Chapter 1

The Arabian Gulf

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1.1 THE REGION

Bound by deserts and located between the north-eastern Arabian Peninsula and Iran, the Arabian Gulf (also known as the Persian Gulf, and hereafter known as "the Gulf") is bordered by eight rapidly developing nations. The Gulf is located in the subtropics between 24°N and 30°N latitude and 48°E and 57°E longitude (Fig. 1.1), and is considered as a biogeographic subprovince of the northwestern Indian Ocean (Spalding et al., 2007). During summers, the Gulf is the hottest sea on the planet, particularly in the shallow southern basin where sea surface temperatures (SSTs) regularly exceed 35°C in August. Sea temperatures are also highly variable among seasons, ranging over 20°C between summer and winter.

Geologically, the Gulf is relatively young with coastlines that formed only in the past 3000–6000 years when polar ice sheets receded (Riegl & Purkis, 2012a). Today, the Gulf is bordered to the northeast by the Zagros mountains in Iran and the Hajar mountains in the Musandam peninsula and in the southwest by the sedimentary Arabian coast (Purser & Seibold, 1973). Presently, it covers an area of 250,000 km^2 (Riegl & Purkis, 2012a). Generally, terrestrial systems surrounding the Gulf are arid to hyperarid (Riegl & Purkis, 2012a), limiting the input of freshwater to this semienclosed sea. The main freshwater input enters at the northern Gulf at the Shatt Al Arab waterway through the Tigris, Euphrates, and the Karun rivers (Sheppard, Price, & Roberts, 1992), although recent damming efforts have resulted in substantial reductions in freshwater discharge from these rivers (Sheppard et al., 2010). Together with smaller outputs from the Hendijan, Hilleh, and Mand rivers in Iran, the annual freshwater input to the Gulf averages 110 km^3 $year^{-1}$ (Reynolds, 2002), while high evaporation rates are estimated to cause the loss of between 360 and 1250 km^3 $year^{-1}$ (Reynolds, 1993), resulting in a net loss of water and creating a marine system that is characterized by unusually high salinity (typically $\gg$40 PSU) compared with open ocean conditions.

The Gulf measures 1000 km long by 200–300 km wide and its average depth is ca. 35 m for much of the Arabian coast and 60 m depth along the Persian coast, with depths exceeding 100 m only at the Strait of Hormuz connecting the Gulf to the Sea of Oman and wider Indian Ocean (Fig. 1.2) (Purser & Seibold, 1973; Sheppard et al., 2010, 1992). The Arabian side is entirely in the photic zone, extending to only 15 m depth through much of its extent (Purser & Seibold, 1973; Sheppard et al., 2010). Although much of the sea-bottom along the Arabian coast of the Gulf is flat and dominated by sands and muds, emergent caprock habitats and hard-bottom salt domes occur fairly regularly (Sheppard et al., 2010). These hard bottom habitats support coral reefs, nonaccreting coral communities, and algal beds; seagrasses are generally constrained to shallow sand-dominated areas (Sheppard et al., 2010).

Surface waters enter the Gulf through the Strait of Hormuz and travel northwest along the Iranian coast before turning south near the Kuwait/Saudi Arabian border; it continues along the western and southern coastline before discharging from the Gulf (Fig. 1.3A) This general circulation is mainly driven by halocline forces caused by the high evaporation rates (Reynolds, 1993). In addition, winds also play an important role in large-scale circulation, in particular the prevailing northwesterly or "*shamal*" wind (Arabic for north) (Perrone, 1979). These drive the formation of large (> 100 km), persistent seasonal eddies in the central Gulf (Fig. 1.3B) (Yao & Johns, 2010), and also strongly influence coastal currents and storm surges in the southern basin (Cavalcante, Feary, & Burt, 2016). Tidal circulation is negligible except along the Iranian coast and in the Strait of Hormuz (Blain, 1998).

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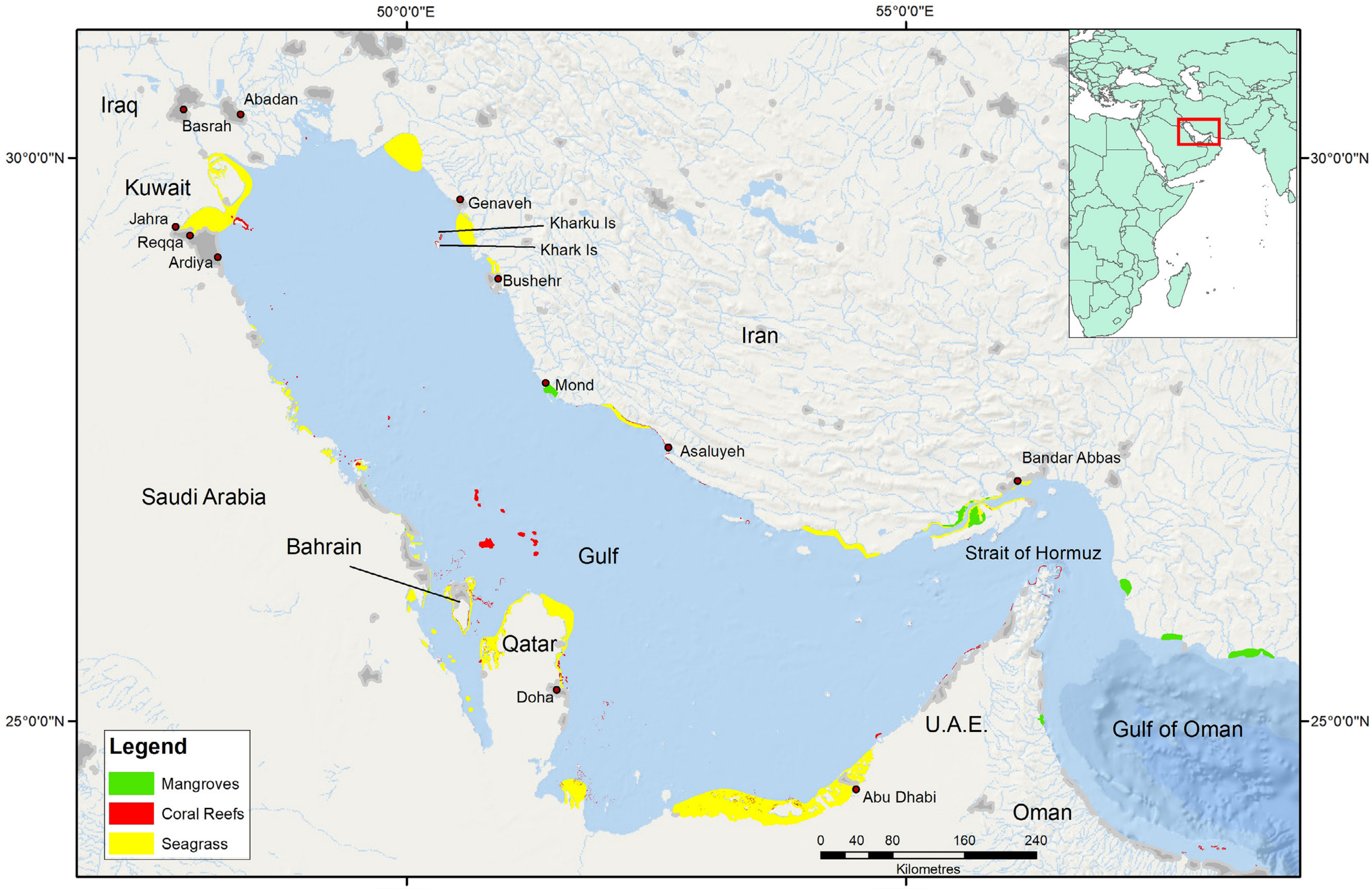


FIG. 1.1 Map of the Arabian/Persian Gulf with the location of major mangrove, coral reef, and seagrass ecosystems indicated.

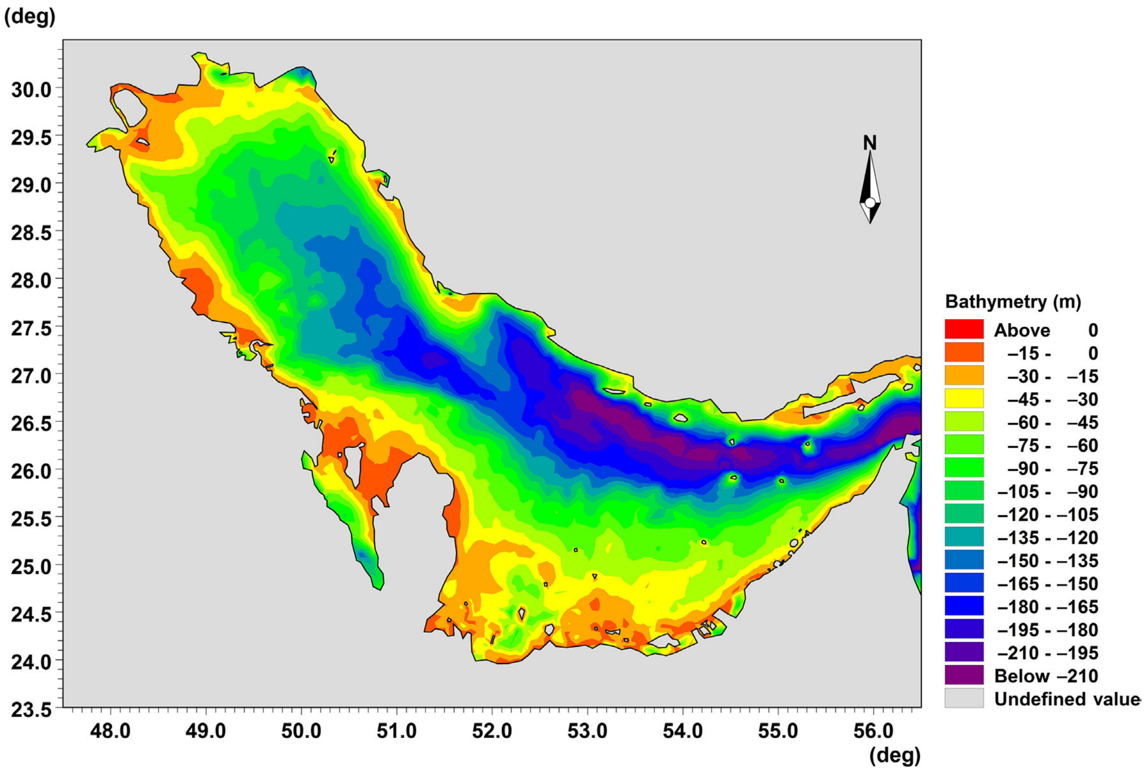


FIG. 1.2 Bathymetric map of the Gulf. *(Modified from Amante, C., & Eakins, B. W. (2009). ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA, doi:10.7289/V5C8276M [accessed 12 March 2018].)*

