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ORIGINAL RESEARCH ARTICLE

Spatial variability of summer hydrography in the central Arabian Gulf

Elnaiem Ali Elobaid*, Ebrahim M.A.S. Al-Ansari, Oguz Yigiterhan, Valliyil Mohammed Aboobacker, Ponnumony Vethamony

Environmental Science Center (ESC), Qatar University, Doha, Qatar

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Abstract The Arabian Gulf is a very significant ocean body, which hosts more than 55% of the oil reserves of the world and produces about 30% of the total production, and thus, it is likely to face high risk and adverse problems by the intensified environmental stressors and severe climatic changes. Therefore, understanding the hydrography of the Gulf is very essential to identify various marine environmental issues and subsequently, developing marine protection and management plans. In this study, hydrography data collected at 11 stations along 3 linear transects in the early summer of 2016 were analyzed. The physicochemical parameters exhibited apparent variations along each transect, both laterally and vertically, connected to stratification, formation of different water masses and excessive heating. The temperature and salinity decreased laterally from nearshore to offshore, while layered density structures were identified in the offshore regions. The pH, dissolved oxygen (DO) and chlorophyll fluorescence (Fo) exhibited distinct horizontal and vertical variations. The observed pH is within the normal ranges, indicating that seawater acidification may not be a threat. The highest DO (6.13—8.37

* Corresponding author at: Environmental Science Center (ESC), Qatar University, P.O. Box 2713, Doha, Qatar.
E-mail addresses: elnaiemali123@gmail.com, elnaiem@qu.edu.qa (E.A. Elobaid).

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mg/l) was observed in a layer of 24—36 m water depth in the deeper regions of the central transect.

1. Introduction

The Arabian/Persian Gulf (hereafter "Gulf") is a significant pathway from regional and international perspectives, hosting more than 55% of the oil reserves of the world and producing about 30% of the total world oil production (BP, 2011; Soliman et al., 2019). Thus, the Gulf is likely to face high risk and adverse environmental problems due to intensified natural and anthropogenic stressors in addition to climate change effects. The semi-enclosed Gulf is a western arm of the Indian Ocean, covering an area of ≈ 233,100 km^2, length of ≈ 1,000 km, the maximum width of ≈ 338 km, with an average depth of about 36 m (Kampf and Sadrinasab, 2006). This unique physical setting extends within the most saline hyper-arid climate zone of the Arabian Peninsula desert belt, situated within the photic zone, as one of the most saline and hottest water bodies (Sheppard, 1993). In general, the Gulf is characterized by a tidal range of more than 1 m everywhere, with diurnal and semi-diurnal oscillations. The central Gulf waters are characterized by high salinity, which varies between 40 and 50 (Hunter, 1986). This is attributed to the high evaporation rate, which ranges from 144 to 500 cm/y (Brewer and Dyrssen, 1985). These combined factors make the system a reverse estuary and create an anticlockwise Mediterranean-like flow (Al-Majed et al., 2000; Reynolds, 1993; Yoshida et al., 1998).

The Gulf is subject to harsh natural and anthropogenic environmental stressors such as high salinity and extreme temperature during summer. The anthropogenic influence on salinity along the Arabian coast of the central part of the Gulf is mainly due to brine discharge from the desalination plants, resulting in adverse impacts on the marine ecosystem, particularly in the spatial distribution, diversity, existence and abundance of living organisms in this environment (Jones et al., 2002; Prasad et al., 2001; Privett, 1959; Soliman et al., 2019). Despite these harsh conditions, the Gulf hosts distinctive assemblage and habitats (Sheppard et al., 2010), but the natural environmental stressors have been reflected and witnessed by a decrease in the species richness levels (Price, 2002). The hypersalinity has adverse issues on the living organisms of the ecosystem (Joydas et al., 2015). For example, unhealthy benthic communities living in the hypersaline (salinity up to 63) region like the Gulf of Salwa are under high risk of radical natural stressors in comparison with the healthiest benthic communities living in relatively lower salinity regions of the Gulf (such as the east coast of Qatar and the coast of UAE). Moreover, the key physicochemical parameters of the water column, namely, temperature and salinity, influence the dissolution processes, affinity adsorption and mobility of pollutants in the marine environment (Ma et al., 2016; Soliman et al., 2019).

The small and limited freshwater input and high evaporation rate have influence and control on the circulation and water masses of the Gulf (Campos et al., 2020; John et al., 1990; Prasad et al., 2001; Reynolds, 1993), and hence the information on physical oceanographic parameters such as temperature, salinity and density is vital to analyze the horizontal and vertical distribution of the water masses and to assess the diffusive and advection transports within the water column (Al Azhar et al., 2016; Kampf and Sadrinasab, 2006; Pous et al., 2015). The circulation characteristics are important to determine the distribution of sediments, dynamics of nutrients and fate of pollutants (Soliman et al., 2019). Beltagy (1983) reported that the main controlling factors of vertical and horizontal salinity distribution in the Gulf are higher rates of evaporation, seepage of fresh water, brine discharges and evaporitic deposits. The spatial distribution pattern of salinity and temperature have been investigated previously by several researchers (Beltagy, 1983; Emery, 1956; Kampf and Sadrinasab, 2006; Reynolds, 2002; Shepherd, 1993). They reported that the salinity decreases towards the offshore areas, and increases within the coastal areas and ports, whereas temperature decreases from the coastline towards the offshore and also decreases as depth increases.

A detailed understanding of spatial variability of physicochemical parameters is important to analyze the physical and biogeochemical interactions and their impact on the marine ecosystem of the central Gulf. There are very few studies in this part of the Gulf on the spatial variability of physical and biogeochemical parameters. The present study aims at understanding the spatial variability in the physicochemical parameters of the central Gulf by analyzing the measured hydrographic data during summer. The role of different water masses and seasonal stratification in the biogeochemical processes of Qatar's Exclusive Economic Zone (QEEZ) have been addressed. The study also explores the statistical relationship between various physicochemical key parameters.

The paper is organized as follows: Section 2 describes the area of study, Section 3 explains the data and methodology used, Section 4 explains the important results and their discussions, and Section 5 summarizes the major inferences.

