

TRANSFORMATIONS OF NUTRIENTS IN THE NORTHEASTERN WATERS OF THE SAKHALIN SHELF: AN ANALYSIS OF MATHEMATICAL MODELING RESULTS

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Transformations of nutrients in marine environments of the Northeastern part of Sakhalin Shelf were studied in Regions 1–4. Three electronic devices were used for the analysis of the oceanographic information:

1. The GIS «Sakhalin Shelf» (to obtain data on the state of thermohaline parameters of sea waters).
2. The oceanic dynamic model of the Bergen University (to estimate the rates of water mass transport across boundaries of regions).
3. The hydroecological CNPSi-model (to calculate the chemical and biological characteristics and estimate qualitatively the features of the marine environment biohydrochemistry in various regions of Northeastern part of Sakhalin Shelf).

In this study the seasonal dynamics of the concentrations of organic and mineral substances of biogenic elements (N and P), and organism biomasses (heterotrophic bacteria, three groups of phytoplankton, and two groups of zooplankton are presented, which were reproduced on the basis of the long-term monthly values of the marine environment parameters (temperature, light intensity, transparency of water environment, biogenic load, water exchange parameters). Indicated organisms are involved in the substance transformations and providing their turnover in the water environment. An analysis of the changes in the nutrient concentrations allowed us to characterize the conditions during a year for the explanations of biomass organism development and change in values of their activity parameters (on the base of specific biomass growth rates and bioproductions).

Keywords: models for analysis of oceanological data; concentrations of nutrients; organism biomasses of lower trophic links – heterotrophic bacteria, three main groups of phytoplankton; herbivorous and predatory; specific growth rate, biomass turnover time, bioproduction

Introduction

Presently, the main tasks of biohydrochemical research, solved with the help of mathematical modeling, are connected with the study of the dynamics of nutrient substances (BS), their chemical and biological transformation in the aquatic environment and in sediments, the rates of chemical and biological processes, the circulation of BS in natural waters, conditions the formation of bioproductivity of water bodies, the balance of organogenic compounds, the study of metabolic processes at the interfaces of river

runoff-sea, water-atmosphere and water-bottom. In the aquatic environment, physical, chemical and biological processes associated with the transformation and chemical-biological transformation of BS of natural and anthropogenic origin are carried out. When studying the composition of the components of the aquatic environment, these processes should be considered not in isolation, but in close interconnection. Therefore, the modern methodology for studying the composition of the components of natural waters is based on the principles of system analysis, combining the results of research on the basic natural disciplines (chemistry, physics, biology, geography, geology), as well as related sciences (biohydrochemistry, geochemistry, biophysics, micro- and hydrobiology).

The degree of complexity of model development is reflected in the received ideas about the subject, the study of certain issues of the composition of the components of natural waters, the availability of information on individual disciplines that study the state of water resources. The methodology of model development is based on a combination of deterministic description of chemical, biological and physical processes developing in the aquatic environment. The studied water bodies are subdivided into regions, each of which is studied separately. As a result, quantitative information on the changes in time of chemical and biological characteristics is obtained depending on the impact on the ecosystem of the water body of the habitat factors – temperature (T_w), light intensity, water transparency, water regime, nutrient load (Leonov, 1999).

The research methodology in these studies is based on the application of third instruments for the analysis of oceanological data:

1. The GIS «Sakhalin Shelf» (Pishchal'nik, Bobkov, 2000) (for processing thermohaline observational data).
2. Hydrodynamic ocean model of the Bergen University (BOM) (Berntsen, 2004) (for calculations on thermohaline data of velocities and directions of currents and rates of water exchange).
3. The hydroecological CNPSi-model of transformation / turnover of BS (compounds of C, N, P, Si (Leonov, 2012) for calculating the dynamics of BS and biomass of organisms involved in their transformation). Instruments (1)–(3) are simultaneously used since 2007 to study the features of hydrodynamics of waters and biohydrochemistry of marine environments (Leonov et. al., 2010 a; b; 2016).

Calculations of currents for the Eastern Sakhalin Shelf were performed with the help of oceanic BOM model (Berntsen, 2004) for each month on the base of thermohaline parameter values (data accumulated in the GIS «Sakhalin Shelf» includes observations for 1948–1995 during the ice-free period at standard oceanographic stations in the offshore area of Sakhalin: for T_w – 18359, water salinity – 13480, values of water pH – 4367, content of O_2 – 6176, of NO_2 – 1457, of P – 1492, and of Si – 1650 (Pishchal'nik, Bobkov, 2000)).

The following features of the dynamics of marine currents on the Northeastern Sakhalin Shelf (NESS) are revealed:

- the restructuring of the water circulation scheme in the surface 100-m layer of shelf in the annual cycle occurs twice: in May–June and September–October;

- the calculated velocities of marine currents under ice in the area of NESS fluctuate from 4 to 7 cm/s, and the maximum velocities of water movement on the surface are observed in November (22.5 cm/s) (Pischal'nik et al., 2014).

Calculated current rates are coincided with measured in observations [Luchin et al., 1998].

The hydroecological CNPSi-model (simulation model of the transformation of C, N, P, Si -substances (Leonov, 2012)) calculates:

- instantaneous rates of changes in substance concentrations over all the considered transformation pathways;

- instantaneous concentrations of the state variables of the aquatic environment and bottom sediments in the studied ecosystem;

- turnover times of each chemical and biological state variables and the rates of biomass productions;

- substance fluxes through internal and external transformation pathways;

- complete balances of C, N, P, Si – substances for regions of the studied water area.

Calculations of the change in the substance concentrations were carried out for two years to assess the values of biohydrochemical parameters at the end of the first year corresponding to the average long-term environmental parameters. These values are taken as an initial concentrations, corresponding to the long-term environmental conditions, for the second year of calculations, to represent the seasonal dynamics of substance concentrations, biomass of organisms, an internal / external substance fluxes for the biohydrochemical characterizing of marine ecosystem behaviour depending on environmental conditions and anthropogenic influence (Leonov, 2012).

The short information for the hydroecological CNPSi-model

The hydroecological CNPSi-model (Leonov, 2012) is the formalized description of the interrelated biohydrochemical cycles of N- and P-substances, the most important processes of transformation of dissolved organic C (DOC), Si, O₂, and N₂ in a two-layered water system. The model is intended to study the effect on the marine ecosystem of the main natural and anthropogenic factors (T_w , light intensity, transparency of the water environment, biogenic load, water exchange). Month variations of these factors regulate the rates of the BS concentration changes, as well as the biomass of biological compartments the marine environment. The CNPSi-model calculates the intra-annual variations in the concentrations of DOC and O₂, detrital fractions of P (PD), N (ND), and Si (SiD), dissolved organic fractions of P (DOP), N (DON) and Si (DOSi), dissolved mineral forms of P (DIP), Si (DISi), and N (ammonium, NH₄, nitrites, NO₂, and nitrates, NO₃). Changes in the concentrations of BS are determined by the activity of organisms of the lower trophic chains – heterotrophic bacteria (*B1*), three dominant phytoplankton groups (*F1*, *F2*, *F3*), and two zooplankton groups – herbivorous (*Z1*) and predatory (*Z2*) (Leonov, 2012).

The structure of CNPSi-model most fully meets the requirements for applied models for studying the conditions in the formation of water quality and the state of

marine ecosystems. The peculiarity of the model is the explicit role of organisms in the mathematical description: in the biochemical oxidation of natural components, BS, and organic matter (OM) of the marine environment and pollutants, as well as in the cycle and regeneration of mineral compounds of biogenic elements (C, N, P, Si). The structure of the CNPSi-model equations was considered in (Leonov, 2012).

The program of the model is written in REM-FORTRAN. Visualization of simulation results (data of calculations) is carried out using the built-in CNPSi-model of the display system, adapted for WINDOWS-XP (Leonov et al., 2012).

Zoning of the water area of the Northeastern Sakhalin shelf

The entire water area of the NESS is divided into Regions 1–4 (Fig. 1). The morphometric parameters of these regions are presented in Table 1. Analysis of the oceanological parameters of the marine environment in the waters of the NESS (Fig. 1) made it possible to distinguish for Regions 1–4 their mean depths (640, 1520, 300 and 730 m, respectively). The smallest values of the water area and the water volume are in Region 2 (15 thousand km²) and in Region 3 (10.5 thousand km³), respectively. The values of water area and water volume are greatest in the Region 1: 48 thousand km² and 30.7 thousand km³ respectively (Table 1).

The next information were used as initial data for the calculations on the CNPSi-model: the morphometric parameters of the selected Regions 1–4 (mean depths, areas and water volumes), concentrations of BS in the tributaries and adjacent water areas, the long-term values of the marine environment state (mean monthly values of water temperature (T_w), light intensity, and the transparency of waters, as well as the values of water exchange (flow rates) between Regions 1–4 and open water areas of the Sea of Okhotsk. The water exchange parameters were calculated on the basis of the current indicators for the water areas of the NESS on the base of the oceanic model of the Bergen University (BOM) on the long-term observations for T_w and salinity (S_w) of the sea waters of the NESS area.

The methodology for preparing the initial data for calculations on the CNPSi-model was used earlier in the study by modeling the transformation conditions for BS and spatial transport of substances in the marine waters washing the shores of Sakhalin Island (Pishchal'nik, Leonov, 2003; Leonov, Pishchal'nik, 2005 a, b; Leonov et al., 2010 a, b; Pishchal'nik, et al., 2011).

Table 1. Morphometric characteristics of the Regions 1–4 of NESS

| Characteristic dimension | 1 | 2 | 3 | 4 |
|--------------------------------------|------|------|------|------|
| Mean depth, m | 640 | 1520 | 300 | 730 |
| Water area, thous. km ² | 48 | 15 | 35 | 18.7 |
| Water volume, thous. km ³ | 30.7 | 22.8 | 10.5 | 13.7 |

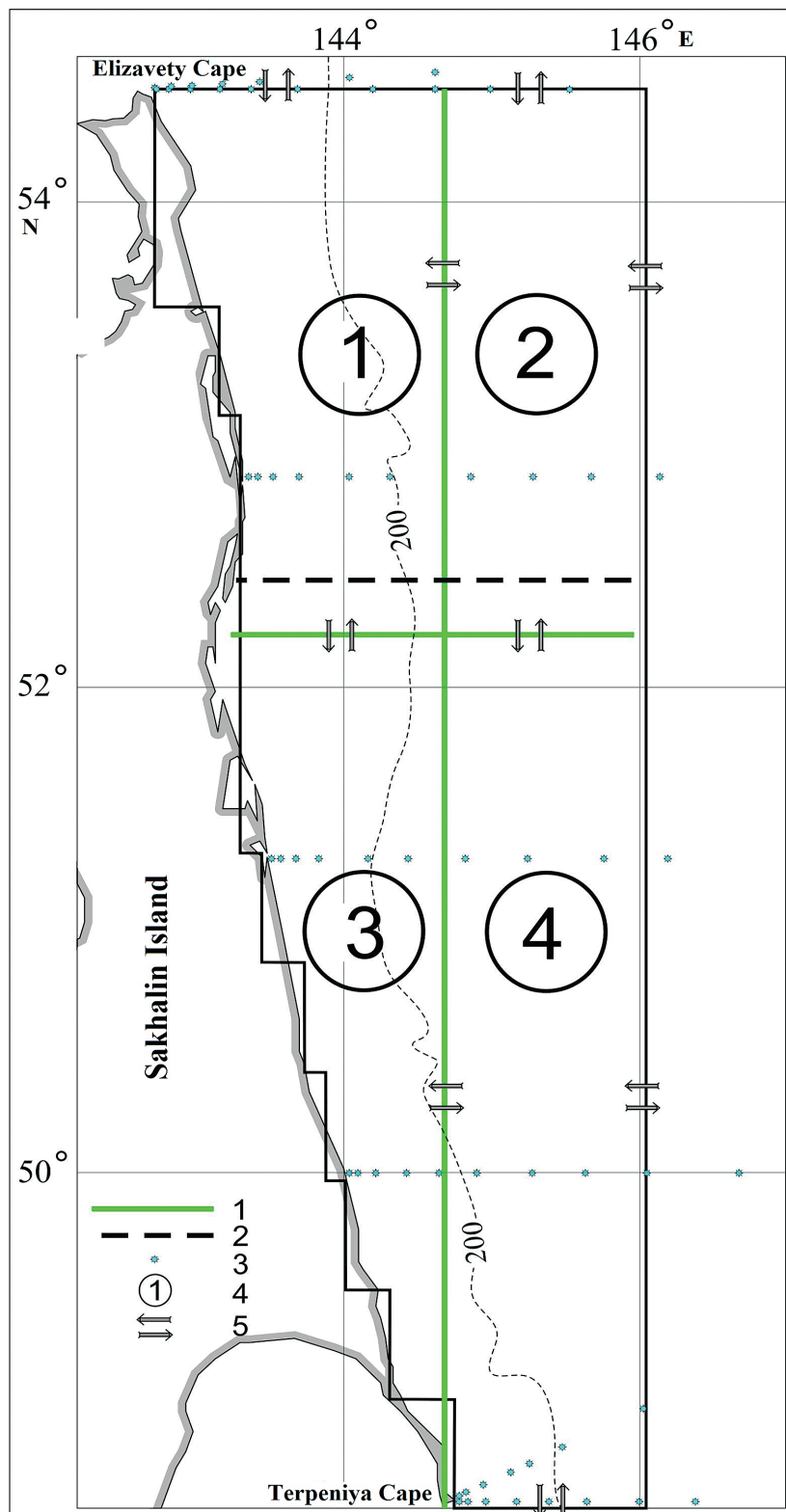


Fig. 1. Map-scheme of the water area of NESS (1 – the boundaries of Regions 1–4; 2 – the standard cross-section for 52°30' N; 3 – the location of standard stations in waters of NESS; 4 – numbers of regions; 5 – directions of water transfer through boundaries between regions and with open-waters of the Sea of Okhotsk

