COMPARATIVE PLANKTON DYNAMICS IN ARABIAN GULF AND SEA OF OMAN AT OPPOSITE SIDES OF THE STRAIT OF HORMUZ

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ABSTRACT

Phytoplankton and zooplankton monthly samples collected from the coastal water stations, located in Ras Al Khaima Emirate (United Arab Emirates) and Sohar governorate (Sultanate of Oman), during 2018-2019, have shown great variations, not only in their community structures, but also in their species abundances. Plankton samples were collected via vertical hauls from 6 m depth to the surface at Ras Al Khaima, while in Sohar, samples were collected from 20 m depth to the surface. The sample analyses revealed the dominance of diatoms during the warmer months at both sample sites, with an increase of dinoflagellates during the colder months, especially at Sohar. The abundances of certain species at each site, could not be explained by the grazing of zooplankton (dominated by calanoid copepods) on species-specific populations of phytoplankton, nor by seasonal temperature variations. The hydrological regime at the Strait of Hormuz, separating the two sample sites, as well as the differences in morphometric features and other environmental parameters, could account for the ecological differentiation in planktonic successions at both locations.

Keywords: *Arabian Gulf, Sea of Oman, Planktonic succession, Hydrological regime*

INTRODUCTION

Algae bloom episodes recorded simultaneously in the Arabian Gulf (AG) and the Sea of Oman (SO) during the last decade have led researchers to believe that these two water bodies, which are connected by the Strait of Hormuz, have similar environmental and ecological features. Detailed studies of planktonic community structures and parallel surveys and analyses of phytoplankton and zooplankton species-specific compositions on either side of the Strait of Hormuz are lacking from literatures. Previous records of algae blooms in the AG and SO in 2008-2009 studied the blooming species and its intensity characteristics [1], [2] in the Arabian Gulf region, and its expansion to the coastal areas at the Sea of Oman. The icthyotoxic dinoflagellate species *Cochlodinium polykrikoides* was the cause of the bloom and fish-kill phenomenon in the AG and SO, especially at Ras Al Khaima (AG) and Fujirah (SO) emirates (both within the United Arab Emirates, UAE). Previous algae blooms in the Sea of Oman by the dinoflagellate species *Noctiluca* *miliaris* were recorded by [3], [4], in the SO and at Kuwait Bay (AG). Recent repeated *Noctiluca scintillans* blooms in the SO have been scantily recorded, and equivalent blooms in the AG have in some cases not been recorded at all [5], [6], and [7].

Water exchange between the AG and the SO through the Strait of Hormuz has long been known. It is characterized by a deeper saline layer (39-40 ppt) outflowing from the AG to the SO, and surface inflow of less saline (36-37 ppt) water from the SO to the AG [8]. The inflow and outflow of water through the Strait of Hormuz is unstable and does not follow the general circulation patterns of either the AG or the SO [9], [8], and [10]. The fluctuation in the water trajectories between the two basins is mainly controlled by wind direction and its duration may extend 2-8 days. Moreover, the speed of the inflow surface current to the AG along the Iranian side is 10 cm s^{-1}, while the outflow deeper current to the SO is slower and reaches 3 m s^{-1} [11]. This important feature, together with the coastal morphometry of the two basins, impacts on the ecology, not only on the pelagic ecosystems, but also on sub-pelagic and benthic systems. The average water depth in the AG is around 36 meters and the maximum depth is about 100 meters at the Strait of Hormuz down to the sandy bottom sediments. The average water depth in the SO is around 250 meters, with maximum depth reaching 3000 meters down to the fine sandy and silty bottom sediments [12].

General characteristics of phytoplankton and zooplankton communities in the AG and SO are described in literature separately and for different periods, and are summarized by [7]. During 2009-2011, diatoms contributed 70% to the total phytoplankton abundance followed by dinoflagellates at 21% in the AG, while small flagellates and diatoms contributed 10 and 25%, respectively, in the SO. For another period [13] in the SO, the contribution of small flagellates and dinoflagellates ranged between 25-40%. Zooplankton densities were found to be 10 times higher in the SO compared to the AG, however, the AG zooplankton community was more diverse (210 species) compared to the 144 species identified in the SO [14]. Copepods are the dominant species in both AG and SO zooplankton communities, with seasonal peaks in winter and early summer seasons in the AG, and multiple peaks in the SO, where there are monthly fluctuations in copepod species abundances.

