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Temperature and irradiance variability on the Egyptian coast of the Red Sea during the 2020 bleaching event

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ABSTRACT

Heat and irradiance stressors are critical factors affecting coral reefs, especially during the summer season. In the present study, daily sea surface temperature (SST), degree heating weeks (DHWs), and photosynthetically active radiation (PAR) remotely collected by NOAA CRW were assessed in three geographical sectors during the summer of 2020. The results indicated that SST had increased along a latitudinal thermal gradient from the north to the south. On the other hand, the overall accumulated heat stress above the usual maximum climatological SST did not decrease below 4°C-weeks in the three studied sectors and most of the heat stress was concentrated in the north. Associating with the pattern of the SST, the mean PAR levels had also increased from the north to the south by only one Einstein m-2 day-1. In the light of the present study, increases in the SST and PAR levels that have coincident with the 2020 bleaching pattern recorded at the Egyptian coast may synergistically threaten coral reefs at the southern coast. Moreover, although the accumulated heat stress exceeded the bleaching threshold (>4°C-weeks), it may still less severe to corals inhabiting the northern reefs.

Keywords:
Climate change, Egypt, Heat stress, Irradiance, Red Sea.

1. INTRODUCTION

Coral reefs are spectacular ecosystems that -exceptionally- accommodate more than 25% of the marine species in <1% of the sea bottom [1, 2]. In addition to the ecological services they offer, coral reefs also house nearly a quarter of the world's marine fisheries and secure the livelihood for several local communities (about 63 million people in 100 countries) [3, 4]. On average, the accessible coral reefs (30% of the world's coral reefs) pump annual revenues estimated at US$37.8 billion of the worldwide tourism industry [3]. However, the majority of the coral reefs are threatened by climate change and there is a significant global decline in the coral cover due to ocean warming [5]. These unprecedented increases in the sea surface temperature (SST) have in parallel increases the frequency of bleaching events worldwide [6].

Coral bleaching is defined as the dissociation of the symbiotic relationship between coral and endosymbiotic dinoflagellates of family Symbiodiniaceae (aka, zooxanthellae). This physiological response usually associates with multiple of environmental stressors. Among all, increases of SST above the usual climatological means can induce loss of the endosymbionts and/or their photosynthetic pigments and result in partial loss of coral color [7, 8]. However, bleaching can be more detrimental when heat-stressed corals suffer complete whitening that may associate with a 90% shortage in the coral's food requirements secured by endosymbionts [7]. Under heat stress, Symbiodiniaceae cells begin to produce protein-damaging free oxygen radicals called reactive oxygen species (ROS). However, when such stress conditions accumulate, the host cell suffers overproduction of ROS to the extent that derives oxidative stress with which coral cannot maintain the algal symbiont [9].

Light is essential for growth and survival of zooxanthellate corals [10]. Therefore, changes in the daily photosynthetically active radiation (PAR) can constitute a clear risk to coral reefs [11, 12]. For instance, high irradiance of >47 Einstein m^{-2} day^{-1} can synergistically increase the severity of heat stress and accelerate bleaching [12-14]. The severity of bleaching can also increase over the offshore than inshore reefs during periods of anomalously high SSTs as a result of the difference in the irradiance levels. In this regard, some field studies have indicated that corals on warm, turbid nearshore reefs cannot bleach as extensively as corals on the warm, yet clear offshore reefs [15, 16].

The Egyptian coast homes exceptional coral systems that are, expectedly, the last to collapse due to climate change. This is not only because of the privileged geographic position of the Egyptian reefs at the high latitudes in the far north of the Red Sea away from the path of the regular southern heat fluxes, but also the thermotolerant traits of corals inhabiting shallow reefs [17]. However, in 2020, corals at the Egyptian coast of the Red Sea had been affected by high thermal stress impacting Red Sea corals in summertime [18, 19]. Despite the pattern of bleaching signs was apparent between specific coral genera, the levels of environmental stressors associated with this event have not reported yet. Therefore, we describe here the environmental conditions of SST and PAR levels during the 2020 bleaching event recorded in [18] and analyze the pattern of three sensed stress products (SST, DHWs, and PAR) during this event.