Table 2. Long-term values of marine environmental characteristics by month for Regions 1–4 of NESS (dash means that the layer was not chosen; here and in Table 3, the numbers above and below the line are for the top and bottom layers, respectively)

| Region | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Depth of vertical mixing of water (XI–V) and thermocline position (VI–X), m | | | | | | | | | | | | |
| 1–4 | 150 | 150 | 150 | 150 | 150 | 20 | 30 | 40 | 50 | 60 | 75 | 100 |
| Water temperature, °C | | | | | | | | | | | | |
| 1 | -0.8 | -1.2 | -1.3 | -1.4 | -1.1 | 1.7 | 4.6 | 5.4 | 6.2 | 3.7 | 1.1 | 0.0 |
| | 1.5 | 1.0 | 1.0 | 1.0 | 1.4 | -0.3 | 0.0 | 0.3 | 0.5 | 0.6 | 0.8 | 0.8 |
| 2 | -0.6 | -1.0 | -1.2 | -1.2 | -0.9 | 3.1 | 6.5 | 6.7 | 6.9 | 4.1 | 1.2 | 0.1 |
| | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 0.8 | 1.0 | 1.0 | 1.0 | 1.2 | 1.3 | 1.3 |
| 3 | -0.6 | -1.2 | -1.4 | -1.4 | -1.1 | 2.4 | 4.8 | 5.5 | 6.1 | 4.0 | 1.9 | 0.2 |
| | 0.2 | -0.2 | -0.6 | -0.7 | -0.6 | -0.7 | -0.3 | -0.1 | 0.2 | 0.4 | 0.5 | 0.2 |
| 4 | -0.4 | -1.1 | -1.3 | -1.3 | -0.9 | 3.0 | 5.7 | 6.0 | 6.3 | 4.3 | 2.0 | 0.3 |
| | 0.8 | 0.6 | 0.5 | 0.5 | 0.5 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 | 0.8 |
| Light intensity, cal/(sm ² day) | | | | | | | | | | | | |
| 1–4 | 90.3 | 114.2 | 167.8 | 213.4 | 219.4 | 240.0 | 219.4 | 206.5 | 200.0 | 128.8 | 120.0 | 90.3 |
| Photoperiod, dimensionless | | | | | | | | | | | | |
| 1–4 | 0.32 | 0.39 | 0.48 | 0.60 | 0.66 | 0.71 | 0.69 | 0.62 | 0.54 | 0.48 | 0.34 | 0.32 |
| Precipitation, km ³ | | | | | | | | | | | | |
| 1–2 | 1.113 | 0.894 | 0.978 | 1.492 | 1.956 | 1.834 | 2.760 | 3.191 | 3.583 | 2.702 | 1.692 | 1.608 |
| 3–4 | 1.575 | 1.143 | 1.134 | 1.253 | 1.609 | 1.524 | 2.269 | 2.379 | 2.642 | 2.261 | 2.159 | 2.057 |
| Secchi depth, m | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1(0) | 3 | 6 | 7 | 7 | 8 | 8 | 9 | 8 |
| 2 | 2 | 3 | 1 | 1 | 5 | 8 | 8 | 7 | 8 | 10 | 11 | 12 |
| 3 | 1 | 2 | 1 | 1(0) | 6 | 7 | 8 | 7 | 8 | 8 | 9 | 10 |
| 4 | 1 | 1 | 1 | 1 | 8 | 7 | 8 | 7 | 8 | 10 | 10 | 12 |

The main seasonal features in changes of thermohaline parameters in the Regions 1–4 of the NESS are singled out. The analysis of the data on the vertical distribution of T_w in the waters of the NESS, performed with the help of GIS «Sakhalin Shelf», revealed a subdivision of the water column into two layers during a year [Pishchal'nik et al., 2014]: in the cold period, this is associated with the development of winter vertical water circulation processes, and in warm weather – with warming up surface layer. Accordingly, in Regions 1–4 during the cold period (January–May), the thickness of the surface layer with negative values of mean T_w (-0.4 – -1.4 °C) reaches 150 m. It should be noted that the mean T_w of the subsurface layer during a year in Regions 2 and 4 remain low, but retain positive values (respectively 0.8–1.4 and 0.1–0.8° C); in the Region 3, the

subsurface waters with the negative T_w ($-0.1 \dots -0.7^\circ \text{C}$) is noted in February–August, and in the remaining months, the average T_w varies here within $0.2\text{--}0.5^\circ \text{C}$. In Region 1 in the subsurface layer, the average T_w has the lowest values in the period of June–August (-0.3 , 0.0 , and 0.3°C , respectively), in the remaining months of a year, the average values of T_w vary within the range of $0.5\text{--}1.5^\circ \text{C}$ (Table 2).

In waters of Regions 1–4, the highest average values of T_w in the surface layer were recorded in September (6.2 , 6.9 , 6.1 , and 6.3°C , respectively). The maximum warming of surface waters is recorded in open waters (Region 2), and the minimum – in the coastal Region 3 (as a result of the clearly pronounced upwelling of waters). In the spring–summer period, water heating does not extend to depths > 30 m, and autumn mixing of water is accompanied by a decrease in the values of mean T_w of the upper quasihomogeneous layer (in October to $3.7\text{--}4.3^\circ \text{C}$, in November to $1.1\text{--}2.0^\circ \text{C}$, in December to $0.0\text{--}0.3^\circ \text{C}$) and an increase in the thickness of this layer (up to 60 , 75 , and 100 m, respectively) (Table 2).

During a year, the highest values of light intensity and photoperiod occur in May–July, while precipitation of atmospheric precipitation falls on August–September (Table 2).

The water transparency was estimated from the depth of visibility of the white Seki disk. Its values in the Regions 1–4 were selected from the reports on the separate expeditions of the Hydrometeorological Service and the fishing industry performed in various years. In Regions 1–4, the average values of the water transparency in individual months varied accordingly within the limits of $1\text{--}9$, $1\text{--}12$, $1\text{--}10$, and $1\text{--}12$ m. The smallest average transparency values of water ($1\text{--}2$ m) in these regions fall within the period January–April, and the highest values ($10\text{--}12$ m) – in November–December (Table 2).

The values of total flow rates calculated with the help of BOM (Table 3, Appendix) determine the expressed bilateral water exchange through the boundaries between Regions 1–4 and with open water areas of the Sea of Okhotsk. The range of water flow rate values varies within one to three orders of magnitude, taking into account the fluctuations in the thickness of the separated upper and lower layers of water in different months.

The water transfer in January–May in the surface layer from Region 1 to Region 2 is characterized by water flow rate values of $192.9\text{--}377.0 \text{ km}^3/\text{month}$, in June–August it is weakening (water flow rate values are reduced to $0.8\text{--}11.0 \text{ km}^3/\text{month}$), in the following months (September–December) – the water exchange is increasing (flow rate values increase to $200.4\text{--}419.0 \text{ km}^3/\text{month}$). For most part of a year, the reverse water transfer in the surface layer (from Region 2 to Region 1) is more active: the periods January–May and June–September are characterized by flow rate values, respectively $467.1\text{--}644.6$ and $64.9\text{--}103.4 \text{ km}^3/\text{month}$, and in October–December, the flow rate values are within $232.2\text{--}412.5 \text{ km}^3/\text{month}$, and comparable with the water transfer from Region 1 to Region 2. The intensity of the water transport in the lower layer (from Region 1 to Region 2 and backward transfer from Region 2 to Region 1) remains high throughout a year, as evidenced by fluctuations in different months of flow rate values – within $1221.6\text{--}2126.5$ and $1382.4\text{--}2094.5 \text{ km}^3/\text{month}$ (Table 3).

Table 3. Long-term monthly values of flow rates at the boundary of Regions 1–4 (NESS), exchange with outer waters of the Sea of Okhotsk, vertical transport, and river runoff (all – in km³/month)

| Transport from | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|-------------------------|-------------------------|-------------------------|------------------------|-------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------------------|
| 1 → 2 | <u>377.0</u> 1607.5 | <u>313.3</u> 1739.6 | <u>356.4</u> 1836.1 | <u>304.9</u> 1773.3 | <u>192.9</u> 2087.0 | <u>6.1</u> 2126.5 | <u>0.8</u> 1885.8 | <u>11.0</u> 1794.6 | <u>200.4</u> 1221.6 | <u>253.6</u> 1304.6 | <u>419.0</u> 1565.2 | <u>284.6</u> 1450.2 |
| 2 → 1 | <u>467.1</u> 1576.4 | <u>500.0</u> 1629.7 | <u>534.4</u> 1752.8 | <u>553.3</u> 1625.8 | <u>644.6</u> 1738.8 | <u>98.0</u> 2094.5 | <u>193.4</u> 1728.9 | <u>163.2</u> 1675.0 | <u>64.9</u> 1382.4 | <u>232.2</u> 1440.4 | <u>412.5</u> 1753.3 | <u>357.7</u> 1521.8 |
| 3 → 1 | <u>88.5</u> 9.0 | <u>89.4</u> 0.3 | <u>128.8</u> 0.2 | <u>132.6</u> 0.7 | <u>138.0</u> 0.2 | <u>52.0</u> 143.6 | <u>124.5</u> 130.4 | <u>98.5</u> 112.8 | <u>49.0</u> 149.4 | <u>54.8</u> 307.2 | <u>52.3</u> 209.9 | <u>83.9</u> 118.3 |
| 1 → 3 | <u>55.1</u> 49.3 | <u>62.6</u> 78.3 | <u>85.8</u> 114.3 | <u>88.7</u> 118.5 | <u>69.8</u> 138.5 | <u>14.8</u> 159.9 | <u>9.5</u> 174.4 | <u>17.8</u> 107.6 | <u>44.1</u> 79.9 | <u>241.8</u> 97.2 | <u>246.0</u> 79.2 | <u>143.7</u> 78.4 |
| 4 → 2 | <u>244.1</u> 417.4 | <u>277.0</u> 416.1 | <u>340.0</u> 468.9 | <u>323.5</u> 495.5 | <u>308.3</u> 524.1 | <u>33.8</u> 672.1 | <u>28.9</u> 830.1 | <u>129.1</u> 452.2 | <u>111.3</u> 443.9 | <u>17.4</u> 711.9 | <u>60.9</u> 696.7 | <u>112.6</u> 632.6 |
| 2 → 4 | <u>30.5</u> 643.3 | <u>14.2</u> 632.6 | <u>8.1</u> 730.5 | <u>6.8</u> 737.2 | <u>17.4</u> 799.5 | <u>4.5</u> 752.8 | <u>69.4</u> 901.2 | <u>0.0</u> 716.6 | <u>5.2</u> 663.7 | <u>88.7</u> 680.6 | <u>40.9</u> 648.3 | <u>25.7</u> 708.9 |
| 3 → 4 | <u>236.1</u> 310.6 | <u>262.2</u> 178.6 | <u>345.6</u> 152.8 | <u>371.9</u> 148.8 | <u>497.6</u> 108.7 | <u>174.9</u> 533.0 | <u>62.2</u> 425.5 | <u>147.9</u> 515.1 | <u>203.9</u> 515.5 | <u>298.8</u> 637.8 | <u>412.0</u> 716.9 | <u>264.7</u> 636.2 |
| 4 → 3 | <u>226.1</u> 265.3 | <u>114.0</u> 234.1 | <u>107.0</u> 277.9 | <u>104.8</u> 303.5 | <u>89.3</u> 458.2 | <u>11.8</u> 676.0 | <u>61.1</u> 460.7 | <u>58.3</u> 645.1 | <u>130.8</u> 625.9 | <u>203.1</u> 724.0 | <u>300.9</u> 732.2 | <u>435.2</u> 404.7 |
| Exchange with outer water area – from the Sea of Okhotsk | | | | | | | | | | | | |
| 1 → N | <u>387.8</u> 357.1 | <u>361.0</u> 328.4 | <u>354.1</u> 312.4 | <u>375.8</u> 320.2 | <u>493.3</u> 224.2 | <u>73.8</u> 476.6 | <u>265.0</u> 629.3 | <u>284.4</u> 484.6 | <u>174.8</u> 552.7 | <u>154.9</u> 517.9 | <u>302.3</u> 488.0 | <u>340.5</u> 610.7 |
| N → 1 | <u>108.8</u> 757.2 | <u>72.5</u> 736.0 | <u>64.2</u> 733.8 | <u>53.8</u> 757.3 | <u>71.5</u> 822.3 | <u>33.2</u> 674.3 | <u>36.6</u> 1014.1 | <u>58.8</u> 891.2 | <u>64.1</u> 766.5 | <u>145.7</u> 674.5 | <u>151.0</u> 785.0 | <u>75.6</u> 1018.3 |
| 2 → N+E | <u>600.5</u> 4661.7 | <u>716.5</u> 4427.6 | <u>581.0</u> 4601.3 | <u>510.4</u> 4043.4 | <u>499.4</u> 4287.4 | <u>38.9</u> 4936.3 | <u>5.8</u> 4832.6 | <u>38.0</u> 4493.2 | <u>216.7</u> 4108.8 | <u>103.3</u> 4796.2 | <u>327.6</u> 4900.6 | <u>326.1</u> 4285.7 |
| N+E → 2 | <u>1127.6</u> 4339.7 | <u>1042.6</u> 4263.3 | <u>1030.7</u> 4029.1 | <u>948.8</u> 3502.2 | <u>1060.0</u> 4522.6 | <u>130.6</u> 4703.0 | <u>324.1</u> 4342.5 | <u>293.0</u> 4019.9 | <u>280.8</u> 3920.3 | <u>457.6</u> 4297.2 | <u>706.6</u> 4390.5 | <u>741.1</u> 3758.8 |
| 4 → E+S | <u>1469.5</u> 2452.5 | <u>1023.5</u> 2284.6 | <u>1013.0</u> 2438.5 | <u>976.6</u> 2375.2 | <u>1282.8</u> 2596.4 | <u>294.0</u> 4391.3 | <u>344.0</u> 4377.9 | <u>397.1</u> 4297.9 | <u>646.4</u> 4041.6 | <u>1190.8</u> 3593.5 | <u>2072.4</u> 3150.0 | <u>1676.0</u> 2502.1 |
| E+S → 4 | <u>595.5</u> 3307.0 | <u>719.8</u> 2570.2 | <u>847.8</u> 2582.5 | <u>900.5</u> 2428.3 | <u>1120.8</u> 2773.7 | <u>290.3</u> 4377.4 | <u>717.4</u> 3996.9 | <u>927.3</u> 3773.7 | <u>984.6</u> 3698.5 | <u>644.3</u> 4096.5 | <u>735.8</u> 4413.7 | <u>629.6</u> 3502.0 |
| Vertical transport in water area: («+») means upward, («-») means downward) | | | | | | | | | | | | |
| 1 | +238.8 | +45.8 | -77.4 | -86.9 | -207.3 | +12.8 | -4.1 | -57.5 | +356.6 | +311.5 | +472.1 | +529.3 |
| 2 | -842.9 | -901.9 | -931.4 | -870.4 | -583.5 | -68.7 | -164.9 | -230.4 | -291.7 | -350.9 | -417.3 | -553.8 |
| 3 | -85.4 | -49.9 | -46.3 | -35.6 | +20.8 | +260.9 | +110.6 | +144.9 | +55.1 | +65.4 | +76.3 | -156.2 |
| 4 | +387.6 | +166.6 | +105.0 | +94.7 | +88.1 | +77.7 | +57.1 | +21.7 | +261.8 | +374.0 | +567.6 | +649.0 |
| River runoff – Tym' River | | | | | | | | | | | | |
| 3 | 0.048 | 0.035 | 0.036 | 0.094 | 0.935 | 0.511 | 0.177 | 0.164 | 0.187 | 0.228 | 0.109 | 0.067 |

The intensity of surface water transfer in different months in the coastal zone (from Region 3 to Region 1 and reverse transfer – from Region 1 to Region 3) is lower, and is characterized by fluctuations in water flow rates, respectively, within 52.0–138.0 and

9.5–246.0 km³/month. The water transfer from Region 3 to Region 1 in the lower layer in January–May is insignificant (fluctuations in flow rates are in the range 0.2–9.0 km³/month), and in June–December its intensity is significantly higher (their values are 112.8–307.2 km³/months). Reverse water transfer in the lower layer (from Region 1 to Region 3) is valid for a year and is characterized by fluctuations of flow rates in the range of 49.3–174.4 km³/months (Table 3).

