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Dissolved Inorganic Nitrogen budget in the inner part of Manila Bay, Philippines

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Abstract: Dissolved Inorganic Nitrogen (DIN) budgets for the vertically three dis tinct layers of the Pasig River estuary in Manila Bay were elucidated for both dry and rainy seasons. The budgets were based on observational data and results of hydro-dynamic model experiments. The obtained results suggest that, in both seasons, DIN fixation by photosynthesis exceeds decomposition of organic matter in the upper layer, and that decomposition of organic matter exceeds DIN fixation in the lower layer. In the middle layer, fixation and decomposition appear to be in equ ilibrium in the d ry season, with decom position exceeding fixation in the rainy season. Fixation thus exceeds decomposition in the water column during the dry season, with the opposite relation observed in the rainy season. The main source of DIN in the middle and lower layers is regenerated DIN in the water column and sediments.

Keywords: *Nitrogen, Material Budget, Manila Bay*

Introduction

The deterioration of the water quality in Manila Bay has resulted in blooms of red tide occur in the bay. VELASQUEZ *et al.* (1997) reported the average nutrient con centrations in Manila Bay, and JACINTO *et al.* (1998) calculated the nitrogen and phosphorus budgets of the bay using the Land Ocean Interaction s in the Coastal Zone (LOICZ) biogeochemical budgeting procedure. However, these studies only estimated average annual values for the whole of Manila Bay, and seasonal variations in nutrient cycling have not yet been described. VILLANORY *et al.* (2006) characterized the horizontal distribution of *Pyrodinium* using a hydrodynamics model, and discussed the relation between *Pyrodinium* blooms and the physical dynamics of the bay, however, the influence of nutrients was not included. HAYASHI *et al.* (2006) and HAYASHI *et al.* (2008) estimated the seasonal variations of nitrogen cycling in the surface layer of Manila Bay by using a numerical ecosystem model. And it clarified the effect of dissolved inorganic nitrogen (DIN) concentrations in the lower layer and nitrog en loading from rivers to the reduction of chlorophyll *a* (Chl.*a*) and DIN concentrations in the upper layer. Nitrogen is considered the limiting nutrient for primary production in Manila Bay, and the vertical transport of nitrogen to the surface layer plays an important role in the primary production. However, a source of DIN unde r the surface layer has not been explored. It is im portant to determine the characteristics of the DIN budget not only the surface layer but also the middle and lower layers in Manila Bay. In this study we describe the DIN budget

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for three vertically distinct layers in the Pasig River estuary of Manila Bay during dry and rainy seasons. And we discuss about primary production that is bound up with DIN budget.

Material and methods

Study area

Figure 1 shows the study area of Manila Bay. The bay has two major inflowing rivers, the Pasig River and Pa mpanga River, with the Pasig River flowing through metropolitan Manila. Concentrations of DIN, Chl.a and Dissolved Oxygen (DO), water temperature and salinity were determined at depths of 1 m, the mid-depth and near the bottom in eight stations (Fig.1) during every month from March 1996 to December 1998. Water samples were collected using a 5–L Niskin sampler (General Oceanics, Inc.). Samples for the inor ganic N species (nitrate, nitrite, and ammonia) and Chl.*a* were filtered through GF/C filte rs, frozen, and analyzed later following the m ethods of PARSONS *et al.* (1984). Sam ples for DO were fixed on site and subsequently analyzed using the Winkler titration method (PARSONS *et al.*, 1984). Salinity and temperature were m easured using the Conducti vity-temperature-depth (CTD) profiler (A ML Oceanographic Ltd.). Water transparency was measured by a Secchi disc. HAYASHI *et al.* (2008) demonstrated the use of the depth-time diagrams of density, DIN and Chl. *a* concentrations in Manila Bay. Under conditions of increased discharge from the Pasig River during the rainy season, stratification is developed and high Chl.*a* concentrations are observed in the upper layer of the estuary. Therefore, the inner part of Manila Bay inside the solid line in Fig. 1 was analyzed in this study. This area is divided into three vertically distinct layers which correspond to fixed depth intervals, as shown in Fig. 2. The surface region of the study area is about 500 km^2, the length of the outer boundary is about 38 km, and the average water depth is approxim ately 10 m. The surface layer depth was fixed at 3m which is the depth of the halocline in the rainy season. The middle layer was set from 3 m to 8 m depth while the lower layer is below 8m.

