

Annual cycles of nutrients and dissolved oxygen in a nutrient-rich temperate coastal bay, Chinhae Bay, Korea

GI HOON HONG, KYUNG TAE KIM, SE JIN PAE, SUK HYUN KIM AND
SOO HYUNG LEE

Korea Ocean Research & Development Institute, Ansan P.O. Box 29, KyungKi-Do 425-600, Korea

영양염류가 풍부한 온대 해역 내만(한국, 진해만)에서의 영양염류와 용존산소의 연변화

홍기훈 · 김경태 · 배세진 · 김석현 · 이수형

한국해양연구소, 425-600, 경기도 안산시 안산우체국 사서함 29호

The annual cycles of plant major nutrients and dissolved oxygen in a nutrients-rich semi-enclosed coastal inlet, Chinhae Bay, of the southern coast of the Korean Peninsula are first presented. The water column of the bay is stratified during summer (April-late September) and well-mixed during winter (October-March). During the summer stratification period, dissolved oxygen contents exceed $400 \mu\text{M}$ in the surface but diminish to less than $50 \mu\text{M}$ in the near bottom waters, which often results in an anoxic environment in the inner part of Chinhae Bay. After the breakdown of the stratification in October, dissolved oxygen concentration remains undersaturated until February. The evidence of allochthonous input of N-nutrients throughout the year is readily seen in the water column; however, crude budget calculations show that the nutrients are efficiently utilized within the bay ecosystem, and that export of the nutrients from the bay to the shelf must be negligible. There is no sign of the enrichment of the nutrients in the water column. The eutrophication phenomenon *sensu stricto* is not observed in Chinhae Bay. Using the standing stock of dissolved oxygen and estimation of the oxygen fluxes across the air-sea boundary, a benthic oxygen respiration rate during winter is estimated conservatively at $21\text{-}24 \text{ mmol Cm}^{-2}\text{d}^{-1}$. This oxygen respiration rate accounts for about 20% of the total phytoplankton production in winter.

한반도 남해안에 위치한 반폐쇄성 연안해역으로 영양염류가 풍부한 진해만에서의 영양염류와 용존산소의 계절적인 순환양상을 최초로 보고하였다. 진해만의 수리학적인 양상은 성층화된 여름(4-9월)과 수직적으로 잘 혼합된 겨울로서 특징지을 수 있다. 진해만의 내부는 여름에 표층에서는 용존산소가 $400 \mu\text{M}$ 을 넘으나 저층에서는 $50 \mu\text{M}$ 이하로 무산소 환경을 이룬다. 10월경 성층이 파괴된 후에도 2월경까지는 물기둥 전체가 용존산소로 불포화 되어 있다. 질소계 영양염류는 육지로부터 일년내내 유입된다. 그러나 간단한 수치 계산결과 모든 영양염류들은 진해만 생태계 내에서 효과적으로 순환되고 외부 대륙붕으로의 유출은 거의 없는 것으로 생각된다. 따라서 엄밀한 의미에서 영양염류의 축적은 거의 일어나지 않는 것으로 보인다. 겨울철 벤틱층(해저표면을 포함하는 인접수층)에서의 호흡률을 용존산소 현존량과 대기-해양 교환량을 이용하여 추정하면 최소 $21\text{-}24 \text{ mmol m}^{-2}\text{d}^{-1}$ 이다. 이는 겨울철 식물플랑크톤에 의한 광합성량의 20% 정도를 차지하는 양이다.

INTRODUCTION

The coastline of the Korean Peninsula is chara-

cterized by a long stretch of a Ria-type coast in the southern and western parts, thus forming numerous inlets whose physiographic features signifi-

cantly differ from each other. Therefore, biogeochemistry in each bay bears little resemblance to each other due to the differences in the external forcing functions, such as, buoyancy production pattern by precipitation, solar radiation, kinetic energy input from wind and tide induced current, timing and amount of nutrient input, and water depth. For example, the inner part of Deukrayng Bay is permanently well mixed due to its shallow depth and its primary productivity peaks in winter (Hong *et al.*, 1988). However, the adjacent Yeoja Bay is strongly influenced by the intermittent freshwater input, and primary productivity peaks in fall (Hong *et al.*, in preparation). A seasonal variation of those environmental forcings is particularly strong due to the prevailing monsoon. Besides the seasonal variation of natural forcing functions, each bay is under diverse man-made stress ranging from the anthropogenic impingement of nutrient input, modification of community structure introduced by practicing aquaculture, damming of the inflowing rivers, reclamation, and dredging of the seafloor.

Chinhae Bay is one of the semi-enclosed bays of the southern coast. The C/N mole ratios (Yang and Hong, 1988) and the δC^{13} values (Hong *et al.*, unpublished data) of sedimentary organic matter suggest that the bay has a phytoplankton based ecosystem. The bay is abundant in nitrogen-nutrients, and supports high primary productivity year round (including red tide). Therefore it is believed to be one of the most heavily polluted bays in Korea.

Chinhae Bay has been extensively studied since 1974 (KORDI, 1974): the statistical analysis of water quality parameters and red tide occurrence (Lee *et al.*, 1981), a short-term variation of nutrients and plant pigment (Yang and Hong, 1982; Yang *et al.*, 1986), sedimentary heavy metals (Lee and Lee, 1983; Hong *et al.*, 1983), diatoms (Lee and Yoo, 1986), dinoflagellates (Cho, 1978; Han and Yoo, 1983), benthos (Hong and Lee, 1983). However, most previous works dealt with the data obtained in a limited time of the year, and a systematic biogeochemical investigation has not been made.

The present paper deals with the first order des-

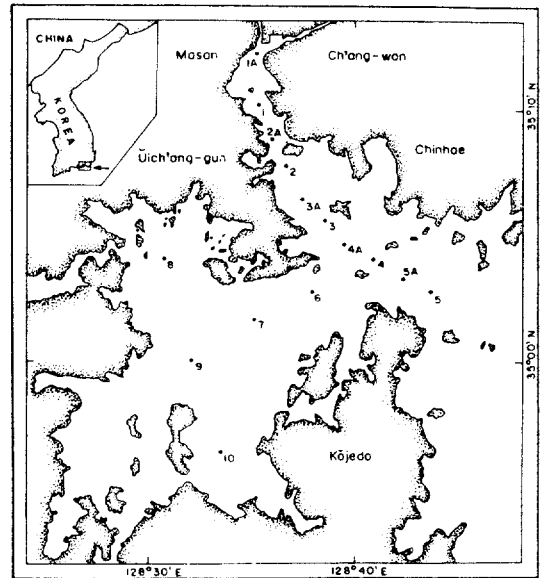


Fig. 1. Station locations in Chinhae Bay, Korea.

cription of Chinhae Bay system by examining the seasonal cycling of nutrients and dissolved oxygen in the water column associated with the external forcing functions, and presents a budget calculation which attempts to place general quantitative limits on the eutrophication. The purposes of this paper are:

1. To elucidate major forcing functions of the biogeochemistry of the biologically important elements.
2. To describe the effects of change in delivery of nutrients from land to sea on the coastal waters.
3. To understand the role of the coastal ocean in the global carbon cycle.

MATERIALS AND METHODS

Five sampling stations were occupied from the head of the bay (Masan Harbor) to the mouth (Fig. 1). Water column was sampled bimonthly from June 1987 to April 1988. Water temperature and salinity were measured using a T-S Bridge (Type M.C.5. National Institute of Oceanography) with the precision of $\pm 0.1^\circ\text{C}$ and ± 0.1 ppt. Dissolved oxygen was measured using a Yellow Springs dissolved oxygen meter (YSI model 57) with its precision of $\pm 0.5 \mu\text{mol l}^{-1}$. Surface water samples

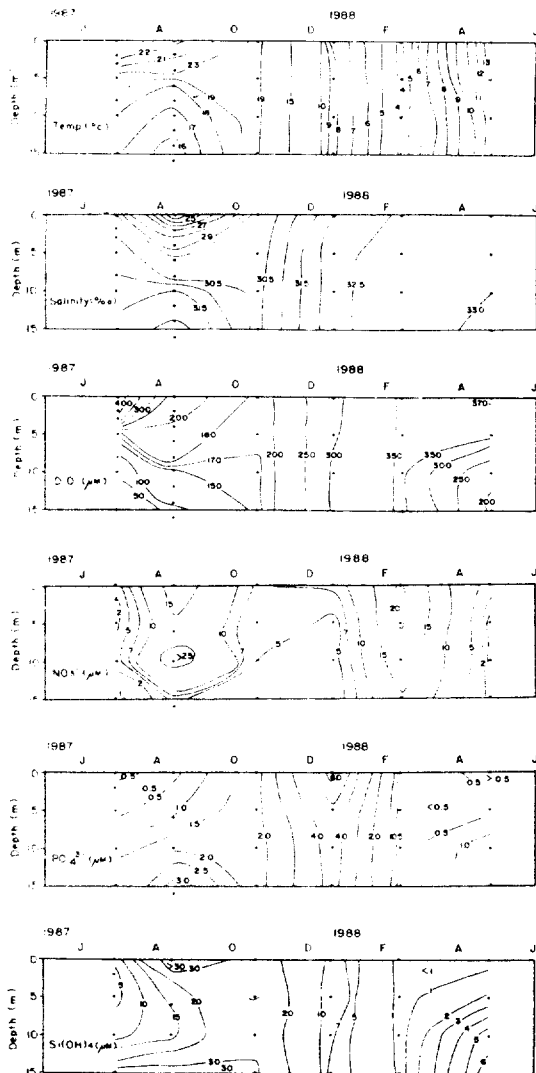


Fig. 2. Time series distribution of temperature ($^{\circ}\text{C}$), salinity (o/oo), dissolved oxygen (μM), nitrate (μM), phosphate (μM), silicate (μM), in Chinhae Bay (St.2).

