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ORIGINAL RESEARCH ARTICLE

Observed variability in physical and biogeochemical parameters in the central Arabian Gulf

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Abstract *In situ* measurements of physical and biogeochemical variables were conducted along a transect in the Exclusive Economic Zone (EEZ) of Qatar during late summer (September 2014) and winter (January 2015) to investigate their vertical, spatial and temporal variability. The study reveals that the water column is characterized by strong stratification during late summer in the deepest station, where the water depth is around 65 m and the surface to bottom temperature variation is around 9.1°C. The water column is vertically homogeneous during winter due to surface cooling and wind mixing. The surface to 23 m water column is characterized by ample dissolved oxygen (DO) during late summer and winter in the offshore regions, however, relatively low DO is found during late summer due to weak mixing and advection under weak winds and currents. Dissolved oxygen drops to hypoxic levels below the summer thermocline, and the winter high DO layer extends up to the bottom. Chlorophyll-*a* (Chl-*a*) is relatively high during late summer in the offshore region, while that in the nearshore regions is very low, which is linked to the anthropogenic stresses from the central east coast of Qatar. The results identified in this study fill an essential gap in the knowledge of regional primary production dynamics.

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1. Introduction

The Arabian Gulf (hereinafter referred to as "the Gulf") is a semi-enclosed shallow water body, located between 24°N and 30°N and connected to the Arabian Sea through the Strait of Hormuz (Figure 1a). The physical and biogeochemical aspects of the Gulf are unique due to its hypersaline nature and are modulated by the seasonal variability of the driving forces (Yigiterhan et al., 2020). The surface circulations in the Gulf are primarily connected to the seasonal winds, excessive heating/cooling and fresh water discharge from the Shatt-al-Arab River (Chao et al., 1992). However, the vertical distribution and spatial variability of physical and biogeochemical parameters in the Gulf are not only linked with the surface circulations, but also formed as a result of the exchange of water masses between the Gulf and the Sea of Oman (Reynolds, 1993). Anthropogenic pollutant influxes from the onshore and offshore facilities will also alter the sea water properties of the Gulf to a good extent (Freije, 2015).

Shamal winds are the dominant wind systems in the Gulf, which occur during summer and winter (Perrone, 1981; Rao et al., 2001). These winds are relatively stronger and persistent during winter, causing relatively high evaporation during winter than summer (Al-Ansari, 2006). Sea surface temperature (SST) in the Gulf is primarily controlled by the excessive heating during summer and cold and dry winds during winter; evaporation is much higher than the net precipitation and river discharges (Alosairi et al., 2020; Noori, et al., 2019; Reynolds, 1993). Such climate-induced variabilities are also evident in other physical and chemical parameters in the Gulf such as salinity, density, dissolved oxygen (DO) and chlorophyll-*a* (Chl-*a*) (Al-Ansari et al., 2015; Quigg et al., 2013; Subba and Al-Yamani, 1998). For instance, Al-Ansari et al. (2015) identified summer hypoxia events below 50 m depth in the central Gulf, which is peculiar to the Exclusive Economic Zone (EEZ) of Qatar in view of the seasonal variation.

During the past few decades, the marine and coastal environments of the Gulf have been subject to increasing human-induced pressures due to extensive infrastructure developmental activities, growth of coastal population, industrial and urban pollution (Rabaoui, et al., 2020; Sheppard et al., 1992). Dredging and land reclamation operations have resulted in ecological imbalances and increased environmental stresses. The impact of these stresses on the long-term sustainability of marine ecosystems in the EEZ of Qatar is not yet fully understood.

The present study aims at investigating the physical and biogeochemical variabilities, especially the distribution of temperature, salinity, density, water masses, DO and Chl-*a* in two different seasons (summer and winter) and the role of currents in the transport of these variables. A preliminary investigation on the physical and biogeochemical parameters in the EEZ of Qatar is important to assess the seasonal and spatial variabilities, and understanding their role in the ecosystem alterations. The significance of this work stems out from the following studies: (i) Regional and seasonal hydrography in the prediction of effects of environmental stress and global change, (ii) water column structure and water mass distribution to determine the properties and status of various habitats and (iii) assessment of water quality, marine productivity and ecological status by monitoring marine biogeochemical parameters.

The paper has been organized as follows: Section 2 frames the area of study, Section 3 details the data and methodology, Section 4 explains the major inferences and discussions and Section 5 summarises the important findings.

2. Area of study

Qatar Peninsula is located at the central Gulf with approximate dimensions of 85 $\times$ 160 km (area: $\approx$ 11,437 km^2) projecting northwards from the Arabian Peninsula into the Gulf, centred at 25°N and 51°E. The geographical setting of Qatar peninsula firmly influences the currents, waves and sedimentation pattern along the central and southern Gulf. Several other elements of the ecosystem such as biological productivity and nutrient regeneration might also be influenced by physical and geographical settings (Al-Ansari, 2006). The EEZ of Qatar occupies the region between the longitudes of 51°00′E and 52°30′E and the latitudes of 24°50′N and 26°58′N (Figure 1b). The total area of the EEZ is about 35,000 km^2 (Al-Ansari, 2006).

3. Data and methods

The vertical profiles of physical variables in the water column were measured using Conductivity-Temperature-Depth (CTD) system (SBE-911plus CTD) onboard r/v *Janan* during September 2014 and January 2015 (hereafter referred to as late summer and winter, respectively) at five sampling locations (Figure 1b), representing different water masses. The density, often represented by potential density (sigma-t), has been obtained from the CTD records using the formula described in Fofonoff and Millard (1983). Sea water samples for the analysis of biogeochemical parameters, DO and Chl-*a*, were collected using new, acid cleaned PVC-Niskin bottles of 12-litre capacity, attached to the Seabird CTD system. Multiple samples were collected from each sampling location at different depths.

