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Ocean Circulation to Blame for Red Tide Outbreak in the Persian Gulf and the Sea of Oman

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ABSTRACT

Red tide is a phenomenon that occurs by rapid growth or proliferation of toxic algae. The growth and spread of this phenomenon can threaten marine ecosystems, human health, aquaculture, water desalination plans, tourism and fisheries industries. Ocean currents are one of the affecting factors of the distribution of this phenomenon. In this study, the role of ocean current in chlorophyll-a distribution is investigated on the north coast of the Arabian Sea, the Sea of Oman and the Persian Gulf. The monthly MODIS satellite chlorophyll-a concentration data is used to study the red tide and the HYCOM model analysis result to study the current ocean pattern from 2002 to 2018 and in 2016 as an example. The currents in this area cause chlorophyll-a spreading and transfer of nutrients necessary for chlorophyll-a proliferation and red tides events. There are four main sources of chlorophyll expansion and proliferation in the region: the eastern shores of the Arabian Sea, the northern shores of the Arabian Sea and the Sea of Oman, the Strait of Hormuz, and the northwestern shores of the Persian Gulf. The northeastern currents in East Oman transport chlorophyll to the north of the Arabian Sea and the northwestern currents in the west of the Arabian Sea move chlorophyll from the coasts of India and Pakistan to the west and dispersed it to the west in the northern shores of the sea of Oman.

1. Introduction

Red Tide occurs by collecting algal in columns and turns water to red and brown colour; it depends on the type of phytoplankton. The harmful red tide events have become more frequent and far-reaching. It created many problems in our aquatic ecosystem, Harmful algal blooms (HABs) may release toxins, that could be dangerous for human and marine life, tourism and fisheries industries [1-6]. By increasing industries activity, the amount of sewage in the ocean has been rising over the past century. There is sufficient research that shows nutrient in sewage water could be the fuel of bloom [7] and they approved relation climate change and increasing sea surface temperature (SST) and the number of Red Tide events [8-13]. The first Red Tide was recorded in Puerto Rico in 1961 [14] and in October 1999, bloom Gymnodinium sp. In Kuwait Bay was the first Red Tide event, which caused to fish kills in the Persian Gulf [15]. The most effective environmental Factors on algal growth are nutrient quantity and quality, light, pH, turbulence, salinity and temperature. The nutritional factor is vital [16, 17]. Upwelling is a process that started by water movement. Longshore currents push water along coastlines then cooler, nutrient-rich water rises to the ocean surface and replaces heated water [18]. Therefore, this phenomenon usually was discovered on near the coastline, coastal cities and location of estuarine freshwater discharge. Sewage and upwelled water are rich sources of nutrient for phytoplankton growth rich source of the nutrients. Therefore, it is important to consider currents for transferring feeding materials. The upwelling area increases the availability of nutrients for chlorophyll-a (Chl) growing.
Measured data by satellite provide needed data for study HABs. This data is more effective in the identification and monitoring of Red Tide events[19]. Satellite data not only cover in spatial and temporal over large scales but also is utilized to validate the result of numerical models [20]. The accuracy of Chl data is gathered by satellite is assessed by some algorithms like OC4, SC4, total suspended matter [21]. In this study, the effect of ocean currents on the

distribution and dispersion of Chl as one of the identification parameters of the red tides events would be investigated. The spatial and temporal variation of the Chl concentration had derived from Moderate Resolution Imaging Spectro-radiometer (MODIS) and results of global model HYCOM had used to study the effect of the pattern of current in the area on Chl dispersion and HAB events. The study area is shown in Sec.2 and all data set used are explained in Sec.3. The evaluated and discussion of results are presented in Sec. 4. This is followed by a summary and conclusion of findings in Sect. 5.

2. Study Area

In recent decades, several Red tide events have recorded in the Persian Gulf and the Sea of Oman [22]. The Persian Gulf is a half-closed marginal sea that is connected to the Sea of Oman by Strait of Hormuz. The average depth of the Persian Gulf is about 35 meters and the deepest parts of the Persian Gulf have 90-100 meter depth [23].

