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МЕЖГОДОВЫЕ ИЗМЕНЕНИЯ БИООПТИЧЕСКИХ ХАРАКТЕРИСТИК ПОВЕРХНОСТНОГО СЛОЯ МОРЕЙ, ОКРУЖАЮЩИХ ЗАПАДНУЮ ЧАСТЬ РОССИИ, ПО ДАННЫМ СПУТНИКОВЫХ СКАНЕРОВ ЦВЕТА

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Представлены результаты анализа межгодовых изменений среднемесячных значений биооптических характеристик поверхностного слоя вод Баренцева, Карского, Белого, Балтийского, Черного и Каспийского морей за период 1998–2018 годы, рассчитанных по данным спутниковых сканеров цвета.

В качестве основных рассматриваются концентрация хлорофилла и показатель рассеяния назад взвешенными частицами, характеризующие изменчивость содержания фитопланктона и взвешенного вещества; привлекаются и другие характеристики, в частности, показатель поглощения окрашенного органического вещества как индикатор речного стока, также параметры, характеризующие цветения массовых видов фитопланктона, таких как кокколитофоридные цветения в Баренцевом и Черном морях, сине-зеленых водорослей в Балтийском. Большинство биооптических характеристик рассчитаны с помощью региональных алгоритмов, выведенных на основе данных натурных измерений, выполненных в исследуемых морях и учитывающих региональные особенности этих морей. В качестве параметра, характеризующего климатические изменения, приведены среднемесячные значения температуры поверхности моря по данным спутникового сканера MODIS-Aqua.

Статья содержит два основных раздела: в первом представлены данные об изменениях, происшедших в вышеуказанных морях в 2016–2018 гг., в сравнении с наблюдавшимися экстремальными значениями биоптических характеристик; во втором разделе дана систематизация и анализ экстремальных изменений характеристик за весь период наблюдений. Выполненный анализ показал, что в последние годы происходят значительные изменения, связанные в большинстве случаев с цветениями фитопланктона. Рекордный размах межгодовых изменений зарегистрирован в южной части Каспийского моря в июле 2001 г. после вселения гребневика *Mnemiopsis* — концентрация хлорофилла выросла более чем на порядок. Другой фактор, обусловливающий рекордную изменчивость биооптических характеристик, — речной сток.

Полученные результаты впервые дали количественные представления о происшедших изменениях биооптических характеристик в период 1998–2018 гг. в шести морях, различных по своим природным условиям, и создали основу для дальнейшего анализа, направленного на выявление процессов и факторов, обусловивших эти изменения.

Ключевые слова: биооптические характеристики, межгодовые изменения, Баренцево, Карское, Белое, Балтийское, Черное, Каспийское моря, спутниковые данные.

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INTERANNUAL CHANGES OF THE BIO-OPTICAL CHARACTERISTICS IN THE SURFACE LAYER OF THE SEAS SURROUNDING THE WESTERN PART OF RUSSIA FROM DATA OF SATELLITE OCEAN COLOR SCANNERS

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The article presents the results of an analysis of inter-annual changes in the monthly means of bio-optical characteristics in the surface layer of the Barents, Kara, White, Baltic, Black and Caspian Seas for the period 1998–2018, calculated from data satellite color scanners. As the main parameters, the chlorophyll-*a* concentration, *Chl* and particle backscattering coefficient, $b_{bp} = b_{bp}(555)$,

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characterizing the variability of phytoplankton and suspended matter, are discussed. The other characteristics, such as the absorption coefficient of colored organic substance $a_g = a_g(440)$ as an indicator of river runoff, the parameters that characterize the phytoplankton bloom (coccolithophore blooms in the Barents and Black Seas, of blue-green algae in the Baltic Sea) are also considered. The monthly means of sea surface temperature, *SST* by MODIS-Aqua data are presented as a parameter characterizing climate change. Most of the bio-optical characteristics were calculated using regional algorithms, derived from field measurements carried out in the considered seas and reflecting their regional features.

The presented data revealed significant changes in bio-optical characteristics that occurred in the considered seas in 2016–2018, in most cases they were associated with phytoplankton blooms. Systematization and analysis of extreme changes in bio-optical characteristics over the entire observation period found a record change in the southern part of the Caspian Sea in July 2001 after the invasion of the *ctenophore Mnemiopsis* — the chlorophyll concentration increased by more than an order. Another factor contributing to the record variability of bio-optical characteristics is river runoff.

The obtained results provided quantitative data on changes in bio-optical characteristics in the period 1998–2018 for six seas, different in their natural conditions, and provided the basis for further analysis aimed at identifying the processes and factors that caused these changes.

Key words: bio-optical characteristics, inter-annual changes, Barents, Kara, White, Baltic, Black, Caspian Seas, satellite data.

1. Introduction

The past decade has been characterized by pronounced climate changes, which are manifested, in particular, in changes in bio-optical characteristics. These changes, in large part, are both a consequence of climate change, and its indicator. One of the advantages of such an indicator is an opportunity to use satellite ocean color observations for quasi-simultaneous monitoring of wide water areas and creating a long-term series of data. Such measurements allow us, among other things, to analyze both seasonal and inter-annual changes.

The Ocean Optics Laboratory Shirshov Institute of Oceanology Russian Academy of Sciences (SIO RAS), since 2002, produces an updateable Atlas of bio-optical characteristics of the seas, surrounding Russia, by data from satellite color scanners. The 10th issue was published in 2018, complete with a monograph [1], it covered the period from 1998 to 2017. The 11th issue, supplemented with data from 2018, was prepared in 2019 [2].

Both issues contain color maps with the mean monthly distributions of the bio-optical characteristics in the Barents, Kara, White, Baltic, Black, and Caspian Seas. The Atlas also includes diagrams, demonstrating the variability of their monthly means in different sub-regions, and tables with parameters of the inter-annual changeability of different characteristics by year. The set of bio-optical parameters comprises chlorophyll concentration, the particle backscattering coefficient and the absorption coefficient of colored organic matter ("yellow substance"), the parameters of coccolithophore blooms in the Barents and Black Seas, cyanobacteria biomass in the Gulf of Finland of the Baltic Sea. As the main parameters, we use the chlorophyll-*a* concentration (*Chl*) and particle backscattering coefficient ($b_{\mathrm{bp}} = b_{\mathrm{bp}}(555)$), characterizing the variability of phytoplankton and suspended matter; we also included the other characteristics, such as the absorption coefficient of colored organic substance ($a_{\mathrm{g}} = a_{\mathrm{g}}(440)$) as an indicator of river runoff, the parameters characterizing the phytoplankton bloom (coccolithophore blooms in the Barents and Black Seas, of blue-green algae in the Baltic Sea for the last ones, we use the coccolithophore plated cell concentration N_{coc} and the biomass of cyanobacteria B_{cyan}. We have not included the phenological characteristics of the blooms; the interested reader can find some results on such characteristics in the Barents and Black Seas in [1], section 8.1).

Most of the bio-optical characteristics were calculated using regional algorithms, derived from field measurements carried out in the considered seas and reflecting their regional features. As a parameter characterizing climatic changes, the MODIS-Aqua data on the monthly means of sea surface temperature SST available since 2003 are included.

The materials in the Atlas allowed us to study inter-annual changes in the above characteristics. The article contains two sections: the first consider the changes during the period of 2016—2018, compared with the extreme monthly means; the second present the extreme changes for the entire period of observation and give their systematization. The volume of the article does not allow for a detailed analysis of the changes that occurred; we limit by the most pronounced ones and some general conclusions about the main factors causing them. For the White Sea, we consider only the Dvina and Onega Bays, for the Baltic — the Eastern part of the Gulf of Finland, for the Black Sea — the Eastern half.

2. Methods and data

We used Level 2 satellite data from SeaWiFS (January 1998—June 2002) and MODIS-Aqua (July 2002-December 2018) color scanners, available on the website http://oceancolor.gsfc.nasa.gov [3]; the data "cross-linking" was performed by using joint data from these scanners in the period from July 2002 to 2007 [3]. A description of the used algorithms can be found in monograph [1].

