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Sub-decadal trends in sea surface physicochemical parameters of Daryabozorg station (Northern Gulf of Oman, Iran)

Gholamrasoul Baskaleh[1*], Amir Ghazilou[1], Hamid Ershadifar[1], Kamalodin Kor[1], Mohammad Reza Salari Fanodi[2]

1- Department of Marine Living Science, Iranian National Institute for Oceanography and Atmospheric Sciences (INIOAS), Tehran, Iran
2- Chabahar Marine Weather Bureau, Chabahar, Iran

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Abstract

Observations from an eight-year ocean station at Chabahar showed that both salinity and electrical conductivity (EC) have increased over the past nine years. Meanwhile, pH remained at steady state levels and there was no significant trend in mean annual temperatures. The best repeating pattern of monthly oscillations was depicted in temperature data with the highest and the lowest temperatures occurring at 4th/ 5th and 10th/ 11th months, respectively. Changes in salinity/EC and temperature were moderately correlated. The mean monthly pH levels rarely fell below 8.00. There were no signs of hypoxia during the study period.

Keywords: Northern Gulf of Oman, Coastal, Hypoxia, Sub-decadal

1. Introduction

Gulf (Sea) of Oman (GO) is a part of Indian Ocean which extends from Arabian Sea to the mainland Iran (22°- 26° N, 56° - 62° E). It is ~545 Km long (Grafton et al., 2010) and has an area of 94000 Km2 (Jawad, 2018). The Gulf climatology is affected by two monsoon seasons i.e. the winter monsoon occurring from November to April, which is associated with northeasterly low-speed winds and the summer monsoon, which occurs from July to September and is characterized by high-speed southerly and southwesterly winds (Chaichitehrani and Allahdadi, 2018).

Earlier oceanographic data on the Gulf area mainly have come from expeditions. For example, the results of Mt. Mitchell expedition (from February to June 1992) showed that at basin scale, the surface temperature (SST) varied from 20°C in winter to 32°C in summer, while relatively smaller seasonal variations occurred in salinity (Michael Reynolds, 1993). According to (Ebrahimi and Sadeghian, 1996), the mean SST of the northern part of the Gulf varies between 25.6°C and 28.6°C. Results of a later study, revealed the formation of summertime thermocline water mass in the upper 25m layer with temperature≈ 30°C and salinity≈ 37 psu (Pous et al., 2004) and (Khosravi et al., 2011) concluded that

[*] *Email: baskaleh@inio.ac.ir*

wintertime precipitations are synchronous to positive anomalies of summer SST. (Wang et al., 2013) found high salinity intrusions during summer 2007 which was caused by Cyclone Gonu.

On the other hand, some oceanographic data on the Gulf came from ecological studies, which used hydrological data to explain variations in ecological assemblages which generally include short-term (usually one-year period) records of physicochemical parameters of water during monsoon and post/pre monsoon seasons. For example, (Fazeli et al., 2010) used hydrological data to described seasonal patterns in copepod assemblages at the Chabahr Bay and (Pourjomeh et al., 2017) followed the same routine to relate changes in jellyfish abundance to environmental variables. These studies are usually local.

Up to date, few studies have established inter-annual trends in hydrology of the area. For example, (Piontkovski and Chiffings, 2014) indicated a long term (i.e. 60 year) increase in summer-time SST of the Gulf while the wintertime temperatures remained stable. At a more local scale, (Chegini and Sanjani, 1992) found a decreasing trend in SST from 2006-2009 at Chabahar Bay, northern GO and (Ebrahimi and Sadeghian, 1996) found a similar trend in SST, EC and DO from 2009-2011 in the whole northern Gulf area.

In this study, a sub-decadal series of weekly measurements of hydrological (i.e. salinity, DO, temperature, conductivity, pH) and climatological data of the GO is reported. The data are gathered from the Daryabozorg ocean station at the Northern GO, Iran.

2. Material and Methods

2.1. Measurements

Weekly measurements of physicochemical parameters were done from March 2010 to March 2019 (Except for dissolved oxygen (DO) which was measured from March 2015 onwards). In doing so, a stainless steel water bottle was used to collect water samples at <1m depth of Daryabozorg station, an oceanography station located at Chabahar (Figure 1). Samplings were performed at 9:00 am and measurement of water temperature, salinity, conductivity, pH, and DO content of the collected samples were done instantly. The parameters were measured to the nearest 0.1 (i.e. conductivity, temperature) or 0.01 (i.e. salinity, pH, DO) units, using WTW digital probes (Xylem, Germany). At the time, the climatological data i.e. air temperature (C), relative humidity (%), rainfall quantity (mm), maximum wind speed (m/s), Evaporation (mm), and sunshine (%) obtained from nearby synoptic weather station. No measurements were done from 21 March 2014 to 20 March 2015 due to instrumental failure.

