The Biogeochemical Features of Kuwaiti Water in the Northwestern Arabian Gulf: Current State of Knowledge and Future

Turki Al-Said, Amit Sarkar, and Rakhesh Madhusoodhanan

Abstract The Northwestern Persian/Arabian Gulf (here after northwestern Arabian Gulf, NWAG) of Kuwait is a distinguished natural environment where hydrography and biogeochemistry change biannually due to unique climatic conditions. Furthermore, this region receives runoff from major river systems in the entire Arabian Gulf. In recent years, the NWAG is subjected to severe anthropogenic stress due to rapid coastal urbanization, dumping of untreated sewage, release of brine from desalination plants, and reduction in riverine discharges. The environmental scenario in this landlocked sea is exacerbated due to its close proximity to the fast-warming Arabian Peninsula and sluggish water exchange with the Indian Ocean. These conditions could threaten the functioning of the NWAG ecosystem under global warming and ocean acidification-related climate change scenario. In the present synthesis, available data were reevaluated to gain insight into the current status of the NWAG in terms of its surface biogeochemical characteristics.

Keywords Northwestern Gulf of Kuwait · Biogeochemistry · Anthropogenic stress · Climate change

1 Introduction and Background

Intensive research pertaining to hydrography and biogeochemistry of the Arabian Gulf has started during the mid-1960s as part of the first International Indian Ocean Expedition (IIOE). High-resolution observations were carried out onboard R. V. Meteor covering 133 stations primarily along the Iranian coast (Grasshoff 1976). In well accordance with the earlier winter estimates, salinity remained at ~40.5 and temperature at 19 °C in the inner Gulf. Most importantly detailed data sets were generated during this expedition on dissolved oxygen, nutrients and pH, and the

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circulation pattern. Oxygen was super saturated (>100%) to support marine life and also gave an idea of strong overturn and short residence time of water in this basin. Phosphate (PO_4^{3-}) concentrations were between 0.1 and 0.4 μM. An inflow of phosphate rich water (tongue of water having PO_4^{3-} concentration > 1 μM) from the northwestern Indian Ocean was also identified. Nitrogenous nutrients (NO_3^-, NO_2^- and NH_4^+) were in surplus, but silicate (SiO_4^{4-}) levels were extremely low and identified as the limiting nutrient during this campaign. However, these observations were restricted along Iranian coast only and do not reflect the status of nutrients in the shallow NWAG. Studies carried out onboard R. V. Atlantis during 1977 covered more geographical area and provided the firsthand information on seawater carbonate system in the Arabian Gulf (Brewer and Dyrssen 1985). The physical conditions and circulation patterns were very similar to that reported during the IIOE cruise. Despite the low SiO_4^{4-} concentrations, the surface water was found to be nitrogen limited (NO_3^- levels were below detection) during this expedition. Massive carbonate loss via $CaCO_3$ precipitation was recorded from this region. From the salinity-alkalinity relationship and comparison with Indian Ocean equivalent surface salinity, it was calculated that Arabian Gulf water losses ~62.5 μM kg^{-1} of $CaCO_3$. Massive organic removal of CO_2 via primary production was also reported. More scientific research emerged from this region after establishment of the ROPME (The Regional Organization for the Protection of Marine Environment) during 1979 aimed to protect the basin from anthropogenic perturbations. ROPME was initiated to implement Kuwait action plan to protect and develop coastal areas of the Arabian Gulf and signed by eight surrounding member states: Islamic Republic of Iran, Kingdom of Bahrain, Kingdom of Saudi Arabia, Republic of Iraq, State of Kuwait, State of Qatar, Sultanate of Oman, and the United Arab Emirates. ROPME has hastened oceanographic research activities in the entire gulf including the territorial waters of the member countries (five major cruises since 1992–2006, www.ropme.org).

Biogeochemical features of the NWAG^ off Kuwait are important being the region of dense deep water formation which flows out of the Gulf (Fig. 1) as subsurface currents into the northern Arabian Sea (Swift and Bower 2003; Al-said et al. 2018a). Any significant variability in water column biogeochemistry of this region therefore affects the Northern Indian Ocean. Because of extreme aridity of terrestrial land, most of the population of Kuwait has been colonized in the coastal area with a doubling time of 30 years (Al-Mutairi et al. 2014). These settlements and the supporting industrial establishments have ultimately put the ecosystem functioning of NWAG under tremendous risk. Moreover, this region receives direct discharges from Shatt-al Arab river system (SAR) which has reduced substantially due to recent damming of the major rivers supplying the SAR, causing significant environmental changes in the NWAG. In this chapter, physico-chemical information on the surface waters of the NWAG off Kuwait published over the past few years are reevaluated and ideas synthesized. Major research gap areas were identified and proposed for future scientific ventures.