The Niskin bottles were pre-cleaned using hot tap water, followed by double distilled (DD) water, then with dilute hydrochloric acid (HCl) and finally rinsed with double distilled de-ionized (DDI) Milli-Q water for 3 times. Samples for the determination of DO were first to be drained from the Niskin bottles. During draining, air bubble formation on the inner surface of hose was prevented. The protocol described by Parsons et al. (1984) was followed for sample preparation. The sample bottles were stored in cold and dark place and further analyses were carried out in the laboratory using classic Winkler method (Winkler, 1888). For the determination of Chl-*a*, the samples were filtered through 47 mm diameter, 0.45 μm Millipore nitrocellulose membrane filters in reduced light using Millipore glass filtration apparatus. During the filtration, a few drops of saturated $MgCO_3$ suspension (1%), shaken vigorously before use, were added. The filter papers were folded into aluminium foil, and instantly frozen at −20°C until the analysis is done using spectrophotometer (Parsons et al., 1984).

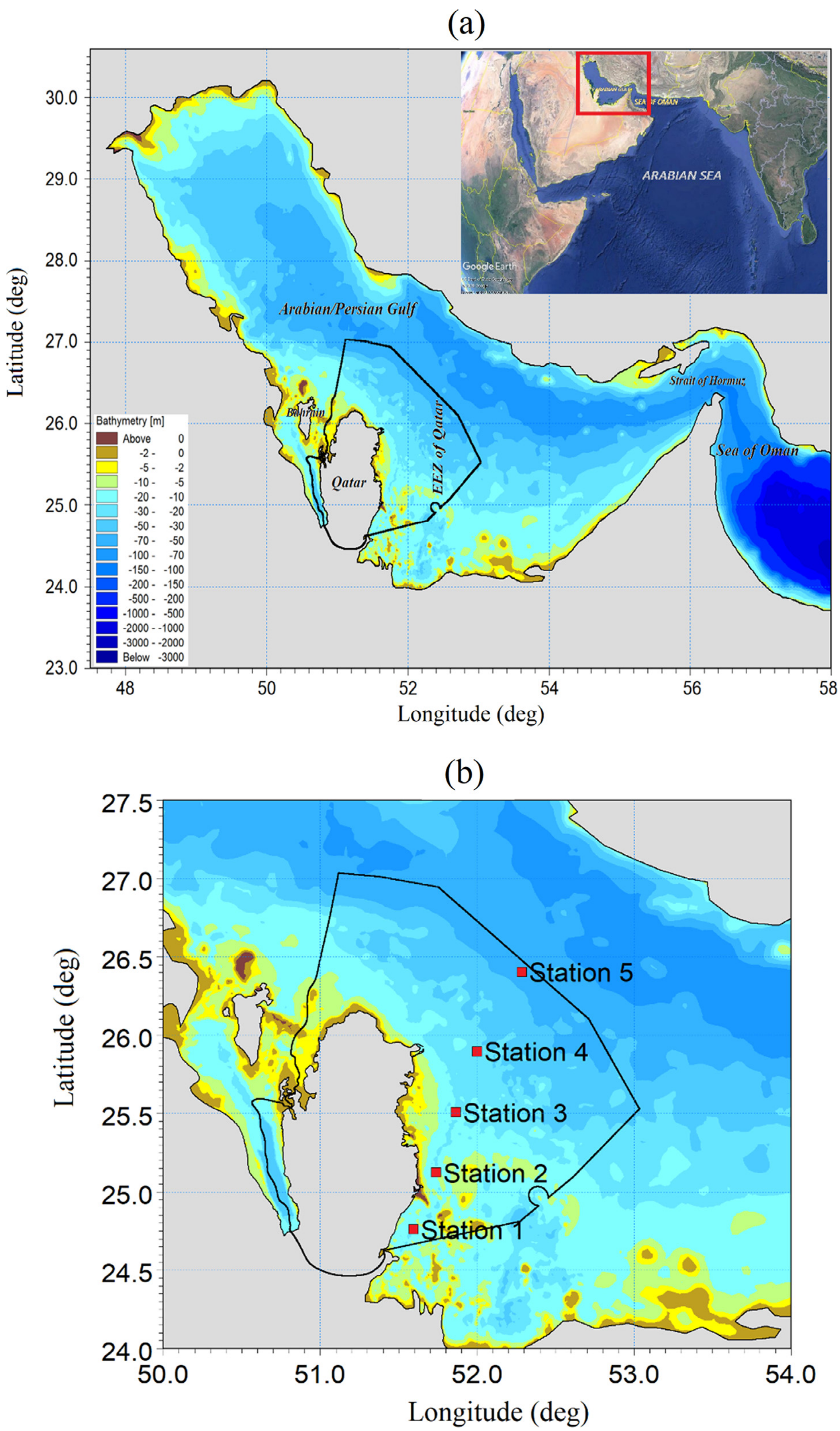

Figure 1 (a) The Arabian Gulf and the Exclusive Economic Zone (EEZ) of Qatar and (b) the sampling stations, located in the EEZ of Qatar.

Table 1 Variation in temperature (°C), salinity, potential density (kg/m^3), DO concentration (mL/L) % and Chl-*a* (μg/L) at five locations in a transect in the EEZ of Qatar during late summer and winter.

