

Study of monthly variations in primary production and their relationships with environmental factors in the Daya Bay based on a general additive model

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Abstract

In this study, the horizontal and vertical distribution of primary production (PP) and its monthly variations were described based on field data collected from the Daya Bay in January–December of 2016. The relationships between PP and environmental factors were analyzed using a general additive model (GAM). Significant seasonal differences were observed in the horizontal distribution of PP, while vertical distribution showed a relatively consistent unimodal pattern. The monthly average PP (calculated by carbon) ranged from 48.03 to 390.56 mg/(m²·h), with an annual average of 182.77 mg/(m²·h). The highest PP was observed in May and the lowest in November. Additionally, the overall trend in PP was spring>summer>winter>autumn, and spring PP was approximately three times that of autumn PP. GAM analysis revealed that temperature, bottom salinity, phytoplankton, and photosynthetically active radiation (PAR) had no significant relationships with PP, while longitude, depth, surface salinity, chlorophyll *a* (Chl *a*) and transparency were significantly correlated with PP. Overall, the results presented herein indicate that monsoonal changes and terrestrial and offshore water systems have crucial effects on environmental factors that are associated with PP changes.

Key words: primary production, environmental factors, general additive model, monthly variations, Daya Bay

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1 Introduction

The Daya Bay, which is located on the eastern side of the Zhujiang Estuary (Pearl River Estuary), is surrounded by the Dapeng Peninsula in Shenzhen City, the southern coast of Huiyang City, and the Pinghai Peninsula in Huidong County, Guangdong Province, China. This bay neighbors Hong Kong to the southwest and is connected to the South China Sea to the south. The system represents the largest mountain drowned valley-type semi-enclosed bay in Guangdong Province, where the Daya Bay Nuclear Power Plant and the Lingao Nuclear Power Plant are located.

Primary production (PP), which is an important carrier of the marine carbon cycle (Falkowski et al., 1998), represents the ability to produce organic matter in the sea and forms a basis for assessing the fishery production potential and maximum sustainable yield, as well as for maintaining the material supply of marine ecosystems (Chassot et al., 2010). The Daya Bay is situated at the confluence of low-salinity waters within the Zhujiang Estuary and high-salinity waters offshore in the South China Sea. Owing to the high PP and abundant sources of food, this water area has become an important site for aquaculture of many economic fish, shellfish, and crustaceans. The area is also an important germplasm bank of subtropical species in China, as well as one of

the most important fishery areas in Guangdong Province (Yu et al., 2017).

Since the Daya Bay Nuclear Power Plant started operations in 1994, environmental pollution caused by frequent intensive development and construction without consideration of the carrying capacity of ecosystems has led to marked structural changes and functional degradation of ecosystems in the Daya Bay. This is mainly reflected by the following aspects. (1) Water is developed from the oligotrophic to mesotrophic state, and there is a trend of eutrophication in some areas. The limiting nutrient factor in the Daya Bay shifted from nitrogen in the 1980s to phosphorus (Wang et al., 2004b). (2) The composition of biotic communities is significantly miniaturized, the biological diversity is reduced, and the biological resources are degraded (Liu et al., 2013; Li et al., 2015a). (3) Eutrophication and bottom trawling because of the development of aquaculture have caused changes in the sedimentary environment and overfishing, which have accelerated ecosystem degradation and thus reduced ecosystem stability in the Daya Bay (Xu, 2013; Song et al., 2012). Therefore, marine ecosystems in this region have received a great deal of attention and many studies have been conducted to investigate PP distribution (Song et al., 2004), changes in water quality (Chen et al., 2012), variations in fish catch (Peng et al., 2001), phytoplankton com-

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munity structure (Liu et al., 2006; Wang et al., 2016), zooplankton species composition (Du et al., 2013), ecosystem structure and function in this sea area (Ke et al., 2009; Mo et al., 2017). Despite extensive studies of different aspects of the ecological environment in the Daya Bay, field measurements of monthly variations of PP throughout the year in this sea area are very rare. Wu et al. (2009) used a neural network prediction model for dynamic prediction and estimation of PP in the Daya Bay. That model predicted PP variations well, but failed to explain the variations of affected variables.

The general additive model (GAM) is a mathematical analysis model that originates from the original data. The GAM has mainly been used to explore the relationship between response variables and independent variables, including linear, nonlinear, and co-existing linear and nonlinear relationships (Wood, 2004). The GAM has been widely employed in the study of catch per unit of effort (CPUE) (Dai et al., 2011; Lu et al., 2013) and its correlation with environmental factors (Li et al., 2015b; Solanki et al., 2017). In the present study, monthly variations in PP and their relationship with environmental factors in the Daya Bay were systematically analyzed by using GAM combined with field data to provide scientific evidence facilitating the sustainable development of marine fisheries and basic information for monitoring and prevention of algal blooms in the Daya Bay.

2 Materials and methods

2.1 Research dates and area

A total of 15 stations were set up in the Daya Bay (Fig. 1) for use in a survey that was conducted from January to December 2016. During the study period, there was one cruise survey in the

middle of each month and a total of 12 cruises.

2.2 Sampling and analytical methods

PP in five stations were measured by the ^{14}C tracer method (Parsons et al., 1984). Water samples were taken from six different depths. Samplings at stations with euphotic zone were at the surface and the 50%, 30%, 10%, 5% and 1% daylight level. Acid-cleaned polycarbonate bottles (two in light and one in dark for each depth) were filled with seawater filtered through 200 μm mesh. Samples were incubated *in situ* for 2–6 h after adding 105 kBq of $\text{NaH}^{14}\text{CO}_3$ tracer, and then filtered onto 0.22 μm polycarbonate filters (Millipore) respectively at 0.04 MPa vacuum pressure immediately. Filters were soaked in 1 mL 0.1 $\mu\text{mol/L}$ HCl and allowed to stand in uncapped polycarbonate 20 mL vials 15 min and stored in dark. Ten microliter cocktail (Perkin Elmer) was added after samples taken to laboratory. Total radioactivity counting on filters was performed on a Tri-Card 3110TR Liquid Scintillation Counter. PP in the other ten stations were calculated by the assimilation index method (Cadée, 1975).

Chlorophyll (Chl *a*) were sampled from the same primary production sampling layer and measured by filtering 370 mL of seawater through Whatman ($\phi 25$ mm) GF/F filters. The filters were kept frozen in the dark for 24 h before they were extracted in 90% acetone. The Chl *a* concentrations were then measured by the fluorometric method according to the formula proposed by the Specifications for Oceanographic Survey (Yentsch and Menzel, 1963) using a Turner Designs 10-AU-005-CE Fluorometer.

Physical parameters (temperature and salinity) were recorded using the HQ Series Portable Meters (HQ40d). PARs were collected data products in MODISA map released by NASA (time accuracy of daily, spatial resolution of 4 km).