1.2 NATURAL ENVIRONMENTAL VARIABLES AND SEASONALITY

1.2.1 Climate

The Gulf climate is transitional between tropical and subtropical. While geographically in the subtropics, the surrounding arid environment promotes a tropical climate during summer. Winter is December to March and summer is June to September, with two transition periods in between (Al Senafi & Anis, 2015). Very high summer air temperatures of up to 51°C (average: 41°C), and winter temperatures as low as 15°C create a considerably variable annual SST range throughout the region (Fig. 1.4) (Sheppard, 1993). Relative humidity values also vary between seasons, ranging from 21% during summer to 55% during winter (Al Senafi & Anis, 2015).

Northwestern shamal wind events typically last between 1 and 5 days and are highly seasonal, occurring in both winter and summer, with the strongest and most persistent events typically occurring between November and March (Al Senafi & Anis, 2015). They are associated with mid-latitudinal frontal systems (Rao, Hatwar, Al-Sulaiti, & Al-Mulla, 2003), and often result in sand and dust storms and a drop in air temperatures, particularly in the northern Gulf (Reynolds, 1993).

1.2.2 The Gulf as an Extreme Marine Environment

The Gulf has a marine environment characterized by physical extremes. Owing to its shallow depth and relative isolation, SSTs range by > 20°C annually (Vaughan & Burt, 2016), with summer SSTs > 36°C and winter minima of < 12°C (Coles, 2003). The region's high evaporation rates and limited freshwater input also cause extreme salinity, with values averaging 42 ppt, increasing to > 50 ppt in the southern bays and reaching > 70 ppt in evaporative lagoons (John, Coles, & Abozed, 1990). The high salinity is relatively consistent throughout the fairly shallow water column (Cavalcante et al., 2016). The physical setting of the Gulf strongly influences marine communities, with diversity of marine organisms across a variety of taxa typically lowest in the southern Gulf where environmental conditions are most extreme (Bauman, Feary, Heron, Pratchett, & Burt, 2013; Burt, Feary, et al., 2011; Price, Sheppard, & Roberts, 1993).

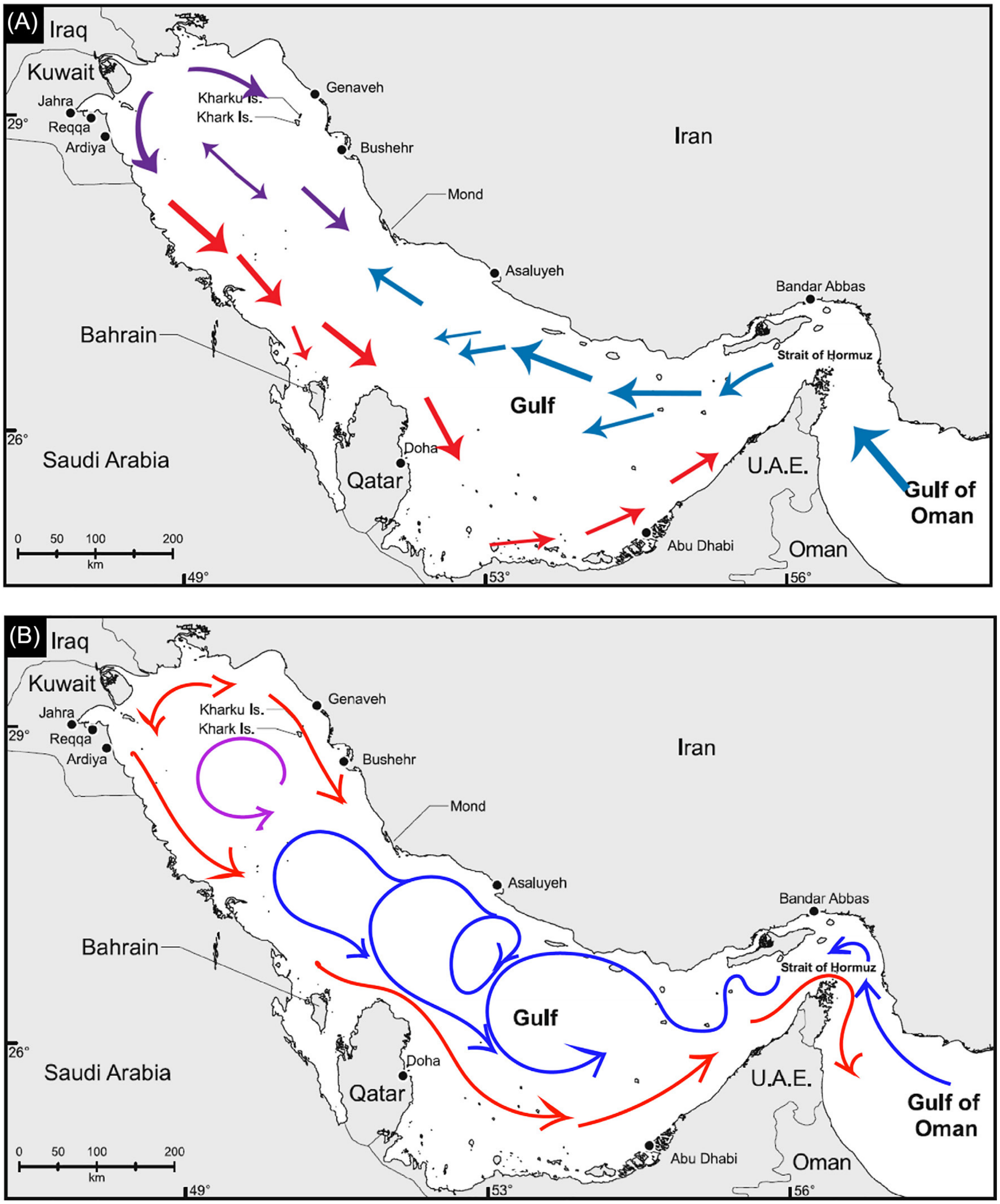


FIG. 1.3 Schematic diagram of the (A) general circulation of the Gulf waters and (B) major eddies that form during summer due to seasonal shamal winds. *Blue arrows* indicate inflow of low salinity water, *red arrows* indicate outflow of high salinity water, while *purple arrows* show the transition zones. *(Modified from Reynolds, R.M. (1993). Physical oceanography of the Gulf, strait of Hormuz, and the Gulf of Oman—results from the Mt Mitchell expedition.* Marine Pollution Bulletin*, 27, 35–59; Thoppil, P. G., & Hogan, P. J. (2010). A modeling study of circulation and eddies in the persian gulf.* Journal of Physical Oceanography*, 40(9), 2122–2134. doi:10.1175/2010JPO4227.1.)*

Because of the extreme temperatures experienced by marine fauna in the Gulf, the region has become a target of intensive research in the past decade as interest in climate change and marginal environments has increased (Burt, Van Lavieren, & Feary, 2014; Vaughan & Burt, 2016). The Gulf serves as a natural laboratory for studying the potential effects of elevated ocean temperatures on various marine ecosystems, and as such many regional and international marine scientists are showing growing interest in studying this region, particularly processes in coral reef environments (Vaughan & Burt, 2016).

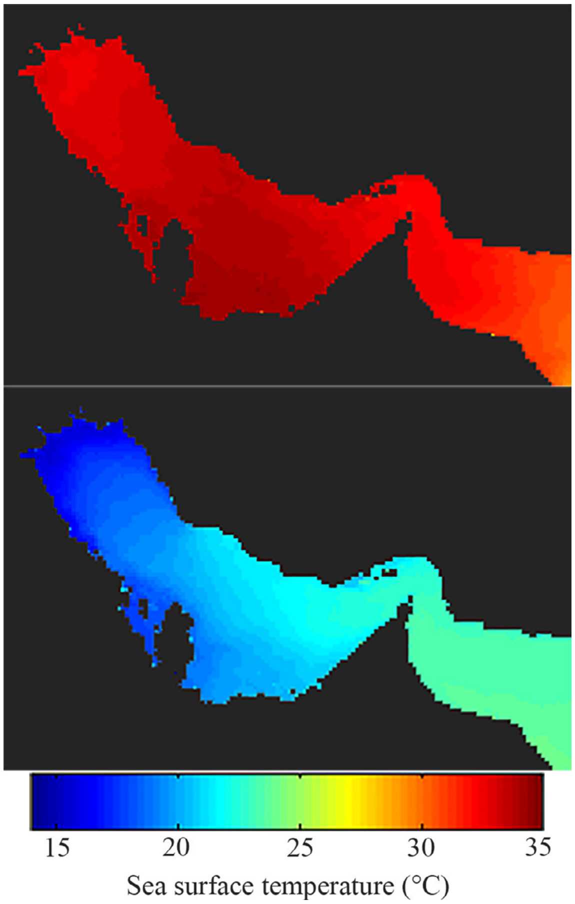


FIG. 1.4 The mean monthly maximum and minimum sea surface temperatures of the Gulf, averaged over a 10-year period (2004–14). *(Data from MODIS level 3, 9 km, 11 μm, daytime SST.)*

1.3 MAJOR COASTAL AND SHALLOW HABITATS

The Gulf's coastlines contain a mosaic of important intertidal habitats including saltmarshes, mudflats, sabkhas (salt flats) and mangrove forests, as well as algal beds, seagrass meadows, and coral reefs in subtidal areas (Burt, 2014). These support substantially higher biodiversity and productivity than the surrounding arid lands and also supply nearly half a billion dollars in commercial fisheries, the second highest value resource after oil (Burt, 2014; Van Lavieren et al., 2011).

