Int J Appl Earth Obs Geoinformation 67 (2018) 173–178

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Monitoring of chlorophyll-a and sea surface silicate concentrations in the south part of Cheju island in the East China sea using MODIS data

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ARTICLE INFO

Keywords:
MODIS
Chlorophyll-a
SST
Surface silicate
Spring bloom

ABSTRACT

Continually supplied with nutrients, phytoplankton maintains high productivity under ideal illumination and temperature conditions. Data in the south part of Cheju Island in the East China Sea (ECS), which has experienced a spring bloom since the 2000s, were acquired during a research cruise in the spring of 2007. Compared with *in-situ* measurements, MODIS chlorophyll-a measurements showed high stability in this area. Excluding some invalid stations data, the relationships between nutrients and chlorophyll-a concentrations in the study area were examined and compared with the results in 2015. A high positive correlation between silicate and chlorophyll-a concentration was identified, and a regression relationship was proposed. MODIS chlorophyll-a measurements and sea surface temperature were utilized to determine surface silicate distribution. The silicate concentration retrieved from MODIS exhibited good agreement with *in-situ* measurements with R^2 of 0.803, root mean square error (RMSE) of 0.326 μmol/L (8.23%), and mean absolute error (MAE) of 0.925 μmol/L (23.38%). The study provides a new solution to identify nutrient distributions using satellite data such as MODIS for water bodies, but the method still needs to be refined to determine the relationship of chlorophyll-a and nutrients during other seasons to monitor water quality in this and other areas.

1. Introduction

With the development of remote sensing technology, ocean color remotely sensed data have proven to be a useful tool for monitoring the marine ecosystem. Global algorithms of chlorophyll-a (O'Reilly et al., 2000) have been empirically derived from a large in-situ database collected in waters around the world, and several studies analyzed the spatial and temporal distribution of chlorophyll-a using MODIS (Ji et al., 2017; Gong and Wong, 2017).

In surface water mass, researchers have widely acknowledged that the growth of phytoplankton relates to the concentration of nutrients. Numerous attempts have been made to estimate nutrient concentrations in water bodies, especially in oceans, using satellite data. Generally, new production constitutes the fraction of primary production supported by nitrogen imported from outside of the euphotic zone (Dugdale and Goering, 1967) and is essentially related to nitrate consumption. Based on coupled dynamic biological models assimilating sea surface height (Oschlies and Garçon, 1998) or wind data (Stoens et al., 1999), researchers have determined nitrate concentration (Simpson and Sharples, 2012; Yamaguchi et al., 2012). Then Traganza et al. (1983) proposed temperature-nitrate relationships. In recent years, the surface nitrate concentration determination method was improved using sea surface temperature (SST) and surface chlorophyll-a concentration (Silió-Calzada et al., 2008; Gong and Wong, 2017). However, surface silicate concentration retrieved from satellite data has hardly been reported.

Spring blooms occurring in the East China Sea (ECS) have been reported in a large body of extant literature in recent years (Liu et al., 2003; Furuya et al., 2003; Endo et al., 2013; Chen et al., 2013; Fu et al., 2015; Ji et al., 2017). High concentrations of chlorophyll-a (2.9ug/L) appeared in the ECS (32°N, 126°E) between 1 and 10 March 1997 (Son et al., 2006), and 1ug/L chlorophyll-a concentration regions were observed in the western part of the Japan Sea, the ECS and the Yellow Sea in April 2003 (EORC, 2004).

When water temperature is lower than 20 °C, diatoms, such as *Chaetoceros lorenzianus* and *Bidduphia sinensis Greville*, dominate in the

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https://doi.org/10.1016/j.jag.2018.01.017
Received 29 September 2017; Received in revised form 21 January 2018; Accepted 29 January 2018