2. DATA AND METHODS

2.1 Dataset

To investigate effects of the heat stress resulted in 2020 bleaching event along the Egyptian coast of the Red Sea, full-year data collected by NOAA Coral Reef Watch program (CRW) had been downloaded from ERDDAP server (https://coastwatch.pfeg.noaa.gov/erddap/index.html) (Dataset ID: NOAA_DHW). Collected data were composed of daily 5km high resolution gridded records (v3.1) of SST and Degree Heating Weeks (DHWs) from the northern Red Sea (NRS), without the two gulfs. The DHWs product was mainly used as a baseline for subsequent analyses to determine the period of the accumulated heat stress in the NRS following [9]. Because the high intensity of irradiance can synergistically increase the severity of bleaching, further 4km gridded data on the daily PAR collected by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) were obtained from ERDDAP (Dataset ID: erdMH1par01day) then were analyzed to determine the level of irradiance stress in the NRS.

2.2 Methodology

Levels of stress received by inshore and offshore reefs were assessed during the bleaching event recorded in [18] by determining the three studied products (i.e., SST, DHWs, and PAR) in roughly equal areas. Briefly, the DHW is usually used to detect the accumulation of the heat stress by calculating the running sum of the positive SST anomalies (HotSpots) above the bleaching threshold (1°C above the climatological maximum monthly mean SST) over a period of 12 weeks [9]. On the other hand, PAR is used as a proxy for light availability and is defined as the amount of solar radiation (between 400-700nm) utilized by zooxanthellate corals for photosynthesis. The study regions are represented by three geographical sectors (each of approximately 117 km × 25 km) and each sector contains two 25 km × 25 km study sites (Fig. 1). As such, the first sector (Sector_1) locates in the north and comprises sites of Hurghada and Safaga. The second sector (Sector_2) locates in the middle between the north and the south and comprises reefs of Al-Quseir and Port Ghaleb. At the south (Sector_3), the heat stress and irradiance products were collected from region of Marsa Alam and Wadi El-Gemal.