2. Area of study

The Qatar Peninsula is situated in the central Gulf with an area of 11,437 km^2, centered at 25°N and 51°E. The EEZ of Qatar is located between the longitudes 51°00′E and 52°30′E and latitudes 24°50′N and 26°58′N (Figure 1), with an area of 35,000 km^2 (Al-Ansari, 2006). The winds are predominantly from the NW-N directional sector, where the highest wind speeds of the order of 22 m/s are due to shamal winds (Aboobacker et al., 2021a). The surface currents within the QEEZ are mainly wind-driven; however, the deeper regions are influenced by thermohaline circulation

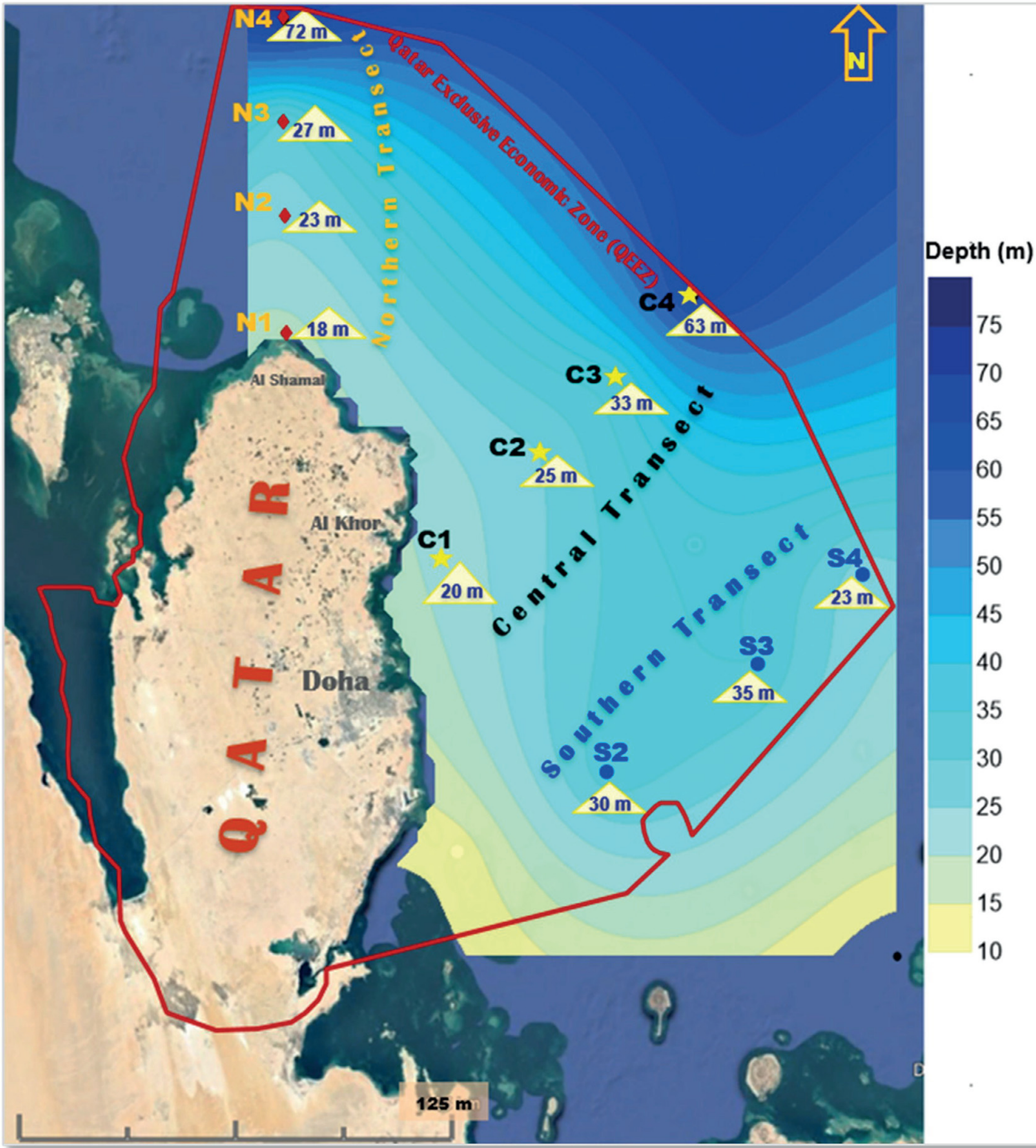

Figure 1 Area of study with sampling stations along the three transects together with generalized bathymetry (bathymetry data is retrieved from Ocean Data View). The water depth of each station, measured using echo-sounder onboard r/v *Janan*, is given inside the yellow triangle. Bathymetry contours are generated using Surfer software.

(Chao et al., 1992; Thoppil and Hogan, 2010). The physical processes such as circulation, eddy formation and sedimentation in the QEEZ are largely influenced by the geographical setting of the Qatar peninsula, which in turn influence the development/survival of the ecosystem (Al-Ansari, 2006).

In this study, we considered 3 major transects with a total of 11 stations. The transects are directed from the coastline towards the deep sea, more or less perpendicular to the coast as shown in Figure 1. The southern transect is about 110 km long, occupying three stations S2, S3 and S4; the central transect is about 100 km long with four stations C1, C2, C3 and C4; the northern transect is about 90 km long with four stations N1, N2, N3 and N4.

3. Data and methodology

The physicochemical parameters such as temperature (T), salinity (S), density (D), pH, dissolved oxygen (DO), chlorophyll fluorescence and the water column depth were measured using SeaBird-911plus CTD and auxiliary sensors, manufactured by Seabird Scientific Company and used onboard R.V Janan. Seasoft software was integrated to the CTD system for the simultaneous processing of the data. The vertical sampling frequency of the CTD was set to 1.0 m. The bin size was 1.0 m and the raw data was averaged over each bin. The accuracies of conductivity, temperature and pressure are ± 0.0003 S/m, $\pm 0.001°$ and 0.015% of full-scale range, respectively. The potential density (sigma-t), calculated using the formula described in Fofonoff and Millard (1983), was obtained from the CTD records.

The processed physicochemical parameters have been analyzed to derive their spatial variabilities. Ocean Data Viewer (ODV) software version 5.03 was used to create the 2D profiles of temperature, salinity, density, pH, dissolved oxygen (DO), and fluorescence (Schlitzer, 2020). The Pearson correlation matrix method was performed using SPSS version 25 to evaluate the statistical relationship between the physicochemical key parameters.

4. Results and discussion

4.1. Distribution of temperature, salinity and density

The distribution of physicochemical parameters in the Gulf is primarily controlled by the geographical settings, air-sea interactions and ocean processes (Figure S1). For instance, higher salinity is observed along the Arabian coast of the Gulf, where the evaporation is much higher (144 cm/y) and the freshwater influx is very low (1,456 m^3/s) (Reynolds, 1993). As a result, higher salinity water masses are formed in the southern coast of the Gulf (Al-Ansari, 2006 and Rivers et al., 2019). In addition to natural processes, anthropogenic forcing in the form of brine discharges from the desalination plants operated along the Arabian coasts may also add an accountable amount of salinity to the nearshore waters, although their impact in the deeper waters is not that significant (Ibrahim et al., 2020; Ibrahim and Eltahir, 2019; Rakib et al., 2021). Our analysis shows that higher salinity in each transect is found in the nearshore stations, and the salinity gradually decreases towards offshore as shown in the generalized spatial contour map (Figure 2).

