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Local bleaching thresholds established by remote sensing techniques vary among reefs with deviating bleaching patterns during the 2012 event in the Arabian/Persian Gulf

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ABSTRACT

A severe bleaching event affected coral communities off the coast of Abu Dhabi, UAE in August/September, 2012. In Saadiyat and Ras Ghanada reefs ~40% of the corals showed signs of bleaching. In contrast, only 15% of the corals were affected on Delma reef. Bleaching threshold temperatures for these sites were established using remotely sensed sea surface temperature (SST) data recorded by MODIS-Aqua. The calculated threshold temperatures varied between locations (34.48 °C, 34.55 °C, 35.05 °C), resulting in site-specific deviations in the numbers of days during which these thresholds were exceeded. Hence, the less severe bleaching of Delma reef might be explained by the lower relative heat stress experienced by this coral community. However, the dominance of *Porites* spp. that is associated with the long-term exposure of Delma reef to elevated temperatures, as well as the more pristine setting may have additionally contributed to the higher coral bleaching threshold for this site.

1. Introduction

Warm water coral reefs are among the most productive and biologically diverse ecosystems on Earth. Many of these reefs are in decline due to the impact of a variety of global and local stressors (Sheppard, 2003, Baker et al., 2008, Logan et al., 2014, van Hooidonk et al., 2013, D'Angelo and Wiedenmann, 2014). Among them are heat stress episodes during which temperatures exceed a regional threshold and induce the often fatal breakdown of the coral/alga symbiosis which manifests as coral bleaching (Baker et al., 2008, Goreau and Hayes, 1994). The globally highest bleaching thresholds are found among corals of the southern Arabian/Persian Gulf, hereafter IRSA (Inner ROPME Sea Area) where they survive peak temperatures above 35 °C (Coles, 2003; Sheppard et al., 1992). However, also these corals can fall victim to bleaching and coral bleaching linked to unusually warm temperatures has been shown to affect the IRSA at least since 1996 contributing to a substantial loss of coral cover (Riegl and Purkis, 2015; Riegl, 2002). The variability of bleaching susceptibility observed among different species resulted in shifts of the coral community structure in the aftermath of bleaching events in the IRSA (Riegl and Purkis, 2015).

The IRSA is a shallow basin at high latitude and therefore, the thermal properties of the waterbody, respond quickly to local factors. Rapid cooling by winds (Thoppil and Hogan, 2010; Cavalcante et al., 2016) or preferential heating/cooling in shallow areas or regions protected by headlands is common (Riegl and Purkis, 2012). Correspondingly, small-scale excursions of thermal stress with consequent variation in the severity of coral bleaching and mortality events have been observed. A severe bleaching event recorded in 2007 off the Iranian coast (Baker et al., 2008) was absent or had negligible impact in the south-eastern IRSA. Bleaching was observed in 2013 in Qatar, but not in eastern Abu Dhabi (B. Riegl pers. obs.). In general, coral stress events in the northern IRSA (Iran) often do not coincide with those in the southern IRSA, and the Western IRSA (Kuwait, KSA, Bahrain) appears to have suffered fewer, or at least differently-timed, events than the south-eastern IRSA. Hence, strong regional variability in the frequency and severity of bleaching events seem to be characteristic for the region.

Bleaching events are frequently characterized by high variability. On an individual level, the within-colony bleaching response can strongly vary depending on light exposure (Coles and Jokiel, 1978; Brown et al., 1994; Hoegh-Guldberg, 1999). Further variability can also arise from the bleaching susceptibility of different zooxanthellae clades/species (Baker, 2001; Pettay et al., 2015). Among them, the year-round prevalent algal partner of corals in the southern IRSA, *Symbiodinium thermophilum*, can be considered to be one of the most thermo-

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tolerant symbionts (D'Angelo et al., 2015; Hume et al., 2015). Marked regional variability is commonly encountered during bleaching events and may be caused by small-scale water-dynamics and flow patterns (Nakamura and Van Woesik, 2001; Davis et al., 2011), by greater adaptation/acclimatization due to previous stress episodes (Brown et al., 2002; Guest et al., 2012) or by differences in the species assemblage of the affected sites (Marshall and Baird, 2000). The onset of bleaching is often not synchronous across several, even nearby, reefs and neither is the severity or the effects of bleaching (Baker et al., 2008). Additional stressors, such as the disturbance of the nutrient environment, can have significant impacts on bleaching susceptibility (Wiedenmann et al., 2012; D'Angelo and Wiedenmann, 2014). In this context, the mean water column productivity, besides mean temperatures, was the best predictor of the variability of coral reef recovery across the Indo-Pacific (Riegl et al., 2015). Also, local adaptions to environmental factors other than temperature can have strong influences on the temperature tolerance of corals. D'Angelo et al. have shown that IRSA corals are characterized by a pronounced local adaptation to the high salinity of their habitat and that their superior heat tolerance is lost when they are exposed to normal oceanic salinity levels (D'Angelo et al., 2015). Global warming will expose the world's reef to positive temperature anomalies with increasing frequency (Logan et al., 2014). The prerequisite for knowledge-based coral reef management that aims to regionally mitigate the effects of climate change is a thorough understanding of how local factors modulate the response to temperature stress. Therefore, we set out to identify the causes for local differences in bleaching severity observed among coral communities in the southern IRSA off the coast of Abu Dhabi. Since remote sensing platforms offer valuable tools to reconstruct environmental conditions prevailing during coral reef disturbance events (Andréfouët et al., 2014), we used satellite data to establish the local bleaching thresholds in the study sites.