The uncertainties estimate was made by comparing data from satellite and field measurements under favorable weather conditions. The actual errors strongly depend on the quality of the used satellite data. In the Arctic seas, frequent cloudiness prevents the getting data from simultaneous ship and satellite measurements ("match-up"); strong horizontal heterogeneity and temporal variability make the error estimation almost impossible.

The accuracy of the estimated monthly means depends on the quality of satellite data used and the data coverage of a given region. This problem was analyzed in [4] by comparing two versions of restrictions on satellite data. The new stricter restrictions provided us with greater reliability, and the "traditional" version, similar to the previous releases, gave more complete but less reliable results. The "strict' restrictions led in many cases to critical data loss and, in particular, significant gaps in charts. The "soft" restrictions provided fewer gaps in the charts, but with lower accuracy in the estimate.

The 11th Atlas issue, as well as the previous 10th, used a version with "soft" restrictions. We only consider months with the acceptable satellite data coverage: for the Barents and White Seas — May-September, the Kara Sea — June-September, the Gulf of Finland — April-October, the Black and Caspian Seas — March-November. The coccolithophore blooms in the Barents Sea we consider in July–September, in the Black Sea — May-June, the cyanobacteria bloom in the Gulf of Finland — July-August.

One of the tasks of our work is to identify extreme monthly means in the studied regions. We do that by using two different options. In Section 3 we analyze the absolute values of the monthly means, in Section 4 — their relative values (the absolute values for a given region, month and year, normalized to "climatic" values). Term "climatic" we use for the monthly means averaged over the period 1998–2011 for the Barents, White, Black and Caspian Seas, and 2003–2011 for the Kara and Baltic Seas [1]. A comparison of the results for two versions is presented in Section 4.

3. Variability of absolute values of the monthly means in the studied regions

This Section presents the changes in absolute values of the monthly means of the selected bio-optical characteristics in each of the considered seas in 2016–2018. The largest changes we compare with the extreme values for the entire observation period.

3.1. The Barents Sea

The top side of fig 1 (see Insert) shows the seasonal changes in chlorophyll concentration (*Chl*), the particle backscattering coefficient (b_{bp}), and sea surface temperature (*SST*) in the three selected sub-regions of the Barents Sea in May-September 2016–2018. Detailed information about the selected sub-regions of this and other seas under consideration can be found in the monograph [1] and the Atlas [2] (freely available on the website http://optics.ocean.ru [3]).

The seasonal variability in fig. 1 in most cases corresponds to the "climatic", but the absolute values are significantly higher. We fixed the highest chlorophyll concentration in the Northern sub-region for the entire observation period in May 2016 (0.41 mg $\cdot$ m^{-3}) and the highest July monthly mean of b_{bp} in the Middle sub-region in 2016 (0.0113 m^{-1}). These record values were associated with phytoplankton blooms: diatom spring blooms in May and coccolithophore blooms in July and August [1, 5–8]; according to direct determinations, the cell concentration at several stations in the Middle sub-region exceeded $6 \cdot 10^6$cell/l. We found the highest monthly means for the whole Barents Sea of chlorophyll concentration (**0.43** mg $\cdot$ m^{-3}) in the Middle sub-region in May 2011 (spring phytoplankton bloom) and the b_{bp} coefficient (**0.0173** m^{-1}) in the Southern sub-region in September 2009, apparently related to the Pechora river runoff (see the diagrams in [2], Appendix 2, Section 2.1).

The right side of fig. 1 shows the *Chl* and b_{bp} monthly mean distributions in June and August 2017. The June map reveals the phytoplankton spring bloom, presumably diatoms (especially pronounced on the *Chl* distribution but also the b_{bp} map). On the bottom maps, one can see the coccolithophore bloom both on the b_{bp} distribution and less clear on the chlorophyll map (specific values of chlorophyll concentration are higher in diatoms than in the coccolithophore cells and, conversely, as to the b_{bp} coefficient). The *SST* monthly means in the considered period in almost all months are noticeably higher than the "climatic" values (see fig. 1).

3.2. The Kara Sea

Fig. 2 (see Insert) shows diagrams for the two sub-regions in the Kara Sea, K1 is the South-Western part of the Sea, K2 is the North-Eastern part. The border between the sub-regions is drawn from Cape Desire on Novaya Zemlya to Dixon Island [1].

As can be seen from fig. 2, the monthly means of chlorophyll concentration in most cases were lower than "climatic" values. We recorded the highest June value for the K1 sub-region (1.23 mg m^{-3}) in 2018, but the highest chlorophyll concentration for this sub-region and the whole Kara Sea was **1.49** mg m^{-3} in July 2002. In K2 the maximum *Chl* value was lower (1.29 mg m^{-3} in September 2015).

The b_{bp} values in K1 were also higher than in K2; the record (**0.0110** m^{-1}) was fixed in September 2010, the close value (0.0109 m^{-1}) was registered in September 2016. The maximum value in K2 was only 0.0079 m^{-1} in July 2003 (see the diagrams in [2], Appendix 3, Section 3.1).

An important factor determining the spatial distribution of bio-optical characteristics in the Kara Sea is a river runoff; its distribution in the Kara Sea depends primarily on the prevailing wind direction [1, 9]. The indicator of the river runoff propagation derivable from satellite data is the yellow substance absorption coefficient a_g. Its lowest values were observed in the K2 sub-region in 2017 (fig. 2, *c*) owing to the prevailing western transport in the summer of that year [4]. The lowest a_g value (0.17 m^{-1}) for the entire observation period was fixed in K2 in June 2010, the highest (1.22 m^{-1}) in K1 in July 2003.

3.3. The White Sea

The bio-optical characteristics of the White Sea undergo noticeable changes during the considered period. Fig. 3 (see Insert) presents diagrams of changes in the monthly means of chlorophyll concentration, the particle backscattering and the yellow substance absorption coefficients a_g in the Dvina and Onega Bays. As seen, these changes are pronounced and differ in these two regions.

In the Dvina Bay we recorded the maximum monthly means of chlorophyll concentrations in June 2017 (3.8 mg m^{-3}) and July 2016 (3.1 mg m^{-3}), in the Onega Bay — in June 2016 (3.5 mg m^{-3}), in July 2017 (3.2 mg m^{-3}), and September 2018 (2.8 mg m^{-3}). The highest *Chl* and b_{bp} values for the whole White Sea we found in the Mezen Bay (**4.0** mg m^{-3} in June 2015 and **0.0183** m^{-1} in May 2017); the maximum b_{bp} value in the Onega Bay was 0.0139 m^{-1} in September 2006; in the Dvina Bay only 0.0080 m^{-1} in May 2000 and 2009 (see the diagrams in [2], Appendix 4, Section 4.1).

We fixed the extreme a_g monthly means for the White Sea over the entire observation period (**4.0** m^{-1}) in the Dvina Bay in May 2013; in the Onega Bay, the a_g value was only 2.2 m^{-1} (in May 2018). The water temperature in both bays was abnormally high in May — July 2016 (in the Dvina Bay also in July 2018); in all months, except May 2017, these values exceeded the "climatic" monthly means (see fig.3).

3.4. The Baltic Sea

In the Baltic Sea, we only considered the eastern part of the Gulf of Finland, where is a regional algorithm for estimating the cyanobacteria biomass. The algorithm is based on the use of a multiple regression equation that relates to the biomass of cyanobacteria (B_{cyan}) to the concentration of chlorophyll *Chl* and the b_{bp} coefficient [1, 10].

Cyanobacteria are also called by blue-green algae because of their photosynthetic ability; their bloom regularly occurs in the Baltic Sea during the summer season. Figure 4 (see Insert) shows seasonal variability of chlorophyll concentration, the particle backscattering coefficient, cyanobacteria biomass, and sea surface temperature.

