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Nitrogen cycling in Manila Bay during dry and rainy seasons

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Abstract—The nitrogen cycling was calculated in Manila Bay during dry and rainy seasons. The primary production in rainy season is higher than that in dry season. The main source of DIN (Dissolved Inorganic Nitrogen) is decomposition in dry season and the advective and diffusive flux from the lower layer in rainy season. River discharge and primary production are small in dry season, and the estuarine circulation is weak. The nitrogen cycling is closed in the upper layer in dry season. On the other hand, river discharge and primary production in rainy season are large. Therefore DIN is assimilated by phytoplankton, and phytoplankton is grazed by zooplankton and/or is moralized, and sank to the lower layer. DIN is regenerated in the lower layer, and is transported to the upper layer due to the strong estuarine circulation. Nitrogen cycling is closed in the upper and lower layers in rainy season. The residence time of TN (Total Nitrogen) in the upper layer in dry season is longer than that in rainy season. Nitrogen is used slowly and many times due to small nitrogen supply and weak estuarine circulation in dry season. But nitrogen is sufficiently supplied, is used quickly by primary production and is also quickly flowed out by strong estuarine circulation in rainy season.

Key words: Manila Bay, Numerical ecosystem model, Nitrogen cycling, Rainy season, Dry season

Introduction

Recently, water quality of Manila Bay has been deteriorated and red tides frequently occur. Rhodora et al. (2004) analyzed the correlations between the cyst density of red tide organism and benthic fluxes of nitrogen (N) and phosphorus (P), and claimed that negative correlations were observed between cyst density and benthic fluxes. However, the generation mechanism of red tides in Manila Bay has not been clarified yet. First of all, we have to reveal the characteristics of the N and P cycling in order to clarify the generation mechanism of red tide. Jacinto et al. (1998) calculated N and P budgets of Manila Bay using LOICZS biogeochemical budgeting procedure. However their budgets were the annual averaged ones, although the seasonal variations of N and P budgets are expected to be very large.

In this paper we calculated N cycling in Manila Bay in dry and rainy seasons by using the numerical ecosystem model, and clarified the difference of N cycling in both seasons.

Calculation by a Numerical Ecosystem Model

Study area

Figure 1 shows the study area of Manila Bay. Observation of water temperature, salinity, chl.*a*, nutrients and so on were carried out at twelve stations shown in Fig. 1 in March and November 1999. Seasonal variations of solar radiation and river discharge in Manila Bay are shown in Fig. 2 (a) and Fig. 2 (b), respectively. March is high solar radiation and low river discharge, that is, the dry season. November is low solar radiation and middle river discharge, namely the end of rainy season. The mixed layer depth in dry season is 10 m from the result of observation on the vertical distribution of density. Therefore we assumed the box which has the 10 m depth and the boundary along 14.5N as shown in Fig. 1. Limiting nutrient of primary production in Manila Bay is nitrogen, because N/P molar ratio from the observation is under 16 throughout the year. Therefore, nitrogen cycling in the box is calculated by using a numerical ecosystem model in March and November 1999.

Numerical Ecosystem Model

The numerical ecosystem model has five compartments, DIN (Dissolved Inorganic Nitrogen), phytoplankton (PHY),

