A Three-Component Model of Phytoplankton Size Classes for The South China Sea

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ABSTRACT The phytoplankton size classes (PSCs) are important to advance our understanding of primary production and the global carbon cycle because different PSCs have specific chemical requirements for their distinct physiological processes. Direct measurements of PSCs are extremely time-consuming, complicated and costly. The present study introduced a newly developed Three-Component Model YE and TANG (TCM-YT) for PSCs analysis research in the South China Sea (SCS). The TCM-YT has been validated by *in situ* measurements obtained in both open sea and coastal areas of the SCS during different seasons.This new TCM-YT showed higher correlations and less error compared to other models. The statistical analysis shows that Root Mean Square Error (RMSE) of Pico-, Nano- and Microplankton were 17.6, 9.9 and 9.8 %Chl-a, respectively. The results show that, in the large marginal SCS, TCM-YT can differentiate PSCs using satellite data; and can be effectively used in the whole SCS.

(Phytoplankton; South China Sea; Phytoplankton Size Classes)

INTRODUCTION

An estimated 40-50% of the total primary production on earth is contributed by phytoplankton communities. Harmful algal blooms can cause large economic losses in aquaculture and wild fisheries[1], need to make urgent research on the phytoplankton size classes(PSCs). In addition, they modulate the overall CO_2 concentration and pH of the ocean; hence, phytoplankton communities play a significant role in the global carbon cycle. Furthermore, the size structure of phytoplankton assemblages strongly influence the energy transfer through the aquatic food chain and carbon cycling in the ocean. For instance, diatoms are responsible for ~20% of global carbon fixation[2].In consideration to primary production and the global carbon cycle, the PSCs have previously been used to describe the principal functional groups[3].According to the pelagic ecosystem structure[3], phytoplankton in the autotrophic pool can be divided into picoplankton(<2 um), nanoplankton(2-20 um) and microplankton(>20 um).

Direct measurements of PSCs are extremely time-consuming, complicated and costly[4]. During recent years, varieties of bio-optical and ecological methods using satellite data have been established to identify, differentiate and quantify PSCs. These models can be categorized into three groups namely: spectral-response-based approaches, abundance-based approaches and ecological based approaches. All these models studying the global oceans are performed with similar accuracy regarding the size of the phytoplankton, the satellite data and types of *in situ* data validation[5].

As the largest marginal and oligotrophic sea in the world, the South China Sea (SCS) can be affected by short-term (typhoon and eddy), medium-term (monsoon), and long-term (EI Nino/Southern Oscillation (ENSO)) physical processes. On short time scale, the SCS is affected by typhoons or tropical cyclones[6] or eddies[7]. On medium term time scale, biogeochemical cycles are largely influenced by the northeast monsoon during October to April and southwest monsoon during May to September[1, 8]. On long term time scale, the circulation is related to ENSO[9]. Most studies in the SCS focused on the abundance and components of picoplankton[10, 11], various aspects of the PSCs[12-16] and phytoplankton functional types[17].Most PSCs studies were carried out in localizedsubregions of the SCS based on one or two cruises in different time scales. Our previous studies found that phytoplankton distribution in the SCS was associated with monsoonal winds[18] and coincided with EI Nino[19].

The aim of this study was to develop a three component-(picoplankton, nanoplankton and microplankton) model(TCM-YT), and validate it using *in situ* PSCs data obtained from the SCS.

DATA AND METHOD

Data

To develop a model which is suitable for use in the SCS, averagedand single PSCs *in situ*data were collected from other studies and references. These data cover both open sea and coastal waters and refer to different seasons. The satellite averaged data, according to the time of measurement, were calculated from SeaWiFS9 km Level-3 daily, 8-d or monthly chlorophyll a (Chl-a)products, which were obtained from National Aeronautics and Space Administration Goddard Space Flight Center Distributed Active Archive Center (NASA GSFC DAAC). The match-up 15 averaged samples cover the coastal areas and open sea the period 1998-2004 (Figure 1).

The single data, according to the time of measurement, were matched to SeaWiFS9 km Level-3 daily, 8-d or monthlyChl-a products, in a 3×3 pixel window,using SeaWiFSobtained fromNASA GSFC DAAC, and those from June-July 2008 were obtained from Moderate Resolution Imaging Spectroradiometer(MODIS)/Aqua satellite data. Mean satellite derived Chl-a values as well as the associated standard deviations were calculated for the nine pixels. In order to minimize the effect of mismatch in spatial scales of *in situ* and satellite observations, any samples for which the standard deviation exceeded three standard devations with respect to the mean were excluded[20]. The match-up 27 single samples covered the coastal areas and open sea in the period 2000-2010 (Figure 1).

