



On Conditions of Phytoplankton Blooms in the Coastal Waters of the North-Western East/Japan Sea

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Abstract – Seasonal changes of abundance of the main phytoplankton groups of species (diatoms, dinoflagellates, chrysophytes, small flagellates and cryptophytes) and a set of environmental parameters were investigated in coastal and pre-estuarine waters of Peter the Great Bay (East/Japan Sea) in May-October of 1998 and 1999. Three periods of mass development were revealed: spring, summer and autumn blooms, with successive change of species. The conditions favourable for each group of species were determined. Driving mechanisms of the succession include nutrients transport through seasonal pycnocline by turbulent mixing, terrestrial nutrients supply by monsoon floods, nutrients supply by upwellings, and light control by the thickness of upper mixed layer. Summer succession could be explained by a simple SST-MLD diagram similar to Pingree S-kh diagram with sea surface temperature as indicator of stratification (S) and mixed layer depth as indicator of light availability (kh).

Key words – phytoplankton bloom, stratification, nutrients, East/Japan Sea

1. Introduction

Seasonal succession of the phytoplankton community is generally described by R. Margalef (1960) scheme of dominant groups change from fast growing, opportunistic species which need a good supply of nutrients and light to slow growing species better adapted to utilize the diminishing nutrient base. For example, during the period of spring bloom, diatoms change to dinoflagellates. However, for understanding the changes in real ecosystems, for

their modelling and estimation of possible anthropogenic influence, seasonal succession of phytoplankton in real conditions of local sea areas should be investigated.

Studies on phytoplankton in the coastal zone of the north-western East/Japan Sea. were started in early XX Century (Kiselev 1934, 1953; Gail 1936) and have been continued recently (Konovalova 1984; Konovalova *et al.* 1989; Selina 1992; Stonik and Orlova 2002; Morozova *et al.* 2002). Detailed data on species composition and seasonal dynamics of phytoplankton groups were received, in particular for Peter the Great Bay (Stonik and Orlova 1998; Selina *et al.* 1999; Stonik and Selina 2001). The main features of the seasonal succession here are diatoms blooming in winter, early summer and autumn, and flagellates blooming in late summer - early autumn (Konovalova 1972; Pautova and Konovalova 1982; Konovalova and Orlova 1988). Environmental control of the succession was never considered.

Meanwhile, it is well known for some other regions that seasonal succession of phytoplankton is accompanied by certain changes of physical and chemical environments (Smayda 1980; Karentz and Smayda 1984). Water turbulence is theoretically a key determinant of the succession: high turbulence is unfavourable for any phytoplankton species because of easy removing of cells out of the euphotic layer; there is an optimal turbulence more favourable for diatoms; and a low degree of turbulence is usually unfavourable for diatoms because of a lack of nutrients, although it is still quite favourable for dinoflagellates (Bode and Fernandez 1992; Smayda 2000). That is the

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reason for successive change of the dominant groups. For example, in deep-water sea the phytoplankton development in winter is restrained by active mixing; diatoms bloom in spring when stratification appears but the surface layer is still rich with nutrients; but further strengthening of stratification leads to dinoflagellates domination. The diatoms and dinoflagellates, the most abundant groups of marine phytoplankton species, have fundamentally different ecologies: diatoms are fast growing, opportunistic species which need a good supply of nutrients and light, while dinoflagellates are slow growing and better adapted to utilize the diminishing nutrient base, as they are able to active move activity. Some of their species are heterotrophic.

Theory of water turbulence control onto phytoplankton succession is highly developed (Margalef 1960; Bowman *et al.* 1981; Smayda 1980, 2000). However, the theoretical approach is not easy to apply to real marine ecosystems, because of the difficulty to measure *in situ* the turbulence that is a fine-scale parameter, very changeable spatially and temporally. So, one of the goals of our study was to define any convenient parameters which could be measured easy and frequently during a routine monitoring of marine environments, and which describe satisfactorily the conditions favourable for mass development of the main groups of phytoplankton in coastal areas of the north-western East/Japan Sea. Besides, regional features of the phytoplankton succession were also focused on in the study. The area of Peter the Great Bay, where samples were collected, is peculiar for summer blooming in addition to usual for any subpolar sea spring and autumn ones (Konovalova 1984; Selina 1992; Stonik and Orlova 1998; Morozova *et al.* 2002).

For these purposes, coupled monitoring observations of both phytoplankton and environmental conditions were conducted in the coastal zone of Peter the Great Bay in the period from spring to autumn, parameters of environment informative for blooms appearance of certain groups of phytoplankton were defined, and physical mechanisms of these parameters influence on the phytoplankton species development were analysed.

2. Observations and Methods

The monitoring was conducted at two stations (Fig. 1) with depth 48 m (St. C) and 18 m (St. P). Climate of the investigated area is characterized by strong seasonal

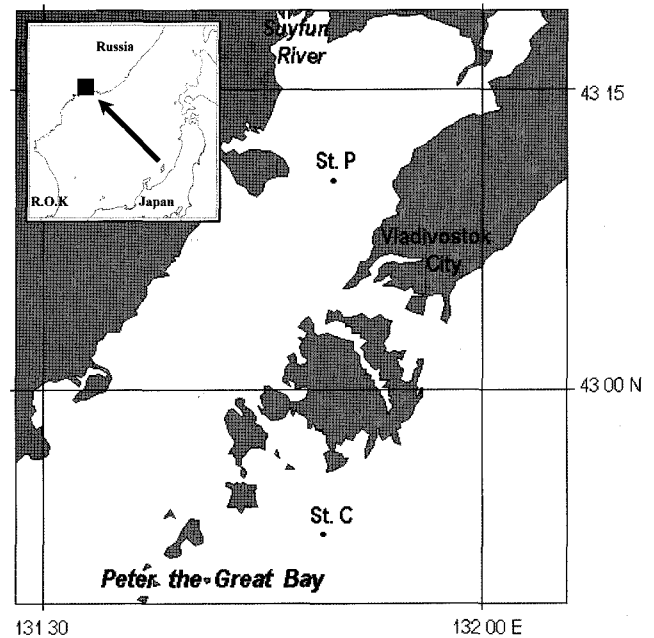


Fig. 1. Area of investigation.