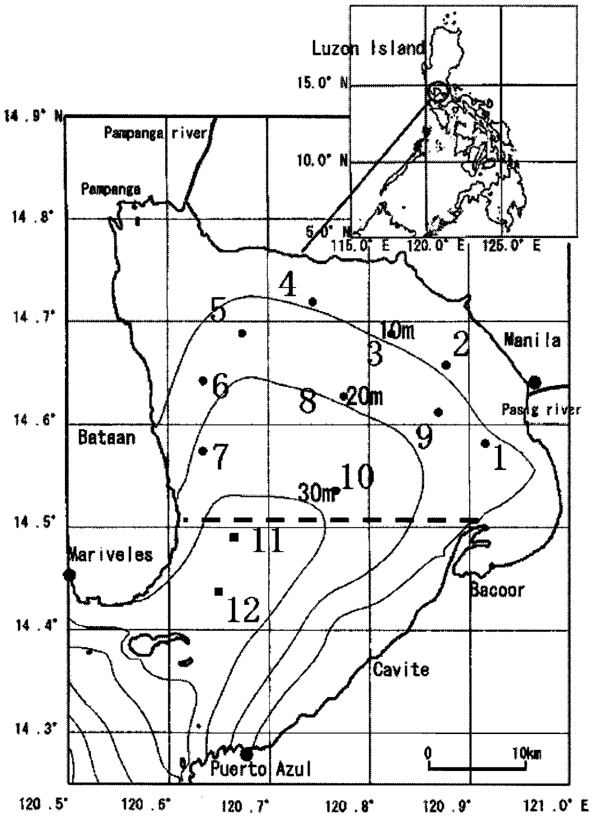


Fig. 1. Study area and the observation stations in Manila Bay. The broken line shows the boundary between the box and the adjacent area.

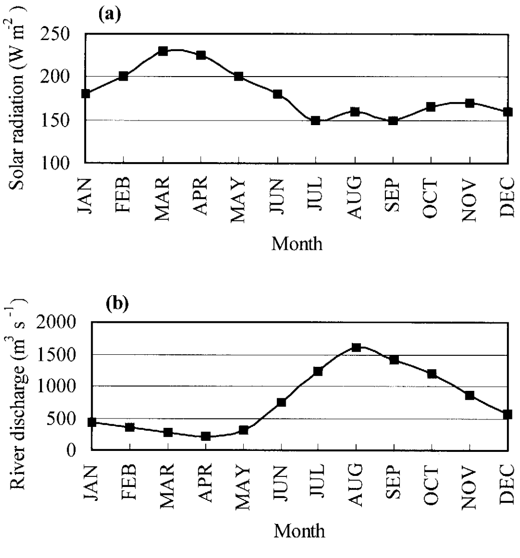


Fig. 2. Seasonal variations of the monthly averaged solar radiation (a) and river discharge (b) in Manila Bay.

zooplankton (ZOO), detritus (DET) and DON (Dissolved Organic Nitrogen), as shown in Fig. 3. Nitrogen cycling in the box is based on the bio-chemical processes in the box. And also, the model includes nitrogen load from the land, sinking of phytoplankton and detritus, and advection and diffusion of nitrogen related to the estuarine circulation.

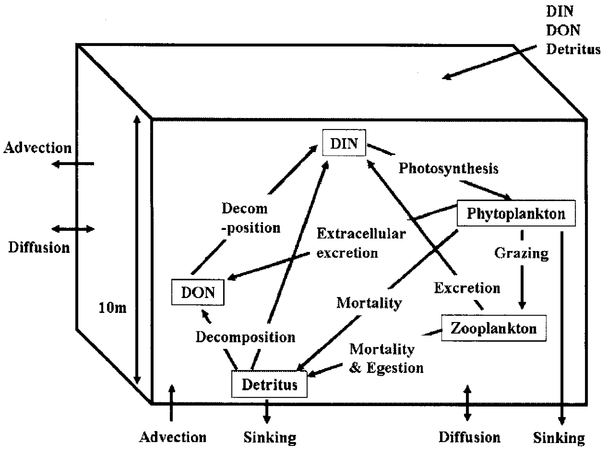


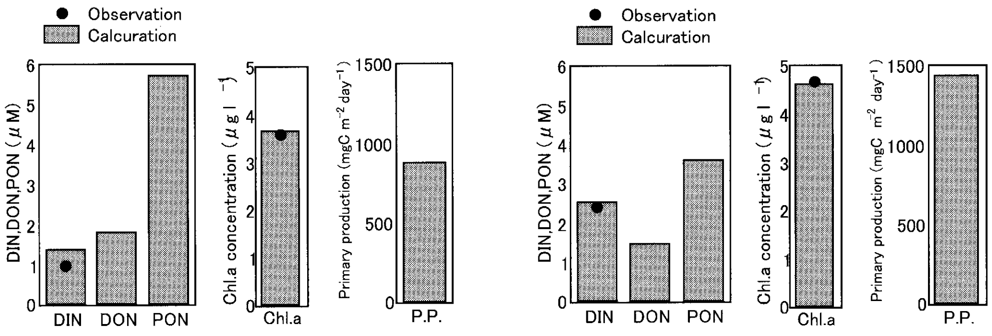
Fig. 3. The numerical ecosystem model.

