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Article

Phytoplankton of the Coastal Waters off Vladivostok (the North-western Part of the East Sea) under Eutrophic Conditions

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Abstract : The qualitative and quantitative composition of the phytoplankton of the coastal waters off Vladivostok during the period 1991-1994 was studied. The following trends in the phytoplankton composition with decreasing distance from the source of eutrophication were revealed: 1) total density and biomass increased; 2) the density of the diatom *Skeletonema costatum*, which reflects a decrease in the Shannon-Weaver species diversity index during the summer microalgal bloom, increased significantly; and 3) the density of the non-diatom component of the phytoplankton increased.

Key words : Phytoplankton, the Northwestern Part of the East Sea, eutrophication, sewage, *Skeletonema costatum* (Grev.) Cl.

1. Introduction

Amurskii and Golden Horn Bays, the coastal waters off Vladivostok, are the most eutrophic waters in the northwestern part of the Sea of Japan. Industrial waste products and municipal sewage from Vladivostok, together with agricultural and municipal sewage from Ussuriysk, are transported to the sea by terrigenous runoff and the Razdolnaya River.

The first data on the phytoplankton of the study area and adjacent waters were reported in the 1920s-1930s (Skvortzow 1931; Kisselew 1934, 1935). Konovalova (1972) was the first researcher to carry out a detailed year-round study of the species composition and dynamics of the phytoplankton.

High concentrations of nitrates and nitrites, as well as an increase in primary production (Tkalin *et al.* 1993), suggest that the eutrophication of the coastal waters off Vladivostok increased during the 1980s and 1990s. In spite of this increase, eutrophication-related changes in the phytoplankton composition have not yet been studied.

This study examined the composition and distribution of phytoplankton in the eutrophic coastal waters off Vladivostok.

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2. Materials and methods

Sampling sites were chosen to study the effects of two sources of eutrophication: the waters of the Razdolnaya River and the sewage effluent from the city of Vladivostok. To study the effect of the river, a survey was carried out in Amurskii Bay at Stations 1 through 5 from June to October 1991. To study the effect of the sewage effluent on phytoplankton, year-round sampling was performed at Station 6 in Golden Horn Bay and at Stations 7 and 9 in Amurskii Bay from January 1993 to January 1994 (Fig. 1).

Samples were taken from the surface waters once or twice per month using a 4-liter Molchanov bathometer. Material was concentrated using a routine sedimentation method or reverse filtration. The samples were fixed with Lugol's iodine solution and then postfixed in 4% formaldehyde. Phytoplankton density was counted in a 0.05 m*l* Nojott chamber. Species diversity was estimated using the Shannon-Weaver index (Shannon and Weaver 1963).

Three water masses could be distinguished in the study area, according to their distance from the major sources of eutrophication: hypereutrophic, eutrophic, and mesotrophic areas.

The hypereutrophic area covered the innermost and north-eastern parts of Amurskii Bay (stations 1, 2, and 7),

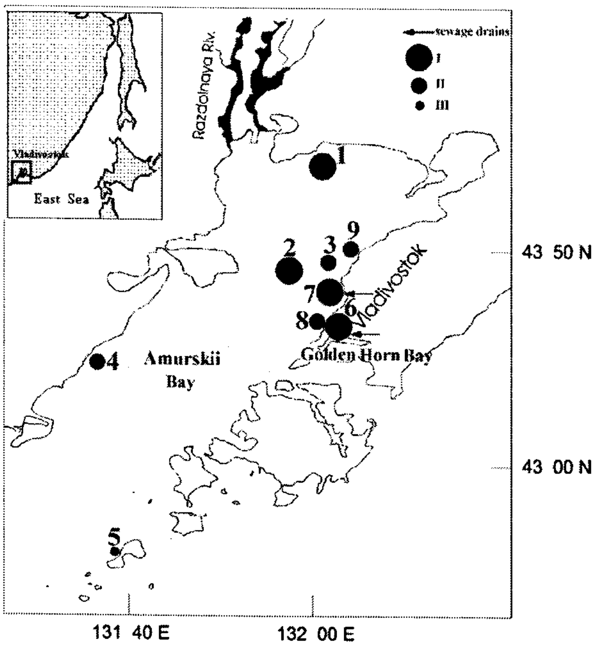

Fig. 1. Location of sampling stations (1-9) around Vladivostok. I-hypereutrophic waters; II-eutrophic waters; III-mesotrophic waters.

