STUDIES OF STRUCTURAL PARAMETERS OF PLANKTONIC COMMUNITIES OF THE OPEN PART OF THE BLACK SEA RELEVANT TO ECOSYSTEM MODELING

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Abstract. The complex biological material taken using unified methods at 110 sites (polygons) in the central part of Black Sea, depth > 2000m, during various seasons since 1978 to 1992. The bulk of material was sampled with 120-150-l big water bottles in order to estimate synchronously the maximal number of ecosystem parameters. In these samples, not only all chemical parameters were analyzed, but also primary production, abundance, composition and biomass of phytoplankton and bacterioplankton, protozoans and mesoplankton <3 mm were estimated. Concentrations of larger mesoplankton and macroplankton was quantitatively estimated by examination of plankton nets samples or by visual observations from manned submersibles and TV cameras. The comparison of catchability of mesoplankton with various gears is presented. Problems of the mesoplankton sample treatment are discussed. Biomass of phytoplankton, bacteria, protozoans, mesoplankton, *Aurelia*, ctenophores *Mnemiopsis* and *Pleurobrachia* is considered, production of mesoplankton is demonstrated. Seasonal (monthly) distribution of these parameters are shown during the intensive growth of *Mnemiopsis* in 1989-1990 and during the following decrease of its biomass. Influence of this invader upon pelagic community is discussed

1. Introduction

The method of mathematical modeling was repeatedly named as a powerful instrument of ecosystem studies [13, 14, 16, 17]. This method is widely used for generalization, testing, and coordination of experimental and field studies, for analysis of our concepts of functioning of aquatic ecosystems. The process of sampling, analysis and comparison of data selected for testing results of modeling is also of great importance.

The problem is complicated by the fact that the main abiotic parameters (temperature, salinity, density, turbidity, nutrients concentrations) and, especially, the

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biotic parameters were measured during different years, by different researchers, and often by different methods. The spatial and temporal variations of fields of temperature, salinity, turbidity, etc., standard equipment and methods are used; however the concentrations of alive elements of ecosystem (phytoplankton, bacteria, protozoa, meso- and macroplankton) are measured by the methods that changed and developed during recent 20-30 years. Hence, the data collected during different years are often unsuitable for comparison; thus it is practically impossible to use them for quantitative verification of results of modeling. This problem is often aggravated by that the concentrations of the listed groups of planktonic organisms were measured during different time of day, during different seasons, and also in different sea regions. Such measurements being compared quite often result in evidently absurd situations. For instance, the concentration of planktonic organisms (of 3-5 mm size) can be higher than the concentration of suspended organic matter, the latter consisting of alive organisms and dead particles of detritus. Only a material collected according to unified methodology and analyzed using unified approach is expedient for quantitative verification of modeling. Besides, even the observations carried out at a same station using different equipment are separated in space due to vessel drift; thus their comparison is not always competent.

During the estimation of processes within the ecosystems, the synchronous measurement of the basic ecosystem parameters becomes the most important factor; these parameters should be taken from the same water body, as proportions between them may alter at even short distance.

The idea of synchronous estimation of abiotic and biotic parameters was put forward several times, and various researchers tried to express this more or less completely [1, 2, 4]. But during the studies of planktonic communities as whole systems, when the estimation of quantitative ratios and interactions between elements becomes very important, availability of such information is strongly required. Therefore, during the planktonic studies in the nearest future, those methods that allow to get synchronous information about significant amount of the ecosystem elements, will obviously become more important.

2. Material and Methods

During the ecosystem expeditions of IO RAS in 1978-92, quantitative sampling was performed by 150-l big water bottles, plankton nets of the BR type (mouth area 1 m^2, sieve 500 μm) Judey nets (mouth area 0.5 m^2, sieve 180 μm), and visual count of macroplankton and larger mesoplankton (chaetognaths, ctenophores, medusae, calanids) from the manned submersible "Argus".

At each site, at least big water bottle and net samples were taken from the surface to the depth of the H_2S layer.

The set of big bottles usually consisted of 12-25 samples. If 3-4 big bottles are used synchronously, the set may be taken during 3-4 hours. Usually, sampling occurred

during the daytime, between 8 a.m. and 0-1 p.m. The control night series were also regularly sampled.

The depths of sampling were chosen after preliminary sounding of the vertical profiles of temperature, salinity, density, oxygen concentration, turbidity, and, usually, chlorophyll fluorescence. This allowed to correct the sampling depths regarding the extremal points of the vertical distribution of the abiotic characters described above.

