DISTRIBUTION CHARACTERISTICS OF NUTRIENTS IN CHINESE BOHAI SEA

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Abstract: Nutrients are key environmental factors in marine ecosystem. They limit algal growth when at low concentrations and cause algal bloom when at high contents. They also control the growth and succession of many other biota including bacteria and zooplankton, either directly or indirectly. Nutrient contents therefore affect both the structure and functions of marine ecosystem. To study the contents and distribution of nutrients in Chinese Bohai Sea, two cruise surveys were undertaken in August 2000 (summer) and January 2001 (winter), respectively. A total of 595 water samples were collected from 91 sites. After collection the samples were transported to the laboratory and five nutrients, i.e., nitrate, nitrite, ammonia, phosphate and silicate, were analyzed. The results showed that the average concentration of total inorganic nitrogen (TIN) in Bohai Sea in winter (6.5293.717 $\mu mol \cdot l^{-1}$) was significantly higher than that in summer (3.717 $\mu mol \cdot l^{-1}$). The phosphorus concentration in winter (0.660 $\mu mol \cdot l^{-1}$) was also significantly higher than that in summer (0.329 $\mu mol \cdot l^{-1}$). Mean silicate concentration in winter (7.858 $\mu mol \cdot l^{-1}$) was not significantly different from that in summer (7.200 $\mu mol \cdot l^{-1}$). Nutrients also varied considerably among different areas within Bohai Sea. TIN concentration in Laizhou Bay (4.444 $\mu mol \cdot l^{-1}$), for example, was significantly higher than those in Bohai Bay (2.270 $\mu mol \cdot l^{-1}$) and Bohai Straight (2.431 $\mu mol \cdot l^{-1}$), which probably reflects the discharge of large amounts of nitrogen into Laizhou Bay via Yellow River. The nutrients also showed vertical distribution pattern. In summer, nutrients in bottom layer were generally higher than those in surface and medium layers. In winter, however, nutrients in different layers were not significantly different. Compared with historic data, TIN contents increased continuously since early 1980s, phosphorus and silicone contents, nevertheless, fell down to some degree. Based on atomic ratios of different nutrients, nitrogen is still the main limiting factor for algal growth in Bohai Sea.

Keywords: Bohai Sea; nitrogen ; phosphorus; silicate distribution

1. INTRODUCTION

Bohai Sea is located in northern China with a longitude of between 117°38'E and 122°31'E and a latitude of between 37°08'N and 41°02'N. The average water depth in Bohai Sea is 18m (Liu and Zhang 2000). It is the only internal sea of China. There are a number of big industrial cities around the coast of Bohai Sea, including Dalian, Tanggu, Yantai and Weihai.

Several big rivers such as Liaohe River, Haihe River and Yellow River, find their way into Bohai Sea and transport large amount of nutrients and suspended matter from the continent into the Sea (Zhang et al. 1994; Zhang 1996). During the last two decades, marine environment in Bohai Sea exhibited great changes. Fishery resources shrinked dramatically and some species disappeared. Environmental degeneration in Bohai Sea has received wide attention from both governmental and scientific communities. Several programs have, therefore, been executed to protect the marine environment in Bohai Sea, including "*Bohai Sea blue sea action plan*", "*Bohai Sea declaration*" and so on.

Because of increased discharge of nutrients into Bohai Sea from both land-based activities and marine aquculture, number of harmful algal bloom (HAB) outbreaks increased substantially. Nutrient distribution patterns may have also been altered. This study, therefore, aims to determine the levels, distribution and changes of various nutrients in Bohai Sea and to provide background information for policy-makers to control the marine environment in the sea.

