The relationship between satellite-derived primary production and vertical mixing and atmospheric inputs in the Yellow Sea cold water mass

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A B S T R A C T

This study examined the spatiotemporal distribution of primary production and its relationship with climatic and environmental factors in the south Yellow Sea Cold Water Mass (YSCWM) from January 1998 to December 2007. Primary production was estimated from satellite ocean color data. The annual primary production cycle was characterized by two peaks: a larger one in April (spring) and a smaller one in November (fall). The first empirical orthogonal function (EOF) mode of monthly primary production showed that two peaks occurred separately in spring and fall, and two high primary production regions appeared in the middle of the YSCWM. The first EOF mode of monthly and spring primary production revealed a high primary production value in spring 2006. Correlation and multiple linear regression analyses suggested that primary production was influenced by the mixed layer depth (MLD), upward sea water velocity, aerosol index, and precipitation. The consistency between the first EOF mode of spring primary production and the aerosol index suggested that Asian dust events are important in the interannual variation of primary production in spring, especially in 2006.

1. Introduction

Primary production in the ocean affects air–sea carbon dioxide exchange and is important in the global carbon cycle and climate change. Typically, the greatest primary production occurs on continental shelves (Walsh, 1991), which account for ≥ 20% of the total global marine primary production (Wollast, 1991), although their surface area accounts for only about 8% of the total ocean surface area.

The Yellow Sea is a marginal sea with an average depth of 44 m and an area of 380 thousand km² (Fig. 1). It is a semi-enclosed sea surrounded by the Chinese coast to the west and north and the Korean coast to the east. From spring–fall, the south Yellow Sea Cold Water Mass (YSCWM; 122°E–33.5°N; see Fig. 1), with a mean depth of 60.8 m, is located in the deep central trough. The YSCWM initiates in early spring, forming in May and developing from June–August. Then, it deteriorates in late fall and disappears in winter. It has important effects on seasonal oceanographic environment changes in surface water at the south Yellow Sea (Tian et al., 2005; Wang, 2000).

Oceanographic chlorophyll and primary productivity studies in the YSCWM and south Yellow Sea have focused on subregions over short time periods based on field measurements (Wang, 2000; Zhu et al., 1993), models (Tian et al., 2005) and remote sensing (Son et al., 2005). Tian et al. (2005) used a three-dimensional physical model to simulate the annual phytoplankton production cycle in the Yellow Sea. Son et al. (2005) estimated primary production in May and September from 1998 to 2003 in the southern Yellow Sea using the primary production algorithm of Platt and Sathyendranath (1988) and ascribed the higher primary production in May than in September to seasonal light variation. Studies have indicated that atmospheric deposition, including dust and rainfall, has important effects on primary production in the Yellow Sea (Cao et al., 1992; Liu et al., 2003; Zhang, 1994; Zou et al., 2000). However, few studies have investigated the combined effects of YSCWM mixing and atmospheric deposition on primary production in the YSCWM, especially over long periods.

In the present study, we examined the long-term monthly primary production variation in the YSCWM and the combined effects of climatic and environmental factors from January 1998 to December 2007. Our goal was to clarify the relationship between primary production changes and changes in climatic and environmental factors, including mixed layer depth (MLD), upward velocity, river inputs, precipitation and atmospheric aerosols inputs, and dust storm events.

2. Methods

2.1. Data

Primary production was estimated by the modified Vertically Generalized Production Model (VGPM, developed by Behrenfeld.
and Falkowski, 1997) proposed by Kameda and Ishizaka (2005). Friedrichs et al. (2009) compared thirty primary production models, and suggested that the modified VGPM model was one of the models tended to be less affected by the input and output data perturbation and was also generally one of the best fitting models. The modified VGPM model needs chlorophyll \(a\) concentration, sea surface temperature (SST), and photosynthetically available radiation (PAR) data as inputs. Both chlorophyll \(a\) concentration and PAR data are Level-3 Standard Mapped Image (SMI) products of the Sea-viewing Wide Field of View Sensor (SeaWiFS) and were provided by the National Aeronautics and Space Administration, Goddard Space Flight Center, Ocean Biology Processing Group (NASA GSFC OBPG). The spatial resolution of chlorophyll \(a\) concentration and PAR dataset is \(9 \times 9\) km. The SST data were obtained from the Advanced Very-High Resolution Radiometer (AVHRR) operated by NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) Jet Propulsion Laboratory (JPL). The SST data have a spatial resolution of \(\sim 4 \times 4\) km and were interpolated to \(9 \times 9\) km.

