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Seasonal Variations in Nutrient Budgets of Hakata Bay, Japan

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Seasonal variations in freshwater, salt, phosphorus and nitrogen budgets of Hakata Bay, Japan were investigated from April 1993 until March 1994. The internal sink of dissolved inorganic phosphorus (DIP) and nitrogen (DIN), and the internal source of dissolved organic phosphorus (DOP) and nitrogen (DON) predominate in the bay. This means that the production of organic matter is larger than respiration, and atmospheric CO_2 is absorbed in the water column of Hakata Bay. Denitrification is more dominant than nitrogen fixation in the bay. Compared to Tokyo and Mikawa Bays, Hakata Bay is harder to eutrophicate, mainly due to the shorter residence time of freshwater.

Keywords:
· Box model analysis,
· nutrient budget,
· CO_2 absorption,
· denitrification.

1. Introduction

Hakata Bay is a small semi-enclosed bay which is located at the northern part of Kyushu, western Japan (Fig. 1). Organic pollution in Hakata Bay has progressed from 1970 due to increased nutrient loading mainly from Fukuoka City, which has a population of about 1,300,000 (Honda *et al*., 1992). Red tides and oxygen deficiency currently occur in the upper and lower layers of the inner bay, respectively, every summer. The local government wants Hakata Bay to be purified by adopting some suitable countermeasures. It is necessary to clarify the nutrient budgets in Hakata Bay in order to establish effective countermeasures for the purification of Hakata Bay water.

In this paper I reveal the seasonal variations in freshwater, salt, phosphorus and nitrogen budgets of Hakata Bay from April 1993 to March 1994 and compare nitrogen budgets in Tokyo, Mikawa and Hakata Bays.

2. Observations

Intensive field observations on salinity, DIP (Dissolved Inorganic Phosphorus), DOP (Dissolved Organic Phosphorus), POP (Particulate Organic Phosphorus), DIN (Dissolved Inorganic Nitrogen = NH_4 + NO_2 + NO_3), DON (Dissolved Organic Nitrogen) and PON (Particulate Organic Nitrogen) concentrations in the surface (0 m), subsurface (–2.5 m), and bottom (1 m above the bottom) layers at three stations (W-3, C-1 and E-2 shown in Fig. 1) were carried out every month from April 1993 to March 1994 by the Harbor Bureau of Fukuoka City (Fukuoka City, 1995).

Samples of DIP, DOP, DIN and DON were filtered through 1 μm glassfiber filter. DIP was determined by the molybdenum blue method (JIS K0102-1993 46.1.1). (DIP + DOP) and (DIP + DOP + POP) were determined by the molybdenum blue method after potassium peroxodisulfate decomposition (JIS K0102-1993 46.3.1). DOP was then estimated by {(DIP + DOP) – DIP} and POP by {(DIP + DOP + POP) – (DIP + DOP)}. NH_4-N was determined by indophenol blue absorptiometry (JIS K0102-1993 42.2), NO_2-N by naphthylethylenediamine absorptiometry (JIS K0102-1993 43.1.1) and NO_3-N by naphthylethylenediamine absorptiometry after copper and cadmium column reduction (JIS K0102-1993 43.2.3). (DIN + DON) was determined by indophenol blue absorptiometry after potassium peroxodisulfate decomposition (JIS K0102-1993 44). DON was then estimated by {(DIN + DON) – DIN}. PON was determined by the coal and coke mechanical method for ultimate analysis (Organic Elemental Analyzer 2400 II CHNS/O, Perkin Elmer Inc.) (Japanese Standard Association, 1995).

At the same time, TP (Total Phosphorus = DIP + DOP + POP) and TN (Total Nitrogen = DIN + DON + PON) were observed every month in three layers at 28 stations (shown in Fig. 2) and the release flux of DIP, DOP, DIN and DON from the bottom sediment were measured in the laboratory from the core samples at Stns. C-1 and E-2 in June, September, November and February by the Environmental Bureau and Harbor Bureau of Fukuoka City (Harbor Bureau of Fukuoka City, 1995). The loads of freshwater, DIP, DOP, POP, DIN, DON and PON from rivers, industrial and sewage treatments (shown by arrows in Fig. 1), which flow into Hakata Bay, were investigated by the Harbor Bureau of Fukuoka City on the basis of daily flow rate and concentration (Harbor Bureau of Fukuoka City, 1995). DIP and DIN loads from the rain were estimated by precipitation data on the basis of the results of field observation at Fukuoka (Saitoh *et al*., 1994). Daily precipitation and

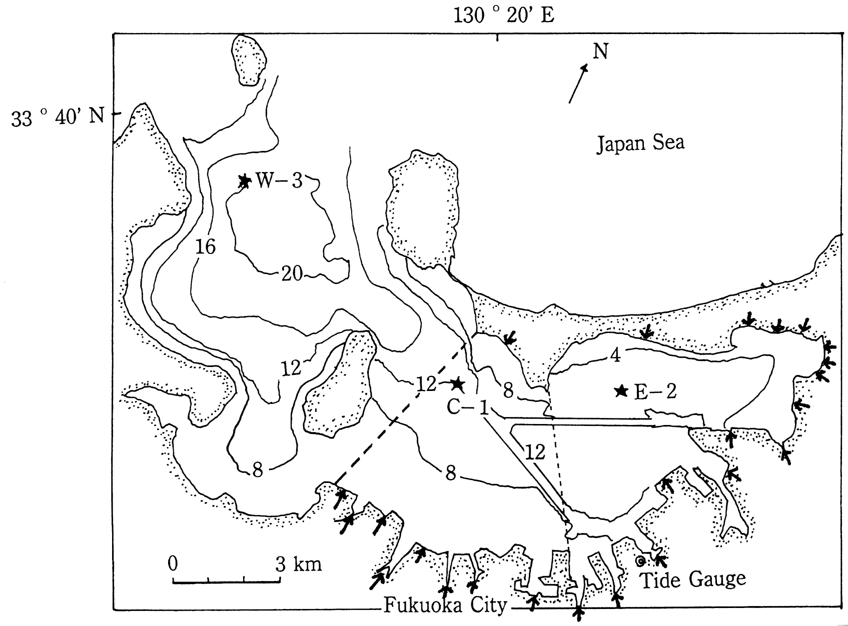

Fig. 1. Hakata Bay and observation stations (stars). Numbers show the depth in meters and arrows river mouth or sewage treatment outlet.

