, penaeid shrimps, pearl oyster, and other molluscs. They provide indirect energy to the detrital food web and they offer a feeding ground for threatened species including sea turtles and dugongs (Preen, 2004; Erftemeijer and Shuail, 2012; Naser, 2014; Vaughan *et al*., 2019). Seagrass beds contribute to stabilising loose sediment and protect against coastal erosion throughout the I-RSA (Duarte *et al*., 2005).

Tropical seagrasses like those found in the RSA can withstand higher than ambient temperatures, with optimal ranges between 25 and 37°C, but are adversely affected by prolonged exposures. Temperatures 4 to 5°C above summer ambient maxima cause extensive defoliation in seagrasses, and conditions above 40°C for an extended time are considered lethal (McMillan, 1984; Erftemeijer and Shuail, 2012). A mean sea surface temperature increase of 2°C by 2100 would exacerbate the stress on seagrasses already living near their thermal tolerance limits. However, the magnitude of impacts will depend on whether seagrasses can adapt fast enough to rising temperatures. Sustained thermal stress also increases the susceptibility of some seagrass species to "wasting disease", which can in turn lead to mass mortality (Rasmussen, 1977).

SLR will increase the depth of water where seagrasses are found, potentially impacting the amount of light available for growth. Changes in turbidity of the water and current patterns may lead to erosion of seagrass beds, or alternatively open up new areas for colonisation (Björk *et al*., 2008). In some environments, where seawater is restricted and productivity reduced, such as in semi-enclosed shallow lagoons, SLR could improve water circulation and thus productivity, provided the beds are able to accrete rapidly enough to maintain their depth relative to mean sea level (Edwards, 1995; Björk *et al*., 2008). It has been suggested that seagrass communities could migrate shoreward as sea level rises (Edwards, 1995), but this would depend on the availability of space, which may be limited due to increased coastal development within the RSA.

Major storms events cause direct damage to seagrasses through scouring and leaf loss, and inputs of freshwater runoff laden with terrestrial nutrients and sediments that cause persistent turbidity and poor water quality, limiting the growth of the seagrass for long periods after storm events (Green and Short, 2003; Björk *et al*., 2008). Sedimentation has been shown to smother and cause deterioration of seagrass beds, when the sedimentation rate exceeds their tolerance and overrides their rate of vertical growth (Marba and Duarte, 1994; Erftemeijer and Shuail, 2012). Pioneer species such as *Halophila ovalis* have very low thresholds for sedimentation (0.05m per year) compared to larger climax species (Vermaat *et al*., 1997; Naser 2014). Future increases in the frequency and/or magnitude of storms and cyclone events may threaten seagrasses throughout the RSA, particularly those in shallow locations, by causing transient turbid and silty conditions (Edwards, 1995; Björk *et al*., 2008). Seagrasses in the RSA also face intense dredging and land reclamation activities, which can lead to turbid and silty conditions and therefore further degradation and/or loss of these habitats is considered likely (Erftemeijer and Shuail, 2012; Naser, 2014).

Seagrasses are carbon limited and, consequently, seagrass productivity is expected to be stimulated under conditions of higher CO_2. This could represent a potential positive feedback, with seagrasses also acting as ocean acidification refugia if they locally buffer pH levels and facilitate improved calcification rates in adjacent coral reefs or calcifying communities within coastal zones (Manzanello *et al*., 2012). Whilst increasing atmospheric CO_2 could positively affect some seagrass species, by stimulating growth and therefore increasing productivity, this could also favour growth of epiphytic algae, which may cause shading over seagrasses (Björk *et al*., 2008).

Seagrasses are known to sequester and store large quantities of carbon, within the plants themselves and the sediment below (Duarte *et al.,* 2005; Duarte *et al.,* 2013b). In the I-RSA, despite the small plant size and the low carbon content per unit of soil (Campbell *et al*., 2015), the largest stock of organic carbon per total area belongs to seagrass beds as a result of their large spatial coverage compared to mangroves and saltmarshes (150Tg of C_{org} stored by seagrass beds in the top meter of sediment, based on a total mapped extent of 7,000 m^2 of seagrass meadows across the I-RSA, according to Cusack *et al*., 2018; and a mean of 49 MgC per ha based on measurements taken in seagrasses in Abu Dhabi by Campbell *et al*., 2015).

3.10 Rocky shores and macroalgae communities (seaweeds)

Rocky shore communities exist throughout in the RSA and have been extensively studied by researchers at some localities (e.g. Qeshm Island, Iran). Anvar Batcha (1997) studied the intertidal macrobenthic fauna at two sites in Saudi Arabia (Half Moon Bay and Dammam Corniche) and demonstrated that several different assemblages exist, the extent and prevalence of which may be determined by temperature. It is possible that rocky shore communities could be impacted by the effect of high and rising air or seawater temperatures, which can cause excess evaporation and therefore extremely hot and saline conditions in rock pool habitats during low tide. However rocky shore animals and plants are already known to be among the most robust organisms on the planet, having to withstand huge variability in temperature, salinity, CO_2 concentrations, physical abrasion, light exposure and desiccation as part of their daily lives.

Vinagre *et al*. (2016) examined the temperature tolerance and acclimation capacity of 35 coastal species from temperate and tropical waters (crabs, shrimp and fish). Tolerance of warming was found to be higher for temperate species than for tropical species and higher for subtidal species than for intertidal species, confirming that species with the highest thermal limits have the lowest warming tolerance. The tropical species tested showed a lower acclimation capacity than their temperate counterparts. Given that tropical rocky shore organisms are already living very close to their thermal limits and that their acclimation capacity is limited, it is possible that the impacts of global warming will be evident sooner in the tropics than in the temperate zone (Vinagre *et al*. 2016). In Half Moon Bay (Saudi Arabia), during the sample collection period, temperature ranged between 32°C to 40°C in May 1994 and these high temperatures were suggested to be one of the important factors that limit the distribution of intertidal benthic macrofauna in this area, when compared to the lower temperatures recorded in the Dammam Corniche area (20.8°C to 32.5°C) where, higher faunal distribution and diversity was recorded (Anvar Batcha 1997).

Schils and Wilson (2006) demonstrated that the easternmost point of the Arabian Peninsula, Ras Al Hadd (Oman), acts as a boundary for marine macroalgae (seaweeds), with distinctly different species composition and richness in the M-RSA (Sea of Oman) to the north of Ras Al Hadd compared to the O-RSA further south, associated with differing temperature affinity of the species observed. A temperature limit at 28°C was identified, using both the temperature affinity data of the plants themselves and the seasonal temperatures recorded for the specific localities. The unique flora of the Dhofar region (Oman) stood out as a hotspot of endemism within the Arabian Sea owing to the number of cold-adapted species associated with upwelling conditions (Schils and Wilson, 2006). With anticipated rises in seawater temperature throughout the RSA, as well as changes to upwelling intensity and frequency, it seems likely that the RSA will begin to witness changes to the biogeography of macroalgae, with particular impacts on the unique assemblage associated with Dhofar.

A unique, commercially important and endemic abalone species *Haliotis mariae* is found associated with the macroalgal assemblage at Dhofar (De Waal *et al*., 2016). The winter north-easterly monsoon and the summer south-westerly monsoon have a significant effect on the incremental growth of juvenile abalone (De Waal *et al*., 2016). Cold upwelling of nutrient-rich waters that promote the growth of *Ulva* sp. and other algae, including macro algal forests of *Sargassopsis zanardinii*, *Sargassum* spp. and *Ecklonia radiata*. These seasonal macro algal communities peak during the post-monsoon season (September to October) and begin to decline during the winter months (November to January) when the northeast monsoon occurs and temperatures are in excess of 20°C. Future climate change could greatly impact the growth and seasonal productivity of abalone, which currently supports an important fishery. The fishery, which lies along the western Dhofar coast between Mirbat and Hassik, has been in decline for a number of years (De Waal *et al*., 2016).

Storms and cyclones can have devastating effects on rocky shores of the RSA. A combination of intense waves and sand scouring can remove all signs of life from large stretches of coast following the passage of a large cyclone. Anecdotal evidence suggests that this was the case after Cyclone Gonu, the most powerful storm in the Region in 60 years, that occurred in June 2007. However, there is a lack of research and virtually no evidence of long-term changes in benthic invertebrate communities that inhabit rocky shores of the RSA. Amini *et al*. (2012) suggest that for Qeshm Island in the Strait of Hormuz, gastropod abundance was not significantly affected by Cyclone Gonu but species diversity was impacted.

4. Current and future impacts on economy and society

In the following section a categorisation scheme for ecosystem services to human society has been adopted, based on the Environmental Benefits Assessment approach suggested by Hooper *et al*. (2014). *Environmental benefits* are identified where a direct gain in human welfare is provided by environmental goods and services, as opposed to the *environmental services* that provide those benefits. For the purposes of this report, benefits are analysed from an anthropocentric perspective and include not only goods, but also intangible gains (e.g. wellbeing). Environmental benefits to society have been grouped into four main types of services (provisioning, carrier, cultural and regulating), each of which provides different benefits or values:

- provisioning services (direct use, consumptive):
  - food;
  - raw materials and energy;
- carrier services, or the space necessary for undertaking certain activities (direct use, non-consumptive);
- cultural services (direct use, non-consumptive):
  - recreation and tourism;
  - heritage and wellbeing;
  - research;
- regulating services (indirect benefits):
  - water and air quality;
  - flood and erosion control;
  - climate regulation;
  - human health.

For illustrative purposes, the benefits provided under each service for a generic UK macrotidal estuary are provided below.

Table 3: An Environmental Benefits inventory for a generic UK macrotidal estuary, adapted from Hooper *et al*. (2014).

Type of value	Service type	Benefit/Value category	Examples of specific benefits
Direct Use (consumptive)	Provisioning	Food Raw materials	Fish, shellfish, marine plants and algae Bait, aggregates, industrial products, biofuels
Direct Use (non-consumptive)	Carrier Cultural	Provision of space Recreation and tourism Cognitive development Heritage and identity Psychological wellbeing	Transport, mooring, energy installations Nature watching, angling, watersports Education, research Archaeology, cultural heritage Visual amenity, inspiration
Indirect Use	Regulating	Contaminat control Disturbance prevention	Clean water and air Flood and erosion control, climate regulation
Non-Use		Existence, Bequest	Knowledge that adequate habitat is available locally and will continue to be so in future
Future Use		Option	Availability for alternative future uses

The impact of climate change is then analysed for each of those types of environmental services, based on the available, or accessible literature.