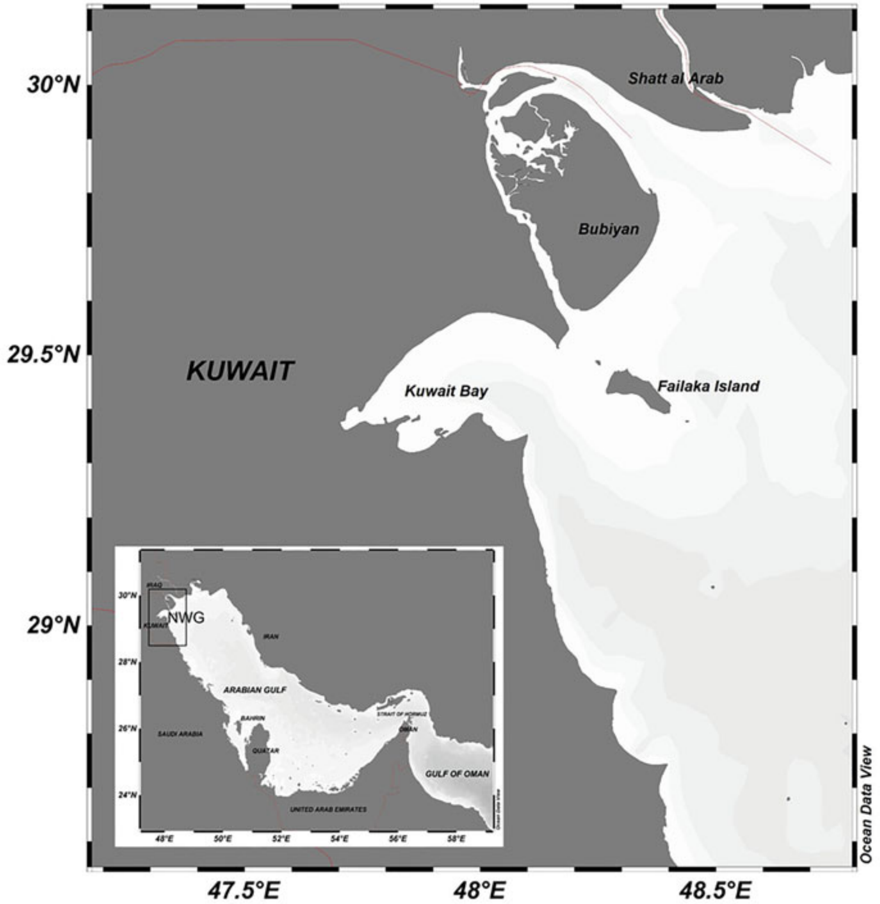

Fig. 1 Schematic map of North Western Gulf of Kuwait (NWG)

2 Hydrography: The Physical Settings

Being an arid environment, changes in the sea surface temperature (SST) and salinity are dependent on regional climate features. In Kuwait, the climate is characterized by hot summer during June to September (or first week October) when air temperature rises up to as high as ~51 °C with an average of 41 °C with extreme diurnal variability (~22–31 °C). In winter (November to February) temperature drops to 0 °C with an average of ~13 °C (Al-Yamani et al. 2004).

Annual mean temperature was reported to be 23.8 °C and salinity 39.6 (Al-Yamani et al. 2004). The first measurements of temperature and salinity in the NWAG were carried out onboard R.V. Atlantis during March 1977. During this study, SST ranged between 19 and 20 °C and salinity ranged between 40.48 and

40.51 (Grice and Gibson 1978). Subsequently, the first comprehensive synthesis of biogeochemical parameters was published in 1999 by Rao and Al-Yamani, in which they have analyzed data collected from 1985 until 1990. Since, the primary goal of their study was to find the relation between light availability and phytoplankton biomass, the authors did mention that temperature (>15–<32 °C) and salinity profiles were taken, but absolute values weren't presented. In fact, studies carried out in this region since 1974 till 1986 were confined to limited spatial and temporal scale, and data were stored as technical report of individual agencies (Al-Yamani et al. 2004 and references therein). At a regional scale, seasonal variation in temperature and salinity during 1997–1998 was provided by Al-Yamani et al. (2006). During summer, SST varied between 29 and 31 °C, while in winter it was 15–20 °C (Fig. 2a, b). Salinity during summer ranged from 27.71 to 40.11, and in winter it was slightly lower and varied between 27.87 and 39.40 (Fig. 2c, d). The lowest salinity (~27) was found in the northernmost station due to the influence of freshwater inflow from Shatt-Al Arab River system (Darmoian and Lindqvist 1988). North-South salinity gradient (difference as high as 7) is prominent in NWAG due to this freshwater influence (Al-Yamani 2008). While spring time snow melting in Turkey, Syria, Iran, and Iraq contributes significantly to the SAR discharge, winter evaporation is also identified as an important factor that determines the salinity of NWAG (Al-Yamani et al. 2004).

Most recent seasonal variability in SST and salinity is shown by Al-Said et al. 2018b based on data collected during 2015. In summer, SST ranged between 26.15 and 30.43 °C, whereas, in winter, it was 17.6–24.55 °C (Fig. 2e, f). Salinity values were 41.71–44.37 in summer and 40.61–45.67 in winter (Fig. 2g, h). Although seasonal patterns were very similar over a two decadal timescale, high salinity values were observed during 2015. According to Al-Said et al. (2017), the rejected brine from several desalination plants located along the coast of Kuwait also contributes to the observed increase in salinity in recent years.

3 Climatically Important Gases and Their Components

Biogeochemical processes in the ocean balances cycling of oxygen (O_2) and other climatically important gases like carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and sulfur compounds (most importantly^ dimethyl sulfide—DMS) as they maintain global radiation balance (Dileepkumar 2006). Information on dissolved gases in the NWAG is very scanty. Dissolved oxygen is the only gas that has been measured in the water column by means of sensor or by standard titrimetric protocol.

Surface oxygen distribution in the NWAG showed distinct seasonal pattern having lower levels in summer than winter which suggests maintaining the law of gas diffusibility. However, data collected during 1997–1998 exhibited under saturation of oxygen in both seasons. In summer, surface concentrations ranged between 138.60 and 165.8 μM which corresponds to ~70–90% saturation, and in winter

