Wind-Dependent Formation of Phytoplankton Spring Bloom in Otsuchi Bay, a Ria in Sanriku, Japan

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Spring blooms of phytoplankton composed of centric diatoms developed in late February, March, and April in Otsuchi Bay on Sanriku ria coast, Japan. During this period, associated with prolonged seasonal west wind (>1 day), intense exchange of waters occurred between inside and outside the bay: outflow of near-surface brackish water over inflow of oceanic water at depth. This circulation interrupted formation of the blooms, and transported phytoplankton populations seaward. By such water movements, a significant amount of nutrients in the bay was carried out, otherwise replenished into the bay, depending on water masses located outside the bay. Owing to irregular features of wind events, a bloom lasted from several days to a week. From February to April, supply of nutrients seemed to be replete except for the latter half of the bloom period, and estimates of the critical depth exceeded the depth of the bottom consistently. Thus, net growth of phytoplankton was expected throughout the observation period, and potentially blooms could be formed. However, the blooms were only formed under calm weather. We hypothesize that the exchange of waters dilutes populations in the bay, and that formation of the bloom, that is, accumulation of biomass depends on a balance between the growth of phytoplankton and the dilution of bay water.

1. Introduction

Seasonal cycles of phytoplankton have been well documented in coastal and oceanic regions. The cycles are most apparent in crop sizes, primary productivity and species composition. Amplitude and duration of phases in the cycles are quite variable according to localities, generally distinctive in temperate to high latitude waters as summarized by Raymont (1980). In these areas, a general picture is a bloom in spring or early summer and followed by lower crops and production during the subsequent period; occasionally a brief autumn bloom occurs, followed by a very low plant activity in winter. The vernal bloom of phytoplankton is generally consequent on increasing insolation, high nutrients' levels and a shallowing of the mixed layer. During the bloom period, a considerable fraction of the annual primary production can be achieved; in shelf waters the period accounts for about half the annual production, and for more than half the new production that is fueled by nitrate (Walsh, 1988). This phase of high abundance and productivity allows active reproduction of herbivores (Riley, 1946). Thus, the seasonal cycle of phytoplankton productivity influences the whole marine community through trophic relation-

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ships and generates seasonal periodicity of animals and other heterotrophs (Barnes, 1956; Cushing, 1975).

Superimposed on such long-term variations associated with seasonal environmental changes, there are smaller-scale fluctuations that modulate a transition from season to season with a series of pulses and remarkable scatter rather than a gradual shift. Various physical and biological processes operate for the fluctuations on a wide range of time scales (Denman and Powell, 1984). In the inshore waters, the interplay of land run-off, tide, currents and local weather often produces unstable environments, resulting in enhanced temporal variations in crop and productivity of phytoplankton (Winter *et al.*, 1975).

To date investigations that describe short-term variations (one to several days) in biological properties are very scarce in Japanese coastal waters. Available information on factors controlling the temporal variations of the vernal-bloom of phytoplankton is limited. The present study aims (1) to describe temporal variations in chlorophyll *a* and inorganic nitrogenous nutrients during a spring bloom in a small bay based on frequent observations, and (2) to examine a possible relationship of formation and duration of the bloom with local weather.

Observations were made in Otsuchi Bay, which is a semi-enclosed small embayment, 8 km long and 2 km wide, on Sanriku ria coast in northeastern Japan. The bay opens onto the Pacific Ocean (39°20' N, 141°56' E; Fig. 1). Three small rivers, Unosumai, Otsuchi, and Kozuchi river flow into the most inner part of the bay, producing a river plume with approximate influx of 3 to 10 m^3·sec^{-1} (Hirano and Hayakawa, 1976). During the spring, runoff into the bay is derived from melting snow in the surrounding mountains as well as local rainfall. However, the runoff
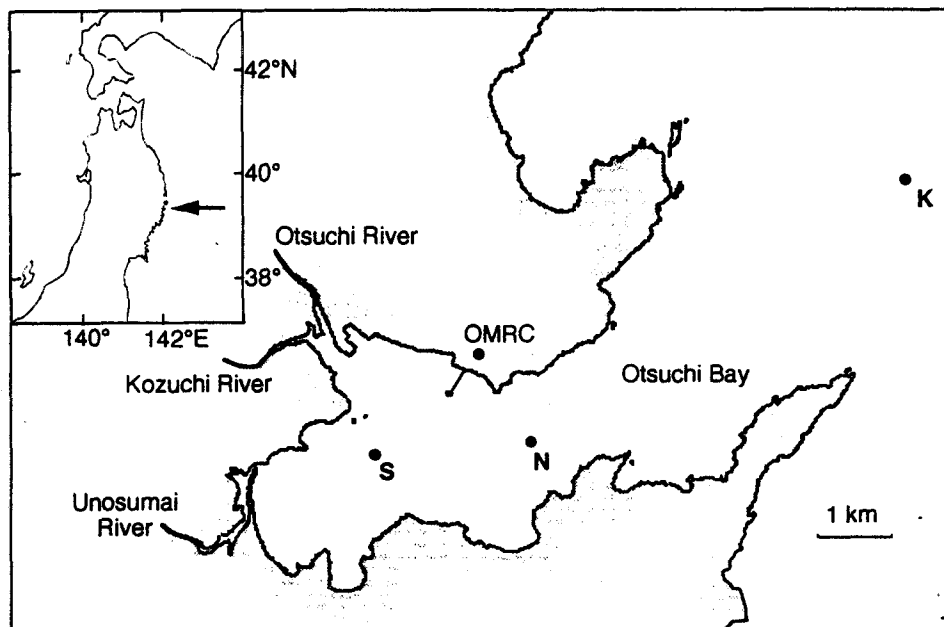

Fig. 1. Sampling locations in Otsuchi Bay. Three stations, Stns. S, N and K were occupied in 1989, and Stn. N in 1990. Measurements of solar insolation were made at Otsuchi Marine Research Center (OMRC). Continuous records of wind speed and temperature were obtained about 400-m offing from OMRC.

water is limited to 1 to 2-m depths. Owing to the presence of the near-surface brackish water and the long and narrow topography of the bay, it is expected that exchange of water in the bay is caused by such a circulation as a seaward outflow of the surface water over landward-moving inflow of denser, more saline water from outside the bay at depth. Conversely, an inflow of surface water over outflow of deeper water is also observed during the summer (Shikama, 1990). The circulation pattern may alter from the former to the latter, and vice versa in summer, depending on difference in water density between inside and outside the bay (Shikama, 1990). The former circulation can be brought about by westerly wind stress along the axis of the bay. This circulation is considered to be prominent in winter and spring when west to northwest wind prevails. This circulation pattern is partially confirmed by current measurements (Hasunuma et al., 1977; Shikama, 1980). Hasunuma et al. (1977) pointed out that tidal currents had little effect on water exchange of the bay in February and March. Thus, the exchange of water inside the bay with offshore water is likely affected by wind. Nevertheless, the bay is influenced as well by currents and distributions of water mass outside the bay as found in subsurface temperature anomaly (Shikama, 1980; Kutsuwada, 1990).