Method

The data we used in this study covered both open sea and coastal areas during different seasons.Due to the essential differences found in in-situ data, 15 averaged data were used for the new model development and 27 single data were reserved for validation.Under the assumption that the total concentration of Chl-a is the sum of the picoplankton, nanoplankton and microplankton, the TCM-YT was developed through the following steps:

- Extract satellite-derived Chl-a value (C_S) from SeaWiFS and MODIS;
- Use C_S and the three componentmodel described by *Brewin et al*(2010)[20](TCMB) model to calcuate the fractions of phytoplankton three components (pico-, nano-, and microplankton);
- Use the fractions of the phytoplankton three components and in situ PSCs values to calculate linear relationships for three components;
- Use the established linear relationships for three components to estimate the fractions of the three components and the new sum of them;
- Use the step 4 results to calculate new fractions of the three components (picoplankton, nanoplankton and microplankton).

RESULTS

Model results

Using the regression analysis to compare between TCMB results and *in situ* data, the contributions of PSCs to the total Chl-a concentration (N_p, N_n and N_m, where subscripts *p*, *n* and *m* denote pico-, nano- and microphytoplankton, and N denotes the contribution of the total Chl-a, %Chl-a) can be expressed as:

N_p=100(11.681X+12.413)/Z,

N_n=100(36.255Y-3.67X +11.912)/Z,

N_m=100(106.129-118.754Y)/Z,

where X, Y and Z can be calculated as:

X=[1-exp(-6.801C)]/C,

Y=[1-exp(-0.851C)]/C,

Z=8.011X-82.499Y+130.447,

C means the surface Chl-a concentration derived from satellite.

The changes in percentage contribution of the three size classes of phytoplankton with increasing Chl-a calculated according to the TCM-YT (Figure 2a) show that, picoplankton dominate the total population when Chl-a is less than 0.65 mg m^{-3}; microplankton began to dominate at Chl-a values higher than 0.65 mg m^{-3}; whereas nanoplankton never dominanted (maximum N_n reached up to 32%Chl-a when Chl-a was 0.65 mg m^{-3}).

Validation of PSCs

To show the effectiveness of TCM-YT to the SCS, TCM-YT was validated by *in situ* PSCs data measured in the SCS (Figure 2b).Estimated $N_p$and $N_n$calculated using TCM-YT were overestimated when *in situ* contributions were high and underestimated when *in situ* contributions were low; estimated N_m were overestimated most of the time (Figure 2b). The mean regression slope over all PSCs is 1.4511, the intercept -15.025, the coefficient of determination R^2=0.91 with Root Mean Square Error(RMSE) =19.2 %Chl-a. The algorithm performance varies depending on the PSCs. The algorithm of Microplankton and Picoplankton performed well (Microplankton, R^2=0.81; Picoplankton R^2=0.80, Figure 2b and Table 1), for Nanoplankton it performed poorly (R^2=0.32, Figure 2b and Table 1).

Comparsion with other models

After *Vidussi et al.*(2001)[21] proposed the Diagnostic Pigment Analysis (DPA) procedure, *Uitz et al.*(2006)[22] refined the DPA procedure to scale three components to satellite-derived Chl-a. In addition, *Brewin et al.* (20) developed a method to quantify the relationship, and *Hirata et al.* (23) further refined DPA to account for ambiguity of the fucoxanthin singal and then developed a new three component model (TCMH). We compared our new model with TCMH.

TCMH was used only in the open ocean (>200 m depth), due to the presence of suspended particulate matter and other coloured dissolved organic matter predominant in coastal areas, which led to overestimated Chl-avalues. Our new modelTCM-YT, on the other hand, can be effectively used in the whole SCS, including the coastal areas, because the data used to modify the model covered both coastal areas and open sea during different seasons in the SCS.

