Environmental Setting and Temporal Trends in Southeastern Gulf Coral Communities

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4.1 Introduction

The majority of coral reefs are found in tropical environments between 25°N and 25°S, where typical seawater temperatures and salinities are between 18°C and 31°C and 34–37 ppt, (Kleypas et al. 1999; Veron 1986). The marine environment of the southeastern Arabian Gulf is singularly harsh; the coral communities in this high-latitude region (i.e. between 24°09′N and 25°40′N) are exposed to natural conditions that exceed threshold limits of corals elsewhere in the world, with temperature ranges between 14°C and 36°C (Kinzie III 1973; Shinn 1976) and salinities above 40 ppt. Less than one-third of the scleractinian species that are found in the neighboring Gulf of Oman have adapted to survive in the Arabian Gulf (e.g. *Acropora* spp., *Porites* spp., faviids and siderastreids) (Riegl 1999; Coles 2003; Rezai et al. 2004; Claereboudt 2006). Other benthic taxa that are common in the Gulf of Oman but are absent from the Arabian Gulf include the coral genera *Montipora*, *Pocillopora*, and *Goniopora* spp., fungiids, oculinids, alcyonaceans, and massive sponges. The adaptations of some taxa to extremes of temperature and salinity and the exclusion of other taxa are of interest to scientists studying the impacts of global climate change on coral reefs and other marine organisms.

The southeastern Arabian Gulf encompasses the coastal and offshore environments of the United Arab Emirates (UAE) and eastern Qatar (Fig. 4.1). The shallow-water coral communities are situated on discontinuous patches along the Qatari and Emirati coasts, near offshore islands and atop limestone domes. Assessments of the coral communities and their respective marine environments were conducted between 2005 and 2009 at multiple sites within Study Area "A", located offshore Qatar and Abu Dhabi (Fig. 4.1, Table 4.1a). These assessments have provided data that describe (i) the typical environmental regimes to which the corals are exposed and (ii) the structure of the recovering coral communities a decade after the mass mortality associated with the 1996 elevated temperature anomaly (Riegl 2002, 2003; Sheppard and Loughland 2002). Similar assessments were conducted in the adjacent northwestern Gulf of Oman within Study Area "B" (Fig. 4.1, Table 4.1b) where the same coral species as those in the Arabian Gulf, along with 60–70 additional species, are found.

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4.2 Environmental Setting

4.2.1 Temperatures

Temperature extremes have been recorded at various locations around the Arabian Gulf (Table 4.2), but little information is available regarding the "normal" conditions to which coral communities are exposed. As part of the assessments described herein, temperature recorders were deployed within Study Areas "A" and "B" approximately 0.5 m above the benthos. Daily mean temperature profiles for ten sites in the southeastern Arabian Gulf and two sites in the northwestern Gulf of Oman are shown in Figs. 4.2, 4.3, and 4.4. The data for the individual sites were combined to provide regional temperature profiles for the southeastern Arabian Gulf and the northwestern Gulf of Oman (Figs. 4.5 and 4.6). Spring cooling rates, autumn warming rates, maximum summer temperatures and minimum winter temperatures are listed in Table 4.3. Results indicated the following with respect to normal temperatures at sites in Study Area "A":

- Minimum daily means varied between the individual sites during the winter season (December 21–March 20), ranging from 16.5°C to 19.5°C (Figs. 4.2 and 4.3). The minimum daily mean for the southeastern Arabian Gulf region was 16.5°C, although this was not reached every year

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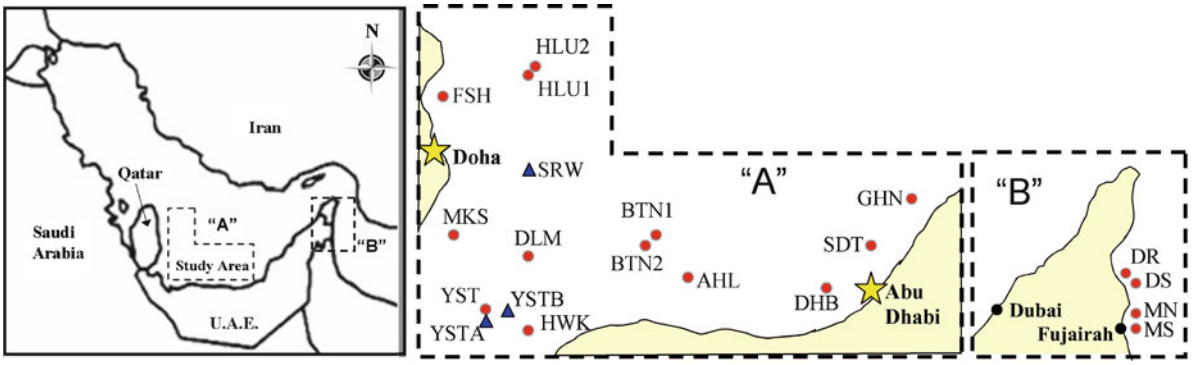

Fig. 4.1 Map of monitoring station locations. (*left*) Map of Arabian Gulf and surrounding region, study areas are outlined; (*center*) Study area "A" locations in the southeastern Arabian Gulf; (*right*) Study area "B" locations in the northwestern Gulf of Oman. *Circles* indicate monitoring station locations. *Triangles* indicate sites with temperature recorders only

Table 4.1 Descriptions of monitoring station locations

Station	Site name	Location	Territory	Depth (m)
(a) Southeastern Arabian Gulf				
HLU2	Halul East	Island	Qatar	4.8–5.2
HLU1	Halul South	Island	Qatar	4.5–5.3
FSH	Fasht Al-Ghabi	Coastal	Qatar	3.5–3.9
SRW	Shra'aw	Island	Qatar	5.0–5.5
MKS	Makaseb	Island	Abu Dhabi, UAE	2.1–5.5
YST	Yasat Ali	Island	Abu Dhabi, UAE	3.0–4.7
YSTA	Yasat Asfl	Island	Abu Dhabi, UAE	5.0–5.5
YSTB	Yasat Buoy #B-08	Offshore	Abu Dhabi, UAE	31
HWK	Hawksbill Reef	Limestone Dome	Abu Dhabi, UAE	7.0–8.5
DLM	Delma	Island	Abu Dhabi, UAE	5.3–5.6
BTN1	Bu Tinah North	Island	Abu Dhabi, UAE	1.8–3.6
BTN2	Bu Tinah West	Island	Abu Dhabi, UAE	2.0–3.5
AHL	Al Hiel	Island	Abu Dhabi, UAE	2.6–4.2
DHB	Dhabiya	Coastal	Abu Dhabi, UAE	6.4–7.2
SDT	Saadiyat	Coastal	Abu Dbahi, UAE	5.7–7.2
GHN	Ras Ghanada	Coastal	Abu Dhabi, UAE	7.6–8.5
(b) Northwestern Gulf of Oman				
DR	Dibba Rock	Coastal	Fujairah, UAE	5.1–7.1
DS	Dibba South	Coastal	Fujairah, UAE	6.7–8.1
MN	Mirbah, North	Coastal	Fujairah, UAE	4.5–6.9
MS	Mirbah South	Coastal	Fujairah, UAE	2.5–3.6

Table 4.2 Temperature extremes recorded from Arabian Gulf coral communities

Location	Latitude	Min (°C)	Max (°C)	Range (°C)	Source
Kuwait	29 N	13.2	31.5	18.3	Downing (1985)
Saudi Arabia	27 N	11.4	36.2	24.8	Coles and Fadlallah (1991)
Abu Dhabi	25 N	16.0	36.0	20.0	Kinsman (1964)
Qatar	24 N	14.1	36.0	21.9	Shinn (1976)
Abu Dhabi (Al Hiel)	24 N	14.9 (2008)	37.2 (2007)	22.3	This study – hourly records
Qatar (Shra'aw)	25 N	18.7 (2006)	35.4 (2006)	16.7	This study – hourly records