changes emphasized by monsoons. South quarter on-shore winds dominate in spring-summer, which cause warm, rainy weather and also gradual thickening of the upper mixed layer because of wind surge and mixing (Zuenko 2001). After monsoon change in late August – early September, off-shore north winds begin to strengthen, which causes upwelling events at the coast. Suifun River, with its basin located both in Russia and China, flows into the Sea close to the observation points and supplies fresh water about 5 km³/year and a huge quantity of nutrients, and has influence at both observation points. Some weather parameters and river run-off during the observation series in 1998 are explained at Fig. 2.

Two weekly-fortnightly series of oceanographic observations and phytoplankton sampling were carried out on both stations in May-October of 1998 and 1999. Thermohaline parameters were measured by profilers AST-1000p (Japan) and Sea-Bird SBE-25 (USA). Samples for dissolved oxygen content were fixed immediately by MnCl₂ and NaOH+KJ and later were analysed in laboratory by the Winkler method of titration. Nutrients (phosphates and silicates) were measured photocolometrically with KFK-3 (USSR). Phytoplankton samples were collected in 5-liter Van-Dorn samplers and fixed with Lugol's solution in 1-liter bottles. After sedimentation, the micro- and nanoplankton cells were counted in Nojott chambers with a volume of

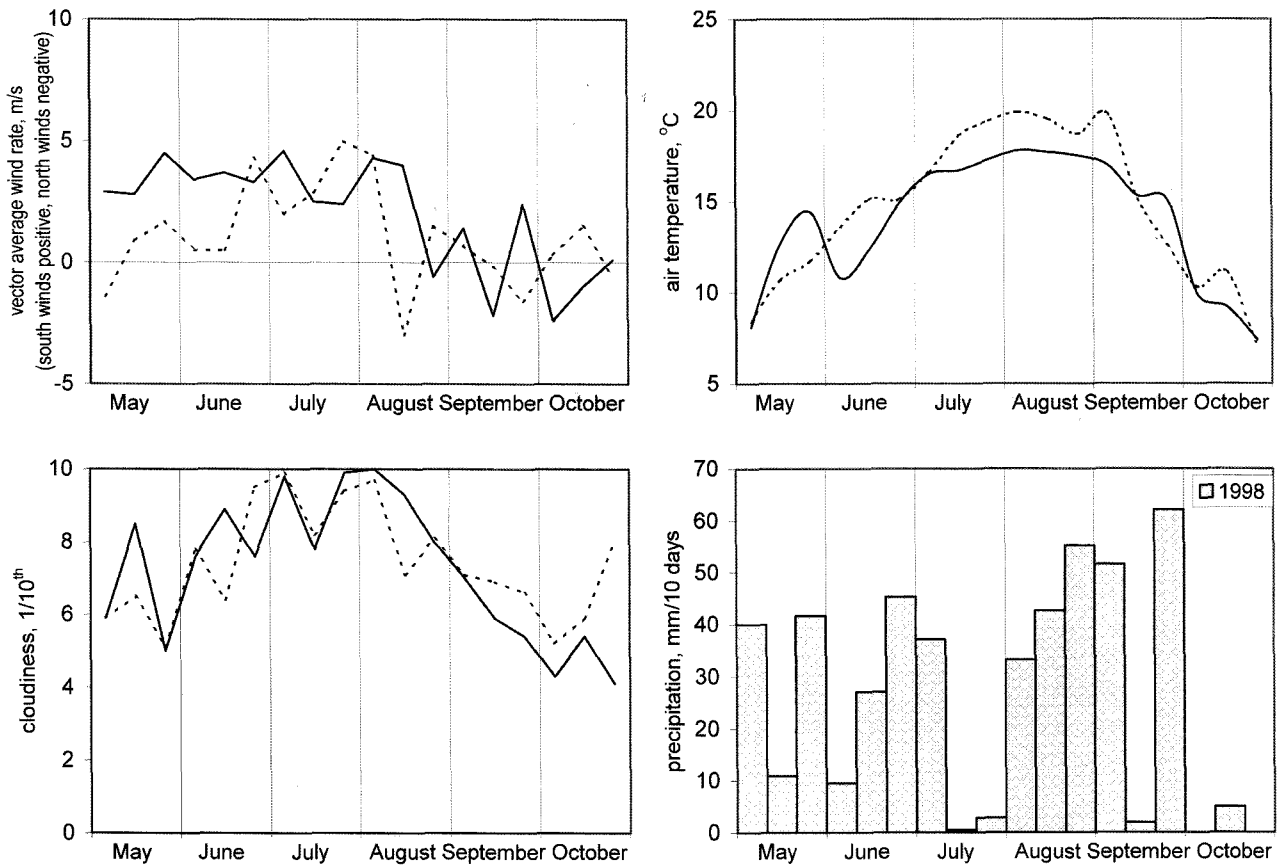


Fig. 2. 10-days averaged weather parameters at Vladivostok meteorological station in May-October of 1998 (solid line) and 1999 (dotted line).