In 2017 we registered the May maximum monthly mean of chlorophyll concentration (4.9 mg m^{-3}); the highest *Chl* all-monthly mean was **7.0** mg m^{-3} in October 2013; the b_{bp} — **0.0223** m^{-1} in October 2009. The above values were not related to cyanobacteria blooming because of the highest biomass monthly mean (673 mg m^{-3}) was registered in July 2004. The highest July *Chl* concentration (5.7 mg m^{-3}), b_{bp} (0.0180 m^{-1}), and a low *SST* value of 16.4 °C accompanied this record value. We fixed the lowest July *SST* (15.8 °C) in 2017, the highest (21.4 °C) in 2010 (see the diagrams in [2], Appendix 5, Section 5.1).

3.5. The Black Sea

Fig. 5 (see Insert) shows seasonal changes in chlorophyll concentration, the particle backscattering coefficient, coccolithophore cell concentration, and sea surface temperature in the Eastern deep-water region (sub-region #7) and Eastern coastal zone (sub-region #8).

We registered the highest monthly mean of chlorophyll concentration in the sub-region # 8 in March 2017 (**0.70** mg · m^{-3}), in the sub-region # 7 — in May 2001 (**0.68** mg · m^{-3}); these values were associated with the spring blooms of diatoms.

We found the record b_{bp} monthly means for the sub-region #8 in May-July 2017 (**0.0303** m^{-1} in June) caused by intensive coccolithophore blooming [3]; in the sub-region #7 the b_{bp} values, although high (0.0242 m^{-1}) were lower than in June 2012 (0.0258 m^{-1}) — see the diagrams in [2], Appendix 6, Section 6.1. In both cases, the above values corresponded to cold winters [1, 11].

In fig. 5, *a–c*, 2017 stands out by high values of *Chl* and b_{bp} in June with the N_{coc} value of about 5.9 · 10^6 cell/l in both sub-regions (**6.5 · 10^6** cell/l in #7 in 2012). On the maps [2], one can see a marked bloom in June 2017, covering almost the whole sea, while in 2018 was no bloom at all. We also found noticeable blooms in May 2017 (see the map in [2], Appendix 6, Section 6.2); the N_{coc} May means were 1.8×10^6 cell/l in #7 and 2.3 · 10^6 cell/l in #8.

For the yellow substance absorption in the coastal zone, we observed an unusual situation — the a_g values in 2018 were noticeably higher than in 2017 [12].

3.6. The Caspian Sea

Fig. 6 (see Insert) shows the seasonal changes in chlorophyll concentration *Chl*, the particle backscattering b_{bp} and yellow substance absorption a_g coefficients, and sea surface temperature *SST* for the North, Middle, and South sub-regions of the Caspian Sea [1].

We met the highest monthly means in the Middle Caspian in 2017 for the b_{bp} coefficient in August (0.0122 m^{-1}) and for a_g in September (0.234 m^{-1}). However, the record values of these parameters for the whole Caspian Sea were observed in the Northern Caspian for b_{bp} in September 2014 (**0.061** m^{-1}) and for a_g in September 2005 (**0.324** m^{-1}). The Volga runoff and stirring-up of the bottom sediments in shallow waters caused these values.

We registered the highest chlorophyll concentration for the whole Caspian Sea (**4.8** mg · m^{-3}) in the Southern Caspian in August 2001, associated with the invasion of the *ctenophore Mnemiopsis* [13–15]. The maximum value for the Northern Caspian was 3.8 mg · m^{-3} (September 2012), for the Middle — 2.15 mg · m^{-3} (September 2001) — see the diagrams in [2], Appendix 7, Section 7.1.

The sea surface temperature in summer 2016–2018 exceeded the “climatic” values, its relationship with the bio-optical parameters was not found.

4. An assessment of inter-annual changes with a correction for seasonal changes

In this Section, we systematize the extreme changes in the monthly means of bio-optical parameters in different regions over the entire observation period.

Figures 1–6 show pronounced seasonal changes in the “climatic” values of the considered characteristics (black curves in the diagrams). To estimate the range of variations in various characteristics related only to inter-annual changes, we normalize the monthly means for a given region, month, and year by their “climatic” values.

The table shows the maximal and minimal normalized values for the considered sub-regions with the month and year of their registration. The able also presents the ratios of maximal values to minimal ones (max-to-min ratio) for normalized and non-normalized values (in parentheses).

The table shows 35 cases for 13 different sub-regions with 3 bio-optical parameters for each. We see that the max-to–min ratio for non-normalized values in 2 cases is significantly lower than for the normalized. We can explain such cases owing to calculating the maximal normalized value with the lower “climatic” value than the minimal. For example, the ag max-to–min non-normalized ratio for the K1 sub-region in the Kara Sea equals 3.7 and the normalized — 4.9; the discrepancy arises from the seasonal change in the “climatic” values — 0.45 m^{-1} in June and 0.81m^{-1} in September.

The highest value of the max-to-min ratio for the normalized quantities is fixed for chlorophyll concentration in the Southern Caspian in July — 13.2 (maximum in 2001, minimum — in 1999); the record value of the max-to-min ratio for the non-normalized quantities is even more — 15.6 (maximum in August 2001, minimum — in July 1999).

Table

Inter-annual variability of bio-optical characteristics in the considered regions:
***value* — the maximal and minimal normalized parameters; *max-to-min ratio* — the ratio of the higher to the lower normalized parameter (in parenthesis for the non-normalized parameters)**

Subregions		b_{bp}				*Chl*				Other parameters			
		Year	Month	Value	max-to-min ratio	Year	Month	Value	max-to-min ratio	Year	Month	Value	max-to-min ratio
The Barents Sea (May–Sep)										N_{coc}			
North (Bar_N)	max	2013	Sep	1.36	**2.0** (1.95)	2016 2017	May June	1.25	**1.8** (2.3)				
	min	2009	Aug	0.69		2003	May	0.68					
Middle (Bar_M)	max	2016	July	2.57	**4.4** (5.6)	2011 2015	May July	1.26	**1.6** (2.05)	2003	July	1.64	**2.6** (2.8)
	min	1998 1999	July	0.58		1999	May	0.79		2009	July	0.64	

Fin table

South (Bar_S)	max	2010	Aug	1.38	**1.9** (2.05)	2014 2015	July Aug	1.17	**1.3** (1.3)				
	min	2011	Sep	0.71		2011	Sep	0.91					
The Kara Sea (June — Sep)												a_g	
K1 — south-west (K1)	max	2014 2018	June	1.53 1.52	**2.4** (2.0)	2018	June	1.21	**1.6** (1.55)	2007	June	2.57	**4.9** (3.7)
	min	2014	Sep	0.63		2009 2012	Aug July	0.81		2014	Sep	0.52	
K2 — north-east (K2)	max	2003	July	1.78	**2.7** (3.0)	2002	July	1.26	**1.6** (1.9)	2002	July	3.37	**5.6** (6.6)
	min	2009	Aug	0.65		2013	July	0.77		2010	June	0.60	
The White Sea (May — Sep)												a_g	
Dvina Bay (Wh_D)	max	2001	June	1.35	**2.45** (4.9)	2017	June	1.48	**1.7** **(2.0)**	2017	June	1.45	**2.7** (4.7)
	min	2007	July	0.55		2008 2009 2007	June July	0.87		2015	June	0.53	
Onega Bay (Wh_O)	max	2000	May	1.65	**2.6** (3.0)	2016	June	1.27	**1.4** (1.55)	2017	Aug	1.57	**2.45** (3.2)
	min	2005	May	0.64		2003	Aug	0.92		2011	Sep	0.64	
The Baltic Sea (Apr — Oct)												B_{cyan}	
Gulf of Finland (GF)	max	2009	Oct	2.18	**3.6–3.7** (4.4)	2013	Sep	2.59	**5.8** (4.85)	2015	Aug	1.68	**3.2** (3.4)
	min	2002 2013	Oct June	0.59 0.60		2009	July	0.45		2009	July	0.52	
The Black Sea (Mar — Nov)												N_{coc}	
# 7 Eastern open part (Bl_7)	max	2012	June	1.97	**6.20** (16.5)	2001	Sep	1.34	**1.6** (2.0)	2012	June	3.26	
	min	2004	Nov	0.32		2004	Nov	0.84		2001 2003	May-June	[*]*No bloom*[*]	
# 8 Eastern and southern shelf (Bl_8)	max	2017	June	1.98	**4.1** (10.5)	2001	Sep	1.27	**1.6** (1.8)	2017	June	3.71	
	min	2013	June	0.48		2011	Sep	0.83		2001 2003 2010	May-June	[*]*No bloom*[*]	
The Caspian Sea (Mar — Nov)												a_g	
North (Casp_N)	max	2016	Oct	1.38	**1.9** (2.2)	2012	Sep	1.60	**2.25** (3.5)	2005	Sep	1.37	**2.1** (2.1)
	min	2003	Mar	0.71		2008	Oct	0.71		2012	Sep	0.66	
Middle (Casp_M)	max	2017	Aug	1.81	**2.6** (2.8)	2017	July	2.21	**4.8** (5.2)	2017	July	1.41	**2.9** (3.0)
	min	2012	May	0.70		2012	Sep	0.46		2012	Nov	0.49	
South (Casp_S)	max	2001	Aug	2.07	**3.3** (4.0)	2001	July	4.37	**13.2** (15.6)	1998	June	1.35	**2.4** (2.4)
	min	2014	Aug	0.62		1999	July	0.33		2018	Nov	0.57	

