Numerical Simulation of the Nutrient Limitation in the Yangtze River Estuary

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Abstract. A Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) type of biogeochemical model is developed to investigate the nutrient limitation in the Yangtze River Estuary. By means of a series of numerical experiments, it is found that the phosphate limitation is dominant especially in the coastal region due to the large amounts of riverine nitrogen input. It is also found that the nutrient limitation tends to shift from the P-limitation to the N-limitation toward the offshore region, since the N/P ratio has decreased drastically in this sea region. The difference in the nutrient source may be responsible for shaping such nutrient limitation in the Yangtze River Estuary, since nitrogen mainly comes from the riverine input whereas phosphate mainly comes from either the regeneration process or the intrusion of the branch of the Kuroshio current.

Keywords: Biogeochemical model, nutrient limitation, phytoplankton, Yangtze River Estuary.

1 Introduction

Nutrients, like nitrogen, phosphate and silicon, are the essential nutrition elements for phytoplankton to grow, and construct the material basis of the primary production in the marine environment. The distribution and variation of these nutritive materials not only depend on the physical process, such as the transport and mixing of the water column, but also rely on the biogeochemical process happening between nutrient, phytoplankton, zooplankton and planktobacteria[1], [2]. In recent years, the nutrient flux into the sea increased drastically due to the human activity and the global climate change, and then led to the serious eutrophication and harmful algae bloom in the coastal area. How will the primary production and the biological resources respond to the nutrient variation? What is the relationship between the nutrient variation and the harmful algae bloom? All the relevant scientific problems invite the concern of the oceanographers. Changjiang is the largest river in China, and carries large amounts of nutrients into the Yangtze River Estuary annually. Therefore, understanding the nutrient dynamics (distribution and variation) is meaningful to prevent the marine environment from the further deterioration in this sea region.

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It is generally believed that the biogeochemical variation of carbon, nitrogen and phosphorus follows the Redfield ratio (106:l6:1) in the marine environment [3]. Currently, the Redfield theory is still used to examine the nutrient limitation, which means if the atomistic N/P ratio in seawaters exceeds 16, the algae growth is thought to be limited by the insufficiency of phosphorus; Vise versa. The hydrodynamics of the Yangtze River Estuary is characterized by the strong vertical mixing [4], which may lead the sediment to suspend, thus the turbid seawater further restricts the photo-production of algae. Additionally, the Changjiang Diluted Water carries large amounts of riverine nutrients into the sea annually [5], so it was generally believed that the phytoplankton growth may be more impacted by the weak light radiation due to the suspended sediment other than by the nutrient insufficiency in this sea region. The Yangtze River Estuary and its adjacent sea were well-known for the high primary production, so the nutrient limitation is less concerned previously. However, some recent observations and experiments have revealed that the nutrient limitation exist in this sea region, which is characterized by the phosphorus limitation onshore and the nitrogen limitation offshore [6]. In order to examine the relevant ecological process, a relatively complicated NPZD biogeochemical model is developed to reproduce the annual cycle and variation of the key biogenic elements. Moreover, a series of numerical experiments are designed and conducted to investigate the feature of the nutrient limitation in this sea region.

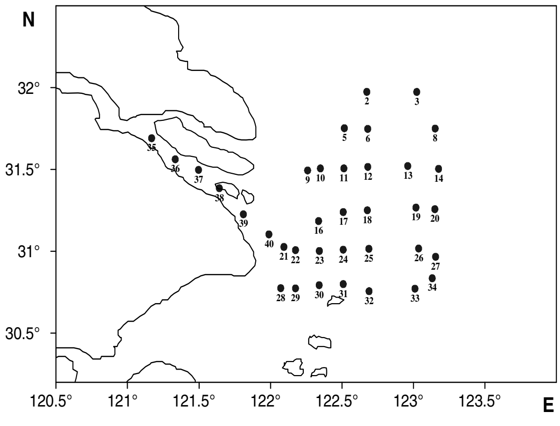

Fig. 1. Yangtze River Estuary and 40 sampling stations. It is noted that station 1, 4, 7 and 15are not shown, since the data are problematic for these stations.

