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The depletion of nutrients and the estimation of the new production in the ice-edge of the Prydz Bay, Antarctica

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Abstract The distributions and changes of nutrients in the Prydz Bay were investigated during CHINARE-6(the 6th Chinese National Antarctic Research Expedition) and CHINARE-9, and the new productions were estimated by using mass balance method. The results showed that in CHINARE-6, the depletion of NO_3-N, PO_4-P, SiO_3-Si were 1064.8, 69.2, 2196.9 mmol/m^2, respectively, the uptake ratios of N and Si to P were 15.3, 31.7, respectively, and new production was 992.4 mgC/(m^2·d); in CHINARE-9, the depletion of NO_3-N, PO_4-P were 551.9, 41.2 mmol/m^2, respectively, the uptake ratio of N to P was 13.4, and the new production was 390.1 mgC/(m^2·d), indicating significant annual and/or seasonal variation. New productions were both greater than the primary production determined by ^{14}C-trace method, demonstrating there existed rather higher new production in the Prydz Bay in austral summer. The uptake ratio of nutrients in the Prydz Bay, however, is different from the previous values obtained from the open sea, showing the regional difference of uptake and regeneration of nutrients in the Southern Ocean. Finally the annual change of new production and the characteristics of phytoplankton production were discussed.

Key words depletion of nutrient, estimation of the new production, Prydz Bay.

1 Introduction

The photosynthesis of organic matter and the export to the deep ocean are key processes to the ocean production, geochemical cycle and the global carbon cycle, and make a great impact on the marine biology, chemistry and sedimentation. These processes involve the primary production in the euphotic layer and the export of the organic matter to the deep ocean, and will remove the nutrients out of the surface water. Thus they will influence the magnitude and variation of primary production, and supply the food to the marine biology and sediments in deeper ocean. Primary production, based on the source of nutrients, can be divided into New Production (NP) and Regenerated Production (RP). NP refers to primary production resulting from nutrients outside the euphotic zone. RP refers to the primary production supported by the regenerated nutrients within euphotic zone (Dugdale and Goering 1967). On the other hand, according to the fate of product of primary production, the production also can be divided into Export Production (EP) and Recycled Production. EP refers to organic matter separated from food web and fluxing into deeper ocean, the Recycle Production is the organic matter recycled within euphotic zone. Epply and Pertson (1979) suggested that the new production is equal to the export production in a steady-state ecosystem. So the new production is a key parameter to understand the function and structure of an ecosystem and biogenic elemental biogeochemical cycle in ocean.

There are lots of methods for determining new production. One type of methods is direct measurement: sediment traps were located at the bottom of euphotic layer to measure the down flux of organic matter, incubation to measure the uptake rate of phytoplankton using the trace of ^{15}N, ^{14}C and ^{234}Th-^{238}U disequilibrium methods (Karl *et al*. 1991). All methods, however, have an intrinsic disadvantage of discontinuity of sampling in time and space, and only measure some local or episodic bloom incidents, and therefore introduce some errors when estimating new production in the long run. The other is to calculate the depletion of nutrients and/or the buildup of oxygen based on the mass balance. The basic principle is to estimate the new production on the basis of the stoichometric ratio and the depletion of nutrients and/or buildup of oxygen after phytoplankton bloom, and take together the growth time and the contributions of some physical processes (such as vertical diffusion and the sea-atmospheric exchange of dissolved oxygen). This approach can provide an average estimate of production in a larger space and longer time periods, and has been used extensively (Jennings *et al*. 1984; Simon 1986; Karl *et al*. 1991; Benner *et al*. 1992).

Some researches have demonstrated that there existed intensive depletion of nutrients in ice-edge zone and some Antarctic coastal locations, and showed that this resulted from high levels of primary production and new production (Karl *et al*. 1991; Treguer and Jacquer 1992). But no such reports have been presented in the Prydz Bay and its adjacent sea area. The previous researches, however, illustrated substantial depletion of nutrients in these regions (Wang *et al*. 1993), and there existed phytoplankton bloom with chlorophyll *a* greater than 5 $\mu g/dm^3$ and primary production greater than 1000 $mgC/(m^2 \cdot d)$ (Ning *et al*. 1993). So high level of new production is expected. In this paper by applying the mass balance approach and on the basis of the nutrients data obtained during CHINARE-6 and CHINARE-9, the depletion of nutrients has been studied and the estimates of new production have been given, and finally the time succession and characteristics of production have been discussed.