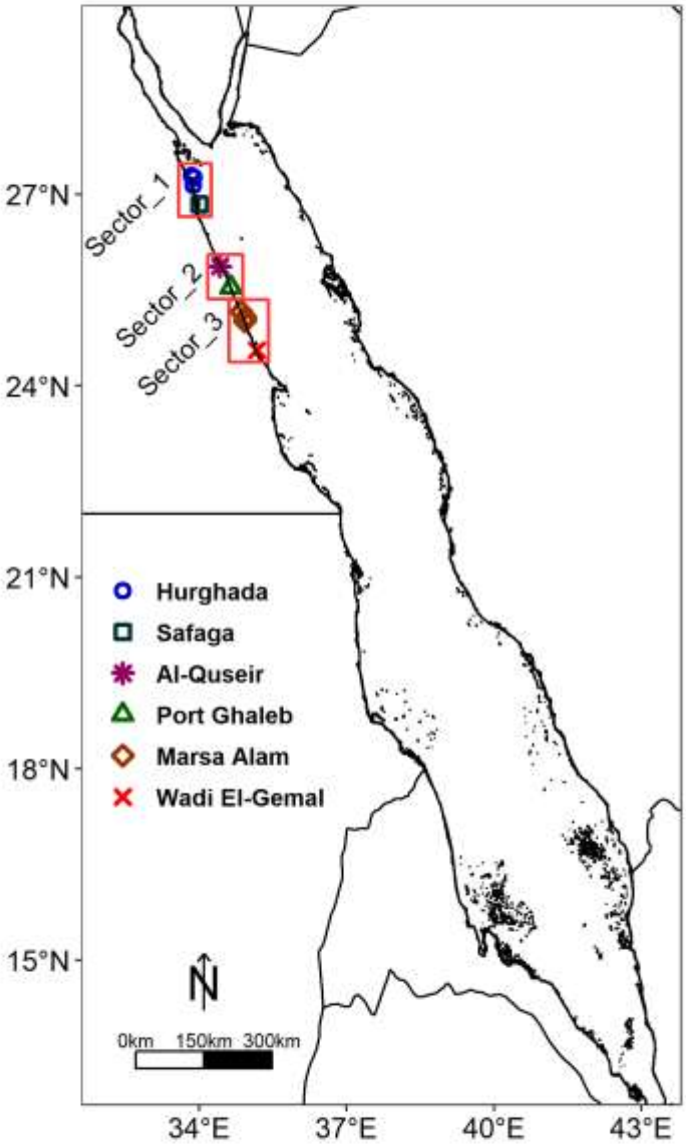

Fig (1): Study sites from which satellite data were collected at the Egyptian coast of the Red Sea. The coordinates of each site are defined as in [18].

2.3 Statistical analysis

Data were primarily tested for normality and homogeneity using Shapiro and Levene's tests, respectively. As the parametric assumptions were violated even after transformation, the Kruskal-Wallis test was applied to test the difference in the DHWs and PAR levels between sectors. Following this, multiple pairwise comparisons between levels of variables were performed. We used Dunn's post hoc non-parametric test in this regard to examine the differences in the levels of heat and irradiance stresses between the study sites and sectors.

3. RESULTS AND DISCUSSION

According to [18], the influence of the heat stress on corals was high on the Egyptian coast in 2020 and the associated bleaching cover had reached 36.66%. However, the levels of that stress were unknown and had been poorly represented in the previous study. Here, we introduce a short-term mapping of the environmental stressors (mainly temperature and irradiance) that caused coral bleaching incidence along the Egyptian coast of the Red Sea during the summer season of 2020 [18].

Our findings indicated that although the heat stress in the NRS spanned six months (started from July till December 2020), coral bleaching was most likely between 04 August to 21 December, when DHWs was ≥4°C-weeks. During this period, SST in the NRS ranged between 23.84°C and 33.49°C (29.22±0.003°C), DHWs ranged between 0 and 23.38°C-weeks (5.56±0.01°C-weeks), and the PAR levels were between 1.02 and 61.58 Einstein m^{-2} day^{-1} (42.91±8.57 Einstein m^{-2} day^{-1}). Mapping of the three products yet revealed a clear pattern of heat and irradiance stresses along the western side of the NRS (Fig. 2). This pattern was consistent with the general pattern of SST in the Red Sea in the last decade and there is a growing body of evidence that the high thermal stress recorded during 2020 has resulted from a marine heatwave affecting corals at the Egyptian coast [18, 20]. In this context, [20] indicated that the duration and frequency of the marine heatwaves had increased significantly by 67% and 35%, respectively, over the period between 2000 and 2019. The high levels of accumulated heat stress recorded here can also be attributed to the increasing warming rate that has been projected in the NRS by [21-23, 17, 24].

In the present study, there was a significant decrease in the accumulated heat stress (i.e., DHWs) and a reverse increase in the irradiance conditions between the three geographical sectors from the north to the south (Kruskal-Wallis test; df= 2, $p<0.05$). Furthermore, our analysis indicated that despite the overall mean DHWs did not decrease below 4°C-weeks in the three sectors, most of the heat stress was concentrated in Sector_1 while its intensity was the lowest in Sector_3 (Table 1). Associating with this, the mean PAR levels were increased by only one Einstein m^{-2} day^{-1} between Sector_1 and Sector_3 during the heat stress period. In all cases, the conditions in Secotor_2 showed intermediate levels in the three studied parameters between the northern and southern sectors. These findings revealed a clear difference in the heat stress pattern between the north and the south along the Egyptian coast. Despite this pattern was in agreement with [23], our results have revealed the occurrence of an unprecedented heat stress conditions in the summer of 2020 (2-3 times higher than stress levels in [23]).

