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The scleractinian fauna of Yemen: diversity and species distribution patterns

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Abstract. Hard coral diversity and species distribution in Yemen are thought to be principally controlled by hydrology and hydrodynamic factors acting in the Arabian region. In particular, a strong seasonal upwelling linked to the SW summer monsoon is typically described as a major forcing function prevailing in the Gulf of Aden and Socotra. The diversity of the hitherto little known scleractinian coral fauna of Yemen was investigated through surveys extending from the Kamaran Island area, in the southern Red Sea, to Socotra in the Arabian Sea, and including Aden, Balhaf, Bir Ali, Burum, and Al Mukallah in the Gulf of Aden. Results showed that the scleractinian fauna of the Gulf of Aden is notably different from that of the Yemen Red Sea and from the Socotra Archipelago. More unexpectedly, striking patterns of species and genera distribution and relative frequency were observed along a relatively short stretch of coastline. It is hypothesized that, at the local scale, the synergistic effects of the seasonal upwelling, of fresh water input from major wadi estuaries, and of westward moving eddies in the Gulf of Aden could play a role as for the observed striking coral species distribution patterns.

Key words: Yemen, scleractinian corals, distribution patterns, Gulf of Aden, Red Sea, Arabian Sea, Socotra.

Introduction

Yemen borders three different bodies of water. A shorter section of the country's coasts faces the Red Sea (ca 760 km long) extending from the Saudi Arabian border in the north to the entrance to the Red Sea at Bab al-Mandeb in the south (Turak et al. 2007). A longer one (ca 1200 km long) faces the Gulf of Aden extending from the Bab al-Mandeb in the south west to the border with Oman in the north east (Spalding et al. 2001) (Fig. 1). Finally, approximately 400 km south of the Yemen mainland, the Socotra archipelago is found in the Arabian Sea.

Reef corals and coral reefs are known to occur along most of the long coastline of Yemen (Spalding et al. 2001). The presence of reefs (Sheppard and Sheppard 1991), the types of coral communities, and the diversity of scleractinian corals (Benzoni et al. 2003; DeVantier et al. 2004; Turak et al. 2007; Pichon et al. 2010) are known to differ in the Yemen Red Sea, Gulf of Aden, and Arabian Sea coasts. These differences have been mainly explained as the result of geologic, climatic, and oceanographic factors of the Arabian region (Sheppard et al. 1992).

The marine climate in Yemen is influenced by the Indian Ocean monsoon system (Sheppard et al. 1992). In the Yemen Red Sea, in the winter winds blow from the east along the coast of Arabia into the Gulf of Aden and are funneled into the Red Sea. During the summer, winds from the northern Red Sea blow to the south along the coast. There, the water temperatures range between 30°C offshore to 38°C inshore during summer with temperatures 5°C cooler in winter (Turak et al. 2007). The marine climate in the Gulf of Aden and in the Arabian Sea is also dominated by the monsoons affecting the seasonal variations in winds regime. There, the monsoons influence the prevailing currents flowing from south west to north east during the summer and reversing during the winter monsoon (Currie et al. 1973) due to the migration of the Inter-Tropical Convergence Zone (ITCZ) (Sheppard et al.

1992; Glynn 1993). During the summer monsoon, the westerly winds blow with strength (over 15 m/sec) along the coast, remove the warm superficial layers of water, and cause the upwelling of deeper waters which are cooler and rich in nutrients (Sheppard et al. 1992). The summer upwelling can lower the water temperature to 16-19°C (Glynn 1993). Moreover, the increase of nutrients provides more favourable conditions for the growth of seaweeds and phytoplankton rather than reef corals. While some species of scleractinian corals, usually flourishing in tropical and oligotrophic waters, can live in these extreme pseudo-temperate conditions, the accretion of coral reefs is severely reduced (Sheppard et al 1993; Benzoni et al 2003).

The Yemen Red Sea coast, and more than 100 islands along it, support different coral communities characterized by a moderately high regional diversity of hermatypic corals including 221 species (Turak et al. 2007). Along the Yemeni coast of the Gulf of Aden, although high cover coral communities (including monospecific coral carpets) have been found (Kemp and Benzoni 1999; Kemp and Benzoni 2000; Benzoni et al. 2003; Richard et al. 2011), the development of coral reefs is limited, and the overall scleractinian coral diversity is of 77 species (Pichon et al. 2012; Stefani et al. 2011). The Socotra Archipelago supports a mix of benthic habitats including coral communities, and the known scleractinian coral diversity is of 253 species (DeVantier et al. 2004).

