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EXAMPLES OF THE WATER DYNAMICS INFLUENCE ON THE SPATIAL DISTRIBUTION OF CHLOROPHYLL *A* FLUORESCENCE INTENSITY IN THE SURFACE LAYER OF THE BARENTS AND NORWEGIAN SEAS

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Abstract

The influence of water dynamics on the spatial distribution of chlorophyll *a* fluorescence intensity in the surface layer of the Barents and Norwegian Seas, obtained during the 80-th cruise of the R/V "Akademik Mstislav Keldysh" using the flow-through measuring complex in August 2020, was demonstrated. The divergence of the current velocity field, calculated according to reanalysis data, was chosen as a parameter describing the dynamics of water masses. The application of the sliding correlations method allowed us to identify areas of the track with positive and negative correlations between the values of divergence and chlorophyll a fluorescence intensity. It is shown that a positive correlation is formed as a result of the vertical movement of the water surface layer, a negative one — may be a consequence of the water masses advection and the daily changes of the values of photosynthetically active radiation. The part of obtained results is confirmed by satellite data on the spatial distribution of chlorophyll *a* concentration.

Keywords: chlorophyll *a*, seawater fluorescence, divergence of the current velocity field, surface layer, satellite data, photosynthetically active radiation, Barents Sea, Norwegian Sea

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ПРИМЕРЫ ВЛИЯНИЯ ДИНАМИКИ ВОД НА ПРОСТРАНСТВЕННОЕ РАСПРЕДЕЛЕНИЕ ИНТЕНСИВНОСТИ ФЛУОРЕСЦЕНЦИИ ХЛОРОФИЛЛА *А* В ПОВЕРХНОСТНОМ СЛОЕ БАРЕНЦЕВА И НОРВЕЖСКОГО МОРЕЙ

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Аннотация

Продемонстрировано влияние динамики вод на пространственное распределение интенсивности флуоресценции хлорофилла *а* в поверхностном слое Баренцева и Норвежского морей, полученное на ходу судна с помощью проточного измерительного комплекса в августе 2020 г. В качестве параметра, характеризующего динамику водных масс, выбрана дивергенция поля течений, рассчитанная по данным реанализа. Применение метода скользящих корреляций позволило выделить участки маршрута с положительной и отрицательной корреляциями значений дивергенции и интенсивности флуоресценции хлорофилла *а*. Показано, что положительная корреляция формируется в результате вертикального движения вод поверхностного слоя, отрицательная — может являться следствием адвекции водных масс и суточного хода значений фотосинтетически активной радиации. Часть полученных результатов подтверждается спутниковыми данными о пространственном распределении концентрации хлорофилла *а*.

Ключевые слова: хлорофилл *а*, флуоресценция, дивергенция поля течений, поверхностный слой, спутниковые данные, фотосинтетически активная радиация, Баренцево море, Норвежское море

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1. Introduction

The movement of water masses affects the distribution of bio-optical characteristics of seawater [1–3]. The emerging processes of upwelling, advection, and vertical mixing redistribute phytoplankton and the mineral elements necessary for its development in the seawater column [4, 5]. As a result, the currents affect the spatiotemporal distribution of the bio-optical characteristics of the seawater surface layer, in particular, the chlorophyll *a* (Chl) fluorescence intensity characterizing the phytoplankton biomass. The spatial distribution of bio-optical characteristics associated with phytoplankton can be effectively studied by optical methods, such as fluorescence [6–8]. The purpose of this research is to demonstrate examples of the relationship between the Chl fluorescence intensity (I_{fl}) spatial distribution in the surface layer of seawater and the values of the surface current field divergence in the Barents and Norwegian Seas that affect this distribution, as well as to analyze the mechanism of occurrence of the registered examples. It should be noted that such a relationship could not be found on most sections of the R/V track. This may be due to a number of reasons, the most probable of which is the uniformity of the spatial distribution of bio-optical characteristics in these areas. In this case, water mixing cannot lead to variability in the Chl concentration. Besides, the I_{fl} values, in addition to the concentration of this pigment, can be influenced by a number of factors, for example, the species composition of phytoplankton, physiological state of cells and adaptation to mineral nutrition and light regime [9]. In this article, the influence of the light regime is considered, the analysis of other factors influence is a subject for a separate study.

