The Research on the Variation of Chlorophyll-a in Bohai Sea Based on MODIS Data

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Abstract. Chlorophyll-a (Chl-a) is an important parameter to characterize the degree of eutrophication in water. It has become an important index for water quality evaluation and is also one of the important water quality parameters that can be directly retrieved by remote sensing method. In this study, MODIS L1B data and OC3M Chl-a inversion model are used to invert Chl-a in the Bohai Sea from 2014 to 2019, the spatial and temporal variations of Chl-a in the Bohai Sea are investigated, and the influencing factors are analyzed. Results demonstrate that (1) the variations of Chl-a in different bays of the Bohai Sea have different trends. The Bohai bay and Laizhou bay show an upward trend, while the Liaodong bay and the central Bohai Sea show a downward trend. The concentration of Chl-a is related to the distance from the coast. The closer to the coast, the higher the concentration of Chl-a. (2) From 2014 to 2019, the overall concentration of Chl-a in Bohai Sea show a downward trend, the seasonal variation trend is relatively small, and the variation of Chl-a in spring is larger than that in summer and autumn. (3) River runoff and sea surface temperature will affect the variation of Chl-a, so the conc.

Keywords: MODIS, Chl-a, Bohai Sea, spatial-temporal variation.

1. Introduction

Marine phytoplankton is a basic component of marine biogeochemical cycles and ecosystems, accounting for about 50% of global organic matter production, affecting marine biodiversity and global climate change processes [1]. Chl-a is the most important pigment in phytoplankton, and its temporal and spatial distribution characteristics can reflect variations in marine primary productivity [2, 3].

With the increase of human economic activities, the problem of seawater pollution has intensified in recent years, and the marine ecological environment is facing huge threats. Red tides occur frequently along the coast, causing heavy losses to fishery and tourism [4, 5]. The concentration of Chl-a is an important indicator reflecting the level of eutrophication of water bodies. Inversion and analysis of the concentration variation are conducive to real-time dynamic monitoring and research of the trophic status of the sea area and provide a theoretical basis for the formulation of marine environmental protection policies [6]. Traditional survey methods mainly rely on field investigation, this method not only consumes a lot of manpower and financial resources, but is also limited by sea
conditions and weather. It is difficult to achieve large-scale and long-term continuous monitoring and cannot reflect the temporal and spatial variations of Chl-a in real time. The application of satellite remote sensing technology provides convenience for ocean monitoring. It has the advantages of wide monitoring range and strong timeliness that traditional methods do not have [7]. Marine monitoring based on remote sensing technology can not only reveal the spatial distribution of Chl-a, but also study the changing laws of time series. Therefore, the advantages of using remote sensing technology to monitor variations in the marine environment are becoming more and more obvious.

Since the first generation of ocean water color sensor, CZCS (Coastal Zone Color Scanner) was put into use in the 1970s, ocean color parameter inversion has developed rapidly, and the algorithm is constantly updated [8, 9]. Many scholars have done a lot of research on ocean color parameter inversion. Fu et al. [10] used MK test and Hurst index to establish an index system, and the study found that Chl-a concentration is non-uniform in time and space and the eutrophication expands from nearshore to offshore. Xu et al. [11] studied the temporal and spatial distribution of Chl-a on the surface of the Bohai Sea, and the study showed that the shallow waters near the land area have higher concentrations and high values are located in the inner bay waters. Tian et al. [12] used SeaWiFS and MODIS sensors to analyze the concentration of Chl-a in the Bohai Sea in the past 20 years, and found that the concentration in the Bohai Sea in the past 20 years has increased significantly, and analyzed the effects of sea surface temperature and wind speed on Chl-a concentration. Zhang et al. [13] divided the Bohai Sea into 6 sub-regions for separate research and found that the peak Chl-a concentration in the Liaodong bay, Qinhuangdao bay and Bohai bay coasts lasted longer from May to September and proposed that water conditions might be an important factor affecting the seasonal variations of Chl-a in the Bohai Sea. The temporal and spatial variations of Chl-a have the characteristics of strong regionality, complex influencing factors, and rapid changes. Therefore, real-time monitoring of Chl-a is needed to provide a reliable basis for scientific management of the marine environment.