Only recently has the diversity of corals been addressed by detailed studies in different parts of Yemen. However, a comprehensive study of the country's diversity of scleractinians and of the species distribution patterns has never been undertaken. In this study the published taxonomic inventories and the species distribution data from 81 sites in the Yemen Red Sea, Gulf of Aden, and Socotra Archipelago are examined together. Moreover, the distribution of the taxa in the three different bodies of water bordered by the country is examined for the first time.

Material and Methods

Sampling

Sampling took place at different localities in Yemen during six different missions between 2007 and 2010 within the frame of the Total E&P - Creocean - University of Milano-Bicocca "Yemen Scleractinia Biodiversity Project". In total, 81 sites were sampled: 16 in an area in the Yemen Red Sea including the Kamaran islands and the coast in front of them (KA, Fig. 1B), 15 on the northern coast of Socotra Island (SO, Fig. 1B), and 50 along the north-western Gulf of Aden coast from Aden (AD, 5 sites), Balhaf (BA, 10 sites), Bir Ali (BI, 17 sites) Burum (BU, 10 sites), and Al Mukallah (MU, 8 sites) (Fig. 1C).

At each site, all scleractinian coral species observed during a 60 minutes SCUBA dives between 1 and 20 m depth were photographed underwater and their presence recorded. Digital images were then analyzed to verify underwater preliminary records and species presence records were used to produce a species per site list. When the species could not be readily identified underwater a fragment of the colony was collected. Identification to species of the collected specimens took place on the basis of skeleton morphology using reference literature and, whenever possible, original species descriptions and type material illustrations.

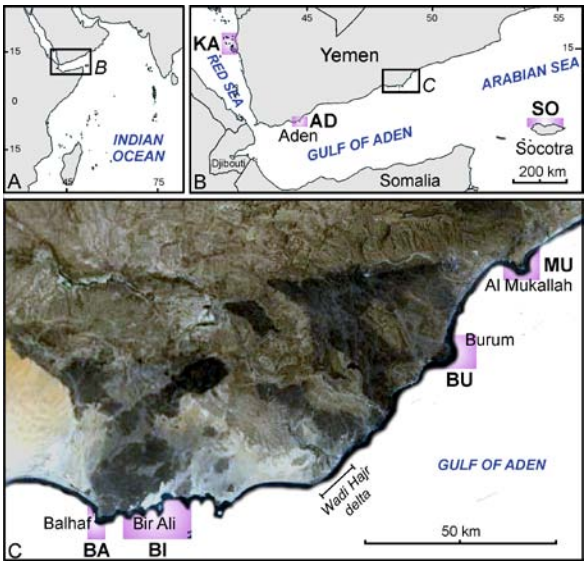


Figure 1: A) map of the Indian Ocean showing the position of the study area in inset B; B) map of Yemen showing the Red Sea and Gulf of Aden coasts of the country, and the position of the Socotra archipelago; C) the coastline from Balhaf to Al Mukallah. Lilac rectangles indicate the position of a sampling area. The code for each sampling area is in bold capital letters close to each lilac rectangle. KA = Kamaran islands and coast area; AD = Aden; SO = Northern Socotra Island; BA = Balhaf headland; BI = Bir Ali coast and islands; BU = Burum headland; MU = Al Mukallah.

Analyses

The species presence data set was explored by means of multivariate statistic techniques using PRIMER statistical package. Hierarchical cluster analysis using Bray-Curtis distance and complete linkage agglomeration algorithm, as well as Principal Component Analysis (PCA), were used to explore the multivariate database and identify groups of sites or areas characterized by a similar coral fauna.

Results

The diversity of scleractinian corals in Yemen

The species *Psammocora albopicta* and *P. stellata* were recorded in the Yemen Red Sea for the first time. These two taxa were also new records in Socotra Island together with *Caulastrea tumida*, *Stylophora madagascarensis*, and *Coscinaraea wellsi*. Overall, taking into account the results of this study and of the published taxonomic accounts (DeVantier et al. 2004; Turak et al. 2007; Pichon et al 2010) 316 species are recorded from Yemen .