2. Equipment and methodology

The results of continuous shipboard measurements of bio-optical characteristics along the vessel route were used in the work. The measurements were made during the 80th cruise of the R/V 'Akademik Mstislav Keldysh' in the Barents and Norwegian Seas in August 2020 [10]. The Chl fluorescence intensity was measured using the PFD-2M two-channel flow-through fluorimeter, which is part of the flow-through measuring complex [11]. The water intake depth was 2–3 m, the spatial resolution was about 50 m. After calibration, the instrument readings are reduced to absolute (Raman) units (R.U.), which makes it possible to compare the obtained results with the data of other fluorimetric measurements.

The cruise also included continuous recording of the photosynthetically active radiation (PAR) incident on the seawater surface, measured by the LI–COR sensor.

The divergence values of the current field in the surface layer were calculated using data obtained from the CMEMS (Copernicus Marine Environment Monitoring Service) oceanographic reanalysis website, the portal of the Copernicus European Marine Forecast Centers system, https://resources.marine.copernicus.eu, product ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a with a spatial resolution of 12,5 km and a temporal resolution of 1 hour. The data of the used product is based on the HYCOM model [12] with weekly data assimilation using the Kalman filter [13].

Unfortunately, on the cruise which data are analyzed in the article, the shipborne ADCP did not work, and we cannot confirm the quality of the reanalysis data by shipboard measurements. A comparison of this model data with the results of direct determinations of current velocities obtained using buoys, presented in the report of the US Navy Research Laboratory for 2020, showed that the deviations of the current velocities average values in the upper ocean layer do not exceed 10 % [14]. We checked the accuracy of the model data used in the region under study in June 2021 during the 1st stage of the 83rd cruise of the R/V 'Akademik Mstislav Keldysh', where we performed passing measurements of the current velocity. Their results showed agreement with the reanalysis data in the area of separation of the Norwegian Current into the North Cape and Svalbard[1].

The values of the current field divergence in the surface layer were averaged over a day (± 12 hours by the time of the vessel measurement by the flow-through measuring complex) to eliminate the contribution of the tides contained in the product used. Due to the significant difference in the spatial resolution of the reanalysis data and the results of vessel continuous measurements, each divergence value corresponds to Chl

[1] https://www.ocean.ru/index.php/vse-novosti/item/2152-pervyj-etap-83-go-rejsa-nis-akademik-mstislav-keldysh

fluorescence intensity values array. For further processing, the median values of these series were used. Using an hourly reanalysis at an average vessel speed of 9 knots leads to doubling the number of data analyzed for each point of the data section (in most cases, the vessel passes each reanalysis pixel in more than an hour, which corresponds to two consecutive time steps of divergence values). The average number of points in each section is $N = 20$.

The onboard automated weather station data obtained during the cruise showed the predominance of NW winds with a speed of 9–12 m/s, less often NE winds with a speed of 7–10 m/s were recorded. The maximum wind speed was 14 m/s; the minimum was 3 m/s. It should be noted that the results of the CMEMS reanalysis take into account wind mixing.

To search for sections of the route with the highest values of the correlation coefficients between the values of the current field divergence and the Chl fluorescence intensity measured along the vessel route, calculations were carried out using the sliding correlation method with a selected scale of 120 km [15]. The correlation coefficient is determined by the equation:

$$R(x,y) = \frac{cov(x,y)}{\sigma_x \sigma_y},$$

where $cov\ (x, y)$ is the covariance of x and y, σ is root-mean-square deviation.