The transfer of surface waters (at the border of Regions 3 and 4) during a year is more active from coastal Region 3 to Region 4 with fluctuations of flow rate (km³/month) values in November–May, June–August and September–October within 262.2–497.6, 62.2–174.9, and 203.9–298.8 respectively. Reverse transfer of surface waters (from Region 4 to Region 3) during the indicated periods of a year occurs at the water flow rates that vary within 89.3–435.2, 11.8–61.1, and 130.8–203.1 respectively. On the contrary, in the lower layer the intensity of the water transport during a year is generally higher from the Region 4 to Region 3 (the range of flow rate fluctuations in certain months is 234.1–732.2 km³/month) than the reverse water transfer from Region 3 to Region 4 (108.7–716.9 km³/month) (Table 3).

The transfer of surface waters in the moraine part of the NESS (at the border of Regions 2 and 4) is more intensive from Region 4 to Region 2 (with fluctuations in water flow rates in January–May, June–August and September–December, respectively, 244.1–340.0, 28.9–129.1, and 17.4–112.6 km³/month) in comparison with the reverse water transfer from Region 2 to Region 4 in the same periods of a year, however, it occurs more intensively from Region 2 to Region 4 (with fluctuations in water flow rates in individual months within 632.6–901.2 km³/month) than from Region 4 to Region 2 (416.1–830.12 km³/month) (Table 3).

During a year, there is also a bilateral water exchange through the boundaries of the NESS regions with open water areas of the Sea of Okhotsk. The calculations took into account the water flow rate values estimated with the help of BOM, which determine the water exchange in the North of the NESS (with Region 1), as well as the total water exchange in the North and East (with Region 2) and in the East and South (with Region 4).

The intensity of surface water transfer from Region 1 to the North from November to May is characterized by water flow rates of 302.3–493.3 km³/month; in June, the water transfer slows down (the water flow rate is reduced to 73.8 km³/month), and from July to October, the water exchange increases (at water flow rates of 154.9–284.4 km³/month). The reverse water transfer (from the North to the Region 1) is carried out with lower water flow rates: in October–February they are within 72.5–151.0 km³/month, and in the remaining months – are reduced to 33.2–64.2 km³/month.

The water transfer from Region 2 to the North and East in January–May is characterized by flow rate values of 499.4–716.5 km³/month; in May–July, its intensity drops significantly (5.8–38.9); and in August–December, it increases (103.3–327.6 km³/month). The reverse water transfer to the Region 2 (in January–May) is developing quite actively (at a water flow rates of 948.8–1127.6); in June–September, its activity is weakening (130.6–324.1), and in October–December, it is increasing (457.6–741.1 km³/month).

From Region 4, the total water transfer develops in the direction of the East and South from October to May with increased flow rates (976.6–2072.4 km³/month); and in June–September – with slightly slower flow rates (294.0–646.4 km³/month). In the most part of a year, the water transfer to the Region 4 from the East and South is active, and it is characterized by water flow rate values of 595.5–1120.8 km³/month, and only in June, the water transfer is carried out at a lower speed (290.3 km³/month).

In the lower layer throughout a year, a high two-way water transport was noted across the boundaries of Regions 1, 2 and 4 of the NESS with open water areas of the Sea of Okhotsk. During a year, the transfer of waters from Region 1 to the North is developing quite actively (with water flow rates of 224.2– 629.3 km³/month), but the reverse water transfer to Region 1 is even more intensive (674.3–1014.1 km³/month) (Table 3).

During a year, the water transfer from Region 2 in the direction to the North and East is much higher and is characterized by water flow rates of 4043.4–4936.3 km³/month, the return water transfer to Region 2 passes with slightly less activity (3502.2–4390.5 km³/month).

Two-way water exchange at the border of the Region 4–E/S is also carried out with high water flow rates: in the direction from Region 4 and in the opposite stream these rates vary accordingly in the ranges 2284.6–4391.3 and 2428.3–4413.7 km³/month (Table 3).

The estimated values of vertical water exchange between the upper and lower layers are significantly different: the total range of changes in water flow rate values in Regions 1–4 are 4.1–529.3, 68.7–931.4, 20.8–260.9, 21.7–649.0 km³/month respectively. The values of vertical exchange are the least in Regions 1–4 in July, June, May, and August respectively, and they are elevated in December, March, June, and December. The highest values of vertical water exchange occur in Regions 1–4, respectively, in September–January (238.8–529.3 km³/month), December–May (553.8–931.4), June–August (110.6–260.9), and September–January (261.8–649.0 km³/month) (Table 3).

Further in the text, the results of intra-annual variations in the calculated concentrations of the main N, P, Si, substances for the second calculated year are presented and discussed. It should be noted a stable tendency of «correspondence» of the concentrations of substances (at the beginning and at the end of a year), which confirms the balance of these processes for the mean long-term conditions in the ecosystem of the NESS.

Calculation of BS inputs in waters of Regions 1–4

The input of BS into the sea water area occurs with the runoff of the Tym' River (to Region 3), from open areas of the Sea of Okhotsk (to Regions 2 and 4), as well as from neighboring water areas and with atmospheric precipitation (in Regions 1–4).

River runoff to the sea waters of the Region 3. Annual flow of the Tym' River is 2.591 km³/year, the average monthly flow rate is 0.216 km³/month. It is the smallest in February (0.035) and the largest in May and June (0.935 and 0.511 km³/month) (Table 3). According to the accepted average concentrations of BS as well as water flow rates, the monthly BS inputs into the surface layer of sea water in Region 3 were calculated. It

should be noted the following peculiarities of the BS inputs with river runoff into sea waters:

- the annual BS inputs with the runoff of Тым' River into the sea waters of Region 3 are: DOC – 5.97 thousand tons of C; DON – 0.12, NH₄ – <0.01, NO₂ – <0.01, NO₃ – 0.08, ND – 0.30 thousand tons of N; DIP and DOP – on 0.02, PD – 0.09 thousand tons of P; DISi – 2.38 thousand tons of Si;

- ~50–79.5% of the annual BS inputs with river runoff into the waters of Region 3 is in May–June; in the winter months it is the smallest (<10%); for the summer and autumn months, there are a total ~15–25% of the annual BS inputs.

Transfer of BS at bilateral water exchange between Regions 1–4. Table 4 shows the calculation results of the BS inputs in each region during water exchange through the boundaries between Regions 1–4, namely: the amplitude ranges of the monthly transfer, the final annual and «net» transfer (taking into account the losses to remove the BS with a counterflow of water). For Region 1, these carry-off losses are significantly lower than their input for water exchange with neighboring areas, in Region 3 – it is higher only for a number of substances (DOC, ND, PD, NH₄, NO₂, and DIP), and in Regions 2 and 4 – the input almost all BS is less of their outputs in the neighboring areas.

Transfer of BS in bilateral water exchange between the open waters of the Sea of Okhotsk and Regions 1–4. Table 5 shows the results of calculations of the BS inputs in Regions 1, 2 and 4 during water exchange with open areas of the Sea of Okhotsk, in which the substance concentrations in individual months were taken as a result of previous calculations (Leonov, Sapozhnikov, 1997).

The BS inputs with atmospheric precipitation into the surface layer of sea water in Regions 1–4 is estimated from monthly precipitation data (Table 2) and taken as constant concentrations of BS in atmospheric moisture (DOC = 2 mg C/L, DON = 0.1, ND = 0.1; NH₄ = 0.3; NO₂ = 0.01; NO₃ = 0.25 mg N/L; DIP = 0.015; DOP = 0.01; PD = 0.01 mg P/L). The least amount of BS comes in the marine environment with atmospheric moisture in February: for Regions 1–2 and 3–4 these amounts in relation to the annual BS input are 3.6 and 5.0%, respectively, and the greatest amount of BS with atmospheric moisture comes in September (in Regions 1–2 and 3–4 – according to 14.1 and 11.5% of annual BS inputs respectively).

Analysis of calculated dynamics of BS concentrations in waters of Regions 1–4

The calculated intra-annual dynamics of BS concentrations and organism biomasses are shown in Fig. 2–5.

Annual changes of the concentrations of NH₄ (Fig. 2a) and NO₂ (Fig. 2b) in the aquatic environment are very similar, since these variables are closely interrelated. The initial values of the concentrations of NH₄ and NO₂ are small and vary in the waters of Regions 1–4 within 0.0002–0.001 mg N/L.

During a year, one expressed maximum of the concentrations of NH₄ is recorded in Regions 1–4: on the 185th, 171st, 178th, and 171st days (0.0285, 0.0198, 0.0037 and 0.0221 mg N/L), respectively. In the second half of a year, three synchronous small peaks

of NH_4 concentrations can be identified in Regions 2 and 4. They are also related with clear NO_2 maxima formed after the formation of intermediate NH_4 peaks. In Regions 1–4, NO_2 maxima fall respectively on the 188th, 173rd, 185th, and 176th days (0.0079, 0.0060, 0.0015, and 0.0068 mg N/L).

Table 4. Estimated number of BS entering the upper water layer monthly (thousand tons of Element /month) and per year (thousand t of Element/year) into waters of regions 1–4 (NESS) at the bilateral water exchange across the boundaries between these regions (1 – the range of changes by months; 2 – the annual input; 3 – the «net» input for a year, or the difference between the input and output by water flow to neighboring areas

| Parameter | Region 1 | | | Region 2 | | |
|---------------|--------------|---------|---------|-------------|---------|----------|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| DOC | 20.39–1258.2 | 7248.57 | 6771.21 | 0.00–694.53 | 3633.57 | –3577.04 |
| DON | 0.00–171.44 | 644.83 | 238.00 | 7.25–180.88 | 1253.67 | 871.55 |
| ND | 1.06–13.04 | 74.28 | 64.15 | 0.00–13.11 | 26.09 | –54.62 |
| PD | 0.01–1.50 | 4.03 | 2.71 | 0.00–0.28 | 0.73 | –3.66 |
| DOP | 0.01–3.53 | 11.41 | 7.85 | 0.01–4.41 | 17.91 | 7.06 |
| NH_4 | 0.01–1.12 | 5.62 | 4.53 | 0.02–0.55 | 2.46 | –3.31 |
| NO_2 | 0.00–0.56 | 2.73 | 2.36 | 0.01–0.16 | 1.10 | –1.33 |
| NO_3 | 0.01–26.97 | 74.55 | 67.68 | 0.12–16.68 | 61.85 | –4.45 |
| DIP | 0.29–11.25 | 47.76 | 34.53 | 0.03–7.98 | 39.81 | –9.45 |
| DISi | 0.00–28.95 | 77.79 | 8.04 | 0.24–57.23 | 240.90 | 211.85 |

| Parameter | Region 3 | | | Region 4 | | |
|---------------|-------------|---------|----------|-------------|---------|----------|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| DOC | 0.00–514.49 | 1843.15 | 699.98 | 0.00–268.58 | 1252.04 | –3740.39 |
| DON | 0.00–124.55 | 349.84 | –1073.67 | 0.19–253.30 | 1158.43 | –37.35 |
| ND | 0.02–8.13 | 40.24 | 38.19 | 0.00–3.83 | 8.39 | –47.82 |
| PD | 0.00–0.75 | 2.23 | 1.42 | 0.00–0.63 | 1.15 | –0.47 |
| DOP | 0.01–1.96 | 4.42 | –11.02 | 0.00–1.98 | 17.91 | –8.38 |
| NH_4 | 0.00–0.48 | 1.75 | 1.20 | 0.00–0.30 | 1.34 | –1.80 |
| NO_2 | 0.00–1.46 | 1.68 | 1.12 | 0.00–0.11 | 1.10 | –0.64 |
| NO_3 | 0.00–2.12 | 5.24 | –58.77 | 0.00–16.07 | 55.20 | –7.01 |
| DIP | 0.00–10.61 | 40.26 | 32.36 | 0.00–2.79 | 9.16 | –53.92 |
| DISi | 0.00–24.98 | 61.69 | –247.51 | 0.00–57.23 | 202.83 | –46.64 |

The initial values of NO_3 concentrations in Regions 1–4 differ and amount to 0.030, 0.028, 0.036, and 0.020 mg N/L, respectively. In general, the same trends are observed in the dynamic of NO_3 concentrations in the waters of all regions. In the first half of a year, NO_3 is accumulated in water environment, and in Regions 1 and 2, the rates of NO_3 accumulation are higher, and NO_3 peaks (0.0640 and 0.0551 mg N/L) are noted here respectively on 168th and 120th days. In Regions 3 and 4, the highest concentrations of NO_3 were recorded respectively at 152nd and 185th days (0.0422 and 0.463 mg N/L). During the period 183–218th days, concentrations of NO_3 are sharply decreased (up to

0.7–2.8 µg N/L) in waters of all regions. These small concentrations of NO₃ persist till 292nd day in the waters of Regions 1–4. The content of NO₃ concentrations in the aquatic environment are restored to their original values in the period autumn – the end of a year (Fig. 2c).

