QUANTITATIVE INVERSION OF CHLOROPHYLL A CONCENTRATION AND ANALYSIS OF TEMPORAL AND SPATIAL CHARACTERISTICS IN HONGKONG OFFSHORE WATERS BASED ON TIME-SERIES HJ-1A/B MULTISPECTRAL DATA

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KEY WORDS: Chlorophyll a concentration, HJ-1A/B satellite correlation, Analysis statistical regression, Remote sensing inversion, Product data evaluation, Temporal and spatial dynamics change

ABSTRACT:

In order to meet the demand of obtaining chlorophyll a concentration distribution in the offshore waters of Hong Kong on a rapid and large scale, based on the daily measured chlorophyll a concentration data and the HJ-1A/B satellite multispectral data in 2009-2019. Taking Modis-Aqua and Himawari series chlorophyll a concentration of remote sensing products as comparative data. Through per-process to extracted the reflectivity of each band combined and statistical correlation analysis with measured data, select the highest correlation band combination as the characteristic variable to statistical regression analysis with two-thirds of the measured chlorophyll a concentration data, constructing multiple regression algorithms. Determination of the best inversion algorithm by verified accuracy of the remaining one-third of the measured data. Inversion of chlorophyll a concentration in the offshore waters of Hong Kong from 2009 to 2019, the results show:1). The best inversion algorithm is a univariate cubic regression algorithm, R^2 is 0.942, RMSE is 0.285μg/L, RPD is 33%; 2). The overall trend of remote products is the same as the measured data, but the value is slightly higher than the measured data;3). The distribution characteristics in the offshore waters of Hong Kong in the recent ten years are "high in the east and low in the west", and the average concentration in the western waters is about 5μg/L lower than the eastern waters.

1. INTRODUCTION

Ocean chlorophyll a concentration is the highest pigment in algae and plankton. As the concentration is closely related to the number of algae in the water, it is the main index of the evaluation of the eutrophication of the water(Lu, et al. 2015). It's also an important parameter for the detection of fishing grounds and the study of marine primary power(Chen, et al. 2013). Therefore, it is particularly important to monitor the change of marine chlorophyll a concentration. Due to the shortcomings of scattered sampling points, high cost and long times cycle, the traditional water quality monitoring methods can not meet the needs of marine fishing ground prediction and red tide detection for rapid acquisition of chlorophyll a concentration distribution(Sid'ko, et al. 2017). Remote sensing inversion of chlorophyll a concentration can meet the needs of water quality monitoring and eutrophication evaluation, marine productivity and other studies to quickly obtain large-scale ocean chlorophyll a concentration distribution, and make up for the shortage of observed sample points in traditional marine monitoring(Watanabe, et al. 2018; Xu, et al. 2018), which makes it possible to monitor the change of chlorophyll a concentration in long time series.

At present, there are mainly empirical statistical methods, semi-analytical semi-empirical methods and analytical model methods for remote sensing inversion of chlorophyll a concentration(Al-Naimi, et al. 2016; Gholizadeh and Robeson 2016). Although the empirical statistical method has poor applicability in the world, it has high applicability in a specific region and has great advantages in practical application. The OC3 algorithm established by O 'Reilly(Ač, et al. 2015).etc, is a representative empirical algorithm. NASA has applied it as a standard business algorithm in the global chlorophyll a concentration data production. Gaoqiang Zheng et al established a chlorophyll a concentration inversion model suitable for the Xiamen sea area by using HJ-1B satellite CCD2 data and measured synchronous chlorophyll a concentration data, and used this model to analyze the chlorophyll a concentration distribution in Xiamen sea area. Using the HJ-1A satellite CCD2 data and the measured chlorophyll a concentration data, Jianmei Luo established a chlorophyll-a-inversion model suitable for the northern part of the river mouth and obtained the conclusion that the HJ satellite data can be used for the inversion of the water quality of the case 2 waters body with complex water quality. The existing water quality inversion research based on HJ satellite multispectral data is mainly focused on inland water bodies or large areas of lakes and reservoirs, but the research on inshore complex case 2 waters bodies is less(Oliveira, et al. 2016). Complex optical properties of the case 2 waters bodies make the inversion algorithm limited by space and time(Frankenbergper-process et al. 2014; Menon and Adhikari 2018), so it is of great practical significance to establish an algorithm model for quantitative inversion of chlorophyll a concentration in coastal water bodies with HJ satellite multispectral data. Nowadays, chlorophyll a concentration remote sensing inversion data products such as Modis-Aqua Chlor_a and Himawari Chlor_a have been widely used in the monitoring and analysis of marine environment in China(Shanmugam, et al. 2018; Yao, et al. 2017), but limited by the lack of high quality and long time series measured data, the

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verification of its accuracy in offshore waters has not yet been carried out systematically.

