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PLANKTON DYNAMIC AT EASTERN ARABIAN GULF AND SEA OF OMAN

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Environmental Sciences

Under the Supervision of Professor Waleed Hamza

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Declaration of Original Work

I, Muzna Mohammed Saeed Al Junaibi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Plankton Dynamic at Eastern Arabian Gulf and Sea of Oman*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Waleed Hamza, in the College of Science at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The present study is part of the collaborative research project entitled "Comparative Analysis and Predictions of Algal Blooms in the Arabian Gulf and the Sea of Oman**",** between the United Arab Emirates University and Sultan Qaboos University (Grant # G00002684- 31S321**)**, in which simultaneous and intensive biweekly plankton and water samples were collected from two opposite coastal stations off the Strait of Hormuz with the aim to study plankton dynamics at the Arabian Gulf and the Sea of Oman and the effect of environmental parameters on their community structures during the period from May 2018 until May 2019. For the Arabian Gulf, samples were collected from Ras Al Khaimah (RAK) station, while for the Sea of Oman samples were collected from Sohar (SOH) station Due to the differences of the morphometric as well as the bathymetric features of the two basins, plankton samples and environmental parameters measurements were collected from 6 meters depth at Ras Al Khaimah and from 20 meters depth from the Sea of Oman. However, similar methodologies have been used for sampling collection and analyses. Phytoplankton and zooplankton samples were collected by using 20 µm and 80 µm respectively. Environmental parameters measured in situ (water temperature, Salinity, pH, and dissolved Oxygen) by using multisensory instruments, while nutrient salts concentration (Nitrate NO_3, Ammonia NH_3, phosphate PO_4), were determined at the designated laboratories using auto analyzer instrument following the approved standard methods. Chlorophyll concentrations at RAK were measured in situ, while at SOH it was extracted from remote sensing data analyses. The obtained results indicated that water temperature at SOH was cooler (maximum 28.7°C) in summer months than that of RAK (maximum 34.8°C). Strikingly, the RAK water temperature in winter was cooler than at SOH station. Due to the Sea of Oman direct connection with the Indian Ocean its water salinity was always close to Oceanic salinity (i.e. 36 ppt); while the semi closed and shallow nature of the Arabian Gulf have increased its water salinity up to 41 ppt. It was clear from the nutrients analyses that the concentrations at SOH station was higher than values resulted from the analyses of water samples collected from RAK. Phytoplankton community structure at RAK was mainly composed of Bacillariophyceae and Dinophyceae with Bacillariophyceae dominance ($\geq$ 90%), along the study period, except in June 2018 where, other groups such as cyanobacteria and Chlorophyceae were representing up to 50% of the community structure. While at SOH, Bacillariophyceae where less dominant during the study period with values ranged between < 1% in August 2018 and April 2019 and between 80% in February 2019 and 10% in May 2019. Both cyanobacteria and Chlorophyceae were alternating the dominance with Bacillariophyceae. Dinophyceae, were sporadically represented, with a maximum of 10% of the community structure occurred during November 2018. At both stations zooplankton was represented by three groups i.e., Calanoids, Cyclopoids and Harpacticoids. At RAK Cyclopoids was dominating the zooplankton community along the study period, while Calanoids was dominating SOH zooplankton community. Harpacticoids was more presented at RAK compared to SOH during the study period. The results also indicated that, although the numbers of phytoplankton community was more diverse (1151 species) at RAK compared to SOH (192 species), the phytoplankton biomass was >10 folds at SOH compared to RAK station. Indeed, the zooplankton density at SOH was 4 times more than that found at RAK station. Based on the obtained results, the present study also analyzed the relationship between phytoplankton biomass and zooplankton densities during the study period and came to the conclusions that:1- Both phytoplankton and zooplankton communities at the studied stations are not similar in its monthly community structures, 2- The variations between the two basins in environmental parameters are also affecting the species dominance and the monthly community structures of both phytoplankton and zooplankton, 3- Wind stress and its directions over the studied period are controlling the surface water current directions through the Strait of Hormuz which control by its time the movements of planktonic organisms between the two basins, 4- At RAK the relationship between phytoplankton and zooplankton is based on grazing of zooplankton on phytoplankton; while at SOH it is mainly based on pray predator interaction, especially with the presence of high densities of fish larvae (especially Sardine and Anchovy), which controlled the zooplankton ability to limit the phytoplankton productivity. Statistical analyses (Principal component Analyses–PCA), has confirmed the negative relationship between phytoplankton and zooplankton at RAK, but it was less able to explain such relationship at SOH station. The present study is the first in its kind to study simultaneously the dynamics of plankton communities at the Arabian Gulf and the Sea of Oman and it could be a baseline for future research.

Keywords: Arabian Gulf, Sea of Oman, Phytoplankton, Zooplankton Algae bloom, Environmental parameters, Hydrodynamics.

Title and Abstract (in Arabic)

ديناميكية العوالق البحرية في منطقة الخليج العربي وبحر عمان

الملخص

الهدف من هذه الأطروحة هو دراسة ديناميكية العوالق البحرية وتأثير العوامل البيئية عليها في الخليج العربي وبحر عمان. تعتبر هذه الدراسة جزءاً لدراسة بحثية بين جامعة الامارات العربية المتحدة وجامعة السلطان قابوس لدراسة ظاهرة المد والتبنؤ بها . تم جمع عينات العوالق البحرية كل اسبوعين خلال فترة مايو 2018 حتى مايو 2019 من خلال محطتيين ساحليتين: رأس الخيمة ومحافظة صحار. نظراً لأختلاف العمق في المنطقتين، تم جمع العينات في محطة رأس الخيمة من عمق 6 أمتار بينما في محطة صحار من عمق 20 متراً. تم جمع عينات العوالق النباتية باستخدام شبكة 20 ميكروميتر و 80 ميكررميتر للعوالق الحيوانية. بالنسبة للعوامل البيئية تم قياسها في الموقع (درجة حرارة الماء، الملوحة، الاس الهيدروجيني والاكسجين المذاب في الماء) بأستخدام معدات ذات حساسية عالية. بينما تم قياس تركيز المعادن (النترات ،الامونيا و الفوسفات) في المعامل من خلال جهاز التحليل .بالنسبه لتركيز الكلورفيل أ، في رأس الخيمة تم قياسه بالمحطة بينما في محطة صحار تم تحليل التركيز من بيانات الاستشعارعن بعد. أهم نتائج هذه الدراسة هي انه درجة حرارة الماء في فصل الصيف في محطة صحار اكثر برودة من محطة رأس الخيمة. على العكس، انه درجة حرارة الماء في فصل الشتاء في محطة رأس الخيمة كانت أكثر برودة من محطة صحار. نظراً لأرتباط بحر عمان بالمحيط الهندي ،تعتبر ملوحة مياهه دائماً قريبة من درجة ملوحة المحيط (36 جزء لكل ألف). في حين أدت الطبيعة الشبه مغلقة والضحلة للخليج العربي إلى زيادة ملوحة مياهه لتصل إلى أعلى من (41 جزء لكل ألف) . تتكون العوالق النباتية في رأس الخيمة بشكل أساسي من: (Bacillariophyceae) وتعتبر أكثر هيمنة بنسبه 90% من (Dinophyceae) والمجموعات الاخرى. خلال فترة الدراسة ، باستثناء شهر يونيو 2018 حيث كانت المجموعات الاخرى مثل : البكتيريا الزرقاء والكلوروفيسيا تمثل ما يصل إلى 50% من المجموع الكلي. بينما في محطة صحار، كانت (Bacillariophyceae) أقل هيمنة خلال فترة الدراسة <1% في شهر اغسطس 2018 وأبريل 2019 بينما بنسبه 80% في فبراير 2018 و10% في مايو 2019. كانت كل من البكتيريا الزرقاء و (Chlorophyceae) تتناوب مع هيمنة (Bacillariophyceae). بينما (Dinophyceae) تمثل 10% من بنية المجتمع في نوفمبر 2018. في كلتا المحطتين تم تمثيل العوالق الحيوانية بثلاث مجموعات، مثل (Calanoids)،

(Cyclopoids) و(Harpacticoids). في رأس الخيمة سيطرت (Cyclopoids) على مجتمع العوالق الحيوانية طوال فترة الدراسة، بينما كانت (Calanoids) تهيمن في منطقة صحار .تم تقديم (Harpacticoids) بشكل أكبر في رأس الخيمة مقارنة بصحار خلال فترة الدراسة .أشارت النتائج أيضًا إلى أنه على الرغم من أن عدد أنواع العوالق النباتية كان أكثر تنوعًا (1151 نوعًا) في رأس الخيمة مقارنةً بـ صحار (192 نوعًا) ، فإن الكتلة الحيوية للعوالق النباتية كانت 10 > أضعاف في صحار مقارنة بمحطة رأس الخيمة . في الواقع ، كانت كثافة العوالق الحيوانية في صحار 4 مرات أكثر من تلك الموجودة في محطة رأس الخيمة. بناءً على النتائج التي تم الحصول عليها ، تم دراسة أيضاً العلاقة بين العوالق النباتية والحيوانية وتوصلت الاستنتاجات إلى:1- عدم وجود تشابهه في الهيكل البنائي في العوالق النباتية والحيوانية في المنطقتين خلال فترة الدراسة 2- تؤثر العوامل البيئية على هيمنة العوالق النباتية والحيوانية. 3- تؤثر قوة الرياح واتجاهاته على مضيق هرمز على حركة العوالق بين المنطقتين. 4- في رأس الخيمة ، العلاقة بين العوالق النباتية و الحيوانية تقوم على أساس تغذية العوالق الحيوانية على العوالق النباتية . بينما في منطقة صحار، تعتمد العلاقة بشكل أساسي على علاقة الأفتراس، خاصه مع وجوج كثافات عالية من سمك السردين والأنشودجة. التي تتحكم في قدرة العوالق الحيوانية في إنتاجية العوالق النباتية. أكدت التحليلات الإحصائية العلاقة السلبية بين العوالق النباتية والعوالق الحيوانية في رأس الخيمة، لكنها كانت أقل قدرة على تفسير هذه العلاقة في محطة صحار. تعتبر هذه الدراسة هي الأولى من نوعها التي تدرس في وقت واحد ديناميكية العوالق في منطقة الخليج العربي وبحر عمان ويمكن أن تكون أساساً للبحث في المستقبل .

مفاهيم البحث الرئيسية: منطقة الخليج العربي، بحر عمان، العوالق النباتية، العوالق الحيوانية، ظاهرة المد الأحمر، العوامل البيئية، الديناميكا المائية.

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Dedication

To my beloved parents and family

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List of Abbreviations

AG	Arabian Gulf
Bac	Bacillariophyceae
Chl	Chlorophyll
Dino	Dinoflagellates
EPDA	Environment Protection and Development Authority
NEM	North East Monsoon
NH_3	Ammonia
NO_3	Nitrate
PCA	Principal Component Analyses
PO_4	Phosphate
RAK	Ras – Al Khaimah
SOH	Sohar
SWM	South West Monsoon

Chapter 1: Introduction

Plankton are part of the many organisms that grace water bodies. They are known to be the main food for most aquatic life, majorly fish. They have the characteristic of inability to swim against water currents and live suspended in the water column in the top surface layer, the epipelagic zone which ranges from 1 m to 30 m in lakes and could extent to depths of more than 200 m in the open ocean (Martin, 2015). However, this does not mean that they cannot found in other areas (Wang et al., 2013). The origin of this word “Plankton” is coming from a Greek word “Planktos”. They usually drifting with the water currents and they may include bacteria, protozoa, archaea and algae. Micro crustaceans, eggs and larvae from larger sea animals are also part of plankton (Wang et al., 2013).

Plankton are also classified according to their size as usually recognized in pelagic planktons: micro-plankton (20–200 μm), nano-plankton (2–20 μm), and pico-plankton (0.2–2.0 μm) (Kasprzak et al., 2002). Moreover, plankton organisms can be also classified based on their ecological niches rather than their taxonomy. They are categorized into two main taxa: phytoplankton and zooplankton. Phytoplankton are primary producers (Autotrophs). This means they manufacture their own food at the same way green higher plants utilize the energy from the sun to make their own food (photosynthesis) by using nutrients from their surrounding water. They take green color because of the chlorophyll pigments (a, b and c), found in its chloroplasts which absorb sunlight used as energy source to support the photosynthesis processes. There are many subdivisions of phytoplankton, which, include golden algae, green algae, blue-green algae, dinoflagellate and diatoms. The blue-green algae had identified as bacteria and known as Cyanobacteria, but since they resemble possess many characters of algae, the previous research on this group classified it as algae (Bilen & Vedaldi, 2017).

On the other hand, part of zooplankton depend on the primary producer's (i.e. phytoplankton) to feed. That mean they are animals even with predatory species (Wang et al., 2013). In addition, zooplanktons consist of several groups. The most important ones in this category are fish larvae, larvae of benthic species, Cladocera, Rotifers and Copepods.

Phytoplankton and zooplankton remain to be poorly considered despite their vital role played in the marine food webs. Moreover, plankton organisms are keystone in managing the biodiversity of aquatic ecosystems (Defriez et al., 2016). Where, the information from the phytoplankton indicators gives a detailed dynamic of their predators (Alfonso et al., 2017). The plankton size distribution is not only an indicator of their biodiversity but also shows efficiency in trophic transfer which affect fish dynamics. They are important in the ocean's food web by providing food for animals such as: fish larvae and blue whales whom feed on them as well as human, who also use green alga *Chlorella* sp. in production of more than 50% of protein that has a balance of necessary amino acids (Enyidi, 2017). Plankton diatoms are responsible about fixing at least a quarter of the inorganic carbon in the ocean each year (Brierley, 2017).

Therefore, phytoplankton play a vital role due to their over 25,000 species which occupy the base of the food web in marine ecosystem (Morán et al., 2010). Based on the research done by Chícharo and Barbosa (2011), phytoplankton are responsible for about 50×10^{15} grams of the carbon which is photosynthetically fixed on earth and this represents about half of the worldwide production. Moreover, they are responsible for the great increase in the dissolved carbon within the water bodies, which means the carbon dioxide maintained below the 300-400 ppm that would not occur without these organisms. Thus, phytoplankton play a leading role in regulating the amount of carbon dioxide in the atmosphere and hence affect the climate variability of the globe. It has reported that, planktons not only maintain the health and balance of the oceans and its food web but also ensure their sustainability through the oxygen, nutrients, and biomass, which they produce.

In Figure 1, Sommer et al. (2017) mentioned that there are several differences in sizes and nutrient intake between the phytoplankton found in lakes and those in oceans. Phytoplankton within the cyanobacteria class is found in tropical open oceans and temperate coastal seas include *Synechococcus sp. and Prochlorococcus sp.* These two species differ; the former are very small while the latter are larger, filamentous and belong to the nitrogen fixing taxa. In lakes, cyanobacteria are diverse and have different sizes, they are non-nitrogen fixing and often have filaments such as *Planktothrix* species. Other groups of phytoplankton such as Dinoflagellates are of the same size in both lakes and oceans while Cryptophytes found in both lake and ocean ecosystems, with larger forms in lakes. Moreover, the *Prymnesiophytes* which are found in both lakes and oceans tend to be nanoplanktic flagellates while calcified *coccolithophorales sp.* which is species of Prymnesiophytes are only found within the marine habitats where colonial *phaeocystis* species.

Based on a research done by Kruk and Segura (2012), planktonic diatoms found in either ocean or freshwater lakes are similar for those within the lower size limit, but a clear difference is found in the upper size limit. The largest diatoms in ocean waters phytoplankton are much larger than those found in the freshwater lakes with needle shaped of the discoid centric diatoms exceeding 100 µm for the freshwater unlike for oceans which rarely exceeds 100 µm. However, the maximum cell volumes for the lakes diatoms does not exceed 10^5 µm^3 while for the marine planktonic diatoms could reach up to 10^7 µm^3 in cell volume.

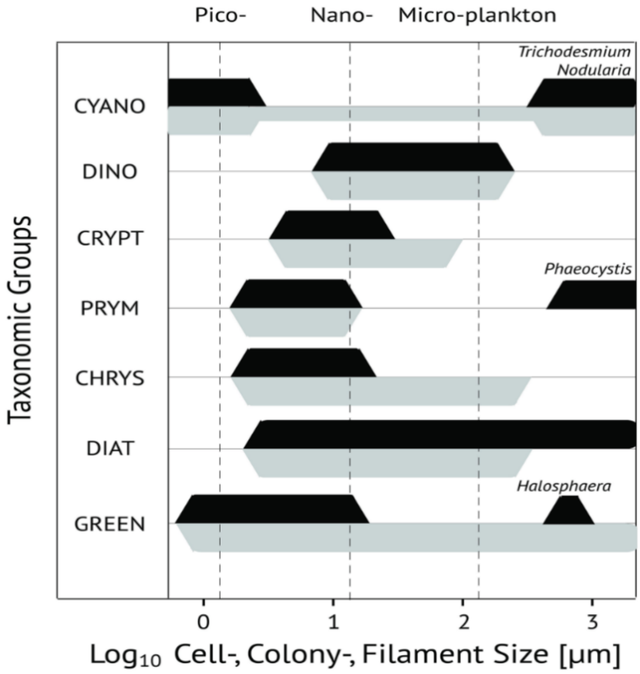


Figure 1: Cell sizes and its variations between phytoplankton groups in marine and freshwater habitats (Sommer et al. 2016). (CYAN: cyanobacteria; DINO: dinoflagellates; CRYPT: cryptophytes; PRYM: prymnesiophytes; CHRYS: chrysophytes; DIAT: diatoms; GREEN: green algae) in marine (black) and freshwater (gray) phytoplankton.

In marine phytoplankton, there is a large size gap between green algae nano-planktonic and giant non-flagellated phycoma while this gap is filled by several flagellated, gelatinous, coccoid, colonial, and filamentous genera among the green algae found in freshwater lakes (Williams et al., 2015). In their research Litchman et al. (2010) argued that due to the nitrogen limitation in oceans, there is either low or high nitrogen supply, which favors the small cell sizes but with the pulsed nutrient supply found in oceans can support cells up to 10^9 µm^3 based on duration of nitrogen pulses. While, due to

Phosphorus limitation found in lakes the constant or the pulsed supply of phosphorus neither would favor the large cell sizes.

Despite the variation of the two ecosystems, planktons able to survive in all conditions due to their ability to balance between behavior and the environment through responding to the ecosystem structure and processes. According to McManus and Woodson (2012), oceans have various factors, which influence the ability of phytoplankton and/or zooplanktons to survive including temperature, winds, tides, and freshwater input. Often upper ocean has lower density but lacks needed nutrients for plankton while deep ocean has high density and it is rich in nutrients. The existing boundary between the upper and deep-sea known as pycnocline due to the rapidly changing density, may limit fast exchange of resources between the water masses. Since ocean density determined by temperature and salinity, often these two coincide with pycnocline. These two-separated water masses having varying hydrographic characteristics and forming oceanfronts that have sharp changes in temperature and salinity. As a result, these gradients mainly the pycnocline and ocean fronts have the best growth conditions in which planktons thrive. According to Grattepanche et al. (2015), majority of the zooplanktons are found within the base of pycnocline due to the increased presence of the phytoplankton within this region.

Because of their planktonic nature, its passive transportation both horizontally and vertically is depending on the direction of water current. Moreover, its distribution and dominance within the different seas and oceans are depending on various environmental factors and on its species - specific tolerance of the surrounded environmental conditions as well as its biotic interactions with other species such as competition, predation (grazing), and disturbances. Such interactions between plankton and other biotic and abiotic factors may lead to the appearance of algae blooms that may also called red tide.

Algae blooms have documented in different parts of the world coastal areas as its was recorded along different coastal areas at the Arabian Gulf and the Sea of Oman during 2008-2009 and it has devastated the entire coastal area of United Arab Emirates and northern parts of the sea of Oman, by the marine ichthyotoxic dinoflagellate *Cochlodinium polykrikoides* which lasted for more than eight months, caused mass mortalities of wild and farmed marine species, limiting traditional fishery operations, damaging coral reefs, impacting coastal tourism, and forcing to stop desalination plants activities in the region (Richlen et al., 2010). Because of this phenomenon, researchers believe that Arabian Gulf and Sea of Oman are similar in their environmental and ecological features as well as in their plankton communities' dynamics and species composition. That is simply because their water bodies are connected through the Strait of Hormuz (Piontkovski et al., 2019; Hamza et al., 2020).

The Arabian Gulf is one of the major high-salinity basins in the region, it lies between (26° 4' 35.4756" N and 52° 37' 28.2432" E); the salinity is more than 40 ppt and can exceed 50 ppt in some area (Vaughan et al., 2019). In the opposite side, the salinity of the Sea of Oman (21° 00' N and 57° 00' E), 36-37 ppt. Saline and dense water flows out from the Arabian Gulf toward the Sea of Oman, with a mean velocity of 0.2 m s^{-1} through the Strait of Hormuz (Johns et al., 2003). While the inflow of less dense water (36-37 ppt) with faster velocity 10 cm s^{-1} from sea of Oman to Arabian Gulf (Wang et al., 2013). According to this, hydrological structure the Arabian Gulf composed of 30 meters thick mixed layer overlying an Arabian Gulf water, while at Sea of Oman, the fresher and colder Indian Ocean is clearly seen above and next to the Arabian Gulf water

(Pous et al., 2004). Wind direction and its duration may extend 2-8 days mainly controlled water trajectories between two basins (Hamza et al., 2020).

Different studies have described the phytoplankton and the zooplankton community's structure and its spatial and temporal distribution at the Arabian Gulf and the Sea of Oman. Piontkovski et al. (2019); have studied the plankton community structures in both basins. They concluded that, during 2009-2011 diatoms contributed 70% of phytoplankton abundance followed by dinoflagellates by 21% in the Arabian Gulf. On the other hand, in the Sea of Oman small flagellates and diatoms contributed 10 and 25%, respectively. Zooplankton densities were found to be 10 times higher in the Sea of Oman compared to the Arabian Gulf, however, the Arabian Gulf zooplankton community was more diverse by 210 species compared to the 144 species identified in the Sea of Oman (ROPME, 2013). Copepods are the dominant species in both opposite side of Strait of Hormuz zooplankton communities, with seasonal peaks in winter and early summer seasons in the Arabian Gulf.

On the other hand, Chiba et al. (2008), mentioned that the distribution of plankton in the Arabian Gulf, and their productivity and availability depend on the monsoon winds. They added that, during the blowing of these winds, it brings a lot of organic and inorganic matter down the currents of the rivers which serving the Indian Ocean, where, during the months of January and February, there is a surge in the population of plankton in the Arabian Gulf and during the month of March, there is a fall in the numbers of plankton in the Arabian Gulf.

Such different opinions in confirming the relationship between plankton communities at the Arabian Gulf and the Sea of Oman ecosystems as well as the absence of simultaneous studies of both communities in relation to other biotic and abiotic parameters make it necessary to carry out the present study. This study aimed to investigate the plankton dynamics at the opposite sides of the Strait of Hormuz with the intension to identify their community structures and their interrelationships at different seasonal variations of the surrounding environmental parameters.

