

Trend and dynamic of chlorophyll-*a* concentration over the Arabian Gulf

A long-term study using MODIS data (2004 – 2019)

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Jasem A Albanai *

** Marine Monitoring Section, Water Quality Monitoring Department, Environmental Public Authority, Kuwait*

** Corresponding Author: Albanay.com@gmail.com*

ABSTRACT

Chlorophyll-*a* concentration in water is an indicator of phytoplankton density, which in turn is crucial, as it represents the base of the ecological life in seas and oceans. Any increase or decrease in the number of phytoplankton may contribute to disruption to the ecological cycle in the seawater. The density of phytoplankton is also an important indicator of water quality. Traditionally, water samples are collected in the field and analysed in the laboratory to find the density of phytoplankton in a specified amount of water. Recently, remote sensing has led to the development of advanced and remote methods to detect phytoplankton density, chiefly by extracting near-surface chlorophyll-*a* concentrations. In this study, MODIS (Aqua) Level 3 data (64 images) were used to extract average chlorophyll-*a* concentration at time points from 2004 to 2019 (over 16 years) for the Arabian Gulf, where the Level 2 (11 images) data were used to determine the accuracy of the estimated values via MODIS (Aqua) using field data taken from the waters of the State of Kuwait (25 points). The results showed good accuracy for MODIS (RMSE = ± 1.066), and it also shows that the temporal seasonal averages change in a annual-cycles, and that the trend decreased from 2004 to 2019, by about 0.7 mg/m^{-3} .

Keywords: Arabian / Persian Gulf; Kuwait; MODIS; chlorophyll-*a*; Coastal engineering.

INTRODUCTION

The water quality of the hydrosphere is determined by measuring a set of its characteristics, such as sea surface temperature, salinity, dissolved oxygen, chlorophyll-*a* concentration and turbidity, among others. The concentration of chlorophyll-*a* is an indication of the phytoplankton density in water (Muller-Karger, Hu, Andréfouët, Varela, & Thunell, 2005), phytoplankton being the basis of ecological life in seas and oceans. There are many methods of monitoring water quality. Traditionally, it relies on field measurements to find out the spatial distribution, and subsequently using statistical analysis methods to identify the temporal pattern and dynamic. Recently, remote sensing methods have been increasingly used to monitor water quality through the interactions of electromagnetic radiation with the water surface. Remote sensing instruments have several advantages that make it an important method for studying and monitoring the earth. The wide spatial coverage and archives provided by the satellites combine to make it a useful tool to save time and effort.

Satellites and sensors vary in their characteristics and features. Some of them have high temporal resolution and moderate spatial resolution, such as MODIS spectrometer, while others offer higher spatial resolution and lower temporal resolution, such as Landsat satellites. The choice of the satellite and sensor depends on several factors, such as the size of the study area, the goals of the study, the spectral bands covered by the satellite, and more. The moderate-resolution sensors launched by NASA, such as MODIS and VIIRS, are among the most frequently used in the study of near-surface chlorophyll-*a* concentration, due to the availability of their data in the form of products extracted from the relationship between field measurements and the spectral bands of the sensor, such as near-surface chlorophyll-*a* and sea surface temperature products. These products are characterized by high temporal resolution up to approximately one day, and they contain a huge archive that extends from the end of the last

century to the present day. On the other hand, some limitations can be found for these sensors; for example, the moderate spatial resolution and weak spatial coverage of marginal seas such as the Arabian Gulf.

Despite the importance of remote sensing methods in measuring water quality and chlorophyll-*a* concentration, a relatively limited number of studies have used satellite data to study the levels of chlorophyll-*a* in the Arabian Gulf. This is chiefly due to several reasons related to the lack of quality in-situ data, the dust storms that limit the usefulness of optical remote sensing (Al-Naimi, Raitos, Ben-Hamadou, & Soliman, 2017; Nezlin, Polikarpov, Al-Yamani, Subba Rao, & Ignatov, 2010; Zhao & Ghedira, 2014), and the weak spatial coverage of marginal seas such as the Arabian Gulf by the moderate spatial resolution sensors. Many studies have dealt with the marine environment of the Arabian Gulf in terms of general circulation and bathymetry (Brewer & Dyrssen, 1985; Nezlin et al., 2010; Reynolds, 1993; Sheppard et al., 2010). The Gulf is relatively shallow and contains a counter-clockwise cyclical flow of water. Nezlin, Polikarpov & Al-Yamani (2007) divided the Arabian Gulf into several sub-regions based on Reynolds' (1993) study of the Gulf's properties. Other studies analyzed the concentration of chlorophyll-*a* in the Gulf and found that the concentration increases near coastal areas, as compared to in open and deep seas (Nezlin et al., 2007). The concentration of chlorophyll-*a* is estimated to range from 0.01 to 10 mg/m⁻³ in the open water of the Arabian Gulf (Sheppard et al., 2010), whereas it reaches as much as 55.4 to 4525 mg/m⁻³ in abnormal conditions in the northwest of the Gulf (Al-Yamani, Saburova, & Polikarpov, 2012). Some studies have dealt with the temporal analysis of chlorophyll concentration, such as Moradi & Kabiri (2015), while other studies measured the accuracy of satellite readings across field data and found a positive correlation (Al-Naimi et al., 2017). However, this study aims to show the long term temporal distribution of chlorophyll-*a* concentration over the Arabian Gulf.