2 Model Description

The biogeochemical model used in this study belongs to the NPZD type. N indicates the nutrient including nitrate, ammonium, and phosphate. P indicates phytoplankton including diatom and dinoflagellate. Z indicates zooplankton which is the forcing term of the model. D is the biological detritus coming from the phytoplankton or zooplankton. The detailed relationships between seven biogenic elements are given in Fig.2

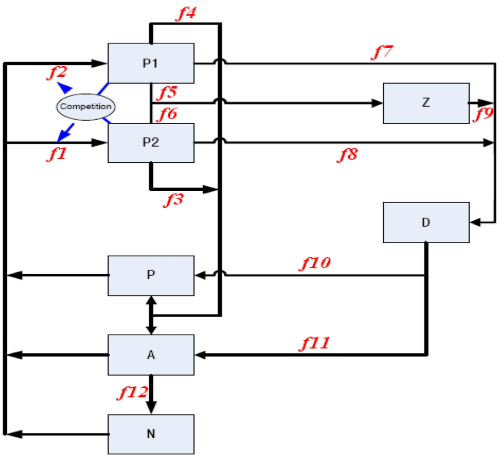

Fig. 2. Scheme of the biogeochemical model. The biogenic elements include three nutrients-nitrate (*N*), ammonium (*A*) and phosphate (*P*); two algae- diatom (P_1) and dinoflagellate (P_2); zooplankton (*Z*) and detritus (*D*). *f1* to *f12* represent the biogeochemical processes.

The biogeochemical processes can be formulated as follows.

$$\begin{cases} \dfrac{dP_1}{dt} = f_1 - f_3 - f_5 - f_7 - Exud \\ \dfrac{dP_2}{dt} = f_2 - f_4 - f_6 - f_8 \\ \dfrac{dZ}{dt} = Ass_{P_1\_Z} f_5 + Ass_{P_2\_Z} f_6 - f_9 - f_{10} \\ \dfrac{dD}{dt} = f_7 + f_8 + f_9 - f_{11} \\ \dfrac{dA}{dt} = (f_3 + f_4 + f_{10} + f_{11}) - k_1(f_1 + f_2) - f_{12} + IN_A \\ \dfrac{dN}{dt} = f_{12} - k_2(f_1 + f_2) + IN_N \\ \dfrac{dP}{dt} = [P:N](f_3 + f_4 + f_{10} + f_{11} - f_1 - f_2] + IN_P \end{cases} \quad \textbf{(1)}$$

In the above equation, f_1 and f_2 represent the growing process of diatom and dinoflagellate, respectively, which are influenced by theseawater temperature (T), the light radiation (I), the concentration of the suspended sediment and the nutrient.

$$\begin{cases} f_1 = r_{\max\_P_1} r_T r_I \min((r_{Nitrate} + r_{Ammonium}), r_{Phosphorus}) r_{sus} P_1 \\ f_2 = r_{\max\_P_2} r_T r_I \min((r_{Nitrate} + r_{Ammonium}), r_{Phosphorus}) r_{sus} P_2 \end{cases} . \quad \textbf{(2)}$$

F_3 and f_4 represent the respiration process of diatom and dinoflagellate, respectively, which are taken as the exponential function of the seawater temperature based on the laboratory experiment [7].

$$\begin{cases} f_3 = r_r \exp(k_r T) P_1 \\ f_4 = r_r \exp(k_r T) P_2 \end{cases}. \quad \textbf{(3)}$$

F_5 and f_6 represent the grazing process of zooplankton on diatom and dinoflagellate, respectively, and the so-called M-M formulation [8] is adopted.

$$\begin{cases} f_5 = g_{m\_P_1} \dfrac{P_1}{P_1 + K_{P_1}} Z \\ f_6 = g_{m\_P_2} \dfrac{P_2}{P_2 + K_{P_2}} Z \end{cases}. \quad \textbf{(4)}$$

F_7 and f_8 represent the mortality process of diatom and dinoflagellate, respectively, and are formulated as follows.

$$\begin{cases} f_7 = r_m P_1 \\ f_8 = r_m P_2 \end{cases}. \quad \textbf{(5)}$$

F_9 and f_{10} represent the zooplankton excretion and mortality processes, respectively, and are formulated as follows.