It was thus possible to analyze not only necessary chemical components (biogenic elements including phosphates and organic phosphorus, nitrates, nitrites, ammonium, urea, etc., concentration of dissolved oxygen, optical characteristics of water, $\mathbf{C_{org.}}$) but also the basic elements of planktonic community: phytoplankton primary production (using mainly ^{14}C method *in situ*), chlorophyll concentration, abundances, composition and biomass of phytoplankton - **p**, including pycoplankton (<2 μm), nano- (2-15 μm) and microplankton (> 15 μm), abundances, biomass and production of bacteria - **b**, abundances and biomass of protozoans (microzooplankton) - **a**, and mesozooplankton (0.2-3.0 mm) - **z**.

During the sampling for chemical analyses and microplankton, the rest (usually 80-120 l of water depending upon water productivity) was filtered through the sieve of 60 μm size to collect mesozooplankton 0.2-3.0 mm. Zooplankton was stained for 1.5-2.0 hours by the neutral red dye in order to count separately alive (bright red or brawn) and dead (usually pale yellow) zooplankters. Preliminary observations have shown that animals' tissues were well stained if animals were dead 1-2 hours or less. Thus, the organisms damaged or perished due to the filtration, were colored as alive.

After the staining for 1.5-2.0 hours, the samples were fixed by 2-% formaline and treated under dissection microscope in the Bogorov chamber.

Larger mesozooplankton (>3 mm), *Pleurobrachia*, *Mnemiopsis*, and medusae were sampled with BR nets (113/140, mesh size 500 μm) cone nets (mouth diameter 80 cm and mesh size 200 μm or mouth diameter 113 cm and mesh size 500 μm).

To estimate concentrations of larger mesoplankton and macroplankton with use of BR or other net types, several samples within the upper mixed layer from the surface to the upper thermocline border, within the thermocline, and below the thermocline down to depths of 150-200 m, were performed.

In addition, larger mesozooplankton >2 mm (*Calanus, Sagitta*) and gelatinous animals (*Pleurobrachia*, medusae, *Mnemiopsis*) were visually counted from the manned submersible "Argus", diving-bell and the screens of TV-cameras. The biomass of medusae obtained by the observations from "Argus" or TV screens was 2-3 times higher than the biomass estimated by BR-net of other types of plankton net. The number of individuals of *Mnemiopsis* in the net samples was 3-4 times lower than the values obtained by direct count from submersible.

The question of the mesoplankton sampling by big water bottles was specially discussed both for oceanic and Black Sea plankton [10, 11, 15]. It was demonstrated that big water bottles sample plankton (<3 mm) better or as well as the Judey net 80/113 (Table 1).

However, big water bottle samples of larger animals, meso- and, especially, macroplankton, are not representative, and one should use planktonic samples and even midwater trawls to sample them.

But catchability of these gears is not high as well, as was shown by direct visual observations from manned submersibles ("Argus", "Osmotr"). Therefore, special coefficients were introduced for estimation of concentrations of medusae and Mnemiopsis of the basis of net samples (Table 2). As to fragile gelatinous animals like ctenophores, syphonophores and some medusae, they get so damaged in the trawls that estimation of their abundance becomes almost impossible. Finally, semi-quantitative data on the commercial carnivorous fishes may be only obtained on the base of echosoundings and statistics of commercial catches.

Table 1. Ratios of estimated abundance (N) and biomasses (B) of various plankton components in the layer 0-200 m, Pacific Ocean, sampled: 150-l big water bottles respective to Judey net (averaged, 41 sample sets, [15]).

	Calanoids, < 1 mm	Calanoids, 1-3 mm	Oithons	Appendicu-larians	Chaeto-gnaths	Total mesoplankton, 0.2-3.0 mm
N	5.0	1.9	24.4	8.8	3.7	-
B	3.1	2.4	12.6	-	-	2.4

Table 2. Comparison of catchability of BR plankton nets and direct visual observations from manned submersibles, exemplified by *Aurelia* and *Mnemiopsis*.

Animals	Size, mm	Coefficient, manned submersible/BR plankton net
Aurelia	d < 50	2.0
Aurelia	50 < d < 100	2.3
Aurelia	100 < d < 150	3.3
Aurelia	d > 150	5.4
Mnemiopsis	l < 10	2.0
Mnemiopsis	10 < l < 45	2.0
Mnemiopsis	l > 45	2.3

During the treatment, plankton was divided into conditional size and trophic groups: nanophags (appendicularians, cladocerans, larvae of benthic animals), calanoids <1 mm (with various body size), euryphags (copepodites of *Calanus, Pseudocalanus* >1 mm, *Paracalanus, Oithona, Acartia* >1 mm, etc.), carnivors (*Sagitta, Pleurobrachia*), etc. All animals were totally counted in the sample, sometimes in 1/2, 1/5, or 1/10 sample. In each elemental group, at least 20-25 individuals were measured with precision of 0.025 mm. Then the data were processed by the computer program PLANKTY, and individual weights, average weight and size, biomass and average biomass were calculated for each group.

