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The study of chlorophyll concentration behavior over southern coasts of Iran with an emphasis on the cold season of the year

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ABSTRACT

The concentration of chlorophyll in marine environments indicates the quantity of photosynthetic plankton (phytoplankton), found in marine ecosystems. Phytoplankton populations are affected by weather conditions such as Sea Surface Temperature and Winds. They are also influenced by Aerosol Optical Depth(AOD), which can show the existence of dust. Moreover, there are seasonal variations and the correlation between these factors varies according to the depths. Despite the decrease in temperature and an increase in pressure on land areas during winter, which is accompanied by a decrease in strong winds, the formation of atmospheric fronts and strong winds caused the transfer of dust from susceptible springs in Saudi Arabia and the UAE and dust was transferred to it from the southern coast of the Persian Gulf. Investigating the long-term relationship between SST changes and the AOD with chlorophyll concentration on the Persian Gulf coasts as well as the Oman Sea, using daily MODIS products in the period of 2003 to 2020 demonstrates a strong correlation in coastal areas with the lowest depth. trend of SST and AOD on the both Seas is similar, along with the lowest values during the winter, while the seasonal trend show, the highest values of chlorophyll concentrations, in winter. Besides examining long-term chlorophyll concentration behavior over the Sea of Oman and the Persian Gulf, an emphasis was applied to the cold season of the year on February 17-22, 2018 for understanding the relationships between chlorophyll, AOD, and SST, showing the possibility of time delay in the correlation between sea surface temperature and optical depth of aerosols with chlorophyll concentration.

1. Introduction

The concentration of chlorophyll in marine ecosystems is an indication of the quantity of plankton in those ecosystems and affects its dynamics. Chlorophyll concentrations are not constant and are affected by seasonal variations, precipitation, water flow, and water surface temperature [1]. Numerous studies have been conducted in this area and the extent of these effects has been demonstrated to vary across ecosystems [1-4]. Chlorophyll concentration can also be affected by changes in salinity that occur due to the evaporation of seawater[5].An increase in wind speed over the Persian Gulf increases the rate of evaporation, which can cause changes in the salinity and hence the concentration of chlorophyll [6]. Aerosols in the atmosphere are a rich source of nutrients that increase the production of marine environments and their carbon sequence, which affects the concentration of carbon dioxide and ultimately the climate [2]. Paytan et al. 2009 demonstrated that the growth response of phytoplankton to aerosols varies according to the specific composition of aerosols and the phytoplankton species [2]. Aerosols contain a variety of natural and synthetic compounds, including mineral dust, sea salt crystals, bacteria, and other microscopic particles. Aerosols add nitrogen and phosphorous compounds to water; however, not all aerosols enhance phytoplankton growth [2]. In another study, Galissai et al. (2014) investigated the possibility of dust storms affecting the growth of phytoplankton in the

Mediterranean Sea [1]. This study was important because the surface of the Mediterranean Sea lacks essentially the nutrients necessary for the growth of plankton, but its proximity to the world's largest and most active desert has led to the influx of minerals. This study revealed that the advent of aerosol accounts for around one to ten percent (on average 5%) of chlorophyll variability in the Mediterranean [1]. This highlights the importance of investigating the impact of dust events on chlorophyll concentrations in marine environments. In order to monitor phytoplankton on synoptic scales, remote sensing is the available technique that can provide data on chlorophyll-a (chl-a) as an indicator of phytoplankton abundance [7]. Globally, West Asia is widely recognized as one of the most affected parts by airborne dust. Taking a closer look, we can designate Khuzestan as one of the dust hotspots. Khuzestan is an Iranian province located in the southwest of the country, bordering Iraq and the Persian Gulf. Dust storms have become a major environmental concern in this oil- and gas-rich province during the last decades [8]. Zarasvandi et al. (2011) estimated a mean dust storm frequency of 47 days per year, rising at a rate of two days per year [8]. They also pointed out that the major dust sources affecting Khuzestan are dry lakebeds, alluvial deposits, and deserts in neighboring countries to the west. In particular, the Mesopotamian marshes are suffering rapid land degradation, caused by natural and human-induced factors, and might vanish soon in the future, thus expanding the source area [9]. On the other hand, local dust sources are also important. They are associated with a desert climate and poor, often salty, river flows that leave bare soils exposed to erosion. 9 percent of Khuzestan plain, equivalent to 349254 hectares, are dust-generating sources [10]. Based on land use type and area, the identified zones include destroyed range, rainfed agriculture lands, bare lands, wetlands, dried ponds, and irrigated agriculture lands, respectively.

An episode that occurred in February 2018 is described to illustrate the severity of dust storms in the Khuzestan Province of Iran. On the morning of Sunday, February 18, 2018, frontal-type dust was activated in Kuwait and Iraq, affecting the Khuzestan province of Iran.

