Regional Organization
for the Protection of the
Marine Environment

ROPME

Status and Trends of Coral Reefs in the ROPME Sea Area Past, Present and Future

January, 2020

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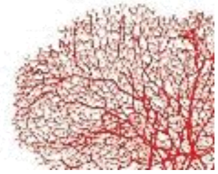

Past, Present and Future

ROPME
January, 2020

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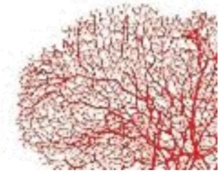

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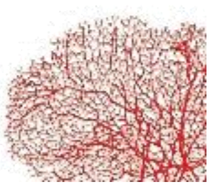

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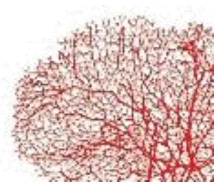


Foreword

The ROPME Sea Area (RSA) is said to have had 8% of the world's Coral Reefs, and its Inner Area is home to the warmest reefs in the world. The RSA coral reef ecosystems support the economies of the countries in the Region, particularly in fisheries and to a lesser extent in tourism sectors, and provide livelihood opportunities and income for local communities. However, anthropogenic pressures at all scales, from development, fishing, and climate change, are all increasing with human population growth and local to Regional development, particularly during the first decade of this millennium.

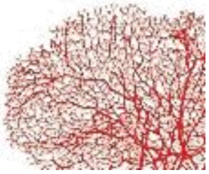
The RSA Coral Reefs experienced widespread coral bleaching during the first global coral bleaching event in 1998, in which >80% of corals died. They were also affected by what has been dubbed the "3rd global coral bleaching event" in 2017, in which mortality surpassed 85-95%. It is timely, therefore, to assess the "State of the Coral Reefs" of the RSA.

The purpose of this status report is to evaluate the status and possible changes of the RSA Coral Reefs, resulting from development and fisheries activities, climate change stressors and other natural drivers including crown-of-thorns starfish (*Acanthaster planci*), diseases and tropical cyclones. The report includes National sections on the status of Coral Reefs by 2019, the impact of the 2017 global bleaching events, and current information on pressures, management, and policy responses to Coral Reefs at the RSA. It also includes Regional synthesis on the overall trends of reef health under climate change IPCC scenario, and large-scale drivers and forecasts for the Region for decades to come.

It is truly felt that the outlook of the RSA Coral Reefs, contained therein, represents a real challenge to all of us in the Region. It clearly demonstrates that serious problems still exist on Coral Reefs in the RSA, in spite of all the dedicated efforts of ROPME and the Member States throughout the 43 years of ROPME's existence. These environmental problems must be effectively addressed and remedied through our collective action.

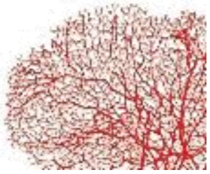
This report has been prepared by Dr. Mohammad Reza Shokri who is based at the Faculty of Life Sciences and Biotechnology at Shahid Beheshti University (Tehran, Iran) under an MOU with ROPME.

EXECUTIVE SUMMARY



- The ROPME Sea Area (RSA) Coral Reefs are impacted by numerous disturbances including climate change stressors, local to Regional development, fisheries activities, tropical cyclones, coral bleaching, disease, and outbreaks of the corallivorous crown-of-thorns starfish (*Acanthaster planci*).
- Over the last two decades, these collective disturbances have caused declines in hard coral cover to minimized (<20%) levels across much of the RSA.
- Reef condition has been variable both within and among three parts of the RSA (i.e., the Inner RSA, the Middle RSA, the Outer RSA).
- Reefs in the Inner RSA have been largely affected from multiple severe disturbances including large scale development, and two episodes of severe coral bleaching over the period 1996 to 2019.
- In response to these disturbances, low hard coral cover in the Inner RSA continues to decline in this Region.
- Reefs in the Middle and Outer RSA relatively escaped major disturbances from 1996 until 2017, during which two episodes of severe coral bleaching occurred over the period 1996 to 2019. Yet, fisheries activities, tropical cyclones, and outbreak of crown-of-thorns starfish impacted the reefs in the Region.
- Large-scale bleaching events in the Inner RSA, are clearly linked to unusual temperatures and the accumulation of heat stress in corals, yet other drivers, such as UV and water acidity, can have compounding effects.
- The Inner RSA warming rate is 2 to 3 times faster than the global average. Thus, future climate projections indicate that the Inner RSA undergoes substantial warming that may exceed 3 °C and 4 °C by the end of the century under moderate mitigation emission scenario Representative Concentration Pathway (RCP 4.5) and business as usual (RCP 8.5) emission scenario.
- According to RCP 8.5, the warming in the Middle RSA and Outer RSA is less than the Inner RSA, increasing by approximately 2.5°C in 2099, relative to 2010.
- The Inner RSA corals can support about 5°C more heat over their relatives in the Great Barrier Reef and in the Caribbean. Therefore, if corals are not subjected to other stressors, there may be a rational

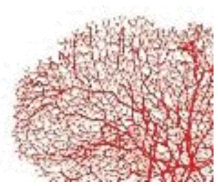
expectation that at least a subset of today's coral fauna may adapt to a



heated world.

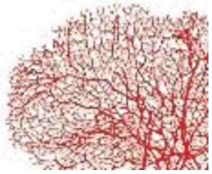
- The supersaturated aragonite in the Inner RSA seawater suggests that acidification is likely to be a less imminent threat to Coral Reefs than the rapid increases in temperatures.
- Decreasing salinity in the eastern side of the Inner RSA by 2099 and in the Outer RSA is expected to adversely affect the Coral Reefs by changing their community structure.
- The Middle RSA and Outer RSA, are projected to experience stronger deoxygenation than the wider Indian Ocean. Therefore, any further reduction in oxygen levels in the RSA can put marine life under serious threat leading to the increased mortality of organisms on Coral Reefs.
- The complete recovery of Coral Reefs in shallow areas of the Inner RSA is unlikely; as forecasts suggest that Sea Surface Temperatures (SSTs) will be undesirable for coral growth in the future.
- The Coral Reef coverage in deeper areas of the Inner RSA will increase, but probably by changing the species composition. Thus, the future composition and structure of the coral communities in the Inner RSA will be shaped by the vulnerability of various species to climate change and local stressors.
- The reefs across Oman and Iran's coastline in the Middle RSA and Outer RSA are under threat from the integrated threats of local stressors (fisheries activities) and thermal stress. Over the next decades, climate change and related ocean acidification in combination with local stressors will cause >75% of the reef area to be under high threats by 2030, and almost all of the Oman reefs under a critical threat by 2050.
- Reefs in the Inner RSA experienced a significant loss due to severe coral bleaching in 2017. To date, recovery has been limited and hard coral cover on survey reefs increased slightly from 10% in 2017 to 20% in 2019.
- Reefs in the Middle and Outer RSA sustained significant coral loss due to severe 2017 bleaching episode. Yet, these reefs are prone to be affected by the concurrent Tropical Cyclones and the continued spread of crown-of-thorns starfish outbreaks.
- Superimposed on natural threats, coastal development will continue in the Inner RSA with increased rates of landfill and dredging causing more stress to the nearshore reefs.
- It is suggested that all the ROPME Member States strengthen the national Coral Reef monitoring network to prepare a National status of

Coral Reefs to report every year and to share metadata on Coral Reefs



with all ROPME Member States.

- The resilience of the Inner RSA corals is probably best maintained by preserving biodiversity in Coral Reefs and adequately incorporating corals from different reefs under a network of protected areas, or managed reserves.
- Placing Coral Reef conservation in the wider context of strategic economic development at the National level will certainly enable the authorities and Non-Governmental Organizations to become more active in shaping a better basis for marine conservation. Implementing Marine Spatial Planning (MSP) is a necessary step in illustrating the strategic planning opportunities that can offer to Coral Reef management and conservation.



1. INTRODUCTION

1.1. Significance of Coral Reefs

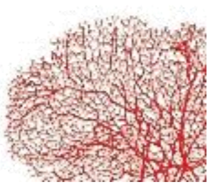
Coral reefs are among the most productive and biodiverse ecosystems on the planet, supporting over a fourth of marine organisms while occupying not exactly a tenth of a percent of marine environment worldwide (Spalding and Grenfell 1997; Spalding *et al.*, 2001). It has been approximated that Coral Reefs occupy 284,300 km^2 of the planet's surface (Goodwin, 2006) and less than 0.1% of the world's ocean area (Spalding and Grenfell 1997; Spalding *et al.*, 2001).

Consistently, corals, reef structures, and Coral Reef ecosystems play a significant role in the cycle of life (Goodwin, 2006). Reefs also provide important services and goods to human populations in coastal areas that are valued in the billions of dollars annually (Costanza *et al.*, 2014); benefits that are most significant in tropical developing states (Moberg and Folke, 1999; (Hernández-Delgado, 2015). Coral reefs are particularly important in tropical developing countries where they can provide economically important services and products for populations in coastal areas (Burt *et al.*, 2014).

> *Coral Reefs, often called “rainforests of the sea", occupying less than 0.1% of the world's ocean area, are home for at least 25% of all marine species*

Besides their ecological importance, reefs are also imperative to support a multi-million-ton fishing industry and hundreds of thousands of employment by providing a range of commercially significant species with food, shelter and nursery habitat (Grandcourt, 2012; FAO, 2017, 2019).

Coral reefs are biological constructions formed mainly by Scleractinian corals, therefore called "Ecosystem Engineers" (Jones *et al.*, 1994). Reef-building corals synthesize a skeleton of calcium carbonate whose accumulation, over millions of years, forms the Coral Reefs. The growth of the Coral Reef is about 4 kg of CaCO$_3$ deposited per year per m^2 (Smith and Kinsey, 1976) but can in some cases reach 35 kg/year.m^2 with linear growth rates of more than 10 cm per year for branching corals (Barnes and Chalker, 1990), The first Coral Reefs appeared nearly 450 million years ago, whereas the



"modern" reefs date from the Triassic, around 237 million years ago (Stanley, 2003; Hoegh-Guldberg, 2014).

Paradoxically, Coral Reefs are a home to about 25% of the marine species described to date, i.e. 93,000 species described in the reefs out of a total of 274,000 known marine species (Porter and Tougas, 2001), including 25% of marine fishes (Allsopp *et al.*, 2009). Coral Reefs are nearly 400 times richer in species diversity than other ocean areas, which is comparable per square kilometer to large rainforests (Reaka-Kudla, 1997).

As hotspots for biodiversity, Coral Reefs provide important ‘ecosystem services’ that generate the conditions for human communities to settle and potentially thrive in coastal areas adjacent to the reefs. The main ecosystem services rendered by Coral Reefs at the global level are, in decreasing order of potential net benefit: incomes from tourism, protection of the coast, production of food for local population (or incomes from the export of these fish) and biodiversity (Moberg and Folke, 1999; Cesar *et al.*, 2003; David *et al.*, 2007; Hilmi *et al.*, 2017; UN Environment *et al.*, 2018) but these incomes show significant Regional disparities. The total annual income of global Coral Reefs is estimated to be between US$ 30 (Conservation International, 2008) and 375 billion / year (Costanza *et al.*, 1997), with huge Regional disparities. The total value of the Great Barrier Reef is estimated at US$ 40 billion (Deloitte Access Economics, 2017).

Among these revenues, the major source comes from tourism and recreational activities: reef tourism accounts for 30% of global reefs and accounts for 9% of coastal tourism worldwide (Spalding *et al.*, 2017).

Coral Reefs also play a major role as a source of food. It is estimated that 500 million people, mainly in the coral triangle area, depend directly on the reefs for their survival (Wilkinson, 2008). One square kilometer of Coral Reefs can produce 10 to 15 tons of fish per year. Revenues from fishing and reef aquaculture represent approximately US$ 126 million/year for the Australian economy or 2% of total reef income. These incomes are all the more important for developing countries. For example, in the Philippines, the annual coral reef economic benefits (direct and indirect) per 1 km^2 of typical healthy coral reef with tourism potential ranges from US$ 31,900 to 113,000 (White *et al.*, 2000). The total global value of reef fisheries would be 5.6 billion US$ / year or about 20% of the total reef income.

The reefs also protect the coast from erosion by waves. Reefs reduce wave

energy by up to 97% (Ferrario *et al.*, 2014).

Apart from these key ecosystem services, reefs are also important reserves for tomorrow's medicines (Bruckner, 2002). They thus contribute significantly to the well-being of man both now and in the future.

1.2. Coral Reefs in the ROPME Sea Area

The ROPME Sea Area (RSA) as shown in figure 1 legally defined by Article II of the Kuwait Regional Convention as bounded in the south by the rhumb lines from Ras Dharbat Ali (16° 39'N, 53° 3'30"E) to a position 16° 00'N, 53° 25'E; then through the following positions: 17° 00'N, 56° 30'E and 20° 30'N, 60° 00'E to Ras Al-Fasteh (25° 04'N, 61° 25'E), adding up approximately to a surface area of 461,937 km^2 comprising three geographically and environmentally distinct parts: the Inner RSA, the Middle RSA and the Outer RSA. The RSA is bordered by eight countries (i.e., Kingdom of Bahrain, the 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) all of which are Member States of ROPME. The Inner RSA comprises of the Sea Area the northwest of the Strait of Hormuz. The Middle RSA covers the Sea of Oman and on the Iranian side, it extends from the Strait of Hormuz to Chah Bahar at the Pakistan border. The Outer RSA extends from Middle RSA to the southern border of Oman (Fig. 1).

The Inner ROPME Sea Area is home to the warmest reefs in the world

Figure 1. Geographical coverage and divisions of the RSA

Coral Reefs in the RSA are of specific curiosity to science because of the

Inner ROPME Sea Area

- *Shallow, semi enclosed sea*
- *Average depth 38 m*
- *Temperature ranging from 12 °C -36 °C*

Middle ROPME Sea Area

- *Strait of Hormuz*
- *Some influence of monsoons*
- *Temperature ranging from 22 °C -31 °C*

Outer ROPME Sea Area

- *Summer monsoon*
- *Upwelling*
- *Temperature ranging from 20 °C -26 °C*

broad variety of environmental settings in which reefs occur and the distinctive biogeographical patterns that result. These are the most diverse ecosystems in the Region and are particularly crucial in the RSA due to the low diversity of the arid terrestrial setting around them (Sheppard *et al.*, 1992; Burt *et al.*, 2014). They also have a range of endemic species of corals and fish (Ormond and Edwards, 1987; Sheppard and Sheppard, 1991; Coles, 2003; Riegl *et al.*, 2012a) and in some areas these may constitute a significant percentage of the total community (Roberts *et al.*, 1992; Sheppard *et al.*, 1992).

In view of the comparatively extreme and wide-ranging thermal conditions encountered by reefs in the RSA, the area is gaining interest from the scientific community in offering insights into how reef fauna can cope with severe environmental circumstances at molecular, physiological and ecological rates (Bauman *et al.*, 2013; Feary *et al.*, 2013; Hume *et al.*, 2015). There is also increasing interest in using the reefs of the RSA as a proxy for climate change to understand how reefs in other parts of the world can react to future thermal stress (Baker *et al.*, 2004; Feary *et al.*, 2010; Burt *et al.*, 2014;).

The eight nations surrounding the Inner RSA- Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates - share a precious ecosystem that is degraded by human effects. Massive financial and population growth have taken place throughout the Inner RSA since the oil boom of the 1970s, resulting in the fast development of urbanized seascape. This has had serious effects on coastal and marine ecosystems, especially the distinctive Inner RSA reefs that contain corals that have adapted to the greatest water temperatures experienced by corals anywhere on the globe.

The Inner RSA reefs are an important chance for science and can serve as a template for the remainder of the world's reefs, where the Inner RSA-like temperatures are not anticipated until the end of the century (Burt, 2014). The Inner RSA is unique and exceptional in any respect, most notably in terms of its water chemistry, inclement climate (hot summers but also cold winters), and the hardiness of the corals that inhabit it (Riegl *et al.*, 2012a). Coral communities in the Inner RSA are a unique by-product of their environment (Burt, 2014). Coral Reefs are of excellent significance for notable biodiversity; coastal protection; supply of seafood and new medicine; and recreational value in the Inner RSA (Bauman, 2013).

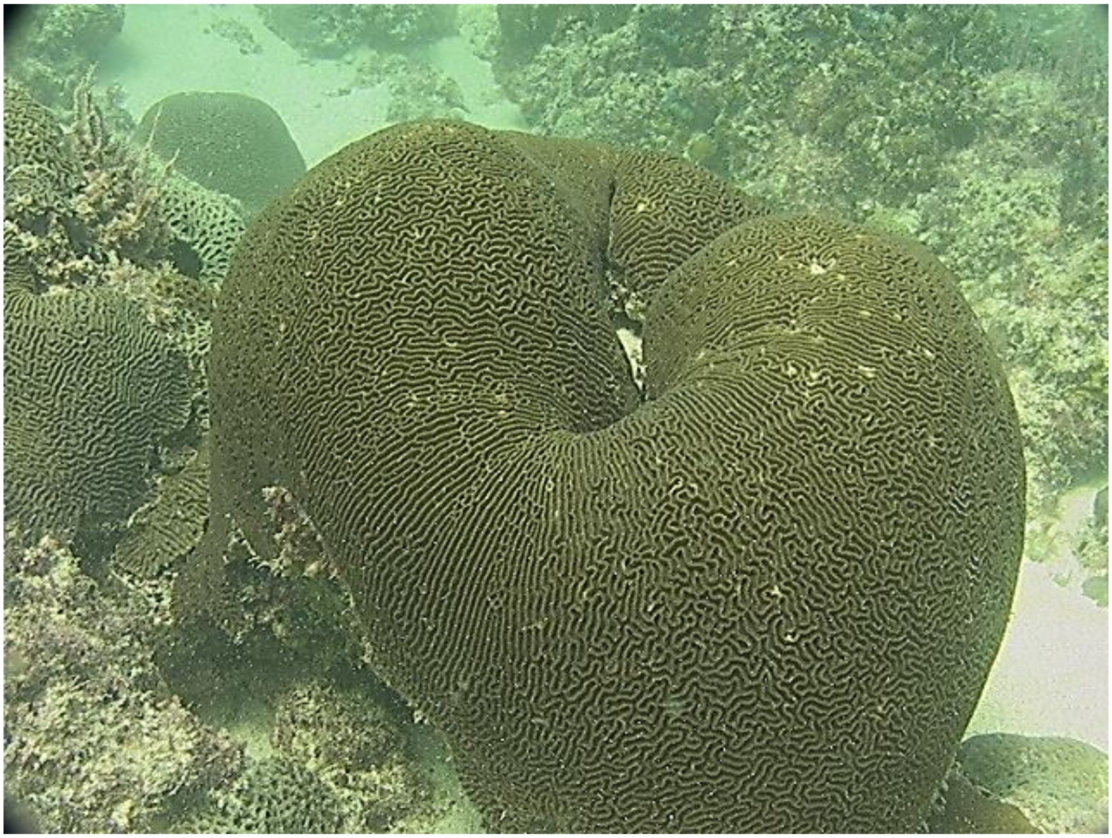


Figure 2. *Platygyra daedalea,* sometimes known as the lesser valley coral, is a colonial species of stony corals in the family Merulinidae. It occurs on reefs in shallow waters in the RSA (Photo by M. Shahnazi, Khark Island, 2003)

2. Coral Reefs Of the RSA: Biodiversity, Distribution, And Adaptation to A Challenging Environment

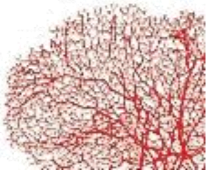
The Inner RSA is a shallow, semi-enclosed water body connected to the Middle RSA (Sea of Oman) through the narrow Strait of Hormuz. The Inner RSA's marine environment is characterized by extreme environmental conditions, often with salinity above 45 ppt and highly fluctuating Sea Surface Temperatures (SSTs) ranging from 12 °C in winter to summer highs above 36 °C (Reynolds, 1993; Coles, 2003). The Inner RSA, as a subtropical epicontnental sea, is home to the northernmost latitude Coral Reefs on the western boundary of the Indo-pacific. The basin has an area of 236,165 km^2 and is shallow and semi-enclosed, which combined with its high-latitude and the presence of mountainous plateaus and deserts nearby, make the Inner RSA's climate the most extreme endured by reef-building corals anywhere in the world (Riegl *et al.*, 2011).

The Inner and Middle RSA are home to about 40 and 68 Scleractinian coral species, respectively, equivalent to about 10% of the Indo-Pacific Species diversity

The species count for the Outer RSA (Arabian Sea sector of the RSA) is likely to be slightly higher than the Inner and Middle RSA

The coastline of Middle RSA (Sea of Oman) is restricted/encircled by a deep basin and has comparatively gentle seasonal changes in SST starting from 22 to 31 °C and salinity (approx. 37 ppt) along the shoreline, tempered by seasonal upwelling from the Arabian sea (Reynolds, 1993; Böhm *et al.*, 1999; Coles, 2003). By comparison, the Arabian Sea coast (the Outer RSA) is one among the world's five biggest upwelling Regions and is dominated by widespread seasonal upwelling, that raises coastal nutrient concentrations within the summer, leading to a 10-fold rise in primary productivity (Smith, 1995; Burkill, 1999; Schils and Wilson, 2006;), with moderate salinity (36-37 ppt) and relatively/comparatively cooler temperatures (range 20-26 °C) in the surface waters bordering the Arabian Peninsula (Elliott and Savidge, 1990; Morrison *et al.*, 1998).

The reef corals of Inner and Middle RSA consist of a significantly decreased



Indo-Pacific coral fauna subset. Only about 10% of the species in the Indo-Pacific are found in the Inner RSA and the composition of the community species is significantly modified by assemblies that usually dominate the Indo-Pacific reef (Coles, 2003).

Estimated numbers of coral genera in the Inner and Middle RSA are 28 and 33, respectively (Veron, 1993). By comparison, estimates of numbers of coral genera in the Red Sea range above 75 including 57 reef-forming genera (Sheppard and Sheppard, 1991), substantially more than the number for the RSA (Coles, 2003). Of the 656 species among 109 genera of reef-building corals for the Indo-Pacific (Cairns, 1999), just about 10%, or 68 species among 28 genera, occur in the Inner RSA and 68 species among 33 genera in the Middle RSA (Coles, 2003). Other studies reported a lower number of scleractinian coral species counting a maximum of 40 in Inner RSA (Rezai *et al.*, 2004; Riegl and Purkis, 2012c). It is believed that a detailed taxonomic reanalysis would reduce the number of reliably recorded species within the Inner RSA to around 40 (Riegl *et al.*, 2012a). In spite of the harsh conditions, the Inner RSA is domestic to approximately 40 species of reef-building corals (Coles, 2003) and 31 Alcyonacean corals (soft corals) (Samimi Namin and Van Ofwegen, 2009), representing a devastated but typical fragment of that of Indo-Pacific (Purkis and Riegl, 2012). A recent study identified 107 zooxantellate hard corals in Middle RSA, while the species count for the Outer RSA is likely to be slightly higher as the influence of the wider Indian Ocean becomes increasingly important along the gradient towards East Africa (Rezai *et al.*, 2004). In both the Middle RSA and the Outer RSA, reef-building potential stays low because of high rates of bioerosion fueled by primary production from the Arabian upwelling system. The RSA coral fauna is a sub-set of the Indo-Pacific fauna, mixed with Regional endemics, with faviids particularly well represented and acroporiids and fungiids significantly under-represented. At least 10 Southern Arabian endemic species are now known, including two endemic genera *Parasimplastrea* and *Calathiscus* and the taxonomic position of several other species have yet to be confirmed (Rezai *et al.*, 2004).

Figure 3. *Goniopora djiboutiensis* (Farur Island, February 2003, Photo by O. Sedighi)

The highest number of species (50 species) was recorded from Saudi Arabian offshore islands (Basson *et al*., 1977; Burchard, 1979), which was suspected to be an over-estimation by Vogt, 1996. This was followed by the UAE with 34 scleractinian species (Riegl, 1999). Iran has a rich coral fauna, probably the richest in the Inner RSA, due to more benign oceanographic conditions (Riegl *et al*., 2012a). Local species richness in the Inner RSA is subject to temporal fluctuations caused by mass mortality events that preferentially affect the branching *Acropora* (Shinn, 1976; Riegl, 1999). Two *Acropora* species including *A. arabensis* (Hodgson and Carpenter, 1995) and *A. downingi* (Wallace, 1999) and one endemic *Porites* (*P. harrisoni*) (Veron, 2000) are restricted to the Inner RSA and nearby Arabian and Red Sea (Riegl *et al*., 2012a). The closest faunistic proximity to other reefs of the Indo-Pacific is naturally to the Sea of Oman and then the Red Sea (Sheppard and Sheppard, 1991; Veron, 2000) which is due to a shared paleoceanographic history of restriction during the last sea-level low stand and simultaneous flooding during the Holocene transgression (Sheppard and Sheppard, 1991; Uchupi *et al*., 1996). While the Red Sea has marked endemism (18 species), the Inner RSA shares its entire species with the Indian Ocean (Hodgson and Carpenter, 1995; Wallace, 1999; Veron, 2000;).

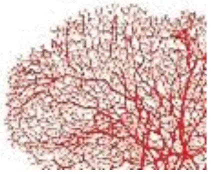


Figure 4 - The endemic *Porites harrisoni* is restricted to the Inner RSA and nearby Arabian Sea and Red Sea (Kish Island, March 2017, Photo by M. R. Shokri)

The Inner RSA coral fauna, with about 40 species is essentially as rich as that in the Caribbean (Chiappone *et al*., 1996). Like in most other reef areas, the scleractinian genus *Acropora* is the most important frame builder and dominates in the shallowest areas. Massive faviids usually occur in slightly deeper water below the zone of *Acropora* dominance. The tabular *Acropora clathrata*/*A. downingi* group of species can form well-developed rigid frameworks. Framework production has been severely hampered by mass mortalities that killed large parts of the frame builder populations. Cause of coral mass mortality is temperature anomalies, either negative or positive (Coles, 1988; Coles and Fadlallah, 1991; Fadlallah *et al*., 1995; Riegl, 2001; Riegl, 2003a). The most important non-*Acropora* frame builders belong to the genus *Porites*. In the Inner RSA, *Porites harrisoni* forms coherent, rigid frameworks. Especially in areas of more extreme salinities and temperature variations, these take the place of the *Acropora* frameworks. *Porites* frameworks are usually smaller than *Acropora* frameworks (Riegl and Purkis, 2012b).

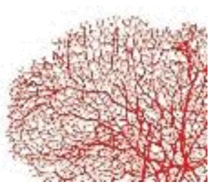


Figure 5- The tabular *Acropora downingi* forms well-developed rigid framework in the RSA (Farur Island, February 2003, Photo by O. Sedighi)

Each summer the Inner RSA is the world’s hottest sea, with SSTs that regularly exceed 35 °C and coral communities that persist for several months at temperatures 34 °C (Riegl *et al.*, 2011). Despite these extreme temperatures, coral communities exist in all eight Nations bordering the Inner RSA (Vaughan *et al.*, 2019) and corals here have the highest known bleaching thresholds in the world (Riegl *et al.*, 2011).