[*]*No bloom* is meant that the mean monthly N_{coc} value < 0.510^6cell/l.

For brevity of the further text, we will use the short names for the sub-regions considered (see table).

5. Conclusion

• We present the results of our analysis of the inter-annual variability of the bio-optical parameters of the surface layer derived from satellite ocean color data for six seas in 1998–2018 by the regional algorithms constructed on a base of in situ measured data. It is worth emphasizing we consider data, not of individual measurements, but the monthly means averaged for a large sub-region.

In Section 3 we demonstrate the changes in absolute values of the monthly means of the bio-optical parameters in different sub-regions in 2016–2018. But fig. 1–6 in this Section show data both in that period and the "climatic" (the black lines in figures); the last ones allow us to obtain a general idea about the factors determining the bio-optical characteristics in a given sub-region, including their absolute values and seasonal changes.

As the main factors, we consider two: mass phytoplankton bloom and river runoff. In the considered seas, we not often observe these factors separately, but in fig. 1–6 we can see several cases of the domination of one of them. As an example, we can take coccolithophore blooms (CB) in the sub-regions Bar_M (fig. 1, *a–b*) and Bl_7–8 of the

Black Sea (fig. 5, *a–b*). In both cases, CB displays itself by a strongly pronounced peak in the b_{bp} values — in August for Bar_M and June for Bl_7–8. In *Chl* values, we see the pronounced peak in the Barents Sea in May, caused by phytoplankton spring bloom, and almost no peak in August (see the explanation in Section 3.5). The similar situation is in Bl_7–8 but with *Chl* peak in March and CB in June. The other cases of mass phytoplankton blooms we observed in the Baltic Sea with cyanobacteria, and in the Southern Caspian after the *ctenophore Mnemiopsis* invasion (see Sections 3.4 and 3.6). In the extremal cases of these blooms, we found the high values of both b_{bp} and *Chl*; in the Southern Caspian, it was even the highest *Chl* value for the whole Caspian (4.8 mg m^{-3}).

• We observed the manifestation of the river runoff impact in the Southern Barents, the Kara and White Seas, in the Southern Caspian; this effect is better seen analyzing the "climatic" values. A characteristic feature of river runoff impact is the high values of the backscattering and absorption coefficients and the similarity of their seasonal changes. We can see this effect rather clear for both sub-regions in the White Sea (fig. 3) and the Casp_N (fig. 6). In Wh_D we registered the absolute record value of a_g for all sub-regions presented in our paper — 4.0 m^{-1}, in Casp_N — the same for the b_{bp} — 61 m^{-1} (but in this case, we can suspect a significant contribution from the bottom sediments stirring-up on the shallow shelf).

• One of our tasks is the assessment of the largest ranges of the variability of the considered bio-optical parameters. Such an estimate with the absolute values of the parameters includes both the inter-annual and seasonal changes. The latter in some cases can be rather high (as an example, the ratio of the maximum (in June) to the minimum (in September) b_{bp} "climatic" values in the BL_7 sub-region equals 4.0, the May/August ratio for the a_g "climatic" values in the Wh_D — 2.6). For correction to the seasonal changes, we use the "normalized" values (see Section 4). The table presents the obtained results; the ratios for the non-normalized values are also given.

We obtained the highest ratio for the normalized values of the b_{bp} values in the Bl_7 sub-region — 6.2 (for the non-normalized 16.5); in the Bl_8 it equals 4.1 (10.5). For the *Chl* values, the maximum ratio equals 5.8 (4.85) in the Gulf of Finland, for the a_g ratio — 5.6 (6.6) in the K2 sub-region; in the K1–4.9 (3.7).

• In this work we did not plan to estimate the trends. This is a serious problem with many difficulties, such as an unsatisfactory quality of initial data, strong variations of analyzed parameters, and insufficiently long series of observations [16–18]. For a preliminary assessment of the inter-annual trends, we compared the average annual (seasonal) values in 2012–2018 with the "climatic" values. It turned out that the differences between the average values within the above periods exceed 10 % only in a few cases. For chlorophyll concentration in the Northern Barents, we obtained 12.5 %, the Dvina Bay — 11 %, the Gulf of Finland — 14 %, and the Northern Caspian — 21.5 %. For the b_{bp} coefficient, in the Northern and Middle Barents — 13 and 20 %, and the Northern Caspian — 17 %. The differences are positive, and it seems we can expect a weak positive trend. The appearance of new scanners with improved characteristics and advanced processing algorithms gives hope of increasing the coverage of regions by satellite data, enhancement of their quality, the possibility to get correct estimates of trends, and the wider use of satellite data for assessment of the ongoing climate change [19–22].

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Литература

1. *Копелевич О.В., Салинг И.В., Вазюля С.В., Глуховец Д.И., Шеберстов С.В., Буренков В.И., Каралли П.Г., Юшманова А.В.* Биооптические характеристики морей, омывающих берега западной половины России, по данным спутниковых сканеров цвета 1998–2017 гг. М.: ООО «ВАШ ФОРМАТ», 2018. 140 с.
2. Электронный атлас. URL: http://optics.ocean.ru / (дата обращения: 01.03.2020).
3. Ocean Color Browse. URL: https://oceancolor.gsfc.nasa.gov/cgi/browse.pl (дата обращения: 17.04.2020).
4. *Копелевич О.В., Вазюля С.В., Салинг И.В., Шеберстов С.В., Буренков В.И.* Электронный атлас «Биооптические характеристики морей России по данным спутниковых сканеров цвета 1998–2014 гг.» // Современные проблемы дистанционного зондирования Земли из космоса. 2015. Т. 12, № 6. С. 99–110.
5. *Копелевич О.В., Шеберстов С.В., Салинг И.В., Вазюля С.В., Буренков В.И.* Сезонная и межгодовая изменчивость биооптических характеристик вод поверхностного слоя Баренцева, Белого, Черного и Каспийского морей по спутниковым данным // Фундаментальная и прикладная гидрофизика. 2015. Т. 8, N 1. С. 7–16.
6. *Копелевич О.В., Артемьев В.А.* Сравнение биооптических характеристик Балтийского, Норвежского и Баренцева морей — лето 2016 г. (65-й рейс научно-исследовательского судна «Академик Мстислав Келдыш») // Океанология. 2017. Т. 57, № 2. С. 374–376.