The concentration of dust in Abadan and Khorramshahr was about 66 times beyond the permitted limit, and the horizontal visibility in these cities decreased to about 100 meters, which resulted in the cancellation of 2 flights of the Abadan International Airport on February 18, 2018. The schools of the Mahshahr, Shadegan, Abadan, and Khorramshahr cities were closed down due to the occurrence of dust phenomena in the afternoon. on addition, the storm at a speed of 50 km/h on the Sunday morning (February 18, 2018), caused local rising dust in some parts of the province, including Ahvaz, Abadan, Omidieh, and Izeh, while horizontal visibility in Ahwaz reduced to 500 m (Islamic Republic News Agency). On Feb.19th, 2018, the recorded dust concentrations of this dust event reported by more than 983 ug/m3, leading to the closing of all schools of 11 cities of Khuzestan (ISNA News Agency).

In this study, dust storm event analysis in Khuzestan province along with the long-term average chlorophyll concentration between 2003 and 2020 in the Oman Sea and the Persian Gulf has been investigated. Also, the relationship between chlorophyll concentration, Sea Surface Temperature (SST), and Aerosol Optical Depth (AOD) has been studied. Where after, examining a sand and dust event on February 19, 2018, the behavior of chlorophyll by changing SST and AOD is investigated. The most important innovation of the research is to consider the time delay in the correlation between chlorophyll concentration with SST and AOD in the long term. The relationship between this correlation and water depth in different parts of the Oman Sea as well as the Persian Gulf has also been interpreted. Additionally, the study of the effect of a large dust event in the region on changes in chlorophyll concentration, SST, and AOD at the time of occurrence and the following days is another innovation of this study.

2. Data and methodology

The data studied in this research were extracted from the GIOVANNI site. The daily average data (8 days) including Sea Surface Temperature (SST), Aerosol Optical Depth (AOD), and chlorophyll concentration from the MODIS instrument on board of AQUA satellite for the period of 2003-2020 has been extracted. Moreover, the MODIS instrument images from the Worldview site, daily images of chlorophyll concentration, AOD, and SST for the period February 17 to February 22 have been obtained.

First of all, by considering the long-term average of the target quantities over the period of 2003 to 2020, trend in long-time changes as well as the correlation patterns between these quantities was analyzed. Afterward, by investigating a sand and dust event on February 19, 2018, the behavior of chlorophyll by changing SST and AOD is investigated.

3. Area of Study

In this paper, the water bodies of the Persian Gulf, the Sea of Oman, and Khuzestan province were studied and presented in Figure 1.

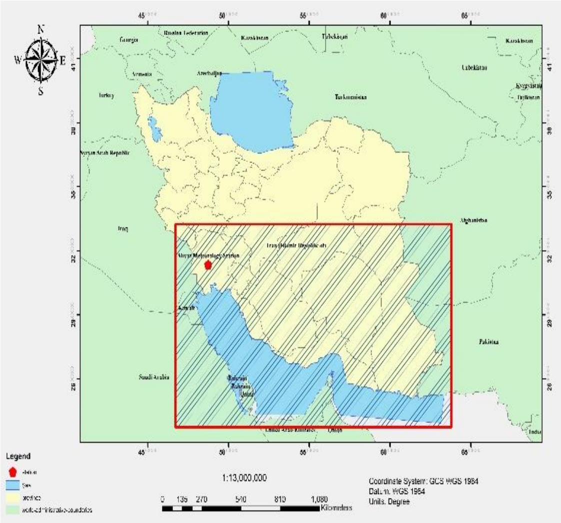


Figure 1. Study area

4. Results and Discussion

4.1. Climatic analysis of the study area

Figure 2 shows the long-term average pattern of meteorological quantities near the ground, including average sea level pressure, 2-meter altitude temperature, sea surface temperature, and wind in the period 2003-2020 is presented separately for the study area. In the spring, low-pressure thermal centers gradually form in the southeastern regions of Iran and the high-pressure center in the highlands of Afghanistan, which corresponds to the maximum and minimum temperature centers in these areas. The low heat pressure tongues are drawn to the central regions of Iran, which are accompanied by ridges in the Zagros highlands. Therefore, pressure gradients are created in the west of Afghanistan and cause north winds in these areas. In the northern and western parts of the Persian Gulf, no significant compressive changes are observed in spring and relatively calm winds prevail. In addition, the sea surface temperature is lower than in its southern and eastern regions. The surface water temperature in the Oman Sea is higher than in the Persian Gulf. Southwest and west winds are forming on the Oman Sea at the beginning of the monsoon season. In summer, with increasing temperature, low-pressure thermal centers are formed in ’s southern and southeastern regions. Simultaneously with that, the high-pressure center on the mountains of Afghanistan is strengthened and with the strengthening of pressure gradients in the border area of Iran and Afghanistan, strong north winds prevail, which, by activating dust springs in these areas, transfer significant amounts of dust to the south. The heat low-pressure tongues extend from the south of Iran to the southwest and west of Iran and enter Iraq, forming relatively strong gradient pressure patterns. As a result, the northwest winds are strengthened and, in these areas, it also strengthens the dust springs, which results in the transfer of dust to the Persian Gulf, especially in its northern and western parts. The Sea Surface Temperature (SST) in the Persian Gulf is higher than in the Oman Sea due to the faster response of water temperature in shallow areas than in deeper areas, which is due to the specific heat capacity of water. Strong southwesterly winds due to the Indian monsoon prevail in the Oman Sea. In autumn, with the decrease in temperature, the average values of sea-level increase in most areas, which weakens the gradient pressure patterns and, consequently, weakens the strong winds. Also, with the monsoon retreat of India, the currents prevailing in the Oman Sea are weakened and the western orbital winds prevail in this region. The formation of atmospheric fronts can be accompanied by strong winds and cause the transfer of dust from susceptible springs in Saudi Arabia and the UAE and the dust is transferred from the southern shores of the Persian Gulf to it. SST in this season in the northern and western parts of the Persian Gulf has decreased more than in other marine areas, which as mentioned is due to the shallower depth of the Persian Gulf than the Oman Sea, due to the heat capacity of water, it has a faster response to lower air temperature than deeper areas.