2. MATERIALS AND METHODS

2.1 Sample collection

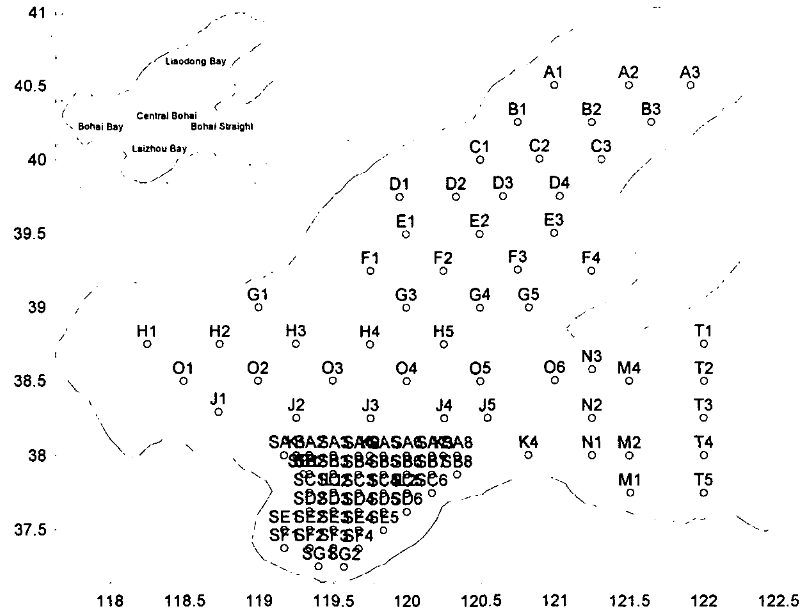

Figure 1. Geographic positions of sampling stations for nutrient analysis in five areas within Bohai Sea (The five areas are shown in the top left graph. Sampling stations for each area are as following, Liaodong Bay: A1-A3, B1-B3, C1-C3, D1-D4, E1-E3, F1-F4; Bohai Bay: G1, H1, H2, O1, O2, J1; Central Bohai: G2-G5, H3-H6, O3-O6 J2-J5; Laizhou Bay: K1-K4, L1, L2, SA1-SA8, SB1-SB8, SC1-SC6, SD1-SD6, SE1-SE5, SF1-SF4, SG1-SG2; Bohai Straight: N1-N3, M1-M3, T1-T5).

Two cruise surveys via *Dong Fang Hong* research vessel were undertaken in August 2000 (summer) and January 2001 (winter), respectively. The exact positions of sampling stations were determined by an onboard GPS system. Water temperature, salinity and depth were measured with an onboard CTD. Water samples were taken with Nelson water sampler from various depths. A total of 595 water samples were collected from 91 sites, geographic positions of which were shown in Figure 1. Based on its geographic features, Bohai Sea can be divided into five areas, Liaodong Bay, Bohai Bay, Laizhou Bay, Central Bohai and Bohai Straight (Figure 1). After collection, the water samples were filtered with 0.45μm GF-C membrane. About 200 ml of filtered seawater was transferred to polyethylene bottles with a volume capacity of ~220 ml, which was soaked with sulfuric acid and rinsed thoroughly with distilled water before use. Several drops of saturated $HgCl_2$ solution were added in the bottles to preserve the sample. The bottles were then stored in the dark and transported to the laboratory, where all samples were analyzed for nutrient contents within three months of collection.

2.2 Nutrient analysis

In the laboratory, five nutrient items, i.e., nitrate, nitrite, ammonia, phosphate and silicate, were analyzed for each water sample. Nitrites were analyzed with hydrochloric naphthalene ethyldiamine spectrophotometric method. Fifty milliliters of water sample were transferred to a capped glass tube. 1.0 ml sulfanilamide was added and the solution was mixed. After five minutes, 1.0 ml hydrochloric naphthalene ethyldiamine was added and the solution was mixed again. After 15 minutes, the solutions were analyzed in a spectrophotometer at 543nm, with distilled water as a control. The nitrite concentration was calculated according to the absorption value based on a standard curve.

Nitrates were measured with Cadmium column reduction method. Nitrates were first reduced to nitrites with a Cadmium column and total nitrites were measured with hydrochloric naphthalene ethyldiamine spectrophotometric method. Nitrates contents can be calculated as a difference between total nitrites and original nitrites.

All nutrients were analyzed by spectrophotometric method at different wavelengths based on colored compounds produced after several chemical reactions. Ammonia was measured with indigophenolic blue method. First, 35 ml of water sample was transferred to a capped glass tube. Then 1.0 ml of sodium citrate solution was added and the solutions were mixed. Following that, 1.0 ml of phenol was added and the solutions were mixed again. Then, 1.0 ml of sodium hypochlorite was added and the solutions were also mixed. After 6 hours, the solutions were analyzed by a spectrophotometer at 640nm, with distilled water as the control. The absorption values were recorded and ammonia concentration calculated according to a standard curve.

Phosphate was measured with phosphoric molybdenum blue method. Fifty milliliters of water sample were transferred to a capped glass tube. After that, 1.0ml mixed solution consisting of ammonium molybdenum, sulfuric acid and potassium antimony tartrate was added and then 1.0 ml Vitamin c solution was added. After 5 minutes, the solutions were analyzed by a spectrophotometer at 882nm, with distilled water as the control. Phosphate concentrations were calculated based on the absorption values.

Silicate concentrations were measured with silicic molybdenum blue method. Three milliliters of ammonium molybdenum was added into a capped glass tube. Twenty milliliters of water sample were then transferred to the tube and the solutions were mixed. After ten minutes, 15ml of reducing agent (mixtures of amino phenol and sodium sulfite solutions) was added. The sample solution was then diluted with distilled water until to 50ml. After 3 hours, the solutions were analyzed by a spectrophotometer at 812nm. The absorption values were recorded and silicate concentrations calculated according to a standard curve. Total inorganic nitrogen (TIN) was calculated as the sum of nitrate, nitrite and ammonia.

