Chapter 4
The Marine Environment of the Emirates

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4.1 The Emirates in a Regional Marine Context

The United Arab Emirates (UAE) is bordered by two water bodies with markedly different environments. These differences are a consequence of a geological history that has resulted in the Arabian Gulf being a shallow semi-enclosed sea that is highly influenced by the regional climatic conditions, while the deep, unenclosed Sea of Oman is well buffered by its connection to the Arabian Sea and wider Indian Ocean. The UAE's east coast borders the Sea of Oman, where the continental slope rapidly increases in depth close to shore. Depths often exceed 50 m within a few km of the coast, dropping to over 1000 m depth offshore. This large depth gradient and the high degree of mixing with the wider Indian Ocean result in a marine environment on the UAE's Sea of Oman coast that is typical of a subtropical ocean and that is well buffered from the considerable environmental variability that characterizes the UAE's western coast.

In contrast, the Strait of Hormuz acts as a geographically and environmentally isolating bottleneck at the entrance of the Arabian Gulf, constricting exchange of Gulf waters with the Indian Ocean through a narrow opening (52 km wide). From an

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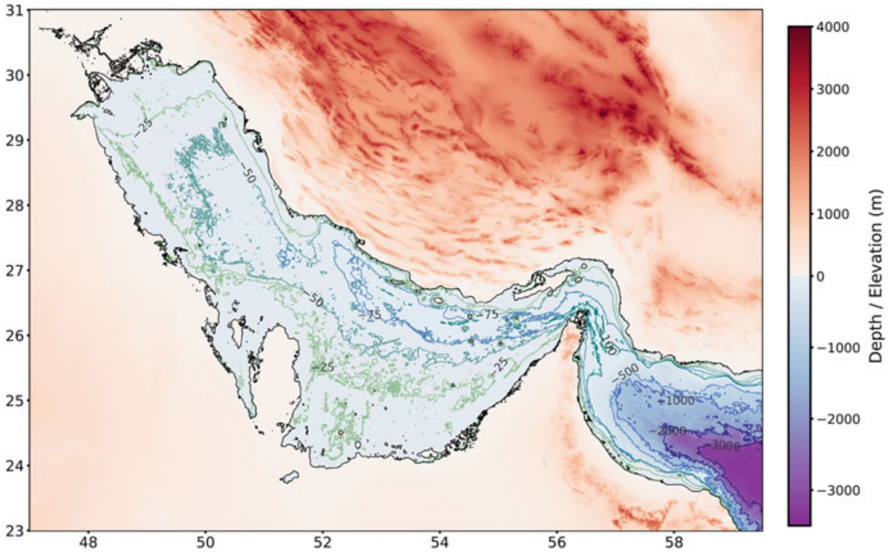

Fig. 4.1 High-resolution bathymetry and elevation of the Gulf region. Degrees of latitude and longitude are provided on the axes. Data from the GEBCO 2022 global terrain model, GEBCO Compilation Group (2021) GEBCO_2022 Grid 10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c (public domain)

oceanographic perspective, the Arabian Gulf is extremely shallow, with an average depth of 30 m and a maximum depth of just over 100 m in a narrow, elongated submarine valley parallel to the Iranian coast (Fig. 4.1). The shallowest, lowest sloping areas in the Gulf occur in the southern basin along the UAE's Abu Dhabi coast, where large areas extending many km from the mainland are less than 15 m depth (Fig. 4.1). More rapid increases in depth only occur offshore from the northern emirates (e.g. Ras Al Khaimah) where the sea-bottom slope is steeper, but even there depths typically do not exceed 30 m within 10 km of the coast. Its shallow depth and isolation from the Indian Ocean, working under the influence of regional climate, are the main conditions responsible for the highly variable and extreme environmental conditions that characterize Arabian Gulf waters.

The geographic history of this region has shaped the distinct bathymetric profiles of the Sea of Oman and the Arabian Gulf. The modern Arabian Gulf is one of the world's youngest seas, having formed only after the peak of the most recent glacial period (Sheppard et al. 1992). At the last glacial maximum sea levels were approximately 120 m lower than today, such that the entire Gulf would have been above sea level and the coastline at that time was located outide the Strait of Hormuz, offshore from modern Fujairah (Lambeck 1996). The only water occurring in the Gulf basin at that time would have been the freshwater flow of the historic Shatt-Ur River system (today's Tigris-Euphrates) that would have extended from Iraq, along the coast of Iran, before emptying into an estuary, possibly a seasonal marshland, where it flowed into the Sea of Oman (Kennett and Kennett 2006). Between 18,000 and 12,000 YBP the glacial ice sheets on the northern continents began to recede,

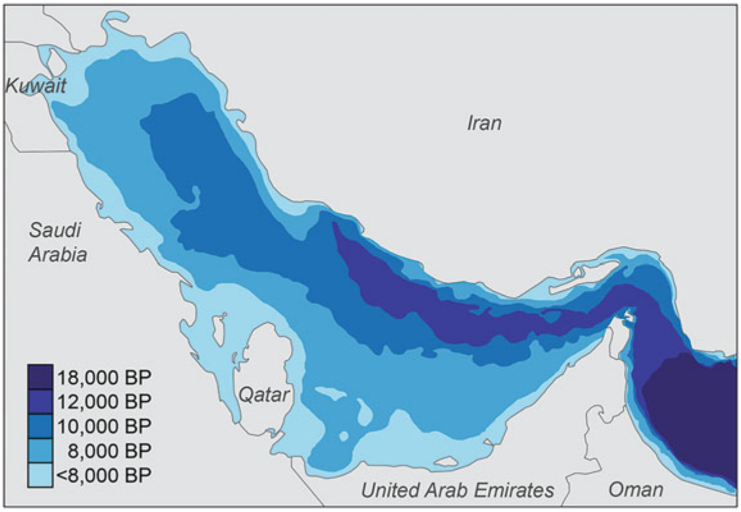

Fig. 4.2 Map illustrating the chronology of Arabian Gulf flooding following the last ice age (BP = before present). Modified from Fig. 4.2 in Smith et al. (2022) under CC-BY-4.0