2. Materials and Methods

Since the spring blooms occur in February to April as revealed by an oceanographic survey made in consecutive months (Iizumi et al., 1990), our field survey was conducted in this period. Sampling and observation were made twice to four times a week between April 13 and May 6, 1989, and from February 19 to April 26, 1990. Two stations (N and S, 41 and 22 m in depth, respectively) were occupied inside the bay and one station (K, 80 m deep) outside the bay between 0800 and 1100 h in 1989. In 1990 field surveys were made at Stn. N between 0800 and 0900 h. Seawater samples for dissolved nutrients, chlorophyll a and phytoplankton composition were collected at fixed depths down to 20-m depth in 1989 and to the bottom in 1990. An STD with built-in memory (Aleck Electric, AST1000S) provided vertical distributions of temperature and salinity down to the bottom or 30-m depth. Profiles of temperature and salinity were not obtained on April 11, 13 and 18, 1989. The sensor was calibrated against thermometer and the standard seawater using a salinometer (Guildline, Autosal 8400). Underwater field of photosynthetically available radiation (PAR) was measured down to the bottom in 1990 using a quanta meter fitted with a 4π sensor (Biospherical, QSP-170B). During the measurement, the surface irradiation was recorded.

Chlorophyll a was determined fluorometrically (Turner design, 10R) for particles collected on Whatman GF/F filters (Suzuki and Ishimaru, 1990). The fluorometer was calibrated against pure chlorophyll a (Sigma Chemicals). Inorganic nitrogenous nutrients (nitrate, nitrite and ammonia) were analyzed immediately after sampling using a Technicon Auto Analyzer II by automated analysis methods (Technicon, 1973, 1977, 1978) with minor modifications. Phosphate was determined for a limited number of samples (Technicon, 1976).

Wind speed, its direction, solar radiation intensity and seawater temperature at 1-, 5- and 10-m depths were recorded at ten mins' interval by an integrated weather- and sea-condition monitor system (Shikama et al., 1978; Kutsuwada et al., 1990). A sensor probe for solar radiation was located at Otsuchi Marine Research Center, and other probes were settled about 400-m offing from the Center. The wind direction and speed were measured at 13-m height. The records of the wind and the insolation were not available for a period from April 26 to May 6, 1989. The temperature probe at 10-m depth was out of use in 1990.

3. Results

3.1 1989 Spring bloom

Water was warming steadily at three stations during the observation period (Fig. 2). A weak temperature gradient was observed in the upper 2- to 4-m water column of Stns. S and N. Below the gradient water temperature was relatively uniform with depth. No distinct temperature gradient existed at Stn. K. Salinity showed a marked variation above two to four meters at Stns. S and N according to river discharge, whereas the influence of freshwater was not apparent at Stn. K. Occasionally, subsurface salinity changed abruptly as observed on April 24 when saline water (>33.4 PSU) appeared below about 15-m depth. Associated with the temperature and salinity distributions, water density was vertically uniform substantially below 5-m depth at Stns. S and N, and in the upper 30 m at Stn. K, indicating vertical mixing of subsurface waters. Above 5 m of Stns. S and N there was consistently a strong density gradient with sigma-*t* difference varying from 0.7 to 15.2 at a 5-m depth interval.

Chlorophyll *a* began to increase as an onset of spring bloom on April 13 near the surface at Stns. S and N. Then a high chlorophyll layer was formed on April 17 at 2- to 4-m depths (Fig. 2). This layer disappeared suddenly on April 18. Second onset was found on April 21, and chlorophyll *a* concentration reached a maximum on April 24. The bloom initiated at subsurface layer around 5-m depth. A zone of high chlorophyll abundance expanded vertically down to >10-m depth (Stns. N and K) or the bottom (Stn. S). This bloom persisted for >3 days, and vanished by May 1. The bloom consisted of centric diatoms: species belonging to genera *Chaetoceros* and *Thalassiosira* constituted a significant portion of phytoplankton community. Among them, *C. curvisetum* numerically predominated and occurred regularly. *T. nordenskiöldii* and *C. radicans* were subdominant.

Nitrate concentration fluctuated considerably ranging from undetectable to 21.7 μM (Fig. 2). Overall alterations of nitrate levels occurred twice throughout the upper 20-m water column at Stns. S and N. First shift took place between April 17 and 18, in which concentrations of >8 μM decreased to <5 μM. Since Stn. K was not sampled on April 17 and 18 owing to a rough weather, it was uncertain whether there was a similar change at Stn. K. However, the same magnitude of the decrease as those at Stns. S and N was observed also at Stn. K between April 13 and 20. Second change occurred between April 21 and 27, during which the nitrate level reduced from >3 μM to undetectable. This exhaustion was most distinct around 5-m depth on April 27. Occasional high concentrations near the surface at Stns. S and N were due to river discharge.

Ammonia and nitrite showed less temporal fluctuations than nitrate, and the influence of river discharge was not apparent. Ammonia concentration decreased sharply on April 20 and 21 at three stations, and the lowest concentration was found on April 24. Thereafter, ammonia level rose up to >1.0 μM on May 1 at subsurface layers. The lowest concentration of nitrite was observed on April 27.

Wind direction was most frequent between 270 and 315° (Fig. 3). Another frequent direction was 90–135°. Both wind directions included daily alterations of land and sea breeze. There were prolonged (>1 day) wind events of a constant direction. All of them were westerly wind, among which records on April 17 and 18 were the most distinctive in terms of both duration and high wind speed (Fig. 4). The westerly wind started to blow strongly during the sampling on April 17. Associated with the high wind, water temperature at both 1- and 10-m depths sharply dropped

down to 5.45°C with a delay of seven hours behind the beginning of the blow (Fig. 4). The cold water of <5.5°C was not found in the upper 30 m of Stns. N and S on April 17, suggesting an inflow of the cold water from outside the bay.