Biodiversity provides an environmental service and as such, it is dealt with separately in Section 3. Biodiversity is difficult to quantify because its value is derived partly through cultural services, as well as more intangible existence and bequest values. However, national, Regional and International legislation requires the conservation of biodiversity and the maintenance of "good environmental status" and therefore the impacts of climate change on the environmental benefits of biodiversity are considered in this context, linking back to environmental protection and legislation (Hooper *et al*., 2014).

A national climate change risk exercise undertaken in the UAE, provides a good example of attempts at the country level to identify (and prioritise) societal impacts. The assessment highlighted the following as priority risks to four main sectors: i) Environment: coral bleaching, loss of wetlands; ii) Health: reduced productivity of outdoor workers due to heat stress; iii) Energy: efficiency losses of power plants, reduced power output due to warmer cooling water, deterioration of power facilities; iv) Infrastructure: damage to coastal and offshore infrastructure, increased infrastructure maintenance cost, loss of business opportunities due to transport disruptions, and reduced reliability of transport infrastructure and buildings (UAE National Climate Change Adaptation Programme, 2019).

4.1 Provisioning benefits: food

4.1.1 Finfish and shrimp fisheries

Marine fisheries make an important contribution to national food security, support the livelihood of coastal communities across the RSA, and are important for cultural heritage and recreation (Sheppard *et al*., 2010; Van Lavieren *et al*., 2011). A large proportion of the population in the RSA live in coastal areas, and many still rely on fish for their protein intake.

The RSA is characterised by a unique assemblage of species of Indo-Pacific origin (Al-Abdulrazzak *et al.,* 2015). The composition of fisheries catches within the RSA varies widely. In the Middle and O-RSA, tunas (skipjack tuna, *Katsuwonus pelamis*; yellowfin tuna, *Thunnus albacares* and longtail tuna, *Thunnus tonggol*) represent more than 40% of the total landings, while in the I-RSA, wild capture is characterised by coastal fishes (silver grunt, *Pomadasys argenteus*; trout sweetlips, *Plectorhinchus pictus*; yellowbar angelfish, *Pomacanthus maculos*us; several species of grouper, *Epinephelidae* family; and seabreams, *Acanthopagrus spp.*) and relatively high landings of penaeid shrimps (RECOFI, 2010). Many fish stocks within the RSA are significantly overexploited, with depletion of traditional demersal fishery stocks in the Region resulting in fishers turning to other low-value species including blue swimming crab, *Portunus segnis*, Rhizostomidae jellyfish and skinnycheek lanternfish, *Benthosema pterotum* (RECOFI, 2010). While there are attempts in some ROPME Member States to maintain commercial fish landing data records, data is still sparse and inconsistent across the Region and the differences and irregularities in the way data are collected, processed and reported makes it difficult to interpret trends of commercial fish landings for many species, including those of emerging importance. More data in terms of catches and biological information such as population dynamics, environmental preferences and tolerances, and distribution ranges is urgently needed (RECOFI, 2010).

This lack of information makes it difficult to understand the potential impact of climate change on many of these key commercial species.

Given the extreme conditions of the I-RSA, many of these species are likely to be near their physiological and environmental limits, and therefore their sensitivity to any further environmental or habitat change could be high (Cheung *et al.,* 2009; Burt, 2015). While some fish and invertebrate species may be more tolerant and could adapt to warm temperatures, the adaptive capacity of fish communities within the I-RSA and M-RSA may be limited due to their low species diversity compared to the adjacent Indian Ocean where conditions are less extreme (Cheung *et al.,* 2009). Other stressors from climate change are also likely to affect fish stocks. For example, impacts of temperature change are generally exacerbated when exposed to additional stressors such as reduced oxygen or ocean acidification (Pörtner and Peck, 2010; Deutsch *et al.,* 2015). Another threat to fisheries is where species' life-cycles are affected by the degradation of reefs, particularly in the I-RSA. A greater understanding of how fish and shellfish within the I-RSA may respond to multiple stressors, alongside tolerance ranges and thresholds of climate change is needed.

Climate change is projected to have significant adverse impacts on commercial fisheries in the I-RSA, particularly as a result of increasing temperature, oxygen depletion and changes in salinity (Wabnitz *et al.,* 2018). Wabnitz *et al*. (2018) generated projections under warming and changing salinity for 47 of the most important fish and invertebrate species to local fisheries (by weight), including narrow-barred Spanish mackerel (*Scomberomorus commerson)*, Indian oil sardine (*Sardinella longiceps*), giant catfish (*Netuma thalassina*) and blue swimming crab (*Portunus segnis*). Overall, by 2050 under an RCP8.5 scenario, highest species losses were projected along the north-western coast of UAE and Bahrain (Wabnitz *et al.,* 2018). However, by 2090, species losses are expected across most of the Region particularly towards the south (Wabnitz *et al.,* 2018). Invasion of any of the selected fish species into formerly un-utilised areas, based on salinity and temperature preferences, is expected to be very low, and mostly confined to the north. Whilst other global studies note that future warming should see fish species move pole-wards (e.g. Poloczanska *et al.,* 2013; Jones and Cheung, 2014), such a response will be limited for fish within the I-RSA due to its enclosed nature and the fact that there isn't a warmer neighbouring marine area from where species could shift their distribution.

Projected losses of key exploited species from certain local areas, are likely to result in declines in fisheries catch potential for most RSA countries (Wabnitz *et al*., 2018). UAE, Qatar, and Oman are projected to experience declines of approximately 30% by 2090. A ranking exercise of the I-RSA countries, in terms of the relative vulnerability of their national economies to climate change impacts on fisheries, based on an integration of changes in catch potential with socio-economic indicators, indicated that Bahrain was the most vulnerable, followed by Iran, Oman, UAE, Iraq, and Qatar. Saudi Arabia and Kuwait were the least vulnerable (Wabnitz *et al.,* 2018). Another recent analysis of the climate risks and vulnerabilities in Kuwait, indicates that climate change stressors are expected to affect the marine and fisheries sector, driven by increases in SST and salinity, and ocean acidification, causing a reduction in biodiversity, declining reproduction rates of fish and other marine organisms and a deterioration of marine water quality (Alsahli, 2019).

A recent study by Buchanan *et al*. (2019) applied the IUCN Red List methodology to the marine bony fishes of the I-RSA, using best available information for each species in order to identify the diversity of marine bony fishes, determine their conservation status, identify primary threats, and determine current species richness patterns within the I-RSA. The results reveal that a substantial portion of the marine fish biodiversity is at an elevated risk of extinction, particularly coral-dependent fishes and those exploited in targeted fisheries, primary threats being climate change and extreme temperature events, which are only expected to increase in the future (Buchanan *et al*., 2019).

Harmful algal blooms are an important emerging issue for fisheries within the I-RSA and M-RSA, which may become an increasing problem under future climate change. HABs can lead to extensive mass mortalities of fish largely due to the hypoxic conditions that they create, with knock-on effects for associated fisheries regarding availability or productivity of stocks and impacts on fishing activities and operations (Muthian *et al.,* 2007; Richlen *et al.,* 2010; Al Gheilani *et al.,* 2011). Several of the recent bloom events within the RSA have been unprecedented in terms of duration, geographical scale and damage caused (Richlen *et al.,* 2010). Such events have become common within the I-RSA (ICES, 2012; ROPME, 2013).

In the O-RSA, projected future declines in average chlorophyll concentrations, due to changes in ocean circulation, timing and strength of vertical mixing, nutrients, and oxygen could have implications for the likelihood of HAB outbreaks. Whilst a lower incidence of HABs would be beneficial, a loss of chlorophyll overall and therefore primary production would be expected to have negative repercussions for the fisheries yields (Wabnitz *et al.,* 2018). Strengthening southwest summer monsoon winds over the RSA appear to be enhancing the upwelling and leading to increased summertime phytoplankton blooms along the western and central I-RSA, which could intensify the OMZ (Goes *et al*., 2005) and have far-reaching detrimental consequences for the fish populations. In the last two decades in the O-RSA particularly, the die-off of these summer blooms has been followed by intense, long-lasting, large-scale winter blooms of *Noctiluca* particularly, and major fish kills (Goes *et al*., 2018).

Resilience of stocks, and therefore wider fisheries, to future climate impacts, may be improved through sustainable fisheries management measures that can restore biomass and enhance stock resilience (Rijnsdorp *et al.,* 2009; Gaines *et al.,* 2018).

4.1.2 Deep Sea fish resources

In recent decades, the Iran Fisheries Organisation working together with the Iran Fisheries Research Organisation have investigated the feasibility of a commercial fishery focused on deep-water mesopelagic fish in the middle and outer RSA. These studies have indicated that such a fishery is viable, especially for *Benthosema pterotum* (Valinassab *et al*., 2007), however periodic changes of the oxygen spatial distribution are known to affect the density and abundance of epipelagic and mesopelagic fish populations. Dissolved oxygen levels less or equal to 0.3 mL/L are considered physiologically limiting for fish species (Ashjian *et al*., 2002; Ekau *et al*., 2010). In the western Arabian Sea, myctophids tend to be concentrated at the upper boundary of the oxygen minimum zone (OMZ). A recent study has suggested that the M-RSA OMZ has transitioned from hypoxic to persistently suboxic, with DO concentrations less than 0.064 mg/L (Queste *et al*., 2018). Regions with low dissolved oxygen concentrations are expected to increase in frequency and extent in the future, partly in response to climate change (Lachkar *et al*. 2019), with the O-RSA and M-RSA projected to undergo stronger deoxygenation than the wider Indian Ocean (Stramma, 2010; Bopp *et al*., 2013; Long *et al*., 2016). Piontkovski and Al-Oufi (2014) have demonstrated that seasonal shoaling of the oxycline tends to shift the deepened layer of myctophids in the Arabian Sea up to the surface and closer to the coast which in turn favours accumulation of pelagic predators and commercial fisheries in the same locality. Both phenomena lead to a compressing of the habitat and increasing artisanal landings (catch-per-unit-effort) of myctophids, thus making these usually deeper-water resources more vulnerable to over-exploitation and to depletion. Therefore, deep-sea fish resources are considered to be at considerable and immediate risk as a result of climate change, in particular related to the expansion of OMZs.