The aerosol index is an effective measure of UV-absorbing aerosol, such as dust and smoke (Herman et al., 1997). Previous studies suggested that it is difficult to estimate deposition fluxes of mineral aerosol from satellite optical depth (Mahowald et al., 2003). Many model studies indicated that modeled dust loading correlates well with Total Ozone Mapping Spectrometer (TOMS) aerosol index over Asian dust region (e.g., Uno et al., 2004). Patra et al. (2007) used TOMS aerosol index as the proxy for land-originated aerosols to ocean surface, so did we. From 2000 to 2004, aerosol index was retrieved from TOMS (resolution \(1.25^\circ \times 1^\circ\)), and from 2005 to 2007 it was from Ozone Monitoring Instrument (OMI, resolution \(1^\circ \times 1^\circ\)), as TOMS was out of service since 2006 and OMI continued similar tasks of TOMS after 1 October 2004. The spatial resolution of TOMS data were interpolated into the same resolution with OMI. The data was provided by Ozone Processing Team of NASA GSFC.

Precipitation amount (mm/day) is Global Precipitation Climatology Project (GPCP) merged precipitation data with spatial resolution of \(2.5^\circ \times 2.5^\circ\). This dataset was developed by a group at NASA GSFC by combining gauge observations with estimates derived from several satellite remote sensors (Xie et al., 2003). The monthly mixed layer depth (m), upward sea water velocity (m/s) and river water flux (m/s) were produced by the second generation fully coupled climate model of Geophysical Fluid Dynamics Laboratory (GFDL-CM2.1) (Delworth et al., 2006). The spatial resolution is \(1^\circ \times 1^\circ\) at the research area. The modeled MLD of GFDL-CM2.1 was also used by Philip and van Oldenborgh (2006). The climatological (1999–2007) monthly averaged ocean surface winds at 10 m height with \(0.25^\circ \times 0.25^\circ\) spatial resolution from microwave scatterometer QuikSCAT were also used. All the above data are from Asia-Pacific Data Research Center (APDRC) of the International Pacific Research Center (IPRC) in the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaii (http://apdrc.soest.hawaii.edu).

2.2. Empirical orthogonal function

To identify the important modes in monthly and interannual primary production variation in the YSCWM from 1998 to 2007, we performed a temporal empirical orthogonal function (EOF) analysis. This analysis is a statistical method that can extract a small number of principal components (PCs) that account for most of the variation in the original dataset. The method decomposes a space-time field into spatial patterns and associated time indices.

For the temporal EOF analysis, which included the monthly variation, we excluded the mean annual average for all months from the monthly data to obtain the monthly deviation fields. For the interannual EOF analysis, we removed the seasonal cycle signal by subtracting the corresponding climatologically monthly means for January–December from 1998 to 2007. Finally, we performed an EOF analysis on the deviation fields for the monthly variation and anomaly fields for the interannual variation. For primary production, about 9% of data were missing and were replaced by the climatological mean when EOF was executed. There were no missing data in the modeled MLD.

2.3. Cross-correlation and multiple linear regression analyses

Cross-correlation analysis was used to study the correlation between time series of two variables, allowing for potential lagged effects. For example, a time lag is likely between high aerosol particle concentrations and phytoplankton production because of the time required for deposition and nutrient release (Yuan and Zhang, 2006). Cross-correlation analysis was performed using SPSS version 13.0. Stepwise multiple linear regression (also in SPSS) was used to examine the relationship between independent variables, including the aerosol index, precipitation, river water flux, MLD, and upward sea water velocity, and the dependent variable (primary production).

At each step, the independent variable with the smallest \(F\) value was included in the regression equation if this value was < 0.05. Variables already in the regression equation were removed if their \(F\) value became too large (\(> 0.1\)). The method terminated when no more variables were eligible for inclusion or removal.