$$\begin{cases} f_9 = r_{r\_Z} Z \\ f_{10} = r_{m\_Z} Z^2 \end{cases}. \quad \textbf{(6)}$$

F_{11} and f_{12} represent the remineralization and the nitrification processes, respectively, which can be expressed in the following form.

$$\begin{cases} f_{11} = r_{mine\_A}\left(1 + \beta_{mine\_A} \dfrac{T^2}{T^2_{mine\_A} + T^2}\right) D \\ f_{12} = r_{A\_N} \exp(\beta_{A\_N} T) A \end{cases}. \quad \textbf{(7)}$$

Besides the biogeochemical processes, the term IN_A, IN_N and IN_P in Equation 1 indicate the nutrient sources, which reflect the influx of ammonium, nitrate and phosphate into the sea. The term *Exud* indicates the sinking process of diatom, meaning the material ouflow from the marine ecosystem. In order to guarantee the mass conservation for the ecosystem, it must have

$$\frac{dP_1}{dt} + \frac{dP_2}{dt} + \frac{dP}{dt} + \frac{dZ}{dt} + \frac{dD}{dt} + \frac{dA}{dt} + \frac{dN}{dt} = IN_P + IN_N + IN_A - Exud \cdot \quad \textbf{(8)}$$

The biological parameters appearing in the above equations are listed and illustrated in Table 1.The parameter value is crucial for the model results, so its choice is an important and difficult task. Unfortunately, the parameter measured or observed directly in this sea region is very scarce, so we have to use publications as reference. It should be stressed that as a process-oriented research, the annual variation of the biogeochemical processes is the major concern of this study, which means that the chosen parameters are not calibrated to match the observations purposely.

Table 1. Biological parameters

Parameter	Explanation	Value
$r_{\max\_P_1}$	The maximum growth rate of diatom	1 d^{-1}
$r_{\max\_P_2}$	The maximum growth rate of dinoflagellate	0.6 d^{-1}
r_I	Light influence on algae growth	By equation
r_T	Temperature influence on algae growth	By equation
r_{sus}	Concentration of SS on algae growth	By equation
r_r	Respiration rate of aigae	0.138 d^{-1}
$g_{m\_P_1}$	Grazing rate of zooplankton on diatom	0.05 d^{-1}
$g_{m\_P_2}$	Grazing rate of zooplankton on dinoflagellate	0.1 d^{-1}
r_m	Mortality rate of algae	0.05 d^{-1}
r_{r_Z}	Excretion rate of zooplankton	0.03 d^{-1}
r_{m_Z}	Mortality rate of zooplankton	0,01 d^{-1}
$r_{\min e\_A}$	Remineralization rate of detritus to ammonium	0.003 d^{-1}
r_{A_N}	Nitrification rate of ammonium to nitrate	0.001 d^{-1}
$Ass_{P_1\_Z}$	Assimilation rate of zooplankton grazing on diatom	0.5
$Ass_{P_2\_Z}$	Assimilation rate of zooplankton grazing on dinoflagellate	0.5
K_{P_1}	Half saturation constant of zooplankton grazing on diatom	0.068 mmol/m^3
K_{P_1}	Half saturation constant of zooplankton grazing on dinoflagellate	0.068 mmol/m^3
k_1	Uptake rate of ammonium by algae	2.0
k_2	Uptake rate of nitrate by algae	1.0
T_{mine_A}	Temperature constant of remineralization	13
β_{mine_A}	Temperature coefficient of remineralization	20
β_{A_N}	Temperature coefficient of nitrification	0.11

3 Simulation and Analysis

In order to compare and analyze the model results easily, the units of the biogenic elements are unified as mmol N/m^3 except phosphate whose unit is mmol P/m^3. The initial conditions of the biogenic elements are based on observations in winter. By averaging the data over 36 stations, the individual value of nitrate, ammonium, phosphate, diatom, dinoflagellate, zooplankton and detritus is 6.58, 2.63, 0.68, 0.02, 0.15, 0.01 and 0.01 mmol/m^3 [9]. Considering the impact of the suspended sediment on the algae photoproduction, the measured concentration of SS (3.5 g/m^3) is also adopted in the model run. As the standard model run, the external nutrient sources are not taken into account tentatively just to reproduce the annual cycle of the biogenic elements.

