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Biodiversity and Abundance of Plankton Communities along the Coastal Waters of Gulf of Aqaba, Saudi Arabia

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Authors' Contribution
AMA conceived the idea of the project. MMS, RPD, EM, AMS and AMA carried out the sampling. MMS and RPD analysed the data and wrote the initial manuscript. EM, AMS and AMA provided suggestions and corrections.

Key words
Microphytoplankton, Mesozooplankton, Diversity, Vertical distribution, Gulf of Aqaba.

ABSTRACT

Spatial variation in the microphytoplankton biomass and diversity as well as the diel variability of the major mesozooplankton taxon, Copepoda was studied with respect to the prevailing hydrographic conditions along the coastal waters of Gulf of Aqaba, Saudi Arabia during the summer period. Conspicuous stratification was evident in the water column while nutrient distribution highlighted the oligotrophic nature of the region. Nitrate showed a notable increase in the deeper layers of almost all the stations and towards the south. Chlorophyll *a* was low throughout (0.05-0.27 mg m^{-3}) though a small peak was observed at a depth of 70m. Diatoms dominated the phytoplankton community in terms of both density and diversity followed by dinoflagellates. A total of 138 phytoplankton species (80 diatoms and 57 dinoflagellates) contributed to the phytoplankton diversity during the study. Zooplankton exhibited clear diel variation in distribution with higher abundance during night. Among the thirty-zooplankton taxa observed, Copepoda formed the dominant taxa. Of the total 70 copepod species observed during the study eight species are new records from the Gulf of Aqaba region. The current study also witness conspicuous diel variation of five copepod species within the water column (*Acartia negligens*, *Clausocalanus furcatus*, *Lucicutia flavicornis*, *Pleuromamma indica* and *Haloptilus longicornis*).

INTRODUCTION

The Red Sea, characterised by high sea surface temperature and highly saline waters is also remarkable (Raitsos *et al*., 2011) for its rich biodiversity supporting high numbers of endemic species (Roberts *et al*., 2002). Its geographical positioning getting partially isolated from the adjacent Indian Ocean waters and the warm and dry tropical climate makes it a unique oceanic province in the world ocean (Halim, 1969). The Gulf of Aqaba (GoA) characterised by a total length of about 170 km and a width of 14-26km lies in the north-eastern part of the Red Sea (Manasrah *et al*., 2004). Due to its positioning in a hot, dry climatic zone with a negative hydrological budget, it always exhibits high salinity (Sofianos *et al*., 2002). Furthermore, the stable stratification makes the region the most oligotrophic within the Red Sea subsequently leading to low productivity (Acker *et al*., 2008). The weak thermocline and halocline, highly oxygenated waters, low nutrient levels and primary production are the characteristic features of this region (Klinker *et al*., 1976). Thermal stratification prevailing throughout the summer eventually result in the depletion of nutrients from the surface layers (Reiss and Hottinger, 2012).

Primary production in the Red Sea displays a latitudinal gradient with increasing production towards the south (Weikert, 1987; Qurban *et al*., 2014). Productivity in the GoA normally increases during winter compared to the summer (Levanon-Spanier *et al*., 1979) because of the convective winter mixing leading to nutrient injection from the deeper waters to the shallows (Weikert, 1987). However, the phytoplankton community exhibits a peak in abundance during the winter when the water column becomes less stratified, the vertical distribution of the primary producers in GoA rely mostly on the seasonal temperature, irradiance and nutrient availability (Lindell and Post, 1995). The micro phytoplankton community (>20µm) in the GoA is less conspicuous and contributes to only a minor fraction (Sommer, 2000) of the total phytoplankton population which in general is dominated by the picophytoplankton (< 2µm) (Lindell and Post, 1995). Henceforth, earlier studies on phytoplankton ecology of

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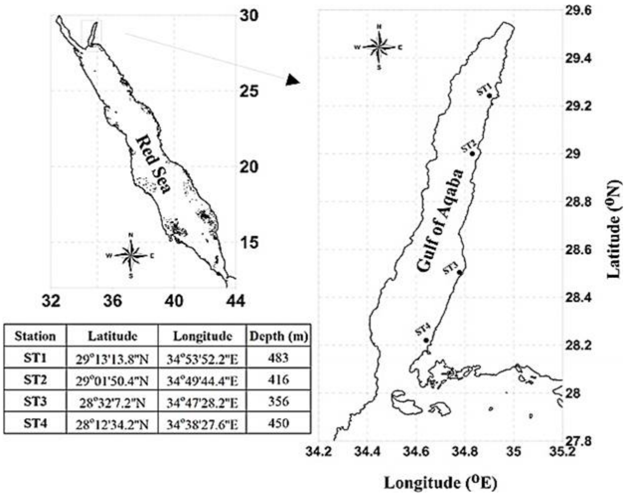
the GoA mostly gave thrust to the picophytoplankton dynamics (Kimor and Golandsky, 1977; Lindell and Post, 1995; Post *et al*., 2002; Stambler, 2005; Laiolo *et al*., 2014) rather than microphytoplankton (Sommer, 2000; Sommer *et al*., 2002; Al-Najjar *et al*., 2007; Nassar, 2007) which hitherto remain poorly addressed.



Station	Latitude	Longitude	Depth (m)
ST1	29°13'13.8"N	34°53'52.2"E	483
ST2	29°01'50.4"N	34°49'44.4"E	416
ST3	28°32'7.2"N	34°47'28.2"E	356
ST4	28°12'34.2"N	34°38'27.6"E	450

Fig. 1. Map showing the study stations along the Saudi Arabian waters of the Gulf of Aqaba.

The seasonal fluctuation of the mesozooplankton community in GoA mainly depends on the annual variation in the vertical mixing in winter and the stratification in summer and also with the availability of food (Cornils *et al*., 2007a). It is well documented that the vertical distribution of zooplankton does not exhibit much variation within the mixed layer of GoA (Cornils *et al*., 2005). As far now, only limited studies are there on the mesozooplankton community from the northern (*e.g.* Almeida Prado-Por, 1985, 1990; Echelman and Fishelson, 1990; Al-Najjar, 2002; Cornils *et al*., 2005, 2007a) and the southern part (El-Sherbiny *et al*., 2007; Dorgham *et al*., 2012) of the Gulf. The upper 100 m gains significance in studying the zooplankton dynamics of GoA, as the vertical distribution of the dominant epipelagic copepod species does not exceed beyond this depth (Almeida Prado-Por, 1990). The particular topography of GoA with narrow shelves, extremely steep shores and submarine slopes contributes to the presence of both neritic and oceanic copepod species, even in the coastal waters (Kimor and Golandsky-Baras, 1981). The present work provides detailed taxonomical insights on the distribution of the diatoms, dinoflagellates and copepods within a single framework from the GoA region. The study aims to determine the influence of the summer water column stratification on the diversity and distribution of both microphytoplankton and mesozooplankton community along the GoA waters, an important oligotrophic ecosystem in the global ocean.

