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An Estimation of the New Production in the Southern East Sea Using Helium Isotopes

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The biological pump is one of the important pumping mechanisms absorbing CO_2 from the atmosphere into the ocean and can be quantified by estimating new production. New production in the open ocean mostly depends on the supply of nitrate from the water below the mixed layer. While nitrate is affected by many biological processes, the helium isotope (^3He) is inert and has very simple physical properties. Using the ^3He flux and the relation between ^3He and NO_3^- within the thermocline, the nitrate flux supporting new production was estimated in the southern East Sea. The average δ^3He within the mixed layer was −14‰ and −15.4‰ in the winter and autumn, respectively. Through the year excess ^3He occurs in the mixed layer except for a slight depletion of −17‰ in summer. The ^3He flux of 13‰md^{-1} associated with the concentration gradient at the air-sea interface was calculated from the product of the piston velocity and the excess ^3He. Tritium decay within the mixed layer could support only 2‰md^{-1} of the flux. Thus, the remaining 11‰md^{-1} could be attributed to the flux of tritiugenic ^3He from the water below the mixed layer. Nitrate and ^3He were positively correlated within the thermocline layer with the slope of 0.21 μmol kg^{-1} ‰$^{-1}$. The annual nitrate flux estimated from the upward flux of ^3He and the NO_3^-–^3He relation was 0.8±0.2 mol(N) $m^{-2}yr^{-1}$. This flux corresponds to an annual new production of 64 g(C) $m^{-2}yr^{-1}$, which is consistent with that in the north-west Pacific.

INTRODUCTION

Nitrogen limits the primary production in most parts of the ocean. Because nitrogen is supplied from various sources in diverse forms, types of primary production are distinguished by the sources and oxidation state of nitrogen. New production is the primary production associated with newly available nitrogen, such as nitrate and nitrogen gas, while regenerated production is associated with nitrogen recycled within the euphotic zone (Dugdale and Goering, 1967; Fig. 1).

The regenerated production fixes carbon and respires it again within the surface ocean, which has access to the atmosphere on a time scale of hours to days. Thus the regenerated production does not play any role in the absorption of atmospheric CO_2 by the ocean. On the other hand, the carbon fixed by new production using allochthonous nutrients should be exported to the deep ocean in a steady state. Once transported below the surface ocean, any fixed carbon wanders over the deep ocean for thousands of years before it has access to the atmosphere. Therefore, the process of new production can be considered as a pump moving carbon dioxide from the atmosphere to the deep ocean (Platt *et al.*, 1992). Sarmiento and Toggweiler (1984) suggest if this process, the so-called biological pump, had ceased operating during the pre-industrial era, the atmospheric pCO_2 would have increased from 280 ppm to 450 ppm instead of 360 ppm. Their research shows the importance of the concept of new production as a mechanism controlling the amount of CO_2 in the atmosphere.

Classical estimates of new production are based on bottle incubations, where new production is defined as the portion of ^{15}N uptake supplied by nitrate from all other nitrogen sources (Dugdale and Goering, 1967). This fraction, the *f-ratio* (Eppley and Peterson, 1979), is multiplied by total primary production to evaluate new production. However, the short length of incubation of 3–6 hours imposes a fundamental limitation on the conversion of the measurements into new production on the time scale of a year. Another

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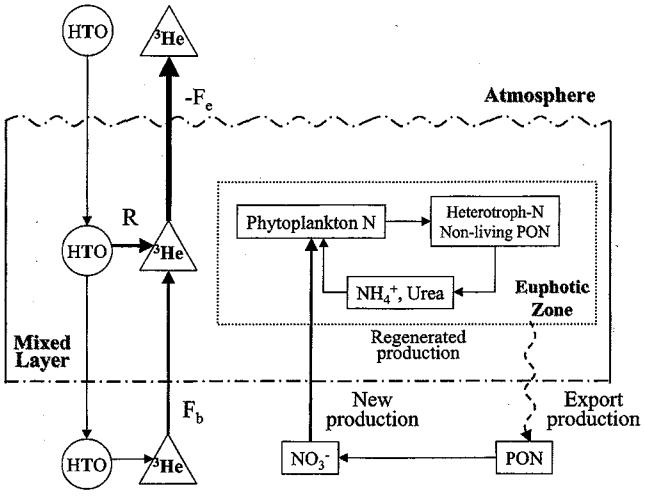