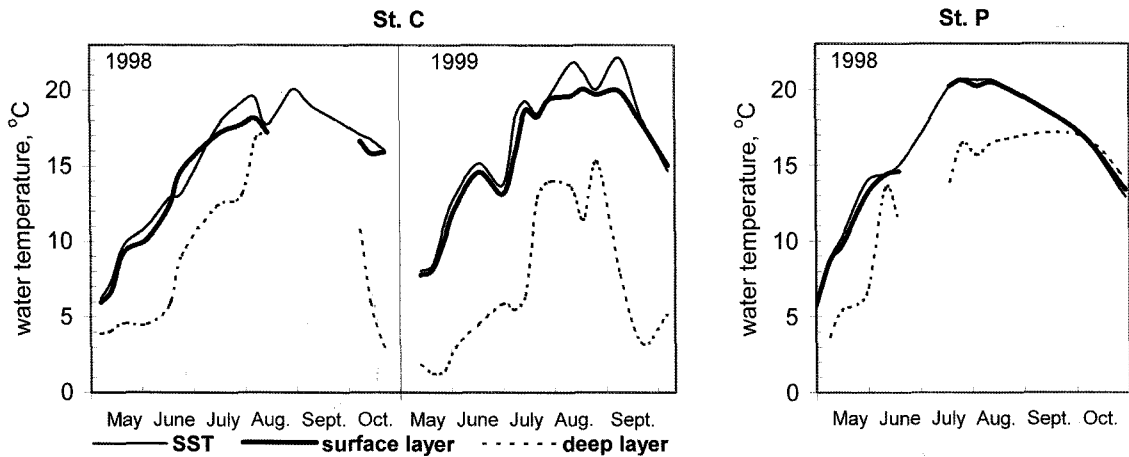


Fig. 3. Water temperature at sea surface (SST), in surface layer, and in deep layer in May-October 1998 and 1999.

1 and 0.5 ml, respectively.

The following environmental parameters were used for analysis: water temperature at sea surface (SST), salinity at sea surface, mean values of temperature and salinity within the upper mixed layer and deep layer,

mixed layer depth (MLD), temperature gradient in seasonal thermocline, dissolved oxygen content at sea surface and within both layers, phosphates and silicates concentration at sea surface and within the layers, Si/P-ratio at sea surface and within the layers. Mixed layer depth, or the

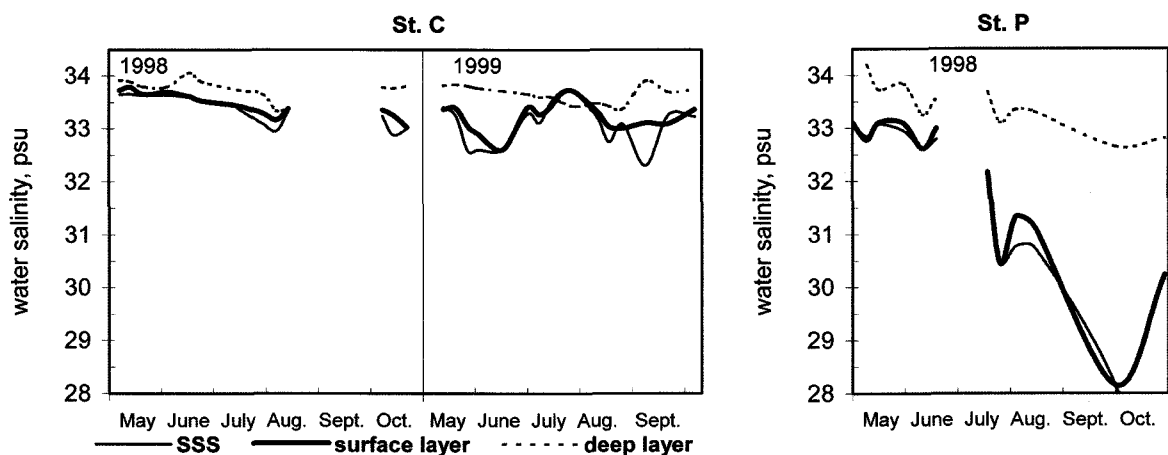


Fig. 4. Water salinity at sea surface (SSS), in surface layer, and in deep layer in May-October 1998 and 1999.

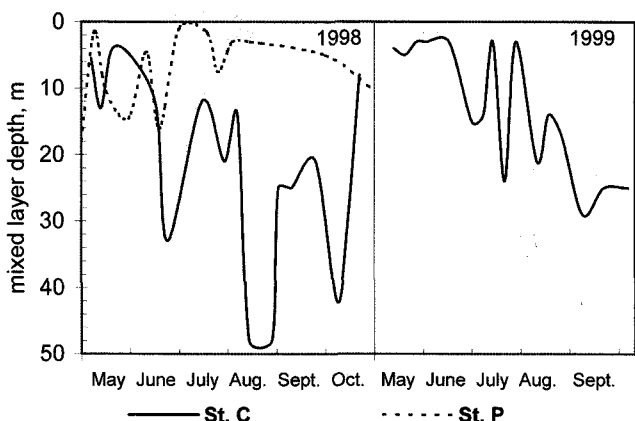


Fig. 5. Changes of mixed layer depth in May-October 1998 and 1999.

depth of seasonal pycnocline was determined as the horizon where specific density vertical gradient is maximal. Graphs of all environmental parameters are presented at Figs. 3-6.