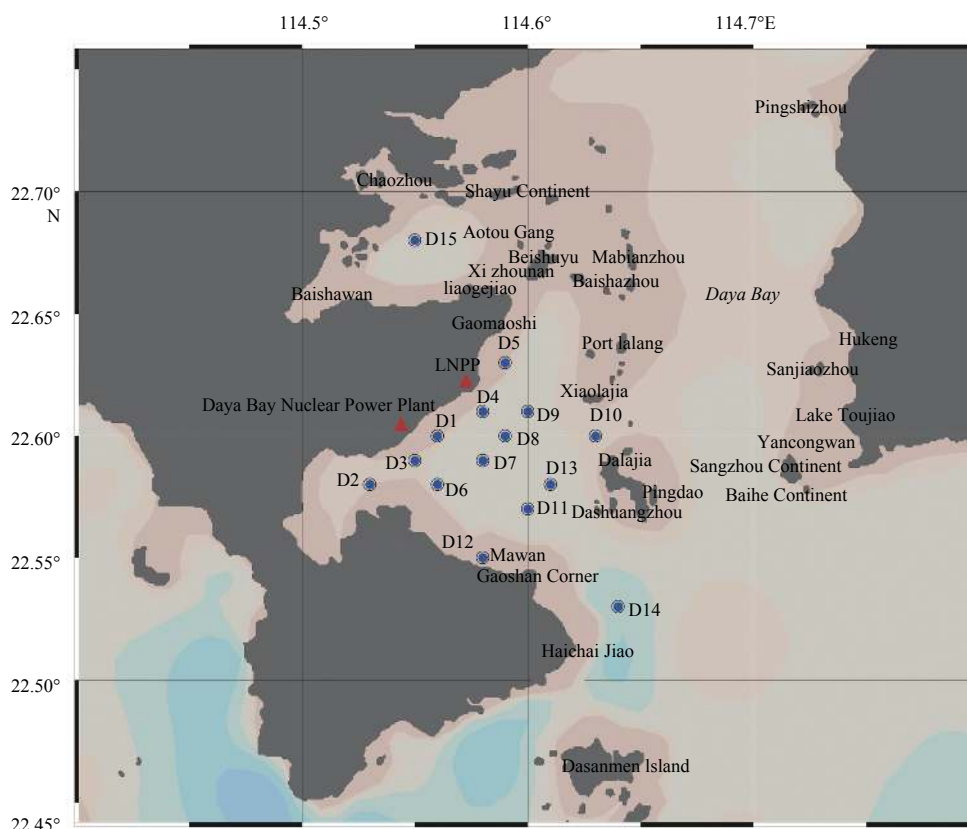


Fig. 1. Sampling stations in the Daya Bay in 2016.

The measure of transparency was calculated using the secchi disc (Tyler, 1968). For phytoplankton quantitative analysis, the settlement method described by Sukhanova (1978) was adopted. Numerical analysis was conducted using an inverted plankton microscope. Phytoplankton was identified according to the identification guides described by Tomas (1997).

2.3 Data processes

The GAM can be used to deal directly with nonlinear relationships between response variables and multiple explanatory variables. The model is generally expressed as follows:

$$g(u_i) = \beta_0 + \sum_{i=1} f_i(x_i) + \varepsilon_i,$$

where g is a known monotonic link function and $u_i = E(Y_i)$ is known explanatory variable of the i th response variable, β_0 is the parameter of model estimation, Y_i is the i th response variable, f_i is smooth, but unknown functions of any number of covariates, and ε_i is the stochastic disturbance term. Based on the significant relationships between different explanatory variables and the response variable (PP), we selected correlated variables for the GAM in this study. The initial GAM is expressed as follows:

$\ln(\text{PP}) = s(\text{longitude}) + s(\text{depth}) + s(\text{surface Chl } a) + s(\text{bottom Chl } a) + s(\text{surface temperature}) + s(\text{surface salinity}) + s(\text{bottom temperature}) + s(\text{bottom salinity}) + s(\text{surface phytoplankton abundance}) + s(\text{bottom phytoplankton abundance}) + s(\text{PAR}) + s(\text{transparency}) + s(\text{month}) + \varepsilon_i$,

where s are smoothing splines, the survey month is a categorical discrete variable and the remaining parameters are continuous variables. Statistical analyses were performed using the R package (mgcv) (Wood, 2011) and Microsoft Excel.

3 Results

3.1 Primary production

3.1.1 Horizontal distribution

The PP in the Daya Bay reached relatively high levels in the coast of the world wide, with wide variations between stations over the year; however, there was no clear trend in the horizontal distribution for each month (Fig. 2). High PP values appeared at Dapengao in January and February. The high values gradually shifted toward Dalajia in March and receded to the area between the inlet and outlet of the Daya Nuclear Power Plant in April. The high values further extended toward the harbor in May and June, with the highest being observed at the port in May. Relatively low PP values were always distributed within Aotou Port from January to June, while high values were observed from July to November. The range of variations in PP gradually decreased in December until there was an even distribution in the bay.

3.1.2 Vertical distribution

The vertical distribution of PP in the Daya Bay is shown in Fig. 3. Since the euphotic layer varied for each station, we used light depth as the ordinate to display the vertical distribution of PP for each month. Photosynthesis can be suppressed by overly-strong light and ultraviolet light; thus, the most vigorous photosynthesis in some sea areas is often not found on the surface of the ocean, whereas photosynthesis rapidly increases with increasing depth in the subsurface until reaching a maximum, after which it decreases exponentially with depth. The PP showed a monomodal vertical distribution for each month. In the present study, the

maximum PP occurred at a light depth (0.5–4 m) of 50% surface illumination in the Daya Bay, while the minimal PP was observed at a light depth of 1% surface illumination.

3.1.3 Productivity index

The productivity index represents the mass of organic carbon assimilated by per unit mass of Chl a per unit of time (Lalli and Parsons, 1997). This index is an indicator of the physiological state of phytoplankton and a good indicator for assessing the quality of marine environments. The results show that the annual average productivity index was 2.42 h^{-1} in the Daya Bay, and the spring, summer, autumn, and winter productivity index values were 1.86, 2.47, 3.10, and 2.24 h^{-1} , respectively. From the monthly perspective, the productivity index was highest in January and lowest in May. In terms of monthly variations (Fig. 4), the productivity index reached the highest value at a light depth of 50% surface illumination, which was followed by the light depth of 100% surface illumination. Conversely, the lowest productivity index appeared at a light depth of 1% surface illumination. At light depths of 100%, 50%, and 30% surface illumination, peak productivity occurred in June, while valleys appeared in March and August. However, at light depths of 10%, 5%, and 1% surface illumination, peak productivity occurred in January, while valleys appeared in May. The above results indicate that the productivity index had no large variations in this sea area, while the measured values varied between 1.09 and 4.81 h^{-1} at various stations. These values were also close to the average productivity index of phytoplankton in the Daya Bay in earlier years, suggesting that the phytoplankton were in a normal physiological and biological state in this area.

3.1.4 Monthly variations

The monthly average PP in the Daya Bay ranged from 48.03 to 390.56 $\text{mg}/(\text{m}^2 \cdot \text{h})$, with an annual average of 182.77 $\text{mg}/(\text{m}^2 \cdot \text{h})$. The monthly variation patterns of PP are shown in Fig. 5. The PP exhibited significantly different monthly variation patterns in the Daya Bay from January to December in 2016. The dynamic variation curve of PP showed a relatively low value of only 133.18 $\text{mg}/(\text{m}^2 \cdot \text{h})$ in January. Starting from this point, the overall PP continued to increase from January to March, until it decreased slightly in April. Shortly thereafter, the value increased sharply in May and peaked at 390.56 $\text{mg}/(\text{m}^2 \cdot \text{h})$ for the whole year. There was a continuous decline from June to November, when the lowest value of 48.03 $\text{mg}/(\text{m}^2 \cdot \text{h})$ occurred. The value once again increased sharply in December.

3.1.5 Seasonal variations

The seasonal averages of PP were 273.94, 224.12, 92.54, and 140.47 $\text{mg}/(\text{m}^2 \cdot \text{h})$ for spring (March–May), summer (June–August), autumn (September–November), and winter (December–February), respectively (Fig. 6). With regard to seasonal variations, the overall PP ranked spring > summer > winter > autumn, and the spring level was approximately three times the autumn level. The seasonal variations in PP were found to be generally consistent with those of the Chl a concentration. The Chl a concentration reflected the phytoplankton standing stock in water and to some extent determined the level of PP. Therefore, these results indicate that the PP occurred at a correspondingly high level in the Daya Bay for the month with high phytoplankton standing stock.