as well as Golden Horn Bay (station 6). Stations 1 and 2 were directly exposed to the effects of the river runoff, whereas Stations 6 and 7 were located close to the industrial and domestic sewage outfalls, which discharged 6,000 and 50,000 m^3 of contaminated water per day to the sea, respectively (Shapovalov 1994). Hydrochemical studies also suggest that this area is more eutrophic than other parts of Amurskii Bay. For instance, the silicon and organic and inorganic phosphorus content of the waters of the northern part of the bay were reported to exceed those in the open southern part by a factor of 1.2-15 (Podorvanova *et al.* 1989). High concentrations of nitrogen-containing and soluble organic compounds were recorded in the south-eastern part of the bay, near the sewage outfalls (Tkalin *et al.* 1993). Golden Horn Bay is becoming increasingly eutrophic, and high concentrations of toxic substances (petroleum hydrocarbons, chlorinated pesticides, and detergents) have been recorded, in both the water column and bottom sediments, as well as thermal pollution (Tkalin 1991; Tkalin *et al.* 1993).

The eutrophic area included Stations 3, 8, and 9 in the north-eastern part of Amurskii Bay, and Station 4 in the south-western part of the bay. Compared to the hyper-eutrophic waters, this intermediate area was less severely affected by eutrophication.

The mesotrophic area was farthest from the sources of

Table 1. Classification of eutrophic levels according to nutrient conditions in the water column in Amurskii Bay and Golden Horn Bay (from Tkalin *et al.* 1993).

Characteristics	Hypereutrophic area	Eutrophic area	Mesotrophic area
	Amurskii Bay		
Phosphate (μg/*l*)			
Nitrate (μg/*l*)	8-11	5-7	4>
	Golden Horn Bay		
Phosphate (μg/*l*)	100	-	-
Nitrate (μg/*l*)	230	-	-

eutrophication; it included Station 5 in the southern part of Amurskii Bay. The nutrient concentrations in the hyper-eutrophic, eutrophic, and mesotrophic areas are given in Table 1.

A comparative study of the phytoplankton in the three areas not only reveals differences between them, but also makes it possible to attempt to determine the seasonal trends of changes in the microalgal communities with increasing eutrophication.

3. Results

At stations 1-5 in Amurskii Bay, the density and biomass of phytoplankton ranged from 0.1 to 31.1 million cells/l and from 0.3 to 29 g/m^3, respectively, during the observation period in 1991. The maximum phytoplankton density was recorded between late July and the middle of August (Table 2). A biomass peak in June was caused by the diatom *Rhizosolenia setigera*, while the greatest summer phytoplankton bloom was caused by the diatom *Skeletonema costatum* in late July. An intensive bloom of the dinoflagellate *Prorocentrum minimum* (about 8 million cells/l) was recorded in August. The density and biomass of phytoplankton decreased in the autumn.

At stations 7-9 in Amurskii Bay, the phytoplankton density varied from 0.1 to 17.9 million cells/l and biomass varied from 0.08 to 11.4 g/m^3 during the investigation in 1993-1994. The greatest phytoplankton density and biomass were recorded in late July to early August (Fig. 2). The summer phytoplankton bloom was determined by the development of the diatom *S. costatum*. The smallest biomass values were observed in autumn.

In Golden Horn Bay, phytoplankton density and biomass ranged from 0.1 to 8 million cells/l and from 0.03 to 8.2 g/m^3, respectively, during the observation period from 1993

Table 2. Density (N, million cells/l) and biomass (B, g/m^3) of phytoplankton and relations between the densities (% of the total phytoplankton density) of diatoms (D) and dinoflagellates (DIN) at stations 1-5 from June to October 1991.

