

# Sedimentary Records of Multidecadal-Scale Variability of Diatom Productivity in the Bungo Channel, Japan, Associated with the Pacific Decadal Oscillation

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**In order to examine the responses of primary productivity in the southern coastal sea of Japan to the Pacific Decadal Oscillation (PDO) in the 20th century, sedimentary records of diatom productivity (diatom valve fluxes) were reconstructed using core samples from the Bungo Channel (BC) in southwest Japan. The record of the *Thalassionema* spp. flux—the best index of fall primary productivity in the BC—indicated a multidecadal-scale duration with a low flux (1943–1982) and those with a high flux (1913–1943 and 1982–2001); apparent shifts were recognized in 1943 and 1982. The shift in 1982 was also recognized in the flux records of other early summer to fall predominant genera in the BC and, previously, in the biogenic silica records from a broad region of the southeast BC. This indicates that in our records, this shift reflects a general trend in the primary production in the southeast BC. A comparison among the *Thalassionema* spp. flux records, meteorological data from an observatory adjacent to the core site, and the PDO index showed that the flux records were more similar to the PDO index than the other meteorological records, which suggests that the multidecadal-scale variability of the BC primary productivity may be associated with some marine-derived forcing. The bottom intrusions of nutrient-rich water that upwelled from the shelf slope into the BC, the axis movement or the transport of the Kuroshio Current off the BC, and a basin-scale wind stress in the North Pacific might play an important role in this forcing and mediate between the BC primary productivity and the PDO.**

Keywords:

- Diatom productivity,
- Bungo Channel,
- regime shifts,
- shelf-sediment,
- Kuroshio Current,
- PDO.

## 1. Introduction

Recent studies have revealed the existence of regime shifts in climate, as identified in the Pacific Decadal Oscillation (PDO: Mantua *et al.*, 1997), and marine ecosystems in the North Pacific. Representative phenomena in marine ecosystems have been observed in sardine biomass in the Pacific (Kawasaki, 1983) and phytoplankton in the central North Pacific (Venrick *et al.*, 1987). In the west North Pacific and its marginal seas, these phenomena have been observed in the zooplankton biomass from the Oyashio region (Sugimoto and Tadokoro, 1997), the chlorophyll concentrations and zooplankton biomass from the

Kuroshio recirculation region (Sugimoto, 2003), and the chlorophyll a concentrations and diatom assemblage from the Japan Sea (Chiba and Saino, 2003). All these studies reported ecosystem variability in open oceans.

Meanwhile, few studies have investigated the responses of marine ecosystems in shallow coastal areas—such as shelves, inland seas, and bays—to regime shifts. In particular, since primary production sustains high productivity in these areas, an understanding of the long-term dynamics of primary production and its forcing mechanisms is crucial for the long-term management of ecosystems and fishery resources.

However, the long-term variability of primary productivity, particularly at multidecadal timescales, cannot be detected from the monitoring records of the last few decades. As a source of information compensating for the

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lack of long-term records, proxy records based on paleoceanographic approaches are useful. Since diatom valves produced in the water column accumulate annually on the bottom, the diatom valve flux reconstructed from sediment core samples functions as an effective proxy for past annual primary productivity. Coastal muddy sediments serve as a record of primary productivity for a period exceeding 100 years; further, they have higher sedimentation rates than those of deep ocean sediments. Thus, records of diatom productivity variability at multidecadal timescales in the 20th century can be detected.

In this study we focus on the Bungo Channel (BC)—a shelf in the southern coastal sea of Japan—and reconstruct the diatom productivity during the 20th century based on the diatom valve flux in the core sediment. In this process we demonstrate a characteristic of the multidecadal-scale variability of primary productivity in the BC and its relationship with the major regime shifts in the North Pacific climate in the 20th century.

## 2. Regional Settings

The BC is located in the shelf region of the southwest part of Japan, connecting the Pacific Ocean with the Seto Inland Sea (Fig. 1). The southern part of this channel is situated adjacent to the northern front of the Kuroshio Current (KC). Its bottom forms a rather flat shelf 70 to 90 m deep, and the bottom of its southern area descends sharply, forming a shelf slope.

The KC flows northeastward along the southeastern coast of the Japanese islands of Kyushu, Shikoku, and Honshu (Fig. 1); however, there are interannual variations in the KC path off the south coast of Japan (e.g., Kawabe, 1995; Marine Information Research Center (MIRC) data from 1955 to 2004).

The nutrient environment and thermal conditions in the BC are strongly influenced by the interannual variations of the KC path (Kaneda *et al.*, 2002a). When the KC assumes a nearshore path (Fig. 1), a strong upwelling (it is noted that the upwelling in this area is formed by friction between KC and the shelf slope, and not by wind as in cases of a typical upwelling) is generated around the shelf slope region located south of the BC. The cold upwelling water mass with enriched nutrients intrudes deep into the BC bottom layer due to the spring-neap tidal modulation; this is referred to as “bottom intrusion” (Kaneda *et al.*, 2002b). Therefore, the temperature of the BC bottom from early summer to fall (May to October) is maintained at the winter level or shows a minor increase in years when the KC assumes a nearshore path. In contrast, when the KC assumes an offshore path (Fig. 1), the upwelling and bottom intrusions become weak; therefore, the temperature of BC bottom increases from early summer to fall (1.5–3°C higher than in the year when the KC assumes a nearshore path).