Fig. 1. Helium-nitrate new production estimation model. The nitrate flux supporting new production could be estimated using the ^{3}He flux and the relation of ^{3}He and NO_3^- within the thermocline, because those two tracers are transported to the mixed layer by the same physical processes. The upward flux of ^{3}He (F_b) can be determined simply by subtracting the flux of tritium decay (R) from the air-sea exchange flux (F_e). After formation, tritium is oxidized to water vapor (HTO) quickly and transferred from the atmosphere to the ocean by precipitation.

approach to estimating new production is to collect the sinking organic matter exported from the euphotic zone with sediment traps and measure its carbon and nitrogen content. The organic matter flux decreases quickly with depth, because the particles are broken and oxidized while they are sinking. The decomposition of organic matter makes it difficult to determine the proper deployment depth of sediment traps and to convert organic matter flux into new production.

A great adjustment in classical new production estimates has come from studies of oxygen consumption in the thermocline and the seasonal cycle of oxygen in the euphotic zone. These measurements of oxygen cycles offer a way to estimate new production *in situ* without bottle incubation (Jenkins and Goldman, 1985; Musgrave *et al.*, 1988). In addition, nitrate has been used to estimate new production. The input of nitrogen to the euphotic zone derived from the content of ^{15}N particulate matter and the distribution of nitrate in the upper ocean were used to calculate new production (Altabet and Deuser, 1985; Lewis *et al.*, 1986). The technique using oxygen and nitrate as tracers presented the new production that has a time scale appropriate for the quantification of the biological pump in the ocean. However, the above methods require consideration of complicated chemical and biological processes as well as physical processes controlling the concentration of each tracer.

In this study ^{3}He (Jenkins, 1988) was adopted to estimate the upward flux of nitrate into the euphotic zone and the resultant new production supported by the nitrate flux. ^{3}He has simpler physical and chemical properties than nitrate. In one-dimensional integrated model, both ^{3}He and nitrate are transported to the mixed layer by vertical advection (F_w), diffusion (F_d), and entrainment (F_h) of water from below. Nitrate in the mixed layer participates with other nitrogen compounds in oxidation-reduction reaction and is affected by various biological processes, such as fixation, decomposition and sinking. However, ^{3}He is affected by air-sea gas exchange (F_e) and radioactive decay of tritium (R; Fig. 1).

In steady state, the upward flux of ^{3}He into the mixed layer (F_b) would be equal to the difference between the rate of air-sea gas exchange and that of tritium decay:

$$F_b \equiv F_w + F_d + F_h = -F_e - R . \quad (1)$$

F_e is the product of piston velocity (V_p) with the concentration gradient:

$$F_e = V_p[(\delta^3He)_{eq} - (\delta^3He)_m] , \quad (2)$$

where $(\delta^3He)_{eq}$ is δ^3He when equilibrated with the atmosphere, and $(\delta^3He)_m$ is the average δ^3He in the mixed layer. δ^3He is defined as

$$\delta^3He = \left[\frac{(^3He/^4He)_{sample}}{(^3He/^4He)_{air}} - 1\right] \times 1000 .$$

The ^{3}He flux from the radioactive decay of tritium can be expressed by a simple exponential function as

$$^3He = {}^3H[1 - \exp(-\lambda t)] , \quad (3)$$

where λ is the decay constant of tritium and t stands for a time. In summary the upward flux of ^{3}He into the mixed layer (F_b) can be simply obtained through calculation of the gas exchange (F_e) and tritium decay rates (R).