Results from different models are shown in Figure 3 and compared with/against *in situ* PSCs data. Predicted values for N_p and N_n(using TCM-YT) are close to *in situ* measurements and more accurate than values predicted by TCMH. For N_m, there is no significant difference between TCM-YT and TCMH. The statistical analysis showed that using TCM-YT and TCMH, RMSE of Pico, Nano and Microplankton were 17.6, 9.9, 9.8 and 32.3, 32.6, 7.7 %Chl-a, respectively. The mean R^2 of PSCs was 0.91 by TCM-YT compared with 0.23 by TCMH (Table 1). For identifying the phytoplankton community structure in the SCS, TCM-YT produced more accurate results/predictions compared with TCMH (Figure 3).

DISCUSSION

Model Applicability

The model presented in this study is devised to observe the major swings in phytoplankton community composition in the SCS. The model is based on *in situ* averaged data (both coastal and open sea) in the SCS. Our newly developed model can be used to identify spatial and temporal variability of PSCs in the SCS. However, at present, this model has not been tested in other marginal seas yet and further validation is needed.

Comparison with other Models

The TCMH has only been used in the open ocean (>200 m depth), due to the presence of suspended particulate matter and other coloured dissolved organic matter predominant in the coastal areas, which led to overestimated Chl-avalues. The TCM-YT, on the other hand, can be effectively used in the whole SCS, including the coastal areas, because the data used to modify and validatethe model covered both open sea and coastal areas during different seasons. According to TCMH, a poor R^2 of mean PSCs was observed due to the difficulties in retrieving the nanoplankton size class from satellite data(Table 1). However, with the modified TCM-YT, strong correlations between *in situ* and satellite data using R^2 and RMSE were obtained. According toR^2 and RMSE analysis, our new model showed higher correlations and less error(Table 1). The PSCs percentages are different when calculated withTCMH or TCM-YT for SeaWiFS composite data from June1999(Figure 4). TCMH was only applied to depths deeper than 200 m while TCM-YT is suitable and applicable to the whole SCS. Both models can be effectively and accurately used to estimate the phytoplankton size structure in the SCS. However, estimates from TCM-YT found that N_p dominated most of the SCS and N_m dominated coastal areas of the SCS which agrees well with previous studies [12, 16, 24] while TCMH found that N_n dominated most of the SCS.

CONCLUSION

A straightforward and accurate three component model (TCM-YT) has been developed to analyze the distribution of three phytoplankton size classes (micro-, nano- and picoplankton) using surface phytoplankton size classes data obtained from the SCS. With a high accuracy,this new model (TCM-YT) is suitable for both coastal waters and open sea of the SCS.

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Table 1. Statistics of the regression analysis for relationship betwee

Phytoplankton Size Class	Type of Relationship	Slope	Intercept	R^2	Number	RMSE [%Chl-a]	Model
Picoplankton	Linear	1.203	3.1918	0.80	27	17.6	TCM-YT
Nanoplankton	Linear	1.2576	-12.886	0.32	27	9.9	TCM-YT
Microplankton	Linear	0.9737	-7.0142	0.81	27	9.8	TCM-YT
Mean	Linear	1.4511	-15.025	0.91	81	19.2	TCM-YT
Picoplankton	Linear	1.4893	9.0474	0.63	27	32.3	TCMH
Nanoplankton	Linear	-0.506	39.267	0.27	27	32.6	TCMH
Microplankton	Linear	0.7407	3.316	0.81	27	7.7	TCMH
Mean	Linear	0.7728	7.573	0.23	81	26.9	TCMH

R^2: determination corelation coefficient; RMSE: Root Mean Square Error; TCM-YT: our new model. TCMH: model from *Hirata et al.*(2011)[23].