2.3 Statistical analysis

Bohai Sea was divided into five areas, Liaodong Bay, Bohai Bay, Laizhou Bay, Central Bohai and Bohai Strait. Three sampling depths, i.e., surface layer (0m), mid-layer (10m) and bottom layer, were selected for the following analysis. Average concentrations of nutrients were calculated as the arithmetic mean of nutrients in surface, medium and bottom layers. Average concentrations in Bohai Sea were calculated as the arithmetic mean of nutrients in five areas of Bohai Sea. Comparison was made for the difference in nutrient concentrations between summer and winter. All above analysis were done with commercial statistical software, SPSS (version 7.5).

3. RESULTS

3.1. Nutrient contents in Bohai Sea

3.1.1 Concentrations of total inorganic nitrogen (TIN) in summer

Table 1. Concentrations of nitrate, nitrite, ammonia and TIN in various areas of Bohai Sea in summer (August 2000) (see Figure 1 for geographic locations of each area; unit: μmol/l).

Nutrient	NO_3-N				NO_2-N			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	0.515	0.246	0.865	0.552	0.019	0.062	0.383	0.161
Bohai Bay	0.426	0.474	0.386	0.423	0.457	0.597	0.681	0.576
Central Bohai	0.320	0.269	0.475	0.356	0.658	0.826	1.100	0.870
Laizhou Bay	1.475	1.544	1.589	1.536	0.756	0.804	0.797	0.786
Liaodong Bay	1.453	1.261	2.138	1.630	0.877	1.085	1.295	1.086
Average	1.123	1.071	1.357	1.186	0.663	0.765	0.890	0.774
Nutrient	NH_4-N				TIN			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	1.153	1.437	2.494	1.718	1.687	1.744	3.743	2.431
Bohai Bay	1.295	1.193	1.299	1.271	2.178	2.264	2.366	2.270
Central Bohai	1.255	1.193	1.195	1.212	2.233	2.288	2.770	2.439
Laizhou Bay	2.141	2.091	2.136	2.122	4.372	4.439	4.522	4.444
Liaodong Bay	1.641	1.414	1.476	1.514	3.971	3.760	4.908	4.229
Average	1.737	1.689	1.840	1.757	3.523	3.525	4.087	3.717

Total inorganic nitrogen (TIN) contents in various sea areas were listed in Table 1 and exhibited in Figure 2. The highest TIN contents in Bohai Sea were recorded in Laizhou Bay. The average concentration in the whole water column was 4.444 μmol/l. The lowest TIN content was recorded in Bohai Bay, which was 2.270 μmol/l. The TIN content in Laizhou Bay was, therefore, about twice as much as that in Bohai Bay. The TIN contents in different areas were in a decreasing order of Laizhou Bay, Liaodong Bay, Central Bohai, Bohai Straight and Bohai Bay (Figure 2). The average TIN concentration in the whole Bohai Sea was recorded as 3.717 μmol/l. The average concentrations of NO_3-N, NO_2-N and NH_4-N in Bohai Sea in summer were 1.186, 0.774 and 1.757 μmol/l, representing 31.9%, 20.8% and 47.3%, respectively, of TIN.

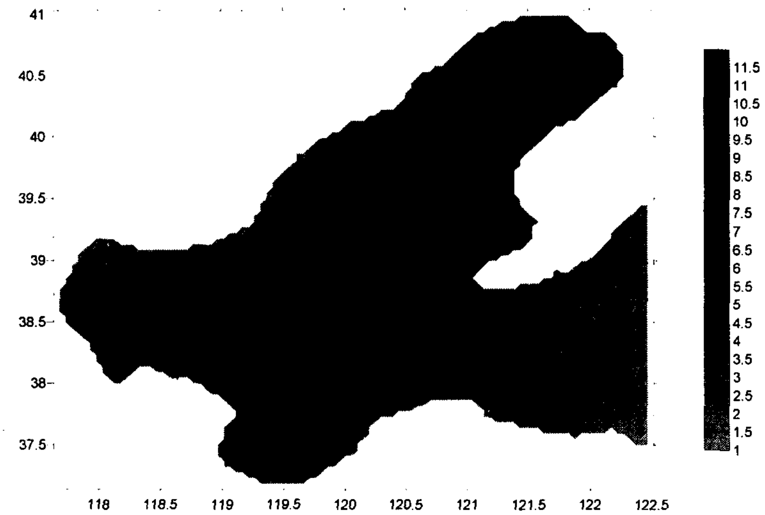

Figure 2. A map of Bohai Sea showing the distribution of total inorganic nitrogen (TIN) in the surface layer (0m) in summer (August 2000). (Unit: μmol/l)

3.1.2 Concentrations of total inorganic nitrogen in winter

TIN contents in winter in various sea areas were shown in Table 2. The highest TIN concentration in Bohai Sea was recorded in Bohai Bay. The average concentration in the whole water column was 9.663 μmol/l. The lowest TIN content was recorded in Bohai Straight, which was 4.691 μmol/l. The TIN contents in different areas were in a decreasing order of Bohai Bay, Laizhou Bay, Liaodong Bay, Central Bohai, Bohai Straight.