The present study was carried out to investigate the phytoplankton and zooplankton dynamics at opposite locations in the AG and SO, with the aim of identifying the relationships between planktonic community structures at these locations, and taking account of the environmental and hydrological features representing these marine basins.

MATERIALS AND METHODS

Studied stations, sampling and analytical procedures

The present study was carried out in locations in the Arabian Gulf (AG) and the Sea of Oman (SO), separated by the Strait of Hormuz, during the period April 2018 through to May 2019. The selected station in the AG was in the coastal waters of the Emirate of Ras Al Khaima (UAE), with geographic coordinates

25°47'22.31"N, 55°56'35.52"E. While, the selected station in the SO was in the coastal waters of Sohar Governorate, at location 24°21'51.48"N, 56°44'48.52"E (Figure 1).

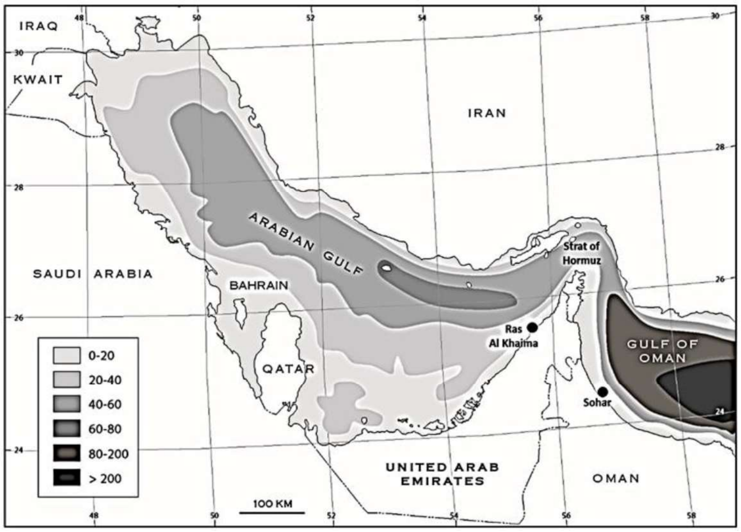

Figure 1. Map of the sampled stations at the AG and SO (●) indicating the bathymetric features of the two basins (Modified from [17]).

During the study period, environmental parameters (water temperatures, water salinities, dissolved oxygen and water pH) were measured in-situ within the water column from which phytoplankton and zooplankton samples were collected. Phytoplankton and zooplankton samples from Ras Al Khaima station (AG) were collected at monthly intervals by vertical haul with a 20-µm nylon net from 6 m depth to the surface. A similar procedure was followed for zooplankton sampling but with an 80-µm nylon net. At the Sohar station (SO), due to water depth differences and euphotic zone expansion, plankton samples were collected using similar net meshes from 20 m depth to the surface.

Phytoplankton and zooplankton samples from both stations were analyzed for their densities, abundances, and their species composition to the lowest taxonomic ranks. The analyses were guided by local, regional and international taxonomic references. Taxonomic ranking of phytoplankton was confirmed by collaboration with M.G. Kholodny Institute of Botany, Ukraine, and for zooplankton with assistance of the Institute of Biology of the Southern Seas, Russia. All counts and numbers are referred to a volume unit of one cubic meter.

Remotely sensed data

Monthly satellite images of chlorophyll concentrations (mg m^{-3}) at the surface water of the studied area, and wind and current vectors (speed and direction) were collected as shared information from the GIS Center at Sultan Qaboos University (Sultanate of Oman). The obtained images represented monthly values during the studied period (2018-2019) and were compared with long-term data analyses from 2002 until 2019.

RESULTS

Monthly variations in average water quality parameters showed marked variations between Ras Al Khaima (RAK) and Sohar stations during the study period. For instance, in RAK, water temperature averages ranged between 34.80°C in July 2018 and 21.77 °C in March 2019. Moreover, water salinity ranged between 41.88 ppt in July 2018 and 36.7 in August 2018. Dissolved oxygen averages ranged between 4.93 $mg.l^{-1}$ in October 2018 and 6.69 $mg.l^{-1}$ in March 2019 $mg.l^{-1}$, and pH averages ranged between 8.3 in September 2018 and 7.4 in April – May 2019 (Table 1). On the other hand, at Sohar station water temperature averages ranged between 29.09°C in October 2018 and 23.40°C in February 2019. Water salinity averages never exceed 36.82 ppt during the entire study period. Dissolved oxygen concentrations averages ranged between 5.12 $mg.l^{-1}$ in November 2018 and 10.84 $mg.l^{-1}$ in May 2019, while water pH averages ranged between 8.00 in August 2018 and 8.60 in both March and April 2019 (Table 1).