The Sea of Oman is located among Iran and Oman coast and is connected to the Indian Ocean from east and Strait of Hormuz and the Persian Gulf from the west. North Coast of the Sea of Oman is from the Strait of Hormuz to Guatr gulf in Iran. The depth in the Sea of Oman is more than the Persian Gulf and Strait of Hormuz It experiences oppressive heat and humidity in summer and in winter, it has a moderate climate. Moreover, there is a High temperature in hot seasons caused strong evaporation. It makes a significant increase in salinity in the Persian Gulf. The surface salinity in the Strait of Hormuz and the Sea of Oman is lower than the Persian Gulf [24] The rate of salinity decrease due to the effect of the Indian Ocean surface water. The main rivers of the Persian Gulf are located in the northwest. The average volume of water imported into the Persian Gulf during the year is 1100 km^2 [24]. Depth changes in the Persian Gulf and the Sea of Oman are shown in 3D in Figure 1.

This area is affected by a powerful wind from the Indian

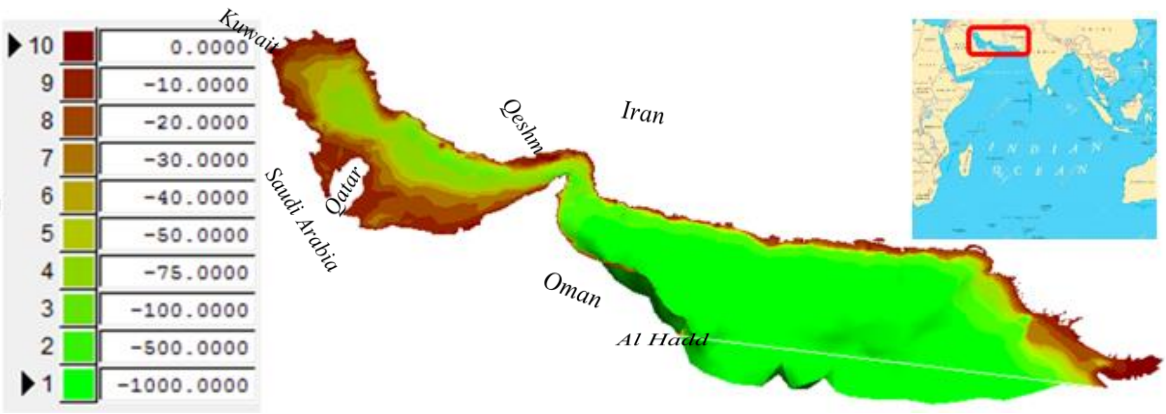

Figure 1. 3Dplot of changing depth in Persian Gulf and Oman Sea

Ocean (Monsoon) and Shamal wind [18]. The Persian Gulf and the Sea of Oman water are exchanging by different kinds of currents like tidal currents, Wind-driven surface currents. The area selected for the study of Chl variations and flow patterns from latitude north 33-31 and longitude east 47-45 had selected.

3. Materials

Satellites are able to record temperature, sea surface elevation, Speed of Ocean Currents, wind flow speed, water quality, oil spills, suspended sediment, sediment transport and other environmental factors[25]. With the development of remote sensing technology, scientists are able to study SST, Chl and other elements of oceanographic in large scale [26].

This study used the results of MODIS satellite data to evaluate the concentration of Chl and the result of Hybrid Coordinate Ocean Model (HYCOM) for the study of ocean flow. The characteristics of both categories of data are explained in this section.

3.1. Satellite data

Since 1978, various environmental data from the earth have been measured and collected by several sensors with remote sensing data. MODIS are operating onboard Terra and Aqua satellite from 1999 and 2002 and are located in a near-polar orbit at an altitude 708 and 705 km respectively [27]. MODIS apperceives all point on the Earth every 1-2 days, basic data on generating more than 40 data types such as land surface temperature, vegetation and land cover products, snow, sea-ice cover, ocean colour, SST, atmospheric profiles, aerosol concentration, optical properties[28]. It provides radiometric sensitivity data in 36 spectral band ranges with wavelength ranging from 0.4 µm to 14.4µm. The Chl data is produced by combines two algorithms, standard OC3/OC4 (OCX) [29] and band ratio algorithm merged with the colour index (CI). The CI algorithm is a three-band reflectance difference algorithm. It considers the difference between remote sensing reflectance (Rrs) in green. This algorithm considers the difference between Rrs in green band and linearly between Rrs in blue and red bands. The Chl concentrations distribution is studied in the spatial resolution of 0.083 degree (9.28 km).