The average TIN concentration in the whole Bohai Sea in winter was recorded as 6.529 μmol/l. The average concentrations of NO_3-N, NO_2-N and NH_4-N in Bohai Sea in winter were 4.194, 0.282 and 2.052 μmol/l, representing 64.2%, 4.3% and 31.4%, respectively, of TIN.

It's also shown that TIN contents in winter were much higher than those in summer. At Liaodong Bay, for example, TIN contents in summer and winter were 4.229 and 7.391 μmol/l, respectively. The average TIN contents in the whole Bohai Sea in summer and winter were 3.717 and 6.529 μmol/l, respectively. The latter was, therefore, 76% higher than the former.

Percentage of nitrate among TIN in winter (64.2%) was also higher than that in summer, while percentage of nitrite and ammonia in winter were lower. This also reflects the reduction of biological production and nutrient uptake in winter. At Bohai Bay, TIN content in summer was the lowest (2.27 μmol/l) within Bohai Sea, but the content in winter was the highest (9.663μmol/l). The biological and hydrodynamic system in Bohai Bay should, therefore, be quite different from those in other areas and this warrants further study.

Table 2. Concentrations of nitrate, nitrite, ammonia and TIN in various areas of Bohai Sea in winter (January 2001) (see Figure 1 for geographic locations of each area; unit: μmol/l).

Nutrient	NO_3-N				NO_2-N			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	2.471	2.640	2.437	2.513	0.125	0.136	0.154	0.139
Bohai Bay	6.743	5.722	6.512	6.425	0.359	0.553	0.294	0.373
Central Bohai	3.343	3.275	3.229	3.283	0.566	0.502	0.577	0.550
Laizhou Bay	5.796	4.526	5.383	5.421	0.202	0.104	0.203	0.187
Liaodong Bay	5.180	5.172	5.566	5.294	0.106	0.106	0.098	0.104
Average	4.318	3.968	4.261	4.194	0.286	0.268	0.291	0.282
Nutrient	NH_4-N				TIN			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	1.861	2.062	2.181	2.039	4.457	4.838	4.772	4.691
Bohai Bay	3.336	1.978	2.917	2.865	10.437	8.253	9.723	9.663
Central Bohai	1.908	1.917	1.886	1.903	5.817	5.694	5.693	5.736
Laizhou Bay	2.047	1.736	2.035	1.993	8.045	6.365	7.620	7.601
Liaodong Bay	2.073	1.953	1.949	1.994	7.359	7.232	7.612	7.391
Average	2.090	1.955	2.096	2.052	6.693	6.191	6.648	6.529

3.1.3. Phosphorus contents in summer and winter

Phosphorous contents in summer in various sea areas were presented in Table 3. The distribution patterns of phosphorus in different areas of Bohai Sea were shown in Figure 3. The highest phosphorous content within Bohai Sea was recorded in Liaodong Bay (0.416 μmol/l). The lowest phosphorous content was recorded in Bohai Bay, which was 0.261 μmol/l. The phosphorous content in Liaodong Bay was ~60% higher than that in Bohai Bay. The phosphorous contents in different areas were in a decreasing order of Liaodong Bay, Central Bohai, Bohai Straight, Laizhou Bay, and Bohai Bay (Figure 3). The average phosphorous concentration in the whole Bohai Sea was recorded as 0.329 μmol/l. Phosphorous contents in winter in various sea areas were also shown in Table 3. The highest phosphorous content within Bohai Sea (0.814 μmol/l) was again recorded in Liaodong Bay. The lowest phosphorous content was recorded in Laizhou Bay, which was 0.463 μmol/l. The phosphorous contents in different areas were in a decreasing order of Liaodong Bay, Bohai Bay, Central Bohai, Bohai Straight, Laizhou Bay. The average phosphorous concentration in the whole Bohai Sea in winter was recorded as 0.660 μmol/l.

Table 3. Phosphorus concentrations in various areas of Bohai Sea in summer (August 2000) and winter (January 2001) (see Figure 1 for geographic locations of each area; unit: μmol/l).