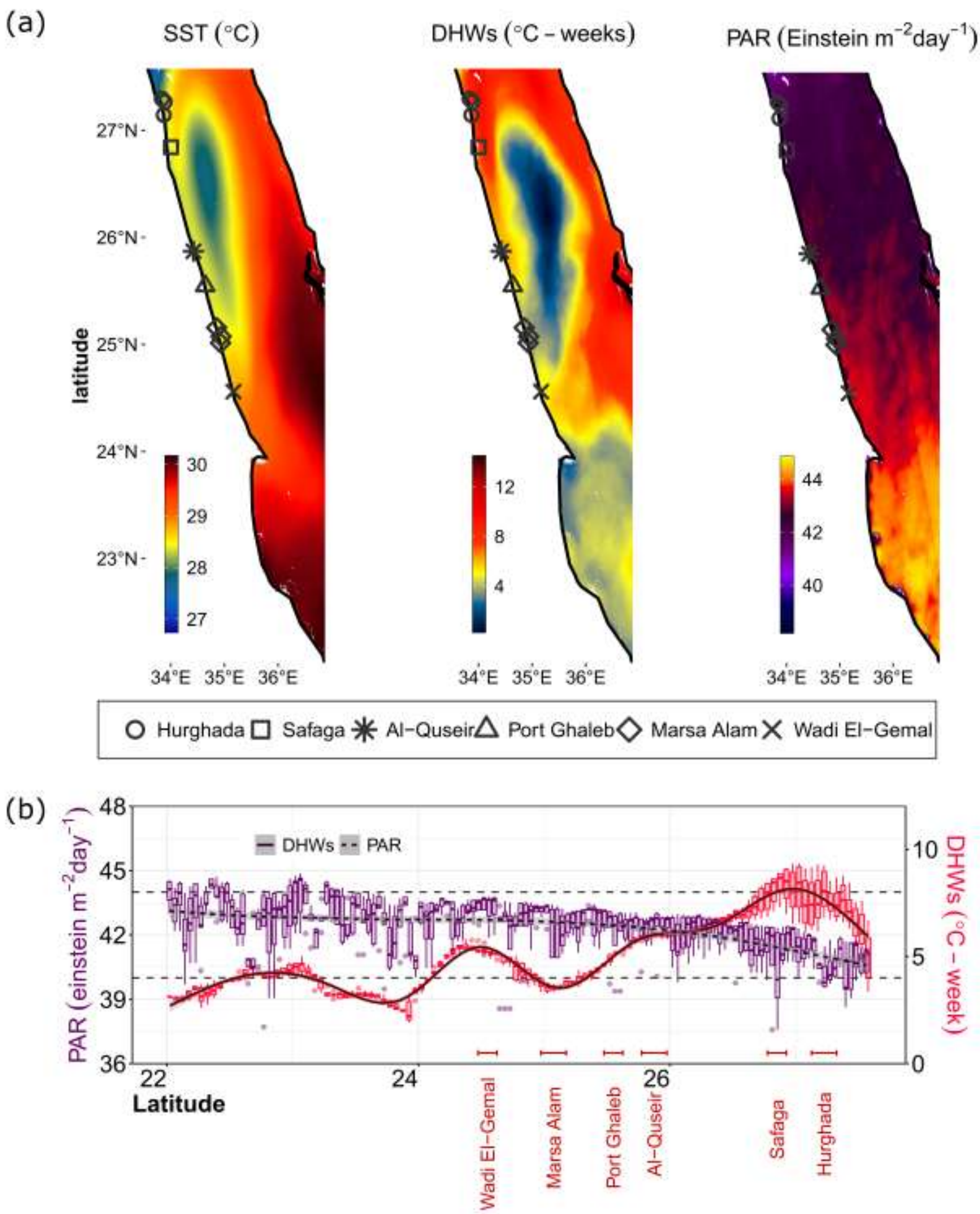

Fig (2): Distribution of the SST, DHWs, and PAR along the Egyptian coast of the Red Sea during 2020 bleaching event. (a) pattern of heat stress and irradiance in the NRS. **(b)** Latitudinal variation in DHWs and PAR levels along the Egyptian coast. Horizontal bars indicate the location of the study sites (25 km × 25 km each), while dashed lines represent DHWs of 4 and 8°C-weeks.

