

# A One-hundred-year Succession of Planktonic and Tychopelagic Diatoms from 20th Century Tokyo Bay

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**Abstract** A distinctive change in the diatom flora of central Tokyo Bay is identified in a sediment core spanning the last one hundred years. The shift is attributed to an ongoing eutrophication process. The change, which took place around 1960, is characterized by a change in the diatom assemblage, from diatoms commonly found in waters entering the bay from the North Pacific through a channel in the bay's southern reaches, to those generally abundant in waters influenced by freshwater and nutrient inputs from large rivers flowing into the northwestern part of the bay. High fluxes of *Thalassionema nitzschioides* and moderate fluxes of *Bacteriastrum* species, *Odonella longicruris* and *Thalassionema frauenfeldii*, are evident in the pre-1950 flora, whereas *Skeletonema costatum* is highly abundant and *Thalassiosira allenii* and *Thalassiosira binata* moderately abundant in the post-1965 flora.

**Key words:** Tokyo Bay, Diatom, the 20th century.

## Introduction

Since the 1940s, Tokyo Bay has become increasingly eutrophic (Kamatani, 1993; Nomura, 1995; Matsumura *et al.*, 2001), as a result of increasing nutrient influx caused by intensive human activities in the catchment area of major rivers flowing into the bay. This has resulted in a drastic change in the hydrochemistry and phytoplankton ecology of the bay (e.g., Furota, 1997; Yamaguchi, 1997).

Tanimura *et al.* (2001) identified geographic variations in both diatom flux and diatom species abundance in surface sediment of the bay, providing a first step towards understanding the diatom responses to the nutrient increase. Together, the data from surface sediment and from analyses of changing total diatom fluxes and diatom-species fluxes in sediment cores will provide a picture of diatom population responses to eutrophication, which can then serve as a modern analogue for

changes in diatom assemblages resulting from eutrophication processes in the geologic past.

Sediment core G79-10, containing diatoms deposited in the past 120 years, was collected from the central part of the bay in 1979, during cruise G-79 of the Geological Survey of Japan. This paper presents the results of diatom flux analyses carried out on 10 sediment samples from the core, and discusses the succession of diatom floras that characterize the eutrophication process.

## Materials and Methods

Core G79-10 was taken from the central part of Tokyo Bay at lat. 139°50'N, long. 35°27.5'E, in 31 m of water depth. For this diatom study, ten samples were taken from the core (Table 1). Each sample was diluted with distilled water to obtain a suspension of appropriate density, and then the suspension was dried on a 18×18 mm cover slip. Dried diatom valves were mounted with StyraX.

Table 1. Stratigraphic distribution of planktonic and tychopelagic diatom species in core G79-10.