were collected using a bucket, and subsurface water samples were collected at 2 m intervals using a Van Dorn water bottle. Water samples for nutrients analysis were filtered through Whatmann GF/F glass fiber filters and deep frozen for later analysis. Ammonium ion was fixed with phenol immediately and was determined by the method of Solorzano (Parsons *et al.*, 1984). Other dissolved inorganic nutrients were determined using an au-

toanalyzer (Technicon II). Nitrate was determined by the Greiss reaction (Armstrong *et al.*, 1967). Phosphate was determined by the procedure of Murphy and Riley (1962). Silicic acid was determined by the molybdate method (Whitledge *et al.*, 1981). Precisions of nutrient analysis are within $\pm 1\%$.

RESULTS

Nutrients and dissolved oxygen data collected over the period of June 1987 to April 1988 are listed in Appendix 1.

1. Temporal variations

Mainly discussed here are the data from St. 2 as a typical temporal variation.

Hydrography

Time series vertical distributions of temperature and salinity show that the water column is stratified from early April to September and destratified for the rest of the year (Fig. 2). Winter mixing appears to be very strong, and virtually no vertical gradient exists in temperature and salinity, although surface salinity is diluted by freshwater input due to the proximity of an narbor. Temperatures vary from less than 4°C in February to more than 22°C in July. Surface salinity is the lowest (less than 24 ppt) in late August and the highest (ca. 33 ppt) in February-March.

Dissolved Oxygen

Time series distribution of dissolved oxygen concentrations closely follows the hydrographical feature (Fig. 2). During the summer stratification period, the dissolved oxygen content exceeds $400 \mu\text{M}$ (ca. 200% saturation with respect to the air) in the surface and diminishes to less than $50 \mu\text{M}$ (ca. 10% saturation with respect to the air) in the near bottom waters. After the breakdown of the stratification, the dissolved oxygen content in the whole water column gradually increases from $200 \mu\text{M}$ (ca. 80% saturation) to $350 \mu\text{M}$ (ca. 100% saturation) at the end of the destratification period.

Nutrients

The ammonium (NH_4^+) content varies from 1 μM (April) to 70 μM (August) in the surface waters, and from 3 μM (April) to 37 μM (August) in the near bottom waters (Appendix 1). Time series distribution patterns of nitrate (NO_3^- plus NO_2^-), phosphate (PO_4^{3-}) and reactive silicate ($\text{Si}(\text{OH})_4$) contents in the water column are quite similar to hydrographical features of the bay. Nitrate concentration is generally higher (more than 10 μM) in the surface waters than in the near bottom waters throughout the study period. However, a significant reduction of nitrate concentration (less than 5 μM) is noted during the onset of stratification in April (Fig. 2). Denitrification in the near bottom waters is also found during the stratification period. The seasonal distribution pattern of phosphate is opposite to that of nitrate. Phosphate concentrations are lower in the surface waters than in the bottom waters (Fig. 2). In the surface waters, phosphate concentrations are less than 1 μM during the stratification period, and after the destratification of the water column in October, phosphate concentration increases to 5 μM in December and decreases to the less than 1 μM during the onset of the stratification in April. During the stratification period, phosphate accumulation is noticeable in the near bottom waters. Silicate concentrations decrease from 30 μM (late August) in summer to 1 μM (February) in winter (Fig. 2). Accumulation of silicate in the near bottom waters is noticeable during the stratification period.

2. Spatial distribution

The temporal variation of the hydrographical features of the inner part of Chinhae Bay shows that the bay may be characterized by two seasons: warm, less saline stratified period (April-September) and cold, more saline destratified period (October-March). Therefore, August and February were selected as the representatives of the two seasons.

Hydrography

Surface water temperature decreases from the

head to the mouth of the bay during the stratified summer period (temperature difference between Sts. 1 and 5 is 5.6°C), however, it increases from the head to the mouth (temperature difference between Sts. 1 and 5 is 1.6°C) during the destratified winter period due to the differential heating of land and seawater (Fig. 3). In winter, the bottom water is warmer than the surface waters. During August, vertical temperature gradient is strong in the head and weak in the mouth, and temperature differences between the surface and near bottom waters are 6.6 and 1.6°C in the head (St.1) and the mouth (St. 5), respectively. During February, water column is fairly well mixed from the top to the bottom.

Salinity increases from the head to the mouth and from the surface to the bottom (Fig. 3). Spatial distribution patterns are quite similar to those of temperature. High temperature and less saline surface plume is developed strongly in the head and weakly in the mouth which results in the formation of salt wedge along the seafloor.

Dissolved Oxygen

In order to compare the warm and the cold seasons, a percentage of dissolved oxygen saturation with respect to the air is presented here instead of absolute value (Fig. 3). Surface dissolved oxygen content decreases from the head to the mouth of the bay for the whole year. During August, vertical gradient of dissolved oxygen is strong in the head and weak in the mouth. The difference in the dissolved oxygen content between the surface and the bottom waters is more than 90% in the head and less than 30% in the mouth. During February, the water column is homogeneous with respect to the dissolved oxygen contents.

Nutrients

In general, nutrients of nitrate, phosphate, silicate concentrations are much higher in summer than in winter (Fig. 3). In the summer stratification period, nitrate and silicate concentrations are both high in the head and mouth but relatively low in the middle. In the winter destratification period, nitrate concentrations decrease from the head to

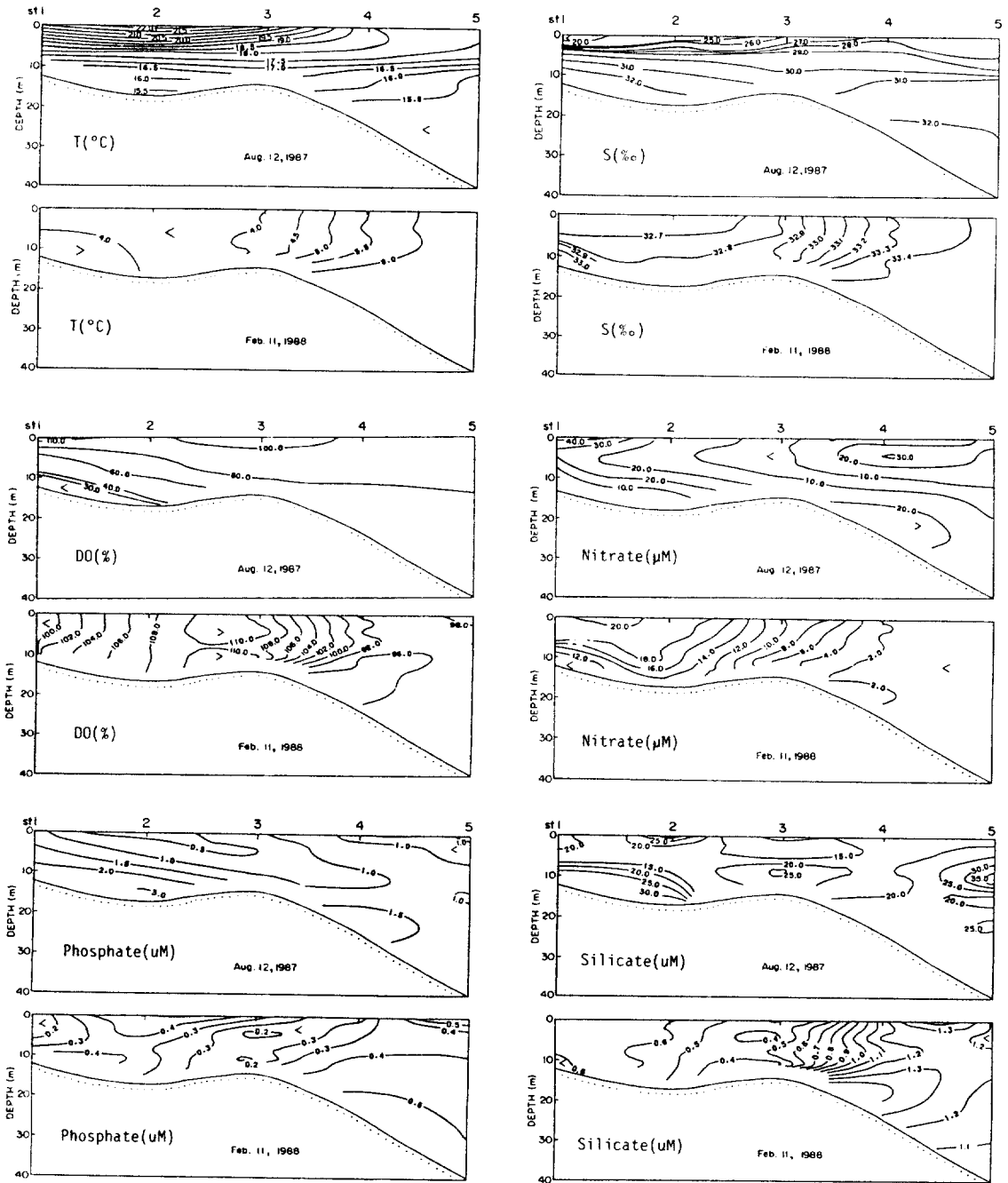


Fig. 3. Temperature (°C), salinity (ppt), dissolved oxygen (%), nitrate (μM), phosphate (μM), silicate (μM): Longitudinal section in Chinhae Bay.

the mouth, silicate and phosphate concentrations, however, increase from the head to the mouth.

