Journal of Oceanography
Vol. 49, pp. 249 to 256. 1993

A Carbon Budget in Tokyo Bay

Tetsuo Yanagi[1], Toshiro Saino[2], Takashi Ishimaru[3] and Shin-ichi Uye[4]

[1]*Department of Civil and Ocean Engineering, Ehime University, Matsuyama 790, Japan*
[2]*Ocean Research Institute, University of Tokyo, Minami-dai 1-15-1, Nakano-ku, Tokyo 130, Japan*
[3]*Tokyo University of Fisheries, Konan 4-5-7, Minato-ku, Tokyo 108, Japan*
[4]*Faculty of Applied Biological Science, Hiroshima University, Higashi-Hiroshima 724, Japan*

(Received 23 June 1992; in revised form 17 August 1992; accepted 1 September 1992)

Organic carbon flux from eutrophicated Tokyo Bay to the Pacific Ocean is estimated as 260 ton C day^{-1} based on the horizontal gradient of COD and the dispersion coefficient at the bay mouth. Also, carbon flux from the air or from the open ocean to Tokyo Bay is estimated as 156 ton C day^{-1}. If we suppose that five percent of the coastal seas in the world might be eutrophicated as Tokyo Bay and the organic carbon flux from the shelf to the open ocean in other coastal seas might be one third of that in Tokyo Bay, 1.12 G tons year^{-1} would be transported from the eutrophicated coastal seas to the open ocean and such carbon flux may account for the "missing sink" in the global carbon budget.

1. Introduction

As for the global carbon cycling, 1.55 Gt/year (G is 10^9) of carbon is missing from the air (Walsh *et al*., 1981). Walsh *et al*. (1981) pointed out that the annual loss of organic carbon from the continental shelf ecosystem to the open sea may represent this "missing sink" in global CO_2 reserves. It is interesting to assess this hypothesis by actual estimation of organic carbon flux in the continental shelf waters where the primary production is generally high, although this hypothesis was rejected in the Mid-Atlantic Bight by Rowe *et al*. (1986).

Tokyo Bay is a heavily eutrophicated inlet and hence it represents a climax of coastal ecosystem. We attempt to reveal the carbon budget in this bay with the use of observational data to estimate the organic carbon flux from the bay to the adjacent Pacific Ocean.

2. Carbon Budget in Tokyo Bay

Tokyo Bay is situated in the central part of Japan (Fig. 1) and is well known as one of the most eutrophicated embayments in Japan. The year-to-year variations in yearly-averaged concentrations of COD (Chemical Oxygen Demand) and nutrients in the surface water of Tokyo Bay are shown in Fig. 2 (Unoki and Kishino, 1977). Concentrations of nutrients increased steeply between 1965 and 1970, and was nearly constant between 1970 and 1974. Concentrations of total inorganic nitrogen (NH_4–N, NO_2–N and NO_3–N) and of phosphate in the surface water did not change much until recently although we do not have sufficient data. For example, concentrations of NH_4, NO_2, NO_3 and PO_4–P in the surface water of the central part of Tokyo Bay were 13.0 μM, 4.5 μM, 22.0 μM and 1.8 μM, respectively, in November 1985 (Saino, 1988).

2.1 Influx and efflux

The influx of COD from the land to Tokyo Bay through rivers is estimated based on the "Unit-Loading-Factor" method, which represents COD loaded by a human being per day (Ogura,