| Diatom taxa/depth (cm)                                                                                                                                    | 0–3  | 3–8  | 8–13 | 13–18 | 18–23 | 28–33 | 38–43 | 48–53 | 58–63 | 68–73 |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------|------|------|-------|-------|-------|-------|-------|-------|-------|
| <i>Actinocyclus curvatulus</i>                                                                                                                            | 7    | 3    | 2    | 1     | 1     | 1     | 2     | 1     | 3     | 5     |
| <i>Actinocyclus octonarius</i>                                                                                                                            | 9    | 7    | 6    | 8     | 12    | 9     | 4     | 5     | 5     | 6     |
| <i>Actinocyclus</i> spp.                                                                                                                                  |      |      |      |       | 1     |       |       |       |       |       |
| <i>Actinoptychus senarius</i>                                                                                                                             | 11   | 6    | 9    | 7     | 6     | 5     | 7     | 9     | 10    | 11    |
| <i>Actinoptychus splendence</i>                                                                                                                           | 1    | 2    | 2    | 2     | 2     | 4     | 3     | 6     | 6     | 2     |
| <i>Asterolampira</i> sp.                                                                                                                                  |      |      |      |       |       |       |       |       | 1     |       |
| <i>Asteromphalus</i> spp.                                                                                                                                 | 1    | 1    |      | 1     |       | 1     |       |       | 1     | 1     |
| <i>Auliscus</i> sp.                                                                                                                                       | 4    | 1    | 1    | 2     |       |       | 1     |       | 2     |       |
| <i>Bacteriastrum</i> spp.                                                                                                                                 | 3    | 6    | 1    | 4     | 3     | 2     | 13    | 19    | 11    | 18    |
| fluxes                                                                                                                                                    | 0.14 | 0.36 | 0.06 | 0.27  | 0.26  | 0.13  | 0.87  | 0.91  | 0.53  | 1.19  |
| <i>Chaetoceros</i> species, including<br><i>C. didymus</i> , <i>C. lorenzianus</i> ,<br><i>C. pseudocurvisetus</i> and fragile<br><i>Chaetoceros</i> spp. | 79   | 62   | 53   | 44    | 39    | 46    | 49    | 100   | 80    | 79    |
| fluxes                                                                                                                                                    | 3.67 | 3.74 | 3.11 | 2.96  | 3.40  | 2.90  | 3.27  | 4.78  | 3.88  | 5.23  |
| <i>Coscinodiscus asteromphalus</i>                                                                                                                        | 3    | 3    | 6    | 2     | 1     | 2     | 2     |       |       |       |
| <i>Coscinodiscus oculus-iridis</i>                                                                                                                        | 1    | 1    | 5    | 5     | 2     | 4     | 3     | 3     |       |       |
| <i>Coscinodiscus wailesii</i>                                                                                                                             |      |      | 1    |       |       |       |       |       |       |       |
| <i>Coscinodiscus</i> spp.                                                                                                                                 | 8    | 8    | 2    | 3     | 4     | 3     |       | 3     | 3     | 3     |
| <i>Cyclotella</i> spp. ( <i>C. meneghiniana</i> ,<br><i>C. striata</i> and unidentified small<br><i>Cyclotella</i> spp.)                                  | 80   | 63   | 51   | 61    | 62    | 52    | 49    | 57    | 53    | 69    |
| fluxes                                                                                                                                                    | 3.72 | 3.80 | 2.99 | 4.11  | 5.40  | 3.28  | 3.27  | 2.73  | 2.57  | 4.57  |
| <i>Cyclotella</i> sp. <i>c</i>                                                                                                                            | 12   | 12   | 16   | 15    | 15    | 8     | 3     | 7     | 7     | 8     |
| fluxes                                                                                                                                                    | 0.56 | 0.72 | 0.94 | 1.01  | 1.31  | 0.51  | 0.20  | 0.33  | 0.34  | 0.53  |
| <i>Eucampia zodiacus</i>                                                                                                                                  | 2    |      | 4    | 4     | 6     | 5     | 2     | 3     | 3     | 1     |