In this work, we based on the multispectral data of HJ-1A/B satellite and the measured chlorophyll a concentration data, In-depth analysis of the characteristics of chlorophyll a concentration in the offshore waters of Hong Kong, and establishment of chlorophyll a concentration inversion Model suitable for this sea area. Using remote sensing inversion product data, such as the Modis-Aqua Chlor_a and Himawari Chlor_a, of the corresponding date as the comparative data, build the time-space matching data of the remote sensing inversion product and the measured data, and the accurate evaluation of the chlorophyll a concentration product of remote sensing inversion. With a view to better service to the ocean biological chemistry and climate research.

2. DATA

2.1 Study Area

The south of Hong Kong sea areas is in contact with the South China Sea, the northern part is in close proximity to the estuary of the Pearl River. Water quality is complicated and pollution, such as industrial pollution, domestic pollution, and aquaculture pollution, which pose a serious threat to the ecological environment of Hong Kong sea areas.

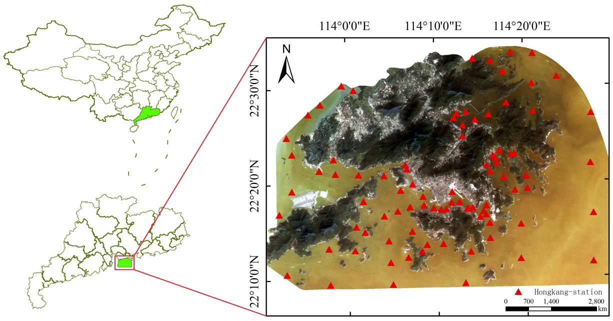

Figure 1. Study area and stations

2.2 Data Processing

2.2.1 Measured Data: Measured chlorophyll a concentration data obtained from the Hong Kong Environmental Protection Department. The whole offshore area of Hong Kong is divided into 10 monitoring areas and 65 monitoring stations. The specific station's distribution is shown in Figure 1. Downloaded the measured data corresponding to the satellite dates in 2009, 2011, 2014 and 2017, a total of 220 data points, of which there may be some outliers, such as cloud-covered points and some abnormal change points, leaving 187 data points after removing the abnormal values, the specific date information is shown in Table 1.

Data	Number	Data	Number
Feb 2009	14	May 2014	7
Aug 2009	15	Oct 2014	23
Oct 2009	5	Dec 2014	7
Nov 2009	5	Jan 2017	12
Apr 2011	13	Feb 2017	28
Nov 2011	18	Oct 2017	12
Jan 2014	15	Dec 2017	46

Table 1. Measured data information

2.2.2 Satellite data: The satellite data is the multi-spectral data acquired by the HJ-1A/ B satellite CCD camera, and a total of 20 available cloud-free data, four scenes per year in 2009, 2011, 2014, 2017 and 2018 (quarterly), and the data is from the China Resource Satellite Application Center. Image processing includes cutting of research area, radiometric calibration, atmospheric correction, geometric correction, water and land separation and band reflectivity extraction. HJ-1A/B CCD data is a grade 2 product, which needs radiometric calibration and atmospheric correction to obtain remote sensing reflectivity (Rrs) on the surface of the water body. Radiometric calibration is to convert DN (digital number) value into radiance value to realize quantitative research, establish the quantitative relationship between numerical output value DN and radiance value of sensor, and the formula is as follows:

$$L = DN / g + L_0 \tag{1}$$

where L = radiance value
g = calibration coefficient gain
L_0 = offset

Atmospheric correction is used to eliminating the influence of water vapor, oxygen, carbon dioxide, methane and the like on the reflection of the surface of the atmosphere and the influence of atmospheric molecules and aerosol scattering, and obtaining the real parameters of the physical models such as the reflectivity and the emissivity of the ground objects. In this paper, used the FLASH model to correct the multispectral data of the HJ-1A/ B satellite. Using the landsat8 OIL image corrected by geometric precision as the reference image, after selecting the same name point to carried out geometric correction by using the cubic convolution method. According to the normalized water body difference index (NDWI), select the suitable threshold for water and land separation to extract the water body information in the study area. Finally, according to the location of stations to extracted the remote sensing reflectivity values of each band.

