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# Spatial patterns in Arabian Gulf coral assemblages (Jebel Ali, Dubai, U.A.E.) in response to temperature-forcing

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**Abstract** We evaluated spatial and temporal patterns using maps from Ikonos satellite imagery in combination with 8 years of line transects and photo-squares and the HadISST1 sea-surface temperature data set to explain why coral assemblages in the southern Arabian Gulf (Dubai) are impoverished and mostly do not build framework reefs. Analysis of archive sea surface temperature (SST) data confirms that the area is subjected to recurrent temperature anomalies. Frequencies of anomalies might suggest at least a partial link to the El Niño Southern Oscillation possibly via the Indian Ocean Zonal Mode. The dominant driver of local temperature was oscillations in the position of the subtropical jetstream. Classification of IKONOS satellite data showed that the spatial expression of four coral assemblages was consistent with reef development on a (multi-)decadal time-scale following recurring episodes of coral mass mortality induced by severe SST anomalies. Merging a remotely sensed map of substrate distribution with a detailed bathymetric digital elevation model revealed no evidence of significant framework development, suggesting that the cycle of temperature induced mortality has been operating for a considerable time.

**Keywords** mass mortality, disturbance, remote sensing, monitoring, spatial pattern, coral reef, Arabian Gulf

## Introduction

Arabian Gulf coral systems persist in probably the most stressful environment for reef-building corals (Downing 1985; Coles and Fadlallah 1991, Riegl 2001) and it has been speculated that they are subjected to repeated temperature-mediated (both by abnormal lows and highs) mass-mortality events that reduce framework-potential and thus alter biogeological dynamics (Riegl 1999, 2002). The latest expressions of such events were seen in 1996 and 1998 (John and George 2001, Riegl 2002; Sheppard and Loughland 2002), warm years with widespread coral mortality throughout the Arabian Gulf. The development of reef growth is linked to disturbance frequency and can only take place when long enough periods of stability allow reef building organisms to use all available stable substratum which then forces the carbonate structure to grow upward and reach the water surface (Braithwaite et al 2000). Therefore, it is important to understand critical disturbance-thresholds and their major environmental drivers. The spatial patterns of coral communities can give important hints to their ecological history.

Hindcasting of disturbances is possible by using synthetic datasets, like the HadISST1 (Sheppard and Rayner 2002, Sheppard and Loughland 2002), that reflect temperature extremes averaged over 1x1 degree tiles. By analysing their frequency content, it may be possible to detect connections to other dominant climate patterns like the ENSO. Understanding spatial coral patterns is made possible by optical remote-sensing, which is a proven tool to quantify spatial extent of shallow benthic habitats (Mumby et al. 1997; Andréfouët et al. 2001; Purkis et al. 2002).

In this study we use a combination of 1) temperature time-series analysis of the HadISST1 dataset 2) spatial analysis using IKONOS satellite imagery, and 3) traditional in situ monitoring data in order to understand patterns caused by the environmental dynamics on coral communities near Jebel Ali (UAE). The aim is to understand the spatial and temporal dynamics of the coral communities in the southeastern Arabian Gulf and to understand what other climate phenomena influence the observed extreme local temperature excursions.

## Materials and Methods

*Study area*

The study area is situated in the south-eastern Arabian Gulf, about halfway between Abu Dhabi and Dubai, near Jebel Ali, in the United Arabian Emirates (Fig. 1).

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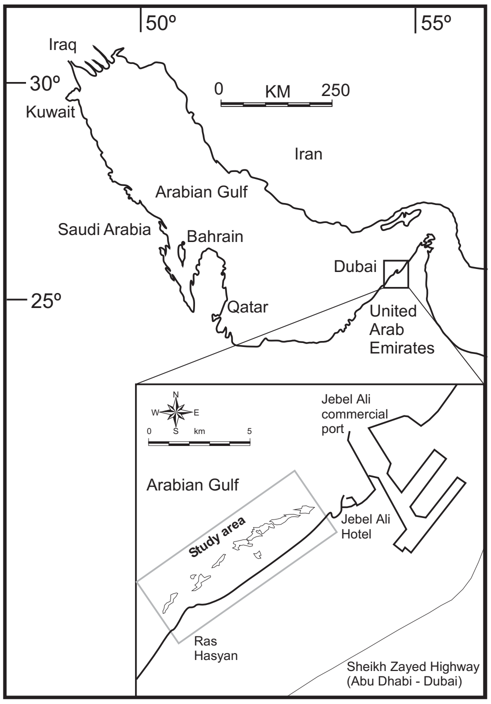