4.1.3 Shoreline harvesting, fish and shellfish farms

Coastal seafood harvesting and farming activities in the RSA are at risk from a number of climate change impacts, including increased temperature and salinity, as well as ocean acidification. The latter is of particular concern for shellfish farming. Any future climate change impacts on HABs and jellyfish outbreaks, and the incidence of marine pathogens such as viruses and bacteria that cause diseases to farmed species, could be a threat. Jellyfish blooms can also cause nuisance by clogging nets and killing fish in net-pens (Purcell *et al.,* 2007). The negative effect of these climate impacts are expected to worsen due to the widespread degradation of coastal water quality caused by human activities. In addition, the lagoons, pens and storage facilities used for seafood aquaculture are at risk of damage from the physical impacts of SLR, coastal flooding and erosion and storms and waves.

Aquaculture is a growing activity, that is emerging as an alternative to declining wild fisheries. The aquaculture industry may face changing species habitability and live feed issues as SST increases, and the risk for disease outbreaks and water quality issues at farms might increase (De Silva and Soto, 2009). Aquaculture businesses may have to bear additional costs to mitigate climate change risks in relation to water and energy, and become less cost-efficient.

Both HAB and marine pathogen outbreaks can co-occur, and climate change may affect the frequency of such compound effects. A specific example of this happened in August and September 2001 at Kuwait Bay in the I-RSA. A massive fish kill involving over >2500 metric tons of wild mullet was caused by *Streptococcus agalactiae* (Glibert *et al.,* 2002). The event was preceded by a small fish kill (100 to 1000 dead fish per day) of gilthead sea bream in aquaculture net pens associated with a dinoflagellate bloom. Unusually warm temperatures and calm conditions prevailed during this period. As the wild fish kill progressed, high counts of HAB species were recorded. It is thought that the initial bacterial outbreak was likely stimulated by warm water conditions, together with other factors, while enriched nutrient conditions contributed to the subsequent HAB outbreaks (Glibert *et al.,* 2002).

4.2 Provisioning benefits: raw materials and energy

4.2.1 Fossil oil and natural gas

RSA countries have at their disposal up to 23% of the world natural gas reserve and account for 8% of the world natural gas production (ROPME, 2013). They also contribute 32% of global oil production. The economies of most of the RSA countries are dominated by the oil and gas sectors (ROPME, 2013) although the relative contribution of other sectors to their gross domestic product have increased over recent years. As the main source of income in the RSA, any change to oil and gas prices and production levels, can affect the GDP widely. Rising air and sea temperatures, changes in precipitation, SLR, and increases in storminess all present potential risks to oil and gas operations and assets (IPIECA, 2013), although overall costs may be relatively low in proportion to revenues generated by these industries.

The effects of climate change on the fossil fuel energy sector will be felt across the globe. Energy demand patterns will change (such as for heating and cooling), power plant cooling and efficiency will be affected, as will hydropower output, and coastal infrastructure (including refineries, liquefied natural gas plants and power plants) will be threatened (IEA, 2013). Other impacts of climate change are likely to be more sudden and destructive, with extreme events such as tropical cyclones, heatwaves and floods, expected to increase in intensity and frequency, while gradual and sudden climate impacts can also interact, such as a sea level rise and storms combining to increase storm surges (IEA, 2013).

High temperature extremes may lead to efficiency losses for processes which are sensitive to ambient temperatures and could also lead to equipment failures if design thresholds are exceeded (IPIECA, 2013). Rising air temperatures could have a negative effect on liquefied natural gas production facilities and gas-fired thermal power plants, which are an important element of the fuel supply mix in the RSA, from the efficiency of the liquefaction process to the level of production (IEA, 2013; IPIECA, 2013; Mokhatab *et al*., 2014; American Petroleum Institute, 2015). Worker health and safety practices may require reviewing in light of the increased likelihood of heatwaves and extreme weather.

Higher sea surface temperature and salinity will cause an increase in both water demand and running costs of power stations and oil and gas installations offshore as well as onshore, through loss of peak cooling capacity and reductions in output and efficiency over time (IPIECA, 2013). Heatwaves will also impact upon peak load energy demand, putting greater stress on grid infrastructure and undermining the ability of power plants to operate at optimum efficiency (IEA, 2013).

While SLR, and any increase in winds and storms could negatively affect the integrity and operations of oil and gas rig superstructures above water, storm and wind conditions can also cause damage by scouring and displacing the pipes and cabling laid on the seabed. An assessment of the baseline economic impacts of extratropical storms across the Middle East (including between 1986 and 2005 using an integrated model found suggested a cost of 0.031 billion USD or 0.0016% GDP; Narita *et al*., 2010). By the year 2100, the model calculates that in the base case the increased direct damages due to the impact of climate change enhanced storms will amount to 2.4 billion USD globally (Narita *et al*., 2010). Oil and gas assets and operations which can be affected include shipping, tug operations, berthing, loading and unloading at ports, jetties, pipelines, power production and helicopter operations (Dell, 2012; IPECA, 2013). In turn, damage to offshore oil and gas assets and disruptions in operations due to extreme weather events can pose significant pollution risks for marine and coastal ecosystems. The oil industry area in Fujairah for example, on the O-RSA, has a higher vulnerability to extreme climate events than other parts of the RSA, owing to its high concentration of oil terminals and its greater exposure to cyclones. The new Duqm industrial harbour in Oman is another example of a major industrial site located in the direct path of cyclone impacts.

Increased rainfall intensity and coastal flooding during surges could overwhelm the capacity of drainage systems at oil and gas facilities and lead to flooding, pollution incidents and ecosystem damage, as well as reputational consequences for oil and gas companies.

4.2.2 Power plants

Most of the industrial and domestic energy demand in the RSA is generated by gas-fired power plants. The majority of power infrastructure in the RSA is located in the coastal zone, and is potentially vulnerable to flooding from rising sea levels and storm surges (Fencl *et al*., 2009) although further research is needed to better evaluate this risk. Studies in the RSA and elsewhere also demonstrate that the thermal efficiency and power output of gas-fired plants is affected by ambient air and sea temperature (Chuang and Sue, 2005; De Sa and Al Zubaidy, 2011). Depending on the technology in place, power output reductions are reported to be in the range 0.1 to 0.8% reported for each 1°C increase in air temperature (Dawaud *et al*., 2005; De Sa and Zubaidy, 2011).

All exposed electricity transmission systems are vulnerable to higher air temperature extremes. Overhead transmission lines, transformers, switchgear and cables can be negatively affected by heat. Higher temperatures expected under climate change will therefore reduce the current carrying capacity of lines, transformers and switchgear.

Estimates of the impacts of rising ambient air temperatures on electric transmission ampacity and peak per-capita electricity load for over a hundred planning areas in the United States using downscaled global climate model projections found that by mid-century (2040–2060), increases in ambient air temperature may reduce average summertime transmission capacity by 1.9 to 5.8% relative to the 1990–2010 reference period (Bartos *et al*., 2016).

In practice, this might mean that overhead lines and transformers are de-rated, and their losses will increase. Higher ambient air temperatures can also reduce transformer lifetimes, depending on equipment rating and peak system load. Some mitigation measures may include for example laying cables underground, although this may be counteractive in very dry soils as the lack of moisture increases the risk of systems overheating, and the use of insulation materials (INMR, 2019).

A study of the impacts of climate change on electric power generation in Western United States found that power facilities are more vulnerable to efficiency losses during extreme heat and drought events so equipment degradation and utilisation of lower quality fuels compound additional long-term efficiency losses; declines ranging from 1.1 to 3% in summertime generating capacity to as high as 8.8% in a ten-year drought scenario in vulnerable power facilities (Bartos and Chester, 2015). A one degree increase in temperature could potentially decrease gas power plant outputs by 0.6% mainly due to thermal efficiency losses, which would translate to a decrease of 25 billion kilowatt-hours of power supply for every 1% percent loss in power generation (Mideksa and Kallbekken, 2010).

Residents in the RSA have one of the highest demands for space cooling. In the UAE for example, air conditioning of buildings comprise the highest proportion of electricity loads in the country and it is estimated that the increasing ambient air temperatures will likely drive this demand up, by 20% or more by mid-century according to a recent research (Smith, 2015). A large proportion of electricity in the UAE is consumed in meeting air conditioning cooling demands in buildings where, up to 80% of a buildings total electricity demand is for cooling. Over 60% of total electricity consumed in the residential, commercial, and institutional sectors in Abu Dhabi is used for air conditioning, and commercial buildings accounted for almost 48% of total electricity demand in 2014, with residential buildings accounting for more than half; under current climate projections for UAE, cooling demand is set to increase by 22.2% by 2050 and 40.0% by 2080 (Radhi, 2010; Shanks and Nezamifar, 2013; Dubai Electric and Water Authority, 2014). Similar current usage and projections can also be applied to other RSA Member States, like Kuwait, where 70% of the annual peak electricity residential demand in the summer months is for air conditioning, and over 45% of the total annual electricity consumption (KISR, 2019). Under a business-as-usual scenario, energy demand in Kuwait is projected to increase by a third in the period to 2035, which is a slower pace than the last two decades due to deceleration of GDP and population growth (KISR, 2019).

Rising temperatures will increase energy demand for cooling beyond current expectations, with recent analysis by the International Energy Agency indicating the Middle East as a whole will see an increase in Cooling Degree Days of 7% by 2035 and 11% by 2050 (IEA, 2013).

4.2.3 Renewable energy

Offshore renewable power installations, such as wave energy converters and wind turbines, might potentially benefit from exploiting wind and wave energy resources if conditions in the Region become windier, and wavier, as has been projected globally (Reguero *et al.,* 2019). The magnitude of this potential increase of Giga Watt output will depend on specific atmospheric conditions that are important to design, and operation as well as corrosion or abrasion that could impact on both offshore and onshore wind turbines due to airborne particles in the wind (Pryor and Barthelmie, 2010).