Table 1. Monthly averages of in-situ measured water quality parameters at both RAK (AG) and Sohar (SO) stations during the study period (2018-2019)

Station	Ras Al-Khaima				Sohar			
Parameters	Temp °C.	Salinity ppt	Dissolved oxygen $mg.l^{-1}$	pH	Temp. °C	Salinity ppt	Dissolved oxygen $mg.l^{-1}$	pH
Apr.2018	28.82	40.05	6.21	-	-	-	-	-
May 2018	-	-	-	-	-	-	-	-
Jun. 2018	32.63	40.62	5.60	8.2	28.70	36.73	5.05	-
Jul. 2018	30.05	41.88	5.77	8.2	26.21	36.53	8.47	-
Aug.2018	34.80	36.70	5.20	8.2	26.46	36.00	5.17	8.0
Sep.2018	33.72	37.58	5.33	8.3	-	-	-	-
Oct. 2018	31.50	38.06	4.93	8.2	29.09	36.82	5.87	8.1
Nov. 2018	28.23	38.93	5.48	8.0	26.49	36.65	5.12	8.3
Dec. 2018	24.57	40.51	6.07	8.8	25.85	36.80	5.38	8.1
Jan. 2019	23.14	40.43	6.20	7.5	24.05	36.58	6.99	8.1
Feb. 2019	22.23	40.23	6.65	7.5	23.40	36.68	5.40	8.3
Mar. 2019	21.77	40.24	6.69	7.4	27.24	36.63	5.76	8.6
Apr. 2019	24.23	40.68	6.57	7.4	27.24	36.61	8.87	8.6
May 2019	26.11	41.51	6.01	7.5	27.75	36.53	10.84	8.5

The analyses of phytoplankton species composition at RAK and Sohar stations has revealed a higher diversity of RAK compared to Sohar, in that species diversity exceeded 60 species in RAK station during November 2018, compared with 44 species at Sohar station during the same month (Figures 2). Although a few monthly samplings were missed during the study periods at both sites, the diversity of phytoplankton species for almost every month was higher at the RAK station than the Sohar station.

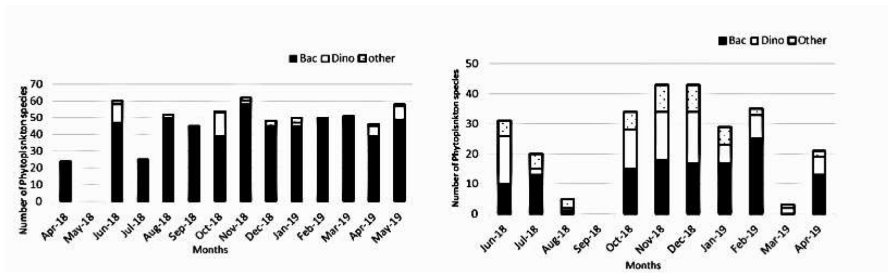

Figure 2. Monthly phytoplankton species numbers and their diversities at RAK (left) and Sohar (right) stations during the study period (2018-2019).

The monthly abundances of phytoplankton groups were dominated by bacillariophyta (Bac.) species, which represented >90% of the phytoplankton community structure at RAK, followed by dinoflagellates (Dino) that only contributed 11-17 % of the community during the months of September and October, 2018. Other groups such as cyanobacteria and chlorophyta never reached more than 5 % except in June 2018, when they contributed about 60% of the phytoplankton community density at RAK (Figure 3). At the Sohar station, cyanobacteria and chlorophyta species dominated the phytoplankton community structure, with values exceed 80 % during the months of August, 2018, as well as March and April, 2019. In contrast, bacillariophyta species were dominant in both June, 2018, and February, 2019, while dinoflagellate species contributed only marginally during November, 2018 (Figure 3).

