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Initial site of *Gymnodinium mikimotoi* blooms in relation to the seawater exchange rate in Gokasho Bay, Japan

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Abstract: The initial development of *Gymnodinium mikimotoi* blooms in Gokasho Bay was investigated over a period of five years (1991–1995) to verify the site of initial appearance of this species. Motile cells of this species initially appeared in the western inlet of the bay each year over the period of the investigation. The pattern of appearance of this species may be a clue to the establishment of a monitoring system for *G. mikimotoi* red tides. The seawater exchange rate was estimated for three inlets of the bay. The results show that the seawater exchange rate was the lowest in the western inlet of the bay. We conclude that weak seawater exchange in the west inlet of the bay permits the initial appearance of *G. mikimotoi* cells at this site.

Key words: *Gymnodinium mikimotoi*, initial appearance site, red tide, seawater exchange

Introduction

Gymnodinium mikimotoi Miyake et Kominami ex Oda is one of the most representative red-tide causing species found in Japan. This species has caused serious economic damage to the mariculture of fish and shellfish around Japan (Honjo 1994). Therefore it has become urgent to establish an effective monitoring system and to develop predictive techniques for red tides caused by this species in embayments around Japan. To this end, it is necessary to examine the ecology of the organism, particularly in its initial phase of population growth and its relationship to the physical mechanisms of dispersion within embayments. If the initial site of bloom formation of the red-tide organism can be determmined, then monitoring the phytoplankton species at this site may allow the prediction of red-tide outbreaks. Takeuchi et al. (1995, 1997) studied the growth of the *G. mikimotoi* population in Tanabe Bay, and reported that red tides caused by this species first appear in the innermost part of this bay. The distribution of red tide blooms of this species was found to be closely related to seawater currents within the bay. Furthermore, they concluded that the occurrence of *G. mikimotoi* red tides depended on the seawater exchange rate in Tanabe Bay. Toda et al. (1994) examined the effect of

water exchange on the population growth of *G. mikimotoi* (=*G. nagasakiense*) in an inlet of Gokasho Bay, and found that the cell density of this species was correlated to the seawater exchange rate of the inlet. Thus, the seawater exchange rate seems to affect population growth of *G. mikimotoi* in embayments.

In this study, we investigated the distribution and abundance of *G. mikimotoi* in Gokasho Bay during the period of its initial occurrence at high concentrations over a 5-year period in order to verify the initial site of appearance of blooms of this species. Moreover, the seawater exchange rate for each inlet in this bay was calculated using a reservoir model (Toda et al. 1990, 1994) in order to examine its correlation to the distribution of motile cells of *G. mikimotoi* in the early stages of population growth.

Materials and Methods

Sampling of seawater and counting of phytoplankton cells

Seawater samples were collected at 16 coastal stations (Fig. 1A) in Gokasho Bay, Mie Prefecture, from May to September during the 1991 to 1995 period. Sampling was usually conducted at 10-d intervals at four depths (0, 2, 5 and 10 m for Stns 2–4, Stns 6–13, and Stn 16, and for the other stations at depths of 0, 2 and 5 m and also at 1 m above the bottom.). Cell counts were conducted under a light microscope for a 100-μl seawater subsample on a Sedgewick-Rafter slide.

Estimation of seawater exchange rate

The bay was divided into four parts as shown in Fig. 1B. The rate of seawater exchange between each inlet (II–IV) and the central area (I) was estimated using a box model (Fig. 1C) assuming that the seawater in each inlet is perfectly mixed and the volume of the seawater is