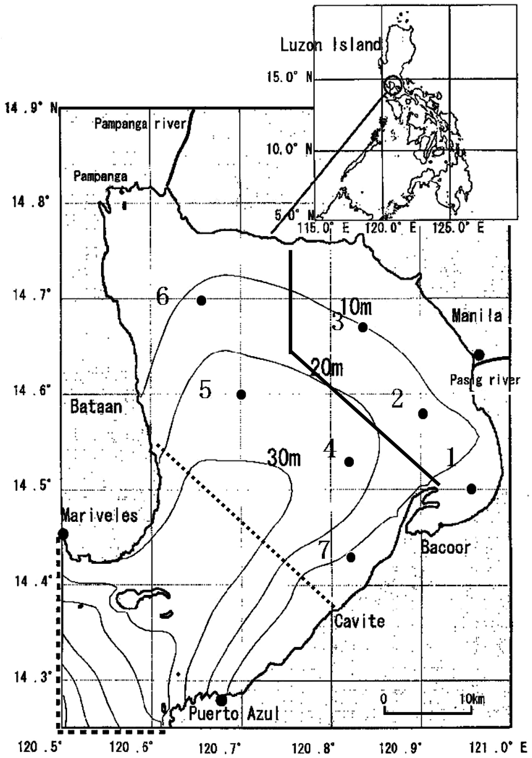

Fig. 1. Study area of Manila Bay. The solid line indicates the boundary of the study area. The dotted line indicates the boundary of the area, where averaged data were obtained. The numbers indicate sample sights.

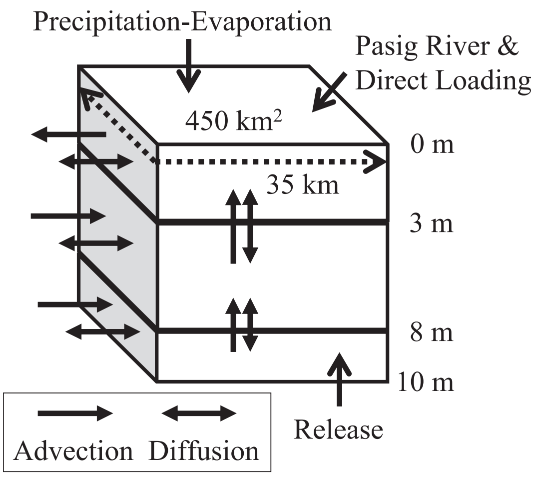

Fig. 2. Scheme of water and DIN budgets in each layer of the Pasig River estuary.

Data

Figure 2 also shows the schemes of water and DIN budget applied to the model in this study. Water and DIN are transported by estuarine circulation, i.e., advection. And DIN is also exchanged by dif fusion across the boundary line between the study area and the outer area and between the layer and layer. The advection and diffusion flux of DIN can be calculated by equation 1 and equation 2, respectively.