Chapter 2: Literature Review

Marine coastal areas are dynamic systems where great variability in abiotic and biotic processes exist, making difficult to standardize phytoplankton growth as well as its interactions with zooplankton densities and its distribution patterns. Zooplankton graze on phytoplankton and reduce their populations by about 75% (Zimmerman et al., 2019). Therefore, a strong relationship between phytoplankton and zooplankton are governing marine coastal productivity both spatially and temporally. For example, zooplankton groups include many taxa, which feed on phytoplankton. Selective grazing by zooplankton is an important factor that affect the structure of phytoplankton communities. However, phytoplankton structure also influences the taxonomic composition and dominance of the zooplankton (Gołdyn & Kowalczewska-Madura, 2008).

Although zooplankton grazing on phytoplankton and its nutrients regenerations are among the main factors influencing phytoplankton dynamics in any aquatic ecosystem, there are many other factors are playing vital roles in regulating their seasonal dominance, as well as their distribution pattern in the water column (Defriez et al., 2016). For instance, physical state of the water column stability, nutrient concentrations, and other parameters such as water temperature, water salinity, light penetration as well as hydrographic regime and wind trajectories are considered of major importance in planktonic interactions and distribution (Bilen & Vedaldi, 2017; Zimmerman et al., 2019).

The effect of physical and chemical parameters on phytoplankton and zooplankton have been studied since long time and still attract the interests of oceanographers and marine biologists (Harrison et al., 2017). Moreover, the frequent phenomenon of red tide observed during the last decades at different coastal areas and has referred mainly to different human activities becomes a topic of intensive research to understand its stimulating parameters. It has documented that diatoms and dinoflagellates are two major phytoplankton groups that play vital roles in ecosystem processes (Menden-Deuer & Lessard, 2000), yet they can form harmful blooms, particularly under eutrophic conditions at different seasons.

2.1 Factors Influencing the Dominance of Plankton

In reviewing literatures studies, the main factors influencing the structures and dominance phytoplankton and the role of zooplankton communities in controlling its blooms, here below those factors have individually reviewed:

2.1.1 Water Temperature

Water temperature has significant impact in determining the abundance of phytoplankton and zooplankton. Moreover, there is a relationship between water temperature and phytoplankton population growth. It has been found that, as water temperature increase by 10°C, the cell division is doubled. In fact, at temperate latitudes on spring, sunlight and rising temperatures will increase phytoplankton rapidly (Zimmerman et al., 2019). Differently, in their studies Chiba et al. (2008), have found that, there was a sharp increase in phytoplankton production in autumn following a gradual decline in summer. That was mainly due to the photo inhibition effect on the chlorophyll pigments efficiency in tolerating the high sun radiation during summer period.

In addition, it has been detected that, temperature affects the enzyme activities, where enzymes are protein substances that are used by both phytoplankton and zooplankton in their biochemical reactions. Low temperature ranges de-active the plankton activities, thus lowers the growth and multiplication of the plankton. Medium temperature enhances the comfortability and optimizes the diffusion of carbon dioxide, thus releasing enough oxygen as a by-product in its processes at phytoplankton (Smith et al., 2019).

In fact, variations in water temperature led to the seasonal variation in the abundance of phytoplankton and zooplankton. According to a study done by Musialik-Koszarowska et al. (2019), the availability and abundance of phytoplankton and zooplankton are greatly affecting by the temperature levels and food availability of a given place. More data collected by the researchers indicated that seasonality of zooplankton has a direct relation to the productivity of phytoplankton.

Recent data showed that increasing sea surface temperatures over the past century have caused a decline about 1% of the global phytoplankton. Numerical modelling showed also that temperature significantly affects phytoplankton metabolism under climatic changes by collected samples from both polar, temperate and tropical zones of the ocean. At higher temperatures phytoplankton look to require lower density of ribosomes to produce the required amounts of cellular protein (Toseland et al., 2013). In their research Nielsen (1986), have reported that *Skeletonema costatum* transferred from 20°C to 8°C, initially decreased the photosynthetic rate by a third, but when the cells were adapted to the low temperature, the rate at 8°C became practically the same as that at 20°C. In addition, Jørgensen (1968) had correlated this finding with the high cell-protein levels at low temperatures and suggested that algae adapt to suboptimal temperatures by increasing the concentration of enzymes.

2.1.2 Light

Light intensity is one of the environmental factors which determines the living of phytoplankton cells. Light used in photosynthesis, which is the food-making process of the plants like creatures (Morabito et al., 2018). Therefore, if the light intensity is high enough, there is suitable food for the phytoplankton growth, this led to a large amount of oxygen release as the byproduct which is used by zooplankton for the living (Smith et al., 2019). The low light intensity will lower the growth of the plankton since not enough food manufactured from the source which corresponding to the released amount of oxygen (Morabito et al., 2018).

In their study, at the largest northern Norwegian fjords during the winter where the darkness prevails for almost 2 months, and backscattered light comes from sky and clouds may influence the water column Eilertsen and Degerlund (2010) found that, extremely low phytoplankton biomass are obtained, and the concentration of chlorophyll were 0.05 – 0.10 µg L^{-1}.

On the other hand, experiments done in a South American wetland to investigate the influence of the light on structure of the microbial plankton community deficiency due to floating macrophytes, indicated that floating macrophytes on the water surface decrease the light penetration and decline of the photosynthetic activities, which by its time, decrease dissolved oxygen. Under these conditions, declining light penetration favored the replacement of obligate autotrophs by mixotrophic and heterotrophic organisms. Heterotrophic nanoflagellates and ciliates increased because of high food availability (picoplankton), and the lack of their predators (Sinistro et al., 2006). Moreover, Wynne & Rhee (1986), concluded in his study that changes in light intensity can strongly affect algal nutrient requirements, and species interrelationships by altering the optimum cellular N: P which changes in cell protein contents.

2.1.3 Water Salinity

Water salinity variations have found to affect the phytoplankton growth and influence the community structure as well as species abundances. In their study Sugie et al. (2020), have found that lower salinity concentration enhances the growth of small-sized phytoplankton or leads to decrease in fucoxanthin-containing algae and diatom diversity. Moreover, Yamaguchi et al. (1997) have found that the flagellate species *Heterocapsa circularisquama* grew faster at the higher temperatures (27.7 to 28.0°C) and salinities (32.6 to 32.83 Psu). While Kim et al. (2004), have found that the growth and cell division increase of a harmful dinoflagellate species was linked with the water salinity increase from 31.7 to 35.8 psu. Moreover, the growth of *C. polykrikoides* has found to depend on salinity and temperature, where maximum growth have observed at 25°C and 34 psu (Kim et al., 2004).

In a long-term study of quantitative and qualitative changes in the zooplankton community of the Vistula Lagoon to establish whether zooplankton abundance and biodiversity are affected by salinity levels variation. Samples for biological analyses were collected in the summer (June-September) of 2007-2011 at eleven sampling sites. Statistical analysis revealed a significant correlation between salinity levels and the number of species (r = -0.2020), abundance (r = 0.1967) and biomass (r = 0.3139) of zooplankton. No significant correlations were found between salinity and the biodiversity of zooplankton. The results of the study suggested also that salinity affects the abundance and structure, but not the diversity of zooplankton communities in the Vistula Lagoon **(**Paturej & Kruk, 2011)**.**

On the other hand, in 2014, Karlsson et al. (2018) investigated response of different populations of the copepod *Eurytemora affinis* from the Baltic Sea to varying temperatures and salinity conditions. They found that, low salinity has a detrimental effect on development time and low salinity have a negative effect on survival. Which mean that there is no single genotype that performs better in low salinity or high salinity; instead, the best development genotype in any given salinity is best in all salinities.

2.1.4 pH

Seawater pH in many coastal environments routinely varies by 1 pH unit from 7.5 to 8.5, which play a role in a seasonal succession of phytoplankton species. However, seawater pH limits the rate of primary production, growth, and total abundance of phytoplankton in blooms (Hinga, 2002). Phytoplankton communities were able to fix C only half as fast at about pH 9 compared to pH 8. This reduction may allow sinking and grazing to reduce the size of the population from which would have been obtained without a pH effect on C fixation. When the range of pH (extremely high or low) is outside the range can preclude the growth of some species. At extreme pH, species with a high tolerance will only grow and dominate the community (Hinga, 2002).

During 2007 -2008 water samples were collected from land in coastal harbour Sharbours in Denmark and Norway to study effect of lowered pH on marine phytoplankton growth rates. It has found that pH has direct effect on growth rate for the 2 species *Heterocapsa triquetra* and *Teleualax ampohioxeia*. The marine dinoflagellate *Alexandrium minutum* was able to grow at maximum rates even down to pH 5.5. Their results indicated that marine phytoplankton are well adapted to do so, even at lower limiting pH levels (Berge et al., 2010).

2.1.5 Nutrients

Nutrients concentration unevenly distributed in the oceans, which affects the abundance and composition of phytoplankton communities (Barcelos et al., 2017). Low-nutrient concentrations near the cell surface limit nutrient uptake, with consequences for growth rate and biomass yield (Moore et al., 2013). The phytoplankton growth limitation by nutrients such as phosphate and inorganic nitrogen affects the population dynamics of phytoplankton in aquatic environments and consequently the zooplankton ones.

Maddux and Jones (1964), showed that the optimum growth temperature for *Nitschia closterium* and *Tetraselmis sp.* were different in culture media with “low” and “high” levels of phosphate and nitrate. Moreover, Barcelos et al. (2017) have studied the phytoplankton community in North Atlantic Gyre and found that phytoplankton biomass and community composition depended on different nutrients. They added that, group-specific responses to single nutrient had observed. While, the addition of phosphate and trace metals, shifted the community to coccolithophore dominance, but diatom and dinoflagellate abundance occur in nitrate replenishment but not dramatically. Which dominated by diazothrophs, that shows the competitive advantage of nitrogen fixers under nutrient replenishment. Finally, the addition of all nutrients increased the biomass of all groups except coccolithophores.

2.1.6 Water Circulation

Water circulations affect the distribution and mix of biological populations as well as nutrients. Different speeds of water flow can influence and shift plankton dynamic. The large- flow speed led to disaggregation of species, which lead to increase the concentration of phytoplankton in the centre of eddies. It has also noticed that the concentration of phytoplankton affects the size of zooplankton. While, at mid-range flow speeds, the zooplankton last more in edge of eddies where the low phytoplankton densities. While at centre of eddies the concentration of phytoplankton increased (Woodward et al., 2019).

In a study of plankton communities in Arabian Gulf and Sea of Oman, Piontkovski et al. (2019) found that both phytoplankton and zooplankton are belonging to the same region, but they affected by different weather systems. Wind is one of the important factors that affects the biomass and productivity of phytoplankton inducing upwelling and downwelling. Moreover, wind also affect the surface water salinity as well as evaporation and precipitation. They added that, there is a strong correlation between chlorophyll concentrations, wind and water current movement on both Arabian Gulf and sea of Oman Previous studies have also found that chlorophyll concentrations in the Arabian Gulf begin to increase in August and reach a peak in December as a result of the upwelling of bottom water currents driven by the north- to north- westerly wind currents, or summer Shamal wind, from June through August. In the Sea of Oman and the northeastern Arabian Sea By contrast, chlorophyll concentrations begin to increase in December and reach their maximum in March, thanks to the increased outflow of nutrient-rich water from the Arabian Gulf to the Sea of Oman from December through February (Abuelgasim & Alhosani, 2014).

The data collected in Arabian Gulf and Sea of Oman about phytoplankton composition and distribution abundance and composition of phytoplankton in winter were related to water circulation pattern. Moreover, there is a strong correlation between water salinity and abundances of phytoplankton groups, which indicated the significant role of water masses circulation in governing phytoplankton composition (Polikarpov et al., 2016). According to the data collected between 2000 and 2013 from stations in Kuwait Bay and offshore southern location the increase in water salinity of about 6 units has affected plankton communities. Data also showed a decrease in the number of taxa and decrease in species diversity and significant changes in phytoplankton community due to increase in water salinity (Al Said et al., 2017).

In coastal water of Arabian Gulf “Saudi Arabia”, El Gammal et al. (2017), found that phytoplankton taxa Bacilirophyta and Dinophyceae have their maximum growth at pH 8. On the other hand, evaporation is one of the most important factors affecting water salinity of the Arabian Gulf. In Saudi Arabia coastal area research results showed the highest average values (40.5‰ – 59.1‰) during summer because of high temperatures and the lowest average values (37.4‰ – 55.3‰) during spring. The study has also concluded that, there was a positive relationship between water salinity variations and the population abundance of Dinophycea and Cyanophyceae (El Gammal et al., 2017). At the same study, El Gammal et al. (2017) indicated that, water temperatures in the Arabian Gulf were lower in winter (21.6°C) than summer (29.3°C) and they found that the ideal temperature for phytoplankton development in the Arabian Gulf is 30°C.

Chapter 3: Material and Methods

The Arabian Gulf is a shallow marginal sea and semi enclosed marine ecosystem located in the subtropical region of the Middle East between latitudes 24^{o} and 30^{o} N and longitudes 48^{o} and 57^{o} E (Abuelgasim & Alhosani, 2014). Its shallow sedimentary basin has an average depth of 36m and a total area of approximately 239, 000 km^{2} (Barzandeh et al., 2018). It connected to the Sea of Oman (21° 00' N and 57° 00' E) through the Strait of Hormuz (Figure 2), which allows water exchange between these two basins. The Arabian Gulf is affected mainly by extra-tropical weather systems from the northwest and subject to strong winds influence on the water circulation and mixing processes. While the Sea of Oman is located at the northern edge of the tropical weather systems of the Arabian Sea and the Indian Ocean that is strongly affected by the monsoon-related seasonal changes (Polikarpov et al., 2016).

The present study has conducted in two stages. The first stage was to study plankton community structures and its dynamics in Arabian Gulf and Sea of Oman. The second stage was to investigate the influence of different environmental parameters on seasonal variabilities on both phytoplankton and zooplankton densities and compositions in the two studied areas.

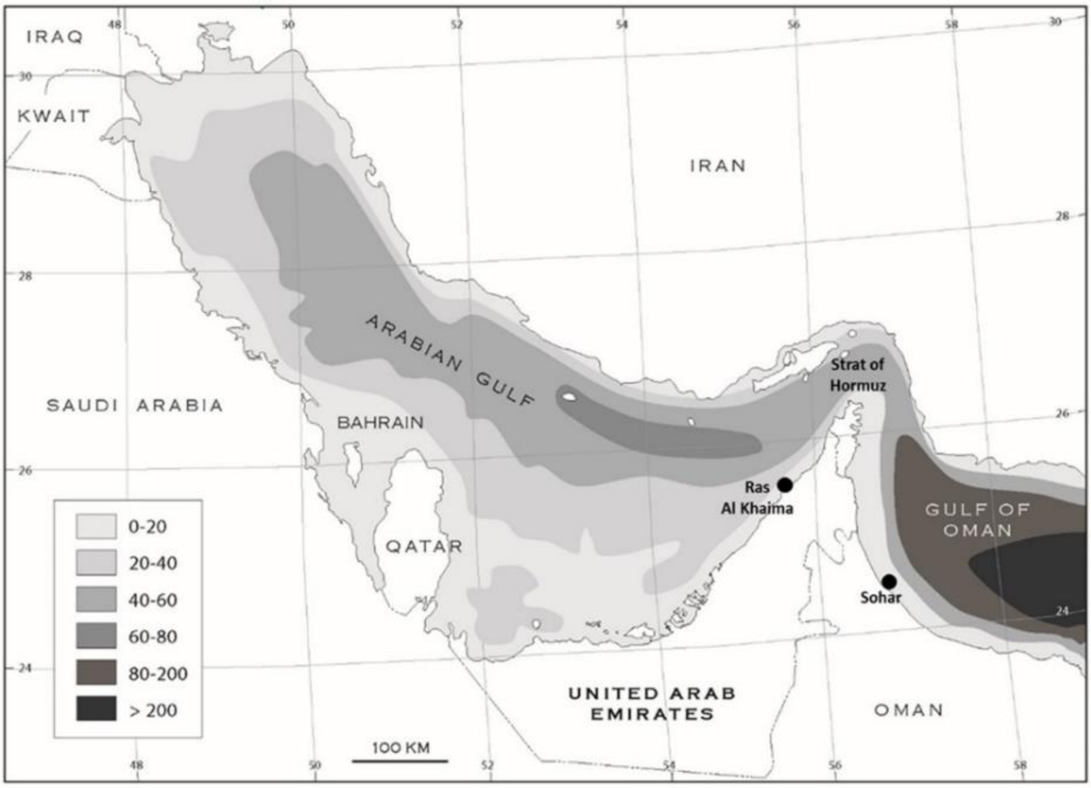


Figure 2: Map of sampled stations (●) in Arabian Gulf and Sea of Oman. (Modified from Hamza et al., 2020).

3.1 Field Study and Analysis

Both water and plankton samples were collected from two different fixed stations, one at each side. Arabian Gulf samples were collected from UAE coastal area of Ras Al Khaimah Emirate (56.82° E, 25.22° N). At the opposite side, samples were collected from coastal water of Sohar governorate (24.35° N and 56.71 °E) at the Sea of Oman (Table 1). The Arabian Gulf is a shallow semi enclosed marginal subtropical sea surrounded by a large, arid land mass, having a water surface area of 239.00 km² and mean depth of about 36 m, with a maximum depth of 100 m at the Strait of Hormuz (Taher et al., 2012). However, the Sea of Oman is situated in the subtropical zone and has the total water surface area 181,000 km^2 and maximum depth 3,700 m (Piontkovski et al., 2013).

3.2 Data Collection

Both water and plankton samples were collected from two different fixed stations, one at each side. Arabian Gulf samples were collected from UAE coastal area of Ras Al Khaimah Emirate (56.82°E, 25.22°N). At the opposite side, samples were collected from coastal water of Sohar governorate (24.35° N and l 56.71 °E) at the Sea of Oman (Table 1). The Arabian Gulf is a shallow semi enclosed marginal subtropical sea surrounded by a large, arid land mass, having a water surface area of 239.00 km^2 and mean depth of about 35 m, with a maximum depth of 100 m at the Strait of Hormuz (Taher et al., 2012). However, the Sea of Oman is situated in the subtropical zone and has the total water surface area 340 km (210 mi) and maximum depth 3,700 m (Piontkovski et al., 2019).

Table 1: Sampling sites and its geographic positions at both Arabian Gulf and Sea of Oman.

Station Name	Latitude	Longitude
Ras Al Khaimah	56.82°E	25.22°N
Sohar	24.35° N	56.71°E

3.3 Environmental Parameters

Analyses of environmental parameters (water temperature, water salinity, water pH, dissolved oxygen) at both sampling stations have measured in situ during the collection of plankton samples using plankton nets and water samples using the Multi-sensor

(Aqua Read- 700). Nutrients salts concentrations (Nitrate NO_3, Ammonia NH_3 and phosphate PO_4) at the collected water samples were analyzed at the designated laboratories of both UAEU and Sultan Qaboos Universities. Auto analyzer instrument has been used to analyses the main nutrient salts (Nitrate (NO_3), Ammonia (NH_3) and Phosphate (PO_4), following the methodologies mentioned by Strickland and Parsons (1972) and can be summarized as follows:

3.3.1 Automated Nutrient Analysis

Nutrients are determined through modification of the sensitive spectrophotometric methods. This happens only though when seawater analysis has done in conventional method where reagents are added to the chosen sample in relative amounts and correct order. In order to determine the times needed to complete the chemical reactions have achieved by passing solutions through coils of glass tubing of different lengths. In case the total length of small-bore glass tubing is very long, it needs the apparatus to inject small air bubbles into the system to avoid the record for bad tailing. On the other hand, the Technical Instruments Corporation is primarily involved in the success of this particular approach, where it is also responsible for the introduction of this automatic analysis of micronutrients in seawater. Through the suitable chemistry, it can obtain colored solutions, which pumped through colorimeters similar in principle when spectrophotometric analysis is used. With the use of incandescent lamps and interference filters, it provides light of the most suitable wavelength. Finally, a pen recorder measures the transmission of a solution, which is about 100% for a blank down to about 10% for samples. Also, nutrients concentration has evaluated after an accurate standardization (Figure 3).

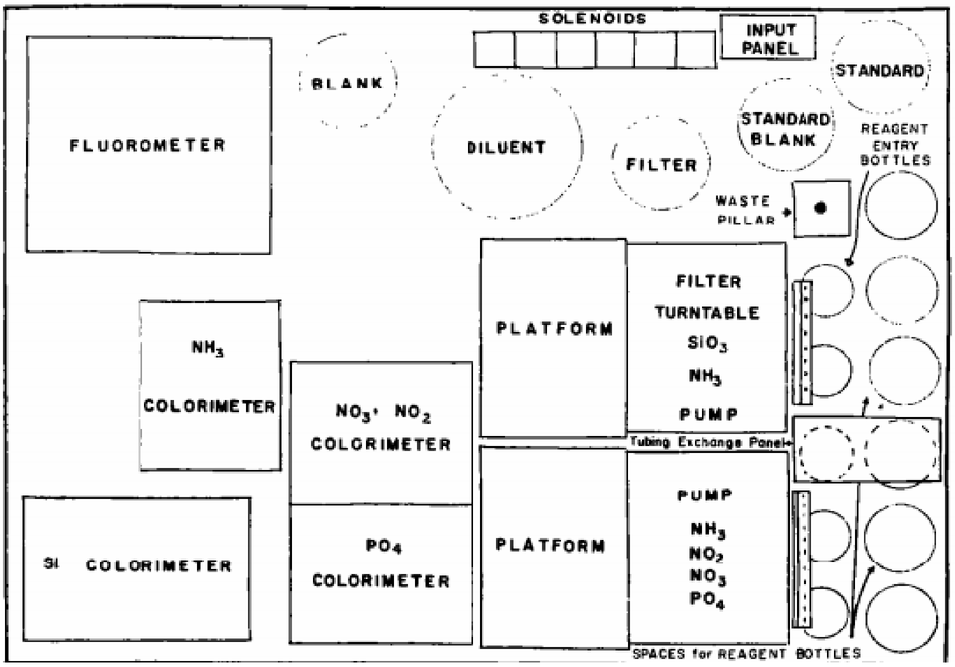


Figure 3: The layout of the apparatus for nutrient analysis.

Firstly, procedure A which uses for measuring the concentration of nutrients in surface waters when the ship is underway. Secondly, procedure B which used when with a profiling hose to obtain the profiles of nutrients reaching 100 - 200 m. Finally, procedures C which use when water samples are to be analyzed from hydro-casts and it utilizes a special turntable of sample tubes.

3.3.1.1 Nitrate Method

The laboratory analyses depend on procedure C (Range of 0.6-40 µg-at N/liter). The reagents used in Nitrate method are: Cadmium, Copper Sulphate Stock Solution, Ammonium Chloride Stock Solution, dilute Ammonium Stock Solution, Sulphanilamide Solution, and Ethylenediamine dihydrochloride solution.

3.3.1.2 Ammonia Method

Ammonia method is used by following procedure C with a Range of 0.2-3.5 µg-at N/liter is considered.

Ammonia method uses the following reagents such as: Alkaline Citrate Solution, Sodium Arsenite, Acidifying Solution, Sodium Bromide, oxidizing reagent Ethylenediamine dihydrochloride solution, prepared as in the Nitrate method.

3.3.1.3 Phosphate Method

The Phosphate method is one of the nutrients seawater analysis has very low concentrations, where with Procedure C a Range of 0.05-3.5 µg-at P/liter, (R=2 or 4) is considered. The reagents which used for this method includes: Molybdate Solution, Stock and Reduction Reagent.