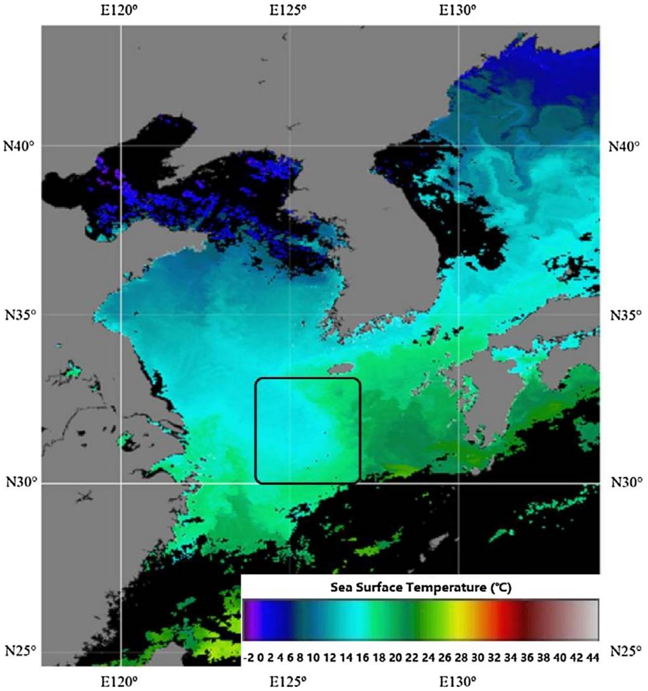

Fig. 1. Standard sea surface temperature image taken at daytime 11 April 2007 by Aqua MODIS (the study area as marked in the black box).

spring in the ECS because they are capable of more rapid growth (Luo et al., 2007). Diatoms are unicellular or chain-forming phytoplankton that used silicon (Si) in cell wall construction. When a water body is richer in nitrates than silicates, with nitrates still available for new production, the diatom bloom is prolonged, where there is a periodic supply of new silicate (Allen et al., 2005).

Owing to discharge from the Changjiang River (Yangtze River), the intrusion of Yellow Sea waters, Taiwan Strait waters and Kuroshio waters, as well as alternating monsoons, the ECS shelf possesses a complex hydrology (Liu et al., 2003). In addition, spring blooms have appeared in the south part of Cheju Island in the ECS, as reported by Son et al. (2006).

A one-month cruise was carried out in the south part of Cheju Island in the ECS (Fig. 1) in the spring of 2007. During the observation, nutrients were pulled up to the sea surface by circulation, which occurs in the spring, and the abundant silicon, the appreciable nitrogen, the phosphorus and the temperature caused a high chlorophyll-a concentration in the study area (Fu et al., 2015). In fact, Fu et al. (2015) observed a linear relationship between *in-situ* measured chlorophyll-a and the silicate concentration with R^2 of 0.7812.

The aims of this study are to: 1) determine the concentration of chlorophyll-a in surface water in the study area using MODIS; and 2) utilize a method that derives sea surface silicate concentrations from SST and surface chlorophyll-a concentration using regression analysis and remotely sensed data.

2. Study area and data collection

2.1. Study area

The field observation was performed at 30°–32.33°N, 124.33°–127.67°E, covering 40,000 km^2, across the shelf edge of the ECS, as shown in Fig. 1, from 9 April to 6 May 2007. In spring, with the rising of the temperature on the upper layer of the water and the appearance of the thermocline, the cold-water mass in the southwest part of Cheju Island possesses the characteristics of low temperature and mesohaline under the shielding effect of the thermocline (Qi et al., 1991; Li, 1995; Yu et al., 2006) with abundant nutrients due to the spreading of the Yellow Sea cold water mass (Fu et al., 2015).

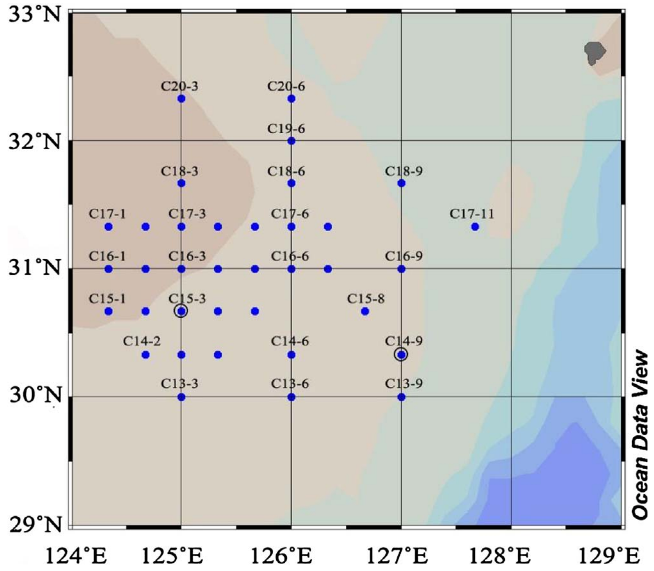

Fig. 2. The sampling stations C13-1 to C13-9, C14-1 to C14-9, C15-1 to C15-8, C16-1 to C16-9, C17-1 to C17-11, C18-1 to C18-9, C20-3 and C20-6 mapped using Ocean Data View.

The study area and the sampling stations (including sections C13-1 to C13-9, C14-1 to C14-9, C15-1 to C15-8, C16-1 to C16-9, C17-1 to C17-11, C18-1 to C18-9, C20-3 and C20-6) are shown in Fig. 2.