Phytoplankton species were divided into 4 main taxonomic groups: diatoms, dinoflagellates, small flagellates + cryptophytes, and chrysophytes. The small flagellates included the microalgae of various taxonomy with size < 10 μm which have undergone deformation in the process of fixation. Each group had 1-2 dominant species of >50% abundance. The data on phytoplankton at sea surface were chosen for the analysis (Fig. 7) because its maximal abundance was observed at the sea surface usually, with some exceptions discussed below.

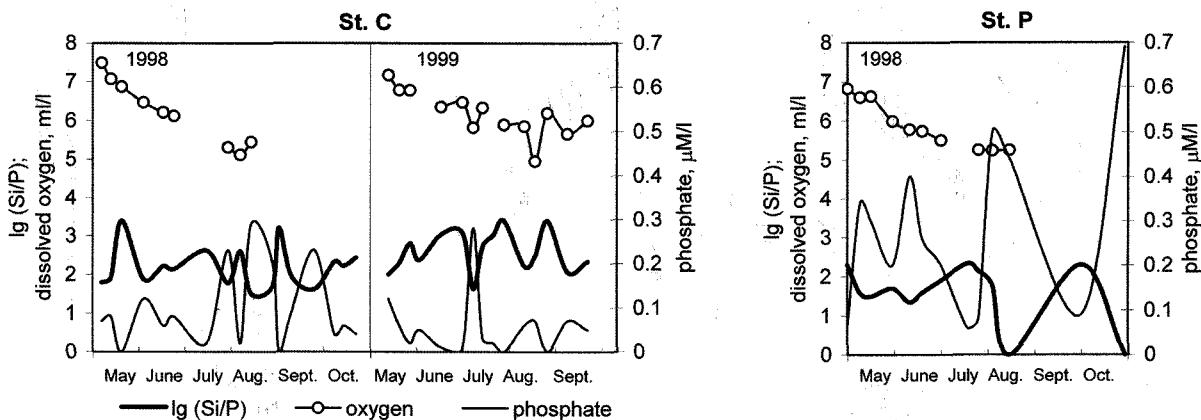


Fig. 6. Some hydrochemical parameters at sea surface in May-October 1998 and 1999: dissolved oxygen content, phosphates concentration, molar ratio Si/P.

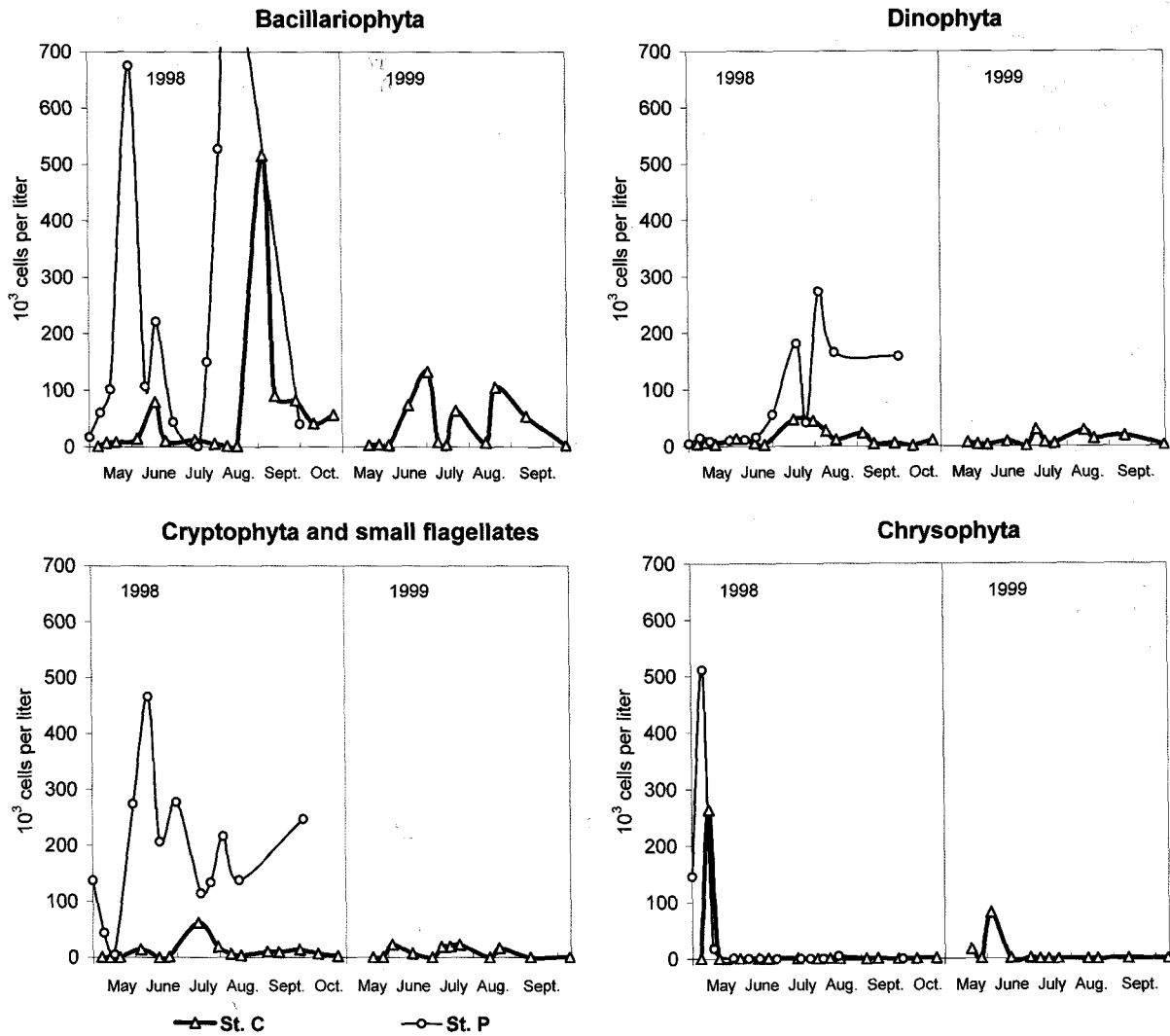


Fig. 7. Abundance of the main groups of phytoplankton at sea surface in May-October of 1998 and 1999.