2. Data and methods

2.1. Study area

The Bohai Sea is located at 37°07′-41°00′N and 117°35′-122°16′E, which is a semi-enclosed inland sea with an area of about 80,000 square kilometers. The coastline of the Bohai Sea is about 3,800 kilometers in length and the average water depth is 18m. There are more than a dozen rivers flowing into the Bohai Sea, mainly including the Yellow River, the Haihe River and the Liaohe River. Among them, the Yellow River has the highest annual runoff and brings a lot of fresh water and nutrients to the Bohai Sea. The temperature variation of the Bohai Sea is affected by the northern continental climate. From late November to February, most of the coast is frozen, and drift ice often occurs in early March. In order to analyze the concentration of Chl-a on the surface of the Bohai Sea, the Bohai Sea is divided into 4 parts: Liaodong bay, Bohai bay, Laizhou bay, and the central Bohai Sea according to the environment and geographical division of the study area.

2.2. Data

The data used in this research is cloudless L1B product with a spatial resolution of 1KM for MODIS data from 2014 to 2019. MODIS is the main sensor mounted on the Terra and Aqua satellites. It has 36 spectral bands, with full spectrum coverage from 0.4 microns to 14.4 microns, and can provide multiple characteristics of land and ocean simultaneously. Data downloaded from the National Aeronautics and Space Administration (NASA) Ocean Water Color Processing Center (http://oceancolor.gsfc.nasa.gov). GLT (Geographic Lookup Table) geometric correction was used for the data. GLT geometric correction can use the geolocation file that comes with the satellite sensor to achieve geometric correction, and 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) atmospheric correction model was used to perform satellite data atmospheric correction [14, 15]. The river flow data is from the 2014-2019 “China River Sediment Bulletin”.

2.3. Inversion method of Chl-a and sea surface temperature

The concentration of Chl-a is retrieved using the OC3M empirical algorithm. The OC3M algorithm model is designed for MODIS data and is also the Chl-a retrieval algorithm adopted by NASA [16, 17]. The model formula is as follows:

\[
\log[\text{chla}] = a_0 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4
\]

\[
X = \log \left( \frac{\max(R_{rs}(443), R_{rs}(489))}{R_{rs}(555)} \right)
\]

where chla is the concentration of Chl-a, and \(a_0, a_1, a_2, a_3\) and \(a_4\) are coefficients, which are 0.2424, -2.7423, 1.8017, 0.0015, and -1.228. \(R_{rs}(443), R_{rs}(489), R_{rs}(555)\) are the remote sensing reflectance at 443nm, 489nm and 555nm, respectively.

Sea surface temperature inversion uses split-window algorithm. The split-window algorithm is based on the surface thermal radiation conduction equation, and uses the difference in atmospheric absorption between two adjacent thermal infrared channels (generally 10.5-11.5μm, 11.5-12.5μm) in an atmospheric window of 10-13μm. Various combinations of channel measurement values eliminate the influence of the atmosphere, and correct the specific emissivity of the atmosphere and the surface to obtain the sea surface temperature [18]. This study uses the improved and proposed earth surface temperature retrieval algorithm suitable for MODIS satellite data by Qin [19] to retrieve sea surface temperature [20].

3. Results

3.1. Variations of Chl-a in Bohai Sea sub-region

The monthly Chl-a variations in the four sub-regions of the Bohai Sea from 2014 to 2019 showed different trends (Figure1). From 2014 to 2016, the Chl-a variations tended to be the same. After 2016, the variations in each sub-region were different. The Chl-a concentrations in the central Bohai Sea were lower than that in the other three regions, and the concentration in the Bohai bay and Laizhou bay was relatively high. The 6-year average Chl-a of the four sub-regions were: Bohai bay (3.57 mg/m³), Laizhou bay (3.55 mg/m³), Liaodong bay (2.97 mg/m³), central Bohai Sea (2.42 mg/m³). In general, Bohai bay and Laizhou bay presented an upward trend, while Liaodong bay and central Bohai Sea presented a downward trend: Bohai bay (0.018), Laizhou bay (0.0041), Liaodong bay (-0.0107), and central Bohai Sea (-0.0048). The increase was greatest in Bohai bay and the decrease was greatest in Liaodong bay.