Temporal change of concentration of each compartment in the box is represented by the equations. For example, Equation 1 represents the temporal change of DIN concentration. It consists of three parts, biochemical process, boundary condition and physical process.

$$\frac{d\mathrm{DIN}_u}{dt} = -A_1\mathrm{PHY}_u + B_2\mathrm{ZOO}_u + C_1\mathrm{DET}_u + D_1\mathrm{DON}_u + \frac{1}{V}\left(\mathrm{DIN}_{\mathrm{land}} - F_u U\mathrm{DIN}_u + F_s W\mathrm{DIN}_l + F_u\frac{K_h}{L}(\mathrm{DIN}_o - \mathrm{DIN}_u) + F_s\frac{K_v}{H}(\mathrm{DIN}_l - \mathrm{DIN}_u)\right), \qquad (1)$$

where A_1, B_2, C_1 and D_1 are the coefficients of biochemical processes, V_u is the volume of box, F_u is the surface area of the box, F_s is the boundary area, L is the horizontal length between the box and the adjacent area, H is the vertical length between the upper and lower layers, U is the horizontal advection speed, W is the vertical advection speed, K_h is the horizontal eddy diffusivity, K_v is the vertical eddy diffusivity, subscript u refers to the upper layer, subscript l refers to the lower layer, subscript o refers to the adjacent area. Biochemical processes are represented by other equations. A_1 represents photosynthesis speed and is the functions of DIN concentration, water temperature (T) and photon in the water (I), as shown by Equation 2.

$$A_1 = V_{\max} \times \frac{\mathrm{DIN}}{\mathrm{DIN}+K_n} \times \left[\frac{T}{T_{\mathrm{opt}}}\right]^2 \exp\left(1-\left[\frac{T}{T_{\mathrm{opt}}}\right]^2\right) \times \left[\frac{I}{I_{\mathrm{opt}}}\right]^2 \exp\left(1-\left[\frac{I}{I_{\mathrm{opt}}}\right]^2\right), \qquad (2)$$



(a) March (Dry season)

(b) November (Rainy season)

Fig. 4. The calculation results with the observed values.

where V_{max} denotes the maximum specific nitrogen uptake rate, K_n is the half saturation constant, T_{opt} is the optimum water temperature, I_{opt} is the optimum photon. Other equations of the temporal change of concentration and the biochemical processes are referred to Hayashi and Yanagi (2002).

K_h and K_v are referred to Fujiie et al. (2002) which calculated the residual current distributions in April (dry season) and November (rainy season). K_h is $10^5\,cm^2\,s^{-1}$. K_v in dry season is $1.4\,cm^2\,s^{-1}$ and K_v in rainy season is $0.7\,cm^2\,s^{-1}$. U is calculated from the average residual current speed along the boundary section between the box and the adjacent area, which is calculated by Fujiie et al. (2002), and it is $0.23\,cm\,s^{-1}$ in dry season and $3.5\,cm\,s^{-1}$ in rainy season. W is estimated from the water budgets, and it is $6.7\times10^{-5}\,cm\,s^{-1}$ in dry season and $1.6\times10^{-3}\,cm\,s^{-1}$ in rainy season.

DIN loads from rivers in March and November were estimated by the DIN load from rivers in a year (900×10^6 moles y^{-1}) and river discharge ratios in March and November shown in Fig. 2(b). And DIN loads from the land area in March and November were added as the direct DIN load (it was 600×10^6 moles y^{-1}). Moreover total nitrogen (TN) loading from rivers is estimated by the ratio of TN loading volume to DIN loading volume which was observed in Hakata Bay (Yanagi and Onitsuka 2000). TN concentration at the boundary is estimated by the ratio of TN concentration to DIN concentration which was observed in Osaka Bay (Hashimoto et al. 1996). The sinking speeds of phytoplankton and detritus are estimated by the TN budget in the box, and they are $6.7\times10^{-6}\,cm\,s^{-1}$ and $6.7\times10^{-5}\,cm\,s^{-1}$, respectively.