3.3.1.4 Phytoplankton Analyses

Phytoplankton quantitative samples were biweekly collected from the sampling locations at both sides of the Strait of Hormuz (Ras Al Khaimah (UAE) and Sohar (SOH)) quantitative sampling of phytoplankton was carried out using plankton nets with 20 µm mesh size from a depth of 6 meters up to surface at Ras Al Khaimah station. However, due to depth differences between the Arabian Gulf and the Sea of Oman as well as the extension of euphotic zone plankton samples in Sohar governorate (Sea of Oman) samples were collected from depth 20 m up to the sea surface. Where about 350 liters of water collected by Nisken water sampler, from the water column between the surface and net sampling depth (Integrated water sample) were filtered through a plankton net of 20 µm mesh size. Then, transferred it to sterilized bottles and preserved with Lughole’s iodine solution. Later, in laboratory, identification and counting of samples collected from both sides, have carried out using inverted microscope (1X50 Olympus) and compound microscopes (model SZ-X7), with mounted camera. Where, 1 ml of a well-shacked and mixed sample pipetted into the counting cell (1 ml) the Sedgwick Rafter. For each sample, the counting and identification have repeated 3 times with new subsamples. The average number was estimated and referred to one unit volume i.e. 1 liter and/or 1 m^3. Phytoplankton samples were analyzed for their species abundance, densities, and species composition. Species taxonomy was confirmed through the collaboration with M.G. Kholodny Institute of Botany, Ukraine; where subsamples have sent for counting and taxonomy confirmation by the phytoplankton taxonomy expert Yulia Bryantseva. All number have referred to a volume unit of one cubic meter.

3.3.1.5 Zooplankton Analyses

At the same time, zooplankton samples were collected also twice a month from both sampling stations and following the same procedure as well as the same depth from which phytoplankton samples were collected. Zooplankton samples collected by using plankton nets with 80 μm mesh size. While preservation occurred in 10% neutralized formalin. An Olympus binocular microscope (model SZ-X7), with mounted Camera was used to identify, enumerate, and measure zooplankton specimens. The species taxonomy has confirmed through collaboration and assistance of the Institute of Biology of the Southern Seas, Russia; by sending subsamples for counting and taxonomy confirmation by the zooplankton taxonomy expert Elena Popova. All counting has referred to a volume unit of one cubic meter.

Both phytoplankton and zooplankton species-specific identification carried out to the possible taxonomic ranks, using both local, regional and international taxonomic guides such as: 1- guide to common marine phytoplankton in Abu Dhabi waters, marine phytoplankton atlas of Kuwait's waters and marine zooplankton practical guide (Al-Yamani et al., 2011a, 2011b).

3.3.1.6 Remotely Sensed Data

During the study period, satellite images (4-km spatial resolution MODIS-Aqua) of monthly Level-3 products for chlorophyll concentration ($mg.l^{-1}$), were produced at the surface water of studied areas. Monthly time series of chlorophyll-a and wind stress over the studied area were assembled using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) software developed at NASA's Goddard Earth Sciences Data and Information Services Center and shared information has obtained from the GIS center at Sultan Qaboos University. The data analysis has considered; wind speed and directions characteristics and transformed into the wind stress magnitude which is the amount of force influencing the sea surface. The wind stress depends upon wind velocity, drag coefficient and air density. It has units of Newton's per square meter. Data of the speed and the direction of the wind were also retrieved from: (1) Aquarius Official Release Level 3 Wind Speed Standard Mapped Image 7-Day Running Mean Data V5.0, (2) the Live Access Server database which provides visualization and sub setting of multi-dimensional data worldwide (Hankin et al.,1998), and (3) Maps of wind speed at 10 meters based on Cross-Calibrated Multi-Platform Ocean Surface Wind Vector L3.5A Pentad First-Look Analyses as described by (GIS center at Sultan Qaboos University). In the present study, only few of assimilated graphs of wind stress as well as chlorophyll concentrations have been utilized to explain seasonal sea conditions variation during different periods of the study.

3.4 Statistical Analyses

Data has been analyzed by R- Software (Ross Ihaka and Robert Gentleman, latest version August 2021) to illustrate the statistical analyses between the plankton community and environmental parameters (Temperature, salinity, pH and dissolved oxygen). The study involved multiple statistical methods, such as; correlation analyses and Principal Component Analyses (PCA).

1. Correlation which refers to the statistical relationship between two entities. In other words, it's how two variables move in relation to one another. In the present study, correlation coefficient between all environmental parameters as well as both phytoplankton and zooplankton biomass.
2. PCA (Principal Component Analyses) a statistical procedure that allows to summarize the information content in large data tables by means of a smaller set of “summary indices” that can be more easily visualized and analyzed. In the present study, PCA between all environmental parameters and both phytoplankton and zooplankton biomass have processed.

Chapter 4: Results

4.1 Water Quality Parameter

Monthly average values of water quality parameter at both RAK and SOH stations during the monthly sampling period 2018-2019 are shown in (Table 2). In RAK station, the highest water temperature average between the highest of 34.80°C in August 2018 and the lowest of 21.77°C in March 2019. Water salinity average between the highest of 41.88 ppt in July 2018 and the lowest of 36.70 ppt in August 2018. However, dissolved oxygen average between the highest of 6.69 $mg.1^{-1}$ in March 2019 and the lowest of 4.93 $mg.1^{-1}$ in October 2018. While pH average between the highest of 8.80 in December 2018 and the lowest of 7.37 in March 2019. On the other side, temperature at SOH station average between the highest of 29.10°C in October 2018 and the lowest of 23.40°C in February 2019. While salinity average between the highest of 36.82 ppt in October 2018 and the lowest of 36.00 ppt in August 2018. Dissolved oxygen average between the highest of 10.84 in May 2019 $mg.1^{-1}$ and the lowest of 5.12 $mg.1^{-1}$ November 2018. Finally, pH average between the highest of 8.6 in March -April 2018 and the lowest of 8.0 of August 2018.

Table 2: Monthly Average values of water quality parameter at both stations (RAK and SOH during study period 2018-2019.

	RAK station				SOH station			
Parameters	**Temperature °C**	**Salinity ppt**	**Dissolved oxygen mg.1^{-1}**	**pH**	**Temperature °C**	**Salinity ppt**	**Dissolved oxygen mg.1^{-1}**	**pH**
Apr.2018	28.82	40.05	6.21	-	-	-	-	-
May.2018	-	-		-	-	-	-	-
Jun.2018	32.63	40.62	5.60	8.18	28.70	36.73	5.05	-
Jul.2018	30.05	41.88	5.77	8.19	26.21	36.53	8.47	-
Aug.2018	34.80	36.70	5.20	8.21	26.46	36.00	5.17	8.0
Sep.2018	33.72	37.58	5.33	8.27	-	-	-	
Oct.2018	31.50	38.06	4.93	8.20	29.10	36.82	5.87	8.1
Nov.2018	28.23	38.93	5.48	7.97	26.50	36.65	5.12	8.3
Dec.2018	24.57	40.51	6.07	8.80	25.85	36.80	5.38	8.1
Jan.2019	23.14	40.43	6.20	7.54	24.05	36.58	6.99	8.1
Feb.2019	22.23	40.23	6.65	7.45	23.40	36.68	5.40	8.3
Mar.2019	21.77	40.24	6.69	7.37	27.24	36.63	5.76	8.6
Apr.2019	24.23	40.68	6.57	7.39	27.24	36.61	8.87	8.6
May.2019	26.11	41.51	6.01	7.48	27.75	36.53	10.84	8.5

As shown in Figure (4 A-B) relationships between all environmental parameters during the sampled period 2018-2019 at both RAK and SOH stations, pH and dissolved oxygen were almost stable. However, oscillations in both temperature and salinity average values are observed.

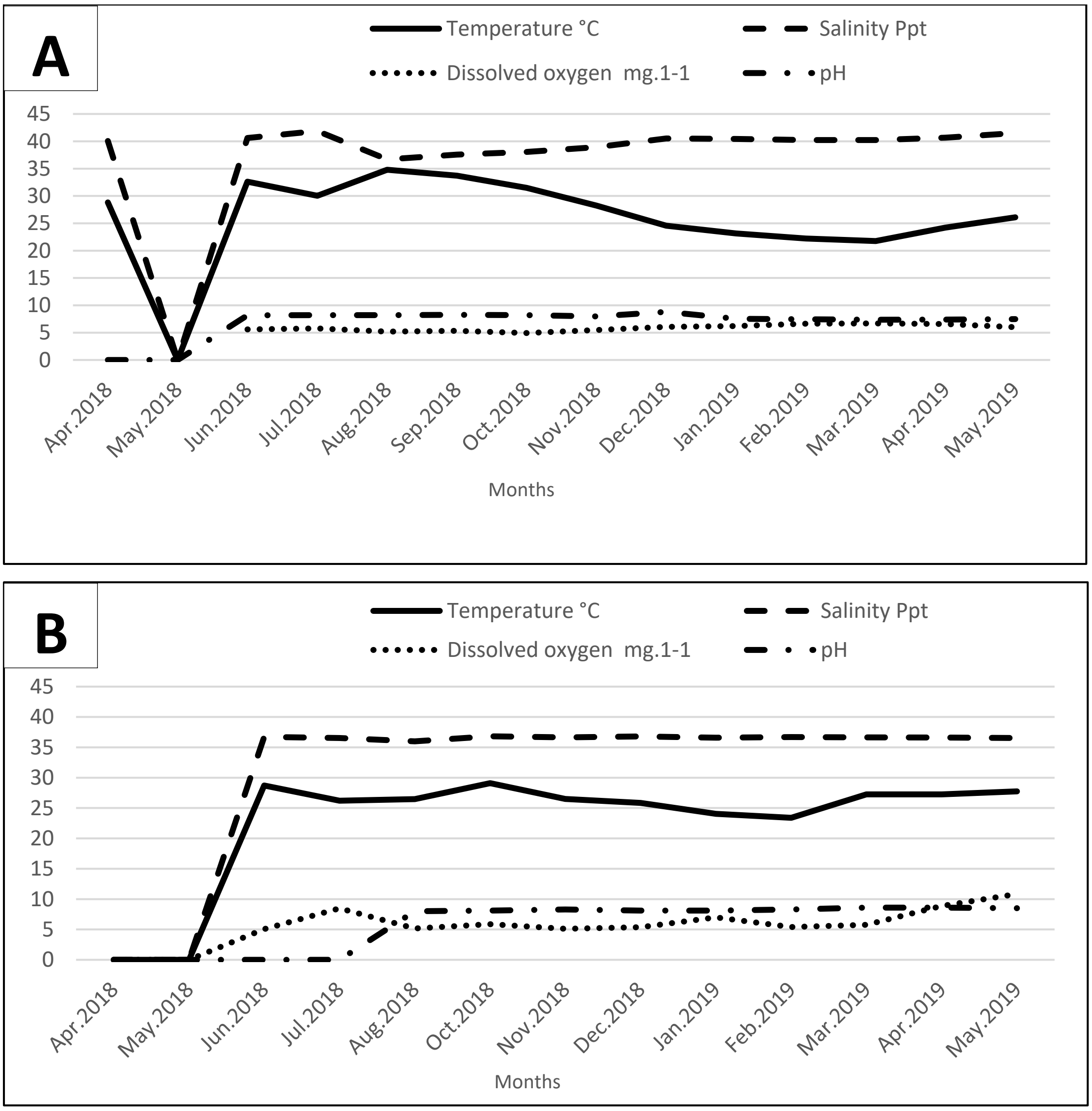


Figure 4: Environmental parameters (temperature, salinity, dissolved oxygen, and pH) at both RAK and SOH stations during the sampled period 2018-2019. (A) RAK, (B) SOH.

Monthly average of nutrients concentration at both RAK and SOH stations during the sampled period 2018-2019 are shown in Table 3. In RAK the average concentration of Nitrate NO_3 ranged between the highest of 0.3 um/l in August 2018 and the lowest of 0.1 um/l in May 2018. While Ammonia NH_3 average concentration ranged between the highest of 15 um/l in May 2019 and the lowest of 1.0 um/l in October 2018. Finally, phosphate average concentration ranged between the highest of 0.01 um/l in July 2018 and the lowest of 0. 6 um/l in September 2018. On the other hand, in SOH station Nitrate NO_3, average concentration between the highest of 4.2 um/l in February 2019 and the lowest of 1.2 um/l April 2019. While Ammonia NH_3 average concentration between the highest of 11.2 um/l in January 2019 to and lowest of 1.6 um/l in May 2019. On the other hand, phosphate average concentration between the highest of 0.5 um/l in May 2019 to the lowest of 1.3 um/l in June 2018. Some water samples were not collected at certain months due to the rough sea conditions.

Table 3: Monthly average values of nutrient salts (um/l) at both stations (RAK and SOH) during study period 2018-2019.

RAK station				**SOH station**		
Month	**Nitrate NO3**	**Ammonia NH3**	**Phosphate PO4**	**Nitrate NO3**	**Ammonia NH3**	**Phosphate PO4**
Apr.18	0.10	-	0.0012	-	-	-
May.18	0.1	-	-	-	-	-
Jun.18	0.12	2.0	0.0011	2.7	5.1	1.3
Jul.18	0.5	2.0	0.0110	-	-	-
Aug.18	0.3	3.0	0.0008	3.2	1.8	1.1
Sep.18	0.10	2.0	0.0006			
Oct.18	0.1	1.0	0.0008	1.4	5.0	0.7
Nov.18	0.3	3.0	0.0008	-	-	-
Dec.18	0.3	5.0	-	-	-	-
Jan.19	0.1	3.0	-	4.0	11.2	0.6
Feb.19	0.10	3.5	-	4.2	2.1	0.7
Mar.19	0.10	2.0	-	1.4	3.1	0.6
Apr.19	0.10	10.0	-	1.2	3.0	0.6
May.19	0.1	15.0	-	2.4	1.6	0.5

4.2 Chlorophyll-a

Chlorophyll-a concentration ($mg.l^{-1}$) has been estimated by using remote sensing data during the sampled period 2018-2019 in SOH station. While it was directly measured in situ at RAK station (Table 4). In RAK station chlorophyll –a surface average concentration ranged between the highest value of 6.61 $mg.l^{-1}$and the lowest value of 0.10 $mg.l^{-1}$in June 2018 and January 2019. However, in SOH station chlorophyll - a average concentration ranged between the highest value of 6.97 $mg.l^{-1}$ and the lowest value of 1.77 $mg.l^{-1}$ in January 2019.

Table 4: Monthly average values of chlorophyll-a ($mg.l^{-1}$) at both stations (RAK and SOH) during study period 2018-2019.

Months – location	**RAK Chl ($mg.l^{-1}$)**	**SOH Chl ($mg.l^{-1}$)**
April.2018	0.28	-
May.2018	-	-
June.2018	6.61	-
July.2018	0.75	-
Aug.2018	0.44	2.11
Sep.2018	0.57	-
Oct.2018	0.13	2.02
Nov.2018	0.18	3.47
Dec.2018	1.11	5.08
Jan.2019	0.10	6.97
Feb.2019	0.37	4.82
Mar.2019	1.71	1.77
Apr.2019	2.37	1.87
May.2019	6.56	3.71

As shown in Figure 5, chlorophyll-a concentration ($mg.l^{-1}$) at both stations (RAK and SOH) during the study period 2018-2019 are different. During the period from October 2018 until February 2019 SOH station recorded high chlorophyll a, concentrations compared to RAK station. In January 2019, chlorophyll a concentration at SOH station was > 6 times higher than at RAK station. An increase in both stations with parallel trend has recorded during the period from March 2019 until May 2019, with high concentrations at SOH station (Figure 5). In general, chlorophyll-a average concentrations in SOH station showed double values compared RAK station during the study period.

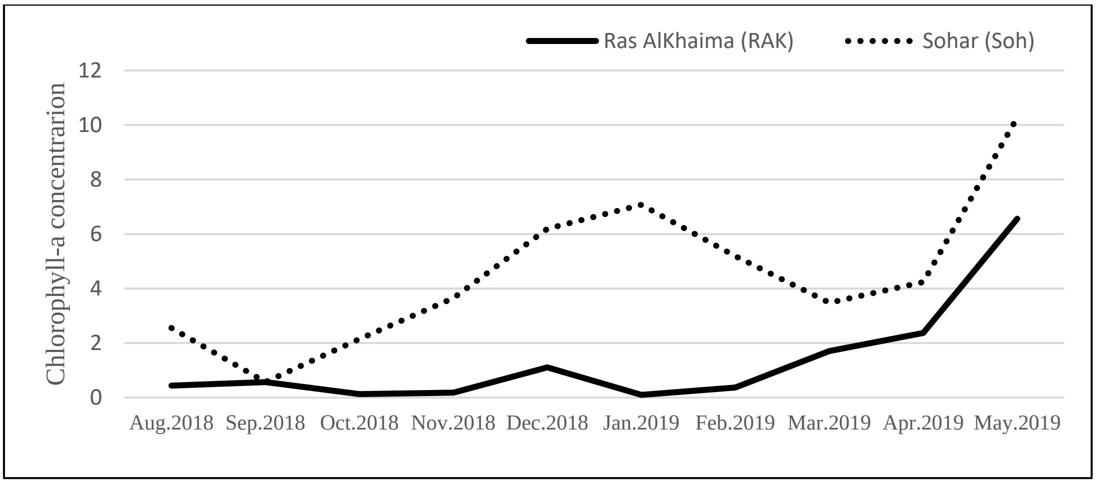


Figure 5: Chlorophyll-a ($mg.l^{-1}$) concentration at both stations during study period 2018-2019.

Chlorophyll-a concentration at both sides of the Strait of Hormuz (Figure 6) has been taken during the study period from October 2018 –May 2019.

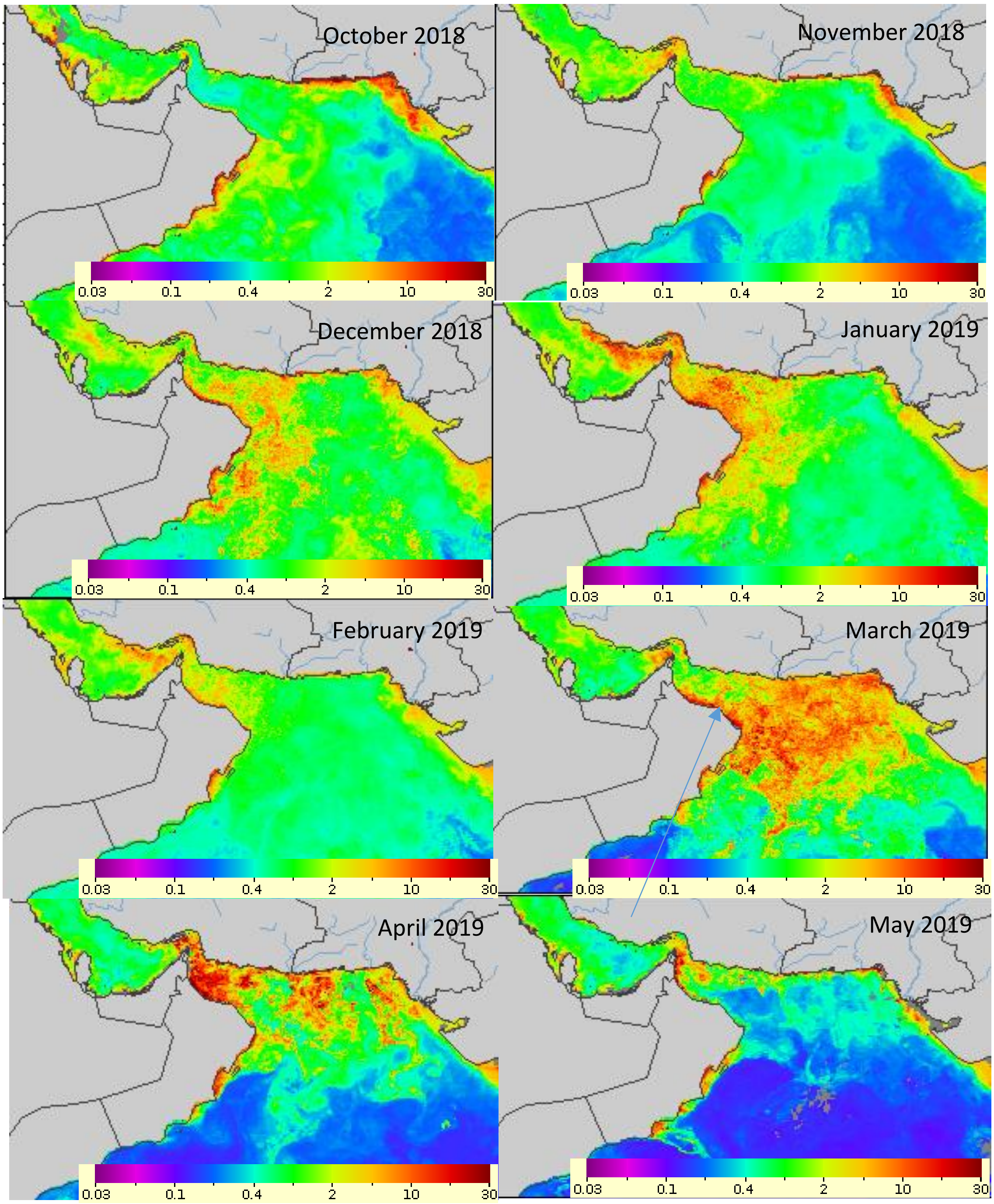


Figure 6: Chlorophyll-a (mg.l^{-1}) concentration at both sides of the Strait of Hormuz form October 2018 to May 2019.

4.3 Wind

Wind direction during the study period at both sides of the Strait of Hormuz (Figure 7), was directly perpendicular on both water basin during January 2019. However, wind direction in April 2018 was from Arabian Gulf to Sea of Oman through the Strait of Hormuz. In August 2018, opposite wind direction was prevailed.