3.2. HYCOM

The energy of water movement in oceans can be provided by three types of forces: tidal forces, wind forces, forces from density differences. The true causes of the 2008 red tide boom in the Persian Gulf are still unknown [30].

HYCOM is a part of the US global ocean data assimilation experiment. It generates several variables including currents, sea surface temperature, and salinity with 1/12 degree (about 9 km) resolution in over the world.

Time step of produced data is 1 day and average month data is considered as flow rate. These data show the two-dimensional current velocity in the Persian Gulf and the Sea of Oman.

4. Results

In this section, the distribution of Chl and flow pattern in the Persian Gulf and the Sea of Oman are investigated. To obtain a usable description, the pattern of Chl change and current velocity in the study area in every season is explained.

4.1. Average Monthly Data from 2002 to 2018

The study of Chl changes and flow patterns in years was divided into two parts. The first half of the year coincides with winter and spring and the second half of the year coincides with summer and autumn. The Chl distribution and flow velocity in the study area from 2002 to 2018 are shown in Figure 3. Satellite images show that there is a seasonal bilateral current the Arabian Sea. Between March and September, flows adjacent to the eastern coast of Oman move to the north. The speed and volume of this stream reach the highest level in June and July, more than 0.65 m/s. These currents have circulated in the northern part of the Arabian Sea into the southeast and have made southeastern flows in the eastern of the Arabian Sea. In this period, in the southern and center of the Arabian Sea, the Somali current makes eastern flows. The currents speed in the Arabian Sea reduce in October and the direction of the flows change during November and January. The mean of Chl concentration in the study area showed that in most time of year the concentration is high near the eastern coast of Oman due to the northeast longshore current. These currents between May and October cause to increase Chl in this area.

In January in coastlines of the Arabian Sea and Sea of Oman the Chl concentration is 6500 (μg/m3) and in some points is higher than 11000 (μg/m3). Currents in the first season of year make circulation patterns in the Sea of Oman and north of the Arabian Sea. These currents circulation develop Chl to the whole of the Sea of Oman and north of the Arabian Sea. The Chl in February and March is spread in the Sea of Oman and north of the Arabian Sea, the mean of Chl concentration is more than 6500 (μg/m3).

By starting north flow from south of the Arabian Sea since April the Chl concentration increases in the east of Oman coast. It reaches to higher concentration and expansion in September. Rainy season in this region is between June and September, most rainfall in India occurs this period. Rivers in these areas bring nutrients from the land to the sea by flow therefore Chl increases on the northern shores of the Arabian Sea during this period, reaching its highest level in September.

The northwest flows in the east of the Arabian Sea have created longshore currents to the west along the northern coasts of the Arabian Sea and the Sea of Oman since October. This longshore current moves Chl to the west to the Iranian coast. The effect of this current can be seen in satellite images of Chl concentration in October and November. This stream continues to the Strait of Hormuz then circulates in the Sea of Oman and creates a counterclockwise flow. This flow has moved along the southern coast of the Sea of Oman then turn to the eastern coast of Oman to the south. The Persian Gulf can be divided into three parts in terms of Chl concentration, East area and Strait of Hormuz, south areas in the middle of the Gulf, northwest area, and Kuwait bay.

The bloom in the Strait of Hormuz emerges in October. In the north and south shoreline of Strait of Hormuz, narrow strips of Chl record in October. The mass entered the Persian Gulf with the flow from the Oman Sea in November and spread along the northern and southern coasts. The currents in the Persian Gulf move along the northern shores and spread Chl along the northern shores in the middle of the Persian Gulf. This expansion peaks in January and covers the entire northern coastal area up to 51° east longitudes. The Chl concentration decreases in the following months and disappears completely in May.

In the area around Bahrain in the first season of the year (winter), Chl is about 3500-5000. This amount reaches about 6500-8000 in spring. In the second half of the year, the concentration of Chl in this area has increased and reached its highest level in September and October.

In the northwestern area of the Persian Gulf, the concentration of Chl is high throughout the year, which is due to the effects of permanent rivers from Iraq and Iran. These rivers bring the nutrients needed for Chl reproduction to the Persian Gulf.