2.2. Data collection

2.2.1. Sea surface temperature (SST) and chlorophyll-a (Chl-a) in-situ measurements

Sea surface temperatures were measured using a probe from a RBR water quality sensor (RBR Inc., Kanate, Ontario, Canada). The calibration equipment from RBR permits traceable calibration for oceanography instruments, including that for temperature with accuracy to ± 0.002° C and conductivity with accuracy to ± 0.003 mS/cm.

Chlorophyll-a (Chl-a) was filtered using a 47 mm GF/F filter, extracted using 90% acetone and determined with a Shimadzu UV2401 spectrophotometer (Shimadzu, Inc., Tokyo).

In sum, 22 stations were probed from 30.33°N to 31.33°N in one month, as shown in Table 1. SST increased continually, and the mean of SST changed from 12.8° C on 9 April 2007–17.4° C on 5 May 2007. A high concentration of chlorophyll-a (> 10 ug/L) was detected in the study area.

2.2.2. Nutrient data

Covering over 40,000 km^2, 22 stations were investigated from 6 April to 6 May 2007. The sample stations are listed in Table 2.

Nutrient data, including dissolved inorganic nitrates (DINs), dissolved inorganic phosphates (DIPs, PO3- 4) and silicates (SiO2- 3), were acquired by *in-situ* measurements. DIN concentrations can be calculated by summing those of nitrate (NO- 3), nitrite (NO- 2) and ammonium

Table 1
Properties of chlorophyll-a data collected from 9 April 2007 to 5 May 2007.

Station name	*Period*	*Latitude*	*n*
C14-2,3,4,6	03 May 2007	30.33°N	4
C15-1,2,3,4,5,8	26 April–05 May 2007	30.67°N	6
C16-1,2,3,4,6, 9	26 April–04 May 2007	31.00°N	6
C17-1,2,3,4,5,6	09 April–04 May 2007	31.33°N	6
Total	09 April–05 May 2007		22

Table 2
Properties of nutrient data collected from 6 April to 6 May 2007.

Station name	*Period*	*Latitude*	*N*
C13-3,6,9	02–06 May 2007	30.00°N	3
C14-3,6,9	03 May 2007	30.33°N	3
C16-1,2,3,5,6,7,9,12	26 April–05 May 2007	31.00°N	8
C17-7,11	04 May 2007	31.33°N	2
C18-3,6,9	09 April–04 May 2007	31.67°N	3
C19-6	06 April 2007	32.00°N	1
C20-3,6	06 April 2007	32.33°N	2
Total	06 April–06 May 2007		22

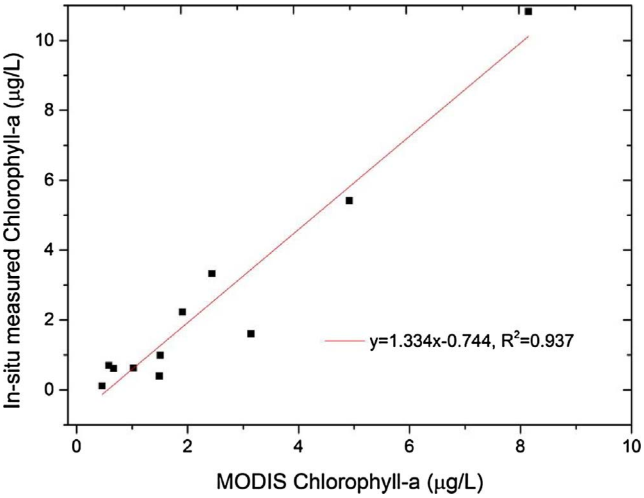

Fig. 3. MODIS-derived versus *in-situ* measured chlorophyll-a for 11 stations. The red line is the regression line with R^2 of 0.937. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(NH+ 4).

The concentrations of NO- 3 and SiO2- 3 with 0.7% and 6.0% accuracy, respectively, were tested using a San^{++} Automated Wet Chemistry Analyzer (Skalar Analytical B.V., Netherlands). The concentrations of NO- 2, NH+ 4 and PO3- 4 were tested using a spectrophotometer with 8.6%, 14.5% and 10.0% accuracy, respectively (Standardization Administration of the People's Republic of China, 2007).

2.2.3. *Remotely sensed data*

Daily level 3 chlorophyll-a concentration products with 4 km resolution and monthly level 3 SST products with 4 km resolution from Aqua/Terra MODIS were acquired for the study area from the Ocean Biology Distributed Active Archive Center (OBDAAC). The standard chlorophyll-a product was derived from the OC3 M algorithm (O'Reilly et al., 2000). Ocean Colour SeaDAS Software was applied to process the chlorophyll-a and SST data.