![Figure 1. Variation of Chl-a in Bohai sub-region.](image-url)
3.2. Variations of Chl-a with distance from the coast
According to the distance from the coast, the Bohai Sea was divided into four regions: 0-20KM, 20-40KM, 40-60KM, >60KM. The trends of the four regions were almost the same, basically consistent with the same increase and decrease (figure 2). In the sea area 0-20KM away from the coast, the concentration of Chl-a varied within the range of 1.6-5.5mg/m$^3$. In the sea area 20-40KM, the concentration fluctuated within 1.1-5.2mg/m$^3$. In the sea area of 40-60KM, the Chl-a concentration was basically in the range of 1-4mg/m$^3$. In the central Bohai Sea, which was more than 60KM away from the coast, the concentration varied within 0.9-3.5mg/m$^3$. It could be concluded that the closer to the coast, the higher the concentration of Chl-a, and the greater the range of variation, which was greatly related to the influence of coastal zones, rivers entering the sea, and nearshore aquaculture.

![Variation of Chl-a at different distances from the coast.](image)

3.3. Inter-annual variations of Chl-a
From 2014 to 2019, the Bohai Sea Chl-a concentration showed an overall downward trend, with a range of 2.7-3.4mg/m$^3$ (figure 3). The concentration of Chl-a reached a high value of about 3.35mg/m$^3$ in 2015, and then began to drop to the lowest value of 2.79mg/m$^3$ in 2017. The decline was the fastest in 2016-2017, with a decrease of about 0.53 mg/m$^3$, after that, the concentration began to increase again, reaching 3.12mg/m$^3$ in 2019.

![Inter-annual variations of Chl-a concentration.](image)

3.4. Seasonal variations of Chl-a
In this study, spring, summer and autumn were defined as March to May, June to August and September to November, respectively. The seasonal variations of Chl-a from 2014 to 2019 did not show a clear trend (figure 4). There was a slight upward trend in spring and downward trend in autumn. Compared with summer and autumn, the fluctuations in spring were larger, it increased in 2014 to reach its peak in 2016, then declined rapidly in 2017, and then gradually increased to 2019.
Although the concentration of Chl-a varied slightly in summer, the trend of change is not obvious. The concentration of Chl-a began to decrease after reaching the maximum in 2015, until it reached the minimum in 2019. The variation of Chl-a in autumn showed a "V"-shaped change. It has been declining from 2014 to 2017 and reached the minimum in 2017. Then the concentration increased, but the increase was not as large as the decrease.

Figure 4. Seasonal variations of Chl-a concentration.

4. Discuss

4.1. Impact of river runoff

The runoff of the three main rivers, the Yellow River, Haihe River, and Liaohe River from 2014 to 2018, was shown in Figure 5. The Yellow River was the largest inflow of Bohai Sea, accounting for about 85% of the total inflow. From the perspective of cumulative inflows, the total inflows increased from 2014 to 2015, and the runoff in the following two years became smaller, showing a downward trend. In 2018, the runoff soared to a maximum of 34.8 billion cubic meters. From 2014 to 2018, the concentration of Chl-a in the Bohai Sea increased first, then decreased, and then increased. This was the same as the change trend of annual runoff, indicating that the river flow into the Bohai Sea has a certain impact on the variation of Chl-a.

Figure 5. The annual runoff data of the three major rivers from 2014 to 2018.