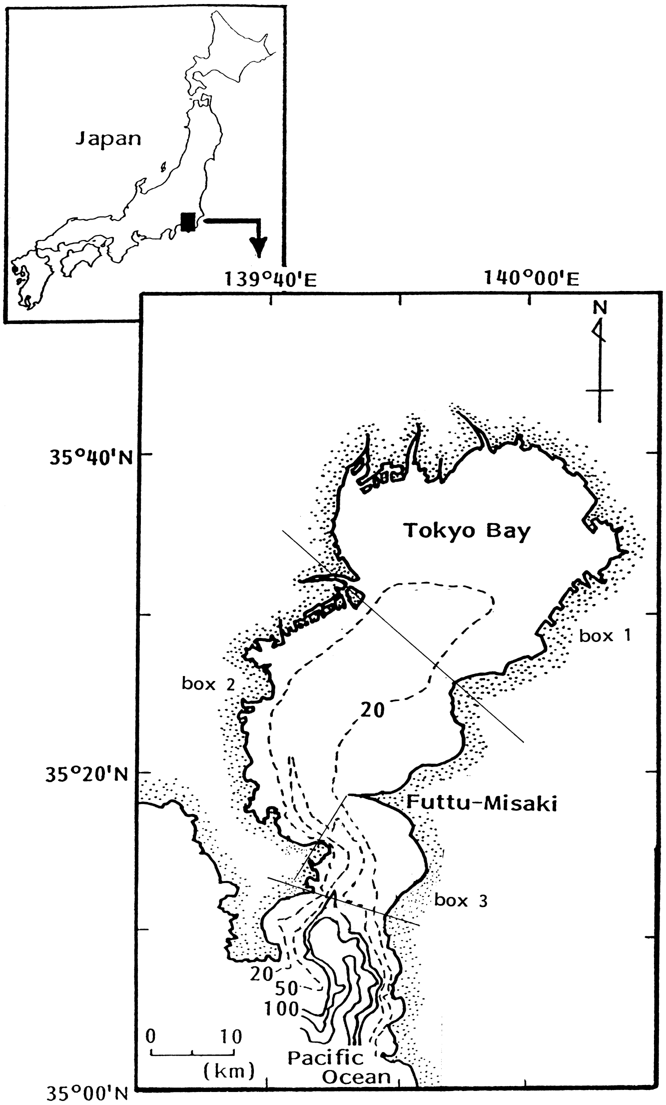


Fig. 1. Tokyo Bay.

1979). The year-to-year variation in COD load to Tokyo Bay is shown in Fig. 3. It dramatically decreased between 1971 and 1975 and stayed nearly the same after 1975, being 350 t day^{-1} (Ogura and Takada, 1991). Ogura (1979) obtained an empirical relation between the concentrations of organic carbon and COD, that is, 1 mg C l^{-1} = 1.6 mg O_2 l^{-1}. On the basis of his result, COD load of 350 t day^{-1} is equivalent to the organic carbon influx of 2.19×10^8 g C day^{-1}.

The burial flux of organic carbon can be obtained by multiplying the sedimentation rate of the surface sediment and the concentration of organic carbon in the surface (0–5 cm) sediment (Fig. 4, Matsumoto, 1983). The burial flux of organic carbon thus estimated is 1.15×10^8 g C day^{-1}. It is equivalent to 0.12 g C m^{-2} day^{-1} because the surface area of Tokyo Bay is 956 km^2.

The efflux of organic carbon from Tokyo Bay to the Pacific Ocean through a bay mouth can

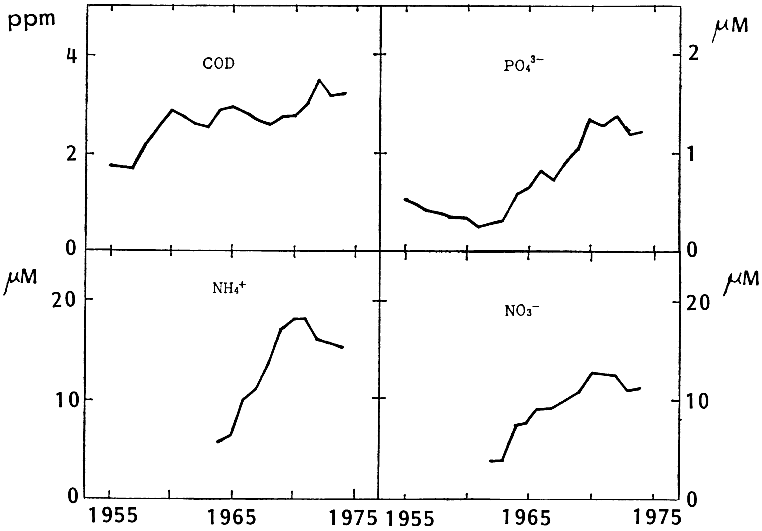


Fig. 2. Year-to-year variations in concentrations of nutrients in the surface water at the central part of Tokyo Bay (Unoki and Kishino, 1977).