Nutrient	PO_4-P in summer				PO_4-P in winter			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	0.154	0.216	0.541	0.311	0.522	0.549	0.541	0.537
Bohai Bay	0.185	0.286	0.321	0.261	0.653	0.872	0.669	0.707
Central Bohai	0.404	0.282	0.318	0.332	0.680	0.648	0.686	0.672
Laizhou Bay	0.286	0.301	0.324	0.304	0.447	0.611	0.423	0.463
Liaodong Bay	0.320	0.400	0.525	0.416	0.816	0.797	0.832	0.814
Average	0.289	0.306	0.391	0.329	0.649	0.684	0.649	0.660

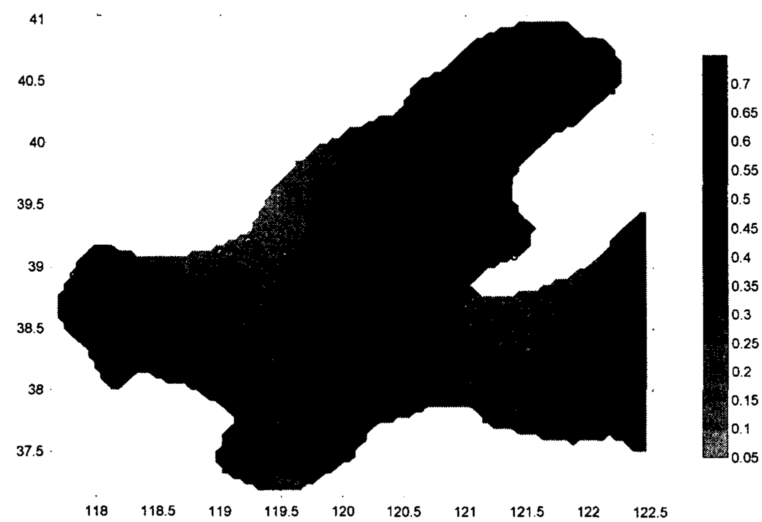

Figure 3. A map of Bohai Sea showing the distribution of PO_4-P in the medium layer (10m) in summer (August 2000). (Unit: μmol/l)

It's also shown that phosphorous content in winter was much higher than that in summer. The average phosphorous contents in the whole Bohai Sea in summer and winter were 0.329 and 0.660 μmol/l, respectively. The latter was, therefore, about twice as much as the former. The seasonal difference in phosphorous content in Bohai Bay was also the highest, with the winter concentration being 2.7 times as much as the summer value.

3.1.4. Silicate contents in summer and winter

Silicate contents in summer in various sea areas were shown in Table 4. The distribution patterns of silicate in different areas of Bohai Sea were demonstrated in Figure 4. The highest silicate content within Bohai Sea was recorded in Liaodong Bay (8.934 μmol/l). The lowest content was recorded in Bohai Bay, which was 4.961 μmol/l. The silicate content in Liaodong Bay was ~80% higher than that in Bohai Bay. The silicate contents in different areas were in a decreasing order of Liaodong Bay, Central Bohai, Bohai Straight, Laizhou Bay, and Bohai Bay (Figure 4). The average silicate concentration in the whole Bohai Sea was recorded as 7.200 μmol/l.

Table 4. Silicate concentrations in various areas of Bohai Sea in summer (August 2000) and winter (January 2001) (see Figure 1 for geographic locations of each area; unit: μmol/l).

Nutrient	SiO_4-Si in summer				SiO_4-Si in winter			
	Surface layer	Medium layer	Bottom layer	Whole column	Surface layer	Medium layer	Bottom layer	Whole column
Bohai Straight	7.198	6.677	9.240	7.750	4.337	4.291	4.347	4.326
Bohai Bay	4.315	4.674	5.799	4.961	9.639	8.530	9.356	9.280
Central Bohai	7.065	8.241	8.995	8.145	8.126	7.214	8.834	8.093
Laizhou Bay	5.984	6.769	5.960	6.238	6.330	9.141	7.140	7.115
Liaodong Bay	6.662	9.607	10.602	8.934	10.082	10.707	9.904	10.246
Average	6.321	7.471	7.795	7.200	7.784	7.852	7.935	7.857

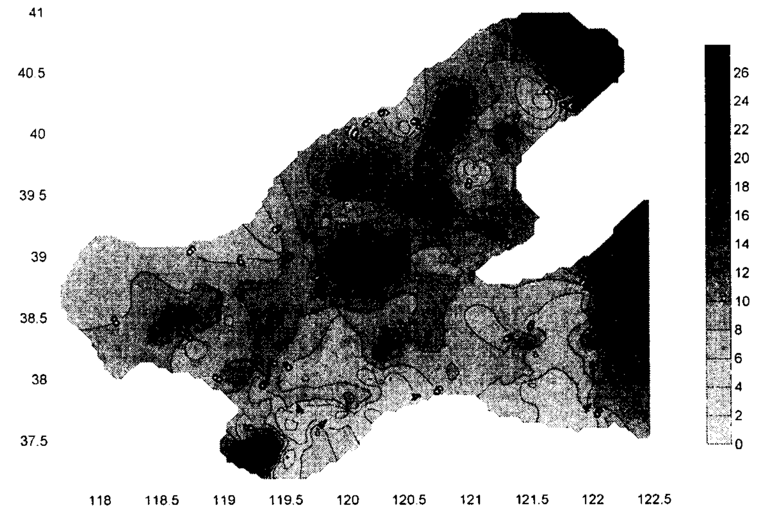

Figure 4. A map of Bohai Sea showing the distribution of SiO_4-Si in the bottom layer in summer (August 2000). (Unit: μmol/l)