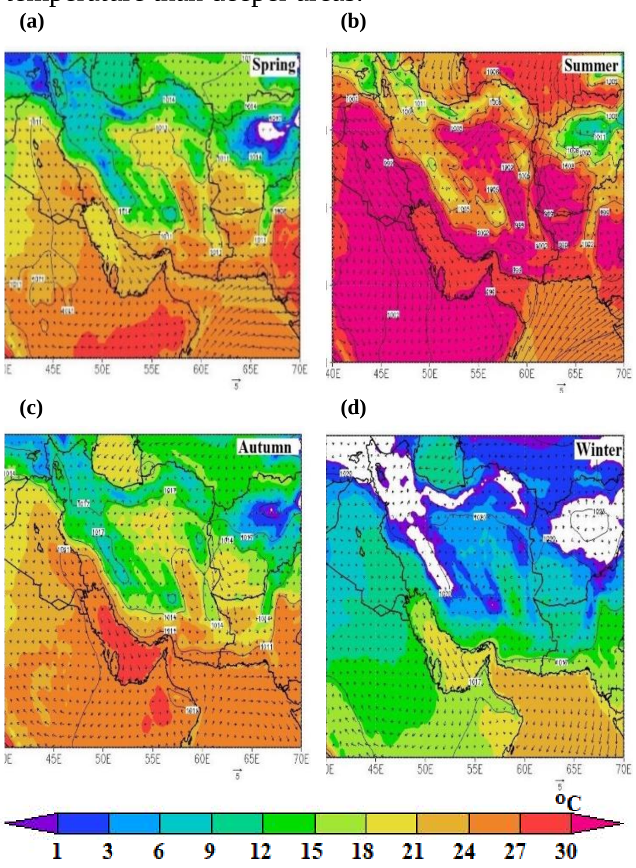


Figure 2. Long-term average pattern of mean sea level pressure (colored contours),2m Temperature and sea surface temperature (shaded regions), and wind at 10m height during a) Spring, b) Summer, c) Autumn and d) Winter (2003-2020)

Figure 3 presents the seasonal model of the long-term average of meteorological quantities including geopotential height, temperature, and wind speed for the period 2003-2020 in the study area and at a pressure level of 850 hPa. As can be seen, in the spring in the southwestern regions of Afghanistan, a low-lying center was established, which is accompanied by the penetration of a ridge from the northeast of Iran on the border between Iran and Afghanistan. This causes a gradient pressure pattern and the formation of north winds in these areas and strengthens the earth's surface patterns. In addition, low-geopotential height centers are observed in the southern regions of Iran due to higher temperatures, while in the higher and colder regions, high-geopotential height centers are located. In summer, with the rise in temperature on land resulting from the movement of the tropical convergence belt, the formation of low-lying centers in the southern half of Iran, western Afghanistan, and the Saudi desert is observable. Also, a geopotential trough has been stretched to the southwest and west of Iran. These patterns enhance the gradient pressure patterns and thus increase the intensity of the winds, which is in harmony with the earth's surface and can activate the dust sources and facilitate the process of emission and transfer of dust. With the beginning of the decreasing trend of temperature in autumn, low-geopotential height centers have weakened, which results in the weakening of gradient pressure and strong winds. This pattern continues in winter and with the cold weather from the northern latitudes and the relatively calm atmosphere (on average) in most areas, emissions and dust transfer also decrease.