| <i>Grammatophora</i> spp.                                                                                                                                 | 1    | 2    | 1    |       |       |       | 1     |       |       | 1     |
| <i>Hemiaulus</i> sp.                                                                                                                                      |      |      |      |       |       |       | 1     | 3     | 4     |       |
| <i>Lithodesmium variable</i>                                                                                                                              | 18   | 7    | 11   | 9     | 10    | 10    | 13    | 6     | 3     | 5     |
| fluxes                                                                                                                                                    | 0.84 | 0.42 | 0.64 | 0.61  | 0.87  | 0.63  | 0.87  | 0.29  | 0.15  | 0.33  |
| <i>Navicula britannica</i>                                                                                                                                | 16   | 3    | 2    | 7     | 6     | 3     | 1     | 4     |       | 3     |
| fluxes                                                                                                                                                    | 0.74 | 0.18 | 0.12 | 0.47  | 0.52  | 0.19  | 0.07  | 0.19  |       | 0.20  |
| <i>Neodelphineis indica</i>                                                                                                                               | 9    | 2    | 2    | 2     |       | 8     | 5     | 1     | 1     | 1     |
| <i>Neodelphineis pelagica</i>                                                                                                                             | 21   | 8    | 28   | 15    | 20    | 136   | 51    | 4     | 2     | 2     |
| fluxes                                                                                                                                                    | 0.98 | 0.48 | 1.64 | 1.01  | 1.74  | 8.59  | 3.40  | 0.19  | 0.10  | 0.13  |
| <i>Nitzschia bicaipitata</i> and <i>N. bifurcata</i>                                                                                                      | 2    | 2    | 2    |       |       | 2     | 3     |       | 4     |       |
| <i>Nitzschia pungens</i>                                                                                                                                  | 17   | 21   | 17   | 9     | 16    | 13    | 6     | 8     | 1     | 5     |
| fluxes                                                                                                                                                    | 0.79 | 1.27 | 1.00 | 0.61  | 1.39  | 0.82  | 0.40  | 0.38  | 0.05  | 0.33  |
| <i>Nitzschia</i> spp.                                                                                                                                     | 3    | 3    | 3    | 3     | 1     |       | 5     |       | 4     | 4     |
| <i>Odontella longicuris</i>                                                                                                                               | 5    | 7    | 4    | 5     | 1     | 8     | 14    | 23    | 18    | 11    |
| fluxes                                                                                                                                                    | 0.23 | 0.42 | 0.23 | 0.34  | 0.09  | 0.51  | 0.93  | 1.10  | 0.87  | 0.73  |
| <i>Odontella</i> spp.                                                                                                                                     | 1    | 1    | 1    | 2     | 2     | 4     | 7     | 15    | 5     | 3     |
| <i>Paralia sulcata</i>                                                                                                                                    | 2    | 10   | 2    | 2     | 3     | 1     |       | 4     | 1     |       |
| <i>Podosira</i> sp.                                                                                                                                       |      | 2    |      |       |       |       |       |       |       |       |
| <i>Pleurosigma</i> spp.                                                                                                                                   | 3    |      | 1    | 1     | 1     |       | 4     | 5     | 12    | 7     |
| <i>Proboscia alata</i>                                                                                                                                    |      |      |      | 1     | 1     |       | 1     | 1     | 3     |       |
| <i>Proboscia</i> sp.                                                                                                                                      |      |      |      |       |       |       | 1     |       |       |       |
| <i>Rhizosolenia hebetata</i>                                                                                                                              |      |      |      |       |       |       |       |       |       | 1     |
| <i>Rhizosolenia imbricata</i>                                                                                                                             |      |      |      |       |       |       | 1     |       | 1     |       |