Date	St.1			St.2			St.3			St.4			St.5		
	N/B	D	DIN	N/B	D	DIN	N/B	D	DIN	N/B	D	DIN	N/B	D	DIN
11.06.	0.58 27	81.91	8.42	0.39 8.14	78.61	1	0.36 14.17	74.33	7.49	0.15 4.71	67.54	14.18	0.16 1.44	28.83	30.71
26.06.	8.52 29.31	95.81	1.55	1.15 1.39	71.26	7.22	3.67 24.6	91.3	4.33	0.39 6.12	64.23	22.81	-	-	-
4.07.	4.1 3.39	91.24	7.67	0.23 1.85	30.11	34.05	1.49 2.27	85.81	12.11	2.75 4.33	94.22	2.81	0.18 1.31	57.81	14.91
31.07.	31.06 26.23	79.72	1.23	-	-	-	14.65 12.08	82.61	15.93	13.28 15.05	65.3	20.51	1.94 2.03	91.4	4.33
12.08.	12.20 15.14	53.33	26.82	12.41 13.23	37.14	61.95	9.46 14	53.31	30.82	0.48 1.63	2.11	52.57	0.30 0.67	6.28	69.22
4.09.	2.78 7.22	78.14	10.71	-	-	-	4.06 4.71	90.32	4.39	-	-	-	1.51 3.38	85.33	1.14
17.09.	1.49 12.43	73.26	10.41	-	-	-	1.02 4.72	56.43	13.76	1.35 9.77	81.14	8.17	0.65 2.66	69.32	8.36
2.10.	0.65 2.95	4	82.43	0.46 1.24	6.2	47.1	0.89 2.79	19.21	58.32	0.67 2.81	18.83	53.36	0.39 1.22	36.34	9.67
29.10.	0.73 6.31	56.78	5.07	0.16 0.30	38.41	4.38	0.47 3.12	67.55	12.74	0.91 5.63	73.71	4.23	0.69 4.18	81.82	2.24

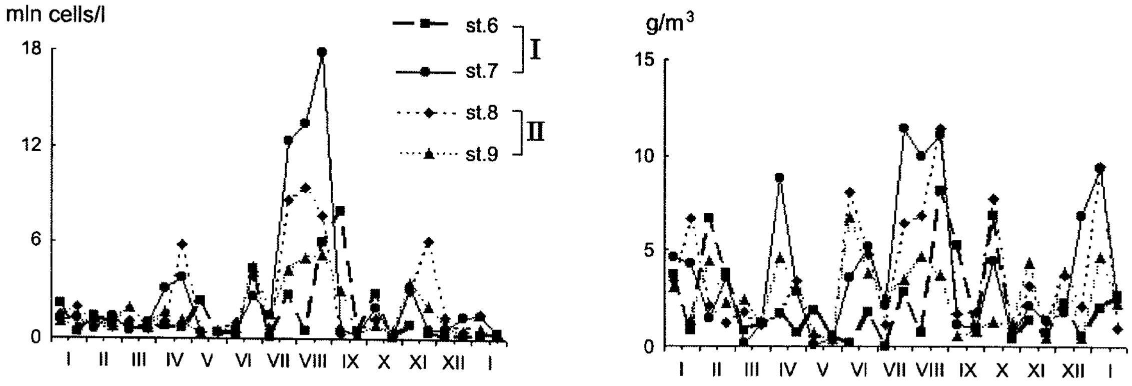

Fig. 2. Seasonal changes in density and biomass of phytoplankton at stations 7-9 from January, 1993 to January, 1994. On abscissa - station number; on ordinate - density, mln cells/l and biomass, g/m^3. I-II-See Fig. 1 for explanation.

to 1994. The maximum density and biomass occurred in late August to early September. This phytoplankton bloom was due to the dominance of the diatoms *Leptocylindrus minimus*, *Thalassiosira* sp. and *S. costatum*. The smallest biomass values were observed in July.