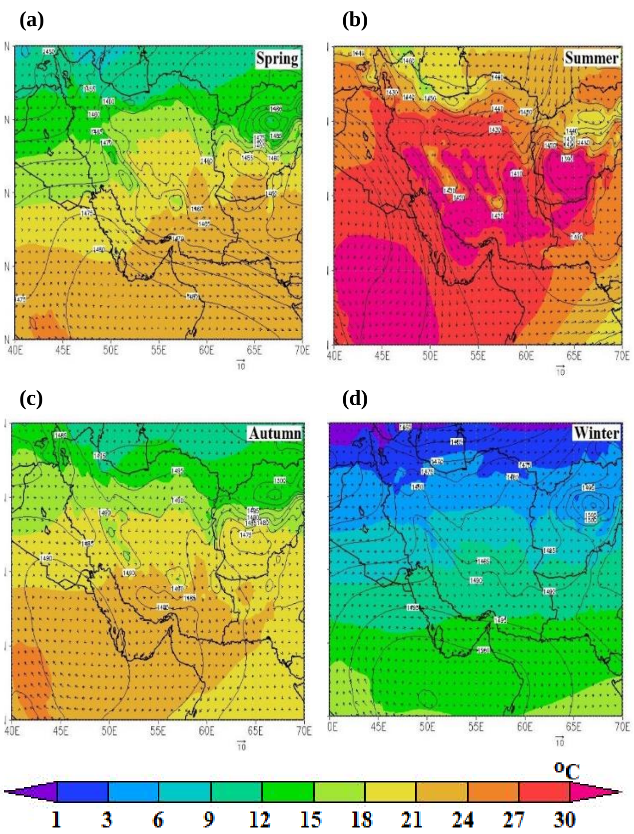


Figure 3. Long-term average pattern of geopotential height (black contours), temperature (shaded regions,) and wind at 850 hPa during a) Spring, b) Summer, c) Autumn and d) Winter (2003-2020).

4.2. Khuzestan province dust event analysis

Figure 4 shows the true color of the Terra satellite and dust RGB of the MSG on February 19, 2018. Because of the cloudiness in the western and northwestern regions of Iran as well as the center of Iraq since this dust event is considered a frontal dust formation type, the extent of the dust mass is not well recognizable, while significant dust concentration in Khuzestan province is observable.

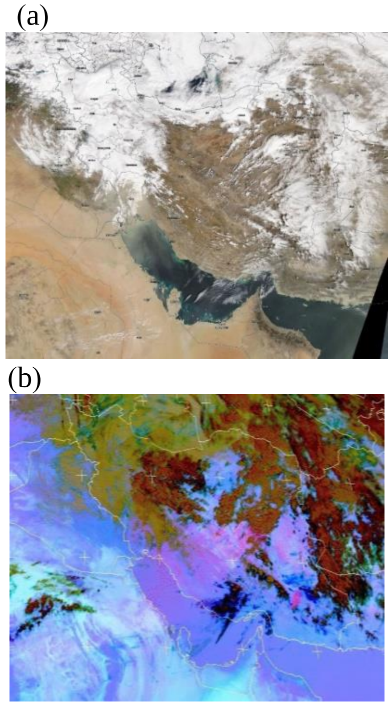


Figure 4. a) The true color of the Terra satellite and b) the dust RGB of the MSG on February 19, 2018.

The Aerosol Optical Depth (AOD) product of the MODIS generated by the combination of dark target and deep blue algorithms is shown in Figure 5. Due to the cloud masses in large parts of the region, AOD is not composed homogenously, but the maximum AOD is seen in Kuwait, northeastern Saudi Arabia, the Persian Gulf, and Khuzestan province in southwestern Iran.

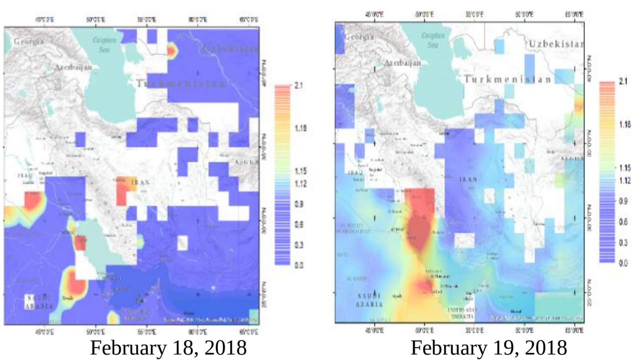


Figure 5. The aerosol optical depth (AOD) product of the MODIS that generated by the combination of dark target and deep blue algorithms for February 18-19, 2018.

The horizontal visibility values of the Meteorological Aerodrome Report (METARs) of Ahwaz city were shown in Figure 6. Horizontal visibility decreased around 09 UTC on February 18 but constantly increased until the first hours of February 19th. Afterward horizontal visibility was reduced to reach its lowest level on February 19^{th}, 2018. Again, mid-February 20th, the horizontal visibility shows gradual improvement.

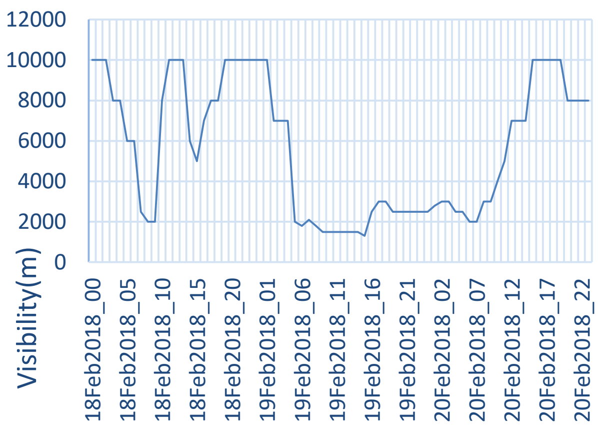


Figure 6. The horizontal visibility values of the METeorological Aerodrome Report (METARs) of Ahwaz city for February 18-19, 2018.