Stn. No.	Depth (m)	Temp. (°C) Sum.'14	Temp. (°C) Win.'15	Salinity Sum.'14	Salinity Win.'15	Sigma-t (kg/m^3) Sum.'14	Sigma-t (kg/m^3) Win.'15	DO (mL/L) Sum.'14	DO (mL/L) Win.'15	Chl-*a* (μg/L) Sum.'14	Chl-*a* (μg/L) Win.'15
1	**2**	32.9	19.3	44.76	44.39	28.002	32.138	3.63	4.89	0.81	4.05
	10	32.9	19.6	44.89	45.77	28.107	33.125	3.50	4.75	1.65	5.13
	26	33.3	19.6	45.70	45.88	28.575	33.195	2.67	4.71	0.73	3.46
2	**2**	33.2	19.6	41.48	41.66	25.439	29.961	3.57	4.94	0.68	4.57
	10	33.0	19.4	41.60	41.74	25.601	30.069	3.65	4.79	1.66	4.63
	23	33.0	19.5	41.88	41.76	25.802	30.077	3.63	4.83	0.80	4.94
3	**2**	33.1	20.7	39.64	40.77	24.108	28.979	3.82	5.01	6.04	3.25
	10	33.1	20.6	39.95	40.83	24.339	29.068	3.68	4.86	7.41	2.91
	23	33.3	20.2	40.84	41.04	24.925	29.319	3.16	4.78	4.83	5.91
4	**2**	32.8	22.0	38.85	40.31	23.626	28.276	4.25	5.06	6.44	5.73
	10	32.9	21.9	39.08	40.34	23.757	28.311	4.08	4.92	1.80	4.46
	28	33.0	21.1	39.81	40.73	24.266	28.841	3.02	4.68	2.55	6.13
5	**2**	32.6	22.3	39.44	40.09	24.136	28.012	3.97	4.59	9.39	4.82
	15	32.4	22.3	39.79	40.09	24.471	28.004	3.29	4.58	7.92	4.58
	32	30.6	22.3	40.25	40.11	25.478	28.014	1.97	4.51	10.00	2.94
	47	26.6	22.3	40.31	40.15	26.854	28.043	1.41	4.49	5.61	6.39
	55	23.6	22.3	40.57	40.17	27.988	28.058	1.46	4.43	9.28	6.69
	63	23.5	22.3	40.58	40.17	28.023	28.057	1.35	4.53	0.41	4.28

The processed data has been analysed and respective distribution plots have been made using Ocean Data View (ODV) 4.0 (Brown, 1998).

4. Results and discussion

4.1. Seasonal variations in the physical variables

The temperature, salinity and density show significant seasonal variations in the EEZ of Qatar (Table 1). The temperature variations during late summer and winter are 23.5—33.3°C, 19.3—22.3°C, respectively, where higher horizontal and vertical variability is found during late summer. This is because the EEZ of Qatar is affected by excessive heating of the sun, resulting in the formation of warm surface layer characterized with low density, which is separated from the bottom cold water by the seasonal thermocline layer (Figure 2a). Though sea water temperature is lower during winter, higher evaporation occurs due to strong winds, especially due to winter shamal winds (Reynolds, 1993), leading to mixing of the water column. There exists seasonal difference in salinity, although it is small; 38.85—45.70 and 40.09—45.88, respectively during late summer and winter. However, the vertical variation in salinity (a difference of 1.14) in the deepest station (Stn. 5) during late summer is not strong enough to have a well-defined stratification (Figure 2b), unlike that found in temperature distribution. There is a well-marked difference in salinity between Stn. 1 and other stations in both the seasons. The higher salinity (>44) observed at Stn. 1 is associated with the brine discharges from the desalination plants situated in the central east coast of Qatar, which remains consistent across the seasons. This impact is also evident in the nearest station (Stn. 2), where the salinity in both the seasons is above 41, while all other stations show relatively low salinity. The cumulative effect of brine discharges in the recent decades along the Arabian coast is evident from the exceptional salinity distributions at respective coastal areas (Ibrahim et al., 2020; Ibrahim and Eltahir, 2019).

Seasonal variability in density is observed in the EEZ of Qatar (Table 1), where the potential densities during late summer and winter are 23.626—28.575 kg/m^3 and 28.004—33.195 kg/m^3, respectively. The higher densities of each season are found in the nearshore station (Stn. 1), where the impact of brine discharge is significant. In the far offshore station (Stn. 5), the vertical variation in density is negligible during winter. This is because the water column is well-mixed due to the influence of strong winter shamal winds. However, there is a sharp increase in density during late summer, from surface to a depth of 55 m; beyond that, the density is constant. Vertical stratification occurs during late summer in the offshore regions, which is distinguished by two-layers, wind-driven and density-driven flows in the Gulf (Figure 3) (Reynolds, 1993). The seasonal variability in density in the offshore regions is clearly evident as seen in the box plots (Figure 4c) to which the major contribution is coming from the temperature (Figure 4a), while the salinity has no remarkable variation between the seasons (Figure 4b).

The spatial averaged values in different depth layers, between surface to 32 m (Table 2) show that the mean temperature is constant in the top two layers (2 m and 10—15 m), while a decrease of 0.3°C has been found in the 32 m depth in late summer and winter. The mean salinity increases with the depth in both the seasons, in which a relatively sharp increase (0.64) is found during late summer