DISCUSSION

The current regime of chinhae Bay is well known (Kim *et al.*, 1989). Kim *et al.* show that tidal current in the inner part of Chinhae Bay (Sts. 1 and 2) is very weak and somewhat isolated

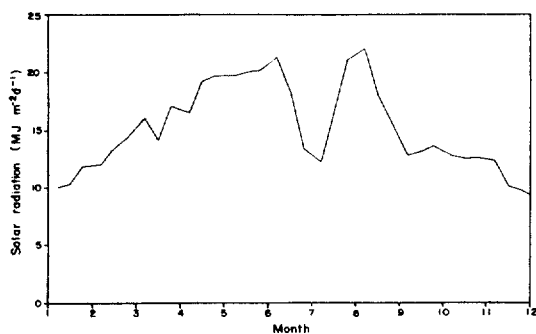


Fig. 4. Mean solar radiation during 1983-1986 near Masan (Pusan). Data from Korea Central Meteorological Office.

from the main axis of tidal current (Sts. 4 and 5) by simulating tidal current. They further show that the bottom waters of the inner part of Chinhae Bay are not well communicated with those of outer bay due to the presence of shallow sill in St. 3 (Fig. 3). Since the distinct nature of the semi-enclosed basin is most pronounced in the inner part of Chinhae Bay, discussion is mainly focused on St. 2.

1. Stratification and destratification

The mechanism of stratification and destratification has not been clearly understood yet. A preliminary thought is given here. Water column stability is determined by the relative strength of the rate of delivery of buoyancy and the rate of dissipation of buoyancy due to tidal, frictionally induced turbulent energy (Seliger *et al.*, 1985). Buoyancy contribution in this region is due to solar radiation and precipitation.

The four-year-mean solar radiation for 1983-1986 near Pusan varies from $8 \text{ MJm}^{-2}\text{d}^{-1}$ in December to more than $20 \text{ MJm}^{-2}\text{d}^{-1}$ in June and September, and significantly reduces in wet monsoon period (July-August; Fig. 4). The amount of solar radiation in winter greatly exceeds the requirement of phytoplankton growth ($0.6\text{-}0.8 \text{ MJm}^{-2}\text{d}^{-1}$; Parsons *et al.*, 1977; Pingree, 1978). The annual mean precipitation is about 1500-2000 mm, of which over 80% is concentrated in the summer stratified period (Fig. 5). High variability of the annual precipi-

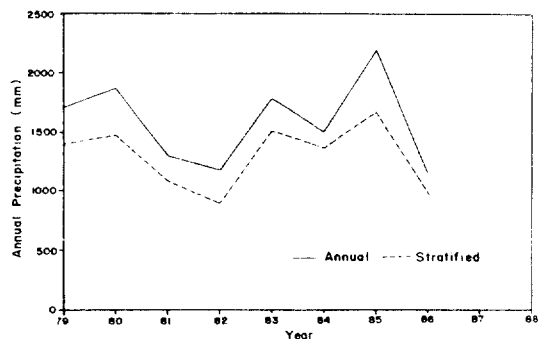


Fig. 5. Annual variation of precipitation in Masan Area. Annual and stratified stand for total precipitation over a year and total precipitation over a summer stratified period, respectively. Data from Korea Central Meteorological Office.

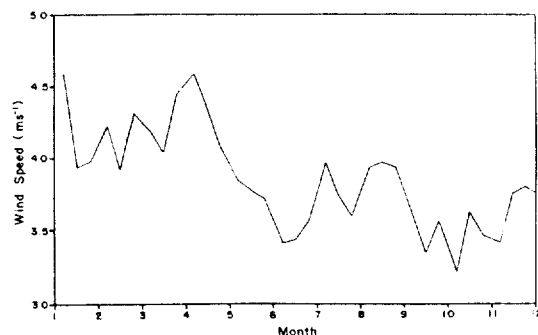


Fig. 6. A 9-year mean wind speed at the coast near Masan (Pusan) during 1978-1986. Data from Korea Central Meteorological Office.

itation in this region is particularly noticeable. For example, annual precipitation of the year 1985 is twice than of the year 1982. The portion of freshwater is estimated to be about 10% of the total water volume, and decreases from the head to the mouth, and its residence time is thought to be about 30 days in wet season and 10 days in the dry season (SNU, 1984).

Dissipation of buoyancy is made by the wind and tide. Tidal current is very weak in this area (Kim *et al.*, 1989). The 10-year mean monthly wind speed shows the winds are strong ($>4 \text{ ms}^{-1}$) during January-April and relatively weak ($3\text{-}4 \text{ ms}^{-1}$) in summer and fall (Fig. 6). However, daily fluctuations of wind speed are much higher due to the surrounding land mass. A wind speed higher

than 3 ms^{-1} may be sufficient to move the whole water column of 17 m deep (St. 2) judged by Ekman depth estimation. Since the temperature variation between the air and surface water is closely resembled, reduced solar radiation may be largely responsible for destroying summer stratification during fall in the presence of tidal motion. Depth of the euphotic zone is estimated to be about 10 m from the Secchi disk readings in winter (KORDI, 1980), which is less than the water depth of 17 m at St. 2.

2. Water column stability and nutrient distribution

Speculation is made on the temporal nutrient variation in terms of hydrographical features of Chingae Bay. In spring, stabilization of water column through thermocline development by the increased solar radiation and fresh water input triggers the intense phytoplankton growth. Relatively high levels of nutrients are maintained via runoff throughout the year. However, temporal depletion of silicate occurs during the low precipitation and low wind periods when the consumption of silicate by diatoms exceeds the supply via surface runoff and upward transport of the silicate-rich bottom water (Pae and Yoo, 1991). In autumn, with the disappearance of the thermocline, nutrients are transported upward and subsequently utilized by phytoplanktons (Fig. 2). Since light decreases but does not limit phytoplankton growth, nutrients do not accumulate in the water column throughout winter (Figs. 2 and 3). However, nutrient accumulation in the water column during winter is usually observed in the seasonally stratified pristine coastal bay (Mann, 1982).

3. Nutrients and planktons

Ammonia, nitrate, and silicate concentration are generally much higher than the half saturation constant for phytoplankton growth, however, these nutrients concentrations are below the half saturation constant during February to early April before the onset of precipitation in spring. The silicate is supplied through land weathering, and usually

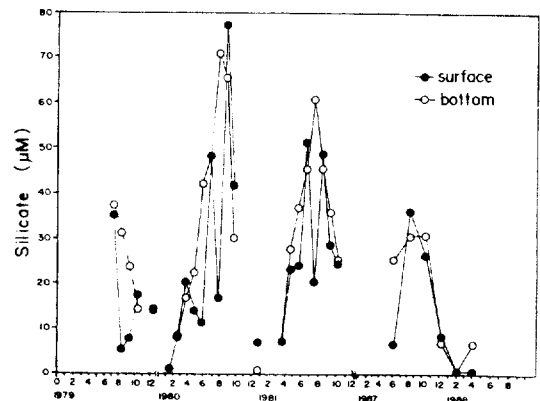


Fig. 7. Annual variation of silicate concentration in the surface and near bottom waters of Chinhae Bay. Data from 1979-1981 are taken from KORDI (1980 and 1981).

does not change due to human perturbation. Therefore diatom growth is limited by silicate concentration in Chinhae Bay due to the relative increase of anthropogenic N and P. Silicate production by diatoms accounts about 1/3 of total phytoplankton production in winter as discussed later and silicate limitation is also found during the summer stratified period in Chinhae Bay (Pae and Yoo, 1991). Similar features are noted in the Dutch coast (Fransz and Verheger, 1985). The increase in N and P and the essentially constant discharge of reactive Si caused a change in nutrient, first depleted by phytoplankton, from N or P some 50 years ago to Si nowadays. The model of Fransz and Verheger on the production cycle of phytoplankton in the southern Bight of the North Sea in relation to riverine nutrient loads suggests that river discharge of nutrients has a limited effect on primary production and algal biomass, because other limiting factors will take over. They further speculate that the area of eutrophication increases rather than the increase of production itself. A change in species composition from diatoms to other algae has been reported in several coastal and estuarine areas as an effect of eutrophication (Officer and Ryther, 1980).

