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Baseline

Dynamic hydrographic variations in northwestern Arabian Gulf over the past three decades: Temporal shifts and trends derived from long-term monitoring data

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ABSTRACT

Hydrographic variables were monitored in northwestern Arabian Gulf over the past three decades and the time-series data were statistically analyzed. The results show that while salinity has undergone several shifts, seawater temperature exhibited a steady increasing trend since the 1980s. The observed salinity shows strong correlation with Shatt Al-Arab River discharge indicating primary contribution of freshwater to salinity among other factors (evaporation and desalination effluent). Recent data show that salinity is at its highest level in the last 30 years with less pronounced seasonal variability in response to severe decline in the freshwater runoff into the northwestern Arabian Gulf. The changes in hydrographic conditions may have significant implications on hydrodynamics, water quality, and ecosystems in the Gulf. Thus, cooperation among the concerned countries - both coastal and riparian nations - would be essential for prevention of further major changes in the Gulf.

The northern Arabian Gulf (NAG) is a productive region of strategic, social and economic importance. The Gulf is an important source of food; petroleum and minerals, pearls, which supported a thriving industry in the past, drinking water through desalination, cooling water for industry and power generation, sands and gravels; highway for navigation, transportation and commerce; and recreation and tourism (Al-Yamani et al., 2004).

The finfish landings of Kuwait waters make up 40 to 50% of the local demand in Kuwait, while shrimp landings are enough to meet local demand and support an export industry (Al-Yamani et al., 2004). However, recent studies (Al-Husaini et al., 2015; Al-Yamani et al., 2007) show that the fish catch (both finfish and shrimp) in Kuwait's waters has declined significantly in the last few decades; landings of five important commercial fishes have declined by over half in the 10 year period since 1995 (Al-Husaini et al., 2015). Among the several possible causes are overfishing and coastal developments; the declines are also considered to be linked with the changed hydrographic conditions in recent years (Al-Husaini et al., 2015; Al-Yamani et al., 2007; Bishop et al., 2011; Morgan, 2006). Plankton community structures are closely related to hydrographic and associated physiochemical conditions in NAG (Subba Rao and Al-Yamani, 1998; Al-Said et al., 2017). Hydrographic conditions (e.g. temperature and salinity) exert primary environmental control on biogeochemical cycling and ecosystem functioning and elevated water temperature also enhances effects of pollution (Schiedek et al., 2007). Therefore, it is important to assess the state of hydrographic conditions in the NAG. Moreover, knowledge of the basic hydrographic characteristics is essential for the planning of shoreline developments in the NAG (e.g., selection of location of new power and desalination plants, construction of offshore structures and management of marine resources). A number of studies have been conducted on oceanographic characteristics of the NAG. However, most of the studies were confined to limited periods of time or to specific localities (e.g., Al-Abdulghani et al., 2013; Al-Mutairi et al., 2014; Al-Yamani et al., 1997; Anderlini et al., 1982; Jacob et al., 1981; Lee et al., 1986). Hydrographic condition in NAG is highly dynamic, and is determined by a combination of several factors including interactions between the atmosphere, terrestrial inputs and anthropogenic activities (Sheppard et al., 2010). Recently, Devlin et al. (2015) analyzed a data set obtained through monitoring of water quality in Kuwait's coastal waters over 3 decades, providing an insight into impacts of diffused and point sources on temporal trends of water quality parameters. Al-Yamani (2008) highlighted the importance of freshwater influx from the Shatt Al Arab River, the main source of freshwater to NAG, and hence, on Kuwait's marine environment. Elhakeem and Elshorbagy (2015) examined impacts of climate change and coastal effluents on temperature and salinity of the entire Arabian Gulf using hydrodynamic simulation. Pokavanich et al. (2014) investigated environmental characteristics of the NAG by hydrodynamic modeling and found strong

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effects of river discharge, meteorology and hydrodynamics. Despite accumulated knowledge provided by the previous studies, understanding of the temporal and spatial hydrographic conditions is still quite limited. A systematic comprehensive investigation is especially needed to provide trends of long-term variability of hydrological variables in the NAG.

Long-term measurements for salinity and water temperature were made for more than three decades at multiple locations in Kuwait's waters by the Kuwait Institute for Scientific Research. This paper reports the results of analysis of this data set and discusses the temporal and spatial hydrographic characteristics in the NAG. The specific objective of this work is to study spatio-temporal hydrographic changes in Kuwait waters by (i) analyzing time-series of the salinity and temperature data, (ii) examining spatial differences of hydrographic parameters in Kuwait waters, and (iii) investigating vertical structure of water density through time at different locations. The likely causes of observed variations in the hydrographic conditions are also discussed. This is the first study providing information on hydrographic changes over the past three decades in Kuwait's waters.