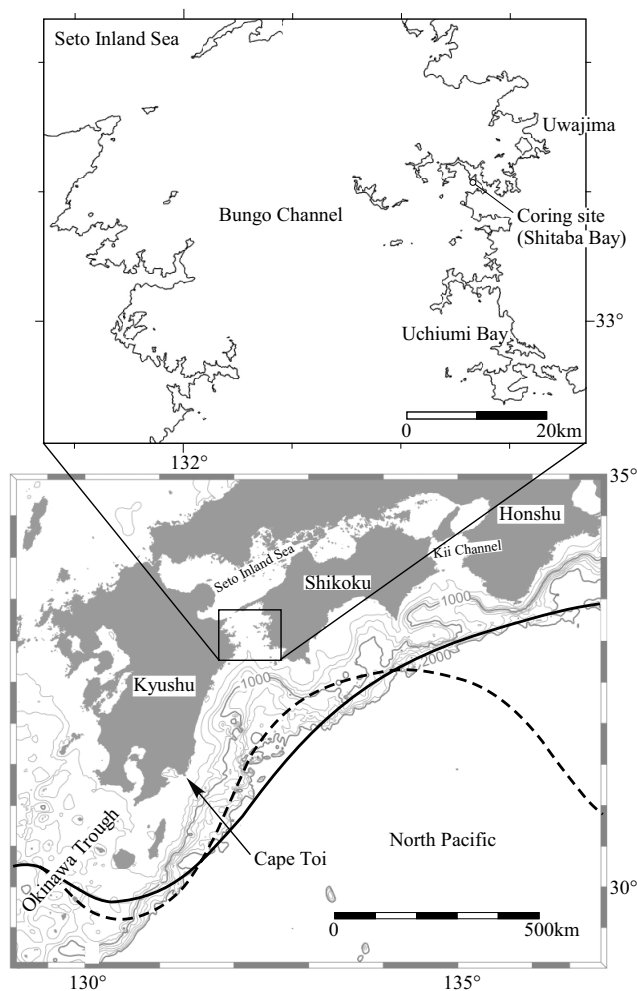


Fig. 1. Study area and the typical meander and non-meander Kuroshio paths (the dashed and solid lines, respectively, in the lower panel) off the southern coast of Japan.

The early summer to fall bottom temperature variations in the BC for three decades are well correlated with the distance between Cape Toi (southeast of Kyushu) and the KC axis (Kaneda *et al.*, 2002a). The observations described earlier suggest that the KC dynamics exert a strong influence on the heat exchange between the BC and KC regions from early summer to fall.

## 3. Samples and Methods

### 3.1 Samples

Core samples were collected from Shitaba Bay at 33°10.82' N, 132°26.71' E (Fig. 1) in October 2003. Using a multiple corer with three 1 m long core tubes, which are close to each other (40 cm apart; Ashura, Rigosha Co., Ltd., Ioka *et al.*, 1997), three sediment cores with a length of 56 cm for SH (Shitaba) 1; 47 cm, SH2; and 60 cm,

SH3, were obtained at a water depth of 51 m. The sediments were composed of very fine sandy silt, pale green to gray in color; an oxic layer was observed in the uppermost 0.5 cm. The core sediments were bulk-sampled in 0.5 cm slices for the analysis of diatom concentrations (SH3) and in 2 cm slices for  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  dating (SH1). Diatom concentrations of 60 samples were determined at intervals of 0.5–1.5 cm.

### 3.2 $^{210}\text{Pb}$ dating

$^{210}\text{Pb}$  dating was performed based on the method proposed by Kanai *et al.* (1995). The sediment samples were collected from the SH1 core at intervals of 4–8 cm. The homogenized samples were dried at 80°C, the water content and dry bulk density were measured. The residue was ground to a fine powder, sealed in plastic jars, and allowed to settle for 30 days. Dating was carried out using an EG&G ORTEC model GXM25P germanium detector equipped with a SEIKO EG&G model MCA7700 at the Center for Marine Environmental Studies, Ehime University, Japan. The activities of  $^{210}\text{Pb}$ ,  $^{214}\text{Pb}$ , and  $^{137}\text{Cs}$  were measured by counting their peaks at 46.5, 351.9, and 661.6 keV, respectively, for 48–72 h. The Radioactivity Standard Gamma Volume Source Set from the Japanese Radioisotope Association was employed as a reference standard.