Recent studies show that the East Sea is a miniature ocean to study oceanic carbon cycle (Kim and Kim, 1996; Kim *et al.*, 1999). That is, from a carbon cycle study in the East Sea, we can predict the change of oceanic carbon cycle. The biological pump is one of the most important factors to study carbon cycle. As mentioned above, new production plays an important role in biological pump of carbon cycle.

The previous measurements of new production in the East Sea were made by bottle incubations in limited seasons (Yang, 1997, 1998; Moon *et al.*, 1998). This work utilizing ^{3}He as a tracer is the first to provide the integrated new production over large space and time scales, and hence represents substantially the biological pump in the East Sea.

MATERIALS AND METHODS

Helium isotopes samples were collected during four expeditions (CREAMS 99W, HAHNARO 7, KH 36 and EARDO 99) in 1999 (Fig. 2). Those samples (~40 g) were contained in copper tubing and sealed off with a cold welding press. Samples were degassed in a vacuum extraction system and the extracted gases were transferred into a glass ampoule using water vapor as a carrier gas. After purification of extracted gases with a getter pump and an activated charcoal trap held at liquid nitrogen temperature, helium isotopes were admitted to the mass spectrometer (MM 5400, Micromass). ^{3}He and ^{4}He were measured simultaneously with an electron multiplier and a Faraday cup, respectively.

Tritium was measured by the ^{3}He ingrowth method (Bayer *et al.*, 1989; Jenkins *et al.*, 1991). A degassed seawater sample was stored in a low helium permeability glass bulb to let ^{3}He be produced by tritium decay. The accumulated tritiugenic helium was measured after a 5-month storage period.

Na's Wind speed in 1994 (Na *et al.*, 1992) was adopted to calculate piston velocity. The wind data were generated by the Cardone model, which is based on the weather chart forecast twice a day. In order to calculate piston velocity and equilibrium δ^3He, $(\delta^3\mathrm{He})_{eq}$, we generated daily variations of temperature and salinity by extrapolation of NODC 1 degree grid monthly data. Nitrate concentrations used to derive the relation between δ^3He and nitrate were measured with a continuous flow nutrients analyzer (TRACCS 2000, BRAN+LUEBBE) and calibrated by a WOCE standard solution (Gordon *et al.*, 1991).

RESULTS AND DISCUSSION

Distribution of ^{3}He and NO_3^-

The average δ^3He in the mixed layer of −10~−15‰ in the winter was higher than that in the summer, −16~−17‰ (Fig. 3). Because deep convection harvests tritiugenic ^{3}He from the waters below, winter has higher δ^3He than summer despite vigorous gas exchange. The abrupt increasing trend of δ^3He below

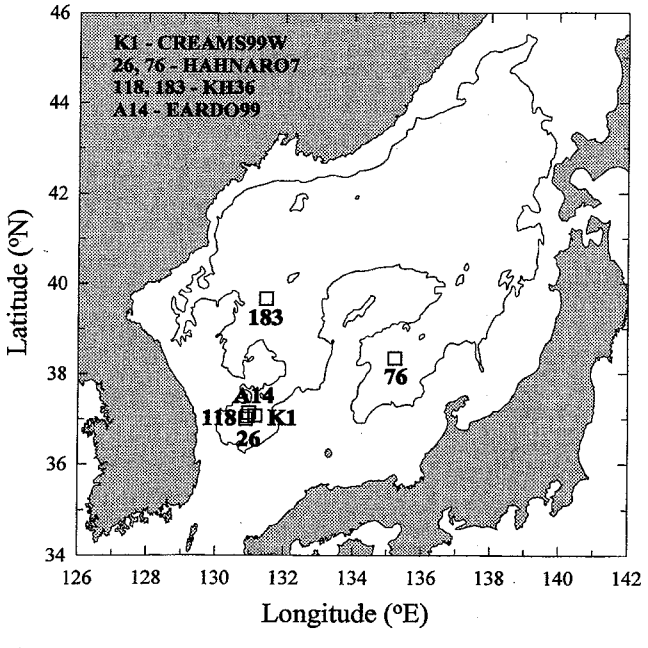

Fig. 2. Helium isotopes samples were collected at the center of the Ulleung Basin in February, June, July and October, 1999. All stations are located in the south of the polar front observed at 40°N.