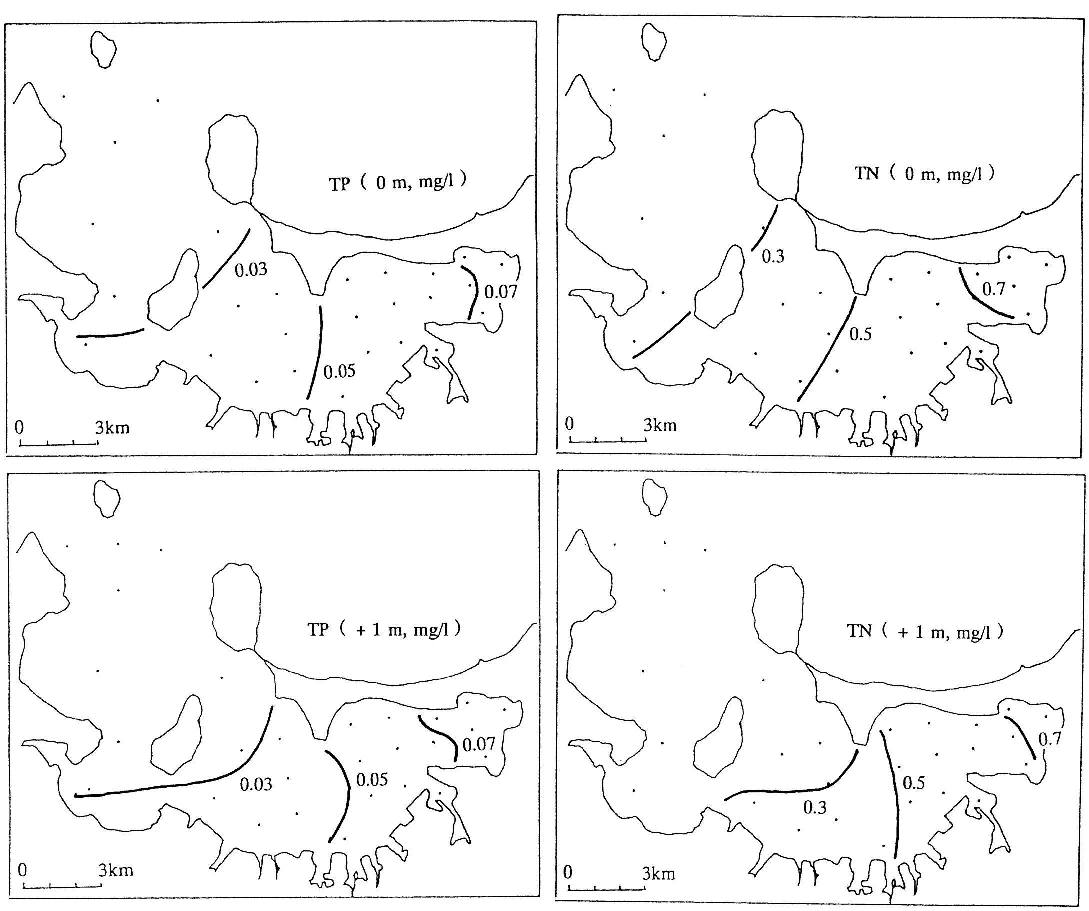

Fig. 2. Horizontal distributions of yearly averaged TP and TN at the sea surface and 1 m above the bottom. Dots show the observation stations.

evaporation data during the same period were obtained at the Fukuoka Meteorological Observatory, and sea level data every hour at the tide gauge station (shown by a double circle in Fig. 1) by the Hydrographic Department.

3. Box Model Analysis

Here we consider the central and eastern parts of Hakata Bay (inner area from the thick broken line in Fig. 1) as a closed bay area with a volume V of 424×10^6 m^3, sea surface area A of 62 km^2 and average depth H of 7.0 m. Data at Stns. C-1 and E-2 are averaged depending on their volumes in order to obtain representative data in the bay. The thin broken line in Fig. 1 denotes the division of representative areas of Stns. C-1 and E-2. Data at Stn. W-3 represent the data out of the bay. Yearly averaged TP and TN concentrations both in the surface (0 m) and bottom (+1 m) layers decrease monotonously from the head to the mouth of Hakata Bay, and the vertical gradient of TP and TN in the bay is small, as shown in Fig. 2. Though two observation stations of C-1 and E-2 are inadequate for data of the inner bay, their representativeness is considered to be reasonable from Fig. 2.

The box model analysis (Gorden *et al*., 1996; Yanagi, 1997) is applied to the closed bay area of Hakata Bay enclosed by the thick broken line in Fig. 1 using the observed data from April 1993 to March 1994.

4. Results and Discussion

4.1 Freshwater budget

Seasonal variations in sea level, precipitation, evaporation and river discharge are shown in Fig. 3. Zero of sea level denotes the yearly average sea level of Hakata Bay from April 1993 to March 1994. Maximum precipitation and river discharge occurred in June (rainy season in Japan) and the temporal rate of increase of sea level becomes large at the same time. Freshwater flux through the open boundary of inner Hakata Bay (shown by thick broken line in Fig. 1) V_R is calculated by

$$V_R = -A\frac{d\eta}{dt} + V_Q + V_P - V_E, \quad (1)$$

where A denotes the sea surface area of inner Hakata Bay, η sea level, t time, V_Q river discharge, V_P precipitation and V_E evaporation. The seasonal variation of V_R is nearly the same as that of V_Q as shown in Fig. 3. V_R becomes large in June at the time of large precipitation and river discharge and small in May and February at the time of small precipitation and river discharge. The residence time of freshwater in Hakata Bay τ_f is estimated by