The Region has a very high potential to exploit solar photovoltaic generation and there are some major projects in the Region, such as the Mohammed bin Rashid Al Maktoum Solar Park in Dubai and Noor Abu Dhabi. Solar energy technologies are sensitive to dust, humidity and high temperatures, all of which are likely to be exacerbated due to climate change (Touati *et al*., 2017). Reliable projections of changes in dust levels are not yet available for the RSA, although increasing air temperatures and expanding desertification point to the likelihood of higher dust levels in the future. Extreme high temperatures can also degrade photovoltaic efficiency by up to 25%, as the temperature of the solar panel increases, its output current increases exponentially, while the voltage output is reduced linearly; as a result, heat can severely reduce the solar panel's production of power[9]. Only a small portion of solar irradiation incident to photovoltaic modules is converted into electricity while the rest is converted into heat, and this heat causes overheating and reduces its performance (Rahman *et al*., 2014). The output of solar cells increases with irradiation, but overheating causes a decrease in the efficiency of the solar cell (Rahman *et al*., 2014).

As with other coastal energy installations, renewable energy structures may also require consideration of rising sea levels. Further research to downscale climate models is needed to understand the geographic distribution and/or the inter- and intra-annual variability of potential wind and wave energy resources (Reguero *et al.,* 2019).

[9] https://www.civicsolar.com/article/how-does-heat-affect-solar-panel-efficiencies

4.2.4 Nuclear energy

Nuclear energy is gaining momentum in the Region as a practical and economical option in mitigating CO_2 emissions (AlFarra and Abu-Hijleh, 2012; IEA, 2016). Even though nuclear power is not yet a major contributor to energy supplies in the RSA, Iran, Saudi Arabia and UAE have advanced nuclear power plans (El-Katiri, 2012). In September 2013, Bushehr Nuclear Power Plant with two 1,000 MW nuclear reactors located in the coast of Iran began producing power for the power grid. The Barakah nuclear power plant in UAE will have four 1,400 MW nuclear reactors and the first reactor is planned to be ready by 2020; once fully operative the plant will be able to supply up about 25% of the country's power (Kim and Jeong, 2013; El-Katiri, 2014). To ensure that the plant can operate successfully in spite of the high ocean temperatures, the Barakah plant includes larger heat exchangers and higher cooling water flow rate than the Korean reference plant (Shin-Kori Units 3 & 4) on which it is based (Kim and Jeong, 2013). However, several site-specific design differences have been addressed to allow for the higher seawater temperature of the I-RSA (the ultimate heat sink), the higher ambient temperature, dust and sandstorms (Kim and Jeong, 2013). The higher seawater temperature for example, resulted in several design changes including an increased electrical capacity of the emergency diesel generators is increased to accommodate the high loads resulting from extreme hot (water and air) temperatures, double number of water pumps designed to be operating during normal shutdown and enlarged circulating water system intake and discharge conduits to accommodate the higher seawater temperature (Kim and Jeong, 2013).

The most salient threat to future nuclear plants in the RSA therefore are likely to be rising sea and air temperatures, and salinity levels, in coastal waters, which has the potential to compromise the efficiency of cooling systems. A one degree increase in temperature could potentially decrease nuclear power plant outputs by 0.8% while due to thermal efficiency losses, which would translate to a decrease of 25 billion kilowatt-hours of power supply for every 1% percent loss in power generation (Mideksa and Kallbekken, 2010). A 1.5°C increase in seawater temperature, which could be seen in the I-RSA by the 2040s due to climate change, would lead to a nuclear power loss of around 0.5 percent, but the combination of heating effects of thermal plumes could yield greater seawater temperature increases and higher power shortfall causing revenues loss to the plants and to businesses (Kim and Jeong, 2013). Adaptation measures are already being incorporated into nuclear plant developments. The Emirates Nuclear Energy Corporation has reported implementation of design modifications to manage the higher seawater temperatures and counteract hotter air temperatures and high volumes of airborne dust (UAE State of Energy Report, 2019). More favourable thermo-aquatically conditions could be considered for future nuclear energy plans via alternate sites for higher plant efficiency, such as Fujairah in UAE on the M-RSA coastline, when new nuclear energy expansion plans (Kim and Jeong, 2013).

In addition, and as it is the case with other coastal infrastructure, nuclear installations would be at risk from coastal erosion, SLR and coastal flooding from storm surge events, and nuisance outbreaks of jellyfish which are already causing blockages to the seawater cooling intakes at desalination plants (Abdulaziz *et al.,* 2000; Purcell *et al.,* 2007). Conversely, the impact of raised temperatures around nuclear sites will locally exacerbate impacts of climate change in the marine environment.

4.2.5 Water for human consumption and agricultural irrigation (including desalination plants)

There are three main sources of fresh water in the RSA: groundwater, desalinated water, and treated wastewater. Groundwater and desalination plants provide the vast majority of the Region's supply, particularly in the case of Kuwait, Saudi Arabia, UAE and Bahrain (WWAP, 2015). Groundwater is typically used for agriculture and in the oil and gas industry, while treated wastewater is increasingly used for irrigation of green spaces and reforestation areas (Al-Senafy *et al*., 2003).

In the RSA, countries are increasingly reliant on seawater desalination plants to produce most of the freshwater supply required by their rapidly growing populations. These desalination plants are therefore essential for water security and maintaining human health. Eighty percent of the drinking water in the GCC countries is from desalinated water (Ulrichsen, 2009), and seventy percent of desalination plants in the world are located in this area, mostly in Saudi Arabia, the UAE, Kuwait, and Bahrain[10]. The combined seawater desalination capacity in the I-RSA exceeds 11 million tons of water per day, which is about half of the world's capacity (Kim and Jeong, 2013). High population growth rate, urbanization and industrialization, coupled with limited availability of natural potable water resources, are leading to serious deficits of fresh water in many parts of the Middle East and therefore increased use of desalted seawater is unavoidable in order to maintain a reasonable level of water supply in the Region[11] (Al-Senafy *et al*., 2003; Verner, 2012). Water scarcity and access to reliable and sustainable water services is at the forefront of the development challenges in the RSA (WWAP, 2015).

Increases in temperature may lead to increased cooling demands at plant sites, while increasing salinity will affect the quality of water that can be used for turning into drinking water, and thus potentially increase operating demands. Although there is some resilience built into the industry to cope with current environmental risks to water supply and quality, future climate change may challenge the industry beyond its current resilience planning.

The large capacity desalination plants that occur in the RSA have necessitated the withdrawal of correspondingly large quantities of seawater from the sea (Abdulaziz *et al.,* 2000), and plants are already experiencing the disruptive effects from jellyfish outbreaks and HABs, that may be increasing in frequency and abundance due to climate change. The threat of HABs to the desalination industry comes, in part, from algal production of neurotoxins as well as bad taste and odour and skin-irritating compounds that may persist in the treated water (Anderson *et al*., 2017). Toxic blooms near desalination plants are therefore a threat, due to the risks to human health should they enter the drinking water supply network. In the I-RSA, operation of desalination plants can be suspended for days during red tides events (Al-Senafy *et al*., 2003). Another major concern is the organic material produced by some algal blooms, as these compounds can clog intake filters and foul membrane surfaces, greatly compromising plant operations (Anderson *et al*., 2017).

Installations on or near the coastline will be at risk from coastal erosion and damage from the impact of storms and sea surges. Jellyfish can block seawater cooling intakes at desalination plants, causing extensive damage to intake screens and seriously affecting the pumping of seawater required for

[10] https://thewaterproject.org/water-crisis/water-in-crisis-middle-east

[11] https://www.ecomena.org/desalination-outlook-mena/

cooling systems[12] and put essential supplies of water at risk (Abdulaziz *et al.,* 2000; Purcell *et al.,* 2007; Anderson *et al*., 2017). In some desalination plants, the intakes are plagued by the ingress of jellyfish every year between March and July with impacts on the operation of the plant (Abdulaziz *et al.,* 2000).

Large-scale co-production plants exist in the RSA, such as the Ras Al-Khair plant in Saudi Arabia which came online in 2014 and supplies water and electricity for most of the capital city of Riyad (Al-Saidi, 2019). These co-location of desalination and energy plants indicates an increased integration between water and energy supply systems and a heavy reliance on centralized supply infrastructure, which can lead to growing risks from potential failures and undermine the resilience of the water and energy supply infrastructure to climatic extremes (Al-Saidi, 2019).

For underground freshwater lenses near the coast, changing precipitation patterns, rising sea levels, storm surges and decreases in average rainfall, will cause desiccation and saltwater intrusion and negatively affect the level and quality of the water, although some areas could benefit from further aquifer recharge and longer growing seasons.

4.2.6 Aggregates and sea sand mining

Sand and gravel used for most construction projects in the RSA, including earthworks and land reclamation, are mainly dredged and mined from beaches and inland dunes, or from the seabed. It is expected that the demand on this industry will continue to rise as the human population continues to grow particularly with urban developments along the coast. For example, UAE hosts some of the largest land reclamation projects in the world, founded wholly on either refilled low-lying coastal salt flats or man-made islands such as Palm Islands and the World archipelago in Dubai (AFED, 2009). Kuwait also has ambitious new plans for island developments as part of what is known as "New Kuwait 2035"[13].

Apart from concerns regarding the environmental impacts of these projects on the marine environment (Nadim *et al*., 2008), the industry itself does not appear particularly vulnerable to climate change impacts, although any changes in storm and wave conditions may disrupt onshore and offshore operations and put workers safety at risk, e.g. the operation of suction dredgers.

In addition to the ongoing population growth and coastal expansion, the negative impacts of erosion, SLR and any increase in storminess on coastal areas may contribute to an increase in demand for this particular activity. In turn, an increase in the erosive action of the sea may play a part in replenishing the sand and gravel resources on the seabed.

4.2.7 Wetland harvesting of plants and raw materials

The coastal wetlands of the RSA are amongst the most diverse habitats in the RSA (Al-Obaid *et al.,* 2017). They provide grass for grazing livestock such as camel, goats and sheep. Traditional remedies and medicines are derived from wetland soils, plants like the Red Mangrove, and animals (Kotze, 2016). Mud for construction and urban developments is made by mixing water with soil, silt and clay

[12] https://gulfnews.com/news/uae/general/jellyfish-choke-oman-desalination-plants-1.355525
[13] https://kif.kdipa.gov.kw/wp-content/uploads/khalid-mahdi-english.pdf

mined from coastal sites and alluvial plains. Sea salt production is also found in coastal sites in countries including Saudi Arabia, Iran and UAE. Most of this sea salt is used in food products, but some is for industrial use.