A wedge-like intrusion of low saline water is visible in the offshore, deeper regions of the central transect, which is quite unique compared to the other two transects. This is in agreement with the pattern of low salinity intrusion identified from the Arabian Sea to the Gulf by Ghaemi et al. (2021). This is linked with the exchanges between the Gulf of Oman and the Arabian Gulf, which are driven by the differences in sea surface heights of the two regions (Swift and Bower, 2003) and also due to baroclinic forcing developed by the density gradients (Chao et al. 1992; Yao and Johns, 2010). The exchanges are intensified following an enhanced two-layer flow during late winter through early summer, whilst the flow diminishes during mid-summer to mid-winter (Vasou et al., 2020). Among the three transects, the highest salinity is found in the northern transect, and it could be attributed to the following reasons: (i) higher evaporation due to relatively stronger winds in the offshore region (deeper) compared to the nearshore region (shallower) (Aboobacker et al., 2021b), (ii) considerable heating because of very shallow depths, (iii) advection of hypersaline Gulf of Salwa Water (GSW) (Al-Ansari et al., 2015) and (iv) dispersion of brine discharged from the desalination plants situated along the northeast coast of Qatar. The higher evaporation along with dense water flow from the northern Gulf has got prime importance in higher salinity in the northern transect (Smith et al., 2007). Recent studies point out that the hypersalinity in the southwestern Gulf at specific locations can also be attributed to the presence of desalination plants (Ibrahim and Eltahir, 2019), though the general surface circulation of the Gulf does not permit building-up of salinity.

In the nearshore regions of the northern transect, temperature, salinity and density are relatively higher compared to the surface layer of other stations (Figure 3a1, a2, a3). The temperature and salinity in the nearshore regions are vertically homogeneous due to limited depths of the water column, whereas they decrease from nearshore to offshore. In the offshore, there is a distinct vertical variability in temperature and salinity, especially with substantially low saline water in the surface layer and low temperature in the bottom layer both leading to vertical stratification. These differences are reflected in the density distribution with distinct patterns, indicating the presence of two water masses. Earlier studies indicate that the low salinity water mass, Indian Ocean Surface Water (IOSW) intrudes up to the central Gulf during summer (Kampf and Sadrinasab, 2006). Although similar features (salinity and density variations) are found in the central transect, more investigations are needed to establish the intrusion of IOSW up to the east coast of Qatar as the salinity differences obtained in this study are relatively small. In addition, the sea surface temperature (SST) has shown little variation from nearshore to offshore (Figure 3b1, b2, b3), which is due to the excessive surface heating distributed equally in the central Gulf during summer compared to the other regions (Van Lavieren et al., 2011). Interestingly, there is a sublayer of intermediate density, indicating the role of eddies in the central Gulf (Reynolds, 1993). The low salinity surface water of the order of 38.5—40.0 and 38.2—39.5 in the northern and central transects, respectively, point to the exchange of low salinity water from the Sea of Oman to the offshore regions of QEEZ. The region of influence of this low salinity surface water and the dense bottom water is small in the southern transect as identified by their minimal vertical variations (Figure 3c2, c3). The vertical variation in temperature is also not significant in this transect (Figure 3c1).

The vertical variation in temperature, salinity and density is significant only in the deepest stations among all the transects (Figures 4a, b, c). The temperature variations in the northern, central and southern transects during early summer are in the range of 19.9°—30.2°C, 20.2°—28.4°C and 26.8°—28.7°C, respectively (Table S1). The salinity variations in the above transects are 38.7—42.2, 38.5—40.9 and 39.6—40.1, respectively. Previous studies identified a significantly higher salinity (above 44) along the nearshore regions of Doha and Mesaieed, the central east coast of Qatar during the summer of 2000 (Abdel-Moati and Al-Ansari, 2000; Rakib et al., 2021). However, our present analysis does not represent these coastal stations as they are far from the transects under consideration. It is worthy to note that the central east coast of Qatar is housing several desalination plants, which are discharging a high amount of brine into the sea. In the GCC countries, for every 1 m^3 fresh water produced, 2 m^3 brine is generated and discharged into the Gulf (Sezer et al., 2017). Brine can drop the level of DO in seawater near desalination plants with "profound impacts" on benthic biota such as shellfish and crabs on the seabed. The ambient salinity in the vicinity of the outfalls might have in-