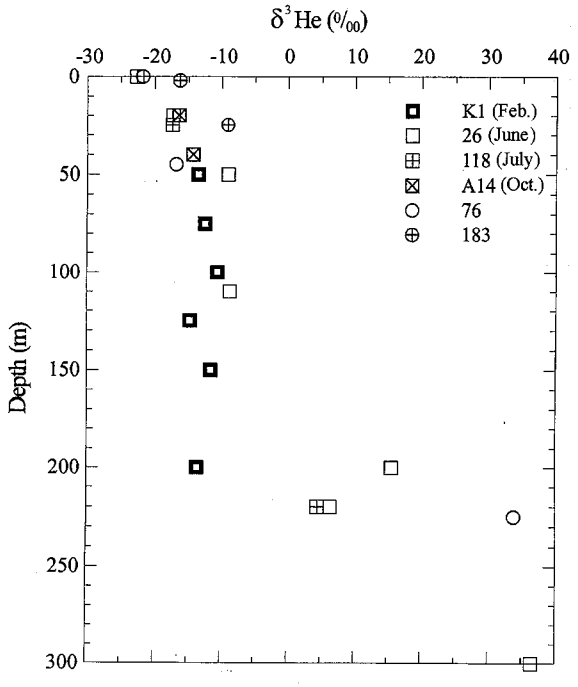

Fig. 3. The vertical distribution of δ^3He in the Ulleung Basin in 1999. In the winter homogeneous δ^3He from −10 to −15‰ was observed within the mixed layer. δ^3He in summer was about −17‰ within the mixed layer.

200 m was consistent with the previous result (Hahm *et al.*, 1998), which shows a maximum of 100‰ at 500 m depth.

In February, average concentration of nitrate was 6 μmol/kg in the mixed layer, developed down to 150 m in the Ulleung Basin at that time. Low biological activity and deep convection keep the nitrate concentration high in the winter, while high biological activity and strong stratification deplete it to near zero in the summer. With depth, the nitrate concentration increased in all seasons. The simulated monthly variation of temperature and salinity (see above section) matched well with the observations in 1999 and that of KODC (Korea Oceanographic Data Center) at station 104–10 in 1998.

^{3}He exchange rate

The magnitude of the piston velocity depends both on the physical properties of the gas and the environmental conditions and is proportional to a power of the Schmidt number, Sc= ν/D, the ratio of kinematic viscosity (ν) to molecular diffusivity (D) (Roether, 1986). The relationship between piston velocity and wind speed is under debate, though many researchers have studied it for a long time (Liss and Merlivat, 1986; Watson *et al.*, 1991; Wanninkhof, 1992; Nightingale *et al.*, 2000). In this study the piston velocity was determined by Liss and Merlivat's (1986) equations, because those appear to explain well the gas exchange of ^{3}He.

$$V_p = 0.17u\left(\frac{600}{Sc}\right)^{2/3}, \quad u \le 3.6$$

$$V_p = (2.85u - 9.65)\left(\frac{600}{Sc}\right)^{1/2}, \quad 3.6 \le u \le 13$$

$$V_p = (5.9u - 49.3)\left(\frac{600}{Sc}\right)^{1/2}, \quad u > 13 \qquad (4)$$

where u (m/s) is the wind speed 10 m above the sea surface. The above equations are normalized to Sc= 600, corresponding to transfer of CO_2, at 20°C. To calculate the piston velocity, the daily wind speed in 1994 (Na *et al.*, 1992) and the relationship between Schmidt number and temperature of Jahne *et al.* (1987) were adopted.

