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Specific Thermal Regime and Coral Bleaching Pattern in Hengam Island, the Eastern Persian Gulf

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Abstract
Thermal anomaly is among factors initiating coral bleaching and mortalities and threatening coral reefs worldwide. Therefore, susceptibility of corals to thermal stress is a central concern in reef conservation. In this study, we evaluated underwater temperature during 2012-13 and bleaching status of corals during summer 2012 in Hengam Island located in the eastern Persian Gulf. Hengam coral community - faced with milder seasonal temperatures compared with more inward coral communities of the Persian Gulf – usually experiences substantial mitigation of underwater temperature (i.e. ~1-5°C) during high-tides in the warm season. In August 2012, some corals of Hengam community including species from the families Faviidae, Pocilloporidae, Poritidae and genus *Coscinaria, Psammocora, Turbinaria, Montipora* and *Symphyllia* bleached after ~3 weeks of exposure to daily average underwater temperature >33°C. Therefore, bleaching threshold (BT) of the corals was ~2°C lower than BT of southeastern counterparts. *Acropora downingi,* the dominant coral with high live coverage was not affected by the bleaching. This contradicts the usual bleaching pattern observed in the Persian Gulf, in which acroporids were the most extensively damaged coral or among the bleached ones. Based on results, it is postulated that bleaching of *Acropora* is slowed down by the fast tidal flows and rapid cooling in Hengam, a promising event for times of increasing temperature.

Keywords: *Hard coral diversity, Non-fatal bleaching, Sea surface temperature (SST), Tidal cooling, Water flow*

1. Introduction

When seawater temperature persists 1-2°C above the long-term summer maxima for few weeks, the obligatory endosymbiosis collapses with loss of algae from coral tissue and coral bleaching occurs (Hoegh-Guldberg, 1999). The bleached colonies lose the ability for photosynthesis and are more susceptible to disease and mortality (Bruno et al., 2007). As the thermal anomaly boosts and extends, coral bleaching and mortality get harsher (Hoegh-Guldberg, 1999). Therefore, with the increase in intensity and frequency of thermal anomalies due to climate change (Hoegh-Guldberg et al., 2014); temperature tolerance of corals constitutes a central concern in reef conservation.

Coral susceptibility to thermal bleaching is adapted by local environmental condition and is therefore, different among species and between regions (Jokiel and Coles, 1990; Marshall and Baird,

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2000). Some of the most thermal tolerant species and populations of reef-building corals are living in the Persian Gulf, a highly oscillating environment that in summer constitutes the world's warmest sea (Kleypas et al., 1999). Therefore, investigation on temperature tolerance of the Persian Gulf coral communities may benefit our general understanding of the ability of corals to adapt or acclimate to temperature variation (Feary et al., 2013).

Water temperature differs spatially in the Persian Gulf (Fig. 1); and susceptibility of corals to bleaching has been variable between species and among populations of the same species living at different regions. The most extensive coral bleaching was associated with thermal anomalies in 1996 and 1998, which resulted in extensive mortality of acroporid corals in 1996 and moderate mortality of massive corals in 1998 in many coral communities of the southern, southeastern and northern Persian Gulf (Goerge and John, 2000; Sheppard and Loughland, 2002). In 2007, bleaching and mortality was only observed in some northern coral communities of the Persian Gulf (Maghsoudlou et al., 2008; Kabiri et al., 2013). In the southeastern Persian Gulf, corals from genera Acropora, Porites and Favites bleached in summer 2002, but regained normal color by November 2002 (Riegl, 2003). Likewise, corals from genus *Acropora*, *Porites*, *Turbinaria*, *Anomastraea*, *Coscinaraea*, *Favites*, *Favia*, *Platygyra*, *Cyphastraea* bleached in summer 2010, but recovered by the late October 2010 (Riegl et al., 2011). Using continuously logged underwater temperature data, bleaching threshold (BT) was estimated as 3 weeks of exposure to >35°C average daily temperatures for coral communities of the southeastern Persian Gulf (Riegl, 2011; Riegl et al., 2012).

In August 2012, corals including *Acropora*, *Pocillopora*, *Goniopora*, *Montipora*, *Porites*, *Platygyra*, *Favites* and *Symphyllia* bleached in coral communities of Qeshm, Larak and Hormoz Islands located in the eastern Persian Gulf (Kavousi et al., 2014). The bleaching occurred when monthly averaged sea surface temperature was 33.8±0.4°C; and hence Kavousi et al. 2014 suggested that the BT of the observed coral communities is ~1.5 to 2.5°C lower than the southern counterparts.