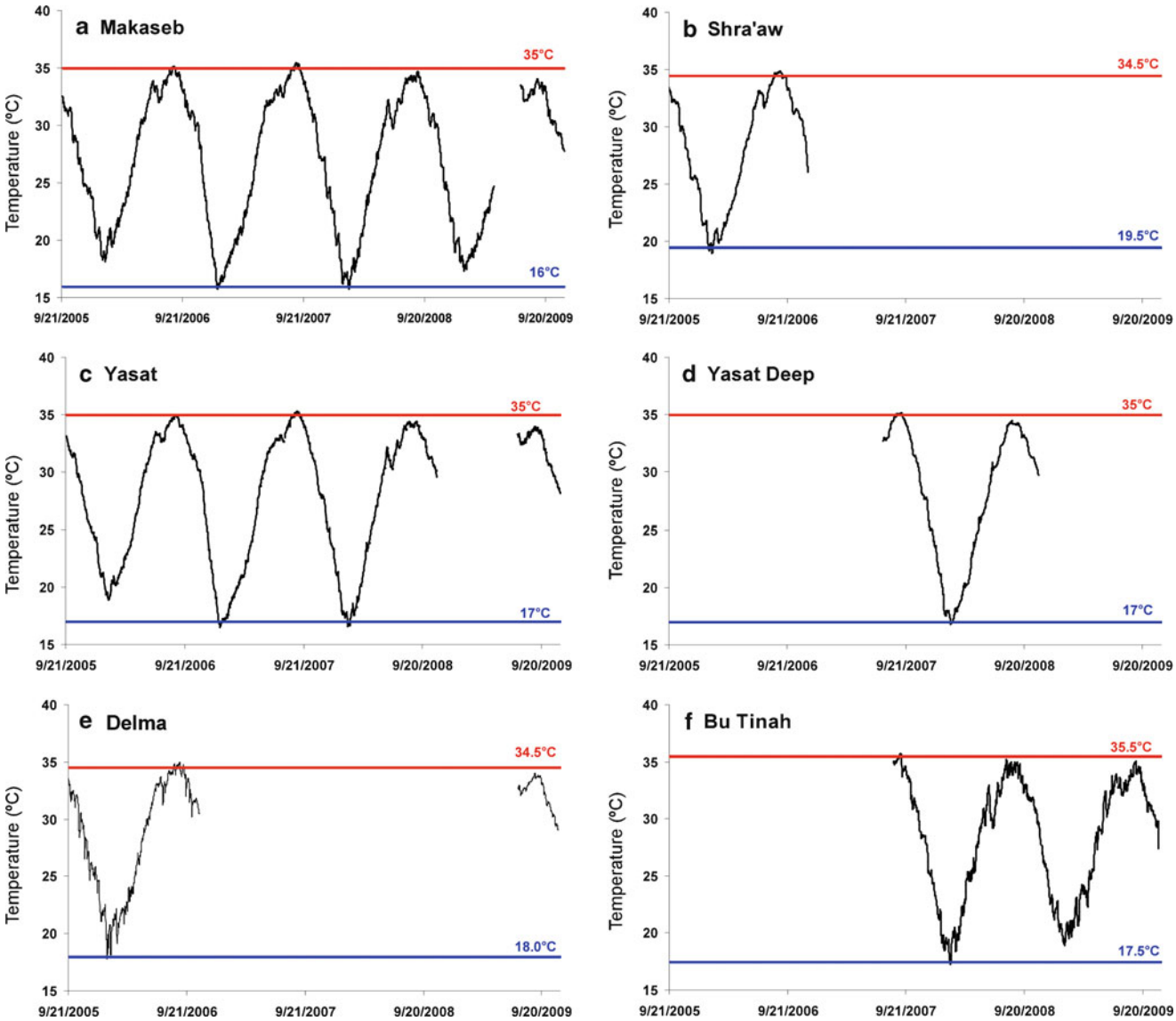

Fig. 4.2 (**a**–**f**) Daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at Abu Dhabi offshore islands (**a**, **c**, **e**, **f**); at a Qatar offshore island (**b**); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (**d**)

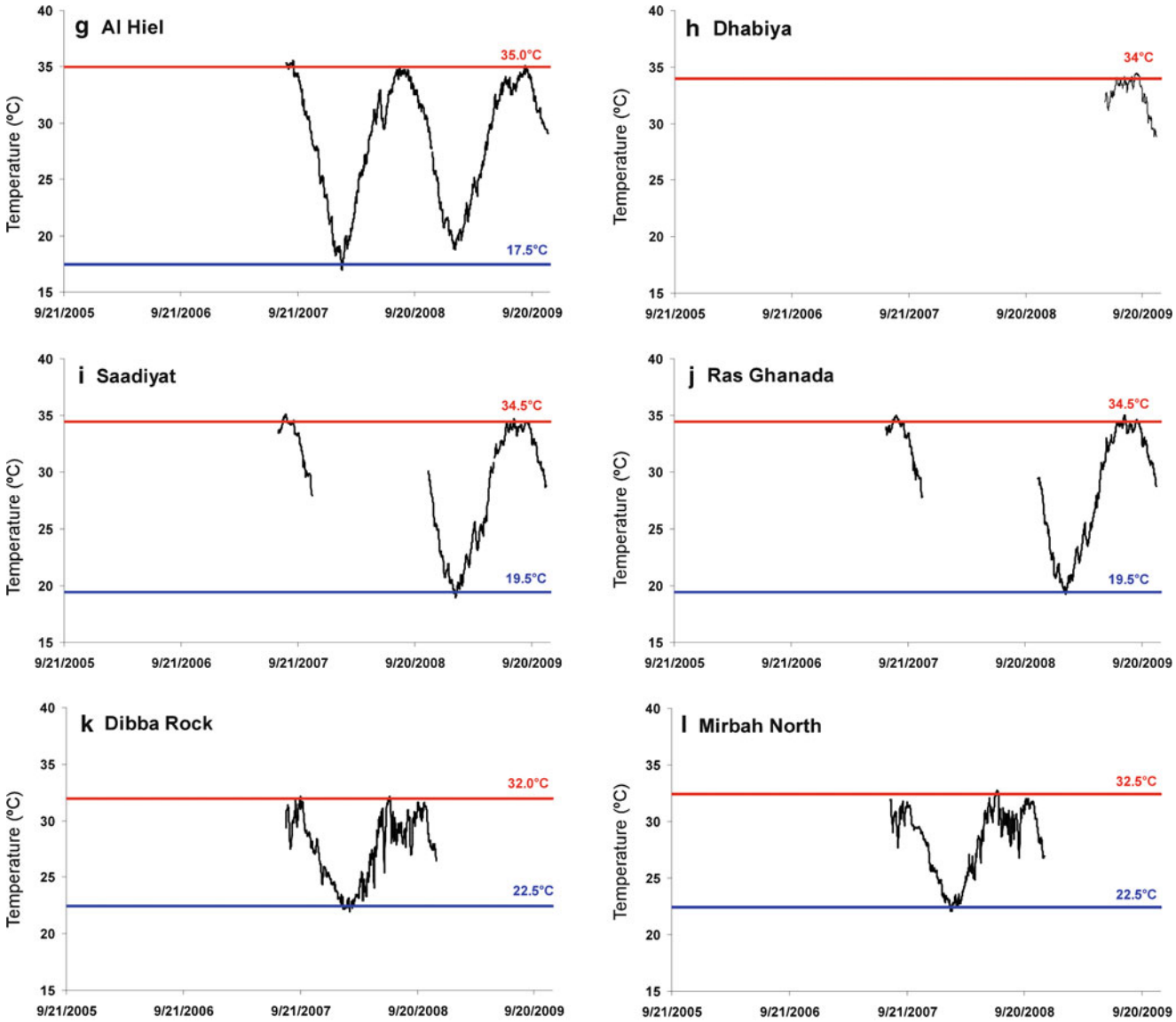

Fig. 4.2 (continued) (**g**–**l**) Daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at an Abu Dhabi offshore island (**g**); along Abu Dhabi coasts (**h**–**j**); and along Fujairah coasts (**k**, **l**)

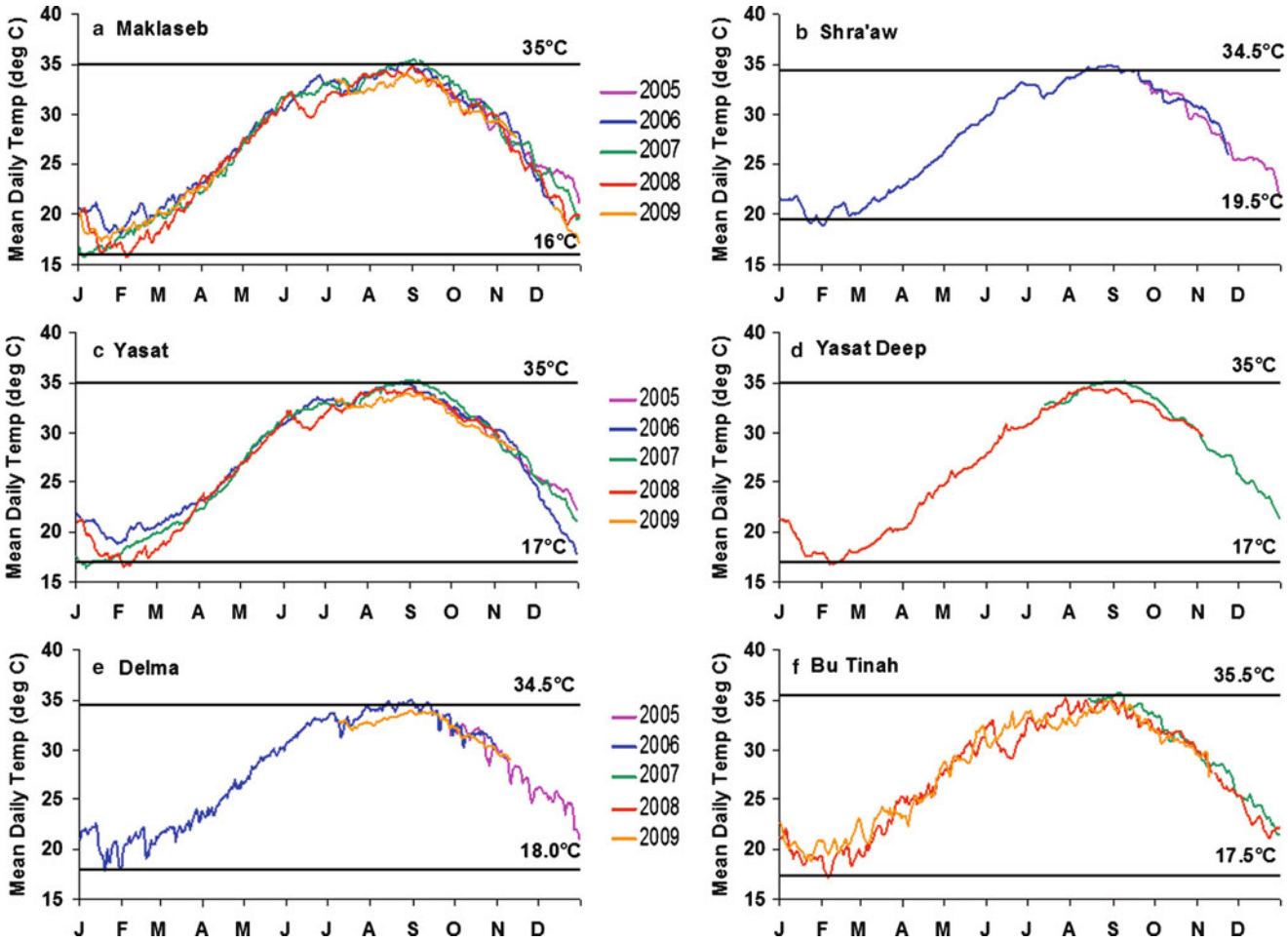

Fig. 4.3 (**a**–**f**) Daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at Abu Dhabi offshore islands (**a**, **c**, **e**, **f**); at a Qatar offshore island (**b**); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (**d**)