2.2.3 Product data: Modis-Aqua Chlor_a is a global ocean wide chlorophyll a concentration remote sensing inversion product released by NASA's Ocean Biology Processing Group since 2002. Its original satellite data is Modis image, the inversion algorithm is the OC_3 model, the maximum spatial resolution is 4 km, the minimum time resolution is 1 day, and there are 8 days average data and monthly synthesis data. Himawari Chlor_a is a chlorophyll a concentration remote sensing inversion product released by Japan Meteorological Agency since 2016, covering 24N-50N and 123E-150E. Its original satellite data is Himawari series images, the spatial resolution is 5km, the sea area near Japan is 1km, the minimum time resolution is 1 hour, and the average data for one day and one month are also available. In order to evaluate the accuracy of the data products, downloaded Modis-Aqua Chlor_a and Himawari Chlor_a data products corresponding to the measured chlorophyll a concentration data dates. After resampling, the spatial resolution is kept in the same dimension.

3. ALGORITHMS

Based on the remote sensing reflectivity values of each band combination and measured chlorophyll a concentration data, after the Pearson correlation analysis between the band combined with the measured data select the largest correlation to be a characteristic variable for build a quantitative inversion algorithm. In this paper, the measured data are divided into two

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groups, in which two-thirds of the sample data are used to build an algorithm, and one-third of the sample data are used to evaluate the accuracy of the algorithm in order to determine the best inversion algorithm. Finally, we extracted the product data values of Modis-Aqua Chlor_a and Himawari Chlor_a corresponding to the station's location, in order to evaluate and analyze the accuracy of the data products and compare them with the measured data and HJ satellite data inversion results.

3.1 Algorithms construction

Through the correlation analysis between the reflectance of each band and measured chlorophyll a concentration data obtained the Pearson correlation coefficient. The results show that the highest correlation is between B1 (blue band) reflectivity and chlorophyll a concentration data, and the Sig is 0.000. It is shown that the reflectance in the 95% confidence interval is significantly related to the reflectance of the B1 band, and the Pearson coefficient is -0.737. Further analysis the spectral characteristic curve of the reflectance image of the sample point, as shown in Figure 2, the order distribution of the sample point reflectance is B1> B2> B3> B4, and the result is similar to that of the seawater reflectance from the blue band to the near-infrared band(He, et al. 2018).

Band	Pearson	Sig
B1	-0.737**	0.000
B2	-0.630**	0.000
B3	-0.395	0.001
B4	0.039	0.599

Table 2. Band correlation

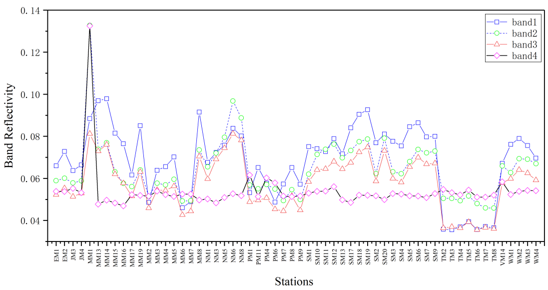


Figure 2. Stations reflectivity

Some studies have shown that the ratio treatment of remote sensing reflectivity in different bands can reduce the influence of the atmosphere on electromagnetic wave signal transmission and eliminate the interference of water surface roughness change in time and space to a certain extent(Huang, et al. 2017; Zheng and DiGiacomo 2017). Therefore, we carried out the correlation analyze between the measured data and different ratio combinations of the four bands. Results show, the reflectivity of the B3/B2 combination is the highest correlation with measured data, and the Sig is 0.000. It is shown that the reflectance in the 95% confidence interval is significantly related to the reflectance of the B3/B2 combination, and the Pearson coefficient is 0.893, Table 3. In summary, selected the B3/B2 combination as the characteristic variable to build quantitative inversion chlorophyll a concentration algorithm in the offshore waters of Hong Kong.