As a biogeographic subset of the Indian Ocean, the Inner RSA was also impacted by increased SSTs. The Inner RSA is also characterized by environmental extremes. Salinity regularly exceeds 45 ppt, and SSTs can annually fluctuate from winter lows less than 12 °C to summer highs above 36 °C (Coles and Fadlallah, 1991; Sheppard *et al.*, 1992). These environmental conditions are selective for corals adapted to these extremes, with corals surviving in temperatures that would normally cause mortality in other areas (Coles, 2003). As a result, dominant taxa in Inner RSA reefs differ from those in the Indo-Pacific, whereas Inner RSA fauna is represented by more tolerant taxa such as faviids and siderastreids while more sensitive acroporids are under-represented (Coles, 2003).

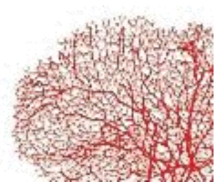
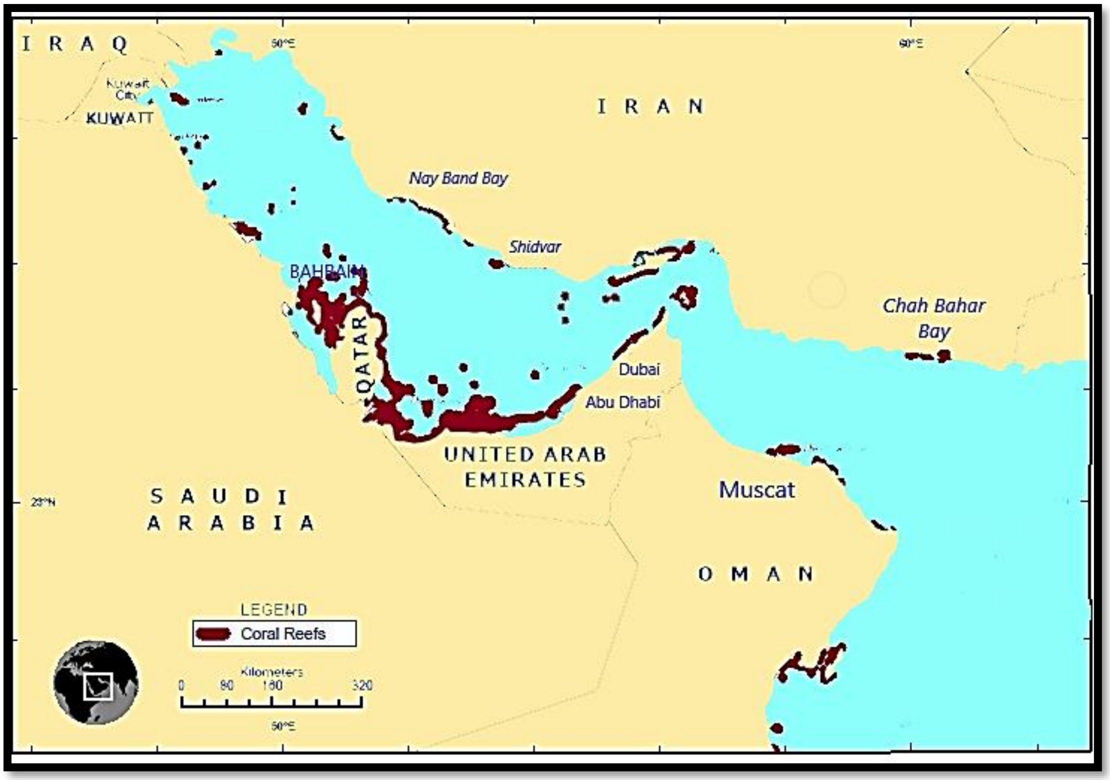


Figure 6. Massive *Porites lutea* in Khark Island (February 2003, Photo by O. Sedighi)

The corals of the Inner RSA display unusual resilience to temperature stress (bleaching). Summer daily mean temperatures routinely top 32 °C while winter winds can chill the water to 12 °C (Sheppard, 2003; Sheppard *et al.*, 2010). Catastrophic bleaching only occurred in the summers of 1996, 1998, 2002 and 2017 when water temperature exceeded 35 °C (Purkis and Riegl, 2005; Sheppard *et al.*, 2010; Vaughan *et al.*, 2019), well above the 25-29 °C range of thermal tolerance for corals elsewhere in the world (Buddemeier and Wilkinson, 1994). While these radical temperature excursions in the Inner RSA impart mortality on coral species such as *Acropora*, dominant frame builders persist with death-rates much lower than would be predicted elsewhere in the Indo-Pacific (Baker *et al.*, 2004). Indeed, such is the ability of the Inner RSA system to rebound from severe temperature events, that the coral community can regenerate to a fully healthy state in only a handful of years (Purkis and Riegl, 2005; Riegl and Purkis, 2009). This resilience implies that the corals of the Inner RSA and their algal symbionts have been capable of acclimatization and selectively adapt to elevated temperatures (Baker *et al.*, 2004; Rowan, 2004; Obura, 2009). Such genetic plasticity is in line with recent observations that Regions of maximal evolutionary potential exist on the geographic periphery of reef growth, such as the isolated high-latitude regime of the Inner RSA (Budd and Pandolfi, 2010).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Abu Dhabi
UNITED ARAB EMIRATES
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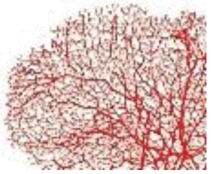


Figure 7. Map of Coral Reefs in the RSA (Map courtesy: The World Fish Center)

Coral Reefs of Bahrain

There are no true fringing reefs in Bahrain. The Coral Reefs around Bahrain have been restricted primarily to the north and east in the form of quite an extensive platform reef structures occupying up to a total area larger than the country itself (Alkhuzai *et al.*, 2009). The main coral habitats occur at Fasht Al-Adhm (200 km^2) to the east, Khawr Fasht and Fasht Al-Jarim 20 km to the north, and Bulthama 70 km northeast; and various other smaller reef habitats scattered around eastern Bahrain (Vousden, 1988). Bahrain's Coral Reefs were considered to be widespread prior to the 1980s supplying planktonic larvae to other reefs at the southern basin of the Inner RSA (Shinn, 1976). Thirty coral species have been recorded with *Acropora* as the dominant species in less saline shallow (<5 m) areas, and poritids and faviids dominated more saline deeper (<20 m) areas (Barratt and Ormond, 1985; Sheppard, 1988; Vousden, 1988, 1995).

Since the last four decades, Bahrain's reefs have significantly degraded as a result of elevated Sea Surface Temperature events and large-scale coastal development (Burt *et al.*, 2013). The results of the most recent survey showed that the major Coral Reef habitats around Bahrain and a reef located 72 km offshore were dominated by fleshy and turf algae (mean: 72% cover), and live coral cover was as low as 5.1% (Burt *et al.*, 2013). They further reported that formerly dominant branching Acropora corals were absent at all surveyed sites. The highest coral cover (16.3%) and species richness (22 of the 23 species observed) were found at offshore Bulthama reef with 13 species exclusive to this site. Burt *et al.* (2013) further argued that under current coastal development and projected climate change impacts, it is unlikely to expect any recovery in Bahrain's Coral Reefs.

Coral Reefs of Iran

The Iranian reefs in the Inner RSA occur as fringing and patch reefs across some parts of the mainland coast (Taheri Port, Kangan and Nay Band Bay all located in Bushehr Province), around Iranian islands and in Sambarun Bank (13 m depth) which are located halfway between Kish and Hendurabi

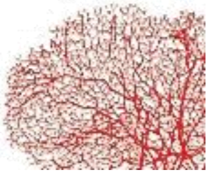
Islands. There are patchy reefs in Chah Bahar and Pozm bays both located

in the northeasternmost of the Middle RSA (Sea of Oman). In contrast to Iran's reefs in the Inner RSA, coral assemblages of Chah Bahar and Pozm bays in the Sea of Oman experience the relatively cool environmental conditions associated with monsoonal upwelling.

The most diverse Iranian reef exists around Larak Island located in the Strait of Hormuz with 40 hermatypic coral species (Vajed-Samiei *et al.*, 2013). The species richness in other reefs are 21 species in Khark and Kharku Islands, 14 in Nay Band Bay, 29 in Farur Island, 26 in Sirri Island, 20 in Hendurabi Island, 28 in Kish Island, 23 in Qeshm Island, 17 in Hengam Island, and 17 in Chah Bahar Bay (Rezai, 1995; Fatemi and Shokri, 2001a; Kavousi *et al.*, 2011; Aminrad and Azini, 2013; Moradi *et al.*, 2014; Ghasemi *et al.*, 2015; Alidoost Salimi *et al.*, 2018).

The Iranian coral communities were historically dominated by *Acropora* corals between depths of 0–6 m, where this species was so abundant (Harger, 1982; Rezai, 1995; Shokri *et al.*, 2000a; Shokri *et al.*, 2000b; Shokri *et al.*, 2000c; Wilson *et al.*, 2002; Rezai *et al.*, 2004). Since 1996/1998 live coral cover, in particular, the Acroporidae declined by over 90% in many areas, primarily as a result of multiple bleaching events caused by rising temperatures (Riegl *et al.*, 2018). In particular, coral bleaching in summer 2017 led to the loss of more than 95% of the *Acropora* corals in all Iranian reefs in Inner RSA (Shokri *et al.*, 2019). Corals in the Chah Bahar Bay located in the northeastern part of Middle RSA escaped the devastating impacts of 1996, 1998 and 2017 bleaching events (Ghazilou, 2019) that severely affected corals in Inner RSA (Rezai *et al.*, 2004). But these reefs experienced a bleaching event in the summer of 2018 when the water temperature raised to more than 30 °C and consequently near 100% of massive corals such as *Dipsastera* and *Cyphastrea* and about 10-50% *Acropora* corals and less than 5% *Pocillopora* corals were bleached (Ghazilou, 2019).

The Iranian reefs have severely damaged due to dredging and port construction around the reefs in Assaluyeh Port near Nay Band Bay, Kish Island, Hendourabi Island and Chah Bahar Bay. The adverse impacts of these activities have been a direct loss of Coral Reef caused by the removal or burial of reefs and lethal or sub-lethal stress to corals caused by elevated turbidity and sedimentation rates. Effects of harmful algal bloom (HAB) of *Cochlodinium polykrikoides* occurred in late 2008/early 2009 starting from August 2008 near the Strait of Hormuz till May 2009 on the Iranian side of the eastern Inner RSA resulting in near-complete extirpations of shallow-



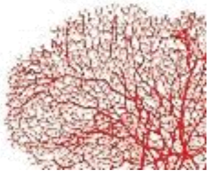
water reef biotas that were due to an increase in sedimentation and asphyxiation (Samimi Namin *et al.*, 2010). Corals experienced colonizing by fouling organisms, specifically serpulid worms primarily settling on dead corals and overgrowing live polyps.

Coral Reefs of Iraq

Iraq has a narrow strip (58 km) of coast in the northwest of Inner RSA which is dominated by the large swampy river delta of Euphrates, Tigris, and Karun, merging into the Shatt al-Arab, representing the main outflow into the Inner RSA. The Coral Reefs of Iraq were first discovered in 2013 (Pohl *et al.*, 2014). The reef has an area of 28 km^2 with 6 by 3 km wide zone of relatively healthy reefs at water depths between 7 and 20 m. This reef is characterized by a tidal variation of about 3 m, rather strong tidal currents (3–4.5 $m.s^{-1}$), high turbidity, and high nutrient load from rivers. There are one octocoral (*Junceella juncea*) and seven hermatypic species dominated by stress-tolerant massive and submassive corals including *Platygyra pini*, *Turbinaria stellata*, *Tubastrea* sp., *Porites lobata*, *Porites* sp., *Astroides calycularis*, and *Goniastrea edwardsi*. This newly discovered Coral Reef differs from those in adjacent Kuwait. The fringing reefs in Kuwait are distributed around islands, or close to the coast at water depths between 0–10 m, being settled on the sandy ground in relatively transparent water. Yet, Iraqi reef is located at greater depths in a zone of low visibility, and rapidly changing conditions (temperature and salinity) due to strong currents.

Coral Reefs of Kuwait

Kuwait's reefs are largely concentrated in the southern part of the country in the form of platform and patch reefs forming on seamounts, extending from Kuwait City to the border with Saudi Arabia. In Addition, there are some fringing reefs around offshore islands. With 35 coral species (29 hermatypic and six ahermatypic species) (Hodgson and Carpenter, 1995), most corals occur in waters shallower than 10 meters (Pilcher *et al.*, 2000). However, there are some corals extending to a maximum of 15 m depth. Coral diversity is limited on offshore reefs at Mudayrah. Qaro Island has the most diverse reefs, dominated by *Acropora* and *Porites*, with above 80%

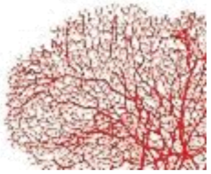


live cover (Pilcher *et al.*, 2000). There is an extensive reef surrounding Um Al-Maradem enclosing a lagoon about 400 m offshore. Nearshore reefs such as Qit'atUraifjan are limited by high sediment loads, although they survived the War of 1991-1992 oil spill and are dominated by massive *Porites*, *Montipora* and *Platygyra* (Pilcher *et al.*, 2000). Kuwait's reefs have been degraded by multiple bleaching and mortality starting since 1998. Overfishing, solid waste disposal and widespread anchor damage are the main cause of coral degradation in Kuwait. These reefs were also among those that most directly suffered by the oil spills during the War in 1990-1991. However, oil spills from this War did not cause the mass coral mortalities (Downing and Roberts, 1993; Mohammed and Al-Ssadh, 1996).

Coral Reefs of Sultanate of Oman

The Sultanate of Oman's reefs with over 350 km^2 area occurs at three biogeographically distinct water bodies including the Inner RSA, the Middle RSA (Sea of Oman), and the Outer RSA (the Arabian Sea) (Spalding *et al.*, 2001). So far over 100 coral species and 570 reef fish species have been reported from Oman's reefs (Claereboudt, 2006; Grandcourt, 2012). The reefs in the Sultanate of Oman occur at four main areas including (1) The fjords, bays and coastlines of the Musandam Peninsula and the adjacent rocky shores located to the south of the Strait of Hormuz between Inner RSA and Middle RSA, (2) the Muscat Capital Area from Sohar to Ra's Abu Dawood, including the Daymaniyat Islands; (3) the southern shore of Barr Al Hikman and the west coast of Masirah Island; and (4) Dhofar from the Hallaniyat Islands to Mirbat (Glynn, 1993). The Musandam peninsula, Dhofar area, and the Capital Area and Ras Al-Hadd contain the highest, intermediate and low coral coverage, respectively (Burt *et al.*, 2016a). In contrast, the highest coral species richness has been reported from corals in the Arabian Sea. In spite of the relatively cool environmental conditions driven from monsoonal upwelling, the reefs in the Arabian Sea are biologically influenced by the environmental condition of east Africa and the Gulf of Aden (Sheppard, 1987; Sheppard and Salm, 1988; Salm, 1991, 1993). It is speculated that in contrast to patterns observed in hard corals, octocorals have higher richness in the southern Arabian Sea than in the areas further north (Burt *et al.*, 2016a).

Oman' reefs have been affected by the past acute stressors leading to loss of



coral cover and shifts in community structure. Although coral bleaching has not proved to be a major problem in Oman, the widespread occurrence of bleaching globally has shown that all reef systems in Oman are potentially at risk. For example, when Sea Surface Temperatures raised to 35 °C and stayed >30 °C for three months, severe bleaching occurred in the summer of 1990 and resulted in the loss of virtually all corals inhabiting <3 m deep in embayed areas (Salm, 1993). As in other stress events, *Acropora* corals were the major species to be affected, although *Stylophora* and *Platygyra* were also bleached. However, bleaching effect occurring as far south as Muscat in 1990 was minimized by cool waters brought by the onset of monsoonal upwelling (Glynn, 1993).

Since the 1970s, Oman's Coral Reefs have been affected by the presence of elevated numbers of Crown of Thorns Starfish (COTS), *Acanthaster planci* with frequency outbreak of at least once per decade (Glynn, 1993; Al-Jufaili *et al*., 1999; Mendonça *et al*., 2010). COTS outbreaks have reported in the Sea of Oman, and particularly on reefs around the Capital Area and the Daymaniyat Islands with densities exceeding 100 ind.ha^{-1} (Glynn, 1993; Mendonça *et al*., 2010). COTS are infrequent in the Musandam and on reefs along Oman's Arabian Sea coast (Salm, 1993; Al-Jufaili *et al*., 1999). In the Sea of Oman, COTS preferentially choose to feed on *Acropora* and *Montipora* leading to the acute shifts in coral community structure (Glynn, 1993). The predominance of poritids and pocilloporids on reefs in the Muscat area has been associated with their differential survival through persistent COTS grazing (Glynn, 1993).

Cyclone Gonu in 2007 as the strongest tropical cyclone on record in the Arabian Sea, with a maximum wind speed of 270 km.h^{-1} and gusts reaching 315 km.h^{-1} (Fritz *et al*., 2010) had also substantial large scale impacts to reefs in Oman (Burt *et al*., 2016a). Oman's corals on exposed shores from Muscat to the northern UAE coast of Fujairah were almost entirely eliminated and habitat complexity was reduced (Maghsoudlou *et al*., 2008; Taylor, 2009; Foster *et al*., 2011).

The largescale (>500 km2) harmful algal bloom (HAB) of *Cochlodinium polykrikoides* with associated hypoxia occurring in late 2008/early 2009 also had substantial impacts to Coral Reefs and associated reef fish around the Musandam peninsula (Bauman *et al*., 2010; Richlen *et al*., 2010). In eastern Musandam, during the bloom all major coral taxa experienced losses. The Coral Reef experienced significant declines in coral cover at one location

(Dibba) decreasing from 53% to 6%. In the Capital Area where bloom density was lower, environmentally sensitive *Pocillopora* at Bandar Jissah experienced up to 95% loss (Burt *et al.*, 2016a). The bloom resulted in mass mortalities and shifts in fish communities by a nearly two-thirds decline in their biomass and diversity.

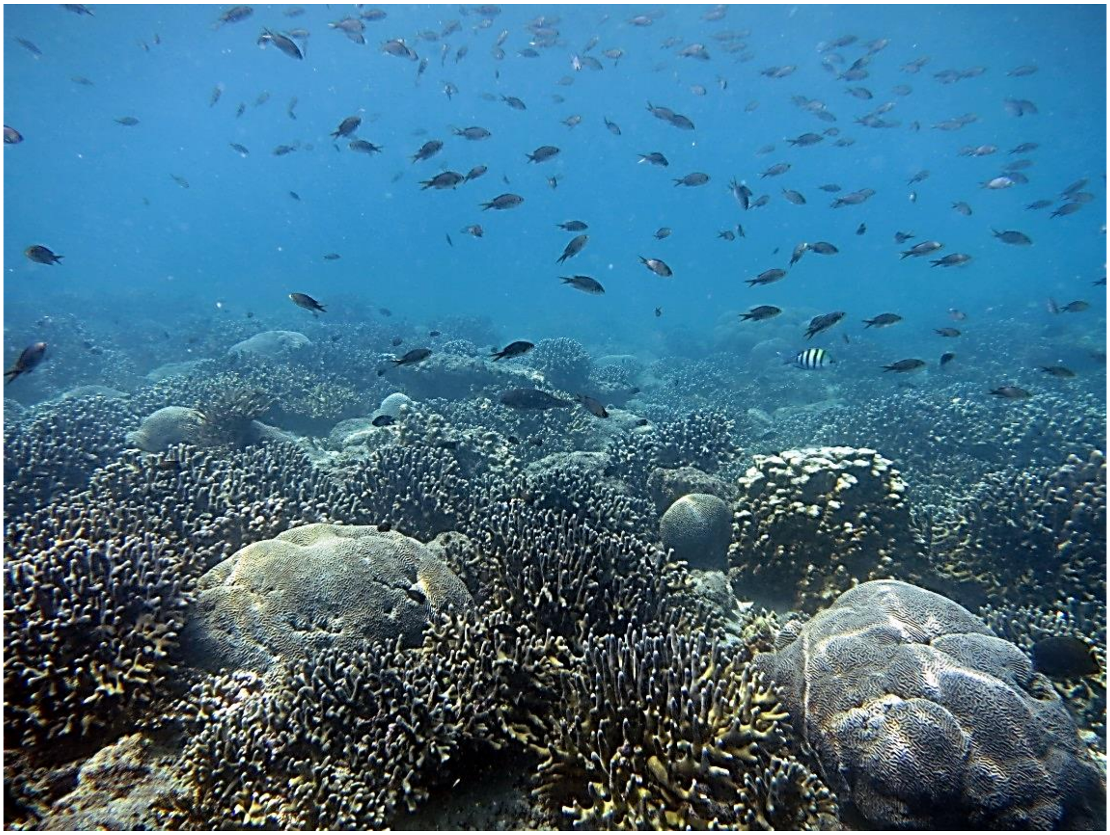
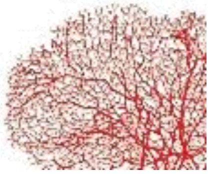


Figure 8. Healthy Coral Reefs at Al-Harf (Khaṣab, Musandam, Oman) (Photo by J. Burt)

Coral Reefs of Qatar

In Qatar, fringing reefs occur along the north and east coasts, with coral communities growing on the coastal shelf to the east. There are also a number of platform reefs further offshore. Yet, there is no real reef structure. According to the recent study (Burt *et al.*, 2016b), the highest species richness (24 of the 26 coral species observed) and high coral cover (29%) occur on seamount Umm Al-Arshan with 14 m depth located 42 km offshore from northern Qatar (Burt *et al.*, 2016b). Fuwayri with a shallow (<3 m depth) nearshore fringing community (<600 m from shore) located 80 km from Doha in northeastern Qatar, and Al-Ashat as an off-shore island



(<6m depth) located 11 km from the southeastern coast, 60 km south of Doha are both characterized with modest coral cover (15% in Fuwayri and 13% in Al-Ashat) and richness (2 species in Fuwayri and 11 in Al-Ashat).

In summary, the results of the studies on Qatar's reef demonstrate that the extensive coral communities in the past (before the 1960s) have undergone dramatic declines in recent decades (Shinn, 1973; Shinn, 1976; Neuman,1979; Burt *et al.*, 2013). Nowadays, the absence of *Acropora* corals in most of Qatar's reefs and the dominance of stress-tolerant species (e.g., merulinids and poritids) are characteristics of environments experiencing chronic or recurrent stress. The absence of *Acropora* corals also suggests that the coral assemblages in Qatar's reef are living at the margins of their tolerance. Therefore, management measures should be aimed at reducing additional stress, driven from man-made activities.

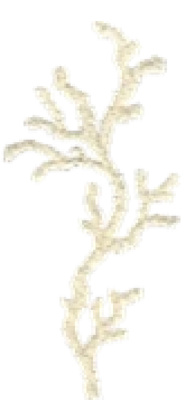
Coral Reefs of Saudi Arabia

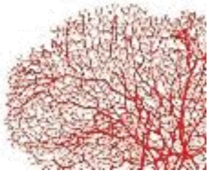
Saudi Arabia has the most extensive and diverse Coral Reefs in the Inner RSA. The reefs along the coast of Saudi Arabia are a mix of small pinnacles and patch reefs closer to the mainland between Ras Al-Mishab Saffaniyah and Abu Ali, and between Abu Ali and Ras Tanura, and fringing reefs around six offshore islands particularly Jana and Karan with coral growth extending to depths of about 18 meters (Spalding *et al.*, 2001). The richest local coral fauna with 50 species was recorded from Saudi Arabia, around Jana and Karan Islands (Basson *et al.*, 1977) that was thought to be an overestimation by Vogt, (1996). About 309 reef fish species (Grandcourt, 2012) is reported with the greatest diversity around the offshore islands. Discharge of sewage from vessels, ship discharge of solid waste, oil spills from exploration, production and transport, illegal disposal of toxic wastes, global warming effect, and diseases are the main threats to the Coral Reefs of Saudi Arabia (Maghsoudlou *et al.*, 2008).

Coral Reefs of United Arab Emirates

United Arab Emirates (UAE)'s reefs occur throughout all seven emirates with a total area of >13,000 ha (>130 km^2) of which 90% are located in the Inner RSA, with the remainder in the Middle RSA (Grizzle *et al.*, 2016).

UAE's coral habitats are largely concentrated in central and western Abu





Dhabi, due to available shallow (<10 m) hard-bottom habitats for coral settlement. There are also some coral formations on some manmade breakwaters (Grizzle *et al.*, 2016). The UAE's reefs are home to 34 scleractinian species (Riegl, 1999).

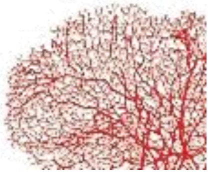
Historically, the Coral Reefs of UAE were among the most extensive in the southeastern Inner RSA. Yet, these reefs suffered widespread bleaching and mortality of corals during the first half of 1998 (Wilkinson, 1998). The Acroporidae were the most affected group on scleractinian coral, showing rapid bleaching and mortality at levels approaching at 90% mortality. The results of the recent study by Grizzle *et al.* (2016) revealed that effects of the cumulative stressors since recent decades still persist on UAE's reefs, and there are very limited signs of recovery. This study reported about 35 coral species with an average of 28.6% live coral coverage at 32 surveyed sites across the UAE.

The UAE' coral communities have undergone dramatic declines due to the Harmful Algal Bloom (HAB) of *Cochlodinium polykrikoides* with associated hypoxia occurring in late 2008/early 2009 (Foster *et al.*, 2011). The bloom impact to Coral Reefs considerably varied depending on taxa; so that *Pocillopora damicornis* experienced mass mortality, *Acropora* spp. displayed a range of responses, and massive colony coral taxa remained unaffected.

Storm damage caused >50% losses of live branching and tabular coral cover by fragmentation and dislodgment of pocilloporid and acroporid colonies. *Pocillopora damicornis* colonies that survived the cyclone experienced mass mortality during the first three months of the HAB, resulting in localized extirpation of this species. Variable *Acropora* mortality during the HAB indicated individual colony, rather than taxa-wide, susceptibility; and massive colony coral taxa were resistant to both disturbances.