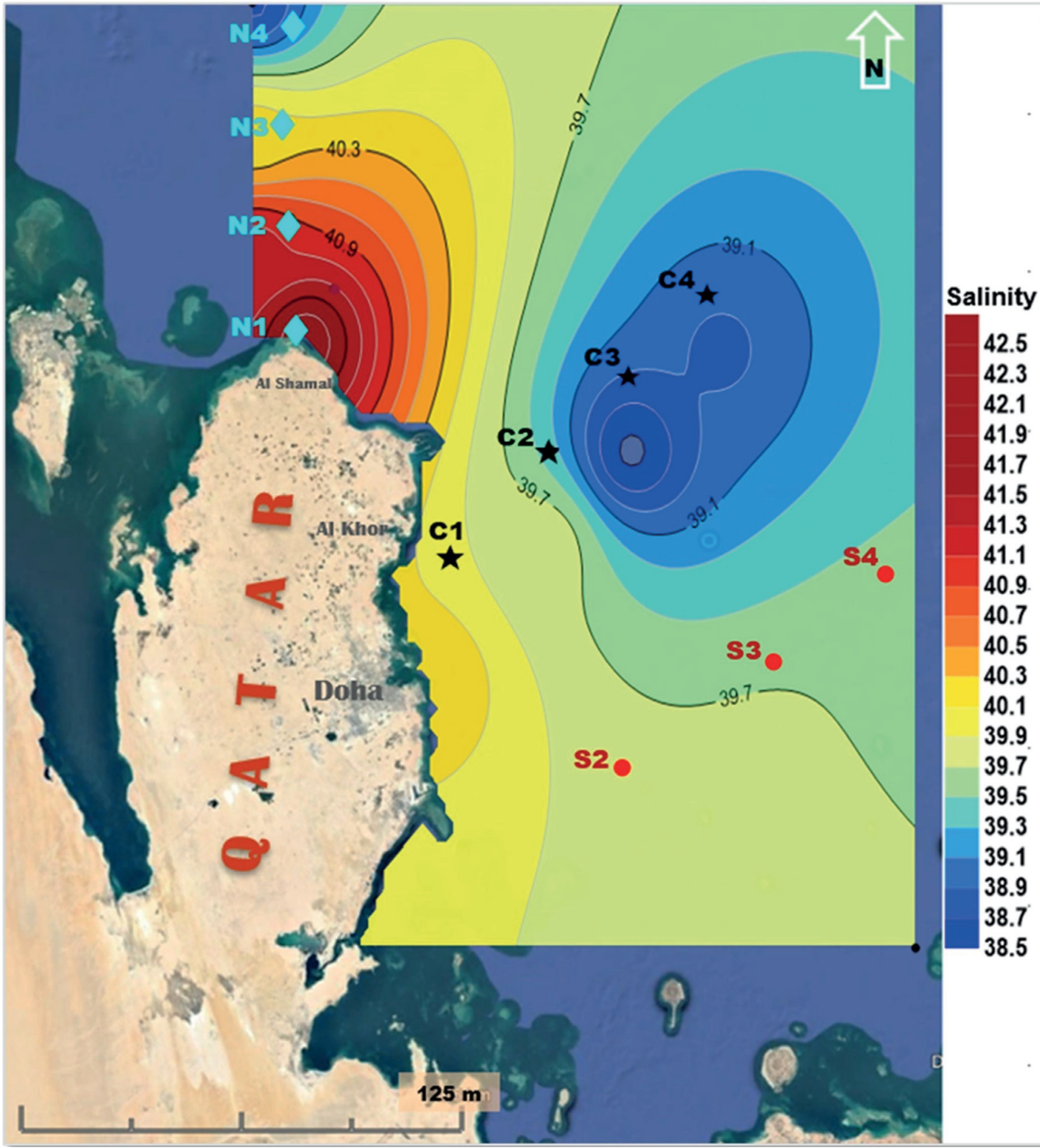

Figure 2 Generalized spatial contours of sea surface salinity (SSS) at 5 m depth derived from the CTD measurements along the three transects.

creased due to the hypersaline influx. A detailed investigation on the cumulative impact of the discharged brine over a longer period of time in the QEEZ is yet to be conducted to quantify the anthropogenic influence on the hyper salinification of the nearshore waters of the central east coast of Qatar. The changes in salinities within the water mass is likely to affect the growth of some of the marine organisms (Joydas et al., 2015). Consequently, brine discharges lead to negative ecological impacts observable throughout the food chain in the Gulf.

4.2. Water masses in the QEEZ

The water masses in the QEEZ have been determined by analyzing the T-S diagram of each transect (Figure 5). The Qatar Shallow Water (QSW) with the density between 24.98 and 27.55 kg/m^3 has been identified at all the transects, which is characterized by high temperature, low salinity and low density (Figure 5a). The Qatar Deep Water (QDW) with the density between 27.87 and 29.32 kg/m^3 has been identified in the northern and central transects, which is characterized by low temperature, high salinity and high density (Figure 5b). Recently, Rakib et al. (2021) identified these two water masses during the late summer (September 2014) in a deep-water location, adjacent to the deepest station in the central transect, but with an increased SST due to seasonal transformation from early summer to late summer. The Qatar Intermediate Water (QIW) with distinct values of temperature, salinity and density has been observed in between QSW and QDW in the central transect (Figure 5c). This

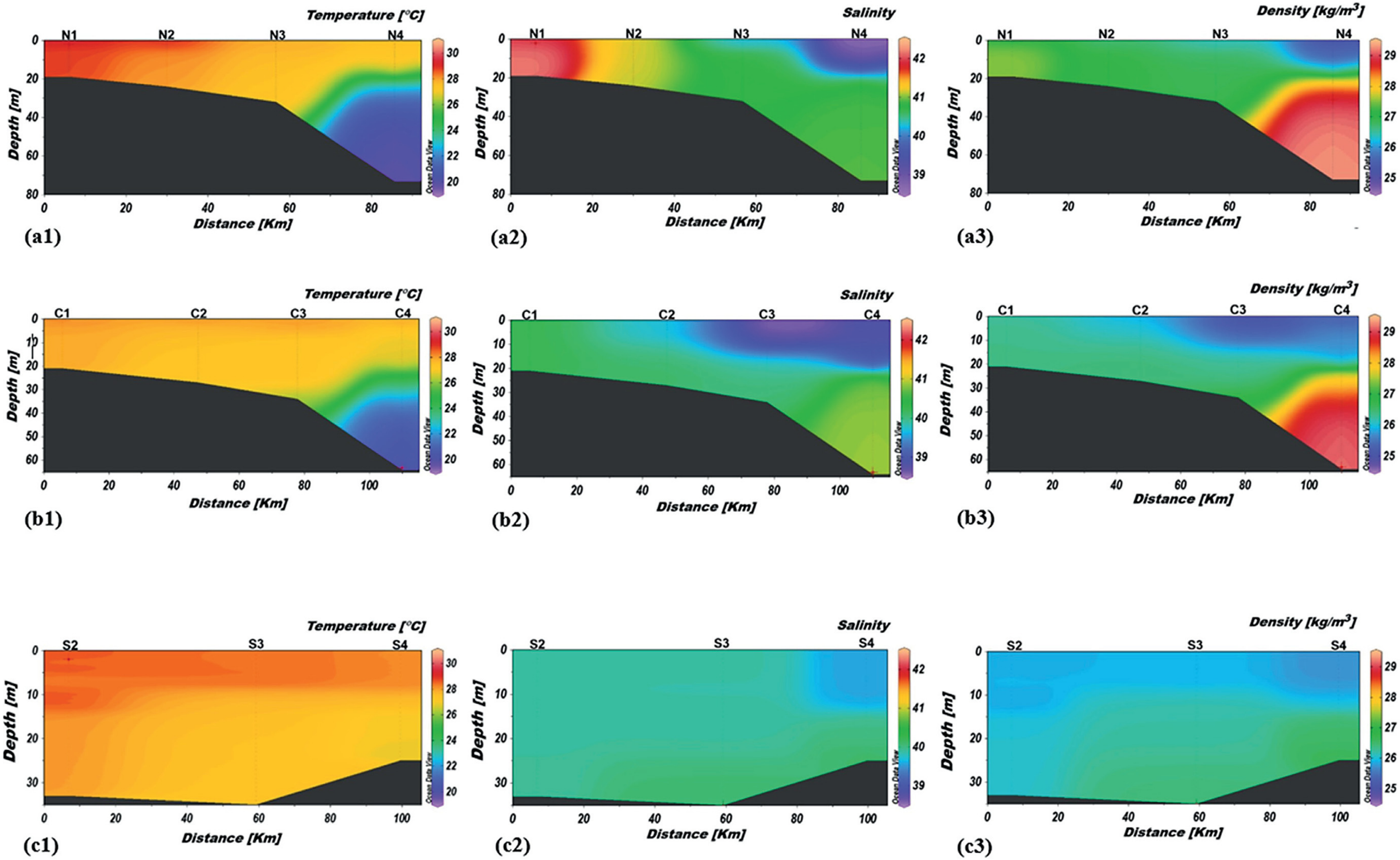

Figure 3 2D profiles of the measured temperature (a1, b1 and c1), salinity (a2, b2, c2) and density (a3, b3, c3) along the northern (a), central (b) and southern (c) transects. The plots are made using Ocean Data View Software, Version 5.03, (Schlitzer, 2020).