The impacts of rising temperatures and salinity, SLR and coastal flooding, changing precipitation patterns and the impact of coastal erosion and storms put these services at risk. According to latest prediction of relative SLR in the I-RSA (2.2 mm per year considering subsidence rates) added to the coastal squeeze, it is suggested that up to 96% of coastal wetlands, including mangroves, are likely to be lost from the Region (Ward *et al*., 2016). While salt marshes and other related coastal habitats are typically tolerant to a wide range of extreme environmental conditions and have the ecological capacity to adapt to climate impacts, they are also experiencing rapid and widespread degradation due to other human pressures, such as pollution, drainage, and urban encroachment. These added stressors will compromise the adaptive capacity of natural systems to future impacts and are likely to accelerate their degradation, ultimately resulting in biodiversity loss and detrimental effects to important goods and services they currently provide.

4.2.8 Pearl oysters and bait fishing

The once extremely productive wild pearl oyster harvesting has been degraded beyond restoration across RSA countries since the early 1990's, mostly caused by human pressures from overfishing and habitat degradation, and exacerbated by the increasingly extreme marine conditions of temperature and salinity (Smyth *et al.,* 2016) driven by global warming. The loss and degradation of expanses of seagrass meadows, which form the nursery ground for oyster larvae, may have also contributed to the overall drop of oyster numbers (Naser, 2014).

The impact of climate change drivers is not overly clear. Some recent studies for example suggest that warming sea temperatures could stimulate calcification in pearl oysters by enhancing certain physiological processes, therefore counteracting the impact of ocean acidification (Li *et al.,* 2016; Liu *et al.,* 2017). There are plans to revive pearl farming, such as the Qatar Pearl Legacy Project[14] and any climate change impacts that could degrade the local quality of the water would be especially detrimental.

Bait fishing involves the capture of live or dead fish for use as bait on hooks for bottom fishing, jigging, trolling and rod fishing, using sardine, shrimp, cuttlefish, squid, ballyhoo, scad, and mackerel[15].

Squid and cuttlefish (cephalopods) appear to adapt well to warming sea temperatures, with reports from around the globe of squid populations expanding their distribution ranges and numbers in line with rises in sea temperatures. This has led to these, and other similarly low value bait species, replacing traditional commercial fisheries in some regions of the world (Doubleday *et al.,* 2016; Monahan, 2016). Cephalopods have a unique set of biological traits, including rapid growth, short lifespans, and strong life-history plasticity, allowing them to adapt quickly to changing environmental conditions such as increasing temperature and salinity, low oxygen and changes in current circulation. The dwindling of other competing fish species is also likely to be a contributing factor to their success

[14] https://www.thenational.ae/arts-culture/the-qatar-pearl-legacy-aims-to-revive-the-gulf-s-pearl-farming-tradition-1.96570
[15] http://www.emiratesfishing.com/bait-fishing/

(Doubleday *et al.,* 2016). More research is needed however to fully understand what factors are driving their population boom across the globe (Doubleday *et al.,* 2016; Monahan, 2016) and how this applies to the RSA.

4.3 Carrier benefits: provision of space

4.3.1 Maritime transport

International maritime transport accounts for over 80% of global merchandise trade (by volume, UNCTAD, 2019). Maritime traffic is critical to the economy of most countries in the RSA, securing the transport of goods and supporting the influx of foreign visitors and tourists, with some destinations like Dubai rapidly becoming a leading global cruise hub.

Changing sea levels combined with storms may result in shipping and fishing vessels experiencing difficulties during navigation and berthing operations. An increase in storm intensity and high winds may cause increased disruption to maritime traffic in the coming decades. Shipping through the Strait of Hormuz, which carries up to 40% of world oil supplies, could experience frequent and long-lasting disruptions in future decades, with global repercussions. However, it is difficult to predict the severity of these disruptions, or where they are most likely to impact, due to uncertainties in downscaling and the natural variability of storminess and wind impacts. The Strait of Hormuz in particular is recognised as a strategic maritime chokepoint (UNCTAD, 2019) and future extreme weather events can disrupt smooth navigation through the Strait, and intensify the risk of maritime accidents with, amongst others, the associated risk of ship-source marine pollution incidents. The impact of adverse climatic conditions on the supply chain and port and traffic control facilities can also have disruptive consequences for shipping activities (Asariotis *et al*., 2017; UNCTAD, 2019).

Fishing vessels, despite the steady decline of the industry in recent decades (RECOFI, 2010), still makes an important contribution to the Regional economy and food security. Vessels, and supporting onshore infrastructure, are highly vulnerable to climate change impacts, particularly the coastal damage caused by intense storms and cyclones. In the UAE for example, there are 16,000 recreational marine vessels and about 18,000 commercial fishermen operating in 5,985 vessels (Al Blooshi, *et al*., 2017). When Cyclone Gonu made landfall in 2007 in UAE, Oman and Iran, the waves along the coastline were reported to be 10m (32ft) high, which destroyed fishing vessels and caused hundreds of boats to be moved from the water or emptied of equipment[16]. Overall damage to some ports was reported as severe, including a boat which sank leaving its passengers missing[17].

4.3.2 Seaports and harbours, container terminals, marinas and bridges and causeways

Seaports are the focus of larger scale investments in the RSA and the wider Middle East, compared to other regions of the world. However, there are considerable gaps in terms of understanding current

[16] https://web.archive.org/web/20121007172109/http://gulfnews.com/news/gulf/uae/environment/gonu-sends-fish-prices-soaring-1.183207#
[17] https://www.upi.com/Top_News/2007/06/09/Iran-surveys-damage-after-cyclone/75861181409342/?ur3=1

and future climate change risks. Whilst new port development designs may be factoring in changes in mean water levels and storm surge, key information is still missing in terms of impacts from extreme weather and climatic events (Asariotis *et al*., 2017).

Coastal facilities and structures will experience increasing exposure to the impacts of climate change. A recent review highlights that the main climatic factors impacting on seaports are SLR, temperature, precipitation and fog, and wind (Table 4).

Table 4: Summary of major climate variability and climate change impacts on ports (Asariotis *et al*., 2017).

Climatic Factor	**Impacts on open sea, estuarine and inland waterway ports**
Sea level (mean and extreme)	
(i) mean sea level changes; (ii) increased destructiveness of storm surges/waves; (iii) changes in the wave energy and direction	Damages in port infrastructure/cargo from incremental and/or catastrophic inundation and wave regimes changes; higher port construction/maintenance costs; potential modulation of tides causing sedimentation/dredging in port/navigation channels and operational time table changes; effects on key transit points; increased risks for coastal road/railway links; relocation of people/businesses; insurance issues
Temperature	
(i) higher mean temperatures; (ii) heat waves and droughts; (iii) increased spatio-temporal variability in temperature extremes	Damage to infrastructure/equipment/cargo and asset lifetime reduction; increases in the staff health risk; higher energy consumption for cooling teminals and cargo; restrictions for inland navigation that may affect estuarine port competitiveness; changes of the construction season; changes in transport demand
Precipitation and Fog	
Changes in the mean and the intensity and frequency of extremes (floods and droughts)	Land infrastructure inundation; damage to cargo/equipment; navigation restrictions in inland waterways; network inundation and vital node damage (e.g. bridges); problems in port equipment operations (e.g. cranes); changes in demand
Increases in fog intensity/duration	Impact on ship and terminal operations (reduced visibility)
Wind	
Extreme harbour winds	Problems in seaport navigation and berthing; operational disruptions due to inability to load/unload

Adverse wave conditions make harbour conditions difficult for the safe navigation and berthing of large freight vessels (Rossouw and Theron, 2012). An analysis by Mentaschi *et al*. (2017) suggests that wave energy fluxes in the O-RSA and M-RSA will increase in the course of the 21st Century due to changes in the intensity and direction of approaching waves, although neither the RSA or the wider Indian Ocean were further analysed by this study due to the high spatial variability of this Region. The extent and distribution of seaport exposure will be controlled by local characteristics, such as the presence of attenuating coastal ecosystems (e.g. wetlands) (Wamsley *et al*., 2010; IPCC SREX, 2012) and efficient water management and land reclamation schemes.

The tidal regime of seaports may also be affected by SLR (see for example the study by Pickering *et al*., 2012 on the effect of SLR on European shelf tides) requiring changes in port infrastructure and in operational timetables (Asariotis *et al*., 2017). In ports and quays facing the open sea in particular, SLR combined with heavy rainfall and/or extreme wind and storm surges may render protection structures obsolete and overtop coastal defences, resulting in increased flood and damage risk for cargo storage areas and disruption to services including vehicle movements within ports and transport off-site (UNCTAD, 2011; Rahmstorf, 2012; UNECE, 2013; 2015; Asariotis *et al*., 2017). Increased risk of intense storms and flooding is a significant threat to marine infrastructure and for some of the main ports that handle a large amount of maritime traffic, this can cause substantial disruption. The Khalifa Port in UAE, with a capacity of about 2.5 million standard 20-foot shipping containers, is linked to the important Kizad industrial zone and facilitates both the movement of raw materials and finished goods. As such, any impact to these facilities will widely affect both businesses and residents (Abu Dhabi Council for Economic Development, 2014). Changes in extreme precipitation may result in coastal riverine floods that can cause direct damage and disruption to rail and road links, requiring emergency responses as well as measures to support the infrastructure's structural integrity (USDOT, 2012; Asariotis *et al*., 2017).

Increased intensities of tropical storms and hurricanes could lead to evacuations, infrastructure damage and failure, transportation interruptions, standing flood waters causing rail track and line side equipment failure, and flood scours at bridges and causeways and culvert washouts (Asariotis, *et al*., 2017). Throughout the RSA, natural and man-made islands in the RSA are connected to the mainland by sea bridges and causeways. These structures are highly exposed and are therefore vulnerable to the impact of extreme weather events such as storms and cyclones. Smaller harbours and marinas are also potentially vulnerable to climate change, although the consequences of damage and disruption may not be as wide-reaching as impacts on large-scale International seaport terminals. Impacts of storms at large ports can include damage to buildings and cargo handling equipment (such as cranes) and disruption to trade and passenger movements. Tropical cyclones and related storm surges, for example those caused by the seasonal shamal winds in the I-RSA, can cause damage in the order of tens of billions of dollars to seaports and surrounding environs (Asariotis *et al*., 2017). Nicholls *et al*. (2008) assessed the population/asset exposure in 136 port cities with more than one million inhabitants (in 2005) including Dubai and found that, by the 2070s, about 120 million people in these cities will be exposed to extreme events in the absence of effective coastal protection responses.