1.3.1 Intertidal Habitats

Shorelines in the Gulf tend to have low slopes (average: 35 cm km^{-1}), leading to intertidal regions several kilometers wide that support highly diverse and productive communities (Basson, Burchard Jr, Hardy, & Price, 1977). Beaches are generally low lying and exposed to tidal flooding (Fig. 1.5A) (Sheppard et al., 1992), and the top 15 cm of beach sand can contain >200 species of invertebrates. Densities of such individuals can exceed 400,000 individuals m^{-2}, and they are important in food web dynamics, decomposition, and nutrient cycling (Basson et al., 1977; Sheppard et al., 1992). They are also vital food sources for wading birds and foraging crabs (Burt, 2014), and seabirds, and turtles depend on these large intertidal beaches for habitat and nesting (Basson et al., 1977; Sheppard et al., 1992).

The high evaporation rates in shallower southwestern parts of the Gulf lead to evaporative coastal salt flats, called *sabkha* (pl. *sabkhat*) in Arabic, which occur in low lying intertidal areas (Fig. 1.5B) (Barth & Böer, 2002). These are very extensive, for example, covering 40% of the total area of Bahrain and 6000 km^2 in the UAE and Qatar (Barth & Böer, 2002). The largest sabkha system in the Gulf is Sabkha Matti, which extends from the eastern Abu Dhabi to the border of Qatar (Evans, Kendall, & Skipwith, 1964; Evans, Schmidt, Bush, & Nelson, 1969). They contain dense algal/cyanobacterial mats near their interface with the sea, making them ecologically important habitats and one of the most productive ecosystems in the Gulf despite their low diversity (Burt, 2014).

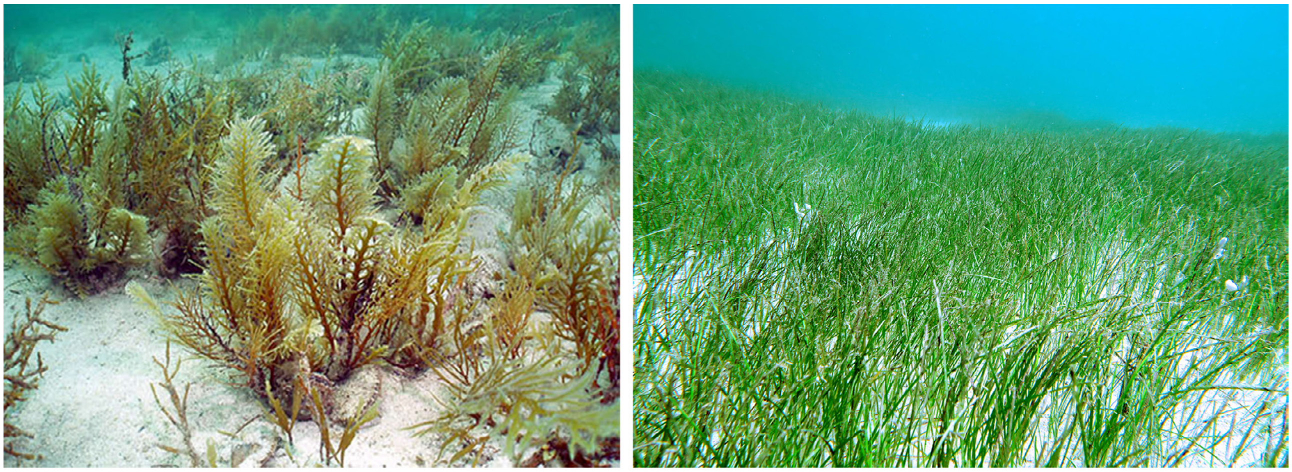
FIG. 1.5 Examples of intertidal habitats: (A) a sea-facing beach in Abu Dhabi, UAE. (B) Coastal sabkha (salt flat) commonly found along the Arabian coast. (C) Mangroves. (D) Tidal mudflat. *(Courtesy: (A) Grace Vaughan. (B–D) Noura Al Mansoori.)*

The dominant mangrove species in the Gulf is *Avicennia marina* (Sheppard et al., 2010), which has adapted to the highly variable seasonal temperature and salinity extremes (Hutchings & Saenger, 1987). *A. marina* occurs in all the Gulf countries except Iraq, but covers only ca. 130 km^2 across the region, three-quarters of which are in Iran (Van Lavieren et al., 2011). A second species, *Rhizophora mucronata,* is known to occur on the Iranian side on the Strait of Hormuz, but only occupies an area of 0.2 km^2 (Sheppard et al., 2010). Mangroves are the only evergreen forest in the Gulf, which makes them an important foraging and nursery habitat as well as a food source for numerous marine and terrestrial species (Burt, 2014). Only a small fraction of the energy produced by mangroves is consumed directly, with 90% of the energy being lost as leaves and decomposed and cycled into the food web of the surrounding community (Hegazy, 1998). Thus, they support a diversity and abundance of invertebrates that is considerably higher than in surrounding ecosystems (Fig. 1.5C) (Burt, 2014), and they are foraging areas for numerous migratory bird populations and roving fish, while additionally acting as nursery habitats for juveniles of a number of commercially important species (Burt, 2014). They also control coastal erosion and capture atmospheric carbon dioxide by sequestering it in sediments (Burt, 2014). Historically, mangroves have also served as fodder crops for domesticated animals, and as building materials (Beech & Hogarth, 2002).

Mudflats occur in the lower intertidal zone in low lying coastal areas that are well flushed by the tide, and are often adjacent to mangrove forests and sabkhas (Fig. 1.5D) (Burt, 2014). Mudflats contribute substantial energy to food webs owing to their shallow nature, abundance of algal mats, and large size (Price, Sheppard, & Roberts, 1993), and they are one of the largest and most productive coastal habitats in the western Gulf (Basson et al., 1977). In some areas, such as in the Kuwait Bay, tidal mudflats support dense algal mats (Al-Zaidan, Kennedy, Jones, & Al-Mohanna, 2006). They also occur on the coasts of Ras Al Khaimah and Umm Al-Quwain in the UAE, and are exceedingly rich in invertebrates, fishes, and other fauna, containing high densities of juvenile fish from over five families and 37 species of birds (Medio, 2006).

1.3.2 Subtidal Habitats

Over 200 species of macroalgae and seaweed occur in the Gulf, forming dense beds that can cover 85% of the sea floor (John, 2012; McCain, 1984). Generally, algal beds occur on subtidal limestone mounds and hardgrounds, with the highest



(A) (B)

FIG. 1.6 Subtidal habitats: (A) typical algal beds in the Gulf (Fasht Jaradah, between Qatar and Bahrain). (B) Seagrass meadow typically found in the southern Gulf (Dhabiya, UAE). *(From (A) Sheppard, C., Al-Husiani, M., Al-Jamali, F., Al-Yamani, F., Baldwin, R., Bishop, J., et al., 2010. The Gulf: a young sea in decline.* Marine Pollution Bulletin*, 60, 13–38. (B) Grace Vaughan.)*

algal densities typically occurring in late winter and spring (Fig. 1.6A) (Sheppard et al., 2010). Since spring is also the spawning season for shrimp and many fish species, algal beds are an important spawning and nursery habitat during these periods (Sheppard et al., 1992). Macroalgal meadows are important for invertebrates and fish, providing them with complex three-dimensional habitat (John, 2012) and they are important foraging areas for adult shrimp (Al-Maslamani, Le Vay, Kennedy, & Jones, 2007). Sand and seagrass patches are sometimes intermixed with macroalgal beds (Sheppard et al., 2010). Macroalgae are rarely a direct food source for most herbivores, but their decomposition to the detrital food web creates a vital input to the microbial loop and the wider food chain in nearshore systems (Sheppard et al., 2010).

Seagrass beds are common in the vast shallow subtidal areas that dominate much of the south and southwestern Gulf, with the most extensive beds occurring off of the coast of the UAE and Qatar (Fig. 1.6B) (Jones, 1985). Four seagrass species occur regionally, *Halodule uninervis, Syringodium isoetifolium, Halophila ovalis*, *and Halophila stipulacea* (Sheppard et al., 2010), with >90% being *H. uninervis* alone (Erftemeijer & Shuail, 2012). Seagrass beds have a heterogeneous distribution and are often intermixed with macroalgal beds and sandy areas (Basson et al., 1977; Sheppard et al., 1992). Seagrasses have significant ecological and economic importance in the Gulf. They are a direct food source for many herbivores, they provide indirect energy to the detrital food web (Coles & McCain, 1990), and provide nursery habitats for a variety of commercially important fishes (Jones, Price, Al-Yamani, & Al-Zaidan, 2002; Sheppard et al., 1992). They are also important breeding and foraging grounds for the endangered green turtle (*Chelonia mydas*), and to the world's second largest population of the vulnerable dugong (*Dugong dugon)* (Sheppard et al., 2010). They are also important nursery habitats for the pearl oyster (*Pinctada radiata*) and commercially important shrimp (*Penaeus semisulcatus*) (Sheppard et al., 2010). Owing to their extensive root system, seagrass beds stabilize sediment and protect against erosion (Erftemeijer & Lewis, 2006; Jones et al., 2002). Seagrass beds are also effective carbon sinks accounting for almost 10% of oceanic carbon burial, or 27.4 Tg C in a year (Duarte, Middelburg, & Caraco, 2005). In the Gulf, they have been estimated to support 4800 kg of fisheries production per square kilometer (Price et al., 1993).