Combination	Pearson	Combination	Pearson
B1/B2	-0.323**	B3/B1	0.836**
B1/B3	-0.753**	B3/B2	0.893**
B1/B4	-0.674**	B3/B4	-0.459*
B2/B1	0.301**	B4/B1	0.767**
B2/B3	-0.832**	B4/B2	0.733**
B2/B4	-0.614**	B4/B3	0.486*

Table 3. Band combination correlation

Based on the results of the above correlation analysis, take statistically analyze the measured chlorophyll a concentration data of two-thirds of the sample points and the combined reflectivity of the B3/B2 band, and obtained a variety of quantitative remote sensing inversion algorithm.

	Algorithm	R^2	RMSE	RPD
Linear	$y = -29.656 + 35.620x$	0.797	1.620	37%
Log	$y = 6.3 + 34.5\ln(x)$	0.748	1.985	31%
Square	$y = 81 - 188x + 110x^2$	0.940	0.320	34%
Cubic	$y = 20 - 79x^2 + 62x^3$	0.942	0.285	33%
Power	$y = 3.246 * x^{5.414}$	0.924	0.260	18%
Index	$y = 0.004 * e^{6.693x}$	0.857	0.255	25%

Table 4 Algorithm and accuracy analysis

3.2 Accuracy evaluation

3.2.1 Algorithm accuracy evaluation: Table 4 shows that there is a significant correlation between the significance (Sig) of each algorithm. In order to compare the advantages and disadvantages of each algorithm, we brought the data points used for verification into each model to calculate the predicted value. Furthermore, the calculated coefficient of determination(R^2), root mean squared error (RMSE), relative percent deviation (RPD) and absolute percent deviation (APD). R^2 reflects the linear fitting between the predicted value and the measured value. RMSE reflects the uncertainty between the predicted value and the measured value. RPD and APD are used to evaluate the accuracy of the prediction (deviation).

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(y_i-x_i)^2}{N}} \quad (2)$$

$$RPD=\frac{1}{N}\sum_{i=1}^{N}\frac{y_i-x_i}{x_i}\times 100\% \quad (3)$$

$$APD=\frac{1}{N}\sum_{i=1}^{N}\frac{|y_i-x_i|}{x_i}\times 100\% \quad (4)$$

where x = measured value
y = predicted value

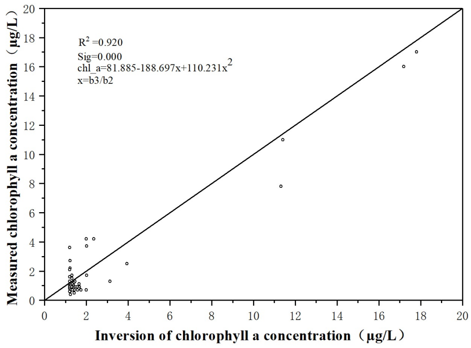
Figure 3 shows the regression analysis results between predicted values and measured values of each algorithm. Results show that different inversion algorithms should be used for different sea areas. So it is necessary to establish chlorophyll a concentration inversion algorithms for the offshore waters of Hong Kong.

Although the RPD of the Univariate Cubic Regression model is only 33%, which is not as good as 18% of the Power exponential model and -25% of the Index model, R^2 is 0.942 higher than other models, and RMSE is 0.285μg/L. Finally, considering the three indexes, this paper uses the Univariate Cubic Regression algorithm as chlorophyll a concentration remote sensing inversion algorithm in the offshore waters of Hong Kong.

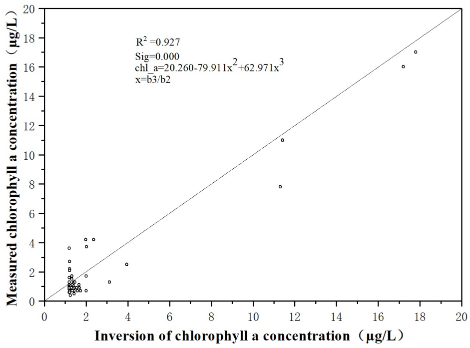
	MODIS	HJ	HIMAWARI	HJ
RMSE	1.723	1.215	1.657	1.390
RPD	80%	47%	78%	46%
APD	84%	57%	82%	70%