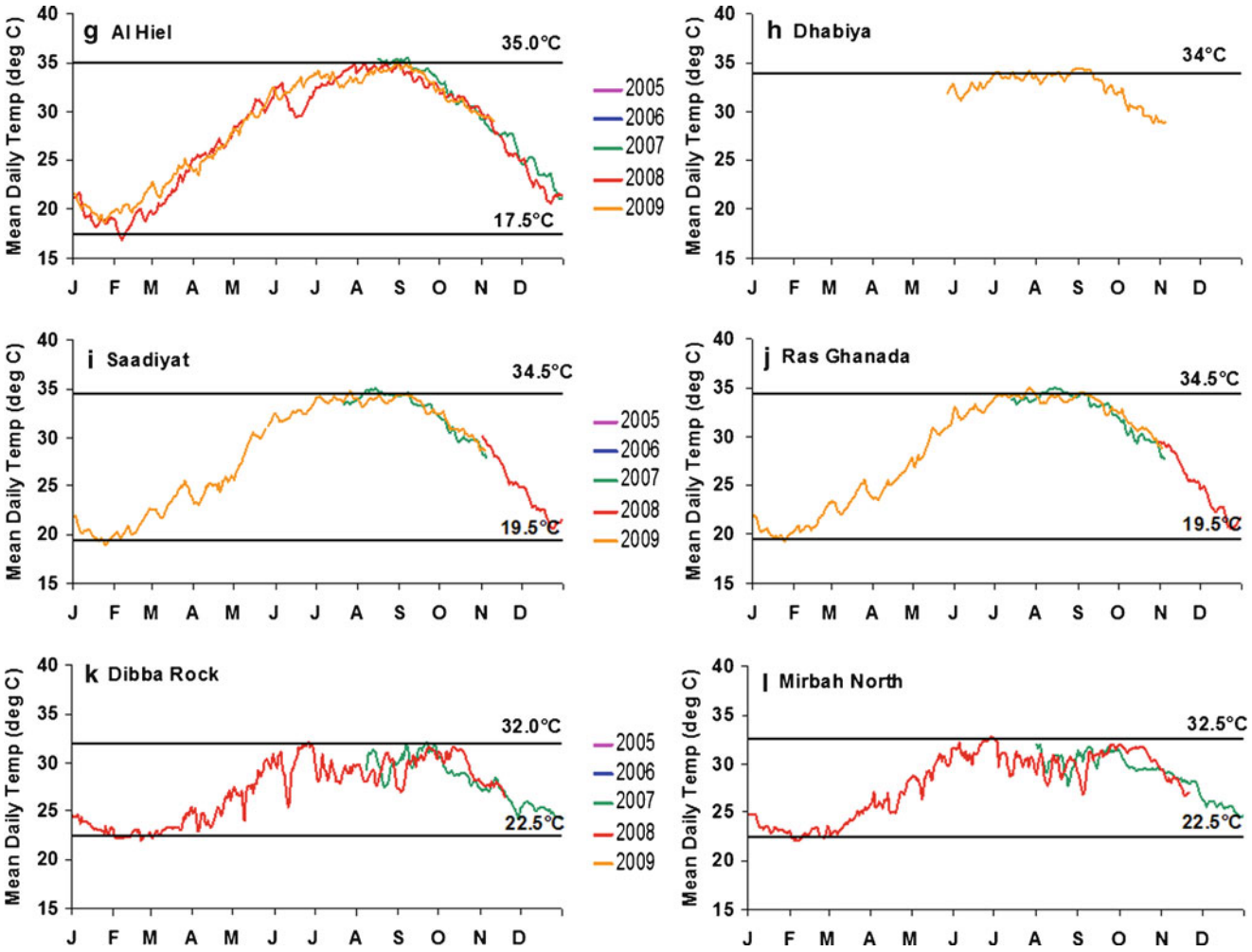

Fig. 4.3 (continued) (**g–l**) Daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at an Abu Dhabi offshore island (**g**); along Abu Dhabi coasts (**h–j**); and along Fujairah coasts (**k**, **l**)

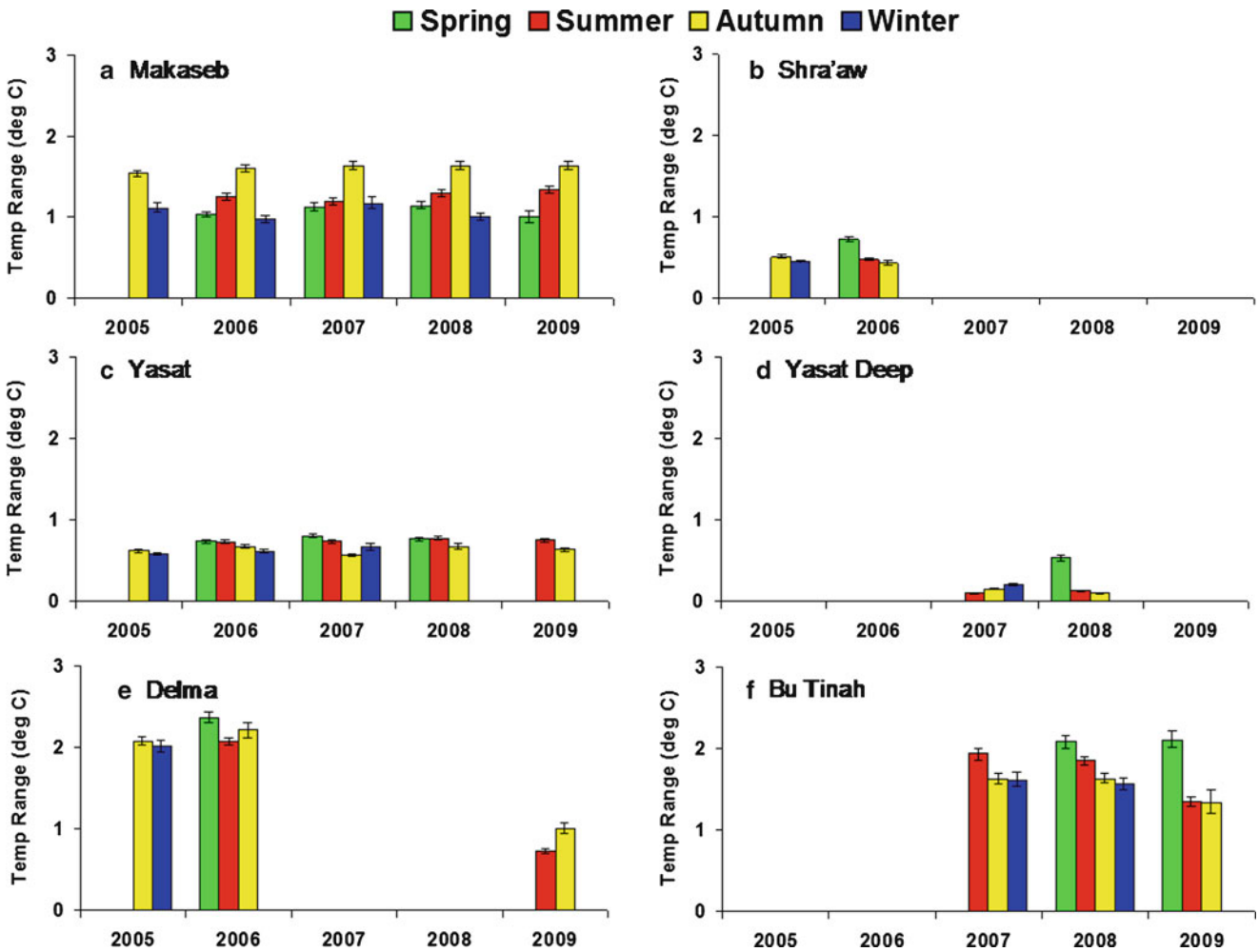

Fig. 4.4 (**a**–**f**) Mean daily temperature ranges by season (2005–2009). Temperature range is the difference between the maximum and minimum hourly records between 00:00 and 23:59 for each calendar day. Seasons are defined as spring (March 21–June 20); summer (June 21–September 20); autumn (September 21–December 20); and winter (December 21–March 20). Temperature loggers were deployed at Abu Dhabi offshore islands (**a**, **c**, **e**, **f**); at a Qatar offshore island (**b**); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (**d**)