3.2 GAM analysis

3.2.1 Statistical distribution of the response variable $\ln(\text{PP})$

The results of a Kolmogorov–Smirnov test show that $\ln(\text{PP})$

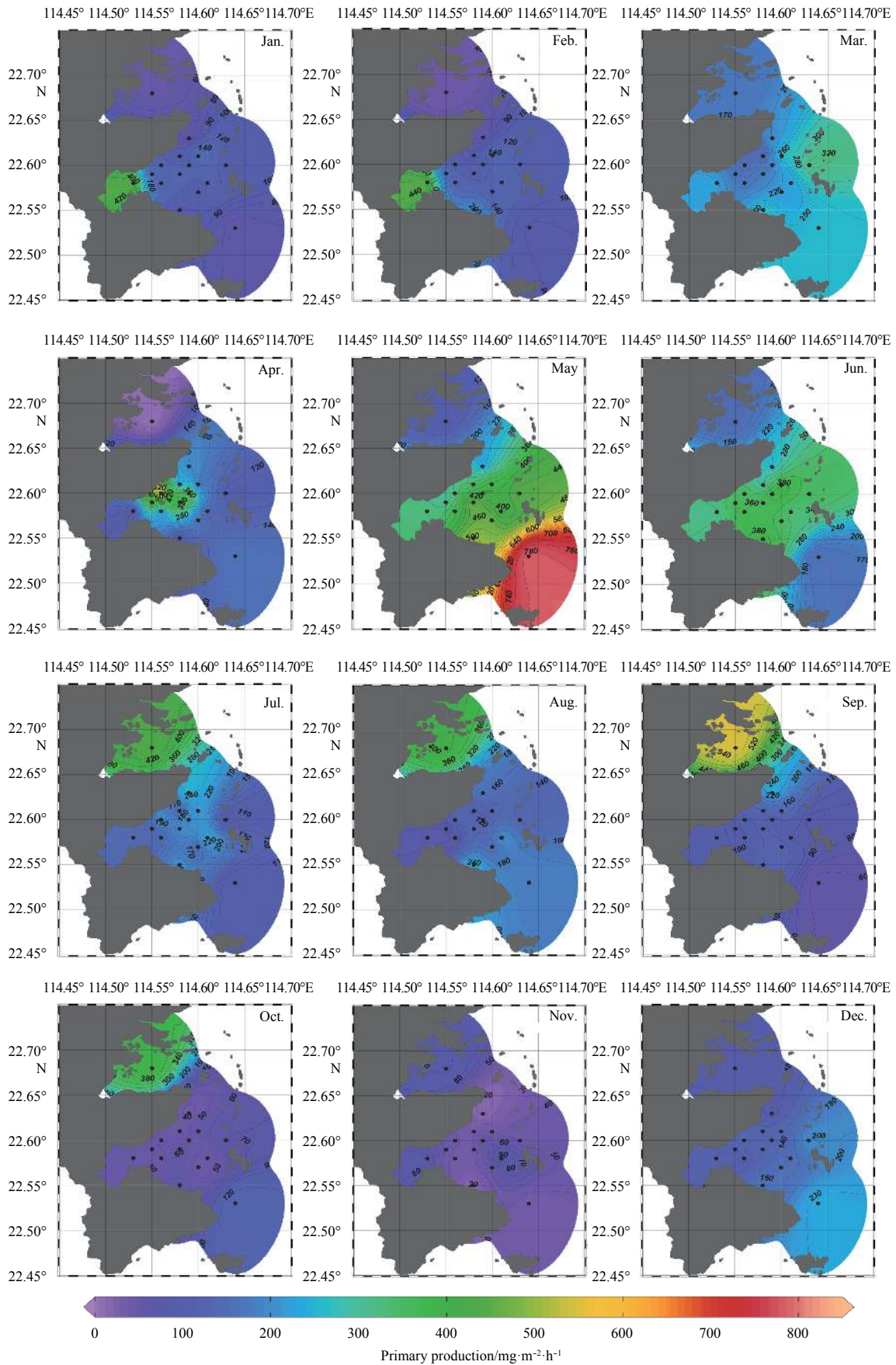


Fig. 2. Horizontal distribution of PP in the Daya Bay.

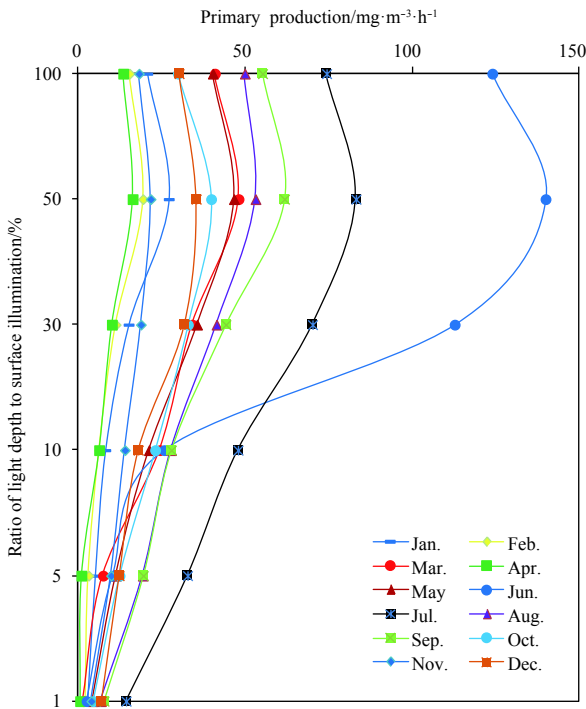


Fig. 3. Vertical distribution of PP in the Daya Bay.

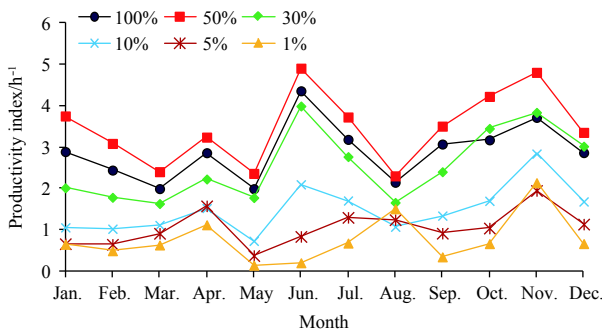


Fig. 4. Monthly variations in productivity index in the Daya Bay.

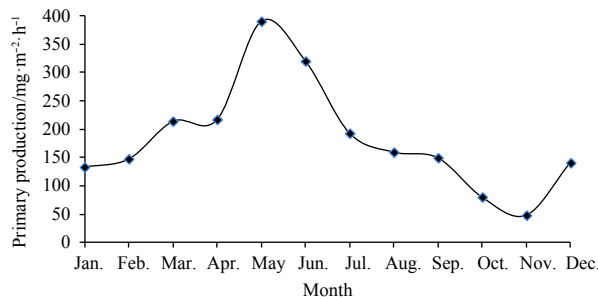


Fig. 5. Monthly variations of PP in the Daya Bay.

tended to follow a normal distribution ($\mu=4.84, \sigma=0.93$). The sample quantiles and theoretical quantiles of $\ln(PP)$ were almost normally distributed on a straight line (Fig. 7). The response basis of a normal distribution is a precondition for further explanation by GAM. Therefore, it is reasonable to describe the response variable using GAM in this study.

We performed an *F*-test on different variables of the initial

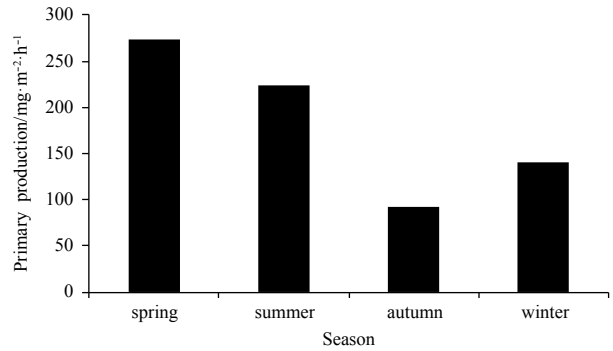


Fig. 6. Seasonal variations of PP in the Daya Bay.

GAM. Temperature, bottom salinity, phytoplankton abundance, and PAR had no significant relationship with the response variable PP ($p>0.05$). Longitude, depth, and surface salinity were significantly related to PP ($p<0.05$) (Table 1). Chl *a* and transparency were significantly related to PP ($p<0.01$). By sequentially introducing significant variables into the GAM, the model can be expressed as

$$\ln(PP)=s(\text{longitude})+s(\text{depth})+s(\text{surface Chl } a)+s(\text{bottom Chl } a)+s(\text{surface salinity})+s(\text{transparency})+s(\text{month})+\varepsilon_i.$$

The PP decreased gently as longitude increased (Fig. 8a). For surface Chl *a*, the PP increased rapidly with increasing surface Chl *a* concentration at 0–20 mg/m³, then increased in a wave pattern with increasing surface Chl *a* concentration at 20–60 mg/m³. However, PP started to decline when the Chl *a* concentration exceeded 60 mg/m³ (Fig. 8c). In contrast, PP always increased slowly with increasing bottom Chl *a* concentration in the range of 0–55 mg/m³ (Fig. 8d). In addition, PP increased slowly as surface salinity increased, and the highest level was reached when the salinity was 31. Finally, PP declined slowly when the salinity was between 31 and 34 (Fig. 8g).