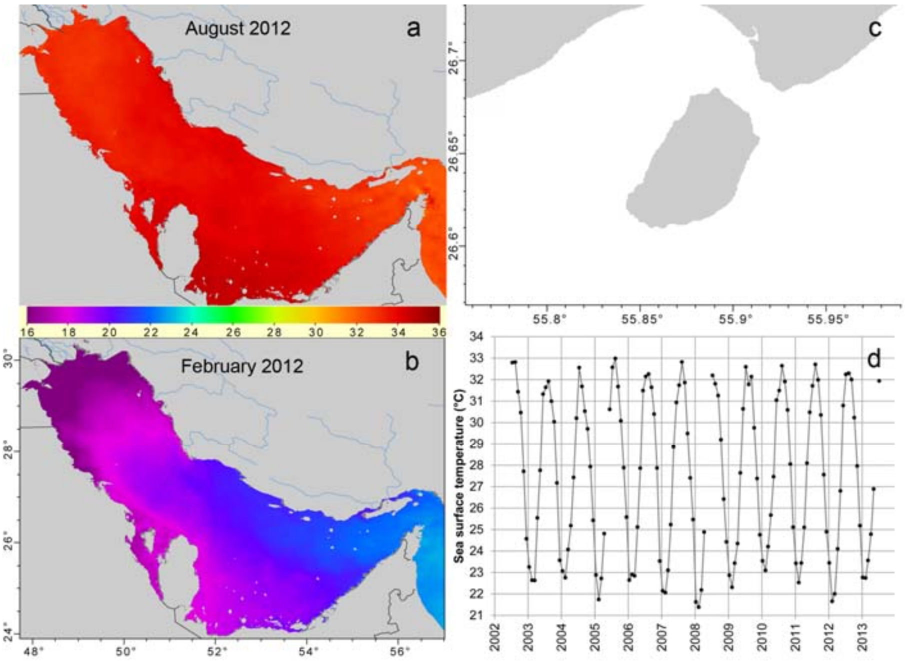

Fig. 1: Averaged monthly Aqua MODIS SST of the Persian Gulf (a-b); the geographical map of Hengam Island (c); averaged monthly 90Aqua MODIS SST of the point (55.9231392, 26.6520027) located nearby the Hengam coral community (d) (Data courtesy of NOAA coast watch (http://coastwatch.pfeg.noaa.gov/erddap)).

The average temperature of an area containing coral reefs can be estimated by day or night–time SST (e.g. Fig. 1). Actual temperature experienced by coral colonies can vary intensely over fine spatial and temporal scales as a result of variation in local weather condition and/or tidal currents and may differ largely from SST (Coles, 1997; Berkelmans et al., 2004; Bird, 2005; Leichter et al., 2006; Sheppard, 2009; Jimenez et al., 2012; Silverman et al., 2012). Therefore, consistent underwater temperature data are needed to reveal the processes mitigating or enhancing magnitude of thermal stress in coral communities (Riegl and Piller, 2003; Skirving et al., 2006; Putnam and Edmund, 2008).

In this report, we provided underwater temperature continuously logged during 2012-13 in Hengam coral patches, the eastern Persian Gulf. We also reported coral bleaching of the study area during summer 2012, when other beaching event also observed in the eastern Persian Gulf (Kavousi et al., 2014). Our observation contradicts the common bleaching patterns observed in the Persian Gulf, in which acroporids were the most extensively damaged coral, or at least among the bleached species. We therefore, discuss the possible reasons behind the unusual bleaching pattern which was also observed in Sir Abu Nuair *Acropora* dominant coral community by Riegl 2003.

2. Material and Methods

2.1. Study Site Description

The study was carried out in the coral community of the eastern Hengam Island located in the eastern Persian Gulf. *Acropora downingi* is the dominant coral in Hengam coral community with ~65 % live covers (Rezai et al., 2010; pers. obs.). The community covered an area of ~30(103) m^2 from depth of 3 to 7m (pers. obs.), and is subjected to semi-diurnal tidal regime.