On the other hand, SST averaged 28.42±0.01°C and corals had been subjected to DHWs of 5.89±0.03°C-weeks in the six sites. All reefs in these sites had been also exposed to PAR levels of 42.16±8.46 Einstein m^{-2} day^{-1}. The northern sites, particularly, showed high accumulated heat stress than the middle and southern sites (Table 2). Such conditions were associated with an extended period of >10°C-weeks for 48-51 days in Hurghada and Safaga. In contrast, in the two sites of Sector_3, the DHWs of >8°C-weeks had prolonged for 53 days in Wadi El-Gemal, while conditions between 4-8°C-weeks dominated for 73 days at Marsa Alam (Fig. 3). It is also important to mention that, despite the operational DHW data obtained from NOAA CRW has shown higher levels of thermal stress over the northern reefs than their conspecifics in the south, this pattern has encountered the bleaching pattern recorded in 2012 and 2020 [18, 25]. Because of the lack of physiological studies, we could not ultimately attribute the low bleaching cover associated with the high thermal accumulation in Sector_1 to the difference in the genetic traits along the Egyptian coast. However, one explanation may be the difference in the intensity of the SST that was higher in Sector_3 than Sector_1. In this regard, in 2020, although the northern reefs have experienced SST that exceeds the usual summer levels, the intensity of such stress may still be less acute despite its extended accumulation.

Table 1: Summary of the SST, DHWs, and PAR levels in the study area. Data were derived from a region of approximately 25 km × 25 km for each site and 117 km × 25 km for each sector.

Site/Sector	SST (°C)			DHWs (°C-weeks)			PAR (Einstein m^{-2} day^{-1})		
	Mean±SE	Min	Max	Mean±SE	Min	Max	Mean±SE	Min	Max
Hurghada	28.16±1.40	24.99	29.87	7.45±3.85	0.64	12.39	40.95±8.74	28.68	59.03
Safaga	28.44±1.51	25.04	30.22	7.81±3.90	0.41	13.10	41.51±8.57	30.13	59.16
Sector_1	28.14±1.52	23.84	30.44	7.41±3.93	0.00	15.77	42.12±8.86	1.12	61.13
Al-Quseir	28.34±1.59	24.87	30.40	5.96±3.50	0.12	9.87	42.42±8.34	30.45	59.86
Port Ghaleb	28.35±1.59	24.86	30.48	5.10±3.15	0.09	8.44	42.38±8.62	14.85	59.79
Sector_2	28.33±1.59	24.75	30.55	5.86±3.45	0.00	11.56	42.57±8.84	1.02	61.58
Marsa Alam	28.46±1.61	24.92	30.55	3.57±2.14	0.00	5.92	42.71±8.28	25.89	59.70
Wadi El-Gemal	28.82±1.86	25.06	31.35	5.12±3.32	0.00	8.48	43.18±7.98	31.30	59.93
Sector_3	28.64±1.76	24.85	31.56	4.44±2.92	0.00	9.62	43.13±8.52	1.08	60.85

Although the decrease in the heat stress and the opposite increase in the irradiance levels were significant between most sites from the north to the south, there was no difference between sites within the same sector (Table 2). The results further showed that the heat stress conditions in Al-Quseir were much higher than in Marsa Alam (mean daily difference= 2.46±0.11°C-weeks) but the irradiance levels were not different in both sites (mean daily difference= 2.06±0.84 Einstein m^{-2} day^{-1}). Contrary, despite the sites of Al-Quseir and Wadi El-Gemal received relatively similar intensities of heat stress (daily mean difference= 0.84±0.04°C-weeks), the irradiance levels in the latter site were significantly higher than the former (daily mean difference= 3.27±1.01 Einstein m^{-2} day^{-1}). In general, coral exposure to high UV levels increases southward along the Red Sea [26]. As such, the current results suggest that the high irradiance levels may have played a secondary role in the prevalence of bleaching in the southern sites in 2020 [18].

In the light of the knowledge that the severity of bleaching can affect the structure of reefs and delay their recovery rate [27, 28], our study denotes that the frequency of heat stress episodes below 8 °C-weeks may threaten southern reefs over time. It also suggests that heat stress exceeding this level, as expected in the near future, can drive acute effects on the southern reefs. Despite the northern reefs tend to be robust to heat stress conditions, they are more threatened by increasing human activities and growing population [29, 30].