To better evaluate the output of the model, the values of the PM10 concentration output of the model are shown in Figure 7 with the PM10 concentration data of the air pollution monitoring station in Ahvaz. The maximum observed PM10 concentration is 983 ug/m3 on 17 UTC of the 19th. Feb.2018. The comparison demonstrates that the model overestimated the amounts of PM concentration from 12-24 UTC on the day Feb.18th. and 20th.

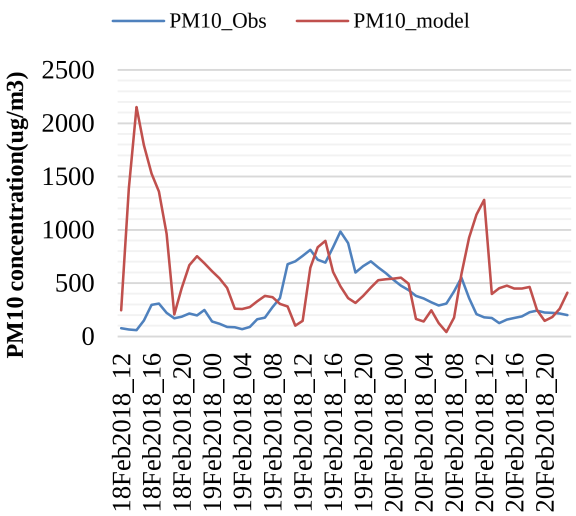


Figure 7. The values of PM10 concentration output of the model and the PM10 concentration data of the air pollution monitoring station in Ahwaz for February 18-20, 2018

4.3. Examining the trend of the long-term average

In this section, the trend of long-term monthly and seasonal changes in SST, AOD, and chlorophyll concentrations for the two regions of the Oman Sea and the Persian Gulf have been studied simultaneously. The graph of the average seasonal changes of the target quantities for 2003 to 2020 in the Oman Sea is presented in Figure 8. As can be seen, in the Oman Sea region, changes in SST and AOD have a similar trend; While changes in chlorophyll concentration were reversed. The highest values of chlorophyll concentration were measured in winter and the lowest in summer. however, the highest/lowest values of SST and AOD were observed in summer/winter respectively. This study has also been done for the Persian Gulf region, the results of which were presented below (Figure 8). The trend of seasonal changes in SST and AOD is to some extent similar, with the highest SST and AOD values in summer and the lowest in winter. In summer, due to the synoptic patterns, conditions were created for the occurrence of sand and dust events in Iraq and the western half of Iran, and due to the flow of northwesterly winds, significant amounts of sand and dust break in to the Persian Gulf. The trend of changes in chlorophyll concentration was observed in contrast to SST and AOD and its highest/lowest amount occurred in winter/summer respectively

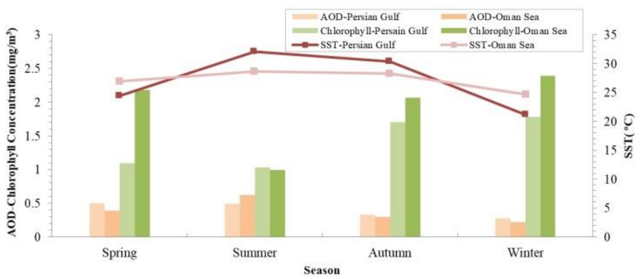


Figure 8. Trend of changes in the long-term average (2003-2020) of the seasonal quantities of AOD, SST, and chlorophyll concentrations in the Oman Sea region .

By examining the trend of monthly changes in the target's quantities in Figure 9, we found that, the highest values of chlorophyll concentration in the Oman Sea occur in March and February, which is associated with the lowest values of SST. while, the lowest values of were found in July, which is in line with the highest SST. The highest value of AOD quantity also occured in July, which coincides with the activity of monsoon flows, which can increase dust events in the southeastern parts of Iran and west of Pakistan and also cause the transfer of sand and dust to the Oman Sea. The pattern of the trend of long-term monthly changes in the quantities in question for the Persian Gulf is also presented in Figure 9. As the figure clearly shows, the highest SST values were obtained in July, August, and September, by more than 30 degrees Celsius. The highest AOD values were also observed in May and July. during July, due to the formation of western currents from Iraq, dust was directed to the western half of Iran, and this caused AOD values in the Persian Gulf to decrease. The trend of changes in the long-term monthly average of chlorophyll concentration also showed that although the highest values were recorded in the cold months of the year from December to February, the lowest values were found in the warm months of the year from May to July.