MATERIAL & METHODS

Study area

The Arabian Gulf (or the Persian Gulf, as it is sometimes called) is marginal water connected to the Arabian Sea by the Strait of Hormuz (Fig.1). The Arabian Sea is part of the Indian Ocean, located specifically in the northern part of the ocean. The Arabian Gulf is located between 23.5° and 30.05° North and 47.5° and 56.4° East. The gulf has a subtropical hyper-arid climate (Al-Yamani, Bishop, Ramadhan, Al-Husaini, & Al-Ghadban, 2004), and is surrounded by desert lands. Due to the hydrometeorological conditions of the Gulf region, the sea surface temperature is relatively high, where it reaches a maximum of roughly 36 °C and a minimum of 14 °C, and the salinity concentration ranges from about 35 to 70 PSU (Al-Naimi et al., 2017; Polikarpov, Al-Yamani, & Saburova, 2019). The Gulf is relatively shallow, with the deepest point reaching just over 100 meters; its average depth is about 35 meters. The Gulf's total water volume is about 6000 km³ (Moradi & Kabiri, 2015). The Gulf has a length and width (range) of approximately 990, and 56 - 338 km respectively, and covers a total area of 240,000 km² (Pokavanich et al., 2014). The water circulation consists of discharges from the Strait of Hormuz, and the Tigris and Euphrates rivers, which flow into the northern Arabian Gulf (Shatt al-Arab). The Arabian Gulf is of great economic importance due to the activity of international oil movement through the Strait of Hormuz, in addition to its wealth of fish, due to its location to the south of the Tigris and Euphrates rivers. These rivers are the main source of fish in the Gulf.



Fig. 1. The study area (Arabian Gulf).

Remote sensing data

The data used in this study are downloaded from the OceanColor website (oceancolor.gsfc.nasa.gov). NASA OceanColor is a platform supported by the Ocean Biology Processing Group (OBPG) at NASA's Goddard Space Flight Center. Since 1996, NASA has provided the global scientific society with different marine products depending on satellite data. MODIS (or Moderate Resolution Imaging Spectroradiometer) is a spectrometer aboard Terra (EOS AM-1) and Aqua (EOS PM-) satellites. Together, Terra and Aqua have a temporal resolution of 1 to 2 days. MODIS has a spectral resolution of 36 bands, ranging from 0.405 to 14.385 μm . The pixel size (spatial resolution) of MODIS images varies by the used band, ranging from 250 to 1000 square meters. Due to the high temporal resolution of MODIS, it helps us to improve our understanding of global dynamics and processes on the earth. MODIS

data comes in various levels. Levels 1 and 2 contain geometric and radiometric calibrated data with full-resolution, time-referenced and derived geophysical variables, such as chlorophyll-*a* concentration. Level 3 data are the time-derived geophysical variables for a specific period (monthly, seasonally, etc.) (see Table 1) (Feldman, 2020). In this study, 64 Level 3 data were measured from 2004 to 2019, and 11 Level 2 data points were used for temporal analysis and validation, respectively.

Table. 1. MODIS properties for the study area.

<i>Spatial resolution</i>	250 – 1000 m
<i>Temporal resolution</i>	1 – 2 days
<i>Spectral resolution</i>	36 bands
<i>Mission</i>	2 satellites (Aqua – Terra)
<i>Local capturing time</i>	11 AM – 2 PM (GMT+3)
<i>Levels and products</i>	Yes

Field data

The used field data were referred to the Environmental Public Authority (KEPA) (epa.org.kw). KEPA started to monitor the marine water quality parameters in 1984, and in 2016, it established a monitoring system for Kuwait’s marine environment based on floating stations (number = 15) spread over the territorial waters of the nation (Fig. 2). The buoys take near-surface parameters every 10 minutes so that the hourly average can be extracted. The monitoring parameters cover sea surface temperature, salinity, chlorophyll-*a*, turbidity, pH and dissolved oxygen, among others. The sensors are calibrated annually, according to NIST standards, and periodically serviced. The chlorophyll-*a* records submitted by the 15 stations

throughout 2017 (10- 11 AM GMT+3) were used in this study. The purpose of using the field data is to evaluate the estimated accuracy of chlorophyll-*a* values extracted by the satellite.