Silicate contents in winter in various sea areas were also shown in Table 4. The highest silicate content within Bohai Sea (10.246 μmol/l) was again recorded in Liaodong Bay. The lowest silicate content was recorded in Bohai Straight, which was 4.326 μmol/l. The silicate contents in different areas were in a decreasing order of Liaodong Bay, Bohai Bay, Central Bohai, Laizhou Bay, Bohai Straight. The average silicate concentration in the whole Bohai Sea in winter was recorded as 7.857 μmol/l. It's also shown that silicate content in winter was higher than that in summer. The average silicate contents in the whole Bohai Sea in summer and winter were 7.200 and 10.246 μmol/l, respectively. The latter was, therefore, about 42% higher than the former.

3.2. Vertical distribution of nutrients in Bohai Sea

3.2.1 Vertical distribution of TIN

Vertical distribution of TIN in summer in Bohai Sea was presented in Figure 5. TIN concentration in bottom layer was higher than those in surface and medium layers. In Bohai Straight, for example, TIN contents in three layers were 1.687, 1.744 and 3.743 μmol/l, respectively. TIN in bottom layer was, therefore, about twice of that in surface and medium layers. The vertical difference in TIN contents in other areas was relatively small. The average TIN in the whole Bohai Sea in three layers were 3.523, 3.525, 4.087 μmol/l, respectively. The average TIN content in bottom layer was, therefore, only 16% higher than those in surface and medium layers. Vertical distribution of TIN in Bohai Sea in winter was not, however, significant. The average TIN concentration in the whole Bohai Sea in three layers were 7.784, 7.852 and 7.935 μmol/l, respectively.

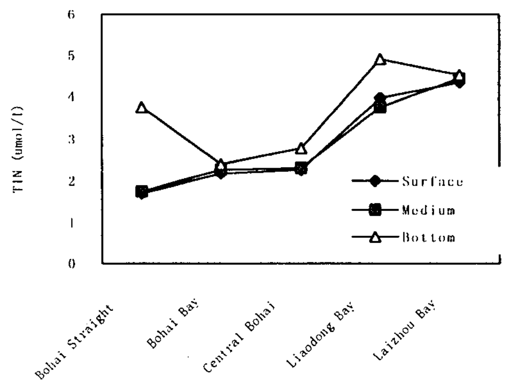

Figure 5. The concentrations of total inorganic nitrogen (TIN) in various areas of Bohai Sea in different sampling depths showing its vertical distribution in summer (August 2000).

3.2.2 Vertical distribution of phosphorus contents

Vertical distribution of phosphorus contents in summer in Bohai Sea was presented in Figure 6. Phosphorus in bottom layer was higher than those in surface and medium layers, except in Central Bohai. In Liaodong Bay, for example, phosphorus contents in surface, medium and bottom layers were 0.320, 0.400 and 0.525 μmol/l, respectively. Phosphorus in bottom layer was, therefore, 1.6 and 1.3 times of those in surface and medium layers. The average phosphorus concentrations in the whole Bohai Sea in three layers were 0.289, 0.306 and 0.391 μmol/l, respectively. The average phosphorus content in bottom layer was, therefore, 1.4 and 1.3 times of those in surface and medium layers (Figure 6). The vertical distribution of phosphorus contents in winter was, however, not significant.

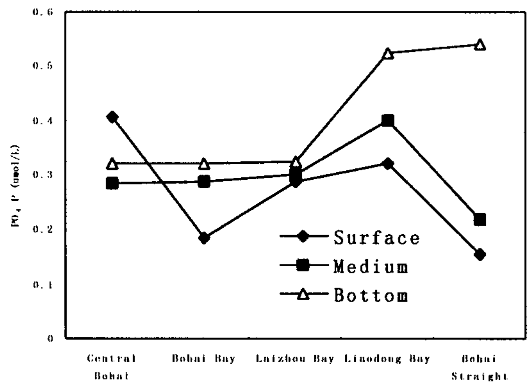

Figure 6. The concentrations of PO_4-P in various areas of Bohai Sea in different sampling depths showing its vertical distribution in summer (August 2000).