$$\tau_f = \frac{V_f}{V_R}, \quad (2)$$

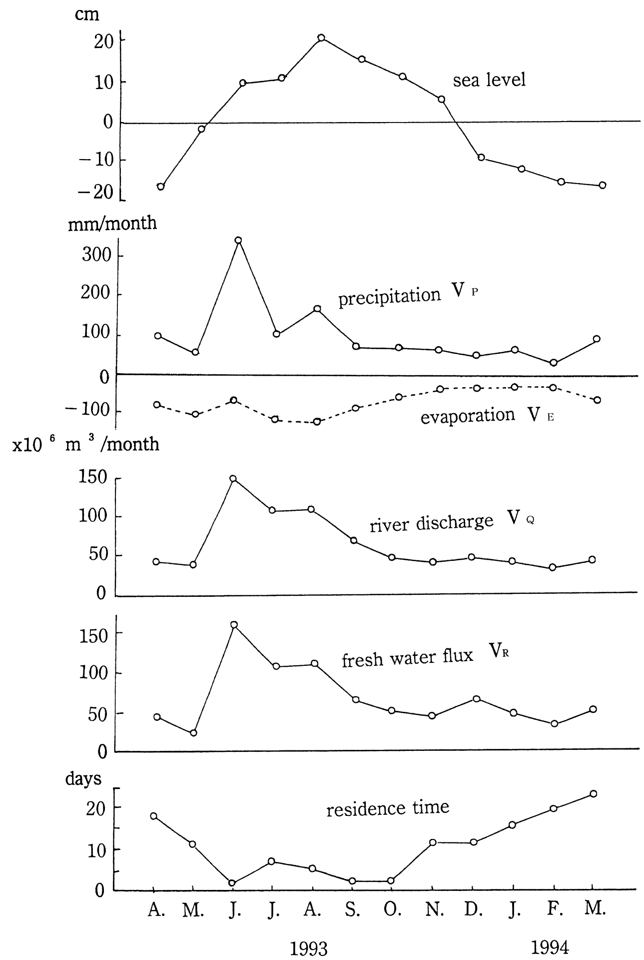

Fig. 3. Seasonal variations in sea level, precipitation, evaporation, river discharge, freshwater export from the bay and average residence time of freshwater.

$$V_f = \frac{(S_o - S_i)V}{S_o}, \quad (3)$$

where V_f denotes the standing stock of freshwater in Hakata Bay, S_o salinity out of the bay and S_i that in the bay, which will be shown in the next section. The residence time of freshwater in Hakata Bay varies from 1 day in June to 24 days in March within a year, and the yearly averaged residence time of freshwater is 8 days.

The yearly averaged freshwater budget of Hakata Bay is shown in Fig. 5(a). Average river discharge is 63.8×10^6 m^{3}month^{-1} and average freshwater flux through the open boundary of the inner bay is 66.0×10^6 m^{3}month^{-1}.

4.2 Salt budget

Seasonal variations of average salinity in the bay and out of the bay are shown in Fig. 4. Salinity values in and out

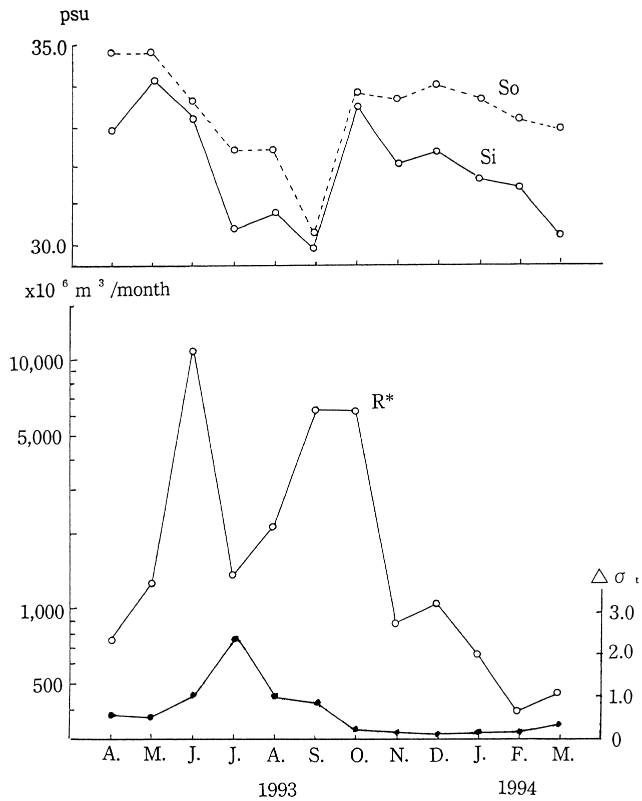

Fig. 4. Seasonal variations in salinity out of the bay (S_o), that in the bay (S_i), water exchange volume across the open boundary of the bay (R*) and density difference between the surface and bottom layers in the bay (full circle).

of the bay were lowest in September after large precipitation and river discharge from June to August. Water exchange rate across the open boundary of the bay R* is calculated by the following equation.

$$R^* = \frac{1}{S_o - S_i}\left(V\frac{dS_i}{dt} + V_R S_i\right). \qquad (4)$$

R* is large from June to October and small from January to March, as shown by open circles in the lower panel of Fig. 4. Such seasonal variation in R* roughly corresponds to that in density difference between the surface and bottom layers in the bay, which is shown by full circles in the lower panel of Fig. 4. Local maxima of R* in June, September and October may be due to large river discharge (shown in Fig. 3), and the passage of typhoons 9313 and 9320 near Hakata Bay, respectively.

The yearly average salt budget of Hakata Bay is shown in Fig. 5(b). The salt export by freshwater flux $V_R S_i$ of 2,106 psu m^{3}month^{-1} is compensated by the salt import due to the water exchange across the open boundary $R^*(S_o - S_i)$. The yearly average water exchange volume across the open boundary of the bay, 2.7 km^3 month^{-1}, is about 40 times the averaged river discharge of 63.8×10^6 m^3 month^{-1}.