With decreasing distance from the main sources of eutrophication (the mouth of Razdolnaya River and sewage outfalls), the following peculiarities of the phytoplankton distribution became more pronounced:

The total density and biomass of microalgae increased

A comparative analysis of the peaks of density and biomass of summer phytoplankton from the areas with different levels of eutrophication showed that both density and biomass were greater in the hypereutrophic waters than in other areas. For instance, the greatest microalgal densities (17.9-31.1 million cells/l) were recorded in the hypereutrophic area (stations 1 and 7); intermediate values (5.3-9.4 million cells/l) were recorded in the intermediate

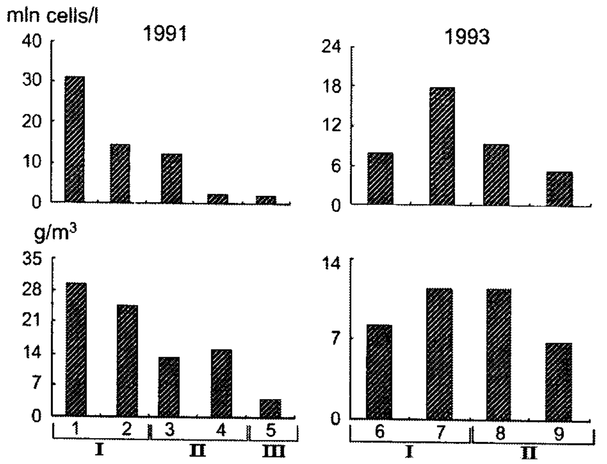

Fig. 3. The greatest values of phytoplankton density and biomass at stations 1-9 during summer in 1991 and in 1993. On abscissa - station number; on ordinate - density, mln cells/l (up) and biomass, g/m³ (down). I-III-See Fig. 1 for explanation.

eutrophic area (stations 8 and 9); and the lowest value (1.9 million cells/l) was in the mesotrophic area (station 5) (Fig. 3). We found different patterns for the distribution of phytoplankton biomass. The microalgal biomass was significantly greater (11.4-29.3 g/m³) in the hypereutrophic waters (stations 1 and 7) than in other areas, with the exception of Station 8 in the eutrophic area, where the maximum biomass recorded equaled that in the hypereutrophic area (Fig. 3). In the hypereutrophic area, the biomass peak was caused by massive occurrences of the diatom *S. costatum*, whereas the considerable increase in biomass in the eutrophic waters was due to occurrences of the large dinoflagellates *Diplopsalis lenticula* and *Polykrikos schwartzii*.

The density of *S. costatum* increased, leading to a decrease in phytoplankton species diversity

During the summer phytoplankton bloom, the microalgal community of Amurskii Bay was dominated by one species, *S. costatum*, which accounted for about 90% of the total density of phytoplankton. Analysis of the samples collected in the summer of 1993 showed that the density of this species (17.4 million cells/l; 96% of the total density of phytoplankton) was greater near the sewage outfall (station 7) in the hypereutrophic waters of Amurskii Bay than in other areas. In the eutrophic area and in Golden Horn Bay, the maximum density of this species was 2-4 times smaller (4.7-8.8 million cells/l, 88-92%) and an order of magnitude smaller (1.7 million cells/l, 29%), respectively, than in the hypereutrophic waters of Amurskii Bay (Fig.