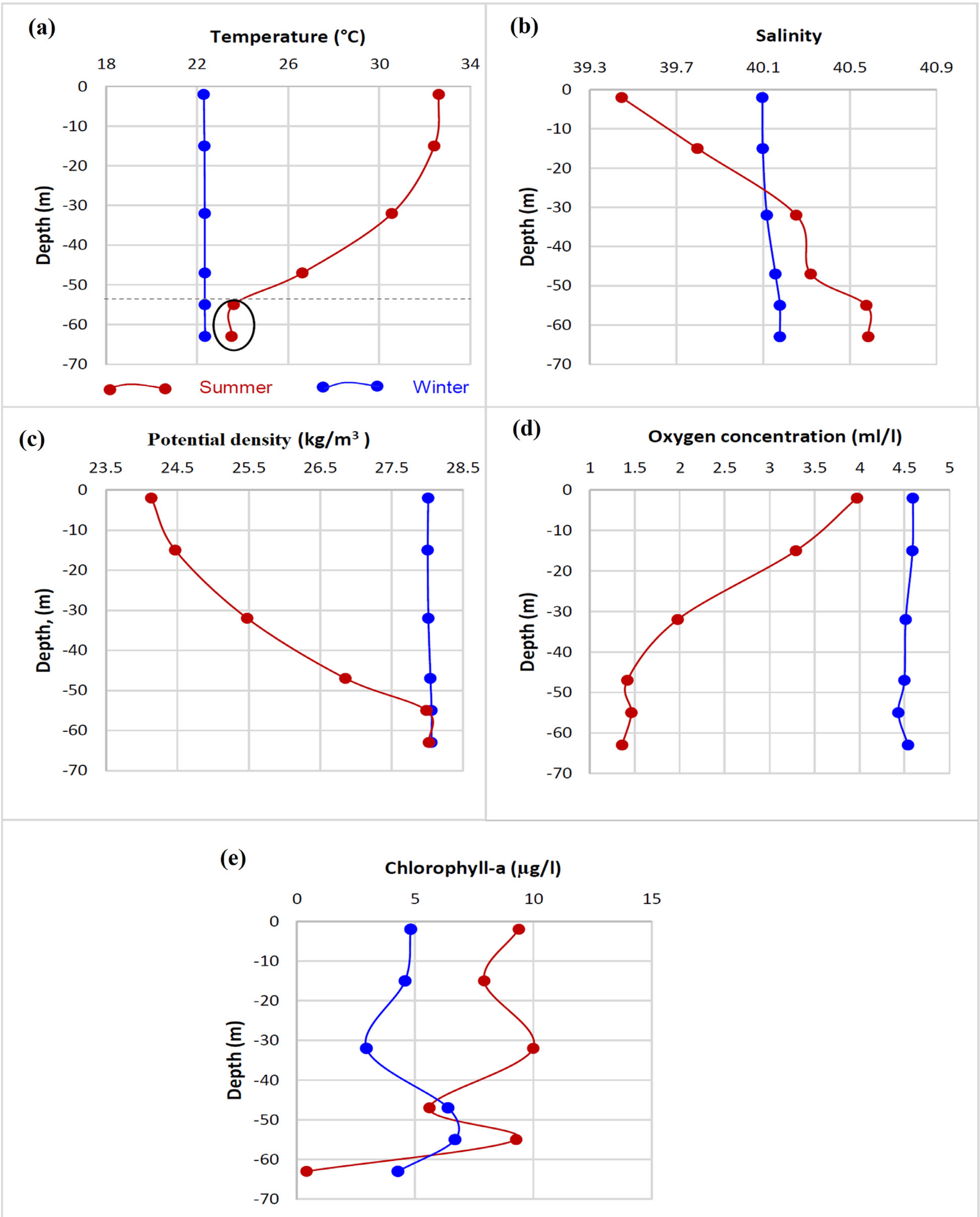

Figure 2 Profiles of (a) temperature (°C), (b) salinity, (c) potential density (kg/m^3), (d) dissolved oxygen concentration (DO, mL/L) and (e) Chl-*a* (µg/L) at Station 5 during summer and winter seasons (September 2014 — red) and (January 2015 — blue). (The plots are made using *Ocean Data View 4.0*.)

Table 2 Statistics of measured temperature (°C), salinity, potential density (sigma-t), DO (mL/L), DO saturation (%) and Chl-*a* concentration (μg/L) at five locations in a transect in the EEZ of Qatar during late summer and winter seasons.

Parameter	Sampling period					
	September 2014 (late summer)			January 2015 (winter)		
Depth	2 m	10—15 m	32 m*	2 m	10 m	32 m*
Temperature (°C)						
Mean	32.9	32.9	32.6	20.8	20.8	20.5
Minimum	32.6	32.4	30.6	19.3	19.4	19.5
Maximum	33.2	33.1	33.3	22.3	22.3	22.3
Salinity (PSU)						
Mean	40.83	41.06	41.70	41.44	41.75	41.90
Minimum	38.85	39.08	39.81	40.09	40.09	40.11
Maximum	44.76	44.89	45.70	44.39	45.77	45.88
Sigma-t (kg/m^3)						
Mean	25.062	25.255	25.809	29.473	29.715	29.889
Minimum	23.626	23.757	24.266	28.012	28.005	28.014
Maximum	28.002	28.108	28.576	32.138	33.125	33.195
Dissolved Oxygen (mL/L)						
Mean	3.85	3.64	2.89	4.90	4.78	4.70
Minimum	3.57	3.29	1.97	4.59	4.58	4.51
Maximum	4.25	4.08	3.63	5.06	4.92	4.83
Chl-*a* (μg/L)						
Mean	4.67	4.09	3.78	4.48	4.34	4.68
Minimum	0.68	1.65	0.73	3.25	2.91	2.94
Maximum	9.39	7.92	10.00	5.73	5.13	6.13

* For the uniformity, the data at 32 m depth is chosen instead of the bottom depth (63 m) to derive the statistics.