4.3 Dissolved phosphorus budget

The budgets in this analysis involve only dissolved materials, i.e. DIP, DOP, DIN and DON, because the salinity-based budget must be treated with caution in constructing a budget for a particulate material. Dissolved materials have no gravitational component of flux within the water, while particles do. Therefore, particle distribution in the water column is likely to be patchy with respect to both time and space, in areas subject to heavy loading with sediments, as well as in systems where wave mixing or active bioturbation stirs the bottom sediments up into the water column. These processes can generate a heterogeneity in estimates of particle concentrations. As a result, the use of salt and water balance calculations are generally not useful when estimating particle budgets (Gorden *et al*., 1996).

Seasonal variations of average DIP, DOP and POP concentrations in the bay are shown in the middle panel of Fig. 6. DIP concentration is high in November and December when DOP and POP concentrations are low.

The internal sink (–) or source (+) of DIP and DOP in the bay, ΔDIP and ΔDOP, is calculated by the following equations.

$$\Delta \mathrm{DIP} = \Big(V\frac{d\mathrm{DIP_i}}{dt} + V_R \mathrm{DIP_i} + R^*\left(\mathrm{DIP_i} - \mathrm{DIP_o}\right) - \mathrm{DIP_{LA}} - \mathrm{DIP_{RA}} - \mathrm{DIP_{RE}}\Big), \qquad (5)$$

$$\Delta \mathrm{DOP} = \Big(V\frac{d\mathrm{DOP_i}}{dt} + V_R \mathrm{DOP_i} + R^*\left(\mathrm{DOP_i} - \mathrm{DOP_o}\right) - \mathrm{DOP_{LA}} - \mathrm{DOP_{RE}}\Big), \qquad (6)$$

where $\mathrm{DIP_i}$ and $\mathrm{DOP_i}$ denote the average concentration of DIP and DOP in the bay, respectively, $\mathrm{DIP_o}$ and $\mathrm{DOP_o}$ those out of the bay, $\mathrm{DIP_{LA}}$ and $\mathrm{DOP_{LA}}$ loads of DIP and DOP from rivers, $\mathrm{DIP_{RA}}$ load of DIP from the rain and $\mathrm{DIP_{RE}}$ and $\mathrm{DOP_{RE}}$ release flux of DIP and DOP from the bottom sediment. Seasonal variations of $\mathrm{DIP_{LA}} + \mathrm{DIP_{RA}}$, $\mathrm{DIP_{RE}}$, $\mathrm{DOP_{LA}}$, $\mathrm{DOP_{RE}}$, DIP outflux $\{= V_R\mathrm{DIP_i} + R^*(\mathrm{DIP_i} - \mathrm{DIP_o})\}$ and DOP outflux $\{= V_R\mathrm{DOP_i} + R^*(\mathrm{DOP_i} - \mathrm{DOP_o})\}$ across the open boundary of the bay are shown in the upper panel of Fig. 6. DIP load from rivers and rain is largest in June when the precipitation is large but DIP release flux from the bottom sediment is larger than DIP load from rivers and rain in September when the oxygen defficieny develops in the lower layer of Hakata Bay. DIP outflux is large in September when R* is large, and it is also large in November and December when $\mathrm{DIP_i}$ is large. However, it is small in October when the difference of $\mathrm{DIP_i}$ and $\mathrm{DIP_o}$ is small. DOP

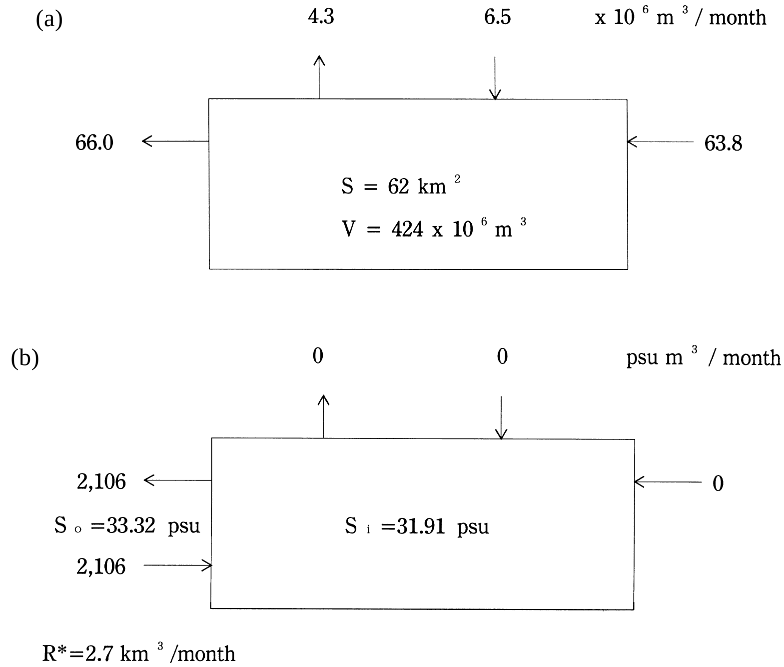

Fig. 5. Yearly average freshwater (a) and salinity (b) budgets of Hakata Bay.

outflux is large from June to December when V_R and R^* are large. DIP_{RE} and DOP_{RE} every month is linearly interpolated from the observed values in June, September, November and February.

A negative ΔDIP in Eq. (5) means that DIP is transformed to POP and/or DOP or absorbed to particles under the aerobic condition in the bay (Joh, 1987), and a positive value means that DIP is supplied from POP and/or DOP or from particles under anaerobic conditions (Joh, 1983). Seasonal variations of ΔDIP and ΔDOP are shown in the lower panel of Fig. 6. Negative ΔDIP, the internal sink of DIP, is large from June to October, but the positive one appears in November and December. The large internal sink of DIP suggests the occurrence of intense phytoplankton blooms in the bay from June to October. A positive ΔDIP in November and December may be related to the decomposition of DOP and POP.