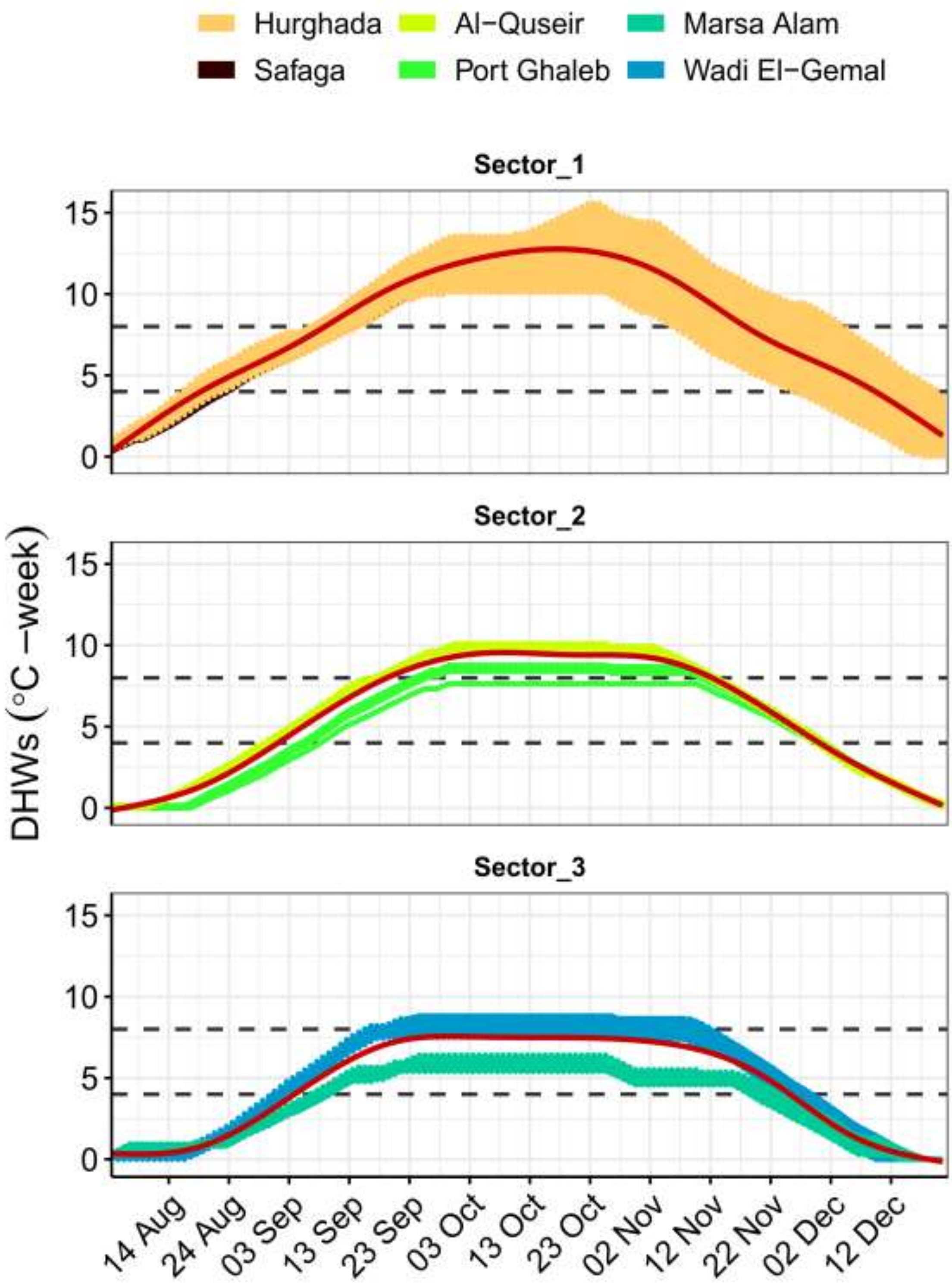

Fig (3): Timeseries of the daily DHWs in the study sites during the period of the heat stress. Red curve summaries daily DHWs within sectors. According to NOAA CRW, coral bleaching is expected when the DHWs exceed 4°C-weeks (lower dashed line) while mass bleaching and mortality are more likely at 8°C-weeks (upper dashed line).