7. *Копелевич О.В., Вазюля С.В., Григорьев А.В., Храпко А.Н., Шеберстов С.В., Салинг И.В.* Проникновение солнечной радиации видимого диапазона в воды Баренцева моря в зависимости от облачности и кокколитофоридных цветений // Океанология. 2017. Т. 57, № 3. С. 445–453. doi:10.7868/S0030157417020095
8. *Копелевич О.В.*, *Каралли П.Г.*, *Лохов А.С.*, *Салинг И.В.*, *Шеберстов С.В.* Перспективы улучшения точности оценки параметров кокколитофоридных цветений в Баренцевом море по спутниковым данным // Современные проблемы дистанционного зондирования Земли из космоса. 2017. Т. 14, № 7. С. 267–279.
9. *Osadchiev A.A.*, *Izhitskiy A.S.*, *Zavialov P.O.*, *Kremenetskiy V.V.*, *Polukhin A.A.*, *Pelevin V.V.*, *Toktamysova Z.M.* Structure of the buoyant plume formed by Ob and Yenisei river discharge in the southern part of the Kara Sea during summer and autumn // J. Geophys. Res. Oceans. 2017. V. 122, N 7. P. 5916–5935.
10. *Vazyulya S.*, *Khrapko A.*, *Kopelevich O.*, *Burenkov V.*, *Eremina T.*, *Isaev A.* Regional algorithms for the estimation of chlorophyll and suspended matter concentration in the Gulf of Finland from MODIS-Aqua satellite data // Oceanologia. 2014. V. 56, N 4. P. 1–19.
11. *Kopelevich O.V.*, *Burenkov V.I.*, *Sheberstov S.V.*, *Vazulya S.V.*, *Sahling I.V.* Coccolithophore Blooms in the North-Eastern Black Sea // Proceedings of the Twelfth International Conference on the Mediterranean Coastal Environment, MEDCOAST 15, 06–10 October 2015, Varna, Bulgaria, MEDCOAST, Mediterranean Coastal Foundation, Dalyan, Mugla, Turkey, 2015. V. 1. P. 363–374.
12. *Yushmanova A.*, *Kopelevich O.*, *Vazyulya S.*, *and Sahling I. Inter-*Annual Variability of the Seawater Light Absorption in Surface Layer of the Northeastern Black Sea in Connection with Hydrometeorological Factors // J. Mar. Sci. Eng. 2019. N 7. P. 326. doi:10.3390/jmse7090326
13. *Kopelevich O.V.*, *Burenkov V.I.*, *Ershova S.V.*, *Sheberstov S.V.*, *Evdoshenko M.A.* Application of SeaWiFS data for studying variability of bio-optical characteristics in the Barents, Black and Caspian Seas // Deep-Sea Research II 51. 2004. P. 1063–1091.
14. *Kopelevich O.V.*, *Burenkov V.I.*, *Sheberstov S.V.* Case Studies of Optical Remote Sensing in the Barents Sea, Black Sea, and Caspian Sea // Remote Sensing of the European Seas, Vittorio Barale, Martin Gade, (Eds.), Springer, 2008, P. 53–66.
15. *Shiganova T.A.*, *Dumont H.J.*, *Sokolsky A.T.*, *Kamakin A.H.*, *Tinenkova D.*, *Kurasheva E.* Population dynamics of Mnemiopsis leidyi in the Caspian Sea, and effects on the Caspian ecosystem // Aquatic Invasions in the Black, Caspian, and Mediterranean Seas: The Ctenophores Mnemiopsis leidyi and Beroe in the Ponto-Caspian and other Aquatic Invasions. Springer, Dordrecht. 2004. P. 71–111.
16. *Kopelevich O.V.*, *Sheberstov S.V.* Assessment of Interannual Variability of Surface Chlophyll and Seawater Temperature in the Atlantic Ocean from Satellite Data // Proceedings of IV International Conference "Current Problems in Optics of Natural Waters (ONW'2007)". Nizhny Novgorod. 2007. P. 161–165.
17. *Шеберстов С.В.*, *Копелевич О.В.*, *Лукьянова Е.А.* Анализ межгодовых трендов температуры поверхности и концентрации хлорофилла в Атлантическом океане по спутниковым данным // Современные проблемы дистанционного зондирования Земли из космоса. 2011. Т. 8, № 4. С. 274–282.
18. *Копелевич О.В.*, *Шеберстов С.В.* Оценка по спутниковым данным межгодовых и сезонных изменений температуры и концентрации хлорофилла в поверхностном слое в период 1998–2008 гг. // Современные проблемы дистанционного зондирования Земли из космоса. 2010. Т. 7, № 1. С. 238–247.
19. *Sathyendranath S.*, *Brewin R.J.W.*, *Brockmann C.* et al. An Ocean-Colour Time Series for Use in Climate Studies: The Experience of the Ocean-Colour Climate Change Initiative (OC–CCI). Sensors 2019, 19, 4285; doi:10.3390/s19194285
20. *Kostianoy A.G.* Satellite monitoring of climatic parameters of the ocean. Part 1 // Fundamental and Applied Climatology. 2017a. V. 2. P. 27–49.
21. *Kostianoy A.G.* Satellite monitoring of climatic parameters of the ocean. Part 2 // Fundamental and Applied Climatology. 2017b. V.3. P. 57–83
22. *Kopelevich O.V.*, *Kostianoy A.G.* The use of bio-optical parameters of the ocean derived from satellite data as essential climate variables // Fundamental and Applied Climatology. 2018. V. 3. P. 8–29.

References

1. *Kopelevich O.V.*, *Saling I.V.*, *Vazyulya S.V.*, *Gluxovec D.I.*, *Sheberstov S.V.*, *Burenkov V.I.*, *Karalli P.G.*, *Yushmanova A.V.* Bio-optical characteristics of the seas, surrounding the western part of Russia, from data of the satellite ocean color scanners of 1998–2017. *Moscow*, *OOO «VASh FORMAT»*, 2018, 140 p. (in Russian).
2. Electronic Atlas. Bio-optical characteristics of the seas, surrounding the western part of Russia, from data of satellite ocean color scanners of 1998–2018. http://optics.ocean.ru (date of access: 01.03.2020).
3. Ocean Color Browse. URL: https://oceancolor.gsfc.nasa.gov/cgi/browse.pl (date of access: 17.04.2020).
4. *Kopelevich O.V.*, *Sheberstov S.V.*, *Saling I.V.*, *Vazyulya S.V.*, *Burenkov V.I.* Seasonal and Inter-Annual Changeability of Bio-Optical Characteristics in the Surface Layer of the Barents, White, Black and Caspian Seas from Satellite Data. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2015, 8, 1, 7–16 (in Russian).
5. *Kopelevich O.V.*, *Vazyulya S.V.*, *Saling I.V.*, *Sheberstov S.V., Burenkov V.I.* Electronic atlas "Biooptical characteristics of the Russian Seas from satellite ocean color data of 1998–2014". *Sovremennye Problemy' Distancionnogo Zondirovaniya Zemli iz Kosmosa*. 2015, 12, 6, 99–110 (in Russian).