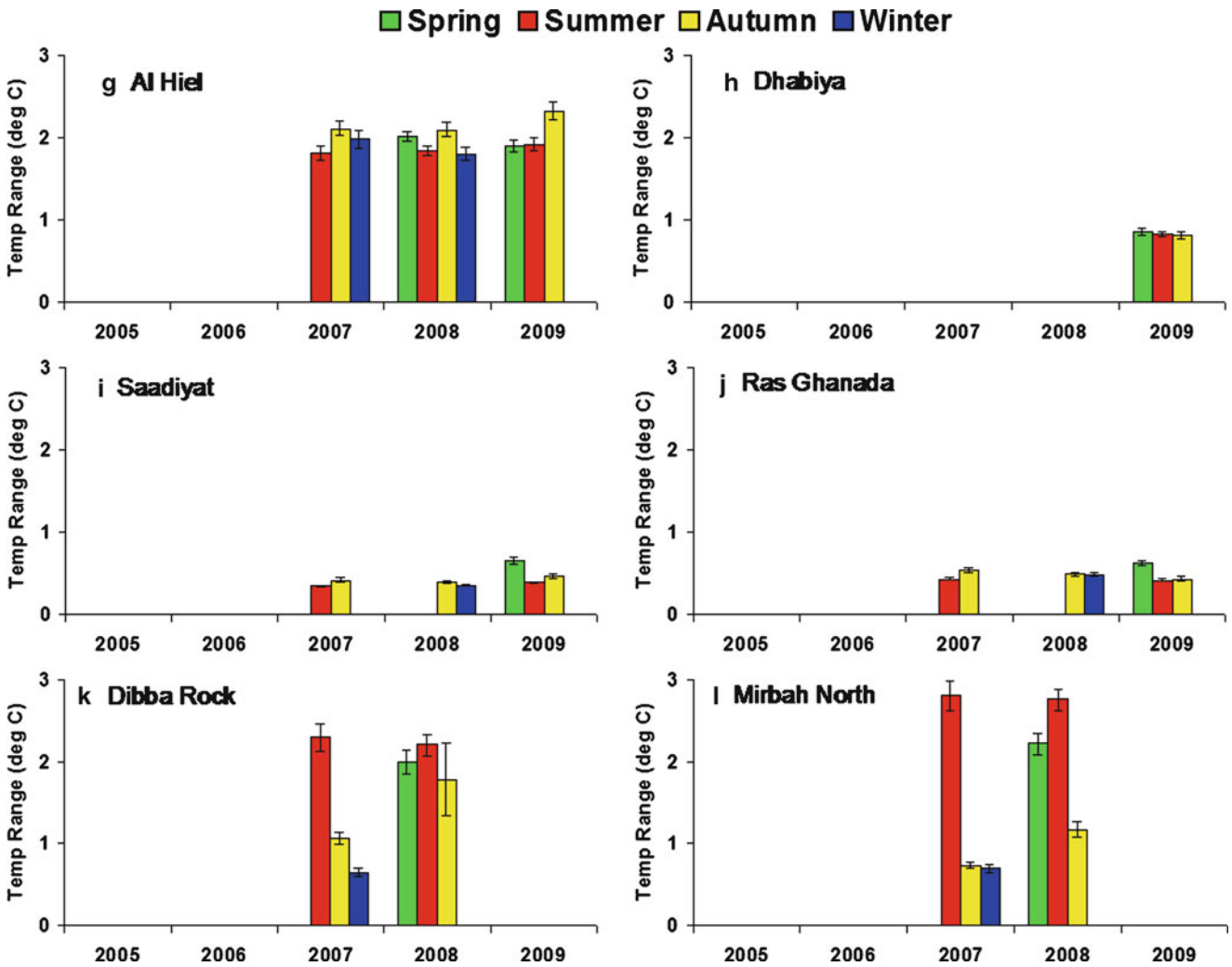

Fig. 4.4 (continued) (**g–l**) Mean daily temperature ranges by season (2005–2009). Temperature range is the difference between the maximum and minimum hourly records between 00:00 and 23:59 for each calendar day. Seasons are defined as spring (March 21–June 20); summer (June 21–September 20); autumn (September 21–December 20); and winter (December 21–March 20). Temperature loggers were deployed at an Abu Dhabi offshore island (**g**); along Abu Dhabi coasts (**h–j**); and along Fujairah coasts (**k**, **l**)

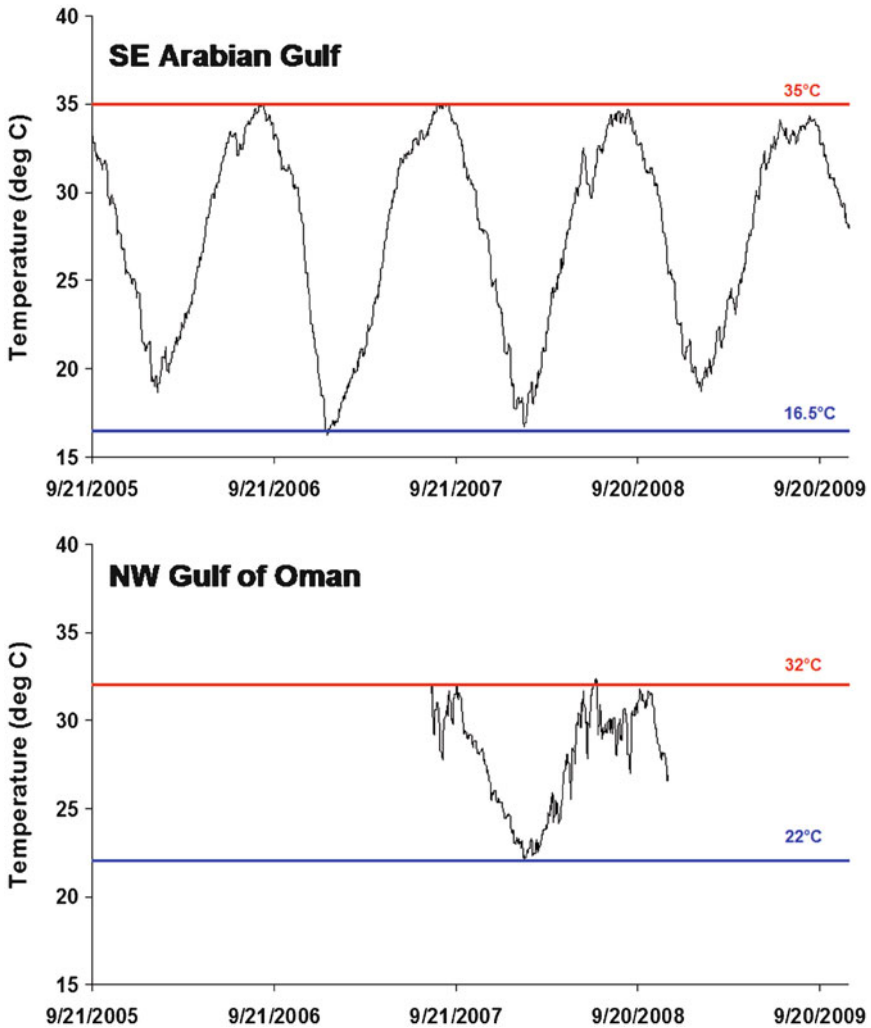

Fig. 4.5 Regional daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day, averaged across all sites (Arabian Gulf = 10 sites; Gulf of Oman = 2 sites). *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures

(Figs. 4.5 and 4.6). These data suggests that the southeastern Arabian Gulf gets colder in the winter than does the central Gulf for which Sheppard et al. (2010) presented HadSST1 data indicating a lower temperature limit of 20°C.

- Daily mean temperatures for the southeastern Arabian Gulf region during the winter season were typically within the range of 18.5–21.0°C (Table 4.3).
- The minimum hourly temperature recorded during this study was 14.9°C at Al Hiel in February 2008 (Table 4.3).
- The mean warming rates during the spring (March 21–June 20) were typically 0.09–0.13°C per day. The warming rates were nearly uniform across the individual sites in a given year. (Table 4.3)
- Temperature data collected near Yasat Island indicated that a thermocline formed during Spring 2008 as shallow waters warmed faster than deeper waters (Fig. 4.7). The lower water layer was 1–4°C colder than the upper water layer. Mixing of the thermally stratified layers was evident by rapid temperature declines in the upper layer during the late spring/early summer, after which the thermocline was no longer present. Similar rapid reductions in temperature occurred at the other sites during the same timeframe (June–July 2008) and during the other years (Fig. 4.2), indicating that the mixing of warmer surface waters with cooler deeper water is an annual and regional phenomenon.
- Maximum daily means varied between the individual sites during the summer season (June 21–September 20),

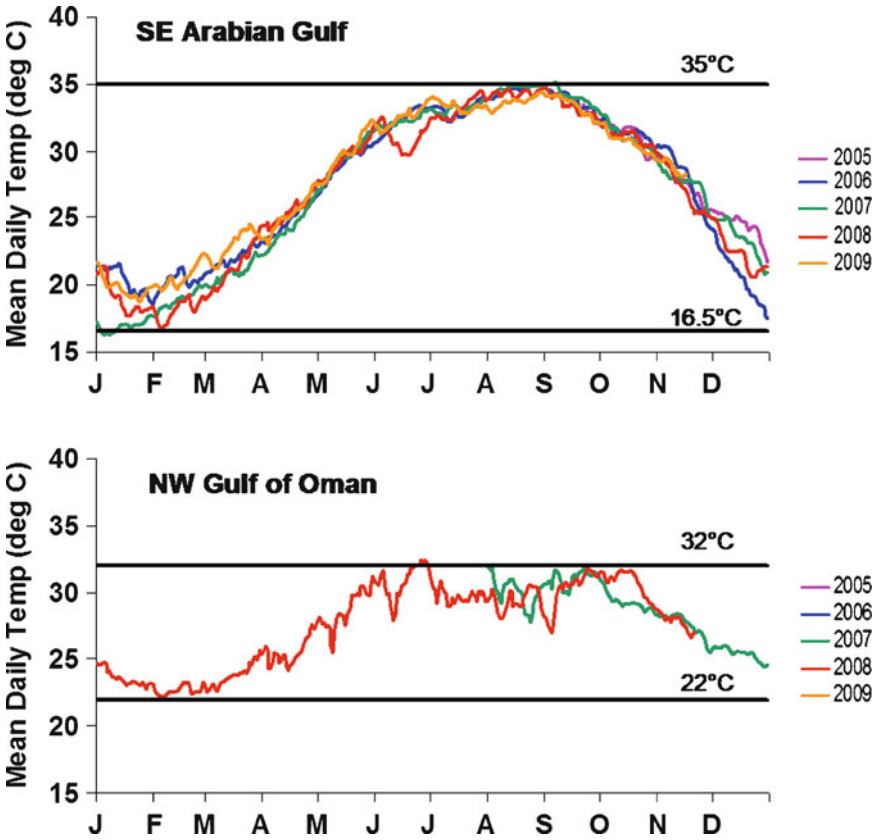

Fig. 4.6 Regional daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day, averaged across all sites (Arabian Gulf = 10 sites; Gulf of Oman = 2 sites). *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures

ranging from 34.0°C to 35.5°C (Figs. 4.2 and 4.3). The maximum daily mean for the southeastern Arabian Gulf region was 35°C, although this was not reached every year (Figs. 4.5 and 4.6). These data suggests that the southeastern Arabian Gulf gets hotter than does the central Gulf which Sheppard et al. (2010) presented HadSST1 data indicating an upper temperature limit of 33°C.

- Daily mean temperatures for the southeastern Arabian Gulf region during the summer season were typically 33.4–33.9°C (Table 4.3).
- The maximum hourly temperature recorded during this study was 37.2°C at Al Hiel in August 2007 (Table 4.3).
- The mean cooling rates during the winter (December 21–March 20) were typically 0.10–0.15°C per day (Table 4.3). The cooling rates were nearly uniform (i) among the individual sites within a given season (Table 4.3) and (ii) throughout the water column (Fig. 4.7).
- The annual temperature ranges at the individual sites and for the southeastern Arabian Gulf region were 15–19°C and 18.5°C, respectively (Figs. 4.2 and 4.3). These ranges are wider than the 13°C range recorded in the Central Gulf (Sheppard et al. 2010).
- Daily temperature ranges of less than 1°C were recorded at the coastal Abu Dhabi sites (i.e. Dhabiya, Saadiyat, Ras Ghanada), one of the Abu Dhabi offshore islands (Yasat) and the Qatari offshore island (Shra'aw). The other Abu Dhabi offshore islands (Makaseb, Delma, Bu Tinah, Al Hiel) experienced daily temperature ranges between 1.0°C and 2.5°C. (Fig. 4.4)

The coral communities in the southeastern Arabian Gulf did not experience mass mortalities during exposure to the lower and upper temperature limits described above, indicating acclimatization to these conditions. Small-scale bleaching and disease were observed on individual corals during the summer months (Fig. 4.8) but subsequent visits in late autumn, when water temperatures had cooled, indicated that (i) bleached corals had returned to normal coloration without mortality and (ii) disease resulted in mortality of affected polyps while the remainder of the colonies survived.