Future extreme heatwaves may limit operations due to surface damage and health risks (UNCTAD, 2017; Vogel *et al*. 2017) and at the same time, energy demand/costs for ventilation and cooling will also increase (Asariotis *et al*., 2007).

The scale of damage and disruption could be considerable, but it is difficult to predict and quantify without a defined, downscaled modelling of these impacts across the RSA. Nevertheless, it is important to enable and encourage proactive plans to address these impacts based on available evidence.

4.3.3 Coastal infrastructure and space for reclamation

In the RSA, there is a high concentration of critical infrastructure that supports large communities and a wide range of industries. Regional studies examining vulnerability have predicted that most of the RSA coastal areas could be extensively inundated by the sea and large sections of shorelines will also migrate inland (AFED, 2009; Van Lavieren *et al*., 2011). This would adversely affect existing coastal cities and infrastructure, offshore developments, valuable coastal ecosystems, and plans for future development (Dasgupta *et al*., 2007; AFED, 2009; Van Lavieren *et al*., 2011). Qatar, Kuwait and the UAE would be particularly susceptible. In the case of the UAE, nearly 85% of its population and over 90% of its infrastructure is concentrated in coastal areas (Van Lavieren *et al*., 2011). A recent assessment of the impacts of a 0.5 m to 0.6 m sea-level rise by 2100 (assuming no additional adaptation), quantified percentage GDP loss, which was greatest in Kuwait (24%), Bahrain (11%) and UAE (9%) (Jevrejeva *et al*., 2018). Whilst these figures are illustrative, and it wouldn't be expected that countries would tolerate such risks, they show the importance of adaptation in reducing these risks to tolerable levels.

Inundation of reclaimed lagoons or land could increase in the future, as could stagnation of water in reclaimed lands. The presence of stationary water and increases in humidity levels could also give rise to various health problems, for example mosquito infestation and moulds and fungi in residential buildings. Further research is required in order to map the likelihood of these impacts, and to produce a finer zonation based on the current and future uses of the coastline around the RSA. Similar to other structures on the coastline in RSA countries, the location of military and naval bases, as well as the space used for training exercises, are expected to be at risk from storms, winds and SLR.

Al-Jeneid *et al*. (2008) suggests that more than 17% of the total land area of Bahrain may be inundated under 1.5 m SLR in 2100. The total area that might be lost under different sea-level scenarios will vary from more than 77 km^2 if SLR reaches 0.5 m, to about 100 km^2 under 1.0 m SLR and may reach 124 km^2 under a 1.5 m SLR scenario (Al-Jeneid *et al*., 2008). The impact of SLR is not limited to direct inundation. Saltwater intrusions are expected to contaminate ground water sources and compromise the availability of fresh water for domestic and agricultural purposes. SLR adaptation policy framework and policy initiatives are being proposed to reduce the likely effects of SLR in the Kingdom of Bahrain[18]. For some other countries, the risk of saltwater intrusion on water resources (e.g. Kuwait) is less acute, where groundwater is a minor source of fresh water as the vast majority of the supply is derived from desalination plants (Alsahli, 2019).

An assessment of the impact of SLR on the entire Omani coastal zone has been undertaken to develop estimates of inundated land area relative to a set of SLR scenarios (0.2, 0.5, 1, 2, 3, 4 and 5 meters). At the national scale, nearly 400 km^2 of total land area is projected to be inundated under the smallest SLR scenario. Under the highest SLR scenario, over 900 km^2 is potentially inundated with the Al-Batinah and Muscat governorates being the most vulnerable under all SLR scenarios (Al-Buloshi *et al*., 2014).

In the case of Iraq, even though or possibly because the shoreline of Iraq is limited to the Shatt Al-Arab estuary at the head of the I-RSA, it is considered one of the most threatened areas in the RSA because of its low elevation with respect to the sea-level (Adamo *et al*., 2018). The low elevation areas (scarcely 1 m above sea-level) extend through to the north of Basra City, and a 3 m SLR would see the intrusion of the sea reaching Amarah city and beyond Nasiriyah city (Adamo *et al*., 2018). On the coastline, Umm Qasr and Al-Faw are the only Iraqi seaports supporting the country's trade and industries including oil export and storage, and they are both vulnerable to SLR and the redistribution of sediments during extreme storm events, which clogs shipping channels and forces frequent dredging (Adamo *et al*., 2018).

4.3.4 Waste disposal

Sewage treatment plants are often located at the coast in RSA countries, and numerous outfalls discharge a mixture of treated and untreated effluents along the coastline (Devlin *et al*., 2015).

[18] http://www.sce.gov.bh/en/Overview?cms=iQRpheuphYtJ6pyXUGiNqpXEhzIp%2bZ3P

The Asian Development Bank has reported that water supply and sanitation are vulnerable to projected climate variability, and particularly sensitive to changes in mean conditions of temperature, rainfall, sea-level and frequency and intensity of extreme weather events, in that the quantity and quality of available water resources, water and wastewater infrastructure will face greater risks of damage and service disruption (ADB, 2017). In the UAE for example, since the majority of the water, sanitation, and waste facilities infrastructure are in close proximity to the coasts, SLR, flooding and storm surges will lead to contamination and saline intrusion into groundwater aquifers and put these services at risk. As the temperature gets warmer, the presence of existing or new microorganisms may be more prevalent leading to costly and more complicated treatment to meet standards (ADB, 2017).

The integrity and function of these critical installations is at risk from climate impacts such as SLR, storminess, erosion and coastal flooding, as well as extreme fluctuations of rainfall levels (Devlin *et al*., 2015) increasing the risk of pollution to the surrounding coastal environment and posing a serious threat to human health. The location of waste and sewage plants with respect to drainage basins can intensify the risk of damage, and therefore pollution of the surrounding area. Most of the solid waste in the Abu Dhabi for instance goes to landfills, with 167 tons of waste generated per km^2 in 2014, and 1.65 kg of waste generated per-capita daily in 2015, making this sites very vulnerable to flooding in terms of gas and leachate collection schemes and increasing the risk of pollution and land contamination from gas and leachate migration, as well as soil erosion (Winne *et al*., 2012; Environment Agency – Abu Dhabi, 2016; Al Braiki *et al*., 2017). In semi-enclosed and shallow bays in the I-RSA, changes in sediment transport dynamics due to erosion and coastal developments, evaporation rates that exceed the combined rainfall and coastal freshwater inputs by a factor of ten (Sheppard, 1993) can distort the diffusion and dilution of effluent water from outlets, increasing the potential risk of coastal pollution incidents (Devlin *et al*., 2015).

4.4 Cultural benefits: recreation and tourism

Given the economic dependence of the RSA on oil exports, the development of sustainable tourism is important. The enjoyment of tourists is influenced by thermal comfort (Perch-Nielsen *et al*. 2010). In addition, humidity is a key driver of the capacity to withstand high temperatures, and a function of the human climate ‘comfort zone’ (Perch-Nielsen *et al*., 2010) followed by probability and duration of precipitation, the number of sunshine hours and intensity of wind (Perch-Nielsen *et al*., 2010). Overall, it is expected that there will be an overall decline in the “tourist comfort climate index” in the RSA in the coming decades (AFED, 2009; Hassan *et al*., 2015).

A study of the effect of climate change on the Tourism Climate Index for Iran calculated the monthly TCI for 40 cities across Iran for each year from 1961 to 2010 (Roshan *et al*., 2015). The results reveal that the best climate conditions for tourists are spring through to summer whilst winter is the least favourable. In winter, the cities located on the coast of the I-RSA and M-RSA have the best climate conditions for tourism, due to warm temperatures, clear skies and rare occurrence of precipitation (Roshan *et al*., 2015).

A study in the UAE, one of the fastest growing tourism destinations in the world which aims to reach 20 million visitors by 2020, shows that if temperatures continue to increase, a reduction in tourism level by over 50% may be expected by the end of the 21st Century. The increased risk of flooding due to SLR will impact negatively in many heritage and tourist resources on the coast (Mfarrej, 2019).

4.4.1 Marine sports and recreation

Marine sports represent an important part of the RSA heritage from a time when the sea shaped the lifestyles of the Region. Member States host a number of Marine Sports Clubs in their main coastal cities, some of which are of International renown such as the Abu Dhabi International Marine Sports Club[19], the Kuwait Sea Sports Club[20] and Oman Sail[21]. Their marinas offer top-class mooring facilities for boats and yachts. Marine sports in the Region are very varied and growing in popularity as governments increasingly support such initiatives as a means to advertise their cities to the rest of the world in terms of tourism and also in trade and commerce: powerboat racing; wakeboard; motor surf or jet surf; jet ski; aqua-bike; remote control boat racing; sailing (dhow and modern); rowing; flyboard; surfing; kitesurf; swimming; scuba diving and snorkelling.

Participation in recreational activities in or near the sea, such as water sports and swimming, could be impacted by higher temperatures and the potential intensification of storminess and wind conditions. SLR and coastal erosion may reduce the appeal of coastal resorts and recreation spots and change the wave dynamics for current surfing spots. Potential increases in frequency and scale of HAB events, presence of marine pathogens, and incidence of jellyfish mass outbreaks, could pose an increased risk to human health by direct exposure. Impacts on reefs and the marine species they support may have negative impacts on the diving industry.

The risk of a higher incidence of dust pollution and sandstorms could negatively affect the seaside experience for visitors and locals alike, and for those who visit the coast, there will be a higher risk of heat-related illnesses due to the prolonged high temperature exposure outdoors.

A study in Abu Dhabi showed that the beach amenity value is estimated at between 8.3 million USD per hectare and 13.8 million USD per hectare based on the beach size (Blignaut *et al*., 2016). Jellyfish outbreaks near coastal areas cause nuisance by stinging bathers and divers[22,23] and washing up on beaches. The Region's coral reefs are a boost for tourism in some areas and have rapidly become a popular diving destination, but extensive bleaching and damage have taken a toll on coral reef habitats and the important revenue they bring in annually.

Further studies are needed however to determine the extent of the risk of these impacts, and to understand the geographical distribution of their effects.