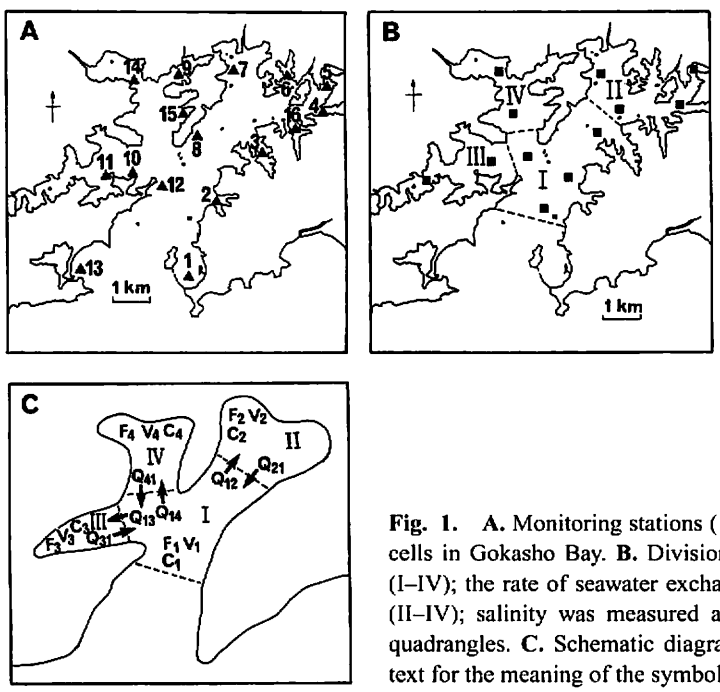

Fig. 1. **A.** Monitoring stations (1–16) for *Gymnodinium mikimotoi* cells in Gokasho Bay. **B.** Division of Gokasho Bay into four areas (I–IV); the rate of seawater exchange was estimated for three inlets (II–IV); salinity was measured at 12 stations indicated by closed quadrangles. **C.** Schematic diagram of the box model; refer to the text for the meaning of the symbols.

steady.

The budgets of water mass and salinity in each inlet (i=2, 3, 4) are as follows:

$$Q_{i1}=Q_{1i}+F_i \tag{1}$$

and

$$V_i \cdot dC_i/dt=C_1Q_{1i}-C_iQ_{i1}. \tag{2}$$

Here, C_i is the average salinity in the inlet i, C_1 the average salinity in the central sea area, V_i the volume of the inlet i, F_i the freshwater inflow into the inlet i, Q_{1i} the flux of water from the central sea area into the inlet i, and Q_{i1} the flux in the opposite direction, i.e., flux out of the inlet i. If the salinity C_1 and C_i are observed at an interval dt and the freshwater inflow F_i is estimated from meteorological data, then we can estimate these fluxes using the following equations:

$$Q_{i1}=(V_i \cdot dC_i/dt+C_1F_i)/(C_1-C_i) \tag{3}$$

and

$$Q_{1i}=Q_{i1}-F_i. \tag{4}$$

The dimension of the flux is volume per unit time, and

$$T_i=V_i/Q_{i1}. \tag{5}$$

T_i is the residence time, which denotes the average time the fluid spends in the inlet i before entering the central area. Further, the reciprocal of the residence time, $1/T_i$, is the ratio of water flux (Q_{i1}) from the inlet i into the central area in relation to the volume (V_i) of the inlet i. In this paper we refer to $1/T_i$ as the seawater exchange rate.

Temperature and salinity were measured at 1 m depth intervals at 12 stations (Fig. 1B) using an STD once a month from January 1991 to December 1995.

C_1 and C_i in equation (3) were estimated by calculating the average, weighted from the observed salinities and the volumes for which the stations in each inlet were representative.

Using meteorological data, the fresh water supply F_i in equation (3) was calculated by the following equations (Toda et al. 1990, 1994):

$$F_i=R_i+P_i+E_i \tag{6}$$

$$R_i=1000rfA_i \tag{7}$$

$$P_i=1000rB_i \tag{8}$$

$$E_i=5.417W(e_w-e_a)B_i. \tag{9}$$

Here, R_i is the river discharge ($m^3\,h^{-1}$), P_i the net precipitation on the inlet surface ($m^3\,h^{-1}$), E_i the freshwater loss by evaporation ($m^3\,h^{-1}$) in the inlet i, r is precipitation ($mm\,h^{-1}$), f the run-off rate (0.64), A_i the area of the drainage basin (km^2), B_i the surface area of the bay (km^2), W wind speed ($m\,s^{-1}$), e_w the saturated vapor pressure (mb), and e_a the vapor pressure (mb). Precipitation (r), vapor pressure (e_a), and wind speed (W) values were from measurements by the Regional Meteorological Station (r, e_a: AMeDASS 53296, W: AMeDASS 53256).