Seasonal variation of ^{3}He

The annual variation of the helium isotope ratio was derived from the observations in February, July, August and October in the Ulleung Basin. Assuming

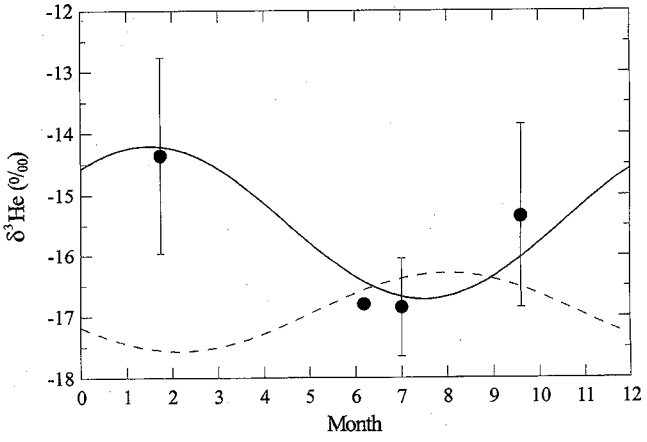

Fig. 4. The monthly variation of mean δ^3He within the mixed layer. Data were generated from sinusoidal fitting of the observed data (filled circles). The error bars show the standard deviations of the means at each time. The maximum d^{3}He was assumed to appear in February when the mixed layer depth is deepest. The broken line indicates the equilibrium δ^3He calculated from the sea surface temperature and salinity. The T, S values are the averages of NODC data during 1932–1994.

that the annual amount of ^{3}He is in steady state, the annual variation could be expressed by a simple sine curve with a frequency of one year. We set the maximum of the sine curve to appear in February when the mixed layer depth was deepest, with the assumption that the excess ^{3}He mostly comes from below the mixed layer. Consequently, the minimum ^{3}He appeared in August (Fig. 4). Observation for several years by Jenkins (1988) supports the assumption of a steady state and a maximum in February.

The equilibrium δ^3He with the atmosphere is ~–17‰, because the ^{3}He is slightly less soluble than ^{4}He. The equilibrium δ^3He is a function of temperature and salinity, and can be calculated by the simple equation (Benson and Krause, 1980):

$$(\delta^3 He)_{eq} = -18.04 + 8.5\times10^{-2}T + 2\times10^{-5}T^2 - 8\times10^{-3}S \quad (5)$$

The equilibrium δ^3He was calculated using the daily variation of temperature and salinity, and is shown as a broken line with the annual variation of δ^3He in the mixed layer in Fig. 4. Most of the year deep convection supplies enough tritiugenic ^{3}He to keep it in excess despite the gas exchange. The strengthened stratification in summer could keep the concentration of ^{3}He in the mixed layer in slight depletion.

^{3}He and NO_3^- flux

The annual variation of gas exchange flux was cal-

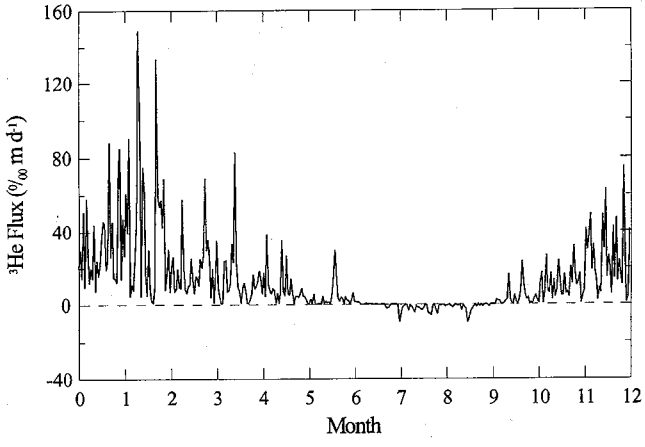

Fig. 5. The seasonal variation of ^{3}He flux from below the mixed layer. This is the product of the piston velocity with the excess ^{3}He in the mixed layer. The mean ^{3}He flux was 13 ‰md^{-1}. The tritium decay within the mixed layer could support only 2‰md^{-1} of the flux. Thus the remaining 11 ‰md^{-1} could be attributed to the flux of tritiugenic ^{3}He from the water below the mixed layer under steady-state.