MATERIALS AND METHODS

Sample collection and analysis

In order to evaluate the plankton distribution of GoA, four stations were selected along the Saudi Arabian coastal waters (Fig. 1) during summer (18-25, August 2016). The depth of the sampling stations ranged from 350 to 480 meters. The hydrographic characteristics of the water column (200m) (salinity, temperature and dissolved oxygen) were measured at each sampling location using a SBE 25plus Sea logger CTD (Sea-Bird Scientific). In order to determine the inorganic nutrient and chlorophyll *a* concentration, seawater samples were collected from five depths (0, 10, 25, 70 and 100m) with a carousel deck unit of Niskin rosette sampler (Seabird Electronics SBE32 with SBE33 real time deck unit). From each depth, 500 ml of seawater were filtered through 0.2µm nucleopore membrane filters for nutrient analysis, while 6-10 litres were filtered through a 0.7µm Whatman GF/F filter paper for the chlorophyll *a* estimation. The nutrients and chlorophyll *a* estimation were carried out following the standard protocol of Parsons *et al*. (1984) using a UV Spectrophotometer (Shimadzu, UV-1700). To determine the phytoplankton abundance and diversity, samples were collected during day from a depth of 100m to the surface by hauling a Hydrobios vertical plankton net of mesh size 20µm. Samples collected were immediately preserved with Lugol's Iodine solution and 3-4ml of concentrated formaldehyde solution (Kürten *et al*., 2015). Phytoplankton enumeration was carried out using an inverted microscope (Leica DMI 3000b) in Sedgewick-rafter counting chamber following the protocols of LeGresley and McDermott (2010) and the taxonomic identification by Taylor (1976) and Tomas (1997). Zooplankton sampling was carried out both during day and night using Hydrobios vertical plankton net of mesh size 180µm. A flowmeter attached to the mouth of the net determined the volume of water filtered. The zooplankton samples were concurrently preserved in absolute ethanol for detailed taxonomic analysis. At the laboratory, the zooplankton samples were passed through a net (mesh size 180 µm) and excess water was removed by absorbent papers. Then the biomass was estimated using the biovolume method and expressed as ml. m^{-3}. For the zooplankton community analysis, three aliquots of the sample were transferred to a Bogorov counting tray and enumerated under a stereo zoom microscope (Wild Heerbrugg M38). Each aliquot was so adjusted that approximately 200-400 individuals were counted. Copepod species identification was carried out following the standard taxonomic identification monographs (Giesbrecht, 1892; Heron and Bradford-Grieve, 1995; Conway *et al*., 2003). Both the phytoplankton and the copepod species were then cross-checked, verified and named according to the latest nomenclature proposed by WoRMS (World Register of Marine Species; www.marinespecies.org).

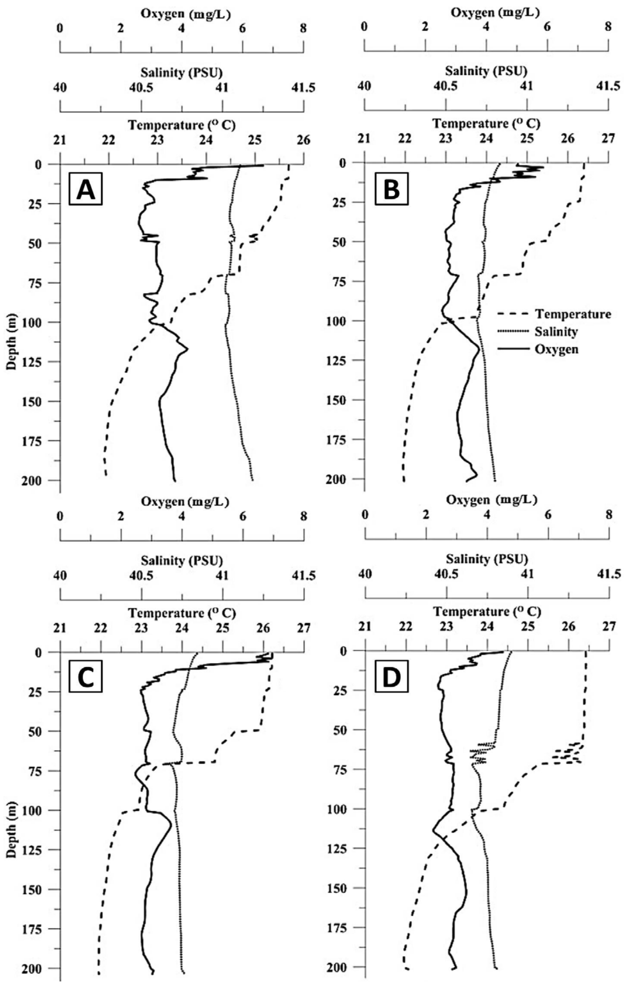


Fig. 2. Vertical profiles of different physical parameters obtained during the study period. A, station 1; B, station 2; C, station 3; D, station 4.

Statistical interpretations

In order to obtain the possible relations between the hydrographic attributes and the plankton community, Pearson correlation coefficient (r) was calculated (SPSS 23). One-Way ANOVA was performed to understand the variations in the biotic and abiotic variables within the different sampling locations during the study (SPSS 23). Diversity indices (Pilou's evenness index J' and Shannon diversity index H') were also calculated for both the phytoplankton and copepod community to obtain the biodiversity patterns in the study region (PRIMER 6).