$$(Advection\ flux\ of\ DIN) = U_i F_i DIN_h \quad (1)$$

$$(Diffusion\ flux\ of\ DIN) = k_i F_i (DIN_h - DIN_l)/l_i \quad (2)$$

where, U_i is an advection velocity, F_i is the area of th e boundary section, DIN_h and DIN_l refer to the average DIN concentration in each layer, k_i is diffusivity and l_i is the distance between the center of the layer an d the center of the next layer . The meaning of the subscrip ts *h* and l refers to higher DIN concentration (*h*) and lower DIN concentration (*l*), respectively. DIN expands from the higher concentration area to the lower concentration area. To estimate advection and diffusion fluxes, U_i and k_i of each boundary section, DIN_h and DIN_l are required. The data for our analysis were only obtained in the dry and rainy seasons. The three-dimensional distributions of the average residual currents for Manila Bay in April (dry season) and November (rainy season) calculated by FUJIIE *et al.* (2002) are used for both advection velocities and diffusivities in th is study. Horizontal diffusivity was constant at 10 m s^{-1} for the entire grid. V ertical diffusivities on the horizon tal boundary at 3 and 8 m were obtained by averaging the calculated values at these two depths. The horizontal advection velocities for the upper and m iddle layers are average values from 0 t o 3 m and 3 to 8 m, respectively, along the boundary line. Horizontal advection velocities of the lower layer and the vertical advection velocities at the 3 and 8 m boundary sections were estim ated by the application of a water budget for each layer. The water balance of the surface layer is $H_u = Q + P - E + V_3$, where H_u is the flow rate from the inside to the outside of the upper layer, and is obtained by m ultiplying the horizontal advection velocity and the area of the vertical section of the upper layer. Q is the river discha rge. P is the precipitation. E is the evaporation measured by the Philippine Atmospheric, Geophysical and Astronomical Services Administration. V_3 is the flow rate from the middle layer to the upper la yer in the box. The vertical advective velocity on the upper boundary section at 3 m is obtained by dividing V3 by the area of the horizontal section at 3 m . The water balance of the middle layer can be represented as $V_3 + H_m = V_8$ where H_m is the flow rate from inside to outside of the middle layer, and is solve d by m ultiplying of the horizon tal advective velocity by the area of the vertical section of the middle layer, and V_8 is the flow rate from the lower layer to the middle layer in the box. The vertical advective velocity at the boundary section at 8 m is obtained by dividing V_8 by the area of the horizontal section at 8 m. The water b alance of the lower layer can be expressed as to $V_8 = H_l$ where H_l is the f low rate from the outside to the inside of the lower layer. The horizontal advective velocity of the lower layer can then be obtained by dividing H_l by the area of the vertical section of the lower layer. The a verage advection velocities and diffusivities obtained using this procedure are shown in Table 1.

The DIN concentration s in each layer in the box in April and November of each year were obtained by the horizontal average of DIN concentrations of Station 1, 2 and 3. Then these concentrations were averaged over three years. The averag e DIN concen trations for outside the model domain were calculated using data

Table 1. Averaged advection velocities and diffusivities. Minus means the flow from the inside to outside.

Item	Layer	April	November
Horizontal advection velocity (m/s)	Upper	-1.54×10^{-2}	-4.97×10^{-2}
	Middle	-0.49×10^{-2}	0.07×10^{-2}
	Lower	0.82×10^{-2}	1.57×10^{-2}
Vertical advection velocity (m/s)	3m	3.82×10^{-6}	11.7×10^{-6}
	8m	9.45×10^{-6}	18.2×10^{-6}
Vertical diffusivities ($m^2\ s^{-1}$)	3m	1.95×10^{-4}	0.98×10^{-4}
	8m	2.07×10^{-4}	0.54×10^{-4}

collected from Stations 4 to 7. The average water temperature, salinity and Chl.*a* concentrations for each layer were calculated by the same protocol described above.

Runoff data for the Pasig, Pampanga and other rivers was obtained from the "River Rehabilitation Program for the Manila Bay Region". Then, the monthly average runof f in April and Novem ber were calculated. Average DIN loading by rivers into Manila Bay is approximately 900×10^6 mol yr^{-1} (Jacinto *et al.* 1998). The estimated values for total DIN loading from all river s in April and November were calculated by dividing the annual DIN loading by the ratio of monthly runoff. We then estimated DIN loads from the Pasig, Pampanga and other rivers by dividing total DI N loading by ratio of monthly runoff of those rivers. DIN may also be derived directly from sources along the coast, such as sewage water, industrial runoff, agriculture and aquaculture ponds. Average direct DIN loading into Manil a Bay is approximately 600×10^6mol yr^{-1} (Jacinto *et al.* 1998). We assumed that 50% of this DIN load is supplied to the study area.

Although DIN may also be released from the sea bottom, DIN flux from pore water by diffusion was not observed during the period 1996 to 1998. We therefore used data from the area collected in March (dry season) and November of 1999. The sampling methods and the method for estimating DIN release were the same as Azanza *et al.* (2004). Water exchange at the water surface was taken to be the difference between precipitation and evaporation, *P-E*.