The model is run for 1200 days, and the simulation of the first year is neglected due to the model stabilization, and the results of the second and the third years are compared for analysis.

3.1 Annual Variation of the Nutrients, Phytoplankton and Zooplankton

Figure 3 shows the annual cycle of the nutrients, phytoplankton and zooplankton simulated by the standard model run. It is found that the highest level of nitrate appears in spring just before the onset of the algae bloom, whereas the highest level of ammonium appears in autumn just after the algae boom. It is generally believed that ammonium is preferentially consumed by algae compared to nitrate. Additionally, ammonium is also transferred to nitrate through the nitrification process, so the ammonium content always declines first compared to that of nitrate in the annual cycle. On the other hand, as soon as the algae bloom happens, the ammonium content begins to resume firstly due to the regeneration process. It is why the ammonium content returns to the highest level just after the algae bloom. Nitrate is generally called the new-nutrient, meaning that it is mainly made up from the external source, so its level declines to the lowest just after the algae bloom. Compared to the nitrogen, the phosphate variation is not marked. Just like ammonium, phosphate can also be regenerated in the marine environment; moreover, the rate of regeneration is quicker than that of ammonium [10]. On the other hand, algae consume phosphate generally according the Redfield ratio, which means that the consumed phosphate is about 1/16 of that nitrogen. The less consumption and the quick makeup lead to the small fluctuation in the annual cycle.

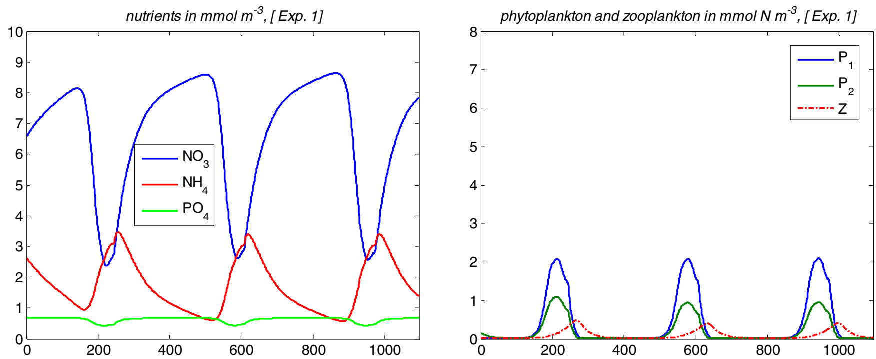

Fig. 3. The time series of nutrients (left plot) and planktons (right plot) based on a standard run

Figure 3 also shows the annual variation of planktons. It is found that the algae biomass reach the highest level after the spring bloom, since the nutrients, light radiation and seawater temperature are conducive to the phytoplankton growth. Thereafter, the algae biomass begins to decrease drastically for two reasons, namely the nutrient depletion and the grazing pressure from zooplankton. From Figure3 it is also found that the summit of the zooplankton biomass lags behind that of algae. In winter, the low seawater temperature limits the algae activity though the nutrient content is sufficient, and it is why both the phytoplankton and zooplankton biomass decrease to the lowest level in the annual cycle.

3.2 Influence of the Suspended Sediment on the Nutrient-Phytoplankton Dynamics

Just as specified previously, the concentration of the suspended sediment is set as 3.5 g/m^3 in the standard model run. In this section, the clear seawater without the suspended sediment is presumed to examine the influence of the suspended sediment on the nutrient-phytoplankton dynamics. The model results are shown in Figure4. Compared to the standard case, the phytoplankton biomass (no matter diatom or dinoflagellate) increases drastically, and meanwhile the nutrient consumption is also considerable. During the course of the algae bloom, the nutrient content may decline to 0 if the seawater is clear, which generally happens in the open ocean. In the coastal waters, the marine ecosystem is generally characterized by the high nutrient level and the low algae biomass, since the suspended sediment has effectively limited the algae photoproduction by weakening the light radiation.