The vertical profile of radionuclide activities in the SH3 core revealed a mixed layer at a depth of 0–9 cm with a decrease in the excess  $^{210}\text{Pb}$  activity below this depth and values below the detection limit of 0.019  $\text{Bq g}^{-1}$  at depths of 49 and 53 cm (Fig. 2). The vertical profile of the  $^{137}\text{Cs}$  data did not show a clear peak as a result of low activities ( $<0.004 \text{ Bq g}^{-1}$ ) close to the detection limit (0.001  $\text{Bq g}^{-1}$ ). This indicates a low flux of  $^{137}\text{Cs}$  into this basin, reflecting a non-inflow of the river into the bay. We therefore used only  $^{210}\text{Pb}$  data for dating. Applying the Constant Initial Concentration (CIC) model to the  $^{210}\text{Pb}$  activity between 17 and 45 cm depth, an accumulation rate of  $0.372 \text{ g cm}^{-2}\text{yr}^{-1}$  (approximately  $0.5\text{--}0.9 \text{ cm yr}^{-1}$ ) was determined. The same depths in the three SH cores do not appear to be necessarily simultaneous because the down-core profiles of water content of each core—the variations are primarily due to the variations of the grain size and the compactions—showed slight down-core sifts (but up to 1.5 cm). Therefore, the dating of the SH2 and SH3 cores was determined based on the correlations of water content data of each core with those of the SH1 core. Although the presence of the mixed layer at a depth of 0–9 cm (corresponding to 1991–2003) indicates bioturbation, it is believed to preserve an accurate record of deposition for the last hundred years for the following reasons. Distinct stratigraphic horizons were found at 16, 22.5, and 41 cm below the surface, indicating that there is no bioturbation at these levels severe

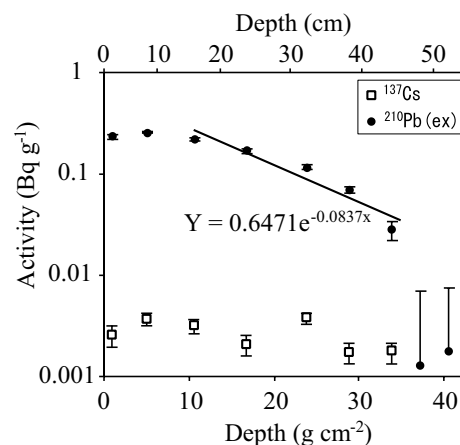


Fig. 2. Plots of  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  counts for the SH2 core, illustrating exponential radioactive decay with the mass depth of the SH2 core. Solid circles show the activity of excess  $^{210}\text{Pb}$  and open squares show the activity of  $^{137}\text{Cs}$ . Each error bar indicates a standard deviation of one.

enough to break the horizons. Within a thickness of 10 cm at any depth as well as in the upper mixed layer, planktonic foraminifera concentrations do not show a constant value; instead, there is a short-term fluctuation (more than 2 peaks within 10 cm) in the foraminifera concentrations of the SH2 core (unpublished data), similar to the diatom fluxes of the SH3 core presented in this paper. If the layer is homogenized vertically by bioturbation, the fluctuation in the mixed layer should diminish in amplitude. However, since the peaks can be detected, this indicates that the original signals would have been more apparent if there was no bioturbation. Furthermore, the bottom temperature, which was reconstructed from benthic foraminiferal Mg/Ca ratios using the SH2 core samples, exhibits a significant correlation with the observed temperature during the interval after 1967 (unpublished data;  $n = 20$ ,  $r = 0.5$ ,  $P = 0.02$ ). These facts suggest that the bioturbation has not caused a major disturbance in these cores, and the age estimation of this  $^{210}\text{Pb}$  dating may be reliable (the age error is approximately within 1–2 years during the interval from 1967 to the present).

### 3.3 Diatom analysis

Diatom analysis involves a pre-procedure using a hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) solution; the sample is mounted onto a glass slide and counting is performed using a light microscope set to a magnification of  $\times 1000$  (this method is explained in detail by Kuwae *et al.*, 2004). We used a procedure that was almost identical to that of Battarbee and Kneen (1982) to accurately estimate the total number of diatom valves on a prepared slide containing microsphere markers; these markers were counted simul-

taneously with diatom valves. The diatom valves were counted until there were at least 100 for each analysis. In this method, the analytical error for diatom valve concentration was generally less than 16% (Kuwaie *et al.*, 2004). The diatom valve fluxes (DVF: valves  $\text{cm}^{-2}\text{yr}^{-1}$ ) were calculated by the following formula:

$$\text{DVF} = \text{DVC} \times \text{AR} \quad (1)$$

where DVC is the diatom valve concentration (valves/g of dry sediment); and AR the accumulation rate ( $0.372 \text{ g cm}^{-2}\text{yr}^{-1}$ ).