6. *Kopelevich O.V.*, *Artemiev V.A.* Comparison of biooptical characteristics of the Baltic, Norwegian, and Barents Seas: summer 2016 (Cruise 65 of the R/V Akademik Mstislav Keldysh). *Oceanology*. Pleiades Publishing, Ltd., 2017, 57, 2, 340–342.
7. *Kopelevich O.V.*, *Vazyulya S.V.*, *Grigoriev A.V.*, *Khrapko A.N.*, *Sheberstov S.V.*, *Sahling I.V.* Penetration of visible solar radiation in waters of the Barents Sea depending on cloudiness and coccolithophore blooms. *Oceanology*. Pleiades Publishing, Ltd., 2017, 57, 3, 402–409.
8. *Kopelevich O.V.*, *Karalli P.G.*, *Lohov A.S.*, *Saling I.V.*, *Sheberstov S.V.* Prospects for improving the accuracy of estimates of the parameters of coccolithophoride blooms in the Barents Sea from satellite data. *Sovremennye Problemy Distancionnogo Zondirovaniya Zemli iz Kosmosa*. 2017, 14, 7, 267–279 (in Russian).
9. *Osadchiev A.A.*, *Izhitskiy A.S.*, *Zavialov P.O.*, *Kremenetskiy V.V.*, *Polukhin A.A.*, *Pelevin V.V.*, *Toktamysova Z.M.* Structure of the buoyant plume formed by Ob and Yenisei river discharge in the southern part of the Kara Sea during summer and autumn. *J. Geophys. Res. Oceans*. 2017, 122, 7, 5916–5935.
10. *Vazyulya S.*, *Khrapko A.*, *Kopelevich O.*, *Burenkov V.*, *Eremina T.*, *Isaev A.* Regional algorithms for the estimation of chlorophyll and suspended matter concentration in the Gulf of Finland from MODIS-Aqua satellite data. *Oceanologia*. 2014, 56, 4, 1–19.
11. *Kopelevich O.V.*, *Burenkov V.I.*, *Sheberstov S.V.*, *Vazulya S.V.*, *Sahling I.V.* Coccolithophore Blooms in the North-Eastern Black Sea. *Proceedings of the Twelfth International Conference on the Mediterranean Coastal Environment*, *MEDCOAST 15*, 06–10 October 2015, *Varna*, *Bulgaria*, *MEDCOAST*, *Mediterranean Coastal Foundation*, *Dalyan*, *Mugla*, *Turkey*, 2015, 1, 363–374.
12. *Yushmanova A.*, *Kopelevich O.*, *Vazyulya S.*, *and Sahling I.* Inter-Annual Variability of the Seawater Light Absorption in Surface Layer of the Northeastern Black Sea in Connection with Hydrometeorological Factors. *J. Mar. Sci. Eng*. 2019, 7, 326. doi:10.3390/jmse7090326
13. *Kopelevich O.V.*, *Burenkov V.I.*, *Ershova S.V.*, *Sheberstov S.V.*, *Evdoshenko M.A.* Application of SeaWiFS data for studying variability of bio-optical characteristics in the Barents, Black and Caspian Seas. *Deep-Sea Research* II 51. 2004, 1063–1091.
14. *Kopelevich O.V.*, *Burenkov V.I.*, *Sheberstov S.V.* Case Studies of Optical Remote Sensing in the Barents Sea, Black Sea, and Caspian Sea. *Remote Sensing of the European Seas*. Vittorio Barale, Martin Gade, (Eds.), *Springer*, 2008, 53–66.
15. *Shiganova T.A.*, *Dumont H.J.*, *Sokolsky A.T.*, *Kamakin A.H.*, *Tinenkova D.*, *Kurasheva E.* Population dynamics of Mnemiopsis leidyi in the Caspian Sea, and effects on the Caspian ecosystem. *Aquatic Invasions in the Black*, *Caspian*, *and Mediterranean Seas*: *The Ctenophores Mnemiopsis leidyi and Beroe in the Ponto-Caspian and other Aquatic Invasions*. *Springer*, *Dordrecht*. 2004, 71–111.
16. *Kopelevich O.V.*, *Sheberstov S.V.* Assessment of Interannual Variability of Surface Chlophyll and Seawater Temperature in the Atlantic Ocean from Satellite Data. *Proceedings of IV International Conference* "*Current Problems in Optics of Natural Waters* (*ONW'2007*)". *Nizhny Novgorod*. 2007, 161–165.
17. *Sheberstov S.V.*, *Kopelevich O.V.*, *Luk'yanova E.A.* Analysis of inter-annual trends of sea surface temperature and chlorophyll concentration in the Atlantic Ocean from satellite data. *Sovremennye Problemy Distancionnogo Zondirovaniya Zemli iz Kosmosa*. 2011, 8, 4, 274–282 (in Russian).
18. *Kopelevich O.V.*, *Sheberstov S.V.* Assessment of inter-annual and seasonal changes in sea surface temperature and chlorophyll concentration in the Atlantic Ocean in 1998–2008 from satellite data. *Sovremennye Problemy Distancionnogo Zondirovaniya Zemli iz Kosmosa*. 2010, 7, 1, 238–247 (in Russian).
19. *Sathyendranath S.*, *Brewin R.J.W.*, *Brockmann C.* et al. An Ocean-Colour Time Series for Use in Climate Studies: The Experience of the Ocean-Colour Climate Change Initiative (OC–CCI). *Sensors*. 2019, 19, 4285. doi:10.3390/s19194285
20. *Kostianoy A.G.* Satellite monitoring of climatic parameters of the ocean. Part 1. *Fundamental and Applied Climatology*. 2017a, 2, 27–49.
21. *Kostianoy A.G.* Satellite monitoring of climatic parameters of the ocean. Part 2. *Fundamental and Applied Climatology*. 2017b, 3, 57–83.
22. *Kopelevich O.V.*, *Kostianoy A.G.* The use of bio-optical parameters of the ocean derived from satellite data as essential climate variables. *Fundamental and Applied Climatology*. 2018, 3, 8–29.

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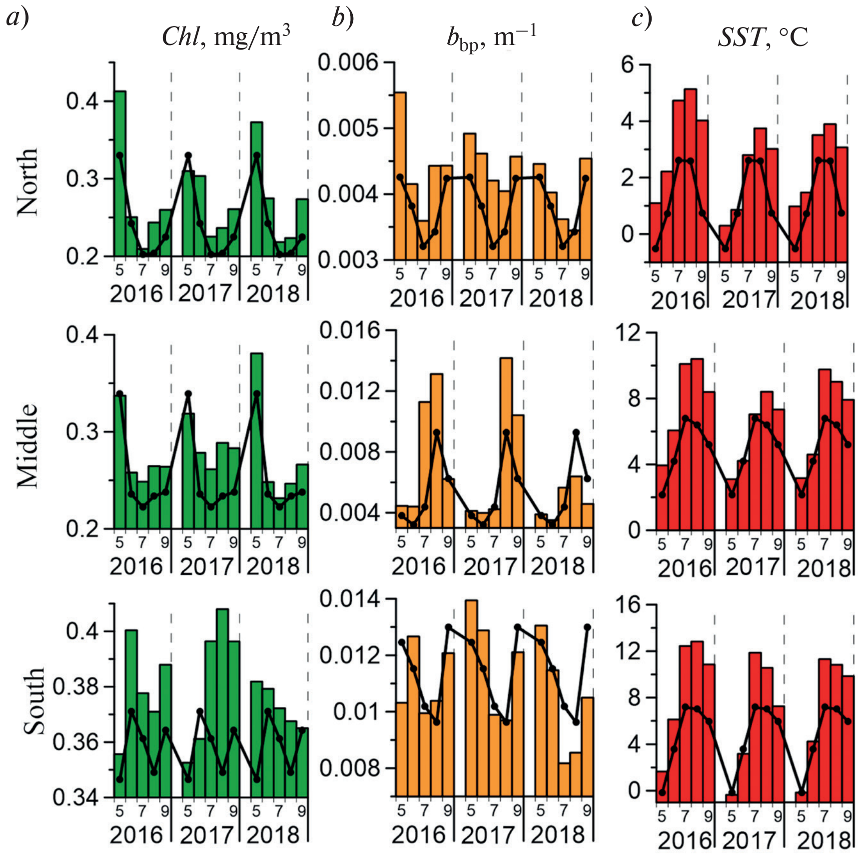