The wet weight of plankton animals was calculated using their size and body shape by known equations [3]. The carbon content of animals was determined by the method of dichromate oxidation or with a help of CHN-analyser. For evaluation of carbon content of gelatinous animals Yu. I. Sorokin developed the method of preliminary remove of salt from animals bodies with a help of phosphorous acid before dichromate oxidation.

In the net samples, only larger (>3 mm) animals were treated. This gave the later possibility to combine different size groups, sampled by big water bottles and nets.

The ecosystem expeditions of this kind were carried out since 1978, all the main biotic and abiotic compounds were estimated during these expeditions. Eight cruises on big vessels were carried out, 50-60 scientists being involved in these investigations; also three expeditions on smaller vessels were carried out, only some characteristics being measured (Table 3). Disposition of sites is shown in Figure 1. It should be pointed out that almost each map point corresponds to the average position of several stations at this point performed during different expeditions. A total of 430 sites (stations-polygons) was the base of the analysis of presented abiotic or biotic environmental parameters.

Table 3. List of IO RAS expeditions, where the data for structural and functional analysis and modeling of the Black sea ecosystem were collected.

Cruise, expedition	Year	Date, month	Number of stations	Study area
64th, R/V "Vityaz"	1978	September-October	11	Total sea
Seasonal observations	1978	January-December (2 times per month)	85	Shelf and Gelenjik Slope
9th, R/V "Orbeli"	1981	June	6	Bulgarian Shelf
11th, R/V "Orbeli"	1982	October-November	9	Bulgarian Shelf
6th, R/V "Vityaz"	1984	April-May	24	Total sea
7th, of R/V "Rift"	1985	September-October	20	Total sea
8th, of R/V "Rift"	1986	May-June	8	Total sea
15th, R/V "Vityaz"	1988	Mar-April	28	Total sea
16th, of R/V "Vityaz"	1988	September	4	Section from Gelenjik to East Gyre
44th, of R/V "Mendeleev"	1989	July-September	37	Total sea
R/V "Yantar'"	1989	February-June, August, November	47	North-East Shelf and deep-sea
Submersible "Osmotic"	1989	October	7	North-East Shelf
R/V "Gigrobiolog" and "Yantar'"	1990	April	45	North-East area
R/V "Aquanaut"	1990	April	6	North-East Shelf
R/V "Boris Petrov"	1990	April-May	26	South-East area
R/V "Gidrobiolog"	1991	August	6	North-East Shelf
21th, R/V "Vityaz"	1991	February-April	27	Total sea
23th, R/V "Vityaz"	1991	August-November	15	Total sea
26th, R/V "Vityaz"	1992	October	15	Total sea

At present is seems to be quite natural to start with the models of small amount of compounds, developed for the least dynamically complex regions of the Black Sea. For this purpose, the most dynamically stable deep part of the Black Sea was chosen for modeling and summarizing the data for modeling verification. This part is limited by 2000 m isobath [7]. Figure 1 illustrates the locations of the stations selected for verification of modeling. The multidisciplinary biological material collected in SIO RAS expeditions on the central part of the Black Sea was analyzed. The data were collected at 110 stations during different months from 1978 to 1992.

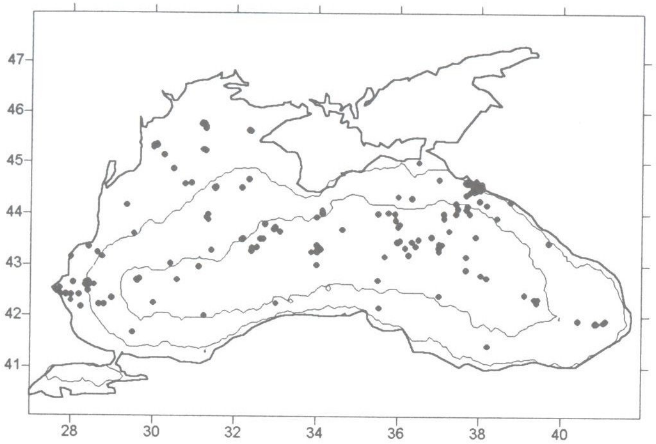

Figure 1. Stations of P. P. Shirshov Institute of Oceanology RAS during the cruises of 1978-1992.

It was impossible to collect the material on all the main size-trophic groups of organisms (compounds of planktonic communities) in the investigated region during summer months (June-August). However, according to the data of other researchers and remote sensing data the biomasses of all the elements of plankton are the most poor during summer period. It is evident in both shelf (Figure 2) and deep regions of the Black Sea [5, 9, 18].

The elements analyzed in the present paper were simulated in the mathematical models [6, 7]. The biomass of the following elements were distinguished: phytoplankton ($\mathbf{B_p}$), bacteria ($\mathbf{B_b}$), protozoa ($\mathbf{B_a}$), mesoplankton ($\mathbf{B_z}$), large carnivorous ctenophore Mnemiopsis ($\mathbf{B_{mnem}}$), and total biomass of medusas *Aurelia* and ctenophore *Pleurobrachia* ($\mathbf{B_{medpl}}$). The biomass of all the named compounds was expressed in terms of carbon units.