Figure 9. Healthy Acropora stands at Dhabiya, UAE (2017, Photo by J. Burt)

3. THREATS TO CORAL REEFS OF THE RSA



3.1. Climate Change and its Impact on Coral Reefs of the RSA

Human activities are estimated to have caused roughly 1.0 °C of global warming above pre-industrial levels, with a likely range of 0.8 °C to 1.2 °C (IPCC, 2018). Global warming is likely to reach over 1.5 °C between 2030 and 2050 if it continues to increase at the current rate (IPCC, 2018). The global warming would lead to changes in ocean heat content, ocean salinity and freshwater fluxes, sea level, oxygen and ocean acidification (Bindoff *et al.*, 2013). On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by an average of 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010 (IPCC, 2014a). Large proportion of reef-building corals in the world was classified as threatened species in 2018 (FAO, 2018), of which 1%, 3%, 23% and 20% are critically endangered, endangered, vulnerable and near threatened, respectively (FAO, 2018) (Fig. 10). The relatively high rate of threatened hard coral species suggests that corals over the world, in particular those in the RSA, are highly vulnerable to ever-increasing magnitude of climate change stressors.

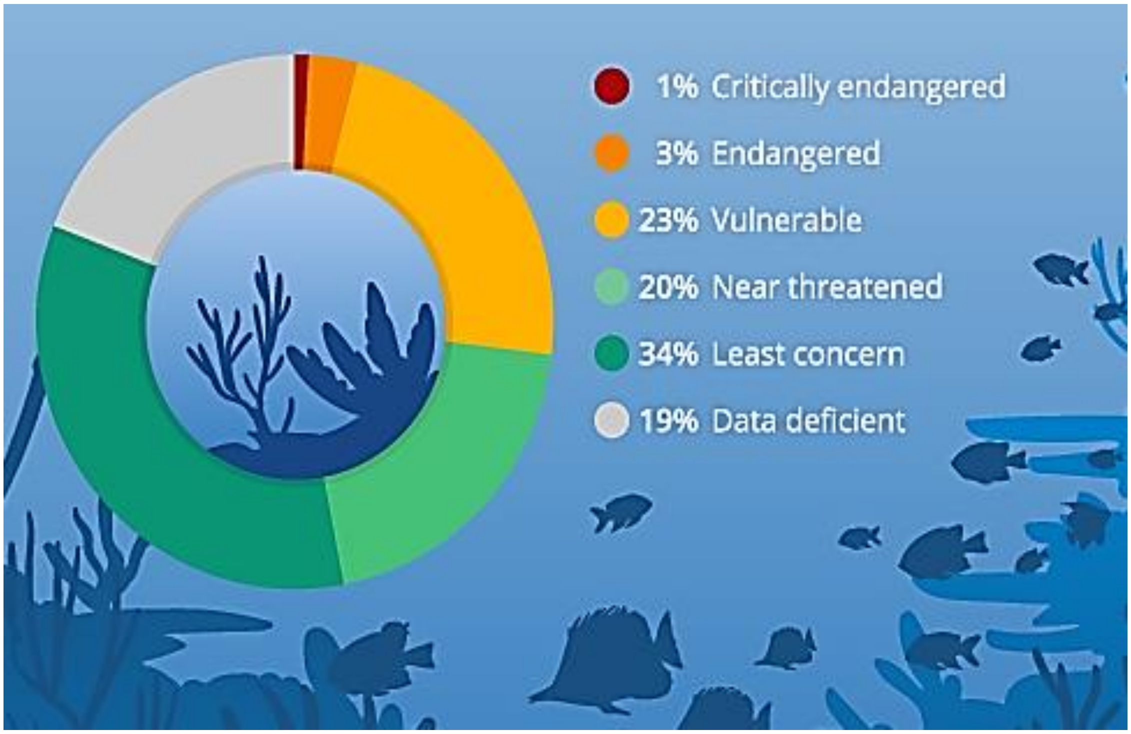
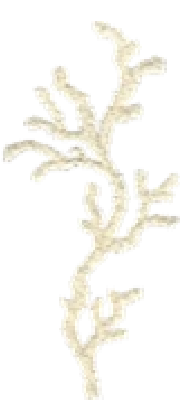
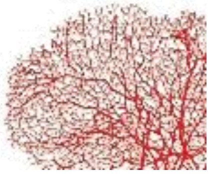


Figure 10. Status of the world's reef-building corals in 2018 (FAO, 2018)

Oxygen as an important physical and biological tracer in the ocean is

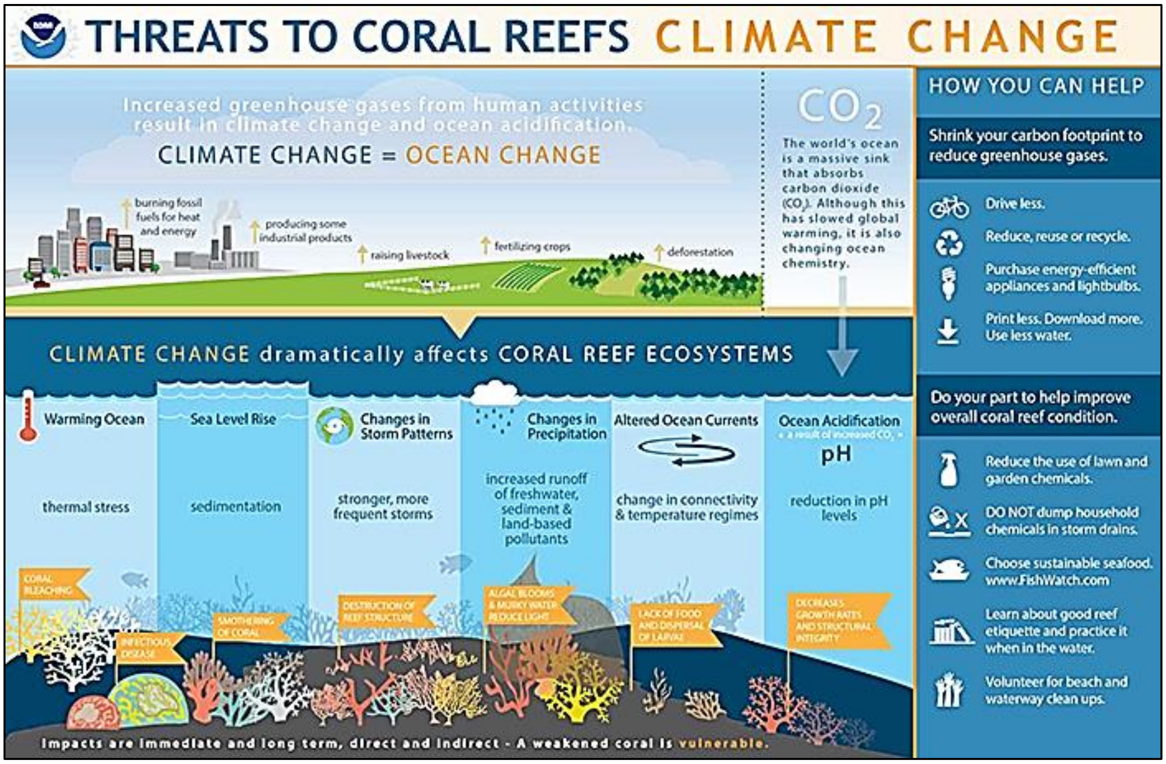




projected to decline by 3 to 6% by 2100 in response to surface warming (Ciais *et al.*, 2013).

The ocean has absorbed about 30% of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry that are unprecedented for at least the last 65 million years (Mikaloff Fletcher *et al.*, 2006; Le Quéré *et al.*, 2010). It is very likely that oceanic uptake of anthropogenic carbon dioxide has resulted in acidification of surface waters which is seen to be between – 0.0014 and – 0.0024 pH units per year (Bindoff *et al.*, 2013). Ocean acidification risks the survival, calcification, growth, development, and abundance of a wide range of marine taxonomic groups, ranging from algae to fish, with remarkable evidence of predictable trait-based sensitivities (Kroeker *et al.*, 2013). There are multiple lines of evidence that ocean warming and acidification corresponding to 1.5 °C of global warming would impact a wide range of marine organisms and ecosystems, as well as sectors such as aquaculture and fisheries (Hoegh-Guldberg *et al.*, 2018).

Coral Reef ecosystems of the world are deteriorating under the effects of climate change (Cinner *et al.*, 2016; Hughes *et al.*, 2017). Likewise, climate change is deteriorating the Coral Reefs of the RSA by a further increase of water temperature and salinity along with the reduction of water acidification and oxygen levels. Thus the understanding of the impact of climate change stressors (i.e., rising water temperature, salinity, water acidification and reducing oxygen level) on Coral Reefs of the RSA and the way corals cope to these changes are of paramount priority. In the following, the state and future trend of climate change stressors in the RSA and their effect on Coral Reefs are discussed.



THREATS TO CORAL REEFS CLIMATE CHANGE

Increased greenhouse gases from human activities result in climate change and ocean acidification.

CLIMATE CHANGE = OCEAN CHANGE

CO_2

The world's ocean is a massive sink that absorbs carbon dioxide (CO_2). Although this has slowed global warming, it is also changing ocean chemistry.

CLIMATE CHANGE dramatically affects CORAL REEF ECOSYSTEMS

Impacts are immediate and long term, direct and indirect - A weakened coral is vulnerable.

HOW YOU CAN HELP

Shrink your carbon footprint to reduce greenhouse gases.

- Drive less.
- Reduce, reuse or recycle.
- Purchase energy-efficient appliances and lightbulbs.
- Print less. Download more. Use less water.

Do your part to help improve overall coral reef condition.

- Reduce the use of lawn and garden chemicals.
- DO NOT dump household chemicals in storm drains.
- Choose sustainable seafood. www.FishWatch.com
- Learn about good reef etiquette and practice it when in the water.
- Volunteer for beach and waterway clean ups.

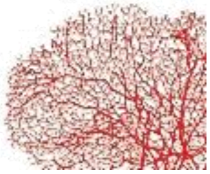


Figure 11. Diagram of the climate change threats to Coral Reefs (NOAA, 2019) (https://oceanservice.noaa.gov/facts/coralreef-climate.html)

3.1.1. Sea Surface Temperature Increase Causing Coral Bleaching and Mass Mortality

Coral bleaching is a process by which coral colonies lose their color, either due to the loss of microscopic algal pigments (zooxanthellae) that coexist with host organs (polyps) or these zooxanthellae have been expelled (Baker *et al.*, 2008). Large-scale and Region-wide bleaching events, such as those occurring in the Inner RSA, are clearly linked to unusual temperatures and the accumulation of heat stress in corals. Yet other drivers, such as UV and water acidity, can also have compounding effects (Baker *et al.*, 2008). The Inner RSA corals are unique in being able to survive the summer temperatures of more than 34 °C or even 35 °C for months (Foster *et al.*, 2012). Coral bleaching in the Inner RSA was found to be moderated by summer winds by which, the winds of 4 $m.s^{-1}$ represent a critical threshold for whether or not corals cross bleaching threshold temperatures (Paparella *et al.*, 2019).

The Inner RSA corals have been exposed to severe temperature anomalies in a recurrence faster than any other coral region in the world. Therefore, it is argued that corals in the Inner RSA already exist in thermal environments, which is in line with the forecasts for 2099 IPPC in tropical oceans (Riegl and Purkis, 2012a). This has generated Regional and international interests in using the Inner RSA corals as a model ecosystem to understand the potential impacts of future climate change (Burt, 2013).

The Inner RSA corals have been exposed to severe temperature anomalies in a recurrence faster than any other coral region in the world

The Inner RSA undergoes substantial warming that may exceed 3 °C and 4 °C by the end of the century under moderate mitigation emission scenario Representative Concentration Pathway (RCP4.5) and business as usual (RCP 8.5) emission scenario, respectively

As a semi-enclosed sea with very shallow depths of 35 m on average the

Since the 1980s, SSTs in the Inner RSA have risen by 0.4 °C every decade - double the global average - with increasing levels of heating in more restricted areas

Inner RSA, is particularly vulnerable to amplified warming under climate change. In fact, recent observations indicate that the Inner RSA warming rate is 2 to 3 times faster than the global average. Sea Surface Temperature Analysis (SST) from the National Oceanic and Atmospheric Administration / National Aeronautics and Space Administration Pathfinder product reveals average warming of the Inner RSA of 0.6 °C per decade between 1985 and 2009 (Strong *et al.*, 2011). In addition, future climate projections indicate that the Inner RSA undergoes substantial warming that exceeds 3 °C and 4 °C by the end of the century under moderate mitigation emission scenario Representative Concentration Pathway (RCP 4.5) and business as usual (RCP 8.5) emission scenario, respectively (IPCC, 2014b). Significant warming is anticipated at all depths throughout the RSA (IPCC, 2014b). Sea Surface Temperatures could rise by 2.8-4.26 °C in 2099, compared to 2010. According to RCP 8.5, the warming in the Middle RSA and Outer RSA is less than the Inner RSA, increasing by approximately 2.5 °C in 2099, relative to 2010 (IPCC, 2014b).

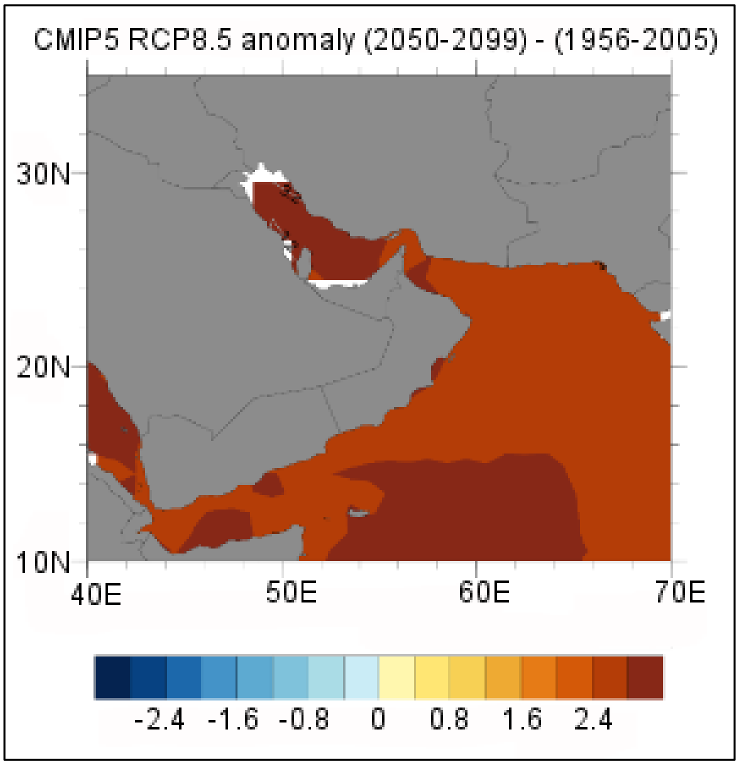


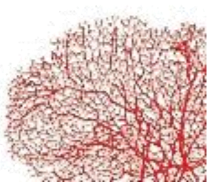
Figure 12. The variation of the annual average Sea Surface Temperature (SST) during the time period of 2050–2099 under RCP 8.5 compared to the historical reference period (1956-2005) in the RSA, based on CMIP5 model. White shading indicates areas with no data (ESRL: PSD: Climate Change Web Portal _ Maps MM" 2018)

Since the 1980s, SSTs in the Inner RSA have risen by 0.4 °C every decade - double the global average - with increasing levels of heating in more restricted areas such as the Kuwait Bay (Al-Rashidi *et al.*, 2009). This rising SST has already caused significant damage to the Inner RSA's marine systems, in particular to Coral Reefs (Riegl and Purkis, 2015). It is estimated that more than 70% of the Inner RSA reefs are effectively lost due to these warming events and other anthropological factors (Burt, 2014). The recent evaluation showed that every reef-dependent fish species in this area is vulnerable to extinction in the coming decades as a result of habitat loss and fragmentation (Buchanan *et al.*, 2016). It has also been suggested that temperature variations may affect the highly seasonal spawning patterns of commercially important finfish and potentially would lead to a lack of compatibility between fish larvae and their prey items, with cascading effects on population dynamics and abundance for species of economic importance to coastal populations (Sheppard *et al.*, 2010).

In summer 2017, one of the highest temperatures was recorded in the Inner RSA causing widespread and Region-wide coral bleaching

Each summer, the Inner RSA is the warmest sea in the world with regular SSTs exceeding 35 °C remaining at 34 °C for several months (Riegl *et al.*, 2011). Despite these extreme temperatures, there are coral communities in all eight countries adjacent to the Inner RSA (Vaughan *et al.*, 2019) and these corals have the highest known bleaching thresholds in the world (Riegl *et al.*, 2011). The RSA has warmed faster than the global average in recent decades (Heron *et al.*, 2016), and SST anomalies have pushed even the Inner RSA's hardy corals beyond their thermal limits through recurrent bleaching events (Riegl *et al.*, 2018). Severe summer bleaching began with two back-to-back events in 1996 and 1998, which resulted in the coral loss of more than 80% in the Inner RSA and the virtual elimination of *Acropora* table corals from nearshore areas (George and John, 2000; Sheppard and Loughland, 2002). A widespread coral bleaching reoccurred in 2002 but with negligible coral mortality (Riegl, 2003b), and in the years after that, the absence of bleaching events allowed a recovery of coral cover across much of the southern Inner RSA and a return to *Acropora* dominance on some reefs (Burt *et al.*, 2008). However, this recovery was triggered by a number of moderate bleaching events that occurred annually between 2010 and 2012, resulting in 15 to 20% coral losses each year (Riegl *et al.*, 2011; Riegl *et al.*, 2012c). After the 2012 event, the corals experienced four years of respite, during which until the summer of 2017 no coral bleaching was reported in the Inner RSA (Burt *et al.*, 2019).

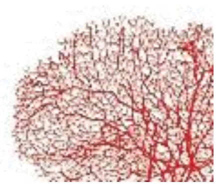
In September 2010, the Inner RSA was one of the warmest ocean areas in the world. In many parts of the northwest Indian Ocean, the Red Sea and the RSA there was a significant positive temperature anomaly, which lasted



from September to October 2010 well into December 2010. During this period, the Inner RSA showed a positive anomaly of 1 to 3 °C. The maximum temperature in 2010 was similar or less than in 2007. In summer 2017, one of the highest temperatures was recorded in the Inner RSA that resulted in widespread and Region-wide bleaching (Burt *et al.*, 2019). This indicates that the total exposure time to the substrate temperature in the range of 33-35 °C determines whether the bleaching occurs or not, instead of the maximum temperature. These average values indicate that, as a general rule, the Inner RSA corals are likely to bleach if exposed to more than three weeks at daily average temperatures or above 35℃ and between eight and nine weeks at a temperature higher than 34 °C. Such conditions are likely to occur in hot summers with heatwave conditions (Burt *et al.*, 2019).

Reef-bottom temperatures in the Inner RSA in 2017 were among the hottest on record, with mean daily maxima averaging 35.9 ± 0.1 °C across sites, with hourly temperatures reaching as high as 37.7 °C (Burt *et al.*, 2019). Throughout the southern Inner RSA, corals spent almost two months (1.55 ± 3.1 d) above bleaching temperatures and nearly two weeks higher than the death rate (11.2 ± 2.4 °C), longer than the non-bleaching years (2013 - 2016) and equivalent to 5.5 °C weeks of thermal stress as degree heating weeks (Burt *et al.*, 2019). As a result, 94.3% of the corals were bleached and two-thirds of the corals were destroyed during April and September 2017. Deaths continued to peak after peak bleaching, and by April 2018, coral cover averaged only 7.5% in the southern basin, representing an overall loss of nearly three-quarters of coral (73%) in 1 year (Burt *et al.*, 2019). These results indicate that with respect to the previous heat-stress accumulation, about one week of the average daily temperature means above 35 °C will cause mild bleaching symptoms, while about three weeks of exposure will cause a severe bleaching event. Therefore, the Inner RSA corals can support about 5 °C more heat over their relatives in the Great Barrier Reef and in the Caribbean (Riegl *et al.*, 2012c).

The Inner RSA corals are possibly the most robust corals anywhere in the world with regards to bleaching and bleaching mortality. The temperature in this area is increasing and the atmospheric temperatures show more, and more closely spaced, positive anomalies since the 1980s. This has been interpreted as global warming signature (Nasrallah *et al.*, 2004; Al-Rashidi *et al.*, 2009), and thus may have contributed to the increase in bleaching thresholds over the past decade due to the selection caused by closely-spaced bleaching events. The remarkable temperature tolerance of the Inner RSA



corals suggests that coral physiology is, in fact, capable of adapting to high temperatures, and it may be hoped that coral compatibility can track continuously increasing temperatures. If corals are not subjected to other stressors, there may be a rational expectation that at least a subset of today's coral fauna may adapt to a heated world (Riegl *et al.*, 2012c).

3.1.2. Carbon Dioxide Rising and Marine Acidification

Climate change driven by increments in atmospheric CO_2 from the consumption of non-renewable energy sources, particularly fossil fuels, stand for the utmost threat to the fate of Coral Reefs (Harley *et al*., 2006; Wilkinson, 2008). Atmospheric CO_2 concentration has amplified from ~280 ppm around 1700 AD to over 380 ppm today (Brohan *et al*., 2006), a pace of increment more than 100 times quicker than experienced in the previous 650,000 (Siegenthaler *et al*., 2005), and possibly outside the capability of reef fauna to adapt and recover (Przeslawski et al., 2008).

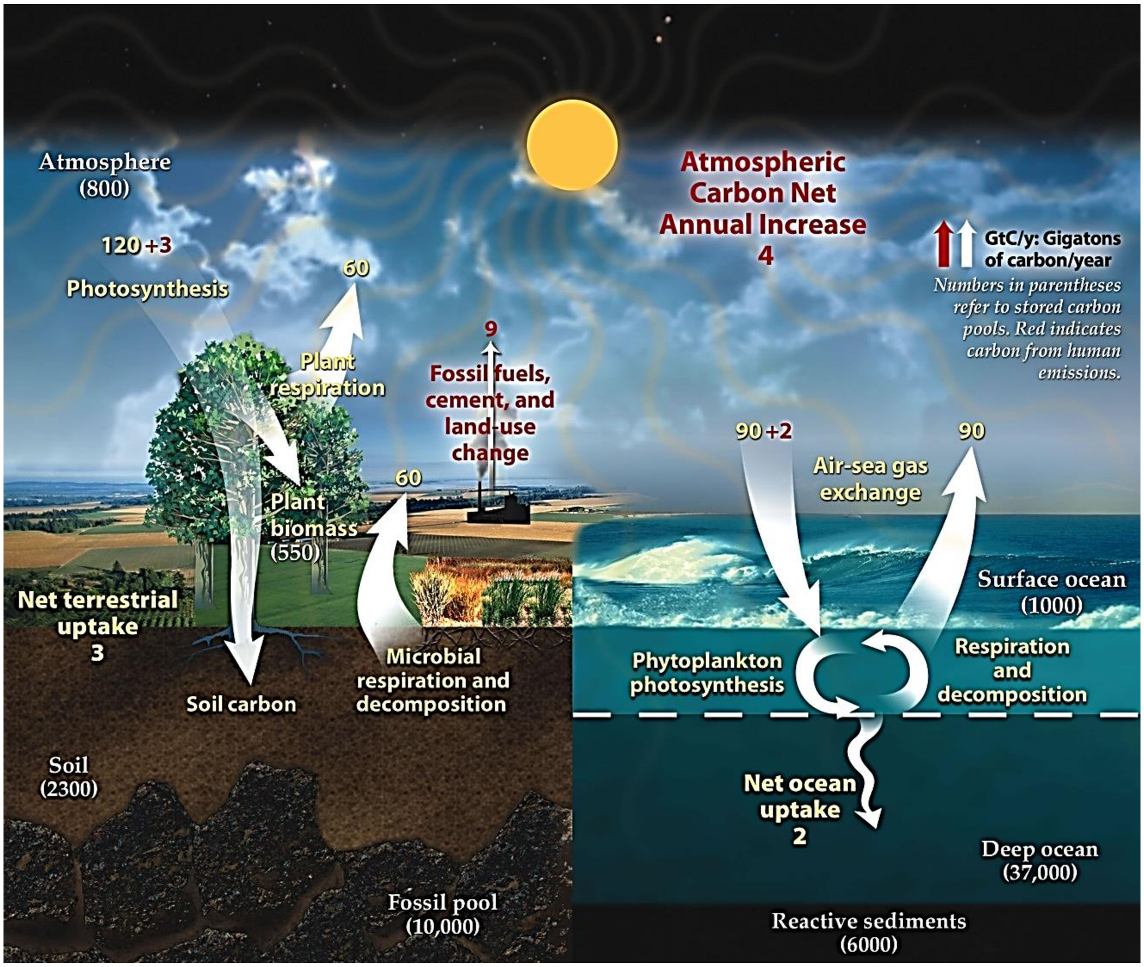
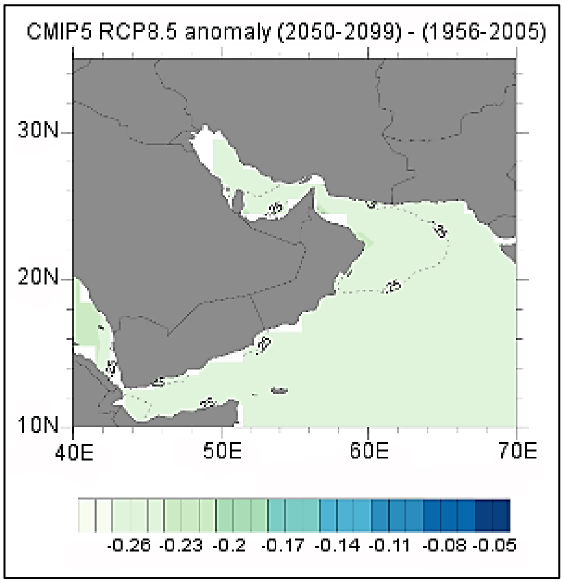
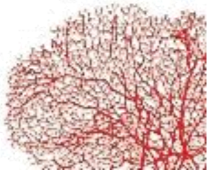


Figure 13. Diagram of the movement of carbon between land, atmosphere, and ocean in billions of tons per year. Yellow numbers are natural fluxes, red are human contributions, white are stored carbon. The effects of volcanic and tectonic activity are not included (*Riebeek, Holli (16 June 2011). "The Carbon Cycle". Earth Observatory. NASA. Archived from the original on 5 March 2016. Retrieved 5 April 2018.)*

In any case, the Coral Reef ecosystems of the RSA are under the developing





risk of climate change with considerable worldwide increments in greenhouse gas emissions over recent decades. Researchers have promoted the significance of constraining atmospheric concentrations of CO_2 to close to 350 ppm and no more - a level considered sustainable for the long term safeguarding of Coral Reefs - though they reached at 400 ppm on April 2014 – and proceeded on an upward direction (Burt, 2014).