Table 5. Estimated amount of BS entering the upper water layer monthly (thousand tons of Element/month) and for a year (thousand t of Element/year) into waters of Regions 1, 2 and 4 (NESS) at the bilateral water exchange through boundaries with the open waters of the Sea of Okhotsk (1 – range of changes by months, 2 – annual input, 3 – «net» annual input, or difference between input and output by water flow to open water areas of the sea) (dash – flux was not estimated)

| Parameter | Region 1 | | | Region 2 | | | Region 4 | | |
|-----------------|--------------|--------|----------|------------------|----------|----------|-----------------|----------|---------|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| DOC | 1.67 – 30.95 | 139.79 | -4335.26 | 398.85 – 3534.06 | 25151.06 | 15487.09 | 85.24 – 1957.54 | 11539.78 | 8107.60 |
| DON | 0.04 – 3.27 | 10.24 | -2106.08 | 0.09 – 6.32 | 29.71 | -1731.35 | 14.22 – 304.08 | 1445.96 | 460.36 |
| ND | 0.01 – 2.94 | 3.83 | -37.75 | 0.10 – 5.27 | 16.91 | 10.54 | 0.11 – 5.04 | 19.65 | -6.67 |
| PD | 0.01 – 0.07 | 0.33 | -3.22 | 0.03 – 2.03 | 7.80 | 1.43 | 0.11 – 1.13 | 6.02 | 3.94 |
| DOP | 0.01 – 0.17 | 0.73 | -38.74 | 0.01 – 5.99 | 13.91 | -31.66 | 0.06 – 7.64 | 35.35 | 29.40 |
| NH ₄ | 0.01 – 0.09 | 0.49 | -5.38 | 0.04 – 0.60 | 4.38 | -1.61 | 0.10 – 0.94 | 4.66 | 3.25 |
| NO ₂ | 0.01 – 0.04 | 0.21 | 1.73 | 0.03 – 0.23 | 1.77 | -1.45 | 0.03 – 0.59 | 3.60 | 3.23 |
| NO ₃ | 0.04 – 3.38 | 13.39 | -102.98 | 2.65 – 45.03 | 246.18 | 104.47 | 0.92 – 20.98 | 111.84 | 92.27 |
| DIP | 0.00 – 0.26 | 1.14 | -66.37 | 0.01 – 2.71 | 12.96 | -81.24 | 0.17 – 16.43 | 77.90 | 37.05 |
| DISi | 0.06 – 0.87 | 4.80 | -224.32 | 0.35 – 15.86 | 99.46 | -62.63 | 2.80 – 125.75 | 720.41 | 617.62 |

In the first part of a year, the dynamics of the total mineral N (N_{min}) concentrations in the waters of Regions 1–4 oscillates synchronously with changes in the NO₃ concentrations as the dominant fraction of N_{min}. In the middle of a year, expressed maxima of N_{min} contents were noted: in Regions 1 and 3 – on the 185th day (0.0971 and 0.0469 mg N/L) and in Regions 2 and 4 – on the 174th day (0.0747 and 0.0668 mg N/L), which is a consequence of the increased concentrations of NH₄ and NO₂, fixed in these regions in almost the same periods of time. In the last third of a year, the dynamics of N_{min} concentrations coincides practically with the NO₃ dynamics since the content of NH₄ and NO₂ remains low in the second half of a year and does not significantly affect the total N_{min} content in different regions of the sea (Fig. 2d)

In the waters of coastal Regions (1 and 3) and in remoted from the coast Regions (2 and 4), concentrations of DON differ significantly. In the waters of Regions 1 and 3, the concentration of DON is higher for most part of a year. Annual amplitude of DON fluctuations in these regions are smaller (respectively, within 0.6423–0.3942 and 0.6400–0.4871 mg N/L) in comparison with Regions 2 and 4. The initial DON concentrations in the waters of Regions 2 and 4 are 0.5 and 0.23 mg N/L respectively. In Region 2 during the first half of a year, the DON content decreases to 0.2092 mg N/L, and in Region 4, it practically does not change. In summer period, the DON content in the waters of Regions 2 and 4 increases significantly: in the Region 2 – to 0.5738 mg N/L (at 274th day), and in the Region 4 – to 0.7538 mg N/L (at 245th day). By the end of a year,

the content of DON in the waters of Regions 2 and 4 is decreasing and approaching the initial values (Fig. 2e).

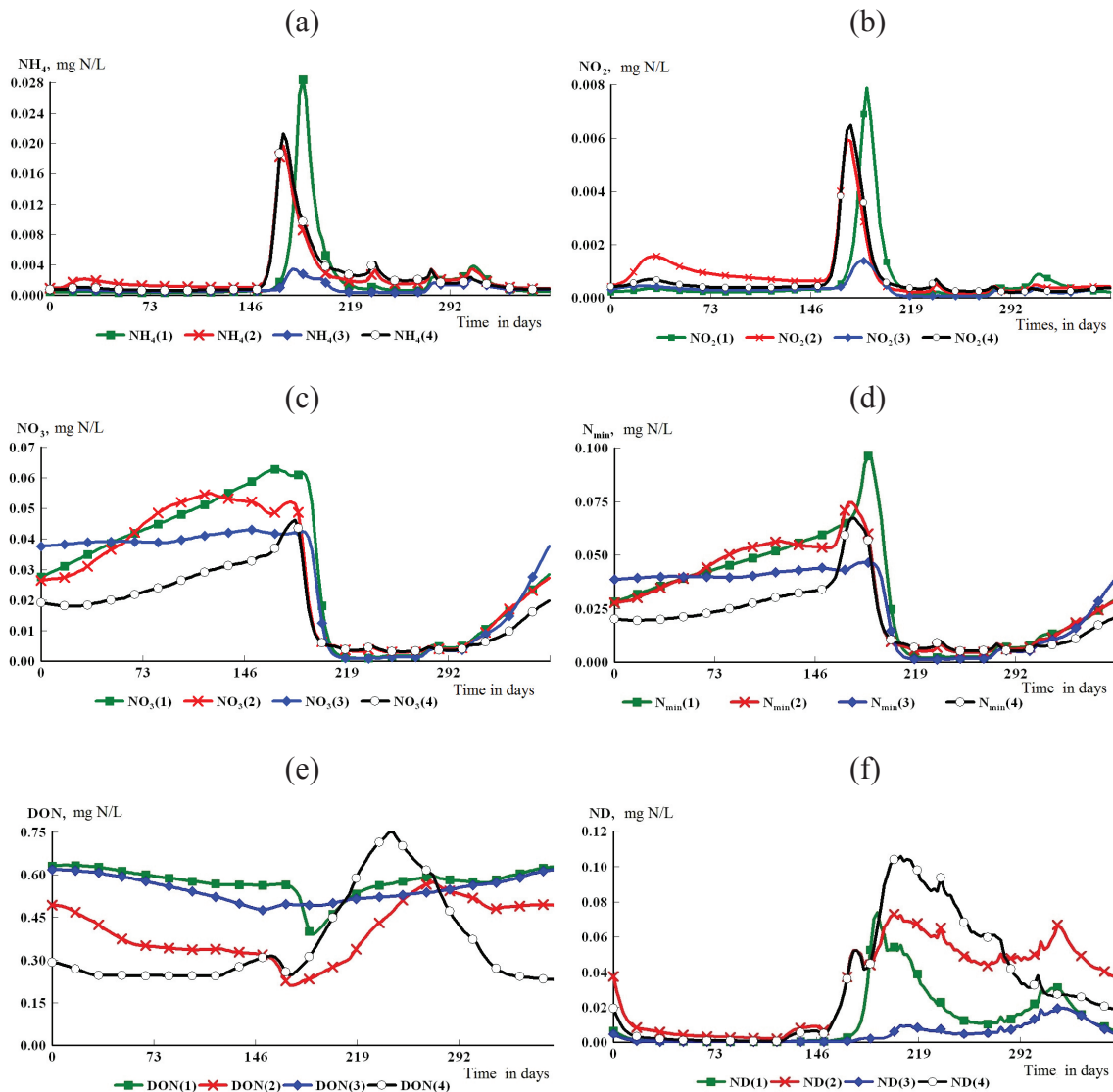


Fig. 2. Dynamics of the N form concentrations for the second calculated year: NH₄ (a), NO₂ (b), NO₃ (c), N_{min} (d), DON (e), ND (f) in the waters of Regions 1–4 (NESS)

In coastal waters (Regions 1 and 3), the initial concentrations of ND are lower (0.007 and 0.005 mg N/L) than in Regions 2 and 4 (0.038 and 0.02 mg N/L). In Regions 1–4, the general trend in the decreasing of ND concentrations persists in January–February, and the ND content in Regions 1 and 3 decreases to 0.1–0.2 µg N/L, and in Regions 2 and 4 – to 0.9–3.2 µg N/L on 60th day. By the beginning of the second half of a year and further till the end of autumn, two maximal concentrations of ND are formed: in Region 1 – on the 190th and 320th days (0.0745 and 0.0312 mg N/L), in Region 2 – on the 207th and 320th days (0.0721 and 0.0666), in the Region 4 – on the 176th and 207th days (0.0530 and 0.1060 mg N/L). In Region 3, the highest concentrations of ND were significantly lower, and they were noted on the 221nd and 322nd days (0.0073 and 0.0193 mg N/L respectively) (Fig. 2f).

In the first half of a year in the waters of Regions 1 and 2, the change in DIP concentrations differs little from each other, showing fluctuations in ranges of 0.0191–0.0220 and 0.0172–0.0236 mg P/L respectively. In the waters of Regions 3 and 4, the DIP concentrations varied between 0.0050–0.0154 and 0.0086–0.0154 mg P/L respectively. In the second part of a year, the pattern of changes in DIP concentrations in the waters of each region is very specific. In the Region 1, to 209 days, the DIP content is reduced on the 209th day to a minimum (0.0070 mg P/L), then the highest concentration of DIP (0.0227 mg P/L) is reached by 312nd day, and by the end of a year, it gradually decreases to 0.0190 mg P/L. In Region 2, an intermediate minimum of the DIP content (0.0135 mg P/L) was noted at the 192nd day, and after which the DIP concentration increased to its maximum by 269th day (0.0407 mg P/L), then decreased to 346th day (up to 0.0150 mg P/L) and by the end of the year it increases to 0.0206 mg P/L. In Region 3, the DIP content reaches its maximum at the 188th day (0.0160 mg P/L), after which its gradual decrease begins and by the end of a year its concentration drops to 0.0019 mg P/L. In Region 4, the maximum DIP concentration (0.0463 mg P/L) was observed on the 245th day, then the DIP content was reduced to 0.0045 mg P/L (344th day), and by the end of a year, it increased to 0.0113 mg P/L (Fig. 3 a).

In almost first half of a year, the DOP concentrations in the waters of Regions 1, 3 and 4 are without significant changes and retains its highest values (0.0167, 0.0079 and 0.0077 mg P/L respectively). A sharp decrease in DOP concentrations in the waters of Regions 3 and 4 occurs from the 160th and by the 175th days (they drop to $<1 \mu\text{g P/L}$), while in Region 1, the decrease of the DOP concentration occurs from 175th to 190th days (down to $<1 \mu\text{g P/L}$). In Region 2, the decrease in DOP concentration occurs from 7 to 171st days: during this period, the DOP concentration decreases from 22.1 to $<1 \mu\text{g P/L}$. In all regions, low DOP concentrations persist up to ~ 300 days. Over the past two months before the end of a year, in the waters of Regions 1–4, the DOP concentrations have increased (correspondingly to 0.0151, 0.0205, 0.0056, and 0.0054 mg P/L), and these values are close to those taken at the beginning of a year (Fig. 3 b).

Since the beginning of a year, the PD content has been sharply reduced, and already at 5 day, low concentrations (in the order of 0.2–0.8 $\mu\text{g P/L}$) are established in the water of Regions 1–4. They are retained in the waters of all regions during the first half of a year, then in the waters of Regions 1, 2 and 4 they increase to 1.5 $\mu\text{g P/L}$, and in Region 3, they remain low for a few months ($<1 \mu\text{g P/L}$). However, during a year, synchronous short-term maxima of PD contents are recorded in Regions 1–4 in the background of low concentrations of PD: by 236th day (1.5, 3.1, 0.6, and 3.67 $\mu\text{g P/L}$), by 279th day (2.25, 3.37, 1.76, and 2.59 $\mu\text{g P/L}$), by the 308th day (3.85, 3.34, 3.03, and 2.03 $\mu\text{g P/L}$). In the past two months, individual PD maxima in the waters of Regions 1–3 have been formed at different times: respectively, on the 322nd day (4.58 $\mu\text{g P/L}$), on the 324th day (7.10) and on the 332nd day (2.57 $\mu\text{g P/L}$). By the end of a year, the concentrations of PD in the waters of Regions 1–3 decrease accordingly to 2.30, 6.17, and 1.06 $\mu\text{g P/L}$, and in Region 4 they increase to 2.66 $\mu\text{g P/L}$ (Fig. 3 c).