Results

Figures 2 and 3 show the locations and densities of blooms corresponding to the initial appearance of *Gymnodinium mikimotoi* cells in each year from 1991 to 1995 in Gokasho Bay.

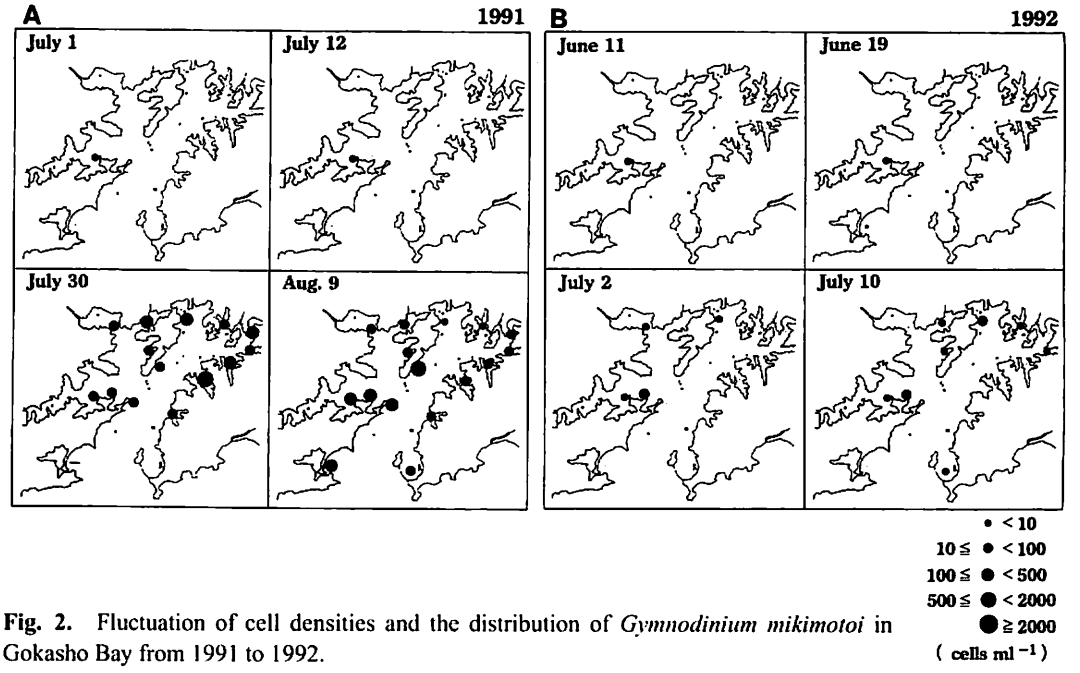

Fig. 2. Fluctuation of cell densities and the distribution of *Gymnodinium mikimotoi* in Gokasho Bay from 1991 to 1992.

Cell densities at each station are expressed as mean values for the water column. *G. mikimotoi* cells first appeared during June–July, and increased in number from July to August in the bay. During daytime most cells of this species concentrated in the middle layer (2–5 m depth) while in the early developmental stage of the bloom.

In 1991 (Fig. 2A), cells of *G. mikimotoi* initially occurred at Stn 11 on 1 July and remained at densities of less than 10 cells ml^{-1} until 12 July. Then, the cell density increased and the area of distribution expanded rapidly to cover the whole bay by 30 July.

In 1992 (Fig. 2B), *G. mikimotoi* appeared at Stn 11 on 11 June and remained at low cell densities for several days as observed in 1991. The area of distribution of this species in the bay subsequently continued to expand until 10 July. However, the cell density of this species in 1992 was low compared to the other years.

In 1993 (Fig. 3A), cells of *G. mikimotoi* were initially observed at Stns 10 and 14 on 18 June. Following this, cells of this species were detected at Stns 11 and 14 on 30 June, and at Stns 5, 6 and 13 on 9 July. However, cells were not observed at any of the monitoring stations in the bay on 20 July, but reappeared on 20 August with the cell density increasing until 30 August.

In 1994 (Fig. 3B), *G. mikimotoi* cells initially appeared at Stns 9 and 11 on 10 June. The cells of this species were not observed on 21 June. However, they were detected again on 30 June, and the cell density of *G. mikimotoi* continued to increase gradually, expanding its area of distribution to cover the whole bay.