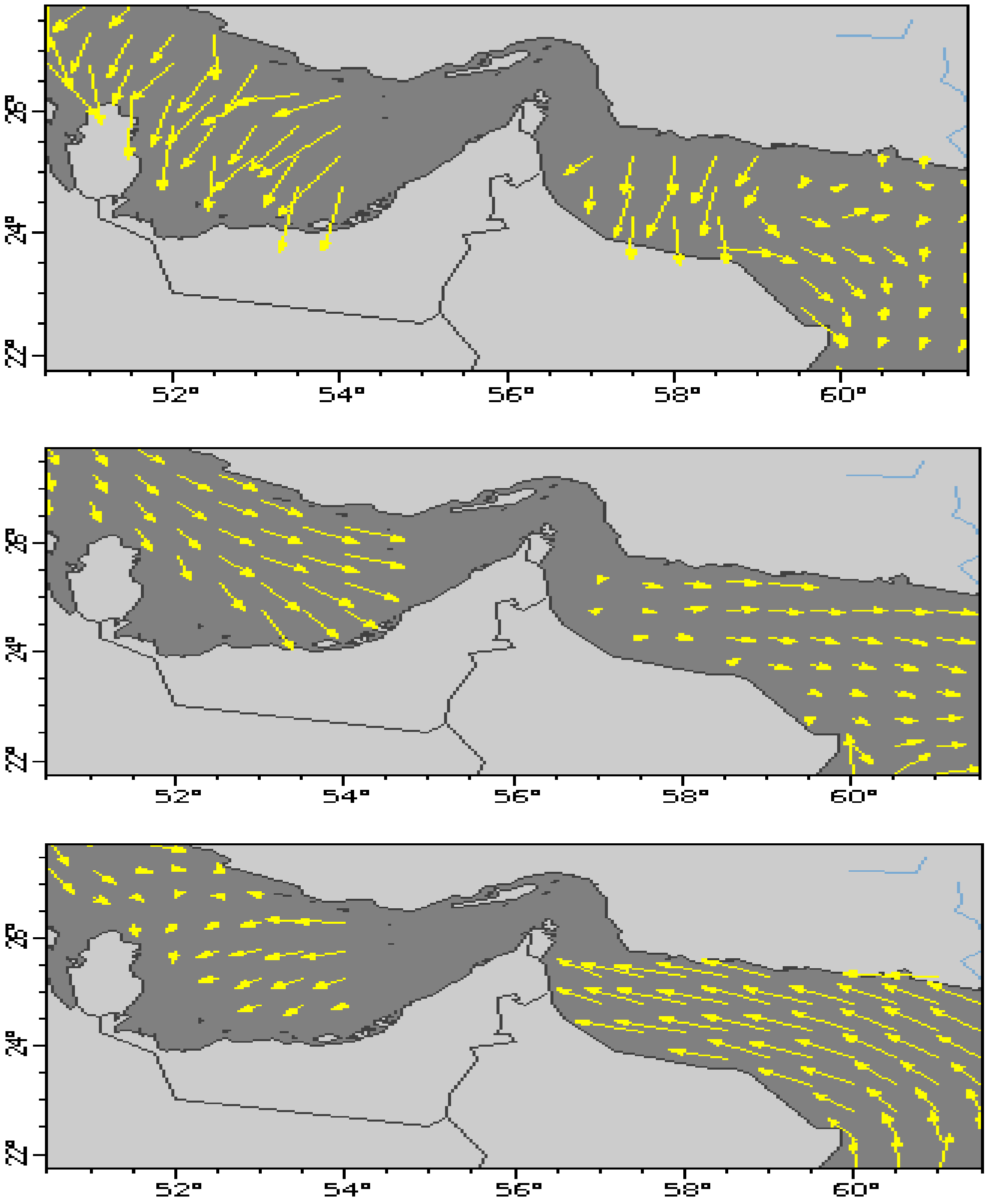


Figure 7: Wind direction over the regions during the study period 2018-2019 for the months January 2019, April 2018 and August 2018. January 2019 (Top), April 2018 (Middle) and August 2018 (Down).

4.4 Plankton

4.4.1 Phytoplankton Analysis

During the study period, there were significant differences in phytoplankton communities at the two studied stations (RAK and SOH; - Appendix – I).

At RAK station, phytoplankton community was mainly composed of three main groups (i.e. Bacillariophyceae; Dinophyceae and other small percentages of cyanobacteria and Chlorophyceae). Phytoplankton biomass average values ranged between the highest value of 277. 73 $mg.m^3$ in March 2019 and it was dominated by *Guinardia flaccida* species and the lowest value of about 1.66 $mg.m^3$ in July 2018 by the dominated species *Paralia sulcate* (Figure 8 A). Bacillariophyceae group average percentage ranged between the highest of 99.47% in November 2018 and the lowest of 37.84% in June 2018. While, for Dinophyceae group average percentage ranged between the highest value of 17.99% in October 2018 and the lowest of 0% in February 2019. Moreover; cyanobacteria and chlorphyceae average percentage ranged between the highest value of 59.89% in June 2018 and the lowest value of 0% in August -September 2018 and February 2019 (Figure 9 A). However, phytoplankton average species number ranged between the highest of 62 species in November 2018 and the lowest of was 24 species in April 2018 (Figure 10 A).

On the other hand, in SOH station Bacillariophyceae group average percentage ranged between the highest value of 82.26% in February 2019 and the lowest value of 0% in April 2019. While, Dinophyceae average percentage ranged between the highest value of 8.62% in November 2018 and the lowest value of 0.18% in August 2018 (Figure 9 B). The average number of phytoplankton species ranged from the highest of 43 species in November and December 2018 to the lowest of 3 species in March 2019 (Figure 10

B). While the, phytoplankton community biomass averaged between the highest value of 13,339.85 mg.m^{-3} in May 2019 that was dominated by *Coscinodiscus wailesii* species and the lowest value of 4.66 mg.m^{-3} in April 2019 by *Flagellata sp.* species (Figure 11 B).

Although some samples were missed but in general phytoplankton biomass in RAK is considered much less (≈10%) in values when it is compared to values at SOH station.

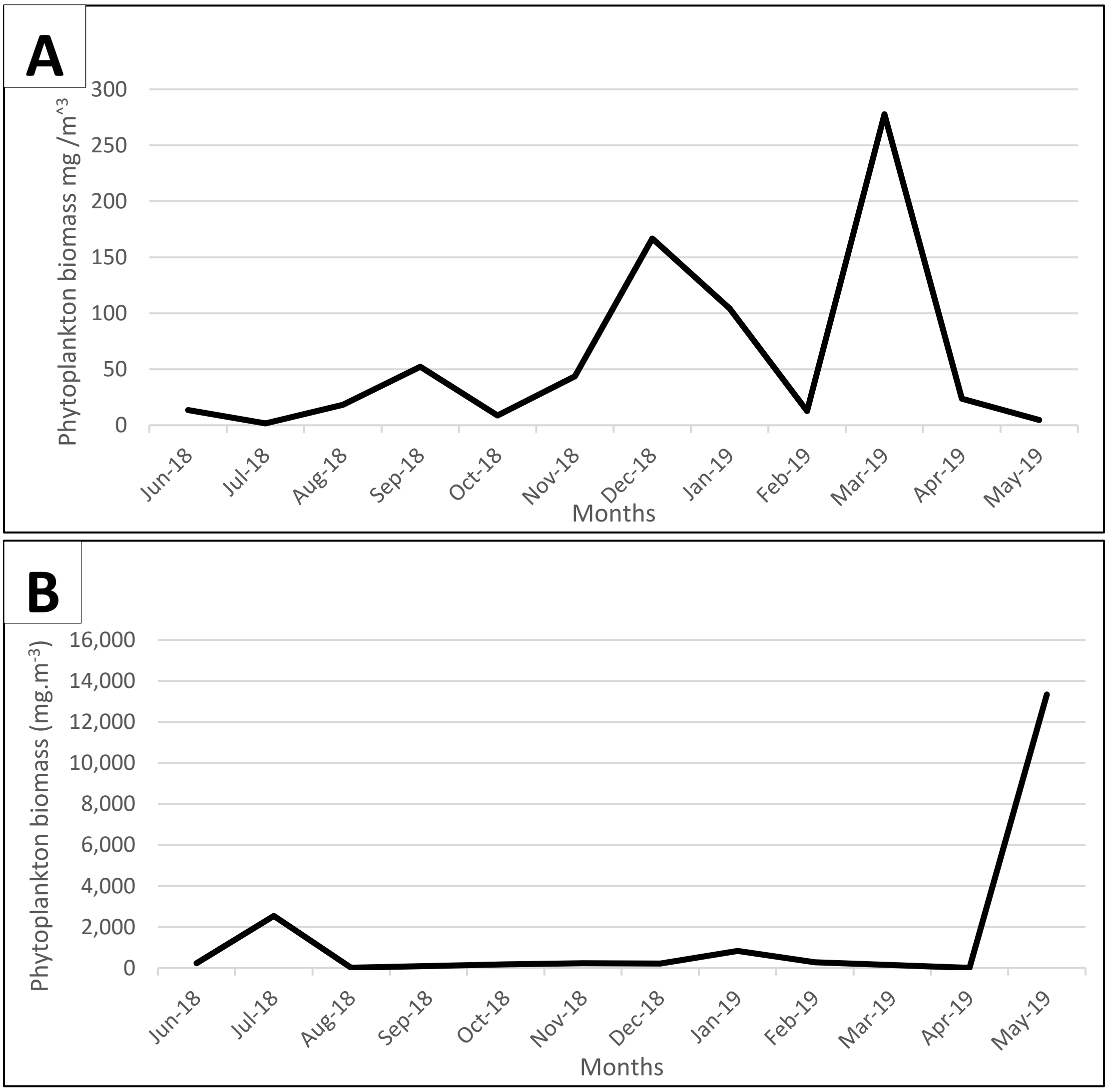


Figure 8: Phytoplankton biomass during the study period at both station. RAK (A), SOH (B).

At RAK station (Figure 9 A), Bacillariophyta (Bac.) group has generally dominated phytoplankton which represented about 90% of phytoplankton community structure during the study period. It followed by Dinoflagellate (Dino) 11-17%. Other groups such as chlorophyte and cyanobacteria almost neglected except in June 2018 where, it reach 5%.

Bacillariophyta exhibited multiple peaks during the sampling period. A peak was recorded in November 2018 with 99.47% of the phytoplankton community, which dominated by *Plagiotropis lepidoptera* species. That was followed by another peak in April 2019 with 99.14% that dominated by *Guinardia flaccida* species. However, a lower peak of Bacillariophyta was recorded in June 2018 - about 37.84% by *Pseudo-nitzschia caliantha* species. While, the highest peak of Dinoflagellate has recorded in October 2018 with 17.99% that has dominated by *Dinophyceae sp. 2* species.

At SOH station, the community structure was composed of different groups such as Bacillariophyceae, Cyanobacteria and Chlorophyta that represented more than 50% of the community structure during the whole study period (Figure 9 B). Dinoflagellates has only represented 30%. Other groups represented low abundance which in total were is less than 20%.

Bacillariophyta (Bac.) group abundance high peak has occurred in February 2019 with about 82% of the phytoplankton community and it was dominated by *Guinardia striata* species. Another peak more than 60% occurred in June 2018 that was dominated by the *Guinardia striata* species.

However, Dinoflagellates group was dominated in November 2018 with 8.62% and it was dominated by *Heterocapsa pygmaea* species. However, lowest peck of dinoflagellate abundance was in July 2018 that reached about 2% by *Bacteriastrum* species (Figure 9 B).

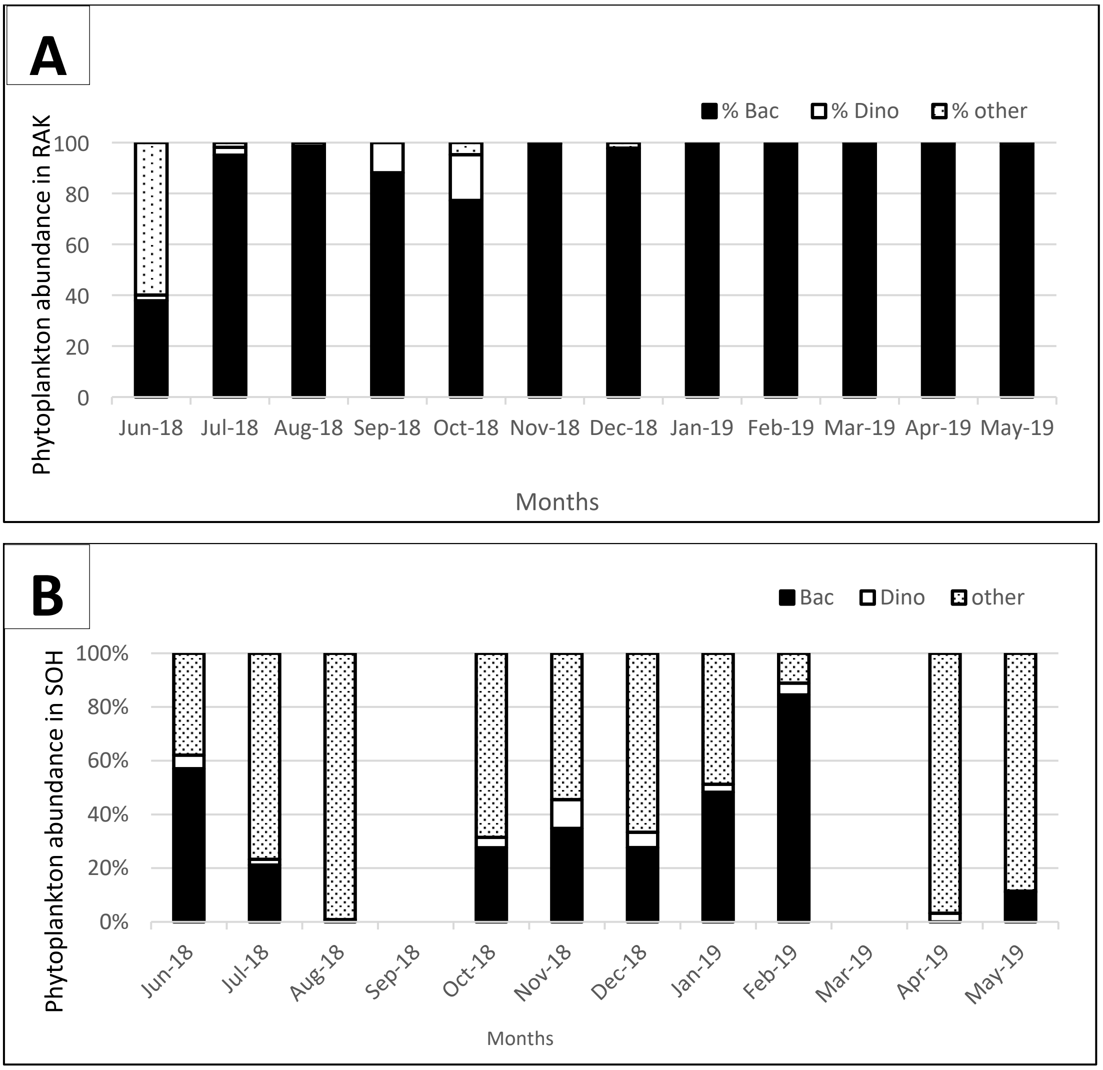


Figure 9: Monthly averages of phytoplankton abundance % at both sampled stations during the study period 2018-2019. RAK (A), SOH (B).

Along the study period, the whole Phytoplankton species number in RAK station were higher than at SOH station (Figure 10 A-B). That records 1151 of identified species in RAK station while at SOH station only 192 species were identified. All over the study period Bacillariophyta was dominant in RAK station. However, at SOH station the dominants species was mainly shared between Bacillariophyceae and Dinophyceae.

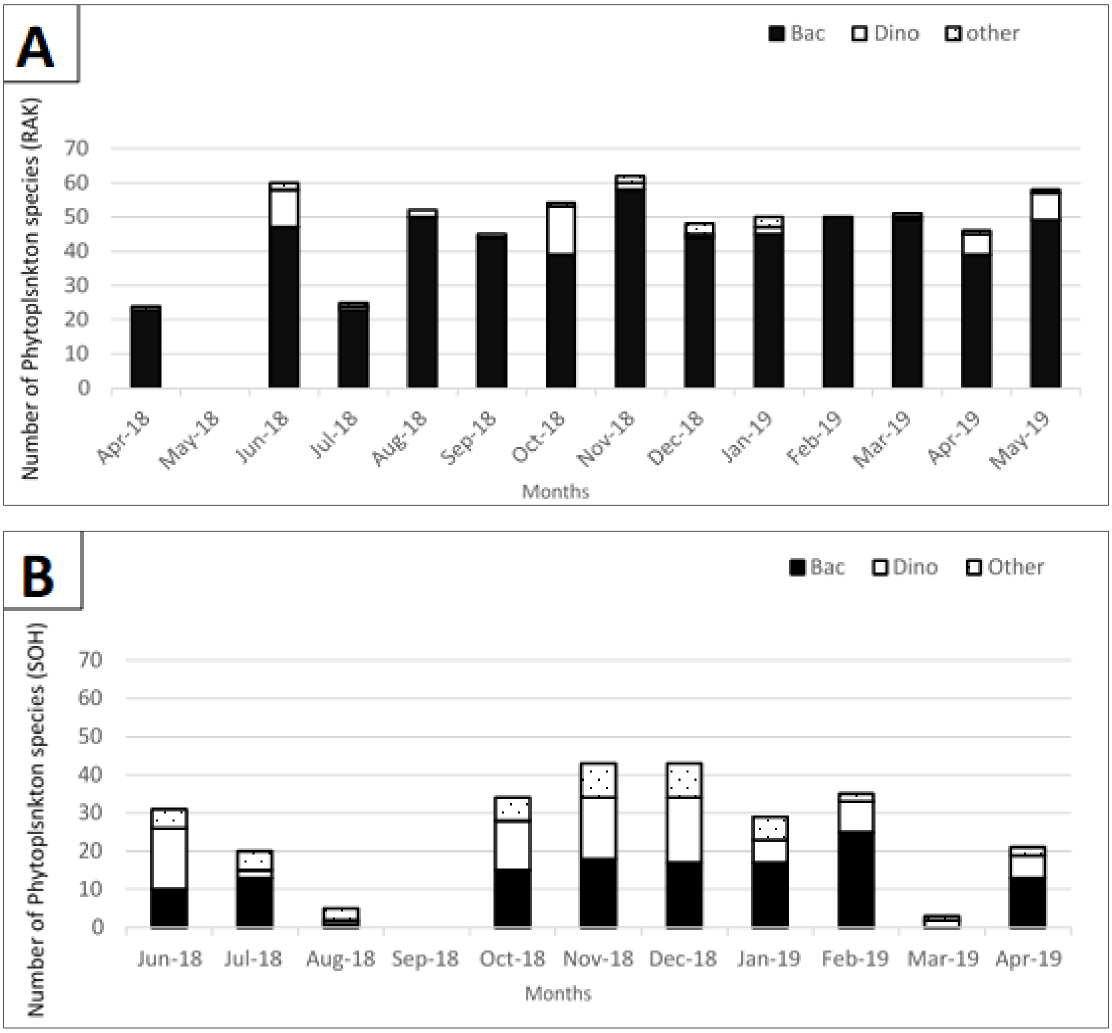


Figure 10: Monthly averages of phytoplankton species numbers identified in both stations during the monthly sampling period 2018-2019. RAK (A) and SOH (B).

4.4.2 Zooplankton Analysis

In both RAK and SOH stations, zooplankton identified groups were belonged to Calanoids, Cyclopoids and Harpacticoids over the sampling period 2018-2019 (RAK and SOH; - Appendix – II).

In RAK stations, zooplankton density average ranged between the highest value of 1101 ind. /m^3 in January 2019 and the lowest value of 7.44 ind. /m^3 in February 2019 (Figure

11 A). While zooplankton average number of species ranged between the highest of 33 species in January 2019 and the lowest of 15 species in September 2018 (Figure 13).

On the other hand, average zooplankton density in SOH ranged between the highest of 4842.15 ind. /m^3 in July 2018 and the lowest of 8.19 ind /m^3 in October 2018. While, zooplankton species number ranged between the highest of 97 species in November 2018 and the lowest of 6 species in March 2019 (Figure 11 B).

Figure (11 A-B) shows the zooplankton density (Ind.$m^{-3}*10^3$), during the study period 2018-2019 in both RAK&SOH stations. Zooplankton density in RAK station, has performed variations in its concentrations from 87.30 Ind.$m^{-3}*10^3$ in June 2018 up to 54.93 Ind.$m^{-3}*10^3$ in October 2018. However, maximum density was recorded in January 2019 to 1101.63 Ind.$m^{-3}*10^3$. Stable concentration between February and March 2019, with a value 7.44 to 8.8 Ind.$m^{-3}*10^3$ were recorded respectively.

On the other hand, zooplankton density in SOH station shown in Figure 11-B, was much higher compared with RAK station. The maximum density was recorded in July 2018 to reach 4842.15 Ind.$m^{-3}*10^3$. While the lowest biomass has recorded in June 2018 with a value of 18.57 Ind.$m^{-3}*10^3$. Although some samples were missed but in general zooplankton densities in SOH is considered much higher (> 4 folds) in values when it is compared to values at RAK station.

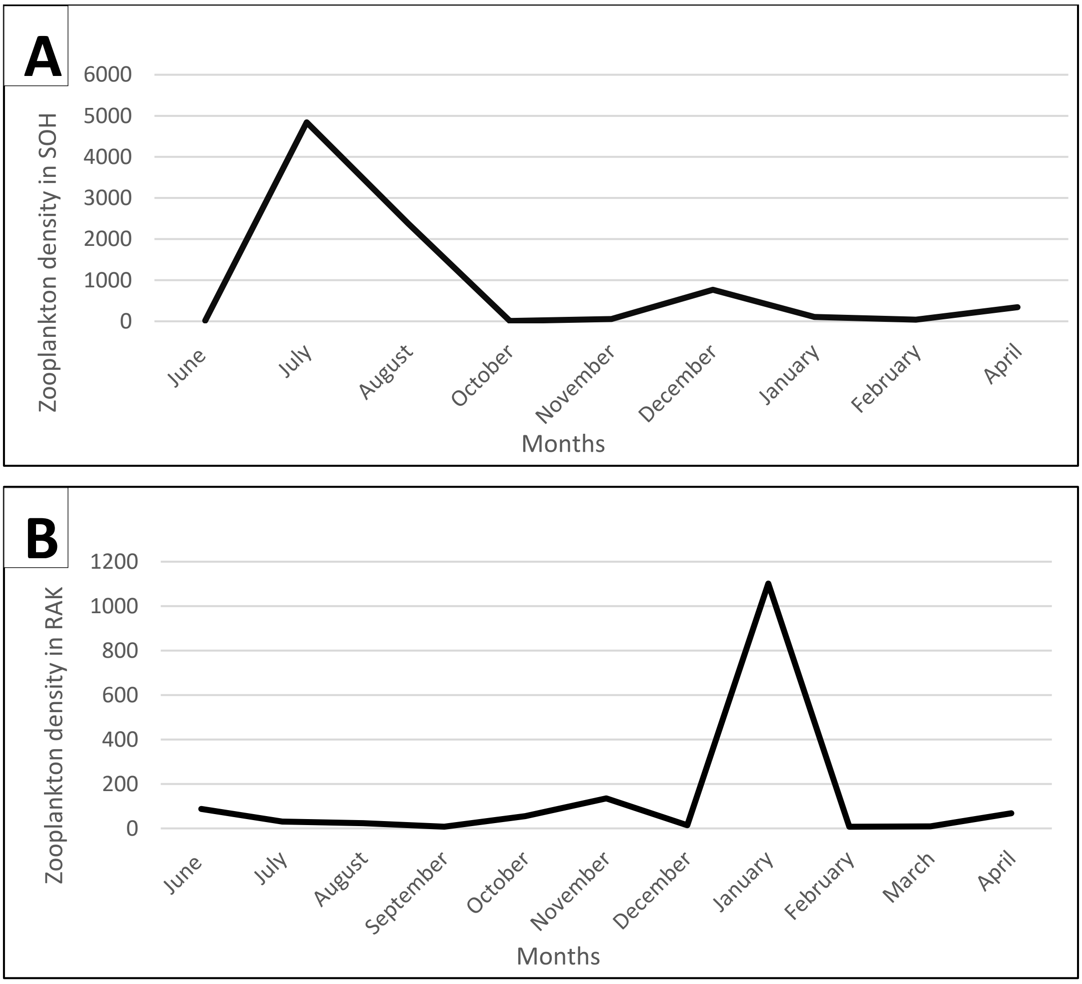


Figure 11: Zooplankton densities (Ind.$m^{-3}*10^3$) in both station during study period 2018-2019. RAK (A) and SOH (B).