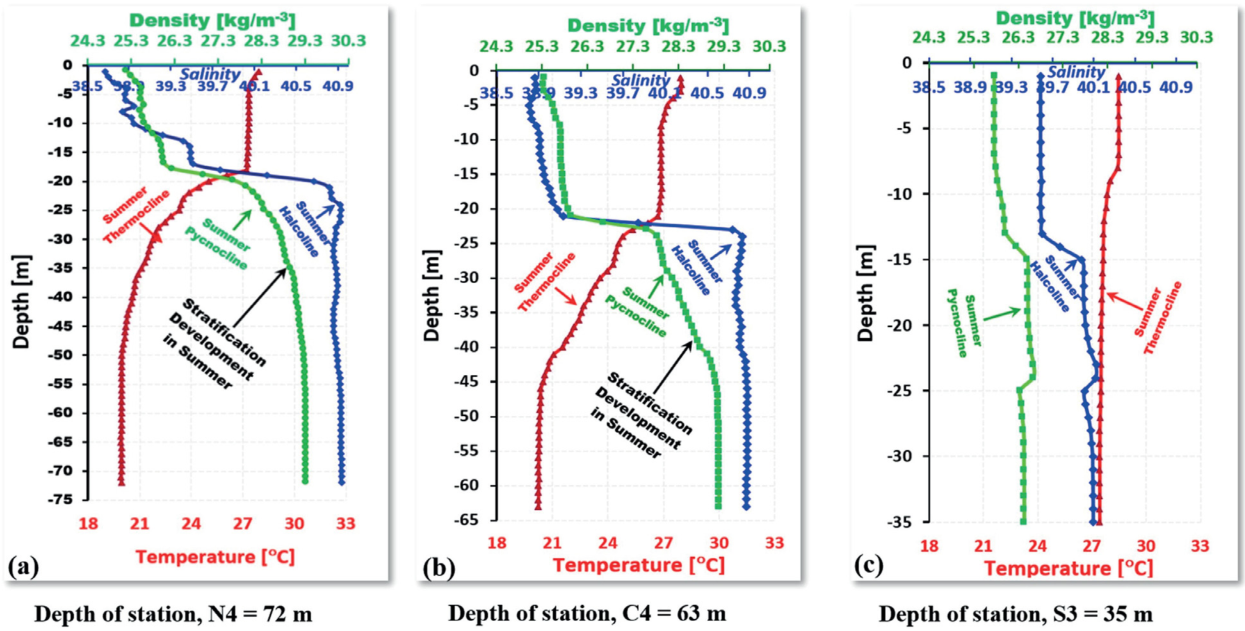

Figure 4 Vertical profiles of temperature, salinity and density at the deepest stations in the northern (a), central (b) and southern (c) transects. The plots are made using Microsoft Excel Data Analysis Tool.

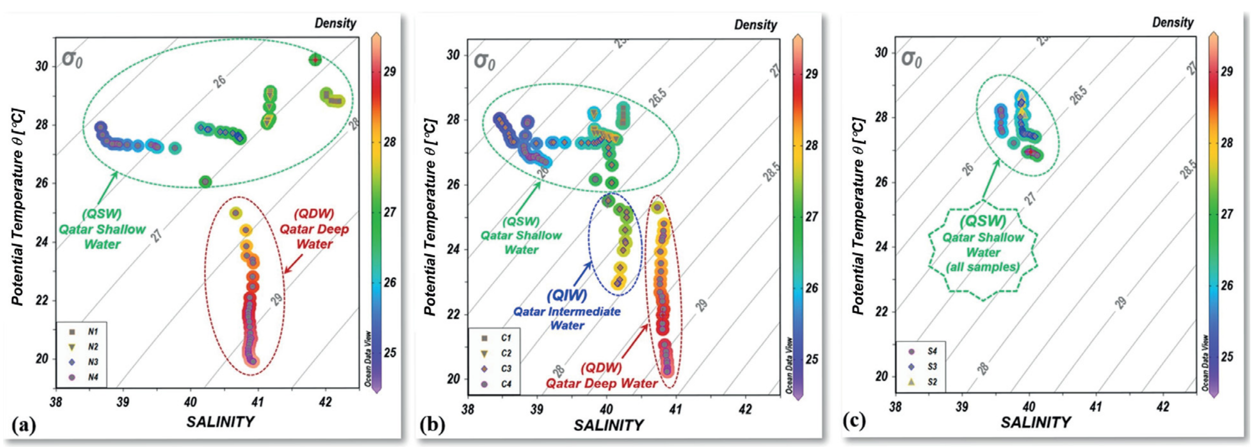

Figure 5 (a) Θ/S diagram derived from the measurements during May 28-30, 2017: (a) Qatar Shallow Water (QSW) and Qatar Deep Water (QDW) identified at the deepest station (N4=72m) in northern transect, (b) Qatar Shallow Water (QSW), Qatar Intermediate Water (QIW) and Qatar Deep Water (QDW) identified at the deepest station (C4=67m) in central transect and (c) Qatar Shallow Water (QSW) identified in the southern transect. The plots are made using Ocean Data View Software, Version 5.03, (Schlitzer, 2020).

is consistent with that identified from the measurements of July 2000.

The physicochemical properties of the water masses in the QEEZ, namely, Qatar Central Arabian Gulf Water (QCAGW) during summer is quite different from those derived for the water masses (listed in Table 1) at different regions in the Gulf (Al-Said et al., 2018). Though the distinct variation in temperature is observed among all the water masses, only in the QCAGW, wider variation is found. The salinity difference in the Indian Ocean Surface Water (IOSW) and Central Arabian Coastal Water (CACW) is relatively small, while that in the QCAGW is relatively higher. DO ranges widely in QCAGW compared to other water masses, and pH has no significant variations among the water masses in the Gulf.