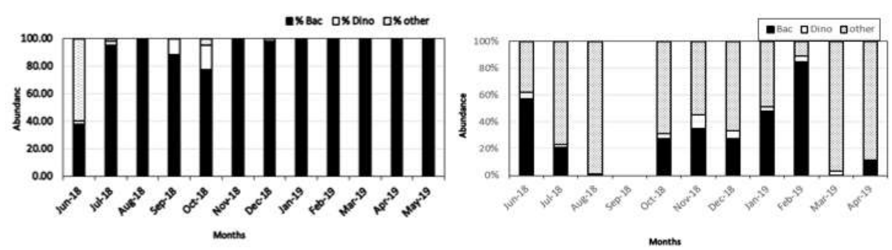

Figure 3. Monthly phytoplankton group abundances at RAK (left) and Sohar (right) stations during the study period 2018-2019.

Zooplankton species diversity almost always showed higher diversity at Sohar (SO) compared to RAK (AG) stations. The number of species identified at Sohar was almost 3 times higher (around 100 species in November, 2018) than those identified at RAK (around 32 species in January, 2019). Similar results were found for the density levels, where the density of zooplankton per m^{-3} at Sohar was >10 times greater than those counted per m^{-3} at RAK (figure 4 and 5).

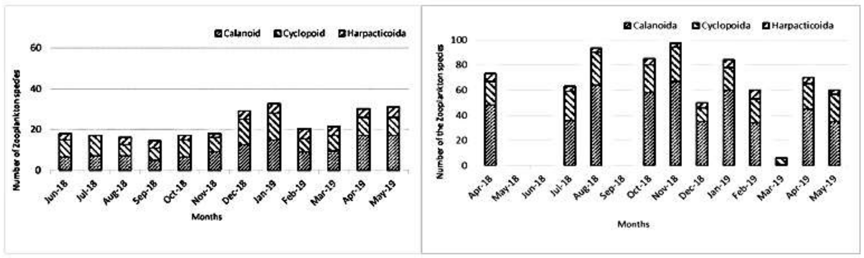

Figure 4. Monthly zooplankton species numbers and their diversities at RAK (left) and Sohar (right) stations during the study period (2018-2019).

In both stations, zooplankton identified groups belonged to the calanoids, cyclopoids and harpactocoids. Calanoid species always dominated the Sohar samples, while in RAK both calanoids and cyclopoids represented almost 80 % of the monthly community structure (figure 4).

The relationship between phytoplankton biomass and zooplankton densities per cubic meter at both stations was plotted by month (figure 5). Apart from the differences in their biomasses and their densities, there was no match in seasonal succession trends between the planktonic communities in the two sampling locations. At the RAK station, the zooplankton community peaked in June, 2018, followed by a sharp decline in September, 2018. After this, moderate densities followed by another decline in March, 2019, and recovery in May, 2019, preceded another peak in early summer. In March, 2019, the phytoplankton community showed a marked peak in its biomass that followed a less marked one in December, 2018 (figure 5).

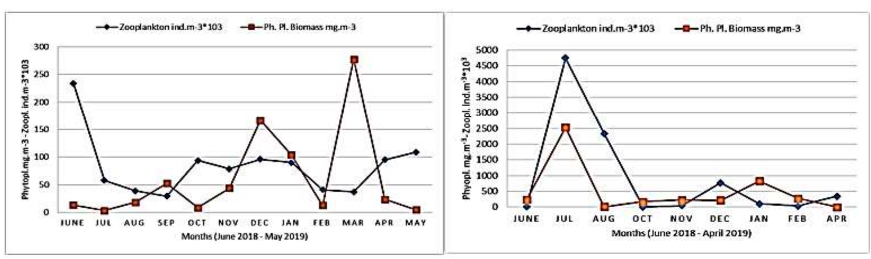

*Figure 5. Monthly succession of phytoplankton biomass (mg.m^{-3}) and zooplankton density (ind.m^{-3}*10^{3}) at RAK (left) and Sohar (right) stations during the study period (2018-2019).*

The zooplankton community at the Sohar station showed very high density during July, 2018, that exceeded 4.5 million individuals per cubic meter. This high density declined in the following months to reach its minimum in October, 2018, with only six thousands (6,000) individuals per cubic meter. From November, 2018, until April, 2019, there was a relatively limited increase in the densities during December, 2018, and April, 2019, to reach only 600 thousand and 300 thousand individuals, respectively. Surprisingly, the phytoplankton reached its high peak biomass (2500 $mg.m^{-3}$) during July, 2018, when zooplankton biomass also peaked (figure 5). The other phytoplankton increased in biomass, but with much less pronounced peak observed in January, 2019, to a value of around 800 $mg.m^{-3}$.