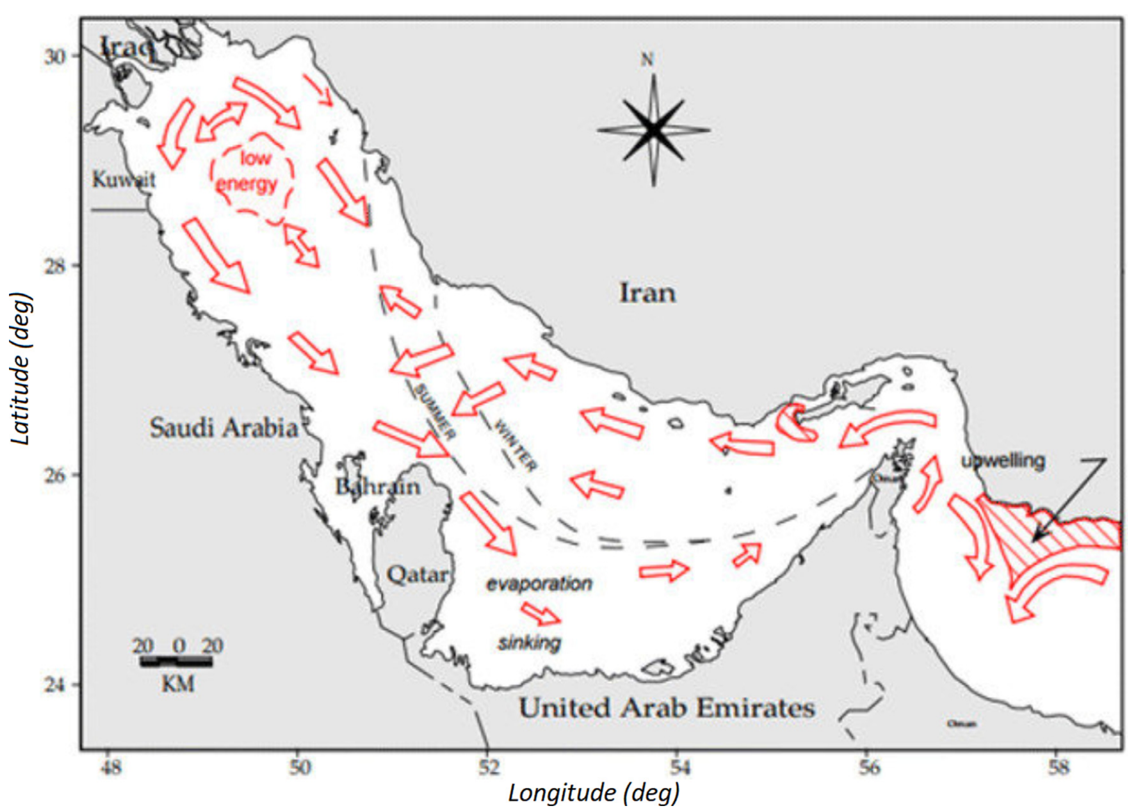

Figure 3 Circulation patterns in the Arabian Gulf (sources: Meshkati and Tabibzadeh (2016), Reynolds, (1993)).

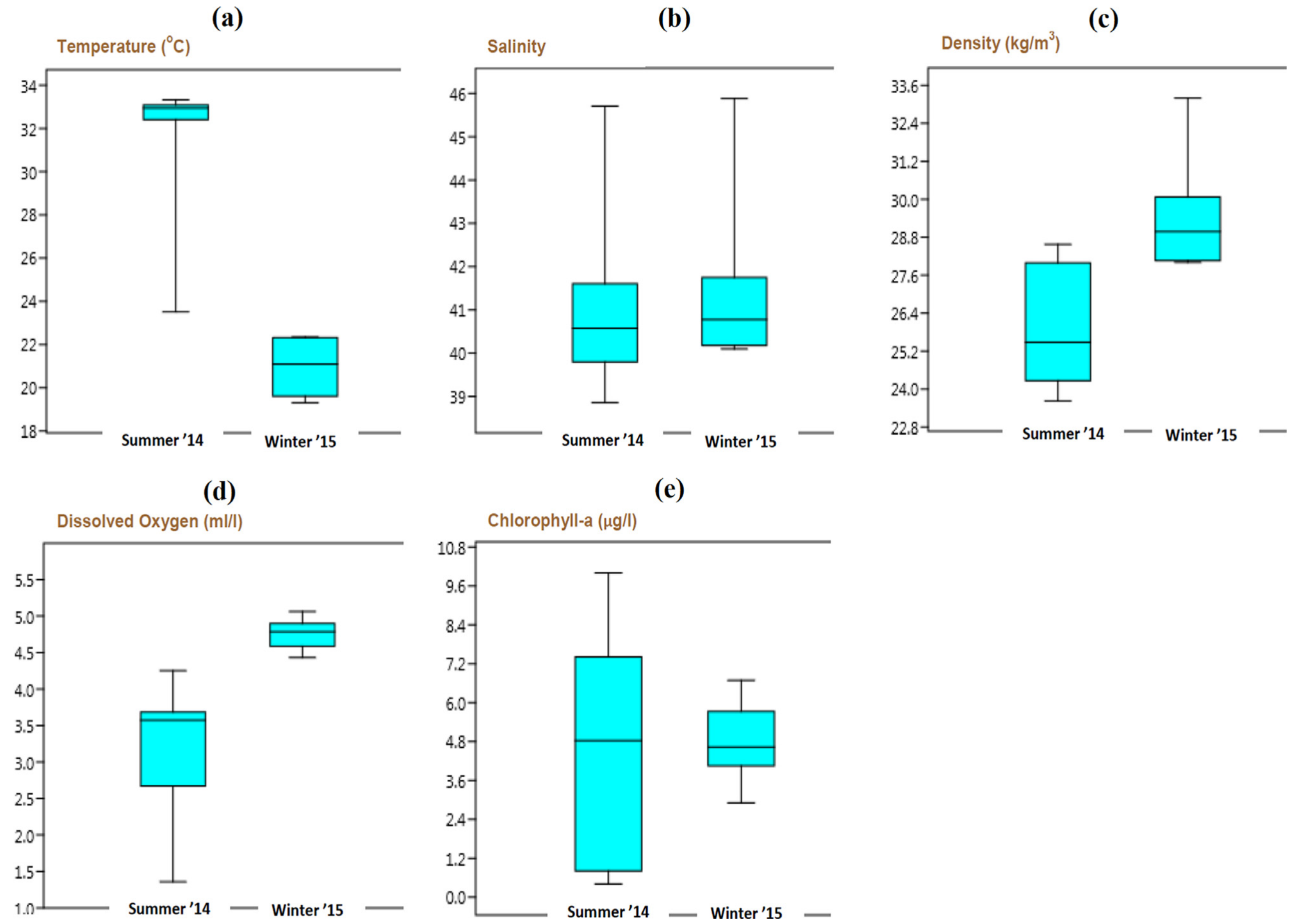

Figure 4 Comparative visualization of (a) temperature, (b) salinity, (c) potential density, (d) DO, and (e) Chl-*a* at Stn. 5 by box plots between late summer 2014 and winter 2015. (The plots are made using *Ocean Data View 4.0.*)

between the bottom two layers (10—15 m and 32 m) compared to the top two layers. Similar variations are found in the mean densities during late summer. These variations are higher than that observed individually in the offshore stations, and reflect the relevance of the nearshore fluxes and processes in maintaining the vertical variations of physical variables in the EEZ of Qatar.