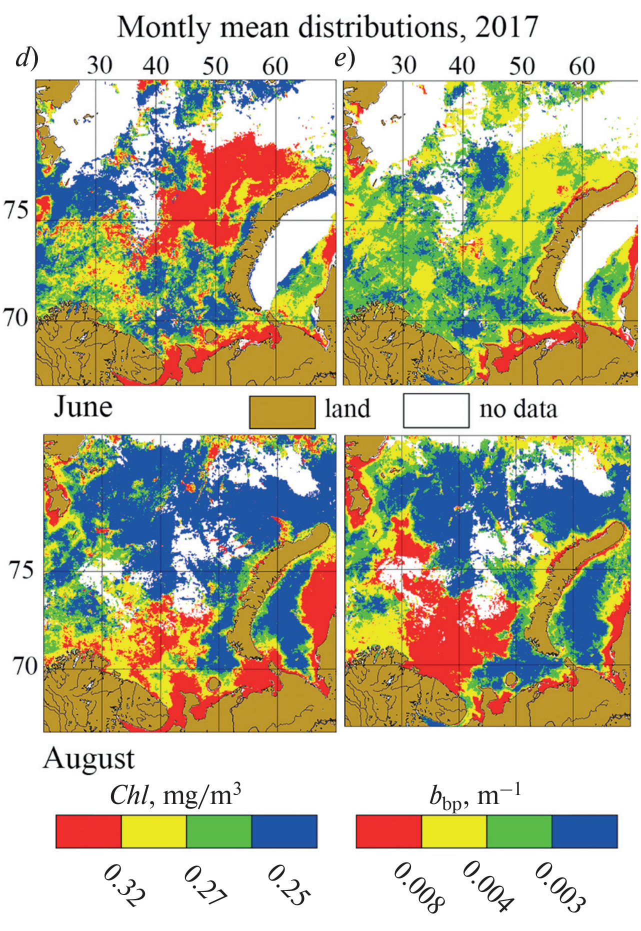

Fig. 1. Seasonal changes of the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), sea surface temperature *SST* (*c*) in the sub-regions of the Barents Sea in 2016–2018; the black lines show the «climatic» values (averaged throughout 1998–2011). Right — the monthly mean distributions of the *Chl* (*d*) and b_{bp} (*e*) values in June and August of 2017.

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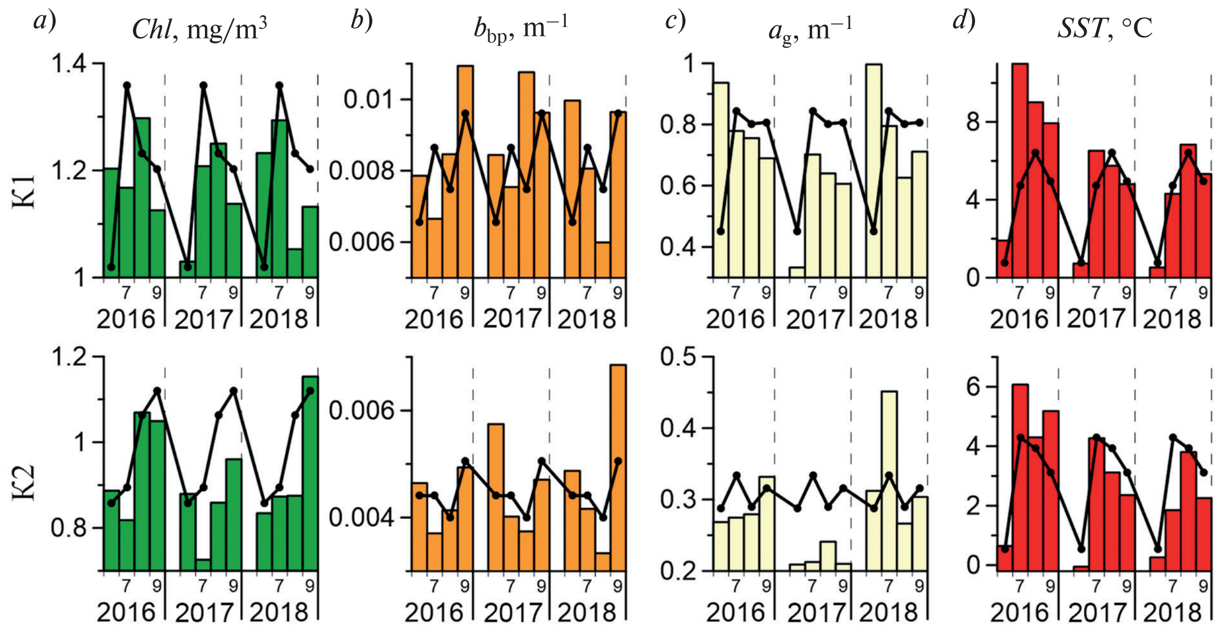

Fig. 2. Seasonal changes of the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), the yellow substance absorption coefficient a_g (*c*), sea surface temperature *SST* (*d*) in the sub-regions of the Kara Sea in 2016–2018; the black lines show the «climatic» values (averaged throughout 2003–2011).

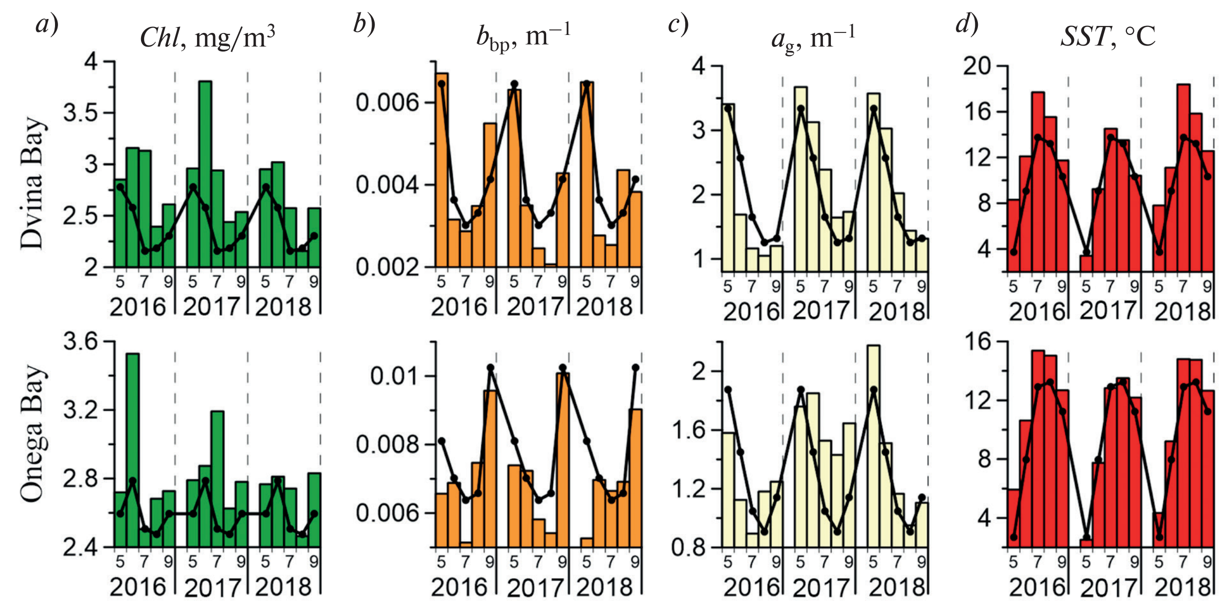

Fig. 3. Seasonal changes in the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), the yellow substance absorption coefficient a_g (*c*), sea surface temperature *SST* (*d*) in the sub-regions of the White Sea in 2016–2018; the black lines show the «climatic» values (averaged throughout 1998–2011).