3.2.3 Vertical distribution of silicate contents

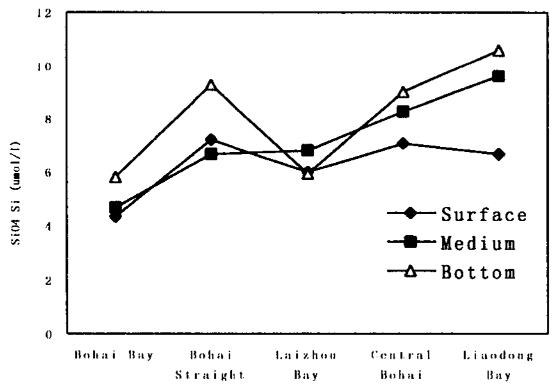

Figure 7. The concentrations of SiO_4-Si in various areas of Bohai Sea in different sampling depths showing its vertical distribution in summer (August 2000).

Vertical distribution of silicate contents in summer in Bohai Sea was presented in Figure 7. Silicate in bottom layer was higher than those in surface and medium layers, except in Laizhou Bay. In Bohai Bay, for example, silicate contents in surface, medium and bottom layers were 4.315, 4.674 and 5.799 μmol/l, respectively. Silicate in bottom layer was, therefore, 34% and 24% higher than those in surface and medium layers.

The average silicate in the whole Bohai Sea in three layers were 6.321, 7.471 and 7.795 μmol/l, respectively. The average silicate content in bottom layer was, therefore, 23% higher than that in surface layers, but similar as that in medium layer (Figure 7). The vertical distribution of silicate contents in winter was, however, not significant.

3.3. Ratios of nitrogen, phosphorus and silicone in Bohai Sea

Table 5. Ratios of TIN/P, Si/TIN and Si/P in different areas of Bohai Sea in summer (August 2000) and winter (January 2001).

	TIN/P ratios in summer				TIN/P ratios in winter			
Area	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**
Bohai Straight	10.94	8.07	6.92	7.82	8.55	8.82	8.82	8.73
Bohai Bay	11.80	7.91	7.37	8.69	15.97	9.46	14.54	13.67
Central Bohai	5.53	8.10	8.70	7.35	8.56	8.78	8.30	8.53
Laizhou Bay	15.30	14.74	13.94	14.63	18.01	10.41	18.03	16.43
Liaodong Bay	12.41	9.41	9.34	10.18	9.02	9.07	9.15	9.08
Average	12.20	11.51	10.46	11.28	10.31	9.05	10.24	9.90
	Si/TIN ratios in summer				**Si/TIN ratios in winter**			
Area	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**
Bohai Straight	4.27	3.83	2.47	3.19	0.97	0.89	0.91	0.92
Bohai Bay	1.98	2.06	2.45	2.19	0.92	1.03	0.96	0.96
Central Bohai	3.16	3.60	3.25	3.34	1.40	1.27	1.55	1.41
Laizhou Bay	1.37	1.52	1.32	1.40	0.79	1.44	0.94	0.94
Liaodong Bay	1.68	2.55	2.16	2.11	1.37	1.48	1.30	1.39
Average	1.79	2.12	1.91	1.94	1.16	1.27	1.19	1.20
	Si/P ratios in summer				**Si/P ratios in winter**			
Area	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**	**Surface layer**	**Medium layer**	**Bottom layer**	**Whole column**
Bohai Straight	46.68	30.91	17.07	24.94	8.32	7.82	8.03	8.05
Bohai Bay	23.39	16.33	18.08	19.00	14.75	9.78	13.99	13.13
Central Bohai	17.48	29.19	28.26	24.54	11.95	11.13	12.89	12.04
Laizhou Bay	20.94	22.47	18.37	20.53	14.17	14.95	16.89	15.38
Liaodong Bay	20.82	24.03	20.18	21.50	12.36	13.43	11.91	12.59
Average	21.89	24.39	19.95	21.86	11.99	11.47	12.22	11.91

Ratios of TIN, P and Si in summer in Bohai Sea were listed in Table 5. The average value of TIN:P ratios in the water column ranges between 7.35 and 14.63 in summer, with the lowest value recorded in Central Bohai and the highest at Laizhou Bay. The average value within Bohai Sea was 11.28 (Table 5). The average value of Si:TIN ratios in the water column lies between 1.40 and 3.34 in summer, with the lowest value recorded in Laizhou Bay and the highest at Central Bohai. The average value within Bohai Sea was 1.94 (Table 5). The average value of Si:P ratios in the water column varies from 19.00 to 24.94 in summer, with the lowest value recorded in Bohai Straight and the highest at Bohai Straight. The average value within Bohai Sea was 21.86 (Table 5). Ratios of TIN, P and Si in winter in Bohai Sea were listed in Table 5. The average value of TIN:P in the water column in winter lies between 8.53 and 16.43, with the lowest value recorded in Central Bohai and the highest at Laizhou Bay. The average value within Bohai Sea was 9.90 (Table 5). The average value of Si:TIN in the water column in summer varies between 0.92 and 1.41, with the lowest value recorded in Baihai Straight Bay and the highest at Central Bohai. The average value within Bohai Sea was 1.20 (Table 5). The average value of Si:P ratios in the water column in summer ranges between 8.05 and 15.38, with the lowest value recorded in Bohai Straight and the highest at Laizhou Bay. The average value within Bohai Sea was 11.91 (Table 5).