The dominant species of phytoplankton and zooplankton showed no complementary trends between the two basins, except for the individual case of the bacillariophyta species *Guinardia flaccida* that was dominant in the Sohar phytoplankton community during June, and dominated the RAK phytoplankton community during the period from January to May, 2019. The Calanoid species *Temora turbinata* that dominated the RAK zooplankton community only during April, 2018, dominated the Sohar zooplankton community during August, 2018, February, 2019 and April, 2019 (table 2).

Table 2. Monthly dominant species of both phytoplankton and zooplankton communities identified in RAK (AG) and Sohar (SO) stations during the study period (2018-2019).

Locations/ Dates	Phytoplankton dominant species		Zooplankton dominant species	
	RAK	SOH	RAK	SOH
Apr-2018	*Coscinodiscus wailesii* *Surirella pandura*	*ND*	*Euterpina acutifrons* *Temora turbinata*	*ND*
Jun-2018	*Pyrophacus steinii* *Pleurosigma elongatum v. fallax*	*Guinardia flaccida* *Nitzschia longissima*	*Oithona brevicornis smaller form* *Copepoda (Nauplius)*	*Paracalanus denudatus* *Acrocalanus longicornis*
Jul-2018	*Tetramphora decussata* *Rhizosolenia imbricata*	*Amphora proteus* *Coscinodiscus wailesii*	*Oithona spp.* *Bivalvia*	*Bestiolina zeylonica* *Centropages furcatus*
Aug-2018	*Pleurosigma elongatum v. fallax* *Tetramphora decussata*	*Dinophyceae sp.* *Ceratium macroceros*	*Oithona brevicornis smaller form* *Oithona spp.*	*Temora turbinata* *Corycaeus spp.*
Sep-2018	*Coscinodiscus marinates* *Amphora arcus*	*ND*	*Bivalvia* *Copepoda (Nauplius)*	*ND*
Oct-2018	*Rhizosolenia imbricata* *Coscinodiscus perforatus*	*Meuniera membranacea* *Proboscia alata*	*Oithona spp.* *Copepoda (Nauplius)*	*Acrocalanus longicornis* *Paracalanus denudatus var.*
Nov-2018	*Plagiotropis lepidoptera* *Coscinodiscus marginatus*	*Rhizosolenia bergonii* *Thalassiosira decipiens*	*Oithona spp.* *Oithona brevicornis smaller form*	*Acrocalanus longicornis* *Acartia amboinensis*
Dec-2018	*Mastoneis biformis* *Coscinodiscus sp.*	*Rhizosolenia hyaline* *Pleurosigma formosa*	*Copepoda (Nauplius)* *Oithona spp.*	*Corycaeus spp.* *Oncaea clevei*
Jan-2019	*Guinardia flaccida* *Hantzschia pulchella*	*Stephanopyxis palmeriana* *Thalassiothrix longissimi*	*Oithona spp.* *Copepoda (Nauplius)*	*Acrocalanus longicornis* *Eucalanidae*
Feb-2019	*Guinardia flaccida* *Coscinodiscus sp.*	*Guinardia striata* *Rhizosolenia hebetata*	*Copepoda (Nauplius)* *Pseudodiaptomus spp.*	*Canthocalanus pauper* *Temora turbinata*
Mar-2019	*Lauderia annulata* *Guinardia flaccida*	*ND*	*Copepoda (Nauplius)* *Pseudodiaptomus spp.*	*Corycaeus lubbocki* *Corycaeus pacificus*
Apr-2019	*Guinardia flaccida* *Rhizosolenia hyaline*	*Flagellata sp.* *Gyrodinium fusiform*	*Copepoda (Nauplius)* *Oithona spp.*	*Temora turbinata* *Acrocalanus longicornis*
May-2019	*Coscinodiscus sp.* *Guinardia flaccida*	*Coscinodiscus wailesii* *Chaetoceros lorenzianus*	*Oithona spp* *Copepoda (Nauplius)*	*Oncaea clevei* *Corycaeus spp.*

The integration of wind components over the studies region during the period May, 2003, to February, 2018 (NOAA/NCDC blend daily 0.25º- 10 m altitude), especially during the months where similar planktonic organisms dominated their communities structure, showed direction changes that may have affected surface water movement directions and velocities. During other months, wind components were analyzed separately for each basin. According to figure 6, wind direction was from the AG towards the SO, through the Strait of Hormuz, during April, while in

August, the opposite direction prevailed. However, in January, a northwestern wind may have prevent the movement of waters between the two basins.