causing sea levels to rise and the marine transgression to begin to flood the Gulf, initially following its lowest topography adjacent to the Iranian coast. Over the subsequent millennia, flooding extended along the Iranian coast towards the northern Gulf by 10,000 YBP before migrating slowly into the shallow southern basin by 8000 YBP, with today's modern Gulf coastline established only about 6000 YBP (Fig. 4.2; Lambeck 1996). This latter period (10,000 to 6000 YBP) was a time of greater humidity in the region known as the 'climatic optimum', and coincided with the beginning of modern human civilization in the marshlands of today's Iraq (Kennett and Kennett 2006). This period was also biologically important because marine organisms such as corals began to re-colonize the Gulf and to experience pressure from natural selection to adapt to the exceptional environmental conditions of this new and peripheral marine basin, compared with the more customary sub-tropical oceanic conditions of their Indian Ocean source populations (see below) (Smith et al. 2022).

4.2 Geographic Features of the UAE's Coasts

The major geographic feature dominating the east coast of the UAE is the Hajar Mountains which extend along the length of the UAE's Sea of Oman coast. In the northern areas of Dibba, Al Aqah and Khor Fakkan, the mountain's foothills sometimes extend directly to the shoreline with headlands piercing into the marine systems as rocky promontories; occasional hilltops also emerge as nearshore islands (e.g. Dibba Rock and 'Snoopy' Island) or barely submerged pinnacles (e.g. the

Fig. 4.3 Rocky headlands of the Hajar Mountains extend into the sea in the northern portions of the UAE's Sea of Oman coast, where they constitute an important habitat for coral reef development (inset: Table corals at Shark Island reef). Photo credits: John Burt

well-known Martini Rock diving site). The presence of these rocky habitats is critically important in providing hard-bottom habitat necessary for coral growth, and as a result well-developed coral reef ecosystems occur across much of the northern portion of the UAE's east coast (Fig. 4.3; see Chap. 11). South of Khor Fakkan and extending to the Oman border near Kalba, the Hajar Mountains are situated slightly further inland, and the coastline is characterized by gravel and sand alluvium eroded from the mountains over many millennia. Here, the nearshore environment is heavily dominated by mobile sands and rocky hard-bottom habitats do not occur, except as occasional cemented intertidal alluvial areas. The coast in this area was historically dominated by sand beaches until modern urbanization resulted in substantial alteration through construction of harbors, breakwaters and groyne fields. At the most southerly end of the UAE's east coast, at Khor Kalba, occurs the only modern lagoon system on the east coast, where an extensive mangrove forest occurs (see Chap. 7). Archaeological evidence from shell middens shows human occupation in the area extending back to the Neolithic (Lindauer et al. 2017).

Unlike the east coast, where the sands are largely derived from erosion of the Hajar Mountains, the white coastal sands of the Arabian Gulf coast are largely carbonate sands generated from the skeletons of deceased marine organisms and swept up on shore (Clarke and Keij 1973). The 600 km UAE Gulf coastline is broken into three sedimentary provinces largely based on their degree of exposure to winds and waves. The northeastern portion extends from the northern border of Ras Al Khaimah to the Dubai/Abu Dhabi border, and is characterized by fully unprotected exposure to northerly 'shamal' winds that typically blow across the entire length of the Gulf from Iraq. As a result of the open exposure of this coast, high wave energy

Fig. 4.4 Satellite image of a large longshore sand-spit system at Umm Al Quwain, which is emblematic of the high-energy wave environments that occur on exposed sandy shorelines of the UAE's Arabian Gulf coast. Historically, such systems were more common, but many have since been heavily modified or removed through coastal dredging and reclamation. Modified from Umm Al Quwain © 2023 by Google Earthview and Cnes/Spot Image, Maxar Technologies and distributed under their Terms of Use

can occur during storms, leading to the formation of large longshore sand-spit or barrier island systems. While many of these have been removed or heavily modified by dredging in recent decades (e.g. around Ras Al Khaimah; Goudie et al. 2000), Siniyah Island, the 15 km long barrier island protecting the Umm Al Quwain lagoon remains as a prime example (Fig. 4.4; see also Chap. 8). Although the coastline north of Ras al-Khaimah is overlooked by the mountains of the Musandam peninsula, those mountains are composed primarily of carbonate rocks (limestone and dolomite), so their contribution to the coastal sands is also in the form of carbonate grains.

The central portion of the Gulf coast extends from the Dubai/Abu Dhabi border west to Jebel Dhanna. In this area wave protection is provided by nearshore pearl banks and coral reefs (Fig. 4.5), resulting in the development of sandy barrier islands that, in turn, protect lagoon systems and tidal flats in their lee (Kendall and Skipwith 1969; Evans et al. 1973). For example, the capital city of Abu Dhabi sits on a barrier island that formed in the lee of a large nearshore coral reef that existed up until the 1970s, but has since been lost following the development of Mina Zayed and Lulu Island (Murray 1970). Examples that still exist today include Saadiyat Island and Dhab'iyah, both of which occur behind coral reefs. The lagoon systems that lie behind these barrier islands are typically characterized by extreme salinity and temperatures (Murray 1970), but often contain large stands of mangrove forests as well as extensive mudflats that can be important feeding grounds for resident and migratory birds (see Chap. 8). Historically, tidal channels near the barrier islands were also occupied by coral reefs, although dredging for navigation has removed

Fig. 4.5 Coral growth occurs in discontinuous areas where lithified sandstone caprock rises above the sand that typically dominates sea-bottoms along the UAE's Arabian Gulf coast. Photo credit: John Burt

most of these habitats (Kinsman 1964). While generally considered environmentally damaging, dredging can sometimes have unintended positive impacts. For example, channel construction around Abu Dhabi city reduced lagoon salinities there to levels amenable to mangrove growth, explaining their rapid expansion in recent years, particularly in areas supported by seedling afforestation programs (Embabi 1993; Friis and Burt 2020).