Table 5. Comparison of the accuracy of the inversion results of the Modis-Aqua product, the Himawari product and the HJ satellite with the measured value

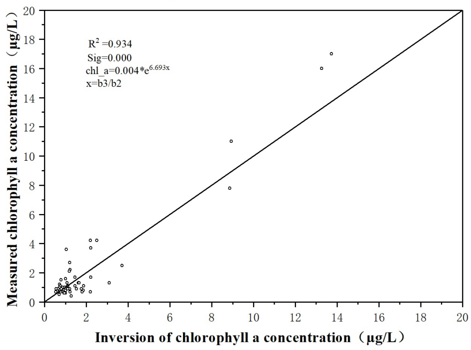
3.2.2 Data product accuracy evaluation: In this paper, by using the measured chlorophyll a concentration data and the corresponding date Modis-Aqua Chlor_a, Himawari Chlor_a product data and HJ-1A/B satellite multispectral data inversion results to establish the spatial and temporal information match. Through resampling, the inversion product data of the corresponding stations are extracted and compared with the measured data. As the results shown in Figure 4 and Table 5, although the overall trend of Modis-Aqua Chlor_a and Himawari Chlor_a products is the same as the measured data, the value is slightly higher than the measured data. The RMSE of Modis-Aqua Chlor_a (N=64) was 1.732μg/L, RPD and APD are 80% and 84%, Himawari Chlor_a (N=88) is 1.657μg/L, RPD and APD are 78% and 82%, the product accuracy of Himawari Chlor_a is slightly higher than that of Modis-Aqua Chlor_a. The main reason should be the different spatial resolution of the image data source and the applicability of the algorithm region. In order to better verify the accuracy of HJ-1A/B satellite multispectral data inversion results that compared with Modis-Aqua Chlor_a and Himawari Chlor_a product data. The comparison results show that the accuracy of HJ satellite data inversion results much higher than Modis-Aqua Chlor_a and Himawari Chlor_a data. Compared with Modis-Aqua Chlor_a product RMSE increased by 0.508μg/L, RPD increased by 33%, compared with Himawari Chlor_a product RMSE increase by 0.267μg/L, RPD increased by 32%.



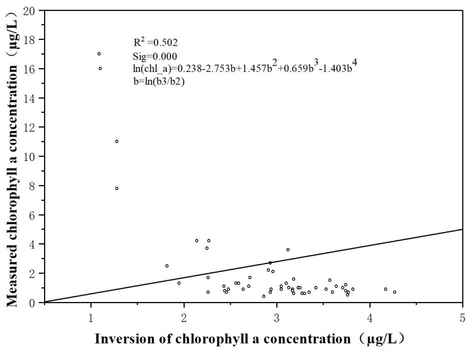
a.Quadratic model



b.Cubic model

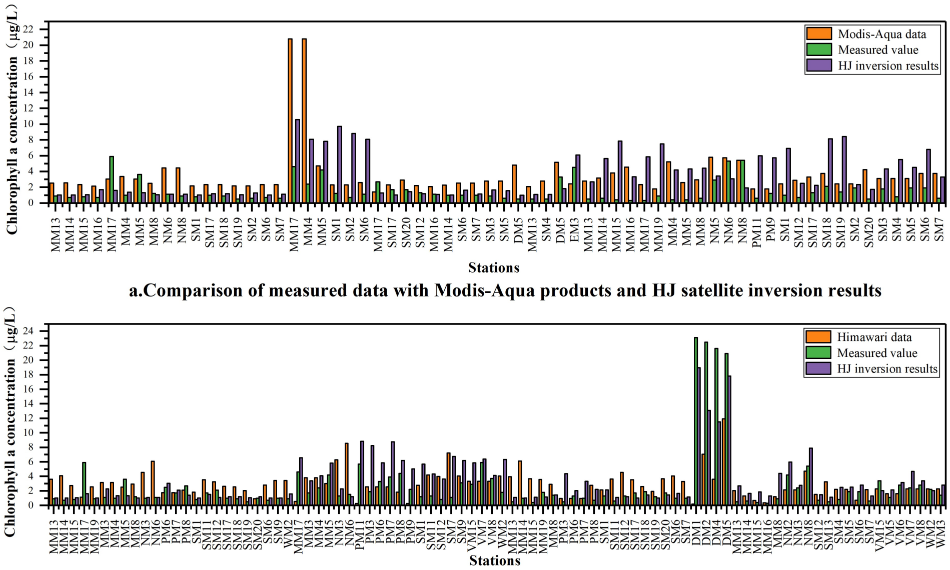


c.Power exponential model



d.OC_3 Algorithm model

Figure 3. Accuracy regression analysis comparison



a.Comparison of measured data with Modis-Aqua products and HJ satellite inversion results

b.Comparison of measured data with Himawari products and HJ satellite inversion results