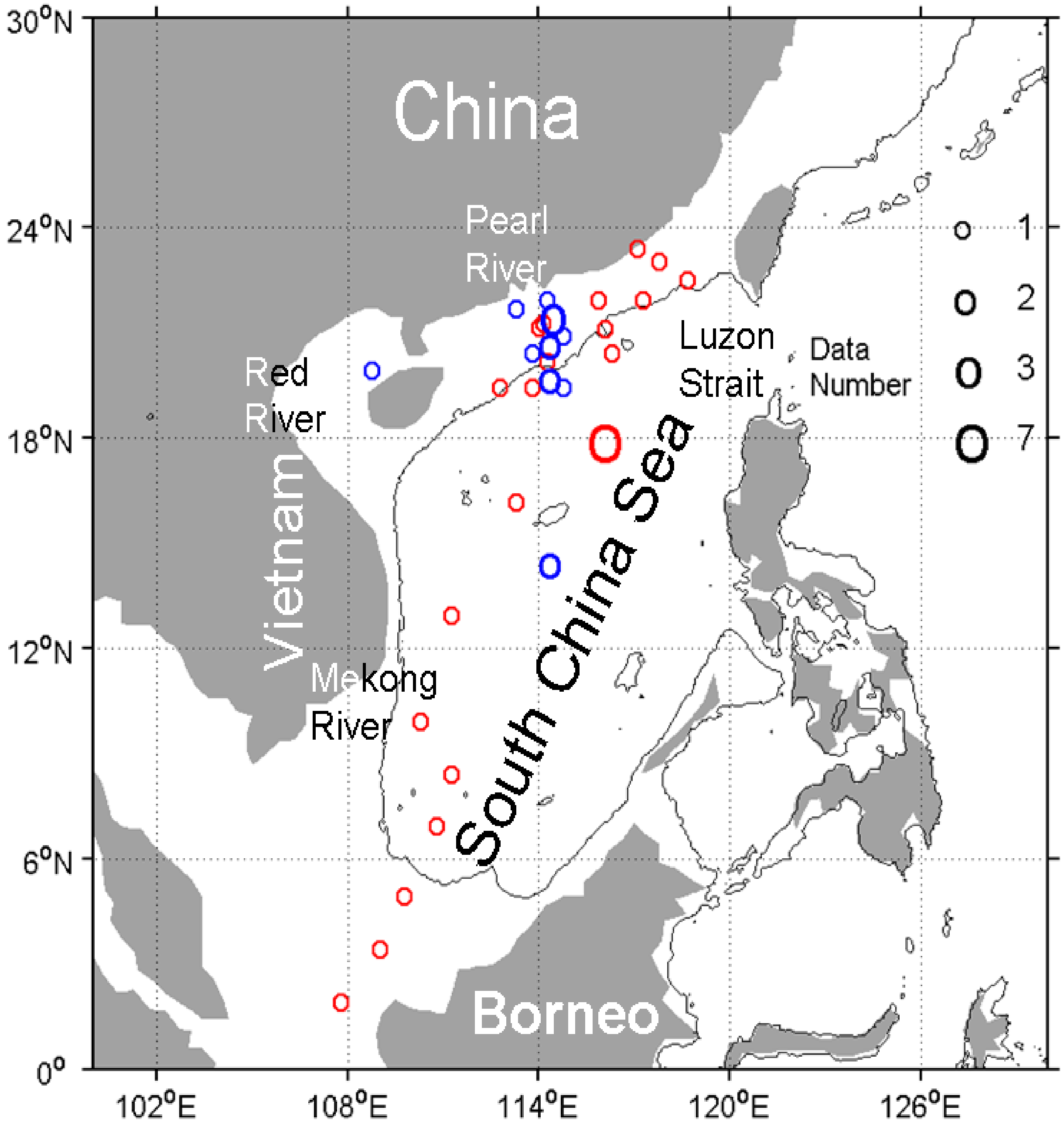

Figure 1. Location of the South China Sea (SCS).Bathymeter of 200 m is marked. The open red circles represent *in situ* single data and the open blue circles represent *in situ* average data. The size of the circle means data number.