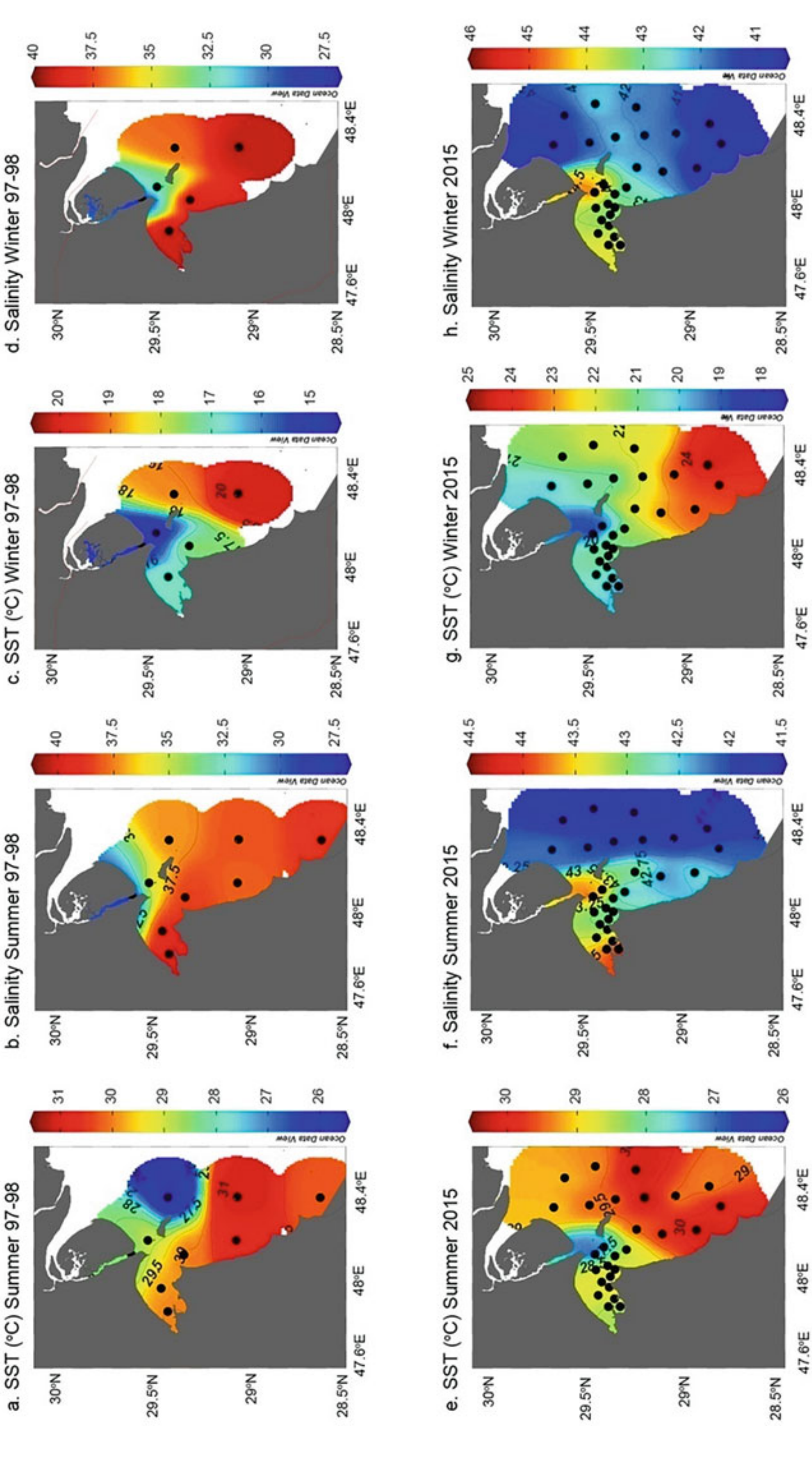

Fig. 2 Seasonal temperature and salinity variation in NWG during 1997–98 (**a–d**) and 2015 (**e–h**)

values went up to 221.8 μM corresponding to 88% saturation only (Fig. 3a, c). It can be speculated that oxygen was under estimated during this study. Apparent oxygen utilization (AOU) often used in biogeochemistry as a measure of respiration extent was computed from the data set. During 1997–1998 respiration signature was moderate. Summer AOU was higher (20–60 μM) compared to winter (maximum 50 μM) (Fig. 3b, d). Interestingly positive AOU reveals heterotrophic nature of the water column. The conditions were contradictory in 2015 although seasonal patterns were similar in comparison with earlier studies in 1997–1998. Oxygen concentrations were higher and super saturated in both seasons during 2015 (Fig. 3e, g). Strong negative AOU suggested highly productive nature of the surface water during the period of study in 2015 (Fig. 3f, h). Both the studies quoted here sampled only the surface water of NWAG, and therefore the effect of coastal eutrophication on oxygen drawdown is not clear. However, studies in central Arabian Gulf revealed near-bottom hypoxic condition during summer and linked it to anthropogenic perturbations (Al-Ansari et al. 2015).

Despite their lower atmospheric concentrations, N_2O and CH_4 are two biogeochemically important gases because of their higher radiative capacity. Dimethyl sulfide (DMS) is another climatically important gas which has cooling effect on the atmosphere and significant oceanographic sources. Hashimoto et al. (1998) studied N_2O in the ROPME Sea Area and reported its supersaturation in the surface (106–186% with a mean of 136 ± 17%) which suggests this region may serve as weak source of atmospheric N_2O. However, this study covered the southern regions of the Arabian Gulf only.

CO_2 cycling in the NWAG is of considerable interest due to large seasonal variations in physical conditions where SST differs by 10 °C between summer and winter. The partial pressure of CO_2 (pCO_2) in the NWAG was believed to be determined by combinations of seasonal temperature fluctuations, biological activities, and carbonate precipitations. However, except the study carried out by Brewer and Dyrssen during 1998, there is a lack of study on inorganic carbon components from this region. A recent study carried out by Al-Said et al. (2018a) provided details of total organic carbon (TOC) levels in Kuwaiti water. Very high TOC (318.4 μM) and even higher during plankton blooms indicated high biological production in the NWAG, especially near the polluted Bay areas. The observed average TOC of 161.2 μM over a 2 years period was 2–4 times higher than global open ocean average (40–80 μM) reported by Hansell et al. (2009) from the deep and surface waters, respectively. These values were also higher than the neighboring Arabian Sea. Although allochthonous sources contribute significantly to the dissolved organic carbon (DOC) pool in Kuwaiti waters, the TOC concentrations were positively correlated with chlorophyll *a* indicating the importance of autochthonous particulate sources too. Such high carbon content in the Arabian Gulf water contributing to the expansion of mesopelagic oxygen minimum zone (OMZ) in the northwestern Indian Ocean is speculated.