If we assume that DIP variation by inorganic absorption to particles under aerobic conditions and that by supply from particles under anaerobic conditions nearly balance during one year, a system with positive ΔDIP is interpreted to be producing CO_2 in the water column via positive respiration (production – respiration < 0), while a system with negative ΔDIP is interpreted to be consuming CO_2 in the water column via positive organic production (production – respiration > 0).The yearly averaged ΔDIP is 15,084 kg month^{-1} = 487 kmol month^{-1} from Fig. 6. The internal sink of inorganic carbon ΔDIC related to ΔDIP is estimated by

$$\Delta DIC = \Delta DIP \times (C{:}P)_{part} \qquad (7)$$

where $(C{:}P)_{part}$ is the mole ratio of carbon to phosphorus of an organic particle. If we adopt the Redfield ratio of 106 as $(C{:}P)_{part}$ (because the main primary producer in Hakata Bay is phytoplankton but there is no observed data on the C:P mole ratio of phytoplankton there), ΔDIC becomes 51,628 kmol month^{-1} = 1,720 kmol day^{-1}. Such a carbon decrease in the water column corresponds to the absorption of atmospheric CO_2 at the rate of 20,640 kgC day^{-1} = 0.33 gC m^{-2}day^{-1}, provided we neglect the supply of inorganic carbon from the open ocean to Hakata Bay. This figure in Hakata Bay is larger than those in Tokyo Bay of 0.16 gC m^{-2}day^{-1} (Yanagi *et al*., 1993) and the East China Sea of 0.11 gC m^{-2}day^{-1} (Tsunogai *et al*., 1997).

ΔDOP takes large positive values from June to October and small negative values in other months except February, i.e. the generation of DOP dominates in the bay. In November, when ΔDOP takes a negative value, DIP concentration rapidly increases and both DOP and POP decrease in the bay, as shown in Fig. 6, i.e. not only DOP but also POP are decomposed to DIP.

The yearly average phosphorus budget is shown in Fig. 9(a). DIP load from rain, land and bottom of 25,000 kg month^{-1} is much larger than DOP load from land and bottom of 3,800 kg month^{-1} but DOP concentration is higher than DIP concentration in and out of Hakata Bay. ΔDIP takes a negative value but ΔDOP a positive one, i.e. the organic

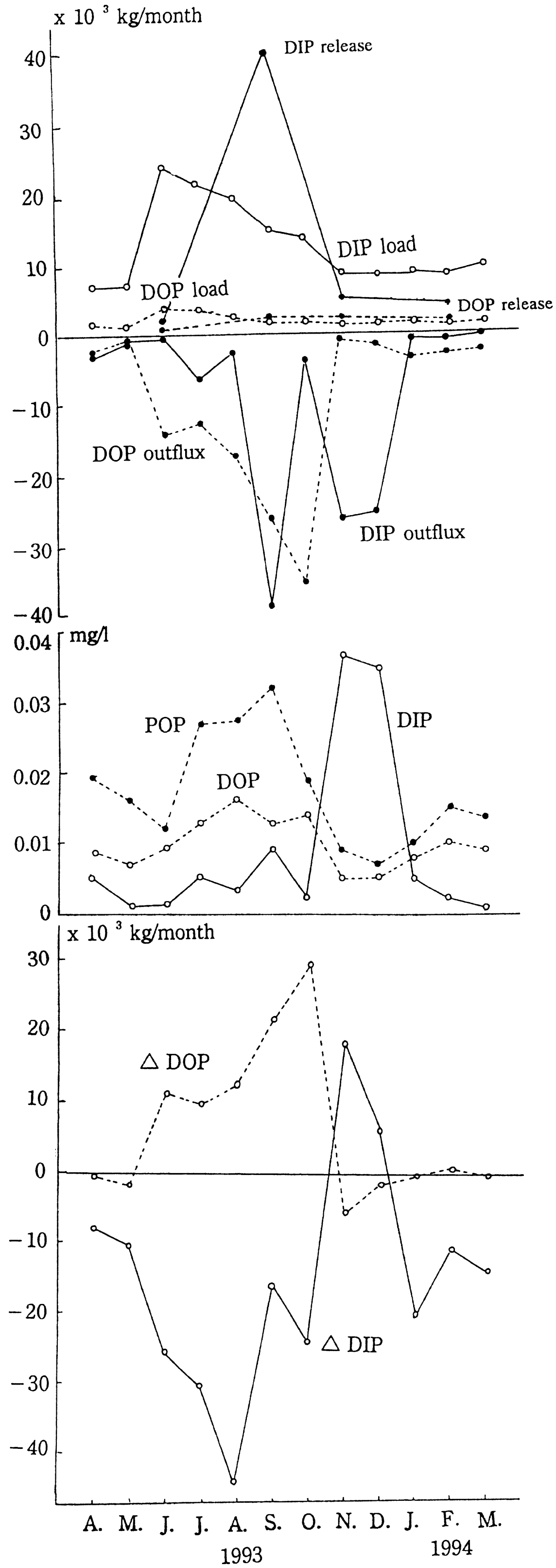

Fig. 6. Seasonal variations in DIP and DOP loads, DIP and DOP release flux, DIP and DOP exports from the bay, DIP, DOP and POP concentrations in the bay, and internal sink or source of DIP and DOP.