In 1995 (Fig. 3C), cells of *G. mikimotoi* were first detected at Stn 11 on 30 June. However, the cells were subsequently not observed from 11 to 20 July. Afterwards the cell density of this species increased at the western sites, and by 18 August blooms occurred throughout the whole bay.

Figure 4 shows the monthly changes in the seawater exchange rate ($1/T_i$) for each inlet (Fig. 1B) of Gokasho Bay. In this figure, the estimated seawater exchange rate is plotted only when

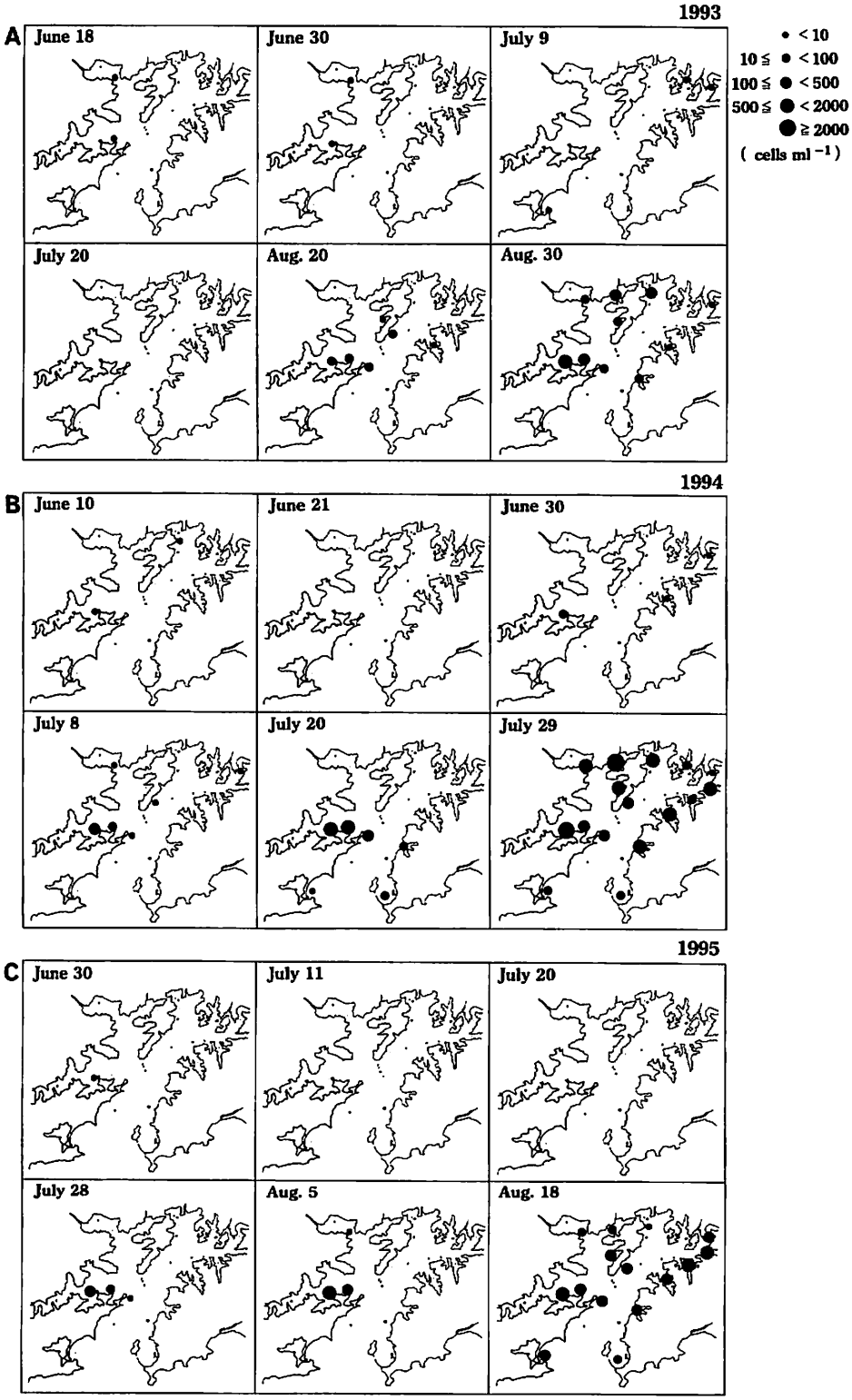

Fig. 3. Fluctuation of cell densities and the distribution of *Gymnodinium mikimotoi* in Gokasho Bay from 1993 to 1995.