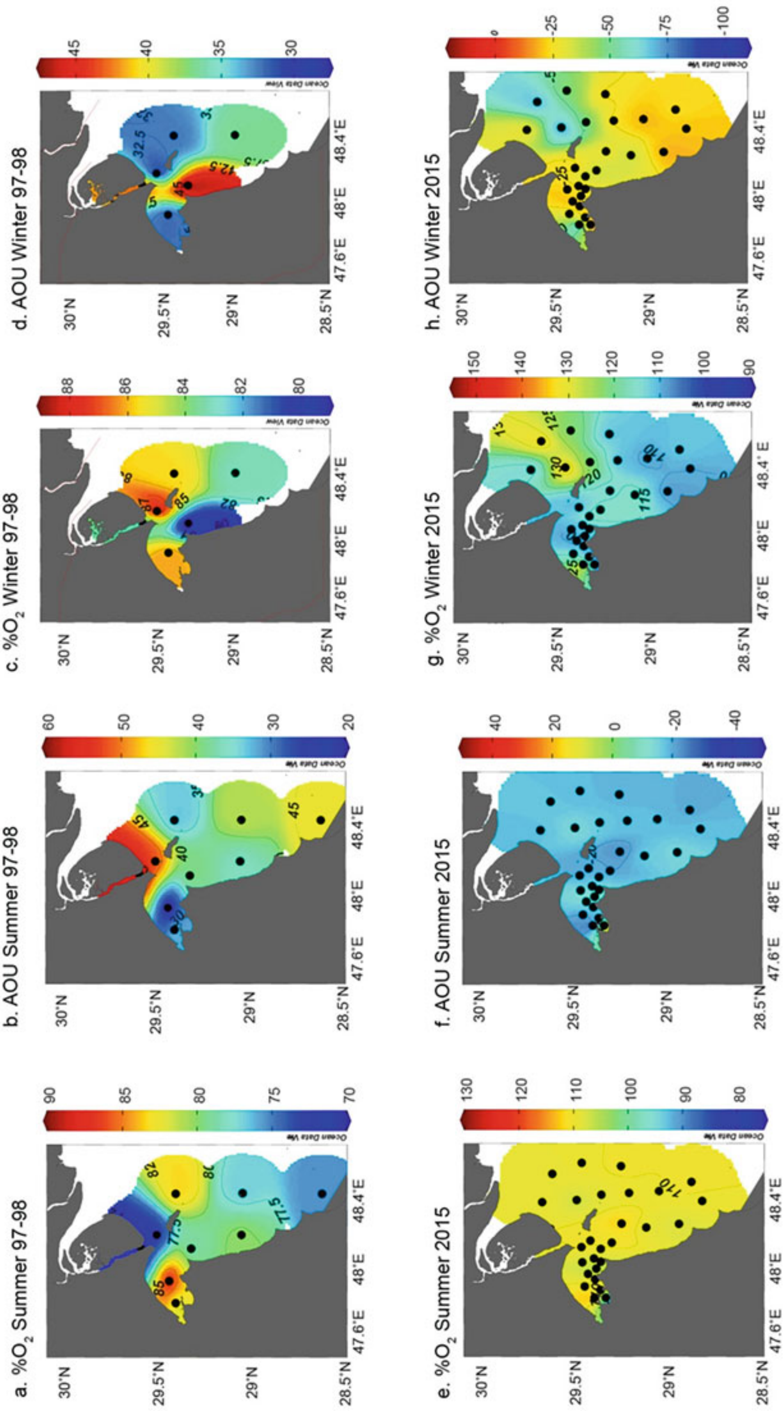

Fig. 3 Seasonal changes in oxygen saturation and apparent oxygen utilization in NGW during 1997–1998 (**a–d**) and 2015 (**e–h**)

4 Biogeochemistry of Bio-essential Macronutrients and Trace Elements

Nitrate, nitrite, ammonium, phosphate, and silicate (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and SiO_4^{4-}) are the most crucial macronutrients (found in micro molar ranges in general) which limits the growth of phytoplankton and also actively cycle through multiple trophic levels in the marine ecosystem. In the NWAG, nutrient concentrations during 1997–1998 summer were fairly higher close to the area of riverine discharge (NO_3^- was~8 μM). Conversely, in the offshore waters, nitrate levels were close to zero at few stations. PO_4^{3-} and SiO_4^{4-} followed a similar trend. Nitrate deficit (N*) and silicate deficit (Si*) were calculated based on Redfield stoichiometry following Gruber and Sarmiento 1997. During summer lowest N* value was −4 which is very closer to the global nitrate deficit average of −3. Si* was never negative indicating ample availability of SiO_4^{4-} in the water to promote phytoplankton growth (Fig. 4a, b). During winter 1997–1998, in comparison with summer, lower concentrations of NO_3^- (maximum ~4 μM), PO_4^{3-}, and SiO_4^{4-} were noticed (Fig. 4c, d). Interestingly higher PO_4^{3-} levels were found in the southern offshore areas unlike other nutrients which were high in the north near the river discharge area. In winter, N* was also found to be lower implying that this basin is seasonally nitrogen deficit; however, Si* was never found in deficit.

Completely opposite scenario was observed during 2015 (Fig. 4e–h). Although the highest seasonal concentration of NO_3^- was reported in the winter of 2015, N* was equally higher compared to 1997–1998. Silica deficiency was also reported from few stations. Irrespective of this seasonal variability, all the nutrients showed lower concentrations in 2015 compared to 1997–1998, except PO_4^{3-} levels which show high values (>1 μM) in summer 2015. These two studies were conducted in the same area in a gap of two decades. If there was anthropogenic nutrient loading into this basin, higher concentrations of nutrient would have been seen in the later study. In fact, NH_4^+ levels were low in all the studies and rarely crossed 1 μM. We believe there are major sink of anthropogenic nutrient in this region which could be through sedimentary reductive processes or fast removal by biological activities in the pelagic realms. Furthermore, significant decrease of nutrients in this region could be attributed to reduction of Shatt Al-Arab discharge over past few decades.