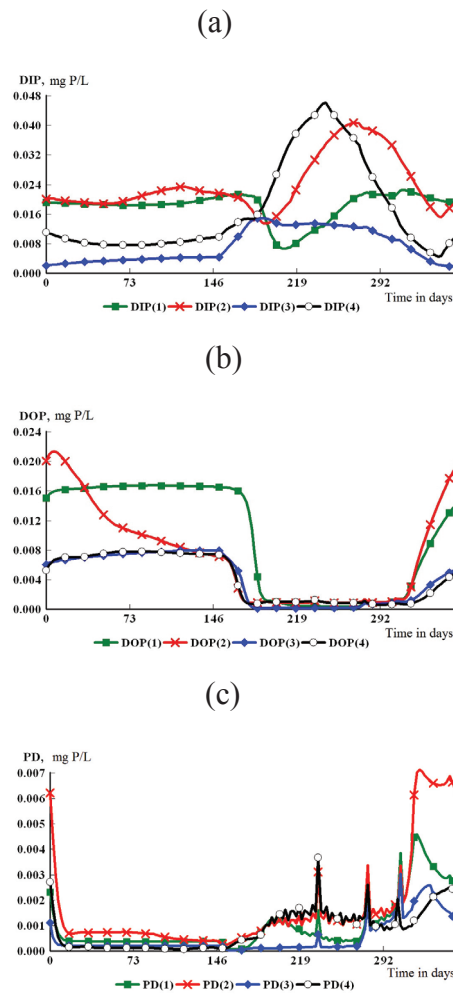


Fig. 3. Dynamics of the concentration of P forms for the second calculated year: DIP (a), DOP (b), PD (c) in the waters of Regions 1–4 (NESS)

The intra-annual changes of the content of N and P in dissolved (N_{dis} , P_{dis}) and suspended (N_{par} , P_{par}) fractions, and also the total content of N and P (N_{tot} , P_{tot}) in Regions 1–4 are shown in Fig 4. Let us estimate the ranges of variability and ratios of these components in different regions of the NESS. The limits of the fluctuations in the waters of the Regions of 1–4 concentrations of N_{dis} are 0.4884–0.6706, 0.2737–0.5789, 0.5146–0.6770, and 0.2497–0.7568 mg N/L (Fig. 4 a), respectively; the concentrations of N_{par} – are 0.3–159.5, 2.4–171.7, 0.1–56.6, and 0.5–216.3 $\mu\text{g N/L}$ (Fig. 4 c), and the concentrations of N_{tot} – are 0.620–0.679, 0.392–0.692, 0.530–0.682, and 0.243–0.932 mg N/L (Fig. 4 e). In the waters of regions 1–4, the changes of P_{dis} concentrations are 7.7–35.9, 14.4–42.2, 6.5–16.3, and 7.5–47.2 $\mu\text{g P/L}$ (Fig. 4 b), concentrations P_{par} – 0.4–21.1, 0.6–26.6, 0.1–18.9, and 0.6–23.0 $\mu\text{g P/L}$ (Fig. 4 d), the concentrations of P_{tot} are 23.3–44.2, 29.5–62.6, 11.2–28.6, and 16.5–70.0 $\mu\text{g P/L}$ (Fig. 4 f).

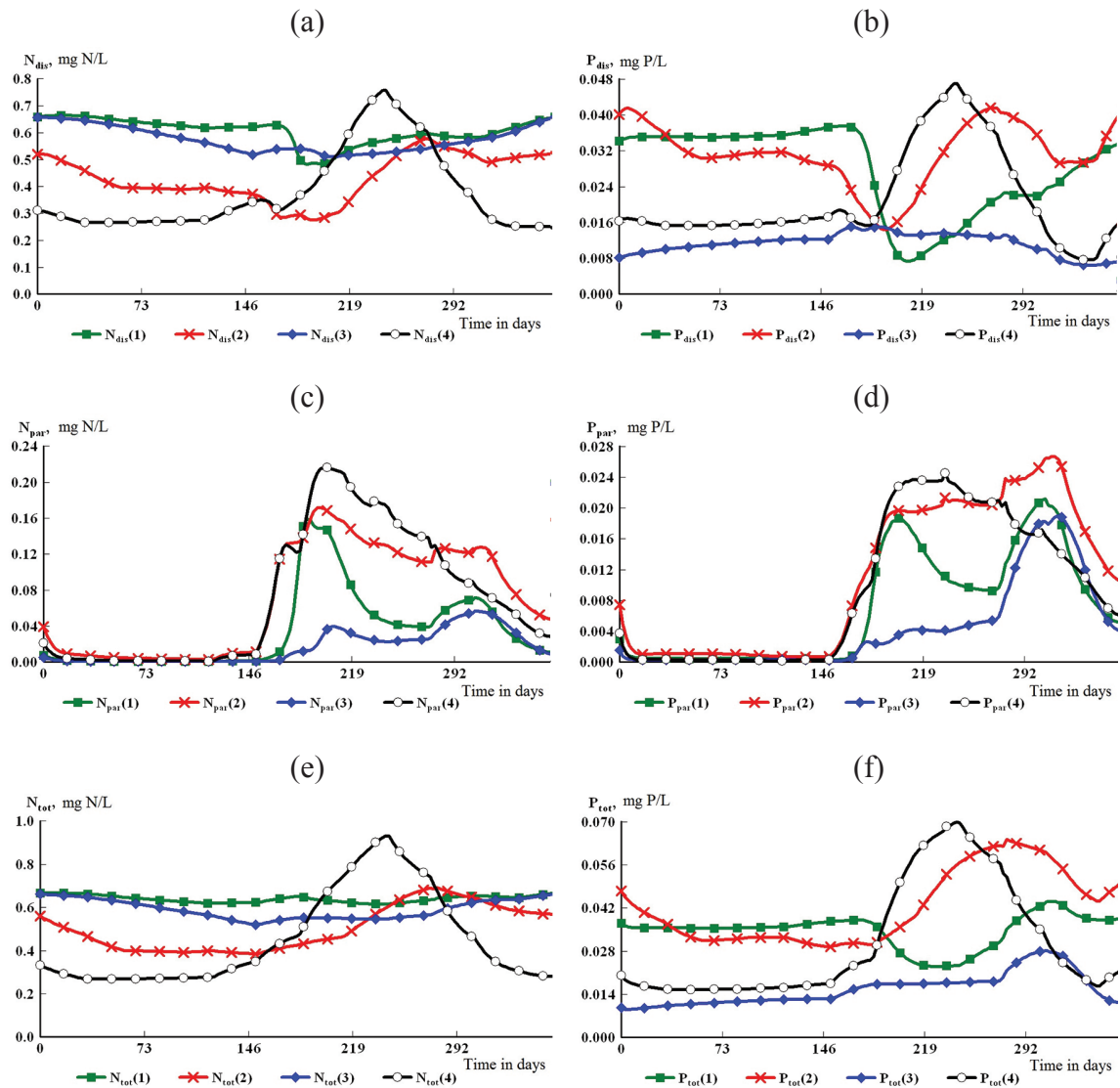


Fig. 4. Dynamics of aggregated concentrations of N (a, c, e) and P (b, d, f) for the second calculated year: N_{dis} (a), P_{dis} (b), N_{par} (c), P_{par} (d), N_{tot} (e), P_{tot} (f) in waters of Regions 1–4 (NESS)

The ratios of $N_{dis} : P_{dis}$ concentrations in the waters of Regions 1–4 are, respectively (18.7–63.4) : 1, (13.7–19.0) : 1, (41.5–79.2) : 1, and (16–33.3) : 1; $N_{par} : P_{par}$ – (0.8–7.6) : 1, (4–6.5) : 1, (1–3) : 1, and (0.8–9.4) : 1; $N_{tot} : P_{tot}$ – (15.4–26.6) : 1, (11.1–13.3) : 1, (23.8–47.3) : 1, and (13.3–14.7) : 1. Thus, a comparison of the values of the ratios of the components N and P shows that:

- in waters of all regions, the range of changes in the proportions of the suspended components $N_{par} : P_{par}$ is generally lower than the ratio of the concentrations of their dissolved and total components;

- waters of Region 3, into which the river runoff arrives, have smaller ranges of variability in the ratios of the suspended fractions $N_{par} : P_{par}$ at higher ranges of ratios of their dissolved and total concentrations;

- there are differences in the ratios of the components N : P depending on the

location of the regions: in coastal Regions 1 and 3, on the whole, the ranges of variability of the ratios of dissolved and total N : P concentrations are higher than in Regions 2 and 4 remote from the coast.

Analysis of calculated dynamics of organism biomasses in waters of Regions 1–4

During a year, the changes of BS concentrations in the waters of Regions 1–4 depend on the development of organisms of the lower trophic links – the heterotrophic bacteria $B1$, different groups of phytoplankton ($F1$, $F2$, $F3$) and zooplanktons ($Z1$, $Z2$). The features of the development of organisms in different regions of the NESS can be traced from the calculated values of their biomass, specific growth rates (k_{0i}) and bioproduction (BP_i). According to the values of biomass, the periods of active development of organisms, associated with the production of organic matter (OM) and BS, are distinguished during a year, the values of the biomass and specific growth rates k_{0i} can characterize the environmental conditions for the biomass development. In different regions, the influence of individual factors and the supply of biomass by nutrition substrates may be substantially different. The BP_i values of each biomass group are calculated on the basis of estimated internal substance fluxes that determine the conditions for the biomass development during their consumption of BS, the release of metabolic products and dead. The maximum values of k_{0i} are fixed one or two weeks before the formation of the highest biomass values of considered group of organisms. For areas of the Sakhalin Shelf, an active dynamics of water masses is characterized, and together with internal substance fluxes, these factors significantly affect on the final indicators of the state and development of organisms of the lower trophic links (Pishchal'nik et al., 2014).

In this serie of calculations, the values of the organism biomass are shown in Fig. 5 in the N units – for heterotrophic bacteria ($B1N$), three groups of phytoplankton ($F1N$, $F2N$, $F3N$) and two groups of zooplankton (herbivorous $Z1N$ and predatory $Z2N$). Until mid-May, the biomass of these organisms in the water Region 1–4 of the NESS remains low, the main changes in the biomass values occur from mid-May to the end of a year. In the waters of Region 3, the values of biomass are significantly lower in comparison with other regions. It should be noted that there are fundamental differences in changes of the biomass values in the second half of a year in the waters of coastal Regions 1 and 3 and in Regions 2 and 4 remote from the coast. In dynamics of $B1N$, $F1N$ and $Z1N$ biomasses, two biomass peaks (spring and autumn) are formed, in the coastal Regions 1 and 3, the minimum values between these two maxima are more expressed. Otherwise, the biomasses of $F2N$, $F3N$ and $Z2N$ are developing: they have distinct differences in the values of biomass in Regions 1–4: in Regions 1 and 3, the biomasses are lowered, and in Regions 2 and 4, they are increased. It should be noted that the biomass values of $F1N$ and $F2N$ are comparable, and in comparison with them, the $F3N$ biomass values are significantly lower.

Positive values of production (BP_i) characterize the conditions of growth of organism biomasses (they occur in the second half of a year). The values of the biomass production are calculated for each region on the basis of the sum of the substance fluxes forming the

biomass of a particular group of organisms at each time step. It is calculated in two dimensions:

1. Per unit of water volume in the layer under consideration for each month (g of Element/($m^3 \times \text{month}$)).

2. For the whole water volume of the this layer (thousand tons of Element/month). Ranges of production biomass values are shown in Table 6 as their total values for production period.

It should be noted that each group of organisms has characteristic production values and duration of the period with their positive values (Fig. 5; Table 6). Let us estimate the changes of parameters characterizing the development of organism biomasses.

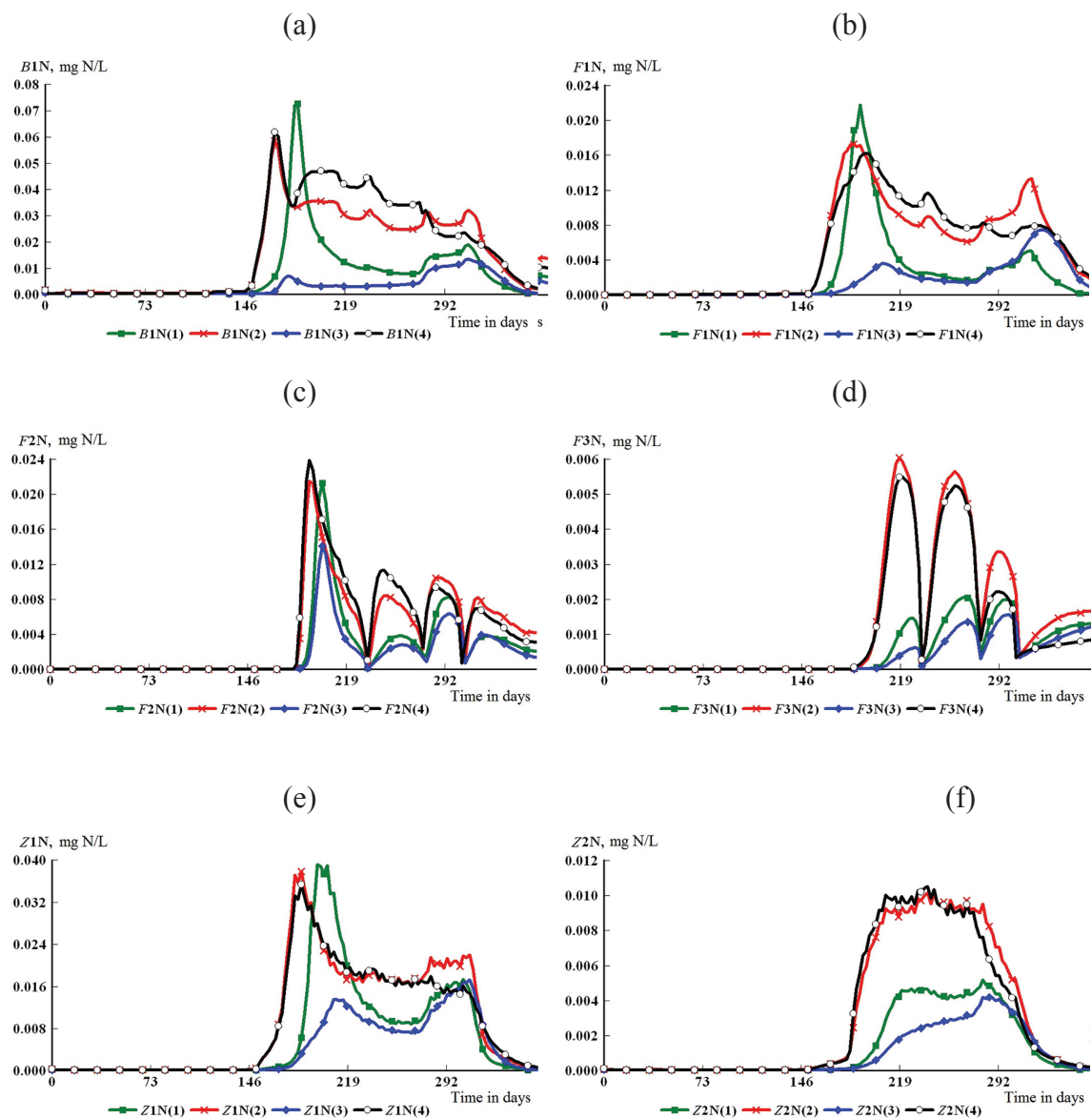


Fig. 5. Dynamics of organism biomasses for the second calculated year: heterotrophic bacteria B1N (a), three phytoplankton groups – F1N (b), F2N (c), and F3N (d), zooplankton: herbivorous, Z1N (e) and predatory, Z2N (f) in waters of Regions 1–4 (NESS)