Annual variations of standing stocks of phytoplankton and zooplankton are also relevant to the nutrient cycling. Some limited available data are

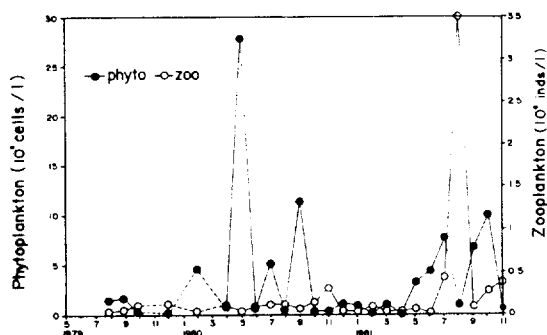


Fig. 8. Annual variation of standing crops of phyto and zooplanktons in Chinhae Bay (St.2) Data from KORDI (1980, 1981).

briefly reviewed here, though highly variable coastal ecosystems require a proper data set (Harris, 1986). More detailed systematic approach is being made by Han *et al.* (1991). In general, there are two maxima in phytoplankton standing stocks, a large one occurring in spring and a small one in autumn (Fig. 8). Zooplankton appears to develop about a month later than phytoplankton bloom and individual numbers of zooplankton are quite low during winter (Fig. 8). Therefore a large fraction of organic matter produced by the phytoplankton may be settled in the seafloor without being eaten by herbivores and remineralized in the sea floor. Large scale sedimentation of "fresh" organic matter produced by the spring bloom is probably a regular feature in areas with low overwintering zooplankton populations (Smetack *et al.*, 1978; Davis and Payne, 1984). Thus benthic oxidation of organic carbon and remineralization of nutrients seem to be important in this area.

4. Are nutrients accumulating in Chinhae Bay?

In recent years, nutrients input, especially N and P, appears to increase in most coastal waters. The increase of nutrient concentrations in the riverine water is usually self-evident (*e. g.* Fransz and Verheger, 1985). However, nutrient enrichment in the water column has not been observed successfully due to the variable hydrographic regimes (*e. g.* Spencer, 1985). Eutrophication is defined as nutrient or organic matter enrichment, or both, that

results in high biological productivity and a decreased volume within ecosystem (Hasler, 1947, referenced in Likens, 1972). Although, the term "eutrophication" is widely used, it is poorly defined for marine systems, and yet there is a syndrome caused by the addition of excess nutrients with resulting undesirable conditions (Kelley and Naugib, 1984).

The increase of nutrient input into the head of Chinhae Bay may be seen in the historical record of population growth. Population in the drainage basin almost quadrupled from 1966 to 1990 (Environmental Year Book, 1988, Environmental Administration, Republic of Korea). Especially the evidence of the nitrogen-nutrient input from the head of the bay is readily seen in winter, despite a significant reduction of the concentration of silicate (Fig. 2). Therefore, the increase of the recent nutrient input is believed to be well established in this study area.

We attempt to assess the accumulation of nutrients in Chinhae Bay by examining the distribution of the dissolved reactive silicate in the water column, even though silicate is not so much affected by human activities. Because silicate and nitrate input is closely associated with precipitation, and silicate accumulation or depletion is easily seen, since silicate is not so reactive as nitrate, silicate may thus be used as a tracer for nutrient accumulation in the bay. Nitrate removal through denitrification in the bottom waters is pronounced during the stratified summer period (Fig. 2). Land usage has been changed through the development of industrial sites in the drainage basin. Silicate concentration data are available over the last 10 years (Fig. 7), and the method of silicate determination in the past is relatively more reliable than N and P species. Annual variation of silicate concentration in the water column does not show any systematic increase, but rather maintains the constant summer high and winter low levels (Fig. 7). Summer high values may be related to the allochthonous input from the adjacent land *via* surface runoff. In the winter destratified period, silicate concentrations decrease with time significantly and reaches less than $1 \mu\text{M}$ (Fig. 2) which is far less

than the limiting concentration for phytoplankton growth (3-5 μM ; Goering *et al.*, 1973; D'Elia *et al.*, 1983). The standing stock of Si (depth integrated Si concentration) is 471, 116 and 9 mmol m^{-2} , in 19 October 1987, 19 December 1987, and 11 February 1988, respectively. Therefore the rate of change in standing stock of Si is 5.9 and 2.0 $\text{mmol m}^{-2}\text{d}^{-1}$ during the periods of 19 October 1987 to 19 December 1987 and 19 December 1987 to 11 February 1988, respectively. If we assume the depletion of Si in the water column to be entirely attributed to the uptake by diatoms, then Si production is 2.0-5.9 $\text{mmol Si m}^{-2}\text{d}^{-1}$. According to Nelson and Gordon (1982) and Harrison *et al.* (1977), the mean carbon/silicon mole ratio for the 10 diatom species is 8.48 ± 4.11 . Thus a C/Si mole ratio should be a reasonable estimate of the amount of organic carbon produced per unit biogenic silica in a natural diatom assemblage consisting of a number of species. Using this conversion factor, organic carbon production by diatoms is 16-47 $\text{mmol C m}^{-2}\text{d}^{-1}$, which is less than 1/3 of the total phytoplankton production of 188 $\text{mmol C m}^{-2}\text{d}^{-1}$ during December of 1988 (Hong *et al.*, unpublished data). Also Si concentrations of the inner part of Chinhae bay (Sts. 1 and 2) are lower than those of the outer part of the bay (Sts. 3, 4 and 5) and the adjacent shelf waters (2-3 μM , November-December 1986; data from KORDI, 1987). Therefore Si pool is fully utilized inside the bay ecosystem and export of Si from the bay to the shelf may be minimal during the destratified winter period.

Nitrate concentrations are generally high, however, by the onset of stratification in April, nitrate concentration reduces to less than limiting concentration of 0.5-2.4 μM (Eppley *et al.*, 1965; Fig. 2). Ammonium concentration also decreases to less than 1 μM (Appendix 1) in April. Similar budget calculations on the change of standing stock of nitrate plus ammonia during 11 February-26 April 1988 (about 24 $\text{mol N m}^{-2}\text{d}^{-1}$) suggest that winter nitrogen standing stock barely meets the requirements of the phytoplankton growth even in winter. Therefore N pool is also efficiently utilized inside the system. Broad-brush budget calculations of si-

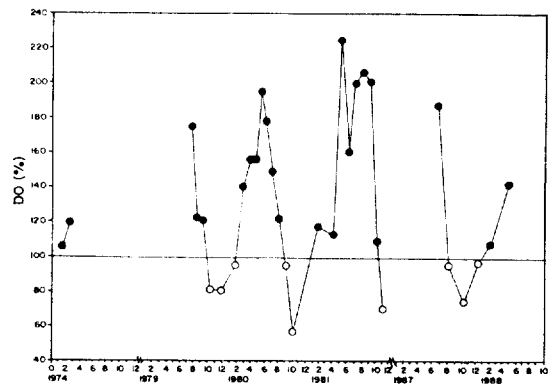


Fig. 9. Annual variation of dissolved oxygen (%) in the surface waters of Chinhae Bay. Data sources (KORDI, 1974, 1980, 1981).

licate and nitrogen clearly show that nutrients are not accumulated in the water column of the bay.

Since the export of nutrients to the shelf waters is thought to be minimal, nutrients burial in the underlying sediments is the only remaining sink for the nutrient introduced into the bay. A significant depletion of sedimentary manganese has occurred in the inner part of the bay (Hong *et al.*, in preparation). The depletion of sedimentary manganese appears to be due to the accelerated flux of phytoplanktonic organic matter into the sediments, hence the burial flux of nutrients (N, P, Si) has also increased. Walsh *et al.* (1981 and 1985) propose that there has been an accelerated rate of storage of planktonic organic C residues in the continental slope sediments during the recent decades. They suggest that this increase has occurred in response to a combination of increased planktonic productivity resulting from large increases in anthropogenic nitrate inputs from rivers and from drastic reductions in the efficiency of recycling of planktonic residues due to overharvesting of higher trophic levels. The increased flux of marine organic C to sediments of continental slopes was calculated by Walsh *et al.* (1981) and recalculated by Emerson (1984) to represent a significant fraction of the anthropogenic CO_2 taken up by the ocean in recent decades. Carpenter (1987) further elaborated the model of Walsh *et al.*

Recent acceleration of C storage in the bottom sediments, through the early diagenesis of organic

Table 1. Annual variations of O₂ fluxes across the air-sea interface over the year in Chinhae Bay (St.2)

Date	T (°C)	S (ppt)	C _{sw} (μM)	C* (μM)	Wind speed (V ₁₀ ; ms ⁻¹)	K _l (O ₂) (cm h ⁻¹)	F ^a (O ₂) (mmol m ⁻² d ⁻¹)
1987	6.27	22.5	30.0	425	2.8	0.6	28.5
	8.12	22.4	23.3	225	1.6	0.3	-1.0
	10.19	19.7	30.1	177	2.2	0.1	-6.4
	12.11	7.9	32.0	292	2.2	0.3	-0.7
1988	2.11	3.6	32.0	365	1.0	0.1	0.8
	4.26	13.8	32.7	375	2.5	0.3	9.0

matter, may have resulted in the undersaturation of dissolved oxygen during the winter destratified period in the inner part of Chinhae Bay.