2 Sampling stations and methods

Water samples were collected during CHINARE-6 and CHINARE-9, the location of the stations was given in Fig. 1. The sea area had weak current and intensive stratification (Dong *et al*. 1984), satisfying the most crucial assumptions in the application of mass balance methods. 6 water samples have been collected within 0 – 200 m at the depth of 0, 25, 50, 100, 150 and 200 m by using high volume bottles. The temperature, salinity, dissolved oxygen and nutrients concentrations (NH_4-N, NO_2-N, NO_3-N, PO_4-P, SiO_3-Si) have been determined. All methods used in the study were given in the book 《Specification for oceanographic survey observation of chemical parameters in sea water》 (National Technique Supervisor Agency 1991). The research period during CHINARE-6 was Jan. 16 – 18, 1990, and CHINARE-9 from Jan. 31 to Feb. 4, 1991, which lagged behind about half of month (about 15 d) as compared to CHINARE-6.

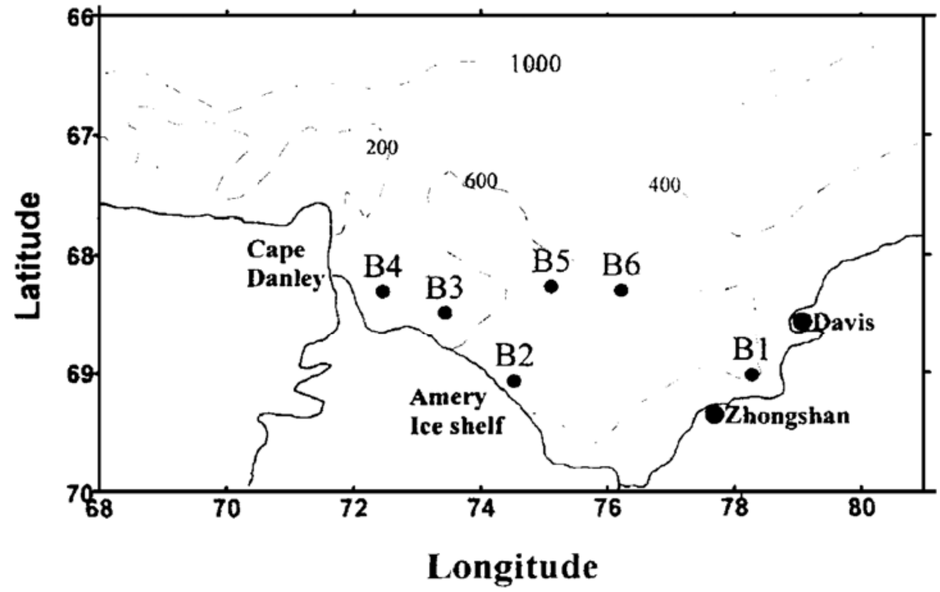

Fig. 1. The sampling stations in CHINARE-6 and CHINARE-9 inside the Prydz Bay.

3 Results and discussion

3.1 The calculation principle and the selection of parameters

To obtain the estimates of nutrients anomalies due to the phytoplankton assimilation, the following assumptions were made:

(1) The depth of mixed layer can be identified according to criteria of $\Delta\sigma_t \geqslant 0.01$ and $\Delta T \geqslant 0.01$. Fig. 2 illustrated the density profiles within a depth of 200 m at stations inside the Prydz Bay. As can see in Fig. 2, the upper 25 m water in CHINARE-6 was mixed better than in CHINARE-9. However, both had the pycnocline between 25 m to 50 m with little change below 50 m. It is, therefore, reasonable to select 50 m as the depth of water body in which the phytoplankton depleted the nutrients.