2.2. Data analyses

Solar Hijri monthly mean data were used for time series analyses (Table 1). The Solar Hijri year begins about 21 March of each Gregorian year and ends about 20 March of the next year. Data were first assessed for normality of residuals and homoscedasticity using Kolmogorov–Smirnov and Levene's test, respectively. The residuals were not normal and normality could not be achieved by square root of log(x+1) transformations. The Mann-Kendall test was used to assess monotonic trends in each parameter over years and months. Spearman rank correlation coefficients were calculated to examine correlation between physicochemical properties of water and the climatological parameters.

Table 1: Solar months and their equivalent Gregorian date intervals

Solar Month	Corresponding Gregorian calendar interval
1 (Farvardin)	21 Mar. - 20 Apr.
2 (Ordibehešt)	21 Apr. - 21 May
3 (Xordâd)	22 May - 21 June
4 (Tir)	22 June - 22 July
5 (Mordâd)	23 July - 22 Aug.
6 (Šahrivar)	23 Aug. - 22 Sep.
7 (Mehr)	23 Sep.- 22 Oct.
8 (Âbân)	23 Oct.- 21 Nov.
9 (Âzar)	22 Nov.- 21 Dec.
10 (Dey)	22 Dec.- 19 Jan.
11 (Bahman)	20 Jan. - 18 Feb.
12 (Esfand)	19 Feb. - 20 Mar.

3. Results

3.1. Salinity

During the study period, salinity varied between 36.90- 37.40 psu. The overall mean salinity was 36.67 psu± 0.30 (mean± SD), and the boxplot of data indicated no outliers (Figure 1a). Highest salinities recorded during late summer (generally at 5th month) while there was no monthly consistency in incidence of salinity-minimum (Figure 1b).

A decreasing trend was found in annual salinity levels (S-statistic= -20, p= 0.007). The observed decreasing trend in mean annual salinity was also consist intent throughout autumn and winter (Table 2).

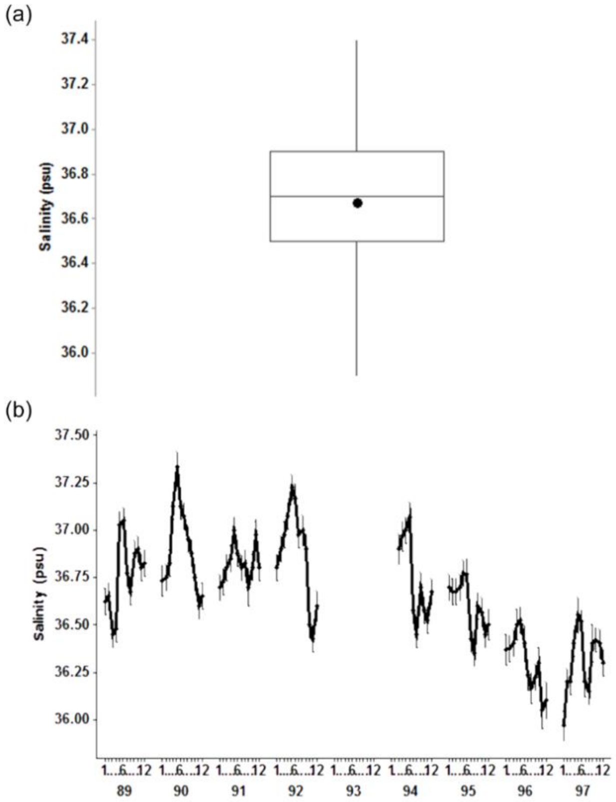

Fig 1: A box plot (a) and time course (b) of salinity variations (1389- 1397) Solar Hijri year)

Table 2: Month-to-month sub-decadal trends in physicochemical properties of surface waters at Daryabozorg station (Northern GO, Iran). D: decreasing; I: increasing; N/T: no trend; pD: probably decreasing; pI: probably increasing; S: stable; EC: electrical conductivity; DO: dissolved oxygen