4. DISCUSSION

4.1 Changes in nutrient status in Bohai Sea.

During the previous two decades, there have been several detailed surveys for nutrient distribution in Bohai Sea. For meaningful comparison, the results of two surveys were selected (Table 6). The data in Table 6 were annual mean values for various nutrients in Central Bohai (Tang and Meng 1997).

Table 6. Average concentrations of nutrients in Central Bohai during the last two decades (μmol/l).

Nutrient item	1982-1983	1992-1993	2000-2001
TIN	1.75	1.72	4.088
NO_3-N	1.10	1.32	1.819
NO_2-N	0.08	0.16	0.710
NH_4-N	0.57	0.24	1.558
PO_4-P	1.06	0.33	0.502
SiO_4-Si	23.00	6.70	8.119

The data shows that TIN concentrations increased substantially since early 1980s. The present TIN concentration was 2.336 times of that in 1982. This is mainly caused by common use of agricultural fertilizers in rural areas around Bohai Sea. The data also showed that phosphorous contents decreased in some degree. Average phosphorus content was 1.06 μmol/l in 1982-1983. It fell down to 0.33 μmol/l in 1992-1993. The present concentration was 0.502 μmol/l. Present phosphorus content was, therefore, half of that in early 1980s, although it slightly increased compared with the value in early 1990s. Silicate concentration also showed substantial decrease. The present silicate concentration (8.119 μmol/l) was only 35% of that in early 1980s. This is probably caused by the diminishing of Yellow River discharge. According to statistics, drying up days of Yellow River at Lijin hydrologic station was 119 days in 1995, compared to 10 days in 1982 (Yu et al. 2000). This demonstrates that Yellow River plays an important role in nutrient status of Bohai Sea (Cui et al. 1992).

4.2. Nutrient limitation in Bohai Sea

It was proposed that phosphorus is a limiting factor when Si:P>22 and TIN:P>22. TIN is a limiting factor if TIN:P<10 and Si:TIN>1. Silicone is a limiting factor if Si:P<10 and Si:TIN<1 (Dortch & Whitledge 1992; Justic et al. 1995). Based on this principal, scattering graphs were made for atomic ratios of TIN, P and Si for Bohai Sea (Figure 8). Figure 8 shows that 44% of the points meet the principal of TIN:P<10 and Si:TIN>1. The occurrence rate of nitrogen limitation in Bohai Sea in summer was, therefore, 44%. Similarly, the occurrence rate of phosphorus and silicate limitation in Bohai Sea in summer was 19% and 20%, respectively. Nitrogen is, therefore, the main factor limiting the growth of phytoplankton in Bohai Sea in summer.

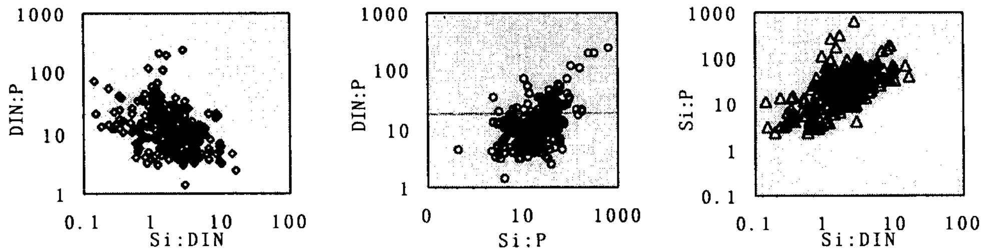

Figure 8. Scattering graphs for atomic ratios of TIN, P and Si in water columns of Bohai Sea in summer (August 2000).

Similar graphs can be made for atomic ratios in Bohai Sea in winter (the graphs are omitted here). The occurrence rates of nitrogen, phosphorus and silicate limitation in winter were 65%, 8% and 34%, respectively. Nitrogen is, again, the main factor limiting the growth of phytoplankton in Bohai Sea in winter.

Phosphorus mainly comes from mariculture and detergents. It is not surprising that phosphorus was not the main limiting factor since there is many aquacultural sites in coastal areas of Bohai Sea. A great amount of phosphorus is discharged into Bohai Sea via surplus feed. Most commercial detergents also contain phosphorus. Chinese governments recently inhibited the sale of phosphorus containing detergents. Further surveys are, therefore, needed to determine if phosphorus contents will decrease in Bohai Sea in the near future.

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