In RAK station, Calanoids was the most dominated group, which represented 45.8% of the total zooplankton community, followed by Cyclopoid 38.9% and finally Harpacticoids 15.5% (Figure 12 A-B).

Figure (12 A), Calanoids abundance average ranged between the highest value of around 48% in February 2019 which mainly represented by *Pseudodiaptomus spp*. and the lowest value of around 2% which was also dominated by *Pseudodiaptomus* species. While, Cyclopoids abundance average ranged between the highest value of 97% in January 2019 and it was dominated by *Oithona spp*. and the lowest value of 30% in

April 2019 represented by *Diothona oculata* species. Moreover, the Harpacticiods abundance average ranged between the highest value of 30% of the total community in April 2019 and it was mainly represented by *Euterpina acutifrons* species and the lowest value of 2% in October 2018 and it was represented by Harpacticoid species.

On the other hand, at SOH station Calanoids was dominated zooplankton group (Figure 12 B), with 65.2% of the total community. However, Cyclopoids and Harpacticoids represented 28.6% and 6.2% of the total number of species respectively during the study period. Although sampling was missed during few month of the study period due to ruff sea conditions. Calanoids abundance average ranged between the highest value of 80% in June and July 2018 and it was mainly represented by *Paracalanus denudatus var*. species and *Bestiolina zeylonica* species, respectively. While the lowest value 9% was in March 2019 which dominated by *Eucalanidae* species. Cyclopoid abundance average ranged between the highest value of 90% of the total community in March 2019 and it was represented by *Corycaeus lubbocki* species and lowest value of 10.02% in January 2019 which mainly represented by *Oncaea venusta* species. Moreover, Harpacticoids abundance average ranged between the highest value of 8% in total February 2019 and the lowest value of 0% of community in March 2019.

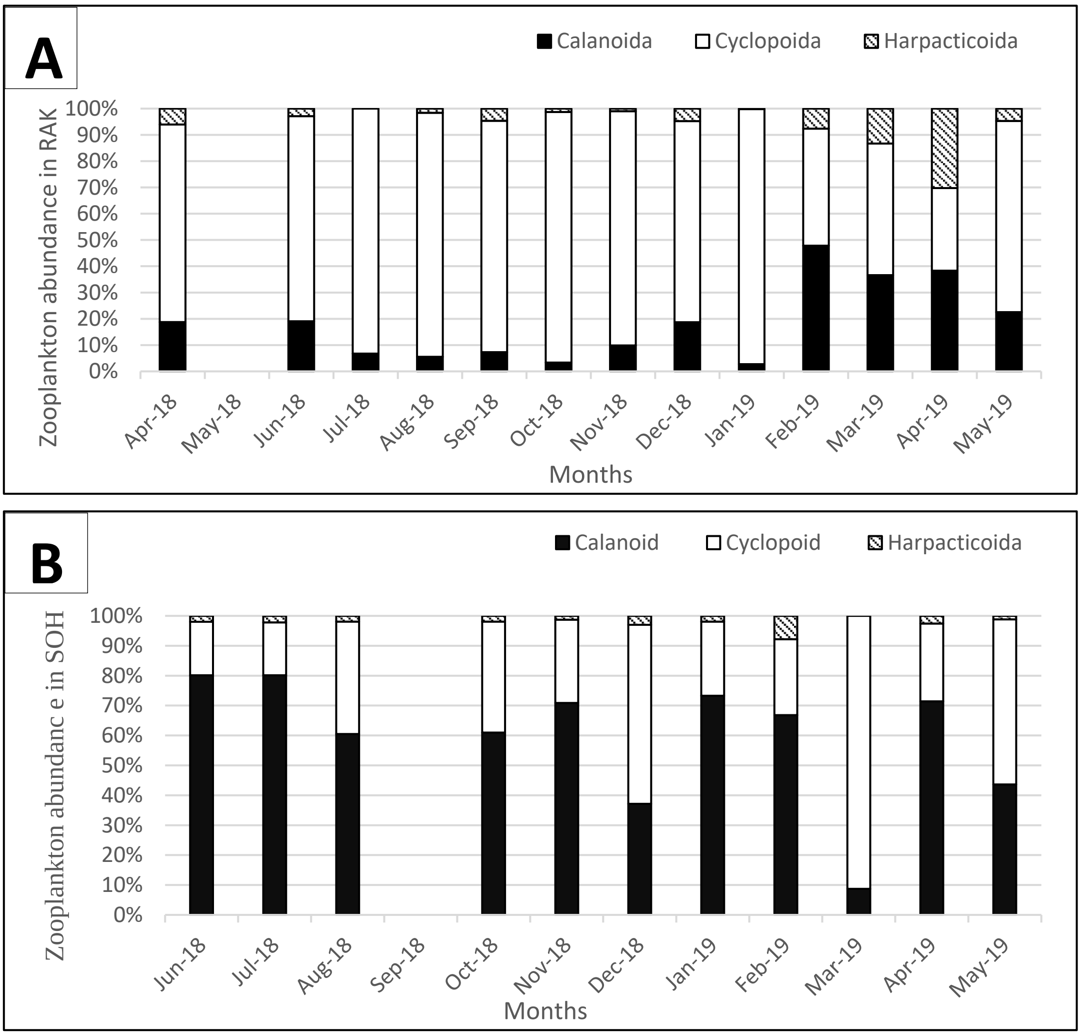


Figure 12: Zooplankton abundance % at both stations during sampling period. RAK (A), SOH (B).

In general, zooplankton species density at SOH station was almost 4 times higher than at RAK station. On July 2018 the number of zooplankton species identified was 63 in SOH stations while, only 18 species were identified in RAK station (Figure 13 A-B).

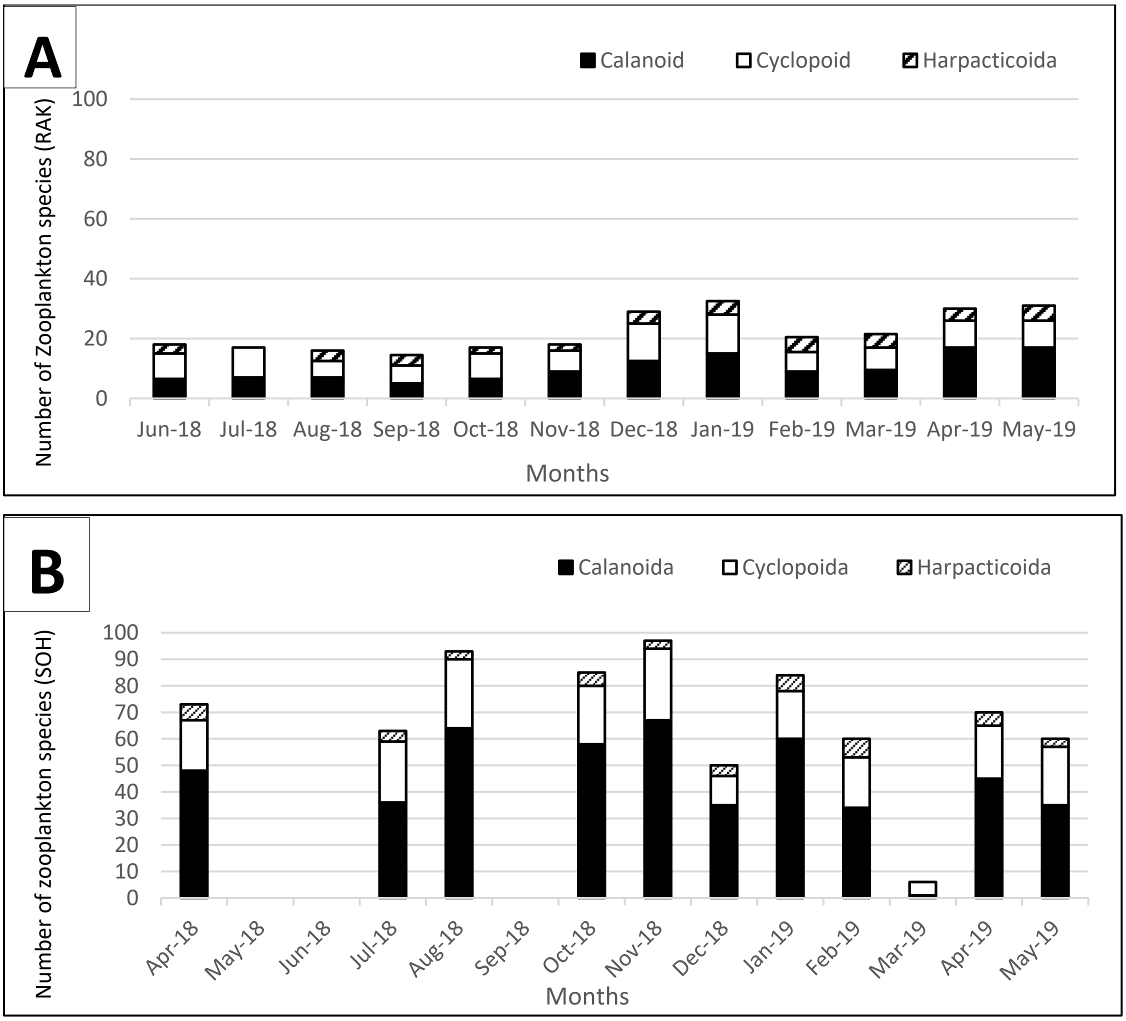


Figure 13: Monthly averages of zooplankton species number identified at both stations during the sampled period 2018-2019. RAK (A), SOH (B).

4.4.3 Relationship between Phytoplankton Biomass and Zooplankton Densities per Cubic Meter at both Stations (RAK) and (SOH)

During the study period, the monthly dominant species of phytoplankton and zooplankton in both RAK and SOH stations showed that there was no similarity of species at the two basins at the same month (Table 5). In June 2018, phytoplankton species *Guinardia flaccida* was dominated in SOH station and it became dominated between December 2018 to May 2019 at RAK station.

On the other hand, the zooplankton species, *Temora turbinate* was the dominant species in April 2018 in RAK station. Then, it became dominant in SOH station in August 2018, February and March 2019 (Table 5).

Table 5: Dominant plankton species at both stations during the study period 2018-2019. RAK(A), SOH (B). Modified from (Hamza et al, 2020).

	Phytoplankton dominant species		**Zooplankton dominant species**	
Stations /Dates	**Ras-Alkaimah (RAK)**	**Sohar (SOH)**	**Ras-Alkaima (RAK)**	**Sohar (SOH)**
Apr.2018	*Coscinodiscus wailesii* *Surirella pandura*		*Euterpina acutifrons* *Temora turbinate**	
Jun.2018	Pyrophacus steinii Pleurosigma elongatum v. fallax	*Guinardia flaccida** *Nitzschia longissimi*	*Oithona brevicornis smaller form* *Copepoda (Nauplius)*	*Paracalanus denudatus var.* *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 turbinate** *Corycaeus spp.*

Table 5: Dominant plankton species at both stations during the study period 2018-2019. RAK(A), SOH (B). Modified from (Hamza et al, 2020) (Contininued)

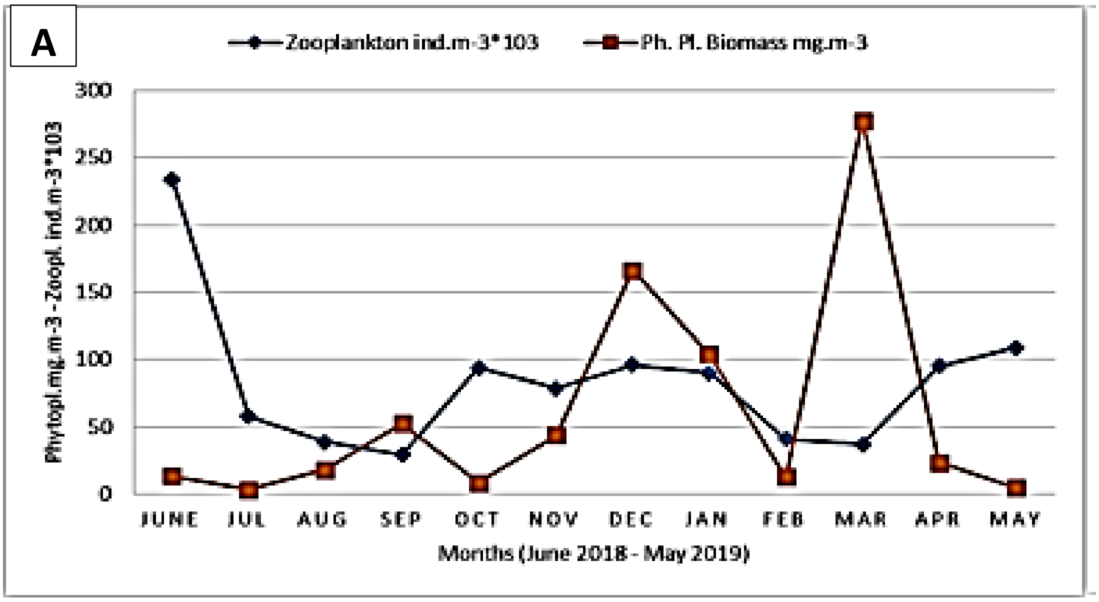
	Phytoplankton dominant species		**Zooplankton dominant species**	
Stations /Dates	**Ras-Alkaimah (RAK)**	**Sohar (SOH)**	**Ras-Alkaima (RAK)**	**Sohar (SOH)**
Sep.2018	*Coscinodiscus marginatus* *Amphora arcus*		*Bivalvia* *Copepoda (Nauplius)*	
Oct.2018	*Rhizosolenia imbricate* *Coscinodiscus perforatus*	*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 formosum*	*Copepoda (Nauplius)* *Oithona spp.*	*Corycaeus spp.* *Oncaea clevei*

Table 5: Dominant plankton species at both stations during the study period 2018-2019. RAK(A), SOH (B). Modified from (Hamza et al, 2020) (Contininued)

	Phytoplankton dominant species		**Zooplankton dominant species**	
Stations /Dates	**Ras-Alkaimah (RAK)**	**Sohar (SOH)**	**Ras-Alkaima (RAK)**	**Sohar (SOH)**
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 hebetate*	*Copepoda (Nauplius)* *Pseudodiaptomus spp.*	*Canthocalanus pauper* *Temora turbinate**
Mar.2019	*Lauderia annulata* *Guinardia flaccida*		*Copepoda (Nauplius)* *Pseudodiaptomus spp.*	*Corycaeus lubbocki* *Corycaeus pacificus*
Apr.2019	*Guinardia flaccida** *Rhizosolenia hyaline*	*Flagellata sp.* *Gyrodinium fusiforme*	*Copepoda (Nauplius)* *Oithona spp.*	*Temora turbinate** *Acrocalanus longicornis*
May.2019	*Coscinodiscus sp.* *Guinardia flaccida**	*Coscinodiscus wailesii* *Chaetoceros lorenzianus*	*Oithona spp* *Copepoda (Nauplius)*	*Oncaea clevei* *Corycaeus spp.*

Monthly relationship between phytoplankton biomass and zooplankton densities per cubic meter at both stations was plotted and illustrated in Figure (14 A-B). At the RAK station, the zooplankton community peak in June 2018, followed by a sharp decline in September 2018. That was 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.

Zooplankton community at the SOH 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 thousand (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. The phytoplankton reached its high biomass peak (2500 $mg.m^{-3}$) during July 2018, when zooplankton biomass also peaked. The other phytoplankton increase in biomass, but less pronounced was observed in January 2019, to value of around 800 $mg.m^{-3}$. However, in January 2019, zooplankton decreased in its densities while phytoplankton increased in its biomass. While, in February 2019, phytoplankton decreased and zooplankton continues to decline (Figure 14 A-B).



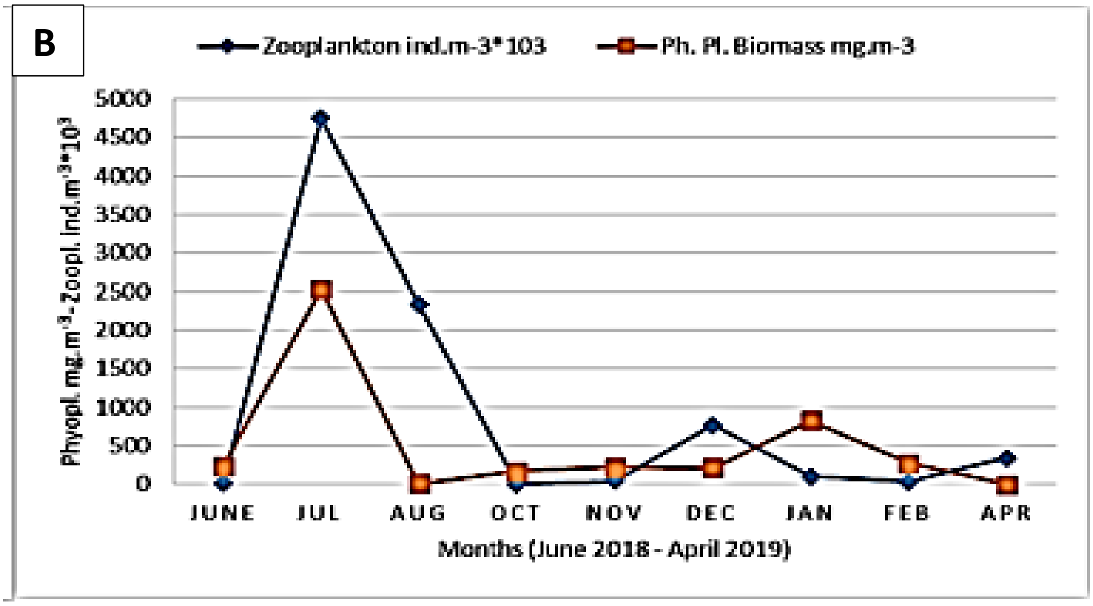


Figure 14: Monthly succession of phytoplankton biomass (mg.m^{-3}) and zooplankton density (ind.m^{-3}*10^{3}) at both stations during the study period (2018-2019). (A): RAK, (B) SOH. Modified from *(*Hamza et. al, 2020).

http://hdl.handle.net/10603/99629.

4.5 Statistical Analyses Results

4.5.1 Correlation Analysis

At RAK, the correlation between temperature and phytoplankton biomass is significant. However, the correlation between pH and other parameters against

Phytoplankton, was not significant. Moreover; the correlation between zooplankton biomass and all other environmental parameters was not significant (Table 6).

Table 6: Correlation analysis between phytoplankton and zooplankton and environmental parameters (temperature, salinity and pH) during study period 2018-2019 in RAK station ($p < 0.05$).

	Temperature	**Salinity**	**pH**	**Zooplankton**	**Phytoplankton**
Temperature	NA	0.15	0.034*	0.80	0.046*
Salinity	0.15	NA	0.41	0.64	0.72
Ph	0.03*	0.41	NA	0.73	0.07
Zooplankton	0.74	0.32	0.70	NA	0.87
Phytoplankton	0.05*	0.72	0.07	0.87	NA

However, at SOH station the correlation between phytoplankton biomass against pH and water salinity were not significant. A slight significance between phytoplankton and temperature ($p = 0.052$) has resulted. While, the correlation between zooplankton and phytoplankton was not significant (Table 7).

Table 7: Correlation analysis between phytoplankton and zooplankton and environmental parameters (temperature, salinity and pH) during study period 2018-2019 in SOH station ($p < 0.05$).

	Temperature	Salinity	pH	Zooplankton	Phytoplankton
Temperature	NA	0.69	0.099	0.74	0.052*
Salinity	0.69	NA	0.86	0.32	0.76
pH	0.99	0.86	NA	0.70	0.71
Zooplankton	0.74	0.32	0.70	NA	0.55
Phytoplankton	0.52	0.76	0.71	0.55	NA

4.5.2 PCA (Principal Component Analyses)

All the data collected in RAK station were subjected to the Principal Component Analysis (Figure 15), in which the first two factor dimensions explained 67.76%. Phytoplankton, showed positive relations with all parameters except with zooplankton and salinity, where its relation was negative.

Dim.1 = - 0.7655789 * Phytoplankton + 0.8882308 * Temp -0.5254623 * Salinity + 0.8234241 * pH + 0.09 * Zooplankton

While, the second dimension is described by positive value of Zooplankton with phytoplankton, but negative with temperature, salinity and pH

Dim.2 = 0.175 * Phytoplankton -0.152 * Temp -0.388 * Salinity -0.024 * pH + 0.919 * Zooplankton

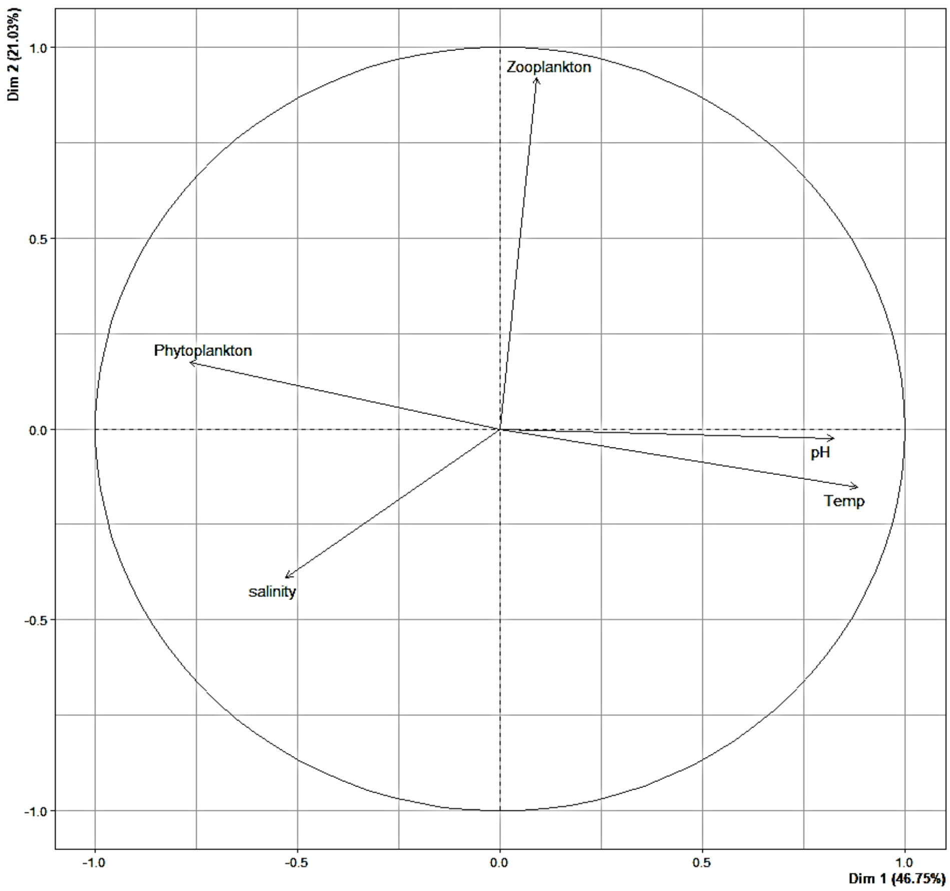


Figure 15: PCA analysis showing phytoplankton and zooplankton abundance and their relationship to environmental parameters (pH, temperature and salinity) at Arabian Gulf during the study period 2018-2019.