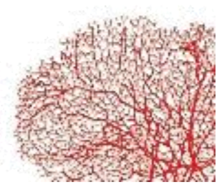
Figure 14. Variation in average annual pH during the time period of 2050–2099, relative to the average during 1956-2005 in the RSA based on the CMIP 5 model, under a high emissions scenario RCP 8.5. White shading indicates areas with no data (ESRL: PSD: Climate Change Web Portal _ Maps MM" 2018)

Climate change is likewise intensifying the acidity of seawater, representing a threat to calcifying organisms including corals, molluscs, and coralline algae that serve a significant function in the Inner RSA's marine environment (Caldeira and Wickett, 2003). Nevertheless, the geochemistry of the Inner RSA seawater, which is supersaturated with aragonite because of the Regional natural conditions, proposes that acidification is probably going to be a less imminent threat to marine fauna than the fast increments in temperatures. Nonetheless, if acidification occurs, it won't just affect the organisms themselves yet, in addition, will cause disbanding of the lithified hard grounds whereupon reefs and different ecosystems occur (Purkis *et al.*, 2011). The chemical and biological reactions of the Inner RSA to potential future sea fermentation remain understudied to date (Vaughan *et al.*, 2019).

Effects of ocean acidification on skeletal growth of Porites coral

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 mixed responses of corals to OA in experiments and field observations. Mollica *et al*. (2018) modeled the skeletal growth of a dominant reef-building coral, Porites, as a function of seawater chemistry and validated the model against observational data. They showed that OA directly and negatively affects one component of the two-step growth process (density) but not the other (linear extension). Combining growth model with Global Climate Model output indicated that skeletal density of Porites corals could decline by up to 20.3% over the 21st century, solely due to OA.

> Source: Mollica, N.R., Guo, W., Cohen, A.L., Huang, K.F., Foster, G.L., Donald, H.K., Solow, A.R., (2018) Ocean acidification affects coral growth by reducing skeletal density, Proceedings of the National Academy of Sciences of the United States of America, pp. 1754-1759.



The level of effect that future climate change will have on Coral Reefs will be dependent upon whether society acts to lessen atmospheric CO_2, how the atmosphere-ocean system (which is as yet not surely known) will react on a physicochemical basis to such warming, and how the organisms which create and live in association with Coral Reefs respond to a quickly changing climate. If Coral Reef fauna is prepared to do rapidly acclimating or even adapting to climate change over the long term, there might be the promise for their proceeded persistence; if not, they are probably going to debase and vanish in our lifetime (Burt, 2014).

3.1.3. Water Chemistry Change (Salinity, Dissolved Oxygen)

The marine biodiversity in the RSA is expected to be impacted by the synergistic effects of climate change (e.g., increases in temperature; declines in oxygen content; sea-level rise) (Sheppard *et al*., 2010; Elhakeem and Elshorbagy, 2015). With respect to the water salinity, it is very likely that regions of high surface salinity, where evaporation dominates (e.g., the Inner RSA), have become more saline since the 1950s (IPCC, 2014b). The shift in water salinity due to increasing water temperature and subsequent evaporation rate has a negative impact on Coral Reefs in the RSA. The water salinity in the Inner RSA ranges widely from 36.5 psu at the Strait of Hormuz to over 70 in shallow semi-enclosed embayments such as Salwa Bay at its southern limit (ROPME, 2013). Salinity in the Inner RSA progressively increases from north to south because of higher evaporation rate that is estimated at 1.5 m.yr-1 (Brewer and Dyrssen, 1985), with lower rates being found along the Iranian side (ROPME, 2013). The effect of largest number of desalination plant in the

Water salinity in the Middle RSA is expected to increase due to rising temperature under RCP 8.5 scenario

Over the past 60 years, surface water salinity in the Outer RSA has increased by 0.5-1.0 percent due to increased evaporation. Yet, water salinity in the Outer RSA is projected to decrease slightly by 2099

Inner RSA with a total seawater desalination capacity of approximately

(20%) of the worldwide daily production is equivalent to the peak salinity increased by 0.42 ppt, in 2008 increased by 0.93 ppt, and in 2050 by 2.24 ppt (Bashitialshaaer *et al.*, 2011). In addition, the increase in salinity in the Inner RSA sub-Region is expected due to repeated droughts and large-scale irrigation reductions (IPCC, 2014b). Thus, local salinity reductions are anticipated in the eastern side of the Inner RSA and increases along the western side (Noori *et al.*, 2019).

In the Middle RSA, from the Strait of Hormuz in the Musandam peninsula to Ra's al-Hadd, the entrance to the Sea of Oman the water salinity ranges from 36.5 to 38.9 psu (ROPME, 2013). In eastern Middle RSA, near the Strait of Hormuz, water salinity is expected to increase as a result of rising temperature under RCP 8.5 scenario (Noori *et al.*, 2019).

Salinity in the Outer RSA, the Arabian Sea from Ra's Al-Hadd toward the southernmost part of the Sultanate of Oman, ranges from 35.50 to 37.70 psu (ROPME, 2013). The variation in salinity from the surface to bottom water of the Sea of Oman and the Arabian Sea is little because of water mixing as such the surface and the bottom readings are either the equivalent or contrast by just a couple (ROPME, 2013). Over the past 60 years, surface water salinity in the Outer RSA has increased by 0.5-1.0 percent due to increased evaporation. Yet, water salinity in the Outer RSA is projected to decrease slightly by 2099.

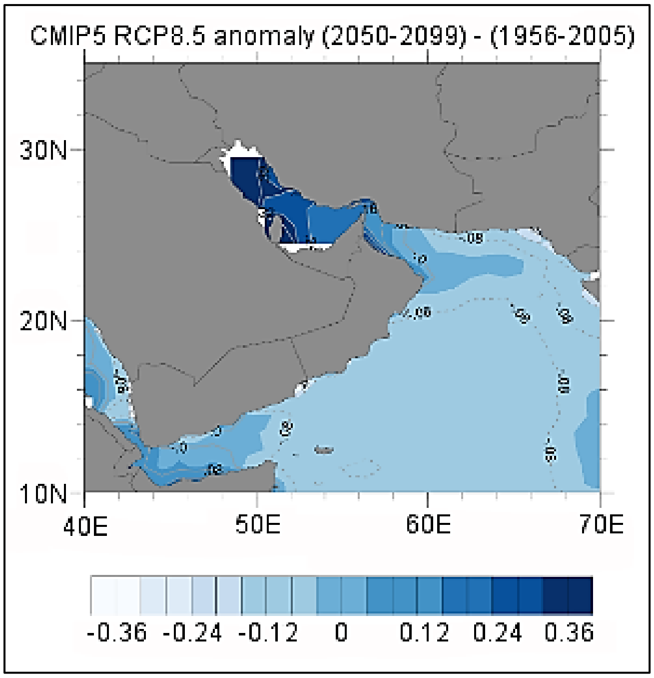
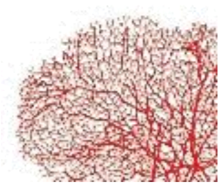


Figure 15. The variation in the annual average sea surface salinity during the time period of 2050–2099 under RCP 8.5 compared to the historical reference period (1956-2005) in the RSA, based on CMIP5 models. White shading indicates areas with no data (ESRL: PSD: Climate Change Web Portal _ Maps MM" 2018)

Corals do not have an osmoregulation mechanism (Muthiga and Szmant, 1987); therefore, salinity changes may affect their metabolism and survival capacities, even if they have shown to possess some abilities for acclimation to physical stresses (Muthiga and Szmant, 1987; Coles, 1992; Brown, 1997;

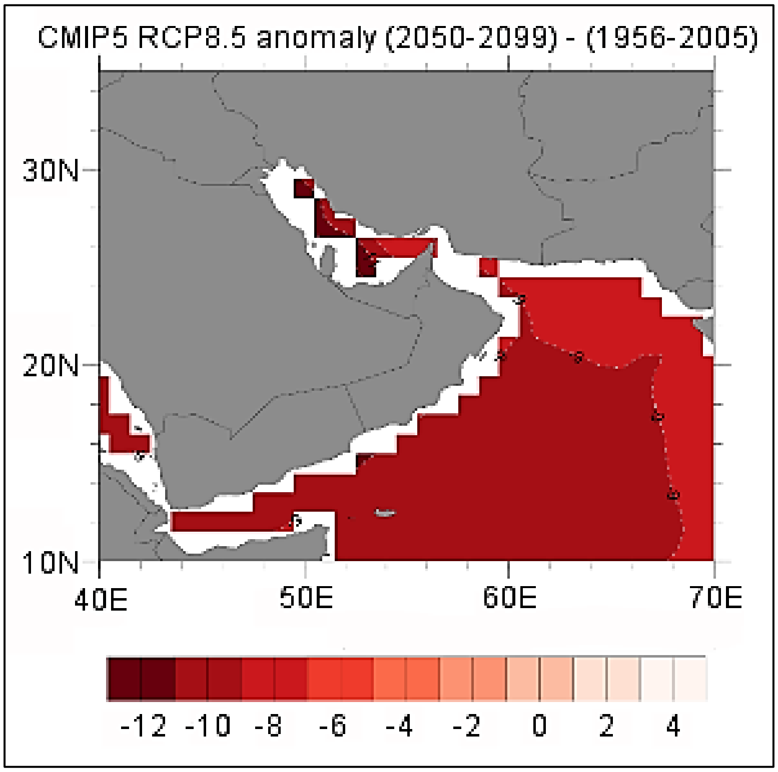


Ferrier-Pages *et al*., 1999;). Given the fact that the decrease in water salinity would damage Coral Reefs (Jokiel *et al*., 1993), therefore, decreasing salinity in the eastern side of the Inner RSA by 2099 (Noori *et al*., 2019) and in the Outer RSA is expected to adversely affect the Coral Reefs by changing their community structure.

Because of global warming, it is expected that rising water temperature, evaporation, and salinity will result in declined oxygen levels in the RSA

The Middle RSA and Outer RSA, are projected to experience stronger deoxygenation than the wider Indian Ocean

Oxygen is a key physical and biological tracer in the sea (Rhein *et al*., 2013) and is projected to decline by 3 to 6% by 2100 in response to sea surface warming (Ciais *et al*., 2013). Because of global warming, it is expected that rising water temperature, evaporation, and salinity (Collins *et al*., 2013; Noori *et al*., 2019) will result in declined oxygen levels in the RSA. Depletion of dissolved oxygen in the shallow water of the Inner RSA has been reported due to increased nutrients (El Samra and El Gindy, 1990). In addition, a hypoxic water layer where the concentration of dissolved oxygen was less than 2 $mg.L^{-1}$ also has been detected in the Inner RSA, in Qatari waters that are the lowest values ever recorded for this Region (Al-Ansari *et al*., 2015). The most common value of dissolved oxygen in the Middle RSA is about 5 $mg.L^{-1}$ (Sana, 2005) that corresponds to the lower limit of healthy life in the marine environment (Duxbury *et al*., 2002). Yet, the measured data for the water quality obtained so far show that the concentration of dissolved oxygen in the coastal waters of the Middle RSA is at a critical level and is transitioning from hypoxic to persistently suboxic, with O_2 concentrations of <2 $mg.L^{-1}$ (Sana, 2005). The Outer RSA is the second-most intense oxygen minimum zone (OMZ) in the world, with near-total depletion of oxygen at depths from 200 to 1000 m (Helly and Levin, 2004; Paulmier and Ruiz-Pino, 2009). Due to climate change, areas with low oxygen concentrations are expected to increase in frequency and extent. The Middle RSA and Outer RSA, are projected to experience stronger deoxygenation than the wider Indian Ocean. Therefore, any further reduction in oxygen levels in the RSA can put marine life under serious threat leading to the increased mortality of marine species. These factors along with the rise in ambient temperature and sea-level rise might lead to additional pressure on vulnerable habitats



of the region, in particular, its Coral Reefs.

Figure 16. Variation in average annual dissolved oxygen during the time period of 2050–2099, relative to the average during 1956–2005 in the RSA, based on the CMIP5 model, under a high emissions scenario RCP 8.5. White shading indicates areas with no data (ESRL: PSD: Climate Change Web Portal _ Maps MM” 2018)

3.2. Impacts of Sea Storms and Cyclones on Coral Reefs of the RSA

A changing climate prompts changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events (IPCC, 2012).

The Arabian Sea experiences 1-2 cyclonic storms each year, but most of these storms are very weak and tend to fizzle out rapidly (ROPME, 2003). During the period 1979–2008, 41 cyclonic storms have occurred in the Arabian Sea of which 23 made landfall with tropical depression or stronger intensities (Evan and Camargo, 2011). Of 41 storms, eight were classified as severe cyclonic, seven classified as a very severe cyclonic and one classified as super cyclonic storm so-called Super-cyclone Gonu with a maximum wind speed of 270 km.h^{-1} and gusts reaching 315 km.h^{-1} (Fritz *et al.*, 2010) that occurred at 1- 6 June 2007 (Evan and Camargo, 2011). Cyclone Phet classified as a very severe cyclonic storm that has occurred during the period 30 May – 6 June 2010 (ROPME, 2013). Over the period of 1979–2008, there has been an average of 4.7 cyclonic storm days over the Arabian Sea, with 1981, 1990, 1991, 2000, 2005, 2008 having zero storms; and 1998 and 2004 had more than 15 cyclonic storm days (ROPME, 2013). Most Arabian Sea cyclones occur near the western coast of the Indian subcontinent and follow a northerly or northeasterly track (ROPME, 2013). A few storms have occurred towards the center of the basin or closer to the equator mostly with the easterly track (ROPME, 2013). Three ROPME Member States that particularly are influenced by the Arabian Sea storms are UAE- if it passes through the Sea of Oman, I. R. Iran, and Sultanate of Oman, listed in order of increasing frequency (ROPME, 2013).

Global models predict an increase (at 46%) in tropical storms frequency in the north of the Indian Ocean

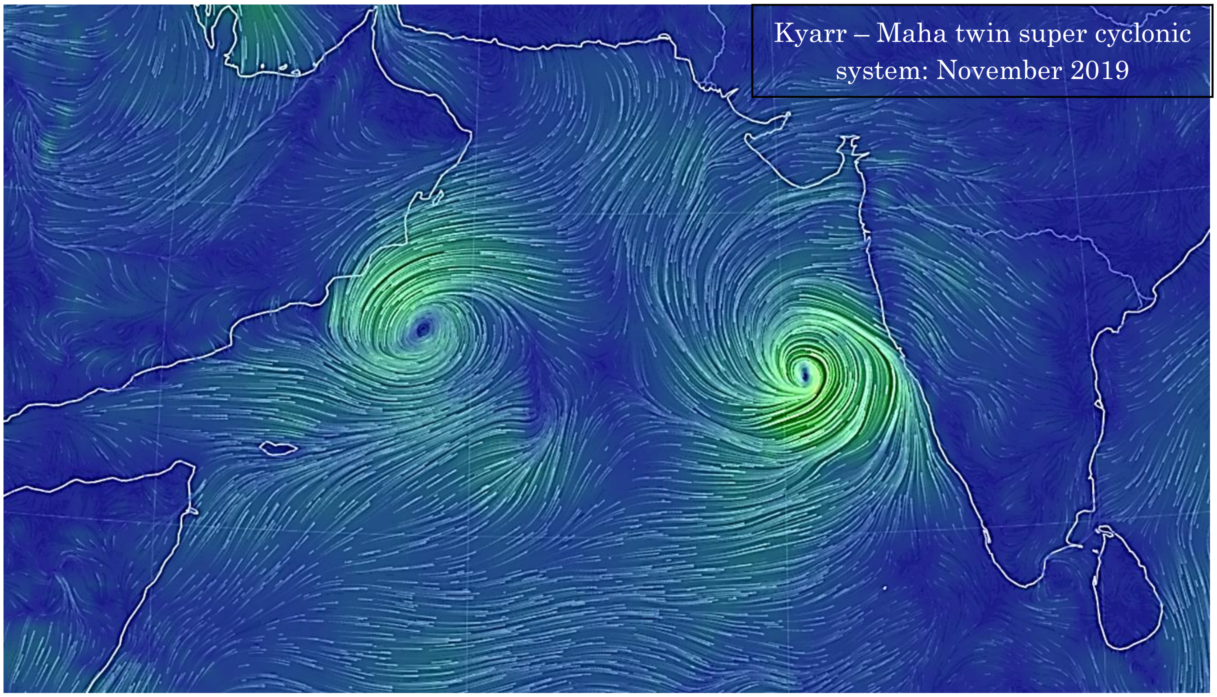
In the Middle RSA, the effects of the cyclone Gonu were limited to many parts of Musandam, as it was dissipated to a tropical storm and moved to the sea after crossing Muscat (Fritz *et al.*, 2010; Coles *et al.*, 2015). As a result, the three-dimensionality of the coral substrate along the Muscat Capital Area coast was reduced and 99.33 percent of corals were devastated particularly at wave-exposed locations (Maghsoudlou *et al.*, 2008; Taylor, 2010). Highest coral damage occurred on exposed areas at the depth of fewer than 6 meters with 17 and 90 percent mortality on Cat Island and Fall (Maghsoudlou *et al.*, 2008). The damage was more severe, but not limited to

Acropora stands and *Pocillopora*, which were less resistant to physical

damage. The massive *Porites*, *Platygyra* and *Favia* species were also affected in the most exposed areas by wave action or wave-associated sand abrasion (Coles *et al*., 2015). In intermediate exposed locations, branching and tabular corals were more affected than massive forms, but, these fast-growing species recovered within a year, especially on islands with living resources (Taylor, 2010). Such a similar trend was observed in the Coral Reefs damaged by the cyclone Gonu further north in the Sea of Oman off Fujairah and Dibba, United Arab Emirates with an indication of recovery within a year (Foster *et al*., 2008). Cyclone Gonu also had some impacts to reefs in UAE (Burt *et al*., 2016a) and resulted in >50% losses of live branching and tabular coral cover by fragmentation and dislodgment of pocilloporid and acroporid colonies (Foster *et al*., 2011). Although, massive colony coral taxa remained unaffected during the cyclone (Burt *et al*., 2016a)

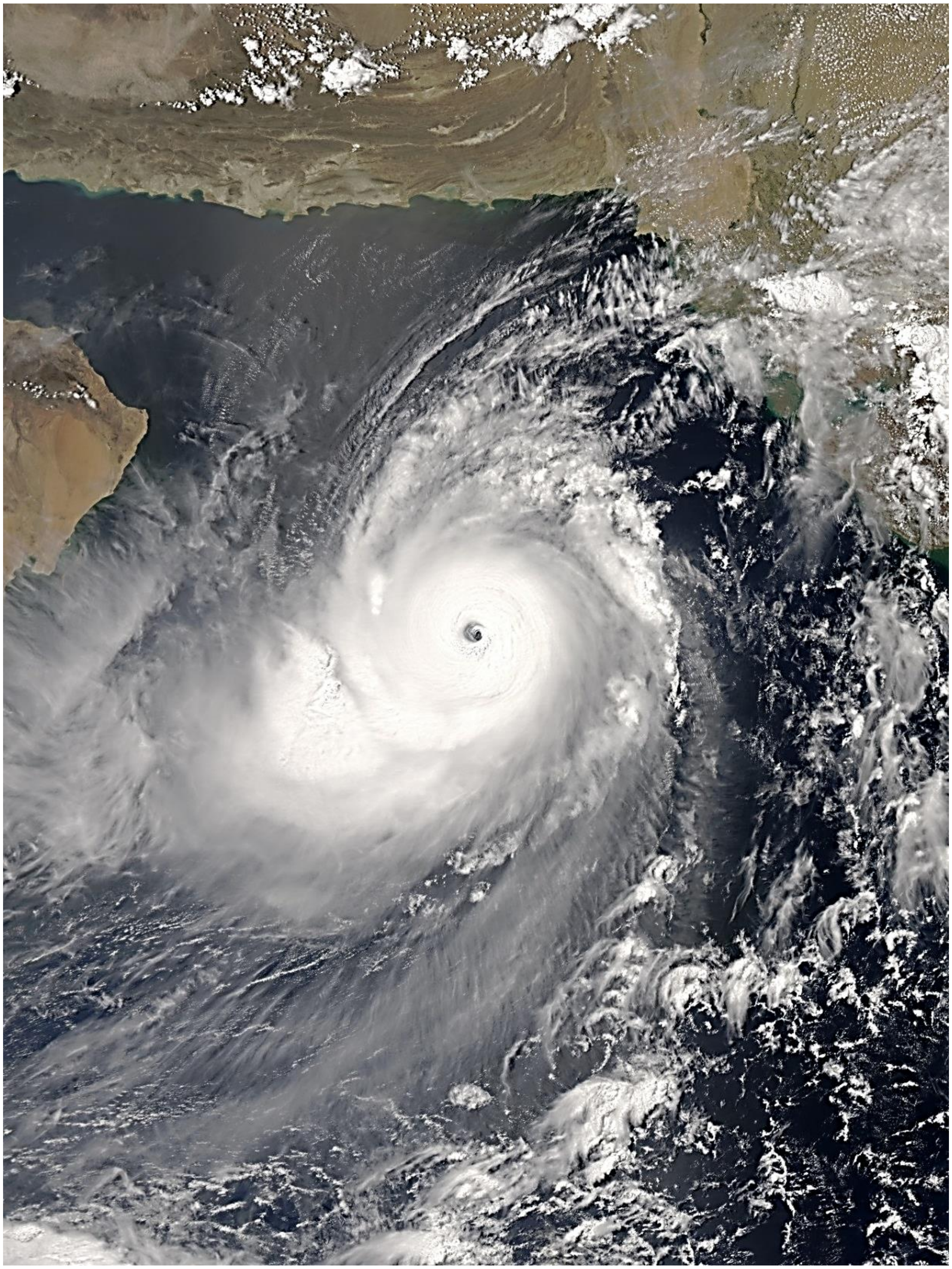
A study shows that strongest cyclone storms can increase in intensity by 2100 to 11%, but the total number of storms could be reduced to 6 to 34% (Murakami *et al*., 2013). The global models of high emission scenarios show no changes in the total number of tropical cyclones formed by 2075-2099 (Murakami *et al*., 2013). Global models predict an increase (at 46%) in tropical storms frequency in the north of the Indian Ocean (Murakami *et al*., 2013).

Tropical Storms/Cyclones over the Arabian Sea/RSA (2007-2019)



Kyarr – Maha twin super cyclonic system: November 2019

Name	Place of Landfall	Severity (IMD Scale)	Date
Gonu	Eastern Oman near Ras al Hadd	Super cyclonic storm	June 6, 2007
Bandu	Southern Oman, Yemen	Cyclonic storm	May 23, 2010
Phet	Eastern Oman northeast of Masirah island	Very severe cyclonic storm	June 3, 2010
Keila	Southern Oman, north of Salalah	Cyclonic storm	November 2, 2011
Nilofar	North-eastern Oman near Al-Rustaq	Extremely severe cyclonic storm	October 31, 2014
Ashobaa	East coast of Oman	Cyclonic storm	June 12, 2015
Chapala	Eastern Yemen	Extremely severe cyclonic storm	November 3, 2015
Megh	Socotra Island, Yemen	Extremely severe cyclonic storm	November 8, 2015
Sagar	Southern Oman, Yemen	Cyclonic storm	May 18, 2018
Mekunu	Southern Oman, Dhofar Governorate	Extremely severe cyclonic storm	May 25, 2018
Luban	Southern Oman / Eastern Yemen	Very severe cyclonic storm	October 14, 2018
Vayu	North west Arabian Sea	Very severe cyclonic storm	June 15, 2019
Kyarr	Eastern Oma, Masirah island, Yemen, UAE	Super cyclonic storm	November 3, 2019
Maha	North west Arabian Sea	Extremely severe cyclonic storm	November 7, 2019



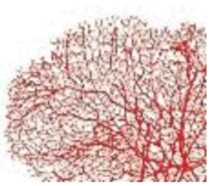


Figure 17. The Aqua satellite acquired the picture of Gonu, the most intense tropical cyclone of the Arabian Sea on record, at 12:00 Arabia Standard Time (09:00 UTC) on 4 June 2007 (NASA Earth Observatory, 2019)

The phenomenon of increasing dust storms, in frequency and intensity, also is an issue that may be adversely affecting Coral Reefs in the RSA. The main sources of contemporary mineral dust in the Region are from the desert areas of the Northern Hemisphere, in the broad "dust belt" that extends from the eastern subtropical Atlantic eastwards through the Sahara Desert to Arabia and southwest Asia, with some also from outside the Region (Prospero *et al.*, 2002). It is estimated that the average monthly dust deposition at various areas in the northwestern part of the RSA can range from 10 to 100 $g.m^{-2}$ (ROPME, 2003), but the maximum deposition of 600 $g.m^{-2}$ also has been reported in some areas that are among the highest in the world (Lindén *et al.*, 1990). Dust storms passing over the northern section of the Inner RSA are the main source of marine sediments, as in July alone, depositing up to 1000 $g.m^{-2}$ of sediment in this area (ROPME, 2003). Maritime aerosols found over the oceans; fine polluted aerosols originating from urban and industrial activities; contributions from burning biomass, as well as fine mode pollution particle sources from petroleum extraction and processing facilities located on islands, offshore platforms and coastal regions are other aerosol types that dominate the atmospheric aerosol load in the RSA (Basart *et al.*, 2009). The onset of dust storms in the Inner RSA is mainly influenced by daily variations in wind speed (ROPME, 2013). Besides, studies have shown that the change in frequency and intensity of dust storms may be linked with both changing land-use practices and a drier climate (Tegen *et al.*, 1996). Climate is thought to be the most key factor in dust transport (Prospero and Nees, 1986; Moulin *et al.*, 1997).