Table 1. (Continued).

| Diatom taxa/depth (cm)                                                                     | 0–3   | 3–8   | 8–13  | 13–18 | 18–23 | 28–33 | 38–43 | 48–53 | 58–63 | 68–73 |
|--------------------------------------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| <i>Rhizosolenia setigera</i>                                                               | 35    | 12    | 39    | 14    | 11    | 23    | 14    | 17    | 15    | 10    |
| fluxes                                                                                     | 1.63  | 0.72  | 2.29  | 0.94  | 0.96  | 1.45  | 0.93  | 0.81  | 0.73  | 0.66  |
| <i>Rhizosolenia styliiformis</i>                                                           | 2     |       |       |       |       |       |       |       |       |       |
| <i>Rhizosolenia</i> spp.                                                                   |       |       |       | 1     |       |       | 2     | 1     |       |       |
| <i>Skeletonema costatum</i> and<br><i>S. pseudocostatum</i>                                | 464   | 353   | 364   | 380   | 233   | 126   | 115   | 196   | 141   | 117   |
| fluxes                                                                                     | 21.57 | 21.27 | 21.34 | 25.58 | 20.30 | 7.96  | 7.67  | 9.38  | 6.84  | 7.74  |
| <i>Thalassionema bacillare</i>                                                             |       | 2     |       | 1     |       |       |       | 5     | 10    | 5     |
| <i>Thalassionema frauenfeldii</i>                                                          | 19    | 13    | 6     | 12    | 17    | 32    | 34    | 50    | 49    | 34    |
| fluxes                                                                                     | 0.88  | 0.78  | 0.35  | 0.81  | 1.48  | 2.02  | 2.27  | 2.39  | 2.38  | 2.25  |
| <i>Thalassionema nitzschioides</i> sensu<br>lato, incl. <i>T. pseudonitzschioides</i>      | 100   | 89    | 124   | 77    | 144   | 266   | 255   | 367   | 299   | 227   |
| fluxes                                                                                     | 4.65  | 5.36  | 7.27  | 5.18  | 12.55 | 16.80 | 17.00 | 17.56 | 14.50 | 15.02 |
| <i>Thalassionema nitzschioides</i> var. <i>inflata</i>                                     | 1     |       |       |       |       |       |       |       |       |       |
| <i>Thalassionema nitzschioides</i> var. <i>parva</i>                                       |       |       |       |       | 2     |       |       |       |       |       |
| <i>Thalassionema</i> spp.                                                                  |       | 4     |       | 7     | 2     | 2     |       | 3     | 2     | 4     |
| <i>Thalassiosira allenii</i>                                                               | 34    | 17    | 16    | 16    | 4     | 4     | 6     | 10    | 4     | 8     |
| fluxes                                                                                     | 1.58  | 1.02  | 0.94  | 1.08  | 0.35  | 0.25  | 0.40  | 0.48  | 0.19  | 0.53  |
| <i>Thalassiosira anguste-lineata</i>                                                       | 10    |       |       | 2     | 3     | 3     | 2     | 1     | 3     | 4     |
| <i>Thalassiosira binata</i>                                                                | 56    | 43    | 55    | 15    | 14    | 6     | 7     | 9     | 7     | 5     |
| fluxes                                                                                     | 2.60  | 2.59  | 3.22  | 1.01  | 1.22  | 0.38  | 0.47  | 0.43  | 0.34  | 0.33  |
| <i>Thalassiosira decipiens</i>                                                             | 26    | 11    | 28    | 49    | 24    | 24    | 14    | 10    | 7     | 3     |
| fluxes                                                                                     | 1.21  | 0.66  | 1.64  | 3.30  | 2.09  | 1.52  | 0.93  | 0.48  | 0.34  | 0.20  |
| <i>Thalassiosira eccentrica</i>                                                            | 2     | 2     | 9     | 3     | 7     | 5     |       | 3     | 3     | 1     |
| <i>Thalassiosira leptopus</i>                                                              |       |       | 2     |       |       |       |       |       |       |       |
| <i>Thalassiosira lineata</i>                                                               | 19    | 14    | 18    | 11    | 14    | 10    | 15    | 13    | 13    | 5     |
| fluxes                                                                                     | 0.88  | 0.84  | 1.06  | 0.74  | 1.22  | 0.63  | 1.00  | 0.62  | 0.63  | 0.33  |
| <i>Thalassiosira nordenskiöldii</i>                                                        | 1     | 1     | 6     | 7     | 7     | 3     |       |       |       |       |
| <i>Thalassiosira oestrupii</i> var. <i>venrickae</i>                                       | 37    | 15    | 16    | 18    | 30    | 49    | 39    | 37    | 32    | 33    |
| fluxes                                                                                     | 1.72  | 0.90  | 0.94  | 1.21  | 2.61  | 3.09  | 2.60  | 1.77  | 1.55  | 2.18  |
| <i>Thalassiosira pacifica</i>                                                              | 15    | 7     | 10    | 5     | 7     | 6     | 6     | 7     | 5     | 3     |
| fluxes                                                                                     | 0.70  | 0.42  | 0.59  | 0.34  | 0.61  | 0.38  | 0.40  | 0.33  | 0.24  | 0.20  |
| <i>Thalassiosira punctigera</i>                                                            | 4     | 8     | 10    | 6     | 3     | 5     | 5     | 8     | 4     | 3     |
| <i>Thalassiosira symmetrica</i>                                                            | 1     |       | 2     | 2     | 14    |       |       | 2     | 3     | 2     |
| <i>Thalassiosira tenera</i>                                                                | 23    | 22    | 19    | 18    | 17    | 20    | 30    | 22    | 19    | 43    |
| fluxes                                                                                     | 1.07  | 1.33  | 1.11  | 1.21  | 1.48  | 1.26  | 2.00  | 1.05  | 0.92  | 2.85  |
| small <i>Thalassiosira</i> species, mostly<br><i>T. proschkiniae</i> var. <i>spinulata</i> | 17    | 12    | 12    | 24    | 14    | 8     | 7     | 7     | 5     | 9     |
| fluxes                                                                                     | 0.79  | 0.72  | 0.70  | 1.62  | 1.22  | 0.51  | 0.47  | 0.33  | 0.24  | 0.60  |
| <i>Thalassiosira</i> spp.                                                                  | 43    | 72    | 59    | 45    | 55    | 22    | 43    | 42    | 27    | 34    |
| <i>Thalassiothrix longissima</i>                                                           |       |       | 2     |       |       |       |       |       |       |       |
| <i>Thalassiothrix</i> spp.                                                                 | 1     |       | 1     |       | 1     |       | 3     | 2     | 1     | 2     |
| others                                                                                     | 79    | 61    | 65    | 48    | 47    | 39    | 37    | 94    | 55    | 57    |
| total valves                                                                               | 1308  | 1001  | 1096  | 976   | 885   | 980   | 886   | 1193  | 948   | 855   |
| total diatom fluxes ( $\times 10^6$ valves/cm <sup>2</sup> /year)                          | 60.80 | 60.32 | 64.26 | 65.71 | 77.12 | 61.88 | 59.07 | 57.08 | 45.97 | 56.57 |