Biomass of heterotrophic bacteria B_{1N} . From the middle of May, there are the differences in development of B_{1N} biomass in the coastal Regions 1 and 3, as well as in Regions 2 and 4 located further from the coast (Fig. 5 a). In the coastal waters of Region 1, two maxima of the B_{1N} biomass are created in the second half of a year: the first – in spring (0.0729 mg N/L on the 185th day) and the second – in autumn (0.0189 mg N/L on the 310th day). The highest values of the specific growth rate of B_{1N} biomass (k_{0B1}) in spring fall on the 178th day (0.186 day⁻¹), and in the autumn – by 308th day (0.092 day⁻¹). In the waters of Region 3 in the second half of a year, the B_{1N} biomass is kept low in comparison with other regions of the NESS: the first small spring maximum here is formed on the 178th day (0.0070 mg N/l) and the second autumn – by 308 day (0.0130 mg N/l). In this region, the highest values of k_{0B1} for the formation of the spring and autumn maximums were on 171st and 278th days (0.297 and 0.178 day⁻¹ respectively). By the end of a year, the B_{1N} biomass in the waters of Regions 1 and 3 decreases to 0.0003 and 0.0002 mg N/l, respectively.

In Regions 2 and 4, one spring maximum of B_{1N} biomass is formed (on the 168th day – 0.0585 and 0.0618 mg N/L respectively) at the highest values of k_{0B1} for the 164th day (0.056 and 0.050 day⁻¹, respectively). In the following period (during summer – autumn), sufficiently high values of B_{1N} biomass are maintained in waters of Regions 2 and 4 with a tendency to gradually decrease by the end of a year (respectively to 0.0013 and 0.0011 mg N/L).

The production period for B_{1N} bacteria continues in the waters of Regions 1, 2, and 4 from June to November, and in the Region 3 – from June to December (Table 6).

In some months in Regions 1–4, the ranges of $BP_{B_{1N}}$ values, expressed per water volume unit of upper layer, are approximately of the same order (only Region 3 is remarkable for their lower values of $BP_{B_{1N}}$). The total values of production of B_{1N} biomass, $BP_{B_{1N}}$, for the production period is higher in the water of Regions 2 and 4 (1.8848 and 2.4893 g N/(m³×month)), which are far from the coast, in comparison with the coastal Regions 1 and 3 (1.1061 and 0.3124 g N/(m³×month)). In principle, the same tendencies are preserved even when expressing the values of $BP_{B_{1N}}$ for the volume of the entire water layer. However, in this case, the value of $BP_{B_{1N}}$ in region of 1 (2002.7 thousand tons N) is higher than in the Regions 2–4 (1.149.3, 583.5, and 1613.9 thousand tons N, respectively). When the $BP_{B_{1N}}$ is expressed per unit volume of the upper layer water, its maximum values in the waters of Regions 1–4 fall on July, June, October, June (0.5113, 0.4614, 0.0998, 0.8824 g N/(m³×month), respectively). In the waters of Regions 1–4, taking into account the entire volumes of water, the largest values of $BP_{B_{1N}}$ are registered in July, October, November, and August (correspondingly 735.8, 266.6, 238.7, and 338.1 thousand tons N/month). These calculated values of $BP_{B_{1N}}$ depend directly on the water volumes of the upper layer and indirectly from the concentrations of BS in the layer, affecting the final values of the production of $BP_{B_{1N}}$ biomass (Table 6).

Table 6. The calculated values of the production (BPi) for organisms in different months and for the whole productive period in Regions 1–4 of NESS (uwl – upper water layer; *for period of positive values of BPi; dash – BPi values are negative)

| Volume, Biota | Dimension | VI | VII | VIII | IX | X | XI | XII | Σ* |
|---------------|---|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|------------------------|--------------------------|
| Region 1 | | | | | | | | | |
| V, uwl | km ³ | 959.4 | 1439.1 | 1918.8 | 2398.4 | 2878.1 | 3597.7 | 4796.9 | – |
| B1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.2072}{198.78}$ | $\frac{0.5113}{735.81}$ | $\frac{0.0896}{171.92}$ | $\frac{0.0575}{137.91}$ | $\frac{0.1481}{426.25}$ | $\frac{0.0923}{332.07}$ | – | $\frac{1.106}{2002.74}$ |
| F1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0405}{38.86}$ | $\frac{0.2242}{322.65}$ | $\frac{0.0237}{45.48}$ | $\frac{0.0048}{11.51}$ | $\frac{0.0231}{66.48}$ | $\frac{0.0224}{80.59}$ | – | $\frac{0.3387}{565.57}$ |
| F2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.1540}{221.62}$ | $\frac{0.0362}{69.46}$ | $\frac{0.0288}{69.07}$ | $\frac{0.0776}{223.41}$ | $\frac{0.0297}{106.85}$ | $\frac{0.0167}{80.11}$ | $\frac{0.3430}{770.52}$ |
| F3N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0007}{1.01}$ | $\frac{0.0084}{16.12}$ | $\frac{0.0183}{43.89}$ | $\frac{0.0141}{40.58}$ | $\frac{0.0045}{16.19}$ | $\frac{0.0054}{25.90}$ | $\frac{0.0460}{143.69}$ |
| Z1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0010}{0.96}$ | $\frac{0.3985}{573.48}$ | $\frac{0.1644}{315.45}$ | $\frac{0.0728}{174.60}$ | $\frac{0.1525}{438.91}$ | $\frac{0.0531}{191.04}$ | – | $\frac{0.8423}{1694.44}$ |
| Z2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0054}{7.77}$ | $\frac{0.0260}{49.89}$ | $\frac{0.0265}{63.56}$ | $\frac{0.0267}{76.84}$ | $\frac{0.0051}{18.35}$ | – | $\frac{0.0897}{216.41}$ |
| Region 2 | | | | | | | | | |
| V, uwl | km ³ | 300.0 | 450.0 | 600.0 | 750.0 | 900.0 | 1125.0 | 1500.0 | – |
| B1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.4614}{138.42}$ | $\frac{0.3868}{174.06}$ | $\frac{0.3298}{197.88}$ | $\frac{0.2388}{179.10}$ | $\frac{0.2964}{266.76}$ | $\frac{0.1717}{193.16}$ | – | $\frac{1.8849}{1149.38}$ |
| F1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.1163}{34.89}$ | $\frac{0.1553}{69.89}$ | $\frac{0.0508}{30.48}$ | $\frac{0.0350}{26.25}$ | $\frac{0.0575}{51.75}$ | $\frac{0.0518}{58.28}$ | – | $\frac{0.4667}{271.54}$ |
| F2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.2076}{93.42}$ | $\frac{0.0707}{42.42}$ | $\frac{0.0662}{49.65}$ | $\frac{0.1193}{107.37}$ | $\frac{0.0456}{51.30}$ | $\frac{0.0234}{35.10}$ | $\frac{0.5328}{379.26}$ |
| F3N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0193}{8.69}$ | $\frac{0.0553}{33.18}$ | $\frac{0.0488}{36.60}$ | $\frac{0.0307}{27.63}$ | $\frac{0.0043}{4.84}$ | $\frac{0.0051}{7.65}$ | $\frac{0.1635}{118.59}$ |
| Z1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.1579}{47.37}$ | $\frac{0.4288}{192.96}$ | $\frac{0.1994}{119.64}$ | $\frac{0.1704}{127.80}$ | $\frac{0.2387}{214.83}$ | $\frac{0.0845}{95.06}$ | – | $\frac{1.2797}{797.66}$ |
| Z2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0003}{0.09}$ | $\frac{0.0435}{19.58}$ | $\frac{0.0881}{52.86}$ | $\frac{0.0814}{61.05}$ | $\frac{0.0614}{55.26}$ | $\frac{0.0108}{12.15}$ | – | $\frac{0.2855}{200.99}$ |
| Region 3 | | | | | | | | | |
| V, uwl | km ³ | 700.0 | 1050.0 | 1400.0 | 1750.0 | 2100.0 | 2625.0 | 3500.0 | – |
| B1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0451}{31.57}$ | $\frac{0.0326}{34.23}$ | $\frac{0.0215}{30.10}$ | $\frac{0.0225}{39.38}$ | $\frac{0.0998}{209.58}$ | $\frac{0.0909}{238.61}$ | – | $\frac{0.3124}{583.47}$ |
| F1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0037}{0.03}$ | $\frac{0.0388}{40.74}$ | $\frac{0.0109}{15.26}$ | $\frac{0.0102}{17.85}$ | $\frac{0.0309}{64.89}$ | $\frac{0.0472}{123.90}$ | $\frac{0.0108}{37.80}$ | $\frac{0.1525}{300.47}$ |
| F2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0892}{93.66}$ | $\frac{0.0194}{27.16}$ | $\frac{0.0206}{36.05}$ | $\frac{0.0532}{111.72}$ | $\frac{0.0352}{92.40}$ | $\frac{0.0155}{54.25}$ | $\frac{0.2331}{415.24}$ |
| F3N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0003}{0.32}$ | $\frac{0.0039}{5.46}$ | $\frac{0.0065}{11.38}$ | $\frac{0.0095}{19.95}$ | $\frac{0.0040}{10.50}$ | $\frac{0.0051}{17.85}$ | $\frac{0.0293}{65.46}$ |
| Z1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0015}{1.05}$ | $\frac{0.1040}{109.20}$ | $\frac{0.0995}{139.30}$ | $\frac{0.0539}{94.33}$ | $\frac{0.1237}{259.77}$ | $\frac{0.0832}{218.40}$ | $\frac{0.0003}{1.05}$ | $\frac{0.4661}{823.10}$ |
| Z2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0031}{3.26}$ | $\frac{0.0146}{20.44}$ | $\frac{0.0155}{27.12}$ | $\frac{0.0218}{45.78}$ | $\frac{0.0078}{20.48}$ | $\frac{0.0006}{2.10}$ | $\frac{0.0634}{119.19}$ |
| Region 4 | | | | | | | | | |
| V, uwl | km ³ | 375.3 | 563.0 | 750.7 | 938.4 | 1126.0 | 1407.5 | 1876.7 | – |
| B1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.8824}{331.16}$ | $\frac{0.5721}{322.09}$ | $\frac{0.4504}{338.12}$ | $\frac{0.3081}{289.12}$ | $\frac{0.1970}{221.82}$ | $\frac{0.0793}{111.62}$ | – | $\frac{2.4893}{1613.93}$ |
| F1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.2718}{102.01}$ | $\frac{0.2906}{163.61}$ | $\frac{0.0990}{74.32}$ | $\frac{0.0584}{54.80}$ | $\frac{0.0501}{56.41}$ | $\frac{0.0355}{49.97}$ | $\frac{0.0010}{1.88}$ | $\frac{0.8064}{503.00}$ |
| F2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.2560}{144.13}$ | $\frac{0.0928}{69.67}$ | $\frac{0.0781}{73.29}$ | $\frac{0.0677}{76.23}$ | $\frac{0.0311}{43.77}$ | $\frac{0.0129}{24.21}$ | $\frac{0.5386}{431.30}$ |

| | | | | | | | | | |
|-----|---|------------------------|-------------------------|-------------------------|-------------------------|-------------------------|------------------------|-----------------------|--------------------------|
| F3N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | – | $\frac{0.0143}{8.05}$ | $\frac{0.0497}{37.31}$ | $\frac{0.0482}{45.23}$ | $\frac{0.0222}{25.00}$ | $\frac{0.0026}{3.66}$ | $\frac{0.0035}{6.57}$ | $\frac{0.1405}{125.82}$ |
| Z1N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.2653}{99.57}$ | $\frac{0.6595}{371.30}$ | $\frac{0.2555}{191.80}$ | $\frac{0.1889}{177.27}$ | $\frac{0.1691}{190.41}$ | $\frac{0.0632}{88.95}$ | – | $\frac{1.6015}{1119.30}$ |
| Z2N | $\frac{\text{g N}/(\text{m}^3 \text{ mon.})}{\text{thous. t N/mon.}}$ | $\frac{0.0008}{0.30}$ | $\frac{0.0499}{28.09}$ | $\frac{0.0867}{65.09}$ | $\frac{0.0778}{73.01}$ | $\frac{0.0459}{51.68}$ | $\frac{0.0076}{10.70}$ | – | $\frac{0.2687}{228.87}$ |

The biomass of the first phytoplankton group, $F1N$, develops with the formation of two maxima (in spring, and in autumn). However, in some cases, the severity of seasonal $F1N$ maximums in regions are different. For example, in Region 3, the spring $F1N$ maximum is smoothed out, and in the Region 4, their autumnal maximum is smoothed (Fig. 5 b). In Regions 1–4, of the spring maximum of the $F1N$ biomass fall respectively on the 190th, 185th, 207th, and 195th days (0.0219, 0.0173, 0.0036, and 0.0163 mg N/L). In Regions 1–4, the largest values of k_{0F1} forming spring $F1N$ peaks are respectively, 0.385, 0.127, 0.166, and 0.125 day⁻¹ (and these are found on 183rd, 178th, 195th, and 183rd days).