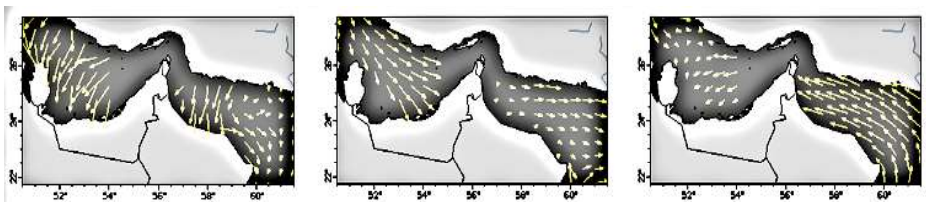

Figure 6. Integrated wind directions over the studied region during the period 2003-2018 for the months of January (left), April (middle) and August (right). Data Courtesy of NOAA-NCEL (modified from [10]).

The calculated wind stress data on the sea surface during 2019, at different months, corresponded to the long-term integrated wind directions (Figure 7), showing fluctuations in surface water interconnection between the two basins.

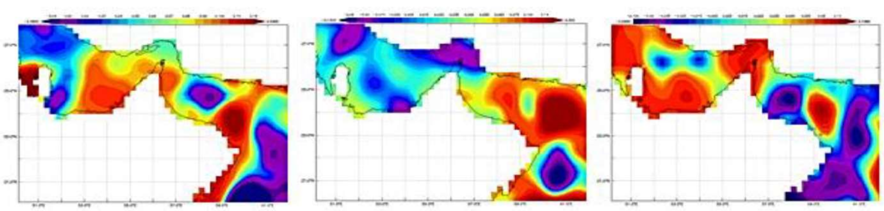

Figure 7. Calculated monthly sea surface anomalies over the studied region during January (left), April (middle) and August (right) 2019.

Although satellite images of Chlorophyll *a* concentrations obtained during 2019 did not assay every month, the obtained results for the months of January and April, 2019, correlate with the calculated wind data and sea surface anomalies during the same months. Very low and dispersed chlorophyll *a* concentrations along the Iranian coast were detected during January, 2019, while in April, 2019, high concentrations of chlorophyll *a* in the coastal area of the Sea of Oman were observed.

DISCUSSION

Both the Arabian Gulf and the Sea of Oman are known for their high phytoplankton production, and their ample nutrient salts concentrations. That has been regularly confirmed by historical data and in recent studies [11], [15], [16], [17], [7], and [10]. However, the differences observed in the present study in the phytoplankton community structures of these water bodies, could be mainly due to the differences in their environmental parameters, namely, high water salinity and high dissolved silicate contributed by dust storms over the AG have favored the domination of the bacillariophyta group over the other phytoplankton [17]. On the other hand, the Oceanic water salinity characterizing the SO may have allowed the growth of other phytoplankton groups. Although dust was also deposited over the SO, the superior area and depth of the SO basin may have decrease the availability of dissolved silicates to bacillariophyta species, allowing other phytoplankton groups to compete with them.

The summarized comparison between dominant phytoplankton groups in the AG and the SO by [7], is confirmed in the present study, though with slight differences in percentages between the two community structures of the studied stations. Moreover, the high densities of zooplankton communities observed in this study in the Sohar station have exceeded by a factor of 15 the densities at the RAK station, which surpassed by a factor of 10 the results reported by [14], when the zooplankton densities at both basins are compared. Although slight differences in temperatures and the possible adaptation of plankton to such variations may be factors, the distinct dynamics of planktonic seasonal successions between the studied stations are best explained by atmospheric and hydrologic regime differences between the studied areas. It has been reported that the SO surface water is dominated by oceanic water that flows along the Iranian coast and mixes with cool advected water during the winter northeast monsoon, while during the summer southwest monsoon, an upwelling persists along the south coast of Oman [10]. [10], also noted that conditions off the northern coast of Oman are mainly controlled by the advected water, the strong heating during summer, the impact of an intense eddy field, the outflow of the Arabian Gulf, and variable wind directions. Furthermore, [7] mentioned that, the AG water outflow spreads in the form of a subsurface salinity maximum (occupying a depth range between 200 and 350 meters). They also found that seasonal variations of atmospheric temperatures create atmospheric pressure anomalies, which could be one of the factors mediating the water mass transport between the AG and SO. These findings, representing a general pattern, may confirm the contribution of wind stresses over the sea surface and water current flow directions between the two basins. In our study, the plankton samples were collected from 6 meters depth from RAK station and from 20 meters depth at Sohar station. These represent the upper mixed layers in the two basins, when compared to their average depths. At such layer passive transportation of planktonic organisms by water currents and the presence of atmospheric anomalies during different months (figures 6 and 7), may result in dispersal of planktonic communities and may also disrupt and/or dilute their structures. By linking the water exchange features and the differences in the bathymetry and the hydrology of the two basins [9], and [7], irregularities in seasonal trends of planktonic successions are expected. Furthermore, absence of harmonization in seasonal productivity peaks, as well as species dominance similarities, may result from surface water movement anomalies that lead to random but regular and harmonized periods where algae blooms occur simultaneously in the two basins.