#### 4. Results

Diatom assemblages in the SH3 core sediments were dominated by several taxa: *Chaetoceros* spp., *Bacteriasrtum* spp., *Thalassiosira* spp., *Thalassionema* spp., *Paralia sulcata*, *Coscinodiscus* spp., *Cyclotella* spp., *Azpeitia* spp., and *Actinocyclus* spp; these taxa comprised more than 10% of the assemblage in at least a sample. Figure 3 shows the 100 year records of the diatom valve flux of the major taxa—*Chaetoceros* spp., *Bacteriasrtum* spp., *Thalassiosira* spp., and *Thalassionema* spp.—which are dominant from early summer to fall (Sano *et al.*, 1966, 1977, 1979; Sakai *et al.*, 1977, 1982; Sakai and Sawada, 1980, 1981; Takimoto *et al.*, 1983; Koizumi and Doi, 1984). The total fluxes of these taxa at the levels with a large peak account for more than 50% of the fluxes of all diatoms (Fig. 3); therefore, diatom productivity in Shitaba Bay is largely contributed by the variability of the flux in the early summer to fall taxa. In this paper we mainly address the fluxes of these taxa. According to the observations of chlorophyll concentrations in the eastern coastal sea of the BC from 1996 to 2000, the variability of the annual primary productivity largely depends on the primary productivity during the interval from May to October as well as the interval of spring bloom from March to April (Takeoka, 2001). In particular, in 2000, unusually high chlorophyll concentrations were detected during the interval from May to September (which showed that the peak concentrations from June to July were found to be two to three times as high as the concentrations in the other years) due to the enhanced bottom intrusions in the BC. Bottom intrusions frequently occur from early summer to fall and play an important role in the year-to-year variations of primary productivity as a mechanism to bring nutrients into the BC (Takeoka, 2001). Therefore, the productivity of early summer to fall taxa is important in understanding the long-term variability of the primary productivity in the BC.

The flux records of each individual taxon exhibited multidecadal-scale or interannual-scale variability. The flux of *Chaetoceros* spp., *Bacteriasrtum* spp., and *Thalassiosira* spp. exhibited low values before 1970, and

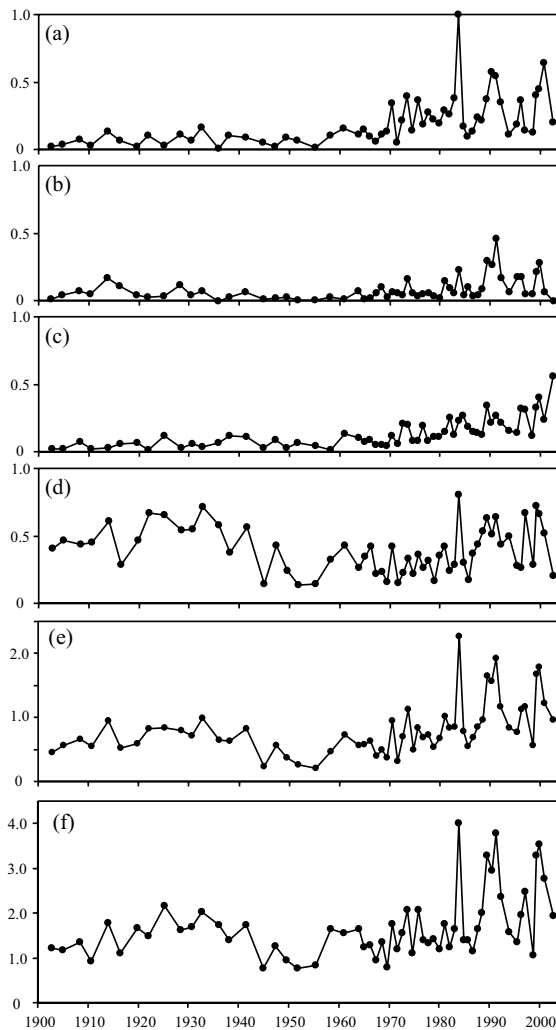


Fig. 3. Diatom valve flux records during the last 100 years in Shitaba Bay, Eastern part of the Bungo Channel. The six panels show the flux records of *Chaetoceros* spp. (a), *Bacteriasrtum* spp. (b), *Thalassiosira* spp. (c), *Thalassionema* spp. (d), their early summer to fall total (e), and total diatoms (f).

an increasing trend thereafter. Moreover, the flux records of *Chaetoceros* spp. and *Bacteriasrtum* spp. revealed an abrupt increase in 1982; thereafter, a bidecadal-scale, high-flux duration was observed with three large peaks at 1982–1984, 1990–1992, and 2000–2001. These large peaks are synchronous with the records of all the taxa, as shown in Fig. 3. Unlike the other three taxa, the *Thalassionema* spp. record shows a unique multidecadal pattern; the record in the interval between 1913–1943 and 1982–2001 often shows high flux values exceeding  $500,000 \text{ valves cm}^{-2}\text{yr}^{-1}$ , whereas that in the interval of 1943–1982 never exceeds the abovementioned values.

Moreover, apparent shifts are observed between these intervals.