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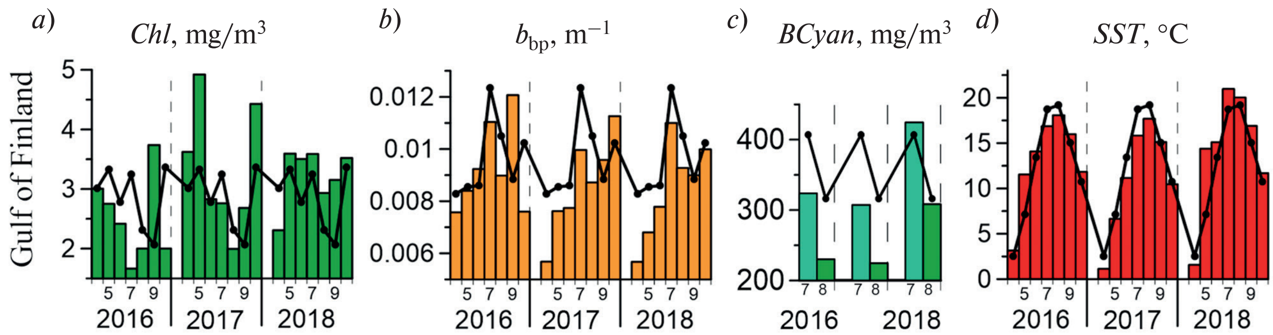

Fig. 4. Seasonal changes of the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), of *Cyanobacteria* biomass B_{cyan} (*c*), and sea surface temperature *SST* (*d*) in the Gulf of Finland of the Baltic Sea in 2016–2018; the black lines show the «climatic» values (averaged throughout 2003–2011).

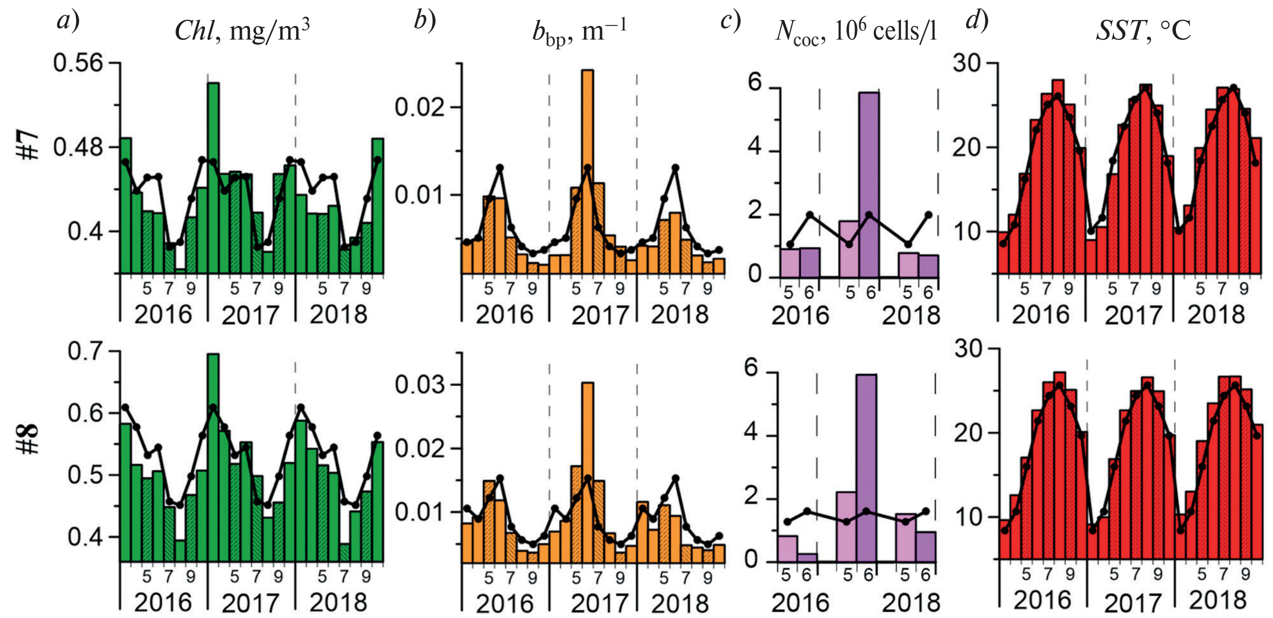

Fig. 5. Seasonal changes of the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), the coccolithophore cell concentration (*c*), sea surface temperature *SST* (*d*) in the subregions #7 and #8 of the Black Sea; the black lines show the «climatic» values (averaged throughout 1998–2011).

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Kopelevich O.V., *Sahling I.V.* Interannual changes of the bio-optical characteristics...

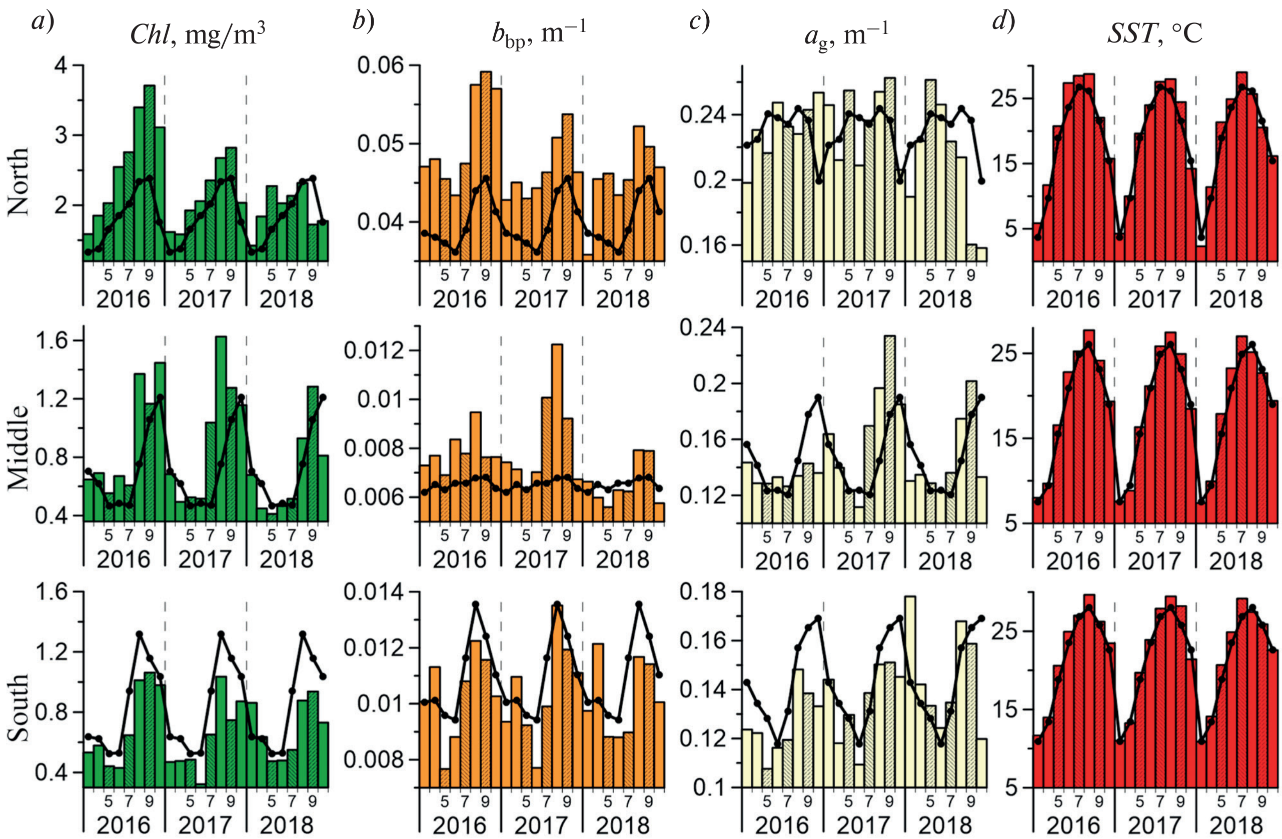

Fig. 6. Seasonal changes of the monthly means of *Chl* concentration (*a*), the particle backscattering coefficient b_{bp} (*b*), the yellow substance absorption coefficient a_g (*c*), sea surface temperature *SST* (*d*) in the sub-regions of the Caspian Sea in 2016–2018; the black lines show the «climatic» values (averaged throughout 1998–2011).