**Figure 1:** The study area between Ras Hasyan and Jebel Ali in Dubai Emirate, United Arab Emirates.

Previous studies and ongoing monitoring using 10m and 50m line transects (Riegl 1999, 2002) identified five typical coral assemblages of variable live cover within the study area:

- (1): widely spaced *Porites* mixed with other massive, species on hardgrounds.
- (2): tabular colonies of *Acropora clathrata* and *A. downingi* with high (40-90%) live cover
- (2.1): Sparse *Acropora* at the edges of dense assemblage.
- (3): either widely spaced or densely packed faviids (most notably *Platygyra lamellina*, *P. daedalea*, *Cyphastrea serailia*, *Favia* spp.).
- (4): Widely spaced *Siderastrea savignyana* colonies on sandy hardgrounds.
- (5): *Porites harrisoni* thickets intermingled with mainly faviids (*Favia* spp., *Platygyra* spp.).

The HadISST1 dataset of monthly and weekly averages of SST since 1870 on a 1×1º grid was obtained from the UK Met Office (Sheppeard and Rayner 2002, Sheppard and Loughland 2002, Sheppard 2003). Data were evaluated with code written in Matlab 6.1. and were plotted as raw data, annual trends were removed by subtracting the annual from the monthly mean data (Middleton 2000) and temperature trend was shown as 8-point cubic spline through annual means. The periodicity of SST oscillations was evaluated using a Fast Fourier Transform (FFT) algorithm (Ingle and Proakis 2000).

We also used 4×4 m pixel-resolution IKONOS imagery for optical discrimination of benthic habitats (scene 75209 acquired on 02 May 2001, 06:49 GMT; sun elevation and nominal collection azimuth 67° and 65°, tidal stage 3 hours after high water, high water clarity, calm surface, no atmospheric dust, no cloud cover). Geocorrection was conducted against 40 ground control points acquired using a portable Leica 500 DGPS system with a horizontal accuracy of ±30 cm, yielding an average root mean square (RMS) error of 0.66 pixel or 2.65 m. Details of image processing are given in Purkis and Pasterkamp (2004). The IKONOS imagery was radiometrically calibrated using the coefficients of Peterson (2001) to yield pixel values of radiance (W m$^{-1}$ ster$^{-1}$ μm$^{-1}$) and further corrected for the effect of atmospheric path radiance using the procedure adopted by Schott et al. (1988) and Lenney et al. (1996) to recover values of apparent surface reflectance (%). The first three bands of the imagery (blue, green and red) were subsequently processed to remove the spectral effect of the water column using the procedure of Purkis and Pasterkamp (2004), resulting in pixel values equivalent to substrate reflectance (%). The thickness of the water column within each pixel was derived from a bathymetric digital elevation model (DEM) constructed from acoustic surveys. Each image pixel was assigned to one of eight substrate classes using a classifier trained solely using the *in situ* optical measurements of substrate reflectance using the multivariate-normal probability density function described by Purkis and Pasterkamp (2004) and smoothed using a median filter constructed using a 3×3 pixel neighbourhood to reduce the number of isolated erroneously classified pixels resulting from image noise (Wilson 1992; Lillesand and Kiefer 1994). In order to express the spatial relationships of the observed seafloor classes quantitatively, we evaluated class-membership of pixels surrounding each other in a selected region of interest. Class membership (as derived from image classification) of the eight neighbours adjacent to each pixel (touching the sides and only the corners of the seed pixel) was tabulated allowing to express which pixel class (representing a specific seafloor type) were most frequently adjacent to each other.