## 5. Discussion

### 5.1 The two shifts in the diatom flux records

The diatom flux records revealed two major shifts in the 20th century; the recent shift occurred in 1982 with an earlier shift in 1943 (Fig. 3). The 1982 shift is common to the records of all the taxa, indicating that the change is not an alternation of diatom assemblage, but may reflect a change in the diatom productivity in Shitaba Bay. Since diatoms are the most dominant of the BC primary producers (Sano *et al.*, 1966, 1977, 1979; Sakai *et al.*, 1977, 1982; Sakai and Sawada, 1980, 1981; Takimoto *et al.*, 1983; Koizumi and Doi, 1984), the 1982 shift may reflect a major change in the primary productivity. Considering that the previous results from the records of biogenic silica, mainly comprising diatom remains, in the south of the BC also exhibited major shifts around 1980 (Omori, 2001), it is possible that the 1982 shift of diatom productivity in Shitaba Bay is a dominant phenomenon in the south of the BC.

The 1943 shift is observed only in the *Thalassionema* spp. record, not in others. However, although *Thalassionema* spp. were the most dominant in the samples corresponding to the period before 1970, the dominance appears to differ from the observed data. The reports of the diatom assemblage in Uwajima, Nishiumi, and Yawatahama in the eastern part of the BC in 1965 do not show such a dominance of *Thalassionema* spp.; rather, they show a dominance of *Chaetoceros* spp. (Sano *et al.*, 1966). This indicates that the record of *Chaetoceros* spp. is strongly influenced by its decomposition or dissolution after sedimentation. It is well documented that the taxa with thin and frangible valves are subjected to dissolution in the ocean (e.g., Kato *et al.*, 2003); the record of *Chaetoceros* spp. as well as those of *Bacteriasartum* spp. and *Thalassiosira* spp. may be influenced by the process of decomposition or dissolution. In fact, these records exhibit an increasing trend after around 1970. Therefore, these records, at least those before 1970, as well as the record of the total flux of early summer to fall taxa and total diatom flux, probably do not represent the inherent variability of each productivity. In contrast, it was reported that *Thalassionema* spp. with thick valves are well preserved in the sediments (Koning *et al.*, 2001); the record may preserve the real variability of the productivity. Moreover, after 1970, corresponding to the levels where there is no severe effect of post-depositional dissolution of all the taxa, the flux of *Thalassionema* spp. exhibits a significant correlation with the total flux of early summer to fall taxa ( $r = 0.87$ ;  $P < 0.01$ ) and the flux of *Chaetoceros* spp. ( $r = 0.65$ ;  $P < 0.01$ ), which is the most

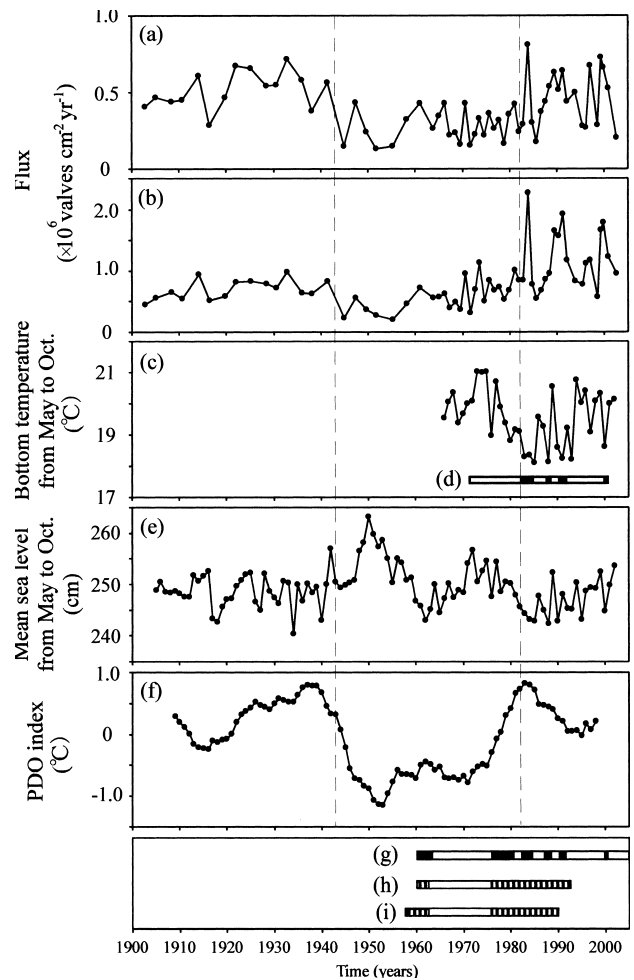


Fig. 4. Comparison of the 100-year flux record of *Thalassionema* spp. (a) and early summer to fall diatoms (b) with bottom temperature (75 m deep) averaged from May to October at the central BC (data from Ehime Prefectural Fisheries Experimental Station) (c). Pattern of two modes between the nearshore (black) and offshore path (empty) of Kuroshio Current off both Cape Toi and Ashizuri (Kaneda *et al.*, 2002a) (d), sea level averaged from May to October at Hosojima, Kyushu Island (e), and the PDO index (Mantua *et al.*, 1997) indicated by a 10-year running average (f). Pattern of two modes between the meander (black) and non-meander path of Kuroshio off the southern coast of Japan (Kawabe, 1995 and MIRC data set for the Kuroshio path (1955–2005) provided by the Marine Information Research Center) (g). Intervals of increased (black) and decreased (empty) volume transport calculated from the PN-line data (Kawabe, 1995) (h), and intervals of increased (black) and decreased (empty) annual mean Sverdrup transport at 30N 130E (Qiu and Miao, 2000) (i). Dashed lines indicate the periods of the shifts of *Thalassionema* spp. flux.