The mean perennial of Chl variations of the Modis satellite data and the HYCOM flow data indicate that the Chl on the eastern coast of Oman does not enter

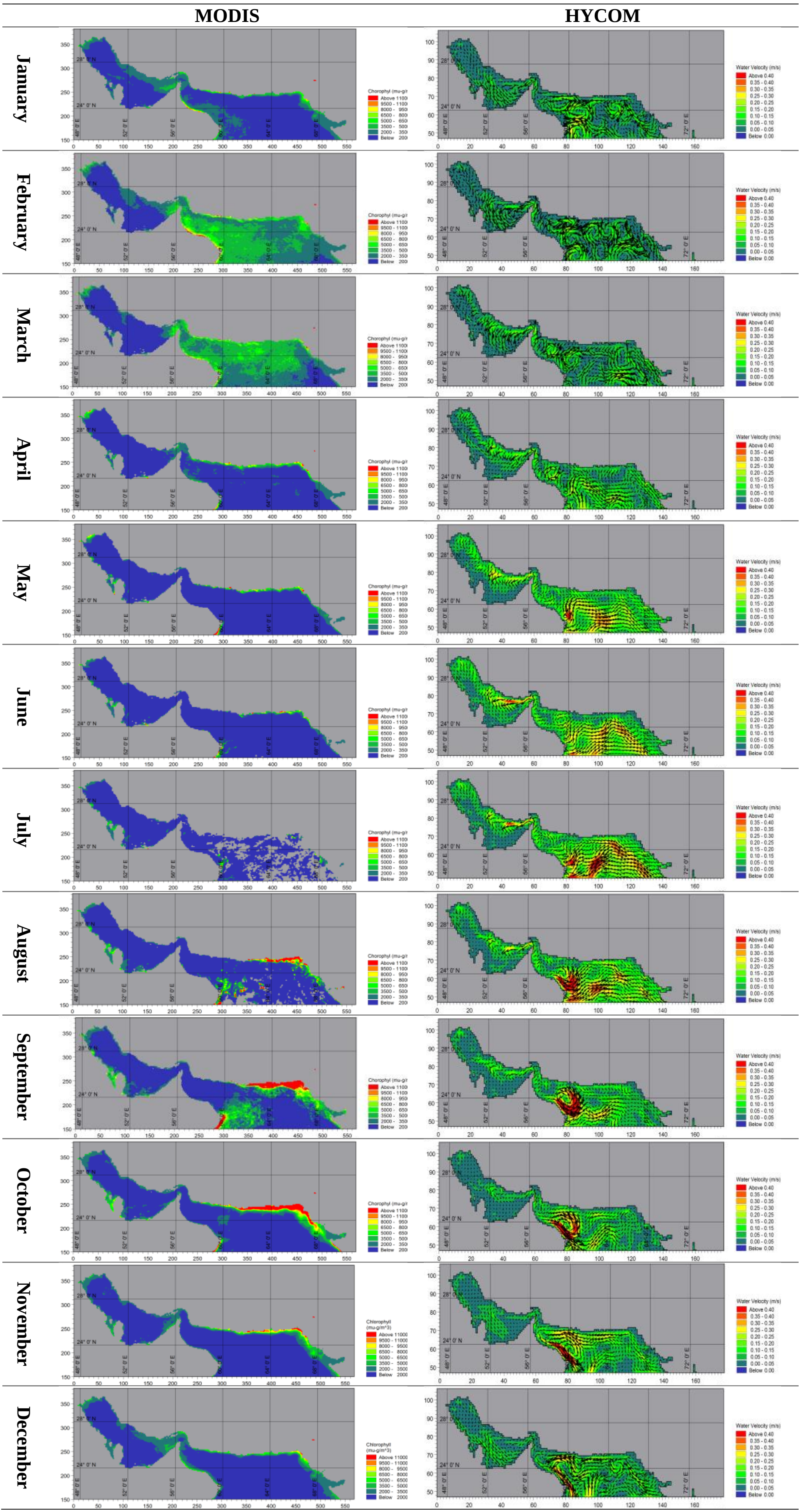

Figure 2. Average Monthly Chl Concentration and Water Velocity from 2002 to 2018

the Sea of Oman. Just the northern part of the Arabian Sea is affected. The longshore flow on the north coast causes Chl development and it has the potential to spread throughout the Sea of Oman. Chl enters into the Sea of Oman if longshore western currents are on the north coast of the Arabian Sea. In the northwestern area of the Persian Gulf and Kuwait bay, the Chl concentration is high in a narrow band near the coast. Due to the permanent rivers in the area, its concentration is high in most times of year.