The western portion of the Gulf coast extends from Jebel Dhanna to the Saudi Arabian border near Al-Sila. The most westerly shoreline in this area lies is protected by the Qatar Peninsula from the northwesterly shamal winds that blow down the Gulf, and from the most severe storms. Much of the bottom is made up of fine sands and muds with occasional rocky outcrops (Purser and Evans 1973). Towards the east, the shoreline becomes more exposed and is characterized by wide, low sloping intertidal flats that grade into sabkha environments, including the Sabkha Matti, which continues far inland—one of the world's largest sabkhas (see Chap. 2), and which is protected by a high (1–3 m) storm beach. The UAE sabkha environments have been the focus of intense research by geologists over more than 50 years and represent unique geochemical and biological systems in their own right (particularly in the nearshore areas) (Böer 2002; Böer and Saenger 2006). Unfortunately, development has reduced the 150 km length of pristine sabkha coastline that occurred in the 1960s to just 54 km by the 2010s (Lokier 2013).

While the offshore environment of the northeastern portion of the UAE's Gulf coast is largely low complexity sands and muds, the central and western portion of the Gulf coast are characterized by extensive shoals and offshore islands formed above salt domes (Riegl et al. 2012). An area of 5500 km^2 of seagrass beds dominates the shallow waters of Abu Dhabi, representing three-quarters of all

Fig. 4.6 Fringing coral reefs are common on the windward northwestern face of islands in the southern Arabian Gulf. Shown here is a photo from the coral reef at Delma Island in 2016. Photo credit: John Burt. Map inset: Delma Island, modified from ESRI World Imagery layer under their Terms of Use (Esri, NASA, NGA, USGS | Esri, HERE, Garmin, Foursquare, METI/NASA, USGS | Earthstar Geographics)

seagrass in the Gulf and 3.4% of the entire global seagrass area (Erftemeijer and Shuail 2012), supporting large populations of dugongs and green turtles (Preen 2004; Pilcher et al. 2021) (see Chap. 9). Extensive coral reefs are also common and widespread in the shallow waters of Abu Dhabi and around offshore islands (Fig. 4.6), particularly on the windward (NNW) shores, although these reefs are typically low in diversity due to the extreme environmental conditions of the southern Gulf (Riegl et al. 2012; Bejarano et al. 2022). From Ras Ghanada to the northern emirates, corals have historically been restricted to lithified sandstone outcrops in a discontinuous narrow band that occurs approximately a kilometer offshore, with the remainder of the area dominated by mobile sands and muds (Grizzle et al. 2016) (Chap. 11). These sandstone 'caprock' outcrops are formed by the cementation of sand grains by dissolved calcium carbonate during periods of low wave action, with modern rock forming in just a few years (Purkis et al. 2011).

4.3 The UAE's Arabian Gulf Coast: An Extreme Marine Environment

4.3.1 Atmospheric Influences on the Arabian Gulf

The UAE is located in a region that straddles 30°N latitude known as the subtropical high pressure zone. The subtropical high pressure zone is itself part of a larger convective circulation phenomenon called the Hadley cell (see Chap. 3). Near the equator, warm air is uplifted to the upper atmosphere where it drops most of its moisture as rain, moves towards the poles, cools and sinks back to the earth's surface at 30° as extremely dry air, before being drawn back towards the Equator along the earth's surface. This results in an environment in the Emirates that is characterized by few clouds, limited rainfall, high solar insolation and high evaporation rates; in short, creating the arid terrestrial desert biome that dominates the region (Chap. 3; Boer 1997). While this has only limited impact on the marine systems of the UAE's Sea of Oman waters, which are buffered by its greater depth and substantial mixing with the Indian Ocean (see below), these atmospheric conditions exert a major influence over the marine environment of the Arabian Gulf.

4.3.2 Sea Temperatures on the Gulf Coast

Due to its shallow depth and limited exchange through the narrow Strait of Hormuz, atmospheric conditions have dramatic impacts on Gulf waters. This is particularly true of the extensive shallow southern Gulf basin that borders Abu Dhabi. Seasonal sea temperatures are extreme (Fig. 4.7). Summer sea temperatures regularly exceed 34 °C for several months, and can exceed 35.5 °C for a week or more during extreme heat waves (Riegl et al. 2011; Burt et al. 2019), while 6 months later winter sea temperatures plummet below 20 °C for several months, reaching as low as 15 °C during winter shamals (J.Burt, unpubl. data). This seasonal variation is the largest annual temperature range occurring in marine systems globally (Sheppard et al. 1992; Coles 2003) and represents an extreme physiological challenge for the UAE's marine organisms that had evolved in more thermally stable tropical environments before colonizing the Gulf (D'Agostino et al. 2020; Smith et al. 2022). Currently the shallow, enclosed Gulf is warming at more than double the global average rate (Lachkar et al. 2021), and recurrent marine heat waves are already having substantial adverse impacts on marine organisms and ecosystems across the UAE's southern Gulf waters (see Chap. 11; Burt et al. 2019).

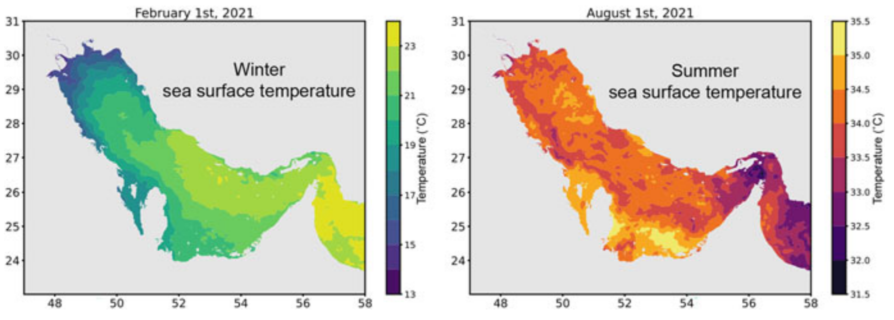

Fig. 4.7 Sea surface temperature map from February 1st, 2021 (left) and August 1st, 2021 (right) illustrating the dramatic shifts in sea temperature that occurs between winter and summer in the Arabian Gulf, while those in the Sea of Oman are less extreme. Data source: GHRSST project (JPL MUR MEaSUREs Project 2015), shared per the PO.DAAC open data policy