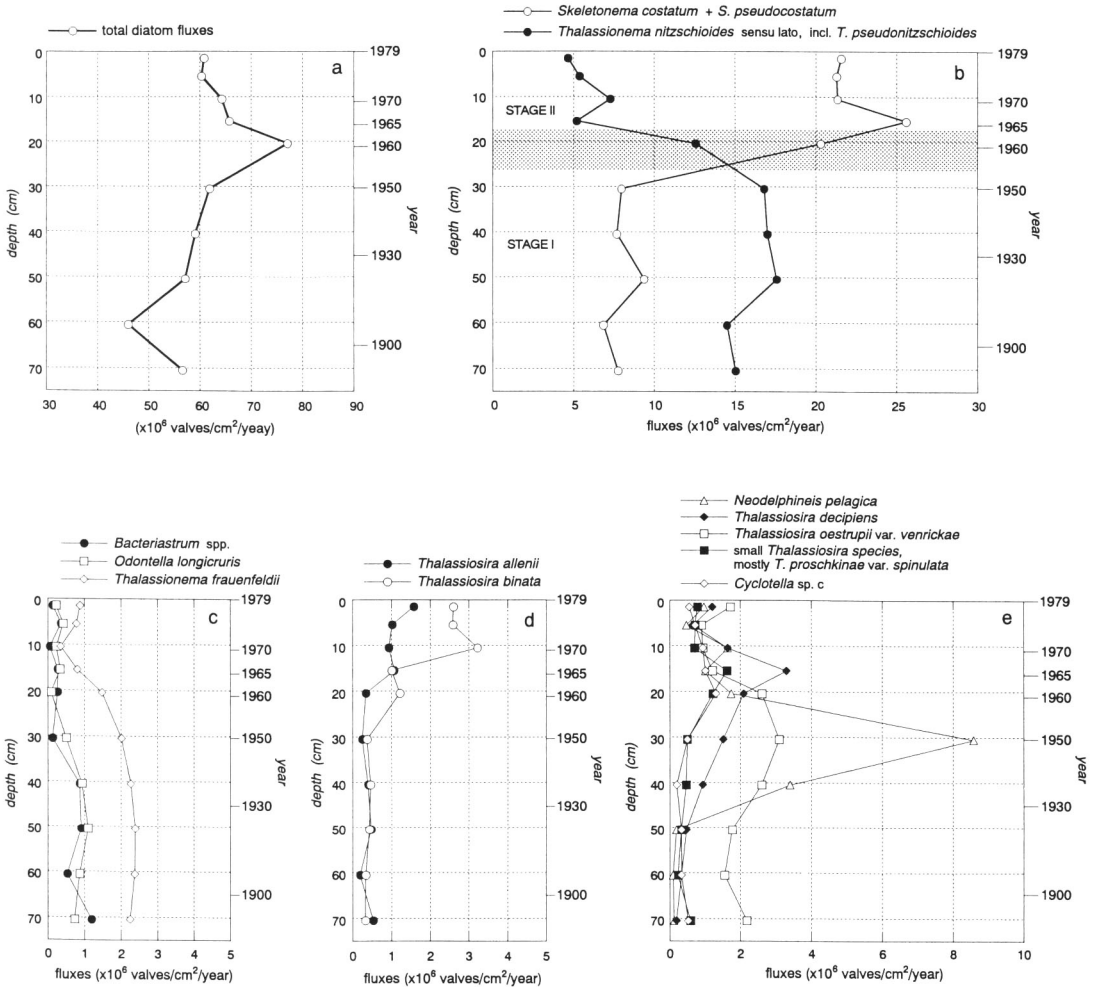


Fig. 2. Changes in total diatom fluxes (2a), and in fluxes of predominant/common diatom species in core G79-10 (2b-e).

(Horie, 1993). The current forms the western boundary of the Subtropical Gyre in the North Pacific, separating warm saline water in the gyre from less saline water to the northwest. *Thalassionema nitzschoides* is the dominant diatom species in sediment deposited from the less-saline water, averaging about 8% of the total count (up to 22.2% in the spring months of 1988; Tanimura, 1992). *Thalassionema nitzschoides* is prevalent in the southeastern part of Tokyo Bay (Tanimura *et al.*, 2001), where it amounts to about 4% of the total count. Kadota and Hirose (1967) reported that *T. nitzschoides* is a predominant constituent of planktonic diatoms collected

along a NW-SE transect across the channel. These data suggest that water in the central part of Tokyo Bay mixed with open-ocean waters from the North Pacific before around 1950.

#### A transition

Inflow of the open-ocean water entering the bay from the North Pacific through the channel in the bay's southern reaches is minimal (Horie, 1993). Tidal currents moving faster than 15 cm/sec are observed in the vicinity of the channel (Unoki, 1993). Using a three-dimensional model, Guo and Yanagi (1995) calculated the inflow and outflow of bay-water due to wind-dri-

ven currents traveling at up to 6 cm/sec.

Freshwater input to the bay is predominantly from river discharge, most of which comes from three major rivers, the Tama, Edo and Ara Rivers, all of which flow into the northwestern part of the bay (Radjawane *et al.*, 2001). Matukawa and Sasaki (1990) estimated the average freshwater input rate to the bay in 1979 as 300 m<sup>3</sup>/sec, and Yu (1995) estimated that the input rate from 18 rivers in 1992 was 428 m<sup>3</sup>/sec.