PP increased with increasing water depth to relatively high levels at a depth of 12 m at most stations, below which it remained relatively stable (Fig. 8b). In addition, PP increased with increasing transparency to 7 m, but began to decline when the transparency exceeded this depth (Fig. 8l).

4 Discussion

The PP in the Daya Bay is influenced by physicochemical and biological factors. The most important physicochemical factors are light intensity and nutrients as well as hydrological conditions associated with these two factors, which directly relate to the physiological process of phytoplankton photosynthesis. The biological factors are mainly phytoplankton biomass and zooplankton feeding, which constantly change under natural conditions (Shen et al., 2010).

Variations in these biotic and abiotic factors are strongly influenced by the hydrological environment. The line chart unfolds a comparison of flow direction in the Daya Bay between summer and winter (Fig. 9). In summer, the current direction points to the inside of the Daya Bay both in the middle and bottom layers, while point to outside of the bay in the upper layer. It was demonstrated that there were completely opposite circulation structures in the upper and lower layers of the Daya Bay. The southwest wind prevailed in the South China Sea during the summer. Under its effect, an upwelling occurs on the coast of eastern Guangdong Province, and brings high-salt cold water from the subsurface of the open sea into the lower inner layer of

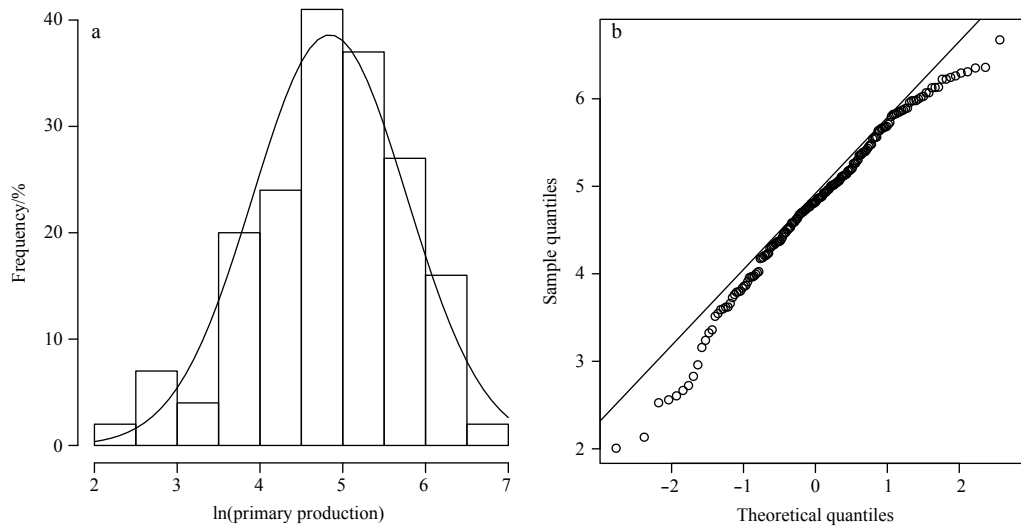


Fig. 7. In(PP) distribution in the Daya Bay and its distribution test.

Table 1. Test of the significant variables in the GAM fitted to the PP in the Daya Bay

| Variables | edf | Ref.df | F | p-value | Correlation |
|------------------------------------|-------|--------|---------|------------------------|-------------|
| s(longitude) | 1 | 1 | 4.927 | 0.028 1 | * |
| s(depth) | 3.135 | 3.870 | 2.622 | 0.035 5 | * |
| s(surface Chl <i>a</i>) | 8.556 | 8.915 | 128.076 | $<2 \times 10^{-16}$ | *** |
| s(bottom Chl <i>a</i>) | 2.813 | 3.524 | 16.708 | 3.04×10^{-10} | *** |
| s(surface temperature) | 1 | 1 | 2.398 | 1.24×10^{-1} | |
| s(bottom temperature) | 1 | 1 | 0.771 | 0.381 5 | |
| s(surface salinity) | 2.636 | 3.336 | 3.459 | 0.017 3 | * |
| s(bottom salinity) | 1.032 | 1.060 | 1.582 | 0.2220 | |
| s(surface phytoplankton abundance) | 1 | 1 | 0.153 | 0.696 2 | |
| s(bottom phytoplankton abundance) | 1.734 | 2.144 | 1.443 | 0.229 3 | |
| s(PAR) | 1 | 1 | 1.243 | 0.266 9 | |
| s(transparency) | 7.339 | 8.308 | 17.961 | $<2 \times 10^{-16}$ | *** |

Note: *** Correlation is significant at the 0.001 level (2-tailed); * correlation is significant at the 0.05 level (2-tailed).

the bay to replace the water from the upper of the bay. In winter, the upper, middle and lower seawaters in the bay all flow clockwise. Contrary to the summer, the northeast monsoon prevails in the coast of eastern Guangdong Province. Affected by this, the seawater moves toward the southwest and is blocked by the Dapeng Peninsula and Sanmen Island in the west of the bay, forming a clockwise pressure gradient, may be the main driving force for driving an anticyclonic horizontal circulation.

Obviously, in summer, seawater shows an upwelling structure, while in winter it presents a circulation structure. These two different phenomena cause a series of changes in the physical, chemical, and biological processes. Many environmental factors are affected, resulting in large differences in biomass and productivity of phytoplankton in the Daya Bay.

4.1 Influence of space effect on PP

GAM analysis showed that PP decreased slowly as longitude increased. However, as shown in Fig. 2, the distribution of PP gradually increased from coastal to offshore areas in May, June, and December. These findings indicate that PP was not only related to geographical location, but also influenced by other factors such as depth.

The Daya Bay is surrounded by mountains on three sides and greatly influenced by terrestrial climate. The depth of the Daya

Bay ranges from 5 to 26 m, with an average of 12 m. The bay is characterized by high transparency in relatively deep waters in the mouth and center of the bay, low transparency in the coastal waters and the inner waters of the bay. The tides in the Daya Bay are informal semi-diurnal tides that have weaker water exchange capacity in summer than winter (Wu et al., 2007). Overall, the Daya Bay has relatively high water exchange ability, but this differs horizontally. Relatively speaking, water is shallow, the sea floor is flat, and the flow field is regular in the Daya Bay. As distance from the coast increases, water depth becomes deeper and less affected by the terrestrial environment. Our results show that the PP reached higher levels at a depth of 12 m. In the coastal area affected by terrestrial pollution, suspended particles reduced water transparency and the photosynthetic capacity was limited, which decreased the PP. As the distance from the coast increased, the concentration of suspended particles declined and the photosynthetic capacity improved, resulting in increased of PP.

4.2 Influence of time on PP

The present study was conducted from January to December in 2016. The highest PP over the study period was 390.56 mg/(m²·h) in May, while the lowest was 48.03 mg/(m²·h) in November. The difference between these two values was more than seven times.