All the data collected in SOH station were subjected to the Principle Component at SOH station the PCA aanalysis (Figure 16), the first two dimension explained 61.66%. The first dimension showed negative relations between phytoplankton and temperature toward zooplankton and pH. While at the second dimension water salinity was negatively affected the other parameters as shown at the following equations.

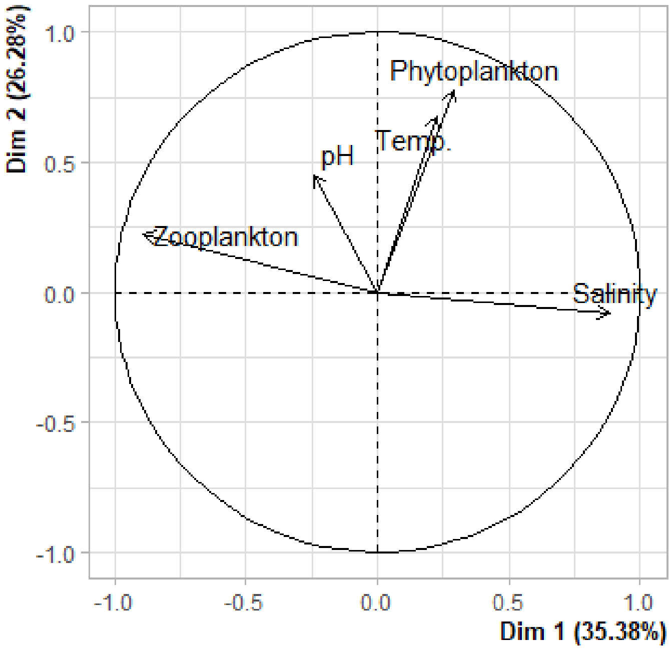


Figure 16: PCA analysis showing phytoplankton and zooplankton abundance and their relationship to environmental parameters (pH, temperature and salinity) at SOH station during the study period 2018-2019.

Dim1 = 0.29 * Phytoplankton + 0.225 * Temperature + 0.886 * Salinity -0.238 * pH - 0.891 * Zooplankton

Dim2 = 0.776 Phytoplankton + 0.675 * Temperature -0.083 * Salinity + 0.448 * pH + 0.221 * Zooplankton

Chapter 4: Discussion

In the present study, it becomes clear that the morphometric differences between the two studied stations which are belonging to the two different basins (i.e. The Arabian Gulf and the Sea of Oman) exist. The greater depth at Sohar station has influenced the water column temperature. As shown in Table 4 during winter months the temperature average at the Arabian Gulf is less that the water temperature average at the Sea of Oman. That is mainly due to the characteristic known as heat capacity of water, where it can conserve heat for longer time compared to land. Since the Arabian Gulf is shallow basin (average depth 36 m), its water is more influenced by the adjacent land temperature during winter and the contrary happens during summer months. According to (Piontkovski et al., 2019) temperatures in a shallow AG are much higher, compared to deep SO.

Arabian Gulf and Sea of Oman belong to the same region but they are affected by different weather systems (Wang et al., 2013). Water enter Arabian Gulf through the Strait of Hormuz from Sea of Oman with low water salinity while outflow of water from Arabian Gulf to Sea of Oman with a high water salinity. As shown in Table 4, water salinity average at RAK is higher than at SOH which exceed 40 ppt because of excessive water evaporation, low rainfall, high discharge of river from Iranian coast and restricted exchange of water with open ocean. However, Sea of Oman is greater in depth than Arabian Gulf and open sea which is connected to Indian Ocean that allowed water exchange. As mentioned by Piontkovski et al. (2019), Indian Ocean water mass forms the upper layer of the SO which characterized by low salinity. Moreover, water cyclonic also affect the salinity. Wang et al. (2013) mentioned that after three months passage of Ccyclone Gonu in summer 2007 in the interior of the

Sea of Oman caused rapidly increase in water temperature and salinity but decline in dissolved oxygen.

The amount of oxygen that can dissolve in water mainly depends on temperature, salinity and pressure of water (Shahjahan et al., 2012). At AG the average dissolved oxygen lower than at SOH was mainly caused by warming of the Gulf water during the summer season. As water surface temperature increase, less dissolved oxygen require. On the other hand, wind induce the upwelling of nutrient, increase biological productivity but decrease the concentration of dissolved oxygen. DiMarco et al. (2010) found that decline in oxygen concentration in the water column during the winter season could be due to monsoonal winds that increase the upwelling process which affect the oxygen availability at surface water layer.

In the present study, the environmental parameters measurements between the two stations (RAK and SOH), except water pH. It has been mentioned that high pH concentration may indicate high photosynthesis process by phytoplankton (Dorgham et al., 1986). In SOH, pH remained constant during both seasons, while, at RAK little decrease has observed in winter months but phytoplankton density increase in this period. Uddin et al. (2012), concluded that after four years period of study and biweekly pH concentration measurements and suggested that the Arabian Gulf waters are becoming increasingly acidic with time because of water warming and Sulfur input from the atmosphere as a consequence of intensive oil industry.

In the present study, nutrient's concentration at the water column of RAK was lower than at SOH. This could be due to the shallowness of the AG basin compared with the SOH. In fact, the shallow depth at the AG and the sun light penetration to its seabed allowed the intensive growth of sea grasses and Macroalgae, which consume nutrients from the water column. While the great depth average of the SO (>300 meters), and the absence of light at its bottom, did not allow such kind of flora to grow. Although such growth of Macrophytes at the bottom of the AG is beneficial for different benthic and nektonic fauna to feed and reproduce at these developed patches, but at the same time it competes with phytoplankton species for nutrients. However, it increases the epiphytic growth of different phytoplankton species (mainly diatoms); and that is confirmed by the dominancy of Bacillariophyceae group at RAK station compared with SOH one. In his study, Sinistro et al. (2006) indicated that floating Macrophytes on the water surface decrease the light penetration and decline of the photosynthetic activities, which by its time, decrease dissolved oxygen. Under these conditions, declining light penetration favored the replacement of obligate autotrophs by mixotrophic and heterotrophic organisms. That can explain the differences in nutrients availability differences between the two stations and may also explain the differences in phytoplankton community structure.

In the present study, the average concentrations of Chlorophyll- a, at SOH were higher than at RAK especially in winter. That could be due to seasonal environmental conditions, where, because of the monsoonal winds which induce the upwelling of nutrient to the water surface and increase phytoplankton productivity at the SO. High peak of chlorophyll-a concentration recorded in February 2019 at SOH because of North East Monsoon (NEM) which extended from November to February (Al-Azri et al., 2010). However, Al-Azri et al. (2010) found that chlorophyll- a concentrations exhibited a major peak in August during the South West Monsoon (SWM). Moreover, according to Piontkovski et al. (2019), high seasonal peaks of chlorophyll-a are associated with high concentrations of nitrates and phosphates. That was confirmed in our study. While the lower chlorophyll concentrations at RAK could be mainly associated with the presence of phytoplankton attached with the benthic macrophytes as epiphytic organisms that are not suspended in water column.

Previous studies on plankton dynamics at both the UAE coastal area and the Sea of Oman have always been sporadic in its nature and mainly linked to specific project and/or catastrophic phenomena such as red tide events happened in 2008 at both sides. In the UAE coastal area, in addition to irregular sampling of plankton from certain areas related to routine work of Municipalities and governmental agencies, an intensive regular and schematic sampling of both phytoplankton and zooplankton had taken place during the Red-tide phenomena occurred along the UAE coastal area in 2008 and extended until 2009. The results of such intensive work have been published by Zhao and Ghedira (2014), and by Richlen et al., 2010. Similar studies have carried out at the Sea of Oman and published by Piontkovski et al. (2013), Al Hashmi et al. (2014) and Harrison et al. (2017). Such studies have conducted separately without understanding the linkage between the water bodies and how the phenomena have transferred from the Sea of Oman to the Arabian Gulf, although of the identification of the same dinoflagellate species responsible about the phenomenon in both areas. Similarly, zooplankton community studies at the two basins were never previously studied simultaneously. This means that no previous studies investigated the dynamics of planktonic communities at the same time in both areas. Moreover, no previous studies investigated the change of plankton communities that may occur when they pass from deep water to shallow water and vice versa. Indeed, what may happen to such communities when they leave low salinity environment and move to high salinity one and vice versa. Such lack of knowledge makes it necessary to conduct the present study.

The dominance of Bacillariophyceae phytoplankton group in AG have during summer and winter seasons is consistent with previous report which indicate the dominance of diatoms at AG during the period December 1993 and 1994 (Al-Zahrani & Husain, 1998). According to Hamza et al., 2011, dissolved silicate from dust storm in AG have favoured Bacillariophyceae over the other phytoplankton group. Although some of the dust deposited in SO but because of water salinity characterize that may be allowed the growth of other group (Hamza et al., 2020).

On the other hand, Bacillariophyceae, cyanobacteria and chlorophyta were the most dominant phytoplankton group in the SO during the sampling period. Normally they are dominants during the high concentration of nutrients especially nitrate. In his research, Gregg et al. (2003) found that diatoms growth rate is higher during the upwelling seasons and wind-inducing mixing. However, Dinoflagellates dominate in low nutrients concentration. As mentioned earlier in this caption, the presence of great patches of macrophyts favored the growth of epiphytic diatoms; which could be the reason of the high percentage of Bacillariophyceae and also the high number of species identified at RAK (1151 species), compared to SOH (192 species) station.

On the other hand, according to the collected zooplankton samples during the study period, zooplankton density at SOH is higher than at RAK. However, zooplankton density in winter season months was higher at RAK than SOH (Figure 11 A-B). In general, species number was almost 4 times higher at SOH compared with RAK one. In RAK station, cyclopoid has dominated the zooplankton community and little changes in their abundance during the different seasons were recorded. On the other hand, Calanoids were the most abundant group in the zooplankton community at Sea of Oman (SOH) station. No seasonal changed were observed over the sampling period. Except two high peaks in August and November 2018. Similar findings are confirming the findings reported by Piontkovski et al. (2019), when he reviewed the plankton status at both the Arabian Gulf and Sea of Oman from 2006-2015.

In the present study, it was important to analyses the relationship between phytoplankton and zooplankton based on their biomasses and densities variations the two dominant species of phytoplankton species. Guinaradia *Flaccide* was dominant phytoplankton species at SOH in June 2018 and showed in RAK from January to May 2019. However, the zooplankton species *Temora turbinate* was dominant in RAK during April 2018 and showed in SOH station in August 2018, as well as in February and April 2019. This explained the transportation of species by currents through the Strait of Hormuz during the water exchange between two basins and anticyclonic gyre that return the flow water (Hamza et al. 2020). In his recent study, Hamza (2021), indicated that, the appearance of the 2008 Red tide was observed at SO two months earlier before being recorded at the AG. This supports the idea of time-lag between the two basins to have a common dominant species.

In this study, because of differences in the depth at two water basins plankton samples were collected from upper mixing layer which is 6 m at RAK and almost representing the maximum station depth (i.e. 6.5 m) and at SOH from 20 m out of 270 meters depth. That explains the selection of sampling depths during this study. The study showed also that, there is a differences between plankton community structure and their seasonal dynamic at the two water basins. The relationship between phytoplankton and zooplankton explained also by statistical analyses showed high pecks of zooplankton densities are accompanied by low biomass of phytoplankton at RAK. Which indicated that, at RAK zooplankton graze on phytoplankton and able to control it. However, at SOH the relationship between phytoplankton and zooplankton are deepened more in other environmental parameters shown by PCA. In their study Al Hashmi et al (2019), mentioned that the presence of high yields of Sardine and Anchovy (filter feeders fish) at the Sea of Oman may be responsible about fluctuations of both phytoplankton and zooplankton communities. This may confirm the similarities found between plankton communities and their dynamics at the two studied basins.

The statistical analysis has indicated that (Table 5), at RAK there is a significant relation between temperature and phytoplankton biomass that mean if temperature increase the phytoplankton biomass will also increase. It showed also, at dimension 1, a very high contribution of zooplankton in controlling phytoplankton explained by a value of - 0.7655789. While at the SOH although zooplankton has controlling on the phytoplankton biomass with only a value of 0.29. This can confirm, the ability of zooplankton community to control the phytoplankton biomass at the RAK (AG), while less control at the SOH (SO).

The present study is considered the first of its kind to study simultaneously the plankton dynamics at the Arabian Gulf and the Sea of Oman and to shed light on their ecosystem’s relationships. Here, it is important to mention that, continuous collaborative studies of the two basins at regular rhythm will help in better understanding how each of them affecting each other and it can help in predicting any future algae blooms and to understand the parameters that contribute to its development.

Chapter 5: Conclusion

The present study is making part of the collaborative research study entitled "Comparative Analysis and Predictions of Algal Blooms in the Arabian Gulf and the Sea of Oman", between the United Arab Emirates University and Sultan Qaboos University (Grant # G00002684- 31S321), in which simultaneous and intensive biweekly plankton and water samples were collected from two opposite coastal stations off the Strait of Hormuz with the aim to study plankton dynamics at the Arabian Gulf and the Sea of Oman and the effect of environmental parameters on their community structures during the period from May 2018 until May 2019. For the Arabian Gulf, samples were collected from Ras Al Khaimah (RAK) station, while for the Sea of Oman samples were collected from Sohar (SOH) station. Based on the obtained results, the present study also analyzed the relationship between phytoplankton biomass and zooplankton densities during the study period and came to the conclusions that:

1. Both phytoplankton and zooplankton communities at the studied stations are not similar in its monthly community structures.
2. The variations between the two basins in environmental parameters are also affecting the species dominance and the monthly community structures of both phytoplankton and zooplankton.
3. Wind stress and its directions over the studied period are controlling the surface water current directions through the Strait of Hormuz which control by its time the movements of planktonic organisms between the two basins.

4. At RAK the relationship between phytoplankton and zooplankton is based on grazing of zooplankton on phytoplankton; while at SOH it is mainly based on pray predator interaction, especially with the presence of high densities of fish larvae (especially Sardine and Anchovy), which controlled the zooplankton ability to control the phytoplankton productivity. Statistical analyses (Principal component Analyses–PCA), has confirmed the negative relationship between phytoplankton and zooplankton at RAK, but it was less able to explain such relationship at SOH station. The present study is the first in its kind to study simultaneously the dynamics of plankton communities at the Arabian Gulf and the Sea of Oman and it could be a baseline for future research.

References

Al-Azri, A. R., Piontkovski, S. A., Al-Hashmi, K. A., Goes, J. I., & Do Gomes, H. R. (2010). Chlorophyll a as a measure of seasonal coupling between phytoplankton and the monsoon periods in the Gulf of Oman. *Aquatic Ecology*, *44*(2), 449-461.

Abuelgasim, A., & Alhosani, N. (2014). Mapping the seasonal variations of chlorophyll concentrations in the Arabian Gulf and the Gulf of Oman using MODIS satellite data. *The Arab World Geographer*, *17*(1), 82-90.

Alfonso, M. B., Zunino, J., & Piccolo, M. C. (2017). Impact of water input on plankton temporal dynamics from a managed shallow saline lake. In *Annales de Limnologie-International Journal of Limnology* (Vol. 53, pp. 391-400). EDP Sciences.

Al Hashmi, K., Goes, J., Claereboudt, M., Piontkovski, S. A., Al-Azri, A., & Smith, S. L. (2014). Variability of dinoflagellates and diatoms in the surface waters of Muscat, Sea of Oman: comparison between enclosed and open ecosystem. *International Journal of Oceans and Oceanography*, *8*(2), 137-152.

Al-Hashmi, K. A, Pinotkovski, S. A, Bruss, G., Hamza, W., Al-Junaibi, M., Bryantseva Y., & Popova (2019). Seasonal variations of planktonic communities in coastal water of Oman. *International Journal of Oceans and Oceanography*. *13*(2), 395-426.

Al-Kandari, M., Al-Yamani, F., & Al-Rifaie, K. (2009). Marine phytoplankton atlas of Kuwait's waters. *Kuwait Institute for Scientific Research*, 1-351.

Al Said, T., Al-Ghunaim, A., Rao, D. S., Al-Yamani, F., Al-Rifaie, K., & Al-Baz, A. (2017). Salinity-driven decadal changes in phytoplankton community in the NW Arabian Gulf of Kuwait. *Environmental monitoring and assessment*, *189*(6),1-268.

Al-Yamani, F. Y., & Saburova, M. A. (2011). Illustrated guide on the benthic diatoms of Kuwait's marine environment. *Kuwait Institute for Scientific Research, Kuwait*, 1-349.

Al-Yamani, F. Y., Skryabin, V., Gubanova, A., Khvorov, S., & Prusova, I. (2011a). Marine zooplankton practical guide. *Kuwait Institute for Scientific Research, Kuwait*, 1-399.

Al-Yamani, F., Skryabin,V., gubanova,A., khvorov,S.& prusova,i. (2011b). Marine zooplankton practical guide (volume 2). *Kuwait Institute for Scientific Research*, 2-210.

Al-Zahrani, M., & Husain, T. (1998). An algorithm for designing a precipitation network in the south-western region of Saudi Arabia. *Journal of Hydrology*, *205*(3-4), 205-216.

Banas, N. S., Zhang, J., Campbell, R. G., Sambrotto, R. N., Lomas, M. W., Sherr, E., ... & Lessard, E. J. (2016). Spring plankton dynamics in the Eastern Bering Sea, 1971–2050: Mechanisms of interannual variability diagnosed with a numerical model. *Journal of Geophysical Research: Oceans*, *121*(2), 1476-1501.

Barcelos e Ramos, J., Schulz, K. G., Voss, M., Narciso, Á., Müller, M. N., Reis, F. V., ... & Azevedo, E. B. (2017). Nutrient-specific responses of a phytoplankton community: a case study of the North Atlantic Gyre, Azores. *Journal of Plankton Research*, *39*(4), 744-761.

Barzandeh, A., Eshghi, N., Hosseinibalam, F., & Hassanzadeh, S. (2018). Wind-driven coastal upwelling along the northern shoreline of the Persian Gulf. *Bollettino di Geofisica Teorica ed Applicata*, *59*(3), 301-312.

Berge, T., Daugbjerg, N., Andersen, B. B., & Hansen, P. J. (2010). Effect of lowered pH on marine phytoplankton growth rates. *Marine Ecology Progress Series*, *416*, 79-91.

Bilen, H., & Vedaldi, A. (2017). Universal representations: The missing link between faces, text, planktons, and cat breeds. *arXiv preprint arXiv:1701.07275*, 1-10.

Branco, P., Egas, M., Elser, J. J., & Huisman, J. (2018). Eco-evolutionary dynamics of ecological stoichiometry in plankton communities. *The American Naturalist*, *192*(1), 1-20.

Brierley, A. S. (2017). Plankton. *Current Biology*, *27*(11), R478-R483.

Chiba, S., Aita, M. N., Tadokoro, K., Saino, T., Sugisaki, H., & Nakata, K. (2008). From climate regime shifts to lower-trophic level phenology: synthesis of recent progress in retrospective studies of the western North Pacific. *Progress in Oceanography*, *77*(2-3), 112-126.

Chícharo, A., & Barbosa, A. B. (2011). Hydrology and biota interactions as driving forces for ecosystem functioning. *Treatise on Estuarine and Coastal Science*, *10*, 7-47.

Defriez, E. J., Sheppard, L. W., Reid, P. C., & Reuman, D. C. (2016). Climate change-related regime shifts have altered spatial synchrony of plankton dynamics in the North Sea. *Global Change Biology*, *22*(6), 2069-2080.

DiMarco, S. F., Chapman, P., Walker, N., & Hetland, R. D. (2010). Does local topography control hypoxia on the eastern Texas–Louisiana shelf?. *Journal of Marine Systems*, *80*(1-2), 25-35.

Khaliullina, L. Y., & Demina, G. V. (2015). Seasonal dynamics of phytoplankton communities residing in different types of shallow waters in the Kuibyshev Reservoir (Russia). *International Aquatic Research, 7*(4), 315-328.

Dorgham, M. M., & Moftah, A. (1989). Environmental conditions and phytoplankton distribution in the Arabian Gulf and Gulf of Oman, September 1986. *Journal of the Marine Biological Association of India. Cochin*, *31*(1), 36-53.

Dorgham, M. M. (2013). Plankton research in the ROPME sea area, achievements and gaps. *Int. J. Env. Res*. *7*, 767- 778.

Eilertsen, H. C., & Degerlund, M. (2010). Phytoplankton and light during the northern high-latitude winter. *Journal of Plankton Research*, *32*(6), 899-912.

El Gammal, M. A. M., Nageeb, M., & Al-Sabeb, S. (2017). Phytoplankton abundance in relation to the quality of the coastal water–Arabian Gulf, Saudi Arabia. *The Egyptian Journal of Aquatic Research*, *43*(4), 275-282.

Enyidi, U., (2017). Chlorella vulgaris as Protein Source in the Diets of African Catfish Clarias gariepinus. *Fishes*, 2(4), 1-17.

Grattepanche, J. D., Santoferrara, L. F., McManus, G. B., & Katz, L. A. (2015). Distinct assemblage of planktonic ciliates dominates both photic and deep waters on the New England shelf. *Marine Ecology Progress Series*, *526*, 1-9.

Gregg, W. W., Ginoux, P., Schopf, P. S., & Casey, N. W. (2003). Phytoplankton and iron: validation of a global three-dimensional ocean biogeochemical model. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*(22-26), 3143-3169.

Gołdyn, R., & Kowalczewska-Madura, K. (2008). Interactions between phytoplankton and zooplankton in the hypertrophic Swarzędzkie Lake in western Poland. *Journal of Plankton Research*, *30*(1), 33-42.

Hamza, W. (2021). Dust Storms and Its Benefits to the Marine Life of the Arabian Gulf. *The Arabian Seas: Biodiversity, Environmental Challenges and Conservation Measures*, 141.

Hamza, W., Enan, M. R., Al-Hassini, H., Stuut, J. B., & De-Beer, D. (2011). Dust storms over the Arabian Gulf: a possible indicator of climate changes consequences. *Aquatic Ecosystem Health & Management*, *14*(3), 260-268.

Hamza, W., Al Junaibi, M., Pintkovski, S., & Al Hashmi, K. (2020). Comparatitive plankton dynamic in Arabian Gulf and Sea of Oman at opposite Sides of the Strait of Hormus. In *Geolinks international conference*. Volume 2 Book 2. doi:10.32008/geolinks2020/b2/v2.

Harrison, P. J., Piontkovski, S., & Al-Hashmi, K. (2017). Understanding how physical-biological coupling influences harmful algal blooms, low oxygen and fish kills in the Sea of Oman and the Western Arabian Sea. *Marine Pollution Bulletin*, *114*(1), 25-34.

Hassan, F. M., Kathim, N. F., & Hussein, F. H. (2008). Effect of chemical and physical properties of river water in Shatt Al-Hilla on phytoplankton communities. *E-Journal of Chemistry*, *5*(2), 323-330.

Hinga, K. R. (2002). Effects of pH on coastal marine phytoplankton. *Marine Ecology Progress Series*, *238*, 281-300.