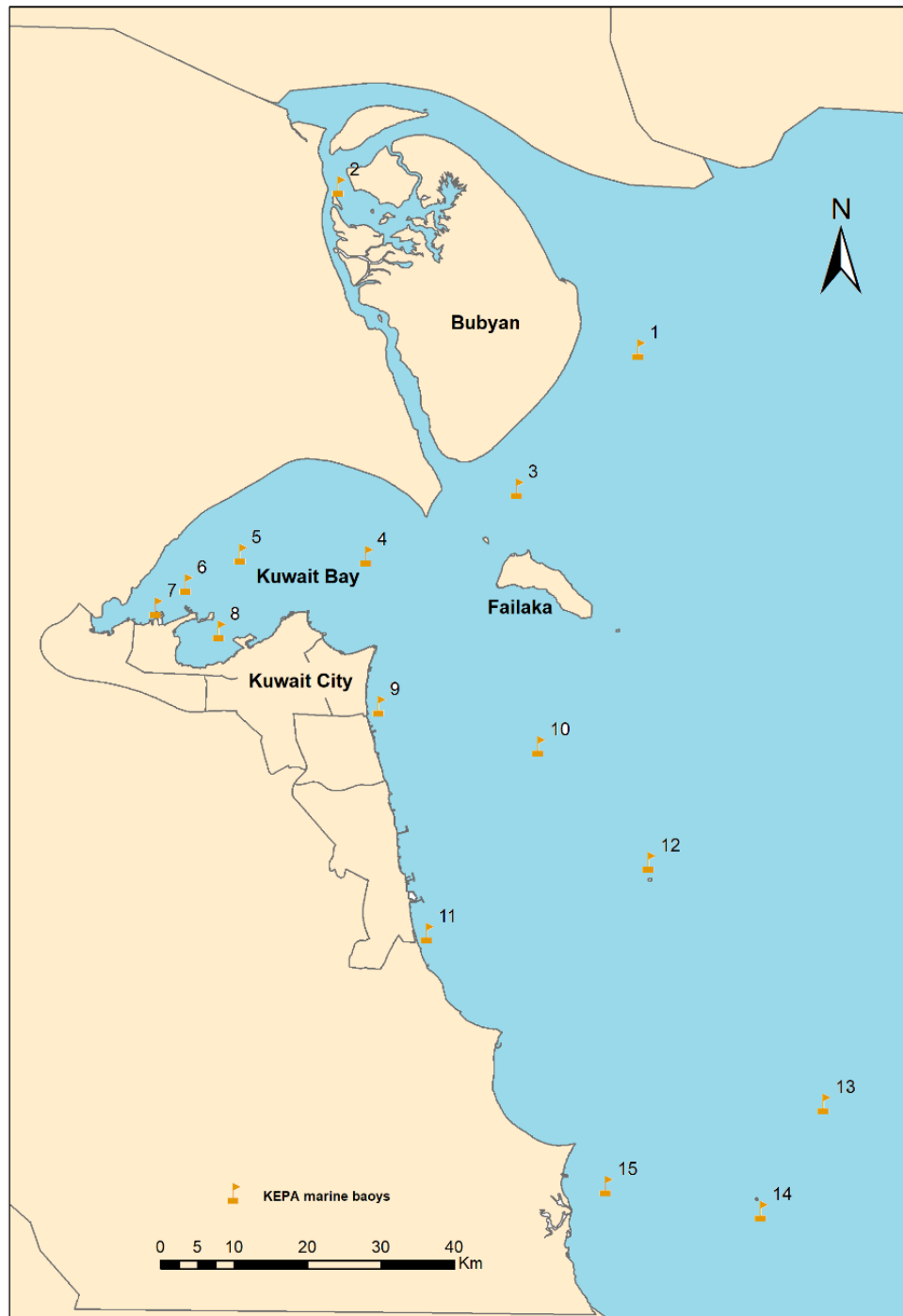


Fig. 2. The 15 buoy locations in Kuwaiti territorial water that were used in this study to validate MODIS data.

Data analysis and validation

The Level 3 chlorophyll-*a* data were analysed using SeaDAS 7.5.3 software. The study area (the Arabian Gulf) was cropped to extract the statistical report. Then, the spatial mean and standard deviation were exported (Fig. 4). The spatial statistical measures are a geostatistical way of summarizing the values of a specific area. The spatial mean is the average of all the pixels values in the study area, while the standard deviation describes how the values deviate from the spatial mean; both can be used to show how chlorophyll-*a* values change over the studied time. Following that, time series analysis was done for each season between 2004 and 2019 separately, and for all the seasons individually.

To verify the accuracy of the estimated chlorophyll-*a* values via MODIS. Level 2 data of MODIS spectrometer (11 images) were used to match the field data taken from KEPA floating stations (24 points) (Fig. 5). MODIS Level 2 is suitable for matching since its data are absolute values for specific days and not arithmetic averages or other statistical summaries. For comparison, a polygon covering 9 pixels of MODIS images was constructed around the sites of the floating stations. Then, the averages of these pixels were compared to the corresponding field values. The pixels' averages are then compared to avoid reliance on a single-pixel result, which may reflect an overestimated value (Albanai, 2019). This methodology has been previously applied in several studies (Albanai, 2020). Pixels with high standard deviation values were avoided in comparison for the sake of the accuracy of the analysis. Then, the root mean square error (RMSE), and the mean absolute error (MAE) were calculated to measure the accuracy of the MODIS chlorophyll-*a* product. These statistical measures are used to compare two variables, and to estimate the difference between them, in terms of both absolute numbers and percentage (Albanai, 2021a, 2021b). The following equations were used to compute RMSE and MAE:

$$RMSE = \pm \sqrt{\frac{1}{n} \sum_{i=1}^n (f_i - f_j)^2}$$

Equation (1)

$$MAE = \frac{1}{n} \sum_{i=1}^n |f_i - f_j|$$

Equation (2)

Where f_i is the value of the chlorophyll-*a* product, and f_j is the field data value.