3. Results

3.1. Validation of satellite-derived primary production in the Yellow Sea

The daily and monthly average chlorophyll \(a\) concentrations and primary production from 1998 to 2007 were validated by observations from the literature. In situ chlorophyll \(a\) concentrations were obtained from Li et al. (2004), Zheng et al. (2006), Fu et al. (2009), and Gao and Li (2009), the data from Li et al. (2004) were station values, while the others were area averages. The measured primary production data was collected from Choi et al. (1995), Ning et al. (1995), Yang et al. (1999), Zheng et al. (2006), and Gao and Li (2009). The data from Zheng et al. (2006) were estimated using an empirical formula from in situ chlorophyll \(a\) concentrations, while the other data were observed using the \(^{14}C\)
middle of the YSCWM (Fig. 3a). The average maximum surface chlorophyll a concentration was weak one. Primary production in October (773 mg C m$^{-2}$) was approximately 1.5 times greater than the averages in Fig. 3b. A strong peak occurred in April and a weak one in August. The bimodal distribution is evident in the monthly primary production in April was almost twice the minimum in late summer and winter. Maximum and minimum primary production values were correlated strongly, with a correlation coefficient ($R^2=0.85$) ($R^2=0.73$), relationship $Y=1.46X^{0.64}$, and standard deviation (SD) = 0.16 (Fig. 2a). Correlations were evaluated on log–log scales due to the lognormal distribution of chlorophyll a concentration (Campbell, 1995). Compared to the observed primary production, the satellite-derived primary production estimated using the modified VGPM model was slightly overestimated for low primary production and underestimated for high values (Fig. 2b). Friedrichs et al. (2008) found that the modified VGPM model underestimated higher primary production values; however, the observations and model estimates were correlated. Large errors occurred in spring with 99% overestimation and 42% underestimation, possibly because the measured time differed from the satellite or because the spring observations varied from other literature, as different observation stations were used. However, the average error was about 25%.

3.2. Annual primary production cycle

Fig. 3 shows the spatial distribution (a) and monthly averages (b) of the climatological monthly mean primary production in the YSCWM from 1998 to 2007. Primary production exhibited seasonal variation; it was high in spring, early summer, and fall, but low in late summer and winter. Maximum and minimum primary production occurred in April (spring) and August (summer), respectively. In April, primary production in most areas ranged from 900 to 1500 mg C m$^{-2}$ d$^{-1}$ and averaged 1134 mg C m$^{-2}$ d$^{-1}$ (for 1998–2007; SD = 124 mg C m$^{-2}$ d$^{-1}$; Fig. 3b). In August, primary production in most areas was 400–1200 mg C m$^{-2}$ d$^{-1}$ and averaged 631 mg C m$^{-2}$ d$^{-1}$ (SD = 68 mg C m$^{-2}$ d$^{-1}$). The maximum primary production in April was almost twice the minimum in August. The bimodal distribution is evident in the monthly averages in Fig. 3b. A strong peak occurred in April and a weak peak in November (776 mg C m$^{-2}$ d$^{-1}$; SD = 119 mg C m$^{-2}$ d$^{-1}$); the strong peak was approximately 1.5 times greater than the weak one. Primary production in October (773 mg C m$^{-2}$ d$^{-1}$; SD = 33 mg C m$^{-2}$ d$^{-1}$) was comparable to that in November. Previous simulations have yielded similar results, including a major spring algae bloom and minor fall bloom in the southern Yellow Sea (Tian et al., 2005).

In April, two high primary production centers occurred in the middle of the YSCWM (Fig. 3a). The average maximum surface chlorophyll a concentration in April (figure not shown) in the middle of the YSCWM during 1998–2007 was about 11.6 mg m$^{-3}$, comparable to the 12.4 mg m$^{-3}$ observed in April 1996 by Wang et al. (1998) and greater than the 5.5 mg m$^{-3}$ obtained by Tian et al. (2005) from a model simulation. These authors ascribed the spring bloom in the southern Yellow Sea to appropriate temperatures, ample light, and nutrients accumulated over winter when strong winter monsoons result in the strongest annual mixing.