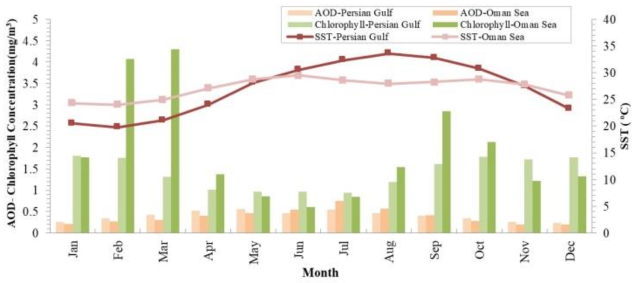
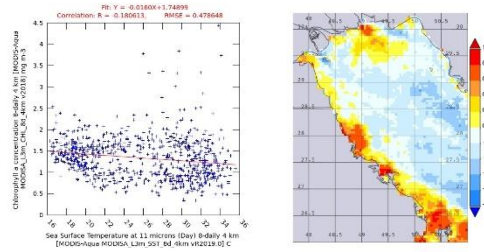


Figure 9. Trend of changes in the long-term average (2003-2003) of the monthly AOD, SST, and chlorophyll concentrations in the Oman Sea region

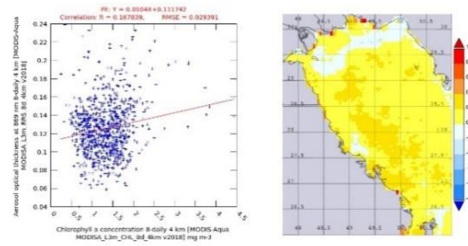
4.3. Calculating the correlation coefficient between SST, AOD, and chlorophyll concentration

In the continuation of this study, the correlation coefficient between the studied quantities has been calculated. As observed in the previous section, the trend of changes in SST, AOD, and chlorophyll concentration fluctuates seasonally and it seems that changes in temperature and salinity in seawater can affect the change in chlorophyll concentration. The scatter plot and correlation pattern between AOD and chlorophyll concentration as well as SST and chlorophyll concentration for the Northwest, North, and south of Persian Gulf and also Oman Sea is shown separately in Figure 10 (a to h). The correlation is not statistically significant, except in coastal areas where there is a relatively good correlation between the quantities. The highest level of correlation was observed in the southern regions of the Persian Gulf (Fig. 10 e and f), which has less depth than other regions. In this region, chlorophyll concentration increases as the SST increases. Furthermore, according to scatter plots, chlorophyll concentrations increase with AOD rises in all regions.

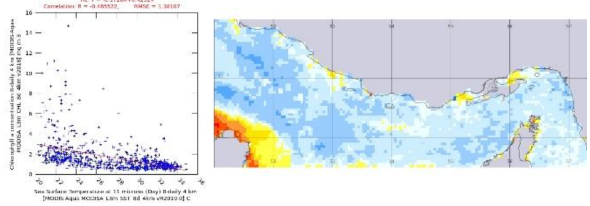
(a)



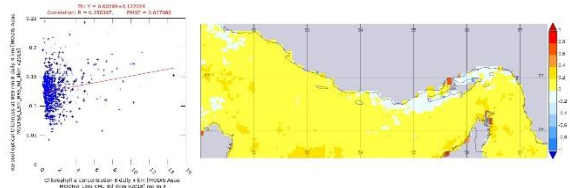
(b)



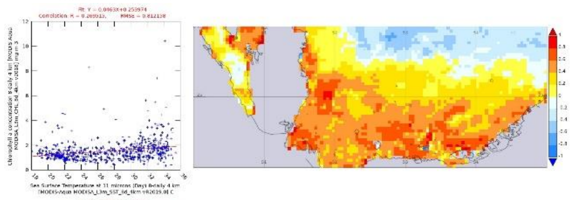
(c)



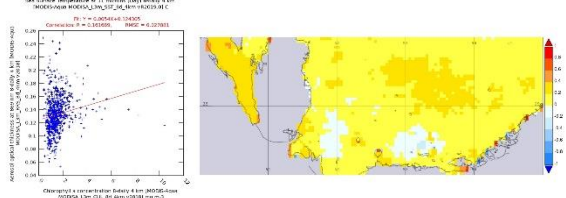
(d)



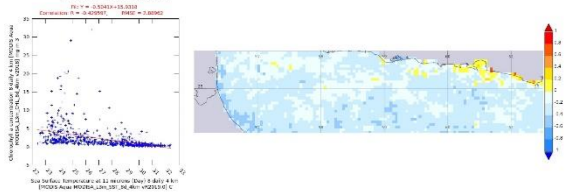
(e)



(f)



(g)



(h)

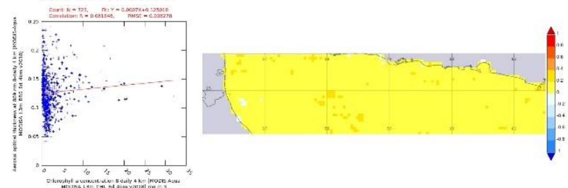


Figure 10. Scatter plot and Correlation pattern between a) chlorophyll concentration and SST and b) chlorophyll concentration and AOD in the study area .

By studying the trend of long-term changes, it seems that there is a possibility of a correlation with a time delay between SST and AOD and chlorophyll concentration. In the continuation of this study, the relationship between chlorophyll concentration and changes in AOD and SST during the occurrence of a dust event is investigated.