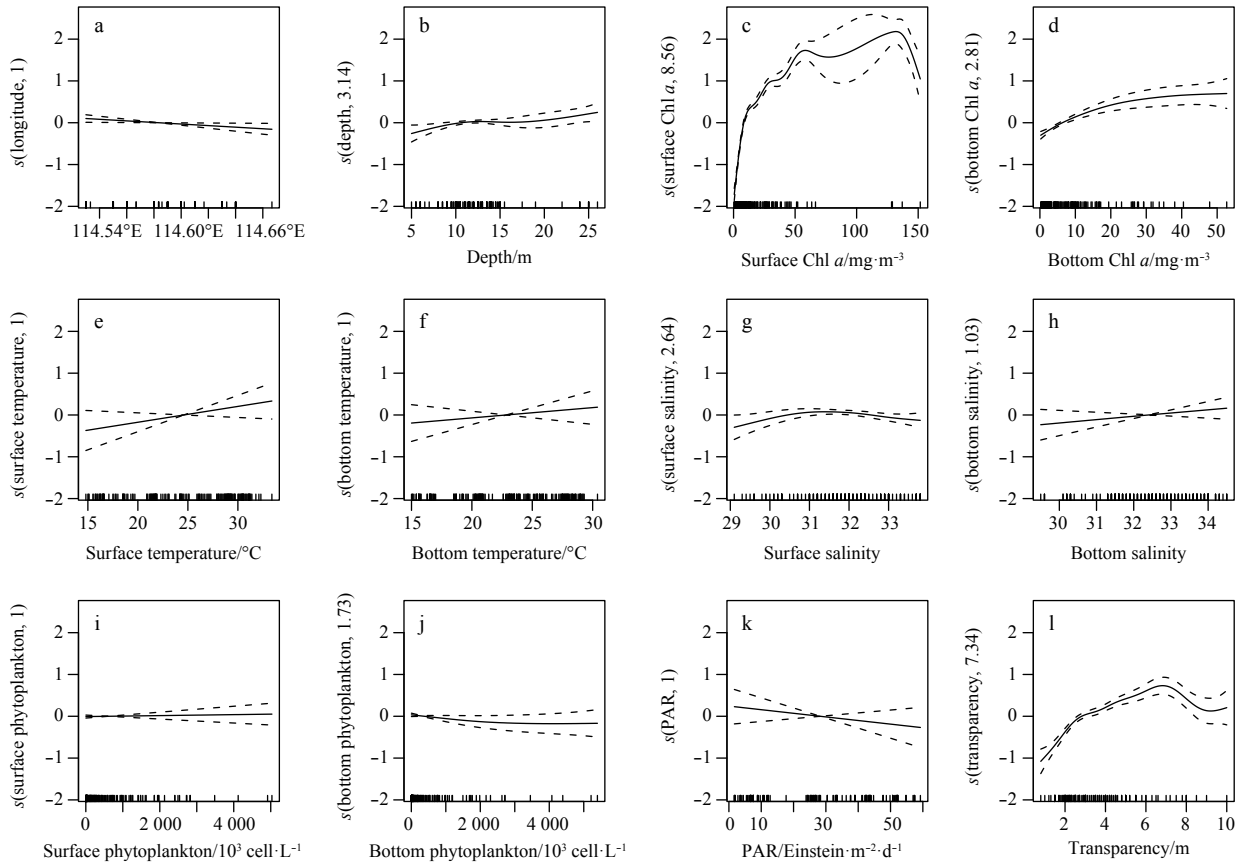


Fig. 8. Effects of environmental parameters on PP derived from GAM analysis in the Daya Bay.

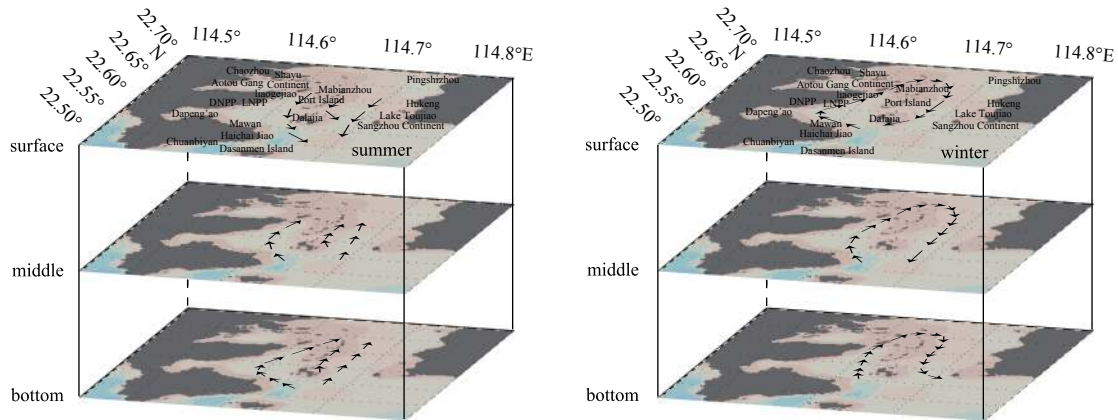


Fig. 9. Current direction between summer and winter in the Daya Bay.

On a long-term scale, seasonal changes had a significant influence on PP. During spring, water temperature generally increased because of increasing temperature and the rich nutrient salts stored in the winter provided favorable conditions for the reproduction and growth of spring phytoplankton. As a result, the PP increased substantially, reaching the highest levels in May. During summer, phytoplankton remained at relatively high levels because of the high water temperatures and good light conditions. In autumn, a large amount of nutrients was consumed after the massive production of phytoplankton, so the PP markedly decreased and remained at low levels across the bay,

with the lowest levels occurring in November. During winter, the PP was greatly increased despite the low water temperature because of a bloom of *Phaeocystis globosa*, which is resistant to low temperature.

4.3 Influence of biomass on PP

The main foundation for PP is the process of photosynthesis, in which phytoplankton transforms light energy into chemical energy through Chl *a*. Therefore, regression analysis of PP was conducted and Chl *a* was measured at the stations, which yielded the following equation: $PP = 0.1816 \times Chl\ a$ ($r=0.728$, $n=60$,

$p < 0.001$) (Fig. 10). There was a significant correlation between Chl *a* and PP in the Daya Bay at the 95% confidence intervals; therefore, this equation provides a reliable empirical formula for estimating the PP in the study area using the productivity index method (Lalli and Parsons, 1997).

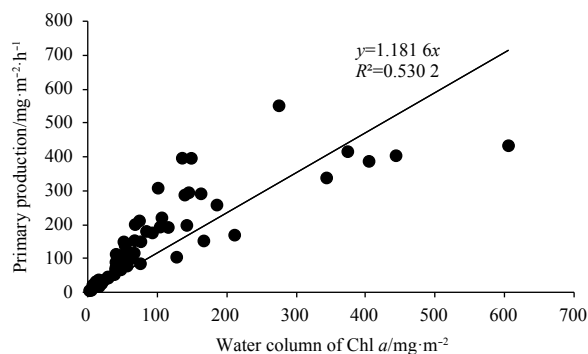


Fig. 10. Relationship between Chl *a* and PP in the Daya Bay.

4.4 Influence of phytoplankton on PP

GAM analysis showed that there was no significant correlation between PP and phytoplankton. However, the results revealed that variations in dominant phytoplankton species were related to PP to a certain degree. The major dominant species of phytoplankton showed significant seasonal succession in the Daya Bay and varied from month to month. As shown in Fig. 5 and Fig. 11, the PP and phytoplankton abundance followed completely opposite trends in February–April and June–September, whereas they showed consistent trends in other months. This may have been because of inconsistent individual sizes of phytoplankton cells. The Daya Bay underwent two unique hydrological processes; namely, the Zhujiang Estuary coastal current in February–April and wind-driven upwelling in June–September. Both of these processes led to introduction of algae with relatively large individual cell volumes, but a small cell number. For example, the dominant phytoplankton species in August were *Scrippsiella trochoidea* and *Skeletonema costatum*, which were larger than those species (*Chaetoceros constrictus* and *Pseudonitzschia delicatissima*) presenting in September, while the dominant phytoplankton species in July were *Asterionella japonica*, which were even larger than species (*Scrippsiella trochoidea* and *Skeletonema costatum*) observed in August. These contrasting trends in phytoplankton number and cell volume led to the completely opposite trends of PP and phytoplankton abundance.