Despite the extreme environmental conditions, the Gulf contains 40 species of scleractinian (hard) corals and 35 alcyonacean (soft) corals (Figs. 1.7 and 1.8) (Riegl & Purkis, 2012a; Sheppard et al., 2010). Although this diversity is low compared with the wider Indian Ocean (Coles, 2003), these corals tolerate wide temperature ranges and high salinities and so are considered important for climate change research and for potential translocation to other climate-stressed regions in the future (Burt et al., 2014; Coles & Riegl, 2013). Their unusual ability to tolerate extreme temperatures is the result of thermal adaptations by both the corals and their photosynthetic symbiotic algae (zooxanthellae) (Howells, Abrego, Meyer, Kirk, & Burt, 2016; Smith, Hume, Delaney, Wiedenmann, & Burt, 2017). The coral symbionts in the northern Gulf are dominated by stress tolerant types of mainly Clade D, while the southern Gulf corals are mainly associated with the novel species *Symbiodinium thermophilum*, which has high tolerance to extreme temperatures and salinities (Ghavam Mostafavi, Fatemi, Shahhosseiny, Hoegh-Guldberg, & Loh, 2007; Hume et al., 2015; Mashini, Parsa, & Mostafavi, 2015).

Spatial patterns of corals broadly follow environmental conditions, with the highest diversity occurring near the Strait of Hormuz and along the Iranian coast where environmental conditions are more favorable, and declining from north to south along the western coast, with the lowest diversity occurring in the southern Gulf (Bauman et al., 2013; Samimi-Namin & Van Ofwegen, 2009b). Soft corals are mainly distributed around the Strait of Hormuz and eastern Iran, although they do occur at lower densities in other parts of the Gulf (Samimi-Namin & van Ofwegen, 2009a, 2009b).

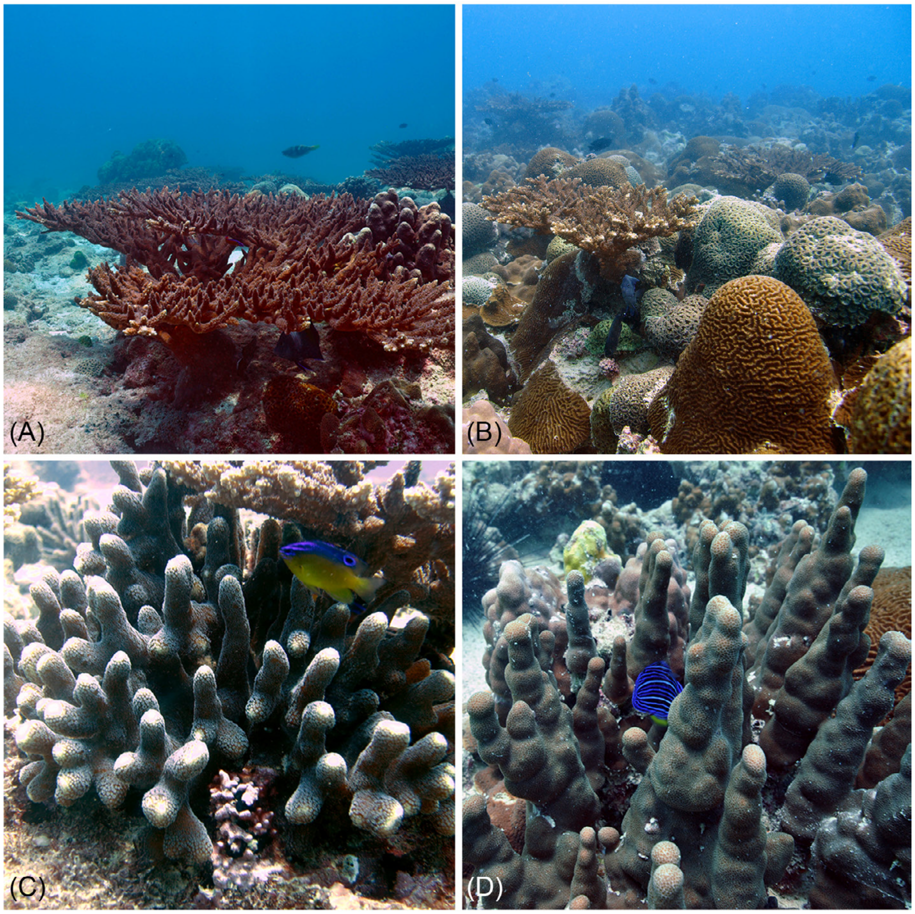


FIG. 1.7 Representative scleractinian corals of the Gulf: (A) branching table corals (*Acropora*) from Sir Bu Nair, UAE. (B) Carpet of faviids (brain-like corals) intermixed with table corals at Ras Ghanada, UAE. (C) Finger-like *Stylophora* from Sir Bu Nair, UAE. (D) A columnar coral (*Porites*) from Saadiyat, UAE. *(Courtesy: (A) Grace Vaughan. (B) John Burt. (C) Grace Vaughan. (D) Grace Vaughan.)*

FIG. 1.8 Examples of the soft corals of the Gulf: (A) and (B) colonies of *Sacrophyton minusculum* at Larak Island, Iran and (C) *Dendronephthya* from Kish Island, Iran. *(Modified from Samimi-Namin, K. S., & van Ofwegen, L. (2012). The octocoral fauna of the Gulf. In B. Riegl & S. Purkis (Eds.), Coral reefs of the Gulf: Adaptation to climatic extremes (pp. 225–252). Springer Science+Business Media B. V.)*

Coral reefs in the Gulf have become widely degraded in the past three decades, with the most extensive losses having resulted from large-scale mass bleaching events during unusually warm summers in 1996 and 1998 (Riegl, 2002; Sheppard et al., 2010). More moderate bleaching events have also been reported most years in the past decade (Riegl & Purkis, 2015). The events of the 1990s particularly affected more sensitive table corals (*Acropora* spp.) which were largely extirpated from much of the southern Gulf along the coast of Bahrain, Qatar, and the UAE, areas where they had historically dominated (Burt, Bartholomew, & Usseglio, 2008; Burt, Al-Khalifa, Khalaf, AlShuwaikh, & Abdulwahab, 2013; Burt, Smith, Warren, & Dupont, 2016); stress-tolerant brain and mound corals now dominate communities in these areas (e.g., mainly faviids and poritids), with the frequency of disturbance preventing *Acropora* recovery (Riegl & Purkis, 2015). Recent research on settlement and recruitment of juvenile corals in the southern Gulf suggests that these community shifts are likely to persist into the foreseeable future (Bauman, Baird, Burt, Pratchett, & Feary, 2014; Bento, Feary, Hoey, & Burt, 2017; Pratchett, Baird, Bauman, & Burt, 2017). At the time of writing (summer 2017), a mass coral bleaching had occurred in the southern Gulf and resulted in the loss of an estimated > 80% of coral, with impacts extending across all taxonomic groups. Although bleaching has periodically been reported for reefs in the more northern reefs of Saudi Arabia, Kuwait, and Iran, the loss of table corals in those areas has typically not been as extensive as in the southern Gulf, likely as a result of the generally less extreme environmental conditions, and *Acropora* still dominates in many areas (Benzoni, Pichon, Al Hazeem, & Galli, 2006; Sheppard et al., 2010). Despite the generally better condition of reefs in the northern parts of the Gulf, increasing anthropogenic pressure has resulted in increasing loss of corals in many of these areas in the past decade (Rezai, Wilson, Claereboudt, & Riegl, 2004; Sheppard et al., 2010). The loss of corals is also having an impact on reef-associated assemblages. A recent assessment found that 23 species of obligate coral-associated fish species are at a high risk of regional extinction owing to loss of coral reefs caused by elevated SSTs and coastal development (Buchanan et al., 2016) (Box. 1.1).