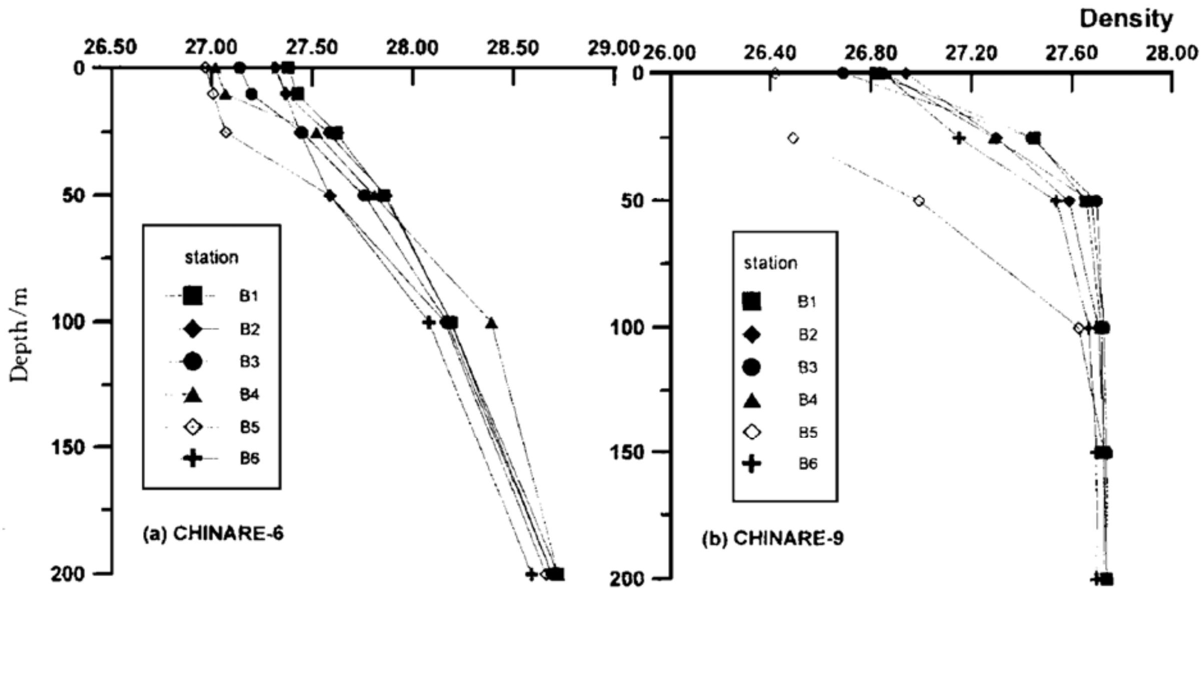

Fig. 2. The density profile of stations inside the Prydz Bay in CHINARE-6 and CHINARE-9.

(2) The salinity and nutrients concentration below the pycnocline are same through all years and can be regarded as the winter water properties before the depletion of nutrients occurs and ice melts in austral summer. Fig. 3 gave the profiles of hydrographic properties and nutrients at the typical station B3. Fig. 3 showed the following features: The first, the salinity (S) of surface water in CHINARE-6 is 34.07‰, temperature (T) being 3.06 ℃, both are larger than those of CHINARE-9 (salinity of 33.50‰, temperature of 2.55 ℃) and S is vertical homogeneity within 50 m, whereas T is closely equal to that of winter water below this depth. The second, the nutrient concentrations of CHINARE-6 are smaller than those of CHINARE-9, and the gradient is so small that there was larger depletion up to 50 m and the pycnocline existed between 50 – 100 m. So the depth of 50 m may under-estimate the depletion of nutrient for CHINARE-6. The nutricline of CHINARE-9 was between 25 m to 50 m, water at 50 m is the same as the winter water. The concen-