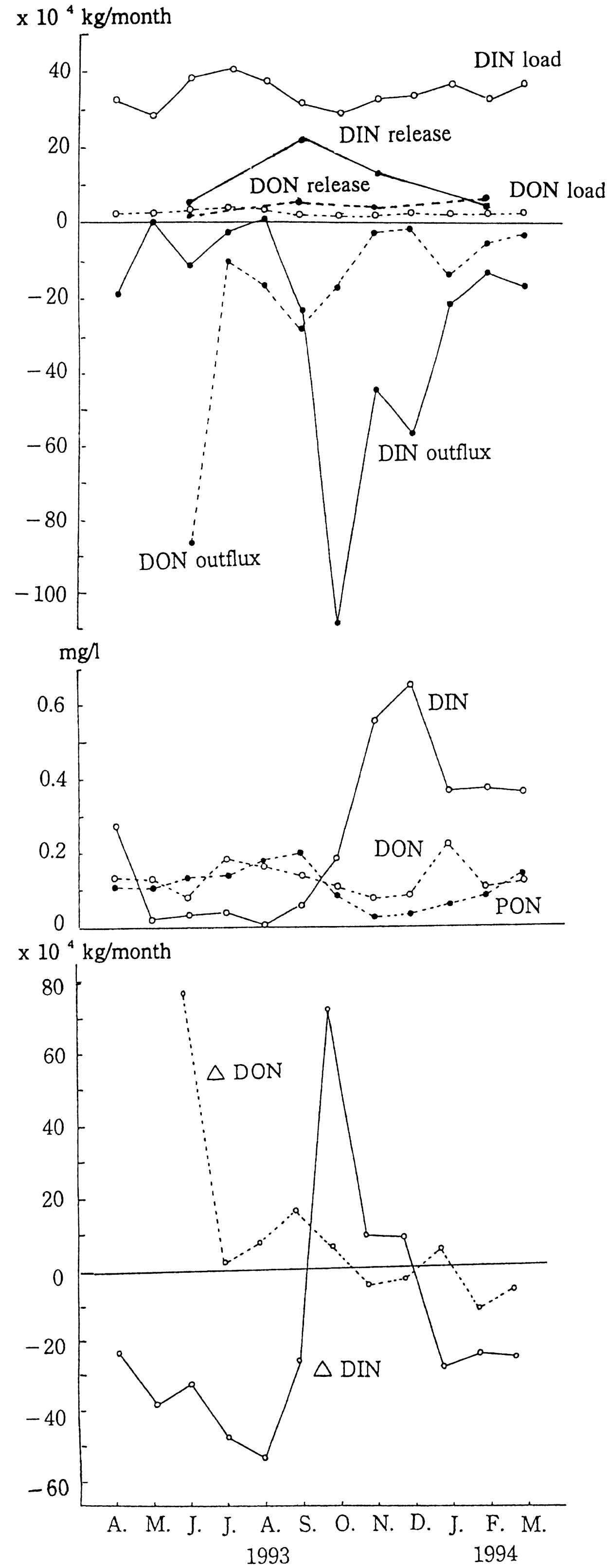

Fig. 7. Seasonal variations in DIN and DON loads, DIN and DON release flux, DIN and DON exports from the bay, DIN, DON and PON concentrations in the bay, and internal sink or source of DIN and DON.

production is larger than the respiration and DIP is transformed to DOP and/or POP in Hakata Bay by photosynthesis. Hakata Bay acts as a sink of DIP and the ratio of the internal sink of DIP to the DIP load ($DIP_{RA} + DIP_{LA} + DIP_{RE}$) is 60%. The burial flux of POP, 2,700 kg month^{-1}, is estimated from the sedimentation rate in Hakata Bay (0.090 g cm^{-2}year^{-1}) and the yearly averaged concentration of organic phosphorus of surface sediment in Hakata Bay (585 mg kg^{-1}), and the outflux of POP, 12,000 kg month^{-1}, by the total budget of phosphorus shown in Fig. 9(a).

4.4 Dissolved nitrogen budget

Seasonal variations of averaged DIN, DON and PON concentrations in the bay are shown in the middle panel of Fig. 7. DIN concentration is high in November and December when DON and PON concentrations are low, as shown in Fig. 6.

The internal sink or source of DIN and DON in the bay, ΔDIN and ΔDON, respectively, is calculated by the following equations.

$$\Delta DIN = \left(V\frac{dDIN_i}{dt} + V_R DIN_i + R^*\left(DIN_i - DIN_o\right) - DIN_{LA} - DIN_{RA} - DIN_{RE} \right), \quad (8)$$

$$\Delta DON = \left(V\frac{dDON_i}{dt} + V_R DON_i + R^*\left(DON_i - DON_o\right) - DON_{LA} - DON_{RE} \right), \quad (9)$$

where DIN_i and DON_i denote the average concentration of DIN and DON in the bay, respectively, DIN_o and DON_o those out of the bay, DIN_{LA} and DON_{LA} loads of DIN and DON from rivers, DIN_{RA} load of DIN from the rain, and DIN_{RE} and DON_{RE} the release flux of DIN and DON from the bottom, respectively. Seasonal variations of DIN_{LA} + DIN_{RA}, DON_{LA}, DIN outflux $\{=V_R DIN_i + R^*(DIN_i - DIN_o)\}$ and DON outflux $\{=V_R DON_i + R^*(DON_i - DON_o)\}$ across the open boundary of the bay are shown in the upper panel of Fig. 7. DIN load from rivers and rain does not show the dominant seasonal variation as that of DIP load and larger than DIN release flux from the bottom even in September. DON outflux and ΔDON cannot be estimated in April and May because the data DON_o are absent in these months. The DIN outflux shown in the upper panel of Fig. 7 is large from October to December when R^* is large and DIN_i is high.

Negative ΔDIN in Eq. (8) means that DIN is transformed to PON and/or DON in the bay or is lost by denitrification. Positive ΔDIN means that DIN is supplied from PON and/or DON mineralization and from air due to nitrogen fixation. Seasonal variations in ΔDIN and ΔDON are shown in the lower panel of Fig. 7. Negative ΔDIN is large from May to August, but a large positive value is found only in October when DON_i and PON_i decrease. ΔDON takes a large positive value only in June.

The dissolved nitrogen flux associated with production and decomposition of particulate material is estimated by the dissolved phosphorus flux (ΔDIP + ΔDOP) multiplied by $(N{:}P)_{part}$, where $(N{:}P)_{part}$ denotes the N:P mole ratio of particulate material in the system. The difference between nitrogen fixation and denitrification, (*nfix* – *denit*), is possible to estimate by the difference between the measured dissolved nitrogen flux (ΔDIN + ΔDON) and that expected from (ΔDIP + ΔDOP) $(N{:}P)_{part}$ if we assume that the generation or decomposition of POP is balanced by the disappearance or regeneration of (DIP + DOP).

$$(nfix - denit) = (\Delta DIN + \Delta DON) - (\Delta DIP + \Delta DOP)\,(N{:}P)_{part}, \quad (10)$$

where $(N{:}P)_{part}$ denotes the N:P mole ratio of organic particle in Hakata Bay, which is shown by full circles in Fig. 8. As Fig. 8 shows, denitrification predominates except in June, October and December. In June and October when large denitrification occurs, bacteria and/or benthic blue-green algae at the tidal flat which develops at the head of Hakata Bay are thought to play an important role in nitrogen fixation. Yearly average (*nfix* – *denit*) in Hakata Bay is –18,930 kg N month^{-1} = –0.73 mmol N m^{-2}day^{-1} = –10.2 mg N m^{-2}day^{-1}.