On the other hand, the spatial gradients in salinity and density are evident along the transect in late summer and winter, irrespective of the vertical homogeneity/stratification (Figure 5a—b). The large difference in salinity and density occurred between the nearshore and offshore stations, indicating that the anthropogenic effects, especially the brine discharge, determine the density variations near the coast. Higher stress from onshore/nearshore anthropogenic sources may gradually advect to the adjacent nearshore/offshore region over a period of time, which may further impact the ecosystem.

4.2. Water masses observed off Qatar

The analysis reveals the existence of a few water masses in the Gulf in late summer with very distinct physical properties. They are: (i) Qatari Deep Water (QDW) that prevails below the summer thermocline, (ii) Gulf of Salwa Outflow Water (GSW), (iii) Open Qatari Water (OQW) and (iv) South-eastern Qatari Water (SEQW) (Figure 6). These water masses within the Gulf are balanced by warm, low salinity Gulf of Oman Water (WLSOW), which is a surface inflow from the Sea of Oman characterized by low density. It is more pronounced during late summer than winter. The excess heating within the Gulf over the inflow of WLSOW leads to further increase in salinity and thereby forms the summer thermocline (Al-Ansari et al., 2015). The intrusion of this low salinity (<40) water mass into the Gulf was clearly identified by several researchers (Hunter, 1986; Johns et al., 2003; Reynolds, 1993, 2002; Yoshida et al., 1998).

4.3. Seasonal variations of biogeochemical parameters

4.3.1. Dissolved Oxygen

DO concentration during late summer (1.41—4.25 mL/L) is lower than winter (4.43—5.06 mL/L) in the EEZ of Qatar (Table 1). The strong winds during winter generate turbulence, which brings more oxygen to the subsurface, leading to vertical homogeneity and conserved DO (Figure 2d). A converse situation is found during late summer, when the temperature is high; DO decreases with depth — common in a stratified water column. In the bottom layer below 47 m, the DO concentration during late summer is below 1.5 mL/L (<2 mg/L), leading to hypoxia as evi-

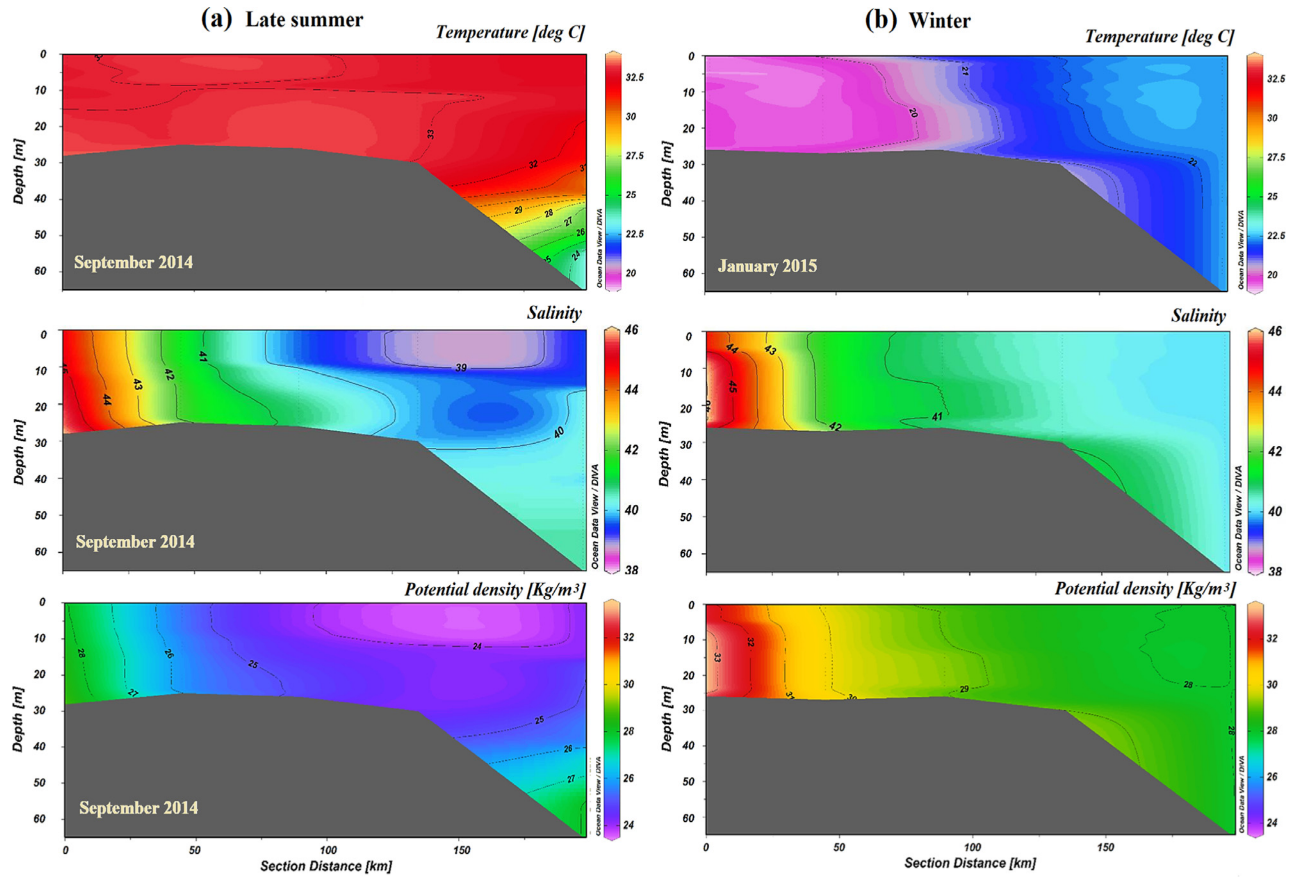

Figure 5 Vertical distribution of temperature (°C), salinity and potential density (kg/m^3) along the transect from Stn. 1 to Stn. 5 during (a) late summer and (b) winter. (The plots are made using *Ocean Data View 4.0.*)