4.2. Average Monthly Data in 2016

Winter (January, February and March): The first month of the year is simultaneous with Commence of winter in the Middle East. The distributions of Chl and currents speed in the study area in 2016 are shown in figure 3. In January, the Chl concentration generally was low in the Persian Gulf and the sea of Oman. The maximal Chl concentration was derived in Kuwait bay. In the Persian Gulf, two currents are detected, a southeastward flow in north areas, and a stronger current in the same direction in south areas. The width of the Persian Gulf in the Strait of Hormuz decreases, the current in the south coastal area circulated nears the Strait of Hormuz and Joined to another current that came from the northern coastal areas of the Strait of Hormuz. These made a semi-cyclone (a current rotates in a counter-clockwise rotation) in the Persian Gulf. In the Sea of Oman, a northward current from the Arabian Sea made a cyclone in the north of Ras al Hadd [31]. This cyclone was separated into two parts, one moved southward to the coast of Oman and another moved westward into Strait of Hormuz. The westward current split into two parts in along Iranian coast. First, the weaker current created an anticyclone in near Strait of Hormuz and the second current circulated and made a counter-clockwise circulation in the middle of the Sea of Oman. The Chl was moved by anticyclone to Striate of Hormuz. Effect of this current in Chl distribution is detected in February. Circulation current in the north of Ras al Hadd brought nutrient from the deep zone to the sea surface.

In February, the flow velocity in the Persian Gulf decreased and the current in the west part of the gulf faded. The cyclone at the East part of the Sea of Oman developed and made a big counterclockwise circulation. There was a clockwise circulation in the east area of Sea of Oman. The cyclone moved nutrient from near shore to the middle of the sea and prepared basic materials to growth phytoplankton and algae bloom in the gulf. The Chl has expanded in the coastline and has moved it from the south shoreline to the middle of the Sea of Oman. The amount of Chl in north and south coastlines of the Sea of Oman has gone up. The Chl concentration increased two times on the south coast.

In the last month of winter, the flow speed in the Persian Gulf decreased. On the north and south coasts of the Sea of Oman, the flow was westward and eastward, respectively. The Chl in Sea of Oman the Gulf moved by current and spread to whole the area. The temperature in this month about 2-degree Celsius increased in the Sea of Oman [32]. Nutrients distributed and rose temperature in the area caused HAB in the Sea of Oman and the Strait of Hormuz. Chl concentrations were high in the middle of the Persian Gulf, near the north coast, and northwest of the Gulf, in Kuwait Bay. The minerals needed to spread Chl in the northwest of the Persian Gulf were supplied by sewage from the Kuwait City and the Arvand River.

Spring (April, May and June): Between March 21 and June 22 is spring season in this area, the temperature increases and the north wind blows from Saudi Arabian. More than half of storm in the north of Arabian Sea and the Sea of Oman occur in May and June [31-33]. In April, a strong clockwise circulation in the east of Ras al Hadd created; current speeds in this circulation were more than 0.5m/s. In the Persian Gulf, some areas have Chl, like on the west coast of Qatar, and the northwest coast.

The Persian Gulf could be separated to two-part in May, there was a counter clock circulation with high speed (0.20-0.45m/s) in the east and a lower speed southeastward currents in western areas. The flow of the Arvand River increases in the spring, transports nutrients from land to the Persian Gulf. Under suitable conditions, algae can continue to grow. The Chl concentration in northwest coast and west of Qatar achieved to about 8mg/m3.

The Chl density in the whole of the Persian Gulf and Sea of Oman was at a low level. It was at a high level just in a point of the north shore of the Arabian Sea and near the Qatar coast. Between June and September, a phenomenon that is called monsoon occurs in the East part of the Sea of Oman [33]. Unfortunately, in some months, the sky usually is covered by clouds, so Chl images have some defects in this area

Summer (July, August and September): In July, a massive flow moves south to the north of the Arabian Sea and turns north to the south.