BOX 1.1 Artificial Habitats

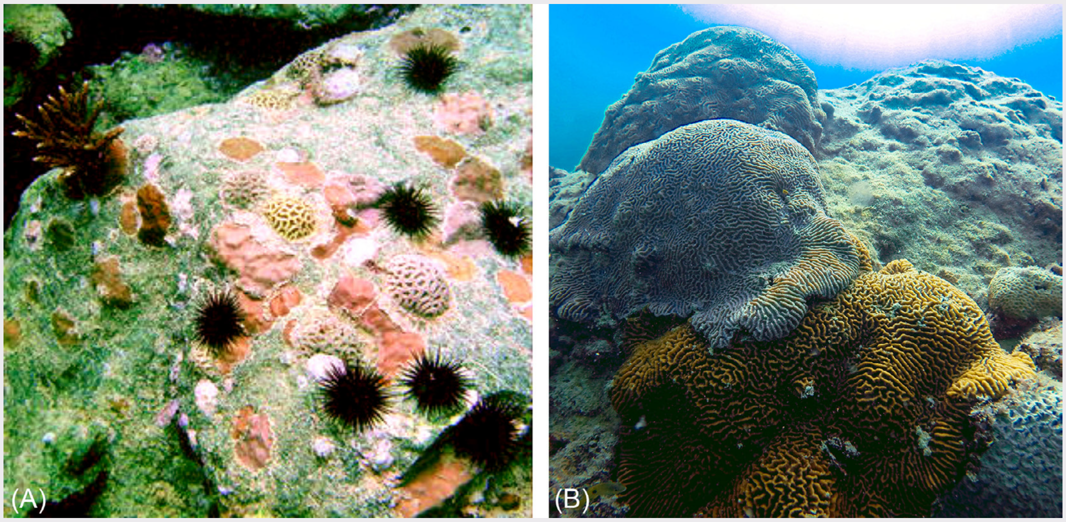


FIG. B.1.1 Breakwaters as artificial habitats: (A) Juvenile corals growing on the Palm Jebel Ali breakwater 5 years after construction in Dubai, UAE. (B) Large coral colonies on 15-year-old breakwater in Abu Dhabi, UAE. *(Courtesy: (A) John Burt. (B) Noura Al Mansoori.)*

In recent decades, coastal development in the Gulf has expanded rapidly (Khan, 2007), resulting in the addition of substantial artificial infrastructure. Breakwaters, seawalls, piers, and related structures now occupy more than half of the shoreline in most of the coastal cities in the region (Burt, Al-Khalifa, et al., 2013; Burt, Feary, Cavalcante, Bauman, & Usseglio, 2013; Price et al., 1993). These hardened structures support diverse and abundant marine communities in areas that are typically dominated by sand (Burt, Bartholomew, Bauman, Saif, & Sale, 2009; John & George, 1998, 1999; Stachowitsch, Kikinger, Herler, Zolda, & Geutebrück, 2002). Their ecological importance has only recently been recognized. For example, oil and gas infrastructure in the Gulf provides large-scale fish habitats as well as hard substrate for corals and other organisms to grow on (Al-Hassan, 1994; Stachowitsch et al., 2002; Torquato et al., 2017). Artificial lagoonal habitats such as the Al-Khiran development in Kuwait support considerably higher intertidal diversity than natural tidal flats within the first year of construction, and within 6 years, the diversity in artificial sand and rocky systems was shown to be similar to nearby open water habitats (Jones, Ealey, Baca, Livesey, & Al-Jamali, 2007; Jones & Nithyanandan, 2013). Similarly, in Dubai, breakwaters surrounding large-scale coastal developments have shown rapid growth of coral within 5 years of construction, with live coral cover exceeding amounts on natural reefs within two decades (Fig. B.1.1A) (Burt, Bartholomew, & Sale, 2011; Burt, Bartholomew, Bauman, et al., 2009). Abundance and diversity of fish communities also becomes similar to and sometimes exceeds that of natural reef systems within 5 years of construction (Burt, Bartholomew, Usseglio, Bauman, & Sale, 2009; Burt, Feary, et al., 2013). Thus, artificial habitats play substantial ecological roles in coastal ecosystems in the Gulf, and there is growing interest in applying ecological engineering principles to future developments to enhance biodiversity and mitigate some of the impacts that widespread coastal development has caused (Fig. B.1.1) (Burt, 2014; Burt, Bartholomew, et al., 2011; Feary, Burt, & Bartholomew, 2011).

1.4 OFFSHORE SYSTEMS

While coastal and nearshore areas contain a variety of productive and diverse ecosystems (Burt, 2014), offshore systems dominate in terms of total area and they include ecologically unique islands and subtidal limestone mounds (Sheppard et al., 1992). Most are associated with salt domes (ca. 200 such islands occur in the Gulf waters; Bruthans et al., 2009), although true coral cays do occur in the northern Gulf as well (Sheppard et al., 1992). Offshore islands and seamounts tend to be isolated from the impacts of coastal development and pollution and buffered by the deeper, cooler surrounding waters (Burt et al., 2016; Cavalcante et al., 2016). As a result, some of the most abundant and diverse coral communities in the Gulf occur around these geological anomalies (Fig. 1.9) (Basson et al., 1977; Burt et al., 2016; Sheppard et al., 1992), and the associated reefs are considered to be an important source of larvae for the degraded coastal systems (Burt et al., 2016; Burt, Bartholomew, et al., 2011). Beaches on offshore islands also provide important nesting habitat for the critically endangered hawksbill turtle and the endangered green turtle which are under increasing pressure from development in mainland coastal areas (Al-Ghais, 2009; Al-Mohanna, Al-Zaidan, & George, 2014; Ficetola, 2008).

While islands and seamounts offer unique hard-bottom habitats in offshore areas, the majority of the offshore seabottom is mainly dominated by sands and muds (Sheppard et al., 1992). Owing to the shallow nature of the Gulf, this habitat is almost entirely within the photic zone and both the seabottom and the overlying water column are highly productive (Rao & Al-Yamani, 1998; Sheppard et al., 1992), supporting a demersal and pelagic fishing industry that is second only to oil in its economic importance as regional resource (Van Lavieren et al., 2011). Studies of reef fish have suggested that some species may migrate from shallow nearshore habitats to offshore systems during the winter where the deeper surrounding

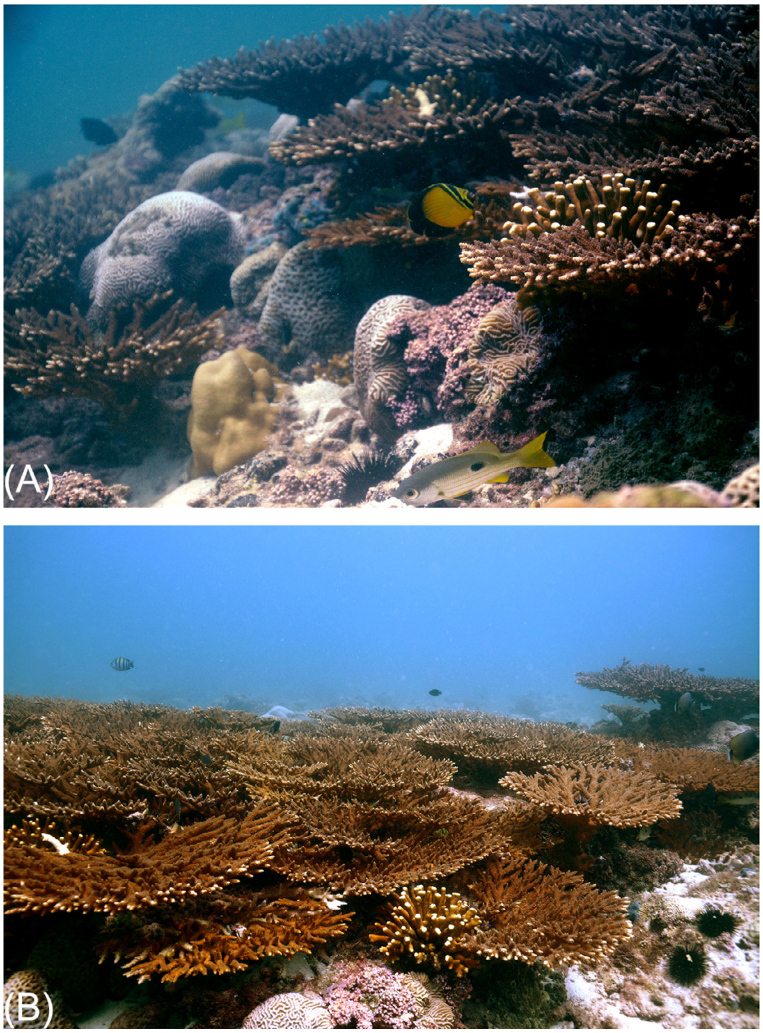


FIG. 1.9 (A) and (B) Coral community around Sir Bu Nair an offshore island in the UAE. *(Courtesy: John Burt and Grace Vaughan.)*

water remains warmer (Coles & Tarr, 1990). Deeper offshore systems are also important for supporting migration and foraging populations of large pelagic species such as the sailfish (*Istiophorus platypterus*), whale sharks (*Rhincodon typus*), and commercially important kingfish (*Scomberomorus commerson)* and tuna (*Thunnus* spp.) (Al-Hosni & Siddeek, 1999; Hoolihan & Luo, 2007; Robinson et al., 2013; Sheppard et al., 1992). Various cetaceans also occur in offshore areas including the resident Indo-pacific humpback dolphin (*Sousa chinensis*) and the bottlenose dolphin (*Tursiops aduncus*) (Preen, 2004), as well as at least 10 other cetacean species that are transient visitors (Baldwin, Gallagher, & Waerebeek, 1999; Gallagher, 1991; Preen, 2004).

1.5 CLIMATE CHANGE IMPACTS

Global climate change is having pronounced effects on marine systems, and the Gulf already experiences high summer sea temperatures (> 35°C) that exceed even the worst-case scenarios predicted for much of the tropics for the next century (Al-Rashidi, El-Gamily, Amos, & Rakha, 2009; Riegl & Purkis, 2012a). Its enclosed nature and unique environmental setting make it highly vulnerable to even marginal increases in temperature because most marine fauna here are already living at the physiological margins of survival (Riegl & Purkis, 2012b). Since the 1980s, SSTs in the Gulf have increased by 0.4°C per decade—double the global average—with warming rates even higher in more constrained areas such as Kuwait Bay (Al-Rashidi et al., 2009). These SST increases have already caused considerable degradation in the Gulf's marine systems, with coral reefs, the most diverse of the coastal ecosystems in the region, having been particularly heavily impacted (Riegl & Purkis, 2015). It is estimated that > 70% of the Gulf reefs have already been effectively lost as a result of these warming events and other anthropogenic factors (Burt, 2014), and a recent assessment showed that every reef-dependent fish species in the Gulf is vulnerable to extinction in the coming decades as a result of habitat loss and fragmentation (Fig. 1.10) (Buchanan et al., 2016). It has also been suggested that changes in temperatures may affect the highly seasonal spawning patterns of commercially important fin fish, potentially causing a mismatch between the arrival of 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). Increased temperatures have also been implicated in the growth of harmful algal blooms (HABs) in the region and their associated fish kills (Al-Ansi, Abdel-Moati, & Al-Ansari, 2002; Heil et al., 2001).