2.2 Underwater Temperature and Tidal Height Data

HOBO underwater temperature loggers (Onset, Massachusetts, U.S.A) were lodged in two points (26.658972, 55.916639; 26.659278, 55.918306 with a horizontal distance of 130 m) at depths of three and six m from date of 12/09/2011 to 03/11/2013. Underwater temperature was logged with different time intervals of 5, 15, 30 and 40 min during the study period. The data collected at both depths were combined and presented in the scatterplot with line of daily average temperature (i.e. running one day mean). The summer mean underwater temperature was calculated by averaging the data collected from 07/01 to 10/01/2012, while the winter mean underwater temperature was calculated by averaging data collected from 01,01 to 04,01,2013. The maximum and minimum annual underwater temperatures and the monthly average temperatures of July, August and September 2012 were also calculated.

The diurnal or semidiurnal acute fluctuation (decrease then increase) of underwater temperature (~1-5°C in 1-3h) was repeatedly observed during the warm season. Thus, we speculated that tides might be the factor initiating the temperature signals. Hence, tidal height data of Hengam Island were obtained from the website of National Cartographic Center of Iran (http://iranhydrography.ncc.org.ir); and then we assessed whether the signals were coincided with high tides (HT) during summer 2012. To calculat the percentage of the big and small HTs (i.e. HTs with heights of 2.5-3 and 2-2.5m respectively) associated with the signal in depth of 6m, we used the data of the time period of 7,6 to 7,26 and 7,31 to 9,9. To compare amount of acute temperature fluctuations between depths, the simultaneous variation of water temperatures in depths of 3 and 6m, and the concurrent variation of tidal height were also plotted for the time period of 9,13 to 9,27. The tidal height and underwater temperature values vs. date/time were also plotted for the time period of 07,31 to 08,20.

2.3. The Coral Status and Diversity

Although, there were no sign of bleaching around the study site on 31 July, the coral bleaching was then observed around mid-August. The bleaching status of corals was assessed by timed swims (Hill and Wilkinson, 2005) at 25 and 27 August 2012. At each day, the scuba diver swam for 20 min around each temperature logging site and took photographs of every non-acroporid colonies encountered. Corals in the photographs were identified (up to genus or species levels) using an identification reference and a local field guide publication (Veron 2000; Vajed Samiei et al., 2013) and their bleaching status was categorized as: 1) not bleached or “N” 2) bleached or “B” 3) partially bleached or “PB”, if >30% of the colonial surface were affected by the bleaching. Whenever all colonies of a species were not in the similar condition, we presented the percentage of colonies recognized as B and/or PB as the bleaching status. The qualitative change in color was presented by the photographs of two colonies in the stage of bleaching and afterward. The maximum monthly and weekly average temperatures of summer 2012 were assessed as the bleaching thresholds of the affected corals.

3. Results

3.1. Underwater Temperature and Tidal Height

The underwater temperature variation in Hengam coral patches from date of 12,09,2011 to 03,11,2013 is presented in Figure 2. The annual variation of underwater temperature was about 14°C. The maximum and minimum underwater temperatures were 34.2 and 20.2°C; which were recorded in August and February 2012, respectively.

The mean daily underwater temperature was 32.4°C in summer 2012 (averaged for the time period of 07,01 to 10,01,2012) and 21.6°C in winter 2013 (averaged for the time period of 01,01 to 04,,1,2013). The monthly average temperatures were 32.4, 32.8 and 31.9°C in July, August and September 2012, respectively.

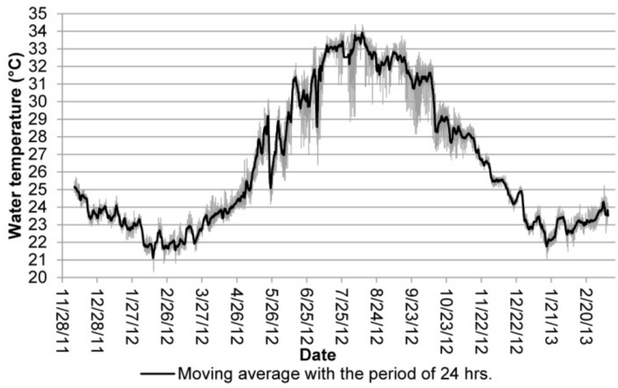

Fig. 2: Fifteen months underwater temperature variation of the studied area (data from 12,09,2011 to 08,01,2012 and from 01,08,2013 to 03,11,2013 were recorded in depth of 3 m while the rest were recorded in depth of 6 m). The black line indicate the running one day mean.