3.3. Dominant modes of primary production determined via EOF analysis

We conducted a temporal EOF analysis to determine the primary modes of monthly primary production variation for each year. Fig. 4 shows the first and second EOF spatial patterns and their PCs for monthly primary production from January 1998 to December 2007. The positive and negative values describe the relative phase. The spatial pattern values indicate the degree of variation relative to the mean. The PC values are the temporal evolution of the variation. High PC amplitudes indicate extreme events.

The first two temporal EOF modes of primary production explained 65% of the total variance. The first mode accounted for 55% of the total variance while the second accounted for 10%. The spatial pattern of the first EOF mode (Fig. 4a) was positive for the YSCWM. Two high value peaks appeared in the middle of the YSCWM around 35.5$^\circ$ N, 123$^\circ$ E and 35.5$^\circ$ N, 124.5$^\circ$ E, similar to the primary production spatial distribution in April (Fig. 3a). The PC of the first EOF mode (PC1, Fig. 4c) was positive in March, April, May, June, and November from 2005–2007, and negative in the other months. The PC1 had two peaks in April/May and October/November most years. The highest April peaks appeared in 2006 and 2007, indicating particularly high primary production in the middle of the YSCWM.

The spatial pattern of the second mode (Fig. 4b) was positive along the coast and negative in the middle of the YSCWM. The PC of the second EOF mode (PC2, Fig. 4d) was positive in April, May, June, September, October, and November. Like PC1, PC2 had two peaks in May/June and September/October each year. Spring primary production was the greatest in May 2006.

4. Discussion and conclusion

4.1. Annual primary production cycle

In general, the surface circulation in the YSCWM is cyclonic in winter and anticyclonic in summer due to the northeast and southwest monsoons, respectively (Naimie et al., 2001). In winter,
instability induced by the decreased SST coupled with mixing by strong northeast monsoon winds increases the MLD (Fig. 5) and brings nutrient-rich water to the surface. Although the mixed layer reaches its greatest depths of ~60 m in winter, low primary production might be due to low SST and PAR (Fig. 5). In spring and early summer, SST and light intensity increase (Fig. 5), and nutrients that accumulated throughout winter contribute to high primary production (Tian et al., 2005; Wang, 2000). In late summer, nutrients become depleted and the MLD is at its thinnest, about 15 m, inducing low primary production in August (Fig. 5). The seasonal variation in nutrients modeled by Tian et al. (2005) was consistent with the seasonal variation in primary production. They reported that in winter and early spring, the surface concentrations of nitrate (3–6 mmol N m^{-3}) and phosphate (0.3–0.5 mmol P m^{-3}) were strong because of strong vertical mixing. The nitrate (< 0.5 mmol N m^{-3}) and phosphate (0.06 mmol P m^{-3}) concentrations in summer were almost depleted owing to the spring bloom. In fall, SST and light decreased, while nutrients were supplemented in the surface layer due to mixing from stronger north winds, causing a weak primary production peak. The integration of light, temperature, and mixing effects was the main cause of the primary production in winter, spring, and fall. In summer, low nutrient concentration was the main cause of the low primary production.

**Fig. 3.** Monthly primary production averaged from 1998 to 2007 in the YSCWM for spatial distribution (a) and averages (b). Error bars show standard deviation of monthly primary production.
4.2. Factors causing monthly variation in primary production

4.2.1. Relationship between primary production and the factors

Table 1 lists the correlation coefficients between climatic and environmental factors and primary production. With no time lag, primary production had a significant positive correlation with the aerosol index and negative correlations with MLD and upward velocity. The highest positive correlation coefficient occurred with a one month lag between aerosol index and primary production. Maximum positive correlation coefficients occurred between primary production and the MLD with a lag of four months and primary production and upward velocity with a lag of three months. A one month lag between aerosol index and primary production was reasonable, as the aerosol particles require time for deposition and nutrient release (Yuan and Zhang, 2006). A three–four-month lag between the upward velocity or MLD and primary production indicated that the spring bloom was affected by nutrients that accumulated in winter by the deepest MLD and strong vertical mixing induced by winter monsoons. The fall bloom was affected by weak vertical mixing induced by summer monsoons. The significant positive correlation between precipitation and river water flux with a 9-month lag to primary production was not deemed meaningful.