An extensive anti-clockwise flow has formed in the Sea of Oman. From the north of the Strait of Hormuz, a flow has entered the Persian Gulf that has created a cyclone in the middle of the Gulf.

In August, strong current moved northeast along the coast of Oman and there is a strong clockwise flow north of Ras al Hadd. Speed current in this circulation is more than 0.45 m/s. At the center of the circulation and on the north coast of the Arabian Sea, a mass of high Chl concentration is observed. The Monsoon

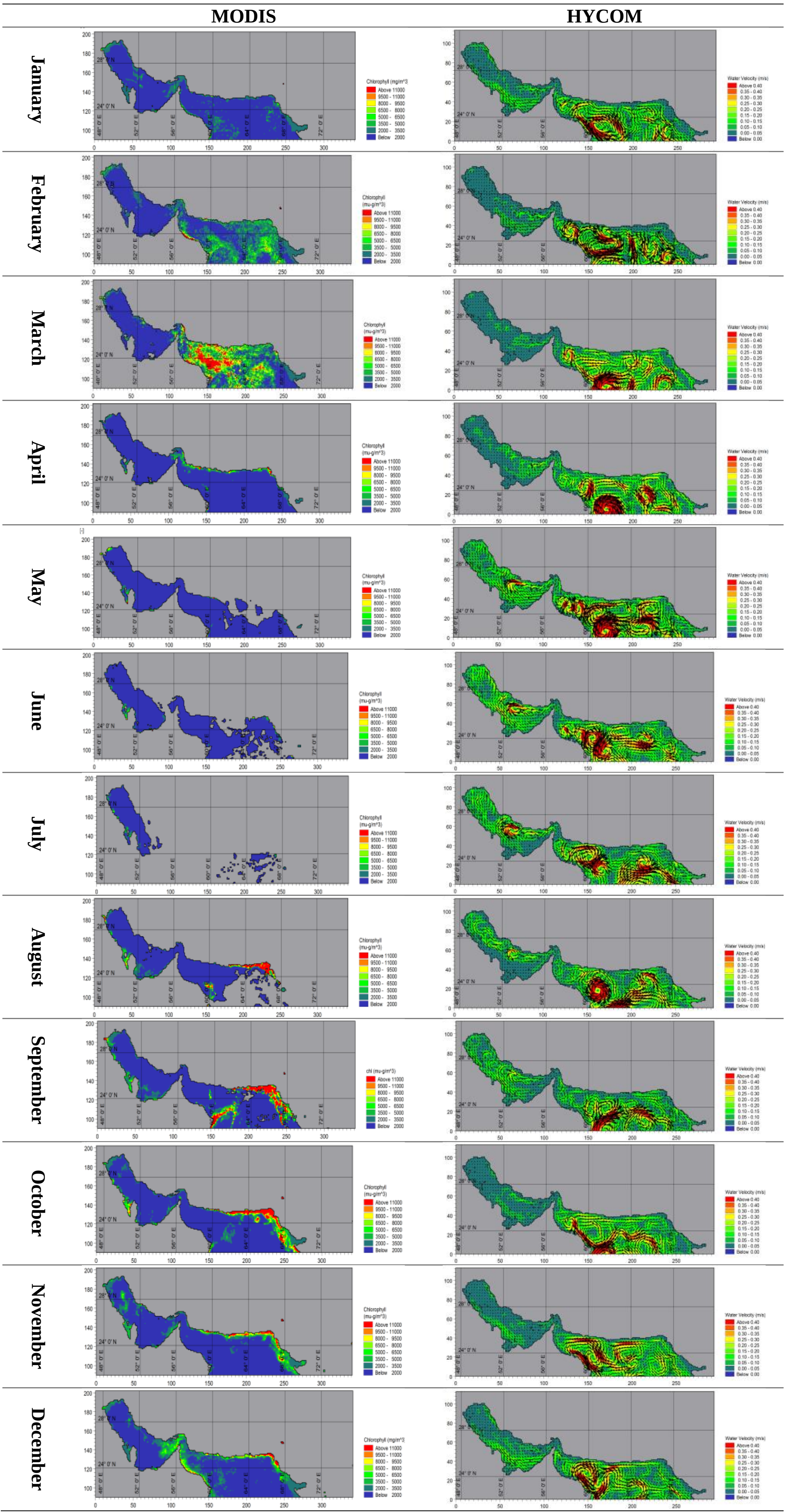

Figure 3. Average Monthly Water Velocity and Chl Concentration in 2016

brings nutrients and provides alga nutrients in the north of the Arabian Sea. The currents in the near north coast of the Arabian Sea had low speed, unfortunately, Chl image in August is incomplete, and so the effect of southward current on Chl in the north is not clear. The Chl concentration was low in the north of the Persian Gulf was a low rate. However, the density of Chl was high on the southern coast, in the Gulf of Kuwait and around Bahrain. The bloom patch stayed around the Bahrain for a while.
In September, anti-Silicon in northern of Ras al Hadd attenuates. The Chl moved to the north by the northward currents and propagated in the northern part of the Arabian Sea. The bloom that detected in the north region of the Arabian Sea spread out this month. However, there was no westward current, therefore Chl developed in west direction slowly.

Autumn (October, November, December): In the first month of autumn, on the north coast was a weak westward current from the Arabian Sea to near the Strait of Hormuz. In November, a counter-clockwise circulation was at the entrance of the Sea of Oman that covers most of the sea. The current in the south shoreline had a higher velocity. Meanwhile, the stream in the north area has accelerated. The westward current in north shoreline became stronger and it helped Chl expand along the north shore and moved the Chl in west direction to the Strait of Hormuz. The cyclone moved Chl from the north area to the south. In the last month of the year, there are two currents from the cyclone in the middle of the Sea of Oman in the south shoreline. Prime, a powerful current to the east direction and second a weak current that is separate from the cyclone and made an anti-cyclone in the west of the cyclone. The transferred Chl by the cyclone is carried over to west by anticyclone. Chl concentration in near Qeshm Island developed to the north shore and grew to the whole of the area. Eastward current in the south area of the Persian Gulf prevented the developing of Chl from the Strait of Hormuz.