The yearly average nitrogen budget is shown in Fig.

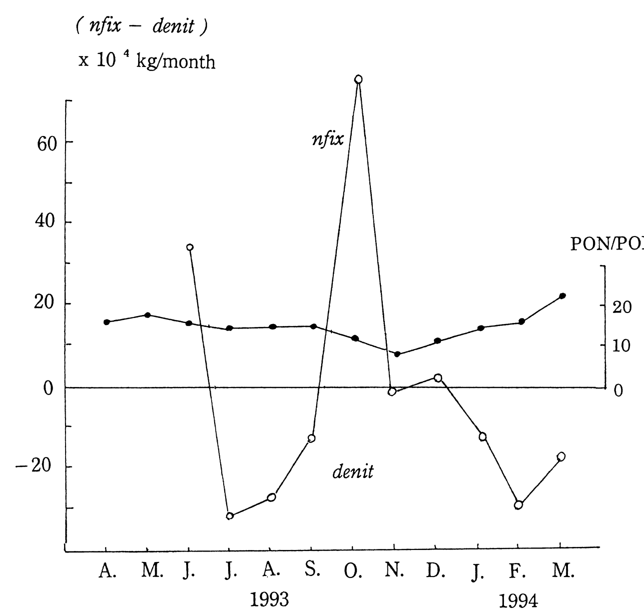

Fig. 8. Seasonal variations in (nitrogen fixation – denitrification) (open circle) and N:P mole ratio of PON/POP (full circle) of Hakata Bay.

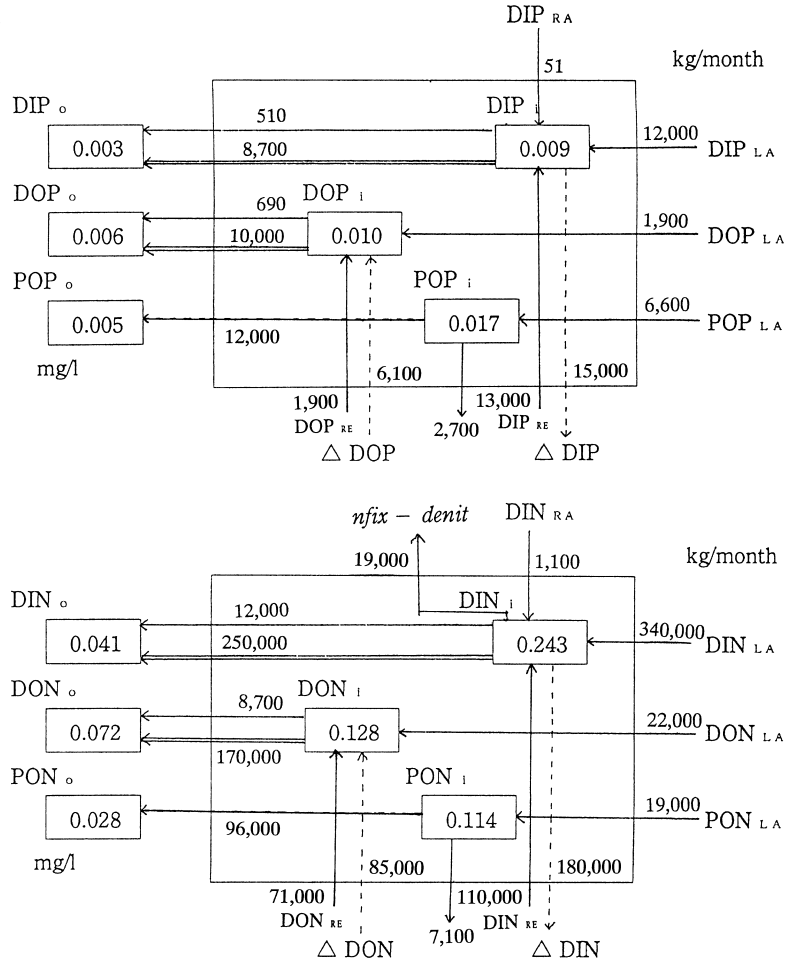

Fig. 9. Yearly average phosphorus and nitrogen budgets of Hakata Bay. Numbers show the flux in kg/month and numbers in the square concentration in mg/l.

9(b). DIN load from rain, rivers and sediment of 450,000 kg month^{-1} is much larger than DON load of 93,000 kg month^{-1} and DIN_i is higher than DON_i. However, DON_o is higher than DIN_o. Hakata Bay acts as a sink of DIN and the ratio of ΔDIN to DIN load ($DIN_{RA} + DIN_{LA} + DIN_{RE}$) is 40%, which is smaller than that of ΔDIP to DIP load of 60%. The burial flux of PON of 7,100 kg month^{-1} and outflux of PON of 96,000 kg month^{-1} in Fig. 9 are estimated in the same manner of POP.

The lower DIP_i than $DOP_i + POP_i$ and higher DIN_i than $DON_i + PON_i$, respectively shown in Fig. 9 suggest that the limiting nutrient for photosynthesis in Hakata Bay is not nitrogen but phosphorus. Seasonal variations in N:P mole ratio of DIN and DIP loads from rain and rivers, DIN and DIP concentrations in and out of the bay are shown in Fig. 10. N:P ratio of DIN and DIP loads is always higher than the Redfield ratio of 16. N:P ratio of DIN_i and DIP_i is lower than 16 only during July to September, the summer season, in Hakata Bay. This fact suggests that DIN may become the limiting factor of photosynthesis in Hakata Bay only during the summer season, probably due to intense denitrification, as shown in Fig. 8.