The Gulf of Oman has a different temperature regime compared to the Arabian Gulf (Figs. 4.2, 4.3, 4.4, 4.5, and

Table 4.3 Spring warming rates, autumn cooling rates, maximum summer temperatures and minimum winter temperatures (2005–2006)

(a) Spring cooling and autumn warming rates

	Mean warming rates (°C per day)		Mean cooling rates (°C per day)	
Year	Arabian Gulf	Gulf of Oman	Arabian Gulf	Gulf of Oman
2005			0.10–0.11	
2006	0.11–0.12		0.15	
2007	0.13		0.12–0.13	0.06–0.08
2008	0.10–0.11	0.08–0.09	0.13–0.15	
2009	0.09–0.10			

(b) Maximum summer temperatures

Summer	Region	Mean daily temp (°C)	Max daily temp (°C)	Max hourly temp (°C)
2006	Arabian Gulf	33.8	34.9	36.2 (Makaseb, 23Aug2006)
2007	Arabian Gulf	33.9	35.1	37.2 (Al Hiel, 29Aug2007)
2008	Arabian Gulf	33.4	34.7	36.8 (Al Hiel, 23Jul2008)
2009	Arabian Gulf	33.5	34.3	36.6 (Al Hiel, 07Aug2009)
2008	Gulf of Oman	29.9	32.8	35.5 (Mirbah North, 01Jul2008)

(c) Minimum winter temperatures

Winter	Region	Mean daily temp (°C)	Min daily temp (°C)	Minx hourly temp (°C)
2005–2006	Arabian Gulf	21.0	18.6	16.2 (Makaseb, 31Jan2006)
2006–2007	Arabian Gulf	18.5	16.3	15.1 (Makaseb, 04Jan2007)
2007–2008	Arabian Gulf	19.4	16.7	14.9 (Al Hiel, 06Feb2008)
2008–2009	Arabian Gulf	20.7	18.7	15.9 (Makaseb, 24Jan2009)
2007–2008	Gulf of Oman	23.4	22.2	21.2 (Dibba Rock, 21Feb2008)

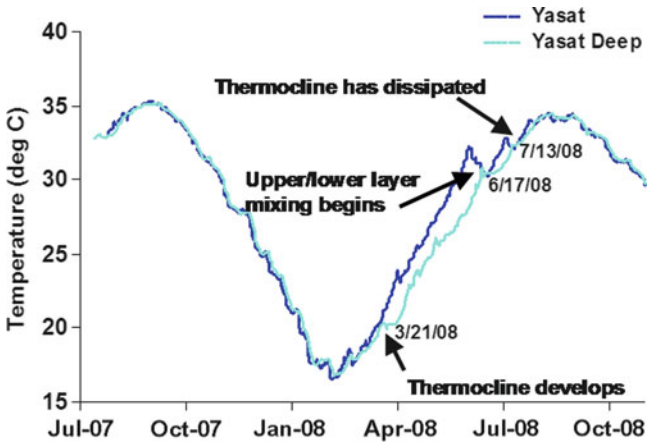

Fig. 4.7 Shallow and deep temperature profiles – Yasat (2007–2008). *Thick line* represents temperatures at the reef (3.0–4.7 m depth). *Thin line* represents temperatures in deep water (31 m)

4.6, Table 4.3). The temperature extremes are milder in the Gulf of Oman, where daily mean temperatures range between 22°C and 32°C throughout the year. However, the coral communities in the Gulf of Oman may be exposed to extreme daily temperature oscillations, especially during the summer when temperatures can fluctuate up to 9°C within a single day due to the rise and fall of a strong thermocline that forms between the heated surface and cool upwelling waters (Rezai et al. 2004). The data collected between 2007 and 2008 indicated that "normal" mean daily temperature ranges in the Gulf of Oman were less than 3°C, with a maximum daily range of 7.1°C recorded. The coral communities did not experience mass mortalities during exposure to these daily temperature fluctuations, indicating acclimation to these conditions.

4.2.2 Sea Urchins

Algal turfs can limit the free space that is available for coral settlement and can increase mortality of recruits by overgrowth, shading, and abrasion (Sammarco 1980, 1982). Sea urchin grazing of algal turf has been positively correlated to coral recruitment and survival (Birrell et al. 2005; Carpenter and Edmunds 2006). Sea urchin densities (*Diadema* and *Echinometra* spp.) were determined as part of the site assessments described herein (Figs. 4.9 and 4.10). Sea urchin densities were typically less than 7 urchins per m^2 in both the southeastern Arabian Gulf and in the northwestern Gulf of Oman. The exception to this was at Al Hiel, where densities up to 12 urchins per m^2 were measured. Al Hiel has a noticeably higher macroalgae cover than the other sites, which can support its slightly larger population of sea urchins.

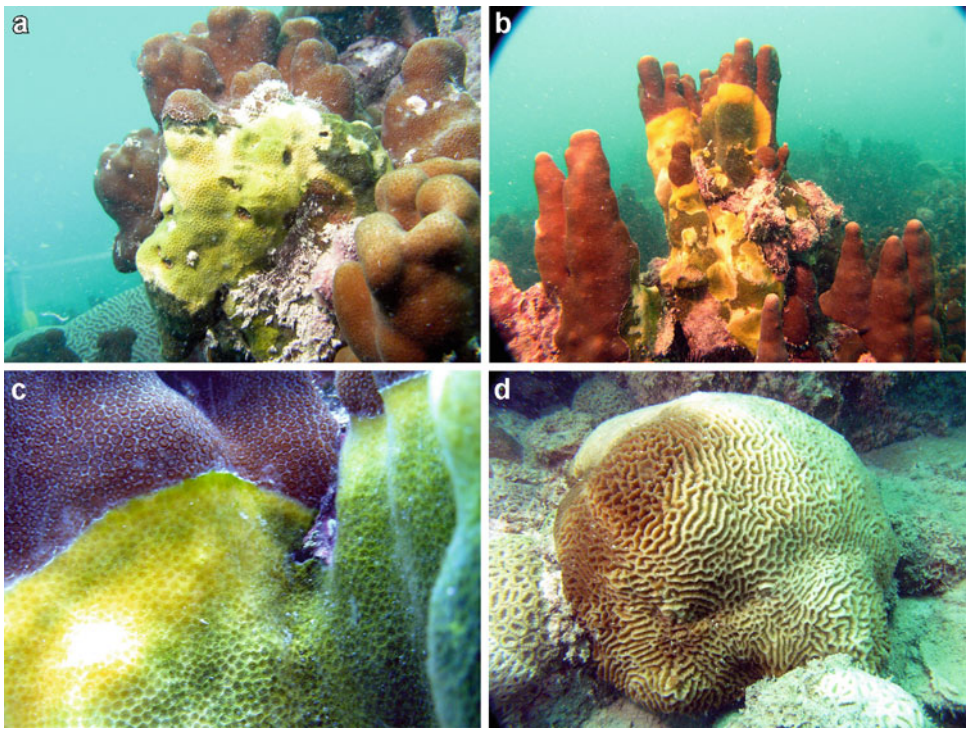

Fig. 4.8 Examples of individual diseased and bleached corals. (**a**–**c**) Yellow band disease in Saadiyat, July 2007; (**d**) bleaching at Abu Dhabi breakwater, July 2007

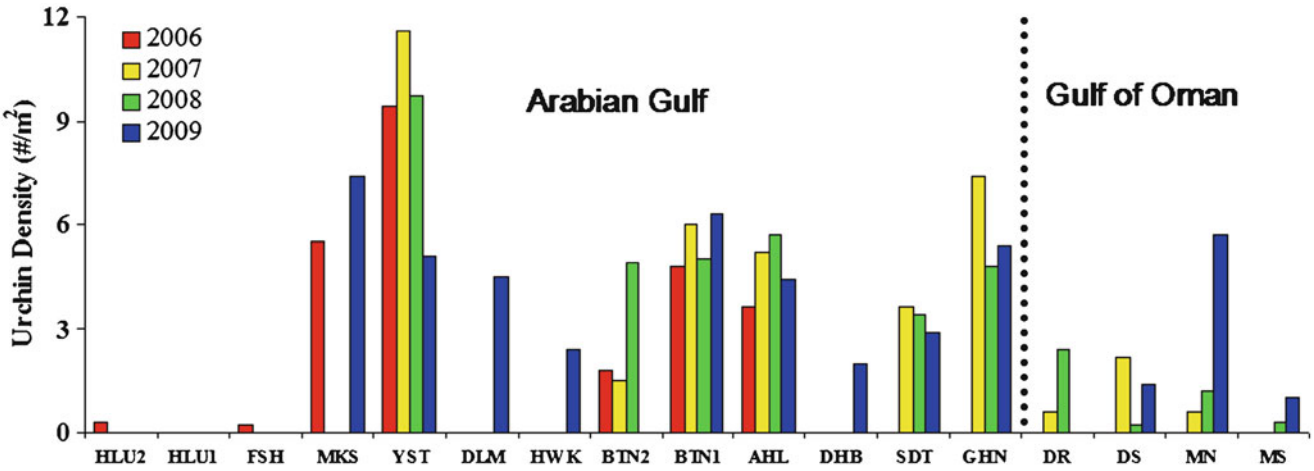

Fig. 4.9 Sea urchin densities (2006–2009). Sea urchins densities include *Diadema* and *Echinometra* spp. (site codes in Table 4.1)

Fig. 4.10 Sea urchins around Yasat Island

4.2.3 Topographical Complexity

Rugosity is a measure of topographical complexity, defined as the ratio of the reef surface contour distance to linear distance (Fig. 4.11) (e.g. a completely flat substrate would have a rugosity of 1.0). Changes in rugosity may be used to quantify reef growth or decline (e.g. increases in rugosity may be the result of coral colony growth; decreases in rugosity may be the result of bioerosion). Rugosities in Study Area "A" ranged between 1.2 and 1.8 (Fig. 4.12).