V_{max} is $1.4\,day^{-1}$. K_n is $0.9\,\mu M$. T_{opt} and I_{opt} are 28.3 degrees and $551{,}623\,cal\,m^{-2}\,day^{-1}$, respectively, which are observed temperature and photon in rainy season at Manila Bay. This is due to that chl.*a* concentration in the surface layer in rainy season is higher than that in dry season. Other parameters referred to Kawamiya et al. (1995) were tuned up to reproduce the observed data, and consequently they were the same as Kawamiya et al. (1995) except the decomposition speeds, which are a quarter of those of Kawamiya et al. (1995). Kawamiya et al. (1995) calculated the primary production in the subarctic zone. Decomposition speed is supposed to be faster in Manila Bay (tropical zone). But the observed data could not be reproduced by the faster decomposition speed in this study. We will examine this point in future. The time step of the calculation is 1 h. We obtained the quasi-steady state on the 10th days after the beginning the calculation.

Results and Discussion

Figure 4 shows the calculation results with the observed values in March, dry season (a) and November, rainy season (b). Calculation results well reproduce the observed one. Chl.*a* concentration in rainy season is 1.3 times of that in dry season. But the primary production (P.P.) in rainy season is 1.6 times of that in dry season. And DIN concentration in rainy season is 1.9 times of that in dry season. It is suggested that photosynthesis speed in rainy season is faster than that in dry season. Photosynthesis is not limited by water temperature and photon but is limited by DIN concentration in both seasons. Therefore photosynthesis speed is faster in rainy season when DIN concentration is higher.

Figure 5 shows the calculated nitrogen concentrations and fluxes in March (a) and November (b). Locations of the compartments in the figure are the same as Fig. 3. Nitrogen load from the land and the advection and diffusion fluxes are TN flux. Unit of concentration is μM, and that of flux is $mol\,s^{-1}$. The value in parenthesis is represented as a ratio to the photosynthesis flux and the units is %.

Detritus in dry season was 1.6 times of that in rainy season as shown in Fig. 4. Therefore, the sinking flux in dry season was higher than that in rainy season. But stratification did not observed in dry season, and 80% of detritus came back to the upper layer due to the vertical diffusion. On the other hand, the vertical diffusion was weak in rainy season, because the stratification developed. Therefore, the vertical

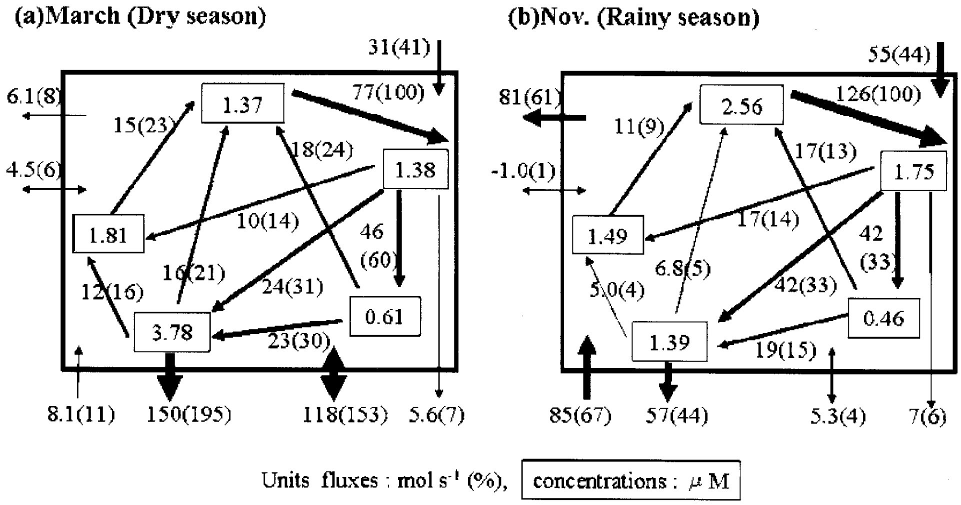
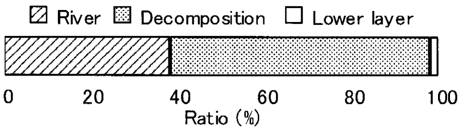


Fig. 5. The calculated nitrogen concentrations and fluxes in March (a) and November (b). Unit of concentration is μM, and that of flux is mol s^{-1}. The value in parenthesis is represented as a ratio to the photosynthesis flux, and the unit is %.