Figure 10 also suggests that the reduction of phosphorus load from land is more effective than that of nitrogen load as a countermeasure of eutrophication prevention in Hakata Bay because the limiting nutrient of photosynthesis in the bay is phosphorus.

5. Comparison with Tokyo and Mikawa Bays

Matsukawa and Suzuki (1985) investigated the phosphorus and nitrogen budgets in Mikawa Bay by the box model analysis and Matsukawa and Sasaki (1990) studied the nitrogen budget in Tokyo Bay by the same method. We compare the results of three nitrogen budgets in Tokyo, Mikawa and Hakata Bay (Table 1). Here the volumes of Tokyo and Mikawa Bays correspond to the inner boxes of Matsukawa and Suzuki (1985) and Matsukawa and Sasaki (1990), respectively. TN load from the rain and land per unit

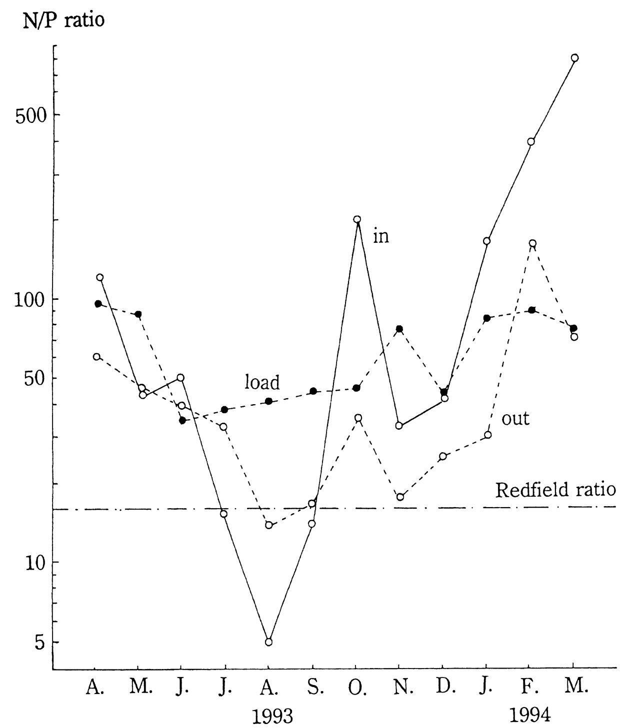

Fig. 10. Seasonal variations in N:P mole ratio of DIN and DIP load, DIN and DIP stocks in the bay and those out of the bay.

bay volume is largest and TN concentration is highest in Tokyo Bay. The ratio of TN concentration in Hakata Bay to that in Tokyo Bay is 0.43, though the ratio of TN load is 0.74, as shown in parentheses in Table 1. On the other hand, the ratio of TN concentration in Mikawa Bay to that in Tokyo Bay is 0.39, though the ratio of TN load is 0.27. These facts mean that Hakata Bay is harder to eutrophicate and Mikawa Bay is easier to eutrophicate than Tokyo Bay, i.e. TN concentration in Hakata Bay becomes lower, and that in Mikawa Bay higher than Tokyo Bay for the same unit TN load. This is reflected in the difference of average residence time of TN in these three bays, viz., average residence time of TN is longest in Mikawa Bay and shortest in Hakata Bay.

On the other hand, DIN concentration is highest in Hakata Bay and lowest in Mikawa Bay and the ratio of DIN concentration to TN concentration is highest in Hakata Bay and lowest in Tokyo Bay. This may be due to the differences of water depth and flow system of the three bays. The average water depth of Tokyo Bay is 20 m and in Mikawa and Hakata Bays it is about 7 m. Estuarine circulation is strongest in Hakata Bay and weakest in Mikawa Bay because the unit freshwater discharge is largest in Hakata Bay (0.152 month^{-1}) and smallest in Mikawa Bay (0.077 month^{-1}) as shown in Table 1. Much PON and/or DON exists in the lower layer without decomposition in Tokyo Bay, but PON and/or DON are quickly decomposed in the shallow Mikawa and Hakata Bays, especially in Hakata

Table 1. Comparison of nitrogen budgets in Tokyo, Mikawa and Hakata Bays.

	Volume $\times 10^9$ m^3	TN load ton/month	load/volume $\times 10^{-9}$ ton/m^3/month	TN μg/l	DIN μg/l	DIN/TN %	τ_{TN} days	Freshwater load $\times 10^6$ m^3/month	Freshwater load/volume /month	τ_f days	Reference
Tokyo Bay	7.34	9,000	1,230 (1.00)	1,123 (1.00)	216	19	27	778	0.106 (1.00)	13	Matsukawa and Sasaki (1990)
Mikawa Bay	0.70	229	327 (0.27)	440 (0.39)	100	23	40	53.6	0.077 (0.73)	40	Matsukawa and Suzuki (1985)
Hakata Bay	0.42	384	906 (0.74)	485 (0.43)	243	50	16	63.8	0.152 (1.43)	8	

Bay, where strong upwelling near the head of the bay, accompanied by strong estuarine circulation, advects PON and DON in the lower layer to the upper layer and they are decomposed to DIN. Such a situation is reflected in the shortest residence time of freshwater in Hakata Bay.

We have to carry out a detailed comparison of these three eutrophicated bays using a numerical ecosystem model in order to examine quantitatively the physical and biochemical processes related to eutrophication mechanism in the semi-enclosed coastal sea.

The sampling interval of 1 month in this study is much longer than the average residence time of freshwater of 8 days in Hakata Bay. Weekly data are desirable for such box model analyses but it is very difficult to obtain such kinds of physical and biochemical data at many points every week, throughout the year. In order to clarify the detailed physical and biochemical processes in Hakata Bay, we will try to obtain physical and biochemical data every week during a limited period, e.g. the typical summer and winter seasons. Moreover, we have to develop a numerical ecosystem model which can help the analysis and interpretation of observed data.

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