**Results**

Both in the Ras Hasyan and the Sir Abu Nuair tile, HadISST seasurface temperatures were variable over a 133-year time period from 1870 to 2003 (Fig. 2, overall linear trend in raw datasets is defined by $y=26.98+0.0003x$ for Ras Hasyan and $y=26.56+0.0003x$ for Sir Abu Nuair) with an increase of 0.4ºC throughout both raw datasets and also the Ras Hasyan tile with the annual component removed, but only 0.32ºC in the corresponding Sir Abu Nuair tile. Temperatures were subject to strong variation, which is shown by marked spikes both in the plot of monthly residuals as well as the plot of yearly averages. Extreme spikes are more common in the second half of the dataset (post 1950) reflecting better data-availability rather than natural absence of similar spikes in the early, more synthetic, part of the dataset. These temperature spikes were higher in the coastal dataset (Ras Hasyan) than the offshore

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dataset (Sir Abu Nuair). Also average temperatures were higher in the nearshore than the offshore. The warmest overall period began in the mid 1990's, with a marked spike in 1998 and a lesser one in 1996. However, other warm periods were observed in the 1940's and 1960's. The 1998 spike coincides with an unusually strong ENSO event. The strongest negative signals were from 1966, 1975, and 1983 in both tiles.

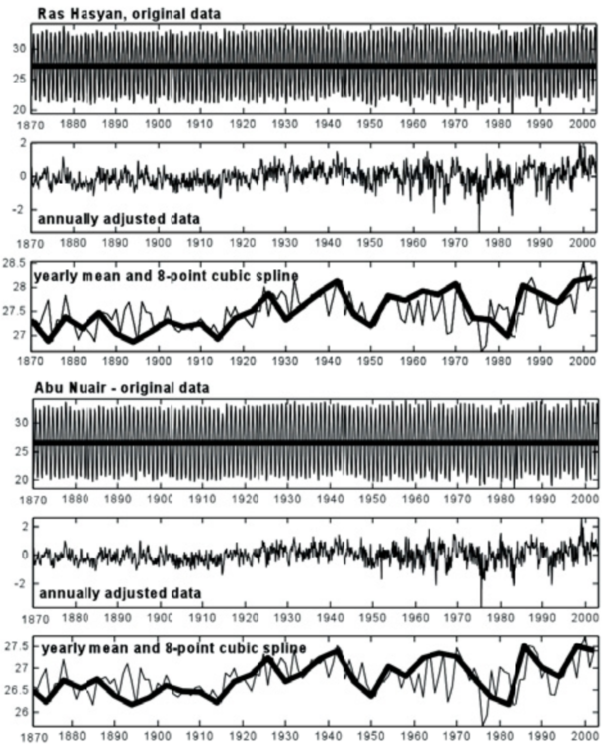


**Figure 2 :** Temperature time series derived from the HadISST1 dataset between 1870 and 2003. Top graphs show raw data, middle graphs show annual mean subtracted from monthly temperature, lower figure is yearly averages (dotted line) with an 8-point cubic spline (heavy line) to show the trend.

The analysis of spectral content of the Ras Hasyan temperature dataset (Fig. 3) showed a significant peak at 12 months, which is the annual temperature signal, and other peaks at a monthly interval, which we believe to be an expression of tidal cycles influencing coastal ocean heat content. Moderately strong, but not significant signals were observed at a frequency of two and four years.

Spatial patterns visible in the classified IKONOS imagery (Fig. 4) show a shore-parallel trend that can be partitioned into three rough parts: (1) a zone without coral growth, dominated by sand, seagrass and algae in the first 500 m from shore. (2) a middle zone consisting mainly of sand and hardground from 500-1000 m offshore. (3) a deep zone characterized by coral growth of variable density, interspersed by dense algal growth.

The ecological data suggested that three coral assemblages were resolved on the image:

- large, but sparse corals (mostly *Porites*) on hardground, mostly alive.
- sparse *Acropora* mixed with faviids and *Porites*. The *Acropora* were mostly dead.
- dense and interlocking growths of *Acropora* which were all dead.

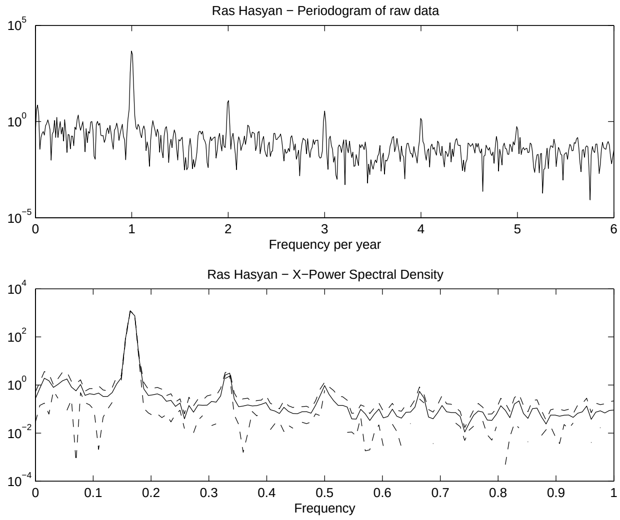


**Figure 3:** Power-spectra of the Ras Hasyan HadISST1 dataset. Peaks in energy are shown, the thin lines in x-power spectrogram are the upper and lower 95% confidence limits. Two- and four-year peaks are on the extreme left (only clearly visible on right figure).