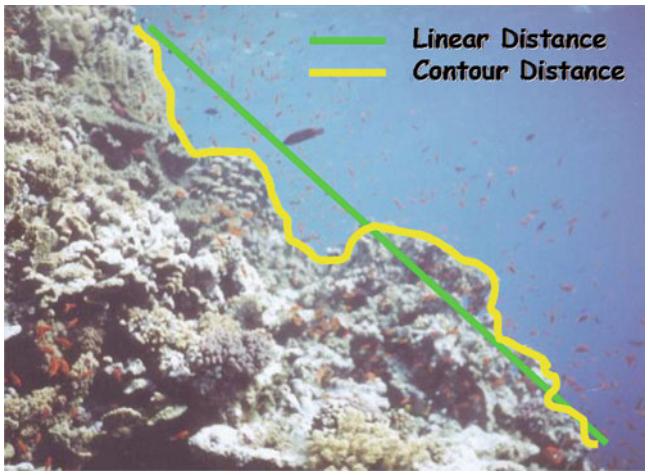

Fig. 4.11 Rugosity: ratio between contour distance and linear distance

4.3 Coral Community Structure

Elevated sea surface temperature anomalies impacted the southeastern Arabian Gulf region in 1996, 1998 and 2002; during which temperatures were 2–4°C above the typical summer maximum (Sheppard and Loughland 2002; Riegl 2003). The 1996 event caused widespread coral bleaching and mortality, with a subsequent reduction of 98.7% of framework-building *Acropora* corals in some areas (Riegl 2002). The 1998 and 2002 anomalies had only minor effects on the remaining coral communities, possibly because the surviving colonies were not susceptible to the elevated temperatures (Riegl 2002). The coral communities in Study Area "A" (Fig. 4.1) were monitored between 2006 and 2009 (i.e. 10–13 years after the mass coral mortality event and 3–7 years after the most recent elevated temperature anomaly). Similar assessments were conducted in the adjacent northwestern Gulf of Oman within Study Area "B" (Fig. 4.1), which did not experience the elevated temperature anomalies or the associated coral mortality.

4.3.1 Taxa Inventories

Nine genera of coral were observed during taxa inventories within the southeastern Arabian Gulf (Table 4.4) between 2006 and 2009. Taxa were inventoried by genus to allow rapid and repeatable identification, regardless of the taxonomic

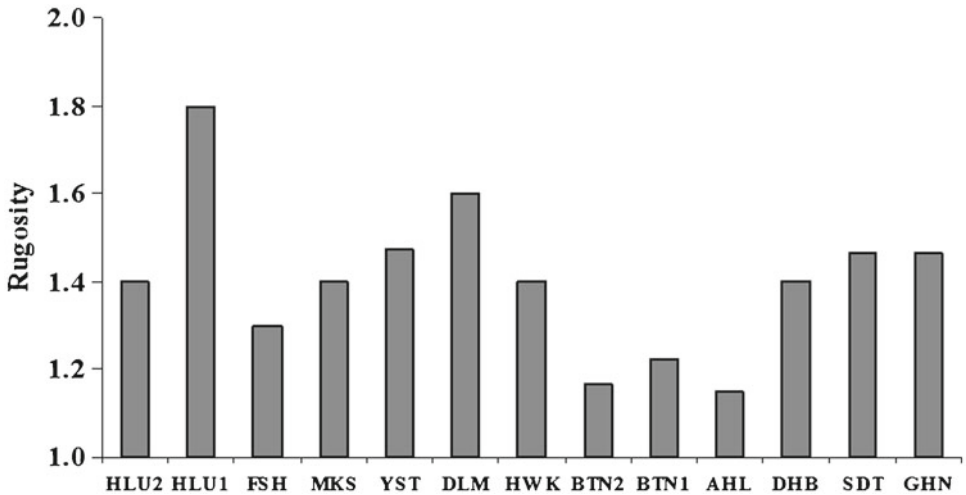

Fig. 4.12 Rugosities of coral communities in the southeastern Arabian Gulf (site codes in Table 4.1)

Table 4.4 Taxa Inventories at each Monitoring Station. Taxa observed within the belt transects at each monitoring station are indicated by "Y" (yes). "Other(s)" category includes *Pocillopora*, *Stylophora*, *Montipora*, *Goniopora* spp.

	Arabian Gulf													Gulf of Oman			
	HLU2	HLU1	FSH	MKS	YST	HWK	DLM	BTN1	BTN2	AHL	DHB	SDT	GHN	DR	DS	MR	MS
Porites spp.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Favia/Favites spp.		Y		Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Platygyra spp.		Y		Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Cyphastrea spp.		Y		Y	Y			Y		Y	Y		Y		Y		
Leptastrea spp.		Y			Y			Y	Y	Y	Y			Y	Y	Y	Y
Acropora spp.	Y	Y					Y				Y	Y	Y	Y	Y	Y	Y
Siderastrea spp.		Y								Y		Y	Y	Y	Y	Y	Y
Coscinaria spp.	Y	Y											Y		Y		Y
Turbinaria spp.											Y	Y	Y				
Other(s)														Y	Y	Y	Y

knowledge of those executing the monitoring program. Results indicated the following with respect to taxa inventories at sites in Study Area "A":

- *Porites* spp. were found at all sites. The most abundant species was *P. harrisoni*. Other species included *P. nodifera*, *P. lutea* and *P. solida*.
- Two sites (Fasht Al-Ghabi and Hawksbill Reef) were comprised solely of *Cyphastrea* sp. and *Porites* spp. Other genera occurred, but were rare and outside the monitoring sites.
- *Favia*, *Favites* and *Platygyra* spp. were common coral taxa found at all sites except at Halul East, Fasht Al-Ghabi and Hawksbill Reef.
- *Acropora* spp. were found at both Qatar sites (Halul East and Halul South), around Delma Island and at the three Abu Dhabi coastal sites (Dhabiya, Saadiyat, and Ras Ganada) (Fig. 4.13). Acroporids were not observed in the vicinity of any of the other Abu Dhabi sites.
- Three species of acroporids were observed; *A. clathrata*, *A, downingi*, and *A. arabensis*. Other subordinate Acropora species (e.g. A. *tenuis, A. valida, A. pharaonis, A. florida*) remain unobserved in the southeastern Arabian Gulf, including in waters offshore Dubai (Burt et al. 2008), suggesting local extirpation.
- Other coral taxa that have been reported offshore Dubai after the elevated temperature anomalies (i.e. *Acanthastraea, Psammacora, Psuedosiderastrea spp*. (Burt et al. 2008)) were not observed at the Qatari or Abu Dhabi sites.
- Other benthic taxa were found among the coral communities including crustose coralline algae, macroalgae, oysters and bryozoans (Fig. 4.14).

4.3.2 Live Coral Cover

Photo transects were taken at each site for subsequent image analysis. Coral Point Count (CPCe) (Kohler and Gill 2006) was used to trace the colony perimeters and calculate surface areas (Fig. 4.15). Average surface areas at the sites ranged from 62 to 500 cm^2. The largest colonies are *Porites* spp., followed by *Platygyra* spp.

The surface area data for all images within a given year were combined to provide percent live coral cover within the belt transects at each site (Fig. 4.16). Results indicated the following with respect to live coral cover at the sites in Study Area "A":

- The offshore island sites (Halul, Makaseb, Yasat, Delma, Bu Tinah, Al Hiel) (Fig. 4.17) were sparsely populated, with live coral cover ranging from 1.9% to 17.1%.
- Fasht Al-Ghabi, the only site surveyed along the coast of Qatar, had a sparsely populated coral community (1.3% live cover) consisting of small *Cyphastrea* spp. on old dead coral that was partially covered by crustose coralline algae (Fig. 4.18).
- The sites along the Abu Dhabi coast (Dhabiya, Saadiyat, Ras Ghanada) (Fig. 4.19b–d) were moderately populated, with live coral cover ranging from 27.5% to 46.5%. The sites most closely resembled the live cover at the northwestern Gulf of Oman sites (Fig. 4.16), which ranged from 23.0% to 44.9%.
- Hawksbill Reef, the only site situated on a limestone dome, had a densely populated coral community (62.2% live coral cover) comprised solely of *Porites harrisoni*.

The majority of the coral communities were comprised of several common families; poritids, faviids, acroporids, and siderastreids. Other families were either uncommon or unobserved at the sites. The composition of a particular family may be described as dominant (>50% of the coral cover), common (20–50%), uncommon (<20%) or unobserved. Results indicated the following with respect to the composition of live coral cover at the sites in Study Area "A":

- Poritids were dominant at all sites except around the Qatar sites. Poritids were common at Halul South, Halul