4.3.3 Gulf Sea Temperatures and Dissolved Oxygen

High summer water temperatures have been implicated in affecting the oxygen dynamics of the UAE's Gulf waters. Virtually all marine organisms are 'cold-blooded' ectotherms whose metabolism is directly tied to water temperature. As temperature climbs, so too does metabolic demand for oxygen by marine organisms. This is generally not an issue during the daytime as photosynthesis by microscopic phytoplankton, algae and corals can compensate for this demand by producing oxygen, but when photosynthesis ceases after sunset the metabolic demand for oxygen can exceed availability, leading to the occurrence of low oxygen conditions (hypoxia) and in rare cases near absence of oxygen (anoxia). Recent research has shown that near-shore coral reefs in Abu Dhabi regularly experience hypoxia for several hours in the pre-dawn period during summer, occasionally dipping to anoxic levels (Fig. 4.8) (de Verneil et al. 2021). Such conditions likely represent a dire—and previously unrecognized—stressor for marine organisms along the UAE's southern Gulf coast, particularly for sedentary or non-mobile organisms such as urchins and corals that are unable to relocate out of the affected area. Alarmingly, hypoxia is also increasing at the Gulf-wide scale as a result of climate change. The near-bottom hypoxic zone in the central Gulf has increased in area from 20,000 km^2 in the 1980s to over 30,000 km^2 in the 2000s (Lachkar et al. 2022), representing a major threat to the future of fisheries and marine ecosystems as it grows towards the UAE's Gulf coast.

4.3.4 Salinity-Driven Circulation in the Gulf

Evaporation in the Gulf far exceeds precipitation and river run-off. On a yearly average, the net evaporation amounts to 1105 million cubic meters per day (± 270) (Johns et al. 2003). The net evaporation has a strong seasonal cycle with an amplitude of 50% the yearly average. The timing of the cycle has a great variability

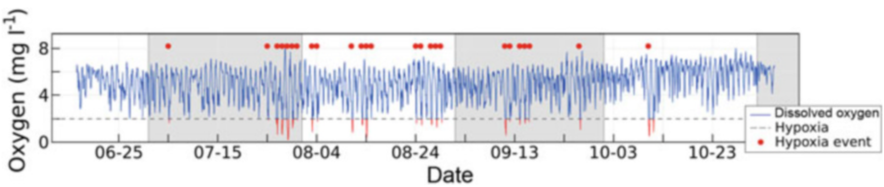

Fig. 4.8 Dissolved oxygen levels (blue line) recorded on Dhab'iya reef, Abu Dhabi, between June and October 2019 (white/gray shading denotes different months), where daily fluctuations between daytime (higher) and night (lower) are due to the balance of photosynthesis and respiration by marine organisms. The dashed line indicates the low-oxygen (hypoxia) threshold of 2 mg/L, under which most marine organisms would suffer hypoxic stress (red lines, bottom). Red dots (top) indicate when a hypoxic event has occurred; 26 events were observed between July and October 2019, many lasting several hours. Modified from Fig. 4.2 in de Verneil et al. 2021 (CC-BY-4.0)

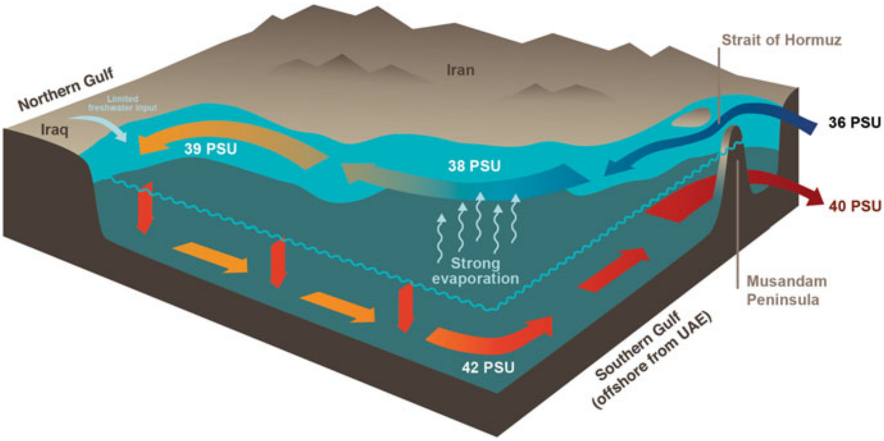

Fig. 4.9 General circulation pattern of Gulf waters, illustrating the importance of evaporation in producing salinity-driven currents. Incoming surface waters are oceanic, and become increasingly saline through evaporation as they move north along the Iranian coast. The denser, saline water then sinks and flows across the bottom (mixing with the incoming water to somewhat reduce bottom-water salinity), exiting into the Sea of Oman. This general circulation passes offshore of the UAE coast, where high salinity (≥42 PSU) occurs in the shallow evaporative basin of the southern Gulf. Modified from Fig. 2.5 in Sheppard et al. 1992 and reprinted with permission of Elsevier

between years, but generally the minimum evaporation occurs in March, and the maximum in November, when Gulf waters still warm from the summer heat are exposed to cool, strong winds (Paparella et al. 2022). Evaporation of surface waters increases their salinity and therefore their density, and they sink downward in the water column. This drives a vigorous overturning circulation in the Gulf, which is characterized by a reverse estuarine circulation through the Strait of Hormuz. Surface water enters the Gulf from the Indian Ocean at normal oceanic salinity (36 PSU) and forms the north westward-flowing Iranian Coastal Current (ICC) which travels against the prevailing winds up to Kuwait. A return, wind-driven current flows along the eastern Saudi Arabian and Qatari coast, then moves towards the Strait of Hormuz, leaving the UAE shallows mostly unaffected. The Gulf is thus dominated by a basin-wide cyclonic (counter-clockwise) circulation. Dense, salty water is formed by evaporation in the shallowest regions of the Gulf. It then sinks into the deeper part of the Gulf, where it follows a broad, gently sloping valley until it flows out into the Sea of Oman (Fig. 4.9). The Kuwait branch of this circulation has been directly observed (Swift and Bower 2003), while the branch close to the UAE shallows has only been studied by means of ocean circulation models (Al-Shehhi et al. 2021).