4.3. Distribution of pH, dissolved oxygen and fluorescence

The pH in each transect shows distinct variations horizontally and vertically (Figure 6a1, b1, c1). Although small, the variations in pH are consistent with the water mass distributions, especially in the deep-water regions of northern and central transects. In the central transect, the highest pH (~8.2) is in the subsurface layer, which clearly depicts the presence of QIW. The variations in pH among all the transects (8.01—8.21) are well within the acceptable limits of the oceanic waters, where the average pH of seawater could be around 8.1 (Fallatah et al., 2018).

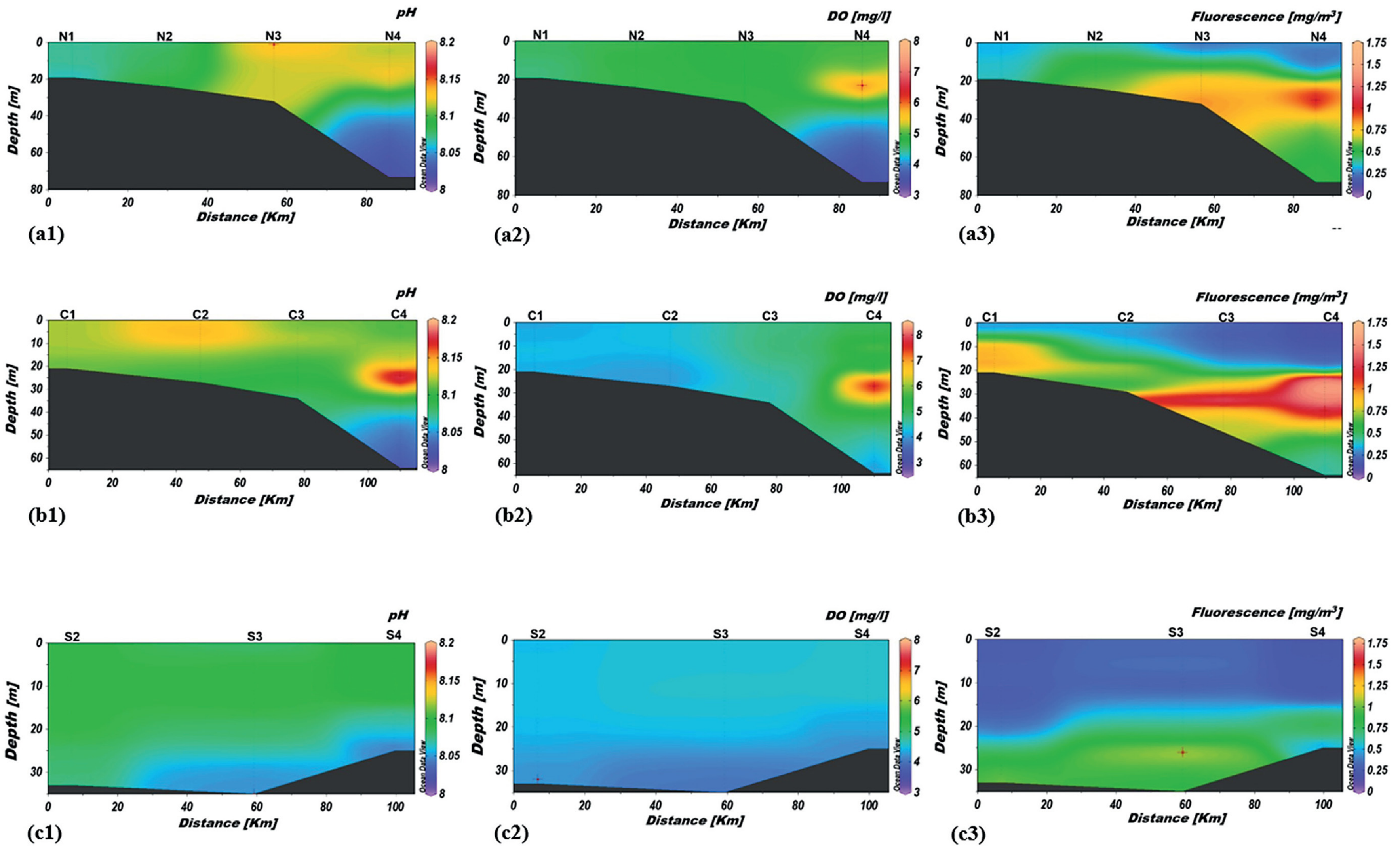

Figure 6 2D profiles of the measured pH (a1, b1, c1), DO (a2, b2, c2) and fluorescence (mg/m^3) (a3, b3, c3) along the northern central and southern transects. The plots are made using Ocean Data View Software, Version 5.03 (Schlitzer, 2020).

Table 1 The physicochemical parameters in the composite water masses in the study area: Qatar Central Arabian Gulf Water (QCAGW) and their comparison with those in the Kuwait Coastal Waters (KCW), Northern Gulf Waters (NGW), Central Arabian Coastal Waters (CACW) and Indian Ocean Surface Water (IOSW) (after Al-Said et al., 2018).

Parameters	KCW*	NGW*	CACW*	IOSW*	QCAGW (present study)
Temperature (°C)	32.4—32.8	32.8—34.0	33.9—34.6	32.7—35.4	19.9—30.23
Salinity	40.8—41.1	39.2—40.7	38.1—39.9	38.8—40.2	38.46—42.20
DO (ml/l)	4.8—5.1	4.7—5.3	4.0—5.8	4.5—5.3	3.43—8.37
pH	7.9—7.9	7.7—8.0	8.0—8.2	7.7—8.1	4.3—8.21

Table 2 Correlation matrix derived for the physicochemical parameters of northern, central and southen transects; [a]positive correlation significant at p=0.01, [b]positive correlation significant at p=0.05, [c]negative correlation significant at p=0.01 and [d]negative correlation significant at p=0.05 (only significant correlations are given).