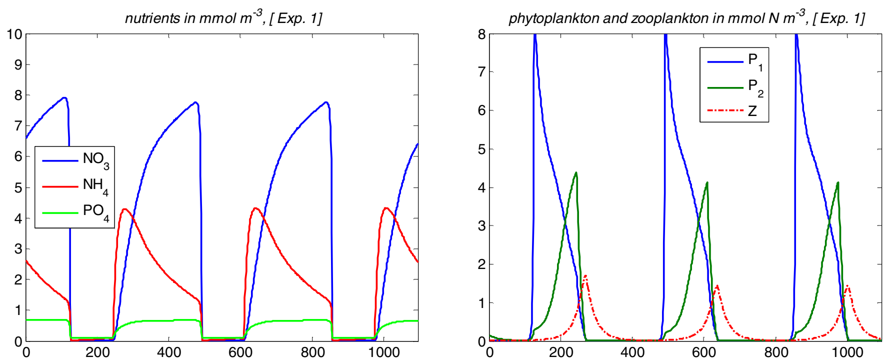

Fig. 4. The simulated time series of nutrients (left plot) and plankton (right plot) as the suspended sediment concentration is set to be 0

3.3 Numerical Experiments on the Nutrient Limitation

The nutrient enrichment experiment was generally used to examine the nutrient limitation in the genuine marine environment. However, the in situ nutrient enrichments may bring about the secondary pollution. In this study, the numerical nutrient enrichment experiment is designed and the model results are analyzed. In order to determine which nutrient may limit the algae growth, only one nutrient is added to the model as the external nutrient source in each model run. Table 2 lists the added nutrient concentration in each experiment: (1) without any nutrient addition (standard model run); (2) only ammonium added; (3) only nitrate added; (4) only phosphate added.

Table 2. Numerical experiments of the nutrient enrichment (mmol/m^3)

Experiment	Nitrate	Ammonium	Phosphate
1	0	0	0
2	0	0.001	0
3	0.001	0	0
4	0	0	0.001

Figure 5 shows the annual variation of the nutrients simulated by different numerical experiments.