4.3.5 Seasonal Eddies on the UAE's Gulf Coast

In addition to Gulf-wide processes driven by salinity, smaller meso-scale (ca. 50–100 km) vortices (eddies) can develop in summer as a result of summer shamal winds. During the late spring and the summer the deepest part of the Gulf develops a thermocline, where warm surface water sits on top of cooler, deep water. This two-layer stratification is favorable to eddy-formation. Thus, every year from late spring until the end of the summer, a small number of meso-scale cyclonic (counter-clockwise) vortices appear in the central Gulf offshore from the UAE (typically four), characterized by current speeds of about 0.5 m/s (Thoppil and Hogan 2010b). These highly unsteady vortices vigorously mix the surface waters of the central Gulf, and have been suggested to be important for the long-distance transport of coral larvae from the diverse and healthy reefs of Iran to various parts of the UAE's Gulf coast,where reefs have become increasingly degraded in recent years and require supply of larvae from external sources to aid their recovery (Burt and Bauman 2019; Cavalcante et al. 2016, 2020; de Verneil et al. 2021).

4.3.6 Spatial and Seasonal Variation in Gulf Salinity

The physical and biological oceanography of UAE waters is poorly known. All of the oceanographic cruises conducted in the last 60 years have focused on the deepest part of the Arabian Gulf, and only two have ventured close to the UAE coastline (Al-Yamani and Naqvi 2019). However, the presence of a southerly gradient of increasing salinity towards the UAE coast is presumed and is supported by satellite-based measurements (Fig. 4.10), although these remain prone to error in shallow

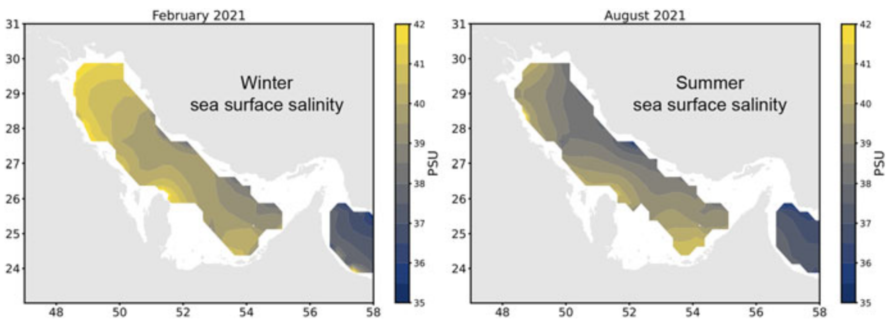

Fig. 4.10 Monthly averaged sea surface salinity in February (left) and August (right), 2021. The uncertainty far from the coastline is <1 psu but it may grow in excess of 5 psu at the land-sea edge (JPL CAP 2020). Areas with no data available represent areas where cell sizes are insufficient for modeling salinity. Paradoxically, surface salinity is higher in early winter (February), as a result of the peak in evaporation in late autumn. Data source: SMAP satellite (JPL CAP SMAP Sea Surface Salinity Products Ver 5.0 2020), shared per the PO.DAAC open data policy

waters and close to the coastline. *In situ* measurements show that water masses close to the UAE coastline may reach 44 PSU (compared with normal oceanic salinity of 36 PSU), while coastal lagoons and embayments regularly exceed 50 PSU, characterizing these areas as hyper-saline (Evans et al. 1973).

Salinity can represent a major stressor for marine fauna, and the hyper-salinity of southern Gulf seawater has been associated with dwarfism in fish and various invertebrate animals as a result of the metabolic costs of coping with osmotic stress (Price 1982; D'Agostino et al. 2021). There have been suggestions that growing desalination activities, particularly in combination with climate change, may exacerbate these salinity issues at the Gulf wide-scale (Le Quesne et al. 2021). However, recent modeling efforts show that natural evaporation is a far more important contributor to salinity at the basin-wide scale (Paparella et al. 2022), although localized impacts immediately adjacent to desalination plant outfalls in the Emirates are likely to be significant at scales of a few hundred meters or less (Lattemann and Höpner 2008).

4.4 The UAE's East Coast: A Sub-Tropical Indian Ocean Margin

The UAE's east coast is a much more ordinary and more benign marine environment than the Arabian Gulf. It constitutes a small segment of the much larger Indian Ocean margin and is influenced by currents driven by the Indian Ocean Monsoon cycle. The winter Northeast Monsoon pushes waters southward along the coast, and induces subsidence (sinking of the surface waters) along the continental shelf. The summer Southwest Monsoon reverses the direction of the coastal current and induces upwelling (uplift of deep waters) along the coast (Schott et al. 2002). Summer upwelling of deep, cold waters is particularly strong all along the southern Oman coast, along the Arabian Sea, causing a pseudo-high-latitude effect on marine systems along that coast, with conditions cooler than would be expected for its location (Sheppard et al. 1992). This results, among other things, in the anomalous association of dense kelp beds mixed with coral communities (Claereboudt 2019). The coastal Oman current does not penetrate as far north into the Sea of Oman as the UAE coastal waters, but it breaks into several highly variable meso-scale eddies, which mix the saline waters exiting from the Strait of Hormuz with the Indian Ocean surface waters (Pous et al. 2004).