Al-Said et al. (2018b) provided first information on micronutrients (bio-reactive trace elements) in the surface waters of the NWAG based on their field observations carried out in 2015 summer and winter seasons. Before this study, no other studies were available on the spatial and temporal variation in dissolved micronutrients from the entire Arabian Gulf. The study focused on the total dissolved fractions of five bio-essential trace elements, viz., copper (Cu), nickel (Ni), cobalt (Co), zinc (Zn), and iron (Fe).

The trace metal concentrations were comparable with those from other tropical marine areas but showed considerable spatial and temporal variability. The values ranged from 3.94 to 27.17 nM for Cu, from 7.80 to 34.80 nM for Ni, from 0.51 to 1.34 nM for Co, from 5.14 to 33.17 for Zn, and from 0.44 to 31.86 nM for

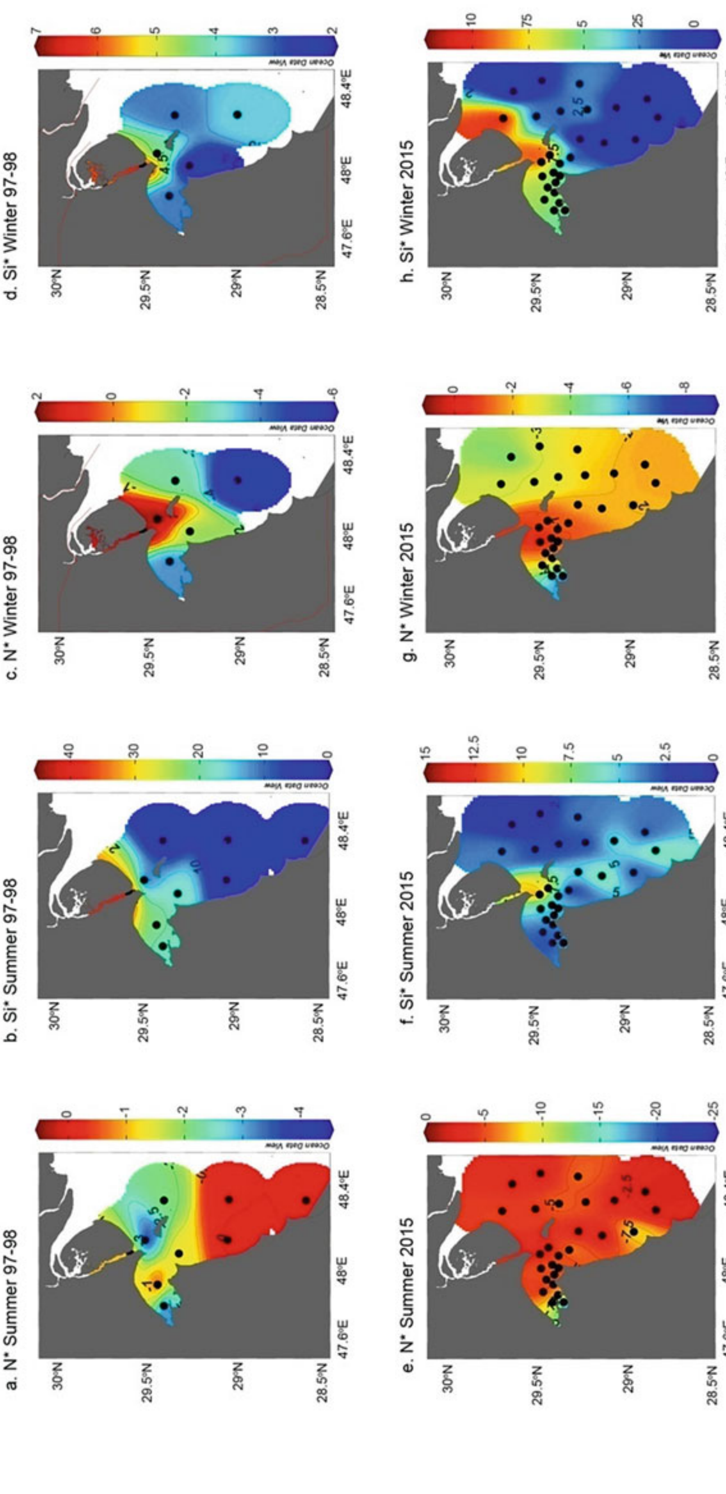

Fig. 4 Nitrate deficit (N*) and silicate deficit (Si*) during summer and winter of 1997–1998 (**a–d**) and 2015 (**e–h**)