An enhanced vertical mixing during the period of April 17 to 20 was indicated by the vertically uniform profiles of temperature, salinity and nutrients (Fig. 2), and by the continuous
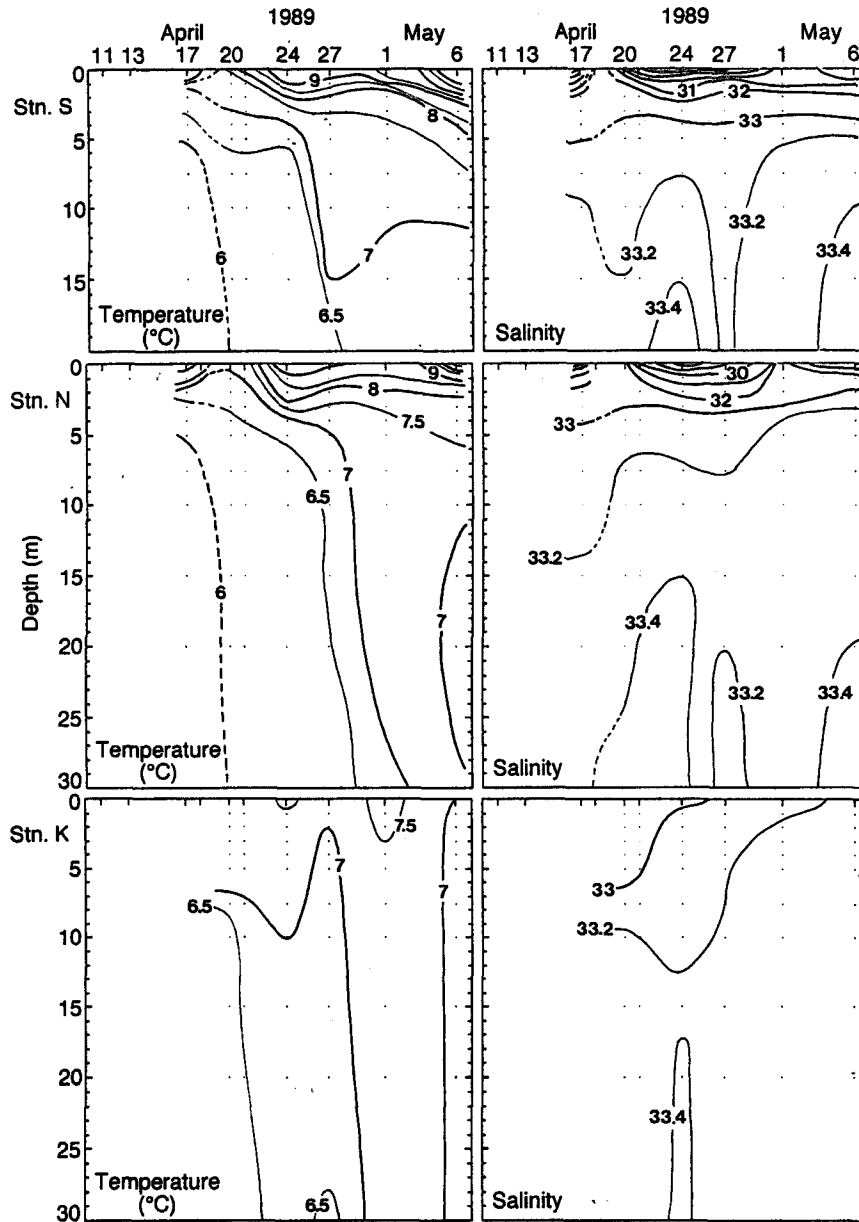