While the Sea of Oman coast of the Emirates is exposed to extreme air temperatures and aridity, the presence of deep, well-mixed offshore waters adjacent to the coast results in environmental conditions that are far more congenial to most marine life than occur on its Arabian Gulf coast. Summer upwelling, and winter subsidence, although mostly occurring in southern Oman, are nevertheless capable of mitigating the amplitude of the seasonal sea surface temperatures fluctuations along the UAE coast of the Sea of Oman, albeit to a lesser extent than occurs in southern Oman. In

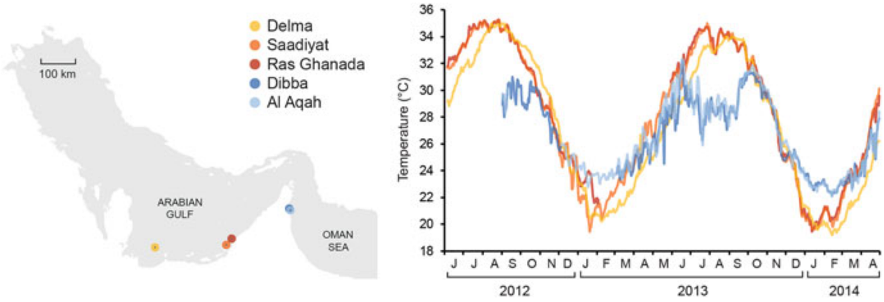

Fig. 4.11 Sea temperature profile at three sites on the UAE's Arabian Gulf coast and two on the Sea of Oman coast from 2012 to 2014. Temperature extremes (both warm and cool) and variability are higher in the Arabian Gulf due to its shallow depth and restricted circulation, while temperatures in the Sea of Oman are more moderate as a result of mixing with deeper offshore water, particularly during the summer monsoon. Modified from Fig. 4.1 in Howells et al. (2020), reprinted with permission

general, sea temperatures are approximately 3–5 °C cooler in the summer (ca. 32 °C), and similarly warmer in the winter (ca. 23 °C), on the UAE's east coast, resulting in far less extreme annual ranges in sea temperatures that are observed on the Arabian Gulf coast (Fig. 4.11) (Reynolds 1993). Similarly, tidally-driven cooling can occur on very short timescales on the east coast, with temperatures dropping by up to 6 °C in 3 h as tides push deep, cold water up onto coastal shoals, with important implications for heat-sensitive ecosystems such as coral reefs (Coles 1997).

4.5 Winds in a Regional Context

One of the principal localized wind systems of importance to the Emirates is the 'shamal' winds (Arabic for north), north-northwesterly winds which funnel down the length of the Gulf. These air masses form as high pressure systems over the Anatolian area of the eastern Mediterranean and flood over Iraq and Kuwait at ground level before crossing the Arabian Gulf as they flow towards a low pressure system developed over the Iranian plateau (Perrone 1979).

Regional physiography plays an important role in structuring these winds, with the Zagros mountain range in Iran serving as an important barrier, funneling and concentrating the strength of the shamal system over the Arabian Gulf on the western flank of the mountains. Wintertime shamal events are occasional, mainly occurring from late January to March. They last up to 5 days and may exceed gale strength, with wind speeds of over 50 km/h, and gusts of over 100 km/h (Thoppil and Hogan 2010a). The weaker summer shamal winds, although highly variable from year to year, are recurrent from May until August, with a recognizable seasonal onset and termination which gives them monsoon-like characteristics (Rao et al. 2003, Yu et al. 2016).

4.5.1 Winds and Waves on the Gulf Coast

Due to the long, unbroken length of the Arabian Gulf, shamal wind events can generate large waves and storm surge across much of the UAE's Arabian Gulf coast, although the Qatar peninsula somewhat shelters areas furthest west and the presence of the Zagros mountains and the oblique curve of the coastline relative to the wind direction also reduces their influence towards Ras Al Khaimah (Alsharhan and Kendall 2003; Vieira et al. 2020). In more exposed areas, such as around the cities of Abu Dhabi or Dubai, sustained (3–5 day) shamal events often lead to waves in excess of 2.5 m, reaching over 6 m in severe 1-in-100 year storms (Mocke and Smit 2008). When storms coincide with high tides, they can induce a storm surge that floods low-lying areas along much of the UAE's Gulf coast, including nearshore urban areas and roadways (El-Sabh and Murty 1989; Mocke and Smit 2008; Smit et al. 2008; Vieira et al. 2020; Aboobacker et al. 2021).

Storm-generated wave action is also sufficient to suspend sea-bottom sediments in near-shore areas along the UAE's Gulf coast, with suspended sediments resulting in turbid, milky-looking water that can last for several days after the cessation of winds (Fig. 4.12) (Van Parys 2006). Such suspended sediments represent a severe stressor for many marine organisms (Riegl and Branch 1995), and near-shore coral communities along the UAE Gulf coast reflect this with an unusually high abundance of sediment-tolerant species (Riegl 1999; Burt et al. 2010).

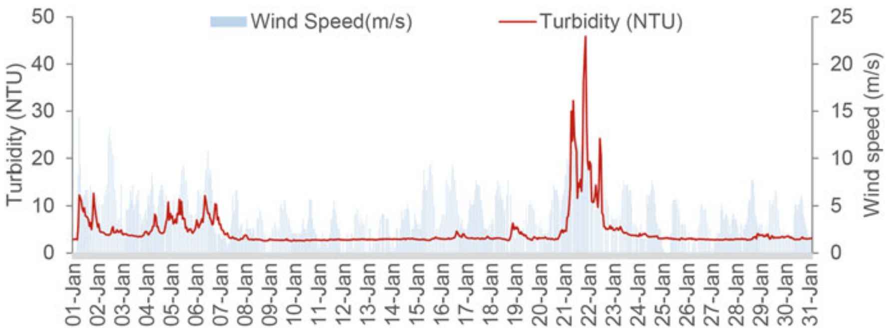

Fig. 4.12 Turbidity (red line) along the southern Gulf coast of the UAE often increases in response to 'shamal' wind events (winds in blue), when wind speed persists above 10 m/s for sustained periods; below this, 'breeze' conditions are not sufficient to cause waves to turn over the sea-bottom sediments. At the left is a period of moderate but recurrent shamal winds (01–06 January), with a sustained shamal event from 21–23 January. Data from January 2022 at Dhab'iya reef, Abu Dhabi. (J. Burt, unpubl. data)