3. Results and Discussion

The period of the last 20 years could be divided into two distinct phases of the Black Sea ecosystem. The first one comprises from 1978 (beginning of observations) to 1988. During this period the ecosystem was highly affected by anthropogenic influence with increasing concentrations of pollutants and nutrients with river discharges. The second period started with the introduction of ctenophore *Mnemiopsis*, the endemic species of the North Atlantic coast of America.

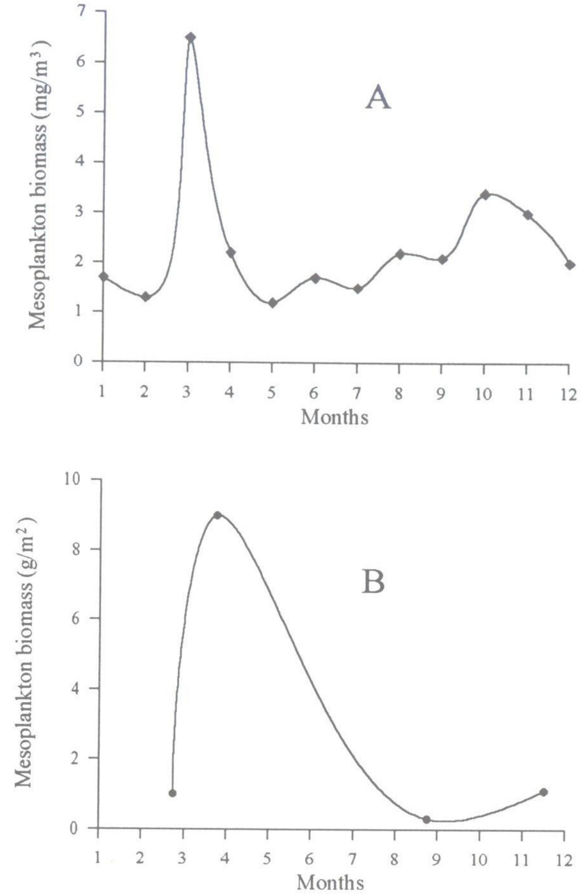

Figure 2. Seasonal variations of mesoplankton biomass B_z (averaged for 1991-1994) at shelf (A) and in deep regions (B) of the northeastern part of the Black Sea.

For the first time *Mnemiopsis* seems to be recorded in the Black Sea waters in 1982 [8]. However, it started to spread widely in coastal waters in 1987; at that time it was caught in the north-western part of the Black Sea and near Bosphorus, as well as in the bays of the Caucasian coast. In April of 1988 during cruise 15 of R/V "Vityaz" we caught few large individuals (about 3-5 cm long) in the deep regions of the south-eastern part of the sea. The biomass of *Mnemiopsis* was about 10 mg C m^{-2}. During that cruise the significant amount of young individuals of *Mnemiopsis* was recorded in the northwestern region. At the end of September of 1988 the biomass at stations in the interior part of the eastern basin was measured within the limits of 350-1430 mg C m^{-2} (cruise 16 of R/V "Vityaz", Figure 3A). In summer of 1989 (cruise 44 of R/V "Dmitriy Mendeleev") the biomass of *Mnemiopsis* in the deep part of the sea (restricted by depth of 2000 m) reached 1700 mg C m^{-2}, with an average of 12 deep-sea stations of about

1000 mg C m^{-2}. The total stock of *Mnemiopsis* in the Black Sea was evaluated as $1 \cdot 10^9$ tons of wet weight.

Mass development of *Mnemiopsis* in the Black sea was observed particularly in coastal bays and shallow regions, primarily at the north-western shelf. Larvae and young individuals of *Mnemiopsis* are distributed over all the periphery of the sea by the Rim Current. Larger individuals (size up to 10-13 cm) usually occur in the central deep part of the sea (the subject of this study). However, in summer of 1990 the bloom of *Mnemiopsis* seemed to be over and in summer of 1991 its biomass was about 500-800 mg C m^{-2} (cruise 23 of R/V "Vityaz"). In September - early October 1992 (cruise 26 of R/V "Vityaz") lower values of about 300-400 mg C m^{-2} occurred.

This decrease of *Mnemiopsis* biomass was slight as compared with the summer of 1989. It seems to be a result of penetration of *Mnemiopsis* from warm upper mixed layer into deeper cooler layers below the thermocline. Almost all the fodder (non-jelly) mesozooplankton in the upper mixed layer was grazed by *Mnemiopsis*, whereas in the lower layers it could consume migrating to that layer during night-time individuals of *Calanus euxinus*. We have observed the penetration of *Mnemiopsis* into deeper layers visually from manned submersible "Argus" in February-March of 1991. *Calanus euxinus* is the main compound of fodder (non-jelly) mesozooplankton. It occupies the cold intermediate layer below seasonal thermocline and was spatially isolated from *Mnemiopsis*. It may be suggested that since 1991 this isolation started to be disordered, that resulted in significant decrease of the biomass of *Calanus euxinus*.