River discharge causes an overall decrease in salinity of the bay, and of its northern part in particular. Furota (1997) documented a decrease in surface water salinity (less than 30‰) in summer months, which was attributed primarily to freshwater discharge from rivers and the onset of thermal surface-water stratification. Radjawane *et al.* (2001) numerically estimated the speed and distribution of density-driven currents induced by freshwater discharge from rivers into the bay, and concluded that, as a result of the Coriolis force, low-density water from rivers spreads more to the right than to the left of each river mouth, with a maximum velocity of 3–5 cm/sec, and thus spreads asymmetrically across the surface layer of the bay. As a result, a NW-SE gradient in surface-water salinity has persisted during the current interglacial interval.

River discharge is also a primary source of nutrients for the bay, particularly for its northern half. In 1989, for example, 319.4 t/day of nitrogen and 25.98 t/day of phosphorus were supplied to the bay, of which 250.1 t/day of the former and 20.3 t/day of the latter came from river discharge (Takada, 1993). About 78% of the total nitrogen-phosphorus input is thus from river discharge, most of which comes from the Tama, Edo, Ara, Naka, and Sumida rivers (Takada, 1993). A general NW-SE gradient in nutrient concentration has likely prevailed for the past 60 years, because of intensive human activity in the rivers' catchment areas.

The salinity and nutrient gradients probably cause comparatively high fluxes of *S. costatum*, *T. allenii* and *T. binata* in the northwestern part of the bay, relative to their fluxes in the south-

eastern part (Tanimura *et al.*, 2001). Fluxes of *S. costatum* reach  $34.4 \times 10^7$  valves/cm<sup>2</sup>/year in the northwestern part, but only up to  $1.2 \times 10^7$  valves/cm<sup>2</sup>/year in the southeastern part. Fluxes of *T. allenii* and *T. binata* are also comparatively high at coastal stations, some of which are located near the mouths of large rivers, including the Sumida, Naka, Ara, Edo and Yoro rivers. Average fluxes of the two species in the northwestern part of the bay are  $2.2 \times 10^7$  and  $1.8 \times 10^7$  valves/cm<sup>2</sup>/year, respectively. Their average fluxes in the southeastern part are up to  $1.9 \times 10^6$  and  $3.5 \times 10^6$  valves/cm<sup>2</sup>/year, respectively.