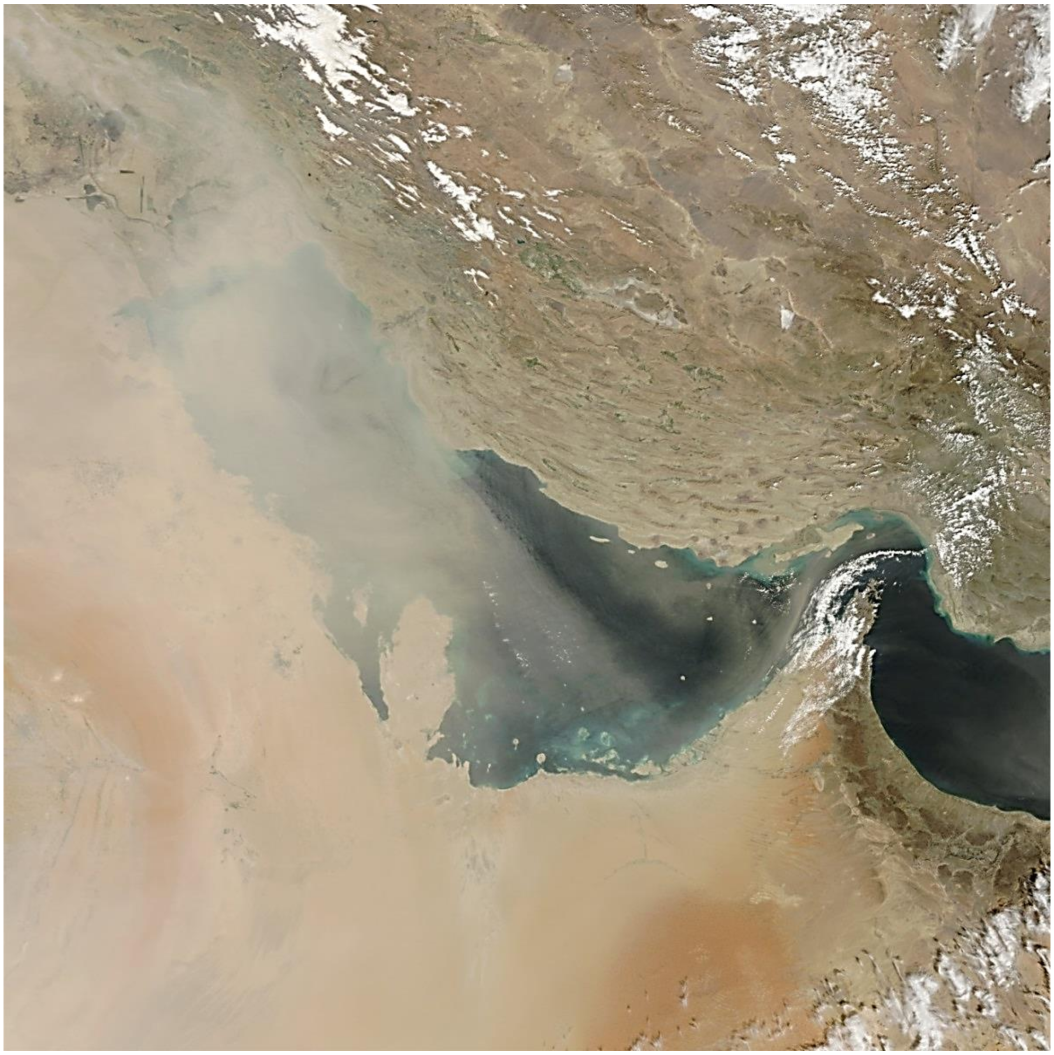


Figure 18. Intense dust storm obscures the Inner RSA (March 9th, 2010) (EOSNAP, 2019)

With regard to reef-building corals, they have evolved to flourish in nutrient-poor environments through coexistence with the symbiotic algae (Griffin and Kellogg, 2004); therefore, slight shifts in the ambient nutrient content can affect reef health via niche displacement through the rapid growth of algae (Selig *et al.*, 2006). Desert dust has been implicated to act as a source of stress to Coral Reefs by viable carrying and depositing microorganisms, macro- and micronutrients, trace metals, and a variety of organic contaminants in the seas (Garrison *et al.*, 2003). The studies also have found a link between the aeolian dust transported from the Saharan region of Africa and the increased incidence of coral disease in the Caribbean over the last forty years (Smith *et al.*, 1996; Garrison *et al.*, 2003; Hunter and Cervone, 2017). Lack of recovery on damaged reefs also has been linked to the stresses driven by dust storms (Garrison *et al.*, 2003).

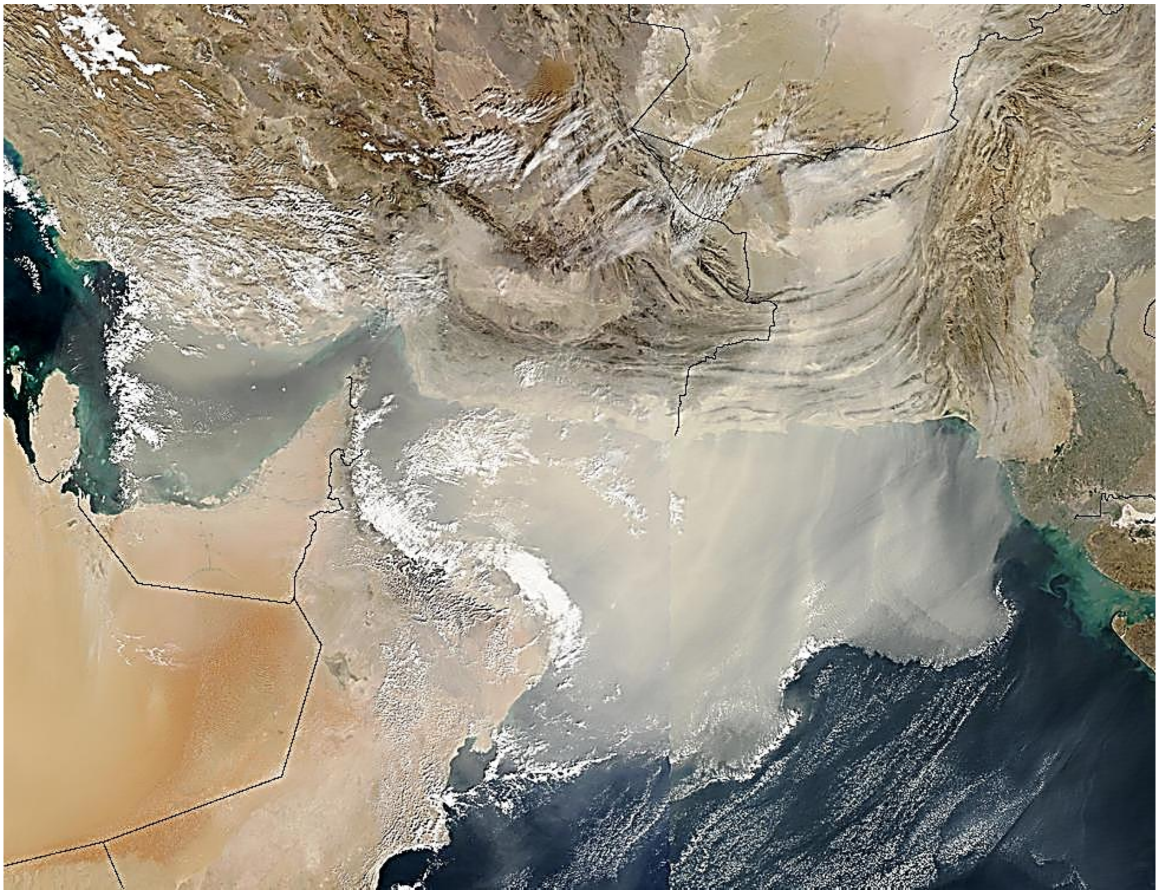


Figure 19. Dust storm over the Arabian Sea and the Inner RSA (December 13, 2003) (Descloitres, 2019)

3.3. Crown of Thorns Starfish (COTS) *Acanthaster planci* Predation

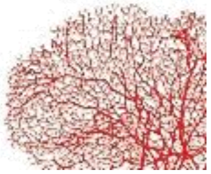
The Crown of Thorns Starfish (COTS) (*Acanthaster planci*), a voracious predator of corals that can expose whole reefs, has been reported from the reefs in Middle RSA (Sultanate of Oman) (Glynn, 1993; Price and Rezai, 1996; Al-Jufaili *et al.*, 1999; Mendonça *et al.*, 2010), and Inner RSA (UAE, Kuwait and Iran) (George, 2012;).

Rising sea temperature as an important co-factor may promote Crown of Thorns Starfish (COTS) outbreaks in the RSA

Up until this point, just two specimens have dependably been recorded in the northern Inner RSA, on the Larak and Lesser Tomb Islands (Price and Rezai, 1996). Likewise, the COTS population on eastern reefs of UAE was not alarming; although this could change as COTS appears to spread from the Sea of Oman to the Inner RSA, with new records from the Musandam Peninsula near the Strait of Hormuz (Mendonça *et al.*, 2010).

While COTS was not alarming in the Inner RSA, recurrent outbreaks of the COTS have affected Oman's reefs in the Outer RSA since the 1970s, with outbreaks generally occurring at least once a decade (Glynn, 1993; Al-Jufaili *et al.*, 1999; Mendonça *et al.*, 2010). Spatially, COTS outbreaks have regularly been in the Sea of Oman, and especially to the reefs around the Capital Area and the Daymaniyat Islands where outbreak densities have frequently surpassed 100 ind.ha^{-1} (Glynn, 1993; Mendonça *et al.*, 2010), Although uncommon, similar outbreaks do happen in the Musandam and on reefs along Oman's Arabian Sea coast (Salm, 1993; Al-Jufaili *et al.*, 1999). In the Sea of Oman, *A. planci* nourishes especially on *Acropora* and *Montipora*, and thus COTS episodes have caused intense shifts in coral community structure. This suggests that the predominance of poritids and pocilloporids on reefs in the Muscat area is the aftereffect of their differential survival through persistent COTS grazing over the long-term (Glynn, 1993). Nevertheless, in recent years *A. planci* were less common. The Sea of Oman was reported to be free of outbreaks in 1993 (Glynn, 1993; Salm, 1993), and no recent large-scale *A. planci* predation has been noted (Coles *et al.*, 2015).

Successive, extensive bleaching events in the RSA have significantly



reduced coral cover and altered species assemblages. Specifically, the populations of acroporid and pocilloporid corals have been declined dramatically, while poritid and faviid corals were less affected and now dominate coral assemblages in the RSA. Subsequent to this perturbation, on some occasions there have been changes in the abundance and distribution of the coral-eating COTS (to densities of >100 ind.ha^{-1}) in Oman's reefs, which had a greater impact on coral communities selectively targeting the coral taxa most susceptible to bleaching, often referred to as climate change "losers". Future acidification as one of the main climate change stressors could increase the success of juvenile starfish, which would increase the number of adult coral-eaters (Kamya *et al.*, 2017). Likewise, the rising sea temperature is an important co-factor promoting COTS outbreaks (Uthicke *et al.*, 2015). COTS also are cautioned to impede the recovery potential of Coral Reefs following bleaching (Haywood *et al.*, 2019; Keesing *et al.*, 2019). In summary, the outcome of these factors, together with any COTS outbreak in the future could lead to more devastating pressure on coral communities in the RSA.

3.4. Coral Diseases

Little is known about the incidence of coral diseases, and the impact it might have on coral community structure in the RSA. Yet, one of the most destructive agents responsible for recent coral losses in Inner RSA is coral diseases (Riegl *et al.*, 2012b).

Coral diseases reported from the RSA's reefs include the Arabian yellow band (AYB) disease (Korrubel and Riegl, 1998; Fatemi and Shokri, 2001a; Rezai *et al.*, 2004), black band disease (BBD) (Riegl, 2002), white band disease (WBD) (Coles, 1994; Riegl *et al.*, 2012b), pink spots and pink line disease, and skeletal growth anomalies (Tavakoli-Kolour *et al.*, 2015).

The Arabian Yellow Band (AYB)

AYB disease has different dynamics from diseases observed elsewhere with similar names (Riegl *et al.*, 2012b). There is some proof from the Indo-Pacific recommending that YBD is an infection of zooxanthellae associated with four types of Vibrio bacteria (Cervino *et al.*, 2001; Cervino *et al.*, 2008).

Sometimes, the band might be associated with a microbial mat, including cyanobacteria (Bruckner and Riegl, 2015).

In the RSA, this disease was initially reported in 1998 from the reefs near Jebel Ali in Dubai, the United Arab Emirates (Korrubel and Riegl, 1998) and later from Iran's reefs (Wilson *et al.*, 2002; Rezai *et al.*, 2004; Rezai and Kabiri, 2017). AYB has also been reported from two sites in the Daymaniyat Islands and Qalhat, in the Middle RSA (Sea of Oman) (Rezai *et al.*, 2004).

One of the most destructive agents responsible for coral losses in the Inner RSA is coral diseases

AYB primarily occurs in *Acropora* and *Porites* spp. (Korrubel and Riegl, 1998), but might infect *Favia*, *Cyphastrea*, *Turbinaria*, and *Platygyra* spp. as well (Korrubel and Riegl, 1998; Fatemi and Shokri, 2001b). This disease displays as a bright yellow band that moves crosswise over coral in a straight to annular pattern creating an edge of rotting tissue nearby healthy tissue and leaving behind dead skeleton (Bruckner and Riegl, 2015). In the most recent study at Kish Island in the northern Inner RSA, the *Porites* peeling tissue loss was reported as a grossly similar lesion to AYB (Alidoost Salimi *et al.*, 2017). AYB is as active in winter as it is in summer (Bruckner and Riegl, 2015).

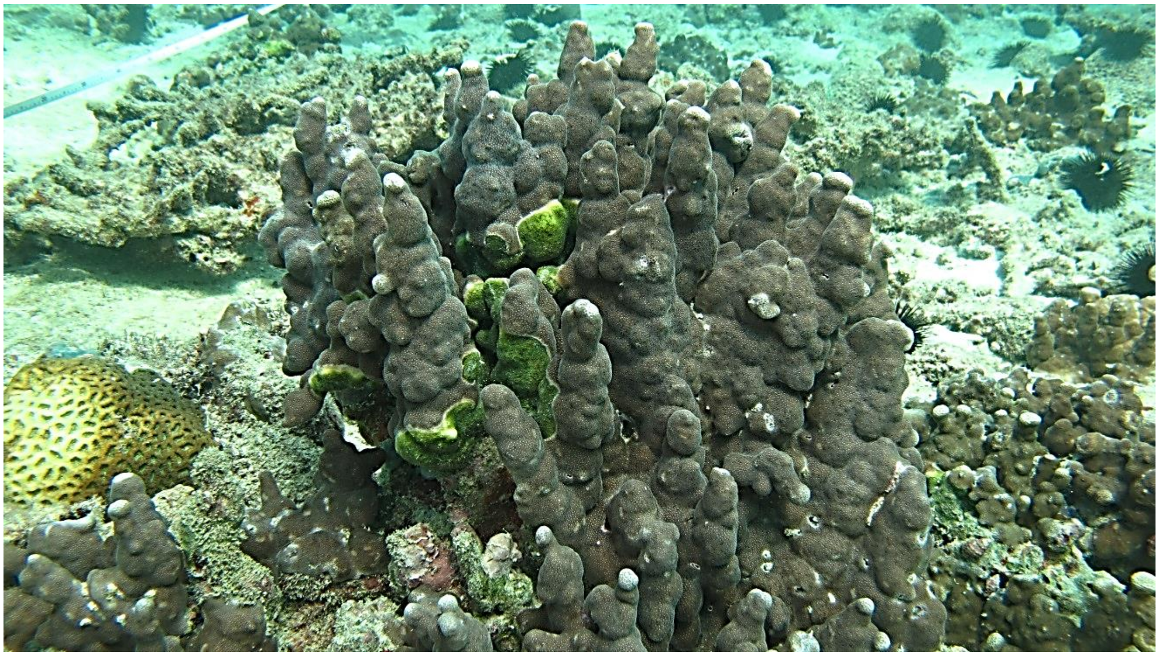
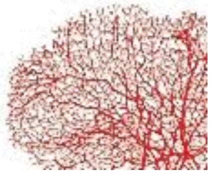


Figure 20. Yellow Band Disease on massive coral *Porites lutea* (Kish Island, March 2017, Photo by M. R. Shokri)



Black Band Disease (BBD)

In BBD, a black band appears in which complete tissue degradation occurs due to a pathogenic microbial consortium (Antonius, 1973). The mat is formed at the interface of healthy and diseased tissue and is dominated by a filamentous cyanobacterium retaining black to reddish black pigmentation (Riegl *et al.*, 2012b). BBD is reported from the reefs in the Inner RSA (UAE) (Riegl, 2002). This disease has not been reported from the Arabian Sea but likely occurs there (Riegl *et al.*, 2012b).

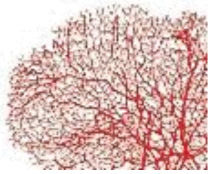
In UAE, BBD was the most common disease on *Acropora* spp., but it also manifests in *Favia* spp., *Platygyra* spp., and *Cyphastraea microphthalma* (Riegl, 2002). This disease, in the Region, advances with the greatest rate and extent of tissue loss occurring in summer, but almost completely disappears in winter (Riegl, 2002).

White Band Disease (WBD)

WBD along with its counterpart terms including white plague, plague-like and white syndrome all with similar disease signs have been reported from throughout the Pacific and Indian Oceans (Sutherland *et al.*, 2004; Willis *et al.*, 2004; Bruckner, 2009).

In the Middle RSA, WBD has been reported from the reefs of Sultanate of Oman on the western side of Fahl Island (Coles, 1994), and in a nearshore cove at Bandar Khayran (Coles and Seapy, 1998). In Fahl Island, damage by BBD was mostly limited to large polyped species particularly on brain corals *Platygyra daedalea* and *Symphyllia radians*, but tissue loss also occurred on *Echinopora gemmacea*, *Hydnophora microconos*, *Favia* sp. and *Montipora aequituberculata*. Other corals including *Acropora* spp., *Porites* spp., *Pavona cactus*, *Montipora foliosa*, *Stylophora pistillata*, and *Psammocora contigua*, remained apparently healthy and unaffected.

In the Inner RSA, this disease has been reported from the reefs in Dubai, UAE (Riegl, 2002) and is becoming more common (Riegl *et al.*, 2012b). In one case, a locally dramatic increase in the frequency of the white syndrome was noted after the 2010 bleaching event in the southeast Inner RSA (Riegl *et al.*, 2012b). In UAE, WBD has been noted on most coral species but seems to affect some more severely in particular in the dominant frame-builders including *Acropora* spp. and *Porites harrisoni* (Riegl, 2002). WBD incidence



in the Inner RSA varies throughout the year and is minimized in winter (Riegl *et al.*, 2012b).

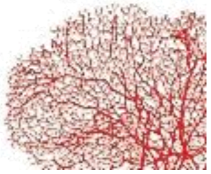
Pink Spots and Pink Line Disease

Pink spots and pink line disease that also has been referred to as "pigmentation response" and "hyper-pigmented irritations" (Laurie *et al.*, 2005; Vargas-Angel and Wheeler, 2009) was first seen in 1996 influencing the scleractinian coral *Porites lutea* at Kavaratti of the Lakshadweep Islands in the Arabian Sea (Ravindran and Raghukumar, 2002). In Lakshadweep Island, this disease occurred in the scleractinian coral *P. lutea* wherein a colored 2–10 mm wide band appeared between the dead and healthy tissue of a colony (Ravindran *et al.*, 2015). While the healthy coral tissue remains normal in color with unaltered morphology, the affected tissue is rapidly colonized by the cyanobacterial filaments and several fungi (Ravindran and Raghukumar, 2002). This disease was more prevalent in the summer than the post-monsoon season in the Lakshadweep Island of Kavaratti suggesting that the rise in seawater temperature may accelerate the disease incidence (Ravindran *et al.*, 2015).

As circular spots, irregular blotches, lines, rings with a pink coloration, this disease has been noted as a response to physical and/or pathogenic stress, including fish bites, parasite infections, burrowing or boring invertebrates (e.g., trematodes, barnacles) and microorganisms (e.g., cyanobacteria) (Ravindran *et al.*, 2001; Ravindran and Raghukumar, 2002; Aeby, 2003; Willis *et al.*, 2004; Raymundo *et al.*, 2008; Benzoni *et al.*, 2010). Pink coloration also has been noted as the result of serpulid larvae growing on the surface of porites colonies and causing mechanical and/or chemical irritation (Riegl *et al.*, 2012b). Following severe coral mortality associated with red tide in Larak Island in the Inner RSA in 2008-2009, the pink pigmentation was found on nearly all surviving massive porites colonies due to serpulid worms overgrowing the colonies surfaces (Samimi Namin *et al.*, 2010). The occurrence of pink spots may also be related to other cases of altered pigmentation such as the various dark spot/band diseases, but evidence from the RSA is, however, to be imminent (Riegl *et al.*, 2012b).

Skeletal growth anomalies

Coral skeletal growth anomaly (GA) is a common coral disease noted in a

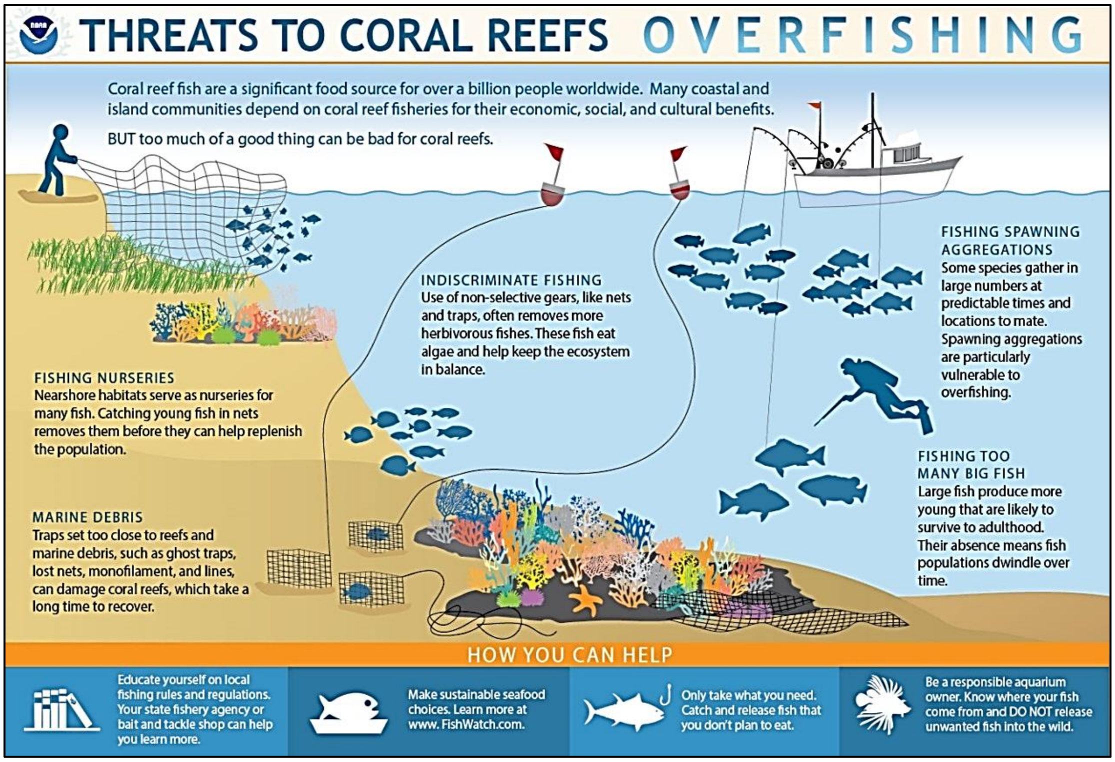


wide range of coral species (Work *et al*., 2015). GA is characterized by an increased polyp growth rate, resulting in rough circular swellings in the affected area of the colony (Loya *et al*., 1984). Albeit skeletal growth anomaly has been noted on at least eight coral families, acroporids are clearly the most susceptible corals to the formation of calico - blastic epitheliomas potentially because of the quick growth rates of acroporids and their affinity to frame unites with broken parts (Peters *et al*., 1986).

GA seems to be a common disease in RSA affecting *Acropora valenciennesi* and *Acropora valida* in Bandar Khayran, Sea of Oman (Coles and Seapy, 1998), *Platygyra daedalea* and *Porites* spp. in Qeshm Island (Tavakoli-Kolour *et al*., 2015) and *Dipsastrea* sp. in Kish Island (Alidoost Salimi *et al*., 2017). The excessive UV radiation (Coles and Seapy, 1998; Loya *et al*., 1984), genetic predisposition (Peters *et al*., 1986), environmental degradation (Longin, 2006), and infectious agents such as viruses (Domart-Coulon *et al*., 2006), bacteria, and fungi (Work *et al*., 2015) have been hypothesized as underlying factors for GA.

3.5. Threats from Resource Extraction Related Activities

Effects of fisheries activities including the impacts of gill nets, anchors, ropes, fishing lines, fish traps, and trash are among the most common impacts on Coral Reefs. Damage to coral colonies is caused as fishing gear strikes and hauls over the substrate and covers, breaks and abrades corals. Damage is mostly caused by discarded gear, which may stay on a reef for a decade, causing acute and chronic degradation. Fishing gears are discarded by fishermen who can't recover ropes, when lines or nets become entangled on the sea bed, or when breakage happens. Nets specifically likewise become trapped on Coral Reefs in the wake of having turned out to be lost during rough seas and storms. Other fishing gears, for instance, those which is assessed by fishermen to be not fixable, is merely dumped at the sea by fishermen. A portion of this gear is carried by current and wave action onto Coral Reefs (Al-Jufaili *et al*., 1999).



THREATS TO CORAL REEFS OVERFISHING

Coral reef fish are a significant food source for over a billion people worldwide. Many coastal and island communities depend on coral reef fisheries for their economic, social, and cultural benefits.

BUT too much of a good thing can be bad for coral reefs.

FISHING NURSERIES
Nearshore habitats serve as nurseries for many fish. Catching young fish in nets removes them before they can help replenish the population.

MARINE DEBRIS
Traps set too close to reefs and marine debris, such as ghost traps, lost nets, monofilament, and lines, can damage coral reefs, which take a long time to recover.

INDISCRIMINATE FISHING
Use of non-selective gears, like nets and traps, often removes more herbivorous fishes. These fish eat algae and help keep the ecosystem in balance.

FISHING SPAWNING AGGREGATIONS
Some species gather in large numbers at predictable times and locations to mate. Spawning aggregations are particularly vulnerable to overfishing.

FISHING TOO MANY BIG FISH
Large fish produce more young that are likely to survive to adulthood. Their absence means fish populations dwindle over time.

HOW YOU CAN HELP

- Educate yourself on local fishing rules and regulations. Your state fishery agency or bait and tackle shop can help you learn more.
- Make sustainable seafood choices. Learn more at www. FishWatch.com.
- Only take what you need. Catch and release fish that you don't plan to eat.
- Be a responsible aquarium owner. Know where your fish come from and DO NOT release unwanted fish into the wild.

Figure 21. Diagram of the overfishing threats to Coral Reefs (NOAA, 2019) (https://oceanservice.noaa.gov/facts/coral-overfishing.html)

Fishing activity in the Sea of Oman certainly contributes to damages and degradation of Coral Reefs. Gill nets, fish traps, and anchors are dropped directly onto reefs of branching corals, breaking them, and repeatedly becoming entrapped. Patches of *Pocillopora damicornis* and *Acropora* spp. are especially vulnerable to harm from abandoned fishing nets (Salm, 1993). Impacts attributable to fisheries activities, including the effects of nets, ropes, fish traps, and fishing lines, were estimated around 69% of all studied reef sites in the Sea of Oman (Al-Jufaili *et al.*, 1999). Gill nets were found to affect Coral Reefs at about 49% of the reef sites all through Oman and represented 70% of all extreme human impacts. Gill nets likewise contributed the utmost proportion of moderate human effects to Coral Reefs and fisheries-related activities, in general, contributed the most astounding level of low-level human effects. Branching corals are possibly to endure greater damage by nets. *Acropora* corals and other branching corals such as *Stylophora pistillata*, and *Pocillopora damicornis*, were observed to be particularly vulnerable to damage by nets. These species are additionally prevalent and common in the Omani waters. The damage caused by nets to *P. damicornis* reefs ranged between 25 and 100% of the total reef area at each site (Al-Jufaili *et al.*, 1999).