The choice of the scale for calculations is determined by the size of the manifestations of the objects under study — frontal zones and mesoscale eddies. The significance of the found correlation coefficients R was determined by the level of *p-value* = 0.01. We used the criterion $|\Delta I_{fl}| > 0.1$ R.U. to exclude the influence of mistakes due to low variability of fluorescence Chl intensity on quasi-homogeneous sections of the route. Application of this criterion makes it possible to exclude from consideration areas where the influence of dynamics has little effect on the spatial distribution of I_{fl}.

Spatial distributions of Chl concentration (standard product chlor_a [16]) were obtained from the data of satellite ocean color scanners MODIS/Aqua (August 5, 2020, 12:10 UTC) and MODIS/Terra (August 16, 2020, 11:35 UTC). The spatial resolution of the data is 1 km.

3. Results

The map of currents in the surface layer of seawater and the calculated values of the currents velocity field divergence, built according to the reanalysis data, are shown in Figure 1. The data are averaged over the period of shipboard measurements (August 5–23, 2020). The greatest inhomogeneity of the current structure is observed in the areas where the Norwegian Atlantic Current divides into the North Cape and Svalbard Current (to the north of a sharp drop in the depths in the region of 70–71°N, 17–18°E) and of the Polar Front [17]. In area near 70°N, 3°E the convective structure in the Lofoten Vortex is clearly manifested [18]. Water dynamics includes vertical movements of water masses, which leads to changes in the spatial distribution of biogeochemical characteristics. These manifestations can be registered in the spatial distributions of the fluorescence intensity in the surface layer.

The results of calculations of sliding correlations between the values of the velocity field divergence and the intensity of Chl fluorescence measured along the vessel route on a scale of 120 km are shown in Figure 2. High absolute values of the correlation were recorded in the areas of the inhomogeneous current field southwest of Svalbard. Variations in the threshold values of R, significant at the *p-value* = 0.01 level, in different regions of the figure occur because of a different number of points fall within the chosen data processing scope. It is important to note that in the approach used in the work, the values of the correlation coefficients in individual areas are affected by the variability of the divergence values, and not by their absolute value and sign in the given area. The characteristics of the areas considered in the work are given in Table.

4. Discussion

Assuming that the contribution of seawater density variability compared to the current velocity is small, we can write a simplified continuity equation:

$$div V = \frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0,$$

where u, v, w are the horizontal and vertical components of the current velocity vector.