RESULTS

Physical and chemical parameters

The extreme northern site (station 1), had slightly higher salinity (average 41.07±0.04 SD) than the other three sampling locations with more or less similar patterns in salinity distribution (average: 40.75±0.04) (Fig. 2). Relatively stable water column salinity was observed up to a depth of 200m in every sampling location. Temperature showed an inverse trend to that of salinity with moderately cooler water at station 1 (23.47±1.40°C) than the southern station 4 (24.15±1.82°C). Dissolved oxygen (DO) concentration exhibited marked variation within the upper 10 meters (average: 4.99±1.05 mg/L), characterised by well-oxygenated waters compared to the deeper layers (average: 2.98±0.04 mg/L) (Fig. 2). The nutrient distribution of the present study depicted the typical oligotrophic conditions common to the Red Sea region. Nitrate (NO_3^-) values was comparatively higher than the other major nutrients characterised by a minimum of 0.83 µg/L at stations 1 and 2, and a maximum of 21.67 µg/L at station 4 (average: 4.79±4.99 µg/L) (Fig. 3). Except at station 1, in all other stations, higher nitrate values were consistently observed at a depth of 100m of water column (100 m) than the other sampling depths (Fig. 3). Nitrite (NO_2^-) followed more or less an even distribution throughout the water column and also among the stations with a minimum of 0.16 µg/L (station 1) and a maximum of 0.27 µg/L (station 2) (average: 0.21±0.03 µg/L) (Fig. 3). Interestingly, ammonia (NH_4^+) showed considerably lower spatial values (average: 0.07±0.05 µg/L) with a slight increase in their concentration (0.12-0.23 µg/L) towards the deeper strata in stations 2 and 4 (Fig. 3). Phosphate (PO_4^{3-}) values were high within the upper 10 meters of station 1 (0.66–0.73 µg/L), while all the other stations displayed relatively uniform concentration throughout the water column (average: 0.26±0.15 µg/L) (Fig. 3). Silicate (SiO_4^{4-}) concentration varied between 2.05 and 5.12 µg/L at stations 2 and 1, respectively, with an average of 3.41±0.87 µg/L (Fig. 3).

Phytoplankton biomass and abundance

The phytoplankton biomass (chlorophyll *a*) displayed lower concentration (0.17-0.27 mg m^{-3}) throughout the water column but with a slight increase in the 70m depth (Fig. 3). The phytoplankton density varied from 24.24×10^3 cells m^{-3} at station 4 to 41.52×10^3 cells m^{-3} at station 3 (Fig. 4A, B). Diatoms formed the major contributor towards the total phytoplankton population and exhibited only a slight variation in their abundances among the stations (18.39×10^3 and 28.68×10^3 cells m^{-3} at stations 4 and 3, respectively) with the centrales (average: $14.69\pm3.73\times10^3$ cells m^{-3}) dominating the pennales (average: $7.15\pm1.27\times10^3$ cells m^{-3}). The dinoflagellates exhibited low densities with a minimum of 5.43×10^3 cells m^{-3} to a maximum of 12.41×10^3 cells m^{-3} at stations 4 and 3, respectively (average: $9.52\pm2.96\times10^3$ cells m^{-3}) (Fig. 4A, B). The cyanophytes, mostly represented by the *Trichodesmium* sp. had lower abundance ranging from 0.41 to 0.46×10^3 cells m^{-3} (average: $0.43\pm0.19\times10^3$ cells m^{-3}). A total of 138 phytoplankton species were recorded during the present study (Supplementary Table I). The diatoms formed the most diverse phytoplankton community with 80 species (57 centrales and 23 pennales), whereas the dinoflagellate community were comprised of 57 species. The genus *Chaetoceros* contributed more to the diatom diversity with 19 species followed by *Rhizosolenia* (8 species). Among dinoflagellates, the genus *Tripos* accounted for the most number of species (24 species) followed by the *Protoperidinium* (5 species) (Supplementary Table I). Among the major dinoflagellates observed, five species (*Alexandrium minutum, Dinophysis fortii, Gonyaulax spinifera, Phalacroma rotundatum* and *Prorocentrum lima*) were previously reported to cause harmful algal blooms (HABs) worldwide.