5. Oxygen utilization in the benthic regime

The annual distribution pattern of the dissolved oxygen contents in the water column shows distinct features especially at St. 2 for the period of 1987 to 1988 (Fig. 2). Following the stratification of the water column in April, the water below the surface mixed layer becomes depleted in the dissolved oxygen, and the whole water column remains to be undersaturated even after destruction of the stratification. Since 1980, winter undersaturation of dissolved oxygen has occurred annually (KORDI, 1980 and 1981; Fig. 9). However, dissolved oxygen was supersaturated in the water column during the winter of 1974 (KORDI, 1974). Anoxia in the near bottom waters during summer was probably first found in 1980 (Hong, 1981) and its influence on the distribution of benthos was assessed (Hong, 1987). Constructing a simple budget of dissolved oxygen, we attempt to provide a first order estimation of the benthic oxygen utilization rates in winter and summer.

The exchange with the atmosphere

The fluxes of oxygen across the air-sea interface, $F^a(O_2)$, was calculated by means of the boundary layer model of gas exchange (Deacon, 1977), because the eddy correlation technique (bubble entrainment) produces an order of magnitude or more larger values than expected from the values obtained by other geochemical techniques (molecular transport through the diffusive boundary la-

yer; Broecker *et al.*, 1986). The net gas flux across the interface is given by

$$F^a(O_2) = K(C_{sw} - \alpha C_a)$$

where K is the gas exchange coefficient (or piston velocity; Broecker and Peng, 1974). C_{sw} and C_a are the gas concentrations in seawater and in air, respectively, and α is the solubility of gas in seawater (Weiss, 1970). The exchange coefficient K , changes from one type of gas to the other, is a function of wind speed and of temperature of seawater through the Schmidt number Sc (= kinematic viscosity/molecular diffusivity, $U/\rho D$) dependency (Oudot, 1989), where D is the molecular diffusion coefficient and ρ is density of fluid. U is the kinematic viscosity. The exchange coefficient of oxygen gas was calculated by largely adopting Oudot's method (1989). Only a brief overview of the computation algorithm is given here. The exchange coefficient $K(O_2)$ is derived from the calculated value for CO_2 taking into account the proportionality of K to $Sc^{-2/3}$ for wind speeds ≤ 3.6 ms⁻¹. That is, $D^{2/3}$ in between the predictions of the film (D^1) and surface renewal ($D^{1/2}$) models (Liss, 1983). The relationships used for the calculations of the CO_2 exchange coefficient are written as follows:

$$K_{20}(CO_2) = 0.17 V_{10} \text{ for } 0 < V_{10} < 3.6 \text{ ms}^{-1}$$

$$K_{20}(CO_2) = 2.85 V_{10}^{-0.65} \text{ for } 3.6 < V_{10} < 13 \text{ ms}^{-1}$$

where $K_{20}(CO_2)$ is the exchange coefficient at 20°C expressed in cm h⁻¹ and V_{10} is the wind speed in ms⁻¹ measured at 10 m above sea surface. The dependency of $K(CO_2)$ on the temperature is evaluated as:

$$K_t = 70.74 K_{20}(Sc_t)^{-2/3} \text{ for } 0 < V_{10} < 3.6 \text{ ms}^{-1}$$

Table 2. Standing stock of oxygen (ΣO_2) for whole water column and the lower layer below the surface mixed layer, and vertical turbulent diffusivity (k_z) below the surface mixed layer

Date	ΣO_2 (mmol m ⁻²) h=whole water column	ΣO_2 (mmol m ⁻²) h=below surface mixed layer	k_z (x10 ⁻⁶ m ² s ⁻¹)
1987	6.27	2537	3.39
	8.12	2698	0.5
	10.19	2720	
	12.19	4805	
1988	2.11	6035	
	4.26	4416	1.48

$$K_s = 24.39K_{20}(Sc_s)^{-1/2} \text{ for } 3.6 < V_{10} < 13 \text{ m s}^{-1}$$

where Sc_s , the Schmidt number for $K(CO_2)$ at $t^\circ C$, is linearly interpolated using,

$$Sc_s = 1065 - 23.5t$$

Taking into account the wind speed effect,

$$K_s(O_2) = 1.17 K_s(CO_2) \text{ for } 0 < V_{10} < 3.6 \text{ m s}^{-1}$$

$$K_s(O_2) = 1.13 K_s(CO_2) \text{ for } 3.6 < V_{10} < 13 \text{ m s}^{-1}$$

Therefore, the O_2 flux formula that we will use for the calculation is

$$F^a(O_2) = 0.24 K_s(O_2)(C_{sw} - C^*)$$

Applying the above equations, oxygen fluxes across the air-sea boundary are calculated (Table 1).

The large uncertainties on $F^a(O_2)$ determinations are mainly due to the wide range of variations of O_2 exchange coefficients, since the wind speed V_{10} data is taken directly from the Masan Meteorological Station and assumed to be the wind speed at 10 m above sea surface.

The vertical diffusional flux

The vertical diffusional flux in the water column is evaluated according to the Fickian diffusion equation of which the flux F^d is given by

$$F^d = k_z \frac{dC}{dz}$$

where F^d is the vertical flux of oxygen, k_z is the vertical eddy diffusivity, C is the concentration of oxygen and z the depth. According to Denman and Gargett (1983), a vertical turbulent diffusion coefficient k_z can be assumed to be a function

of observable quantities of ϵ the dissipation of turbulent energy and N the buoyancy frequency on dimensional grounds. $k_z = A\epsilon N^{-2}$. Various values for A have been suggested, but recent studies of the onset of turbulence in stratified fluids suggest a value near 0.25, and ϵ is $2 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$ in a thermocline in low wind environments (compiled in Denman and Gargett, 1983).

In order to estimate the first-order conservative benthic oxygen respiration rate, biological oxygen production and oxygen consumption in the water column are assumed to be negligible in the winter period. Two sets of data (October 19 and December 19) are chosen during the well-mixed period (Table 2). Change of dissolved oxygen content, δO_2 , is:

$$\delta O_2 = F^a O_2 - F^b O_2$$

where $F^a O_2$ is the flux across the air-sea interface and $F^b O_2$ is the flux across the sediment-water interface. The benthic respiration rate during October 19 to December 19, 1987 is estimated to be $31 \text{ mmol } O_2 \text{ m}^{-2} \text{ d}^{-1}$, which is the equivalent of $21\text{-}24 \text{ mmol } C \text{ m}^{-2} \text{ d}^{-1}$, assuming the organic matter being oxidized in the benthic regime is made of the hypothetical Redfield molecule (Takahashi *et al.*, 1985). This value is equivalent to the 13% of the total phytoplankton production in winter and similar to the one observed in the shallow waters (Forsskahl *et al.*, 1982). The benthic oxygen respiration in Chinhae Bay is comparable to the $21\text{-}52 \text{ mmol } O_2 \text{ m}^{-2} \text{ d}^{-1}$ of Narragansett Bay, RI (Seitzinger *et al.*, 1983) and $56 \text{ mmol } O_2 \text{ m}^{-2} \text{ d}^{-1}$ of South River Estuary, NC, USA (Fisher *et al.*, 1982). During the stratification period, an attempt

was also made utilizing the change of oxygen contents below the surface mixed layer during April to June, assuming the oxygen content in April 1988 is the same in April 1987. The vertical diffusivity was calculated below the surface mixed layer. Due to the scarcity of hydrographical data and the nature of the rapid response of the thermocline to surface forcing (Dillon and Caldwell, 1980), large uncertainty in the evaluation of K_v is involved. Change of dissolved oxygen content below the surface mixed layer is $\delta O_2 = F^s O_2 - F^b O_2$. Then the benthic oxygen respiration rate is $25.9 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$.

CONCLUSIONS

A preliminary description of some constraints on the biogeochemical cycling of biologically important elements in the nitrogen-rich Chinhae Bay of Korea has been discussed. The major findings of this work are:

1. Hydrographical features show that water column is stratified from early April to late October and destratified for the rest of the year. Winter mixing appears to be strong. Stratification is strong in the head and progressively weaker towards the mouth.
2. In the inner part of Chinhae Bay, dissolved oxygen concentrations exceed $400 \mu\text{M}$ in the surface but diminish to less than $50 \mu\text{M}$ in the near bottom waters, which often results in anoxic environments during the summer stratification period. After the breakdown of stratification, dissolved oxygen concentrations remain undersaturated until the onset of stratification in April.
3. In general, ammonia, nitrate, phosphate and silicate concentrations are higher than the limiting concentrations for phytoplankton growth. However, diatom growth is often limited by low silicate concentrations. Nitrate is being lost due to denitrification.
4. Solar radiation appears to be largely responsible for the creation and destruction of water column stratification.
5. Nutrients accumulation in the water column has not been detected. Phytoplankton appear to

fully utilize the available nutrients either allochthonous or regenerated ones. Nutrients are thought to be efficiently utilized in the bay ecosystem, and export of nutrients from the bay to the shelf may be negligible.