The acute fluctuation (decrease then increase) of underwater temperature (~1-5°C in 1-3h) occurred in the warm season only during high tides (Fig. 2,3& and 4). During the 60 days period, ~52% of the big high tides (2.5-3m) and ~15% of small high tides (2-2.5m) was associated with substantial water cooling (i.e. >1°C) at depth of 6 m, respectively. During that period, big and small high tides constituted ~64 and 36% of whole high tidal levels respectively. Acute temperature fluctuations were larger at depth of 6m comparing with 3m for the time period of 9,13 to 9,27 (Fig. 4). Mean underwater temperature was ~0.1°C higher in depth of 3m comparing with 6m for the latter time period.

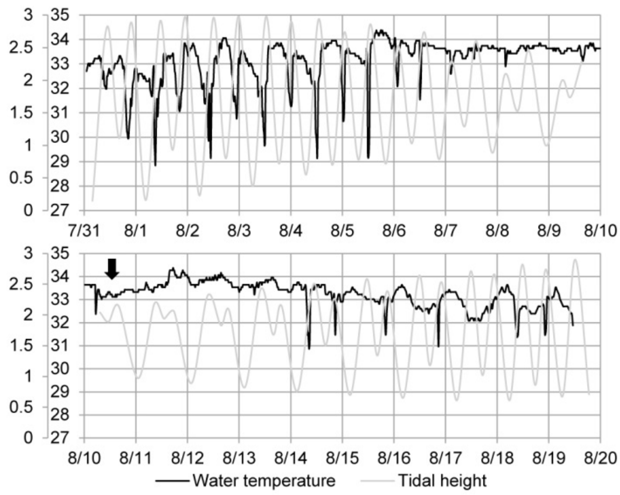

Fig. 3: Concurrent variation of underwater temperature (°C) and tidal height (m) in the Hengam coral community is indicated. The black arrow indicates the time point of first observation of bleaching. Data of tidal height were obtained from the website of National Cartographic Center of Iran (http://iranhydrography.ncc.org.ir).

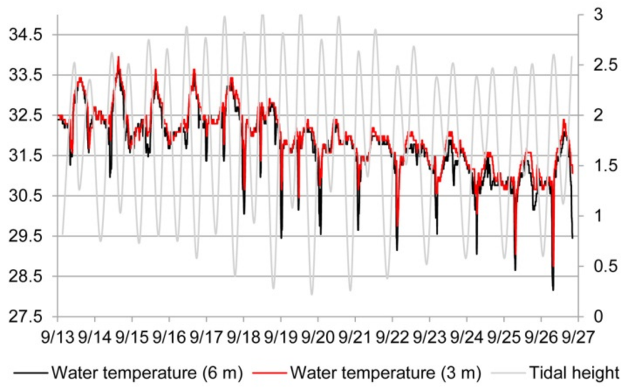

Fig. 4: Simultaneous variation of water temperatures (°C) in depths of 3 and 6 m; and the concurrent variation of tidal height in Hengam Island. Tidal heights were obtained from the website of National Cartographic Center of Iran (http://iranhydrography.ncc.org.ir).

3.2. The Coral Bleaching

The name, number and bleaching status of twenty four species are presented in Table 1. Based on our observation, 15 species of hard corals were affected by the bleaching event in Hengam community in 2012. Among the identified species, *Pavona* cf. *diffluens* was recorded for the first time from the northeastern Persian Gulf (Fig. 5a,b). No newly died colony was detected five months after the bleaching event (Fig. 5). The maximum monthly average temperature was 33.2°C and maximum weekly average temperature was 33.6°C during summer 2012. In detail, Hengam corals were exposed to >32°C for 65 days of which 23 days were above 33°C.

4. Discussion

Among coral communities of the Persian Gulf, those located in the eastern (i.e. nearby Strait of Hormoz) and in the southeastern parts experience the mildest and the most extreme summer temperatures, respectively (Fig. 1). The annual variation of underwater temperature in Hengam coral community located nearby the Strait of Hormoz was 20.2-34.2°C during 2012-2013; which is narrower than the thermal ranges experienced by the southern and southeastern coral communities of the Persian Gulf (11.2-36.2°C in Sheppard, 1993 and 14.9-37.2°C in Foster et al., 2012).