Coral species distribution in Yemen

Multivariate analyses of the species per site data set showed that the distribution of coral species is substantially different in the Red Sea, in the Yemen coast of the Gulf of Aden, and on the northern coast of Socotra (Fig. 2).

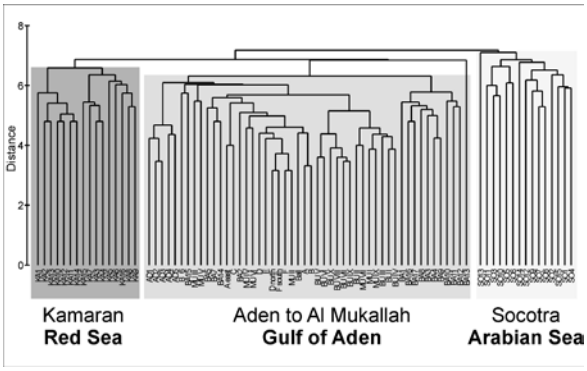


Figure 2: Cluster analyses of the whole species data set from this study. Each leaf of the tree represents one of the 81 studied sites.

The differences between the three main clades in Fig. 2 are explained by the presence in Socotra of taxa which were neither recorded from the north-western coast of the Gulf of Aden nor from the Yemen Red Sea, namely *Madracis kirbyi*, *Stylocoeniella guentheri*, *Pachyseris speciosa*, and *Plesiastrea devantieri*. Moreover, the genus *Acropora*, represented by 41 species in the Red Sea, and by 31 in Socotra, is only present with 3 species in the Gulf of Aden. Notably only 14 species were recorded both in the Red Sea and in Socotra. *Stylophora madagascarensis* originally described from Madagascar (Veron 2000) and recorded in the Gulf of Aden (Stefani et al. 2011) was found in Socotra, but not in the Red Sea. The genera *Ctenactis* and *Diploastrea*, occurring in the Indian Ocean, were only recorded in Yemen from the Red Sea. Finally a disjunct distribution was observed for taxa found in the Yemen Red Sea and in Socotra, but never recorded in the north-western Gulf of Aden, such as the genera *Plerogyra*, *Oulophyllia*, *Mycedium*, *Seriatopora*, *Alveopora*, and *Montastraea*.

Species distribution along the Gulf of Aden coast

Along the Yemen Gulf of Aden coast, the results of the multivariate analyses indicate that the coral species presence and relative frequency are different in Aden, in the Balhaf and Bir Ali sector, and in the Burum and Al Mukallah sector (PCA, Fig. 3). This is the result of rather striking patterns of scleractinian corals species distribution occurring sharply along a relatively short stretch of coast (Fig. 1C). Given the small sample size in Aden we concentrated our analyses and discussion mainly on the coast from Balhaf to Al Mukallah (Table 1).

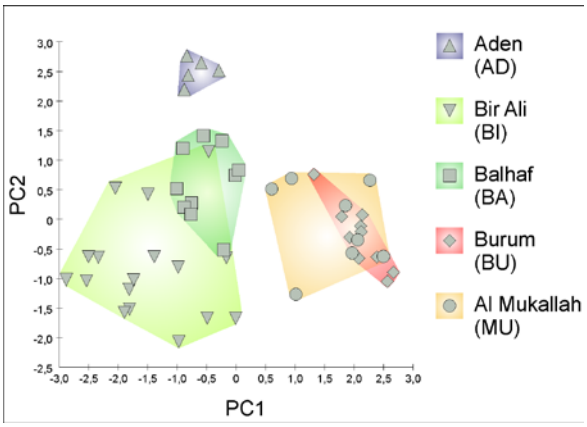


Figure 3: Principal Component Analysis of the species presence data set in the Yemen Gulf of Aden.