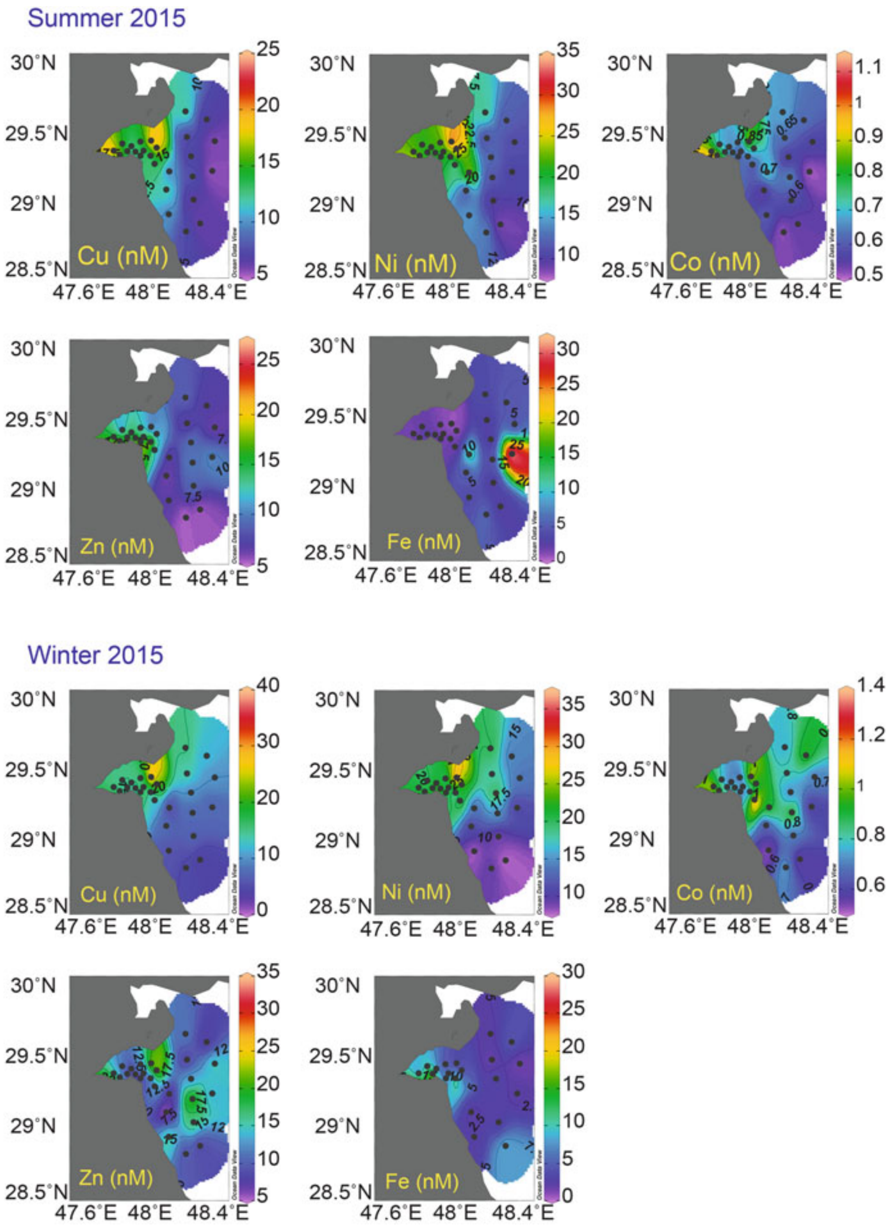

Fig. 5 Spatiotemporal distribution of trace elements in NWG

Fe. Dissolved Ni was predominating in this region in both the summer and winter having maximum concentrations (~35 nM) around riverine discharge area (Fig. 5). Availability of dissolved cobalt was lowest and didn't show any significant spatio-temporal variations. Dissolved Cu and Zn both have increased considerably in winter with maximum concentrations around coastal and riverine discharge area. These elevated concentrations were hypothesized to be linked with sedimentary resuspension followed by winter mixing. Statistical calculations revealed Cu, Co, and Ni played crucial roles in seasonal biological production along with salinity and availability of NH_4^+. Offshore water exhibited higher dissolved iron during summer and near the coast during winter. This variability suggests sources, and sinks of iron in this region changes with the seasons as the physical and biological processes in this region also changes.

5 Chlorophyll *a* and Productivity

Biologically, NWAG was identified as very unique system (Rao and Al-Yamani 1998). This region is fairly productive with annual chlorophyll *a* concentrations falling in the range of 0.52–3.25 μg l^{-1} as reported earlier by Huq et al. (1981). Strong temporal variations were reported with 0.56–2.06 μg Chl*a* l^{-1} in the month October to as high as ~9 μg l^{-1} in autumn (Huq 1977; Huq et al. 1978). The concentrations were even higher along the coast (10–13 μg l^{-1}, Jacob et al. 1982). This basin suffers sporadic coastal algal blooms, and during such events chlorophyll *a* concentrations can shoots up to 55.4–262.7 μg l^{-1} (Rao et al. 1999). At one instance it reached 1212 μg l^{-1} during a bloom of *Nitzschia* in 2002 (Al-Yamani et al. 2004). Al-Yamani et al. (2006), reported ranges of 0.44–4.39 μg l^{-1} in summer and 0.95–9.2 μg l^{-1} in winter of 1997–1998. They also reported high chlorophyll concentration (~23 μg l^{-1}) during spring (April 1997). Satellite (AVHRR, SeaWiFS, and MODIS)-based chlorophyll *a* distribution maps also supported this region being the most productive in the entire Arabian Gulf (Nezlin et al. 2007). Seasonality was reported to be strongly correlated with SST, PAR (photosynthetically available radiation), and wind stress curl. Also remote forcing like El-Nino and North Atlantic Oscillation events were linked to the chlorophyll *a* variability in this region. A decadal shift in phytoplankton community was observed in this region which is linked to salinity increase during 1999–2013 (Fig. 6). Apart from community level changes, chlorophyll *a* concentrations decreased steadily by 0.03 μg l^{-1} per year over time (Al-Said et al. 2017). During 2015, chlorophyll *a* ranged 0.33–7.37 μg l^{-1} in summer and 0.86–6.99 μg l^{-1} in winter. Although ranges were very similar during both the seasons, average winter concentration (3.42 μg l^{-1}) was almost double to the average summer value (1.88 μg l^{-1}). Chlorophyll *a* data averaged across the seasons over the last two decades shows a decrease of 0.05 μg l^{-1} and 0.08 μg l^{-1} per year during the summer and winter periods, respectively. Unlike chlorophyll *a* measurements and phytoplankton composition studies in this basin, direct measurements of primary production by means of carbon fixation are very scanty.