Carnivore *Mnemiopsis* actively consume various plankton organisms (from protozoa to fish larvae), hence its introduction to the semi-relict weakened ecosystem of the Black Sea inevitably altered the structure of plankton community and fish stocks.

Thus there is good reason to analyze two stages of development of the ecosystem of the Black Sea: (A) - before introduction of *Mnemiopsis*; and (B) - after its mass development over the whole sea area.

Regular observations on the distribution and concentration of large gelatinous animals (medusas and ctenophores *Pleurobrachia*) started in 1978 using the modern equipment and methods described above.

Two seasonal maxima of biomass of medusa *Aurelia aurita* are evident: the spring maximum in April-May and the late summer-autumn one in September-October (Figure 4). B. E. Anninskiy (personal communication) confirmed the existence of these two maxima on the basis of the independent observations carried out by IBSS. The absolute values of both seasonal maxima were about the same (4-4.5 g C m^{-2}). The available data are insufficient to analyze the interannual variations of medusas and *Pleurobrachia*.

After the introduction of *Mnemiopsis*, the double-peak pattern of the medusas and *Pleurobrachia* total biomass seemed to remain unchanged, but the absolute values were significantly decreased: about 1.5 g C m^{-2}, i. e., about 2 times lower as compared with the biomass before the introduction of *Mnemiopsis*. It should be noted that the introduction of *Mnemiopsis* influenced more catastrophically the biomass of medusas as compared with *Pleurobrachia*. The reason seems to be that the bulk of

Pleurobrachia population in the central gyres of the sea is concentrated with the cold intermediate layer at the depth of 30-40 m, whereas

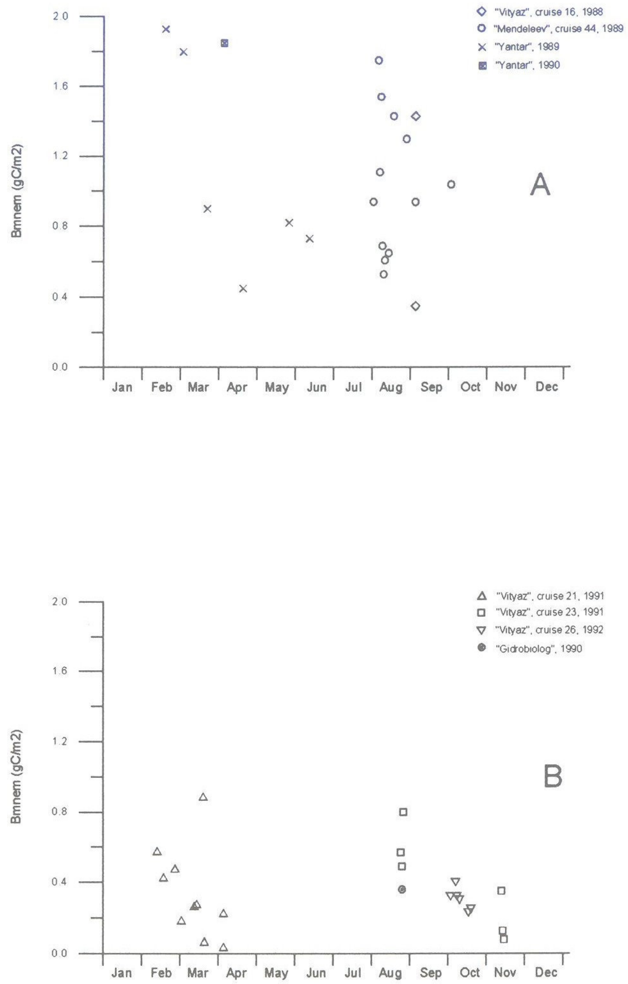

Figure 3. Seasonal variations of the biomass of *Mnemiopsis leidyi* B_{mnem} during its bloom in 1989-1990 (A) and after the bloom in 1991-1992 (B).

medusas prefer surface mixed layer above the depth of seasonal thermocline (0-30 m layer). Thus, once the *Mnemiopsis* was introduced into the system, medusas had to compete for food with them in the upper layer, where the bulk of small fodder mesozooplankton was concentrated. *Mnemiopsis* had advantage in this competition, because it is characterized by higher rates of growth and reproduction and much wider variety of food objects, thus it dislodged *Aurelia* and its biomass sharply decreased. In August-September of 1978-1985 it was on average 3.3 g C m^{-2}, whereas in 1989 during the same season it was about 0.7 g C m^{-2}. In other words, during *Mnemiopsis* bloom the biomass of *Aurelia* decreased about five-fold. At the same time the biomass of the second species of gelatinous animals (*Pleurobrachia*) had not changed, because this cold-loving species lives at a deeper layer isolated from those of medusas and *Mnemiopsis*. During all the period of observations both before and after the