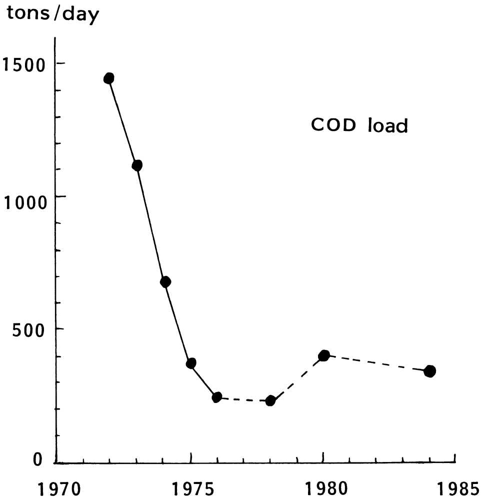
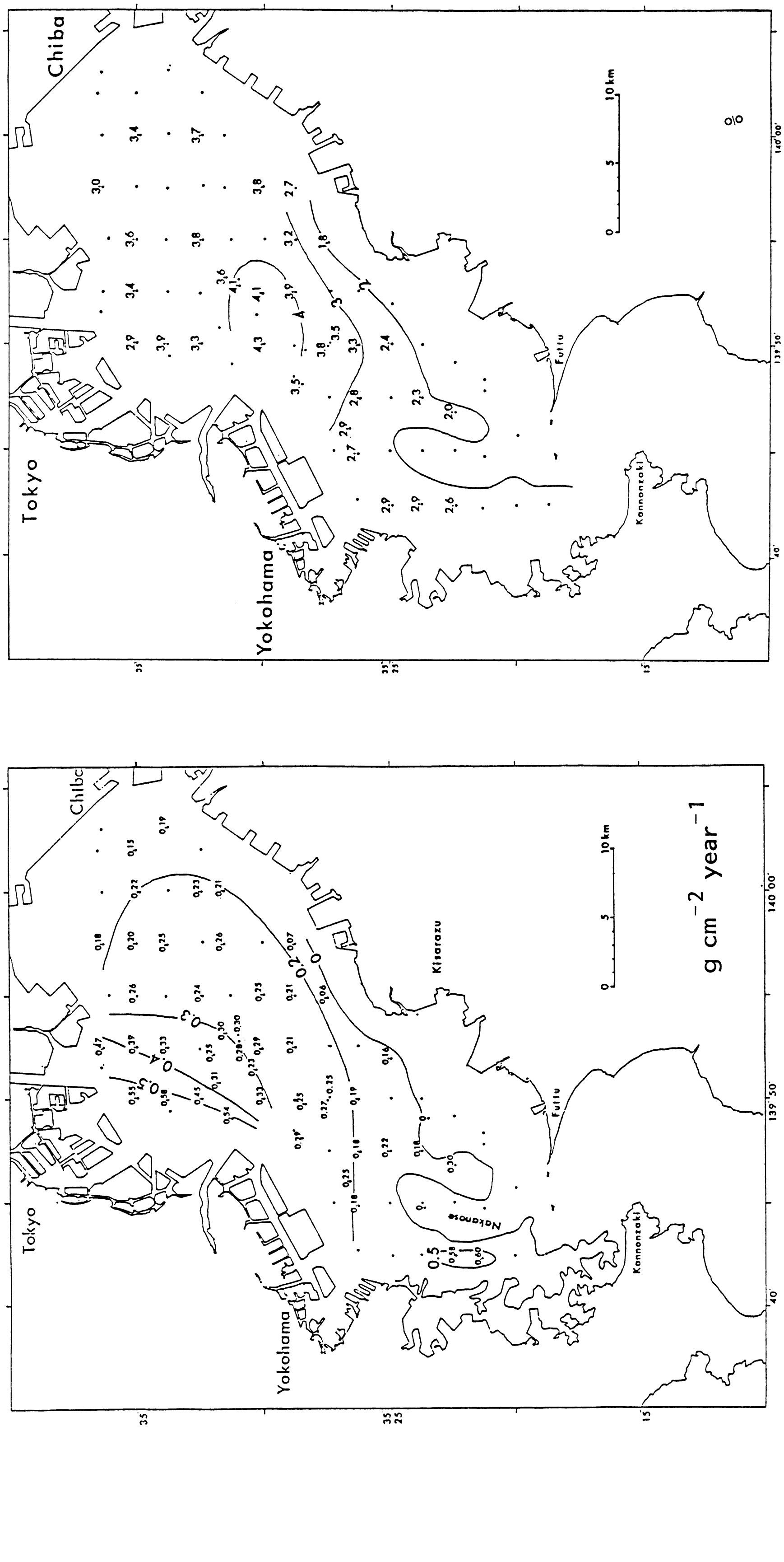