dominant among the primary producers in the BC; the seasonality of *Thalassionema* spp. (September–October) is also similar to *Chaetoceros* spp. (mainly May–October). Therefore, the record of *Thalassionema* spp. broadly represents the variability of the primary productivity in Shitaba Bay. In consideration of this, it is possible that the shift of 1943 and 1982 and the low and high abundance regimes before and after these shifts represent the characteristics of the multidecadal-scale variability of the primary productivity in Shitaba Bay.

### 5.2 Forcing factors of the primary productivity variability in Shitaba Bay

What types of forcing factors are responsible for the multidecadal-scale variability of coastal primary productivity observed in Shitaba Bay? The timings of the major shifts in the *Thalassionema* spp. record coincide with the well-known major regime shifts in the North Pacific climate variability (Minobe, 1997), e.g., as shown in the PDO index (Mantua *et al.*, 1997; Fig. 4). Furthermore, 10-year moving averaged values of the *Thalassionema* spp. fluxes, which were converted previously into the evenly annual data from the original data using a simple linear interpolation, showed a good correlation with the 10-year moving average values of the PDO index ( $r = 0.76$ ,  $P < 0.01$ ). These observations suggest a close relationship between the primary productivity and the PDO.

This cannot be explained by atmospheric forcing because there are no similar multidecadal patterns and shifts (1943 and 1980) in the meteorological data for the last 40–100 years, reported by the observational stations around the BC; the meteorological data include the monthly sunshine duration, amount of solar radiation, precipitation, wind velocity, and temperature (Uwajima, Oita, Miyazaki and Matsuyama: Japan Meteorological Agency, 1999). This suggests that the primary productivity in the Bungo Channel may be not related to light availability, nutrient supply from the watersheds around the BC and direct rainfalls, or vertical mixing by wind and heat exchange through the sea surface. Moreover, the absence of any report on an abrupt increase in fish farming or prey consumption in Shitaba Bay (Ehime Prefectural Marine Fishery Council, 1998) indicates that the 1982 shift is not due to human-induced eutrophication. Therefore, the shifts in the *Thalassionema* spp. record are possibly associated with some oceanic forcing around the BC that is linked to the North Pacific climate.

### 5.3 The role of upwelling and bottom intrusions in the multidecadal-scale variability of the BC primary productivity

It is possible that the shifts in the *Thalassionema* spp. record are associated with some oceanic forcing in the stratified seasons around the BC and are linked to the

North Pacific climate. But, what kind of forcing is related to the multidecadal-scale variability of the BC primary productivity? One of the most likely possibilities is the bottom intrusions of the offshore upwelled waters into the BC. Recent observational studies on marine physical and chemical environments in the BC demonstrated the importance of the role of the bottom intrusions as a mechanism of nutrient supply into the BC (Takeoka, 2001; Kaneda *et al.*, 2002b). The bottom intrusions frequently occur during early summer to fall and originate from upwelled, nutrient-rich, cold water in the shelf slope off the BC (Kaneda *et al.*, 2002b). The BC bottom environment frequently experienced interannual-scale cold periods after 1980 (Fig. 4(c)), during which it is considered that the bottom intrusions are enhanced. According to the estimation by Fujiwara *et al.* (1997) and Yuasa (1994), the annual input of nutrients into the BC from the Pacific Ocean is approximately 6 times as large as that originating from rainfalls and rivers around the BC. Furthermore, during the interval 1996–2000, the chlorophyll concentrations in the year with enhanced bottom intrusions (2000) are much higher than those in other years with weak bottom intrusions (Takeoka, 2001). These observations suggest that the nutrient supply by bottom intrusions plays a significant role in the long-term variability of the primary productivity in the BC.

Figure 4 shows that the three peaks in the flux of *Thalassionema* spp. and the total flux of four early summer to fall taxa after 1982 (1983, 1990–1992, and 2000–2001) are synchronous with the cold periods in the bottom of the central part of the BC (Fig. 4(c)), i.e., the periods of enhanced bottom intrusion. Furthermore, despite an uncertainty in the age estimation of the SH cores on an interannual basis, the *Thalassionema* spp. flux and the total flux of four early summer to fall taxa showed a statistically significant correlation with the bottom temperature ( $r = -0.36$ ,  $P = 0.03$ ;  $r = -0.37$ ,  $P = 0.04$ ). These observations indicate that interannual- or annual-scale fluctuations of the primary productivity may be related to the variability of frequency and/or the intensity of bottom intrusions. The fluctuation with large amplitudes after 1982 as recognized in the flux record of *Thalassionema* spp. forms the bidecadal-scale high-abundance regime; therefore, the bidecadal pattern of the flux records during this period may be closely related to the dynamics of bottom intrusions.