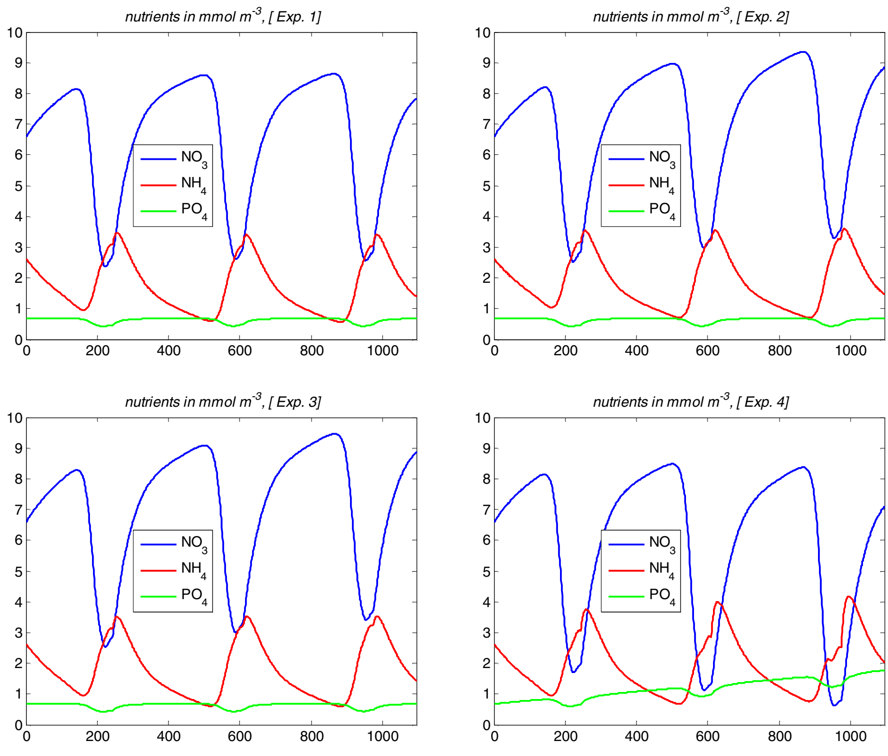

Fig. 5. The time series of the nutrients obtained from Exp.1 to Exp.4

Compared to the standard case which is characterized by the mass conservation, every enriched nutrient can enhance its content ultimately in the annual cycle. The exception is the ammonium enrichment, which can not only improve its own content, but also enhance the nitrate content due to the nitrification process. In addition, the phosphate enrichment can enhance the ammonium content and reduce the nitrate content simultaneously. It is an interesting phenomenon. Both ammonium and phosphate can regenerate from planktons, implying that the more plankton biomass create more phosphate and ammonium.

Figure 6 shows the annual variation of planktons simulated by different numerical experiments. It can be also found that the phosphate enrichment enhance the phytoplankton biomass markedly, and the ammonium and nitrate enrichments do not embody such an influence, implying that the phosphate limitation may be dominant in the standard case run, which agrees with the recent observations [5], [6].

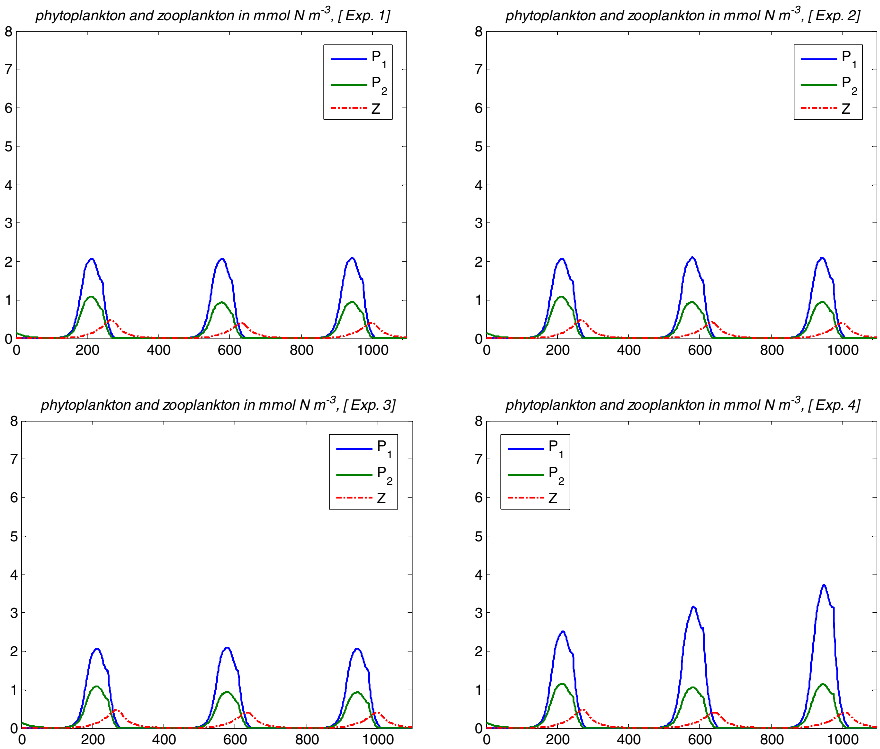

Fig. 6. The time series of phytoplankton and zooplankton obtained from Exp.1 to Exp.4

4 Discussion and Conclusion

In this study, a NPZD biogeochemical model is developed to simulate the annual variation of the key biogenic elements in the Yangtze River Estuary. The nutrient limitation is further investigated by a series of numerical nutrient enrichment experiment, and it is found that the phosphate limitation may be dominant in this sea region.

Given that the high level of N/P ratio is mainly induced by the riverine nutrients, the phosphate limitation concentrates in the coastal waters, especially in the region of the fresh water influence (RFWI). The recent investigation and simulation reveal that the phosphate content carried by the branch of Kuroshio Current into this region is much higher than the riverine phosphate carried by the Changjiang Diluted Water [11], so the nitrogen limitation may appear in the offshore region.

Admittedly, the model used in this study only belongs to the box type, in which the physical process is not considered tentatively. The further study is to develop a coupled bio-physical model to reproduce the biochemical process in the genuine physical background.

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