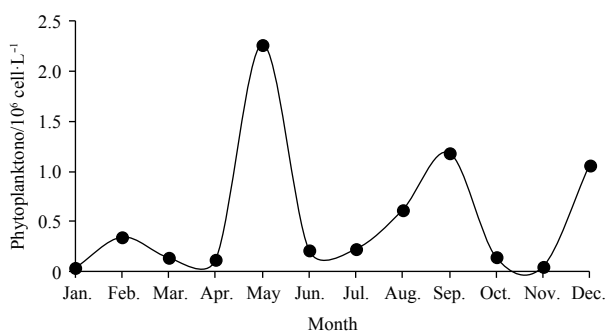


Fig. 11. Monthly variations in phytoplankton abundance in the Daya Bay.

4.5 Influence of other environmental factors on PP

4.5.1 Temperature and salinity

(1) Seasonal variation

The Daya Bay is located in a subtropical sea area. In 2016, water temperatures were relatively high (14.8–33.4°C) and suitable for phytoplankton reproduction and growth. In the present study, GAM analysis revealed that water temperature did not significantly influence PP. Temperature and salinity can reflect the hydrological features of the ocean. In April (rainy season), seawater temperature increased and surface seawater salinity dropped to 30.91. Surface flow caused by rainfall brought rich nutrients to the sea and allowed massive reproduction of phytoplankton; therefore, the PP showed a gradual upward trend. In summer, the southwest monsoon prevailed, which drove upwelling in coastal areas of eastern Guangdong Province. The extension of the upwelling in eastern Guangdong Province obviously controlled the hydrological conditions in the Daya Bay during summer and formed remarkable thermoclines and haloclines (Li, 1998), which directly influenced the ecological environment. The upwelling contributed to dominance of the eurythermal coastal species *Asterionella japonica* and the offshore eurythermal species *Scrippsiella trochoidea*, which were characterized by a small quantity and a large volume. Because of this change, bottom Chl *a* gradually decreased; therefore, PP was eventually reduced in the strengthening process by upwelling.

During autumn, the vertical stratification disappeared in mid-October, and the distribution of isohalines gradually shifted toward the winter type by mid-November. When surface offshore waters from the South China Sea invaded the coastal areas of eastern Guangdong Province, numerous oceanic warm water species were carried. Consequently, the total phytoplankton abundance generally declined when compared with that in September, and the PP gradually decreased.

During winter, the northeast monsoon began to prevail in December, which drove the occurrence of southwestward coastal currents in the coastal area of eastern Guangdong Province (Yin et al., 2006). Driven by the low-temperature and low-salinity coastal waters of eastern Guangdong Province, the eurythermal coastal species *Phaeocystis globosa* (pymnesiophyta) bloomed in offshore waters of the Daya Bay mouth and became the major dominant species during December, which to some extent improved the PP compared with that in autumn.

(2) Thermal discharge

The nuclear power plant cooling waters has a strong thermal shock effect on the surrounding marine organisms, especially for phytoplankton, the primary producers who play a key role in the marine ecosystem (Barnett, 1972).

The long-term changes in the phytoplankton community structure under the influence of nuclear power plant thermal effluent in the Daya Bay have been studied in the summer season from 1982 to 2005. The results showed that water temperature at the outfall station was increased by 6.8°C during the 23-year study period. Dinoflagellates increased to about 50% of the total phytoplankton abundance. On the contrary, the diatoms contribution decreased from 82% in 1982 to 53% in 2005 (Li et al., 2011). These results suggest that phytoplankton community has a clear trend of transformation from diatoms to dinoflagellates when temperature increases to a threshold level in the Daya Bay. The survey of relevant scholars in recent years has also confirmed this view (Tang et al., 2013). Yu et al. (2007) comprehensively analyzed the historical observation data of the Daya Bay from 1970 to 2005 and satellite remote sensing images from 1997

to 2004. The results indicated that the annual mean surface water temperature and Chl *a* contents increased by 1.1°C and 1.9 mg/m³, respectively after 1994, due to the influence of thermal discharge from the nuclear power plant.

In the current study, the phytoplankton biomass represented by Chl *a* concentration is also generally accepted as an indicator of water quality, algal bloom, and productivity (Boyer et al., 2009). There is a significant positive correlation between Chl *a* and PP of phytoplankton in the Daya Bay (Fig. 10). There are reasons to believe that thermal discharge can increase the concentration of Chl *a* within a certain extent, while it will promote PP at the same time.

4.5.2 Light

(1) Photosynthesis

As shown in Fig. 12, measurements of photosynthesis rate show that maximum production occurs in the subsurface, usually somewhere between 0.3 m and 4 m depending upon light intensity. The most vigorous photosynthesis is often not carried out at the surface in some natural sea areas. Photosynthesis is inhibited by strong light and ultraviolet end of the spectrum, which is harmful and depresses photosynthesis (Tait and Dipper, 1998).

The rate of photosynthesis increases with the enhancement of light intensity until light-saturated. In bright daylight the illumination usually light-saturated at the sea surface, whereas light-limited at the sea bottom. Therefore, although the sea bottom is rich in nutrients, photosynthesis is also very low due to light restrictions in the Daya Bay. When the bottom water diffuses through the critical depth to the subsurface layer within the euphotic zone, the maximum production occurs under sufficient light and nutrient having the most favorable effects.

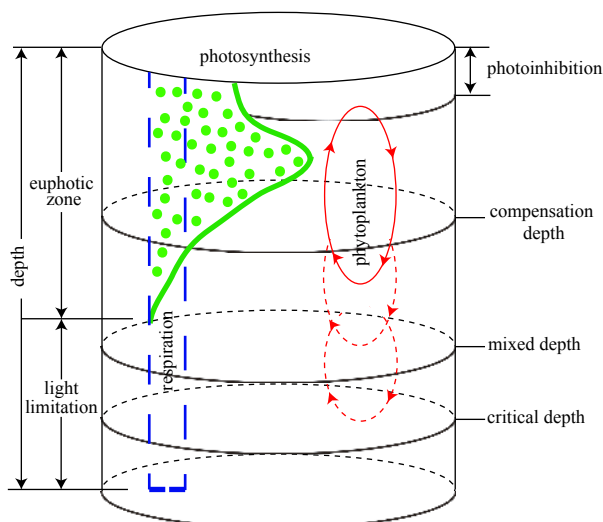


Fig. 12. An illustration of the relationships among photosynthesis rate, illumination and critical depth (Shen et al., 2010).

(2) Transparency

Transparency is a measure of the visibility of seawater that reflects the turbidity. The light energy that penetrates into seawater is a requirement for photosynthesis by phytoplankton. The depth of seawater to which sunlight can reach determines the level of the productivity layer. Therefore, the transparency of seawater is an important influencing factor for PP. The results of regression analysis showed that there was a significant positive correlation between PP and transparency.

The analysis showed that offshore water could affect transparency in the Daya Bay, and thus influence the PP. The variations of transparency in the Daya Bay were related to different water masses in different seasons and the optical properties of offshore waters outside the bay (Fig. 13). During summer, the Daya Bay was subjected to cold water intrusion because of the effects of the southwestern monsoon, and a large amount of sediment was brought into the upper layer by strong upwelling, leading to an overall decrease in the transparency of seawater (1.87 and 2.23 m in June and July, respectively). In winter, the bay was dominated by coastal waters of eastern Guangdong Province, which had higher sediment content than the waters of the South China Sea; therefore, the transparency was generally reduced. This reduction was particularly high in December, when the average transparency of the sampling stations was only 2.29 m and the value was even lower in the bay mouth area, indicating a serious influence of coastal waters. Because transparency was significantly influenced in both of the critical oceanic hydrological processes during summer and winter, these findings further indicate that PP is also controlled by offshore water systems.

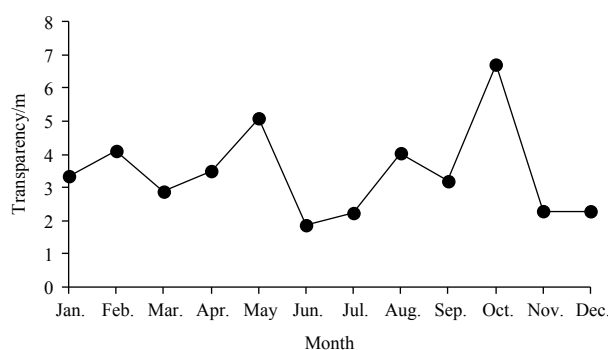


Fig. 13. Monthly variations of transparency in the Daya Bay.