QuikScat (or SeaWinds) data (including rain contaminated data) were acquired from remote sensing systems and sponsored by the NASA Ocean Vector Winds Science Team (data are available at www.remss.com).

3. Results and discussion

3.1. *Testing MODIS standard Chl-a*

The revision of Chl-a data could not include all areas due to thick clouds blocking the light during the observation period. All revised chlorophyll-a data were obtained within one or two days of the sampling time by each station to reduce error. Although data at 22 stations had been measured, as shown in Table 2, only the data from 13 stations could be revised using remote sensing data. Chlorophyll-a concentration at the sea surface was investigated using satellite data. The *in-situ* measured chlorophyll-a at the sea surface (water depth ≤ 2m) was compared with the revised chlorophyll-a data by MODIS.

The results show a high linear correlation between both the satellite and *in-situ* data (see Fig. 3), which means that the MODIS chlorophyll-a concentration product can be used directly to explore sea surface chlorophyll-a in the study area.

According to Tables 1 and 2, nine stations (C14-3, 6 and 9, and C16-1, 2, 3, 6, and 9) measured both Chl-a and nutrient concentrations at the same time. MODIS chlorophyll product can provide Chl-a data for those stations that only observed nutrient concentrations, but missed Chl-a concentrations. The MODIS chlorophyll product data will be directly applied in this study. This is because the recalculated Chl-a concentration using the linear relationship identified in this section (*in-situ* measured Ch-a = 1.334 × MODIS chlorophyll product − 0.744) will be a negative number when the MODIS chlorophyll product data are less than 0.55 μg/L.

3.2. *Adjusted correlation analysis*

A cluster analysis by Fu et al. (2015) indicated that algal species that can survive in 13.9–18.5 °C dominated the study area. The low temperature might have reduced the consumption rate of nutrients and the growth rate of phytoplankton. A previous study by Luo et al. (2007) reported that *Chaetoceros lorenzianus* and *Bidduphia sinensis Greville* could survive in a wider temperature range (12–28 °C), which enables them to dominate in the spring in the ECS. When water temperature increased, *Prorocentrum dentatum*, which grows well within a temperature range of 20–27 °C and grows optimally at 24 °C, has become the major algal species in the ECS. This has occurred since the 2000 s (Chai et al., 2009). In this study, samples collected in low temperature environments (lower than 12 °C) will be removed to reduce the error of the correlation relationship.

Moreover, weather conditions highly affect sea surface nutrient concentrations. Strong winds not only re-supply nutrients but also bring phytoplankton to the surface (Simpson and Jonathan, 2012). Containing phosphorus and nitrogen from air pollution, rainwater also introduces new nutrients into sea waters. To bridge the nutrient and Chl-a concentrations, some external factors should be excluded. Data collected in such weather conditions will be removed from this study.

Based on QuikScat data, rainy weather occurred on 3 May 2007 (as shown in Fig. 4). This means that the data collected on this day was removed.

The relationship between Chl-a and silicate concentrations was described as chlorophyll-a concentrations ($\mu g/m^3$) = 0.7519 × silicate concentration ($mmol/m^3$) − 0.8431 with $R^2 = 0.7812$ (Fu et al., 2015). The aim of this section is to optimize the correlation between phytoplankton and nutrients by removing some external factors. We excluded some invalid stations data affected by external factors, such as weather condition, air pollution, and rainwater. The remaining stations data are listed in Table 3.

Revised chlorophyll-a data were used as a dependent variable in the correlation analysis, while nutrient factors (N:P, N:Si, DIN, DIP, and silicates) measured at the sea surface were set as independent variables. The Pearson product-moment correlation coefficient (Pearson's r) between chlorophyll-a and N:P is −0.305, and the coefficient between chlorophyll-a and N:Si is −0.429, which means that correlations were not notable. A low correlation between chlorophyll-a and DIN appeared, with a correlation coefficient of −0.156. No correlation occurred between chlorophyll-a and DIP, as the correlation coefficient was −0.056. A high correlation between chlorophyll-a and silicates appeared, with a correlation coefficient of 0.808.