Fig. 2. Vertical profiles of temperature, salinity, nitrate, nitrite, ammonia and chlorophyll *a* at Stns. S (upper), N (middle) and K (lower) over the 1989 spring bloom. Small dots indicate sampling depths. Temperature and salinity profiles were not obtained on April 17 and 18, as indicated by broken lines.
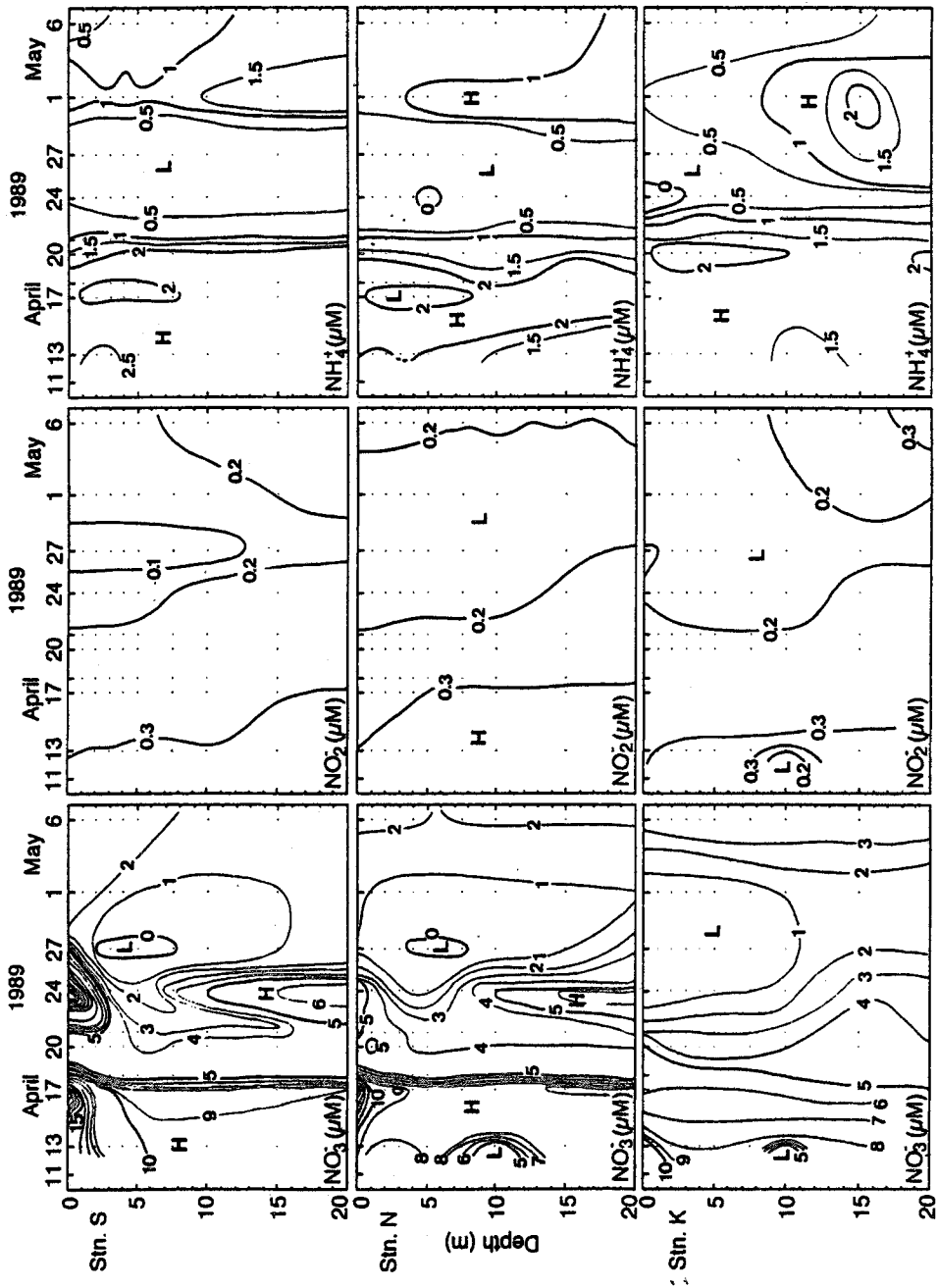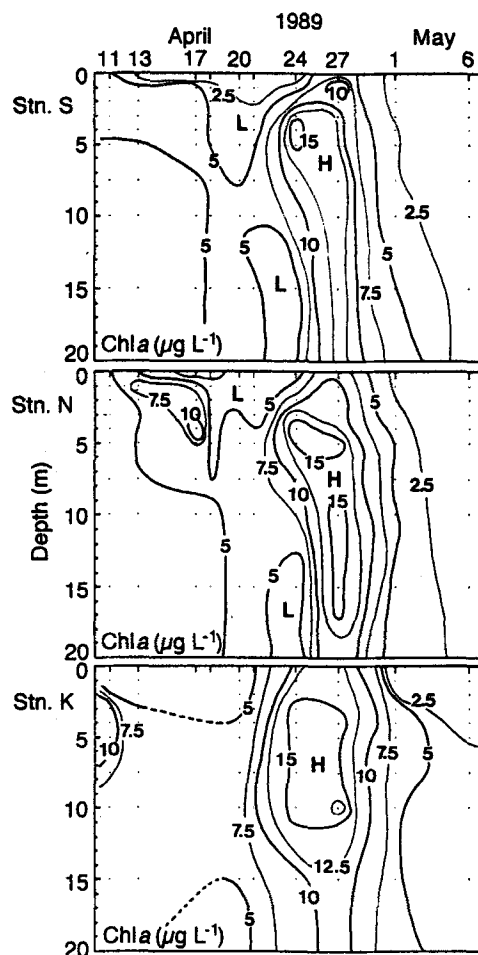
Fig. 2. (continued).

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records of temperature at 1- and 10-m depths (Fig. 4). There were a considerable amount of debris, abioseston and empty frustules of diatoms in seawater samples taken from 10- to 20-m depths of Stns. N and S on April 18, indicating intense vertical mixing of the water columns extended to the bottom. Difference in water temperature between 1- and 10-m depths tended to be smaller during other prolonged westerly wind events.

Developments of phytoplankton bloom during the periods of April 13 to 17 and April 21 to 24 was supported by calm weather and high daily insolation (Fig. 4). Stratification in the upper 10-m water column (Fig. 4) in these periods seemed to favor the bloom.

3.2 1990 Spring bloom

Since the development of spring bloom and temporal variations in nitrate, nitrite and ammonia were generally synchronous at three stations in 1989, the investigation was made at Stn. N as a typical station of the bay in 1990.

Temperature and salinity were generally higher in 1990 than 1989 (Fig. 5). There existed a two-layer structure in the water column as observed in 1989: overlying less saline surface water
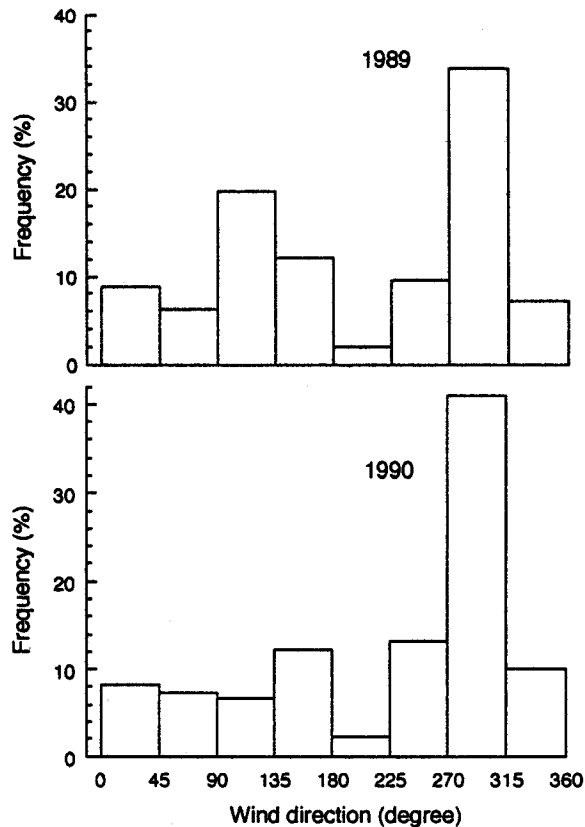
Fig. 3. Frequency (%) of wind direction over the 1989 (upper) and 1990 (lower) spring blooms. Calculation was made for the periods shown in Figs. 4 and 6.

of several meters thickness and vertically uniform subsurface water. A cold water of <6°C appeared near the bottom on March 22. Since then temperature remained to be low (<7.5°C) until April 10.

High chlorophyll *a* concentrations of >5 $\mu g \cdot L^{-1}$ were observed twice: one on February 19 and another between March 29 and April 16 (Fig. 5). The former bloom was composed of *Hyalochaete* and *Thalassiosira* species, among which *Chaetoceros curvisetum, C. debile, T. rotula*, and *T. nordenskiöldii* were most abundant. Although no phytoplankton sample is available before February 19, this bloom seemed to be short lived, judging from a greenish coloring of the sea surface.