Transects	Parameters	Temperature (°C)	Salinity	Density (kg/m^3)	pH	DO (mg/l)	Fluorescence (mg/m^3)
Northern	Depth (m)	-0.91[c]		0.86[a]	-0.70[c]	-0.59[c]	0.28[a]
	Temperature (°C)			-0.87[c]	0.58[a]	0.38[a]	-0.36[c]
	Salinity			0.47[a]	-0.46[c]	-0.20[d]	0.17[b]
	Density (kg/m^3)				-0.74[c]	-0.43[c]	0.41[a]
	pH					0.81[a]	
	DO (mg/l)						
	Fluorescence (mg/m^3)						
Central	Depth (m)	-0.92[c]	0.72[a]	0.91[a]	-0.70[c]		0.37[a]
	Temperature (°C)		-0.67[c]	-0.95[c]	0.63[a]	0.17[b]	-0.31[c]
	Salinity			0.87[a]	-0.30[c]		0.66[b]
	Density (kg/m^3)				-0.53[c]		0.50[a]
	pH					0.52[a]	
	DO (mg/l)						0.50[a]
	Fluorescence (mg/m^3)						
Southern	Depth (m)	-0.58[c]	0.63[a]	0.70[a]	-0.74[c]	-0.83[c]	0.86[a]
	Temperature (°C)		-0.43[c]	-0.91[c]	0.65[a]	0.43[a]	-0.56[c]
	Salinity			0.76[a]	-0.83[c]	-0.73[c]	0.65[a]
	Density (kg/m^3)				-0.84[c]	-0.64[c]	0.70[a]
	pH					0.90[a]	-0.77[c]
	DO (mg/l)						-0.81[c]
	Fluorescence (mg/m^3)						

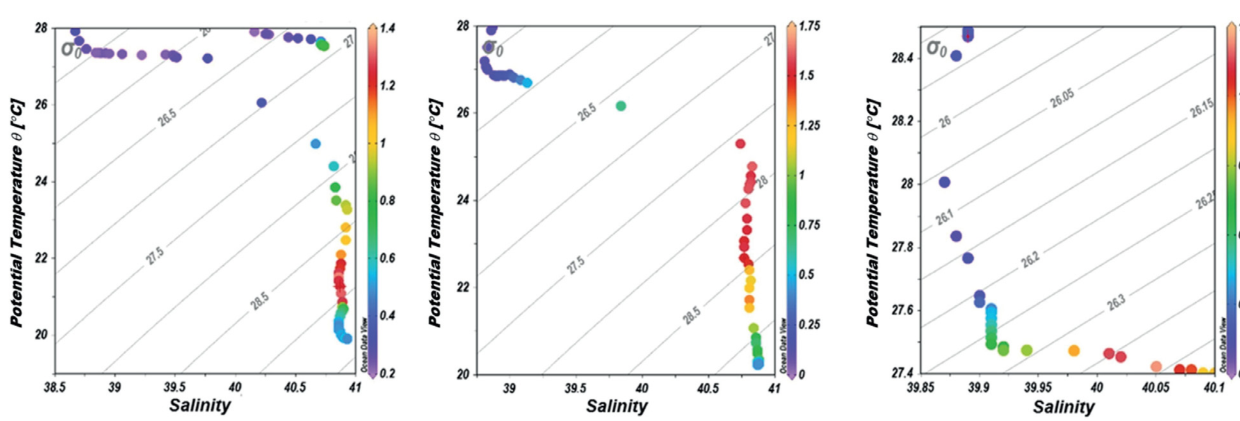

Figure 7 Fluorescence profiles along the northern (a), central (b) and southern (c) transects, indicating the most productive zone associated with high values of fluorescence (mg/m^{3}). In the potential temperature-salinity-fluorescence plots, high values are shown in yellow and red colors.

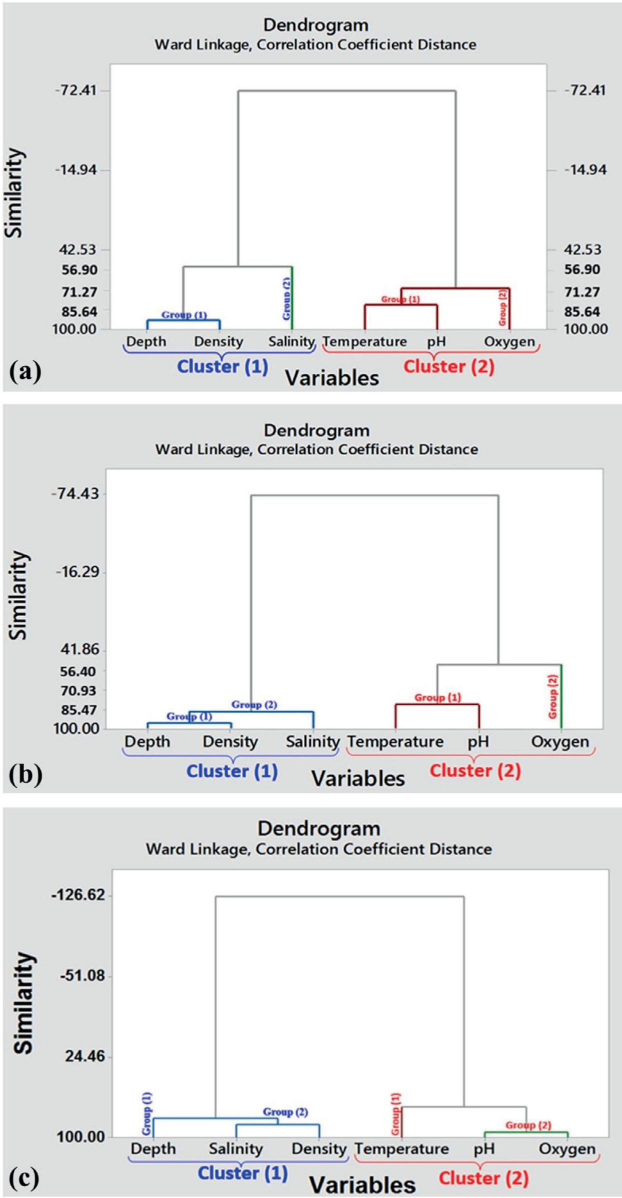

Figure 8 Hierarchical cluster analysis (HCA) of the physicochemical parameters in the: (a) northern transect, (b) central transect and (c) southern transect. (Dendrograms are made using Minitab Software Version 17).

DO varies between 3 and 7 mg/l in the northern transect and between 3.5 and 8.5 mg/l in the central transect, while the southern transect has no significant variation, which is between 4.0 and 4.6 mg/l (Figure 6a2, b2, c2). The highest DO is found in the subsurface layer (20—30 m) in the deep-water locations of the northern and central transects. This indicates that the subsurface layer in the QEEZ is well oxygenated during early summer. Earlier studies reported hypoxia at a depth of 60 m in the central Gulf in the mid/late summer developed by summer stratification (Al-Ansari et al., 2015; Rakib et al., 2021). However, the minimum recorded DO in early summer in the present study is 3.43 mg/l, quite a comfortable situation compared to hypoxic conditions in the later stage. This shows that the Gulf is still relatively healthy, despite several coastal development activities in the last few decades.