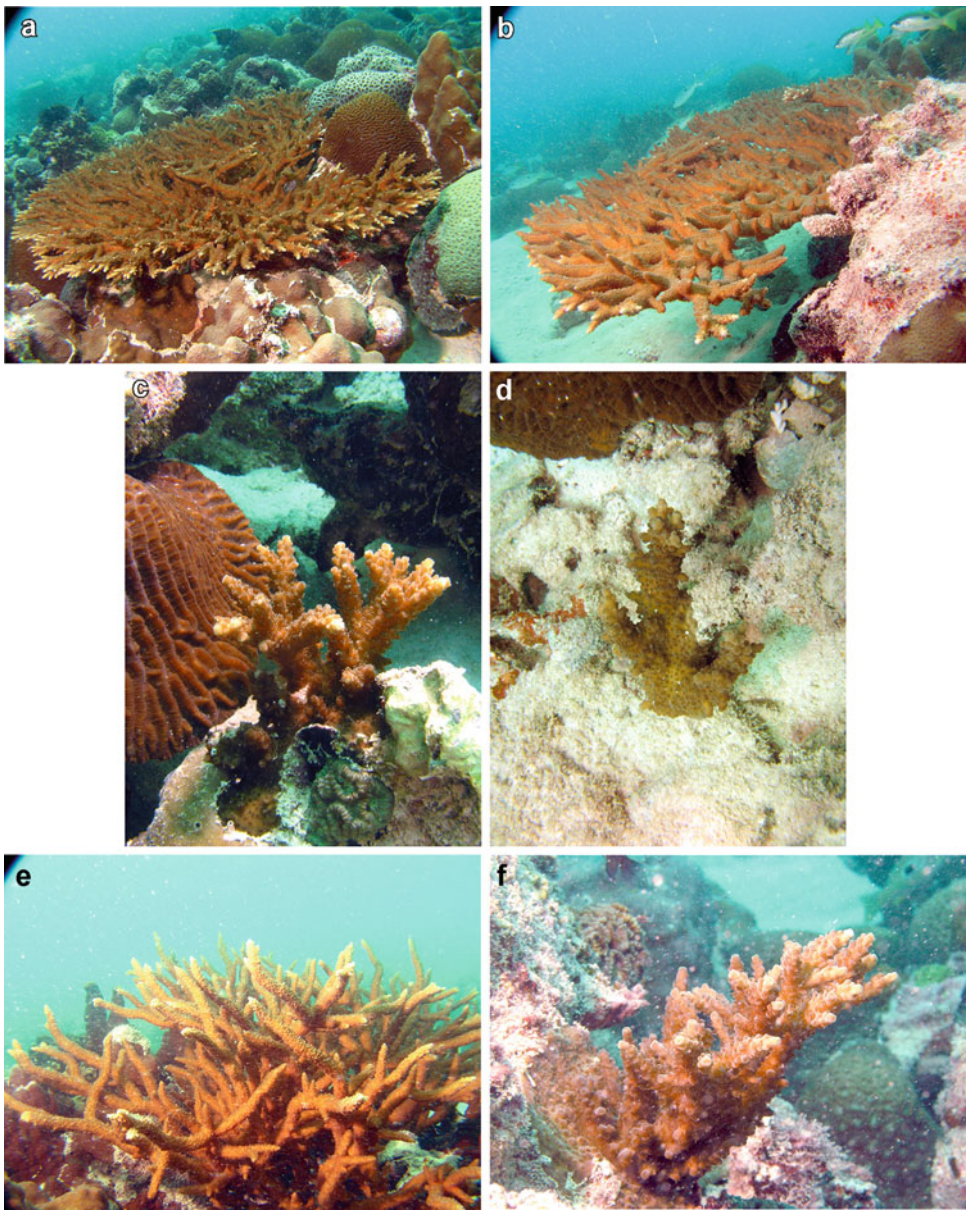

Fig. 4.13 Examples of *Acropora* spp. in the southeastern Arabian Gulf (see also Chap. 11, for taxonomic information). (**a–b**) *A. clathrata* near Halul Island; (**c, d, f**) juvenile colonies at Ras Ghanada; (**e**) *A. arabensis* near Saadiyat

East. Poritids comprised 100% of the coral cover at Hawksbill Reef.

- Faviids were (i) dominant at Halul South and Fasht Al-Ghabi, (ii) common at Al Hiel and Ras Ghanada and (iii) uncommon or unobserved at the remaining locations.
- Acroporids were present at six of the thirteen sites: they were (i) dominant at Halul East; (ii) common at Halul South; and uncommon at Delma, Dhabiya, Saadiyat and Ras Ghanada.
- Siderastreids were uncommon at five sites (Halul East, Halul South, Al Hiel, Saadiyat and Ras Ghanada) and unobserved at the remaining locations.
- Corals in the "Other families" category were uncommon at three sites (Dhabiya, Saadiyat and Ras Ghanada) and unobserved at the remaining locations. The "other" corals were all from the dendrophyllid family, specifically *Turbinaria* spp. No other coral families were observed.

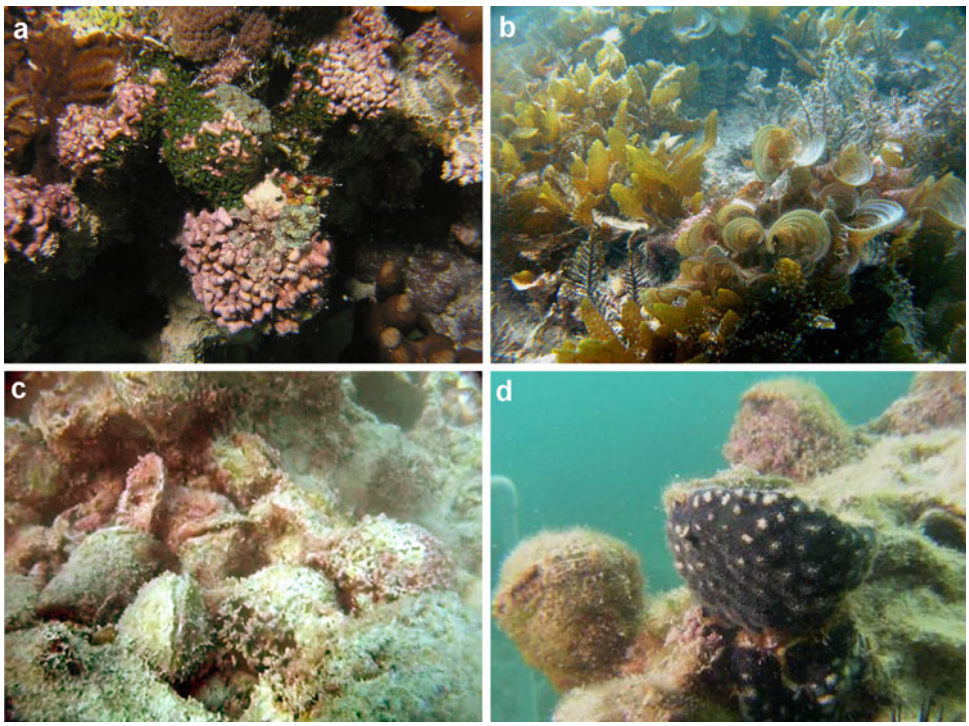

Fig. 4.14 Examples of other benthic taxa: (**a**) crustose coralline algae, Ras Ghanada; (**b**) macroalgae, Al Hiel; (**c**) oysters, Al Hiel; (**d**) bryozoans (see also Chaps. 13 and 14 for taxonomic information and species identifications)

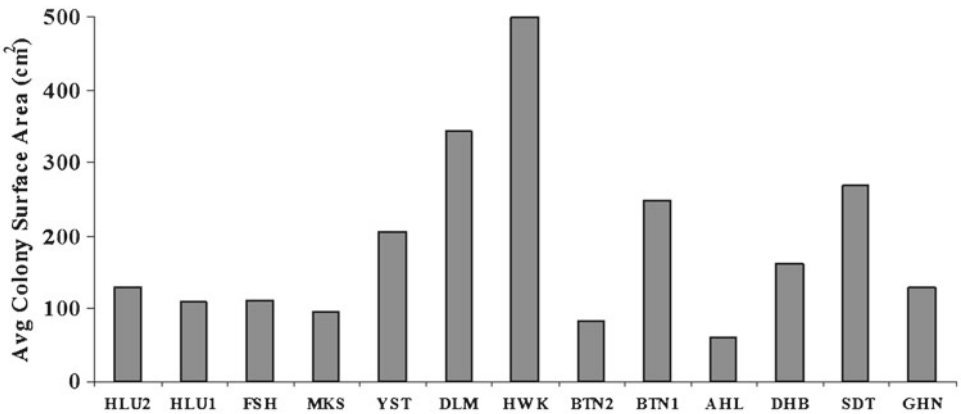

Fig. 4.15 Average coral colony surface areas (site codes in Table 4.1)

4.3.3 Coral Density

Digital photos were taken along belt transects at each site for subsequent image analysis. The number of corals within the belt transects were combined provide coral density (i.e. the number of corals per m^2) for each site (Fig. 4.20). Results indicated the following with respect to coral density at the sites in Study Area "A":

- The offshore island sites (Halul, Makaseb, Yasat, Delma, Bu Tinah, Al Hiel) (Fig. 4.17) were sparsely populated, with coral densities for these sites range from 1.2 to 8.0 corals per m^2.

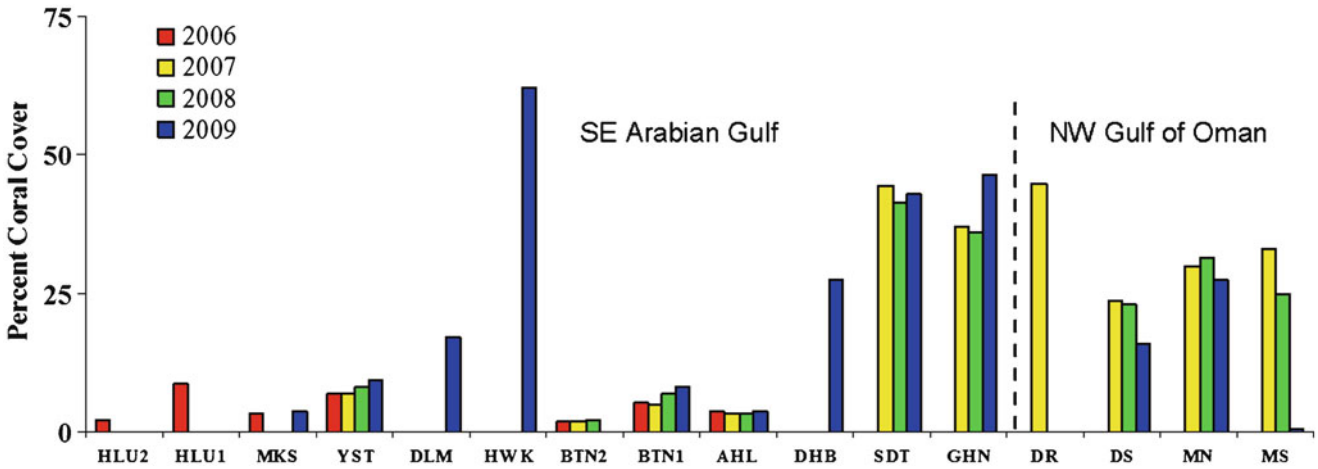

Fig. 4.16 Percent live coral cover (2006–2009) (site codes in Table 4.1)