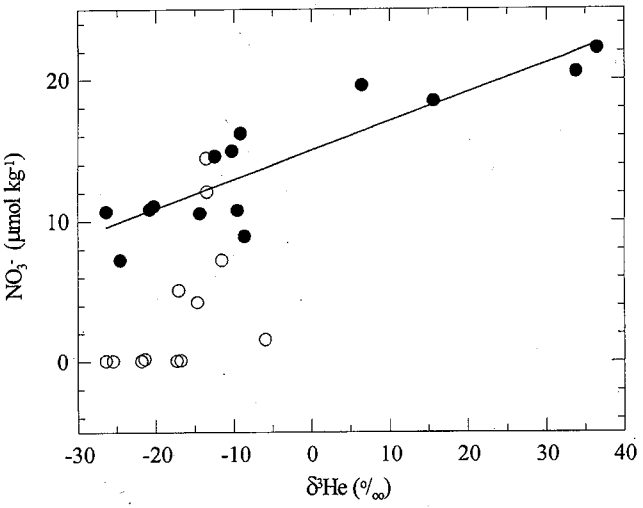

Fig. 6. The relation between nitrate and δ^{3}He was obtained from a linear regression of the data in the thermocline (solid circles). The sharp decline of nitrate concentration at low δ^{3}He shows the biological utilization of the nitrate in the mixed layer (open circles). The slope adpoted for calculation of the nitrate flux was 0.21 μmol kg^{-1} ‰$^{-1}$.

culated from the product of excess ^{3}He with the piston velocity (Fig. 5). The biggest flux from the sea to the atmosphere appeared in the winter because of high δ^{3}He and piston velocity. In contrast, the ^{3}He flux from the atmosphere to the sea was found in summer. This phenomenon could have been caused by the restricted supply of tritiugenic ^{3}He by the strong thermocline and the dominant air injection through the air-sea interface in this season.

The average daily flux of ^{3}He was 13 ± 3‰md^{-1}. The error of average flux mostly originated from the equations (4) that describe the relation between the wind speed and the piston velocity (20 − 25%; Liss, 1988). To estimate the tritiugenic ^{3}He flux in the mixed layer we applied 1.7 TU (Tritium Unit; 1 TU = 1 ^{3}H atom per 10^{18} H atoms) as a mean concentration of tritium (Hahm *et al.*, 1998). This value was obtained by the integration of tritium concentration at depths shallower than 70 m, which is the average mixed layer depth in the Ulleung Basin. Considering that the tritium concentration decreases, as the latitude is lower, 1.7 TU in the Japan Basin (42°06'N, 136°12'E) could be regarded as an upper limit (Watanabe *et al.*, 1991). The tritium concentration in the mixed layer could produce a ^{3}He flux of 2.3‰ md^{-1}. Therefore, the net ^{3}He flux from below into the mixed layer was determined as 11 ± 2‰ md^{-1}.

The nitrate flux supplied into the mixed layer along with the net ^{3}He flux was determined by the relationship between ^{3}He and nitrate in the thermocline. As the age of water becomes older, both the amounts of tritiugenic ^{3}He and those of nitrate become greater. Hence the two tracers have a positive correlation in the thermocline (Fig. 6). The excess ^{3}He in the mixed layer decreased to near equilibrium owing to the gas exchange, while the nitrate concentration dropped abruptly to near zero because of the biological activity. Applying the relation (a slope of 0.21 ± 0.03 μmol kg^{-1} ‰$^{-1}$) between the two tracers within the thermocline, the estimated nitrate flux into the mixed layer was 0.8 ± 0.2 mol (N)m^{-2} yr^{-1}. The nitrate flux was calculated from the product of the ^{3}He flux with the slope of the line representing the relationship between those two tracers.