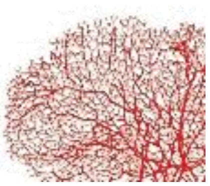
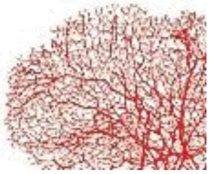


Figure 22. Smothered corals by abandoned gill net (Kharku Island, January 2007, Photo by Late H. Valavi)

The current fisheries operating in the Inner RSA focus on numerous species through a multi-year approach. Most of the catch (75% of the total reported landings) is referred to as artisanal (Al-Abdulrazzak *et al*., 2015) because of the traditional techniques being utilized (Sale *et al*., 2011) in spite of the fact that the scale at which they are operating is of commercial nature (Grandcourt, 2012). Fisheries segments in the Region can be categorized into four groups; recreational, traditional, commercial, and industrial. The recreational and traditional fisheries are commonly nondestructive in terms of impact on fish populaces and their related ecosystem health, using intertidal weirs, spears, or hand lines to target different demersal species including emperors (Lethrinidae), sweetlips and grunts (Haemulidae), seabreams (Sparidae), and groupers (Serranidae) (Grandcourt, 2012). Commercial fisheries are mainly worked from traditional wooden boats (dhows) and employ traps (gargoors) to nonselective target demersal species (Grandcourt, 2012). Commercial trawlers target shrimp during the open season in nations where it is allowed (e.g., Kuwait, Bahrain) and switch to finfish during the closed season (Carpenter *et al*., 1997) because of their damaging impact on seagrass beds and Coral Reefs (Valinassab *et al*., 2006). The fishing intensity in the Inner RSA waters has expanded over the past 30 years because of increased demand from growing population and concurrent enhancements in fishing technologies, leading to steep increments in the total fish catch (Al-Abdulrazzak *et al*., 2015; Sheppard, 2016). During the previous 15 years, the total landing of the Inner RSA fisheries has found the average value of 331,827 mt per annum, with the low of 208,520 in 2004, and a high 421,606 mt in 2012 (FAO, 2017). Reef-associated species represent around 70% of the total landed load of finfish caught in the Inner RSA, even though the species composition of landing across the Region is reliant upon the habitats where fishing is performed, capture techniques and seasonal changes in abundance, which fluctuate from country to country (Grandcourt, 2012). In spite of the distinctions in target species between nations, there are resemblance across the Inner RSA; >10% of annual landing are composed of species belonging to the families Carangidae, Lethrinidae, and Serranidae (Grandcourt, 2012). Regardless of the intense fishing activity in the Inner RSA, the consumption rate of the population surpass total fisheries production,



leaving the Region dependent upon imports of fish and fish-based items. This has powered growing interest for the aquaculture industry in the course of recent decades after investigation into the procedure started in the late 1970s (Al-Jamali *et al.*, 2005). In addition to the negative impacts of contamination and habitat devastation, extreme fishing pressure has resulted in overexploitation of 66% of economically important species, and full exploitation of a further 5% species (Grandcourt, 2012). Truly, fisheries in the Inner RSA were open access, with practically no exertion limitation implemented until a couple of decades back (Grandcourt, 2012). Most recently the absence of robust fish stock assessment (National or Regional) has additionally added to overfishing activities in the Region (Hamza and Munawar, 2009). This has been exacerbated by inaccurate catch reporting and illegal fishing practices (Daliri *et al.*, 2016). Devastating fishing practices such as shrimp trawling still occur in some countries in the Inner RSA and are probably going to have contributed notably to ecosystem decline through direct seabed devastation in their operating regions (Al-Husaini *et al.*, 2015). Trawling likewise brings about high fish by catch, and since juvenile of numerous commercial fish species are found inside shrimp fishing grounds, there is a worry that trawling practices are contributing to further decreases in fish stocks by eliminating the immature fish of nontarget species (Eighani and Paighambari, 2013). Juvenile fish are also regularly caught in demersal fisheries that use extensive wire mesh fish traps (ghargoor), such as those in the UAE. In Abu Dhabi alone, over 50%

of all landed catch of sparids (*Acanthopagrus bifasciatus* and *Argyrops* *spinifer*) are composed of immature fish (Grandcourt, 2012).

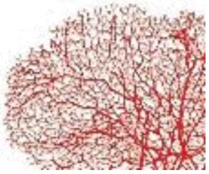
Figure 23. Abandoned wire mesh trap (Gargoor) on *Acropra* corals (Kish Island, September 2007, Photo by H. Valavi)

3.6. Threats from Unsustainable Development Practices

Coral Reefs in the RSA have been severely threatened by coastal and offshore development, causing a serious decline in associated habitats, species diversity, and overall ecosystem function. The major unsustainable development practices threatening Coral Reefs in this area include shoreline hardening, dredging, causeway construction, harbor, and airport construction, laying of pipelines and cables, sand mining, land reclamation and infilling. These threats are more prominent in the Inner RSA.

The construction of large-scale offshore and coastal dev s

Shoreline hardening, dredging, causeway construction, harbor, and airport construction, laying of pipelines and cables, sand mining, land reclamation and infilling are the major unsustainable development practices threatening coral reefs in the RSA, particularly in the Inner RSA



Iran's Pars Special Economic Energy Zone (PSEEZ) in the Inner RSA encouraging commercial activities in the field of oil, gas and petrochemical industries, the Dubai Palms, the Khalifa Port in Abu Dhabi, Qatar International Airport, and the proposed, Qatar-Bahrain causeway require huge dredging, landfilling, coastal development, and artificial waterways, which have caused enormous changes in the natural ecosystems. Nearly 70% of the original reef cover in the Inner RSA is estimated as being lost and a further 27% threatened or at critical stages of degradation (Wilkinson, 2008). In particular, hundreds of acres of marine habitats have been built over in Dubai, Abu Dhabi, and Bahrain, or otherwise affected (Purkis and Riegl, 2005). The permanent loss of intertidal and shallow sub-tidal nursery grounds has led to a decrease in fish and shellfish catches in many areas of the Inner RSA (Bishop, 2002). Coral coverage in Bahrain has declined from at least 50% since the 1980s to around zero percent (Zainal, 2009).

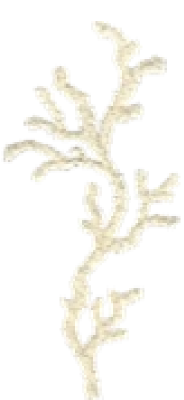
Tourist activities in the RSA have been reported to cause damage to coral reefs. Therefore, the crucial step is to determine the ecological carrying capacity for coral reefs, which is defined as the ability of a resource to bear recreational use without improper damage to its ecological components

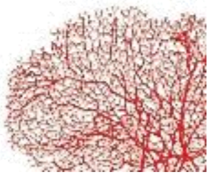
Across the northern coast of the Inner RSA (Iranian coast), the development of petrochemical complexes for the South and North Pars Gas fields has caused the degradation of coral ecosystems due to land reclamation, infilling, dredging and causeway construction. As an instance, coral cover in Assaluyeh Port adjacent to the South Pars petrochemical complex dropped from at least 50% in the 2000s to 17% much less than that observed on nearby Coral Reefs at the Zahedeh Bay (65%), and southern Nayband Bay (23%) (Ghazilou *et al.*, 2016).

In other cases in Kish and Hendourabi Islands across the northern Inner RSA, the port construction has led to dredging, land reclamation and degradation of coral ecosystems. The reefs of Chah Bahar Bay located in the northeastern Middle RSA also have been severely damaged due to port construction and large-scale dredging and infilling resulting in removal or burial of reefs causing lethal or sub-lethal stress to corals due to elevated turbidity and sedimentation rates (Sadatipour *et al.*, 2009; Ajdari *et al.*, 2013). Consequently, large-scale, short-distance coral relocation projects were conducted as mitigation for impacts to hard coral habitat associated with port construction in these areas in which 28,000, 3,000 and 65,000 hard coral colonies were salvaged and relocated in Chah Bahar Bay, Kish and Hendourabi Islands, respectively, out of which about 40, 30 and 90 percent of rescued corals survived (Sadatipour *et al.*, 2009; Ajdari *et al.*, 2013).

The deployment of submerged pipelines and power cables on coral areas is also a common threat to Coral Reefs in the RSA. The deployment of pipelines in coral areas in Qatar and Iran is just such an example. In a recent project for the deployment of an oil pipeline at Khark Island in the northern Inner RSA, it destroyed about 12 hectares of Coral Reef, yet damaged corals are still expected to be restored. In order to mitigate for pipeline installation impacts in Qatar's North field, 4,500 coral colonies were salvaged and relocated from pipeline corridors, of which after one year, 99% of the reattached monitored colonies survived (Kilbane *et al.*, 2008). Compared to the other Inner RSA countries, Oman's reefs have been impacted at more localized scales by coastal development, eutrophication and pollution associated with urban expansion (Al-Jufaili *et al.*, 1999; Maghsoudlou *et al.*, 2008; Coles *et al.*, 2015).

Coastal and marine tourism activities are very diverse and include onshore activities (e.g., walking, curio collection, animal watching, off-road vehicle tours), coastal activities (e.g., swimming, surfing, boating), offshore activities (cruising, marine mammal watching, fishing), underwater activities (e.g., diving, shark feeding), and specialized niche activities (e.g., marine research tourism, adventure tourism) (Hall, 2001; Orams, 2007; Wood, 2010). It is clearly specified that excessive, un-planned tourism can have adverse impacts on Coral Reefs including direct contact of tourists, anchor damage, pollution, and sedimentation from coastal erosion and over-development (Diedrich, 2007). Compared to the intensive coastal and marine recreational activities in the Red Sea, these activities are not pronounced in the RSA, but the countries in the Region are planning to encourage a substantial increase (Gladstone *et al.*, 2013). Tourist activities in the RSA have been reported to cause habitat damage, particularly in Iran and UAE (Gladstone *et al.*, 2013) followed by Kuwait and Oman (Al-Jufaili *et al.*, 1999; Baporikar, 2011). In a comprehensive study at Kish Island (Iran), the current recreational use of heavily utilized Coral Reefs by recreational divers is estimated to be about 6 to 7 times more than the acceptable carrying capacity suggesting an unsustainable use for these reefs (Shokri *et al.*,





2019).

The damage by recreational divers, spearfishers, and boaters incorporates breakage of corals by divers and snorkelers, trampling of intertidal areas, anchor damage to corals, and land and ship-based litter (Gladstone *et al.*, 2013). Accordingly, it is critical to managing Coral Reef-based tourism to minimize its adverse effect on Coral Reefs and to guarantee its sustainable development. In doing so, the crucial step is to determine the ecological carrying capacity for Coral Reefs which is defined as the ability of a resource to bear recreational use without improper damage to its ecological components (Shelby and Heberlein, 1986).

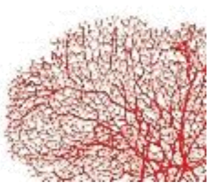
3.7. Threats from Pollution Related Activities

Wastewater Impact on Coral Reefs

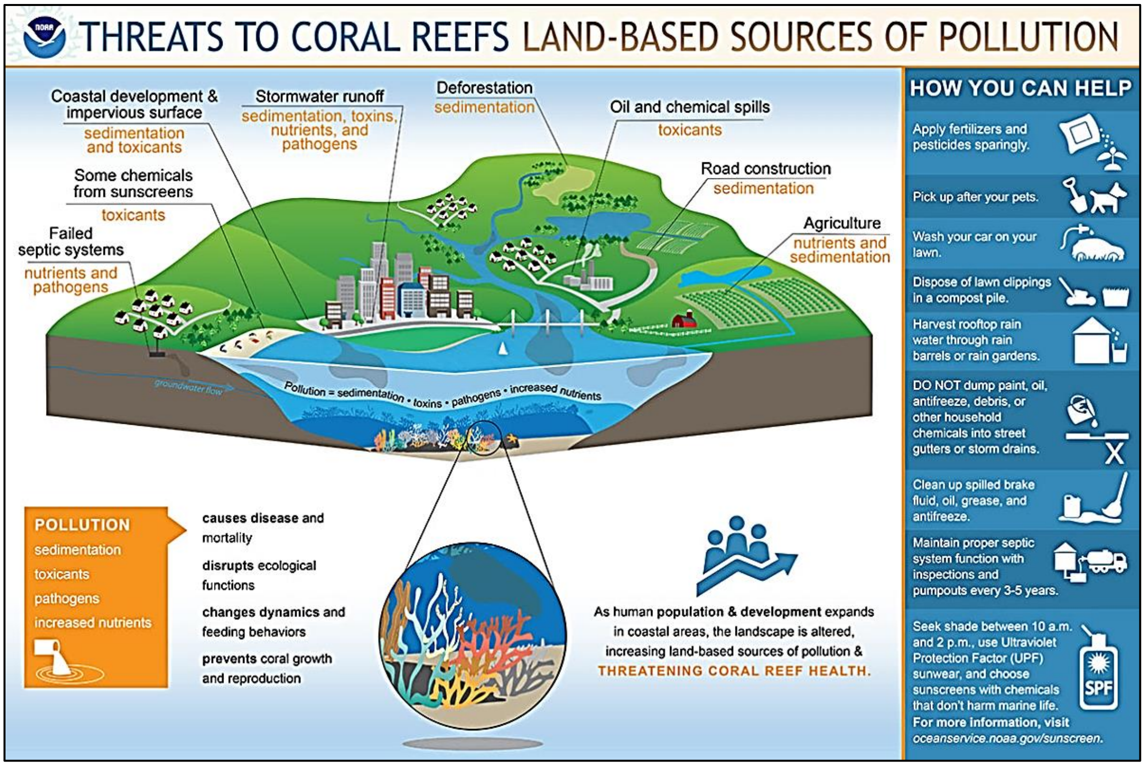
Large quantities of industrial and domestic wastewater enter the shallow waters of Inner RSA that affect sensitive habitats of coral reefs

Increased nutrient content originating from persistent sewage input causes frequent HABs outbreaks and consequent fish kill alongside coral damage

Large quantities of industrial and domestic wastewater enter the Inner RSA despite high standards for wastewater treatment throughout the Region (Hamza and Munawar, 2009; Sheppard *et al.*, 2010). Industrial effluents originate from a multitude of major manufacturing industries producing products such as fertilizers, plastics, chemicals, petrochemicals, and minerals (Gevao *et al.*, 2006) resulting in chemicals like hydrocarbons and heavy metals continually being introduced into the Inner RSA. Since the flushing time of the Inner RSA may range more than 3 to 5 years, such harmful pollutants reside in the Region for substantial periods of time (Naser, 2014). Despite the majority of studies demonstrating that current levels of heavy metals within marine sediments, fish and shellfish are within the safe international thresholds (Ashraf, 2005; Naji *et al.*, 2016), marine ecosystems located adjacent to various wastewater discharges have shown to contain elevated concentrations at potentially harmful concentrations (Beg *et al.*, 2001; Naser, 2013). Localized eutrophication and hypoxia can also result from nutrient runoff entering the Inner RSA through river systems and in areas of increased coastal development, particularly as a result of sewage treatment plants (Darwish *et al*., 2005; Sale *et al*., 2011).



Domestic effluents entering the Inner RSA typically receive secondary treatment, but these effluents are still characterized by high-suspended solids and high levels of nutrients such as ammonia, nitrates, and phosphates (Naser, 2014). Since sewage effluents are most commonly discharged into shallow coastal areas, the effect on the local environment is exacerbated by the naturally extreme temperature and salinity profile of the Inner RSA's coastal waters, often alongside low flushing rates (Sheppard *et al.*, 2010). Such discharge areas tend to be low in biodiversity (Naser, 2011; Naser, 2013), with water degradation associated with disease in some organisms (Khan, 2007). Several large-scale HABs have been documented in Kuwait Bay over the last few decades which have been attributed to elevated nutrients originating from industrial and sewage inputs, causing widespread fish kills (Heil *et al.*, 2001; Glibert *et al.*, 2002; Khan, 2007; Sheppard *et al.*, 2010). The enhanced nutrient content of these waters has also been implicated in algal blooms and the triggering of mass coral bleaching events (Wiedenmann *et al.*, 2012).



THREATS TO CORAL REEFS LAND-BASED SOURCES OF POLLUTION

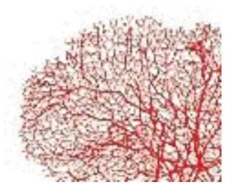
As human population & development expands in coastal areas, the landscape is altered, increasing land-based sources of pollution & THREATENING CORAL REEF HEALTH.

HOW YOU CAN HELP

- Apply fertilizers and pesticides sparingly.
- Pick up after your pets.
- Wash your car on your lawn.
- Dispose of lawn clippings in a compost pile.
- Harvest rooftop rain water through rain barrels or rain gardens.
- DO NOT dump paint, oil, antifreeze, debris, or other household chemicals into street gutters or storm drains.
- Clean up spilled brake fluid, oil, grease, and antifreeze.
- Maintain proper septic system function with inspections and pumpouts every 3-5 years.
- Seek shade between 10 a.m. and 2 p.m., use Ultraviolet Protection Factor (UPF) sunwear, and choose sunscreens with chemicals that don't harm marine life.

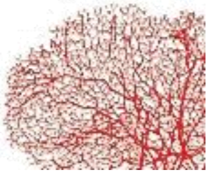
For more information, visit *oceanservice.noaa.gov/sunscreen.*

Figure 24. Diagram of the land-based sources of pollution threating the Coral Reefs (NOAA, https://aamboceanservice.blob.core.windows.net/oceanservice-prod/facts/coral-pollution.pdf)



Due to the arid climate and restricted freshwater input, desalination of seawater is heavily relied upon as it is the main source of potable water in the Inner RSA countries (Sale *et al.*, 2011). The total volume of water produced through desalination in the Inner RSA has expanded from 0.04 million m^3 for each day in 1970 (GCC, 2014) to more than 21 million m3 per day in 2018 (GWI, 2018) which records for over 20% of total global desalination production capacity (Jones *et al.*, 2019). It is anticipated this could ascend to 80 million m^3 /day by 2050 (Le Quesne *et al.*, 2019). In the Region, desalination utilizing distillation techniques represents 83% of desalinated water production, with the remaining 17% produced through reverse osmosis (Dawoud, 2012). Concerns with respect to desalination plants mainly center on the effluents which are discharged into adjacent coastal waters. More than 1000 m^3 of waste brine is discharged into the Inner RSA consistently every second, causing limited discharge plumes that can reach out as much as several kilometers (Burt *et al.*, 2013), impacting bordering coastal ecosystems and affecting Regional marine water quality (Hamza and Munawar, 2009). Released waste brine in both reverse osmosis and distillation plant outfalls are ordinarily high in saltiness and are significantly warmer than ambient conditions (Burt, 2014), and outfalls frequently contain a variety of toxins such as heavy metals, chlorates, and radioactive isotopes (Alshahri, 2017). Such pollutants are suggested to be contributing to the increasing heavy metal concentration found in tissues of a large number of marine organisms in the Inner RSA (Shahsavani *et al.*, 2017). In spite of continuous progress in the efficiency of the desalination process, the administration encompassing the treatment of related wastewater brine has seen of little improvement (Dawoud, 2012).

The total volume of water produced through desalination plants in The Inner-RSA recorded over 21 million m3 per day in 2018 which records for over 20% of total global capacity. Huge seawater desalination in Inner-RSA imposes various impacts on marine environment, including discharge of saline brine, discharge of heat brine, impingement and entrainment of organisms and chemical discharge which have adverse impact on coastal habitats and organisms such as Coral Reefs

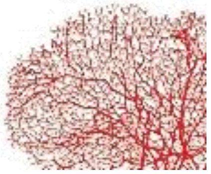


Petroleum Industry Impact on Coral Reefs

Over 50 percent of the world's oil and gas reserves are estimated to have been located in the RSA, and associated industrial infrastructure and practices have had dramatic effects for the marine environment in the Region. Huge stores of 76 billion metric tons of recoverable oil and 32.4 trillion m^3 of natural gas are available in the Inner RSA (Hamza and Munawar, 2009) representing the production of ca. 19 million barrels of oil, and 2.5 million barrels of liquid gas per day (Seznec, 2008). There are roughly 800 offshore platform and 25 major oil terminals in the Inner RSA that are serviced by 25,000 yearly tanker shipments (van Lavieren *et al.*, 2011; Sale *et al.*, 2011) which together export ca. 88% of the Inner RSA's oil (Le Billon and El Khatib, 2004). Oil and gas have turned into the most important financial resource in the Region (Kubursi, 2015).

In Saudi Arabia alone, oil income expanded from an expected US$ 42 billion in 1999 to US$ 307 billion out of 2008, in the UAE from US$ 13 to US$ 87 billion, and in Kuwait from US $4 to US $27 billion during the period (Seznec, 2008). Qatar has the third-biggest reserve of natural gas on the planet and has considerably developed its liquefied natural gas (LNG) infrastructure over the previous decade. Economic growth in Qatar arrived at the midpoint of 13% per year until 2010 when the peak of 77 million tons was created, doubling up the revenue produced from oil that year (Kubursi, 2015). These improvements have unavoidably led to a dramatic increment in inshore and offshore industrial infrastructure. These infrastructures function as unplanned artificial reef habitats for an assortment of fauna in seaward regions that are to a great extent featureless (Feary *et al.*, 2011). These artificial habitats accommodate diverse communities of bivalves, corals, fish, and other fauna (Stachowitsch *et al.*, 2002; Feary *et al.*, 2011; Albano *et al.*, 2016; Torquato *et al.*, 2017).

Activities associated with the hydrocarbon industry are also viewed as the paramount contributors to marine contamination in the Inner RSA (Naser, 2013). Oil spill in the Inner RSA originates from offshore oil wells, terminals, submerged pipelines, and tanker collisions (Tseng and Chiu, 1994; Naser, 2014). The most prominent episode of the oil spill was during the War in 1991 when an approximated 10.8 million barrels of oil were discharged into the Inner RSA from damaged oil wells, abandoned tankers, oil terminals and sunken vessels (Massoud *et al.*, 1998), affecting more than 700 km of coastline and affecting intertidal fauna, including seabirds, invertebrates, and fishes (Sale *et al.*, 2011; Naser, 2014). Aside from



enormous scale spills leading to a significant impact, there is additionally persistent low-volume discharge of oil and related wastes from harbors, tank washouts, terminals, and ballast tanks (Madany *et al.*, 1998). Thus, there are constantly elevated amounts of hydrocarbons (Sale *et al.*, 2011), and other by-products of oil and gas production including heavy metals and polycyclic aromatic hydrocarbons (PAHs) that have demonstrated expanded concentration in coastal waters since the late 1970s (Gevao *et al.*, 2006).

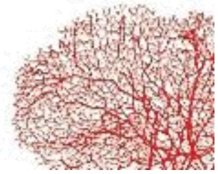
Shipping Traffic Impact on Coral Reefs

Due to the vigorous transportation of oil and gas products and the local dependence on imported sustenance and materials, the Inner RSA is exposed to significant shipping traffic every year. The increase in shipping traffic has led to introduction of invasive biota to the Inner RSA through the discharge of ballast water and sediment contained in ballast tanks (Sheppard *et al.*, 2010).

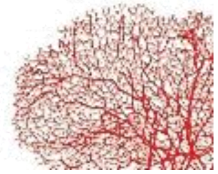
It is evaluated that 53,000 ships enter the Inner RSA through the Strait of Hormuz every year (Al-Yamani *et al.*, 2015). This increases the presence of conceivably unsafe conspicuous species, with a few significant HABs being brought about by invasive species (Richlen *et al.*, 2010). Combined with the large amounts of shipping traffic, the Inner RSA's enclosed nature and moderately restricted water exchange with the Indian Ocean make it prone to HAB episodes (Sale *et al.*, 2011).

The most devastating HAB outbreaks have regularly occurred in areas with high nutrient loads from inland sources (e.g., sewage outfalls) (Glibert *et al.*, 2002) that has led to mass fish mortality and shifts in reef fish community structure (Bauman *et al.*, 2010).

A widespread algal bloom associated with the introduced dinoflagellate species *Cochlodinium polykrikoides* impacted vast areas of the Inner RSA from August 2008 to May 2009. This led to the deterioration of Coral Reefs, limiting fishing activities, disruption of desalination plants, mass fish mortality and loss of the tourism industry income (Naser, 2014). The impact of *C. polykrikoides* blooms on Coral Reefs has been noted across the Inner RSA with near-complete extirpations of shallow-water reef biota that were due to an increase in sedimentation and asphyxiation (Samimi Namin *et al.*, 2010; Foster *et al.*, 2011; Burt *et al.*, 2016a;). With the growing human



population in the Inner RSA, HABs are expected to increasingly occur because of amplified eutrophication, shipping traffic, and stressors associated with global warming. Thus, appropriate guidelines on ballast water must be developed to diminish the risk of future episodes (Hallegraeff, 2015).



4. CORAL REEFS STATUS AND TREND IN THE RSA: PAST, PRESENT, AND FUTURE OUTLOOK

The past of the RSA reefs

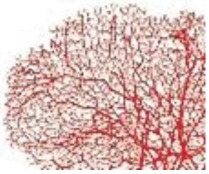
A hundred years ago in the RSA, when the vast oil reserves of the Region were not developed, and the human uses of the marine area were mainly limited to small fishing and pearling activities, the reef corals were almost healthy, made of simple reefs (Rezai *et al*., 2004). The hard corals in this area were mainly dominated by *Acropora* (staghorn) corals to about 4-5 m depth followed by massive corals (*Porites*, faviids) from 5 m to about 10 m (Rezai *et al*., 2004). In general, the coral diversity in this area was lower than that of the Indian Ocean that was due to natural causes including limited recruitment since the last ice age (Holocene) (Pirazzoli *et al*., 2004; Bruthans *et al*., 2006), severe annual variation of temperature, and extreme salinity (Sheppard *et al*., 2010).

Since the 1970s, there has been an overall warming trend in the Inner RSA with SSTs in some areas warming at rates three times the global average leading to the first sever bleaching events in the southern Inner RSA in the late 1970s (80% loss)

Since the 1970s, there has been an overall warming trend in the Inner RSA with SSTs in some areas rising at rates three times the global average (Al-Rashidi *et al*., 2009; Riegl *et al*., 2011). This led to the first severe bleaching events in the southern Inner RSA in the late 1970s (80% loss) (Sheppard, 2003), that was marked by extreme heating events happening with longer-than-usual duration and increasing frequency (Riegl, 2007; Riegl *et al*., 2018).