The Arabian Gulf has a subtropical climate with a limited annual precipitation averaging < 100 mm (Al Senafi and Anis, 2015; Xue and Eltahir, 2015). A pronounced seasonality can be observed with hot and dry summer from June to September, and relatively wet and milder seasons from October to May (Devlin et al., 2015). Total evaporation from the Gulf surpasses freshwater inflow and precipitation (Sheppard, 1993; Xue and Eltahir, 2015). Under the hyper-arid climate condition (Middleton and Thomas, 1997) and the relatively long residence time of the Gulf, which is estimated to fall in the range of 1 to 6 years (Reynolds, 1993; Sadrinasab and Kämpf, 2004; Xue and Eltahir, 2015), salinity exceeds 39 psu in most parts of the Arabian Gulf (Sheppard et al., 2010). At the head of northwestern Arabian Gulf, the Shatt Al-Arab River (SAR), which is a combined flow of the Euphrates and Tigris rivers, provides main freshwater inflow from the highlands of eastern Anatolia in Turkey and the Syrian and Iraqi plateaus during the periods of rainfall in winter and melting of snow in spring (Abdullah et al., 2015). The Karun River is the main tributary that joins SAR during its course to the Gulf. Anderlini et al. (1982) reported a salinity range between 37 and 50 in the NAG based on their year-long observation. However, due to the freshwater input, salinity near the mouth of SAR was reported to fall to 35 psu or less during winter season (Al-Yamani et al., 1997). Circulation pattern in NAG is typified by seasonal counterclockwise gyre (Alosairi and Pokavanich, 2017; Azam et al., 2006; Kämpf and Sadrinasab, 2006), which carries outflow from the SAR in a westerly direction and down the Kuwaiti coast (Alosairi and Pokavanich, 2017; Reynolds, 1993). Kuwait's mean annual seawater temperature is reported to be 23.8 °C with the mean highest and lowest temperatures occurring in July to August and January to February respectively (Al-Yamani et al., 2004). Water temperature in the northern part of the NAG are generally cooler than those in the south especially during winter and spring; however, spatial variation of water temperature is smaller as compared to that of salinity (Al-Yamani et al., 2004).

Salinity and water temperature data analyzed in this study were obtained since January 1982. Measurements were made on a monthly to bimonthly basis except during and a few months after the 1991 Gulf War (Table 1). The data were obtained with Conductivity-Temperature-Depth (CTD) profilers. Four types of CTD profilers were used in this study: NBA model TDS-7 M (NBA CONTROLS), SBE 25 (Sea-Bird Electronics), AAQ 1183 (JFE Advantech), and AAQ-RINKO (JFE Advantech) for the periods 1982–1996, 1996–2004, 2004–2012, and 2012–2015, respectively. To ensure accurate measurements, the profilers were calibrated periodically according to the instrument-specific protocols provided by the manufacturers and were also sent to the manufacturers for periodical overhaul of the sensors. The data presented in this paper were obtained from three stations located off Kuwait in northwestern Arabian Gulf (Fig. 1). Of these stations, station K6 is located in the middle of Kuwait Bay, station 6 is located at the mouth of the Bay and station 18 is an offshore station approximately 40 km away from shore; average depths are 8.5 m for station K6, 22 m for station 6, and 26.5 m for station 18 (Table 1).

Table 1
Location and depth of the monitoring stations and the data acquisition periods at each station.

Stations	Latitude	Longitude	Depth (m)	Measurement period	
K6	N 29.450	E 47.967	8.5	1982 Apr–1990 Jul	1994 Apr–2015Dec
6	N 29.333	E 48.167	22.0	1982 Jan–1990 Jul	1992 Mar–2015Dec
18	N 29.062	E 48.506	26.5	1982 Jan–1987 Jun	1995 Sep–2015Dec

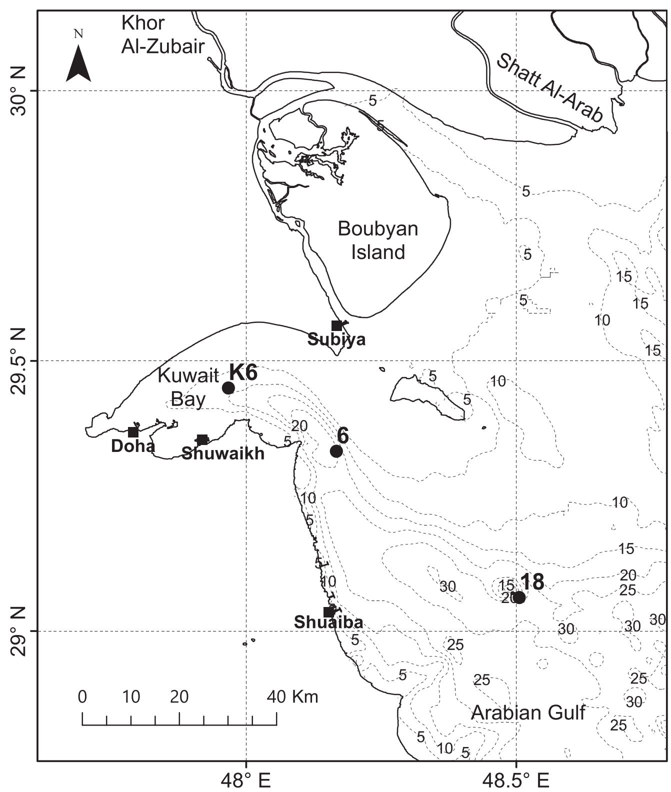

Fig. 1. Study area in northwestern Arabian Gulf. Monitoring locations are indicated by circle points. Locations of desalination and power plants in Kuwait are also shown by square points. Contour indicates bathymetry (m).

Hydrographic time series data analyses include different components such as trend, seasonal, step and irregular components. In this study, the following statistical analyses were applied to the salinity and the temperature data to extract the underlying patterns: step detection and trend test. The statistical analyses were performed using statistical language R (R Core Team, 2015).

Time series data containing step component show an abrupt change in the pattern at some point in time. It is necessary to take the step effect into account when applying other time series analyses to avoid misinterpretation (Xu et al., 2002). Time series data x_t, which contain a level shift δ, can be expressed as follows.

$$x_t = \varepsilon_t \quad t = 1, 2, \cdots, n_{step} - 1 \tag{1}$$

$$x_t = \varepsilon_t + \delta, \quad t = n_{step}, n_{step} + 1, \cdots n \tag{2}$$

Where, ε_t is independent stationary stochastic process, n_{step} is time when level shift occurred. The time series data expressed by (1) and (2) have average μ_1, μ_2 and unbiased variance σ_1, σ_2 respectively. The level