Comparing Pearson's *r* between SST and chlorophyll-a concentration (-0.322), SST affected nutrient concentration more than the growth of

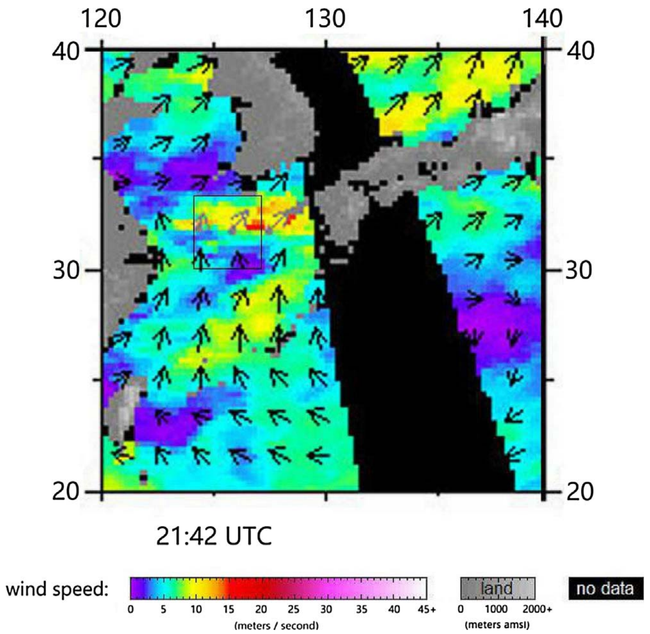

Fig. 4. QuikScat v4 wind vectors mapped on 3 May 2007. The red lines show that strong winds (15–20m/s) and rain (gray arrows) occurred in the study area (marked in a black square). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phytoplankton. The Pearson's r between SST and DIN, DIP and silicates was −0.652, −0.668 and −0.630, respectively.

These results show that the silicate concentrations in the water body can be estimated using Chl-a concentration (Figs. 5 and 6).

3.3. Regression analysis

Acquiring Chl-a concentration data is simple, since the reliability of the MODIS chlorophyll product has been analyzed previously. The silicate concentration can be described as in Eq. (1).

$$S = -0.0103.\,C^2 + 1.0793.\,C + 1.9566 \tag{1}$$

where S stands for silicate concentration in μmol/L; and C is the Chl-a concentration in μg/L. The reliability of calculated silicate retrieved from the Chl-a concentration was acceptable with R^2 of 0.650, RMSE of 0.434 μmol/L (10.97%), and MAE of 1.411 μmol/L (36.66%).

The correlation analysis also demonstrated that water temperature can affect silicate concentration. Considering the SST, the regression relationship can be improved as in Eq. (2):

$$S = 15.5 + 0.837\,C - 0.818\,Temp \tag{2}$$

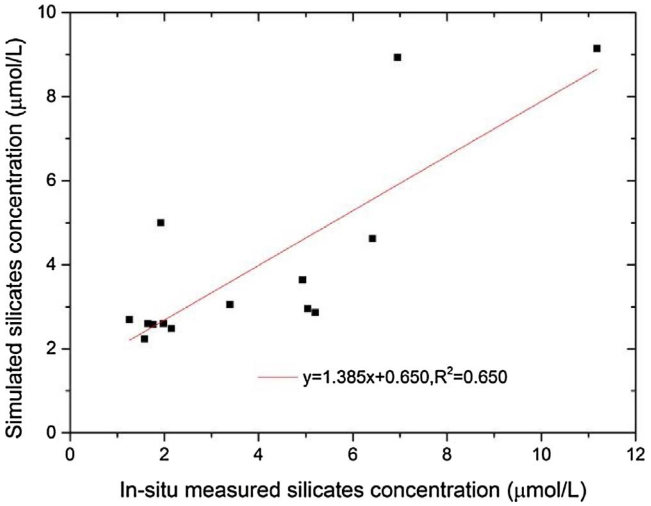

Fig. 5. Validation result using data from the 2007-cruise. *In-situ* measured silicate concentration versus calculated concentration using a Chl-a model.

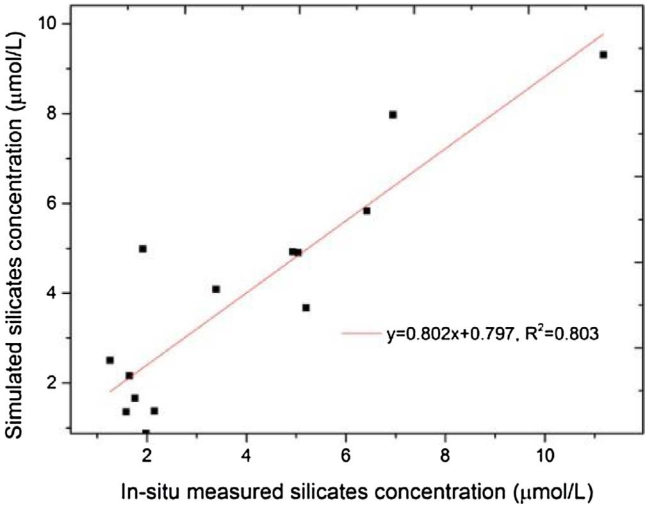

Fig. 6. Validation result using data from the 2007-cruise. *In-situ* measured silicate concentration versus the calculated concentration using a Chl-a-SST model.

where *Temp* is the SST in °C. Comparing the calculated silicate concentration values with measured ones, a good match was found between them with R^2 of 0.803, RMSE of 0.326 μmol/L (8.23%), and MAE of 0.925 μmol/L (23.38%).