The new production studies in the East Sea have been conducted by the ^{15}N-incubation method (Yang, 1997, 1998; Moon *et al.*, 1998). Regarding the incubation results as the representatives of the month, the seasonal trend of the nitrate flux was roughly matched with that of this study (Fig. 7). However, two things should be noted for the comparison of the results. One is that those two approaches have intrinsic differences in time and space scales. The other is that the nitrate flux determined by the ^{3}He flux and the ^{3}He − NO_3^- relation would not be expected to coincide with the new production rate determined by the ^{15}N-incubation.

New production

Deriving the new production in terms of carbon

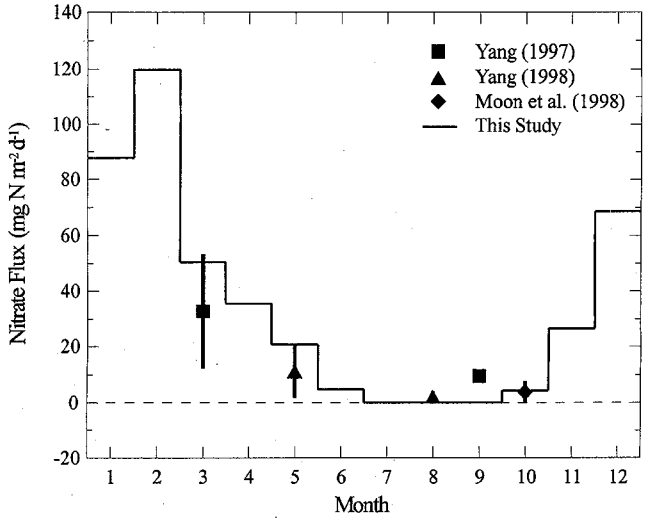

Fig. 7. The monthly mean nitrate flux into the mixed layer. The seasonal variation of the flux is similar to the new production rates of Yang (1997, 1998) and Moon *et al.* (1998).

from the nitrate flux requires knowledge of the C:N ratio of organic matter. Yang (1997) reported that the C:N ratio varies seasonally from 1.0 to 24.1 in the Ulleung Basin. However, the results based on short time incubation are not applicable to the calculation of the annual nitrate flux of this study. In contrast, the annually averaged data obtained by using a sediment trap (Hong, 1998) give a C:N ratio ranging from 6.2 to 7.1, which is similar to those obtained in the open ocean, e.g. 106:16 (Redfield *et al.*, 1963) and 103:16 (Takahashi *et al.*, 1985). We adopted Redfield ratio to convert the nitrate flux to the corresponding new production. The ratio agrees with the result of Chen *et al.* (1996) which suggests that the C:N ratio in the upper ocean (300−600 m) of the East Sea is 6.0. Applying the Redfield ratio to the conversion, the annual nitrate flux of 0.8 ± 0.2 mol(N) m^{-2} yr^{-1} would support a new production of 5.3 mol(C) m^{-2} yr^{-1} or 64 g(C) m^{-2} yr^{-1} (Table 1).

A relation between the new production and the total primary production (Eppley and Peterson, 1979; Berger *et al.*, 1989) was applied to verify the estimation, for there is no previous result suggesting new production with comparable time and space coverage. Many researchers measured the primary production (Shim *et al.*, 1985, 1992; Moon *et al.*, 1998) by the ^{14}C uptake method in the Ulleung Basin. However, the results are inadequate to allow deduction of the annual primary production because of the great variance among themselves and the limited number of experiments in winter. The particulate flux measured with a sediment trap at 1000 m (Hong, 1998) was used to derive primary production instead. An annual particulate organic flux of 8.3 g(C) m^{-2} yr^{-1} corresponds to a primary production of ~200 g(C) m^{-2} yr^{-1} in the euphotic zone (Suess, 1980; Betzer *et al.*, 1984). Another estimation of primary production was obtained with CZCS climatological chlorophyll distributions according to several empirical algorithms (Smith and Baker, 1982; Brown *et al.*, 1985; Balch *et al.*, 1989). The calculated primary production of 180 ± 20 g(C) m^{-2} yr^{-1} is consistent with the estimate from particulate flux.