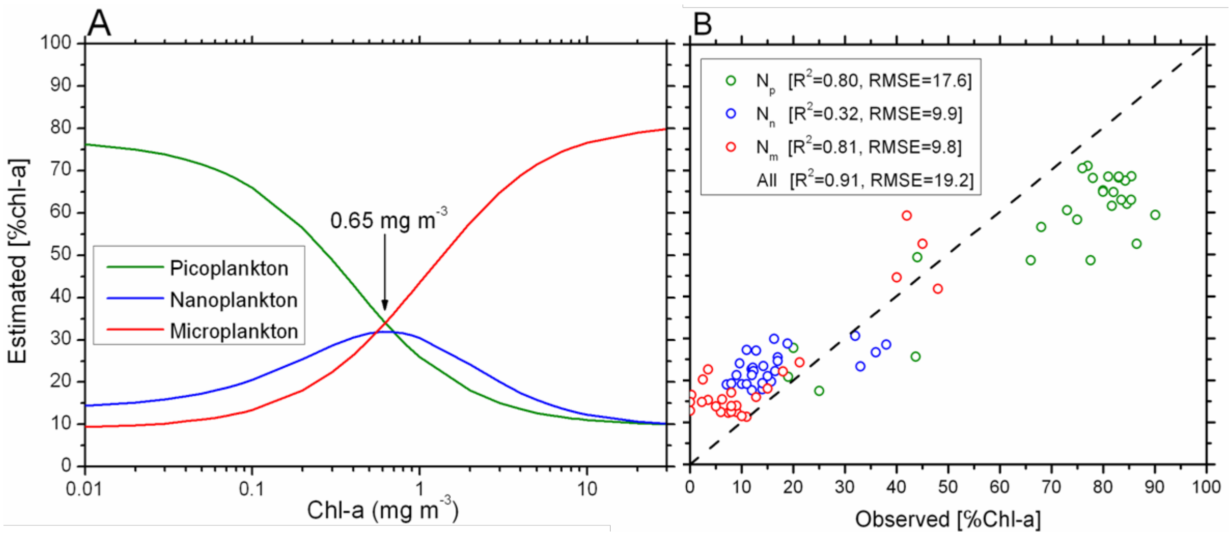

Figure 2. (a)The change in percentage of the three size classes of phytoplankton with increasing Chl-a on a log *x*-axis, 0.65 mg m^{-3} represents the maximum of Nanoplankton contribution.(b)The relationships between the measured phytoplankton size classes(PSCs) and the PSCs estimated by the TCM-YT model, using the independent satellite and *in situ* match-up data (27 measurements). R^2: the coefficient of determination; RMSE: Root Mean Square Error.