Figure 4. Modis product, Himawari product, HJ satellite inversion results are compared with measured values.

The confidence of the statistical results is based on a large number of statistical samples, so it is the premise of effective inspection to obtain more high quality measured data. The method used in the field measurement of chlorophyll a concentration is also a factor that can not be ignored in the test error[14]. In addition, the remote sensing inversion products reflect the comprehensive effect in a certain range[15], because this work only uses the surface measured values, it lacks the information of chlorophyll a concentration vertical distribution. This is also a factor that the high value of inversion products.

4. RESULTS AND DISCUSSION

Using HJ-1A/B satellite multispectral data and univariate cubic regression algorithm to inversed the chlorophyll a concentration in the offshore waters of Hong Kong. The temporal and spatial distribution of chlorophyll a concentration in the recent 10 years is shown in Figure 5. From 2009 to 2019, the chlorophyll a concentration in the offshore waters of Hong Kong as a whole showed an upward trend, but the change was not significant. The areas with high concentration are mainly concentrated in the eastern waters such as Tolo Harbour, Deep Bay Strait and some waters in the New Territories. The reasons are that the exchange and renewal capacity of semi-closed waters is weak, coupled with the discharge of domestic sewage, the polluted water bodies can not exchange with other water bodies in time, and the accumulation of water quality index leads to the increase of chlorophyll a concentration. In contrast, the northwest sea area is close to the estuary of the Pearl River, and the water body renewal is fast and the chlorophyll a concentration is in a relatively low state all year-round. It is found that human factors have huge influence on algae growth in water body, and chlorophyll a concentration in far shore water with less artificial influence is relatively low, so chlorophyll a concentration in Hong Kong waters as a whole shows the spatial distribution characteristics of "high in the east and low in the west". Chlorophyll a concentration shows a regular change with time, and then increases first and then decreases and then increases from January 2018 to January 2019, which is main reasons that temperature changes in different seasons affect the growth of phytoplankton.

5. SUMMARY AND CONCLUSIONS

In this paper, taking the offshore waters of Hong Kong as the study area, using the multispectral data of HJ-1A/B satellite and the measured chlorophyll a concentration data, through analysis of the relationship between each band combination and measured data to select the best band combination which using to constructed the chlorophyll a concentration remote sensing inversion algorithm suitable for Hong Kong waters. Verify the applicability of the classical algorithm OC_3 in the inversion of chlorophyll a concentration in Hong Kong waters base on HJ satellite multispectral data. Precision Evaluation and Analysis of Modis-Aqua Chlor_a, Himawari Chlor_a products. Finally, using the optimal inversion algorithm to invert the chlorophyll a concentration in the offshore waters of Hong Kong in recent 10 years, to explore the interannual temporal and spatial dynamic distribution of chlorophyll a concentration from 2009 to 2019 and to clarify the seasonal differences in the offshore waters of Hong Kong.