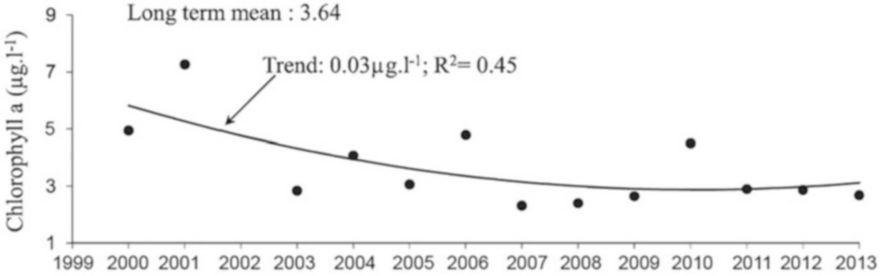

Fig. 6 Long-term (1999–2013) decrease in average chlorophyll a concentration sat two stations in Kuwait waters

Primary productivity measured using ^{14}C technique, in the riverine outflow areas, ranges between 5.44 and 10.3 μgC l^{-1} h^{-1} (Al-Saadi 1989) in summer and 18.5–52.3 μgC l^{-1} h^{-1} in winter (Hadi et al. 1989). Al-Yamani et al. (2006) reported wide spatial and seasonal variability in primary productivity (^{14}C based) in Kuwaiti waters. During their study, carbon uptake rates varied from 31.67 to 653.31 μgC l^{-1} day^{-1}. Productivity attained peak (453.4 μgC l^{-1} day^{-1}) around riverine out flow areas and gradually decreased toward south where it was only ~40 μgC l^{-1} day^{-1}. Considerable seasonal variations were reported with lower carbon uptake in winter. In the NWAG, with changing biomass over time, seasonal alterations in biological fixation of carbon is expectable; however, lack of recent measurements hinder quantifying such changes.

6 Impact of Anthropogenic Perturbations and Climate Change in Kuwaiti Waters

Being, a shallow, landlocked marginal sea, the biogeochemistry of the NWAG off Kuwait is highly vulnerable to anthropogenic activities and climate change-related global warming and ocean acidification. Over the last few decades, several environmental changes were noticed in this region. One of the major phenomena is the decadal change (2000–2013) in salinity. Al-Said et al. (2017) reported salinity increased by ~3 units over the time which also affected the phytoplankton community composition. Reduction in freshwater influx from the SAR system was assigned the principal factor responsible for elevated salinity in the NWAG. It can also be seen in the data collected during summer cruise (August 2001) of R V Al-Quds in northern ROPME sea area. Highest density of Kuwaiti waters in winter due to increase in salinity will adversely affect the hydrography within and beyond the Arabian Gulf since it is the region of deep water formation. This will also affect the carbon cycling and nutrient biogeochemistry of this region which has already reflected on the reduced fish landings in Kuwait (Sheppard et al. 2010; Al-Husaini et al. 2015).

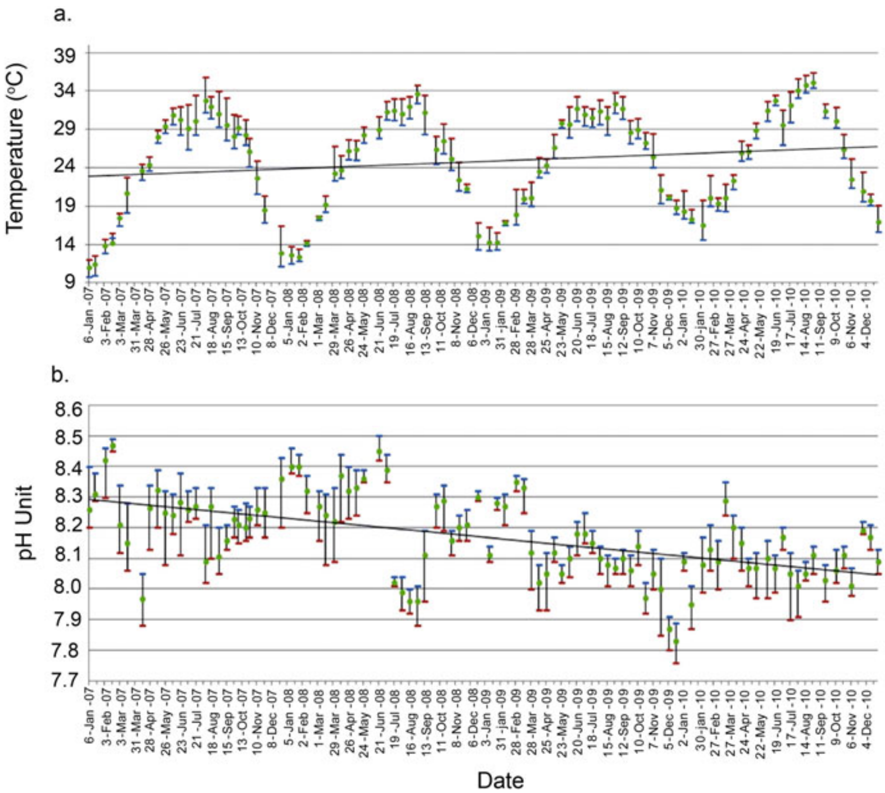

Fig. 7 Increasing SST (**a**) and decreasing trend in pH (**b**) between January 2007 and December 2010 in Kuwait territorial waters (Uddin et al. 2012)

Unlike salinity increment which is due to regional perturbations, SST also increased in this basin which is linked to increase in global CO_2 concentrations due to fossil fuel burning. Uddin et al. (2012) show strong inter seasonal and interannual variation in Kuwait Bay SST but with a steady increase between the years 2007 and 2010 in (Fig. 7a). Al-Yamani et al. (2017) also observed several intra- and interannual shifts in salinity and SST but with a steady increase since 1980s. Increasing atmospheric CO_2 is a major concern for oceanographic community around the globe since the pH of seawater is also decreasing simultaneously in a process popularly known as ocean acidification. Uddin et al. (2012) reveal that the pH of NWAG has decreased considerably with a concomitant increase in temperature (Fig. 7b) between 2007 and 2010.