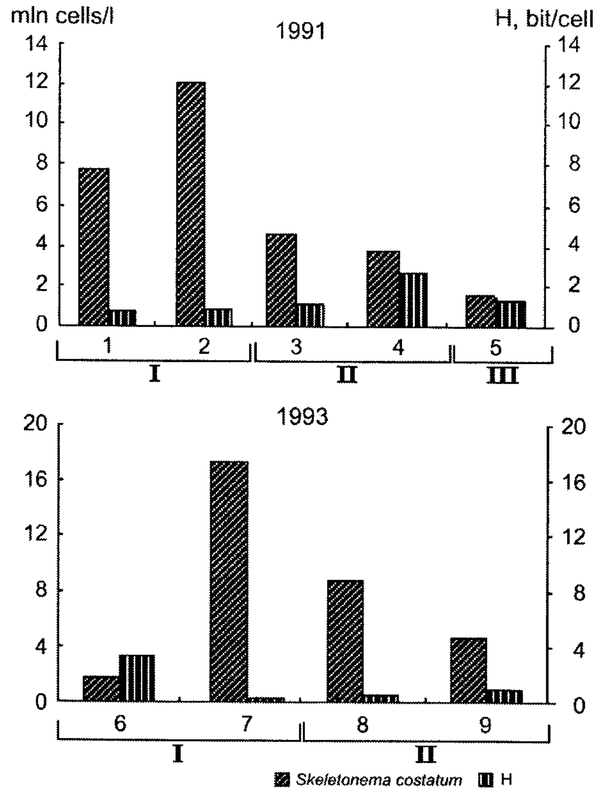

Fig. 4. The greatest density values of diatom *Skeletonema costatum* and species diversity of phytoplankton during the summer phytoplankton blooms in 1991 and in 1993 at stations 1-9. On abscissa - station number; on ordinate - right: Shannon-Weaver diversity index, bit/cell, left: cell density, mln cells/ l. I-III- See Fig. 1 for explanation.

4). These differences were responsible for the smaller species diversity index (0.3 bit/cell) in the hypereutrophic waters (station 7) in comparison with the eutrophic waters (0.5-0.9 bit/cell). Along with S. *costatum*, the diatoms *L. minimus* and *Thalassiosira* sp. also increased in numbers during the summer bloom in the hypereutrophic waters of Golden Horn Bay (station 6), where the species diversity index for the microalgal community was relatively high (3.3 bit/cell). A seasonal analysis of the phytoplankton showed that in the summer of 1991 the density of *S. costatum* increased with decreasing distance from the source of eutrophication (the mouth of Razdolnaya River). The greatest density of *Skeletonema* (7.7 and 12.1 million cells/l) was observed in the hypereutrophic area area (station 1 and 2, respectively), whereas the lowest (1.6 million cells/l) was recorded in the mesotrophic area (station 5). The smallest (0.7 bit/cell) and greatest (2.7 bit/ cell) species diversity indexes were recorded in the

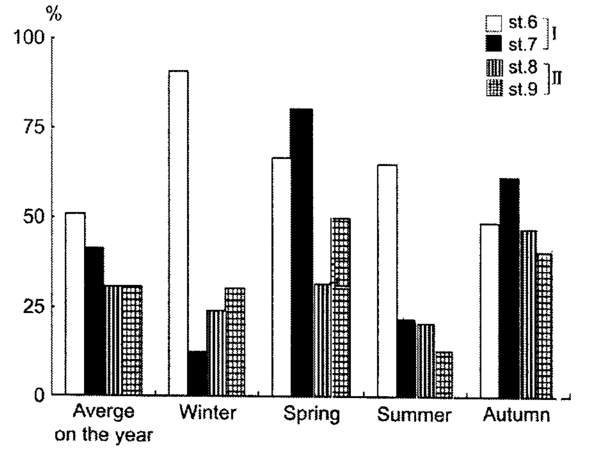

Fig. 5. Percentage of non diatom phytoplankton density (total density of dinoflagellates, chrysophytes, cryptophytes, chlorophytes, cyanophytes, euglenophytes, and raphidophytes) at stations 6-9 in 1993. On abscissa - average values during the year (from January to December), average values during the winter (from January to February), average values during the spring (from March to May), average values during the summer (from June to August), average values during the autumn (from September to November); on ordinate - density, % of total phytoplankton density. I-II-See Fig. 1 for explanation.

hypereutrophic (station 1) and eutrophic (station 4) areas, respectively.