4.5.3 Nutrients

Economic development and population growth coupled with mariculture pollution caused tremendous changes in the trophic structure of sea areas of the Daya Bay in the early 21st century (Wang et al., 2008). Since 2000, the dissolved inorganic nitrogen (DIN) concentration has markedly increased, while the dissolved inorganic phosphorus (P) concentration has dropped, resulting in a sharp rise in the DIN/P ratio from 4.96 in 2000 to 31.49 in 2006 (Fig. 14). Meanwhile, the growth of phytoplankton shifted slowly from DIN limitation to P limitation (Wang et al., 2004a). From 2008 to 2011, the pollution situation has clearly improved. The concentrations of DIN and P have generally shown a downward trend, and the ratio of DIN/P has remained at a relatively low figure (<9). The DIN limitation indicated that the pollution level in the Daya Bay has declined. After 2011, the concentration of DIN and P showed an overall upward trend again, and the ratio of DIN/P also slowly increased from 7.52 in 2011 to 15.6 in 2016 (Fig. 14). Because of continuous pollution by large amounts of DIN, phytoplankton showed a trend of miniaturization, and the original dominant species with large sizes were gradually replaced by smaller ones. The frequency and number of non-diatom species such as dinoflagellates, prymnesiophyta, and cyanobacteria increased significantly (Wang et al., 2009). In the present study, although the dominant phytoplankton species mainly comprised small diatoms in most months, the diversity, number, and percentage of dinoflagellates were significantly higher than in previous surveys (Wang et al., 2014). Especially in

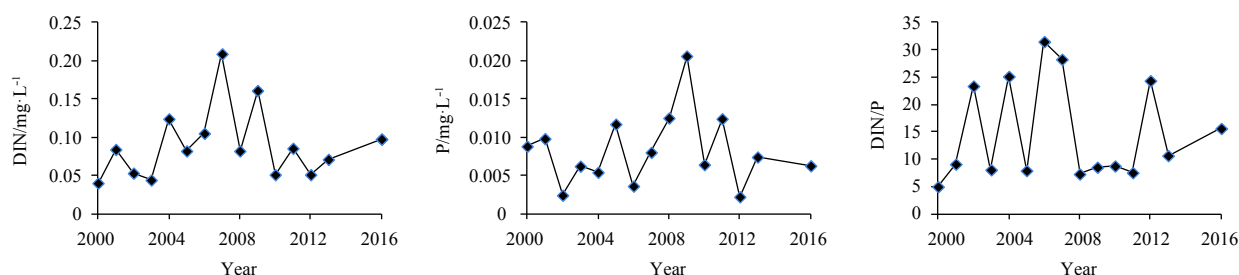


Fig. 14. Trends of nutrients from 2000 to 2016 in the Daya Bay (the majority of nutrients data are from Huan et al. (2016), the rest few are taken from the Bulletin of Shenzhen Marine Environmental Status announced by Municipality Oceanic Administration of Shenzhen).

January–April, dinoflagellates accounted for up to 72.5% of the total abundance on average, and this percentage fluctuated monthly (50.9% in January, 73.8% in February, 66.8% in March, and 98.4% in April). The PP also became significantly higher than before, indirectly suggesting the presence of nutrient pollution in the Daya Bay over recent years; accordingly, further study investigating pollution of the Daya Bay and its effects are warranted.

5 Conclusions

The PP in the Daya Bay showed significant monthly variations, with the highest levels being observed in May and the lowest in November. The overall PP ranking were spring>summer>winter>autumn.

GAM analysis showed that the temperature, bottom salinity, phytoplankton, and PAR had no significant relationships with PP, while longitude, depth, surface salinity, Chl *a* and transparency were significantly related to PP.

Our analysis showed that the environmental factors significantly related to PP were controlled by changes in the monsoonal period and different terrestrial and offshore water systems. For example, the upwelling due to South China Sea water intrusion driven by the southwest monsoon led to decreased temperature, increased salinity, and an abrupt decrease in transparency throughout the sea area. Meanwhile, the upwelling brought the eurythermal coastal species *Asterionella japonica* and the offshore eurythermal species *Scrippsiella trochoidea*, which are characterized by small numbers and large volume. Consequently, the distribution of biomass and PP showed a gradually decreasing trend, despite being present at relatively high levels. In winter, the northeast monsoon prevailed in the Daya Bay, resulting in the formation of southwestwardly low-temperature low-salinity coastal currents in the coastal area of eastern Guangdong. The waters were well mixed and had low transparency. Therefore, the growth of phytoplankton was inhibited, and the dominant phytoplankton species changed from diatoms to dinoflagellates. In January, with phytoplankton abundance dropping to the lowest point of the year and phytoplankton biomass decreasing, the corresponding concentrations of PP in January remained stable lower than those in February to September.

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References

Barnett P R O. 1972. Effects of warm water effluents from power sta-

- tions on marine life. *Proceedings of the Royal Society B: Biological Sciences*, 180(1061): 497–509, doi: [10.1098/rspb.1972.0034](https://doi.org/10.1098/rspb.1972.0034)
- Boyer J N, Kelble C R, Ortner P B, et al. 2009. Phytoplankton bloom status: chlorophyll *a* biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. *Ecological Indicators*, 9(6): S56–S67, doi: [10.1016/j.ecolind.2008.11.013](https://doi.org/10.1016/j.ecolind.2008.11.013)
- Cadée G C. 1975. Primary production off the Guyana coast. *Netherlands Journal of Sea Research*, 9(1): 128–143, doi: [10.1016/0077-7579\(75\)90027-7](https://doi.org/10.1016/0077-7579(75)90027-7)
- Chassot E, Bonhommeau S, Dulvy N K, et al. 2010. Global marine primary production constrains fisheries catches. *Ecology Letters*, 13(4): 495–505, doi: [10.1111/ele.2010.13.issue-4](https://doi.org/10.1111/ele.2010.13.issue-4)
- Chen Wenjing, Zhou Jingfeng, Li Yaochu, et al. 2012. Tendency and causes analysis of marine water quality of Daya Bay. *Environmental Science & Technology (in Chinese)*, 33(S2): 28–32
- Dai Xiaojie, Ma Chao, Tian Siqun. 2011. CPUE standardization of Chinese longline fishery for targeting bigeye tuna, *Thunnus obesus* in the Indian Ocean. *Journal of Shanghai Ocean University (in Chinese)*, 20(2): 275–283
- Du Feiyan, Wang Xuehui, Jia Xiaoping, et al. 2013. Seasonal succession of zooplankton species composition and dominant species in the Daya Bay, northern South China Sea. *Journal of Fisheries of China (in Chinese)*, 37(8): 1213–1219, doi: [10.3724/SP.J.1231.2013.38591](https://doi.org/10.3724/SP.J.1231.2013.38591)
- Huan Qingliu, Pang Rensong, Zhou Qiuling, et al. 2016. Variation trends of nitrogen and phosphorus and the relationship with HABs in Shenzhen coastal waters. *Marine Environmental Science (in Chinese)*, 35(6): 908–914
- Falkowski P G, Barber R T, Smetacek V. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science*, 281(5374): 200–206, doi: [10.1126/science.281.5374.200](https://doi.org/10.1126/science.281.5374.200)
- Ke Dongsheng, Peng Xiaojuan, Wu Lingling, et al. 2009. Survey and analysis of typical ecosystem status in Daya Bay. *Marine Environmental Science (in Chinese)*, 28(4): 421–425
- Lalli C M, Parsons T R. 1997. *Biological Oceanography: An Introduction*. 2nd ed. Oxford: Butterworth Heinemann, 1–269
- Li Li. 1998. Subtidal sea level variability in Daya Bay and its coupling with South China Sea during winter. *Journal of Oceanography in Taiwan Strait (in Chinese)*, 17(4): 383–390
- Li Tao, Liu Sheng, Huang Liangmin, et al. 2011. Diatom to dinoflagellate shift in the summer phytoplankton community in a bay impacted by nuclear power plant thermal effluent. *Marine Ecology Progress Series*, 424: 75–85, doi: [10.3354/meps08974](https://doi.org/10.3354/meps08974)
- Li Chunhou, Xu Shannan, Du Feiyan, et al. 2015a. Responses of the Daya Bay ecosystem to human activities and health assessment. *Chinese Fishery Quality and Standards (in Chinese)*, 5: 1–10
- Li Dewei, Zhang Long, Wang Yang, et al. 2015b. Study on the relationship between *Illex argentinus* CPUE and environmental factors based on GAM. *Fishery Modernization (in Chinese)*, 42(4): 56–61
- Liu Sheng, Huang Hui, Huang Liangmin, et al. 2006. Ecological response of phytoplankton to the operation of Daya Bay nuclear power station. *Marine Environmental Science (in Chinese)*,