Fig. 3. Year-to-year variation in COD load to Tokyo Bay.

be estimated by multiplying the horizontal gradient of COD concentration between inside (box 2 in Fig. 1) and outside (box 3 in Fig. 1) of the bay, the cross-area of the bay mouth (= 0.22 km^2) and the dispersion coefficient at the mouth (= 5.38×10^6 cm^2 sec^{-1}, Unoki and Kishino, 1977). The seasonal variations in averaged COD concentrations in the box 1, 2 and 3 of Tokyo Bay in 1979 and 1980 are shown in Fig. 5 (Japan Fishery Resources Preservation Agency, 1987). The number of observation stations in box 1, 2 and 3 are 15, 7 and 2, respectively. The seasonal variation in COD concentration is large in the upper layer (<10 m) though it is small in the lower layer (>10 m). The gradient of COD concentration at the bay mouth is 4.0×10^{-7} mg l^{-1} cm^{-1}



(b)

(a)

Fig. 4. Sedimentation rate (a) and concentration of organic carbon (b) in surface sediment in Tokyo Bay (Matsumoto, 1985).

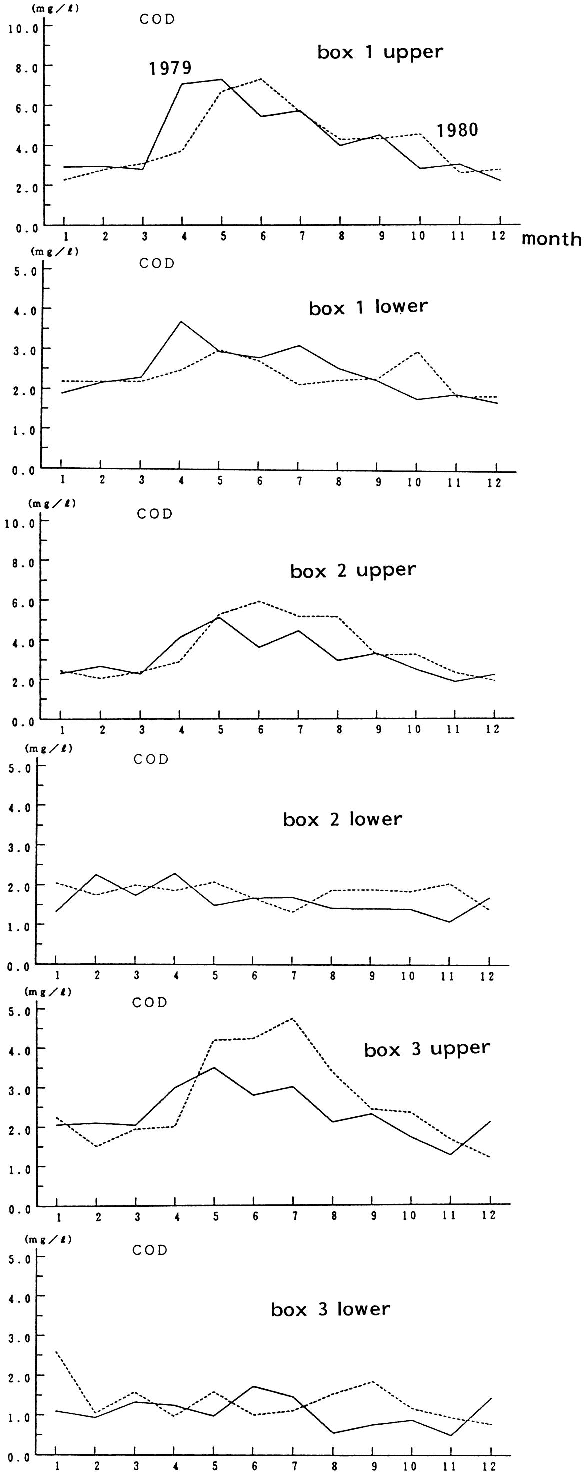


Fig. 5. Seasonal variations in the concentration of COD in the upper and lower layers of boxes 1, 2 and 3 in Tokyo Bay (Japan Fishery Resources Preservation Agency, 1987).

because the average concentration of COD in box 2 is 2.7 mg l^{-1} and that in box 3 is 1.9 mg l^{-1} and the length between both boxes is 20 km. The resultant average efflux of the organic carbon in 1979 and 1980 was 2.60×10^8 g C day^{-1}.

Therefore, the influx of carbon from the air or from the open ocean to Tokyo Bay is calculated as a subtraction of the riverine input from the total output from the sea bed and bay mouth and it is 1.56×10^8 g C day^{-1}.