Residence time

The residence time of fresh water in Manila Bay is estimated by the following equation:

$$(Residence\ time) = V\frac{S_o - S_m}{S_o} \Big/ (Q + P - E) \quad (3)$$

where V is the volume in the water column, S_o is the maximum salinity in the outer part of the bay, and S_m is the average salinity in the water column.

Results

Water budget

Figure 3 shows our derived water budget, as well as the water temperature and salinity measurements for each layer in the dry (a) and rainy (b) seasons. The results are typical for an estuarine circulation pattern, with flows into the lower layer and flows out in the upper layer . Because the river discharge in the rainy season is greater than in the dry season, the difference in salinity of the upper and lower layers is enhanced during the rainy season when estuarine circulation and stratification

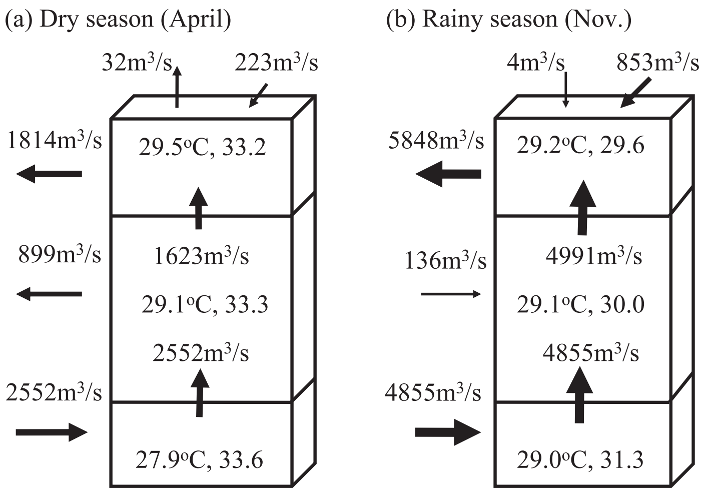

Fig. 3. Water budget ($m^3\ s^{-1}$), water temperature (℃) and salin ity in each layer. Width of vectors represents the magnitude of flux.