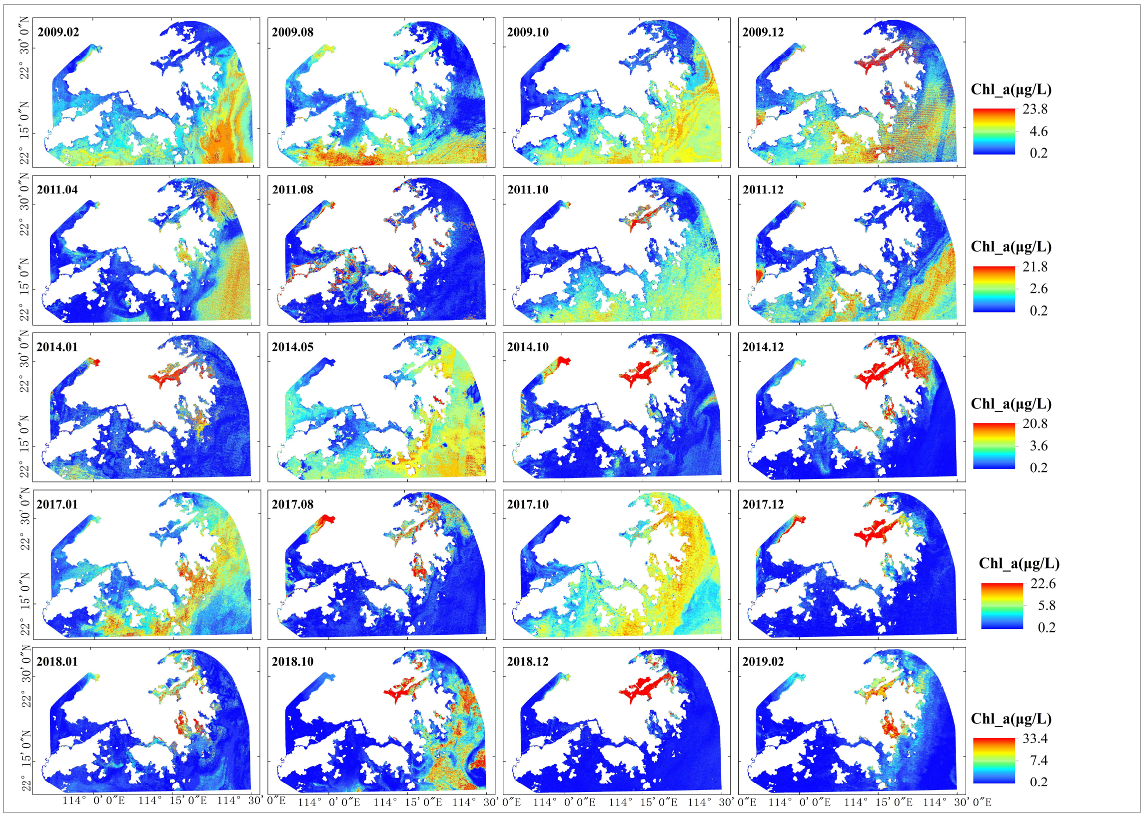


Figure 5 Temporal and spatial variation of chlorophyll a concentration in Hong Kong oceans form2009 to 2019

Several new findings were obtained from this study, namely:

1).The best inversion algorithm of chlorophyll a concentration in the offshore waters of Hong Kong using HJ-1A/B satellite multispectral data is a univariate cubic regression algorithm. The measured chlorophyll a concentration is significantly correlated with remote sensing inversion results in 95% confidence interval, R^2 is 0.942, RMSE is 0.285μg/L, RPD is 43%, and the inversion accuracy is improved to a certain extent;

2).The overall trend of Modis-Aqua Chlor_a and Himawari Chlor_a products is the same as the measured data, but the value is slightly higher than that of measured data;

3).The spatial and temporal variation of chlorophyll a concentration in the offshore waters of Hong Kong in recent ten years: the distribution characteristics are "high in the east and low in the west", and the average concentration in the western waters is about 5μg/L lower than the eastern waters, and the highest value in February 2009 is only 10.6μg/L but on February 2019 the highest value has increased to 33.4μg/L. During the year, the seasonal difference was characterized by "low autumn and high spring", the highest value of chlorophyll a concentration in January 2018 reached 27.1μg/L, and the lowest value was only 0.2μg/L in April.

Due to the complexity of spectral characteristics caused by the diversity of water quality components in inshore water bodies, it is difficult to retrieve chlorophyll a concentration accurately because of the serious influence of atmospheric conditions on radiation signals, and the sampling time of measured data is not strictly synchronous with satellite transit time, and the influence of sea surface wind field on phytoplankton is easy to cause drift. As a result, the reflectivity information of specific sample points on satellite images can not accurately correspond to the actual reflectivity of ground measured points, which affects the inversion accuracy to a certain extent.

This study provides technical support for quantitative estimation of marine chlorophyll a concentration remote sensing, dynamic monitoring of water quality and prediction of fishing grounds.

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