3. Results

Phytoplankton abundance varied significantly during the observations: from 6×10^2 to 5.5×10^5 cells/litre at St. C and from 1.3×10^5 to 1.2×10^6 cells/litre at St.P. The periods with any phytoplankton groups abundance at sea surface $> 2 \times 10^4$ cells/litre at St.C and $> 10^5$ cells/litre at St.P were regarded as the blooms of these groups of species. Three large periods of phytoplankton mass development were recognized, noted as “spring”, “summer” and “autumn” blooms (Table, Fig. 7).

Results of preliminary analysis of environmental influence on phytoplankton state carried out by visual comparison of the rows (Figs. 3-6 and 7) and by linear correlation

analysis show a strong synchronic link between all groups of phytoplankton and nutrients: the nutrients concentration decreased when any group of species had mass development, and Si/P-ratio decreased when diatoms were abundant. The reason of this link is very natural – it is consumption of nutrients by phytoplankton. However, the links of that kind are not useful for studying the conditions of phytoplankton blooms, so far as nutrients’ concentrations are controlled by phytoplankton, whereas we are interested in environmental influence on phytoplankton. Of course, this fact does not contradict phytoplankton growth dependence on nutrients’ fluxes, but the concentration of nutrients cannot indicate these fluxes because of its high dependence on the nutrients consumption for photosynthesis.

Table 1. Terms of the main phytoplankton groups' blooms in Peter the Great Bay in 1998-1999. Dominant species are shown: Db - *Dinobryon balticum* (Chrysophyta), Tn - *Thalassionema nitzschioides* (Bacillariophyta), Pp - *Pseudo-nitzschia pungens* (Bacillariophyta), Sc - *Skeletonema costatum* (Bacillariophyta), Gs - *Guinardia striata* (Bacillariophyta), Pt - *Prorocentrum triestinum* (Dinophyta), Gds - *Gymnodinium simplex* (Dinophyta), Pm - *Prorocentrum micans* (Dinophyta), St - *Scrippsiella trochoidea* (Dinophyta), CF - cryptophytes or small flagellates. Empty cells - no bloom in the period; "no" - no survey in the period.

month, dates	Diatoms			Dinoflagellates			Chrysophytes			Small flagellates and cryptophytes		
	St.C 1998	St.C 1999	St.P 1998	St.C 1998	St.C 1999	St.P 1998	St.C 1998	St.C 1999	St.P 1998	St.C 1998	St.C 1999	St.P 1998
May 1-10		no			no			no	Db		no	CF
11-20							Db	Db	Db			
21-31	no		Tn	no			no			no		
June 1-10			Tn					Db			CF	CF
11-20	Tn	Tn	Tn									CF
21-30		Pp	Tn									CF
July 1-10	no		no		Gds	no	no		no	no	CF	no
11-20				Gds						CF	CF	CF
21-31		Sc		Pt, Gds		Pt					CF	CF
Aug. 1-10			no	Gds	Gds	no			no			no
11-20		Sc	Sc									
21-31	no	no	Sc	no	no	Pm	no	no		no	no	CF
Sept. 1-10	Pp, Gs		no	Pm	Pm	no			no			no
11-20	no	no	no	no	no	no	no	no	no	no	no	no
21-30	Sc, Gs	no	Gs, Sc			no	St		no		no	
Oct. 1-10	Gs		no			no			no			no
11-20	Gs	no	no		no	no		no	no		no	no
21-31	Gs	no			no	St		no			no	CF

That is why the nutrients concentrations were excluded from further analysis.

Relations between other parameters (temperature, salinity, their vertical gradients, mixed layer depth) and phytoplankton abundance were investigated using the Principle Component Analysis technique (Clarke and Warwick 1986) that allowed us to determine the complexes of the parameters values responsible for bloom. The surveys carried out in the periods of blooms form coherent areas or clusters in the space of principal components. The dominant contributions to principal components were made by two environmental parameters: sea surface temperature (SST) and mixed layer depth (MLD). So, the space of principal components can be approximated by two-dimensional space with easily interpreted axes. The periods with blooms and without blooms separate well on the diagrams with co-ordinates "SST-MLD" (Fig. 8). On these diagrams, the SST-MLD combinations favourable for each case of mass development are determined. They are similar for both stations of monitoring.