Coral assemblages showed patches of dense dead coral surrounded by sparse live coral and finally by hardground with only occasional corals (inset in Fig. 4). Dense dead coral pixels (*Acropora* thickets killed during the 1996 heat event) were mostly in contact with dense live coral pixels (dominated by poritids and faviids), which in turn were mostly in contact with dense dead, followed by sparse live coral pixels (also poritids and faviids). Sparse live pixels were mostly in contact with algae followed by hardground pixels, which were mostly in contact with sand pixels (Fig. 5). Corals did not form aggrading frameworks that reached the surface, but only one single generation of corals was growing directly on the hardground. After death, coral skeletons were subject to intense bioerosion and breakdown of skeletons. This situation is typical of nearshore coral communities in the south-eastern Arabian Gulf, but this is not the only type of coral community or framework occurring in the Arabian Gulf and other dynamics may be encountered.

**Discussion**

The HadISST1 dataset indicates that coral communities near Ras Hasyan, as well as many other similar nearshore coral systems in the southeastern Arabian Gulf, are forced by repetitive mass coral mortality caused by temperature extremes (Riegl 1999, 2002). In other settings (offshore island fringing reefs, nearshore Porites frameworks, offshore banks) it is less clear what specific factors may act. These events are shown as well-defined temperature spikes (both positive and negative) in Fig. 2. The temperature extremes can be correlated with known mass mortalities (see below). The

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differences in temperatures between the onshore (Ras Hasyan) and offshore (Abu Nuair) data-tile suggest that although temperature extremes occur synchronously over wide areas, the size of the excursion differs locally. Thus, nearshore corals experience more extreme temperatures than offshore corals. This was reflected in higher coral cover, in particular of the more temperature-sensitive *Acropora* species (Coles and Fadlallah 1991, John and George 2001, Riegl 2002), at Sir Abu Nuair, which had denser *Acropora* growth covering bigger areas than Ras Hasyan, where *Acropora* regeneration was sparse in 2003.

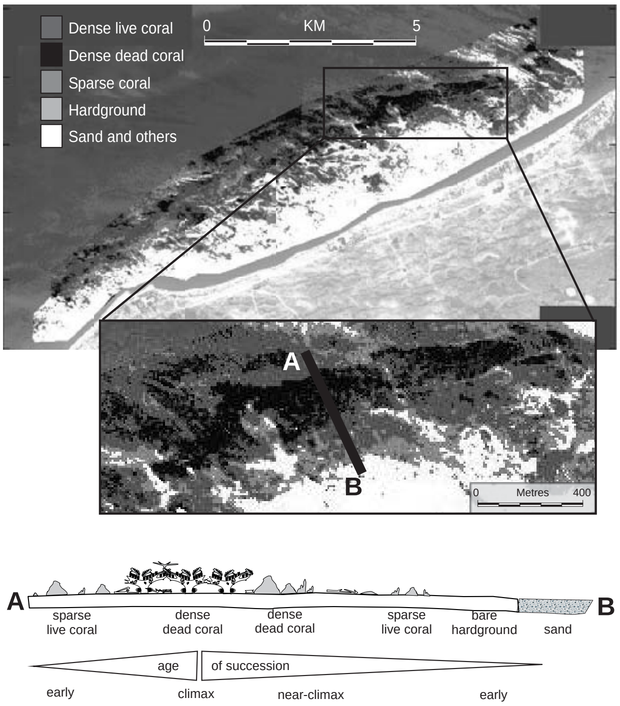


**Figure 4:** Simplified classification of IKONOS satellite image and enlargement for demonstration of adjacent pixel classes dense coral-sparse coral-hardground. Transect A-B is illustrated as cartoon and mentioned in discussion.