4.5.2 The Importance of Shamal Winds for Cooling the Gulf

Shamal winds are extremely important in controlling water temperatures in the southern Gulf during the summer. Much like blowing on a coffee cools it through evaporative heat loss, summer winds can pull tremendous amounts of thermal energy out of the Gulf. A single shamal event can cool summer sea temperatures by 2–3 °C through evaporation, with these cooler temperatures persisting for several days after wind cessation (Fig. 4.13a; Paparella et al. 2019). This has important implications in the southern Arabian Gulf as most marine organisms there live very close to their upper thermal limits each summer, and any extended period of calm can lead to temperatures that push marine fauna beyond their physiological thresholds. As an example, in the summer of 2017 calm conditions persisted for over 5 weeks and allowed sea temperatures to reach as high as 37.7 °C, causing widespread coral bleaching and the loss of over two-thirds of corals across the UAE's Gulf coast reefs (Fig. 4.13b,c; Burt et al. 2019). Whether continuing climate change will produce more or fewer summer shamal wind events remains uncertain (Paparella et al. 2019), but if summer shamals become less common it is nearly certain that this will have substantial negative impacts on already stressed marine systems on the UAE's Gulf coast.

Winds can also play an important role on the UAE's Sea of Oman coast, but the mechanism and effect differs. Even on the east coast, shamal winds are a predominant feature of the wind climate for much of the year, but with the presence of the Hajar mountain range and the land serving as barrier to wind-driven wave development, these northerly winds have a limited impact on the marine environment in the Sea of Oman. Instead, the marine system is much more strongly influenced by the occurrence of the summer monsoon and associated cold-water upwelling, when

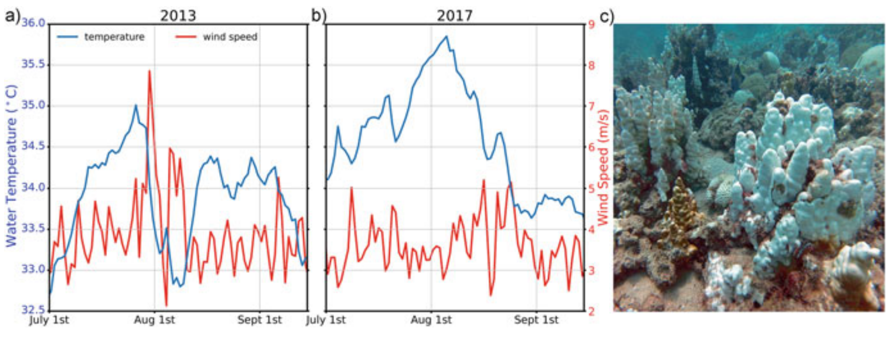

Fig. 4.13 The influence of summer winds on seawater temperatures and the impacts of calm conditions. (**a**) Sea temperatures in summer 2013 show dramatic declines after the onset of a shamal wind event, while (**b**) extended weak breeze conditions in summer 2017 resulted in temperatures rising to extreme levels due to a lack of evaporative cooling. In consequence, (**c**) coral bleaching was widespread across the Gulf coast of the UAE, leading to loss of over two-thirds of corals by October 2017. Graphs modified from Fig. 4.4 in Paparella et al. (2019) and reused under Creative Commons license (CC-BY-4.0)

winds shift from being predominantly from the northwest and instead become dominated by east-southeasterly winds that travel up the coast of Oman and across the eastern emirates of the UAE from late June through to mid-October.

4.6 Tides in the Emirates

Variations of sea-level height on time scales ranging from hours to weeks are commonly called ‘tides’. All tides have a wave-like nature, and are strongly affected by depth and coastal features such as channels, islands, and sills. The name ‘tides’, however, lumps together different phenomena, stemming from different causes: seiches, meteotsunamis and astronomical tides.

In enclosed or semi-enclosed basins, the action of winds and atmospheric pressure differences may induce large-scale oscillations of the water masses, producing waves with wavelengths comparable with the size of the basin. These are called ‘seiches’, the best known ones being those occurring in the Adriatic sea, because they cause the high waters in Venice. Seiches have been observed in the Gulf (Afshar-Kaveh et al. 2020), but have not been extensively studied.

Meteotsunamis are also due to resonances between atmospheric features (typically a fast-moving front) and long-wavelength sea waves. But, just like an ordinary tsunami, they take the form of a fast-moving wave, which, in proximity to a coastline, turns into a destructive bore. The latest of such events occurred in the Gulf on 19 March 2017, resulting in a bore up to 3 m tall that flooded about 100 km of coastline in the southeastern Bushehr province of Iran (Kazeminezhad et al. 2021). The very shallow waters of the UAE’s Gulf coast make the occurrence of severe meteotsunamis unlikely, because a large portion of the energy would be dissipated through friction with the sea-bottom offshore from the coast. The UAE’s east coast is also unlikely to experience destructive waves triggered by atmospheric forcing, but for the opposite reason, because the great depth makes a resonance between the atmospheric forcing and the ocean long waves nearly impossible to attain.

Proper tides (AKA astronomical tides) are generated by the perturbation of the Earth’s gravitational field caused by the Moon and the Sun. These perturbations may be expressed as the sum of a small number of periodic constituents, each characterized by a well-defined period. The dominant tidal constituent is due to the Moon, and it is called ‘M2’, which produces a rise and fall of the waters approximately twice a day. M2 is thus called a ‘semidiurnal’ tide. Many other constituents, each with its own well-defined period, contribute to the total astronomical tide. The relative importance of each component is determined by the latitude and by the shape of the bathymetry and of the coastline. The Gulf is one of the few places in the world where a diurnal constituent (that is, a constituents having a period close to 1 day) attains a magnitude comparable with that of M2. The two components contributing the most to the total astronomical tide in the Gulf are the Principal Lunar Semidiurnal M2, with a period of 12.421 h (Fig. 4.14), and the Lunar Diurnal K1 with a period of