Genus	***species***	**% frequency**			
		BA (10)	**BI** (17)	**BU** (10)	**MU** (8)
Turbinaria	*peltata*	**0**	**0**	10	13
Leptoseris	cf *hawaiiensis*	**0**	**0**	10	38
Coscinaraea	*wellsi*	**0**	**0**	10	38
Cycloseris	*vaughani*	**0**	**0**	30	38
Acanthastrea	*maxima*	**0**	4	40	50
Leptoseris	*glabra*	**0**	11	20	25
Parasimplastrea	*omanensis*	11	**0**	40	50
Anomastraea	*irregularis*	70	12	100	100
Siderastrea	*savignyana*	100	41	100	100
Astreopora	*myriophthalma*	0	7	80	13
Blastomussa	*merleti*	10	6	50	13
Micromussa	*amakusensis*	10	12	70	38
Symphyllia	*radians*	**0**	18	60	13
Pavona	*maldivensis*	20	**0**	**0**	**0**
Tubastraea	*micranthus*	10	18	**0**	**0**
Pavona	*clavus*	10	18	**0**	**0**
Acropora	*hyacinthus*	20	12	**0**	**0**
Psammocora	*contigua*	20	29	**0**	**0**
Acropora	*muricata*	20	26	10	**0**
Galaxea	*astreata*	60	59	**0**	**0**
Goniastrea	*retiformis*	90	76	10	**0**
Leptoria	*phrygia*	50	53	**0**	**0**

Table 1: Scleractinian corals with different distribution patterns between Balhaf (BA), Bir Ali (BI), Burum (BU), and Al Mukallah

(MU). The total number of sites for each location in given in brackets. For each species the % frequency in each area is given.

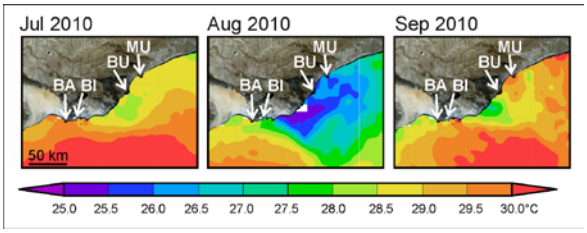
For example, *Turbinaria peltata*, *Leptoseris cf hawaiiensis*, *Coscinaraea wellsi*, and *Cycloseris vaughani* were recorded in Burum and Al Mukallah but were not found in Balhaf-Bir Ali (Table 1). Conversely, *Pavona maldivensis*, *P. clavus*, *Tubastraea micranthus*, *Acropora hyacinthus*, *Leptoria phrygia*, *Galaxea astreata*, and *Psammocora contigua* were recorded in the Balhaf-Bir Ali sector, but were not found either in Burum or in Al Mukallah (Table 1). Finally, some species were found in Balhaf-Bir Ali and in Burum but not in Al Mukallah (*Goniastrea retiformis*, *Acropora muricata*). Other coral taxa distributed throughout the study area were observed more frequently in the eastern sectors than in the Balhaf-Bir Ali area (e.g. the Arabian endemic *Acanthastrea maxima* and *Siderastrea savignyana*) (Table 1).

Discussion

The Arabian Sea upwelling causes at least seasonally environmental conditions similar to those typically found at higher latitudes in the northern hemisphere (the "pseudo-high latitude effect") (Sheppard et al. 1992). Its influence is highest in the Arabian Sea. In the Gulf of Aden it is stronger in the East and becomes less important going West. The effects of the upwelling are not only known to limit the presence of certain species of some organisms, but also have profound influence on the general marine ecology and on the different processes which lead to the construction of coral reefs in the Gulf of Aden and Arabian Sea (Benzoni et al 2003; Sheppard et al. 1992).

Formerly, the Arabian region was divided in six areas based on coral presence (Sheppard and Sheppard 1991) and the Gulf of Aden and Arabian Sea were included in the same area. More recently, according to the criteria used for the definition of marine ecoregions (ME) of the world (Spalding et al. 2007) the Yemen coasts of the Red Sea were assigned to ME88 (Southern Red Sea), and the Yemen Gulf of Aden and Socotra Archipelago to ME89 (Gulf of Aden) mainly as a result of a supposedly rather homogeneous influence of the upwelling. Our data, however, indicate that based on the diversity and distribution patterns of scleractinian corals, three different regions can be recognized in Yemen. ME89 as such is highly inhomogeneous with differences in coral community types, coral species and genera distributions between the Gulf of Aden and the Socotra Archipelago. A similar subdivision was found by Kemp (1998) based on reef fish distribution. This author suggested that closer affinities with the rest of the Indian Ocean fauna in the Archipelago could explain this pattern, a likely explanation for corals too.