Table 3
The remaining stations with some external factors.

Station	date(yyyy-mm-dd)	SST(°C)	DIP(μmol/L)	Silicates (μmol/L)	DIN(μmol/L)	Chlorophyll-a(μg/L)
C20-6	2007 – 04-06	13.93	0.28	5.04	3.17	0.93
C20-9	2007 – 04-06	16.61	0.16	1.26	1.27	0.69
C16-1	2007 – 04-26	14.57	0.19	4.93	4.73	1.58
C16-2	2007 – 04-27	15.35	0.20	5.20	4.36	0.85
C16-3	2007 – 04-28	14.43	0.07	6.42	0.73	2.53
C16-5	2007 – 04-29	14.90	0.09	11.18	1.26	7.15
C16-7	2007 – 05-04	16.30	0.06	6.95	0.32	6.92
C16-9	2007 – 05-04	17.53	0.02	1.76	0.20	0.58
C14-9	2007 – 05 – 05	17.79	0.03	2.15	0.28	0.49
C17-11	2007 – 05 – 05	17.58	0.02	1.58	0.66	0.26
C13-9	2007 – 05-06	18.51	0.03	1.98	0.45	0.60
C17-7	2007 – 05-06	15.85	0.03	1.92	0.84	2.90
C18-6	2007 – 05-07	15.02	0.06	3.39	2.36	1.03
C18-9	2007 – 05-08	16.94	0.01	1.65	0.61	0.60

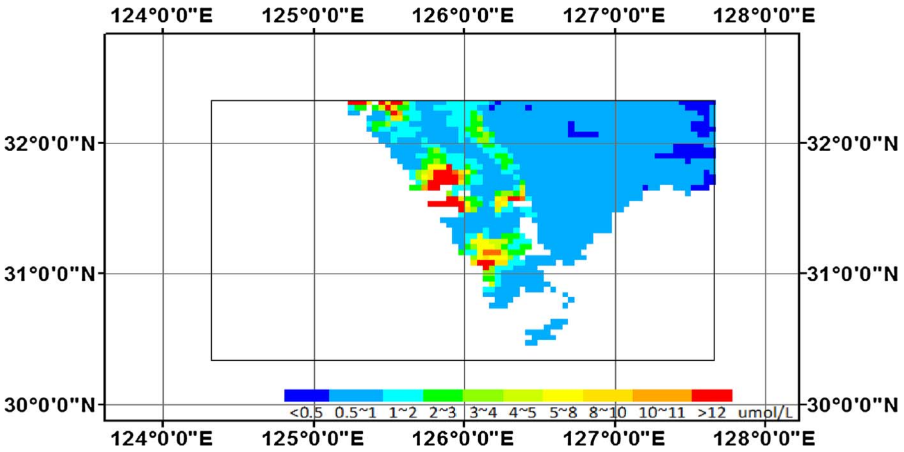

Fig. 7. Silicate (μmol/L) distribution in the surface water between 30 and 32.33°N and 124.33–127.67°E on 25 April 2007. No data are available for the white area due to cloud cover.

3.4. Silicate distribution at the sea surface

A previous study reported a high correlation between Chl-a-SST and silicates in the sea surface of the study area (Chen, 2009). To obtain a more accurate silicate distribution at the sea surface, one can use MODIS, as MODIS product data, such as Chl-a and SST, may not be affected by wind stress or rainy weather. We utilized MODIS to determine the Chl-a concentration and SST for 25 April 2007 and incorporated those values in the analysis. The distribution of silicates at the sea surface of the shelf-sea front of the ESC retrieved using MODIS data is shown in Fig. 7.

A high silicate concentration was spotted in the center of the map, as shown in Fig. 7. Moreover, the surface silicate front took the same shape and location as the thermal fronts at the Yangtze bank, which was also reported in Chen's (2009) study.

4. Conclusions

Spring blooms in the south part of Cheju Island in the ECS have been consistently reported. According to our study, diatoms constituted the dominant species when the front occurred in spring, and silicate limited the growth of phytoplankton in the study area. These conclusions can also be supported by the survival temperature for algae species.