Increasing temperature is also causing sea-level rise (SLR) as a result of thermal expansion and the melt of land-based ice elsewhere on the globe, with storm surge risk increasing as a result of the increased thermal energy in the atmosphere (Church et al., 2013). Long-term tide gauge data in the western Gulf has shown that absolute SLR has increased at a rate of 2.2 mm $year^{-1}$ since the 1970s (Alothman, Bos, Fernandes, & Ayhan, 2014), which is higher than the 1.8 mm $year^{-1}$ global rise for the 20th century (IPCC, 2007), with the higher regional SLR resulting from both absolute SLR and associated regional land subsidence that is presumably related to oil and groundwater extraction. Much of the coastal zone, particularly on the southern and western Arabian coasts, is low lying with a very gradual slope and is thus highly vulnerable to rising seas (Sheppard et al., 2010). As a result, research and policy development on SLR and storm surge risks to coastal populations and infrastructure has grown rapidly in recent years (Alsahli & AlHasem, 2016; Babu, Sivalingam, & Machado, 2012;

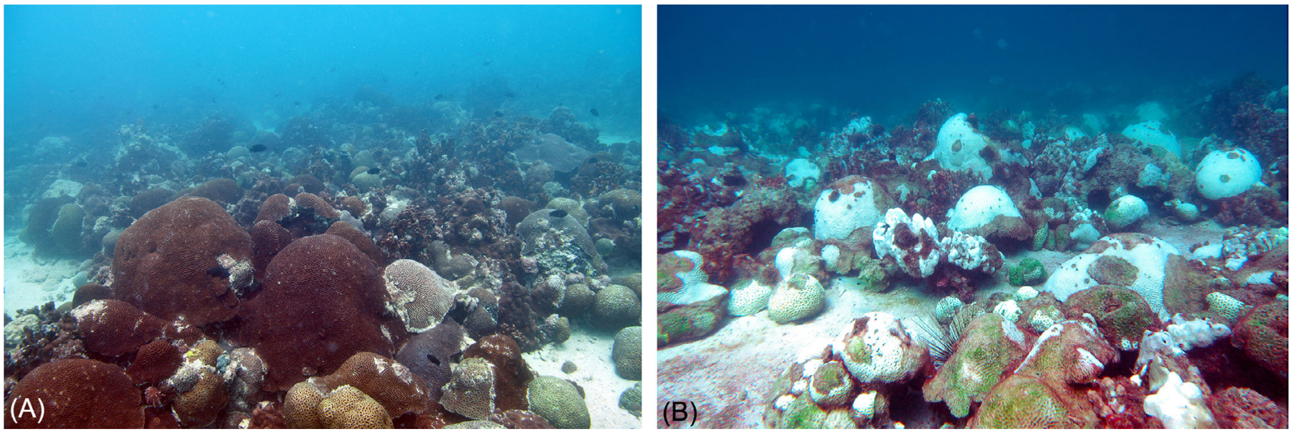


FIG. 1.10 Mass coral bleaching events are occurring with increasing frequency in the Gulf. The recent 2017 bleaching event is estimated to have resulted in > 80% loss of corals from reefs in the southern Gulf, including those at Dhabiya reef (above, (A) April 2017 before the bleaching event and (B) September 2017 during the bleaching event) in Abu Dhabi, UAE. *(Courtesy: Grace Vaughan.)*

Salam, 2015). Several large and important coastal ecosystems are at risk of inundation due to their low lying, shallow sloping nature (e.g., sabkhas, intertidal mudflats) (Riegl, 2003; Sheppard et al., 2010), and offshore systems such as seagrass beds and coral reefs may be vulnerable to increased sedimentation and turbidity that could result from increased storm activity caused by increasing regional temperatures (Larcombe, Carter, Dye, Gagan, & Johnson, 1995).

Climate change is also increasing the acidity of sea water, representing a threat to calcifying organisms such as corals, molluscs, and coralline algae that serve important functions in the Gulf's marine systems (Caldeira & Wickett, 2003). However, the geochemistry of Gulf seawater, which are supersaturated with aragonite as a result of the regional environmental conditions, suggests that acidification is likely to be a less imminent threat to marine fauna than the rapid increases in temperatures. However, if acidification does occur, it will not only affect the organisms themselves, but also will result in dissolution of the lithified hardgrounds upon which reefs and various other ecosystems occur (Purkis, Renegar, & Riegl, 2011). The chemical and biological responses of the Gulf to potential future ocean acidification remain understudied to date.

1.6 RESOURCES

1.6.1 Fisheries

Fisheries currently represents the second most important natural resource within the Gulf after oil (Sale et al., 2011), and the most important renewable resource within the region (Grandcourt, 2012), making an important contribution to food security as well as being important for cultural heritage and recreation (Sheppard et al., 2010). Historically, it was pearl diving that drove the fisheries sector, providing the region's primary source of income for hundreds of years prior to the discovery of oil and natural gas. During the early 20th century, around half of the coastal population of the southern Gulf was involved in the pearl fisheries industry, producing 80% of the world's natural pearls (Carter, 2005). The introduction of cultured pearls, along with a global recession and the discovery of oil and gas led to a decline in the pearling industry from 1930s onwards (Grandcourt, 2012; Price et al., 1993), and fishing practices transitioned to target primarily demersal finfish stocks.

Fisheries currently operating in the Gulf target multiple species through a multigear approach. The majority of catches are referred to as artisanal (75% of the total reported the Gulf landings (Al-Abdulrazzak, Zeller, Belhabib, Tesfamichael, & Pauly, 2015) due to the traditional methods being used (Sale et al., 2011), although the scale at which they are operating is of a more commercial nature (Grandcourt, 2012). Fisheries sectors within the region can be classified into four groups; recreational, traditional, commercial, and industrial. The recreational and traditional fisheries are generally nondestructive in terms of impact on fish populations and their associated ecosystem health, utilizing intertidal weirs, harpoons, or hand lines to target various demersal species including emperors (Lethrinidae), sweetlips and grunts (Haemulidae), seabreams (Sparidae), and groupers (Serranidae) (Grandcourt, 2012). Commercial fisheries are largely operated from traditional wooden boats (dhows) and use traps (gargoors) to nonselectively target demersal species (Grandcourt, 2012). Commercial trawlers target shrimp during the open season in countries where it is permitted (e.g., Kuwait, Bahrain) and switch to targeting finfish during the closed season (Carpenter, Krupp, Jones, & Zajonz, 1997). Trawling has been banned in some countries (e.g., UAE, Qatar) due to their detrimental impacts on seagrass beds and coral reefs (Valinassab, Daryanabard, Dehghani, & Pierce, 2006).

Fishing intensity in the Gulf waters has increased over the past 30 years due to increased demand from growing populations and coincident improvements in fishing technologies, leading to steep increases in total fish catch (Al-Abdulrazzak et al., 2015; Sheppard, 2016). During the past 15 years, total landing of the Gulf fisheries have averaged 331,827 mt annually, varying from a minimum of 208,520 in 2004, to a maximum of 421,606 mt in 2012 (FAO, 2017). Reef-associated species represent approximately 70% of the total landed weight of finfish catch in the Gulf, although the species composition of landings across the region are dependent upon the habitats where fishing is conducted, capture techniques and seasonal changes in abundance which vary from nation to nation (Grandcourt, 2012). Despite the differences in target species between countries, there are similarities at a Gulf wide scale; > 10% of annual landings are composed of species belonging to the families Carangidae, Lethrinidae, and Serranidae across the Gulf as a whole (Grandcourt, 2012).

Despite the intense fishing activity in the Gulf, the consumption rates of the Gulf populations exceed total fisheries production, leaving the region reliant upon imports of fish and fish-based products. This has fueled growing interest in the aquaculture industry over the past few decades after research into the process began in the late 1970s (Al-Jamali, Bishop, Jones, Osment, & LeVay, 2005). Shrimp hatcheries have long been established along Iran's coastline, and Kuwait, Bahrain, and the UAE are engaged in commercial grow-out production of fish which focus on the gilt-head seabream, European seabass, sobaity, and hamour (Al-Jamali et al., 2005).

1.6.2 Tourism

Tourism has grown exponentially in the region in recent years as a result of enhanced development of tourism-related infrastructure in various Gulf countries, most notably Bahrain, Qatar, and the UAE (Nadim, Bagtzoglou, & Iranmahboob, 2008). The Gulf Corporation Council (GCC) states are currently ranked among the most competitive in the Middle East and North Africa by the World Travel and Tourism council, with experts citing political stability in an otherwise volatile region along with rapid modernization of urban areas as the causative factors (Henderson, 2015). The improved development and advancement of communication and transport links have enabled ease of travel to the region, and the attraction of developed coastlines, state of the art shopping malls, and world-class hotels in cities such as Dubai and Doha have led to substantial tourism growth over the past decade (Henderson, 2015). The number of tourists annually visiting the Gulf countries nearly tripled from 8.2 million in 1995 to 22.9 million in 2010 (Gladstone, Curley, & Shokri, 2013). In some Gulf countries, such as the UAE, recent development projects are centered around an economic diversification policy initiated in response to the continued depletion of oil reserves (Stephenson, 2014). Coastal resorts and activities such as SCUBA diving, deep-sea fishing, and wildlife watching are promoted with the Gulf's rapidly growing tourism industry, proving particularly popular within the southern Gulf countries where winter temperatures remain warm (Gladstone et al., 2013). The potential for further development of the currently small-scale ecotourism sector exists within the region, which could potentially benefit coastal and marine conservation efforts through enhanced education and awareness (Lokier, 2013). There are increasing efforts to quantify the economic value of coastal resources to tourism in order to aid in justifying their long-term conservation. For example, in Abu Dhabi, it has been estimated that the amenity value of coastal beaches represents US$824 million in tourism income for the emirate, with beach habitats valued between US$8.3 and 13.8 million per hectare (Blignaut, Mander, Inglesi-Lotz, Glavan, & Parr, 2016).