The following conditions are determined:

- chrysophytes *Dinobryon balticum* had mass development under SST 7-13°C, MLD > 5 m;

- summer bloom of diatoms *Thalassionema nitzschioides* and *Pseudo-nitzschia pungens* was in June under SST 12-16°C (up to 18°C at St. P) and MLD < 20 m;

- autumn bloom of diatoms *Guinardia striata* and *Skeletonema costatum* was in September-October under SST falling from 20 to 16°C, MLD 3-25 m; moreover, short-terms blooms of *Skeletonema costatum* were observed several times earlier (in late July - August) under similar conditions;

- summer bloom of dinoflagellates (mainly *Prorocentrum triestinum* and *Gymnodinium simplex*) began in July-August under SST > 17°C and MLD 12-22 m (> 7 m at St. P) and continued in September with *Prorocentrum micans* under MLD thickening to 30 m, until the SST decreasing below 17°C;

- autumn bloom of dinoflagellate *Scrippsiella trochoidea* was observed at St. P only under SST < 18°C, MLD > 5 m;

- small-size flagellates had a short bloom at St. C in early June (together with diatoms) and more continuous

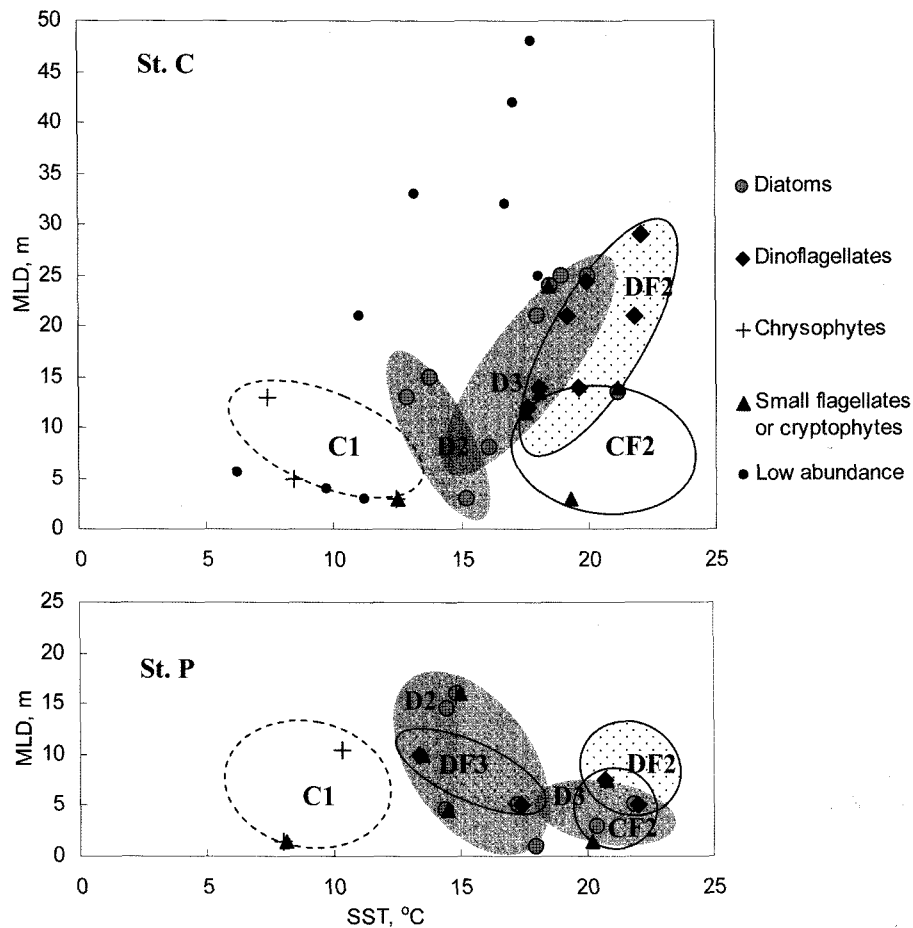


Fig. 8. Conditions of blooms of the main groups of phytoplankton at sea surface (indicated by ellipses of different color). C1 – spring bloom of chrysophytes, D2 – summer bloom of diatoms, DF2 – summer bloom of dinoflagellates, CF2 – summer bloom of small flagellates or cryptophytes, D3 – autumn bloom of diatoms, DF3 – autumn bloom of dinoflagellates.

one in July under the same maximal SST as summer dinoflagellates and MLD < 14 m; at St. P they showed high abundance during almost the whole period of observations.

Sometimes the environments were unfavourable for any phytoplankton group. In late spring there were cases of too shallow MLD. However, shallow MLD did not prevent bloom in summer-autumn, but thick MLD (> 25–30 m) was unfavourable for phytoplankton. So far as the depth at St. P was shallower than this value, a mass development of phytoplankton was almost permanent there in summer.

4. Discussion

Sea surface heating is the main reason for summer

stratification of water column, so the SST can be regarded as an indicator of water stratification. Light availability for phytoplankton stock within the upper mixed layer depends directly on the mixed layer depth, so the MLD is an indicator of light supply. Therefore, the conditions of certain phytoplankton species blooms, presented above in terms of SST and MLD, could be interpreted by nutrients and light supply.

Mass development of chrysophytic algae in May–early June is typical for Peter the Great Bay (Pautova and Konovalova 1982; Stonik and Orlova 1998), and we regard it as the latest phase of spring succession. In deep-sea part of the north-western East/Japan Sea, the spring bloom terminates in April, when winter deposit of nutrients is exhausted, but in shelf zones it is prolonged because additional nutrients are supplied through the seasonal