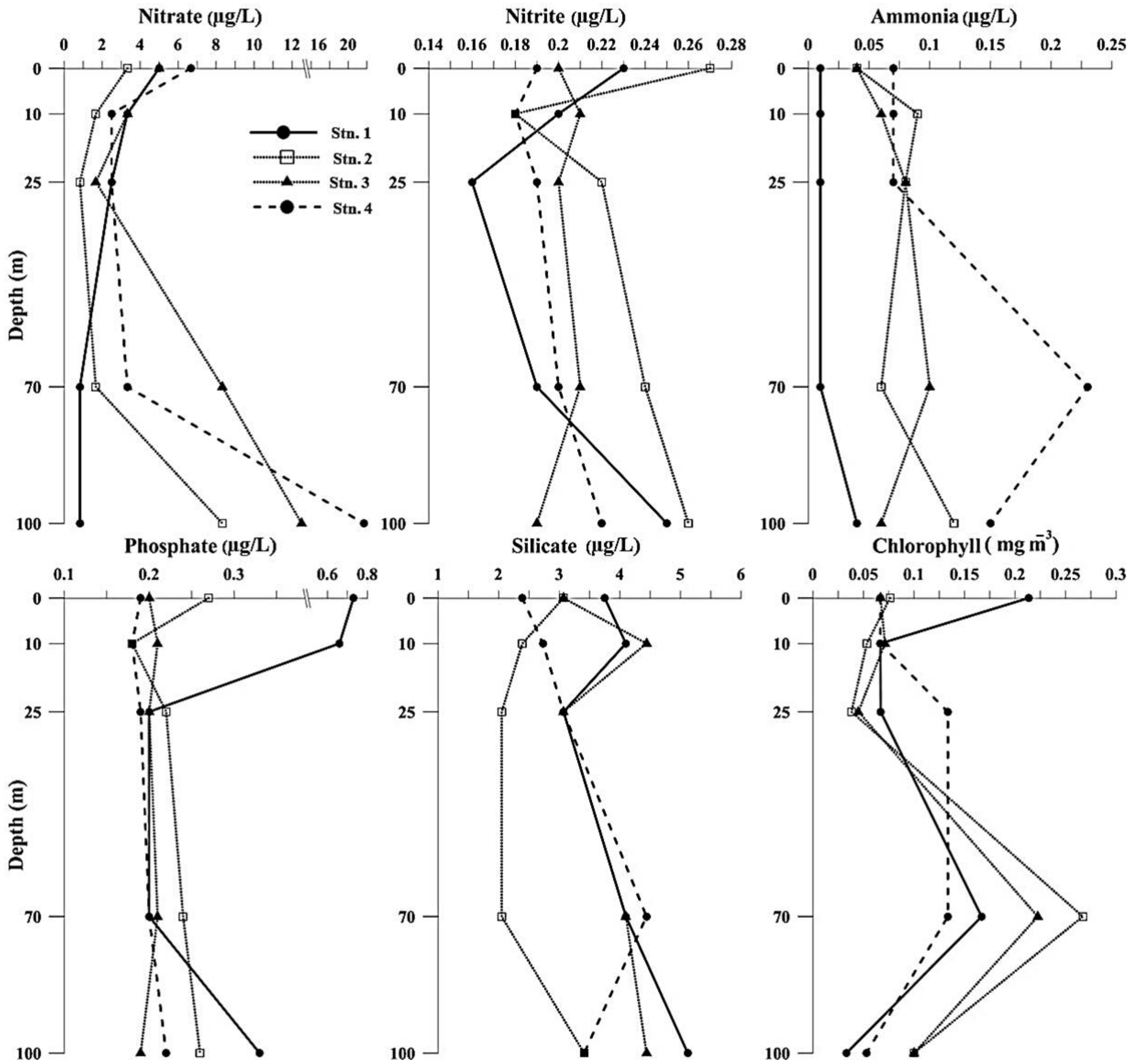


Fig. 3. Vertical profiles of various nutrients and chlorophyll *a* obtained during the study period.

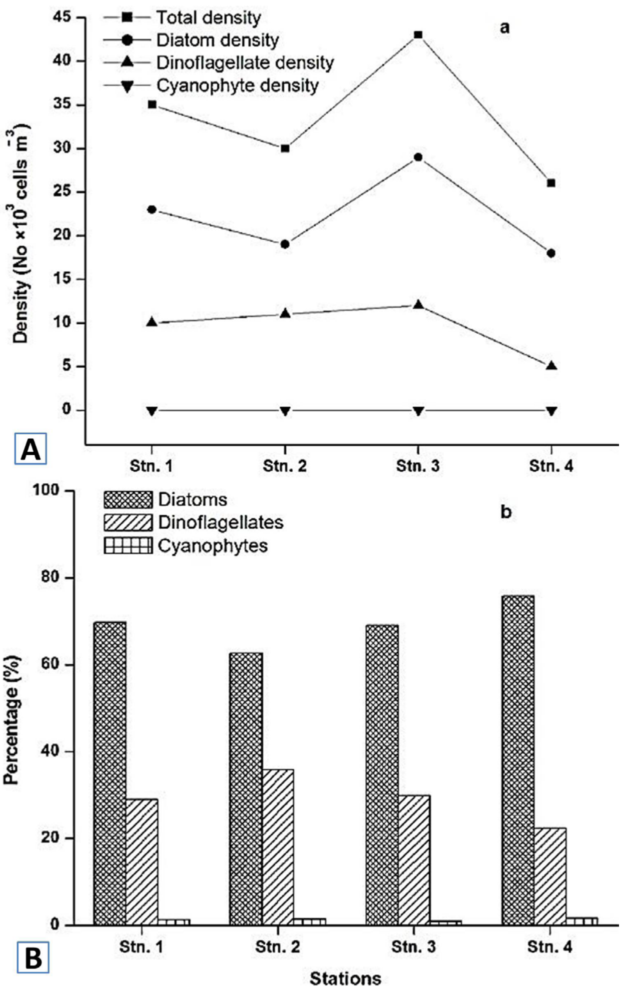


Fig. 4. Abundance (A) and percentage (B) of different phytoplankton groups observed during the study period.

Zooplankton abundance and diversity

The zooplankton abundance in the upper 200m varied between 230 ind. m^{-3} (station 3) during the day to 894.4 ind. m^{-3} (station 2) at night with an average of 490.5 ind. m^3 (Fig. 5A). The spatial variations in zooplankton abundance among the sampling locations was statistically insignificant (F= 7.874, p > 0.05). Zooplankton biomass expressed as displacement volume also followed a similar trend to that of the abundance with values fluctuating between 35 and 42.5 ml. m^{-3} from the day samples of stations 1 and night sample of station 2 (average: 38.2 ml. m^{-3}). The average night biomass (40.0±2.9 ml. m^{-3}) was comparatively higher than the day (36.4±1.1 ml. m^{-3}) with less spatial variation among the stations (day, F= 1.36, p > 0.05 and night F= 4.015, p > 0.05). Copepods by far were the most ubiquitous and dominant taxon among the various zooplankton groups, with an abundance ranging between 140.8 ind. m^{-3} (station 4, day) to 517.3 ind. m^{-3} (station 2, night) with an average of 292.3±117.3 ind. m^{-3}. It contributed heavily towards the total zooplankton abundance (51.3 to 72.9%, average: 59.8±7.6) (Table I) of each station. The contribution of other zooplankton taxa towards the total abundance is displayed in Table I. There was no significant difference of these groups within the different stations, except for molluscs (F= 19.618, p < 0.05) and cladocerans (F= 17.605, p < 0.05). Cladocera, represented mainly by *Pseudevadne tergestina* showed slightly higher densities at station 1 compared to the other stations. All the major zooplankton groups displayed higher abundance during the night compared to the day (Fig. 5B-F) but the differences were statistically insignificant, except for molluscs (F= 23.328, p < 0.05) and copepods (F= 21.467, p < 0.05).

Table I.- Mean abundance (ind. m^{-3}) and dominance (%) of the zooplankton taxa from different stations during the study period.

Taxa	Abundance	Geometrical mean (%)	Min.	Max.
Radiolaria	8.5	1.74	0.13	3.26
Cnidaria				
Medusae	2.0	0.40	0.00	1.11
Siphonophora	1.3	0.27	0.00	0.62
Mollusca				
Bivalvia	15.7	3.20	0.36	7.93
Gastropoda	52.3	10.67	2.00	18.38
Pteropoda	8.9	1.82	0.11	5.06
Annelida				
Polychaete larvae	1.5	0.30	0.16	0.69
Polychaeta	1.3	0.26	0.08	0.58
Crustacea				
Cladocera	3.5	0.71	0.23	1.64
Copepoda	293.3	59.80	51.27	72.87
Ostracoda	8.9	1.80	0.13	4.46
Euphausiacea	1.4	0.28	0.05	0.51
Decapod larvae	2.4	0.48	0.05	0.98
Cirripede larvae	0.8	0.16	0.00	0.36
Mysidacea	4.0	0.82	0.38	1.51
Isopoda	0.3	0.06	0.00	0.17
Amphipoda	0.2	0.04	0.00	0.12
Cumacea	0.5	0.11	0.00	0.35
Luciferidae	0.1	0.01	0.00	0.06
Chaetognatha	43.4	8.85	4.07	13.04
Tunicata	38.3	7.81	3.49	12.56
Echinodermata				
Echinoderm larvae	0.9	0.18	0.00	0.69
Starfish juveniles	0.1	0.02	0.00	0.12
Chordata				
Fish larvae	0.9	0.19	0.00	0.44