2.2 Cycling

In this section, we consider the organic carbon cycling in Tokyo Bay. We confined the carbon cycling to the lower trophic levels to avoid a complexity of the processes. Published data on the primary production in Tokyo Bay measured by ^{14}C method and other techniques fall within the range of 1–20 g C m^{-2} day^{-1} ($9.56–191 \times 10^8$ g C day^{-1}) and the primary production is higher (4–20 g C m^{-2} day^{-1}) during periods of red tide outbreaks (Hunakoshi *et al.*, 1974; Yamaguchi and Shibata, 1979; Shibata and Aruga, 1982).

The grazing rate of phytoplankton by macro- (retained by a plankton net with ca. 100 μm mesh opening) and microzooplankton (<100 μm) is estimated based on their biomasses determined in summer of 1990 (Uye, unpublished) and an empirical relationship with size. The grazing rate of phytoplankton by macrozooplankton is 1.12×10^8 g C day^{-1} and by microzooplankton 19.9×10^8 g C day^{-1}. The production rates of fecal pellets by macro- and microzooplankton are 0.40×10^8 g C day^{-1} and 5.9×10^8 g C day^{-1}, respectively. The respiration rates by macro- and microzooplankton are 0.52×10^8 g C day^{-1} and 7.9×10^8 g C day^{-1}, respectively.

The sinking particles which was caught at 20 m in the central part of Tokyo Bay in June, July and August 1988 by sediment traps were estimated as 458–1,122 mg C m^{-2} day^{-1} ($4.38–10.7 \times 10^8$ g C day^{-1}) by Sasaki *et al.* (1989).