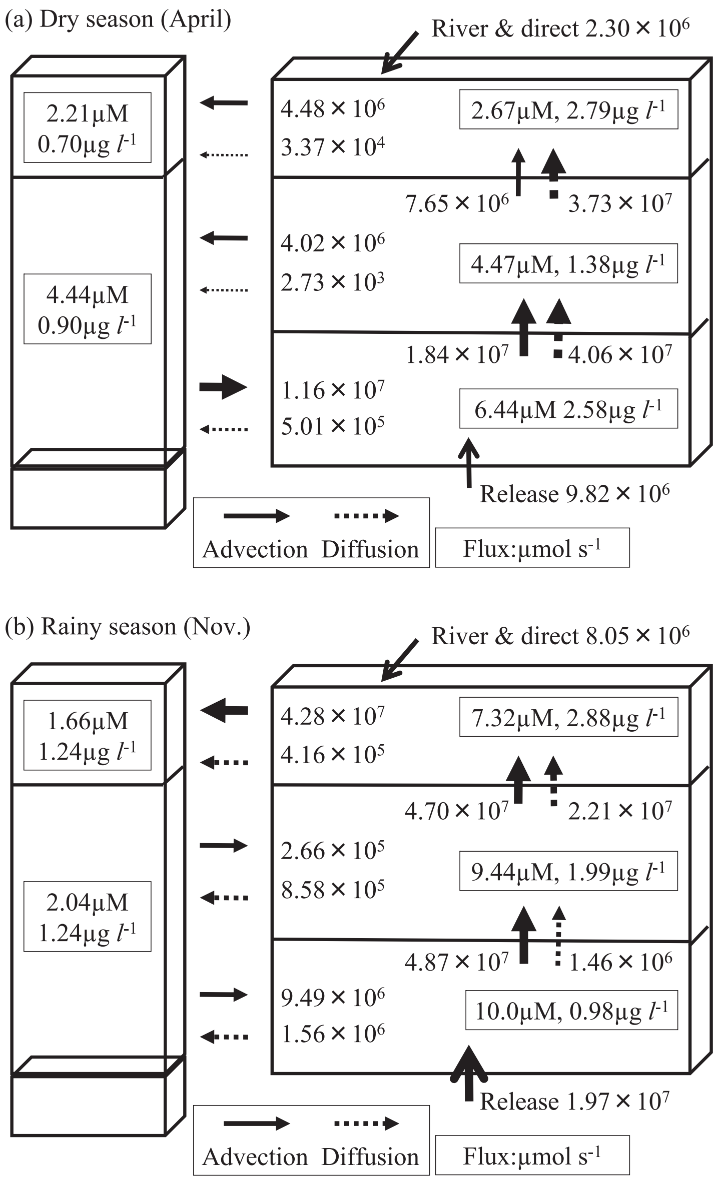

Fig. 4. DIN budget (μ mol s^{-1}), DIN concentration (μM) and Chl.*a* co ncentration ($\mu g\ l^{-1}$) in each layer. Width of vectors represents magnitude of flux.

are more apparent, with the inflow of bay water occurring even in the middle layer. The estuarine circulation is weaker, and water flows out from the middle layer during the dry season. Estimated residence times are 33 days in April (dry season) and as short as 16 days in November (rainy season).

DIN budgets

Figure 4 shows our calculated DIN budget, DIN concentrations and Chl.*a* concentrations for each layer in the dry (a) and rainy (b) seasons. Fig. 5 simplifies these diagrams by normalizing the DIN flux during each season when N loading from rivers and the coast in the dry season is set to 1.0 . If the inf low flux of DIN

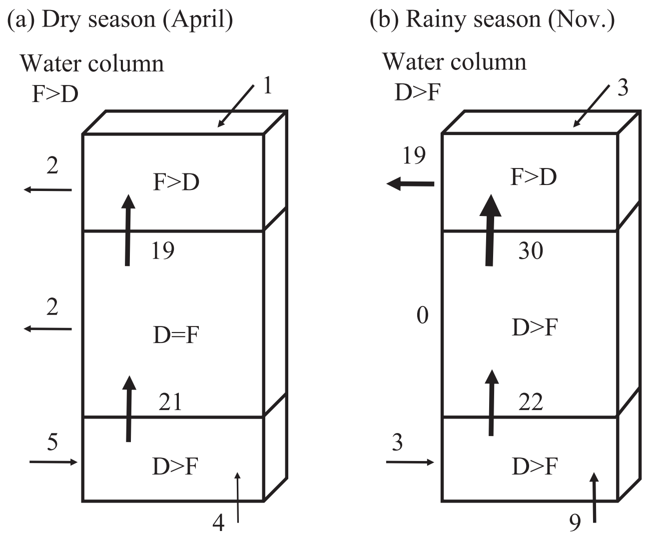

Fig. 5. DIN flux normalized by DIN flux from rivers and the coast, and com parison between DIN fixation and organic matter decomposition. Width of vectors represents magnitude of flux. F indicates nitrogen fixation. D indicates decomposition of organic matter.

in any compartment is lar ger than the outflow flux, then there is fixation of DIN to organic matter, and this is shown as “F” in the diagram. Conversely, if the out flow flux exceeds the inflow flux of DIN then decomposition of organic matter must occur and this is shown as “D”.

During the dry season, the total inflow flux is 10 (=1+5+4) and the outflow flux is 4 (=2+2) in the water co lumn, implying that fixation exceeds decomposition. However, this cond ition is observed to differ in each layer, with fixa tion being dom inant in the upper layer and being balanced in the middle layer. On the other hand, decomposition is dominant in the lower layer, as the DIN regenerated by decom position in the lower layer (12=21−9) exceeds the DIN supplied from the outside and the bottom (9=5+4). The DIN concentration is h ighest in the deeper layer. Chl.*a* concentration is high in the deeper layer as well as in the upper layer. In the rainy season, the inflow flux and outflow flux in the water column are 15 (=3+3+9) and 19, respectively, indicating that decomposition exceeds nitrogen fixation, which is the opposite of the situation in the dry season. These finding are consistent with the observation that the DIN concentration in the water column in the rainy season is higher than that in the dry season. At this time, fixation in the upper layer dominates, as it does in the dry season, but the outflow flux by advection is greater compared to that of the dry season. The DIN that is not consumed by prim ary production is exported from the system in lar ge volumes due to estuarine circulation in the rainy season. At this time, decomposition in the middle layer exceeds fixation, while they were the same in the dry season. As in the dry season, decomposition is dom inant in the lower laye r. In addition to reg enerated DIN derived via decomposition in the lower layer, release from bottom sediments during the rainy season is greater than in the dry season by a factor of two.