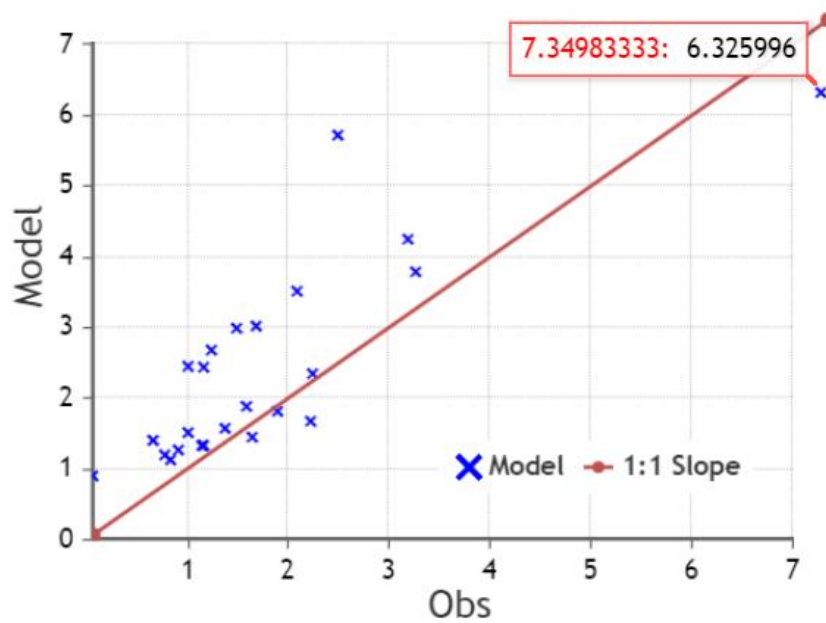


Fig. 3. The VIIRS chlorophyll-*a* level 2 product and the field data (mg.m⁻³) scattering plots indicates the correlation between the two variables.

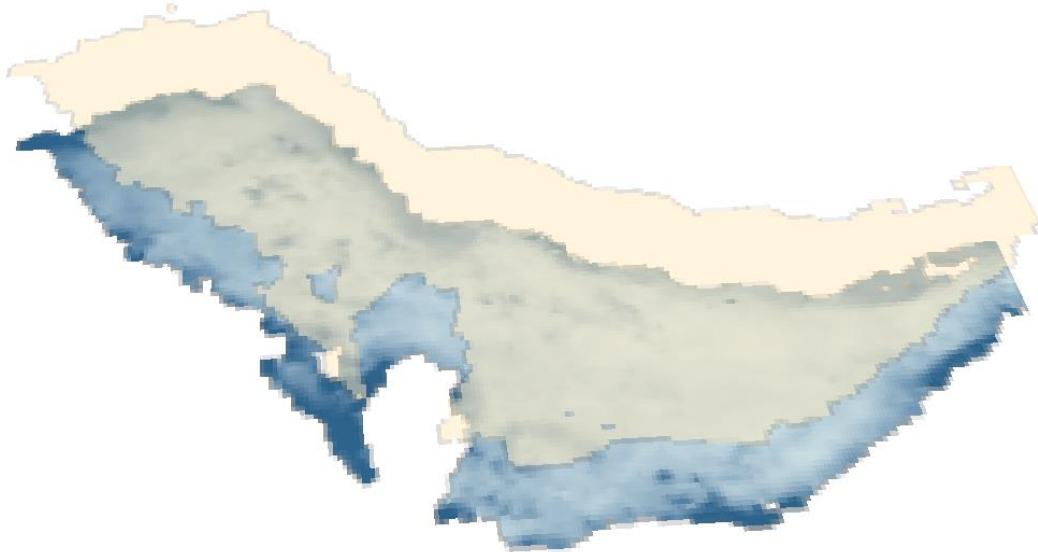


Fig. 4. The spatial mean and standard deviation values were extracted for the whole area of the Arabian Gulf.