dent by Al-Ansari et al. (2015), causing loss of marine life (Breitburg et al., 2018). The hypoxia in the Gulf occurs when respiration rate exceeds the rate of photosynthesis in the bottom waters (Al-Ansari et al., 2015). The vertical distribution of DO in the offshore station is in direct proportion with that of temperature, and inverse proportion with that of salinity and density, indicating that changes in DO are linked with changes in physical variables (Figure 2a—d). Variation in water temperature has a direct effect on the amount of dissolved gases (Chipman et al., 1992). There exists distinct variability in DO in the EEZ of Qatar among the two seasons as seen in the physical variables (Figure 4a—d). The impact of the water masses (Figure 6) along with the seasonal heating/winds are quite evident in this variability. Typically, DO is a representative of a healthy and functioning ecosystem supporting aquatic life (Desa et al., 2005; EFI, 2010).

The spatial distribution of DO along the transect (Figure 7) shows that DO is at a maximum level during late summer in the surface layer of the offshore regions, while in the nearshore regions it is relatively low. However, the lowest DO during this season is found in the deeper layers of the offshore region. There is no distinct spatial variation in DO during winter in the surface layer of the transect, while a slight decrease is found in the sub-surface and bottom layers of the offshore region. The mean DO concentrations in the surface layers along the transect in the EEZ of Qatar are 3.85 mL/L and 4.90 mL/L, respectively during late summer and winter, which is slightly lower than that observed in a well-oxygenated region in the Gulf (Al-Ansari, 2006).

4.3.2. Chlorophyll-*a*

The EEZ of Qatar is receiving huge amount of solar radiation during summer, and being shallow regions, sunlight reaches to the bottom. This brings a relatively higher Chl-*a* concentration in the surface and subsurface layers during late summer, especially in stations 3 to 5 (Table 1). It is observed that the nutrient levels are low in the euphotic zone of the EEZ of Qatar and Chl-*a* is generally nutrient-limited throughout the year (Al-Ansari, 1998). In the thermocline layer, with the presence of oxygen and sufficient sunlight, the nutrient concentration increases in the subsurface, allowing it to increase the Chl-*a* at the intermediate depths during late summer (Figure 2e). However, in the bottom layers, though nutrients are high, the absence of oxygen and sunlight restricts the values of Chl-*a*, and hence lower values are observed. On the contrary, mixing of water column during winter allows transport of sufficient oxygen to the bottom, and this favours a relatively high Chl-*a* in the bottom layers.

The Chl-*a* concentration in the EEZ of Qatar during late summer varies between 0.41 μg/L and 10 μg/L, and during winter varies between 2.91 μg/L and 6.69 μg/L (Table 2). This shows high spatial variability during late summer than winter (Figure 3e), because the nearshore regions (Stns. 1 and 2) have much lower Chl-*a* concentration during

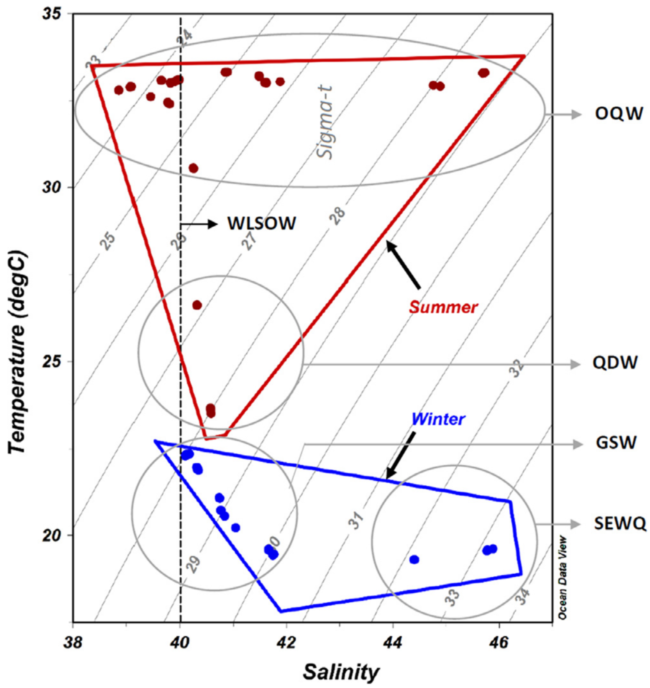

Figure 6 Θ/S diagram and local currents at Stn. 5, representing late summer and winter seasons. The contours indicate the potential density (sigma-t). (The plots are made using *Ocean Data View 4.0.*)

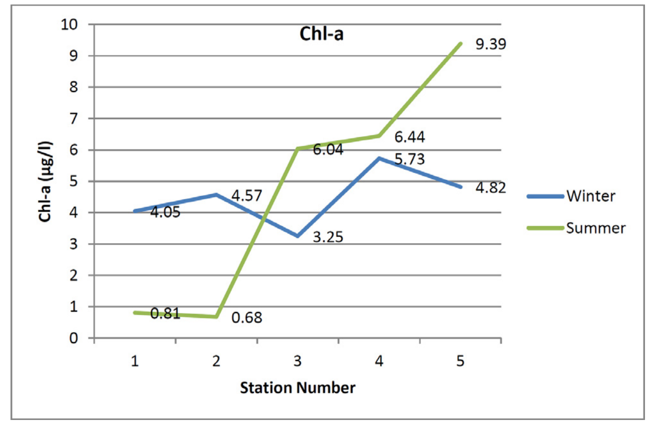

Figure 8 Surface Chl-*a* concentration (µg/L) along the transect from Stn. 1 to Stn. 5 during late summer and winter. (The plots are made using *Ocean Data View 4.0.*)

late summer (Figure 7). The very low wind speeds during September (Aboobacker et al., 2020) restrict mixing of water column, and subsequently advection through wind-induced currents in these regions. Furthermore, the higher salinity induced by brine discharge can also impact the nutrient levels, in the absence of well-mixed behaviour of the water column.