- 25(2): 9–12
- Liu Aiping, Ren Xiuwen, Jiang Guoqiang, et al. 2013. Evaluation and analysis on aquatic ecological environmental quality in Daya Bay. *China Environmental Science (in Chinese)*, 33(S1): 66–73
- Lu Huajie, Chen Xinjun, Cao Jie, et al. 2013. CPUE standardization of *Illex argentinus* for Chinese squid-jigging fishery in southwest Atlantic Ocean. *Journal of Fisheries of China (in Chinese)*, 37(6): 951–959, doi: [10.3724/SP.J.1231.2013.37897](https://doi.org/10.3724/SP.J.1231.2013.37897)
- Mo Baolin, Qin Chuanxin, Chen Pimao, et al. 2017. Preliminary analysis of structure and function of Daya Bay ecosystem based on Ecopath model. *South China Fisheries Science (in Chinese)*, 13(2): 9–19
- Parsons T R, Maita Y, Lalli C M. 1984. *A manual of chemical and biological methods for seawater analysis*. Oxford: Pergamon Press, 184
- Peng Yunhui, Chen Haoru, Pan Mingxiang, et al. 2001. The primary production and potential fishery production in the sea area around the Daya Bay Nuclear Power Station before and after the operation of DBNPS. *Journal of Fisheries of China (in Chinese)*, 25(2): 161–165
- Shen Guoying, Huang Lingfeng, Guo Feng, et al. 2010. *Marine Ecology (in Chinese)*. 3rd ed. Beijing: Science Press, 119–136
- Solanki H U, Bhatpuria D, Chauhan P. 2017. Applications of generalized additive model (GAM) to satellite-derived variables and fishery data for prediction of fishery resources distributions in the Arabian Sea. *Geocarto International*, 32(1): 30–43, doi: [10.1080/10106049.2015.1120357](https://doi.org/10.1080/10106049.2015.1120357)
- Song Xingyu, Huang Liangmin, Zhang Jianlin, et al. 2004. Variation of phytoplankton biomass and primary production in Daya Bay during spring and summer. *Marine Pollution Bulletin*, 49(11–12): 1036–1044, doi: [10.1016/j.marpolbul.2004.07.008](https://doi.org/10.1016/j.marpolbul.2004.07.008)
- Song Xingyu, Wang Shengfu, Li Kaizhi, et al. 2012. Basic biological production and potential fishery production in Daya Bay. *Ecological Science (in Chinese)*, 31(1): 13–17
- Sukhanova Z N. 1978. Settling without inverted microscope. In: Sournia A, ed. *Phytoplankton Manual*. Paris: UNESCO, Page Brothers (Nourich) Ltd, 97
- Tait R V, Dipper F A. 1998. *Elements of Marine Ecology*. 4th ed. Oxford: Butterworth Heinemann, 179–180
- Tang Senming, Yan Yan, Chen Bin. 2013. Impacts of thermal effluent on the phytoplankton community structures nearby Dayawan Nuclear Power Station in spring and summer. *Journal of Applied Oceanography (in Chinese)*, 32(3): 373–382
- Tomas C R. 1997. *Identifying Marine Phytoplankton*. San Diego: Academic Press, 1–858
- Tyler J E. 1968. The secchi disc. *Limnology and Oceanography*, 13(1): 1–6, doi: [10.4319/lo.1968.13.1.0001](https://doi.org/10.4319/lo.1968.13.1.0001)
- Wang Zhaohui, Liang Weibiao, Shao Juan. 2016. Seasonal changes of phytoplankton community in Daya Bay, South China Sea, between 2011 and 2012. *Marine Sciences (in Chinese)*, 40(3): 53–58
- Wang Youshao, Lou Zhiping, Sun Cuici, et al. 2008. Ecological environment changes in Daya Bay, China, from 1982 to 2004. *Marine Pollution Bulletin*, 56(11): 1871–1879, doi: [10.1016/j.marpolbul.2008.07.017](https://doi.org/10.1016/j.marpolbul.2008.07.017)
- Wang Zhaohui, Qi Yuzao, Li Jingrong, et al. 2004a. Analysis and evaluation trophic status in aquaculture areas of Daya Bay. *Marine Environmental Science (in Chinese)*, 23(2): 25–28
- Wang Zhaohui, Song Shuhua, Qi Yuzao. 2014. A comparative study of phytoplankton and the phytoplankton community structure in Daya Bay, South China Sea. *Journal of Sea Research*, 85: 474–482, doi: [10.1016/j.seares.2013.08.002](https://doi.org/10.1016/j.seares.2013.08.002)
- Wang Youshao, Wang Zhaoding, Huang Liangmin. 2004b. Environment changes and trends in Daya Bay in recent 20 years. *Journal of Tropical Oceanography (in Chinese)*, 23(5): 85–95
- Wang Zhaohui, Zhao Jiangang, Zhang Yujuan, et al. 2009. Phytoplankton community structure and environmental parameters in aquaculture areas of Daya Bay, South China Sea. *Journal of Environmental Sciences*, 21(9): 1268–1275, doi: [10.1016/S1001-0742\(08\)62414-6](https://doi.org/10.1016/S1001-0742(08)62414-6)
- Wood S N. 2004. Stable and efficient multiple smoothing parameter estimation for generalized additive models. *Journal of the American Statistical Association*, 99(467): 673–686, doi: [10.1198/01621450400000980](https://doi.org/10.1198/01621450400000980)
- Wood S N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society, Series B (Statistical Methodology)*, 73(1): 3–36, doi: [10.1111/rssb.2010.73.issue-1](https://doi.org/10.1111/rssb.2010.73.issue-1)
- Wu Renhao, Cai Shuqun, Wang Shengan, et al. 2007. Three-dimensional numerical simulation of tidal current and residual current at Daya Bay. *Journal of Tropical Oceanography (in Chinese)*, 26(3): 18–23
- Wu Fengxia, Li Chunhou, Dai Ming, et al. 2009. Study on forecasting model of artificial neural networks of primary productivity in Daya Bay. *Marine Environmental Science (in Chinese)*, 28(6): 652–656
- Xu Jiaojiao. 2013. *Effect of petrochemical sewage on the adjacent marine ecological environment in Daya Bay and ecosystem health assessment (in Chinese) [dissertation]*. Shanghai: Shanghai Ocean University, 1–80
- Yentsch C S, Menzel D W. 1963. A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. *Deep Sea Research and Oceanographic Abstracts*, 10(3): 221–231, doi: [10.1016/0011-7471\(63\)90358-9](https://doi.org/10.1016/0011-7471(63)90358-9)
- Yin Jianping, Wang Youshao, Xu Jirong, et al. 2006. Seasonal Thermocline in the Daya Bay and its influence on the environmental factors of seawater. *Marine Science Bulletin (in Chinese)*, 25(4): 1–8
- Yu Jing, Hu Qiwei, Yuan Huarong, et al. 2017. Effects assessment of summer fishing moratorium in Daya Bay in the northern South China Sea. *Journal of Geoscience and Environment Protection*, 5(7): 96–108, doi: [10.4236/gep.2017.57010](https://doi.org/10.4236/gep.2017.57010)
- Yu Jing, Tang Danling, Wang Sufen, et al. 2007. Changes of water temperature and harmful algal bloom in the Daya Bay in the northern South China Sea. *Marine Science Bulletin*, 9(2): 25–33