Month (solar calendar)	Salinity	EC	Temperature	pH	DO
1	S	S	D	S	S
2	S	pD	S	N/T	S
3	S	S	N/T	N/T	S
4	pD	pD	N/T	N/T	S
5	D	D	N/T	S	S
6	pD	D	S	S	S
7	D	D	S	S	N/T
8	D	D	D	S	N/T
9	D	D	S	S	S
10	D	D	I	N/T	S
11	D	D	N/T	N/T	N/T
12	D	D	S	pI	N/T

3.2. EC

The EC varied between 54.10- 56.00 mS/cm during the study period. The mean EC was 55.17 mS/cm± 0.39 (mean± SD). Similar to the salinity data, there were no outliers in the EC data (Figure 2a). In contrast to the salinity data, the occurrence times for either highest or lowest EC were not fixed among years (Figure 2b).

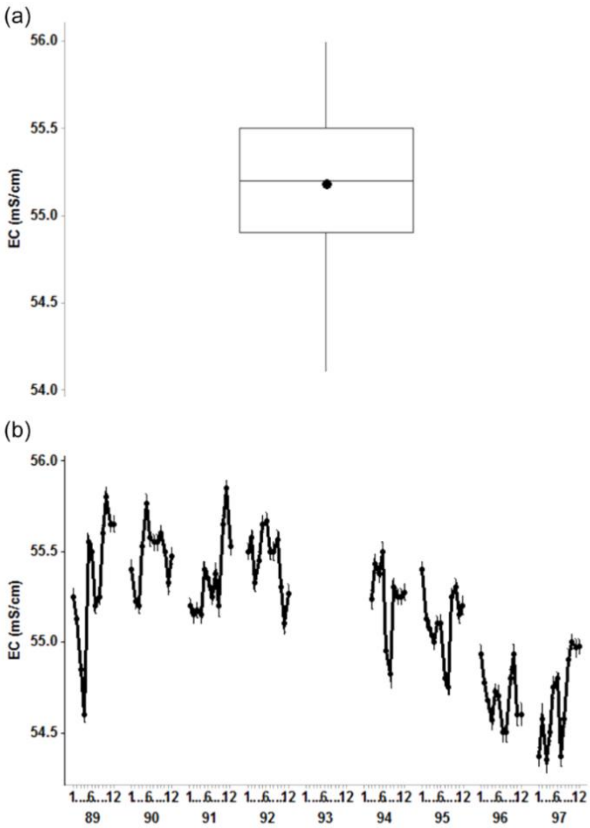

Fig 2: A box plot (a) and time course (b) of EC variations (1389- 1397 Solar Hijri year)

Calculated coefficients of variations indicated smaller temporal viability in EC when compared to salinity (C.V. $_{salinity}$=0.83, C.V. $_{EC}$= 0.71). Similar to the salinity data, a decreasing trend was recorded in annual salinity levels (S-statistic= -22, *p*= 0.007). The same trend was found at 5th month onwards (Table 2).

3.3. Temperature

The lowest (i.e. 21.6°C) and highest (i.e. 32.9°C) temperatures occurred during winter 2017 and summer 2018, respectively. The mean temperature was 27.10 °C±2.89 (mean± SD) and there was no outliers in SST data (Figure 3a). The overall variation (expressed as C.V.) was 10.67, during the study period. There were no signs of temperature spikes (Figure 3b). Month to month variations in mean temperature followed a clear repeating pattern with highest and lowest temperatures occurring at 4th/ 5th and 10th/ 11th months, respectively (Figure 3).