6. A large fraction of organic matter produced by phytoplankton seems to settle in the seafloor without being eaten by herbivores, due to the time lag between the phyto- and zooplankton developments.

7. Organic carbon produced by diatoms in winter is estimated to be $16\text{--}47 \text{ mmol Cm}^{-2} \text{ d}^{-1}$, which is less than 1/3 of total phytoplankton production in winter.

8. Benthic oxygen respiration rate is conservatively estimated to be $21\text{--}24 \text{ mmol Cm}^{-2} \text{ d}^{-1}$.

ACKNOWLEDGMENTS

This work was supported in part by the Ministry of Science and Technology through the grant to Korea Ocean Research & Development Institute (BSPG 00057-184-4). We are very grateful to Profs. C.B. Lee and C.H. Koh of Seoul National University and Prof. M.W. Han of Pusan National University for their enthusiastic criticism.

REFERENCES

- Armstrong, F.A.J., C.R. Steams, and J.D.H. Strickland, 1967. The measurement of upwelling and subsequent biological processes by means of the Technicon Auto-Analyzer and associated equipment. *Deep-Sea Res.* **14**: 381-389
- Broecker, W.S. and T.-H. Peng, 1974. Gas exchange rates between air and sea. *Tellus*, **26**: 21-35.
- Broecker, W.S., J.R. Ledwell, T. Takahashi, R. Weiss, L. Merlivat, L. Memery, T.-H. Peng, B. Jahne, and K.O. Munnich, 1986. Isotopic versus micrometeorologic ocean CO_2 fluxes: A serious conflict. *J. Geophys. Res.* **91**: 517-527.
- Carpenter, R., 1987. Has man altered the cycling of nutrients and organic C on the Washington continental shelf and slope? *Deep-Sea Res.* **34**: 881-896.
- Cho, C.H., 1978. On the *Gonyaulax* red tide in Jinhae Bay. *Bull. Korean Fish. Soc.* **11**: 111-114.
- D'Elia, C.F., D.M. Nelson and W.R. Boynton, 1983. Chesapeake Bay nutrient and phytoplankton dynamics. III. The annual cycle of dissolved silicon. *Geochim. Cosmochim. Acta.* **47**: 1945-1955.
- Davis, J.M. and R. Payne, 1984. Supply of organic ma-

- ter to the sediment in the northern North Sea during a spring phytoplankton bloom. *Mar. Biol.* **78**: 315-324.
- Deacon, E.L., 1977. Gas transfer to and across an air-water interface. *Tellus*, **29**: 363-374.
- Denman, K.L. And A.E. Gargett, 1983. Time and space scales of vertical mixing and advection of phytoplankton in the upper ocean. *Limnol. Oceanogr.*, **28**: 801-815.
- Dillon, T.M. And D.R. Caldwell, 1980. The Bachelor spectrum and dissipation in the upper ocean. *J. Geophys. Res.*, **85**: 1910-1916.
- Emerson, S., 1984. Organic carbon preservation in marine sediments. In: *The carbon cycle and atmospheric CO₂: natural variation archean to present. Geophysical Monograph* 32. Eds. by E.T. Sundquist and W.S. Broecker. University of Washington Press, Seattle, 151-175.
- Eppley, R.W., J.N. Rogers and J.J. McCarthy., 1969. Half saturation constants for uptake of nitrate and ammonia by marine phytoplankton. *Limnol. Oceanogr.* **14**: 912-920.
- Fisher, T.R., P.R. Carlson and R.T. Barber, 1982. Sediment nutrient regeneration in the North Carolina estuaries. *Estuar. Coast. Shelf Sci.*, **14**: 101-116.
- Forsskahl, M., A. Laakkonen, J.-M. Lappanen, A. Nitmi, A. Sunberg and G. Tamelander, 1982. Seasonal cycle of production and sedimentation of organic matter at the entrance to the Gulf of Finland. *Netherlands J. Sea Res.*, **16**: 290-299.
- Fransz, H.G. And J.H.G. Verhagen, 1985. Modelling research on the production cycle of phytoplankton in the southern bight of the North Sea in relation to riverborne nutrient loads. *Netherlands J. Sea Res.*, **19**: 241-250.
- Goering, J.J., D.M. Nelson and J.A. Carter, 1973. Silicic uptake by natural populations of marine phytoplankton. *Deep-Sea Res.*, **20**: 777-789.
- Han, M.S. And K.-I. Yoo, 1983. A taxonomical study on the dinoflagellates in Jinhae Bay. 1. Armored and unarmored dinoflagellates. *Bull. KORDI*, **5**: 37-47.
- Han, M.-S., Y.-O. Kim and J.-K. Jeon, in press. Changes in phytoplankton communities in the two different ecosystem of a semi-enclosed waters.
- Harris, G.P., 1986. Phytoplankton ecology: structure, function and fluctuation. Chapman and Hall, 384pp.
- Harrison, P.J., H.L. Conway, R.W. Holmes and C.O. Davis, 1977. Marine diatoms growth in chemostats under silicate or ammonium limitation III. Cellular chemical competition and morphology of *Chaetoceros debilis*, *Skeletonema costatum* and *Thalassiosira gravida*. *Mar. Biol.* **43**: 19-31.
- Hong, G.H., Y.A. Park and K.W. Lee, 1983. Heavy metals in sediments from Jinhae Bay, Korea. *J. Oceanol. Soc. Korea*, **18**: 180-184.
- Hong, G.H., D.B. Yang and K.W. Lee, 1988. Nutrients and trace metals in permanently well-mixed coastal waters of Korea. *J. Oceanol. Soc. Korea*, **23**: 159-168.
- Hong, G.H., 1981. A study on the geochemistry of suspended and bottom sediments in the Jingae Bay Korea. M.S. Thesis, Seoul National Univ. 57pp.
- Hong, J.-S., 1987. Summer oxygen deficiency and benthic biomass in the Chinhae Bay system, Korea. *J. Oceanol. Soc. Korea*, **22**: 246-256.
- Hong, J.-S. And J.H. Lee, 1983. Effects of the pollution on the benthic macrofauna in Masan Bay, Korea. *J. Oceanol. Soc. Korea*, **18**: 69-179.
- Kelley, M. And M. Naguib, 1984. Eutrophication in coastal marine areas and lagoons: a case study of 'Iad de Tunis', Unesco report in marine science 29, 54pp.
- Kim, C.S., J.C. Lee, T.S. Jung, and S.W. Kang, 1989. Application of a three-dimensional hydrodynamic model. *Ocean Res.*, **11**: 45-55.
- KORDI, 1974. Oceanographic characteristics of Chinhae Bay during winter of 1973-1974. Report BSHGI-136-5.
- KORDI, 1980. A preliminary investigation on the monitoring system for the red tides in Jinhae Bay. Report BSPE 00022-43-7.
- KORDI, 1981. A study on the monitoring system for the red tides in Jinhae Bay. Report BSPE 00031-56-7.
- KORDI, 1987. A study on the atlas of marine resources in the adjacent seas to Korea-South Sea (Preliminary study). Report BSPG 00046-163-7.
- KORDI, 1988. A study on the coastal water pollution and monitoring. Report BSPG 00083-242-4.
- Lee, K.W., G.H. Hong, D.-B. Yang, S.H. Lee, 1981. Sea-water quality and red tides in Jinhae Bay: I. Relationships between water quality parameters and red tides. *J. Oceanol. Soc. Korea*, **16**: 43-49.
- Lee, J.H. And K.-I. Yoo, 1986. A study on fine structure of the marine diatoms of Korean coastal waters. *Genus Thalassiosira*, **21**: 184-190.
- Lee, S.H. And K.W. Lee, 1983. Heavy metals in sediments from Jinhae Bay, Korea. *J. Oceanol. Soc. Korea*, **18**: 49-54.
- Likens, G.E., 1972. Eutrophication and aquatic ecosystems. In: *Nutrients and Eutrophication: The limiting-nutrient controversy* Ed. by G.E. Likens, Am. Soc. Limnol. Oceanogr., 3-13.
- Liss, P.S., 1983. Gas transfer: experiments and geochemical implications. In: *Air-sea exchange of gasses and particles*. Eds. by P.S. Liss and W.G.N. Slinn. D. Reidel Publ. Co., 241-298.
- Mann, K.H., 1982. Ecology of coastal waters. A systems approach. Univ. California Press, 322pp.
- Murphy, J. And J.P. Riley, 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.*, **27**: 31-36.
- Nelson, D.M. And L.I. Gordon, 1982. Production and pelagic dissolution of biogenic silica in the Southern Ocean. *Geochim. Cosmochim. Acta*, **46**: 491-501.
- Officer, C.B. And J.H. Ryther, 1980. The possible importance of silicon in marine eutrophication. *Mar. Ecol. Prog. Ser.*, **3**: 83-91.
- Oudot, C., 1989. O₂ and CO₂ balance approach for estimating biological production in the mixed layer of the tropical Atlantic Ocean (Guinea Dome Area).