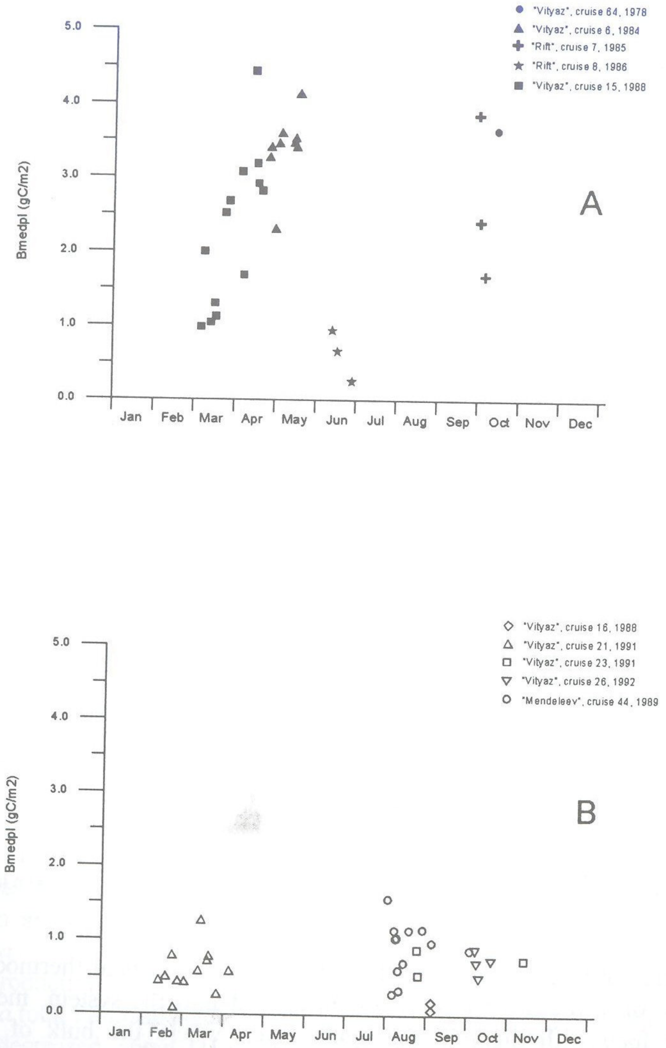

Figure 4. Seasonal variations of the biomass *Aurelia aurita* and *Pleurobrachia pileus* B_{medpl} during the bloom of *Mnemiopsis* in 1989-1990 (A) and after the bloom in 1991-1992 (B).

introduction of *Mnemiopsis* the biomass of *Pleurobrachia* slightly varied with season and year-to-year and was about 0.3-0.5 g C m^{-2}. It resulted in that before the introduction of *Mnemiopsis* the biomass of *Pleurobrachia* was about 10% of the biomass of medusas, and after the introduction it was about 20-40%. Sometimes (for example, in autumn of 1992) the biomass of medusas and *Pleurobrachia* was equal. In this connection it is well to bear in mind that before the introduction of *Mnemiopsis* 90% of the biomass of large gelatinous animals consisted of medusas *Aurelia*, whereas after the introduction this value was about 70%.