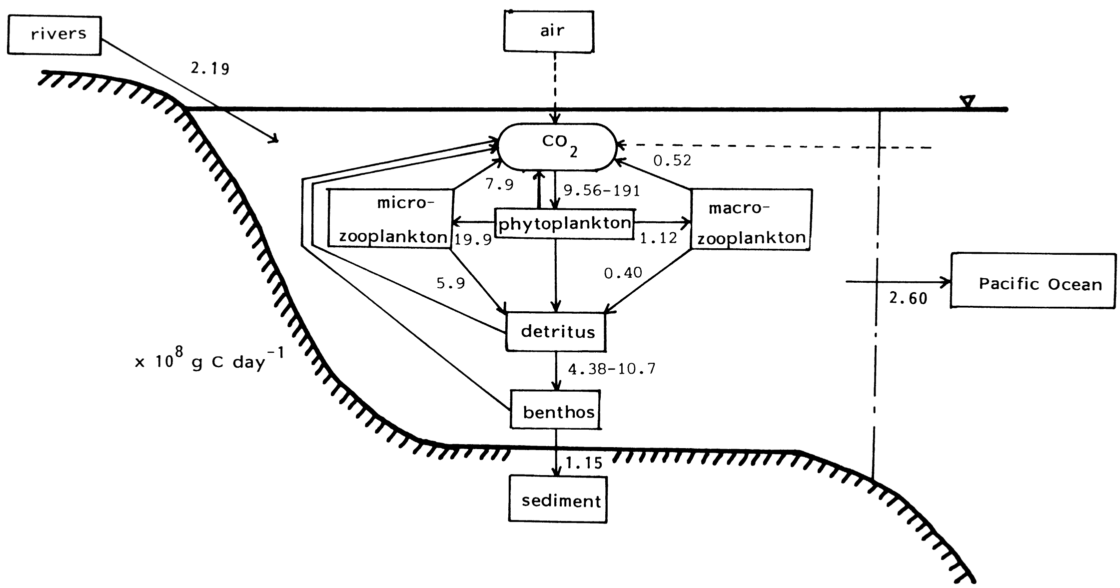


Fig. 6. A carbon budget in Tokyo Bay.

Although we have no quantitative data available in the rate process from detritus or benthos to CO_2 (which may represent respiration rates by bacteria or benthos), a general picture of the carbon cycling in Tokyo Bay may be considered as that shown in Fig. 6.

The total mass of organic carbon in Tokyo Bay can be estimated from Fig. 5 and it is 33,800 ton. The residence time of organic carbon in Tokyo Bay can be obtained by dividing the mass of organic carbon by the efflux of organic carbon through sea bed and bay mouth. It is $33{,}800/(2.60 + 1.15) \times 10^2 = 90$ days = 3.0 month and is twice greater than those of phosphorus (1.4 month) and nitrogen (1.5 month) (Matsumoto, 1985). Such facts suggests that the cycling of organic carbon is much slower than those of phosphorus and nitrogen in Tokyo Bay. The refractory parts of organic carbon is larger than those of phosphorus and nitrogen and they sink to the lower layer being advected to the head of Tokyo Bay.

3. Relation to the Global Carbon Budget

The total area of continental shelf waters of the world is 30×10^6 km^2 (Walsh *et al*., 1981). Not only Tokyo Bay, but also the coastal areas such as Ise Bay and Osaka Bay in Japan, Chinhae Bay in Korea, the head of the Gulf of Thailand, southern part of the North Sea and the Baltic Sea are well known as the eutrophicated waters. If we assume that five percent of the world continental shelf waters might become eutrophicated and the organic carbon flux from the shelf to the open ocean in such eutrophicated waters might be the same as that in Tokyo Bay, and the organic carbon flux from the shelf to the open ocean in other areas might be one third of that in Tokyo Bay, the total carbon flux from continental shelf to the open sea would be estimated as 2.6×10^8 g C day^{-1}/956 km$^2 \times 1.5 \times 10^6$ km^2 + $2.6/3 \times 10^8$ g C day^{-1}/956 km$^2 \times 28.5 \times 10^6$ km^2 = 1.12×10^{15} g C year^{-1} (1.12 G tons C year^{-1}). This value is nearly the same as that of "missing sink" in global carbon budget.

We admit that the picture of carbon flux in Tokyo Bay shown in Fig. 6 is rather rough and need more detailed analysis, e.g. the exact relation between the concentrations of organic carbon and COD, the role of DOC (Dissolved Organic Carbon) and the observed value of pCO_2 in Tokyo Bay, but we would like to point out here the possibility that the organic carbon flux from the eutrophicated coastal seas to the adjacent open ocean may account for the "missing sink" in the global carbon budget.

Acknowledgements

The authors express their sincere thanks to Dr. Y. Suzuki of Meteorological Institute, Japan, Dr. S. Montani of Kagawa University, Dr. K. Iseki of Seikai National Fisheries Research Institute, Prof. N. Handa of Nagoya University and Prof. S. Tsunogai of Hokkaido University for their valuable discussions. This study was supported, in part, by the scientific research fund (04232217) defrayed by The Ministry of Education, Science and Culture, Japan.

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