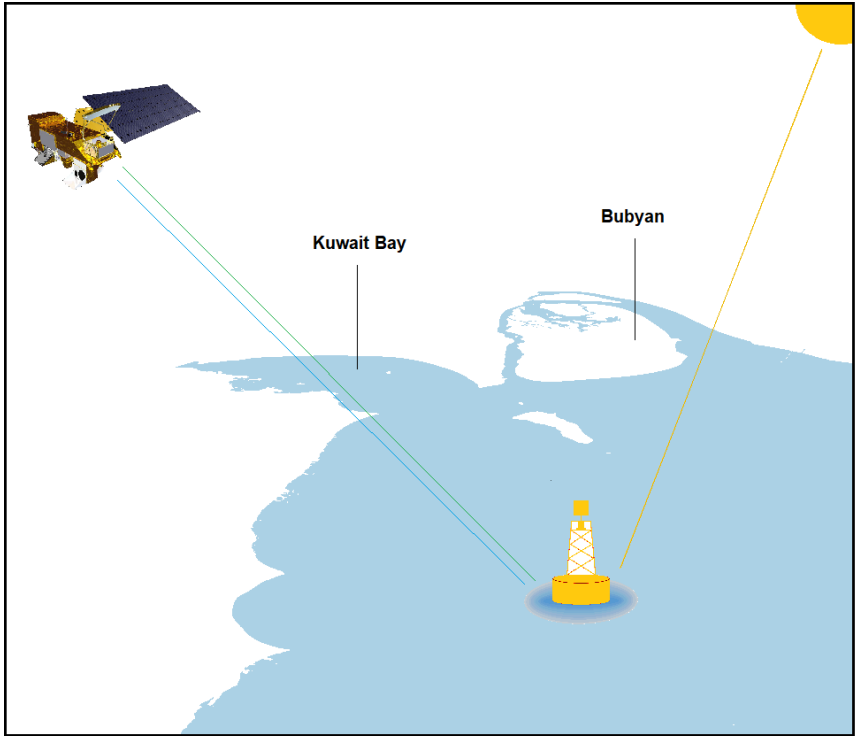


Fig. 5. The process of comparing field data from Kuwaiti waters to satellite geophysical extracted data for the same geographical location.

RESULTS AND DISCUSSION

The results of the temporal distribution analysis of chlorophyll-*a* from 2004 to 2019 (over 16 years) showed that the concentration takes a semi-regular annual cycle, which increases in winter and decreases in summer (Fig. 6). The results indicated that this cycle is prevalent in the Arab Gulf throughout the years included in the study. However, chlorophyll-*a* concentration values deviate from the mean by 1.02 for summer, 0.99 for fall, 0.93 for winter, and 1.03 for spring (mg.m^{-3}) (mean deviation from 2004 to 2019). Also, the results showed that there are peaks in the seasonal averages of chlorophyll-*a* concentration – perhaps the most important of which was observed in 2008, when the average chlorophyll-*a* concentration in spring reached 3.09 mg.m^{-3} . The rest of the peaks are semi-moderated and regular with an average of 1.59 mg.m^{-3} (in spring). No sharp reductions in chlorophyll-*a* concentration were reported, where the average chlorophyll-*a* concentration reported in summer (bottom) was 1.05 mg.m^{-3} . The average chlorophyll-*a* concentration during the fall and winter were 1.18 and 1.59 mg.m^{-3} , respectively. Trend analysis showed that the chlorophyll-*a* concentration was declining from 2004 to 2019 by about 0.7 mg.m^{-3} . The results show that the decline is observed in the averages for all seasons, and the decrease was most pronounced during fall and winter (Fig. 7 and Fig. 9). We note that the 2008 peak was very clear in the trend during spring, to a lesser degree for both summer (Fig. 10) and winter (Fig. 8), and was relatively clear in fall (Fig. 7).

The results of investigating the accuracy of chlorophyll-*a* product for MODIS using field data monitored through KEPA floating monitoring stations indicated that there is a positive correlation between the two variables ($r^2 = 0.6649$) This relationship was reflected in the observed statistical measures (Table 2.).

Satellite data increase our understanding of ocean dynamics and the temporal changes that occur. However, this does not mean that the analysis is free from some restrictions that may

reduce its accuracy. Reilly et al. (2000) explained that the values of satellite sensors are affected by seabed reflections in shallow areas, and this is one of the most prominent features of the Arab Gulf. However, the spatial coverage of the moderate resolution satellite sensors weakens for marginal seas such as the Arabian Gulf, and this was evident when analyzing MODIS data, as coverage on narrow coasts and waterways is relatively limited. Also, the missing data noticed in summer seasons must be taken into consideration, due to the impediment of dust storms when monitoring concentration from space.

The drop in chlorophyll-*a* concentration in fall is often due to depleted nutrients by the phytoplankton bloom in winter (Al-Naimi et al., 2017). Previous research by Nezlin et al. (2007) clearly shows that the seasonal cycle of chlorophyll-*a* concentration in tropical and subtropical oceans is typical. This is because the phytoplankton growth is affected by the low nutrient concentration, because of the strong pycnocline formation, in addition to the effects of thermal stratification in the water column; all of this limits the vertical mixing so that the nutrients can rise to the surface (Doney, 2006). This study result is consistent with other studies regarding the seasonal changes (Al-Naimi et al., 2017; Zhang, Jiang, Chen, Zhang, & Wang, 2012; Zhao & Ghedira, 2014)

The validation results of the product showed better accuracy to monitor low-concentration waters, while the accuracy in high-concentration waters decreases. Reviewing the extracted chlorophyll-*a* concentration using different equations and the OceanColor satellite sensors for several seas and different bays around the world, with different numbers of GTPs (30-114), we find that the accuracy varied in some literature from 0.18 to 0.64 mg.m⁻³ (Al-Yamani & Naqvi, 2019; Husar, Prospero, & Stowe, 1997; Johns, Yao, & Olson, 2003; Polikarpov, Saburova, & Al-Yamani, 2016). The accuracy was estimated at 0.23 mg/m⁻³ in the middle of the Arabian Gulf using 29 GTPs (Al-Naimi et al., 2017), and thus the accuracy of the product falls within a

reasonable range, especially in a difficult environment such as the north-west corner of the Arabian Gulf.