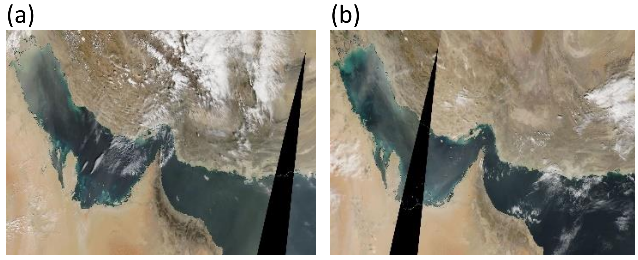
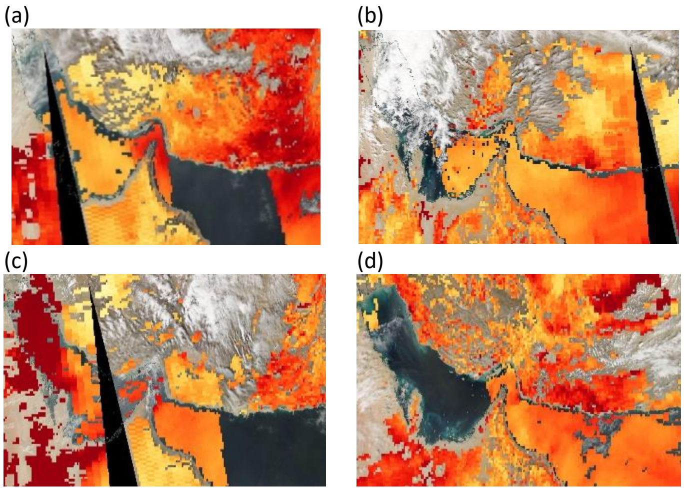


Figure 11. True-color image of MODIS-Terra for February a) 19 and b) 20, 2018.

According to Figure 11, on February 18-20, 2018, there was a severe pressure gradient in the central and southern parts of Iraq due to the the presence of a low system in the west and northwest of Iraq accompanied by the penetration of a ridge from the south and southwest of Iran to the western borders of country. So, the northwesterly strengthen in this area, which causes to activate the dust sources. This weather pattern caused large amounts of dust to be emitted to the southwestern Iran and the Persian Gulf from February 18 to 20.
The study of changes in the pattern of chlorophyll concentration, SST, and AOD, which are presented in Figure 12 to Figure 14, also demonstrates that, with the onset of dust storms, the amount of AOD gradually increased and from February 21, a decreasing trend of AOD in the Persian Gulf was occurred; However, owing to the increase in clouds on this day, the satellite image was not well visible. The pattern of sea surface temperature showed that at the same time with the occurrence of dust, especially on February 19 and 20, the temperature has decreased because of the reduction of radiation entering the water surface due to the presence of dust particles. After that, the temperature gradually increased with the end of the dust event on February 22. Additionally, the pattern of changes in chlorophyll concentration revealed that the chlorophyll concentration increased from February 18 and reached its maximum on February 19, then decreased after the end of the dust event.



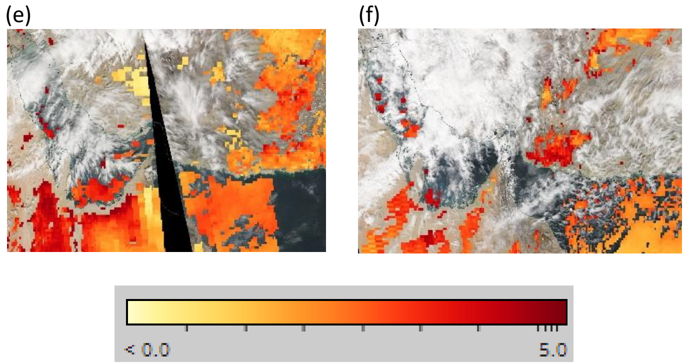


Figure 12. AOD change pattern of Aqua satellite MODIS instrument product (product of DB and DT algorithm) for February a)17, b) 18, c) 19, d) 20, e)21 and f) 22, 2018 at 00:00 UTC .