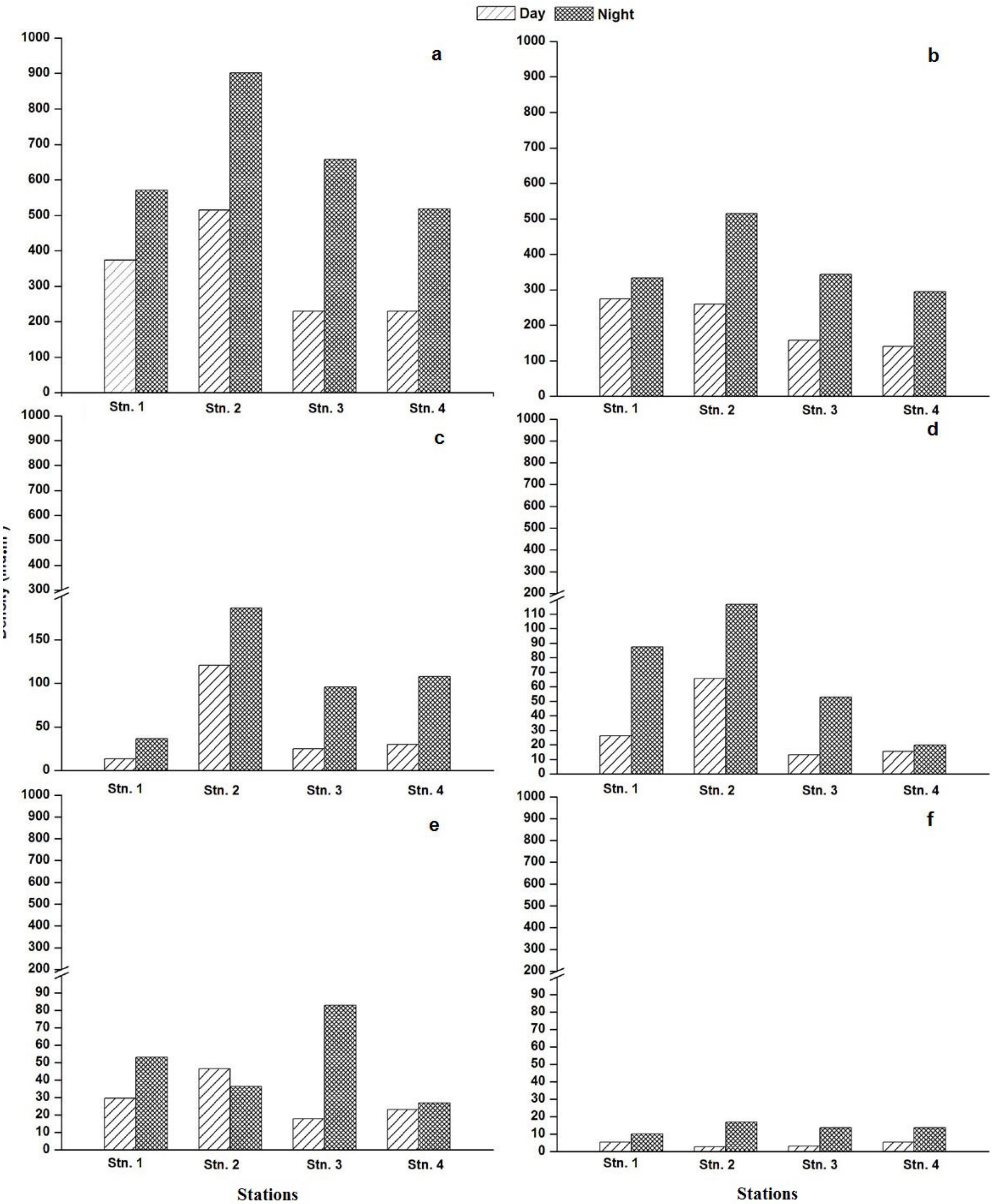


Fig. 5. Diel variability in the abundance of different zooplankton groups observed during the study period. A, total zooplankton density; B, total copepods; C, total molluscs; D, total chaetognaths; E, total tunicates; F, other crustacean.