In the Yemen Gulf of Aden substantial differences in benthic assemblages composition and coral community capacity for bioconstruction (Benzoni et al 2003; Pichon et al 2010; Richard et al. 2011) have been described between ~~the~~ Al Mukallah and Balhaf along a relatively short stretch of coast (Fig. 3, Table 1). The existence of disjunct Red Sea and Indian Ocean species distributions and the striking differences between the eastern and the western Gulf of Aden were also remarked by a study of reef fish biogeography in this area (Kemp 1998). Our results showed that similarly very marked coral species distribution patterns occur. These changes along a longitudinal gradient in the Gulf of Aden have been so far explained based on the stronger influence in the East rather than the West of the pseudo-high latitude effect brought by the seasonal upwelling. In fact, a 10 years database of sea water surface temperature (NASA Giovanni online data system) shows that between July and September the sea surface temperature between Balhaf and Al Mukallah can change abruptly, and not necessarily linearly, with up to 1.5°C (1°C on average) difference between the east and the west of the study area (Fig. 5). These apparently small differences may actually have a very strong impact on the life of marine organisms and lead to differences in species distribution, benthic assemblages composition, and capacity for bioconstruction of the hard coral communities.



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The discontinuous presence of available hard substrate has been indicated by several authors as another factor limiting the distribution of coral communities in the north-western Gulf of Aden (Benzoni et al. 2003). However, recent investigations have shown that although high cover coral communities are found on hard substrates in the Balhaf, Bir Ali, Burum, and Al Mukallah sectors, they are absent along the rocky coastline between Burum and Bir Ali (Richard et al. 2011). Hence, other factors ~~rather~~ than water temperature and hard substrate availability could explain the lack of coral dominated

assemblages and represent a barrier acting at the local scale on coral species distribution. One likely explanation could be the presence of some major wadi (intermittent watercourse) estuaries occurring where coral communities do not form despite the presence of hard substrate. In the Gulf of Aden the freshwater and sediment input brought by the wadis onto the coastal marine communities is generally highly seasonal, and several small wadis may not have any major effect on the coral dominated assemblages. However, larger wadi systems, such as Wadi Hajr (Fig. 1C) may actually play a major limiting role. This important wadi discharges into the sea approximately 40 km east of Bir Ali and 70 west of Al Mukallah with an average discharge into the Gulf of Aden of 6 m3/s with a total annual runoff of 470 million m3 (Girgirah et al. 1987). In fact, in correspondence of this and of other wadis between Bir Ali and Burum, the hard substrate available is usually covered in macroalgae or in mixed macroalgal and coral benthic assemblages and only a very limited number of coral species is typically found (Ormond and Banaimoon 1994; Richard et al. 2011). Unfortunately, the current knowledge of the effect of wadis on the composition of benthic assemblages is scanty. However, in the Yemen Gulf of Aden the co-occurrence of freshwater and nutrients inputs from wadis and of upwelling generated temperature and nutrients gradients may synergistically determine the striking coral and reef fish species distribution patterns described above even along such a short stretch of coast.

Finally, the recent findings on the peculiar hydrology of the Gulf of Aden could also contribute to the explanation of the complex patterns of species distribution observed there. Until a decade ago, it was thought that the Red Sea Water moved into and through the Gulf of Aden in a long, narrow boundary undercurrent. However, the existence of mesoscale eddies coming from the Arabian Sea and stirring the Red Sea water in the Gulf of Aden with their westward movement was recently revealed (Bower et al. 2002; Al Saafani et al. 2007). These eddies survive and move westward within the gulf in spite of the frictional effect of the boundaries of the gulf (Al Saafani et al. 2007). Hence, they not only mix the Red Sea water with the Arabian Sea water in the Gulf of Aden, but also potentially influence the transport of larvae in highly variable and so far unexpected ways.

In conclusion, in Yemen the Red Sea, Gulf of Aden, and Socotra Archipelago represent three different regions in terms of coral reef fish and coral biogeography. In the Gulf of Aden, the seasonal upwelling may not be the only factor playing a role in the peculiar patterns of coral species distribution. In fact, the input of freshwater from wadi estuaries and the water mixing caused by westwards moving eddies may play a significant role in the species distribution patterns along the Yemen Gulf of Aden coast.

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