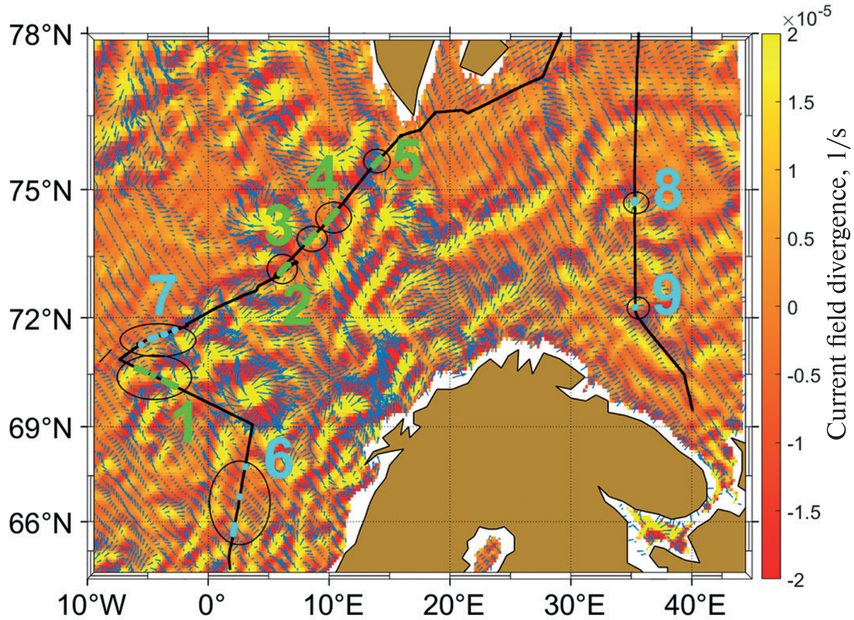

Fig. 1. The map of currents (blue arrows, the maximum length corresponds to 0.35 m/s) and the values of divergence of the currents field (shades of orange), with the added part of the route of 80th cruise of the R/V "Akademik Mstislav Keldysh", August 5–23, 2020 (black line). Areas with a significant positive correlation between the values of the Chl fluorescence intensity and divergence are highlighted in green, the negative correlation areas are highlighted in cyan. The numbers indicate the numbering of these areas

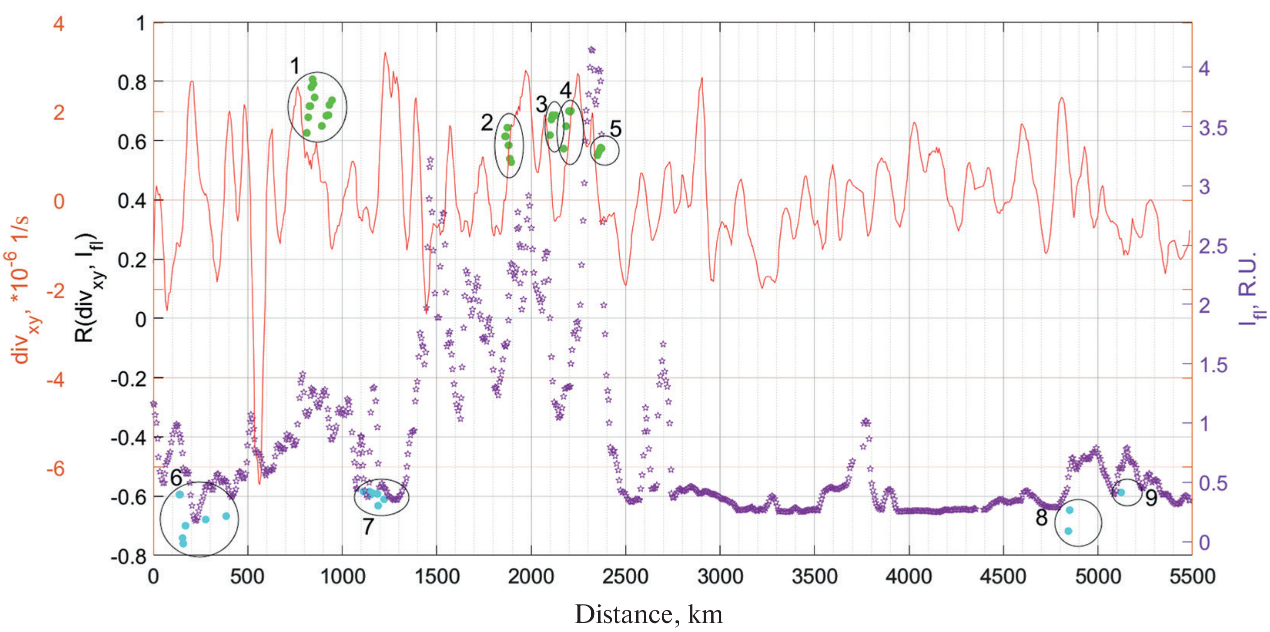

Fig. 2. Change in median values of the Chl fluorescence intensity (purple) and the value of divergence of the currents field (brown) along the R/V track. The circles highlight the positions of the route tracks with significant (*p*-value = 0.01) correlation coefficients (R) between the value of the divergence of the current field and the Chl fluorescence intensity (green — with a positive value of R, blue — with a negative R)

Table

Characteristics of the considered route tracks. The average number of points in each plot is $N = 20$