Johns, W. E., Yao, F., Olson, D. B., Josey, S. A., Grist, J. P., & Smeed, D. A. (2003). Observations of seasonal exchange through the Straits of Hormuz and the inferred heat and freshwater budgets of the Persian Gulf. *Journal of Geophysical Research: Oceans*, *108*(C12), doi: 10.1029/2003JC001881.

Jørgensen, E. G. (1968). The adaptation of plankton algae: II. Aspects of the temperature adaptation of Skeletonema costatum. *Physiologia Plantarum*, *21*(2), 423-427.

Karlsson, K., Puiac, S., & Winder, M. (2018). Life-history responses to changing temperature and salinity of the Baltic Sea copepod Eurytemora affinis. *Marine Biology*, *165*(2), 1-11.

Kasprzak, P., Benndorf, J., Mehner, T., & Koschel, R. (2002). Biomanipulation of lake ecosystems: an introduction. *Freshwater Biology*, *47*(12), 2277-2281.

Kim, D. I., Matsuyama, Y., Nagasoe, S., Yamaguchi, M., Yoon, Y. H., Oshima, Y., ... & Honjo, T. (2004). Effects of temperature, salinity and irradiance on the growth of the harmful red tide dinoflagellate Cochlodinium polykrikoides Margalef (Dinophyceae). *Journal of Plankton Research*, *26*(1), 61-66.

Kruk, C., & Segura, A. M. (2012). The habitat template of phytoplankton morphology-based functional groups. In *Phytoplankton Responses to Human Impacts at Different Scales* (pp. 191-202). Springer, Dordrecht.

Lennuk, L., Kotta, J., Lauringson, V., Taits, K., & Jänes, H. (2016). Which environmental scales and factors matter for mesozooplankton communities in a shallow brackish water ecosystem?. *Journal of Plankton Research*, *38*(1), 139-153.

Litchman, E., de Tezanos Pinto, P., Klausmeier, C. A., Thomas, M. K., & Yoshiyama, K. (2010). Linking traits to species diversity and community structure in phytoplankton. *Fifty years after the ''Homage to Santa Rosalia'': Old and new paradigms on biodiversity in aquatic ecosystems*, 15-28.

Lumini, A., & Nanni, L. (2019). Ocean ecosystems plankton classification. In *Recent Advances in Computer Vision* (pp. 261-280). Springer, Cham.

Maberly, C. (2009). Phytoplankton Nutrition and Related Mixotrophy. *Academic Press*, 192-196.

Martin, R. H. (2015). Euphotic zone. In *A Dictionary of Biology* (7th ed.). Oxford.

Maddux, W. S., & Jones, R. F. (1964). Some Interactions of Temperature, Light Intensity, and Nutrient Concentration during the Continuous Culture of Nitzschia Closterium and Tetraselmis SP 1. *Limnology and Oceanography*, *9*(1), 79-86.

McManus, M. A., & Woodson, C. B. (2012). Plankton distribution and ocean dispersal. *Journal of Experimental Biology*, *215*(6), 1008-1016.

Menden-Deuer, S., & Lessard, E. J. (2000). Carbon to volume relationships for dinoflagellates, diatoms, and other protist plankton. *Limnology and Oceanography*, *45*(3), 569-579.

Morabito, G., Mazzocchi, M. G., Salmaso, N., Zingone, A., Bergami, C., Flaim, G., ... & Pugnetti, A. (2018). Plankton dynamics across the freshwater, transitional and marine research sites of the LTER-Italy Network. Patterns, fluctuations, drivers. *Science of the Total Environment*, *627*, 373-387.

Morán, X. A. G., LÓPEZ-URRUTIA, Á. N. G. E. L., CALVO-DÍAZ, A. L. E. J. A. N. D. R. A., & Li, W. K. (2010). Increasing importance of small phytoplankton in a warmer ocean. *Global Change Biology*, *16*(3), 1137-1144.

Moore, C. M., Mills, M. M., Arrigo, K. R., Berman-Frank, I., Bopp, L., Boyd, P. W., ... & Ulloa, O. (2013). Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, *6*(9), 701-710.

Musialik-Koszarowska, M., Dzierzbicka-Głowacka, L., & Weydmann, A. (2019). Influence of environmental factors on the population dynamics of key zooplankton species in the Gulf of Gdańsk (southern Baltic Sea). *Oceanologia*, *61*(1), 17-25.

Nielsen Steemann, E. (1968). The adaptation of plankton algae. *Physiol Plant*, *21*, 401-413.

Paturej, E., & Kruk, M. (2011). The impact of environmental factors on zooplankton communities in the Vistula Lagoon. *Oceanological and Hydrobiological Studies*, *40*(2), 37-48.

Piontkovski, S. A., Claereboudt, M. R., & Al-Jufaili, S. (2013). Seasonal and interannual changes in epipelagic ecosystem of the western Arabian Sea. *Int J Ocean Oceanogr*, *7*, 117-130.

Piontkovski, S.A., Hamza, W., Al-Abri, N., Al-Busaid, i S., & Al-Hashmi, K.A., (2019), A comparison of seasonal variability of Arabian Gulf and the Sea of Oman pelagic ecosystems. *Aquatic Ecosystem Health and Management*, 22, 08-130.

Polikarpov, I., Saburova, M., & Al-Yamani, F. (2016). Diversity and distribution of winter phytoplankton in the Arabian Gulf and the Sea of Oman. *Continental Shelf Research*, *119*, 85-99.

Pous, S. P., Carton, X., & Lazure, P. (2004). Hydrology and circulation in the Strait of Hormuz and the Gulf of Oman—Results from the GOGP99 Experiment: 2. Gulf of Oman. *Journal of Geophysical Research: Oceans*, *109*(C12).

Ravens, C J.A. and Raven, J. A., & Maberly, S. C. (2009). Phytoplankton nutrition and related mixotrophy. *Encyclopedia of Inland Waters*, 192-196.

Richlen, M. L., Morton, S. L., Jamali, E. A., Rajan, A., & Anderson, D. M. (2010). The catastrophic 2008–2009 red tide in the Arabian Gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate Cochlodinium polykrikoides. *Harmful Algae*, *9*(2), 163-172.

Richlen, M. L., Morton, S. L., Jamali, E. A., Rajan, A., & Anderson, D. M. (2010). The catastrophic 2008–2009 red tide in the Arabian Gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate Cochlodinium polykrikoides. *Harmful Algae*, *9*(2), 163-172.

Riegman, R., Stolte, W., Noordeloos, A. A., & Slezak, D. (2000). Nutrient uptake and alkaline phosphatase (EC 3: 1: 3: 1) activity of Emiliania huxleyi (Prymnesiophyceae) during growth under N and P limitation in continuous cultures. *Journal of Phycology*, *36*(1), 87-96.

ROPME, (2013). State of the marine environment report. ROPME / GC - 16 / 1 - i. Regional Organization for the Protection of the Marine Environment. Kuwait, pp 1-225.

Shahjahan, Ferzoz , S.& Saha, R. (2012). Analysis of seasonal varations of hydro-meteorological ,general and particulates in sea water alonge the coastlline of Sultanate of Oman . *International Journal of Engineering Research and Technology*, 1(10), 152-156.

Sinistro, R., Izaguirre, I., & Asikian, V. (2006). Experimental study on the microbial plankton community in a South American wetland (Lower Paraná River Basin) and the effect of the light deficiency due to the floating macrophytes. *Journal of Plankton Research*, *28*(8), 753-768.

Smith, S. L., Mandal, S., Priyadarshi, A., Chen, B., & Yamazaki, H. (2019). Modeling the combined effects of physiological flexibility and micro-scale variability for plankton ecosystem dynamics. In *Encyclopedia of Ocean Sciences: Volume 5: Technology, Instrumentation* (pp. 527-535).

Sommer, U., Charalampous, E., Genitsaris, S., & Moustaka-Gouni, M. (2017). Benefits, costs and taxonomic distribution of marine phytoplankton body size. *Journal of Plankton Research*, *39*(3), 494-508.

Strickland, J. D. H., & Parsons, T. R. (1972). A practical handbook of seawater analysis (2nd ed.). Fisheries Research Board of Canada

Sugie, K., Fujiwara, A., Nishino, S., Kameyama, S., & Harada, N. (2020). Impacts of temperature, CO2, and salinity on phytoplankton community composition in the Western Arctic Ocean. *Frontiers in Marine Science*, *6*, 821. doi: 10.3389/fmars.2019.00821.

Taher, M. M., Mohamed, A. R. M., & Al-Ali, A. K. H. (2012). Some ecological characteristics and ichthyofauna of surrounding Sammaliah Island, Abu Dhabi, UAE. *Basrah Journal of Science*, *30*(2), 31-49.

Toseland, A. D. S. J., Daines, S. J., Clark, J. R., Kirkham, A., Strauss, J., Uhlig, C., ... & Mock, T. (2013). The impact of temperature on marine phytoplankton resource allocation and metabolism. *Nature Climate Change*, *3*(11), 979-984.

Uddin, S., Gevao, B., Al-Ghadban, A. N., Nithyanandan, M., & Al-Shamroukh, D. (2012). Acidification in Arabian Gulf–Insights from pH and temperature measurements. *Journal of Environmental Monitoring*, *14*(5), 1479-1482.

Vaughan, G. O., Al-Mansoori, N., & Burt, J. A. (2019). The Arabian Gulf. In *World seas: An environmental evaluation* (pp. 1-23). Academic Press.

Wang, Z., DiMarco, S. F., Jochens, A. E., & Ingle, S. (2013). High salinity events in the northern Arabian Sea and Sea of Oman. *Deep Sea Research Part I: Oceanographic Research Papers*, *74*, 14-24.

Williams, A. K., McInnes, A. S., Rooker, J. R., & Quigg, A. (2015). Changes in microbial plankton assemblages induced by mesoscale oceanographic features in the northern Gulf of Mexico. *PloS One*, *10*(9), e0138230.

Woodward, J. R., Pitchford, J. W., & Bees, M. A. (2019). Physical flow effects can dictate plankton population dynamics. *Journal of the Royal Society Interface*, *16*(157), 20190247.

Wu, J. T., & Chou, J. W. (1998). Dinoflagellate associations in Feitsui Reservoir, Taiwan. *Botanical Bulletin of Academia Sinica*, *39*, 137-145.

Wynne, D., & Rhee, G. Y. (1986). Effects of light intensity and quality on the relative N and P requirement (the optimum N: P ratio) of marine planktonic algae. *Journal of Plankton Research*, *8*(1), 91-103.

Yamaguchi, M., Shigeru, I., Nagasaki, K., Matsuyama, Y., Uchida, T., & Imai, I. (1997). Effects of temperature and salinity on the growth of the red tide flagellates Heterocapsa circularisquama (Dinophyceae) and Chattonella verruculosa (Raphidophyceae). *Journal of Plankton Research*, *19*(8), 1167-1174.

Yao, F. (2008). Water mass formation and circulation in the Persian Gulf and water exchange with the Indian Ocean - PhD, University of Miami. Florida, USA.

Zimmerman, R. C., Hill, V. J., Long, M. H., & Burdige, D. (2019, December). Ocean Acidification, Climate Warming and Seagrass Meadows in the Anthropocene. In *AGU Fall Meeting Abstracts* (Vol. 2019, pp. OS11C-1492).

Zhao, J., & Ghedira, H. (2014). Monitoring red tide with satellite imagery and numerical models: a case study in the Arabian Gulf. *Marine Pollution Bulletin*, *79*(1-2), 305-313.

List of Publication

Al-Hashmi, K. A., Piontkovski, S. A., Bruss, G., Hamza, W., Al-Junaibi, M., Bryantseva, Y., & Popova, E. (2019). Seasonal variations of plankton communities in coastal waters of Oman. Int J Oceans Oceanogr, 13(2), 395-426.

Hamza, W., Al Junaibi, M., Pintkovski, S., & Al Hashmi, K. (2020). Comparatitive plankton dynamic in Arabian Gulf and Sea of Oman at opposite Sides of the Strait of Hormus. In *Geolinks international conference*. Volume 2 Book 2. doi:10.32008/geolinks2020/b2/v2.

Appendices

Appendix – I

Table 8: List of monthly identified Phytoplankton species composition during study period from April 2018- until May 2019 at RAK station.

Species name / Months	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Bacillariophyta														
Achnanthes fimbriata	■													
Amphiprora angustata			■			■				■				
Amphiprora gigantea v. sulcata						■					■		■	
Amphiprora sp.												■		
Amphora acutiscula			■		■	■		■	■	■	■	■		
Amphora arcuate						■		■						
Amphora arcus					■	■								
Amphora bigibba	■													
Amphora cf. laevissima							■							
Amphora coffeaformis						■		■	■	■				■
Amphora crassa	■				■									
Amphora cuneate					■			■		■				
Amphora cymbaphora								■						
Amphora cymbifera	■				■			■		■	■			■
Amphora graeffeana	■			■	■		■	■			■	■		
Amphora holsatica			■	■			■	■		■	■			■
Amphora laevis					■					■				■
Amphora lineolate			■											
Amphora marina			■	■	■		■	■	■	■	■		■	
Amphora obtuse						■		■				■		■
Amphora obtussa v. crassa								■						
Amphora ocellata								■						
Amphora ostrearia			■	■										

Amphora plativalvata								■						
Amphora proteus			■	■	■	■	■	■	■	■	■	■	■	■
Amphora rhombica v. intermedia														
Amphora sp.			■	■	■	■	■	■	■			■	■	
Amphora sp. 1	■			■		■					■			
Amphora sp. 2						■								
Amphora sp. 3						■								
Amphora spectabilis							■	■						
Amphora subangularis						■		■					■	
Amphora subcuneata								■	■		■			
Amphora turgida			■		■	■	■				■	■		
Ardissonea Formosa					■									
Ardissonea fulgens					■						■			
Ardissonea sp.					■									
Asterionellopsis glacialis														■
Bacillaria paxillifera			■	■	■	■	■	■			■			■
Bacillariophyceae sp.	■			■	■	■	■	■	■	■	■	■	■	■
Bacillariophyceae sp. 1								■	■					
Bacillariophyceae sp. 2								■						
Bacillariophyceae sp. 3								■						
Biremis ambigua	■							■						
Caloneis excentrica			■								■			
Caloneis sp.								■						
Campilodiscus sp.									■	■			■	
Ceratoneis closterium			■	■		■	■			■		■	■	■
Cocconeis sp.						■								
Diploneis bombus v. bombiformis										■		■		
Diploneis chersonensis									■					
Diploneis crabro					■									
Diploneis crabro v. excavata							■	■						

Diploneis crabro v. pandura														■
Diploneis didyma								■		■	■	■	■	
Diploneis smithii							■							
Diploneis smithii v. rombica										■				
Diploneis sp.			■		■									
Diploneis weissflogii			■				■	■		■	■		■	
Donkinia carinata			■											
Donkinia recta			■			■		■						
Donkinia sp.						■								
Entomoneis sp.					■									
Fallacia nummularia								■						
Fallacia sp.									■					
Fragilaria distans			■											
Fragilaria nana								■						
Fragilaria sp.	■													
Fragillariopsis sp.					■						■			
Grammatophora marina			■											
Grammatophora oceanica					■			■						
Gyrosigma acuminatum	■		■		■			■		■	■			
Gyrosigma balticum					■					■			■	
Gyrosigma cf. macrum										■	■			
Gyrosigma cf. wansbeckii	■		■		■	■	■		■	■	■			
Gyrosigma reversa			■	■	■	■				■	■			
Gyrosigma sp.					■			■						
Gyrosigma tenuissimum	■						■	■			■			
Halamphora angularis					■		■	■			■		■	
Hantzschia distinctepunctata							■	■	■					
Hantzschia marina			■											
Hantzschia pulchella							■			■				
Hantzschia sp.								■						

Hantzschia virgate							■							
Haslea balearica									■				■	
Haslea crusigera			■											
Haslea gigantean									■	■				
Haslea howeana			■	■										
Haslea ostrearia			■											
Haslea sp.											■		■	
Haslea wawrikia							■							
Lampriscus shadboltianum										■	■		■	■
Licmophora abbreviate				■	■									
Licmophora sp.					■						■			■
Lioloma pasifica			■			■	■		■			■		■
Lithodesmium minuta												■	■	
Lithodesmium undulatum								■						
Lyrella hennedyi			■											
Lyrella abrupta			■								■			
Lyrella atlantica					■							■		
Lyrella clavata								■						
Lyrella lyra v. subcarinata			■			■	■		■					
Lyrella lyroides					■		■							
Lyrella sp.			■											
Lyrella sp. 1					■									
Lyrella sp. 2					■									
Mastogloia Arabica			■			■	■				■			
Mastogloia decussate				■	■	■		■			■			■
Mastogloia erythraea						■								
Mastogloia macdonaldii								■						
Mastogloia sp.					■	■								
Mastoneis biformis			■	■	■	■	■	■		■		■		
Meuniera membranacea												■	■	

Navicula arenaria v. rostellata								■	■					
Navicula besarensis			■				■							
Navicula cancellata					■			■			■			
Navicula directa												■		■
Navicula erifuga			■					■						
Navicula johannrossii							■				■			
Navicula palpebralis			■											
Navicula pavillardii					■									
Navicula perrhombus			■											
Navicula platyventris			■											
Navicula sp.	■		■	■	■	■	■	■		■	■	■		
Navicula sp. 1					■	■				■				■
Navicula sp. 2						■				■				
Navicula sp. 3					■					■				
Nitzschia distans				■	■									
Nitzschia distans v. tumenses										■				
Nitzschia flanatica			■											
Nitzschia fluminensis			■											
Nitzschia incurvata v. lorenziana			■	■	■	■	■	■	■	■	■	■	■	
Nitzschia laceolata			■											
Nitzschia laevis			■					■			■			
Nitzschia lanceolate												■		
Nitzschia linkei							■							
Nitzschia longissimi			■		■	■			■					
Nitzschia longissima v. parva			■								■			
Nitzschia reversa			■							■				
Nitzschia rhopaloides			■											
Nitzschia scalpelliformis				■									■	
Nitzschia sigma			■		■	■	■	■		■	■	■		
Nitzschia sp.				■	■	■	■	■		■	■	■	■	

Nitzschia sp. 1			■		■	■		■		■				
Nitzschia sp. 2			■		■	■		■		■				
Nitzschia sp. 3			■		■	■								
Nitzschia tenuirostris						■	■	■	■	■	■	■	■	■
Nitzschia ventricosa						■			■					
Oestrupia Musca					■			■			■		■	
Opephora pacifica					■									
Opephora schwarzii										■				
Petrodictyon gemma			■											
Petroneis marina						■								
Pinnularia bistriata			■											
Pinnularia crusiformis			■											
Pinnularia sp.					■									
Plagiogrammopsis sp.											■	■	■	
Plagiogrammopsis vanheurckii											■			
Plagiotropis lepidoptera			■	■	■	■	■	■		■	■	■	■	■
Plagiotropis tayrecta					■		■							
Pleurosigma cuspidatum			■	■										■
Pleurosigma diverse-striatum			■				■	■			■	■		
Pleurosigma elongatum					■									
Pleurosigma elongatum v. fallax			■	■	■	■	■		■					
Pleurosigma formosum			■	■	■		■					■		
Pleurosigma inflatum			■	■	■				■	■		■		■
Pleurosigma intermedium			■	■	■	■								
Pleurosigma marinum					■									
Pleurosigma sp.							■							
Pleurosigma strigosum						■								
Protoraphys hustedtiana						■								
Protoraphys sp.					■									
Psammodictyon panduriforme	■				■			■						

Psammodictyon panduriforme v. continua							■	■	■	■	■	■		
Psammodictyon roridum			■	■						■				
Pseudo-nitzschia caliantha			■	■	■	■	■	■		■		■	■	■
Pseudo-nitzschia cf. americana									■		■			■
Pseudo-nitzschia cf. multistriata			■			■	■		■		■	■		■
Pseudo-nitzschia cf. subfraudulenta	■		■						■				■	■
Pseudo-nitzschia delicatissima									■	■	■			
Pseudo-nitzschia pungens										■	■	■	■	■
Pseudo-nitzschia sp.				■	■								■	■
Rhopalodia sp.										■				
Roperia tesselata			■											
Seminavis strigose			■											
Shionodiscus oestrupii							■	■	■		■			■
Stauroneis glacialis								■						
Striatella unipunctata				■	■									
Surirella fastuosa v. cuneata														■
Surirella hybrid					■									
Surirella pandura	■													
Tetramphora decussate			■	■	■	■	■				■	■	■	
Thalassionema fraunfeldii			■			■	■	■	■	■	■	■		■
Thalassionema nitzschioides					■	■	■	■	■	■	■	■	■	■
Thalassionema pseudonitzschioides					■	■		■		■	■	■	■	■
Toxarium hennedyanum						■								
Trachyneis aspera	■			■	■			■						
Trachyneis sp.					■						■			
Trachyneis sp. 1					■									
Trachyneis sp. 2					■									
Trachyneis valata							■							
Triblionella marginulata			■											

Dinophyta														
Alexandrium catenella									■					
Alexandrium minutum												■		
Alexandrium ostenfeldii			■											
Alexandrium pseudogonyaulax							■							
Alexandrium tamarense							■							
Alexandrium tamiyavanichii														■
Ceratium furca			■				■						■	
Ceratium fusus			■				■							
Ceratium kofoidii														■
Ceratium tripos	■						■							
Dinophyceae sp.	■				■			■	■	■				■
Dinophyceae sp. 1							■							
Dinophyceae sp. 2							■							
Dinophyceae sp. 3							■							
Dinophysis caudate			■											
Dinophysis miles	■													
Dinophysis sacullus										■				
Diplopelta bomba			■											
Diplopsalis lenticular			■				■						■	
Diplopsalopsis orbicularis							■							
Gonyaulax fragilis					■									
Gonyaulax monocantha							■							
Gonyaulax spinifera			■											
Gymnodinium sp.								■						
Heterocapsa rotundata							■						■	■
Karenia brevis								■						
Karenia mikimotoi						■								
Margalefidinium polykrikoides							■							
Oblea rotunda							■							

Ornithocercus magnificus							■							
Phalacroma rotundatum							■							
Prorocentrum balticum							■							
Prorocentrum compressum					■									
Prorocentrum cordatum			■	■										
Prorocentrum lima			■				■							
Prorocentrum micans				■			■							
Prorocentrum nux							■							
Prorocentrum rhathymum			■											
Prorocentrum scutellum			■											
Prorocentrum sp.			■											
Prorocentrum triestinum						■	■						■	
Protoceratium reticulatum	■													
Protoperidinium brevipes													■	■
Protoperidinium claudicans										■				
Protoperidinium conicum			■											
Protoperidinium curvipes													■	
Protoperidinium depressum													■	
Protoperidinium divergens							■						■	
Protoperidinium oceanicum			■				■						■	
Protoperidinium ovum			■											
Protoperidinium pentagonum			■											
Protoperidinium quadrioblongum			■											
Protoperidinium sp.			■		■									■
Protoperidinium steinii							■							
Protoperidinium subinerme														■
Pseudophalacroma nasutum							■							
Pyrophacus steinii			■				■							
Scrippsiella trochoidea			■											■
Other														

Chlorophyceae sp.	■								■					■
Coccolithophyceae sp.										■				
Crucigenia tetrapedia								■						
Cyanophyceae sp.			■									■		
Dictyocha fibula									■	■		■	■	
Ebria tripartite								■						
Halosphaera viridis				■					■					
Phaeocystis pouchetii			■											
Pterosperma cristatum									■	■				
Trichodesmium errythraeum			■				■							
Umbilicosphaera sibogae								■						

Table 9: List of monthly identified Phytoplankton species composition during study period from April 2018- until May 2019 at SOH station.