(a) March (Dry season)



(b) November (Rainy season)

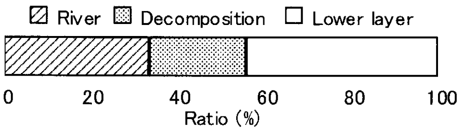


Fig. 6. DIN supply ratio to the upper layer from every DIN sources.

diffusion flux was 8% of total sinking fluxes but 130% of substance detritus came back to the upper layer by the vertical advection of the estuarine circulation. In this case the major part of nitrogen transported from the lower layer was DIN. That is to say, detritus was decomposed in the lower layer and was transported to the upper layer by the estuarine circulation in rainy season, whereas detritus was shuttled between the upper and lower layers and was mainly decomposed in the upper layer in dry season.

Figure 6 shows the DIN supply ratio to the upper layer from every DIN sources in dry (a) and rainy (b) seasons. The main sources are decomposition in dry season and the lower layer in rainy season. And also, main route of nitrogen cycling in dry season is from DIN to phytoplankton, to zooplankton, to detritus and to DIN. River discharge and primary production are small in dry season, and the estuarine circulation is weak. Detritus shuttles between the upper and lower layers, but the nitrogen cycling is closed in the upper layer in dry season. In contrast to dry season, river discharge and primary production in rainy season are large. Therefore DIN is quickly consumed by phytoplankton, and phytoplankton is grazed by zooplankton or is moralized and sank to the lower layer. DIN is regenerated in the lower layer, and is transported to the upper layer due to the strong estuarine circulation. Nitrogen cycling is closed not in the upper layer but includes the lower layer in rainy season.

By the way, outflow flux in rainy season is large due to the strong estuarine circulation as shown in Fig. 5. The residence time of TN in the box (TN in the box/TN flux from outside) is 378 h in dry season and 88 h in rainy season. It is longer in dry season. Therefore the number of times where nitrogen is used by primary production is more in dry season than in rainy season. Nitrogen is used 24 times in dry season and 10 times in rainy season by primary production. Unit time of nitrogen assimilation for primary production is 15 h (378/24) in dry season and 8.8 h (88/10) in rainy season. In other words, nitrogen is used slowly and many times due to small nitrogen supply in dry season. But nitrogen is sufficiently supplied, is used quickly by primary production and is flowed out also quickly in rainy season.

Conclusion

We calculated the nitrogen cycling in Manila Bay during dry and rainy seasons. The difference of nitrogen cycling related to the lower trophic level ecosystem in both seasons was clarified.

Primary production in rainy season is 1.6 times of that in dry season. And the consumption speed of DIN in dry season is 2 times of that in rainy season. Photosynthetic rate in rainy season is faster than that in dry season. The main source of DIN is the decomposition in dry season and the advection from the lower layer in rainy season. River discharge and primary production are small in dry season, and the estuarine circulation is weak. Detritus shuttles between the upper and lower layers, but the nitrogen cycling is closed in the upper layer in dry season. On the other hand, river discharge and primary production in rainy season are large. And DIN is consumed by phytoplankton, phytoplankton is grazed by zooplankton and/or is moralized, and sank to the lower layer. DIN is regenerated in the lower layer, and is transported to the upper layer due to the strong estuarine circulation. Nitrogen cycling is not closed in the upper layer but includes the lower layer in rainy season. The residence time of TN in dry season is longer than that in rainy season. Nitrogen is used slowly and many times due to small nitrogen supply in dry season. But nitrogen is sufficiently supplied, is used quickly by primary production and is flowed out also quickly to the adjacent area in rainy season.

The used data in this study did not include red tides. The generation mechanism of red tides in Manila Bay will be analyzed in detail by using another data set which includes the case of red tides with higher chl.*a* concentration than 10 μg/l.

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