The Chlorophyll Fluorescence parameter (Fo) is used as a tracer in biological studies to estimate the primary productivity (Chen et al., 2017). Distinct variation in fluorescence is identified in all the transects (Figure 6a3, b3, c3). The surface layer of the deep-water locations has the lowest fluorescence (0—0.2 mg/m^3), while the subsurface layer (20—40 m) produces the highest fluorescence (1.0—1.6 mg/m^3). Overall, the central transect is characterized by high fluorescence and thus high primary productivity. The northern transect also has a wide range of primary productive zone with reasonably high fluorescence, but relatively low compared to the central transect.

The higher fluorescence values are associated with a potential density of 28.100—29.020 and 27.590—29.000 kg/m^3, respectively, as shown in the northern and central transects, while Fo is associated with a lower potential density of 26.320—26.427 kg/m^3 in the southern transect (Figure 7a, b, c). The salinity associated with the higher fluorescence is around 40.8 in the northern and central transects, while that is around 40.0 in the southern transect. The temperature associated with higher fluorescence is 20.5—22.5°C, 21.0—25.5°C and 27.4—27.5°C, respectively, in the northern, central and southern transects. The central transect has a wider range of temperature variations in the productive zone compared to the other two transects.

4.4. Correlation matrix between the physicochemical parameters

The statistical relationship between the physicochemical key parameters has been analyzed using the correlation matrix (Table 2) as well as the dendrograms (Figure 8). A higher positive correlation is found between density and depth in all the transects, which is quite common in oceanic waters. The depth versus salinity as well as density versus salinity has a strong positive correlation in the central and southern transects. This may be because of the sinking of high salinity water and the formation of dense bottom water; however, more in situ observations are needed to substantiate this feature. High negative correlations are found between the depth and temperature as well as density versus temperature in all transects. Although it is normal in oceanic waters, such a high correlation within the shallower depths of the Gulf is notable. The pH versus DO in the northern and southern transects, and pH versus temperature in the central and southern transects have high positive correlations. The pH has negative correlations with depth and density in all the transects, but within the shorter and normal range of pH (8.01—8.21), the shallow QEEZ does not yield any harmful impacts. The DO versus salinity has a strong negative correlation in the southern transect, within the limited data points. In the southern transect, the fluorescence has a strong positive correlation with depth, salinity and density. It suggests that although the salinity and density increase with depth, the reasonable amount of fluorescence (above 1.0 mg/m^3) present in this region supports the primary productivity.

The hierarchical cluster analysis (HCA) produces the similarity percentage between the physicochemical parameters at each transect, which is represented by dendrograms (Figure 8). In the northern transect, the cluster (1) consists of depth, density and salinity, in which depth and density have high similarity (85%), whereas the cluster (2) consists of temperature, pH and DO, in which the temperature and DO have high similarity (75%) (Figure 8a). However, clusters (1) and (2) mutually exhibit a high negative similarity (—70%) in the northern transect. In the central and southern transects, the cluster components remain the same but differ in their similarity index compared to that in the northern transect. In the central transect, the depth and density in the cluster (1) have very high similarity (around 95%), indicating that density increases with depth, as reflected in the profiles, while both together show high similarity with salinity (around 85%) (Figure 8b). In the cluster (2), the temperature and pH show high similarity (around 80%). Similar to the northern transect, the clusters (1) and (2) in the central transect produce a high negative similarity (around —70%). In the southern transect, the density and salinity in the cluster (1) and pH and temeperature in cluster (2) show high similarities (80% and 90%, respectively) (Figure 8c). The clusters (1) and (2) are mutually in a moderate negative similarity (—65%). These similarities suggest that salinity and density in the QEEZ are directly proportional to each other and have strong link between them, while both are inversely proportional to temperature and pH. Furthermore, density is more or less independent of temperature and pH, and salinity determines the water column density and stability.

5. Summary and conclusions

This study investigated the spatial variability of key physicochemical parameters — temperature, salinity, density, pH, DO and fluorescence, in the Qatar's Exclusive Economic Zone (QEEZ) during early summer. There were 11 sampling stations across 3 transects — northern, central and southern. The results indicate that physicochemical parameters show distinct spatial variability, which is connected to the stratification and formation of different water masses in the QEEZ. The variations in temperature, salinity and potential density are in the range 19.9°—30.2°C, 38.46—42.20, 24.98—29.32 kg/m^3, respectively. The minimum recorded salinity was in the intermediate region of the central transect, while the maximum recorded salinity was in the nearshore region of the northern transect. The higher salinity in the northern transect is primarily attributed to the higher evaporation rates along with dense water flow from the northern Gulf. A detailed investigation is required to evaluate the relative contribution of desalination plants in the hypersalinity of this region.

The pH in all the transects shows a little spatial variation (in the range of 8.01—8.21). Although small, the variations in pH are consistent with the water mass distributions, especially in the deep-water regions of northern and central transects. The DO was minimum (3.43 mg/l) in the deepest region of the northern transect, and maximum (8.37 mg/l) in the deepest region of the central transect. The summer stratification often leads to hypoxia in the central Gulf as literature reports, however, that is not quite evident in early summer based on the present study. The maximum recorded fluorescence was 1.61 mg/m^3 in the deepest region of the northern transect. The high fluorescence in the QEEZ was confined to a depth of 20—40 m, where the primary productivity was relatively higher.

The northern and the central transects are situated in the deep-water zone and exhibited similar vertical and horizontal distribution patterns and layering of physicochemical key parameters, whereas the southern transect is situated in a relatively shallow water zone, exhibiting a weak stratification. The correlation matrix and hierarchical cluster analysis indicate that depth, salinity and density are in cluster 1 and pH, DO and Temperature are in cluster 2, and both are inversely correlated to each other. The inferences derived in this study are preliminary in nature due to a limited number of datasets available in the QEEZ. A detailed investigation is planned by executing further measurements in the QEEZ, not only in summer but also in other seasons with the aim of studying the temporal variability of physicochemical parameters.

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Declaration of competing interest

The authors of this study would like to declare that they have no conflict of interest.

Disclaimer

The manuscript contents are solely the responsibility of the authors, and do not necessarily represent the official views of the Qatar University and the Environmental Science Center (ESC).

CRediT Authorship contribution statements

Elnaiem Ali Elobaid: Conceptualization, research methodology, project administration, collection of samples, investigation, formal analysis, visualization, resources, writing the original draft of the manuscript, reviewing and editing.

Ebrahim S. Al Ansari: Conceptualization, methodology, project administration, resources, visualization, writing up, reviewing, and editing.

Oguz Yigiterhan: Conceptualization, research methodology, collection of samples methodology, resources, visualization, writing, reviewing, and editing.

V.M. Aboobacker: Conceptualization, research methodology, writing, reviewing, and editing.
P. Vethamony: reviewing and editing.

Supplementary materials

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