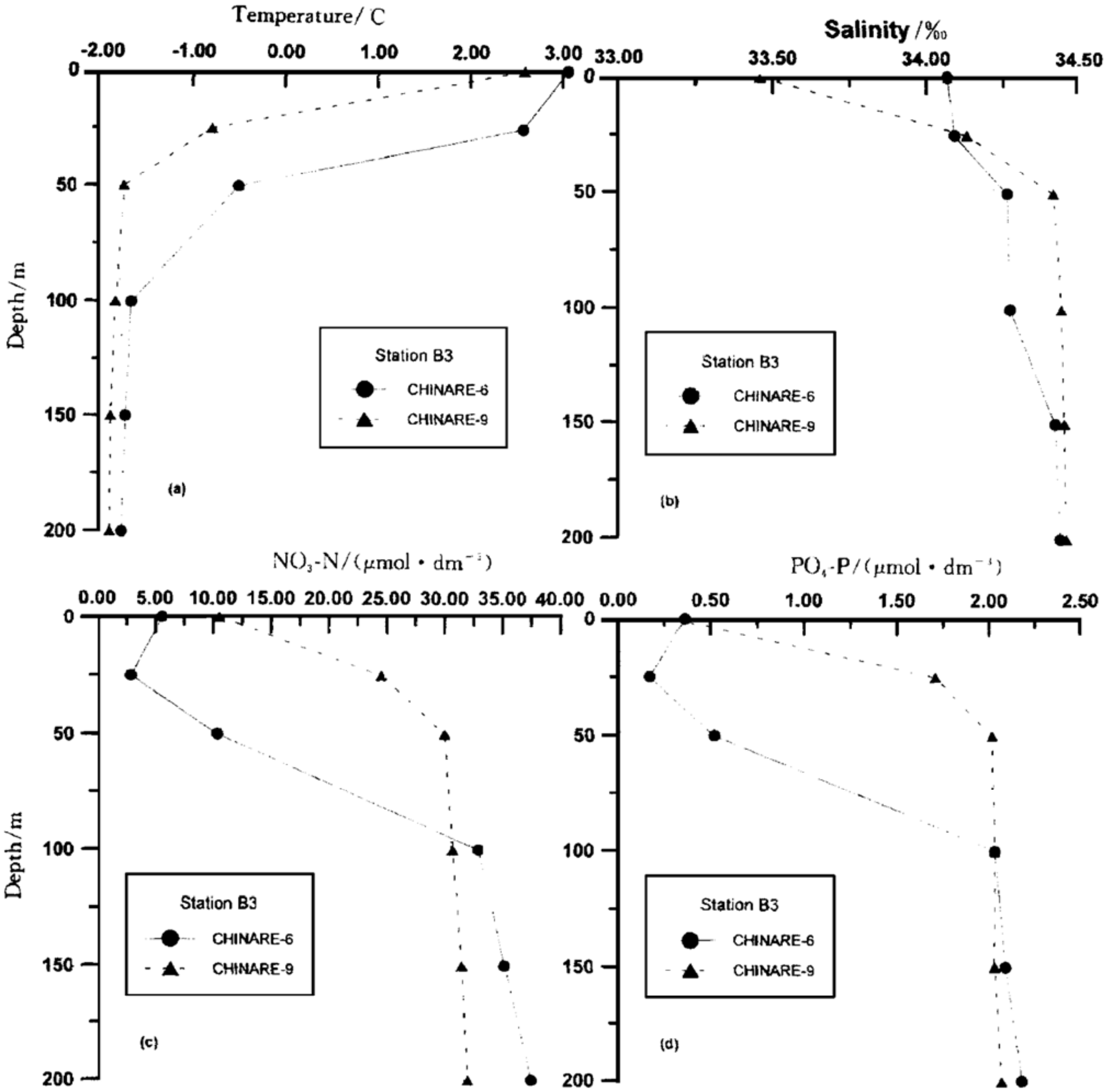

Fig. 3. The temperature, salinity and nutrient profile of B3 Station in CHINARE-6 and CHINARE-9.

tration at 50 m is characteristic of the winter water and can be selected as the base values to calculate the consumption of nutrients, that is, NO_3-N=32.00 $\mu mol/dm^3$, SiO_3-Si=65.00 $\mu mol/dm^3$, PO_4-P=2.10 $\mu mol/dm^3$.

(3) Little or no vertical or lateral mixing takes place to alter nutrients concentration in either the surface layer or the WW layer beneath pycnocline, and the dilution effects due to ice-melt are negligible. Based on the model of impact of ice-melt on nutrient concentration (Whitehouse *et al*. 1995) and the hydrographic data during CHINAER-6 and CHINARE-9, the dilution effect of ice-melt on nutrient concentration is less than 10%.

(4) A realistic time frame can be assigned in which the depletion of nutrient occurs. Although we lack the accurate time data when the austral bloom begins, the average time (November) is reasonably selected to estimate production. This time will introduce some errors because there is difference in production time of the same sea region and in different regions and seasons. In the Weddle Sea, Jenning *et al*. (1984) selected the middle of November as the starting time, while Karl *et al*. (1991) considered the starting time not to be later than November, this variation was related to the content of ice coverage. The ice coverage in the Prydz Bay was found to vary very much between different years (Dong *et al*. 1984). Hydrographic data during CHINARE-6 showed that although the temperature increased very much, salinity was still at the winter state. Therefore, if the starting time was assigned to November, the growth time frames for CHINARE-6 and CHINARE-9 were 75, 90 d, respectively. This may be an underestimated time frame, and the estimated production may be a minimum estimate.