During the summer of 1990, widespread and locally severe bleaching occurred for the first time in the Sea of Oman when Sea Surface Temperatures reached 35 °C and stayed >30 °C for three months, resulting in loss of virtually all corals <3 m deep in embayed areas (Salm, 1993). This led to <2% of *Acropora* die-off near Muscat, with greater mortality ranging from <1% to >95% in Musandam (the Middle RSA) mainly affecting *Acropora* and *Stylopora* and partially affecting *Platygyra*.

In 1991, coastal habitats in the Inner RSA damaged due to the war when



huge amounts of crude oil swept into the sea. However, corals recovered and supported a healthy fish community later on (Downing and Roberts, 1993; Mohammed and Al-Ssadh, 1996).

In 1994, corals were in similar condition in most areas (Rezai *et al.*, 2004). However, substantial nearshore construction, landfilling, and oil and civil development removed many coastal habitats in the RSA, especially at the Inner RSA. This impacted seagrass beds as much as corals in the southern Inner RSA, though the sedimentation particularly affected the nearshore reefs (Rezai *et al.*, 2004). Shipments, in particular, tanker traffic for oil transportation, also vastly expanded with the development of oil fields, with a significant increase in ship-derived pollution (Rezai *et al.*, 2004). By 1994, there were few activities to conservation and managing Coral Reef resources (Rezai *et al.*, 2004). Reefs of Jubilee Wildlife were the first MPA to be established after the War of 1991. By 1994, there was no Coral Reef monitoring activity and there was minimal awareness of the potential economic and biodiversity value of Coral Reefs and the need for them to be preserved (Rezai *et al.*, 2004).

The severe beaching in the late 1970s was followed by a period of relative calm for two decades before consecutive severe bleaching events recurred again in 1996 and 1998 with >80% coral die-off when SSTs reached 37.7 °C, and persisted for several months at 2–2.5 °C above normal summer maxima (George and John, 2000; Riegl, 2002; Sheppard and Loughland, 2002). Coral bleaching events in 1996 and 1998 had a substantial effect on reefs by killing the entire shallow water staghorn zones in many areas of the RSA (Rezai *et al.*, 2004). In 2004, many of these areas were reduced to rubble, with no sign of recovery, and the mobile rubble may have impeded new recruitment. Some sites did show some recovery, especially in deeper water where there was significant recruitment of faviid species that were previously relatively minor components of the reefs. Consequently, there appeared to be a shift in the species that were dominating the Inner RSA reefs. 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). Over the next few years, reefs recovered through the growth of survivors and colonization by planktonic coral larvae provided elsewhere in the Inner RSA (Sheppard and Loughland, 2002). This recovery was disturbed five years later in 2002, when SST reached 37 °C and resulted in widespread bleaching across most corals, but did not induce mass mortality (Riegl, 2003b). Corals in the Musandam area (the Middle RSA) escaped the

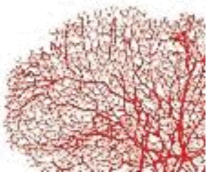
devastating impacts of the 1996 and 1998 bleaching events (Rezai *et al.*, 2004), but locally affected by a smaller bleaching event in the summer of 2002. During this time, nearly two-thirds of corals in protected embayments bleached, while areas with strong currents remained unaffected (Wilson *et al.*, 2002).

In the Inner RSA, a very mild bleaching event occurred in 2007, but corals quickly recovered and no mortality was recorded to pre-1996 levels in several locations (Burt *et al.*, 2008; Foster *et al.*, 2012).

Figure 25. Bleached *Acropora downingi* due to the severe bleaching of summer 2017 (Kish Island, September 2007 Photo by H. Valavi)

After several years of calm, corals in the Inner RSA experienced several consecutive bleaching events in quick succession starting in 2010 when a moderate bleaching event affected a fifth of corals and resulted in loss of

Coral reefs in the Inner RSA, affected by what has been dubbed the "3rd global coral bleaching event" in 2017, witnessed mortality that surpassed 85-95%



20% of coral cover when the leading hourly maxima reached 36.4 °C and temperatures were >33 °C twice as long as in non-bleaching years (Riegl and Purkis, 2015). This was followed by a stronger bleaching event in 2011 when over two-thirds of corals were bleached or partially bleached and a further 20% of coral cover was lost to mortality (Riegl and Purkis, 2015). Another strong bleaching event recurred in 2012 in which >40% of corals showed signs of bleaching, although only limited mortality occurred (<15% loss of coral cover) (Riegl and Purkis, 2015; Shuail *et al.*, 2016). The 2012 bleaching in the reefs of the northern Inner RSA (Iranian reefs) resulted in profound coral bleaching (~84% coral colonies affected) in which *Acropora* was less affected than *Porites* corals (Kavousi *et al.*, 2014).

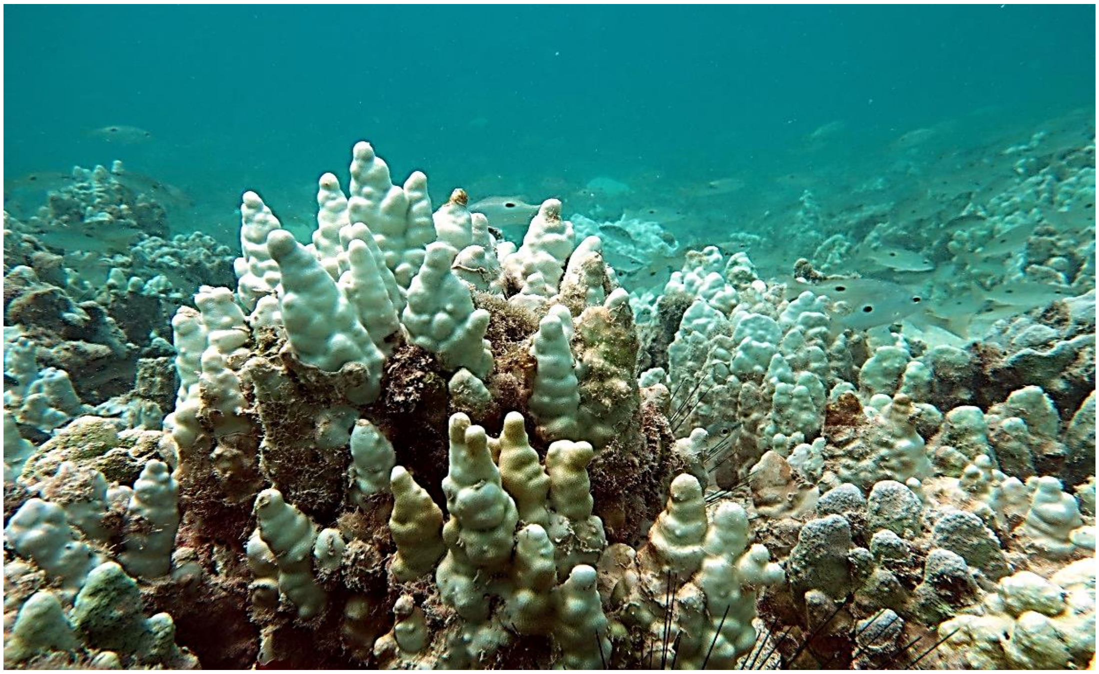
These recurrent events from 2010 till 2012 were followed by a period of recovery in the summers of 2013 through 2016 when bleaching levels were negligible (Paparella *et al.*, 2019). In summer 2017, one of the most severe bleaching events on record occurred in the RSA. During summer 2017, reef corals across the southern Inner RSA experienced nearly two months (55.1 ± 3.9 d) above bleaching temperatures and approximately two weeks beyond lethal temperatures (11.8 ± 2.4 d), markedly longer than in the non-bleaching years (2013–2016) and equating with 5.5 °C-weeks of thermal stress as degree heating weeks (Burt *et al.*, 2019). The 2017 bleaching event resulted in mass mortality of corals across the entire southern and northern Inner RSA in which mortality surpassed 85-95% by the end of summer (Riegl *et al.*, 2018; Burt *et al.*, 2019; Shokri *et al.*, 2019). The impact of exceeding temperature during summer 2017 appeared afterward when two-third of corals were lost to mortality between April and September 2017 (Burt *et al.*, 2019). Mortality sustained after peak bleaching, and by April 2018 coral cover averaged just 7.5% across the southern Inner RSA, representing an overall loss of nearly three-quarters of coral (73%) in one year (Burt *et al.*, 2019). Coral bleaching in summer 2017 also had a substantial adverse impact on reefs across the northern Inner RSA by killing the entire shallow water *Acropora* zones. For example, the reefs in Kish Island experienced a 95% loss during peak bleaching in summer 2017. Mortality sustained after peak bleaching in this island, and by March 2018 coral cover averaged just 6.5%, but this was followed by a slow recovery in which by February 2019 coral cover reached to 13.2% (Shokri *et al.*, 2019). The 2017 bleaching did not cause intense shifts in the coral community composition, because earlier events have eliminated the most sensitive taxa

(Burt *et al*., 2019; Shokri *et al*., 2019). The only exception was already rare

Acropora, which was locally extirpated in summer 2017 (Burt *et al*., 2019).

Figure 26. Stands of Porites showing signs of paling and bleaching at Dhabiya reef (UAE) in summer 2017 (Photo by J. Burt)

Corals in the Chah Bahar Bay located in the northeastern of the Middle RSA escaped the devastating impacts of 1996, 1998 and 2017 bleaching events that severely affected corals in the Inner RSA (Rezai *et al*., 2004). But these reefs experienced bleaching event in the summer of 2018 when the water temperature raised to more than 30 °C and consequently nearly 100% of massive corals such as *Dipsastera* and *Cyphastrea* and about 10-50% *Acropora* corals and less than 5% *Pocillopora* corals were bleached (Ghazilou, 2019).



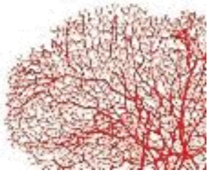


Figure 27. The impact of exceeding temperature during summer 2017 appeared afterward when two-thirds of corals and >99% of branching *Acropra* corals were lost to mortality between April and September 2017 (Photo by M.R. Shokri, Kish Island, 2017)

The present of RSA reefs: 2019

The recent 2017 bleaching event resulted in 85-95% coral cover loss across the entire southern and northern Inner RSA (Burt *et al.*, 2019; Riegl *et al.*, 2018; Shokri *et al.*, 2019). In 2019, some sites across the Inner RSA showed slow recovery, particularly in deeper waters where a significant recruitment of faviid species, which were previously relatively minor component of the reefs (Burt *et al.*, 2019; Shokri *et al.*, 2019). Yet, the recovery of reefs in shallow areas relies on deep reef metapopulation as a repository of resilience (Riegl *et al.*, 2011). Yet, the 2017 bleaching has not caused intense shifts in the coral community composition, because earlier events have eliminated the most sensitive taxa (Burt *et al.*, 2019; Shokri *et al.*, 2019).

The future of RSA reefs

Climate change is anticipated to have intense, partly unforeseeable effects on the composition of functional traits of Coral Reefs in the RSA. Prediction of future SST in the RSA using the proper orthogonal decomposition (POD) model has revealed the highest warming during summer in the entire Inner and Middle RSA by 2100 and the lowest warming during fall and winter in these areas, respectively (Noori *et al.*, 2019). This model has demonstrated that monthly SST in the Inner RSA may increase by up to 4.3 ˚C in August by the end of the century. Similarly, mean annual changes in SST across

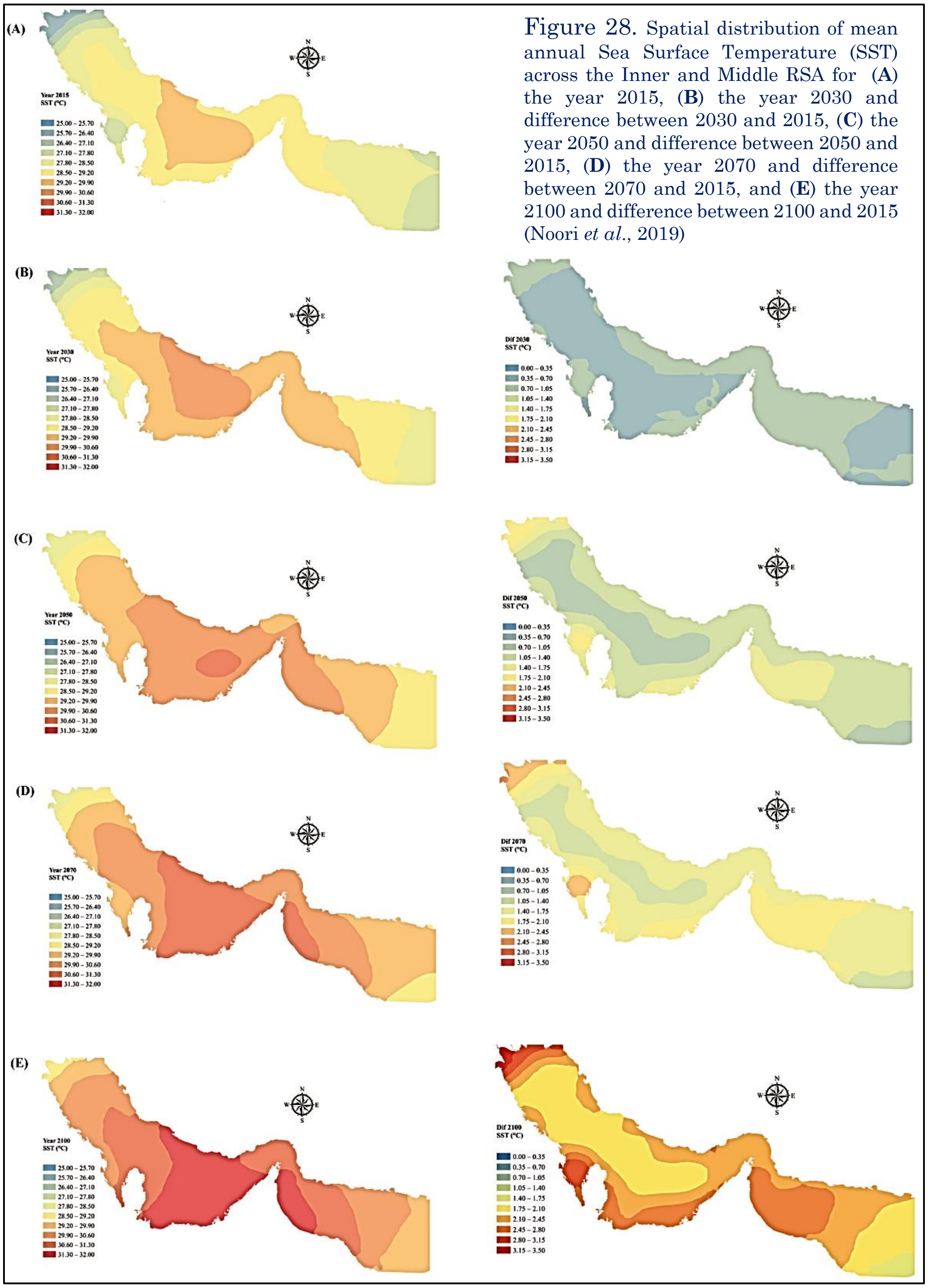
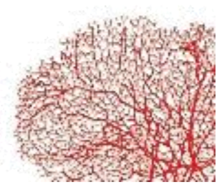


Figure 28. Spatial distribution of mean annual Sea Surface Temperature (SST) across the Inner and Middle RSA for (**A**) the year 2015, (**B**) the year 2030 and difference between 2030 and 2015, (**C**) the year 2050 and difference between 2050 and 2015, (**D**) the year 2070 and difference between 2070 and 2015, and (**E**) the year 2100 and difference between 2100 and 2015 (Noori *et al.*, 2019)



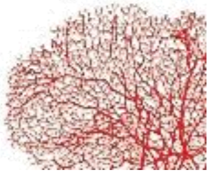
the Inner and Middle RSA may increase by about 2.2 ˚C by 2100 (Fig. 28) (Noori *et al*., 2019).

Climate change ocean acidification in combination with local stressors will cause >75% of the reef area in the Middle RSA and Outer RSA to be under high threats by 2030, and almost all of the Oman reefs under a critical threat by 2050

Thermally-induced mass bleaching events are recurring with increasing frequency and intensity both locally and globally (Hughes *et al*., 2017) and as the seas warm, corals are pushed beyond the thermal thresholds to which they have evolved. Even under the most favorable IPCC scenario (Representative Concentration Pathway, RCP 2.6), model results show that shifts in the trait space are plausible, and coral communities will be composed of a few temperature-tolerant and fast-growing species (Kubicek *et al*., 2019).

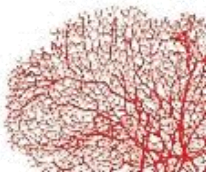
The complete recovery of Coral Reefs in shallow areas of the Inner RSA is unlikely; as forecasts suggest that Sea Surface Temperatures will not be congenial for coral growth in the future. The Coral Reef coverage in deeper areas will increase, but probably by changing the species composition. Thus, the future composition and structure of the coral communities in the Inner RSA will be shaped by the vulnerability of various species to climate change and local stressors. This explicitly has been featured in the population collapse of *Acropora downingi* across the Inner RSA reefs in which this species is heading toward at least functional extinction (Riegl *et al*., 2018). Considering the increasing frequency and intensity of bleaching events in the Inner RSA and the above global rates of Regional warming, the capacity for recovery and the projection for the future of the Inner RSA reefs are not optimistic (Burt *et al*., 2019). Superimposed on natural threats, coastal development will continue in the Inner RSA with increased rates of landfill and dredging causing more stress to the nearshore reefs.

The reefs across Oman and Iran's coastline in the Middle RSA and Outer RSA are under threat from the integrated threats of local stressors and thermal stress (Burke *et al*., 2011). Aside from the numerous large-scale natural impact events, the reefs of Oman in the Middle RSA and the Outer RSA have been extensively degraded by fisheries activity, both as a result of direct impacts to reefs by fishing gear (e.g. drifting nets, anchor damage, snared ropes) but also as a result of extraction of functionally important fish species that feed on organisms that compete or prey on corals



(Salm, 1993; Salm *et al*., 1993; Al-Jufaili *et al*., 1999; Mendonça *et al*., 2010). Superimposed on these natural and fishing threats, the reefs of Oman also have been locally affected by coastal developments and eutrophication and pollution associated with urban expansion (Al-Jufaili *et al*., 1999; Maghsoudlou *et al*., 2008; Coles *et al*., 2015). Aside from the thermal stress, the reefs at Chah Bahar Bay in the northeastern section of the Middle RSA (Sea of Oman) have been largely degraded by coastal developments and port construction. As a result of this and other stressors, the reefs in the Middle RSA and Outer RSA are under threats (Halpern *et al*., 2008), and now more than half of the reefs in these areas are under severe risk as a result of these integrated threats (Burke *et al*., 2011). Climate change and related ocean acidification in combination with local stressors will cause >75% of the reef area to be under high threats by 2030, and almost all of the Oman reefs under a critical threat by 2050 (Burke *et al*., 2011).

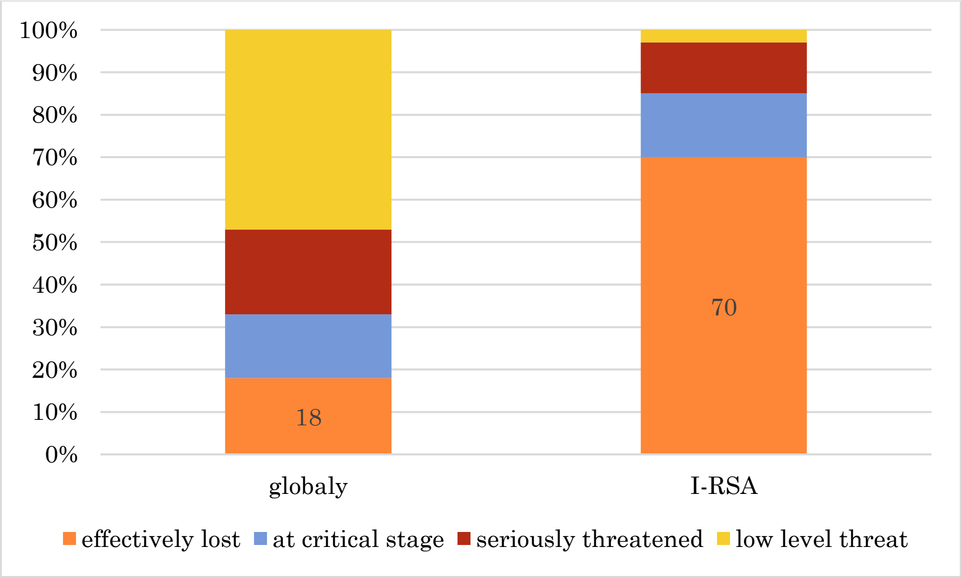
In summary, it is hoped that increased awareness of the value of Coral Reefs would trigger an intense monitoring and effective management of the reefs in the Inner RSA, and a stronger awareness and management of unusual reefs in the Middle RSA and the Outer RSA.



5. Key Management Actions

5.1. Management and Policy Responses

It is well-known that the Coral Reef change is driven by local and global pressures, as such, conserving a Coral Reef in the long term needs to address both of these. The coastal management policies of any water body should come from an agreed partnership of all neighboring countries in order to ensure effective management, even in case of the Inner RSA's semi-enclosed and extreme environment (van Lavieren *et al*., 2011). The ROPME Sea Area (RSA), was designated in 1979 to serve the water bodies of the Inner RSA, Sea of Oman, and the southeastern coast of Oman in the Arabian Sea (Van Lavieren and Klaus, 2013). The RSA with 6200 km includes all eight countries and forms the only pan-Regional marine organization (Nadim *et al*., 2008). In the broad sense, this Regional analysis found a substantial Region-wide decline in the Coral Reef percent cover and a significant change in the coral community structure and architectural complexity in particular in the Inner RSA. Because of the expansion in extent and frequency of natural and anthropogenic stressors, the global assessment in Status of Coral Reefs of the World believes reefs in the Inner RSA to be 'among the most damaged in the world', with over 70% of the its reefs considered seriously threatened (Fig. 29). Critically, at the Regional scale, major events of acute stress caused by bleaching episodes have to date led to Region-wide declines in coral cover. Yet, major events of other stresses (such as Cyclone Gonu, coral disease, and crown of thorns starfish outbreaks) have resulted in localized declines in coral cover. Loss of reef structure and architectural complexity may jeopardize the ecological services provided (Rogers *et al*., 2015). In addition, Coral Reefs in the RSA are increasingly impacted by rapid development involving substantial coastline alterations, habitat loss, and formation of beds by shifting or suspended sediments, coastal and marine tourism activities, and temperature and salinity changes in restricted water flows along the coast, marine traffic, and fisheries activities. Of course, it should be noted that these anthropogenic impacts in the Inner RSA are mostly due to coastal changes, while the effects of fishing activities are more evident on the coast of Oman in the Middle RSA and the Outer RSA.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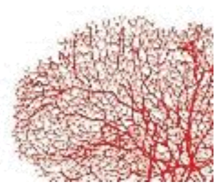


Figure 29. An assessment of the status of global reefs versus that in the Inner RSA (Adapted from data in Status of Coral Reefs of the World)

5.2. Strengthening Coral Reef Monitoring and Network

Monitoring and assessment as important tools for effective management can provide information for identifying changes in condition that may trigger management responses, determine the cause of changes of concern, and evaluate the effectiveness of management measures (Reef Resilience Network, 2019). Assessment typically refers to a one-time measuring or evaluating variables related to ecological or social conditions or pressures (Reef Resilience Network, 2019). Yet, monitoring refers to repeating surveys through time, usually aimed at identifying changes, such as trends in coral cover or fish abundance (Reef Resilience Network, 2019). Monitoring programs are traditionally divided into two categories: participatory monitoring and responsive monitoring. Participatory monitoring programs involve non-expert observers (sometimes called citizens' scientists) in monitoring activities. These activities may be directed by scientists or managers or have observers monitoring the reefs independently. Coral Reef managers often use participatory monitoring programs to assess the reef condition status, disturbance detection, evaluate the effects of disturbances, and evaluate the effectiveness of management practices (Reef Resilience Network, 2019). Responsive monitoring programs that complement routine monitoring may be developed at any time and may be reviewed and modified when impacts occur. Impacts from acute disturbances to Coral Reefs, such as bleaching, storm damage, ship groundings, and disease outbreaks, require managers to have a responsive monitoring plan (Reef Resilience Network, 2019).

Coral Reef monitoring and assessment in the RSA has evolved relatively, especially over the last decade, but continuity is challenging in particular where monitoring is dependent on external project funding. Some ROPME Member States have their own monitoring programs or are a member of international Coral Reef monitoring networks (e.g., GCRMN, ReefCheck). However, due to the unstable nature of funding for Coral Reef monitoring in the ROPME member States and personnel and institutional changes, most National datasets suffer from substantial discontinuities in the data series. In addition, inconsistency in monitoring methods employed in different States can undermine the value of the monitoring data. This raises significant gaps and challenges that reduce the monitoring capability for Regional and National reporting, reduce the applicability of monitoring data used for policy and management decisions, and limit its use in informing the community about environmental change or supporting research.