Furthermore, it is possible that the flux record of *Thalassionema* spp. may be related to the decadal-scale variability of the intensity of a bottom intrusion and upwelling over the shelf slope, south of the BC. *Thalassionema nitzschioides*, which is the most abundant species within *Thalassionema* spp. in the SH3 core sediments, is one of the species whose productivity is closely related to upwellings; it was reported to occur

commonly in upwelling areas (Abrantes, 1988; Romero *et al.*, 2001), and it is proposed that the abundance of this species is an indicator of high productivity in the upwelling zone (Sancetta, 1982; Schrader and Sorknes, 1990). Moreover, this species, which is present on the sediment surface at Effingham inlet off the west coast of Vancouver Island, is more abundant toward the inlet mouth, suggesting that the productivity is related to the intrusions of the offshore upwelled waters during intervals of increased coastal upwelling (Hay *et al.*, 2003). These observations suggest that *Thalassionema nitzschioides* is a favorable species in those waters with a nutrient supply from an upwelling area to an inner basin. In the BC, the bottom intrusions related to the dynamics of the upwelling play an important role in the nutrient supply; therefore, it is possible that this species can adapt to such a marine environment, and its productivity is closely related to the intensity of the bottom intrusions and the upwelling. Therefore, the flux record of *Thalassionema* spp. including this species is useful for inferring the intensity of the bottom intrusions and the upwelling. In consideration of this, the decadal pattern of the flux record of *Thalassionema* spp. possibly reflects the decadal-scale variability of the intensity of the bottom intrusions and the upwelling.

The decadal-scale variability of the intensity of the upwelling inferred from the *Thalassionema* spp. flux record is supported by the records of coastal sea level, which were collected in the past 100 years (Fig. 4(d)). The sea level observed at the coasts facing the Pacific Ocean in Japan is influenced by the thermal expansion of a water column in the shelf slope region; therefore, the changes in the thermal condition would induce a variation in the coastal sea level, i.e., when the water temperature is warmer (colder), the sea level becomes higher (lower) (Fujiwara *et al.*, 2004). Since the thermal condition in the shelf slope is greatly influenced by the intensity of the upwelling, the variability of the intensity of the upwelling may be indicated by that of the sea level. The intensity of the bottom intrusions may also be indicated by the sea levels because of the great influence of the upwelling on the bottom intrusions. In fact, the bottom temperature in the central BC (Fig. 4(c)) showed a good correlation with the sea levels at Hosojima ( $r = 0.74$ ,  $P < 0.01$ ). In Fig. 4, the flux record of *Thalassionema* spp. shows a high abundance regime during the interval 1929–1943 and 1982–2000 and a low abundance regime during the interval 1943–1982. This pattern is consistent with the sea level in the opposite phase, and the 10-year moving average data of both records shows a good correlation ( $r = -0.62$ ,  $P < 0.01$ ), although the sea level record shows low values in 1960s and the corresponding signal of the *Thalassionema* spp. flux is somewhat inconsistent. Therefore, the synchronous pattern between both the

records suggests that the intensity of the upwelling and the bottom intrusions varied at multidecadal timescales, and the primary productivity in the BC responded to the variability of the intensity of the upwelling and the bottom intrusions.

Meanwhile, even at interannual timescales, both the records after 1980 show a synchronous pattern (Fig. 4). The three peaks after 1980 (1983, 1990–1992, and 2000–2001), except for the 1997 peak, correspond to the periods with low sea levels. These peaks are also found in the flux records of other early summer to fall taxa (Fig. 3) and their total (Fig. 4(b)), which correspond to the periods of the intensified bottom intrusions, i.e., cold periods (1983–1985, 1990–1993, and 2000; Fig. 4(c)).

#### 5.4 Processes connected between upwelling south of the BC and PDO

As discussed earlier, we emphasized the importance of the intensity of the bottom intrusions and upwelling as potential oceanic forcing that caused the multidecadal-scale variability of the primary productivity in the BC. A good correlation of the sea level at Hosojima with the PDO index ( $r = -0.67$ ,  $P < 0.01$ ) suggests a close relationship between the intensity of upwelling and the PDO index. However, it is difficult to elucidate a process that connects the upwelling off the BC and the PDO index. Currently, some of the most likely processes might be related to the dynamics of the KC and wind stress in the North Pacific.