5. Conclusion

The results of analyzes on the flow and Chl images show that the flow had two very important effects on the development of Chl.
1. It provides the nutrients needed for Chl growth and reproduction.
2. It increases the range of Chl expansion in the area.
According to satellite imagery, there are four main sources of chlorophyll expansion and proliferation in the region: the northwestern shores of the Persian Gulf, the Strait of Hormuz, the east coast of Oman, the northern shores of the Arabian Sea and the Sea of Oman. During the period under investigation, most of the red tides occurred in Kuwait Bay, the northwestern coast of the Persian Gulf, the area around Bahrain, the Strait of Hormuz, and the northern and southern coasts of the Sea of Oman. In Kuwait bay, Chl concentration levels have been high in most months of the year. The depth of the bay was about 10 meters; the shallow depth of water allows algae to use substrate minerals. In the area around Bahrain, the red tide has occurred in May and June, July, September, October, and November. In this area are also tidal currents influential. The minerals needed for surviving, growth, and duplication in the area are supplied by the substrate (shallow water, about 10 m depth) and wastewater discharged into the sea and dust storms from the Arabian Peninsula. The pattern of incoming currents into the Persian Gulf through the Strait of Hormuz is bilateral flow. The flows along the north shore move west and currents off the south shore toward the east. This flow corresponds to the pattern of rotation in the eastern part of the Persian Gulf that occurs in some months.
The current flow of the Arabian Sea is a seasonal two-way flow. During the seasonal storms between March-May and August, there are form regular circular clockwise currents and Inlet currents to the Sea of Oman from the Arabian Sea, they produce a counter-clockwise circulation that has westward in the north coast, the stream carries the nutrients needed for Chl growing and from October to November, there is longshore current from northwest current in the east of the Arabian Sea.
The current flow of the Arabian Sea is a seasonal two-way flow. From July to October, the northward flows bring Chl to the north along the east coast of Oman and distribute it in the north of the Arabian sea. In the last month of the year, the direction of flow in the north of the Arabian Sea changed and the current in the east of Oman is southward. The flow on the northern shores of the Arabian Sea is westward and causes to develop the Chl in the Oman Sea.

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