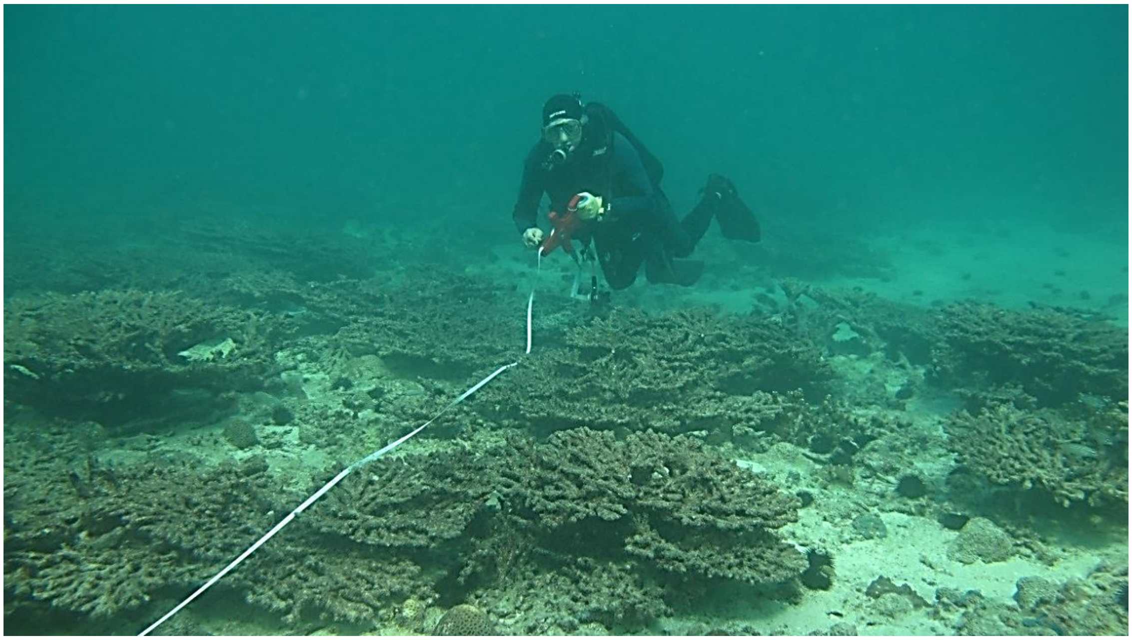
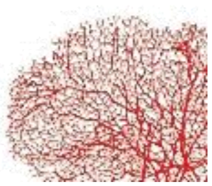


Figure 30**.** Internationally accepted transect survey tracking the changes in coral coverage over years (Photo by H. Bargahi, Kish Island, 2018)

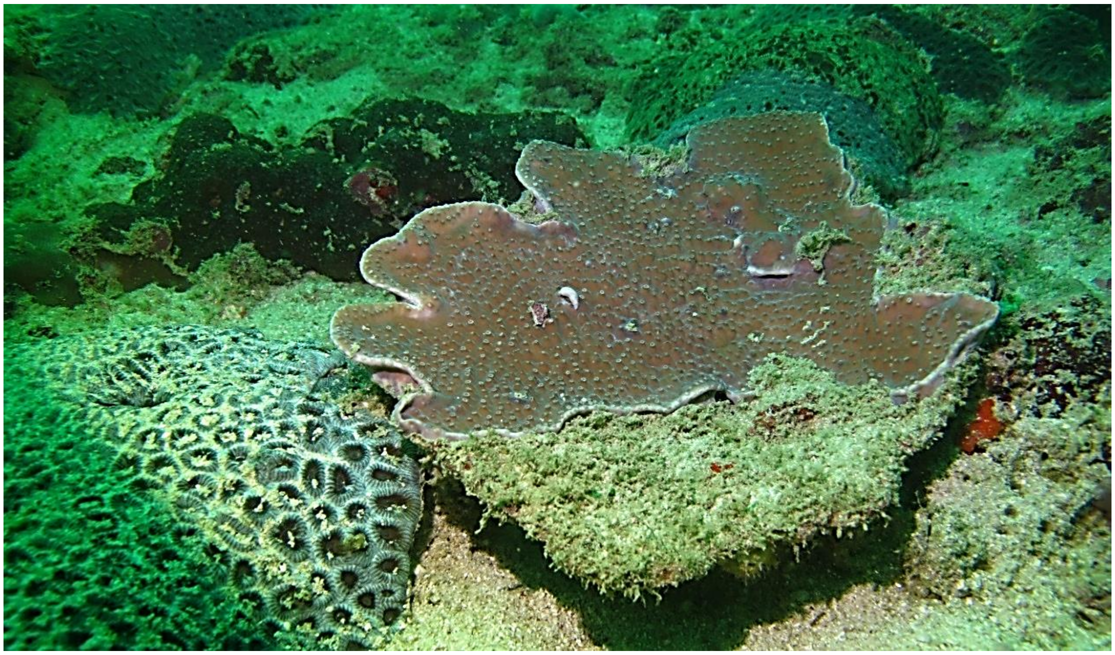
5.3. Adaptation to Ecological Changes to Cope with Climate Changes

Coral Reefs are impacted by climate change over the globe and face rising risks in future climate predictions (IPCC, 2014a). Even under the mitigation scenarios agreed at the Conference of Parties 21 in Paris in 2015, climate change is likely to cause significant changes in ecosystem functional characteristics and diminished trait diversity in communities (Schleussner et al., 2016). The increasing level of atmospheric greenhouse gas in the Indian Ocean led to an increase in sea surface temperatures (SSTs) by ~0.65 °C between 1950-2009 (Hoegh-Guldberg *et al.*, 2014), and severe heat anomalies became more common during the same era (Harley *et al.*, 2006).

As a result of climate change, the average SSTs in the Inner RSA have been increasing over the past three decades (Riegl *et al.*, 2011) and consequently, the frequency and magnitude of mass bleaching events have been increased pushing corals beyond their thermal limits (Riegl *et al.*, 2018). Intense



bleaching with widespread mass coral mortality (>80% loss) was first reported in the late 1970s, then recurred in 1996, 1998, and 2017, with slight to moderate bleaching events that led to more limited coral mortality (0 ~20% loss) also occurring in 2002, 2010, 2011, and 2012 (Sheppard and Loughland, 2002; Riegl and Purkis, 2015; Shuail *et al.*, 2016; Riegl *et al.*, 2018; Burt *et al.*, 2019;). Coral Reefs of the RSA are under enormous pressure from a range of different human activities. Superimposed on these local threats, the reefs in the Inner RSA live very near the thresholds of their thermal tolerance (Buchanan et al., 2016) because they live in a place with naturally elevated salinity and extensive temperature fluctuations that are due to intense evaporation (Sheppard et al., 1992; Sheppard *et al.*, 2000). While naturally warm and high salinity has been common in the Inner RSA for thousands of years, it is not without outcome to overall biodiversity, since it is generally low and only about a quarter or less of corals occurring in the Indian Ocean have a natural tolerance to survive in the Inner RSA (Sheppard, 2016). Corals of the Inner RSA have the highest upper-temperature thresholds for bleaching (35-36 °C) (Riegl and Purkis, 2012c; Coles and Riegl, 2013), yet at the same time remain exceptionally susceptible to blanching when temperatures surpass their local maximum summer temperatures (Coles and Riegl, 2013; Kavousi *et al.*, 2014). Therefore, rising atmospheric carbon dioxide triggered by anthropogenic activities that lead to sea warming and acidification is the greatest threat to Coral Reefs of the RSA in particular to those in the Inner RSA.



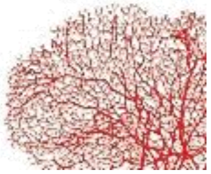
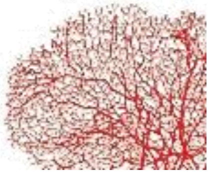


Figure 31. The deeper sections of Coral Reefs provide a refuge against thermal bleaching (Photo by M.R. Shokri, Kish Island (17 m depth), 2018)

So far, three major strategies have been proposed by which corals cope with high sea surface temperatures (Oliver and Palumbi, 2011) including: (1) development of the heat-tolerant genotypes by algal endosymbiont that enhance the capacity of coral symbioses for adaptation to thermal stress; (2) development of inherent physiological tolerance to environmental stress by different coral genotypes; and (3) acclimatization responses in the form of increased capacity for cellular stress defense and thermos tolerance arising from previous experiences of challenging conditions. Protection of cellular components by improved antioxidant protection (Lesser, 1996), elevated level of heat shock proteins (Choresh *et al.*, 2004), and increased levels of photoprotective substances such as mycosporine-like amino acids (Dunlap and Shick, 1998) or green fluorescent protein (GFP)-like pigments (Dove *et al.*, 2001; Salih *et al.*, 2000) are such strategies that are supposedly used by corals to cope with high Sea Surface Temperatures.

Corals in the Inner RSA are known to be genetically adapted to the prevailing unusual extreme conditions (Howells *et al.*, 2016; Smith *et al.*, 2017; Kirk *et al.*, 2018). For example, the genetic divergence of the broad spawning coral *Platygyra daedalea* on reefs within the thermally extreme Inner RSA (UAE) with those in the neighboring Sea of Oman in the Middle RSA has been regarded as a potential coping strategy enforced by naturally warm water that has been common in the Inner RSA for thousands of years (Smith *et al.*, 2017).

The compromised process of reef-framework production in the Inner RSA also has been suggested as a response to the recurrent mass mortality driven by SSTs high anomalies (Riegl, 2001). Marked coral population fluctuations at any one site and increased reliance on the metapopulation as a repository of resilience has been suggested as a strategy under rapid disturbance recurrence in the Inner RSA (Riegl *et al.*, 2011). This would lead to the increasingly frequent mortality that disadvantages the major frame builders including first *Acropora* then *Porites*, resulting in a faviid-dominated community (Riegl *et al.*, 2011). This also would cease reef-building process and makes corals become sparser with fluctuating metapopulations among patches (Riegl *et al.*, 2011).

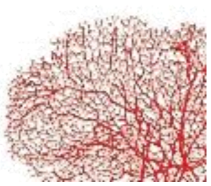


coral species have been linked to climate warming (Cooper *et al*., 2008; De'ath *et al*., 2009; Cantin *et al*., 2010; Carricart-Ganivet *et al*., 2012; De'ath *et al*., 2013; Tanzil *et al*., 2013) as the energetic costs of bleaching survival often involves a period of stunted growth (Carilli *et al*., 2010; Goreau and Macfarlane, 1990). Such adverse effects of warming on coral growth also have been reported in several coral species in the Inner RSA (Lough, 2008; Vajed-Samiei *et al*., 2013; Bolouki Kourandeh *et al*., 2018; Howells *et al*., 2018;). Therefore, declines in the linear extension and calcification rates are expected to be exacerbated by an increase in coral bleaching episodes which already occur at relatively high frequency in the Inner RSA (Coles and Riegl, 2013). Yet, the increase in winter minima alleviating cold constraints on coral growth has been suggested as an alternative outcome of sea temperature rise for the Inner RSA corals (Howells *et al*., 2018).

Marked impaired coral reproduction is known as a response to climatic pressure (Albright and Mason, 2013; Fabricius *et al*., 2017). Yet, lack of significant difference detected in fecundity and gamete size between some coral species in the Inner RSA and conspecifics elsewhere (Bauman, 2013) suggest that adaptation to environmental conditions projected under climate change is possible (Baird and Maynard, 2008). In any case, SST increment, which is anticipated to be increasingly extreme in high latitude regions, particularly in the northern hemisphere (IPCC, 2007; Strong *et al*., 2008), could push individual coral species and populations in the Inner RSA beyond local thermal thresholds, thereby adversely affecting reproductive processes (Bauman *et al*., 2011).

Another strategy of corals to deal with the 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;). The dominant incidence of *Durusdinium* spp. Clade D and *Cladocopium thermophilum* type c3, believed to convey an enhanced heat stress tolerance, has been recorded in corals collected from the Inner RSA (Baker *et al*., 2004; Ghavam Mostafavi *et al*., 2007; Shahhosseiny *et al*., 2011; Hume *et al*., 2015; Smith *et al*., 2017; Varasteh *et al*., 2018; Oladi *et al*., 2019;) and the Middle RSA (Chah Bahar Bay) (Oladi *et al*., 2019). Therefore, the resilience of the Inner

RSA corals seemed to be at least partially due to the association with these



specific algal symbionts.

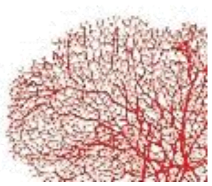
5.4. Priority Knowledge Gaps for further Research

Although the corals in the Inner RSA have been largely affected by recurrent bleaching events and coastal developments, the corals in the Middle RSA and the Outer RSA are mostly impacted by fisheries activities, coral disease, cyclonic storms, and crown of thorns starfish outbreaks.

In an expert-based evaluation in the Inner RSA, ten research questions, in six major research areas, were highlighted for both understanding the Coral Reef ecosystems as well as the effective use of limited research resources (Feary *et al.*, 2013). These questions paralleled worldwide assessments of the significance of understanding and evaluating biodiversity, identifying climate change potential impacts, the role of anthropological impacts in structuring Coral Reef communities and economically evaluating Coral Reef communities. The higher recurrence of disturbances in the Inner RSA Coral Reefs has made these ecosystems an ideal laboratory for studying the response of Coral Reef organisms to global climate change. Accordingly, further studies on coral responses to stressors including increases in salinity and temperature, eutrophication, oil, tourism, overfishing, and acidification are required in the Inner RSA.

Since the corals in the Middle RSA and Outer RSA are mostly impacted by fisheries activities, coral disease, cyclonic storms, and crown of thorns starfish outbreaks, further researches are needed to bridge the gap of information on the impact of these issues on Coral Reefs of these areas. In doing so, further and more in-depth analyses of the dataset, including in relation to pressures/drivers of reef change in the Middle RSA and Outer RSA are needed.

In summary, in order to sharpen recommendations for management, further researches are required to gain a better understanding of the processes that control reef change in the RSA. There is also a need for greater understanding of bleaching sensitivity and impacts on the RSA Coral Reefs, by enhancing observation of bleaching mortality and recovery.

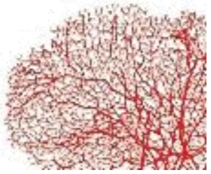


5.5. Dissemination of Findings

Knowledge translation techniques benefit researchers by making them more active, context-aware, and collaborative in disseminating of research results. Utilization of these strategies helps make research results progressively applicable to target audiences, and at last increasingly useful. Various dissemination tools are accessible to research groups seeking after the take-up of research discoveries. Everyone of these instruments ought to be viewed as less as individual pieces and more as parts of an entirety. The dissemination tools include research reports, peer review papers, press releases, and policy briefs.

It is equally essential to interpret study results, disseminate and make data available, and to include them in management and legislative decision-making. These actions involve engagement with decision-makers and managers, and a forum for results dissemination is recommended.

One of the problems with studies on Coral Reefs in the RSA is the lack of integration in research topics. This is partially due to a lack of knowledge about ongoing research projects in the Regional countries that suffer from a lack of publication and free access to the research topics. To resolve this problem, creating a database is the first step, which can be established and managed by the ROPME. The second solution is to create a forum such as the 'Coral-List' which is to provide a forum for Internet discussions and announcements pertaining to Coral Reef ecosystem research, conservation, and education. Such a specific forum for the Coral Reef ecosystems in the RSA can be primarily used by Coral Reef ecosystem researchers, scientists, and educators, but may also be applicable to everyone interested in Coral Reef ecosystems. Having an exclusive forum for the coral researches in the RSA may help to define integrative research topics to bridge the gap of information on Coral Reefs and their associated organisms in the Region. This is especially true in research topics that need to be addressed in all Member States. For example, the establishment of a network of Marine Protected Areas (MPAs) for Coral Reefs throughout the Region requires an investigation on the relationship and exchange of larvae among a large number of reefs in all Member States. The degree to which marine populations are connected has important consequences for how Coral Reef populations persist, how they respond to stressors and how they can be managed. The scale of population connectivity also helps managers and policymakers determine the optimal size and spacing of Marine Protected



Areas. The extent to which the reefs in the RSA are effectively connected to one another, and their potential to serve as sources of larval replenishment following disturbance are of such examples.

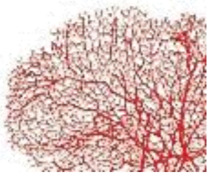
5.6. The Way Forward

Specifically, in the Inner RSA, Coral Reefs and mangrove forests are more threatened than any other sea. According to Wilkinson (2008), only 3% of all reef habitats in the Inner RSA are under low threat levels. Although the Region has the world's largest oilfields and the second-largest gas reserves, and despite the deliberate spillage of at least 10 million barrels of oil to the Inner RSA in 1991, oil is not the most harmful ecological disturbance. Coastal dredging, infilling and conversion of shallow waters into the land is now a very serious threat (Al-Ghadban and Price, 2002). In addition to the pressures originating within the Inner RSA, its environment is affected by severe external disturbances. Particularly important is the episodic warming of the sea and consequent coral mortality, sea-level rise and diversion of rivers entering the Inner RSA. Despite the relatively extensive marine research carried out at the Inner RSA, the environmental damage caused by coastal development continues to be on an unprecedented and alarming scale. The impact of scores of individual environmental impacts is clearly the greatest threat to the region.

Extensive research, environmental assessments and baseline surveys have no guarantees for the conservation of resource or coastal protection. Short-term and often ill-conceived investments continue to be major drivers for coastal use and the allocation of beach frontage in the area. The crisis over the next decade will be the degree to which the Inner RSA can absorb additional shocks and disturbances, but it continues to provide valuable ecosystems and economic services. Damage to resources will increase on such a scale, which will probably lead to the resilience of the system.

In order to prevent further degradation of marine habitats, in particular, Coral Reefs, each project should consider existing, planned and ongoing projects together. Increasing the Protected Areas in the Inner RSA (Krupp *et al.*, 1996) may be a practical way of maintaining or re-instilling functionality and robustness. These will help to cope with many of the uncertainties that currently affect the Inner RSA productive habitats.

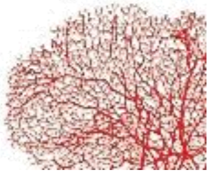
To this end, a number of proposals have been considered in many countries,



and some Marine Protected Areas have been announced over the past two decades. But given the small spatial scale of the Inner RSA and apparent cumulative and transboundary impacts, only a large network of closely monitored and protected sites can effectively counteract many of the ongoing and planned threats. In other words, stronger environmental considerations, greater interactions among projects, increased sharing of information between government departments, a longer-term viewpoint and agreed basin-wide strategic approaches are needed to ensure the environmental and economic sustainability of this area.

Management tools employed to protect the Inner RSA Coral Reefs barely achieve conservation objectives and many Coral Reefs continue to degrade. Protecting corals should be proactive (Rinkevich, 2008) and it is important to establish the need for further training and empowerment of the RSA experts with a good professional background in the research, monitoring, and management of ecosystems, by understanding environmental law and National socio-economic requirements. Environmental awareness has been created, but the participation of the RSA Regional experts in maritime and coastal management, as well as cross-border research, is still inadequate. Efforts must focus on how to preserve what remains (Young, 2000), as well as on active efforts on how to restore reef resources. Currently, "management" and "conservation" are considered by many authorities in the Region as synonyms. Instead of running active rehabilitation or conservation instruments, management concentrates on the act of managing from behind a desk. This has caused numerous setbacks in providing adequate protection of corals.

The resilience of the Inner RSA corals is probably best maintained by preserving biodiversity in Coral Reefs and adequately incorporating corals from different reefs under a network of protected areas, or managed reserves (Levin and Lubchenco, 2008). Many Coral Reefs in the Inner RSA suffer from "avoidable" and often destructive methods of fishing and sedimentation. To better tackle resilience building in an ecosystem that shares the interests of many societal sectors, Marine Spatial Planning (MSP) (Gilliland and Laffoley, 2008) can contribute positively by addressing social, economic and environmental aspects within long term policy prospects. MSP can be applied over extended periods and responds to changes in the environmental and technological context. Many of the Inner RSA countries have adopted the economic strategies that have expanded over the past decades (such as Abu Dhabi plan of 2030 and Bahrain's 2030



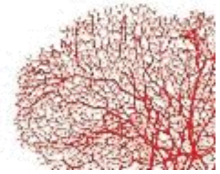
vision). These economic strategies are aimed at strengthening economic resilience and reform in various sectors of the economy. Although these programs are based on the economy, they include other aspects such as urban planning and environmental conservation.

Placing Coral Reef conservation in the wider context of strategic economic development at the national level will certainly enable the authorities and non-governmental organizations to become more active in shaping a better basis for marine conservation. Early stages of an MSP have been drafted in Abu Dhabi and Bahrain as part of the economic vision, which illustrates the strategic planning opportunities that can offer to Coral Reef management and conservation.

Another strength these protocols add to marine conservation is the ability to monitor and evaluate the progress of interventions under the surveillance of the economic strategy that has been neglected in many coral conservation initiatives in the Inner RSA. The ecological services provided by Coral Reef ecosystems in the Inner RSA have been neglected in past development plans. However, recent economic changes have forced the RSA States' strategic plans to examine the diversification of national income sources and the various sources of income related to environmental services. Protecting Coral Reefs can, in fact, play an important role in economic diversification by supporting extractive and non-extractive uses, such as sustainable tourism activities. The RSA States are responsible for protecting the marine environment and Coral Reefs.

Oman has demonstrated some notable momentum in environmental protection and long-term protection commitment (Al-Cibahy *et al*., 2012). Oman now is a party to 13 key Regional and International Environmental Agreements and Protocols that provide guiding principles, international reviews, and in some cases legal backing for the environmental protection in the marine and coastal environment (van Lavieren *et al*., 2011). In addition, Oman has passed national legislation to support marine conservation with eight Royal Decrees that are backed up by Ministerial Decisions that pertain in some way to marine environmental protection issues (Ashrad and Sayer, 2012).

Similarly, every Member State along the RSA has borne eminent vision in conserving and restoring Coral Reefs, by way of developing significant policy decisions and executive actions.



6. Strategic Recommendations

Management and Policy Responses

Overall, local factors are important in controlling observed reef trends. Bearing in mind current Regional development as well as global climate change trends, we need strengthened efforts to maintain healthy reefs in the RSA. Based on this, we recommend:

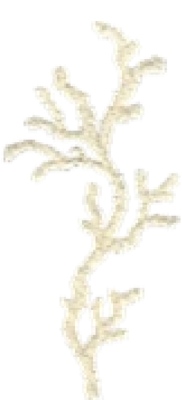
- Recognize, prioritize and actualize activities that decrease local, chronic pressures on Coral Reefs emerging from land-use change, unsustainable development, and fisheries activities.

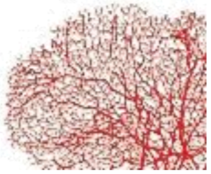
- Bring utilization of Coral Reefs to sustainable levels by reinforcing the usage of fisheries and tourism legislation, regulation, and implementation with a specific spotlight on ending the change in Coral Reef coverage and associated fish, and by further growing marine area-based management.

- Establish a network of Marine Protected Areas (MPAs) aiming to protect the sensitive marine ecosystems particularly Coral Reefs across the RSA. The efficiency of MPAs is directly linked to the management of such areas, and of the existing MPAs within the RSA. Now, only a few MPAs have management plans in the RSA that incorporate conservation, recreational, and development zones (van Lavieren *et al.*, 2011), and according to the recent assessment the Regional marine management has low effectiveness (averaging 34% effectiveness, with a range from 11% to 58% on a national basis (Van Lavieren and Klaus, 2013). Thus, existing and new MPAs should have a comprehensive management plan in the RSA.

- Ecosystem-based Management (EBM) should be prepared and implemented by all ROPME countries at the National level. Since the implementation of EBM is one of the main areas of Regional cooperation, greater attention could be paid to Marine Spatial Planning (MSP) as a tool to manage coastal activities based on the ecosystem approach.

- There is a special need for a strengthened National and Regional Coral Reef monitoring and assessment network to track the trend of changes in Coral Reefs across the RSA aiming to provide a baseline data and information for decision-making process on Coral Reef restoration, conservation, and





management.

- A Regional monitoring network should be established through National and Regional partnerships for integrated management of the Region. Community-based organizations, NGOs, governments, and ROPME all should play an important role in creating and implementing such initiatives.

- A panel of experts drawn from across the region should be formed to coordinate and oversee the monitoring network and counseling on Regional issues such as the COTS outbreak, mass bleaching events, oil spills affecting reef areas, the publication of reef-related research and improved knowledge of the coral taxonomy in the region.

Strengthening Coral Reef Monitoring and Network

In our strides of conserving and protecting the Coral Reefs of the Region, one of the most important goal should be to strengthen the reef monitoring networks. Some important recommendations are as follows:

- It is suggested that all the ROPME Member States adopt and implement a globally recognized method such as the GCRMN Protocol (English *et al.*, 1997; Hill and Wilkinson, 2004). GCRMN is a global network to strengthen the provision of best available scientific information on and communication of the status and trends of Coral Reef ecosystems, for their conservation and management. This cannot be achieved without prior training of the personnel involved.

- It is suggested to select at least one permanent monitoring site on some Coral Reef areas including those occurring in the vicinity of the mainland and those in offshore islands covering all ROPME Member States.

- Regular yearly monitoring of selected areas should be carried out.

- Strengthen the national Coral Reef monitoring network to prepare a national status of Coral Reefs to report every year and to share metadata on Coral Reefs with all ROPME Member States.

- Develop a common database platform for use by monitoring teams supported by the ROPME to provide a secure platform.

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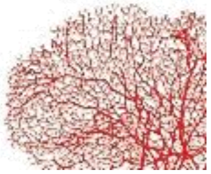

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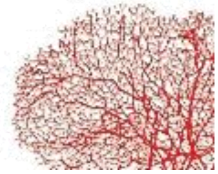

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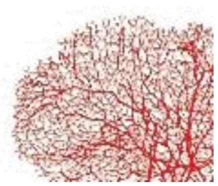

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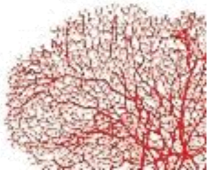

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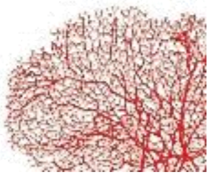

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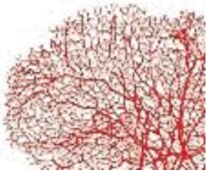

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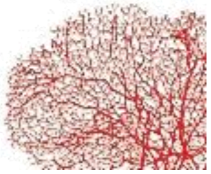

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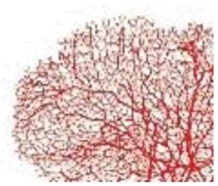

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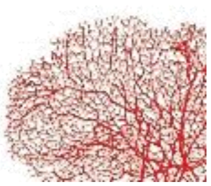

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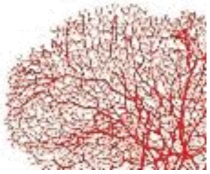

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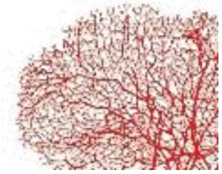

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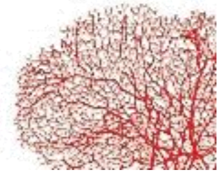

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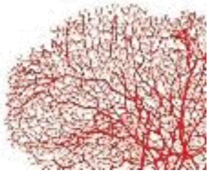

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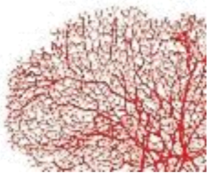

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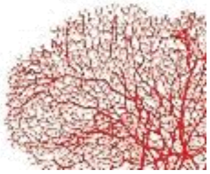

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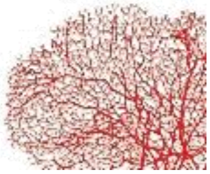

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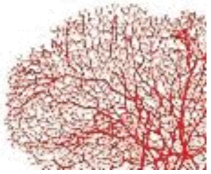

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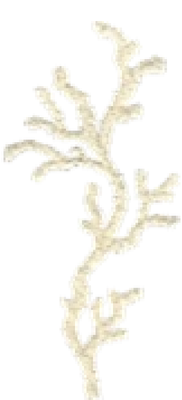

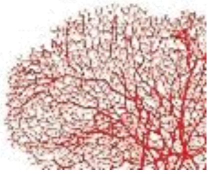

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