There was a significant increase in the density of the non-diatom component of phytoplankton near the sewage outfalls in the hypereutrophic parts of Golden Horn and Amurskii Bays (stations 6 and 7)

In the spring and autumn of 1993, the relative densities of flagellates and blue-green algae at stations 6 and 7, located near the sewage outfalls, were significantly greater than at other stations (Fig. 5, 6). In the summer of 1993, high densities of non-diatom microalgae were observed only in the hypereutrophic waters of Golden Horn Bay. This was due to the massive development of euglenophytes and chlorophytes belonging to the genus *Pyramimonas*. The proportion of non-diatom algae in the hypereutrophic area of Amurskii Bay (22%) was slightly greater than that in the eutrophic area (13-21%). This difference was insignificant, owing to the bloom of *S. costatum* observed throughout the bay. In winter, the relative density of non-diatom microalgae obtained from the hypereutrophic waters of Amurskii Bay was even smaller than that in the eutrophic area. This was due to growth of the diatom *Thalassiosira nordenskioeldii*. However, the relative densities of flagellates

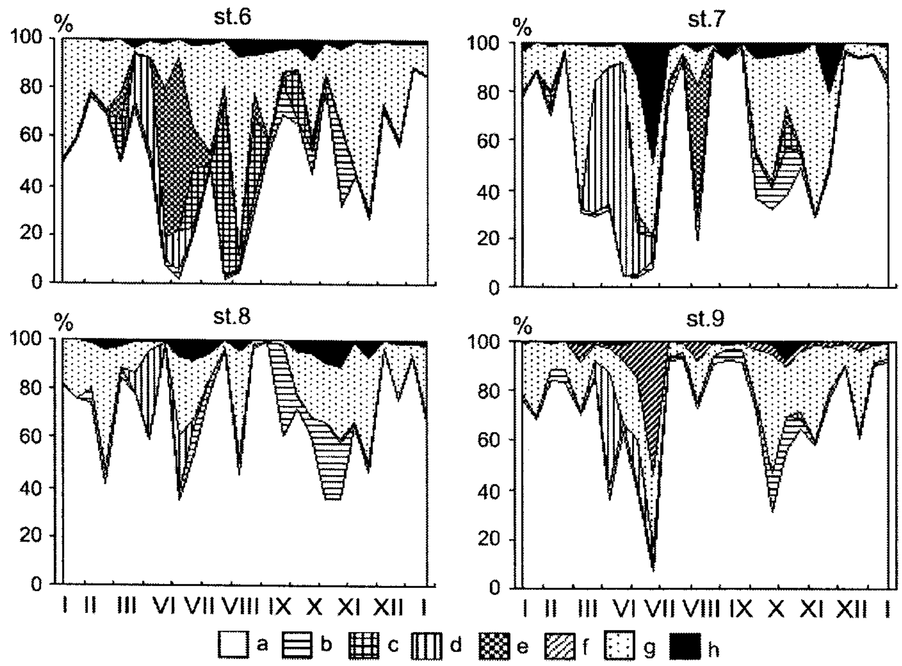

Fig. 6. Relations between the densities of major phytoplankton groups at stations 6-9 from January 1993 to January 1994. On abscissa - months; on ordinate - density, % of the total phytoplankton density. a-diatoms, b-dinoflagellates, c-Prasinophyceae, d-chrysophytes, e-euglenophytes, f-cryptophytes, g-small flagellates, h-other microalgae.

and blue-green algae at the hypereutrophic stations (42-51%) located close to the sewage outfalls (stations 6 and 7) were significantly greater than those at stations 8 and 9 (31%), located in the eutrophic waters. Between the summer and autumn of 1991, no significant increase in the density of the non-diatom phytoplankton component was recorded in the innermost part of the bay. However, an intense bloom of the dinoflagellate *P. minimum* was observed in the hypereutrophic and eutrophic waters of Amurskii Bay in the summer of 1991. In the hypereutrophic and eutrophic areas of Amurskii Bay (stations 1, 2, and 3), the density of this species was more than two orders of magnitude greater than that in the mesotrophic area (station 5).