- J. Mar. Res.*, **47**: 385-409.
- Pac, S.J. And S. Yoo, 1991. Short-term variability of the phytoplankton populations in Masan Bay: I. Dynamics. *J. Oceanol. Soc. Korea*, **26**: 67-76.
- Parsons, T.R., M. Takahashi and B. Hargrave, 1977. Biological oceanographic processes, 2ed. 332pp.
- Parsons, T.R., Y. Maita and C.M. Lalli, 1984. A manual of chemical and biological methods for seawater analysis. Pergamon Press. 173pp.
- Peng, T. And W.S. Broecker, 1984. Ocean life cycles and the atmospheric CO₂ content. *J. Geophys. Res.* **89**: 8170-8180.
- Pingree, R.D., 1978. Mixing and stabilization of phytoplankton distributions on the Northwest European continental shelf. In: *Spatial pattern in plankton communities*. Ed. by J.U. Steele. Plenum Press. 81-220.
- Seitzinger, S.P., S.W. Nixon and M.E.Q. Pilson, 1984. Denitrification and nitrous oxide production in a coastal marine ecosystem. *Limnol. Oceanogr.* **29**: 73-84.
- Seliger, H.H., J.A. Boggs and W.H. Biggley, 1985. Catastrophic anoxia in the Chesapeake Bay in 1984. *Sci.* **228**: 70-73.
- Smetack, V.K. von Broeckel, B. Zeitzschel and W. Zenk, 1978. Sedimentation of particulate matter during a phytoplankton spring bloom in relation to hydrographical regime. *Mar. Biol.* **47**: 211-226.
- SNU, 1984. A study on the marine pollution status and simulation for the minimize the effect of wastes in Masan Bay. Seoul National University Report (in Korean).
- Spencer, C.P., 1985. The use of plant micro-nutrient and chlorophyll records as indices of eutrophication in inshore waters. *Netherlands J. Sea Res.* **19**: 269-275.
- Takahashi, T., W.S. Broecker and S. Langes, 1985. Red-field ratio based on chemical data from isopycnal surface. *J. Geophys. Res.* **90**: 6907-6924.
- Walsh, J.J., E.T. Premuzic, J.S. Gaffney, G.T. Rowe, G. Harbottle, W.L. Balsam, P.R. Petzer and S.A. Mac-ko, 1985. Organic storage of CO₂ on the continental slope off the Mid-Atlantic Bight, the southeastern Bering Sea, and the Peru coast. *Deep-Sea Res.* **32**: 853-883.
- Walsh, J.J., G.T. Rowe, R.L. Everson and C.P.M. McRoy, 1981. Biological export of shelf carbon is a sink of the global CO₂ cycle. *Nature*, **291**: 196-201.
- Weiss, R.F., 1970. The solubility of nitrogen, oxygen, and argon in water and seawater *Deep-Sea Res.* **17**: 721-735.
- Whitledge, T.E., S.C. Malloy, C.J. Patton and C.D. Wrick, 1981. Automated nutrient analysis in seawater. Brokhamen Nat. Lab. Pub. 51398, New York, 216pp.
- Yang, D.-B. And G.H. Hong, 1982. Nutrients and chlorophyll-a variations at a fixed station during the red tides in the Jinhae Bay. *J. Oceanol. Soc. Korea*, **17**: 19-26.
- Yang, D.-B., S.H. Kim and K.W. Lee, 1986. Vertical distributions of chemical oceanographic parameters in Jinhae Bay in July, 1983. *J. Oceanol. Soc. Korea*, **19**: 89-93.
- Yang, D.-B. And J.-S. Hong, 1988. On the biogeochemical characteristic of surface sediments in Chinhae Bay in September 1983. *Bull. Korea Fish. Soc.*, **21**: 195-205.

Received January 30, 1991

Accepted August 17, 1991

Appendix 1-1. Water column chemistry of Chinhae Bay in 27 June 1987

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
1A 1	0	22.9	29.1	419	24.21	28.74	2.84	0.40	5.28
	0	22.0	29.2	413	1.14	8.23	2.19	0.55	4.43
	2	21.9	29.4	325		13.73	0.95	0.73	18.38
	3	21.1	29.6	225					
	5	19.7	30.6	128		5.11	0.06	0.88	5.14
	8	18.7	30.9	72					
2A 2	10	18.1	31.1	19	4.21	0.75	0.02	3.93	13.11
	0	20.2	29.6	431	1.01	1.66	0.38	0.21	1.86
	0	22.5	30.0	425	8.70	3.16	0.75	0.65	6.56
	2	22.1	30.3	419		1.47	0.02	0.35	3.43
	3	21.8	30.5	363					
	5	19.8	30.8	175		1.47	0.02	0.35	3.43
3A 3	8	18.7	31.0	100					
	10	18.0	31.2	59		2.55	0.02	1.28	8.27
	15	17.2	31.8	16	30.93	0.45	0.02	2.07	25.50
	0	22.6	30.4	419	0.60	1.42	0.34	1.66	0.73
	0	22.5	30.2	409	0.62	0.70	0.02	0.18	0.44
	2	21.3	30.7	400		0.51	0.02	0.18	0.73
4A 4	3	20.3	30.9	325					
	5	19.7	31.2	288		0.89	0.02	0.18	4.71
	8	19.4	31.2	272					
	10	19.0	31.2	194	1.47	1.85	0.02	0.58	7.70
	12	18.1	31.5	131					
	0	20.7	30.9	313	0.79	4.62	0.26	1.66	0.73
5A 5	0	20.8	31.0	300	0.67	1.72	0.02	0.18	3.86
	2	20.3	31.0	300		0.96	0.02	0.25	6.71
	5	19.9	31.1	309		2.36	0.02	0.38	6.56
	10	18.9	31.2	266		0.58	0.02	0.22	7.99
	15	18.7	31.2	238		2.51	0.06	0.48	3.57
	20	17.2	31.8	178	2.10	2.59	0.30	0.68	7.84
5A 5	0	19.6	31.0	272	0.41	0.75	0.02	0.92	4.71
	0	19.9	31.0	272	0.40	0.42	2.05	0.48	25.07
	2	19.9	30.9	278		2.80	0.02	0.41	29.34
	5	19.4	31.0	278		0.73	0.18	0.22	6.71
	10	19.4	31.0	281		1.34	0.02	0.28	2.58
	15	18.8	31.2	263		2.09	0.10	0.31	5.00
	20	18.1	31.4	234		0.94	0.18	0.36	7.27
	25	17.5	31.7	219					
	30	17.3	31.7	213					
35	16.6	32.0	200	2.35	2.22	1.11	0.62	13.66	

Appendix 1-2. Water column chemistry of Chinhae Bay in 12 August 1987

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
1A 1	0					49.23	5.82	3.09	29.78
	0	23.2	17.9	275	68.47	43.93	5.63	1.23	23.50
	5	18.6	30.1	131		23.45	1.04	1.67	18.37
	10	16.6	32.0	72	4.34	1.89	0.28	4.52	27.50

Appendix 1-2. Continued

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH)4 μM
2A 2	0				54.56	40.09	8.37	0.29	14.37
	0	22.4	23.0	225	70.65	12.44	5.90	0.36	36.35
	2	21.2	27.0	222					
	4	20.1	28.5	197					
	6	18.0	30.2	184		13.58	0.80	1.02	16.08
	8	17.6	30.4	184					
	10	16.6	31.5	147		28.10	0.57	1.89	14.08
	12	16.2	31.5	138					
3A 3	14	15.8	32.0	119					
	16	15.3	32.4	69	36.64	2.26	0.60	3.39	30.64
	0				5.56	15.41	2.05	0.54	10.94
	0	21.3	26.1	278	26.14	0.02	2.81	0.80	17.22
4A 4	5	18.3	29.7	228		6.41	1.60	0.43	12.94
	9	17.4	30.0	216	8.28	8.28	2.36	0.83	27.21
	0					23.02	0.82	1.53	14.94
	0	18.0	27.5	234	8.15	12.67	0.61	0.54	19.51
5A 5	5	18.0	29.5	225		31.12	0.63	1.49	16.37
	8	17.5	29.9	206					
	10	16.5	30.9	206		8.04	0.63	0.91	16.37
	15	16.0	31.1	194		15.47	1.33	1.12	20.36
	20	15.2	32.0	184	8.42	30.03	1.94	1.78	23.50
	0				16.26	12.48	0.80	0.47	19.79
5A 5	0	17.6	27.7	231	16.60	24.51	1.08	1.31	16.37
	5	17.4	28.0	234		16.19	1.71	0.61	25.79
	8	16.8	29.0	219					
	10	15.8	31.0	216		12.92	3.88	1.38	38.63
	15	15.4	31.5	203		6.89	1.33	0.94	17.22
	20	15.4	31.9	191		10.20	1.10	1.20	25.22
	25	15.1	32.0	191					
	30	15.0	32.0	191		16.30	1.60	1.20	20.65
35	15.0	32.0	191	1.74	10.00	1.52	1.05	21.22	