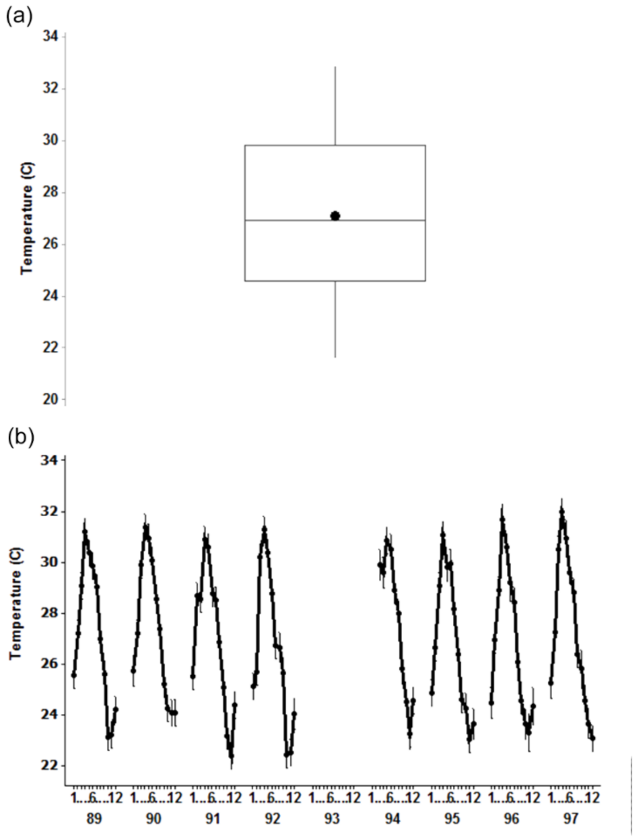

Fig 3:A box plot (a) and time course (b) of temperature variations (1389- 1397 Solar Hijri year)

There was no significant trend in mean annual temperatures (S-statistic= 2, *p*= 0.54), but a decreasing trend was detected at months 1 and 8 (Table 2).

3.4. pH

During the study period, the mean monthly sea-surface pH levels rarely fallen behind 8.00. The boxplot of data presented three outliers (Figure 4a) which referred to extreme low pH values at 3rd month. The overall mean pH was 8.12±0.10 (mean± SD). The course of monthly variations in mean pH varied from year to year (Figure 4b), and the total range of variations was 0.62.

The annual pH levels were found stable during the study (S-statistic= 0, p= 0.45). In terms of month to month trends, a stable pH levels were also detected at month 1, 5, 6,7, 8, and 9 while no significant trend was found for 2nd, 3rd, 4th, 10th and 11th months, but a weak increasing trend at month 12 (Table 2).

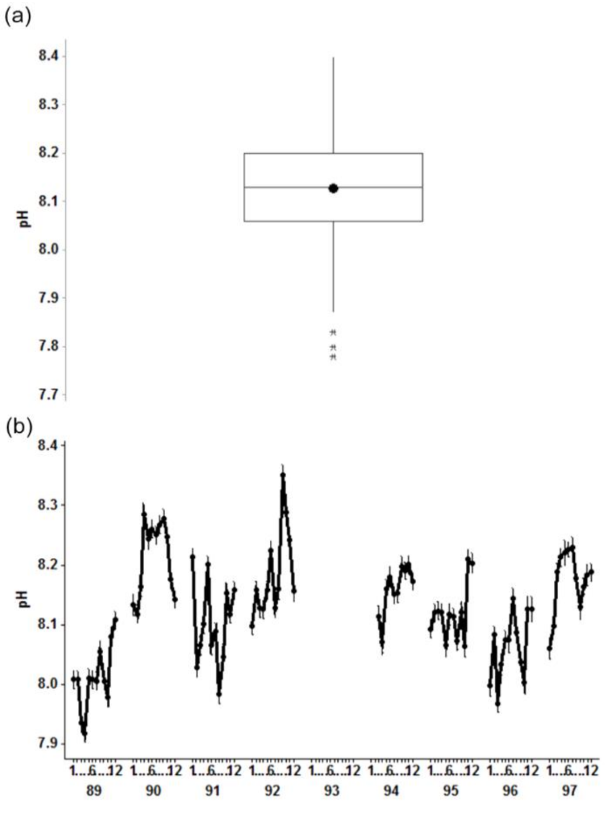

Fig 4: A box plot (a) and time course (b) of pH variations (1389- 1397 Solar Hijri year)

3.5. DO

The mean DO was 5.31± 0.85 (mean± SD) over the three years (Figure 5). Maximal or minimal DO records varied among years, but no signs of hypoxia (i.e. DO < 0.5 mg/l, (Helly and Levin, 2004)) occurred during the study (Figure 5). Similar to temperature data, there was no significant trend in mean annual DO levels (S-statistic= 2, p= 0.62).