The latter bloom was the primary spring bloom in terms of duration and maximum chlorophyll *a* concentration. This bloom initiated around 60% light level. Judging from surface water coloring, the primary bloom progressed in the whole area of the bay since the end of March. During this bloom, centric diatoms constituted a major portion of phytoplankton populations, of which numerically dominant species were *C. curvisetum, C. debile* and *T. nordenskiöldii* on April 2, and *C. curvisetum, C. debile* and *T. rotula* on April 12.

As the second bloom developed since March 29, nitrate rapidly decreased, and became depleted in the top 5-meter water column at the maximum abundance of chlorophyll *a* on April 2. The development of the bloom ceased temporarily between April 5 and 10, when nitrate
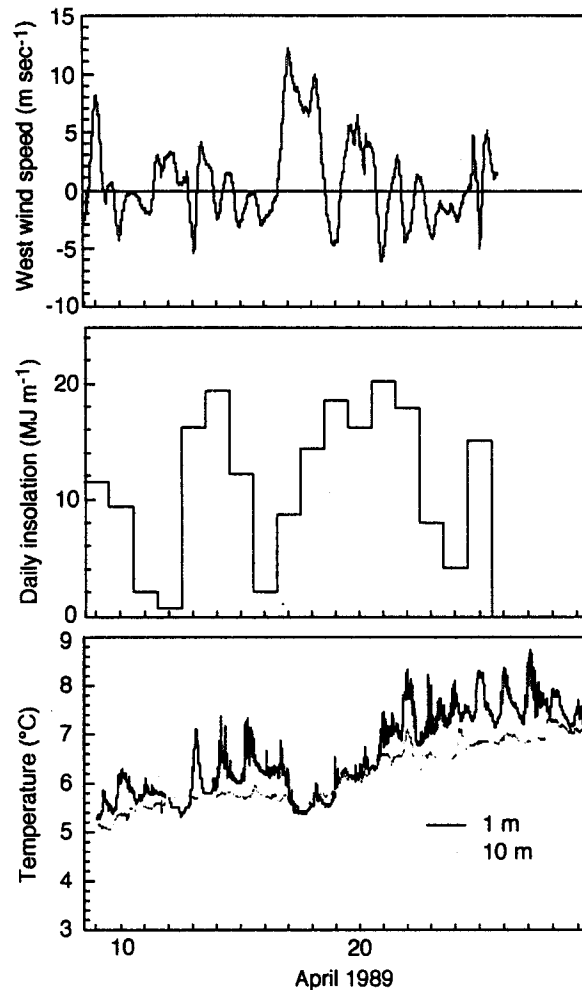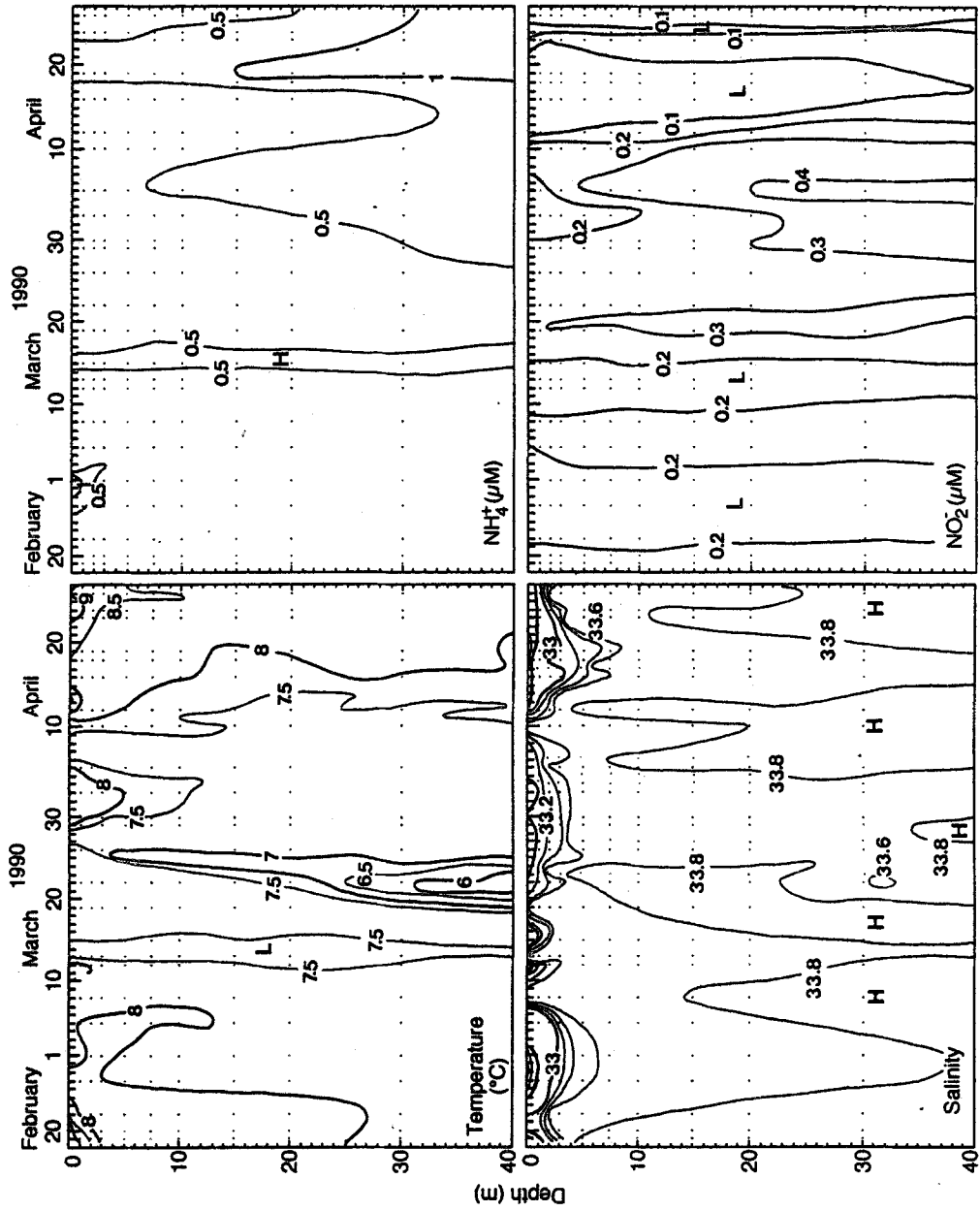
Fig. 4. Variations of wind speed of a west component (upper), daily insolation (middle) and water temperature at 1- and 10-m depths (lower) in April 1989. The wind speed is smoothed by a 6-hr running mean.

concentration recovered. Then, nitrate decreased again along with reformation of the bloom, and was almost exhausted throughout the water column on April 16 and 18. As the bloom extended down to the bottom (0.2% light level) from April 12 to 19, the exhaustion of nitrate was observed below the 1% light depth down to the bottom. In contrast to nitrate, temporal fluctuations of ammonia and nitrite were small. Nevertheless, both nutrients decreased with the development of the bloom.