Extreme negative (cold) excursions were observed in the study area in 1966, 1975 and 1983. Extreme cold mortality excursions were reported by Shinn (1972) for 1966, Coles and Fadlallah (1991) for 1989, Fadlallah et al. (1995) for 1992. Also in 1983, coral mortality was observed on Saudi reefs (Coles, pers. comm.). An extreme positive (warm) excursion was observed in 1998. We believe that at least the 1975 cold event led to mass coral mortality near Ras Hasyan since Titgen (1981) reported a pre-1980 mass mortality of *Acropora* without specifying a year. It is interesting that the 1996 heat event, which killed all *Acropora* near Ras Hasyan (Riegl 1999, 2002), is not seen as a strong temperature excursion in the 1×1 geographic degree tile. The lethal temperatures appear to have been a localized event. The 1998 heat event, which caused mass coral mortality Gulf-wide, is well represented both onshore and offshore.

The periodogram of the temperature datasets clearly shows annual and monthly variability. There were also weaker, non-significant energy peaks at periods 2 and 4 years. It is known that the Indian Ocean Dipole/Zonal Mode (Saji et al 1999, Webster et al 1999, Loschnigg et al. 2003) oscillates at a roughly two-year period, and the ENSO at a roughly four-year period (Wang and Wang 1996). Therefore, these two energy peaks could be reflections of weak teleconnections to these phenomena. The dominant phenomenon in driving local atmospheric temperature extremes appears to be the position of the subtropical jetstream (Nasrallah et al. 2004). It is likely that jetstream-position is influenced by ENSO and IOZM.

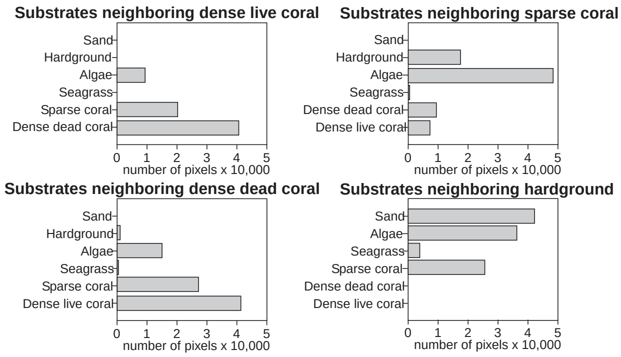


**Figure 5**: Statistics regarding neighboring pixel-classes. The frequency counts confirm that dense coral is mostly adjacent to sparse coral which is mostly adjacent to hardground.

Not only the temperature record, but also the spatial patterns in the coral assemblage suggest, at least locally in the study area, repeated (multi)decadal-scale mortality. Dense coral patches are surrounded by increasingly sparse coral growth. We believe that this is caused by temperature events frequently affecting compensatory mortality on the dominant space competitor *Acropora* (Riegl 1999, 2002), which keeps them from 1) dominating the coral community entirely – thus, the dense peripheral assemblage of weaker competitors (faviids and poritids) can persist. 2) using all available substratum and begin to build aggrading reef frameworks - thus, dense *Acropora* growth remains confined to relatively few dense patches and does not spread over the entire available hardground area. Because dense coral growth is repeatedly stunted by disturbances and frameworks are reduced to rubble by bioerosion, the reef-building process has to repeatedly start anew and no aggrading frameworks are built (Riegl 2002). The spatial expression of this process is the "halo-like" pattern of dense dead corals (mainly *Acropora*), surrounded by dense live corals (mainly poritids and faviids), surrounded by sparse corals (mainly poritids and faviids), surrounded by hardgrounds. This spatial sequence represents the lateral spreading of framework growth from the centers of hardgrounds (where environmental conditions, i.e. less mobile sand, are presumably more conducive to the settlement of corals) with dense coral growth from where the density of corals is thinning outward due to declining environmental quality and/or insufficient time to cover the entire hardground patches.

The dead centers indicate the repeated need to "refill" framework lost due to extreme temperature excursions.

In conclusion, the patterns in the temperature dataset are helpful to explain the spatial patterns in the coral community as observed by remote sensing. It is understood, however, that while we believe extreme temperature excursions to be one of the primary drivers of framebuilding potential in the Arabian Gulf, other drivers (such as physiography, erosion, bioerosion, salinity and tidally-driven hydrodynamics) may play an equally important role.

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