The pronounced minima of the $F1N$ biomass between the spring and autumn peaks in the waters of Regions 1–3 are registered for the 269–272nd days (0.0016, 0.0061, and 0.0014 mg N/L, respectively), and in waters of Region 4 – in the above-mentioned period of the $F1N$ minimum is formed later – on the 300th day (0.0067 mg N/L).

The autumn $F1N$ maximum was observed in Regions 1–2 at 317th day (0.0050 and 0.0133 mg N/L), and in Regions 3–4 – at 323nd day (0.0074 and 0.0079 mg N/L). The highest k_{0F1} values in the Regions 1–4 forming the autumn $F1N$ peaks fall on the 310th day (0.319, 0.100, 0.156, and 0.091 day⁻¹, respectively). By the end of a year, the $F1N$ values decrease to 0.0001–0.0005 and 0.0013–0.0012 mg N/L respectively in the coastal Regions 1 and 3 and in Regions 2 and 4 located further from the coast.

In Regions 1–2 and 3–4, the formation of $F1N$ production, BP_{F1N} , occurs respectively in periods of June–November and June–December. The ranges of BP_{F1N} changes for the production period in Regions 1–2 are 0.0048–0.2242 and 0.0350–0.1553 g N/(m³×month) (at the total values of 0.3387 and 0.4667 grams N/m³), and in Regions 3 and 4 – (0.0037–0.0472 and 0.0010–0.2906 g N/(m³×month) (at the total of 0.1525 and 0.8064 g N/m³)). The BP_{F1N} values based on the water volume of the upper layer in the coastal part of the sea are higher in Region 1 (11.5–322.7 thousand tons N/month (the total amount is 565.6 thousand tons N) than in the Region 3 (0.03–123.9, 303.5), and in regions remote from the coast, it is higher in Region 4 (1.9–163.6, 503.0) than in Region 2 (26.3–69.9, 271.5 thousand tons N/month). In Regions 1, 2 and 4, the BP_{F1N} highest values on the unit water volume of the upper layer were recorded in July (0.2242, 0.1553, and 0.2906 g N/(m³×month), and in Region 3 – in November (0.0472 grams N/(m³×month)).

In calculations of the BP_{F1N} values for the volume of the whole layer, in Regions 1, 2 and 4 in July, the largest values are 322.7, 69.9, and 163.6 thousand tons N/(m³×month), and in Region 3 – in November (123.8 thousand tons N/(m³×month)). The total BP_{F1N} values for the production period in the waters of Regions 1–4 are 565.6, 271.5, 300.5, and 503.0 thousand tons of N (Table 6).

The phytoplankton biomasses of the second and third groups, $F2N$ and $F3N$, in the second half of a year, develop similarly to each region with rather rapid alternations of intermediate biomass maxima and minima (Fig. 5 c, d). Generally, the formation of $F2N$ maxima occurs earlier than the maximum of $F3N$. A sharp change in the extremes of the $F2N$ and $F3N$ biomasses is caused by the conditions of water exchange between the regions in the period 182–365th days. The maximums are formed simultaneously – first in the Regions 2 and 4 located further from the coast, and then in the coastal Regions 1 and 3.

The first $F2N$ maximum in Regions 2 and 4 is formed on the 192th day (0.0214 and 0.0237 mg N/L) with the largest values of k_{0F2} 0.498–0.564 and 0.533–0.540 day⁻¹ fixed in these regions on the 178–183th days. In the waters of Regions 1 and 3, the first maximum of $F2N$ biomass falls on the 202nd day (0.0213 and 0.0139 mg N/L at the highest values of k_{0F2} 0.427–0.436 and 0.516–0.527 day⁻¹ on the 190–192th days). Then, at the 236th day, simultaneous formation of the first intermediate minimum $F2N$ (0.0001–0.0010 mg N/L) in Regions 1–4 was noted (Fig. 5 c).

The second maximum of $F2N$ (0.0084 and 0.0113 mg N/L) in Regions 2 and 4 was marked on the 248th day at the corresponding maximum values of k_{0F2} 0.300 and 0.230 day⁻¹ (at the 238th day). In the waters of Regions 1 and 3, the second maximum of $F2N$ falls on the 260th day (0.0038 and 0.0028 mg N/L), and the largest values of k_{0F2} in these regions (0.389 and 0.330 day⁻¹) were also noted on the 238th day. The second $F2N$ minimum (0.0008–0.0024 mg N/L) is formed on the 277th day simultaneously in Regions 1–4 (Fig. 5 c).

The third maximum of $F2N$ in Regions 2 and 4 (0.0104 and 0.0093 mg N/L) falls on the 288th day and the largest values of k_{0F2} (0.278 and 0.230 day⁻¹) – on the 276th day. In Regions 1 and 3, the values of the third $F2N$ maximum (0.0082 and 0.0063 mg N/L) were recorded on the 296th day, and the largest values of k_{0F2} (0.377 and 0.416 day⁻¹) – on the 278th day. The third minimum of $F2N$ (0.7–1.2 µg N/L) was recorded on the 306th day (Fig. 5 c).

In Regions 2 and 4, the fourth $F2N$ maximum of (0.0082 and 0.0069 mg N/L) occurs on the 317th day, and they are formed at the highest values of k_{0F2} (0.383 and 0.430 day⁻¹) by the 305–308th days. In the waters of Regions 1 and 3, the fourth $F2N$ maximum (0.0038 and 0.0039 mg N/L) are fixed for the 324th day, and the largest values of k_{0F2} (0.322 and 0.383 day⁻¹) – on the 308th day. By the end of a year, the $F2N$ biomass values in Regions 1–4 decrease to 0.0019, 0.0040, 0.0013, 0.0029 mg N/L respectively (Fig. 5 c).

In the waters of Regions 1–2 and 3–4, the production values of $F2N$, BP_{F2N} , are formed respectively in July–December and June–December. The fluctuation limits of the BP_{F2N} values for the production period in the Regions 1–2 are 0.0167–0.1540 and 0.0234–0.2076 g N/(m³×month) respectively (at the total values – 0.3430 and 0.5328 g N/m³), and in regions 3 and 4 – (0.0155–0.0892 and 0.0311–0.2560 g N/(m³×month) at total values - 0.2331 and 0.5398 grams N/m³). The values of BP_{F2N} in terms of the volume of the upper layer water in the coastal part of the sea are higher in the Region 1 (69.1–223.4 thousand tons N/month with the total value of 770.5 thousand tons N) than in the Region 3 (27.2–111.7, 415.2 thousand tons N), and in Regions 2 and 4, these values

are higher: in the Region 4 – 24.2–144.1 thousand tons N/month (with the total value of 431.3 thousand tons N) and in the Region 2 – (35.1–107.4, 379.3 thousand tons N). In Regions 1–4, the largest values of BP_{F2N} were recorded in July (0.1540, 0.2076, 0.0892, and 0.2560 grams N/($m^3 \times month$)) per unit volume of the upper layer. When calculating the $F2N$ production values for the entire layer, the increased values of BP_{F2N} in the Regions 1–4 are for July and October (221.6 and 223.4, 93.4 and 107.4, 93.7 and 111.7, and 144.1 and 76.2 thousand tons N/month). The total values of BP_{F2N} for the production season in the waters of Regions 1–4 are 770.5, 379.3, 415.2, and 431.3 thousand tons N (Table 6).

The development of $F3N$ biomass differs from $F2N$ in the values and dates in the formation of intermediate peaks (the formation of $F3N$ maxima occurs later and their values are lower). There are also similar features in the dynamics of biomasses $F3N$ and $F2N$: their peaks in time are earlier formed in the waters of Regions 2 and 4 (remoted from the coast) than in coastal Regions 1 and 3 (Fig. 5 c, d).

In Regions 2 and 4, the first intermediate maximum of $F3N$ biomass (6.03×10^{-3} and 5.47×10^{-3} mg N/L respectively) is formed on the 219th day at the largest values of k_{0F3} (0.277 and 0.213 day^{-1} at 201st day). In Regions 1 and 3, the first intermediate maximum of $F3N$ (1.46×10^{-3} and 6.02×10^{-3} mg N/L) is formed on the 228th day with the largest values of k_{0F3} (0.148 and 0.141 day^{-1}) on the 214th day. Further quickly enough, the $F3N$ values in all regions are reduced to the first intermediate minimum (9.90×10^{-5} – 2.63×10^{-4} mg N/L).

The second maximum of $F3N$ in Regions 2 and 4 (5.64×10^{-3} and 5.23×10^{-3} mg N/L) is fixed on the 260th day with the corresponding largest values of k_{0F3} (0.436 and 0.383 day^{-1}), which fall on the 238th day. In the Regions 1 and 3, the second maximum of $F3N$ (2.03×10^{-3} and 1.34×10^{-3} mg N/L) was recorded on the 269th day, and the largest values of k_{0F3} (0.265 and 0.233 day^{-1}) were also on the 238th day. However, already on the 279th day, the $F3N$ biomass in waters of all regions is reduced to its second minimum, the values of which fall within the range $(2.89$ – $9.40) \times 10^{-4}$ mg N/L.

The third intermediate maximum of $F3N$ in Regions 2 and 4 (3.34×10^{-3} and 2.20×10^{-3} mg N/L) falls on 293nd day, and the maximum values of k_{0F3} (0.347 and 0.300 day^{-1}) on the 279 th day. In Regions 1 and 3, the third maximum of $F3N$ (1.99×10^{-3} and 1.55×10^{-3} mg N/L) was recorded on the 298th day at the highest values k_{0F3} (0.275 and 0.280 day^{-1}) which also falls on the 279th day. Further by the 308th day, the third intermediate minimum of the $F3N$ biomass is reached, and their values in all regions lie within the limits $(3.16$ – $4.10) \times 10^{-4}$ mg N/L. In Regions 1–4 by the end of a year, $F3N$ biomass values increase to 1.30×10^{-3} , 1.67×10^{-3} , 1.25×10^{-3} , 8.57×10^{-4} mg N/L respectively (Fig. 5d).

It should be noted that each regular maximum of $F3N$ biomass in the waters of Regions 2 and 4, removed from the coast, becomes lower, and in coastal Regions 1 and 3, on the contrary, higher than the corresponding previous $F3N$ maximum. There is also a regularity for the following minimum $F3N$ biomasses: as a whole, each subsequent minimum of $F3N$ biomass in each region is higher than the it's fixed previous minimum (Fig 5 d).

In the waters of Regions 1–4, the production of BP_{F3N} is formed in July–December. The ranges of changes in the BP_{F3N} values for the production period in Regions 1–4 are 0.0007–0.0183, 0.0043–0.0553, 0.0003–0.0095, and 0.0026–0.0497 g N/(m³×month) (at total values of 0.0460, 0.1635, 0.0293, and 0.1405 g N/ m³). The values of BP_{F3N} in terms of the volume of the upper layer water in the coastal part of the sea are higher in the Region 1 (1.0–43.9 thousand tons N/month with a total of 143.7 thousand tons N) than in the Region 3 (0.3–19.9, 85.5), and in regions far from the coast – these values are higher in the Region 4 (3.7–45.2, 125.8) than in the Region 2 (4.8–36.6 thousand tons N/month and total 118.6 thousand tons N).

The largest values of BP_{F3N} in coastal Regions 1 and 3 were recorded in September and October (respectively 0.0183 and 0.0095 g N/ (m³×month)), and in Regions 2 and 4, remoted from the coast – in August (0.0553 and 0.0497 g N/(m³×month)). When calculating the values of $F3N$ production for the entire layer, the higher values of BP_{F2N} in Regions 1, 2, and 4 occur in September (correspondingly 43.9, 36.6, and 45.2 thousand tons N/month), and in the Region 3 – on October (19.9 thousand tons N/month). The total values of BP_{F3N} in the waters of Regions 1–4 during the production season are 143.7, 118.6, 65.5, and 125.8 thousand tons N, respectively (Table 6).

The biomass of the herbivorous (Z1N) and predatory (Z2N) zooplankton. There are significant differences in the zooplankton dynamics of the NESS waters. In each region in the second half of a year, two intermediate maximums of Z1N biomass are created, while only one enough long period of increased values of Z2N biomass is found in summer–autumn with its small fluctuations (some exception is for Region 3 in which a slower development of Z2N biomass is noted as a whole) (Fig. 5 e, f).

In remoted from the coast Regions 2 and 4, the development of Z1N biomass begins earlier than in coastal Regions 1 and 3. The first maximum of Z1N biomass in Regions 2 and 4 (3.78×10^{-2} and 3.54×10^{-2} mg N/L) was recorded in the 185th day at largest values of k_{0Z1} (0.551 and 0.528 day⁻¹) at 173rd day. The first maximum of Z1N biomass in the Region 1 (3.94×10^{-2} mg N/L) falls on the 197th day, and in the region 3 (1.35×10^{-2} mg N/L) - by the 209th day at the largest k_{0Z1} (0.605 and 0.411 day⁻¹) on the 185th day. The intermediate Z1N biomass minimum in all regions, within the limits of $(0.70–1.60) \times 10^{-2}$ mg N/L, is fixed on the 267th day (Fig. 5 e).

The second maximum of Z1N biomass in the waters of regions 1–4 is 1.73×10^{-2} , 2.20×10^{-2} , 1.72×10^{-2} , and 1.61×10^{-2} mg N/L respectively, and is formed on the 305–310th days at the highest values k_{0Z1} (0.306–0.332 day⁻¹) fixed on the 298th day. By the end of a year, the values of Z1N biomass in waters of Regions 1–4 are reduced to 7.80×10^{-5} , 2.45×10^{-4} , 6.40×10^{-5} , and 2.44×10^{-4} mg N/L respectively (Fig. 5 e).