The extinction coefficient of PAR varied from a low of 0.088 to a high of 0.248 (Table 1). The high value of 0.248 was obtained on March 16 when the surface water became turbid caused by land washout due to heavy rainfall.

The most frequent direction of winds was 270–315° during the observation periods (Fig. 3). In particular, strong westerly wind frequently persisted for longer than one day in March (Fig. 6). Strong winds above 5 m sec^{-1} of a west component blew over 21.1% of the time in March.
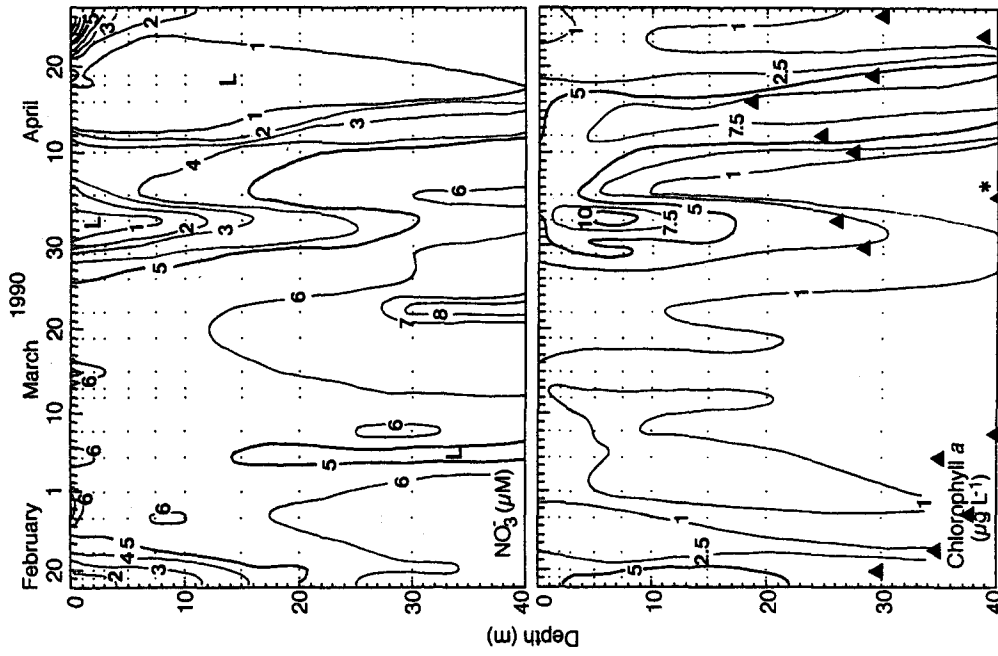
Fig. 5. Vertical profiles of temperature, salinity, nitrate, nitrite, ammonia and chlorophyll a at Stn. N over the 1990 spring bloom. Closed triangles denote 1% light level of that just below the surface. The 1% level was calculated 52 m deep on April 5 (*). The underwater light field was not measured during the period between March 9 and 29.
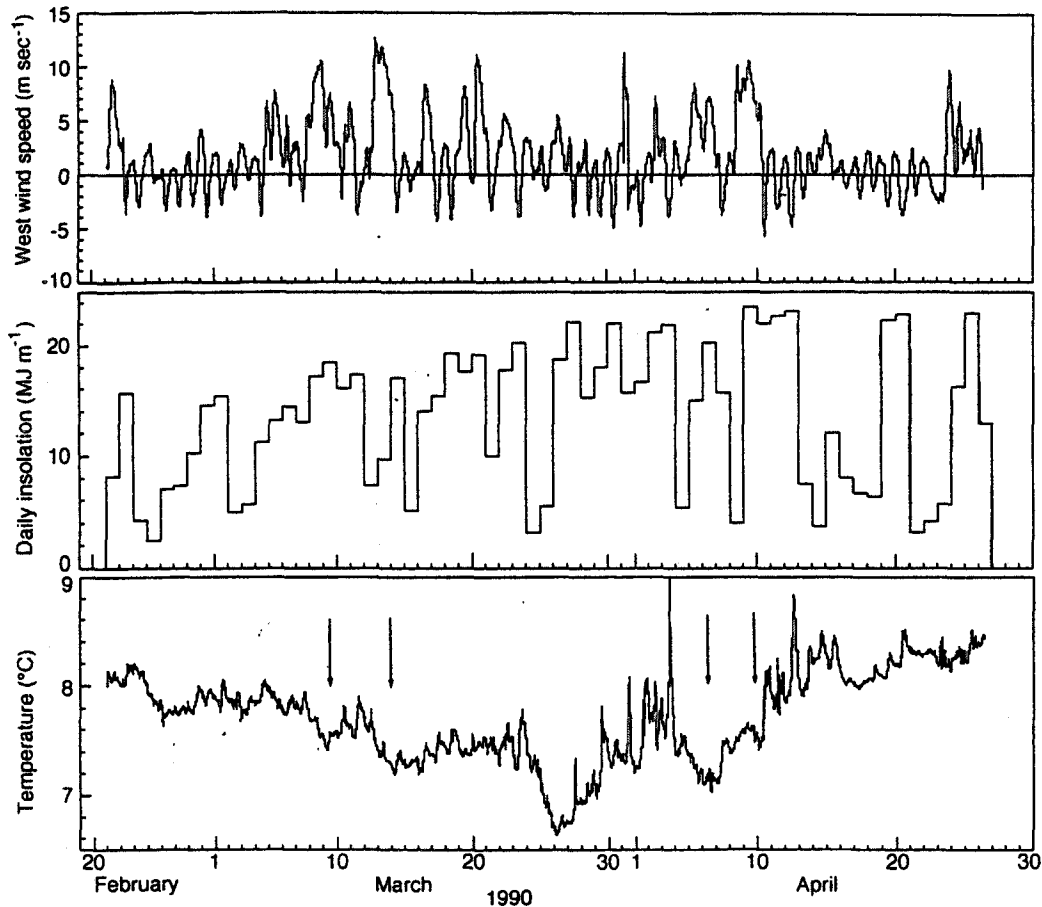
Fig. 6. Variations of wind speed of a west component (upper), daily insolation (middle) and water temperature at a 5-m depth (lower) over the 1990 spring bloom. The wind speed is smoothed by a 6-hr running mean. Arrows denote distinct drops in temperature associated with prolonged (>1 day) westerly wind.