1.7 HUMAN POPULATIONS AFFECTING THE AREA

1.7.1 Coastal Development

The eight nations bordering the Arabian Gulf have experienced unprecedented population growth in the past 50 years due to the regional oil boom of the 1970s (Burt, 2014). Such rapid growth has resulted in an overwhelming increase of large-scale urban development, and this has primarily occurred in coastal areas. Today, it is estimated that 40% of the Gulf's coastline has been modified through extensive housing, tourism, and industrial development required to sustain the increasing population, and considerable degradation of coastal ecosystems through dredging and land reclamation has occurred as a result (Naser, 2014). Environmental damage through coastal modifications can have significant economic costs. It has been estimated that the various marine ecosystems of Bahrain were worth ca. $2 billion to the Kingdom, however, through continued extensive coastal development, the majority of Bahrain's marine habitats are seriously degraded (Sheppard, 2016). Such impacts are likely to continue to rise as large-scale coastal developments continue to expand across many of the Gulf countries in an effort to attract investors and tourists to the region. Examples of mixed-use developments created by dredging and/or reclamation include the Pearl in Qatar, the Half Moon Bay in Saudi Arabia, and the Palm Islands in Dubai where residential, economic, and leisure infrastructure exists together to create waterfront communities (Fig. 1.11).

Dredging, reclamation, and coastal infilling cause both direct and indirect impacts on coastal habitats, resulting in increased pressure on the already fragile marine ecosystems of the Gulf. The typical reclamation practice in the Gulf includes the extraction of sand and mud from so-called "borrow areas" areas which is then dumped into shallow subtidal areas either along the coastline or at offshore sites (Naser, 2014). This process has resulted in a direct burial of mudflats and seagrass beds, reduced beach areas for turtle nesting, and decreased areas of mangrove forests (Burt, 2014). Indirect effects of dredging and reclamation are primarily focused around changes in circulation patterns and water flow. Altered biogeophysical and hydrological characteristics of coastal ecosystem habitats have led to a reduction in biodiversity as well as a decline in species richness and abundance within affected coastal habitats (Lokier, 2013; Vousden & Price, 1985).

1.7.2 Wastewater

Large quantities of industrial and domestic wastewater enter the Gulf despite high standards for wastewater treatment throughout the region (Hamza & Munawar, 2009; Sheppard et al., 2010). Industrial effluents originate from a multitude

FIG. 1.11 Examples of large-scale coastal development in the Arabian Gulf. From top left: Tarut Bay in Saudi Arabia, Durrat Al Bahrain in Bahrain, the new and old town of Doha, Qatar, the Palm Jumeirah and The World developments in Dubai, UAE, and Kuwait City, Kuwait. *(Modified from Burt, J.A. (2014). The environmental costs of coastal urbanization in the Arabian Gulf.* City, 18*, 760–770.)*

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 Gulf. Since the flushing time of the Gulf ranges between 3 and 5 years, such harmful pollutants reside in the region for substantial periods of time (Naser, 2014). Despite the majority of studies concluding that current levels of heavy metals within marine sediments, fish and shellfish are within the safe international thresholds (Ashraf, 2005; Naji, Khan, & Hashemi, 2016), marine ecosystems located adjacent to various wastewater discharges have been 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 Gulf through river systems and in areas of increased coastal development, particularly as a result of sewage treatment plants (Al Darwish, El-Gawad, Mohammed, & Lotfy, 2005; Sale et al., 2011).

Domestic effluents entering the Gulf 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 Gulf's coastal waters, often alongside low flushing rates (Sheppard et al., 2010). Such discharge areas tend to be low in biodiversity (Naser, 2011, 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 (Glibert et al., 2002; Heil et al., 2001; 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., 2013).

1.7.3 Desalination

Owing to the arid climate and limited freshwater input, desalination of seawater is heavily relied upon as the principal source of potable water in the Gulf countries (Sale et al., 2011). Over 5 billion m^3 of water are produced annually in the Gulf, equating to almost half of the world's total desalinated water supply (Burt, 2014; Dawoud & Mohamed, 2012). Across the region desalination using distillation methods accounts for 83% of desalinated water production, with the remaining 17% produced through reverse osmosis (Dawoud & Mohamed, 2012). Concerns regarding desalination processes primarily focus on the effluents which are released into surrounding coastal waters. Over 1000 m^3 of waste brine is released into the Gulf every second, causing localized discharge plumes that can extend up to several kilometers (Burt, Al-Khalifa, et al., 2013), impacting adjacent coastal ecosystems and affecting regional marine water quality (Hamza & Munawar, 2009). Discharge brines in both reverse osmosis and distillation plant outfalls are typically high in salinity and are substantially warmer than ambient conditions (Burt, 2014), and outfalls often 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 multitude of aquatic organisms in the Gulf (Shahsavani et al., 2017). Despite continuous advances in the efficiency of the desalination process, the management surrounding treatment of associated wastewater brine has seen little improvement (Dawoud & Mohamed, 2012).

1.7.4 Shipping Traffic

Owing to the robust oil and gas transport industry and the regional reliance on imported foods and materials, the Gulf is exposed to considerable shipping traffic annually, and exotic biota have been introduced to the marine system through the water and sediments contained within ships ballast tanks (Sheppard et al., 2010). For the purpose of oil transport alone, it is estimated that 53,000 ships pass through the Straits of Hormuz into the Gulf each year (Al-Yamani, Skryabin, & Durvasula, 2015), enhancing potential for introduction of potentially harmful invasive species, with several substantial HABs being caused by invasive species in recent years (Richlen, Morton, Jamali, Rajan, & Anderson, 2010). Coupled with the high levels of shipping traffic, the Gulf's isolated physical geography and relatively limited water exchange with the Indian Ocean make it prone to HAB outbreaks (Sale et al., 2011). The most devastating HAB outbreaks have often occurred in areas with high nutrient loads from sources such as sewage outfalls (Glibert et al., 2002). Where HABs have occurred, they have been directly associated with large-scale fish kills and shifts in reef fish community structure (Bauman, Burt, Feary, Marquis, & Usseglio, 2010). An extensive algal bloom associated with the newly introduced dinoflagellate species *Cochlodinium polykrikoides* affected large areas of the Gulf from August 2008 to May 2009, causing damage to coral reefs, restricting fishing activities, interrupting desalination operations, and inducing widespread fish kills in addition to resulting in loss of tourism revenue (Naser, 2014).

As the human population continues to grow in the Gulf, more frequent HABs are anticipated due to increased eutrophication, shipping traffic, and stressors associated with ocean warming, and it is therefore recognized that better regulations concerning ballast water must be developed in order to reduce the threat of future outbreaks (Hallegraeff, 2015).

1.7.5 Overfishing

In addition to the negative effects of pollution and habitat destruction, intense fishing pressure has resulted in overexploitation of two-thirds of commercially important species, and full exploitation of a further 5% of species (Grandcourt, 2012). Historically, fisheries within the Gulf were open access, with little to no effort restrictions enforced until a few decades ago (Grandcourt, Al Abdessalaam, Hartmann, Al Shamsi, & Franklin, 2011). Most recently, the lack of robust fish stock assessments (national or regional) has further contributed to overfishing practices in the region (Hamza & Munawar, 2009). This has been exacerbated by inaccurate catch reporting and illegal fishing activities (Daliri, Kamrani, Jentoft, & Paighambari, 2016).

Destructive fishing practices such as shrimp trawling still take place in some Gulf nations, and are likely to have contributed significantly to ecosystem decline through direct seabed destruction in their operating areas (Al-Husaini, Bishop, Al-Foudari, & Al-Baz, 2015). Trawling also results in high fish bycatch, and since juveniles of many commercial fish species are found within shrimp fishing grounds, there is concern that trawling practices are contributing to further declines in fish stocks by removing the immature individuals of nontarget species (Eighani & Paighambari, 2013). Juvenile fish are also commonly caught in demersal fisheries that utilize extensive wire mesh fish traps (*ghargoor*) such as those in the UAE. In Abu Dhabi alone, more than half of all landed catches of sparids (*Acanthopagrus bifasciatus* and *Argyrops spinifer*) are composed of immature fish (Grandcourt et al., 2011) (Box 1.2).

BOX 1.2 The Gulf's Petroleum Industry

More than half of the world's oil and natural gas reserves are located within the Gulf, and associated industrial infrastructure and practices have had dramatic consequences for marine systems in the region. Reserves of 76 billion metric tonnes of recoverable oil and 32.4 trillion m^3 of natural gas are present within the Gulf (Hamza & Munawar, 2009) accounting for the production of ca. 19 million barrels of oil, and 2.5 million barrels of natural-gas liquids per day (2008 data; Seznec, 2008). There are approximately 800 offshore platforms and 25 major oil terminals in the Gulf that are serviced by 25,000 annual tanker shipments (Sale et al., 2011; Van Lavieren et al., 2011) which together export ca. 88% of the Gulf's oil (Le Billon & El Khatib, 2004). Oil and gas have become the most important economic resource in the region (Kubursi, 2015). In Saudi Arabia alone, oil income increased from an estimated US$42 billion in 1999 to US$307 billion in 2008, in the UAE from US$13 to US$87 billion, and in Kuwait US$4 to US$27 billion during the same time (Seznec, 2008). Qatar has the third largest reserve of natural gas in the world, and has significantly developed its liquefied natural gas (LNG) infrastructure over the past decade. Annual economic growth in Qatar averaged 13% per year until 2010 when the peak of 77 million tonnes was produced, doubling the income generated from oil that year (Kubursi, 2015) (Fig. B.1.2).