The main source of DIN in the middle and lower layers is regenerated DIN which arises from the decomposition of organic matter in the m iddle and lower layers and f rom sediments, and that the DIN supply from outside the system is relatively small.

Discussions

HAYASHI *et al.* (2008) also discus sed the factors limiting for primary production in the upper layer in Manila Bay using a numerical ecosystem model. The same observational data as this study were used in the model analysis. The limiting factors were defined as being a function of the maximum rate of specific nitrogen uptake, DIN concentration, water temperature and light intensity in the water.

That results suggested that light conditions were considered to be the most effective limiting factor in the upper layer in April, and photo-inhibition occurs in the upper layer during the dry season due to strong light intensity. Average transparencies were 2.8 m in April (dry season) and 2.4 m in November (rainy season), and the average dissolved oxygen concentrations in the lower layer were 4.96 m g l^{-1} in April and 3.47 m g l^{-1} in November. We assumed that the light intensity immediately under the sea su rface is 50% of solar radiation and an ex tinction coefficient is estimated by 1.7/ (transparency) (PARSONS *et al.*, 1984). Usins this approach, the compensation depths of 1% was estimated to be 7.6 m in April and 6.5 m in Nove mber. Thus light should reach the deeper layer somewhat more easily in the dry season compared to the rainy season. Then, the primary production should be possible in the middle and lower layers in the dry season, and fixation exceeds decom position in the water column. Regenerated DIN in the lower layer could support primary production throughout the water colum n during the dry season.

On the other hand, water temperature was consid ered more important in the upper layer in November (HAYASHI *et al.*, 2008). Since light intensity is weaker in the rainy season, Chl.*a* concentration was higher in the shallower layer. And Chl.*a* concentration in the lower layer was lower than that of the dry season. It is likely that the light intensity in the lower layer was too low for the primary production due to the self-shading effect by phytoplankton. Therefore, decomposition was greater than fixation not only in the lower layer but also in the middle layer in the rainy season.

Conclusions

We constructed DIN budgets of horizontal three layers in the Pasig River estuary in Manila Bay during both the dry and rainy seasons using observational data and the results of numerical hydrodynamic modeling. DIN fixation by photosynthesis exceeds the decomposition of organic matter in the upper laye r during both dry and rainy seasons. On the other hand, the decomposition of organic matter exceeds DIN fixation in the lower layer at all times. In the m iddle layer, the ra te of fixation is similar to that of decomposition in the dry season, but the rate of decomposition exceeds that of fixation in the rainy season. Fixation exceeds decomposition in the water column in the dry season and DIN budget in the rainy season is the opposite of the situation in the dry season.

The main source of DIN is regenerated DIN derived from the decomposition of organic matter in the water column and from bottom sediments. Thus, one would have to control the decomposition activity or the amount of particulate matter to reduce red tides in the Pasig River estuary of Manila Bay. However, these approaches are im possible to realize it immediately. A more reasonable present approach is to reduce the DIN load from the land area. HAYASHI *et al.* (2008) showed that if total nitrogen loaded from rivers is decreased to half, Chl.*a* and DIN concentrations in the upper layer are also reduced to 94% and 73% par one year, respectively. Lowering DIN loading by half is extreme, but this kind of attempt is necessary to have a significant effect. In addition, to clarify the behavior of organic matter, we should assess the effect of reduced nitrogen loading from the land area to Manila Bay by using a numerical ecosystem model.

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