The observed increase in chlorophyll-*a* concentration in 2008 was due to an extensive bloom of ichthyotoxic dinoflagellate *Cochlodinium polykrikoides* in the Arabian Gulf, the Strait of Hormuz, and the Gulf of Oman. The bloom was notable for its unusual coverage, intensity, and duration from August 2008 through May 2009. It caused large numbers of fish kill and coral reefs damaged, restricted fishing activities, and forced desalination plants in the Arabian Gulf. Harmful Algal Blooms (HABs) and fish kills are relatively new phenomena (linked to climate change and anthropogenic activities) in the area except the sporadic red tide caused by some harmless species of plankton (Polikarpov, Al-Yamani, & Saburova, 2019). However, a significant increase in nutrients has been identified, caused chiefly by the sewage discharge from the urban coastal areas along the coasts of the Gulf (Al-Yamani & Naqvi, 2019). Recently, anthropogenic stresses have been cited as one of the biggest challenges facing the marine ecological environment of the Arabian Gulf besides climate change. Climate change affects the sea surface temperature and hence the concentration of dissolved oxygen, which represents one of the most important challenges for an extreme environment such as the Arabian Gulf. Additionally, Al-Yamani and Naqvi (2019) study showed that salinity has increased in the northern area of the Gulf because of the reduction of river runoff, which may be one of the most observed changes by both climate change and anthropogenic activities.

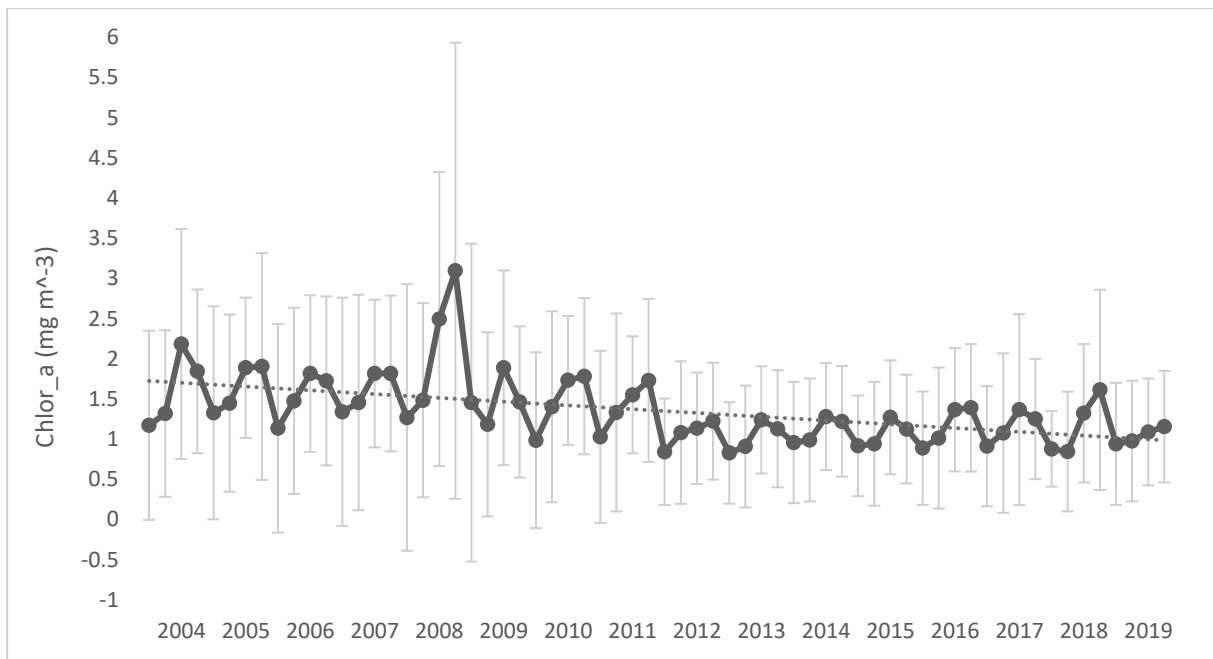


Fig. 6. The overall trend from 2004 to 2019.