4.4.2 Recreational modern and traditional fisheries

Recreational fisheries such as mackerel and cobia fishing and traditional pearl diving festivals will be vulnerable to similar climate impacts as commercial fisheries if species abundance declines. Whilst

[19] Abu Dhabi International Marine Sports Club: http://adimsc.ae/
[20] Kuwait Sea Sports Club: http://kssclub.com/#/
[21] Oman Sail: https://www.omansail.com/
[22] https://dohanews.co/qatar-beachgoers-warned-to-keep-an-eye-out-for-jellyfish/
[23] https://www.thenational.ae/uae/could-jellyfish-rise-in-uae-be-sting-in-the-tale-for-climate-change-1.795730

modern sport fisheries may be able to turn to novel non-native species as they become more abundant in future decades, some traditional fisheries may be permanently lost in areas of the RSA if target fish species experience a decline in abundance. The impact of climate change on all aspects of recreational fisheries (target species, fishing operations, participation and motivation) has been explored by Townhill *et al*. (2019), with gradual changes in species availability expected, requiring incremental changes in fishing behaviour. However, changing storm patterns and sea-level rise could cause significant changes to coastlines or operating practices in short periods of time.

4.4.3 Marine and coastal wildlife watching

Wildlife watching activities at sea and on the coast often attract a significant number of tourists to visit the RSA, as well as visitors from within the RSA, and are rapidly rising in popularity. These places are also of interest to researchers and nature conservation professionals from within the RSA and elsewhere in the world. Some of the wetland areas in the RSA are globally famous for the diversity of bird species, some of which are rare.

All of the climate change impacts that threaten the coastline (higher temperatures and salinity, SLR, erosion, storminess, coastal flooding and changing rain patterns) are likely to cause degradation of the habitat required by wetland birds, mammals and turtles causing a decline in the expected numbers of both migratory and residing populations. The extreme climatic conditions and the loss of appeal in these nature spots could also dissuade some visitors.

The effects of climate impacts on some of the populations of charismatic species such as turtles, dugongs, and dolphins are difficult to predict, but projected declines in habitat suitability and possible distribution shifts (AGEDI, 2015b) will likely disrupt these wildlife watching activities to a certain extent. This may have particular impacts on locations such as Iran's Kish Island (snorkelling and scuba diving on coral reefs) and Hengam Island (famous for dolphin watching), and Abu Dhabi's Saadiyat Island (famous for hawksbill turtle), Umm Al Quwain wetlands (flamingos) and Fujairah (snorkelling and scuba diving on coral reefs) in UAE.

4.5 Cultural benefits: heritage and wellbeing

4.5.1 Archaeology, cultural heritage, freshwater springs, and wells

Ancient forts, seaports[24] and valuable historic settlements containing archaeological finds as well as culturally important locations including traditional freshwater wells and springs, are scattered along the coastlines of the RSA countries, some of which are recognised sites of outstanding universal value. An example is Tarout Island in Saudi Arabia, where finds have been unearthed from civilisations that date as far as 5,000 BC (Kumar, 2017). The Qal'at al-Bahrain fort in Bahrain is a UNESCO Outstanding Universal Value site. The fort mound was created by millennia of continuous human occupation from about 2300 BC to the 16th Century AD, and excavations have revealed residential, public, commercial, religious and military structures that testify the importance of the site as a trading port and as the

[24] http://www.ancientportsantiques.com/the-catalogue/indian-ocean/

capital of the Dilmun, one of the most important ancient civilisations of the Region, hitherto only known from written Sumerian references[25].

The pearling heritage site in Muharraq City, Bahrain is another example of UNESCO Outstanding Universal Value site. It consists of buildings, offshore oyster beds, part of the seashore and the Qal'at Bu Mahir fortress on Muharraq Island, from where boats used to set off for the oyster beds. The listed buildings include residences of wealthy merchants, shops, storehouses and a mosque and are the last remaining complete example of the tradition of pearling and the wealth it generated, as well as an outstanding example of traditional utilisation of the sea's resources and human interaction with the environment[26].

Additionally, Bahrain and Oman are famous for wells, aquifers and freshwater springs at the seaside, which are highly valued by local communities and are very important to their national and historical identity. In Oman, an assessment of two coastal aquifers: the Jamma aquifer mainly used for irrigation, and the Samail Lower Catchment aquifer, a strategic reserve for domestic water supply, showed that the salinized area in the already stressed Jamma site will increase by 32 and 38% by years 2050 and 2070, respectively, compared to the situation for the base case year 2015, which will severely affect the farming community that depends on it, while the Samail Lower Catchment maintains a positive seaward hydraulic gradient that helps combat significant intrusion of saltwater (Al-Maktoumi *et al*., 2018). The study found that SLR is the main climatic factor that will significantly affect stressed coastal aquifers, and that the extent of the effect of climate change on aquifers is site-specific and is likely to have a worse impact on those aquifers already stressed (Al-Maktoumi *et al*., 2018).

Depending on their specific location on the coastline, the conservation and persistence of archaeological sites may be under threat due to the increasing risk of erosion, flooding and SLR. Archaeological evidence buried in the ground could be lost rapidly if the stratigraphic integrity of the soils were to change as a result of increased floods and changes in precipitation (UNESCO, 2007). Changing precipitation patterns and decreases in average rainfall may potentially affect the level and quality of the water in the traditional coastal freshwater wells.

To date there has been very limited research accomplished on the process of preserving cultural heritage threatened by climate change globally, mostly restricted to built environments in Europe and Latin America, as very few tools or methods exist to collect and analyse data on the actual situation, and at the same time estimate the ongoing and expected risks (Bertolin, 2019). Cultural Heritage sites are typically closely embedded into their natural environment with its natural resources and are part of a landscape, meaning that changes in land-use due to climate change or human effects that alter the availability or quality of water resources and the structure of the soil, will have an impact (Von Shorlemer and Maus, 2014).

4.5.2 Visual appeal inspiration, relaxation and wellbeing

These wellbeing services very much depend on a safe and pleasing visual aspect of the marine and coastal environments. The damages and alterations caused by extreme climate-driven weather

[25] https://whc.unesco.org/en/list/1192/
[26] https://whc.unesco.org/en/list/1364/

events, coastal erosion, and flooding and the proliferation of nuisance HABs and jellyfish blooms may compromise this aesthetic appeal, as well as creating public health hazards, which may dissuade both local visitors and tourists alike from visiting those areas. Coastal tourist destinations in the RSA are particularly vulnerable to extreme events, dust storms, floods, saline intrusion and loss of coastal areas, although further research is required to further understand and predict the impacts of climate change on the coastlines of the RSA (Verner, 2012). Measures to protect the coast from erosion and flooding (hard defences; re-alignment) may in themselves reduce the visual appeal of destinations.

The high sensitivity of coral reef ecosystems to climate change may have serious negative implications for popular tourist attractions across the RSA (AFED, 2009), with economic repercussions. Tourism is an important sector of the economy for the RSA and as such is highly vulnerable to climate change. An increase of between 1–4°C in average temperature will cause a drastic decline in the index of tourism comfort all over the Region. Areas classified between "good" and "excellent" are likely to become "marginal" to "unfavourable" by the year 2080, mainly because of hotter summers, extreme weather events, water scarcity and ecosystems degradation. Bleaching of coral reefs, beach erosion, HABs and SLR will affect coastal tourist destinations especially in locations where sandy beach stretches are narrow and buildings are close to the shoreline. Tourism contributes a significant and growing share of employment across the Middle East, providing direct employment to about 5 percent of the labour force and additional auxiliary services (2010 data; Verner, 2012). Other options to diversify into more climate-proof, alternative tourism should be explored, such as cultural tourism and inland tourist destinations (AFED, 2009; Verner, 2012). Climate change impacts may also lead to the Region becoming less attractive for expatriates to live and work, but more specific research on preferences for both visitors and expatriates is needed to validate this.

Climatic conditions are the third most common attribute in tourists' decision-making when choosing a destination and determine the length of a tourism season (Hassan *et al*., 2015). Indicators of tourism comfort combine data on temperature, precipitation, sun and wind conditions, and humidity, to indicate the degree of climatic comfort that tourists feel at a given site (Hassan *et al*., 2015). The increasing trend towards warmer temperatures could have major consequences for the tourism industry, but the most serious impacts will result from the effects of SLR on small island states followed by other impacts such as coral bleaching, changed migration patterns of animals and birds, flooding and the spread of vector-borne diseases (Agnew and Viner, 2001).

4.6 Regulating benefits: water and air quality and disturbance control

4.6.1 Human health

Climate change endangers human health, affecting all sectors of society (Portier *et al*., 2010). SLR, changes in precipitation resulting in flooding and drought, heatwaves, more intense cyclones and storms, and degraded air quality, will affect human health both directly and indirectly (Portier *et al*., 2010). For example, increases in frequency and severity of heatwaves – likely outcomes of climate change – have the potential to harm a lot of people, particularly sensitive that are both susceptible and vulnerable, for example within the displaced population that evacuated New Orleans following

Hurricane Katrina, older people (susceptible) who were of low income (vulnerable) were the slowest to recover from the disaster (Eisenman *et al*., 2007).

In the case of diseases linked to climate change, those particularly susceptible include children, pregnant women, and the elderly, especially for heat- and weather-related illness and death, vector-borne and zoonotic diseases, and waterborne and foodborne illnesses (Balbus *et al*., 2009). Also, children and some minority groups are very susceptible to asthma and allergies that may be exacerbated by poor the air quality caused by climate change (Portier *et al*., 2010).

Climate change is likely to induce changes in the seasonal windows of growth, and geographic range shifts of marine pathogens across the globe, with longer annual periods of time when there is increased risk for outbreaks. As a consequence, human health will be put at risk, as well as further threats to economies and societies (Jacobs *et al.,* 2015). Harmful phytoplankton as well as other marine pathogens like *Vibrio* bacteria and viruses correlate significantly with rises in SST and are expected to expand their biogeographical range into new areas as sea temperatures warm (Baker-Austin *et al.,* 2013; Jacobs *et al.,* 2015). A study off the eastern coast of Saudi Arabia detected the presence of pathogenic *Vibrio* species at five sites tested, with the incidence of some species, such as *V. parahaemolyticus* shown to be highest during summer months of the year (Elhadi, 2012). These *Vibrio* species have the potential to cause serious gastroenteritis, through ingestion of raw or undercooked seafood, and infection via wounds in contact with seawater.