Table 1. The values obtained from the present work.

Air-sea exchange flux of ^{3}He	13 ± 3 ‰md^{-1}
Tritium decay flux in the mixed layer	2.3 ‰md^{-1}
^{3}He upward flux into the mixed layer	11 ± 2 ‰md^{-1}
^{3}He-NO_3^- relation	0.21 μmol kg^{-1} ‰$^{-1}$
Annual nitrate flux	0.8 ± 0.2 mol(N) m^{-2} yr^{-1}
Annual new production	64 g(C) m^{-2} yr^{-1}

Regarding the primary production rate as 200 g(C) m^{-2} yr^{-1}, based on the sediment trap experiment, the equation suggested by Berger *et al.* (1989) provides a new production estimate of 76 g(C) m^{-2} yr^{-1}. The estimate from Berger and co-authors' equation agrees with the result from the ^{3}He-method considering the error of 25% in the flux. However, the relations between new and primary production, and between chlorophyll and primary production have not been verified in southern East Sea yet. To understand precisely the role of the biological pump in this region, a time-space integrated experiment on primary production is also required.

New production in the southern East Sea looks similar to that in the north-west Pacific. Goes *et al.* (2000) estimated sea surface nitrate concentration and new production from remotely sensed sea surface temperature and chlorophyll. They suggest that new production in the western Pacific is much higher than that in the eastern Pacific and the highest values reach over 50 g(C) m^{-2} yr^{-1}. Export flux values in excess of 50 g(C) m^{-2} yr^{-1} have also been measured by sediment trap (Noriki and Tsunogai, 1986). With regard to the high production rate, the southern East Sea, like the north-west Pacific (Honjo, 1997), would play an important role in the biogeochemical cycle.

CONCLUSION

To estimate large space and time integrated new production in the southern East Sea, the seasonal

variation of ^{3}He was observed in the mixed layer in 1999. A ^{3}He flux of 13‰md^{-1} associated with the concentration gradient at the air-sea interface was calculated from the product of the piston velocity with the excess ^{3}He. A tritium decay corrected ^{3}He flux of 11‰md^{-1} could be attributed to the flux of tritiugenic ^{3}He from the water below the mixed layer. The amount of nitrate coming with the ^{3}He to the mixed layer was estimated from the linear relationship between NO_3^- and ^{3}He within the thermocline. The resultant nitrate flux of 0.8 ± 0.2 mol (N) m^{-2} yr^{-1} corresponds to an annual new production of 64 g(C) m^{-2} yr^{-1}.

Primary production in the Ulleung Basin was calculated from both the particulate flux (Hong, 1998) and the CZCS chlorophyll concentration to validate the new production estimate. The primary production of over 200 g (C) m^{-2} yr^{-1} supports the new production estimate using ^{3}He in this region (Berger *et al.*, 1989). The new production in the southern East Sea was close to that in the north-west Pacific, which reaches 50 g (C) m^{-2} yr^{-1} (Noriki and Tsunogai, 1986; Goes *et al.*, 2000).

The ^{3}He-tracer approach could be improved by incorporating the air injection component, which could change the equilibrated δ^3He, into the calculation of gas-exchange rate (Jenkins, 1988; Schundlich and Emerson, 1996). However, a comparative research of the new production is inevitable to derive a reliable estimate owing to the difference in the time-space scale among the various methods. The particulate flux measured by sediment trap at near surface (~100 m) is expected to represent the export production directly (Martin *et al.*, 1987). The flux could be compared with the tracer-based measurements. The derivation of the annual primary production using time-series bottle incubation or remotely sensed chlorophyll concentration would be also a valuable effort for setting limits to the new production in the East Sea.

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