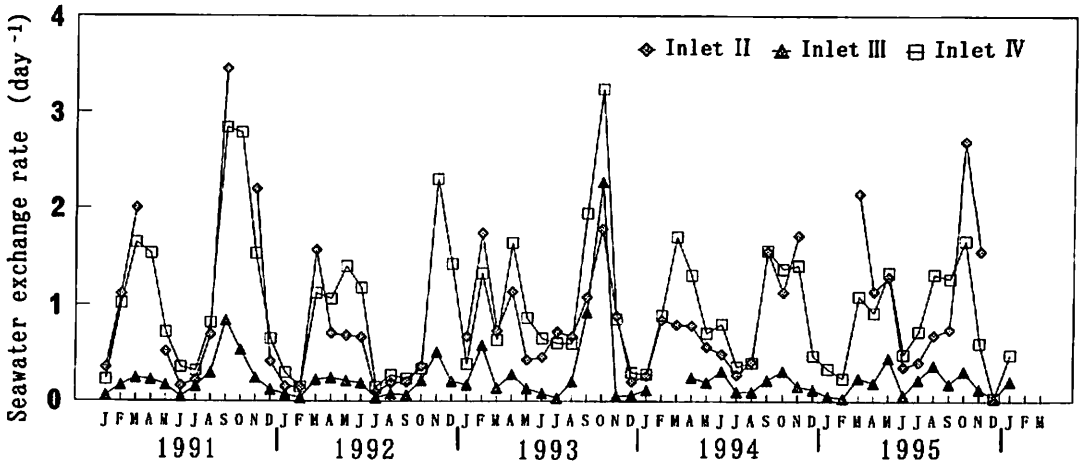

Fig. 4. Monthly changes in the seawater exchange rate in the three inlets of Gokasho Bay.

the salinity differences between C_1 and C_i are larger than 0.05 psu, which is the lowest limit of accuracy for a salinometer (Toda et al. 1990). The seawater exchange rates were low in inlet III. The seawater exchange rates in this inlet were less than 1 d^{-1} throughout the investigation period except for in October 1993. In contrast, the seawater exchange rates were highly variable in inlet II and IV, fluctuating from 0.15 to 3.45 d^{-1} for inlet II and from 0.15 to 3.24 d^{-1} for inlet IV. The monthly mean of the seawater exchange rates over the 5-year period is shown in Fig. 5. It is clear that the mean seawater exchange rates of inlet II and IV did not differ greatly from each other, and remained at higher levels compared to inlet III. As shown in Fig. 4, periods of higher exchange rates were observed in both spring and autumn. In contrast, the water exchange rate was lower in winter and summer. A bimodal pattern in the seawater exchange rate seems to be the case in each inlet.

Discussion

The present study showed that most cells of *G. mikimotoi* were concentrated in the median layers in early stages of their growth. This vertical distribution pattern in this species has been documented in several previous studies (Honjo et al. 1990; Yamaguchi 1994; Takeuchi et al. 1995).

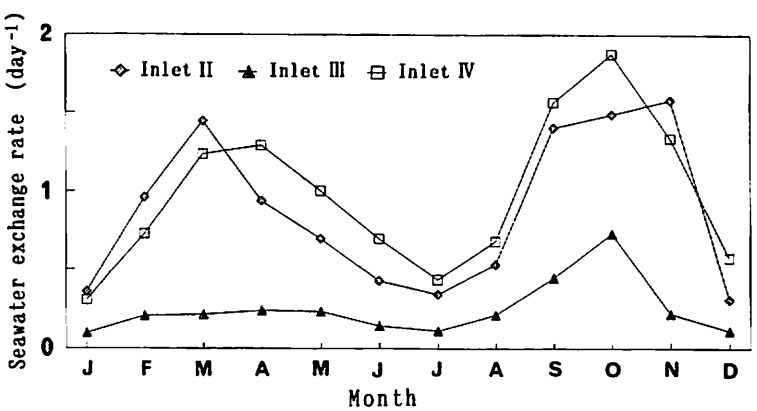

Fig. 5. Monthly mean values of the seawater exchange rate over five years in the three inlets of Gokasho Bay.