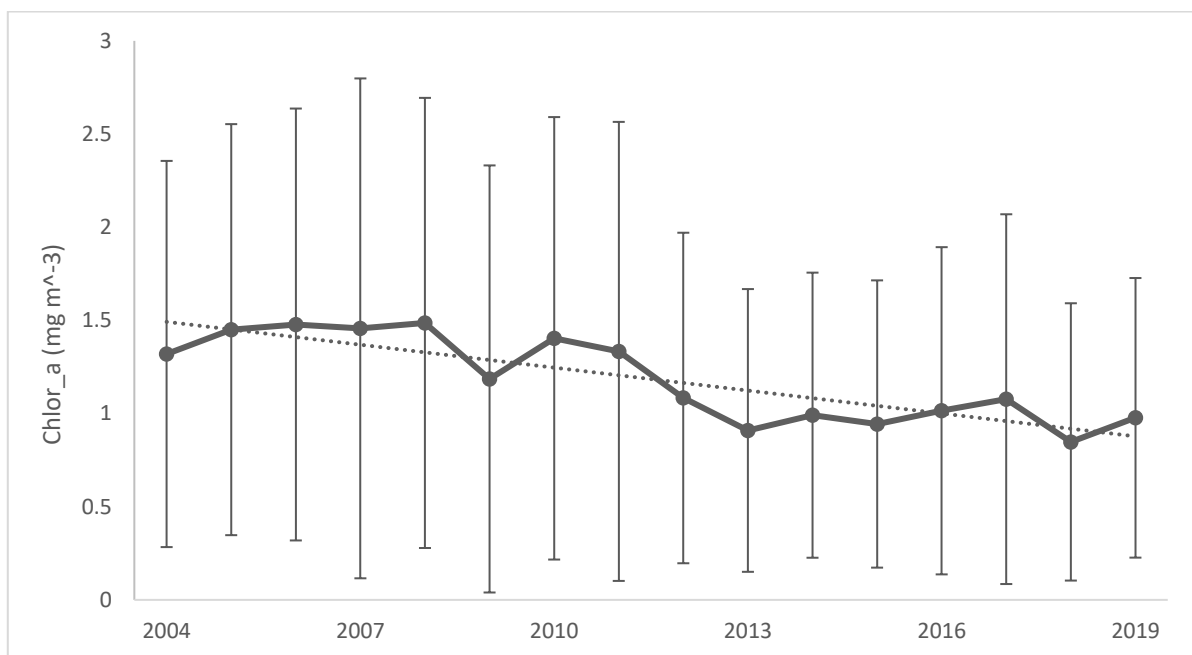


Fig. 7. The fall trend from 2004 to 2019.

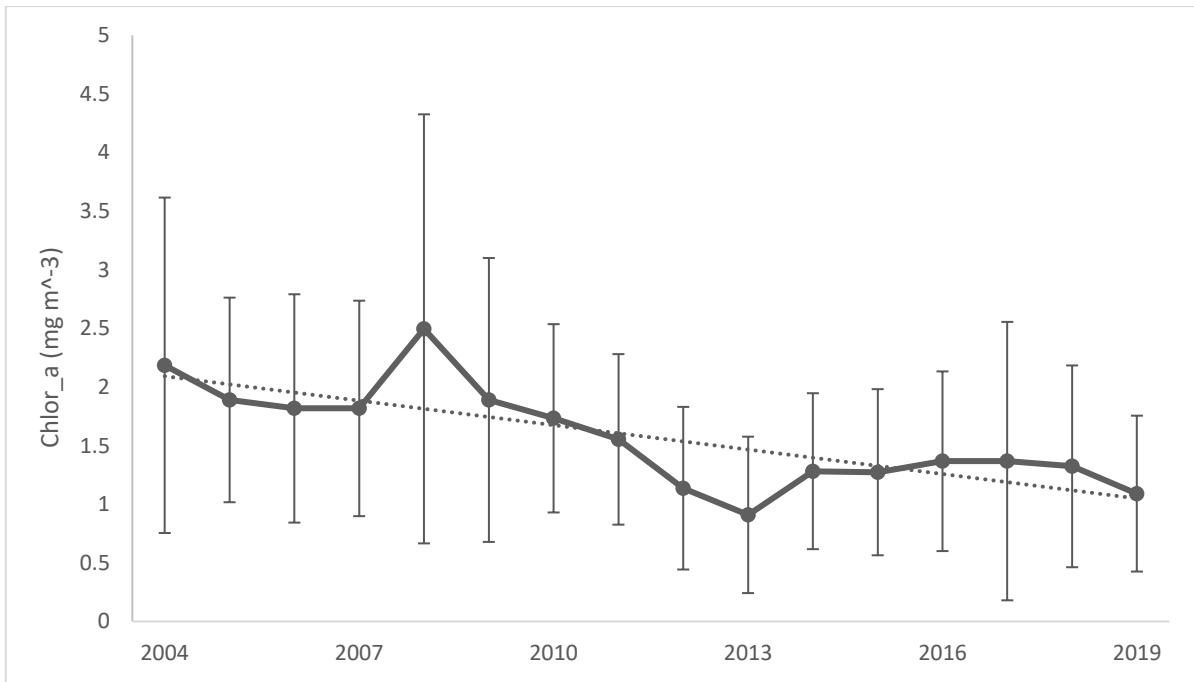


Fig. 8. The winter trend from 2004 to 2019.