3.2 Results and discussion

Based on the above assumption, the depletion of nutrient and the estimates of new production of CHINARE-6、CHINARE-9 are listed in Table 1.

Table 1. The depletions of nutrients and the estimates of new production in CHINARE-6 and CHINARE-9 at the Prydz Bay(mgC/(m^2·d))

	Stations	ΔNO_3	ΔPO_4	ΔSiO_3	$\Delta N:\Delta P$	$\Delta Si:\Delta P$
Jan. 1990 (75 d)	B1	914.1	57.8	2191.4	15.8	37.9
	B2	1113.4	74.2	2317.6	15.0	31.2
	B3	1353.6	82.8	2152.0	16.3	26.0
	B4	1213.2	78.3	1879.0	15.5	24.0
	B5	990.6	69.3	2254.2	14.3	32.5
	B6	804.2	52.5	2386.9	15.3	45.3
	Average	1064.8	69.2	2196.9	15.3	31.7
	New production	902.9	897.8	1176.6		
Feb. 1993 (90 d)	B1	568.8	35.9	ND	15.8	
	B2	491.0	33.0	ND	15.0	
	B3	430.0	28.6	ND	15.0	
	B4	457.9	41.6	ND	11.0	
	B5	745.8	57.4	ND	13.0	
	B6	618.0	50.5	ND	12.0	
	Average	551.9	41.2		13.4	
	New production	390.0	390.1			

ND: Data on SiO_3-Si are not determined in CHINARE-9.

In Table 1, the following features can be seen:

(1)The depletions of NO_3-N, PO_4-P during CHINARE-6 and CHINARE-9 were

1064.8, 551.9, 69.2, 41.2 mmol/m^2, respectively, the depletion of SiO_3-Si in CHINARE-6 was 2196.9 mmol/m^2, the ratio of N to P and Si to P were 13.4 – 15.3, 31.7, respectively. The ratio of Si to P is greater than that obtained by Copin-Montegut and Copin-Montegut(1978), but is between the range in research area (Table 2). Table 2 lists the assimilation ratio range in research area. The values indicated that the ratio of nutrient uptake and particulate composition varied to larger degree. This change may be due to the different sampling stations. The previous research was focused on open sea, while the study is centered on coastal water where there are high production and the organic matters contribute to more particulate composition than those in open sea, this regional difference is related with the features of mosaic of subsystems in the Antarctic Ocean.

Table 2. The particulate composition and the uptake ratios of nutrients in the Southern Indian Ocean

Authors	N:P	Si:P
Copin-Montegut and Copin-Montegut(1978)	11	25
Le and Tregue(1985)	9.1 – 13.6	10 – 56
Simon(1986)	12 – 13.6	50 – 72
Treguer *et al.* (1988)	13.6	18.5
Wang *et al.* (1993)	14.4	14 –41
This paper	13.4 –15.3	31.7

The estimation of primary production from nutrient depletion requires knowledge of the stoichiometry of nutrients assimilation and carbon fixation by phytoplankton. The average composition of marine phytoplankton in the Southern Ocean is less than the Redfield ratio and has a wide range at different regions (Jenning *et al.* 1984). So the estimate will be different according to the nutrient assimilation ratio. In this study, the value of 5.3 of C:N ratio obtained by Leynaert *et al.* (1991) at the ice-edge in the Indian Ocean was used to estimate the new production of CHINARE-6 and CHINARE-9, and accordingly the estimates were 902.9, 390.0 mgC/(m^2·d), respectively. If the ratio of N to P was 15:1, the new production of CHINARE-6, CHINARE-9 from the depletion of phosphate were 897.8, 390.1 mgC/(m^2·d), respectively. The equivalent value can be got from the depletion of both nitrate and phosphate (Table 1). The ratio of biological silica to POC in particulate changes in different space and time in the Southern Ocean, it ranges from 0.01 to 0.65 (Leynaert *et al.* 1991). The Si:P ratio at the Prydz Bay ranges from 14 – 41 (Wang *et al* 1993), accordingly the ratio of Si to C is from 0.17 to 0.38 with the average being 0.29. Treguer *et al.* (1988) observed that the average ratio of Si to POC was 0.19 in the Southern Indian Ocean, and 0.30 in ice-edge and the productive coastal water. So the Si:POC ratio of 0.30 was selected in this estimation, and new production was 1171.6 mgC/(m^2·d), which is larger than those obtained from the depletion of nitrate and phosphate, this could be attributed to the fact that particulate phosphorus and nitrogen are easier to be mineralized and to cycle quicklier within euphonic zone than particulate silica (Copin-Montegut and Copin-Montegut 1978).