As observed in 1989, the interruption of the bloom formation coincided with a prolonged westerly wind event between April 5 and 7 (Fig. 6). The reformation of the bloom started just after another strong westerly wind period of April 8 to 10 was over. Then the bloom developed under a calm weather. The sustained high westerly wind periods were accompanied by distinct drops in continuous temperature records as marked in Fig. 6. The drops set in with four- to eight-hr delay after the westerly wind started to blow.

4. Discussion

In both years the interruption of the bloom formation occurred in association with the prolonged strong wind events. On April 17, 1989, the integrated nitrate in the upper 20-m water column was 179 m mole·m^{-2} at Stn. N. This amount reduced to 74 m mole·m^{-2} on April 18. A similar magnitude of reduction (51%) was also observed at Stn. S. Although this calculation does not cover the whole water column of Stn. N, a considerable portion of nitrate was likely gone, in that the water column was well mixed down to the bottom as evidenced by the resuspension

Table 1. Light conditions and critical depths at Stn. N in 1990 as calculated by Talling's model (Kirk, 1983). Day length and average solar insolation at the surface during daylight hours (I_o) were obtained by the integrated weather- and sea-condition monitor system. I_d: an average value of downward irradiance of PAR just below the surface. k: extinction coefficient for PAR. I_k: irradiance value defining the onset of light saturation in P-I curve (Takahashi, 1991).

Date	Day length (hour)	I_o (W m^{-2})	I_d (μE m^{-2} sec^{-1})	k (m^{-1})	I_k (μE m^{-2} sec^{-1})	Critical depth (m)
Feb. 20	10.5	341	800	0.160	248	51.0
Feb. 22	10.8	398	776	0.132	261	61.0
Feb. 26	11.0	181	706	0.122	217	70.4
Mar. 5	11.5	313	612	0.129	142	80.1
Mar. 8	11.5	409	799	0.114	210	85.4
Mar. 30	12.5	484	945	0.164	153	79.9
Apr. 2	12.5	465	908	0.180	286	53.5
Apr. 5	12.3	332	649	0.088	225	102.2
Apr. 10	12.8	473	923	0.168	214	68.6
Apr. 12	13.0	490	957	0.192	263	56.0
Apr. 16	12.8	170	665	0.248	214	39.4
Apr. 19	13.3	459	896	0.158	200	77.1
Apr. 23	12.3	124	482	0.117	257	58.1
Apr. 26	13.3	243	665	0.154	260	58.8

of sediments. Since the integrated chlorophyll a did not change in this period, 95.6 mg·m^{-2} to 94.0 for the upper 20-m water column of Stn. N, it is unlikely to ascribe the decrease in nitrate to algal consumption. Instead, taking account of the occurrence of the cold water of <5.5°C on April 18, a net water exchange in the bay is suggested: a net inflow of cold water with lower nitrate concentration. This inference is consistent with the distributions of surface temperature derived from NOAA-10 images: a cold water mass of 5–7°C has been located alongside Sanriku coast. The entrance area of Otsuchi Bay was considered to be under the influence of this water mass in this period (Japan Fisheries Information Service Center, 1989).

In 1990, the bloom formation discontinued on April 5. Following the high wind event, the integrated nitrate from the surface to the bottom increased from 127 m mole·m^{-2} on April 2 to 207 on April 5. This was accompanied by a rapid decrease in the integrated chlorophyll a, varying from 205 mg·m^{-2} to 48 between April 2 and 5, 1990. These observations strongly indicate a net water exchange between inside and outside the bay: an incursion of an oceanic water with high nitrate and low chlorophyll a, and an outflow of the bay water. This view is supported by the lowest extinction coefficient on April 5 (Table 1).

Two mechanisms can cause the water exchange of the bay. Firstly, as above cases in our observations, strong westerly wind can drive a vertical circulation in the bay. Although no current measurement was made for direct evidence of water transport in the present study, Shikama (1980, 1990) deployed current meters near Stn. N in winter and early spring. He observed that, when west to northwest wind prevailed with a mean wind speed of about 3 m·sec^{-1}, there existed a rather steady circulation: an outflow in the upper layer with a mean velocity of 7 to 8 cm· sec^{-1} over a deeper inflow of 3 to 5 cm·sec^{-1} equivalent to 6 to 7, and 3 to 4 km day^{-1}, respectively, suggesting that a whole body of water in the western half of the bay (west of Stn. N) can be

exchanged in a day. Furthermore, even more rapid exchange was occasionally probable during our observation with instantaneous velocity of the west wind frequently exceeding 10 m·sec⁻¹ (Figs. 4 and 6). Therefore, as a consequence of the prolonged strong wind, the rapid horizontal advection results in outward transport of the population, and terminates or interrupts the formation of the spring bloom. Moreover, the vertical mixing enhanced by the wind events tends to disperse phytoplankton cells in the water column, retarding the bloom formation. In other words, a combination of the water exchange and vertical mixing both enhanced by the wind events interrupts bloom formation. On the other hand, a net inflow of nitrate-rich oceanic water replenishes the supply of nutrients to the population as observed in early April 1990 (Fig. 5).

Secondly, there can be an abrupt subsurface inflow of oceanic water that shows no apparent relationship with the wind stress. On March 22, 1990, a cold and less saline (<33.8 PSU) water with a high nitrate concentration of >7 μM was found near the bottom, and mixed with the upper water (Fig. 5). NOAA-10 images show an existence of a cold water mass with surface temperature of 6°C originated from Oyashio on Sanriku coast (Japan Fisheries Information Service Center, 1990). Thus, the exchange of bay water can be caused directly by entrainment of water masses outside the bay as well. However, the first type of the water exchange occurred more frequently than the second type. Together by the prolonged strong wind events of irregular nature, phytoplankton dynamics in Otsuchi Bay are subject to the episodic physical processes.