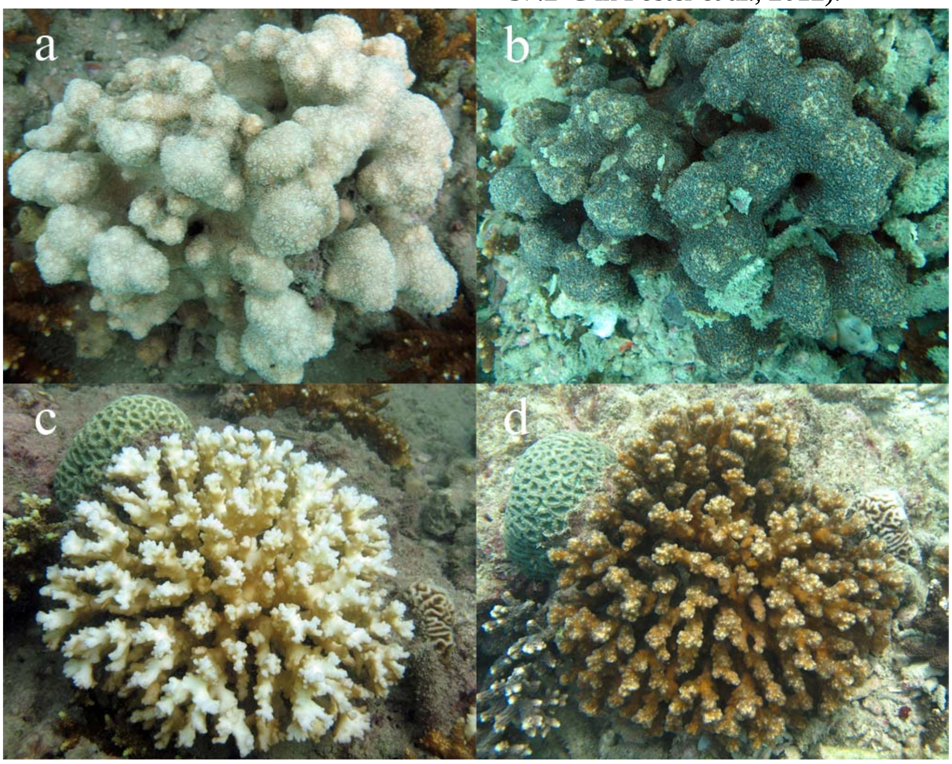

Fig. 5: The above photographs are *Pavona* cf. *diffluens*; photograph (a) was taken at date of 08/10/2012. Photograph (b) was also taken 5 months after the bleaching. The beneath photographs are *Pocillopora damicornis*; Photograph (c) was taken at date of 08/10/2012. Photograph (d) was also taken 5 months after the bleaching.

Table 1. The bleaching status of corals observed in Hengam coral community during summer 2012.

Name	Bleaching status of colonies	No. of OC	Name	Bleaching status of colonies	No. of OC
Acropora downingi	N	> 50	*Favia speciosa*	B	20
Acropora arabensis	N	> 20	*Favites pentagona*	B 75%	4
Montipora	PB	5	*Cyphastrea microphtalma*	N	4
Stylophora pistilata	B	2	*Cyphastrea calcidicum*	B	1
Pocillopora	B	5	*Leptastrea transversa*	N	2
Pavona decussata	N	3	*Leptastrea purpurea*	N	1
Pavona cf. diffluens	B or PB	5	*Platygyra acuta*	B 75%	8
Porites	B 20% & PB	10	*Coscinaria monile*	B	3
Goniopora collumna	B	8	*Acanthastrea echinata*	N	3
Psammocora stellata.	B 50%	4	*Symphillia*	B 50%	2
Siderastrea	N	1	*Turbinaria peltata*	B	2
Echinopora grandicula	B	1	*Turbinaria* sp.	N	1

Abbreviations: No. of OC: number of observed colonies; B: bleached; N: not bleached; PB: partially bleached or >30% of the Colonial surface were affected by the bleaching; e.g. B 50%: 50% of the observed colonies were bleached.