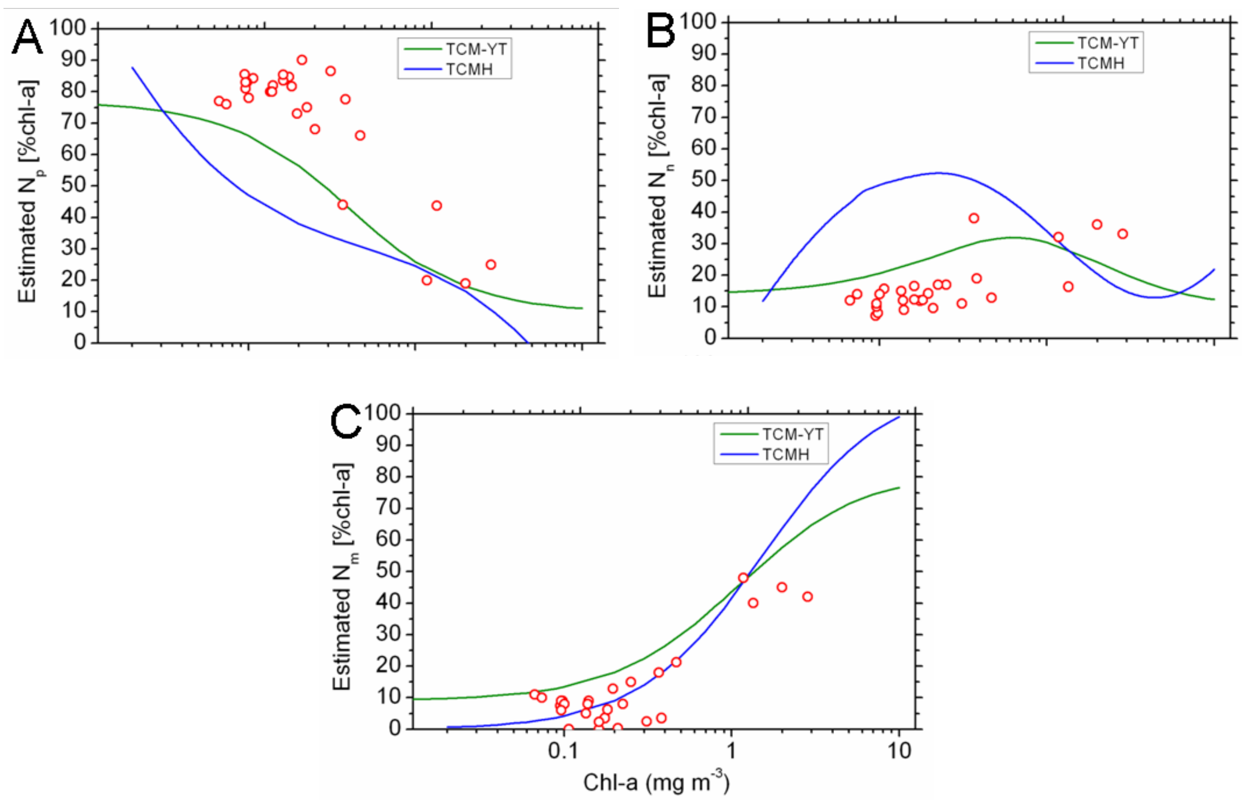

Figure 3. The three size classes of phytoplankton contributions calculated according to TCM-YT and TCMH against with *in situ* measurements. (a)N_p, (b)N_n, (c) N_m. The green lines represent TCM-YT; the blue lines represent TCMH; the red circles represent *in situ* measurements.

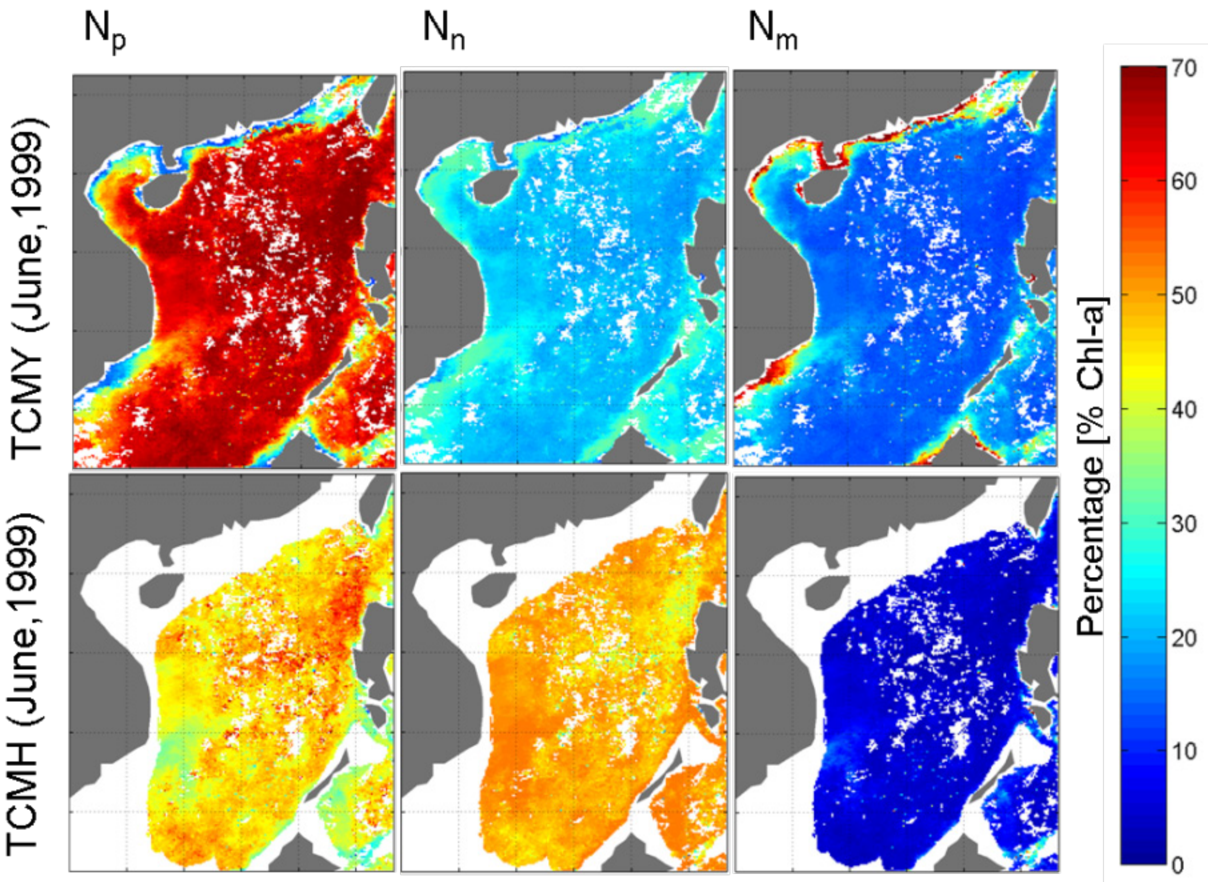

Figure 4. The comparison of PSC using different models on June1999.TCM-YT, TCMH represent our new model, model from *Hirata et al.*(2011)[23].