The relative importance of the above five factors to primary production was further examined by a stepwise multiple linear regression method (Table 2). First, the aerosol index was entered into the regression equation with a correlation coefficient of 0.52. When MLD was added, the correlation coefficient and standard error improved by 27% (from 0.52 to 0.66) and 12% (from 147.6 to 130.4), respectively. When precipitation was added, the standard error decreased by 1.3% (from 130.4 to 128.7) and the correlation coefficient increased by 1.5% (from 0.66 to 0.67).

Cross-correlation and stepwise linear regression analyses suggest that monthly primary production variation in the YSCWM was influenced mostly by mixing (MLD and upward velocity) and atmospheric deposition, including deposition of aerosols and precipitation. Because the YSCWM is far from the Yangtze River (Wang et al., 2003), river water flux has a lesser impact. The correlation coefficient of river water flux to primary production was the smallest (Table 1).

4.2.2. Primary EOF modes of the MLD

The thermocline or MLD is important for nutrient transport from the deep layer to the surface euphotic layer (Tian et al.,
Fig. 6 shows the first two primary EOF modes for the MLD in the YSCWM. The first temporal mode of the MLD accounted for 95% of the total variance. The spatial patterns of the first EOF mode of the MLD were consistent with the first EOF mode of primary production. They were positive across the YSCWM and had a high value in the middle of the YSCWM around 124.25°E, 35°N (Fig. 6(a)). This suggests that the MLD has a positive relationship with primary production, as discussed in Section 4.2.1. The PC of the first EOF mode of the MLD (PC1 of MLD, Fig. 6c) was positive from October–March owing to strong vertical mixing induced by winter monsoons, and negative in the other months. A minimum appeared in summer as a result of strong stratification.

The second temporal mode of the MLD accounted for 2.3% of the total variance. The peak value of the first MLD EOF mode was located more to the east, while that of the second one was more to the west. This could contribute to the differing center values of primary production. The PC of the second EOF mode of the MLD (PC2 of MLD, Fig. 6d) was positive from November–February owing to strong vertical mixing. Another relatively low positive value appeared during May–August, possibly owing to weak summer monsoons (Fig. 5).
Fig. 7. Spatial pattern (a) and corresponding principle component (PC) (b) of the first EOF mode of spring (averaged for March–May) primary production (PP) anomaly in the YSCWM from 1998 to 2007. The figure b also shows spring aerosol index averaged over the YSCWM.

The MLD explained the spatial pattern of primary production well, but not the high amplitude that appeared in the spring of 2006, as discussed below.

4.3. Interannual variation in spring primary production

As discussed in Sections 3.2 and 3.3, a high primary production peak appeared in spring each year. To clarify the spatial distribution and temporal variation of primary spring production, we conducted an EOF analysis for spring primary production.

Fig. 7 shows the first EOF mode of primary production in spring (March–May), which explained 49% of the total variance. The spatial pattern (Fig. 7a) of this mode had high values in the middle of the YSCWM on the left side and low ones in surrounding regions. Fig. 7b shows the first principal component of primary production in spring each year. To clarify the spatial distribution and temporal variation of primary spring production, we conducted an EOF analysis for spring primary production.

Fig. 7a) of this mode had high values in the middle of the YSCWM on the left side and low ones in surrounding regions. Fig. 7b shows the first principal component of primary production (PC1 of PP) and its relationship with the aerosol index in spring. The PC1 of the PP curve correlated well with the aerosol index and characterized the abnormal spring troughs in 1998 and 2005 and ridges in 2000, 2001, and especially 2006. This demonstrated that atmospheric aerosol inputs, especially dust aerosol, had strong effects on the interannual variation of primary production in the YSCWM in spring. Our previous work indicated that dust frequency correlated well with the chlorophyll a concentration and primary production in the south Yellow Sea (Tan et al., 2011), consistent with the EOF results.

Acknowledgments

The authors would like to thank the National Natural Science Foundation of China (Grant no. 41005080) for funding this study. Thank Kameda Takahiko, Japan from the National Research Institute of Far Seas Fisheries, Japan, for generously helping us with the primary production calculations.

References