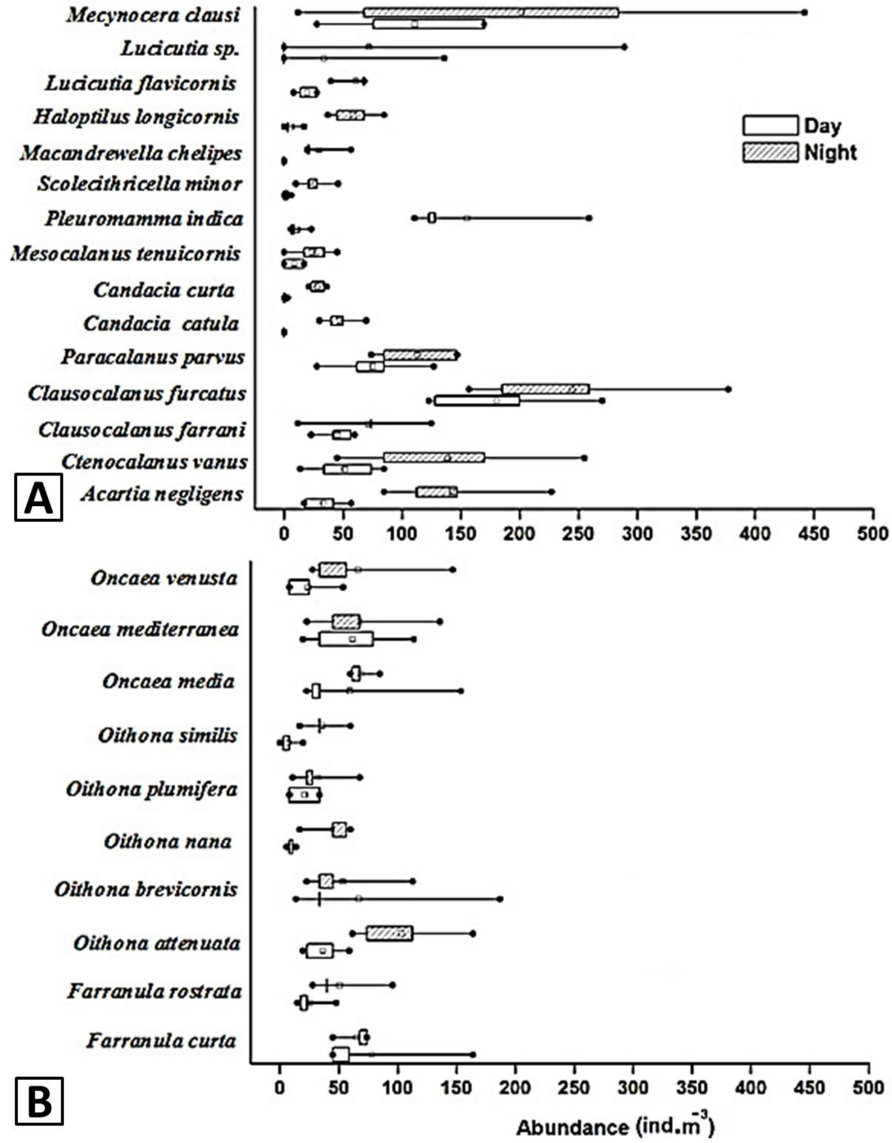


Fig. 6. Diel variability observed in the distribution of major calanoids (A) and cyclopoids (B) copepod species during the study period.

Copepods abundance and diversity

A total of 70 (37 calanoids, 30 cyclopoids and 3 harpacticoids) copepod species were recorded from the study area (Supplementary Table II). Among these, eight species (*Acartia amboinensis*, *Centropages uedai, Corycaeus (Onychocorycaeus) agilis, Corycaeus (Onychocorycaeus) catus, Clytemnestra farrani, Lubbockia aculeata, Oithona attenuata* and *Vettoria granulosa*) were new records to the GoA copepod diversity. Calanoids contributed the bigger fraction of adult copepods (63.8%), followed by cyclopoids (35.9%). The harpacticoids were less both in abundance and diversity throughout the study period. Within the calanoids, 23 different genera belongs to 17 families were observed, out of which ten species (*Clausocalanus furcatus* (11.7%), *Mecynocera clausi* (8.6%), *Lucicutia flavicornis* (5.2%), *Ctenocalanus vanus* (5.3%), *Paracalanus parvus* (5.2%), *Acartia negligens* (4.8%), *Pleuromamma indica* (4.6%), *Clausocalanus farrani* (3.2%) and *Haloptilus longicornis* (1.8%) showed their predominance by contributing almost 48.1% of the total adult copepod community. All the dominant copepod species observed during the study period, exhibited an even distribution among stations, except *C. furcatus* which showed a considerable spatial variation ($F= 29.210$, $p < 0.05$). It further accounted for the highest abundance (37.7 ind. m^{-3}) obtained for the different calanoid species during this study. Regarding cyclopoids, 30 species belonging to 10 genera were recorded from the region. Family Corycaeidae was the dominant, with 10 species, followed by Oithonidae (6 species), Oncaeidae (6 species), and Sapphirinidae (5 species). Family Oithonidae had abundance of 23 ind. m^{-3} followed by Oncaeidae (20.8 ind. m^{-3}) and Corycaeidae (16.7 ind. m^{-3}). Within the cyclopoids, *Farranula curta*, *Oithona.attenuata*, *Oncaea media*, *Oncaeamediterranea*, *Oithona brevicornis*, *Oncaea venusta* and *Farranula rostrata* were the dominant species contributing to 4, 3.9, 3.6, 3.3, 3.4, 2.5 and 2.1 % of the total adult copepods, respectively. Harpacticoids, were observed in low abundance and contributed to less than 0.2% of the total adult copepod community.

The mean abundance of total adult copepods was higher during the night (average 243.9±61.2 ind. m^{-3}) compared to day (118.3±44.3 ind. m^3) and the species diversity too followed a similar trend with night samples (70 species) being more diverse than the day (61 species). The higher diversity observed during the night was mostly due to the migration of some large-sized and/or mesopelagic calanoid species (*Candacia catula*, *Centropages calaninus*, *C. gracilis*, *C. uedai*, *Euchaeta marina*, *Macandrewella chelipes*, *Pontellina plumata* and *Rhincalanus nasutus*) which were absent during the day. Out of the ten major calanoid copepods exhibiting diel variation within the water column, five species (*A. negligens*, *C. furcatus*, *Lucicutia flavicornis*, *P. indica* and *H. longicornis*) had conspicuous variation in their day and night abundances (Fig. 6). Moreover, many species (*C. catula*, *C. curta*, *M. chelipes*, *Mesocalanus tenuicornis*, *Nannocalanus minor*, *P. parvus* and *Scolecithricella minor*) which were observed in low densities during day or were absent during the day collection displayed comparatively higher abundance during night. The other dominant cyclopoids (7 species) did not exhibit clear diel variation except *O. attenuata* and *O. nana*, which varied significantly in their abundances over a diel scale ($F= 22.626$, $p < 0.05$; $F= 15.410$, $p < 0.05$, respectively) with a night: day ratio of 2.8 and 4.5, respectively. Most of the other species (*F. rostrata*, *O. similis* and *O. venusta*) exhibited higher abundances at night compared to day while some (*L. squillimana* and *O. ovalis*) were observed only during night (Fig. 6).

Statistical analysis

The Pearson correlation (r) analysis revealed the possible association between the different environmental factors though none of them had any significant variation between them (Table II). One-way ANOVA exhibited the variation in the spatial and vertical distribution of various physical parameters (salinity, temperature and DO). Salinity exhibited significant variation among stations ($F= 3016$, $P <0.05$), while the temperature and the dissolved oxygen showed variation within the water column ($F= 7.45$, $P <0.05$ and $F= 34.13$, $P <0.05$, respectively). Diversity indices further revealed the pattern of distribution for both the phytoplankton and zooplankton (Table III). Both, the evenness (Pilou's evenness index J′) and richness (Shannon diversity index H′) values for phytoplankton did not show any considerable difference between the stations. The copepods community structure was diverse within the study area. The number of species in each sample varied between 40 (at station 3 during the day) to 54 during night at station 4. Diversity was generally less during day than night. The Shannon diversity index and evenness fluctuated within a narrow range (3.51-3.80 and 0.94-0.96, respectively) reflecting the high similarity among stations as well as sampling time (Table III).

Table II.- Pearson correlation (r) values between the various environmental parameters obtained during the study period.