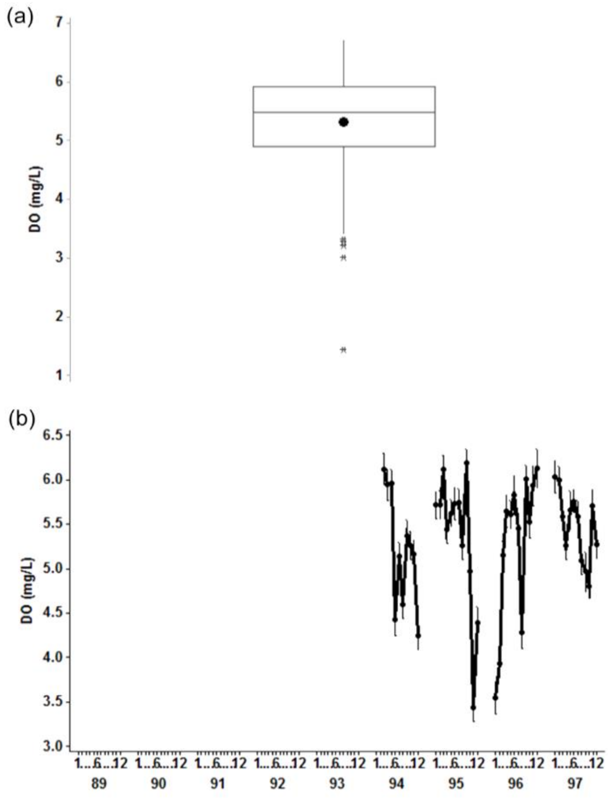

Fig 5: A box plot (a) and time course (b) of DO variations (1389- 1397 Solar Hijri year)

3.6. Environmental correlations

The significant correlations among the examined physicochemical parameters included a strong positive correlation between salinity and EC, a weak positive correlation between salinity and temperature, a weak positive correlation between EC and pH, a weak negative correlation between EC and temperature, and a weak positive correlation between DO and temperature. In terms of monthly correlations, the positive correlation between salinity and EC was consistent throughout all months, the negative correlation between EC and temperature and the positive correlation between DO and temperature was only significant at 10th and 5th month, respectively.

Annual trends in climatological metrics are presented in Table 4. The overall annual trends were only significant for surface air temperature which was depicted by increasing trends at 2nd, 3rd, 8th, and 9th months. At some other month, there were also a significant increasing trends in other parameters, but no case of a dressing trend could be detected (Table 4).

Table 3: monotonic correlation among physicochemical parameters at Daryabozorg station, Northern GO

		Salinity (psu)	**Temperature (C)**	**EC (mS/cm)**	**pH**
Temperature (C)	Spearman's Rho	**0.28**			
	p-value	**0.0001**			
EC (mS/cm)	Spearman's Rho	**0.85**	**-0.17**		
	p-value	**0.0001**	**0.001**		
pH	Spearman's Rho	0.089	-0.06	**0.14**	
	p-value	0.098	0.23	**0.008**	
DO (mg/L)	Spearman's Rho	0.03	**0.24**	-0.10	-0.04
	p-value	0.68	**0.002**	0.19	0.56

Table 4: Month-to-month and overall sub-decadal trends of Daryabozorg climatology (Northern GO, Iran). D: decreasing; I: increasing; N/T: no trend; pD: probably decreasing; pI: probably increasing; S: stable; EC: electrical conductivity; DO: dissolved oxygen

Month (solar calendar)	**Surface air temperature (C)**	**Relative humidity (%)**	**Rain (mm)**	**Maximum wind speed (m/s)**	**Evaporation (mm)**	**Sun**
1	N/T	S	N/T	N/T	N/T	N/T
2	I	S	N/T	I	N/T	S
3	pI	N/T	-	I	pI	D
4	N/T	S	-	pI	S	S
5	N/T	N/T	-	N/T	S	N/T
6	N/T	pI	-	N/T	S	N/T
7	S	pI	-	N/T	S	pI
8	PI	I	-	N/T	S	D
9	pI	N/T	-	pI	N/T	S
10	N/T	pI	-	N/T	S	S
11	N/T	N/T	N/T	N/T	N/T	pI
12	N/T	N/T	-	I	pI	S
Annual	I	N/T	N/T	N/T	N/T	S

In general, the physicochemical parameters and climatological data were weakly correlated. The strongest significantly positive correlations were found between air temperature and SST (Table 1). There was no significant correlation between rainfall and hydrological parameters.