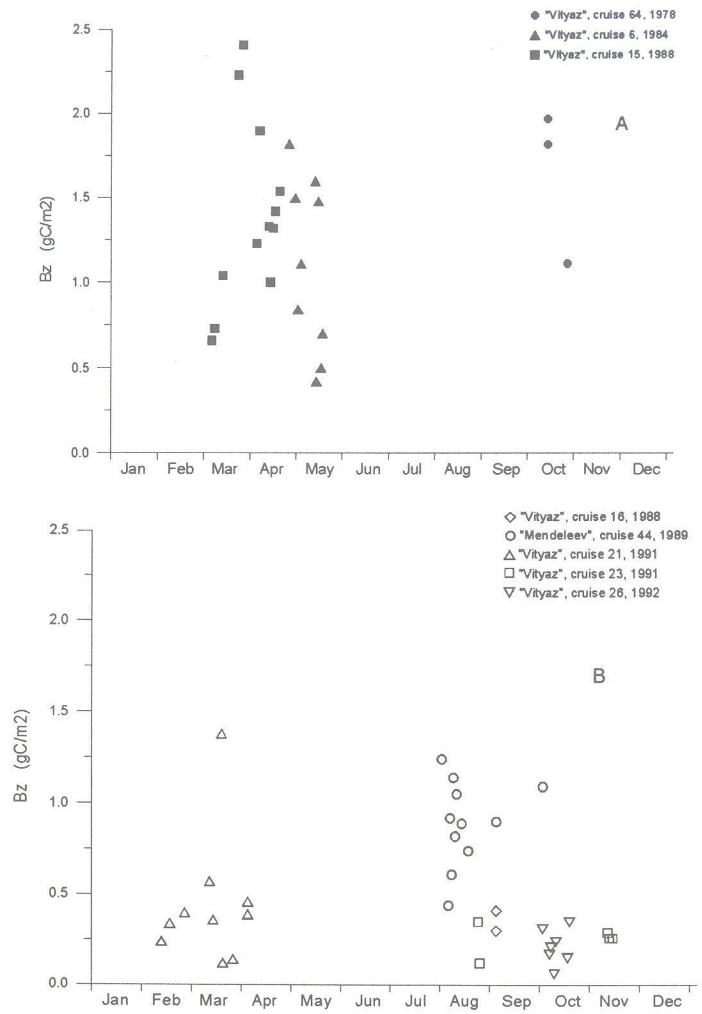

Figure 5. Seasonal variations of mesoplankton biomass B_z during the bloom of *Mnemiopsis* in 1989-1990 (A) and after the bloom in 1991-1992 (B).

The introduction of *Mnemiopsis* also influenced the structure (taxonomic, trophic, size) and the biomass of mesozooplankton (Figure 5, A, B). The total biomass of mesozooplankton during spring period decreased on average about 3 times. The taxonomic structure of mesozooplankton also significantly changed. The biomass of *Calanus euxinus*, the main compound of mesozooplankton suitable for fish feeding, decreased since 1989 about 10 times. *Sagitta* practically disappeared from the plankton community, their concentration decreased 100-fold. The total biomass of fodder (non-jelly) plankton decreased one order of magnitude. At the same time the concentration of gelatinous plankton seems to increase (i. e., ctenophore *Pleurobrachia*). Total percentage of gelatinous plankton increased from 10-12% in 1978-1984 to 80% in 1992. The sharp changes of structure and concentration of zooplankton resulted in decrease of catch of the main commercial fish (anchovy, sprat and horse-mackerel). According to FAO data the total yield in the Black Sea and the Sea of Azov decreased from 1988 to 1992 twenty-five-fold.

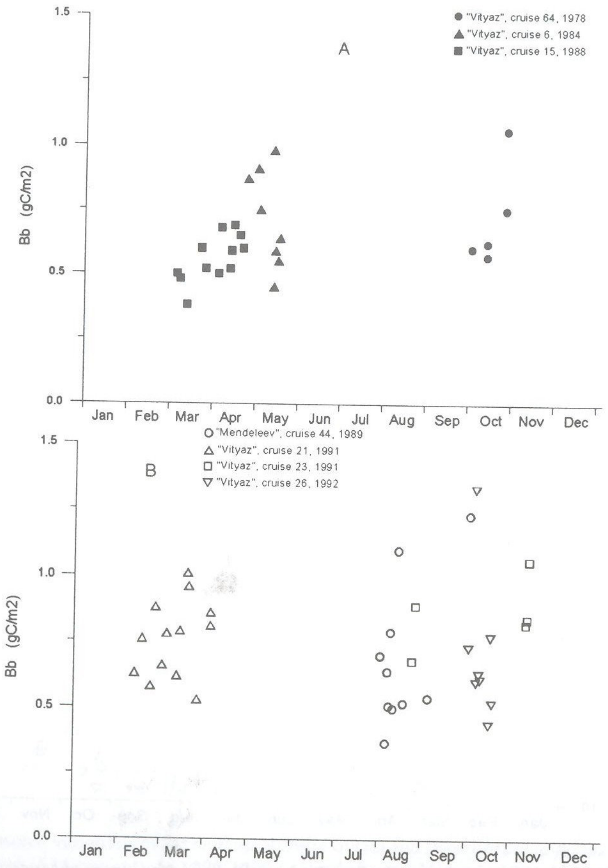

Figure 6. Seasonal variations of the biomass of bacteria B_b during the bloom of *Mnemiopsis* in 1989-1990 (A) and after the bloom in 1991-1992 (B). The data of Yu. I. Sorokin (SB SIO RAS).

Whereas the zooplankton community changed greatly, the changes of bacteria (Figure 6) (microzooplankton) and protozoa (Figure 7) before and after the *Mnemiopsis* bloom were insignificant.