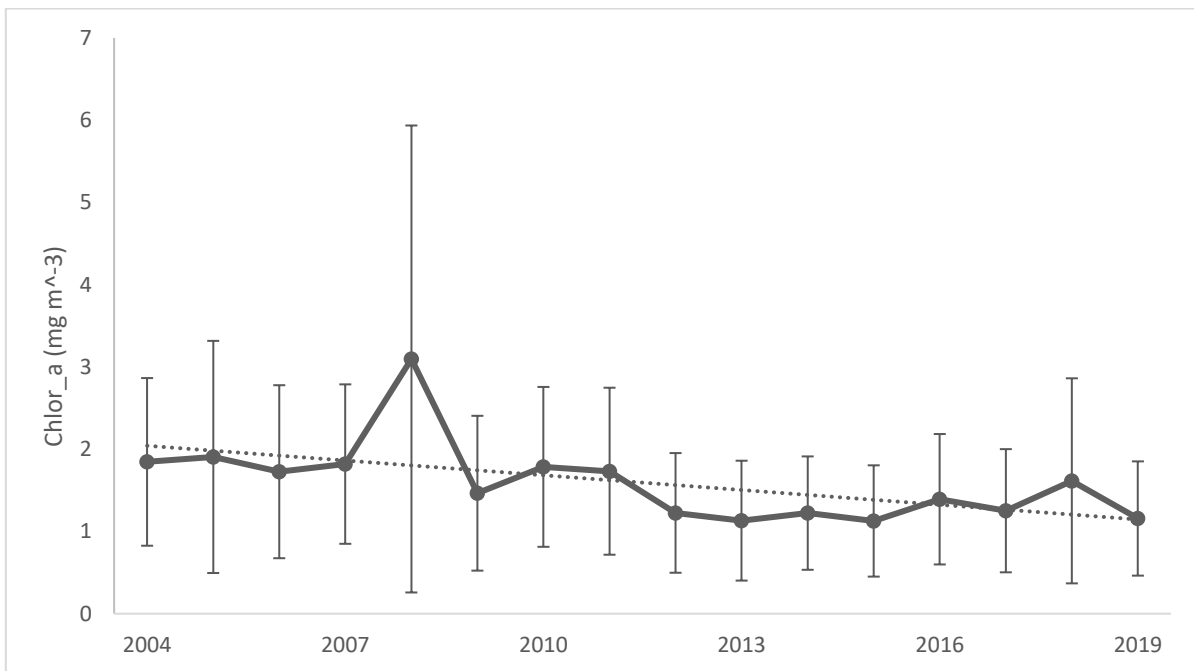


Fig. 9. The spring trend from 2004 to 2019.

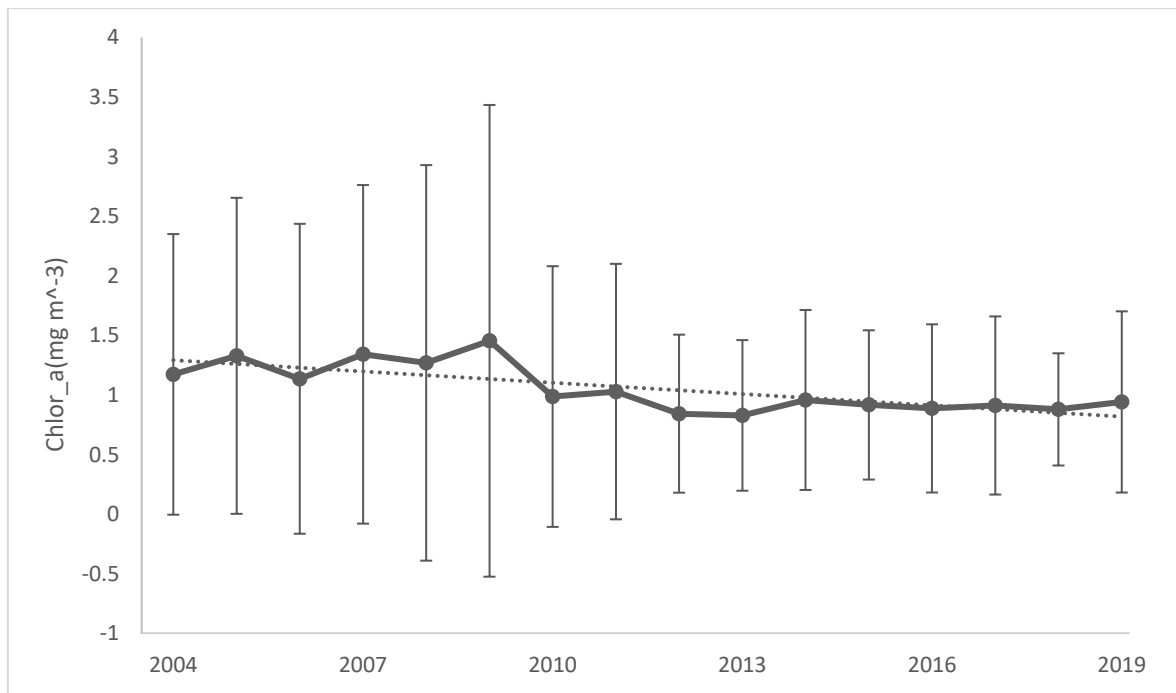


Fig. 10. The summer trend from 2004 to 2019.

Table. 2. RMSE, MAE, MAPE and r^2 scores.

<i>RMSE</i>	1.066
<i>MAE</i>	0.802
r^2	0.6649

CONCLUSION

In this study, the MODIS (Aqua) Levels 2 and 3 data were used to extract the spatial mean and the seasonal standard deviation from 2004 to 2019 (across 16 years) for the Arab Gulf, and to estimate the accuracy of MODIS values by matching the MODIS data to the field data taken from KEPA monitoring floating stations. The results showed a good accuracy of the sensor data (RMSE = ± 1.066), and they indicated that the temporal average gradually decreased by about 0.7 mg/m^{-3} from 2004 to 2019. The study recommends relying on satellites with higher-specification properties to understand the spatial and temporal distribution of chlorophyll. It

also recommends relying on field measurements taken from different regions of the Arabian Gulf as a whole, in addition to building an empirical model to estimate chlorophyll-*a* concentration in the Gulf.

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