In the present study, the dominance of the bacillariophyta species *Guinardia flaccida* at Sohar station in June, 2018, and its dominance in the RAK phytoplankton community from January, 2019, until May, 2019 (table 2), could be a result of the different hydrological processes associated with the entry of SO surface water into the AG through the Strait of Hormuz. This surface water flow follows the anticyclonic gyre front in Qatari waters [9] and [8]. The return flow of waters through the RAK station may carry the same species. On the other hand, the dominance of the calanoid copepod *Temora turbinate* of the RAK zooplankton community during April, 2018, and its dominance in Sohar during August, 2018, as well as in February and April, 2019 could also be an indication of possible sharing of dominant species between the two basins, though at different seasons or different years. This could be the result of water exchange between the two basins and sporadic dispersal of certain planktonic species, due to their high densities and their passive transportation during water circulation.

By observing the relationship between phytoplankton and zooplankton communities in the present study at RAK station, it is evident that there is an ecological succession that characterizes its planktonic community dynamics. The high peaks of the zooplankton density period are always accompanied by low phytoplankton biomass and vice versa (figure 5). In contrast, at the Sohar station, equivalent correlation between phytoplankton and zooplankton communities is quite absent. Indeed, the zooplankton density peak observed in July, 2018, was accompanied by a peak in phytoplankton biomass (Figure 5). These features, lead us to conclude that the RAK (AG) zooplankton community is able to control the phytoplankton biomass, while at Sohar (SO), both zooplankton and phytoplankton communities are governed by other factors. In their study, [18], [7] and [10] mentioned that the SO is characterized by high fish landings, with major contribution of the filter feeder sardine and juvenile fish that may play substantial role in controlling planktonic communities. By this means, the planktonic interactions at Sohar station would be governed mainly by predation-prey interactions, while at RAK, grazing interactions are the key feature of its ecological succession. This conclusion provides an improved model to explain the effects of hydrological interactions between the AG and SO stations that are separated by the Strait of Hormuz. It also expands our understanding of simultaneous algae bloom phenomena in the two basins.

CONCLUSION

This study was carried out during 2018-2019 in the form of detailed monthly investigations of planktonic communities and relevant environmental parameters at two stations: the Arabian Gulf (RAK) and the Sea of Oman (Sohar), on opposite sides of the Strait of Hormuz. The study shows that both morphometric and hydrologic differences between the two basins play major roles in controlling their planktonic community structures and their seasonal dynamics. It is concluded that the ecological succession in the Arabian Gulf is characterized by grazing of zooplankton on phytoplankton, while predation-prey interaction more appropriately describes the ecological succession in the Sea of Oman.

ACKNOWLEDGEMENTS

This research funded by the SQU-UAEU Collaborative Research Grant CL/SQU-UAEU/ /18/04 and 31S321). We would like to thank Y. Bryantseva (M.G. Kholodny Institute of Botany, Ukraine) and E. Popova (Institute of Biology of the Southern Seas, Russia) for their assistance in identifying and confirming the taxonomy of phytoplankton and zooplankton samples respectively. Our gratitude extended to Dr. S. Al-Ghais and Dr. S. Varadharajulu from EPDA –Ras Al Khaima

Government, for their approval and assistance in sampling and samples processing at RAK station and for Mr. S. Al-Khusaibi, H. Al-Habsi. B. Al-Bawaiqi and H. Al-Lawati for their technical assistance in sampling of Sohar station and in data processing for the Sea of Oman. A special thanks to Dr. A. Fowler for his careful revision of the manuscript editing.

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