Formation of Z1N productions in waters of Regions 1, 2 and 4 is carried out in June–November, and in Region 3 – in June–December. The range of changes in the values of BP_{Z1N} for Regions 1–4 is 0.0010–0.3985, 0.0845–0.4288, 0.0003–0.1237, and 0.0632–0.6595 g N/(m³×month), respectively, with their total values of 0.8423, 1.2797, 0.4661, and 1.6015 thousand tons N. When expressing the Z1N production on the volume of the upper layer water, the ranges of values of BP_{Z1N} for Regions 1–4 are 1.0–573.4,

47.4–214.8, 1.0–259.8, and 89.0–371.3 thousand tons N/month with the total values for the entire production period respectively, 1694.5, 797.7, 823.1, and 1119.3 thousand tons N. The highest values of BP_{Z1N} in the waters of Regions 1, 2, and 4 fall in July (0.3985, 0.4288, and 0.6595 g N/(m³×month) or 573.5, 193.0, and 371.3 thousand tons N/month), and in the Region of 3 – in October (0.1237 g N/(m³×month) or 259.8 thousand tons N/month).

As in the case of Z1N biomass, the development of Z2N biomass begins earlier in Regions 2 and 4 removed from the coast, and the first maximum of Z2N biomass falls in these regions respectively on the 209th and 204th days (9.22×10^{-3} and 9.14×10^{-3} mg N/L) with the largest values of k_{0Z2} 0.179 and 0.118 day⁻¹ (on the 197th day). The second maximum of Z2N in these regions is formed respectively on the 281th and 274th days (9.48×10^{-3} and 9.04×10^{-3} mg N/L) with increased values of k_{0Z2} on 272 day (0.248 day⁻¹) and by 266th day (0.213 day⁻¹). In the coastal Regions 1 and 3, the first maximum of the Z2N biomass is formed respectively on the 221st and 257th days (4.23×10^{-3} and 2.91×10^{-3} mg N/L), and the increased values of k_{0Z2} are fixed in the specified areas by 209th day (0.242 day⁻¹) and on the 250th day (0.162 day⁻¹). The second broad maximum of Z2N occurs in Regions 1 and 3, respectively, at 267–293rd days (4.33 – 5.17) $\times 10^{-3}$ mg N/L and at 281–293rd days (3.96 – 4.18) $\times 10^{-3}$ mg N/L at elevated k_{0Z2} values, fixed in the specified Regions on the 274th day (0.223 day⁻¹) and on the 286th day (0.191 day⁻¹) (Fig. 5 d).

The formation of Z2N production in the waters of Regions 1 and 3 occurs in July–November and July–December, respectively, and in Regions 2 and 4 – in June–November. The limits of changes in the values of BP_{Z2N} for Regions 1–4 are 0.0051–0.0267, 0.0003–0.0881, 0.0006–0.0218, and 0.0008–0.0867, g N/(m³×month) respectively for the total values of 0.0897, 0.2855, 0.0634, and 0.2687 thousand tons N. At the expression of Z2N production on the volume of the upper layer water, the ranges of values of BP_{Z2N} for Regions 1–4 are 7.8–76.8, 0.1–61.1, 1.9–45.8, and 0.3–73.0 thousand tons N/month with the total values for the entire production period respectively 216.4, 201.0, 119.2, and 228.9 thousand tons N.

The highest values of BP_{Z2N} in the waters of coastal Regions 1 and 3 occur in October (0.0267 and 0.0218 g N/(m³×month) respectively, or 76.8 and 45.8 thousand tons N/month), and in Regions 2 and 4 offshore – in August, with the expression of BP_{Z2N} per unit volume of the upper layer water (0.0881 and 0.0867 g N/(m³×month)), or in the expression of BP_{Z2N} for the whole volume of the upper layer water in September (61.1 and 65.1 thousand tons N/month).

Conclusions

Intra-annual dynamics of the BS concentrations was reproduced in Regions 1–4 (NESS) using the CNPSi-model and the long-term measurements with the monthly mean values of the sea water state parameters (temperature, light intensity, transparency, biogen load, water exchange parameters between Regions 1-4 and open water areas of the Sea of Okhotsk). The parameters of water exchange between regions and the rates of vertical

water exchange between the upper and lower layers were calculated with the help of BOM on the basis of long-term values of the thermohaline parameters of the marine environment averaged for each month. The mean morphometric characteristics of Regions 1–4 of NESS were also used in calculations. The subdivision of the water column into the upper and lower layers was determined during the cold months by the depth of penetration of the winter vertical circulation (100–150 m), and in the warm season – by the warming up of the water column varying from 10–20 m in May to 40–50 m in September.

Calculations showed that the Tym' River annual runoff provides the input of relatively small amount of BS in the marine environment of Region 3: DOC – 5.97 thous. tons of C, DON – 0.12, NH_4 – <0.01, NO_2 – <0.01, NO_3 – 0.08, ND – 0.30 thousand tons of N, DIP and DOP – to 0.02, PD – 0.09 thousand tons of P, DISi – 2.38 thousand tons of Si. During a year, the intensity of BS outflow by the river runoff into the sea waters of Region 3 varies: in May–June, it is ~ 50–79.5% of annual BS discharges, in winter months it decreases to <10%, and in summer and the autumn months – amounts to ~15–25% of the annual river flow.

Bilateral water exchange between regions 1–4 differently forms the nutrient load of each region: in Region 1, the loss of BS for output by the counterflow is substantially lower than their input at the water exchange with neighboring areas; in Regions 2 and 4, the BS input is less than their removal to neighboring areas; in Region 3, the input of BS is higher for some compounds (for DOC, ND, PD, NH_4 , NO_2 and DIP). During a year, the input of BS into the marine environment with atmospheric moisture was the lowest in February (3.6 and 5.0% in relation to annual assessment for Regions 1–2 and 3–4, respectively) and the largest in September (14.1 and 11.5% for these regions).

The main BS input into the marine environment provides an internal recycle and turnover of BS which plays an important role in maintaining the vital activity of organisms and in the development of biohydrochemical processes in the marine environment.

Analysis of modeling results showed significant seasonal differences in the values of BS concentrations, their amplitudes and ratios in waters of Regions 1–4 in this section of the Sakhalin Shelf. In general, in waters of Regions 1–4, smaller changes in the ratios of the suspended components N and P were revealed in comparison with the dissolved and total concentrations of these elements. This is special feature of the sea waters in Region 3 which are influenced by the runoff of Tym' River. It should also be noted that in coastal Regions 1 and 3, the ranges of variability of the ratios of dissolved and total concentrations of N and P are higher than in the waters of Regions 2 and 4 located far from the coast.

The calculated values of biomasses, specific rates of their growth and bioproductions are used for a general characterization of the conditions for the development of organism biomasses in the Regions 1–4. Until the middle of May, biomasses of heterotrophic bacteria *B1N*, phytoplanktons (*F1N*, *F2N*, and *F3N*), and zooplanktons (herbivorous *Z1N*, and predatory *Z2N*) remain low in this area of the Sakhalin Shelf, and the main biomass changes occur from mid-May to late-December. These changes differ in coastal waters (in Regions 1 and 3) and in waters of Regions 2 and 4 (located far from the coast).

During a year in the considered development of organism, two seasonal maxima (in spring, and in autumn) were shown for biomasses of $B1N$, $F1N$, and $Z1N$. In coastal Regions 1 and 3, between the spring and autumn peaks of organism biomasses, their minimal values are marked. During a year, three-four peaks of the phytoplankton biomasses ($F2N$ and $F3N$) are formed, as well as one maximum of $Z2N$ biomass. In the coastal Regions 1 and 3, they are decreased in comparison with Regions 2 and 4. Biomasses of phytoplankton $F1N$ and $F2N$ are comparable in terms of the formation dates and their values, and the biomass of phytoplankton $F3N$ is created later and its values is lower. In Regions 2 and 4, the biomasses of phytoplankton $F2N$ and $F3N$ peaks are formed earlier in time than in coastal Regions 1 and 3. The values of successively formed peaks of the $F3N$ biomasses in Regions 1 and 3 are increased, and in Regions 2 and 4 they are decreased. As a whole in all regions, the each next $F3N$ biomass minimum between their maximal values are higher than their previous minimal values.

In Region 1, the development of biomass of heterotrophic bacteria $B1N$ in spring and autumn is characterized by the values k_{0B1} 0.186 and 0.092 day⁻¹ respectively, and in Region 3 – 0.297 and 0.178 day⁻¹. In Regions 2 and 4, the formation of the spring peak of $B1N$ biomass is characterized by the values of k_{0B1} 0.050–0.056 day⁻¹. The autumn peak of $B1N$ biomass is not expressed here.

Biomass of phytoplankton $F1N$ is formed in spring with the largest values of k_{0F1} in Regions 1 and 3 – 0.385 and 0.166 day⁻¹, and in autumn – 0.319 and 0.156 day⁻¹, respectively. In Regions 2 and 4, the largest values of k_{0F1} for the development of the $F1N$ biomass were lower – 0.127–0.125 day⁻¹ (in spring) and 0.100–0.091 day⁻¹ (in autumn).

The alternating four maxima of $F2N$ biomass were formed more rapidly and simultaneously in remoted from the coast regions, and they were characterized in Regions 2 and 4 by the following values of k_{0F2} – on the 178–183-rd days: 0.498–0.524 and 0.533–0.540 day⁻¹; on the 238th day: 0.300 and 0.230 day⁻¹; on the 276th day: 0.278 and 0.230 day⁻¹; on the 306th day: 0.383 and 0.430 day⁻¹. A week later, the same $F2N$ maxima were formed in the coastal regions, and their formation occurred at the following elevated values of k_{0F2} in Regions 1 and 3: on the 191st day: 0.431 and 0.520 day⁻¹; on the 238th day: 0.389 and 0.330 day⁻¹; on the 278th day: 0.377 and 0.416 day⁻¹; and on the 308 day: 0.322 and 0.383 day⁻¹.

The formation of alternating three maxima of $F3N$ biomass is also faster in Regions 2 and 4. The following increased values of k_{0F3} were observed respectively in Regions 2 and 4: 0.277 and 0.213 day⁻¹ (on 201st day); 0.436 and 0.383 day⁻¹ (on 238th days); 0.347 and 0.303 day⁻¹ (on 279th day). The formation of $F3N$ maxima in the coastal regions occurs with a delay of two weeks, while in the Regions 1 and 3 the following increased values of k_{0F3} were recorded: 0.148 and 0.141 day⁻¹ (on the 214th days), 0.265 and 0.233 day⁻¹ (on the 238th day), 0.275 and 0.280 day⁻¹ (on the 279th day).

The spring peak of the $Z1N$ biomass is also formed earlier in the regions remote from the coast. They are characterized by elevated values of k_{0Z1} in Regions 2 and 4 (respectively 0.551 and 0.528 day⁻¹ on the 173rd day). In coastal Regions 1 and 3, the largest values of k_{0Z1} for the spring maximum of $Z1N$ biomass were fixed on the 185th

day (0.605 and 0.411 day⁻¹ respectively). In Regions 1–4 for the autumn peak of Z2N biomass, the largest values of k_{0Z1} were 0.325, 0.332, 0.319, and 0.300 day⁻¹, respectively, and these largest values of k_{0Z1} were noted in the 298th day.

The first maximum of the Z2N biomass is formed earlier in the Regions 2 and 4 remote from the coast, and they are characterized by elevated values of k_{0Z2} (0.179 and 0.118 day⁻¹, respectively, at the 197th day). In the coastal regions, the first maximum of Z2N is formed almost two weeks later, and in Regions 1 and 3, they are characterized by the largest values of k_{0Z2} (0.242 and 0.162 day⁻¹, respectively, recorded on the 209th and 250th days). The second maximum of the Z2N biomass in the waters of Regions 1–4 is characterized by the corresponding largest values of k_{0Z2} 0.223, 0.248, 0.191, and 0.213 day⁻¹ (they were noted in the indicated regions respectively on the 274th, 272nd, 286th, and 266th days).

The values of the organism production, BP_i , are positive in the second half of a year. These values characterize the conditions for the development of organism biomasses, and values of BP_i are calculated in two dimensions for each region on the basis of the sum of the substance fluxes that form the biomass of the considered group of organisms at each step in time: 1. per unit volume of water in the layer under consideration for each month (g of Element/(m³×month)) and 2. for the whole water volume of the layer considered (in thousand tons of Element / month). The analysis of biomass development indices showed that each group of organisms are characterized by the values of their activity indicators for a particular period of a year.

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ТРАНСФОРМАЦИЯ БИОГЕННЫХ ВЕЩЕСТВ В ВОДАХ СЕВЕРО-ВОСТОЧНОЙ ЧАСТИ ШЕЛЬФА САХАЛИНА: АНАЛИЗ РЕЗУЛЬТАТОВ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ

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Трансформация биогенных веществ в морской среде исследовалась в районах 1–4 в акватории северо-восточной части шельфа Сахалина. Три электронных инструмента использовано для анализа океанографических данных:

1. ГИС «Сахалинский шельф» (для получения данных по термохалинным параметрам морских вод);
2. океаническая динамическая модель Бергенского университета (для оценки скоростей и направлений переноса водных масс через границы районов);
3. гидрoэкологическая CNPSi-модель (для расчетов динамики химико-биологических характеристик и количественной оценки особенностей биогидрохимии морской среды северо-восточной части шельфа Сахалина).

В данном исследовании обсуждается сезонная динамика концентраций органических и минеральных соединений биогенных элементов (N и P) и биомасс организмов (гетеротрофные бактерии, три группы фито- и две зоопланктона). Динамика была воспроизведена на основе долгосрочных среднемесячных значений параметров морской среды (температура, освещенность, прозрачность водной среды, биогенная нагрузка, параметры водообмена). Указанные организмы вовлечены в трансформацию биогенных веществ и обеспечивают их круговорот в водной среде. Анализ изменений концентраций биогенных веществ позволил характеризовать сезонные условия развития биомасс и изменения параметров их активности (на основе оценки удельных скоростей роста биомасс и биопродукции).

Ключевые слова: модели для анализа океанологических данных; концентрации биогенных веществ; биомассы организмов низших трофических звеньев – гетеротрофные бактерии, три доминирующих группы фитопланктона, две группы зоопланктона (растительный и хищный); параметры активности организмов (удельные скорости роста, круговорот биомассы, биопродукция)

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