The intensified or weakened upwelling and bottom intrusions after 1980 are related to the interannual variability of nearshore/offshore movements of the KC path. Kaneda *et al.* (2002a) demonstrated that when the KC assumes a nearshore path, the upwelling is intensified by bottom friction of the KC against the shelf slope; the intensified upwelling leads to enhanced bottom intrusions. In fact, cold periods at the bottom of the central BC are synchronous with periods of the nearshore path (Fig. 4(d)), and the bottom temperature shows a good correlation with the distances between the coasts (Cape Toi and Ashizuri) and the KC path ( $r = 0.71$  and  $0.45$ ; respectively; Kaneda *et al.*, 2002a). Therefore, the interannual variabilities of the intensity of upwelling and bottom intrusions are possibly forced by the axis movements of the KC path (Kaneda *et al.*, 2002a).

This variability of the KC path off the Shikoku and Kyushu coasts might be related to the decadal-scale variability of the KC transport. Kawabe (1995) reported that when the transport was increased at decadal timescales (Figs. 4(h) and (i)), the two modes of the KC path, i.e., the meander path and non-meander path (Fig. 1), occurred alternately (Fig. 4(g)). In contrast, when the transport was decreased at decadal timescales, only the non-meander path occurred. This observation confirms a connection

between the decadal-scale variability of the KC transport and the interannual-scale variability of the KC path. Although there is no report on how the variability of the KC path movements off the Kyushu and Shikoku coasts (Fig. 4(d)) is related to the alternate occurrence of the meander and non-meander paths, the KC off the Kyushu and Shikoku coasts tends to assume a nearshore (offshore) path in the year with the meander (non-meander) path (Figs. 4(d) and (g)). These observations suggest that the variability of the axis movement of the KC path off the Kyushu and Shikoku coasts may be related to the decadal-scale variability of the KC transport.

Meanwhile, many observational and model studies of the North Pacific environment have reported that the variation of the KC transport is related to that of the spinup or spindown of the subtropical gyre, which is driven by the wind stress associated with the North Pacific climate variability, which is closely associated with the Aleutian low pressure system (Yasuda and Hanawa, 1997; Deser *et al.*, 1999). The PDO index is associated with the intensity of the Aleutian low pressure system; therefore, it can be expected that the KC transport is also associated with the PDO. In this scenario, when the PDO index is high, the intensified wind stress at decadal timescales results in the spinup of the subtropical gyre; the resulting increased KC transport would cause the KC path off the Kyushu and Shikoku coasts to assume the nearshore route at interannual timescales. This condition would result in the intensified upwelling and bottom intrusions. Therefore, the decadal-scale variability of the KC transport and basin-scale wind stress in the North Pacific might serve as a link between the intensity of the upwelling off the BC and the PDO index.

In this scenario, the absence of constant enhancement in the upwelling and diatom productivity in the BC during the interval of 1980–2000 associated with the constantly-high-value regime of the PDO index can be explained in terms of the interannual-scale occurrence of the offshore path associated with the decadal-scale increased KC transport. Meanwhile, the forcing factors of the interannual-scale variability of the axis movement of the KC path can be related to either the interannual-scale variability of the upwelling barotropic Rossby waves, which are driven by winds related to El Niño and the temperature anomaly of the eastern equatorial water (Kawabe, 2000) or the spinup/spindown of the recirculation gyre of the KC (Qiu and Miao, 2000).

Nevertheless, the record of the *Thalassionema* spp. flux in the BC in the 20th century exhibited the existence of the 1943 shift to the low abundance regime which lasted for 35 years; this revealed an important characteristic of a long-term trend of the BC primary productivity that possibly responds to the multidecadal-scale climate variability in the North Pacific. Although the present stage is

characterized by a high flux regime, as indicated by the *Thalassionema* spp. flux record; the existence of the 1943 shift suggests the possibility of the occurrence of the next shift to a low abundance regime. Although an understanding of the physical processes and testing by model simulations is required for the prediction of the shift of BC primary productivity, it may be important to consider the perspective on “regime shift.”

## 6. Conclusions and Remarks

The flux records of early summer to fall diatoms from the BC demonstrated the multidecadal-scale variability of primary productivity in the BC. A comparison among the flux records, meteorological data obtained from the observatories around the BC, and the PDO index suggests that the primary productivity in the BC has possibly responded to some marine-derived forcing; this forcing is associated with the multidecadal-scale climate variability in the North Pacific such as that of the PDO. The bottom intrusions of nutrient-rich water upwelled from the shelf slope into the BC, the axis movement and transport of the KC off the BC, and a basin-scale wind stress in the North Pacific might play an important role in this forcing, serving as a link between the BC primary productivity and the PDO. Our results also suggest the possibility of a shift of primary productivity in the BC to a low abundance regime that lasts for several decades without any anthropogenic impacts. This suggests the importance of considering the perspective on “regime shift” for the sustainable management of ecosystems and fishery resources, which depends on the internal primary production in the BC. A shift in the primary productivity responding to the multidecadal-scale North Pacific climate might also have occurred in another area, e.g., the inner basin—the Seto Inland Sea—connecting the BC and the Kii Channel. This is because they are also affected by nutrient supplies caused by bottom intrusions in the BC and the Kii Channel (Fujiwara *et al.*, 1997; Takeoka, 2001). Further studies on diatom flux records in such regions are required to confirm this phenomenon.

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