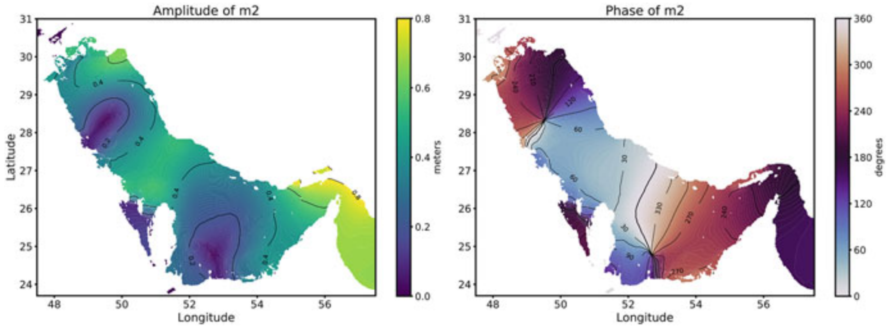

Fig. 4.14 Elevation amplitude (left: height above average sea level) and co-tidal lines (right) of the M2 semidiurnal tidal component in the Gulf. Data from the 1/60 degree Arabian Sea TPXO barotropic tide model (Egbert and Erofeeva 2002), reused under the terms of use for research

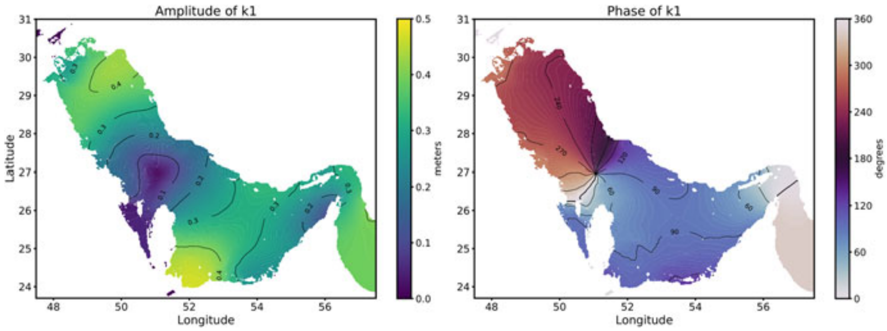

Fig. 4.15 As in Fig. 4.14, but for the K1 diurnal tidal component. The interaction of the semidiurnal and diurnal tidal forces illustrated in Figs. 4.14 and 4.15 is the primary determinant of tidal patterns in the Arabian Gulf. Data from the 1/60 degree Arabian Sea TPXO barotropic tide model (Egbert and Erofeeva 2002), reused under the terms of use for research

23.934 h (Fig. 4.15). The Principal Solar Semidiurnal S1 (12 h) and Lunar Diurnal O1 (25.819 h) also give small contributions to Gulf tides.

When all the components reach their maximum simultaneously, the height of the astronomical tide on the east coast of the UAE slightly exceeds 3 m. In addition (and somewhat singularly), tides are synchronized along the whole of the east coast, including that of northern Oman (i.e. when it is high tide in Dibba, it is also high tide in Fujairah and in Muscat).

In the Gulf (as along most coastlines), the tidal cycle does not rise and fall simultaneously at all locations. When the diurnal K1 is at its maximum, say, in Bahrain, it will be already dropping in Qatar, and will be halfway down along the UAE coastline, and at its lowest near the estuary of the Mond river (on the north-western Iranian coast near Bushehr), while rising and halfway to its maximum in Kuwait. The points where a tidal constituent has the same phase are called co-tidal lines. The co-tidal lines of K1 are shown in Fig. 4.15b, (right panel). They radiate from a single central hub, which is called an amphidromic point, like rays of a wheel. As time goes on, the K1 tidal wave rotates around this point in a counter-clockwise direction, around the Gulf. The height of the tidal wave is zero at the amphidromic point, and increases moving away from it. The semidiurnal M2 tidal constituent in the Gulf has two amphidromic points: one in the western part of the UAE shallows, and the other in the northern part of the basin, off the Saudi coast (Fig. 4.14b). The interaction of the various tidal constituents (e.g. K1 and M2), each with its own different period and co-tidal lines, produces surprisingly complicated tidal patterns that change from place to place throughout the Gulf.

The largest height (approximately 4 m) of the total astronomical tide is attained in the northernmost part of the Gulf, and in the Strait of Hormuz. In the western part of the UAE shallows along the Abu Dhabi coast, the tidal height is lowest, generally less than 2 m. This is still sufficient to generate very strong currents where the coastal features choke the free flow of the tide. For example, in the channel between the mainland and Sir Bani Yas Island, tidal currents in excess of two knots are the norm.

Even though tides are periodic in time, a water parcel starting at any given position would hardly return to that same position at the end of the tidal cycle, even neglecting the effect of all other currents. This displacement of water parcels, over a large number of tidal cycles, is known as residual tidal current. This is not very high in the central part of the Gulf, but it can reach 5 cm/s in the UAE's Gulf coast shallows, where the residual tidal current may induce a net transport from west to east. Given that the eddying, wind-driven currents that dominate the central Gulf in the spring and summer are unable to reach the shallows, tides and evaporation-driven flows are thus the main mechanism that transport the water in and out of the shallows.

4.7 Conclusion

The marine environment of the Emirates is among the most unique and interesting on earth, principally due to the unusual climatic conditions, geomorphology and hydrology that characterize the Arabian Gulf, and make it one of the most extreme and variable marine environments known. Those conditions are emphasized by comparison with the UAE's east coast, along the Sea of Oman, which is largely characterized by normal oceanic conditions for the northwest Indian Ocean margin. Those differences explain the differences in composition, diversity and ecology of the marine communities that occur on the two coasts of the Emirates, topics that will be explored in detail in subsequent chapters.

4.8 Recommended Readings

For further information on the marine environment of the UAE written towards a broad audience we recommend Sheppard et al. (1992), which covers the Arabian region broadly, and Riegl et al. (2012), which specifically focuses on the Arabian Gulf and includes a variety of data from the Emirates and is available in both print and online formats.

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