Apart from the climate change-related atrocities, excessive loads of nutrients in coastal waters can cause eutrophication, producing harmful algal blooms (HABs) which progressively turn the system oxygen deficient and make it difficult for life to sustain. In the beginning of the oceanographic research in the Arabian Gulf, the basin was either NO_3^- or SiO_4^{4-} limited. But, discharges of partially treated/untreated domestic sewage in the Gulf became a major concern in recent years. A recent estimate shows that the population of Kuwait has grown 27 times compared to 1950s. Such large-scale urbanization has negatively impacted the coastal waters. Devlin et al. (2015) suggest significant increase in nutrient levels in Kuwait Bay, however, with a decrease in chlorophyll *a* concentrations over the past 30 years. Notwithstanding this fact increased HAB occurrences, and fish kill incidents are noticed in recent years (Al-Yamani et al. 2004; Sheppard et al. 2010). Only one bloom of *Phaeocystis* was recorded in the late 1980s (Al-Hasan et al. 1990) which has become more frequent since the 1990s including blooms of toxin producing *Karenia* and *Gymnodinium* which led to massive fish kills in 1999 (Al-Yamani et al. 2004). TOC concentrations in the NWAG were higher, but impact of anthropogenic perturbations is not clear since there was no base line data. However, it is clear from the spatial distribution (highest values in polluted bay water) that autochthonous TOC may be produced by biological production fuelled by anthropogenic nutrient loadings in the coastal areas.

The NWAG is well oxygenated due to shallow depths, very well-mixed water column during winter and short residence time. Hypoxic conditions in the Arabian Gulf were found off Qatar (0.86 ml l^{-1} oxygen) over an area exceeding 7000 km^2 (Al-Ansari et al. 2015). Very recent study revealed low oxygen in the shallow areas of Kuwait Bay (Al-Mutairi et al. 2014). It has been proposed that high TOC in this region through degradation of the organic carbon must be contributing to the formation of hypoxia. Furthermore, semi-labile components are expected to conserve and gets exported to the neighboring Arabian Sea by the out flowing Arabian Gulf deep water that flows along the western Arabian Gulf contributing to the expansion of the denitrification zones in perennial oxygen minimum zones (OMZs) in the northwestern Indian Ocean (Al-Said et al. 2018a).

7 Concluding Remarks and Future Recommendations

The ocean science community has undertaken the challenge of exploring the Arabian Gulf domain and over the past few decades has made remarkable advancement in the understanding of the physics, biology, and chemistry of the Arabian Gulf waters. We now have a fair understanding on the salinity changes in the system which is largely attributed to the cumulative effect reduction in riverine freshwater discharge due to excessive damming of major rivers supplying Shatt Al-Arab river system and the brine release from desalination plants. Decadal changes increment of SST was 0.5 to >1 °C which has impacted the system adversely. Surface dissolved oxygen didn't show any considerable changes over time. However, pH, an important component of carbon dioxide system, showed steady decrease over the years pointing to ocean acidification scenario. But this reduction is more prominent in summer season. Probability of high organic carbon load in the NWAG contributing to the expansion of OMZ in the northwestern Indian Ocean is discussed.

Macronutrient levels were not found in deficit except at few stations and are subjected to seasonal variations. Although trace elements levels were also not bio-limiting, the demand for these micronutrients varied both spatially and temporally, with a possible change in phytoplankton community composition. Effect of sediment resuspension followed by winter mixing can elevate concentrations of few elements. Spatial variability reveals different sources of metal ions. Phytoplankton biomass showed considerable reduction over time with chlorophyll *a* concentrations showing decreasing trend by 0.05 (in summer) and 0.08 μg l^{-1} per year (in winter) over last two decades.

However, there exist several short comings, and several new questions have emerged from the above synthesis that should be answered by future research. The biogeochemistry of CO_2 and other climatically important gases such as N_2O, CH_4, and DMS is not well-known from this system despite we spoke about decadal decrease in pH which largely dependent of carbonate chemistry of the water. Carbonate chemistry is largely dependent on its solubility and biological pumping. Decadal shifts in SST and salinity bound to change the pCO_2 in the water and so is the reduction in phytoplankton biomass affecting the efficacy of biological pump. The fate of fixed carbon flow through different trophic levels and its sequestration was never studied. Therefore systematic investigations on carbon fixation and particulate element fluxes should be given priority. The Arabian Gulf has been identified as a moderately productive region that supports 50% carbonate precipitation. CO_2 sequestrations in this part of the world are majorly dependent on ocean carbon uptake due to deserted terrestrial ecosystem. Changes in ocean pH will affect the biotic components and ecosystem functioning which in turn regulate the atmospheric carbon dioxide. Effects of ocean acidification on phytoplankton community and other calcareous organisms need to be assessed from this region based on both laboratory and field-based micro/mesocosom experimental studies. This system receives domestic sewage and industrial waste. However, from the present synthesis, we do not see high macronutrient levels in the water. Moreover, NH_4^+, an important composition nitrogenous waste, were never higher than >1 μM. In this context, the role of nanosized flagellated phytoplankton sequestering ammonium needs to be investigated in detail. If anthropogenic nutrients don't end to the sea, they must undergo rigorous processing and get modified in the sediment of the massive intertidal zone of the NWAG. Therefore sedimentary reductive nitrogen processing needs to be studied thoroughly. Strong spatial and temporal variations in trace metal concentrations arise intuitions on their multiple sources and utilization in Kuwaiti waters. It was hypothesized that due to high wind-induced mixing of bottom sediments, sedimentary fluxes are strong in winter. Moreover, due to its close proximity to the desert, frequent sandstorm in this region bring aerosol nutrients into this system. These sources are needed to be quantified based on dedicated oceanographic surveys, benthic flux experiments, and analysis of atmospheric dry/wet deposition (dust and rain). Speciation studies of trace metals must be carried out to understanding their bioavailability and effect on phytoplankton community composition and biomass. Information on phytoplankton productivity is very rudimentary in this region. Stable isotope studies with ^{13}C- and ^{15}N-based productivity measurements should be carried out. These measurements will give insight into primary, new, regenerated, and exportable production in the Arabian Gulf basin. Successful answering of the above concerns will open opportunities to understanding how biogeochemistry and physical processes in the Arabian Gulf waters have contributed to the regional climate and its variability and how the ecosystem of the Arabian Gulf will change over the next century.

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