Table 2: Pairwise Dunn's test of SST, DHWs, and PAR between study sites and sectors. The mean difference (Mean diff.) represents the overall average of daily difference between each two sites/sectors during the period of the heat stress.

Site/Sector		SST			DHWs			PAR		
		Mean diff. (°C)	Z	*p*	Mean diff. (°C-weeks)	Z	*p*	Mean diff. (Einstein m^{-2} day^{-1})	Z	*p*
Hurghada	Safaga	0.28±0.01	-4.80	**<0.0001**	0.71±0.03	-0.37	1.00	0.66±0.05	-1.61	0.43
Al-Quseir	Hurghada	0.29±0.03	2.29	0.11	1.49±0.07	-2.60	0.06	2.55±0.63	3.94	**<0.01**
Hurghada	Port Ghaleb	0.35±0.02	-2.41	0.09	2.35±0.11	4.59	**<0.0001**	4.17±1.02	-4.03	**<0.01**
Al-Quseir	Safaga	0.29±0.02	-2.74	0.06	1.85±0.05	-2.79	**0.04**	2.03±0.64	2.70	**0.04**
Port Ghaleb	Safaga	0.32±0.02	-2.15	0.13	2.71±0.09	-4.67	**<0.0001**	3.64±1.03	2.82	**0.03**
Sector_1	**Sector_2**	0.23±0.02	0.48	0.63	1.55±0.05	7.48	**<0.0001**	2.16±0.74	-23.28	**<0.0001**
Al-Quseir	Port Ghaleb	0.09±0.01	-0.37	0.71	0.88±0.05	2.28	0.11	1.90±0.86	-0.20	0.84
Al-Quseir	Marsa Alam	0.18±0.01	-3.39	**0.01**	2.46±0.11	4.61	**<0.0001**	2.06±0.84	-1.34	0.54
Al-Quseir	Wadi El-Gemal	0.51±0.03	-5.53	**<0.0001**	0.84±0.04	2.44	0.09	3.27±1.01	-3.51	**<0.01**
Marsa Alam	Port Ghaleb	0.14±0.01	2.72	0.05	1.67±0.08	-2.01	0.13	0.48±0.10	1.11	0.54
Port Ghaleb	Wadi El-Gemal	0.49±0.03	-4.66	**<0.0001**	0.40±0.03	0.05	0.96	1.82±0.62	-3.22	**0.01**
Sector_2	**Sector_3**	0.34±0.02	-11.39	**<0.0001**	1.43±0.06	7.78	**<0.0001**	1.67±0.63	-28.85	**<0.0001**
Marsa Alam	Wadi El-Gemal	0.38±0.03	-2.02	0.13	1.69±0.09	-2.05	0.16	1.62±0.61	-2.11	0.17
Hurghada	Marsa Alam	0.4±0.03	-5.49	**<0.0001**	3.87±0.15	7.00	**<0.0001**	4.21±1.01	-5.10	**<0.0001**
Marsa Alam	Safaga	0.36±0.02	0.55	1.00	4.24±0.16	-6.91	**<0.0001**	3.72±1.02	4.02	**<0.01**
Hurghada	Wadi El-Gemal	0.72±0.06	-7.60	**<0.0001**	2.32±0.09	4.85	**<0.0001**	5.31±1.13	-7.14	**<0.0001**
Safaga	Wadi El-Gemal	0.58±0.04	-2.53	0.08	2.69±0.08	4.90	**<0.0001**	4.84±1.14	-6.30	**<0.0001**
Sector_1	**Sector_3**	0.54±0.04	-10.91	**<0.0001**	2.96±0.10	15.26	**<0.0001**	3.53±0.94	-51.73	**<0.0001**

4. CONCLUSION

In the light of the present study, increases in the SST and PAR levels that have coincident with the 2020 bleaching pattern recorded at the Egyptian coast may synergistically threaten southern reefs. Moreover, although the accumulated heat stress exceeded the bleaching threshold (>4°C-weeks), it may still less severe to corals inhabiting the northern reefs.

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