(2) When the estimates are compared with the primary production with ^{14}C method, the estimates of CHINARE-6, CHINARE-9 were both larger than the primary production (The primary production of CHINARE-6, CHINARE-9 were 950, 340 mgC/(m^2·d), respectively (Ning *et al.* 1993)). These results are consistent with

the others' observations(Jenning *et al*. 1984;Karl *et al*. 1991). The observations are understandable for the known effects of temporal and space undersampling and production and accumulation of dissolved organic matter which was not included in the mass balance calculation(Benner *et al*. 1992). However, these high values indicate that there existed a high level of new production inside the Prydz Bay in austral summer.

(3)It is worth while pointing out that the estimate obtained in Jan. 1990 is twice that in Feb. 1993. This marked difference can be partially attributed to the different primary production. As both primary production and new production have larger annual change, and new production coupled to the magnitude of primary production with the positive relationship, these observations have been reported in other regions (Karl *et al*. 1991). However, the variation found in the study is also indicative of seasonal variation of production in Antarctic ecosystem. The observed time difference between CHINARE-6 and CHINARE-9 is about two weeks, this time period is a "longer time" for the "transient summer" in Antarctica. Sun irradiation melt such substantial ice that the water salinity is markedly reduced, creating a favorable situation for intense phytoplankton bloom, and the standing crops notably increase. However, during CHINARE-9, concentrations of NO_3-N, PO_4-P have not been reduced but increased instead. The nutricline rises up from 100 m to 50 m, this nutrient increasing has been observed in other researches(Karl *et al*. 1991). In the mean time, the NH_4-N concentration in research area is more than 2.0 $\mu mol/dm^3$, indicating the intensive heterotrophic activity. The high concentration of NH_4-N will also limit the uptake of NO_3-N, this competition between NO_3-N and NH_4-N will reduce the ratio of N to P and the new production (Treguer and Jacquer 1992). Thus the production was sustained by assimilating the regenerated nutrient, the ecosystem function has shifted into regenerated system. So the magnitude of primary production is both related to the primary production and to the production stage(Treguer and Jacquer 1992).

If this time series change is a general pattern in the Antarctic Ocean, the primary production of the Southern Ocean, biogenic elemental biogeochemical cycle and its effect on the global change would be more complicated than conceived before. On the south of the Polar Front, there are about 16×10^6 km^2 sea areas covered by the ice, when the austral summer comes, ice would melt and the ice-edge zone would retreat and produce a narrow ice-edge zone, where intensively stratified and stable water favors phytoplankton production, and has great primary production and new production, and has larger vertical fluxes to deep ocean. With the pass of time, the packed ice moved forward southerly, the stability of water became weak. This cause the production function shifts into a predominant regeneration, new production becomes smaller with smaller standing crop and low concentration of organic particulate. But larger organic matters have been exported into the bottom water in spring and summer, so apparent low production will not influence the particulate flux of the whole year. This change caused by the ice retreat is similar with the seasonal variation in the production function.

So the larger flux is not contradictory to low standing crop and primary production measured in open sea and in late summer, because these processes have a "phase time difference".

4 Conclusions

(1)The average new productions during CHINARE-6, CHINARE-9 inside the Prydz Bay were 992.4, 390 mgC/(m^2·d), respectively, this difference was related with the annual and seasonal variation of primary production.

(2)The uptake ratio of N to P inside the Prydz Bay range from 13.7 to 15.4 and is larger than that in open sea; the ratio of Si to P is 24 and smaller than that in open sea, indicating there is different subsystem of nutrient uptake and phytoplankton production.

(3)The production at ice-edge zone has an important contribution to whole production and has effect on the whole Antarctic ecosystem.

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