The temporal fluctuations of nutrients are considered to reflect phytoplankton consumption as well as the water exchange. The water exchange distinctly affected nitrate concentration, whereas not apparent in ammonia. Nitrate and ammonia were quickly exhausted with the bloom formation; the exhaustion of ammonia preceded that of nitrate in 1989 (Fig. 2), whereas depletion of ammonia was less evident in 1990 (Fig. 5). During non-bloom period, the nitrogenous nutrients seemed to be supplied sufficiently (Figs. 2 and 5). Further, supply of phosphate is considered to be plenty in Otsuchi Bay, because the ratio of nitrate to phosphate is generally lower than 16:1 (Iizumi *et al.*, 1990). A limited number of determinations in the present study suggested phosphate was probably replete, varying from 0.36 to 1.04 μM.

Temperature and salinity indicated that below the surface layer of several-meter thickness, the water mass in the bay belonged to either Tsugaru Warm Water current, Oyashio water or surface-layer water system, *sensu* Hanawa and Mitsudera (1987). Although limited hydrographic data were available in the offshore waters during the periods of the present study, there was an obvious continuity of water mass between the bay water and offshore waters in a horizontal scale of several to ten miles from the bay (Iwate Prefectural Fisheries Laboratory, 1989, 1990). Therefore, together with the algal consumption, the nutrient level in the bay was likely governed by the water mass outside the bay, except the upper several meters where there were occasional supplies of nutrient from the land runoff. Nitrate of the offshore water varied around 5 to 8 μM in March (Iwate Prefectural Fisheries Laboratory, 1989, 1990), approximately falling in with the ranges of nitrate concentration below the less saline surface layer in the bay (Figs. 2 and 5).

Provided that the supply of nutrients was ample, under what conditions was phytoplankton growth controlled during non-bloom period? Although many factors are known to be attributable to the growth of phytoplankton, available information is quite limited in the present study. Hence, the following should be a preliminary examination. Table 1 summarizes light conditions during the 1990 observation. The 1% light level varied from 19 to 52 m (Fig. 5). Owing to the vertical mixing of the subsurface water (Fig. 5), population could be transported below the 1% light level, resulting in a possible light-limitation. We estimate the critical depth (D_{cr}) using an equation

derived from Talling's model (Kirk, 1983):

$$D_{cr} = \frac{N}{24k\rho} \ln\left(\frac{\bar{I}_d}{0.5I_k}\right)$$

where N is day length in hours, k is extinction coefficient of PAR, ρ is the ratio of respiration rate to light-saturated photosynthetic rate, I_d is the average value of downward PAR just below the surface during daylight hours, and I_k is the irradiance value defining the onset of light saturation. I_d is calculated from solar insolation (I_0) with assumptions of (1) a mean value of 15% for total surface losses, (2) 550 nm as the average wavelength of PAR for conversion from energy unit to photon unit, and (3) a ratio of PAR in the total solar radiation being 0.5 on a clear day, 1.0 at the overcast condition, and intermediate value in proportion to the cloud coverage (Parsons *et al.*, 1984). ρ is constant to be 0.1. I_k was obtained from the deepest P-I curves available each day (the 1% light level or around 15- to 20-m depth; Takahashi, 1991).

The critical depth ranges from 39 to 102 m (Table 1). The shallowest value is largely a product of the anomalously high extinction coefficient as noted above. Another estimation using Sverdrup's model (1953) tends to yield deeper critical depths than those calculated by the above equation. Although an estimate of neither light conditions nor the critical depth is available between March 8 and 30, the critical depth for this period is considered to have been deeper than the bottom depth, since the consistently low abundance of chlorophyll *a* is indicative of deep light penetration, and the magnitude of solar insolation seems to have been sufficient (Fig. 6). Hence, light-limitation of phytoplankton growth has been improbable. Consequently, the supply of nutrients and availability of light do not explain a question why phytoplankton bloom has not been formed from the end of February through March 1990 in Otsuchi Bay.

On the basis of the above discussion, we postulate a possible effect of the wind-driven water exchange across the entrance of the bay that dilutes the growing population inside the bay. The intense exchanges of the water, which has been suggested by the frequent occurrence of the prolonged strong wind events from the first to third week of March 1990 (Fig. 6), probably do not allow biomass to build up to bloom. On the other hand, when calm weather brings inactive water exchange, and growth rate of phytoplankton surpasses "dilution rate" of the bay water by waters outside the bay, an accumulation of biomass starts and a bloom is formed. Thus, the dilution of the bay water regulated by the wind stress likely affects population density. According to this view, the interruption of the bloom formation observed on April 18, 1989 and on April 5, 1990 can be interpreted that the "dilution rate" has surpassed growth rate of phytoplankton. In case of a long duration of the extensive dilution compared to the growth of phytoplankton, the population can be washed out. To examine this scenario, a further investigation is needed, especially for direct evidence of currents and transport of water, and their relations with growth of phytoplankton.

In conclusion, the seasonal westerly wind plays an important role in the formation of the spring bloom and temporal variations of nutrients in Otsuchi Bay, and significantly contributes to short-term dynamics of phytoplankton population in a time scale of days. With a consistently ample supply of nutrients and availability of light, phytoplankton can form a bloom potentially from the end of February to April. During this period, the wind events likely control the formation. According to a similar land topography and bay configuration of other bays on Sanriku ria coast, a common relationship between the wind events and phytoplankton dynamics

is expected in the wide range of Sanriku area. In the offshore water, the deep vertical mixing of the water column compared with the critical depth did not seem to allow active growth of phytoplankton (Iwate Prefectural Fisheries Laboratory, 1989, 1990; Table 1). Once the water is introduced into rias where the bottom depths are shallower than the critical depths, net increase of algal biomass occurs and nutrient is consumed rapidly. Organic materials produced in the rias can be transported toward offshore by the water exchange in turn. Thus, rias are considered to function as an important area of primary production in March and April. Since primary productivity of phytoplankton in rias is dependent on the wind events of an irregular feature in time scales of days to years, herbivorous production is expected to have subsequent irregular features (Barnes, 1956; Cushing, 1975; Parsons, 1988).

Acknowledgements

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