These developments have inevitably led to a dramatic increase in coastal and offshore industrial infrastructure. This infrastructure acts as unplanned artificial reef habitats for a variety of fauna in offshore areas that are largely featureless (Feary et al., 2011). They contain diverse communities of bivalves, corals, fish, and other fauna (Albano et al., 2016; Feary et al., 2011; Stachowitsch et al., 2002; Torquato et al., 2017). Furthermore, offshore platforms are heavily protected for security reasons, preventing fishing and other boating activities and resulting in the creation of hundreds of *de facto* marine protected areas throughout the Gulf (Rabaoui et al., 2015). Protection from environmentally harmful fishing methods such as trawling further contributes to the increased biodiversity on and around such structures (Rabaoui et al., 2015; Stachowitsch et al., 2002). A globally significant hotspot for whale sharks *(Rhincodon typus)* has also been identified within the Al-Shaheen oil field, 90 km offshore from Qatar, where aggregations reach up to 100 sharks per km^2 between May and August, when there is high food source availability due to the presence of spawning tuna (Robinson et al., 2013).

Despite these purported benefits, activities associated with the hydrocarbon industry are also considered to be the highest contributors to marine pollution in the Gulf (Naser, 2013). Oil spills include those from offshore oil wells, terminals, underwater pipelines, and tanker collisions (Naser, 2014; Tseng & Chiu, 1994). The most notable incident was the Gulf War oil spill of 1991 where an estimated 10.8 million barrels of oil were released into the Gulf from abandoned tankers, oil terminals and sunken ships (Massoud, Al-Abdali, & Al-Ghadban, 1998), impacting over 700 km of coastline and affecting intertidal fauna such as seabirds, invertebrates, and fishes (Naser, 2014; Sale et al., 2011). It is not only large-scale spills that cause important impacts, but also continuous low-volume discharges of oil and related wastes from harbors, tank washouts, terminals, and ballast tanks (Madany, Jaffar, & Al-Shirbini, 1998). There are consistently high levels of hydrocarbons (Sale et al., 2011), and other by-products of oil and gas production such as metals and polycyclic aromatic hydrocarbons (PAHs) which have shown increased concentrations in coastal areas since the late 1970s (Gevao et al., 2016).

FIG. B.1.2 (A) Mubarak oil field (UAE) and (B) the Al Basra oil terminal (Iraq). *((A) By Crescent Petroleum/Icethorn (Own work) [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. (B) By U.S. Navy photo by Photographer's Mate 2nd Class Samuel W. Shavers (http://www.navy.mil; exact source) [Public domain], via Wikimedia Commons.)*

1.8 MANAGEMENT

Coastal management policies of any water body should have the agreed cooperation of all bordering countries in order to ensure effective management, even more so in the case of the semienclosed, extreme environment of the Gulf. The Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area (RSA) was established in 1979 to encompass the water bodies of the Gulf, the Gulf of Oman, and the south eastern coast of Oman in the Arabian Sea (Van Lavieren & Klaus, 2013). Comprised of an estimated coastline of 6200 km, the RSA includes all eight Gulf countries and forms the only pan-regional marine organization (Nadim et al., 2008). ROPME serves as a platform on which member states can coordinate legal activities and policies enabling the protection of their shared marine environment. ROPME has published three State of the Marine Environment Reports (SOMER) to date (2000, 2003, 2013) as well as various technical reports detailing marine pollution and related issues for the region. The ROPME protocols and guidelines primarily focus on the protection of the marine environment from various marine pollution causative activities such as exploration and exploitation of the continental shelf, as well as land-based pollutants (Van Lavieren et al., 2011).

The Gulf accommodates numerous rare and endangered marine species that are considered of high value for regional management. Examples include the dugong *(D. dugon)*, various sharks, the hawksbill and green turtles, several dolphins, and a variety of resident and migratory seabirds (Van Lavieren & Klaus, 2013), each of which are dependent upon crucial habitats that are being increasingly degraded by anthropogenic activities in the region. In 1996, it was proposed that a network of marine protected areas (MPAs) be established within the Gulf to facilitate enhanced protection by incorporating representative proportions of each major habitat, ecosystem, and species community type (Krupp, Abuzinada, & Nader, 1996), and further recommendations regarding an effective MPA network within the region have since followed (Munawar et al., 2002; Sheppard et al., 2010; Van Lavieren et al., 2011) In 2002, it was estimated that established MPAs covered 1% of the Gulf's sea surface area or 3% of total area (7500 km^2) and this including terrestrial zones (Krupp, 2002). A further 2% of total area was identified as "proposed." A decade later, in 2012, the total area of the Gulf that had been designated or proposed as an MPA had risen to 7.23%, demonstrating governmental support for expansion of regional MPAs.

The efficacy of MPAs is directly linked to the management of such areas, and of the existing MPAs within the Gulf, only a few have management plans that incorporate conservation, recreational, and development zones (Van Lavieren et al., 2011), and a recent assessment showed that regional marine management has low effectiveness (averaging 34% effectiveness, with a range from 11% to 58% on a national basis (Van Lavieren & Klaus, 2013). Regional collaboration and management plans of multinational or pan-regional scales need to be developed to replace the current fragmented management framework. If this were integrated with greater sharing of environmental data and trans-boundary information on proposed coastal developments, interactions upon the Gulf's marine habitats may be better understood and further degradation mitigated (Sheppard et al., 2010).

Such regional efforts could be underpinned by the growing body of knowledge being developed by marine science in the region to lead even more robust and cohesive regional marine policies and management effort (Vaughan & Burt, 2016). In addition, an increased number of marine science-related academic programs within regional universities can further contribute to building the long-term research capacity in the region (Nadim et al., 2008) and enhance integrated management plans.

1.9 SUMMARY

The preceding sections have illustrated the incredible importance of the largely underappreciated marine ecosystems in the Gulf. But the review has also highlighted the highly vulnerable nature of this young, isolated, and environmentally extreme sea and the increasing pressure that is being applied by coastal populations and climate change. Coastal areas along the edge of the Gulf are composed of a highly productive mosaic of sabkhas, mudflats, saltmarshes, and mangrove forests, and these are surrounded by diverse offshore systems such as seagrass beds and coral reefs (Burt, 2014). Each of these ecosystems is individually important, but together they represent an interconnected network of critical marine assets that support far higher diversity than is found in terrestrial systems in this region and support many hundreds of millions of dollars in commercial fisheries for the various countries that border the Gulf (Van Lavieren et al., 2011).

Global marine ecosystems are currently under increasing threat from climate change and its associated impacts, and due to the Gulf's already extreme temperature fluctuations, its marine ecosystems are highly vulnerable to even modest increases in temperature (Riegl & Purkis, 2012a). SST anomalies have already caused substantial degradation of marine systems within the Gulf, with coral reefs being the most significantly impacted through recurrent coral bleaching events (Riegl & Purkis, 2015). The frequency of such disturbances are increasing, and are being further exacerbated by anthropogenic stressors caused primarily by rapid population growth (Sheppard, 2016). Impacts originating from coastal urbanization and industrial pollution have contributed to widespread degradation and loss of various other important coastal ecosystems such as sabkhas, mudflats, and mangrove forests (Burt, 2014; Van Lavieren et al., 2011), while many fish populations are becoming increasingly depleted due to overexploitation (Grandcourt, 2012).

While the current status of marine ecosystems in the Gulf is precarious, projections for the future are alarmingly dire. The growth rate of populations in the Gulf nations is nearly double that of the global average (Van Lavieren et al., 2011), suggesting that population-related pressures are likely to accelerate. Aside from continuing encroachment of coastal development into remaining natural habitats to accommodate growing urban areas, growth of cities is likely to have consequences that are as yet underappreciated. For example, over 14 million m^3 of water are currently produced by desalination in the Gulf every day (AGEDI, 2016), with hot salt brine wastes being discharged into shallow coastal areas after processing. Recent modeling efforts have shown that projected growth of desalination capacity and consequent increases in brine discharge in the Gulf are likely to have substantial region-wide impacts on the already extreme temperatures and salinity, further increasing sea temperatures between 0.5°C and 1.4°C and elevating salinity by 10–18 PSU at basin-wide scales by 2050 (AGEDI, 2016). Given that the Gulf is already warming at twice the rate of other regions (Al-Rashidi et al., 2009), such stressors will amplify the impacts of climate change. Many marine organisms in the Gulf are living very close to the margins of their physiological tolerance (Price et al., 1993; Sheppard et al., 1992), and the changes in temperatures and other conditions that are expected as a result of climate change and population-related pressures are likely to push many of them over the edge unless mitigative management efforts are rapidly put in place.

Given the economic and ecological importance of marine ecosystems in the Gulf, there is an urgent need to reduce any further cumulative effects of natural and anthropogenic stressors. As the Gulf is a shared body of water, it is imperative that management plans are of multinational or pan-regional scale, incorporating trans-boundary information sharing and data collection. Destructive coastal development practices such as dredging and landfilling must be properly managed (Sheppard, 2016), and the designation of strictly managed marine national parks and MPAs can help buffer both anthropogenic and natural stressors upon marine ecosystems (Sale et al., 2011; Van Lavieren et al., 2011). In recent years, there has been unprecedented growth of research that utilizes the Gulf as a natural laboratory for climate change research (Vaughan & Burt, 2016). Such studies have provided a wealth of important information on how marine fauna have responded to extreme environmental conditions, and insights into what might happen in other parts of the world in the future. Unless dramatic action is taken immediately to limit the stressors affecting this vulnerable marine system, it is very likely that we will witness the ecological collapse of this unique and important natural asset for Arabia.

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