Susceptibility of corals to bleaching varied between species and among populations of the same species living at different regions. In the southeastern coral patches of the Persian Gulf, corals including *Acropora, Porites, Turbinaria, Anomastraea, Coscinaraea, Favites, Favia, Platygyra* and *Cyphastraea* bleached after exposure to >34°C for ~8 weeks of which 3 weeks were >35°C; while the bleached corals had recovered by the late October 2010 (Riegl et al., 2011).

In some eastern Islands of the Persian Gulf including Larak, Hormoz and Qeshm Islands located nearby Strait of Hormoz, *Acropora, Pocillopora, Goniopora, Montipora, Porites, Platygyra,* and *Favites* bleached in summer 2012 when average monthly SST was ~33.5-34°C (Kavousi et al., 2014). Thus, Kavousi et al. 2014 suggested that bleaching threshold (BT) of latter corals is ~1.5-2.5°C lower than the southeastern counterparts. In accordance with the latter statement, our study indicated that some minor corals including species from the families Faviidae, Pocilloporidae, Poritidae and genus *Coscinaria, Psammocora, Turbinaria, Montipora* and *Symphyllia* (Table 1) bleached after exposure to daily average underwater temperature of >32°C for ~ 65 days of which ~3 weeks were >33°C in coral community of Hengam Island located in the eastern Persian Gulf. In our study sites, the maximum monthly and weekly average underwater temperatures were 33.2°C and 33.6°C respectively during summer 2012.

In Hengam Island, *Acropora downingi*- the dominant coral of the community – and *A. arabensis* were not affected by the bleaching; while in southwestern Larak Island and Bu-Musa Island ~70 and 100% of *Acropora* colonies were partially or totally bleached, respectively (Kavousi et al., 2014). The bleaching pattern observed in Hengam contradicts the usually observed pattern of higher temperature sensitivity of branching versus massive corals (Loya et al., 2001; McClanahan, 2004). Acroporids are also referred as one of the most thermal sensitive taxa in the Persian Gulf region, since they have been usually among the taxa extensively damaged by thermal bleachings in the last decades. Tabular acroporid corals including *A. downingi* and *A. clathrata* underwent extensive bleaching and mortality in 1996 and slight mortality in 1998, while massive corals (e.g. poritids and faviids) experienced moderate bleaching and mortality in 1998 in coastal areas of United Arab Emirate (UAE) (Goerge and John, 2000; Sheppard and Loughland, 2002; Riegl, 2003). In 2007, acroporids also suffered from bleaching more than other massive corals in some coral communities of the northern

Persian Gulf (Maghsoudlou et al., 2008; Kabiri et al., 2013). In summer 2002, corals including *Acropora, Porites*, Favia and Favites bleached in the southeastern coral communities, but had regained normal color by November 2002 (Riegl, 2003).

In contrast with the latter observation and similar to our observation, in summer 2002, Riegl observed that in the coral community of Sir Abu Nuair Island all coral species except *A. downingi*, *A. clathrata* and some *Porites harrisoni* were bleached (Riegl, 2003). In Sir Abu Nuair Island, one of the densest stands of large, tabular *Acropora* of the southeastern Persian Gulf was present in 2002; suggesting that neither in 1996 nor in 1998. an extensive *Acropora* mortality occurred in the area (Riegl, 2003). To explain the observed bleaching pattern, Riegl suggested that *Acropora* dominated coral community of Sir Abu Nuair was an offshore site and surrounded by areas with depths of >30m; thus, the water column may heat less readily than in the coastal areas. However, the latter statement cannot totally explain why massive corals were affected by the bleaching and not acroporids.

Variation in bleaching susceptibility of corals in the same community could be induced by inherent or environmental factors including types of symbionts, host elements and microhabitat conditions (Baker, 2003; Rowan, 2004; Fabricious et al., 2004; Fabricious, 2006; Abrego et al., 2008; van Woesik et al., 2012). It has been suggested that high thermal tolerance might be linked to prevalence of clade D *Symbiodinium* in the northern Persian Gulf corals (Mostafavi et al., 2007; Mostafavi et al., 2013). The latter studies found *Symbiodinium* clade D in *Acropora*, *Pocillopora, Favia, Platygyra, Cyphastrea*, *Pavona, Turbinara, clade C in Porites* and *Psammocora*, and clade A in Stylophora and Goniopora. All of the latter taxa, except *Acropora* were affected by 2012 bleaching in Hengam coral community; and even *Acropora* was affected by the bleaching in Larak and Bu-Musa Islands (Kavousi et al. 2014). Therefore, the unusual bleaching patterns observed in Hengam and Sir Abu Nuair cannot be explained by the variation in symbiont type. In addition, a recent study on symbiont diversity of the Persian Gulf corals indicated that the “generalist” clade C3 is the prevalent symbiont type in the southeastern Persian Gulf; suggesting that the association with thermal tolerant clades “D1a and C15” cannot be the only reason behind high thermal resistance of the Persian Gulf corals (Hume et al., 2013).