These data suggest that the change in diatom flora from stage I to II represents a shift from a diatom assemblage typical of the open-ocean water flowing into the bay from the North Pacific, to one characteristic of less-saline water, with a high nutrient concentration. This succession is signalled in the core by the change from *T. nitzschoides* in the lower part, to *S. costatum* in the upper part. This shift is in the interval at 18–23 cm core depth, and corresponds to about 1960. It was probably triggered by the expansion of northwestern nutrient-rich/low-salinity waters over the central part of the bay, which resulted from a continuous increase in freshwater and nutrient inputs from rivers, caused by the intensification of human activities during a time of rapid economic growth in Japan.

Tanimura *et al.* (2001) identified *N. pelagica*, *T. decipiens*, *T. oestrupii* var. *venrickae* and small *Thalassiosira* species (mostly *T. proschkiniae* var. *spinulata*) as minor constituents (up to 4.3%) of the sediment's diatom flora. Minor peaks in each of these forms are recognized in the transition from stage I to stage II. Favorable growth conditions for these taxa probably developed as eutrophication progressed.

#### *Formation of a modern diatom flora (Stage II)*

In stage II of core G79-10, *Skeletonema costatum* is the predominant species, and *T. allenii* and *T. binata* are common constituents; the same pattern is evident in surface sediment surrounding the core sample site (Tanimura *et al.*, 2001).

Fluxes for *S. costatum* (incl. *S. pseudocostatum*) determined for the 4 sediment samples of stage II range from  $2.1 \times 10^7$  to  $2.6 \times 10^7$  valves/cm<sup>2</sup>/year, and flux of *S. costatum* sensu stricto in the surface sediment around the station is  $1 \times 10^7$  valves/cm<sup>2</sup>/year. Average fluxes for *T. allenii* and *T. binata* in stage II are  $1.2 \times 10^6$  and  $2.2 \times 10^6$  valves/cm<sup>2</sup>/year, respectively. Fluxes for the two species in the surface sediments around the station are  $1 \times 10^6$  and  $1 \times 10^6$  valves/cm<sup>2</sup>/year, respectively (Tanimura *et al.*, 2001). The similarity in dominant/common constituents of diatom floras of stage II of the core and surface sediment around the station suggests that the current diatom flora assumed its geographic distribution in the bay around 1965, corresponding to the base of stage II.

Nomura and Yoshida (1997) reported concentrations of *S. costatum* in plankton from the bay (35°30.5'N, 139°50.0'E) between 2,000 and 8,000 cells/ml for 1991 and 1993. This suggests that *S. costatum* was the predominant taxon of the bay's diatom flora in the 1990s.

### Taxonomic Notes

*Cyclotella* sp. c: Tanimura *et al.*, 2001: Mem. Nat. Sci. Mus. 37, 46, figs. 15–18.

About 90% of specimens possess a marginal wall with alveoli composed of costae on which 3–5 fuloportulae and a rimoportula are located, indicating that they should be assigned to the genus *Cyclotella*.

*Thalassionema nitzschioides* (Grunow) Grunow *sensu lato*

Three different morphotypes of *T. nitzschioides* (Tanimura, 1999) were identified as *T. nitzschioides* sensu lato in this study. *Thalassionema nitzschioides* specimens in core G79-10 consisted mostly of morphotypes *b* and *c*. In addition to the three morphotypes, another morphotype, exhibiting linear lanceolate valves with narrow ends, is also identified as *T. nitzschioides* sensu lato in this study.

### Acknowledgments

The Geological Survey of Japan is gratefully acknowledged as the provider of sediment samples from Core G79-10, collected during one of its cruises, that were used in this study. We appreciate the critical review of Mr. Fumio Akiba.

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