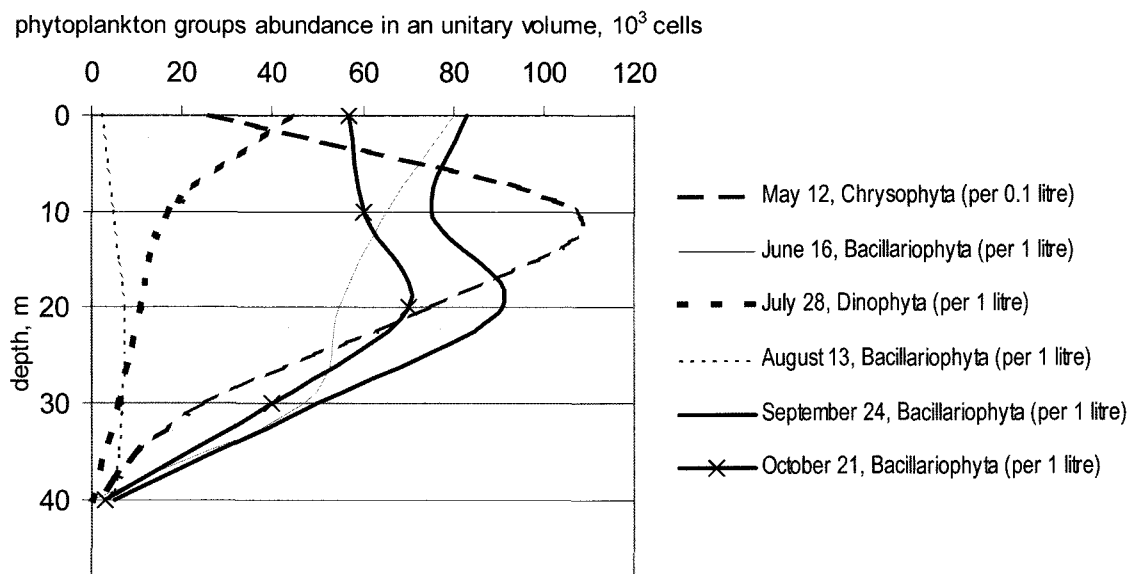


Fig. 9. Vertical profiles of certain phytoplankton groups concentration at St. C in 1998.

pycnocline by tidal mixing. That is why the maximal concentration of phytoplankton was observed within the pycnocline at the end of spring (Fig. 9, profile May 12). The sharper pycnocline and thinner MLD, the earlier spring bloom finishes.

Summer bloom is not usual for deep-water sea but occurs in coastal waters of Peter the Great Bay (Konovalova 1972; Konovalova and Orlova 1988; Selina 1992) and other seas (Zernova 1980; Queguiner and Treguer 1984). In deep-sea it is prevented by strong stratification that impedes the nutrients upward flux. Coastal waters are enriched by terrestrial nutrients, and this additional flux increases considerably through summer floods of North-East Asia rivers after monsoon rains. The summer blooms are supported by coincidence of moderate (not strong) stratification and terrestrial nutrients supply. The period of summer blooms begins in early summer when stratification is still weak and river run-off is already considerable (see salinity decrease at Fig. 4). Diatom bloom appears the first - in June. In opposite to late spring bloom of chrysophytes, the strongest summer bloom was observed at sea surface (Fig. 9, profile Jun. 16).

Further SST increasing and pycnocline strengthening lead to weakening of nutrients supply from deep layers by mixing, that causes the diatoms bloom changing to flagellates one. This change was not accompanied by decreasing of nutrients concentration (it was permanently low because

of immediate utilization of nutrients for photosynthesis), but the weakening of nutrients flux could be supposed under physical reasons and physical indicators, as vertical gradient of density and SST. In worsening conditions, either dinoflagellates or small flagellates are able to form blooms depending on MLD value: the dinoflagellates dominated in the cases with optimal MLD, and small flagellates - in the worst nutrition conditions of thin MLD (poorest nutrients supply). The highest abundance of these species during summer bloom was observed at sea surface (Fig. 9, profile Jul. 28). On the other hand, too thick MLD caused all blooms termination because of light limitation (Fig. 9, profile Aug. 13).

Some short-term blooms of diatoms are possible in July-August; after cessation of the main summer bloom, in times of strong floods. *S. costatum* dominates in these blooms. This species is able to grow very fast in conditions of high temperature and rich nutrients, in particular silicon (Smayda 1973; Tsuruta *et al.* 1987). Obviously, the summer floods provide both these stipulations.

When SST begins to fall in late August, summer monsoon changes to winter one with strong northern off-shore winds that causes a new effective mechanism of nutrients supply as upwelling. It is obviously the reason of an autumn period of phytoplankton blooms that begins earlier than in deep-water areas. Diatoms (*G. striata*) bloom formerly first. The bloom of diatoms continues