Health effects from marine HABs include paralytic and diarrheic shellfish poisoning associated with toxin-producing dinoflagellates; diatoms causing domoic acid poisoning; fish killing microalgae species (some species have a direct human health risk through aerosol); microalgae that cause high-biomass, large-scale and long-lasting nuisance blooms; euryhaline cyanobacteria causing persistent high-biomass outbreaks stimulated by eutrophication; and ciguatera fish poisoning. Any of these HAB-associated problems carry serious direct or indirect human health risks, as well as environmental and socio-economic implications (Wells *et al*., 2015; Berdalet *et al*., 2015).

Ciguatoxins that cause ciguatera fish poisoning are produced by *Gambierdiscus* spp. and *Fukuyoa* spp. dinoflagellates (Kibler *et al*., 2015). In the RSA, ciguatera fish poisoning is associated with *Gambierdiscus toxicus*, which is present in the Inner RSA and was reported in Kuwait's shores at the time when large numbers of dead fish were seen along its shores (Albinali, 2011). Although human ciguatera fish poisoning may be underreported or not yet diagnosed, ciguatoxins are also known to be present in the I-RSA. The toxin usually accumulates in big reef fish like grouper, wrasse, triggerfish, lionfish, and amberjack. If larger fish eat many contaminated fish, the poison can build up to a dangerous level (Albinali, 2011). A study of the effects of ocean warming on the dinoflagellates causing ciguatera fish poisoning in the Gulf of Mexico and Caribbean Sea indicated that where water temperatures were higher, species with higher thermal tolerance will become increasingly dominant, prompting shifts in ciguatera fish poisoning risk in the coming decades (Kibler *et al*., 2015). However, the degree to which those risks will change will depend largely on the toxicity of each dinoflagellate species (Kibler *et al*., 2015). The proliferation of HABs and fish kill events have been associated to the increasing average sea temperatures of the RSA, although further research is needed to ascertain the climate signal such as increasing temperatures versus other factors like poor water quality and eutrophication (Heil *et al*., 2001; Bauman *et al*., 2010; Sale *et al*., 2011).

Recent findings as part of the UAE's climate risk assessment, identifies heat stress leading to reduced labour productivity as one of the priority risks, emphasizing that given the magnitude of the construction sector and the large number of outdoor workers, the potential socio-economic impacts of heat stress requires urgent attention and action (UAE National Climate Change Adaptation Programme, 2019). Stronger storm and cyclone conditions in some coastal areas will increase risk to human life situations.

4.6.2 Clean water and air

Mangrove forests fringing the coast help maintain coastal water quality by retaining suspended particles from land sources and removing and recycling nutrients and pollutants. The mangroves filter these materials from water before they reach coral reef and seagrass habitats further out at sea. The dense root systems of the mangrove forest slow water flow, allowing the deposition of sediment. In addition, just like any other tree cover on land, mangrove forests help improve air quality and actively absorb CO_2 and store it away in the sediments below-ground for long periods of time (Cusack *et al.,* 2018). Seagrass beds also help stabilise otherwise loose sediments on the seabed and increase water clarity (Waycott *et al.,* 2011), and like mangroves are a very active blue carbon sink and equally active at removing CO_2 from the atmosphere (Cusack *et al*., 2018).

A combination of habitat degradation and destruction caused by human activities, and climate change impacts (increased sea temperature and salinity, ocean acidification, SLR, erosion and coastal flooding, changing storminess, and altered rain patterns) are already contributing to the loss and degradation of these important habitats. As these impacts intensify in future decades, this will have negative repercussions for these ecosystems, thus limiting their ability to enhance water and air quality.

4.6.3 Flood and erosion control

Coastal wetlands including mangroves and salt marshes, in synergy with seagrass beds and coral reefs, can protect coastlines (and therefore lives and properties) through helping to control coastal flooding and erosion (Potouroglou *et al.,* 2017; Paul, 2018). In the absence of these natural, physical barriers the coast is further exposed to the daily pounding action of wind and waves, particularly during extreme events such as cyclones and coastal flooding.

If mangroves were lost, it has been estimated globally that 32% more people would be flooded by 1-in-10 year events, whereas 16% more people would be flooded by 1-in-100 year events (Beck *et al*., 2018). Based on three climate change scenarios for sea-level rise, a coastal vulnerability model classifies between 4 and 32% of the UAE coast (within one km of the shoreline inland) as highest exposure areas, currently home to more than 175,000 people and extensive coastal assets (AGEDI, 2016b).

As per above, these important coastal and marine habitats are under threat from a combination of pressures from climate change and human activities.

4.6.4 Carbon sequestration and storage by coastal and marine habitats

Mangroves, coastal salt marshes, and seagrasses represent the three main coastal and marine blue carbon sinks. These three coastal and marine habitats play a role in mitigating climate change, storing a disproportionate amount of carbon per square meter compared to tropical forests and vegetated ecosystems (McLeod *et al.,* 2011). In the I-RSA, mangroves, seagrass and saltmarshes along the western coast are acting as active CO_2 sinks, burying carbon in their sediments on an annual basis (Cusack *et al.,* 2018).

Empirical data for *Avicennia marina* show only small increases of net primary production in response to higher atmospheric CO_2 concentrations, so that a doubling of current CO_2 concentrations with a 2°C increase in temperature would result in a 14–19% increase in net primary production across geographically separate forests, and a 12–68% increase among monocultural stands (Alongi, 2015).

The degradation and loss of these habitats due to change climate impacts, as well as human intervention, will not only compromise their capacity to remove and store more carbon, but could potentially release carbon that is already stored, and feedback further global warming as it re-enters the atmosphere as CO_2.

5. Conclusions

The RSA is being increasingly affected by climate change, leading to ecological, social and economic impacts. This report has reviewed current literature regarding climate change within the RSA, highlighting how the physical environment may change, and how this in turn will affect marine and coastal biodiversity and the wider society.

While the RSA is an area of extreme environmental conditions, an increase in sea temperature and salinity, coupled with declining pH and oxygen, present further challenges to the species and habitats of the Region. SLR and a potential increase in storminess present major risks. These physical impacts are geographically variable due to the enclosed nature of the I-RSA and the more open O-RSA. Projections downscaled to the Regional scale would help to provide greater insight into future impacts across the RSA, which are needed to fully appreciate resulting effects on biodiversity and wider RSA economies and society. This research will require a substantial amount of commitment, technology and funding from ROPME Member States.

Whilst many coastal and marine species have adapted to the extreme conditions they currently experience, particularly within the I-RSA, further climate change could push some species beyond their environmental tolerances. This has the potential to lead to substantial declines in abundance and impact on habitat suitability and distribution, with wider ecosystem level changes likely (although currently relatively unknown within an RSA context). Some species may benefit; for example cephalopods, jellyfish and algae, leading to possible increased “bloom” events and increases in the prevalence of nuisance marine pathogens with warmer waters.

In order to develop strategies to help manage the ecological impacts, a greater understanding of the risks and relative vulnerabilities of species and habitats is needed to help determine which may require greater intervention and management. An integrated management approach will be crucial, and consideration of the interacting effects of other human pressures on these species and habitats is also important to generate a more holistic understanding of the resilience of species, habitats, ecosystems, and economies to climate change impacts.

The social and economic implications of climate change within the RSA are diverse. Impacts can be direct, such as the effects of storms on port and energy infrastructure; and indirect, through changes in the marine ecosystem, such as declines in fisheries catch potential and effects of jellyfish blooms on leisure activities. For some sectors, the implications of climate change are relatively well known compared to others (e.g. fisheries), but overall there is still a general lack of information regarding the impacts of climate change on society in the Region. Greater research attention to understand and address these evidence gaps will be important to help inform future decision-making to support adaptation of sectors and communities to climate change impacts. There is an imperative need to gain a better understanding of the relative vulnerabilities of different social and economic groups to future climate change impacts and explore how to enhance their adaptive capacity.

6. Knowledge gaps

The RSA remains relatively understudied compared to other regions of the world, especially with regards to the impacts of climate change on marine and coastal ecosystems. However, there is increasing evidence that climate change is impacting the RSA, one of the world's warmest sea areas (Hoegh-Guldberg *et al.,* 2014), and a detailed review of the current evidence base is urgently needed.

A preliminary knowledge gap analysis was carried out as part of this Marine Climate Change Impacts Evidence Report. Where evidence on physical drivers of climate change was not available or accessible for the ROPME Region, or where evidence was sparse, this was been highlighted to help direct future research efforts.

A classification of the types of data sources mined for this report, together with some examples, was summarised in Table 1 from systematic monitoring, to local research studies, to Regional studies and global trends.

Table 5 represents the level of evidence in the English language that was accessible to the authors in terms of observed and future impacts of the main physical drivers of climate change: sea surface temperature, salinity, ocean acidification, dissolved oxygen concentrations, SLR and storms and cyclones, for each of the distinct parts in the RSA: I-RSA, M-RSA and O-RSA.

Table 5: Gap analysis showing the levels of evidence available for the observed and projected (future) trends of each of the physical drivers of climate change, assessed across each distinct part of the RSA.

		I-RSA	M-RSA	O-RSA
Sea temperature	Observed	Local research studies	Local research studies	Local research studies
	Future	Local research studies	Regional studies	Regional studies
Salinity	Observed	Local research studies	Local research studies	Local research studies
	Future	Local research studies	Global trends	Global trends
Ocean acidification	Observed	Systematic monitoring	Global trends	Global trends
	Future	Global trends	Global trends	Global trends
Oxygen	Observed	Local research studies	Local research studies	Local research studies
	Future	Global trends	Global trends	Global trends
Sea level rise	Observed	Local research studies	Regional studies	Regional studies
	Future	Local research studies	Regional studies	Regional studies
Storms and cyclones	Observed	Regional studies	Regional studies	Regional studies
	Future	Regional studies	Regional studies	Regional studies

Systematic monitoring
Local research studies
Regional studies
Global trends

The analysis highlighted that far more studies were found for the I-RSA compared to the M-RSA or O-RSA. Across all parts of the RSA, observed trends of temperature, salinity and dissolved oxygen had the best level of locally relevant information, while future changes in dissolved oxygen and seawater pH were mostly lacking and had to be derived from global models.

7. References

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