4. Discussion

There was a strong correlation between the spatial variation in the phytoplankton composition and eutrophic levels in the coastal waters off Vladivostok. The most marked differences among the stations were observed in summer. For example, during the summer phytoplankton bloom, the total density and biomass increased, whereas the species diversity decreased from mesotrophic towards hypereutrophic waters. These changes in the composition of phytoplankton were due to massive increases in the numbers of the diatom *S. costatum*, an indicator of eutrophication. The density of this species near the sewage outfall in the hypereutrophic area of Amurskii Bay (station 7) was 2-3.5 times greater than at the other stations. Sewage pollution is known to stimulate the growth of the diatom *S. costatum*, which prefers a heterotrophic mode of nutrition (Yamada *et al.* 1983; Kondo *et al.* 1990a). According to some researchers (Smayda 1973), the ecological interaction between biogenic substances and labile organic components of sewage is a critical factor that accelerates photosynthesis, causing blooms of *S. costatum* in waters that are heavily polluted with industrial waste and domestic sewage.

The densities of flagellates (especially euglenophytes and dinoflagellates) in the coastal waters off Vladivostok increased with decreasing distance from the sources of wastewater (Fig. 6). All the known colored species of Euglenophyta are regarded as mixotrophic organisms (South and Whittick 1990; Walne and Kivic 1990). *Eutreptia lanowii* had the highest euglenoid density (0.9-1.3 million cells/l) in the hypereutrophic waters near Vladivostok. This species is a typical mesosaprobe that is common in coastal waters that are heavily polluted with organic waste (Schiller 1925; Fanuko 1980). The increased density of flagellates in the hypereutrophic waters of Amurskii Bay in the summer of 1991 was due to a bloom of the dinoflagellate *P. minimum*. In laboratory cultures, the growth of *P. minimum* (Stonik 1994) is stimulated by organic matter, especially nitrogen compounds (Graneli and Moreira 1990; Kondo *et al.* 1990b). In nature, this species consumes nitrogen contained in organic compounds, either directly or after demineralization by bacteria (Carlsson and Graneli 1993). The high densities of *E. lanowii* and the dinoflagellate *P. minimum* in the hypereutrophic waters near Vladivostok appeared to be supported by pollution from industrial waste and domestic sewage. Continuous enrichment with organic substances makes the conditions in these areas favorable for the growth of mixotrophic flagellates. Studies of chemical oxygen demand (COD) have shown that the oxygen content in wastewater varies with the concentration of organic compounds. In 1993, the COD in the wastewater near stations 6 and 7 in Golden Horn and Amurskii Bays exceeded maximum permissible values by a factor of 4-30 (Shapovalov 1994).

High concentrations of petroleum hydrocarbons seem to be another factor promoting an increase in the density of flagellates in the hypertrophic waters of Golden Horn Bay (Tkalin *et al.* 1993). Compared with diatoms, whose density decreases in polluted waters, flagellates are more tolerant of petroleum hydrocarbons (Curds 1982; South and Whittick 1990).

The long-term flagellate blooms in Golden Horn Bay may also be caused by thermal pollution. Gren and Vinogradskaya (1968) demonstrated the stimulatory effect of thermal pollution on chlorophyte growth. This was confirmed by our data, as four density peaks of the chlorophyte *Pyramimonas* were recorded in Golden Horn Bay, the region experiencing thermal pollution (Zvyagintsev 2000). According to our observations, the water in this area (station 6) during January-April of 1993 was 1-2.5°C warmer than that in Amurskii Bay. This peculiarity of the thermal regime seems to be one of the causes of spring blooms of chlorophytes belonging to the genus *Pyramimonas* in Golden Horn Bay. In Amurskii Bay, no such blooms were observed (Fig. 6).

This study revealed several trends in the composition of phytoplankton in the coastal waters off Vladivostok with decreasing distance from the sources of eutrophication. First, the total phytoplankton density and biomass increased. Second, an increase in the density of the diatoms, specifically *S. costatum*, led to a decrease in microalgal species diversity. Finally, the density of flagellates increased. Our results are consistent with previous data on changes in the composition of phytoplankton in other eutrophic waters (Marasovic and Pucher-Petcovic 1991; Mihnea 1997), as well as with the results of hydrochemical investigations of the study area (Tkalin *et al.* 1993).

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