Appendix 1-3. Water column chemistry of Chinhae Bay in 19 October 1987

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH)4 μM
1A 1	0				68.20	26.78	3.87	4.14	35.65
	0	19.8	29.9	183	38.27	16.80	2.49	2.56	32.85
	5	19.7	30.1	163		6.90	1.54	2.15	33.14
	10	19.8	30.3	158	23.21	5.08	0.89	2.11	27.30
2A 2	0				37.80	6.95	1.15	1.82	22.84
	0	19.7	30.1	177	32.14	5.59	1.34	1.86	26.46
	5	19.7	30.2	175		5.34	1.42	1.86	30.91
	10	19.8	30.3	169		3.70	1.03	1.52	28.41
	15	19.8	30.4	163	12.78	3.66	1.01	1.67	30.91
3A 3	0				28.39	3.57	1.05	1.23	22.01
	0	19.6	30.4	206	9.92	3.19	0.87	1.12	20.61
	5	19.6	30.4	203		3.26	0.85	1.19	20.61
	10	19.6	30.4	202	5.62	3.58	0.87	1.27	21.17

Appendix 1-3. Continued

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
4A	0				24.09	2.79	0.71	0.97	15.05
4	0	19.7	30.5	211	6.24	1.01	0.63	0.68	13.93
	5	19.8	30.5	212		2.11	0.55	0.90	13.10
	10	19.8	30.5	210		2.56	0.77	1.12	16.99
	15	19.7	30.5	208		1.52	0.91	0.90	21.61
	20	19.7	30.6	206	14.01	3.14	0.47	1.08	13.10
5A	0				4.32	1.63	0.97	0.79	21.45
5	0	19.8	30.5	309	21.16	1.92	0.51	0.79	12.82
	5	19.8	30.5	312		1.50	0.65	0.79	16.44
	10	19.8	30.5	312		2.08	0.63	0.86	19.93
	15	19.8	30.5	312		1.54	0.83	0.68	19.50
	20	19.8	30.5	310		2.00	0.77	0.90	17.55
	25	19.8	30.5	310					
	30	19.8	30.5	310		1.99	0.55	0.82	12.54
	35	19.8	30.5	310					
	40	19.8	30.5	310	10.12	2.36	0.69	0.90	14.21

Appendix 1-4. Water column chemistry of Chinhae Bay in 19 December 1987

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
1A	0				52.93	8.89	1.98	9.39	11.43
1	0	8.2	32.1	299	34.59	8.30	1.74	5.85	9.85
	5	8.2	32.1	302		3.46	1.51	4.98	8.40
	10	8.4	32.4	299	14.45	2.17	1.37	4.78	7.61
	20	8.4	32.4	299	14.45	2.17	1.37	4.78	7.61
2A	0				39.57	8.63	2.03	7.52	11.70
2	0	7.9	32.0	292	33.84	5.82	1.51	6.32	8.40
	5	8.4	32.4	299		2.94	1.40	4.98	7.21
	10	8.4	32.4	304		2.45	1.33	4.58	7.08
	15	8.3	32.4	306	9.85	1.76	1.33	4.38	6.82
3A	0				21.16	3.58	1.49	7.25	7.74
3	0	8.0	32.2	307	21.89	2.61	0.88	3.58	4.84
	5	8.0	32.2	304		4.22	1.54	5.58	8.66
	10	8.6	32.4	298	27.98	2.45	1.33	4.58	7.08
4A	0				6.44	0.04	0.81	2.17	10.41
4	0	9.8	32.7	289	3.85	0.84	0.85	3.44	10.51
	5	9.7	32.8	287		0.79	0.88	3.84	10.25
	10	9.7	32.8	285		0.81	0.88	3.91	9.98
	15	9.8	32.8	285		1.01	0.86	5.72	9.59
	20	9.8	32.8	283	4.19	0.86	0.86	3.38	9.19
5A	0				9.23	0.06	0.78	3.04	9.19
5	0	9.6	32.9	289	2.01	0.75	0.85	2.78	8.53
	5	10.1	32.8	287		0.75	0.83	2.98	8.66
	10	10.3	32.8	285		0.79	0.81	3.78	8.80
	15	10.4	32.9	282		0.82	0.81	3.84	8.66
	20	10.4	32.9	283		0.88	0.79	3.98	8.27
	30	10.3	32.9	286	6.44	0.68	0.83	2.78	7.74

Appendix 1-5. Water column chemistry of Chinhae Bay in 11 February 1988

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
1A	0				72.47	28.35	1.85	2.17	3.16
1	0	3.8	32.7	325	9.99	19.63	0.99	0.17	0.67
	5	4.0	32.7	324		18.93	0.97	0.17	0.62
	10	4.4	33.0	323	3.44	10.73	0.72	0.33	0.54
					11.21	20.84	1.01	0.37	0.62
2A	0				36.71	19.44	0.97	0.40	0.62
	0	3.8	32.6	356		19.40	1.01	0.37	0.62
	5	3.8	32.7	356		17.65	0.80	0.33	0.54
	10	3.9	32.8	355		13.82	0.82	0.30	0.50
3A	0				6.71	17.32	0.93	0.40	0.50
	0	3.9	32.8	362	2.62	9.91	0.70	0.33	0.37
	5	4.0	32.8	367		9.56	0.70	0.17	0.37
	10	4.1	32.9	362	2.08	5.63	0.51	0.20	0.37
4A	0				2.49	7.70	0.66	0.24	0.58
	0	5.5	33.3	307	1.26	1.30	0.31	0.20	1.18
	5	5.6	33.3	308		1.54	0.33	0.30	1.23
	10	5.6	33.4	301		1.46	0.31	0.43	1.23
	15	6.2	33.4	296		1.98	0.35	0.43	1.40
5A	20	6.2	33.4	296	1.81	2.06	0.37	0.53	1.40
	0				2.35	1.72	0.35	0.47	1.49
	0	6.4	33.4	309	1.40	1.49	0.33	0.50	1.18
	5	6.4	33.4	300		1.74	0.33	0.37	1.14
	10	6.4	33.4	302		1.56	0.31	0.40	1.23
	15	6.4	33.4	302		1.51	0.31	0.47	1.18
	20	6.4	33.4	302		1.48	0.29	0.47	1.14
	30	6.4	33.4	302	1.40	1.32	0.29	0.50	1.10

Appendix 1-6. Water column chemistry of Chinhae Bay in 26 April 1988

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH) ₄ μM
1A	0	14.9	31.3	546	0.73	15.04	1.90	0.27	0.54
1	0	13.8	32.0	411	1.11	10.56	1.04	0.42	0.64
	5	11.6	32.6	225		15.65	1.19	0.58	2.01
	10	11.2	32.9	208	2.84	0.19	1.21	1.73	2.01
					2.57	9.99	0.86	1.22	1.19
2A	0	13.8	32.5	369	0.77	2.37	0.30	0.55	0.54
	0	13.8	32.7	375		0.37	0.15	0.44	2.21
	5	13.0	32.8	355		0.70	0.22	1.34	5.52
	10	11.0	33.0	206		1.02	0.18	1.43	6.54
3A	15	11.4	33.1	197	2.63	2.42	0.39	0.26	0.95
	0	13.0	32.7	324	0.57	2.42	0.39	0.26	0.95
	0	13.2	32.9	314	0.66	0.77	0.31	0.33	1.62
	5	12.8	33.0	315		0.71	0.21	0.31	1.13
4A	10	12.2	33.3	275	0.56	0.43	0.15	0.37	1.07
	0	12.8	33.0	308	0.65	1.20	0.24	0.31	1.00
	0	12.4	33.1	304	0.44	0.81	0.26	0.25	1.03
	5	12.2	33.1	304		0.33	0.15	0.48	0.73
	10	12.1	33.2	293		0.19	0.17	0.30	0.99
	15	12.1	33.3	285		0.17	0.15	0.24	0.73

Appendix 1-6. Continued

St.	Depth m	T C	S ppt	DO μM	NH4 μM	NO3 μM	NO2 μM	PO4 μM	Si(OH)4 μM
	20	12.0	33.6	275	0.26	0.14	0.18	0.26	1.50
5A	0	12.4	33.0	299	0.65	0.18	0.14	0.19	0.64
5	0	12.8	33.1	299	0.30	0.12	0.18	0.14	0.53
	5	12.2	33.1	299		0.02	0.13	0.17	0.83
	10	12.2	33.2	292		0.02	0.16	0.17	1.03
	15	12.2	33.3	285		0.43	0.11	0.17	0.85
	20	12.1	33.4	277		0.47	0.14	0.25	0.77
	30	12.0	33.7	273	0.15	0.50	0.15	0.25	0.87