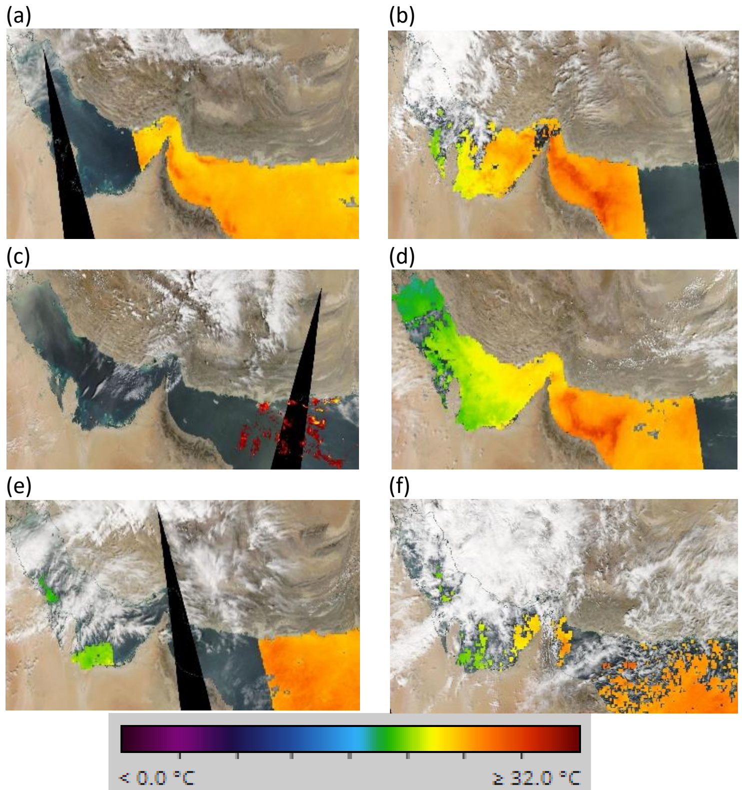


Figure 13. SST change pattern of Aqua satellite MODIS instrument product for February a)17, b) 18, c) 19, d) 20, e)21 and f) 22, 2018 at 00:00 UTC.

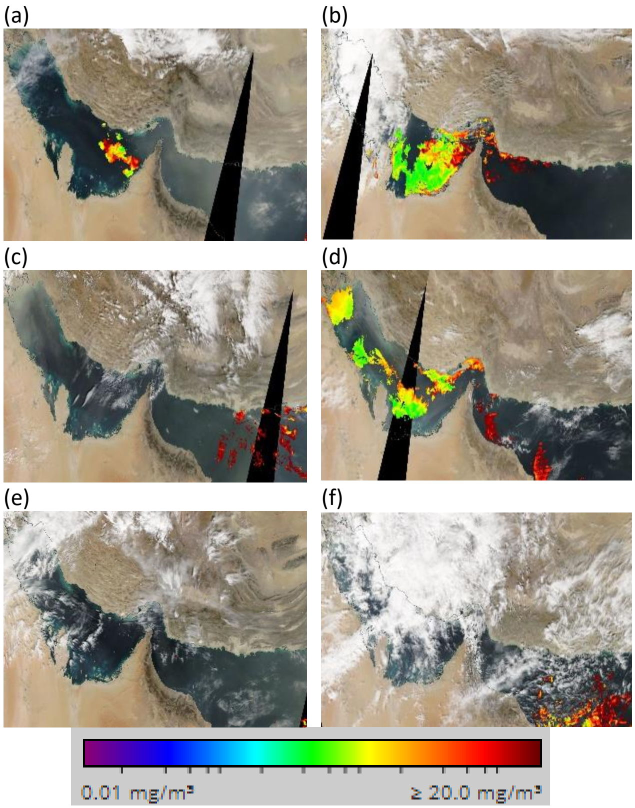


Figure 14. Chlorophyll concentration of the Aqua satellite MODIS instrument product for February a)17, b) 18, c) 19, d)20, e)21, and f) 22, 2018 at 00:00 UTC

5. Conclusions

In this study, the long-term average chlorophyll concentration and its relationship with changes in sea surface temperature and optical depth of aerosols, along with their spatial distribution over the Oman Sea and the Persian Gulf using daily average data (8 days) including SST, AOD, and chlorophyll concentration from MODIS instrument on board of the AQUA satellite were investigated monthly from 2003 to 2020. The results indicated that the seasonal changes in SST and AOD are somewhat similar; the highest/lowest SST and AOD values were found in summer/winter respectively. In summer, due to the synoptic patterns, conditions were created for the occurrence of dust events in Iraq and the western half of Iran, and due to the flow of northwesterly winds, significant amounts of dust enter the Persian Gulf. The trend of changes in chlorophyll concentration is observed in contrast to SST and AOD, and its highest amount occurred in winter and its lowest in summer. In the Oman Sea region, changes in sea surface temperature and optical depth of aerosols have a similar trend; While changes in chlorophyll concentration are reversed. The highest values of chlorophyll concentration were measured in winter and the lowest in summer. however, the highest values of SST and AOD were observed in summer, the lowest were found in winter. Meanwhile, the lowest values of chlorophyll concentration were seen in July, which was in line with the highest SST. The highest quantity of AOD also occurred in July, which coincides with the activity of monsoon flows, which can increase sand and dust events in the southeastern regions of Iran and west of Pakistan and cause the transfer of sand and dust to the Oman Sea.

The trend of changes in SST, AOD, and chlorophyll concentration fluctuates seasonally and it seems that changes in temperature and salinity in seawater can affect the change in chlorophyll concentration. The correlation between AOD and chlorophyll concentration as well as SST and chlorophyll concentration for the Persian Gulf and the Sea of Oman was statistically relatively good in the coastal areas between the quantities. The highest level of correlation was observed in the southern regions of the Persian Gulf, which has less depth than other regions. By studying the trend of long-term changes, it seems that there is a possibility of a correlation with a time delay between SST and AOD and chlorophyll concentration, which is well shown in the case study of dust occurrence in the cold season of the year in February 19, 2018.

6. References

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