In this study, the MODIS chlorophyll-a product was evaluated with *in-situ* measured chlorophyll-a. The result showed the reliability of MODIS products, with R^2 of 0.937. With the assistance of remotely sensed data, the relationship between nutrient and chlorophyll-a was identified.

Moreover, an improved silicate concentration retrieval method was proposed by adding an independent variable: SST. The improved linear relationship between chlorophyll-a-SST and silicate concentration with R^2 of 0.803, RMSE of 0.326 μmol/L (8.23%), and MAE of 0.925 μmol/L (23.38%) has been established. Through chlorophyll-a retrieved from MODIS and the SST data, the silicate distribution for the study area was mapped.

This method provided a new solution to identify nutrient distributions using satellite data such as MODIS for water bodies. As the method appears reasonable, further studies should focus on the relationship of chlorophyll-a and nutrients during other seasons to monitor water quality in this and other areas.

Acknowledgments

The authors are grateful for the data from NASA's Ocean Biology Processing Group for MODIS Aqua/Terra, Level 3 (4-km equi-rectangular projection) daily for chlorophyll-a and sea surface temperature (SST); the NASA Web SeaDAS development group for providing Ocean Colour SeaDAS software for processing chlorophyll-a and SST data; and Remote Sensing Systems and the NASA Ocean Vector Winds Science Team for providing QuikScat (or SeaWinds) data. This research is jointly supported by the National Key Research and Development Program of China (No. 2016YFC1402003), the "2015 Innovation Program for Research and Entrepreneurship Teams, Jiangsu Province, China", and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

Allen, J.T., Brown, L., Sanders, R., Mark Moore, C., Mustard, A., Fielding, S., Lucas, M., Rixen, M., Savidge, G., Henson, S., Mayor, D., 2005. Diatom carbon export enhanced by silicate upwelling in the northeast Atlantic. Nature 437, 728–732. http://dx.doi.org/10.1038/nature03948.

Chai, C., Yu, Z., Shen, Z., Song, X., Cao, X., Yao, Y., 2009. Nutrient characteristics in the Yangtze river estuary and the adjacent East China sea before and after impoundment of the Three Gorges Dam. Sci. Total Environ. 407, 4687–4695. http://dx.doi.org/10.1016/j.scitotenv.2009.05.011.

Chen, C., Jiang, H., Zhang, Y., 2013. Anthropogenic impact on spring bloom dynamics in the Yangtze river estuary based on SeaWiFS mission (1998–2010) and MODIS (2003–2010) observations. Int. J. Remote Sens. 34, 5296–5316. http://dx.doi.org/10.1080/01431161.2013.786851.

Chen, C.-T.A., 2009. Chemical and physical fronts in the Bohai, Yellow and East China seas. J. Mar. Syst. Spec. Issue Observational Stud. Ocean. Fronts 78, 394–410. http://dx.doi.org/10.1016/j.jmarsys.2008.11.016.

Dugdale, R.C., Goering, J.J., 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnol. Oceanogr. 12, 196–206. http://dx.doi.org/10.4319/lo.1967.12.2.0196.

EORC Seen from Space − Phytoplankton bloom in spring in seas around Japan [WWW Document], n.d. URL http://www.eorc.jaxa.jp/en/imgdata/topics/2004/tp040126.html (Accessed 9.4.15).

Endo, H., Yoshimura, T., Kataoka, T., Suzuki, K., 2013. Effects of CO2 and iron availability on phytoplankton and eubacterial community compositions in the northwest subarctic. Pacific. J Exp Mar Biol Ecol. 439, 160–175.

Fu, D., Huang, Z., Zhang, Y., Pan, D., Ding, Y., Liu, D., Zhang, Y., Mao, Z., Chen, J., 2015. Factors affecting spring bloom in the South of Cheju island in the east China sea. Acta Oceanolog. Sin. 34, 51–58. http://dx.doi.org/10.1007/s13131-015-0633-8.

Furuya, K., Hayashi, M., Yabushita, Y., Ishikawa, A., 2003. Phytoplankton dynamics in the east China sea in spring and summer as revealed by HPLC-derived pigment signatures. Deep Sea Res. Part II 50, 367–387. http://dx.doi.org/10.1016/S0967-0645(02)00460-5.

Gong, S., Wong, K., 2017. Spatio-Temporal Analysis of Sea Surface Temperature in the East China Sea Using TERRA/MODIS Products Data, Sea Level Rise and Coastal Infrastructure. InTech, accepted, Croatia.

Ji, C., Zhang, Y., Cheng, Q., Tsou, J.Y., Jiang, T., Liang, X.S., 2017. Evaluating the impact of sea surface temperature (SST) on spatial distribution of chlorophyll-a concentration in the east China sea. Int. J. Appl. Earth Obs. Geoinf (in this special issue).