The circulation in the Gulf is dominated by a basin scale, elongated cyclonic eddy during March-July (Thoppil and Hogan, 2010). The northern flank of the cyclonic eddy flows as an intense northwestward coastal current along the Iranian coast and the southern side is characterized with the return flow (southeastward), north of Qatar where Stns. 3, 4 and 5 are located. The cyclonic eddy weakens during July—August and disintegrates into smaller cyclonic eddies. These are upwelling eddies and are capable of supplying nutrients to the upper layers through divergence. These eddies present till November, and become unstable and dissipate during winter period. In the context of currents prevailing in these eddy regimes, the variation of surface layer Chl-*a* is analysed for both summer and winter periods for Stn. 5 (Figure 8). During September, higher values of Chl-*a* are observed in the offshore stations 3, 4 and 5

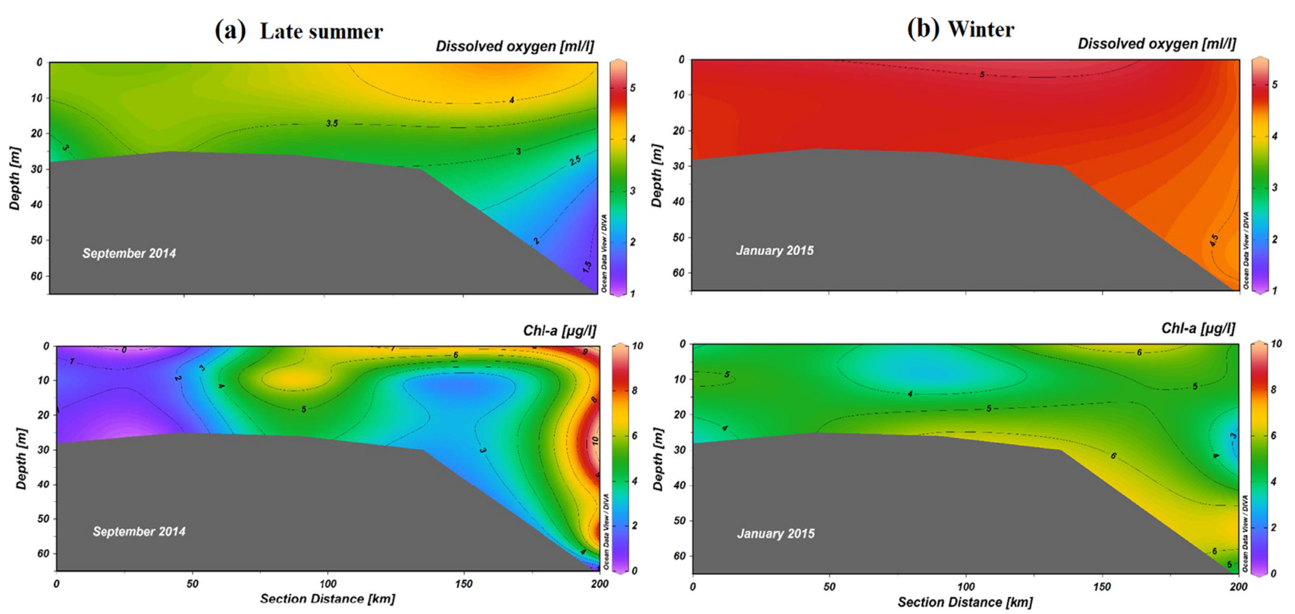

Figure 7 Vertical distribution of DO (mL/L) and Chl-*a* concentration (µg/L) along the transect (Stn. 1 to Stn. 5) during (a) late summer and (b) winter. (The plots are made using *Ocean Data View 4.0.*)

with values ranging between 6.04 and 9.39 μg/L. It is evident that relatively stronger southeasterly currents during September bring in nutrient rich waters of the upwelling eddies present in the central Gulf, and leads to the enhancement of Chl-*a*. However, during winter these eddies collapse and the nutrient supply through cyclonic eddies are reduced to the minimum. At a lower scale, the winter cooling and enhanced wind mixing sustain the Chl-*a* off the east and north coasts of Qatar (surface average of all the 5 stations is 4.48 μg/L).

5. Conclusions

The spatial, temporal and vertical distribution of physical (temperature, salinity, density) and biogeochemical parameters (dissolved oxygen and phytoplankton biomass (Chl-*a*)) were studied in the EEZ of Qatar, central Arabian Gulf. The temperature distribution along the transect shows well-defined variations between late summer and winter, which is a characteristic feature of the Arabian Gulf waters. In winter, the upper layers are more homogenous than the late summer, with less vertical salinity variations. The salinity differences are not significantly different between the two seasons, but the temperature presents distinct variations. The well-mixed, cold waters during January allows the DO to be uniformly distributed with depth, while the stratified waters during September reduce the DO towards the deeper layers in the water column, leading to hypoxic conditions below 47 m depth. Furthermore, interesting variation is observed in Chl-*a* concentration between late summer and winter, and the fluctuation is quite high with depth during late summer, and homogenous during winter. The findings conclude that the productivity of the EEZ waters of Qatar is directly linked to eddy circulation in the central Gulf, winter cooling, wind mixing and disintegration of the cyclonic eddies. Hence, in order to make any assessment of the productivity of Qatari EEZ, the general circulation in the central Gulf has to be investigated in detail.

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