The cells of *G. mikimotoi* initially appeared in the western inlet of the bay that includes Stn 11 (Fig. 1A, B) in each year. Takeuchi et al. (1995, 1997) reported that *G. mikimotoi* initially increases to red-tide-causing levels in the innermost part of southern Tanabe Bay and then the blooms spread over the whole bay. The fact that cells of this species initially appear and/or cell densities increase at a particular area within an embayment may be important in the monitoring of red tides of this species. Early detection of *G. mikimotoi* cells at these particular areas may allow predictions on red tide formation and timing within a bay.

In the present study, we used a one-reservoir model for the calculation of the seawater exchange rate, assuming that the seawater in each inlet was perfectly mixed. This model is justifiable in the present case since *G. mikimotoi* does not stay in a specific layer of seawater all day, but undergoes diel vertical migration (Honjo et al. 1990; Koizumi et al. 1996). However, a two-layer model should be developed in the future to allow more detailed studies by incorporating the vertical migration pattern of this species. The seawater exchange rates were calculated based on differences in salinity between two adjacent areas. It is possible that the percentage error increased when differences in salinity were too small. Therefore, care should be exercised when dealing with high values for seawater exchange rates in this study. However, the seawater exchange rate for inlet III is obviously lower when compared to the other two inlets (II, IV). This study shows that *G. mikimotoi* cells first appear in the western inlet where the seawater exchange rate is the lowest of the three inlets in Gokasho Bay. Toda et al. (1994) reported that in situ changes in *G. mikimotoi* cell densities in Gokasho Bay closely correspond to theoretical cell densities calculated using the seawater exchange rate and growth rate determined by Yamaguchi & Honjo (1989) with the assumption that population growth was not limited by nutrients or light. Hayakawa et al. (1996) also speculated that the increase in *G. mikimotoi* cell density in Tanabe Bay is strongly affected by the rate of seawater exchange. The seawater exchange rate was found to be lower in the summer in Gokasho Bay. The presence of summer blooms of this species from 1991 to 1995 illustrates that the summer environment of the bay during this period was suitable for the population growth of *G. mikimotoi* cells.

Thus, seawater flow is considered to be an important factor determining the cell density of *G. mikimotoi* in embayments. Honjo et al. (1991) showed that overwintering of *G. mikimotoi* occurs in the motile form in Gokasho Bay. Motile cells of this species were observed in this bay throughout the year in 1987 and 1988. The overwintering of *G. mikimotoi* motile cells has also been reported in other embayments in western Japan (Nakata & Iizuka 1987; Terada et al. 1987; Itakura et al. 1990; Hosaka 1990; Baba et al. 1994). It is likely that overwintering motile cells of *G. mikimotoi* act as seeds for bloom formation in summer (Honjo et al. 1991). This supposition is supported by the life cycle pattern of this species. Overwintering hypnocysts of *G. mikimotoi* have not been found although sexual reproduction has been demonstrated (Ouchi et al. 1993; Takayama 1995). Many phytoplankton species are considered able to survive unfavourable conditions as resting benthic forms (Pfiester & Anderson 1987; Imai 1990; Itakura et al. 1997). If motile cells that survive the winter become seeds for summer blooms, overwintering cell stock acting as inoculi for bloom initiation may be more strongly affected by the seawater exchange rate than other phytoplankton species that overwinter as benthic forms such as hypnocysts or resting cells.

Seawater exchange rates are thus considered to play an important role in regulating the distribution of *G. mikimotoi* cells in the early phase of bloom initiation in Gokasho Bay as well as regulating seasonal changes in this species' abundance as reported previously (Toda et al. 1994). It is necessary hereafter to evaluate the form of population growth in *G. mikimotoi* in

each inlet of the bay in order to develop a general technique for the prediction of red tides of this species.

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