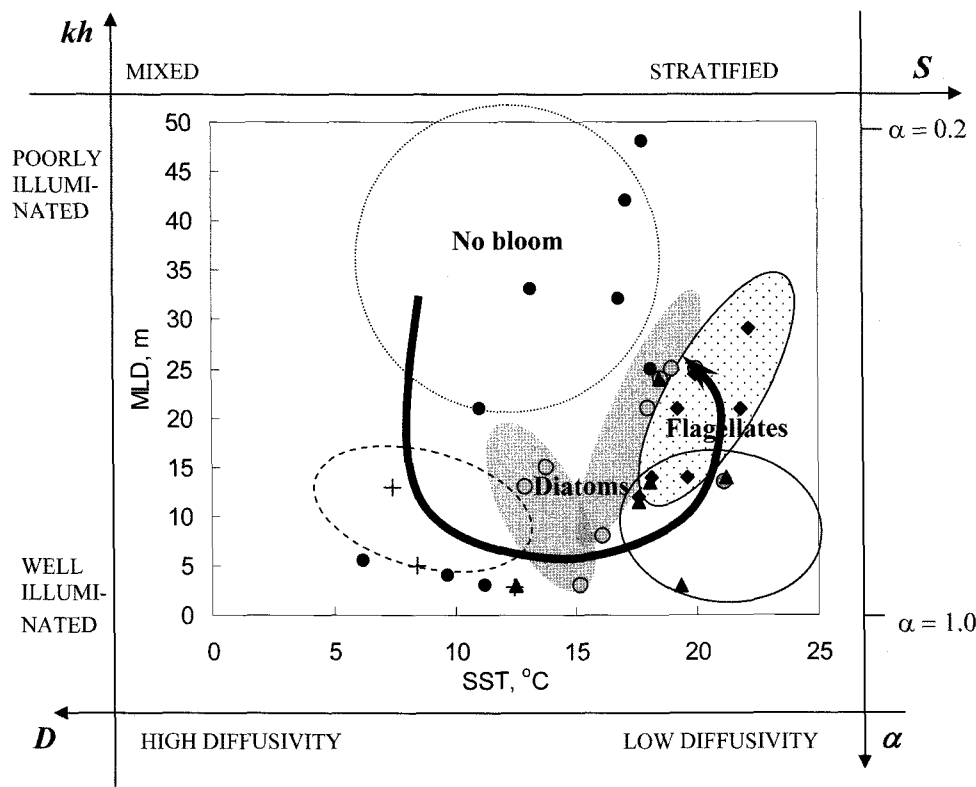


Fig. 10. Conceptual equivalence the SST-MLD diagram from Fig. 8 (St.C) with Pingree S - kh diagram (from Smayda, 2000) having explained the blooms of diatoms and dinoflagellates in dependence on stratification index S and number of optical depth kh , or vertical diffusivity D and growth rate a . Bold arrow shows the direction of summer succession. See the legend for the blooms at Fig. 8.

until MLD is thin enough. In our surveys it was soon: the MLD thickening in October caused low abundance of all groups of phytoplankton at St. C and substitution of diatoms by dinoflagellates at St. P. However, according to previous studies (Konovalova 1984; Stonik and Orlova 1998), autumn bloom could continue till late October – early November, with change from diatoms to small flagellates in its late phase. So far as the main source of nutrients during autumn bloom is located in the deeps, the maximum of phytoplankton concentration is located in pycnocline (Fig. 9, profiles Sep. 24, Oct. 21).

The cases of unfavourable environmental conditions are explained by different reasons in spring and summer-autumn. In spring, blooming stopped in the cases of very thin mixed layer that caused a very quick exhaustion of the nutrients deposit. In summer and autumn, the thin upper layer was not dangerous for phytoplankton because the source of terrestrial nutrients supply was located at sea surface, but an extreme increasing of MLD (over 25-

30 m) was unfavourable for blooming because of its cells sinking out of the euphotic layer.

Our results are in good agreement with a number of studies of phytoplankton seasonal cycle on the north-western shelf of Europe and in coastal waters of the USA; these studies determined a turbulence generally and a pycnocline depth particularly as the main factors of phytoplankton dynamics and succession (Bowman *et al.* 1981; Roden 1984; Cloern *et al.* 1985). Scheme of phytoplankton succession presented at SST-MLD diagram (Fig. 8) could be easily co-ordinated with Pingree S - kh diagram (Fig. 10). The Pingree diagram conditions the succession by a stratification-mixing index (S , depending on depth and cubed semi-diurnal tidal current velocity) and a light ability index (kh – the depth h multiplied by diffusive extinction coefficient k). In our scheme the water column stratification is indicated by SST, and light ability - by MLD. As is shown by Bowman *et al.* (1981), the Pingree diagram is conceptually equivalent to theoretical

Margalef's Mandala that conditions the succession by cells' growth rate (proportional to nutrients supply) and diffusivity (Margalef 1960). Our scheme for summer period is a particular case of Pingree diagram (or Mandala) for the real environments of Peter the Great Bay coastal zone, where the stratification depends mostly on sea surface heating and light ability – on mixed layer depth.

This analogy is true for summer period of bloom and supposedly for spring one (the spring blooms develop under lower SST). Autumn blooms develop under different conditions (caused by different physical processes) and are formed by different species. In spring and summer, successive changes of dominant groups are caused by conditions worsening, mainly under nutrients supply weakening. On the contrary, the autumn successive cycle develops under SST lowering and stratification destruction, which facilitate nutrients supply better. That is why the autumn succession could not be simply coordinated with Pingree and Margalef schemes. Unfortunately, the data of our surveys do not allow us to investigate the autumn period in detail.

5. Conclusion

Three cycles of phytoplankton succession in coastal zone are conditioned by different mechanisms of light and nutrients supply. Our study has allowed us to recognize these mechanisms and to estimate their parameters quantitatively.

The spring bloom in the coastal zone is prolonged because of intense nutrients upward flux supported by tidal mixing. It finishes in late May – early June by mass development of chrysophytes in the layer of seasonal pycnocline. Seasonal increase of fresh water discharge by rivers in June after monsoon rains gives a new nutrients source and the summer period of blooming begins by diatoms bloom. In contrast to the final phase of spring bloom, the summer blooms are the most intensive at sea surface. However, weakening of nutrients influx from the deeps because of sharp stratification in the middle of summer forces a change of the diatoms bloom to a flagellates bloom, large-size or small-size ones depending on the upper mixed layer depth (or no blooms when this layer is too thick). In a short period of the strongest stratification (in August) there could be no blooms of any group of algae. Then a new source of nutrients as upwelling starts after monsoon change, in early September usually,

and the autumn bloom of diatoms begins. It is supposed to be controlled by light limitation because of mixed layer depth increasing in autumn. In the end of the autumn period of mass development, the diatoms bloom is succeeded by flagellates bloom in conditions of thicker mixed layer.

Thus, our study shows that even in real conditions with complex oceanographic regime, the phytoplankton development is ruled by a rather simple way: nutrients are supplied by very few physical processes (the main of them as vertical mixing is controlled by SST) and light ability depends on mixed layer depth.

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