Parameters	S	T	DO	Chl *a*	NO_2^-	NO_3^-	NH_4^+	PO_4^{3-}	SiO_4^{4-}
S	1								
T	0.178	1							
DO	0.336	0.37	1						
Chl *a*	-0.06	-0.209	0.024	1					
NO_2^-	-0.173	-0.296	0.138	0.153	1				
NO_3^-	-0.436	-.483*	-0.064	-0.047	0.088	1			
NH_4^+	-.698**	-0.021	-0.381	-0.04	0.066	0.366	1		
PO_4^{3-}	.610**	-0.009	0.352	0.197	0.272	-0.054	-0.399	1	
SiO_4^{4-}	0.235	-.500*	-0.067	0.013	0.107	0.15	0.031	0.263	1

S, Salinity; T, temperature; DO, dissolved oxygen; Chl *a*, chlorophyll *a*.

Table III.- Biodiversity indices of zooplankton and phytoplankton from different stations during the study period.

Stations	Phytoplankton			Zooplankton					
	S	J'	H'	S		J'		H'	
	Day	Day	Day	Day	Night	Day	Night	Day	Night
1	67	1.00	4.19	43	49	0.94	0.94	3.52	3.68
2	55	0.99	3.99	42	50	0.95	0.95	3.54	3.73
3	89	1.00	4.47	40	48	0.95	0.96	3.51	3.73
4	51	0.99	3.91	41	54	0.95	0.95	3.53	3.80

S, number of species; J', Pilou's evenness index; H', Shannon diversity index.

Table IV.- A comparison of zooplankton abundance and diversity obtained in the present study with the previous ones carried out along the Gulf of Aqaba.

Area	Date	Mesh size used	Count range of total zooplankton (ind. m^{-3})	No. of copepod species	References
Egyptian side of Gulf of Aqaba	1994–1995	55 µm	1906–4138	27	Khalil and Abd El-Rahman (1997)
Egyptian side of Gulf of Aqaba	1993–1994	50 µm	–	44	El-Sherif and AboulEzz (2000)
Egyptian side of Gulf of Aqaba	1999	55 µm	–	74	El-Serehy and Abdel-Rahman (2004)
Egyptian side of Gulf of Aqaba	2008	90 µm	251–7460	81	El-Serehy *et al.* (2013)
Sharm El-Mayia Bay, Sharm El-Sheikh	2000–2001	100 µm	1326–9825	51	Aamer *et al.* (2006)
Off Sharm El-Sheikh area	2005–2006	100 µm	1510–2712	68	El-Sherbiny *et al.* (2007)
Off Sharm El-Sheikh area	1995–1996	100 µm	1124–4952	52	Dorgham *et al.* (2012)
Northern Gulf of Aqaba	1986–1989	500 µm	33–317	30	Echelman and Fishelson (1990)
Northern Gulf of Aqaba	1998–1999	150 µm	–	55	Al-Najjar (2002)
Northern Gulf of Aqaba	2002–2003	200 µm	943–3065	–	Cornils *et al.* (2007a)
Along Saudi coast of Gulf of Aqaba	August 2016	180 µm	230–894	70	Present study

DISCUSSION

Prominent latitudinal gradient was evident in temperature and salinity distribution with the salinity displaying an increasing towards the north and temperature towards south. Uniform saline layers up to 200m, together with slightly changing temperature, made almost a stable stratified water column, a typical characteristic of the GoA surface waters during summer (Badran, 2001; Grossart and Simon, 2002). Hot, arid climate with high evaporation and less precipitation rates makes the Red sea a high saline ecosystem (Sofianos *et al.*, 2002), which is clearly reflected in the present observation also. As the current study was conducted during the peak summer period (August), water column temperature was relatively high and was in good accordance with the earlier studies from this region (Al-Rousan *et al.*, 2002; Labiosa *et al.*, 2003; Carlson *et al.*, 2014). Water column temperature exhibited marked variability throughout the study region thus contributing to the formation of a shallow but stable thermocline (Lindell and Post, 1995; Manasrah *et al.*, 2007). Dissolved oxygen exhibited a marked pattern with well-oxygenated waters in the surface which gradually decreased towards the deeper layers in the present study (Klinker *et al.*, 1976; Badran, 2001). All these hydrographic factors clearly evident in the current study had a determining role in the ultra-oligotrophic nature and the vertical distribution of nutrients during summer of GoA (Reiss and Hottinger, 2012). On the contrary, the nitrate concentrations were comparatively higher, mostly in the deeper layers. The summer water circulation patterns in GoA leading to the intrusion of nutrient rich, high saline deep waters of GoA to the Red Sea through the Tiran strait might have contributed to this higher nitrate concentration in the deeper waters (Klinker *et al.*, 1976; Plähn *et al.*, 2002). During this process, deep waters of southern GoA can be observed with higher nutrient concentrations (Klinker *et al.*, 1978) and can be considered as the possible reasons for the occurrence of higher nitrate values from those regions during the present study. Also, the observation of increased nitrate concentration from the coastal waters of GoA during late winter by Batayneh *et al*. (2014) further corroborates the present study. The distribution of other inorganic nutrients was in accordance with the earlier observations from this region (Badran, 2001; Rasheed *et al*., 2002; Fuller *et al*., 2005; Batayneh *et al*., 2014). The relatively high phosphate concentration in the upper 10 m of the northern site (station 1) might have happened from the accidental spills occurring in association with the shipment process from the phosphate shipping port in the Jordanian waters (Abu-Hilal *et al*., 2008).