Species name / Months	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Bacillariophyta														
Amphora proteus				■							■			
Bacillariophyceae sp.			■	■					■		■			
Bacteriastrum delicatulum							■	■			■			
Bacteriastrum hyalinum								■	■					■
Bellerochea horologicalis										■				
Cerataulina dentate														
Cerataulina pelagica							■	■		■	■			
Chaetoceros affinis			■						■					
Chaetoceros brevis											■			
Chaetoceros compressus											■			■
Chaetoceros costatus								■		■				
Chaetoceros curvisetus							■							

Chaetoceros decipiens										■				■
Chaetoceros diversus														■
Chaetoceros lorenzianus											■			■
Chaetoceros pseudocurvisetus										■	■			■
Chaetoceros socialis							■	■		■	■			
Chaetoceros tortissimus											■			■
Corethron histrix									■	■	■			
Coscinodiscus marginatus									■	■				
Coscinodiscus wailesii				■										■
Cyclotella litoralis									■					
Cyclotella striata					■									
Cylindrotheca closterium							■	■	■		■			
Dactyliosolen fragilissimus							■	■	■	■				
Diploneis bombus								■			■			
Eucampia cornuta									■	■	■			
Eucampia zodiacus								■		■	■			
Guinardia delicatula											■			
Guinardia flaccida			■				■							
Guinardia striata			■				■				■			
Gyrosigma macrum									■					
Gyrosigma tenuissimum										■				
Haslea balearica							■		■		■			
Haslea sp.										■				
Hemiaulus chinensis							■	■		■				
Hemiaulus hauckii			■				■							

Hemiaulus membranaceus							■			■				
Lauderia annulata							■	■		■	■			■
Leptocylindrus danicus			■		■		■	■			■			
Leptocylindrus mediterraneus								■						
Leptocylindrus minimus							■	■						
Lioloma pasifica			■	■			■	■		■				
Meuniera membranacea							■	■		■				
Navicula flanatica											■			
Navicula pavillardii									■					
Navicula platyventris										■				
Navicula sp.				■			■							
Nitzschia bicapitata							■			■				
Nitzschia longissima			■											
Nitzschia lorenziana								■	■					
Nitzschia reversa				■										
Nitzschia sigma							■							
Nitzschia sigma							■							■
Nitzschia sp. 1								■						
Nitzschia sp. 2								■						
Nitzschia tenuirostris			■				■							
Planktoniella sol				■			■	■	■	■				
Pleurosigma decorum				■										
Pleurosigma elongatum									■					
Pleurosigma formosum									■					
Pleurosigma inflatum									■					

Proboscia alata					■		■		■	■	■			
Pseudo-nitzschia cf. calliantha								■	■		■			
Pseudo-nitzschia delicatissima			■	■	■		■	■	■	■	■			■
Pseudo-nitzschia multistriata								■			■			
Pseudo-nitzschia pungens					■		■	■	■	■	■			■
Pseudo-nitzschia seriata			■		■		■	■			■			
Rhizosolenia bergonii								■	■					
Rhizosolenia cochlea											■			
Rhizosolenia hebetata											■			
Rhizosolenia hyalina									■					
Rhizosolenia robusta				■										■
Rhizosolenia setigera							■	■			■			
Rhizosolenia shrubsolei							■	■		■	■			
Rhizosolenia sp.										■				
Rhizosolenia styliformis									■					
Skeletonema grevillei								■	■	■	■			
Stephanopyxis palmeriana										■				
Thalassionema frauenfeldii								■						
Thalassionema nitzschioides				■				■	■	■	■			
Thalassiosira concava				■	■		■			■				
Thalassiosira decipiens							■	■	■					
Thalassiosira delicatula					■			■	■	■	■			
Thalassiosira diporocyclus											■			
Thalassiosira eccentrica										■				
Thalassiosira minima								■			■			

Thalassiothrix longissima								■		■				
Dinophyceae														
Akashiwo sanguinea								■						
Alexandrium catenella							■							
Alexandrium pseudogonyaulax							■							
Alexandrium tamiyavanichii									■					
Amphidinium carterae								■						
Ceratium furca									■					
Ceratium kofoidii								■						■
Ceratium macroceros					■									
Ceratium pentagonum									■					
Ceratium trichoceros														■
Ceratium tripos			■											
Dinophyceae sp.			■		■		■	■	■	■	■			■
Dinophyceae sp. 1								■	■					
Dinophyceae sp. 2								■	■					
Dinophysis acuminata					■									
Dinophysis caudata									■					
Dinophysis miles			■											
Diplopelta bomba										■				
Diplopsalis lenticula									■		■			
Gonyaulax polygramma									■					
Gonyaulax sp.									■					
Gymnodinium najadeum										■	■			
Gymnodinium simplex			■		■		■	■	■		■			■
Gymnodinium sp.			■					■		■				

Gymnodinium sp. 1							■		■					
Gymnodinium sp. 2							■		■					
Gymnodinium uberrimum								■						
Gymnodinium wulffii					■									
Gyrodinium fusiforme								■					■	
Gyrodinium fussus								■						
Gyrodinium nasutum								■						
Gyrodinium pingue								■						
Gyrodinium sp.								■						
Heterocapsa circularisquama			■				■							
Heterocapsa pygmaea								■						
Heterocapsa rotundata			■				■	■	■		■			■
Heterocapsa triquetra							■	■						
Heterocorys horrida								■						
Karenia seliformis							■							
Karenia umbella							■							
Margalefydinium polykrikoides							■							
Mesoporos perforatus								■						
Monaster rete			■											
Oxytoxum scolopax			■											
Oxytoxum variabile							■		■					
Phalacroma rotundatum			■											
Podolampas bipes			■											
Prorocentrum balticum							■	■			■			
Prorocentrum compressum			■							■	■			

Prorocentrum cordatum			■				■	■	■	■	■			■
Prorocentrum gracile			■				■				■			
Prorocentrum micans									■		■			
Prorocentrum rathimum								■	■					
Prorocentrum sp.								■	■					
Prorocentrum triestinum											■			
Protoceratium reticulatum										■				
Protoperidinium bipes				■			■							
Protoperidinium brevipes							■							
Protoperidinium conicum								■	■					
Protoperidinium divergens								■	■					
Protoperidinium oblongum			■											
Protoperidinium oviforme			■				■	■						
Protoperidinium sinaicum			■											
Protoperidinium sp.											■		■	
Scrippsiella irregularis				■			■	■	■	■	■			
Scrippsiella spinifera							■		■					
Other														
Calciosolenia murrayi							■							
Chlorophyceae sp.					■		■							
Chlorophyceae sp. 1								■						
Chlorophyceae sp. 2								■						
Chrysochromulina parkeae									■					
Coccolithophyceae sp.							■	■	■					
Coccolithophyceae sp. 1									■					
Coccolithophyceae sp. 2									■					

Coccolithus pelagicus					■		■							
Cryptophyceae sp.			■	■	■		■		■					
Cryptophyceae sp. 1								■						
Cryptophyceae sp. 2								■						
Cyanophyceae sp.			■	■			■		■					
Desmodesmus seratus					■									
Dictyocha fibula									■	■	■			
Dictyocha speculum				■										
Dinematomonas litoralis								■						
Emiliania huxleyi			■				■		■	■				
Euglenophyceae sp. 1									■					
Euglenophyceae sp. 2									■					
Eutreptiella sp.								■						
Flagellata sp.				■	■		■	■	■	■	■		■	■
Flagellata sp. 1			■					■	■					
Flagellata sp. 2			■					■	■					
Gephyrocapsa sp.								■						
Heterosigma akashiwo								■	■					
Hillea fusiformis							■							
Hyalosphaera viridis									■					
Microcystis sp.							■							
Octactis octonaria				■										
Phaeocystis globose								■						
Phaeocystis pouchetii														■
Pontosphaera nigra					■					■				

Pronoctiluca sp.							■							
Rhodomonas sp.								■						
Scenedesmus sp.											■			
Trichodesmium errythraeum							■	■						
Umbilicosphaera sibogae								■		■				

Appendix – II

Table 10: List of monthly identified Zooplankton species composition during study period from April 2018- until May 2019 at RAK station.

Species name / Months	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Calanoida														
Acartia amboinensis		╲											■	■
Acartia plumose		╲						■			■	■	■	■
Acartia spp.		╲	■	■	■	■	■							
Acrocalanus spp.		╲							■	■				
Bestiolina Arabica		╲											■	
Bestiolina spp.		╲	■	■	■	■	■	■	■	■				■
Bestiolina zeylonica	■	╲	■		■					■				
Calanidae		╲							■				■	
Calanoida	■	╲	■	■	■	■	■	■	■	■	■	■	■	■
Calanopia spp.		╲	■			■	■		■	■		■		
Centropages spp.		╲		■		■	■	■	■	■	■	■	■	■
Centropages tenuiremis		╲												■
Clausocalanus spp.		╲											■	
Eucalanidae		╲											■	
Paracalanus aculeatus minor		╲							■					
Paracalanus indicus	■	╲							■	■			■	■
Paracalanus spp.		╲							■	■	■		■	
Parvocalanus crassirostris var.	■	╲	■	■	■			■		■	■	■	■	■
Parvocalanus elegans	■	╲							■	■	■	■	■	■
Parvocalanus spp.	■	╲	■	■	■	■	■	■	■	■	■	■	■	■
Pontellidae		╲							■					

Pseudodiaptomus arabicus
Pseudodiaptomus spp.
Subeucalanus spp.
Subeucalanus subcrassus
Temora spp.
Temora turbinate
Cyclopoida
Corycaeus lubbocki
Corycaeus spp.
Cyclopoida
Dioithona oculata
Oithona attenuate
Oithona brevicornis smaller form
Oithona brevicornis typical form
Oithona plumifera
Oithona simplex
Oithona spp.
Oncaea clevei
Oncaea spp.
Harpacticoida
Euterpina acutifrons
Ectinosomatidae
Harpacticoida
Microsetella spp.

Table 11: List of monthly identified Zooplankton species composition during study period from April 2018- until May 2019 at SOH station.

Species name / Months	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Calanoida														
Acartia amboinensis	╲	╲	■	■	■	╲	■	■	■	■	■	╲		■
Acrocalanus gibber	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	
Acrocalanus gracilis	╲	╲	■		■	╲		■	■	■		╲		
Acrocalanus longicornis	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	■
Bestiolina Arabica	╲	╲		■		╲						╲		
Bestiolina spp.	╲	╲		■	■	╲		■	■			╲		
Bestiolina zeylonica	╲	╲		■		╲						╲		
Calanidae	╲	╲	■		■	╲	■	■	■	■		╲	■	
Calanoida	╲	╲	■		■	╲	■	■	■	■		╲	■	■
Calanopia elliptica	╲	╲	■			╲	■					╲		
Calanopia minor	╲	╲				╲	■	■				╲		
Calanopia spp.	╲	╲	■			╲	■	■		■		╲	■	
Calocalanus plumulosus	╲	╲		■	■	╲	■	■	■	■	■	╲		■
Calocalanus spp.	╲	╲			■	╲				■		╲		
Candacia bradyi	╲	╲	■		■	╲	■			■		╲		
Candacia curta	╲	╲				╲	■				■	╲		
Candacia spp.	╲	╲	■		■	╲	■	■				╲		
Canthocalanus pauper	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	■
Centropages furcatus	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	■
Centropages orsinii	╲	╲		■	■	╲	■	■	■		■	╲	■	■
Centropages spp.	╲	╲	■			╲						╲		
Centropages tenuiremis	╲	╲	■			╲						╲	■	■

Clausocalanus farrani	╲	╲				╲			■	■		╲	■	
Clausocalanus furcatus	╲	╲				╲	■		■	■	■	╲	■	
Clausocalanus minor	╲	╲				╲	■			■		╲	■	
Clausocalanus spp.	╲	╲				╲		■	■	■	■	╲	■	■
Cosmocalanus darwinii	╲	╲				╲		■			■	╲		
Eucalanidae	╲	╲	■			╲	■	■	■	■	■	■		■
Euchaeta indica	╲	╲				╲				■		╲		■
Euchaeta spp.	╲	╲	■		■	╲	■	■	■	■	■	╲		
Labidocera acuta	╲	╲	■		■	╲				■		╲		■
Labidocera minuta	╲	╲	■			╲		■		■		╲		
Labidocera pavo	╲	╲		■		╲						╲		
Labidocera spp.	╲	╲	■	■	■	╲				■		╲		
Nannocalanus minor	╲	╲				╲	■	■		■		╲		
Paracalanus aculeatus	╲	╲			■	╲	■	■	■	■	■	╲	■	■
Paracalanus aculeatus minor	╲	╲		■	■	╲	■	■			■	╲	■	■
Paracalanus denudatus var.	╲	╲	■	■	■	╲	■	■		■	■	╲	■	■
Paracalanus indicus	╲	╲	■		■	╲	■	■	■	■	■	╲	■	■
Paracalanus spp.	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	
Paracalanus tropicus	╲	╲				╲	■			■		╲	■	
Paraeuchaeta concinna	╲	╲				╲		■		■	■	╲		
Parvocalanus elegans	╲	╲	■		■	╲	■	■	■		■	╲		
Pontellidae	╲	╲				╲		■	■	■	■	╲		
Pseudodiaptomus arabicus	╲	╲				╲	■					╲	■	
Pseudodiaptomus serricaudatus	╲	╲			■	╲	■	■		■		╲	■	■
Scolecithricella spp.	╲	╲			■	╲						╲		

Subeucalanus crassus	╲	╲			■	╲	■			■		╲		
Subeucalanus mucronatus	╲	╲	■			╲						╲		
Subeucalanus pileatus	╲	╲	■		■	╲	■	■	■	■	■	╲	■	
Subeucalanus pileatus var. "right"	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	■
Subeucalanus pileatus+subcrassus	╲	╲		■	■	╲		■	■	■		╲	■	
Subeucalanus subcrassus	╲	╲	■	■	■	╲	■	■	■	■	■	╲		■
Temora discaudata	╲	╲		■	■	╲		■				╲		
Temora turbinata	╲	╲		■	■	╲	■	■	■	■	■	╲	■	■
Cyclopoida														
Copilia mirabilis	╲	╲	■	■	■	╲	■	■		■	■	╲	■	■
Copilia quadrata	╲	╲		■		╲		■				╲		
Copilia spp.	╲	╲				╲				■		╲		
Corycaeus agilis	╲	╲	■	■		╲	■	■	■	■		■	■	■
Corycaeus andrewsi	╲	╲	■	■	■	╲	■	■	■			╲		■
Corycaeus catus	╲	╲				╲		■			■	╲		
Corycaeus crassiusculus	╲	╲			■	╲				■	■	╲		
Corycaeus dahli	╲	╲			■	╲						╲	■	■
Corycaeus erythraeus	╲	╲			■	╲	■	■	■			■	■	■
Corycaeus lubbocki	╲	╲		■	■	╲		■	■		■	■	■	■
Corycaeus pacificus	╲	╲		■	■	╲	■					■		■
Corycaeus pumilus	╲	╲	■	■	■	╲	■			■		╲	■	
Corycaeus speciosus	╲	╲			■	╲				■		╲		
Corycaeus spp.	╲	╲	■	■	■	╲	■	■	■	■	■	╲	■	■
Corycaeus subtilis	╲	╲				╲	■			■		■	■	■
Cyclopoida	╲	╲	■			╲				■		╲		

Farranula gibbula											■			
Oithona attenuata			■	■			■	■	■		■			
Oithona brevicornis									■	■			■	
Oithona fallax								■		■				■
Oithona nana			■					■	■	■	■		■	■
Oithona plumifera			■	■	■		■	■	■	■	■		■	■
Oithona spp.			■	■	■		■	■	■	■	■		■	■
Oncaea clevei			■	■	■		■	■	■	■	■		■	■
Oncaea mediterranea										■				
Oncaea venusta			■		■		■	■	■	■	■		■	■
Oncaeidae			■	■	■		■	■	■	■	■		■	■
Sapphirina nigromaculata								■						
Sapphirina spp.			■		■		■	■		■				
Triconia conifer					■			■						
Harpacticoida														
Clytemnestra spp.			■	■	■		■		■	■	■		■	■
Ectinosomatidae			■		■			■	■	■	■		■	
Euterpina acutifrons			■	■				■	■	■	■		■	■
Harpacticoida									■					
Macrosetella gracilis			■				■	■		■	■			

Table 12: Monthly comparison between the dominated Phytoplankton and Zooplankton species at RAK and SOH stations during April 2018- May 2019.

	Phytoplankton dominant species		**Zooplankton dominant species**	
Stations /Dates	Ras-Alkaima (RAK)	Sohar (SOH)	Ras-Alkaima (RAK)	Sohar (SOH)
Apr.2018	*Coscinodiscus wailesii* *Surirella pandura* *Biddulphia tuomeyi* *Biremis ambigua* *Psammodictyon panduriforme*		*Euterpina acutifrons* *Temora turbinate* *Oncaea spp.* *Paracalanus indicus* *Oithona nana*	
Jun.2018	*Pyrophacus steinii* *Pleurosigma elongatum v. fallax* *Nitzschia sigma* *Rhizosolenia imbricate* *Pleurosigma diverse-striatum*	Guinardia flaccida Nitzschia longissimi Dinophysis miles Ceratium tripos Prorocentrum compressum	*Oithona brevicornis smaller form* *Copepoda* *Oithona spp.* *Oithona spp.* *Copepoda*	*Paracalanus denudatus var.* *Acrocalanus longicornis* *Paracalanus spp.* *Calanopia spp.* *Canthocalanus pauper*
Jul.2018	*Tetramphora decussate* *Rhizosolenia imbricate* *Pleurosigma intermedium* *Biddulphia tuomeyi* *Pleurosigma formosum*	*Amphora proteus* *Coscinodiscus wailesii* *Rhizosolenia robusta* *Pleurosigma decorum* *Lioloma pasifica*	*Oithona spp.* *Bivalvia* *Copepoda* *Gastropoda* *Oithona brevicornis smaller form*	*Bestiolina zeylonica* *Centropages furcatus* *Centropages furcatus* *Temora turbinate* *Paracalanus aculeatus minor*
Aug.2018	*Tetramphora decussate* *Mastogloia decussate* *Mastoneis biformis* *Pleurosigma formosum* *Coscinodiscus marginatus*	*Dinophyceae sp.* *Ceratium macroceros* *Proboscia alata* *Dinophysis acuminate* *Thalassiosira concava*	*Oithona brevicornis smaller form* *Oithona spp.* *Oithona spp.* *Bivalvia* *Copepoda*	*Temora turbinate* *Corycaeus spp.* *Oncaea clevei* *Bestiolina spp.* *Temora turbinata*
Sep.2018	*Coscinodiscus marginatus* *Amphora arcus*		*Oithona brevicornis smaller form* *Bivalvia* *Copepoda*	

	Amphiprora gigantea v. sulcate *Amphiprora angustata* *Amphora rhombica v. intermedia*		*Oithona spp.* *Oithona spp.*	
Oct.2018	*Rhizosolenia imbricate* *Coscinodiscus perforates* *Rhizosolenia setigera f. pungens* *Pleurosigma intermedium*	*Meuniera membranacea* *Proboscia alata* *Haslea balearica* *Guinardia flaccida* *Haslea balearica*	*Oithona spp.* *Copepoda* *Copepoda* *Gastropoda*	*Acrocalanus longicornis* *Paracalanus denudatus var.* *Acartia amboinensis* *Canthocalanus pauper* *Oncaeidae*
Nov.2018	*Plagiotropis lepidoptera* *Coscinodiscus marginatus* *Rhizosolenia cf. Formosa* *Planktoniella sol* *Amphora spectabilis*	*Thalassiothrix longissimi* *Gyrodinium nasutum* *Rhizosolenia bergonii* *Protoperidinium divergens* *Heterocorys horrida*	*Oithona spp.* *Oithona brevicornis smaller form* *Oithona spp.* *Oithona brevicornis smaller form* *Oithona spp.*	*Acrocalanus longicornis* *Acartia amboinensis* *Acrocalanus gibber* *Corycaeus spp.* *Corycaeus spp.*
Dec.2018	*Guinardia flaccida* *Haslea gigantea* *Lauderia annulata* *Coscinodiscus perforates* *Lyrella lyra v. subcarinata*	*Rhizosolenia hyaline* *Pleurosigma formosum* *Rhizosolenia bergonii* *Haslea balearica* *Pleurosigma formosum*	*Copepoda* *Oithona spp.* *Oithona simplex* *Copepoda* *Calanoida*	*Macrosetella gracilis* *Corycaeus spp.* *Corycaeus spp.* *Calanoida* ***Oncaea clevei***
Jan.2019	*Guinardia flaccida* *Rhizosolenia setigera* *Hantzschia pulchella* *Coscinodiscus wailesii* *Rhizosolenia imbricata*	*Stephanopyxis palmeriana* *Thalassiothrix longissimi* *Lioloma pasifica* *Rhizosolenia sp.*	*Oithona spp.* *Copepoda* *Copepoda* *Oithona spp.* *Calanoida*	*Acrocalanus longicornis* *Eucalanidae* *Temora turbinate* *Clausocalanus farrani* *Clausocalanus spp.*
Feb.2019	*Guinardia flaccida* *Coscinodiscus sp.* *Navicula cancellata*	*Guinardia striata* *Rhizosolenia hebetate* *Rhizosolenia cochlea*	*Copepoda* *Copepoda* *Copepoda*	*Canthocalanus pauper* *Temora turbinate* *Temora turbinate*

	Coscinodiscus perforates *Trieres mobiliensis*	*Proboscia alata*	*Pseudodiaptomus spp.* *Oithona spp.*	*Oithona spp.* *Temora turbinate*
Mar.2019	*Lauderia annulata* *Guinardia flaccida* *Coscinodiscus marginatus* *Pleurosigma formosum* *Coscinodiscus marginatus*	*Coscinodiscus wailesii* *Chaetoceros lorenzianus* *Rhizosolenia robusta* *Ceratium trichoceros* *Lauderia annulata*	*Pseudodiaptomus spp.* *Copepoda* *Copepoda* *Pseudodiaptomus spp.* *Oithona spp.*	*Corycaeus lubbocki* *Corycaeus pacificus* *Corycaeus subtilis* *Corycaeus erythraeus* *Corycaeus agilis*
Apr.2019	*Guinardia flaccida* *Rhizosolenia hyaline* *Rhizosolenia imbricate* *Guinardia flaccida* *Proboscia indica*		*Oithona spp.* *Oithona spp.* *Copepoda* *Oithona spp.* *Euterpina acutifrons*	*Temora turbinate* *Temora turbinate* *Temora turbinate* *Acrocalanus longicornis* *Oncaeidae*
May.2019	*Coscinodiscus sp.* *Guinardia flaccida* *Rhizosolenia hyaline* *Haslea sp.* *Amphiprora gigantea v. sulcate*		*Oithona spp.* *Copepoda* *Oithona brevicornis typical form* *Oithona spp.* *Pseudodiaptomus spp.*	*Oncaea clevei* *Corycaeus spp.* *Temora turbinate* *Corycaeus spp.* *Subeucalanus pileatus var. "right"*