Li, F.R., 1995. On the relationship between the distribution of dissolved oxygen and water masses in the Yellow sea and east China sea late in spring. J. Ocean Univ. Qingdao 25 (2), 255–263 (in Chinese).

Liu, K.-K., Peng, T.-H., Shaw, P.-T., Shiah, F.-K., 2003. Circulation and biogeochemical processes in the east China sea and the vicinity of Taiwan: an overview and a brief synthesis. Deep Sea Res. Part I. 50, 1055–1064. http://dx.doi.org/10.1016/S0967-0645(03)00009-2.

Luo, M.B., Lu, J.J., Wang, Y.L., Shen, X.Q., Chao, M., 2007. Horizontal distribution and dominant species of phytoplankton in the east China sea. Acta Ecol. Sin. 27 (12), 5076–5085 (in Chinese).

O'Reilly, J.E., Maritorena, S., Siegel, D., O'Brien, M., Toole, D., Greg, B., Mitchell Kahru, M., Chavez, F., Strutton, P., Cota, G., Hooker, S., McClain, C., Carder, K., Muller-Karger, F., Harding, L., Magnuson, A., Phinney, D., Moore, G., Aiken, J., Arrigo, K., Letelier, R., Culver, M., 2000. Ocean color Chl-a algorithms for SeaWiFS, OC2, and OC4: version 4. In: In: O'Reilly, J.E., 24 coauthors, Hooker, S.B., Firestone, E.R. (Eds.), 2000 SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3. NASA Technical Memorandom 2000-206892, vol. 11. NASA Goddard Space Flight Center, Greenbelt, Maryland, pp. 9–23.

Oschlies, A., Garçon, V., 1998. Eddy-induced enhancement of primary production in a model of the North Atlantic ocean. Nature 394, 266–269. http://dx.doi.org/10.1038/28373.

Qi, J.H., Li, F.Q., Su, Y.S., 1991. Fuzzy discrimination and analysis of the spring water masses in Yellow sea and east China sea. J. Ocean Univ. Qingdao 21 (2), 13–20 (in Chinese).

Silió-Calzada, A., Bricaud, A., Gentili, B., 2008. Estimates of sea surface nitrate concentrations from sea surface temperature and chlorophyll concentration in upwelling areas: a case study for the Benguela system. Remote Sens. Environ. 112, 3173–3180. http://dx.doi.org/10.1016/j.rse.2008.03.014.

Simpson, J.H., Sharples, J., 2012. Introduction to the Physical and Biological Oceanography of Shelf Seas. pp. 466 Cambridge.

Son, S., Yoo, S., Noh, J.-H., 2006. Spring phytoplankton bloom in the fronts of the east China sea. Ocean Sci. J. 41, 181–189. http://dx.doi.org/10.1007/BF03022423.

Standardization Administration of the People's Republic of China, 2007. Specifications for Oceanographic Survey-Part4: Survey of Chemical Parameters in Sea Water. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

Stoens, A., Menkès, C., Radenac, M.-H., Dandonneau, Y., Grima, N., Eldin, G., Mémery, L., Navarette, C., André, J.-M., Moutin, T., Raimbault, P., 1999. The coupled physical-new production system in the equatorial Pacific during the 1992–1995 El Niño. J. Geophys. Res. 104, 3323–3339. http://dx.doi.org/10.1029/98JC02713.

Traganza, E.D., Silva, V.M., Austin, D.M., Hanson, W.L., Bronsink, S.H., 1983. Nutrient mapping and recurrence of coastal upwelling centers by satellite remote sensing: its implication to primary production and the sediment record. In: Suess, E., Thiede, J. (Eds.), Coastal Upwelling Its Sediment Record, NATO Conference Series. Springer, US, pp. 61–83.

Yamaguchi, H., Kim, H.-C., Son, Y.B., Kim, S.W., Okamura, K., Kiyomoto, Y., Ishizaka, J., 2012. Seasonal and summer interannual variations of SeaWiFS chlorophyll a in the Yellow sea and east China sea. Prog. Oceanogr. Spec. Issue Pac. Asian Marg. Seas 105, 22–29. http://dx.doi.org/10.1016/j.pocean.2012.04.004.

Yu, F., Zhang, Z.X., Diao, X.Y., Gou, J.S., Tang, Y.X., 2006. Analysis of evolution of the Huanghai Sea Cold Water Mass and its relationship with adjacent water masses. Acta Oceanolog. Sin. 28 (5), 26–34 (in Chinese).