In order to further investigate the relationship between the variation of Chl-a and the river runoff, the correlation coefficients between the Chl-a and annual runoff in the Liaodong bay, Bohai bay, Laizhou bay and central Bohai Sea were calculated (Table 1): Bohai bay (0.45), Laizhou bay (0.18), Liaodong Bay (-0.65), and central Bohai Sea (-0.54). There was a positive correlation between Bohai bay and Laizhou bay, indicating that fresh water imported from rivers provided a large amount of nutrients to the waters in the bay area, which was conducive to the growth of phytoplankton. In particular, the correlation coefficient of Bohai bay was close to the value of 0.5, which was also consistent with the fastest growth rate of Chl-a in Bohai bay. The concentration in the Liaodong bay and the central Bohai Sea was negatively correlated with runoff, and the correlation coefficient was greater than 0.5. Liaodong bay was located in the northernmost part of the Bohai Sea, surrounded mostly by heavy industrial cities. In recent years, the development of heavy industry in Liaoning Province and Hebei Province has slowed down, and land-based pollution has decreased, which has
also greatly reduced the concentration of Chl-a. In the central Bohai Sea, due to the existence of the Bohai Strait, the frequent exchanges of seawater between the Bohai Sea and the Yellow Sea did not provide stable nutrients for phytoplankton, which led to a decrease in the concentration of Chl-a.

### Table 1. Correlation coefficient between annual runoff and Chl-a.

| Area           | Liaodong Bay | Bohai Bay | Laizhou Bay | Central Bohai Sea |
|----------------|--------------|-----------|-------------|-------------------|
| Correlation coefficient | -0.65       | 0.45      | 0.18        | -0.54             |

#### 4.2. Impact of sea surface temperature (SST)

The variation of sea surface temperature will affect the stratification of sea water, thereby affecting the variation of nutrient salt concentration, and then the variation of Chl-a. From the analysis of the inter-annual variation of the sea surface temperature (figure 6a), the sea surface temperature showed a fluctuating upward trend. After reaching a small peak in 2015, it dropped to a minimum in 2016, and then quickly rose to a maximum in 2018. The variation ranged from 14°C to 15.5°C. The inter-annual variation of sea surface temperature was basically the same as that of Chl-a, except that the sea surface temperature was the minimum in 2016. The Chl-a concentration decreased from March to June, then the concentration began to rise to September, after which the concentration began to decrease again (figure 6b). The sea surface temperature rose from March to July. The rise in temperature will cause the seawater to stratify. Nutrients cannot flow up with the seawater. Phytoplankton can only consume surface nutrients, thereby limiting growth and reducing the concentration of Chl-a. From July to September, the sea surface temperature began to drop, which was conducive to the convection on the surface of the sea, thereby increasing the upwelling of nutrients, which was conducive to the growth of phytoplankton, leading to an increase in the concentration of Chl-a. After September, the nutrients were exhausted and the sea surface temperature dropped too fast, which was not suitable for the growth of phytoplankton, so the Chl-a concentration began to decrease. Due to the appearance of sea ice in the Bohai Sea in winter, which affects the calculation of Chl-a concentration, further analysis is needed for the variations in a complete time period.

![Figure 6](image)

Figure 6. Inter-annual variations of SST (a). Monthly variations of Chl-a and SST (b).

#### 5. Conclusion

Quantitative analysis of Chl-a concentration and revealing its temporal and spatial variation characteristics were conducive to understanding the basic situation of eutrophication, controlling seawater pollution, and scientifically monitoring the sea water environment. In this study, the concentration of Chl-a was retrieved from MODIS data to study the variation of Chl-a in Bohai Sea from 2014 to 2019, and the influencing factors of the variation were analyzed. From 2014 to 2019, the Chl-a concentration in the Bohai Sea showed an overall downward trend, and with little difference in seasonal variations. The concentration of Chl-a varied with the distance from the coast. The concentration increased the most in Bohai bay and decreased the most in Liaodong bay. Both
river runoff and sea surface temperature were related to the Chl-a, indicating that the input of terrestrial nutrients and seawater stratification had impact on the variation of Chl-a. The analysis of factors affecting Chl-a concentration in this study was not comprehensive enough. Other environmental variables such as light and precipitation may also affect the variation of Chl-a, which can be studied in the future.

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