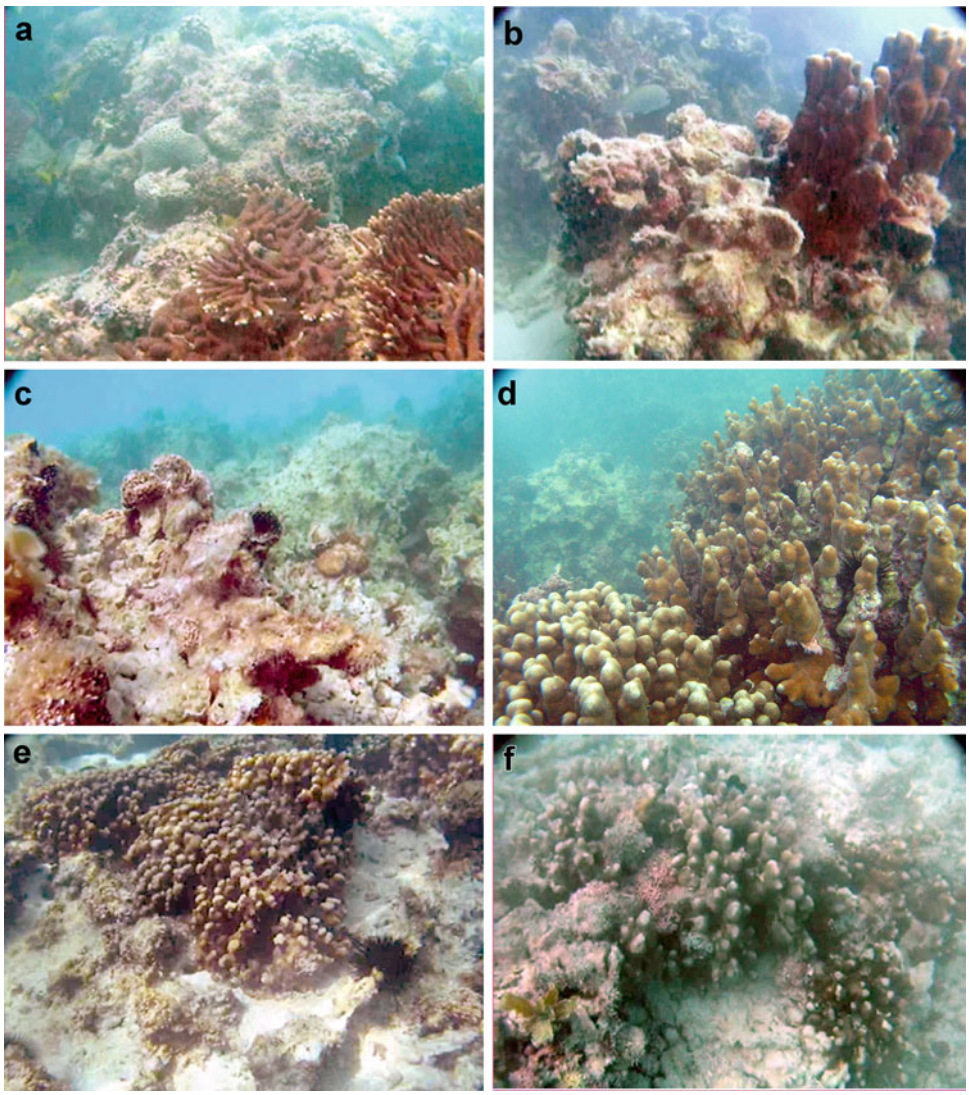

Fig. 4.17 *Landscape views* of sparsely-populated "near-island" sites. (**a**) Halul South; (**b**) Makaseb; (**c**) Yasat; (**d**) Delma; (**e**) Bu Tinah North; (**f**) Al Hiel

Fig. 4.18 *Planar view* of sparsely-populated coastal site (Fasht Al-Ghabi, Qatar)

- Fasht Al-Ghabi, the only site surveyed along the coast of Qatar, had a sparsely populated coral community with a coral density of 1.1 corals per m^2.
- Two of sites along the Abu Dhabi coast (Dhabiya, Saadiyat) and Hawksbill Reef were moderately populated, with coral densities ranging from 12.5 to 16.9 corals per m^2.
- Ras Ghanada, the third site located along the Abu Dhabi coast, was a densely populated coral community with a coral density >24 corals per m^2.

4.4 Conclusions

The information presented in this chapter described (i) the typical environmental setting to which the Arabian Gulf corals were exposed and (ii) the structure of the recovering coral

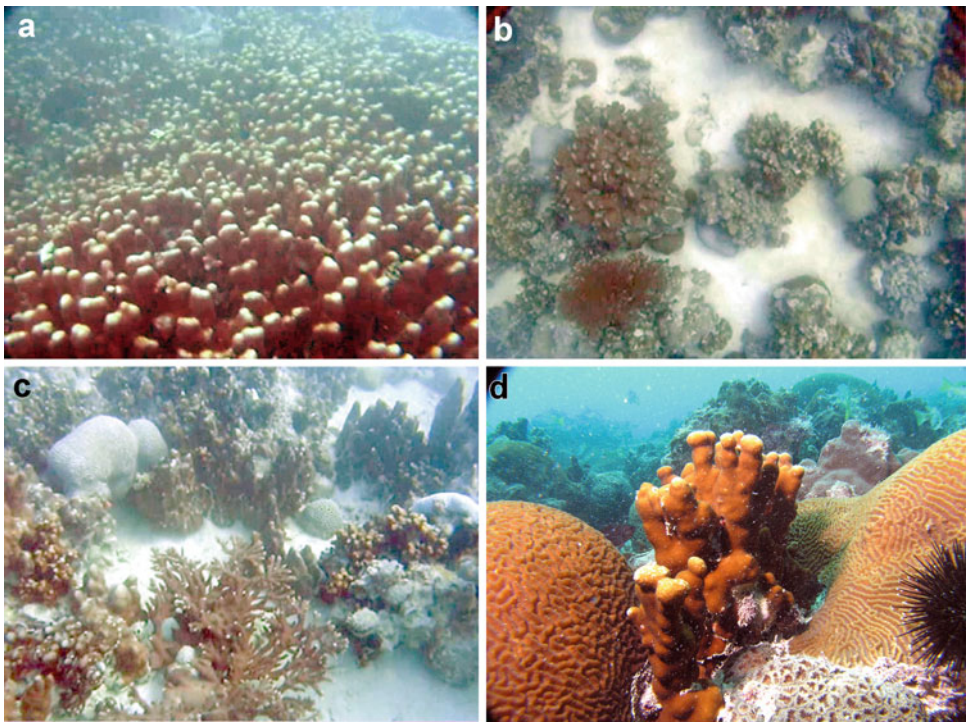

Fig. 4.19 *Landscape views* of densely- and moderately-populated sites. (**a**) Hawksbill Reef; (**b**) Dhabiya; (**c**) Saadiyat; (**d**) Ras Ghanada

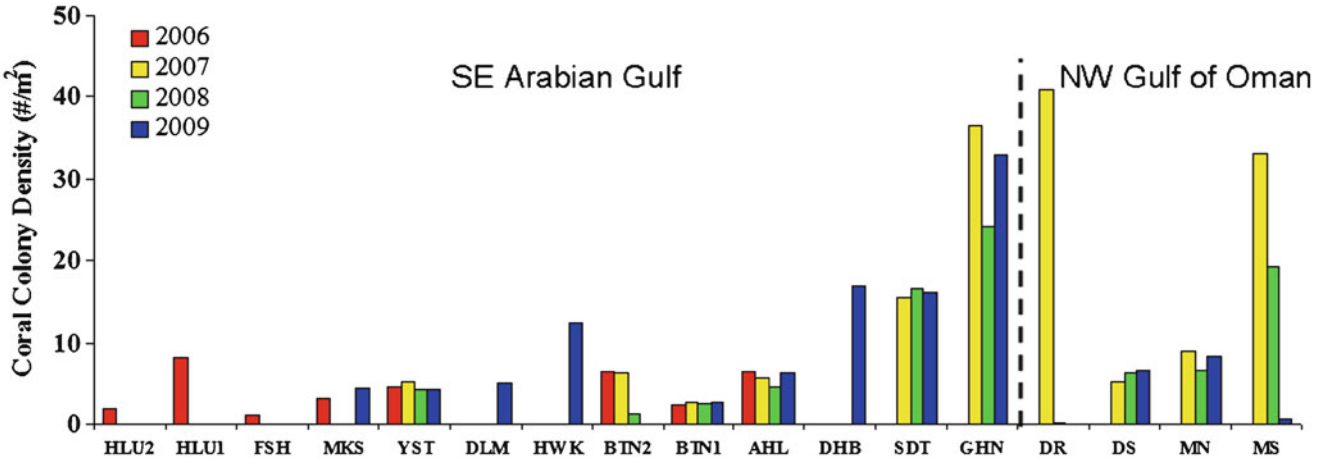

Fig. 4.20 Coral colony densities (2006–2009) (site codes in Table 4.1)

communities a decade after the mass mortality associated with the 1996 elevated temperature anomaly. These descriptions, as summarized below, may serve as baselines for normal conditions within the southeastern Arabian Gulf and as benchmarks of extreme conditions to which certain coral species are capable of adapting.

- The normal temperature range within the southeastern Arabian Gulf was 16.5°C–35.0°C. Temperature anomalies may, therefore, be defined as conditions that are 2–3°C below this minimum or above this maximum.
- The spring warming and autumn cooling rates were uniform across the region, ranging between 0.09–0.13°C per day and 0.10–0.15°C per day, respectively. A 1–4°C thermocline formed in the spring and dissipated in early summer. Autumn and winter thermoclines have not been recorded.
- The mean daily temperature range in the southeastern Arabian Gulf was <2.5°C. The same coral species found in the Arabian Gulf withstood normal daily temperature fluctuations up to 7.1°C, as measured in the adjacent Gulf of Oman.
- Sea urchin densities were typically below 7 urchins per m^2.
- The coral communities exposed to the above conditions were dominated by *Porites*, followed by *Favia/Favites* and *Platygyra* spp. Each of the six other coral genera that were inventoried within the communities comprised <1% to the regional population.
- Three species of acroporids were observed in the region following the 1996 mass mortality event; *A. clathrata*, *A. downingi*, and *A. arabensis*. The live coral cover for these species represented <1% of the coral cover in the southeastern Arabian Gulf, indicating that recovery to pre-event levels (>40%) had not occurred more than a decade later. The coral community structure has shifted from *Acropora* to *Porites* dominance. Other acroporid species that were recorded prior to 1996 were not observed and may now be regionally extinct.
- Live coral cover and coral density varied among sites, with ranges of 1.9–62.2% and 1.1–36.5 colonies per m^2, respectively. The locations near the Abu Dhabi coast and Hawksbill Reef (on top of a limestone dome) had higher live coral covers and densities than those locations near the Abu Dhabi and Qatar islands and the Qatar coast.

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