The existence of a stratified water column clearly affected the phytoplankton distribution as evident from the observed lower values through the study period. The low phytoplankton biomass distribution in the surface waters with relatively lower values in summer compared to winter is a common feature in GoA (Klinker *et al*., 1978; Yahel *et al*., 1998; Badran, 2001; Post *et al*., 2002; Rasheed *et al*., 2002; Stambler, 2006; Al-Najjar *et al*., 2007; Laiolo *et al*., 2014). The convective mixing during winter bringing in more nutrients towards the surface might be leading to the higher phytoplankton biomass in winter. The confrontation of upward diffusing nutrients with ample sunlight at some particular depth eventually will support the primary production in those areas and was evident in the present study with the occurrence of a deep chlorophyll maximum at 70m (Lindell and Post, 1995; Badran, 2001; Stambler, 2006). The phytoplankton density observed in the present study was lower compared to the prior studies from the region (Post *et al*., 2002; Stambler, 2006; Al-Najjar *et al*., 2007). It has been an established fact that ultra-phytoplankton of size <8 µm predominates the phytoplankton community of the GoA (Lindell and Post, 1995; Yahel *et al*., 1998) while the microphytoplankton (diatoms and dinoflagellates) contributes only 5% of the total phytoplankton population (Al-Najjar *et al*., 2007). Seasonal phytoplankton distribution along Egyptian coastal waters of GoA by Nassar (2007) have reported on the lesser species density and diversity during summer compared to the other seasons. In contrast, 138 phytoplankton species observed during the summer season alone in the present study in comparison to the 127 species by Nassar (2007) suggests GoA supporting a diverse phytoplankton community. Nutrient depleted surface waters might have limited the growth of microphytoplankton in summer in GoA thus leading to lower phytoplankton abundance during the summer in comparison to the winter period. Very similar to the study of Post *et al*. (2002), the centric diatoms were the major contributor to the total phytoplankton diversity (57 species). The dinoflagellates community also were dominated by the genus *Tripos* (synonym *Ceratium*) (24 species) and *Protoperidinium* (5 species) similar to Post *et al*. (2002), who mentioned the clear dominance of these two species among the dinoflagellate community of GoA. Presence of few HAB causing dinoflagellates indicates the possibility of occurrence of similar harmful dinoflagellates in this region. Biodiversity indices displayed a similarity in the evenness (J′) and diversity (H′) values, further pointing towards the less spatial variability leading to the conclusion that the summer microphytoplankton distribution in GoA is heavily influenced by water column stratification during summer. The summer stratification that determined the phytoplankton distribution in turn also affected the spatial distribution of mesozooplankton abundance and composition, which also did not show significant spatial variability in distribution in the study region (Longhurst, 1985; Farstey *et al*., 2002). Differences in the collection methods such as mesh size of the plankton nets used, type of collection as well as the sampling period might have contributed to the observed lower standing stock of mesozooplankton when compared to the earlier studies from the region (Table IV). In accordance to prior observations (Echelman and Fishelson, 1990; Khalil and Abdel-Rahman, 1997; Al-Najjar, 2000; Cornils *et al*., 2005, 2007a; El-Sherbiny *et al*., 2007; Dorgham *et al*., 2012) the zooplankton in the current study were also dominated by copepods represented by 70 species (Table IV).

Eight new records of copepod species from this region indicating towards the rich copepod diversity is another highlight of the current study. The new records further points towards the least explored nature of the region in terms of copepod biodiversity. The dominance of small-sized copepods in the current study is a clear depiction of the successful proliferation of these organisms in these oligotrophic marine ecosystems (Almeida Prado-Por, 1985; Al-Najjar, 2002; Cornils *et al*., 2007a). These small-sized copepods are considered to play a crucial role in the classical and microbial food web (Roff *et al*., 1995; Calbet *et al*., 2000). The microbial food webs are known to contribute more to the trophic functioning of the oligotrophic ecosystems, where the community is normally dominated by small sized organisms (Li *et al*., 1992). The lower abundance and diversity of the microphytoplankton in the present study further substantiates the view of microbial food web dominating the GoA waters. The dominance of small-sized non-selective particle feeding acartiid, clausocalanid and paracalanid copepods point towards the prevailing food web dynamics of the GoA (Lindell and Post, 1995). These organisms are well adapted to survive in the natural food scarce situations happening in such oligotrophic environments worldwide (*e.g.* Paffenhöfer, 1984; Calbet *et al*., 2000; Cornils, 2005;

Cornils *et al*., 2007b). Among the small-sized calanoid species, the dominance of *C. furcatus*, *M. clausi* and *L. flavicornis* was particularly distinctive. Cornils *et al*. (2005, 2007a) and Al-Najjar (2002) reported on the similar dominance of the epipelagic copepod *C. furcatus* from the northern part of GoA. Cornils *et al*. (2007a) further observed that the abundance of this particular species reached its peak during the late summer and is supposed to adapt well to the conditions such as higher irradiances and temperatures. *Mecynocera clausi,* is a common oceanic species with a wide distribution in tropical-subtropical oceans (Nowaczyk *et al*., 2011) including the GoA (Cornils, 2005). *Lucicutia flavicornis* another dominant copepod of the current study is well known for their variation in their diel distribution (Almeida Prado-Por, 1985) as can be seen as marked aggregations in the surface waters during night. In the present study, species such as *A. negligens*, *P. parvus*, *C. furcatus*, *C. vanus*, *L. flavicornis*, *O. attenuata*, *O. brevicornis* and *O. venusta* exhibited clear diel variation in abundance with evidently higher abundance during night. The predominance of calanoid copepods in the upper layers indicates their trophic association with the protozoans, which in turn is dependent on the occurrence of deep chlorophyll *a* maxima (50-70m) and associated ultraphytoplankton (<5µm) dominance. Interestingly, some other large-sized genera such as *Pleuromamma*, *Haloptilus*, *Scolecithricella*, *Candacia* and *Macandrewella* were observed with very low abundance during the day and witnessed a higher abundance during the night. These genera are known to occupy deeper waters during the day (> 300-400m) in order to avoid elevated levels of UV radiation and/or predation, and they subsequently migrate towards the upper 100m during night for feeding. It is worth mentioning that the euphausiids, isopods, and amphipods were recorded with higher abundance in the night samples because of their migratory behaviour and is in well accordance with the observations of Farstey *et al*. (2002) from the northern part of the gulf. The occurrence of molluscs (mainly gastropods) in relatively high numbers throughout the GoA compared to the previous studies (Cornils *et al*., 2005, 2007a; El-Sherbiny *et al*., 2007; Dorgham *et al*., 2012) might have been contributed by the proximity of the sampling stations to the coastal waters of the GoA characterised by rich benthic diversity (Loya, 1972; Richter *et al*., 2001).

CONCLUSIONS

The GoA exhibited clear stratification in the water column during the summer, which in turn influenced both the spatial and vertical distribution of microphytoplankton and mesozooplankton community. A deep chlorophyll maximum was observed in the GoA, probably due to the dominance of ultra-phytoplankton. Less spatial variability but an evident diel variation in zooplankton distribution was a notable feature of the zooplankton distribution in the present study. Dominance of small-sized copepods, which are well adapted for survival in oligotrophic systems, was conspicuous during the study. The present study showed that the summer stratification significantly influences the plankton distribution in the GoA and the whole system behaves as a uniform water body during this season. Eight new records of copepod species from this region further demands continuous monitoring of this bio-diversely rich and ecologically unique ecosystem in the global ocean.

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Supplementary material

There is supplementary material associated with this article. Access the material online at: http://dx.doi.org/10.17582/journal.pjz/2019.51.5.1823.1836

Statement of conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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