Many characteristics of branching corals including lower metabolic rate, higher growth rate and lower tissue thickness and so on, were attributed to lower temperature susceptibility of branching corals comparing with the massive ones (reviewed by Wooldridge 2014). However, in some areas including our study sites, *Acropora* is being favored over other corals by some factors even during temperature peak periods. In the Persian Gulf, higher bleaching resistance of *Acropora* comparing with massive opponents has been observed only in coral communities with high *Acropora* cover. We therefore, speculate that the observed bleaching pattern might be related to high *Acropora* cover or factors favoring its development. Since, sensitivity and demand of corals to water-flow differ among species, water flow is an important factor influencing coral community structure (Done, 1982; Mergner and Schuhmacher, 1985). In the northern Red Sea and across indo-pacific regions, dominancy of tabular *Acropora* at coral communities with high hydro-dynamic exposure is a common pattern (Riegl and Velimirov, 1994).

As well, in the Persian Gulf, high live cover of tabular acroporids have usually been found on the more waves exposed windward fringes of offshore shoals and islands (John, 2012; Riegl et al., 2012). Hengam coral community also experiences fast water-flow moving particles with velocity of ~50-100 cm.s-1 above coral colonies during rising and falling of tides (pers. obs.). In contrast with Hengam community, the communities on nearby break waters (with distance of ~2km from Hengam coral community) experiencing very limited water flow are dominated by massive corals including faviids and poritids (pers. obs.). Hence, exposure to high water flow might be an important factor for development of dense *Acropora* carpets in the region.

Loya et al. (2001) reported that the only site where they found intact *Acropora* colonies after extensive 1998 bleaching in Sesoko Island of Japan was characterized by very strong currents. In theory, increase in water-flow velocity decreases diffusive boundary layer; which improves passive diffusion of metabolites and heat (Nakamura, 2010).

In recent years, experimental observation has also indicated that flow rate is positively correlated with rates of photosynthesis, growth, phosphate uptake, micosporine-like amino acid accumulation under ultraviolet light exposure, survival under high irradiance and SSTs and recovery after bleaching; and is negatively correlated with photoinhibition of photosynthesis (reviewed by Nakamura 2010). Wooldridge 2014 proposed the ‘‘CO_2 limitation model’’ and explained that branching corals with thin tissue layers, are heavily reliant on a sea water supply chain of CO_2, while massive and encrusting growth forms with thick tissue layers, have lower photosynthetic demand for CO_2 and/or increased basal respiration rates, and therefore are less reliant on the sea water supply. Considering these, we suggest that the observed bleaching pattern in Hengam coral community might be the, indicators of a state in which fast water flow is favoring corals using the strategy of being reliant on a sea water supply over the others, using the strategy of being self-sustained.

Our study site is located nearby the Strait of Hormoz where thermal stratification of water column occurs during the warm season (Delphi and Mosaddad, 2010; unpublished data of the second author), and strong tidal currents influence shallow areas (Pous et al. 2012). We therefore, postulate that high tides induce movement of cold water from deeper areas toward the study site; which results in diurnal or semidiurnal short-term decreases in water temperature. Riegl and Piller, 2003 suggested that areas washed by cold water currents may be possible refugia for corals facing with global warming. In addition, some recent studies linked exposure to intermittent tidal flows to lower bleaching susceptibility of corals (Bird, 2005; Leichter et al., 2006; Smith and Birkeland, 2007; Skirving et al., 2006). Therefore, based on results, it is postulated that bleaching of *Acropora* is slowed down by the fast tidal flows and rapid cooling in Hengam a promising event for times of increasing temperature. It is also suggested that future studies evaluate water flow velocity as a potential factor influencing coral community structure in the Persian Gulf.

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