2. Material and methods

2.1. Measuring SST using remote sensing products

The SST (°C) data was extracted from the Aqua\Terra Ocean Color 3 (OC3) Moderate Resolution Imaging Spectroradiometer (MODIS) imagery downloaded from the NASA ocean color data website (http://oceancolor.gsfc.nasa.gov/) and by the Regional Organization for the Protection of the Marine Environment (ROPME) archived in Kuwait. MODIS data are recorded by two instruments. The first is integrated in the Terra satellite (MODIS-Terra) and launched in December, 1999. The second instrument is installed on the Aqua satellite (MODIS-Aqua), and was launched in May, 2002. Both satellites are in sun-synchronous orbits: Terra crosses the equator in a descending node at 10:00, and Aqua crosses in an ascending node at 12:00 noon. Satellite imagery was used for the periods between February, 2000 to December, 2014 (MODIS Terra) and from July, 2002 to December, 2014. (MODIS Aqua). Level-2 images were used for which the sensors were calibrated, geo-located with atmospheric corrections and bio-optical algorithms had been applied. Temperatures were determined for 1 km^2 areas covering the study sites, the highest spatial resolution provided by the MODIS product. Images were analyzed using the SeaWiFS Data Analysis System (SeaDAS) software program Version 7.2 and VISAT BEAM software Version 4.10.3. Images in which the SST signal was affected by

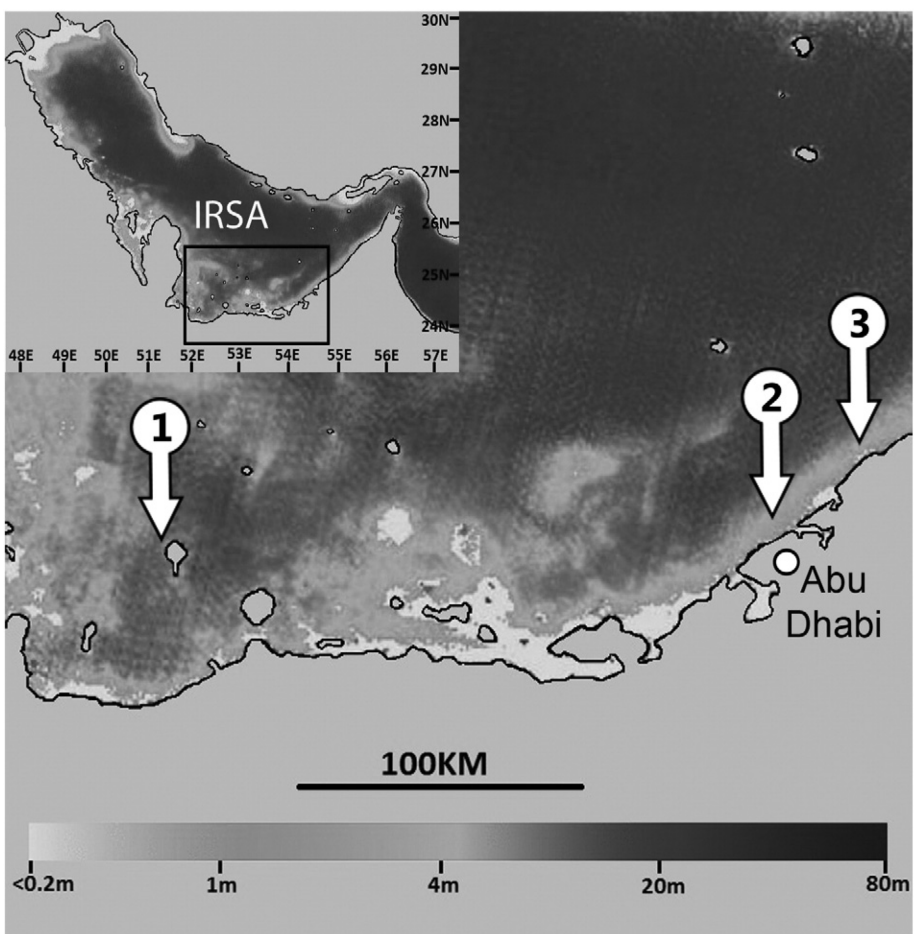

Fig. 1. Bathymetric map of the southern IRSA. Numbers identify the three study sites: (1) Delma, (2) Saadiyat and (3) Ras Ghanada. The Map was constructed using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Ocean Color Data provided by NASA Ocean Biology (OB.DAAC). Gray-level scale defines the depth in meters.