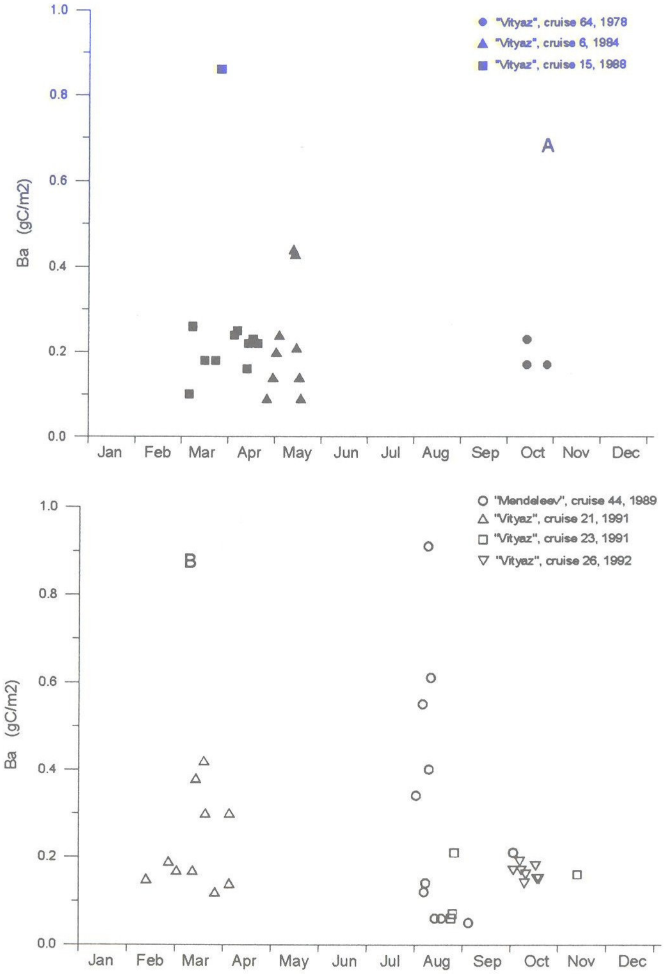

Figure 7. Seasonal variations of the biomass of protozoa B_a during the bloom of *Mnemiopsis* in 1989-1990 (A) and after the bloom in 1991-1992 (B). The data of Yu. I. Sorokin, E. V. Moiseev (SB SIO RAS), N. I. Tumantseva (SIO RAS), et. al.

The decrease of zooplankton biomass after *Mnemiopsis* bloom seems to result in increase of phytoplankton, the main food source of plankton phytophagous animals (Figure 8, A, B). The same trend was noted concerning primary production, the data analyzed by Vedernikov and Demidov [12].

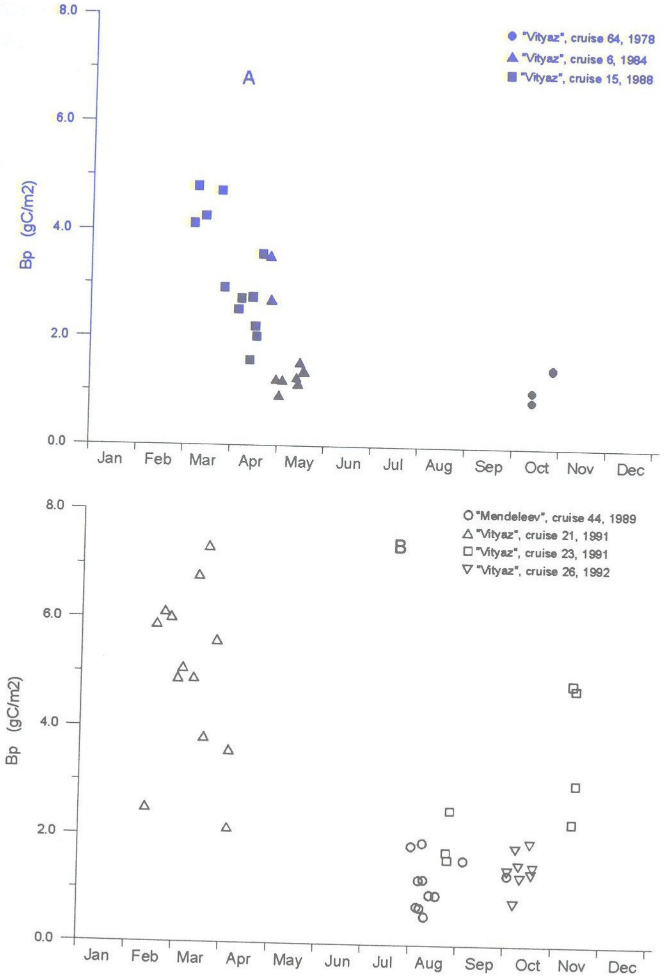

Figure 8. Seasonal variations of the biomass of phytoplankton $\mathbf{B_p}$ during the bloom of *Mnemiopsis* in 1989-1990 (A) and after the bloom in 1991-1992 (B). The data of A. S. Mikaelyan, I. N. Sukhanova (SIO RAS), L. V. Georgieva, L. G. Senichkina (IBSS).

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