Table 5: Correlation matrix calculated for physicochemical parameters and climatological data

		SST (C)	Salinity (psu)	EC (mS/cm)	pH	DO (mg/L)
Air temperature (C)	*Spearman's Rho*	0.84	0.17	-0.24	-0.21	0.20
	p-value	0.0001	0.001	0.001	0.007	0.007
Relative humidity (%)	*Spearman's Rho*	0.63	0.25	-0.07	-0.04	-0.13
	p-value	0.0001	0.0001	0.18	0.39	0.08
Rain (mm)	*Spearman's Rho*	-0.09	-0.02	0.02	0.02	0.01
	p-value	0.19	0.63	0.70	0.68	0.89
Maximum wind speed (m/s)	*Spearman's Rho*	-0.03	-0.13	-0.14	0.30	0.12
	p-value	0.49	0.01	0.004	0.001	0.10
Evaporation (mm)	*Spearman's Rho*	0.46	0.11	-0.10	0.03	0.11
	p-value	0.0001	0.03	0.052	0.27	0.16
Sun	*Spearman's Rho*	-0.17	-0.09	-0.02	-0.05	0.002
	p-value	0.001	0.06	0.60	0.30	0.97

4. Conclusions

4.1. Salinity

Temporal variations over the course of the study period included two salinity peaks occurring. Yet, inter-annual variability existed in the observed pattern, with only one peaks in some years. Seasonal variability of salinity is usually larger over the western part of the Indian Ocean (and adjacent water bodies), when compared to its eastern part (Donguy and Meyers, 1996). Morrison, (1997) listed main factors controlling monsoon-related variations in salinity in the northern Arabian Sea, i.e. upwelling, Ekman pumping, highly saline-water outflow from the Persian Gulf, riverine runoffs, evaporation, and participation. The same parameters may also be responsible for temporal variations in the Northern GO. For example, lower temperature and higher wind velocities may cause increased evaporation, thereby resulting in relatively higher SSS during fall, when compared to springtime levels (Ebrahimi and Sadeghian, 1996).

Irrespective of seasonal variability, there was an annually decreasing trend in salinity. Previous global-scale studies on salinity trends revealed ambiguous results. For example, (Boyer et al., 2005) reported increased salinity at subtropical waters at sub-decadal scales, (Cravatte et al., 2009) found decreased salinity from 1955 to 2003 and (Grodsky et al., 2006) found a two-phase pattern characterized by an increased salinity during 1965-1985 period followed by freshening from 1995 to 2005. As such, a large anomaly may be existed both in global and local scale (Dickson et al., 1988), but persistent trends may also be found at some localities. At global regional scale, the Walker Circulation may be considered a key factor regulating salinity trends (Du and Zhang, 2015).

4.2. Temperature

In our study, the best recorded sequences of repeating trends was found in sea-surface temperature data which was characterized by maxima and minima occurring at late summer and mid/late winter, respectively. Results of a recent modelling study predicted an increasing trend in SST over the GO with about 2.2 C increase by 2100 (Noori et al., 2019). Yet, we did not find any signs of significant increase in mean annual temperature during the study period. Also month-to month analyses indicated a rather stable temperature in all months except the 10^{th} month. (Noori et al., 2019) used a 34 year data for concluded that the increased temperature pattern are more pronounced during 1982- 1998 period and thereafter, a rather steady state achieved. Greater water depths, higher latent heat of vaporization and less extent in vicinity to dry lands may play a key role in moderating the warming of GO when compared to Persian Gulf (Noori et al., 2019).

4.3. pH

We found an increasing trend in pH of surface waters while month analyses revealed more stable status of pH in the study area. There has been a decreasing trend in pH of global ocean which is brought about by anthropogenic ocean acidification (Orr et al., 2005, Doney et al., 2009). Yet, changes in pH may be more dynamic at coastal waters (Duarte et al., 2013). For example, uptake of NO_3^- by phytoplankton may increase alkalinity and raise pH (Kenneth, 2002). As such, high frequency phytoplankton blooms in the northern gulf of Oman may drive pH raising in the area (Ghazilou et al., 2017).

4.4. DO

In our study, monthly variations in DO exhibited to some extent a multimodal pattern which was also reported from the southern part of the Gulf (Al-Azri et al., 2010). The hydrology of the coastal waters of the Gulf of Oman is mainly affected by monsoon events. During monsoon seasons, the influx of deep oxygen-depleted waters into the coastal shelf may attributes to decreased DO (Al-Azri et al., 2010). Yet, algal blooms may alleviate these effects.

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