Section number	R	Confidence interval	Change I_{fl}	Change $divV_{xy}$	$\lvert\Delta div\rvert$, $*10^{-6}$	div sign	Cause
1	0.7	(0.24, 0.9)	↓	↓	3.6	+	Reducing the lifting speed
2	0.6	(0.07, 0.87)	↑	↑	3.6	+	Increasing the lifting speed
3	0.65	(0.15, 0.89)	↓	↓	2.3	+	Reducing the lifting speed
4	0.63	(0.12, 0.88)	↑	↑	3.2	+	Increasing the lifting speed
5	0.57	(0.02, 0.85)	↓	↓	2.5	+	Reducing the lifting speed
6	−0.7	(−0.90, −0.25)	↓↑	↓↑	4.8	+	Advection
7	−0.6	(−0.87, −0.07)	↓	↑	4.1	–	Daytime PAR
8	−0.7	(−0.90, −0.25)	↑	↓	2.6	+	Not related to vert. dynamics
9	−0.59	(−0.86, −0.05)	↑	↓	0.4	–	Not related to vert. dynamics

Value of $divV_{xy} = \frac{du}{dx} + \frac{dv}{dy}$ is calculated from the reanalysis data, and the $\frac{dw}{dz} = -divV_{xy}$ component responds for the law of conservation of mass. Taking into account the vertical direction of the z axis and the boundary condition $w(0) = 0$, we find that negative values $divV_{xy}$ correspond to the lowering of surface waters, and positive values correspond to the rise of waters from the underlying layers to the surface.

A positive correlation is formed both with a direct increase in the concentration of phytoplankton, and with the influx of biogenic elements necessary for its development, due to an increase in the intensity of upwelling (Fig. 1,2, Table, sections 2 and 4). Similarly, a positive correlation can be observed with a decrease in the upwelling speed with simultaneously reducing the Chl fluorescence intensity (sections 1, 3, and 5).

It is not possible to explain the reasons for the negative correlation of the studied characteristics within the framework of such a simple model. As will be shown below, the values of the negative correlation obtained as a result of the calculation are not related to the influence of vertical water movement on the intensity of Chl fluorescence in the surface layer of seawater, but to other factors. In fact, this situation is equivalent to the case of the absence of a statistical relationship, that is, insignificant or low values of $R(divV_{xy}, I_{fl})$. To search for and analyze the factors leading to the case of a negative correlation, data on the direction of currents, satellite data on the Chl concentration, and the results of shipboard measurements of the PAR flux were used.

A significant negative correlation was registered on four sections of the route. There are considered the first two (6, 7) in more detail. For these areas, maps of surface currents averaged a day before shipboard measurements were constructed (Fig. 3). It should be noted that for section 6 it was able to select satellite data corresponding to the day of the shipboard measurements. For the 7th, due to dense cloud cover, the difference was a week. In the area of the 6th section with a negative correlation, the direction of currents in the surface layer is northwestern. Satellite data on the spatial distribution of the Chl concentration show that the Chl concentration is highly variable southeast of the studied section of the route. It is important to note that in this section, with the most intensive vertical movement of water, the smallest values of I_{fl} are observed (Fig. 2, about 200 km). Apparently, intense vertical movement blocks the horizontal transport of waters characterized by higher I_{fl} values. This forms the registered negative correlation.

In the area of the 7th section with a significant negative correlation, an intense vortex dynamic is observed (Fig. 3 on the right). This does not allow the use of satellite data obtained with a weekly interval from the time of shipboard measurements for analysis.

The light regime is considered as another factor that can affect the relationship between water dynamics and Chl fluorescence intensity. To analyze the influence of the light regime on the Chl fluorescence intensity, we used the data of accompanying continuous measurements of the PAR flux. Phytoplankton can adapt to different lighting conditions [9], which in some cases leads to an increase in the Chl fluorescence intensity at night and vice versa. To assess the influence of this factor, the latitudinal dependence of the PAR values and the Chl fluorescence intensity along the vessel track in section 7 was plotted (Fig. 4). This area is marked on the

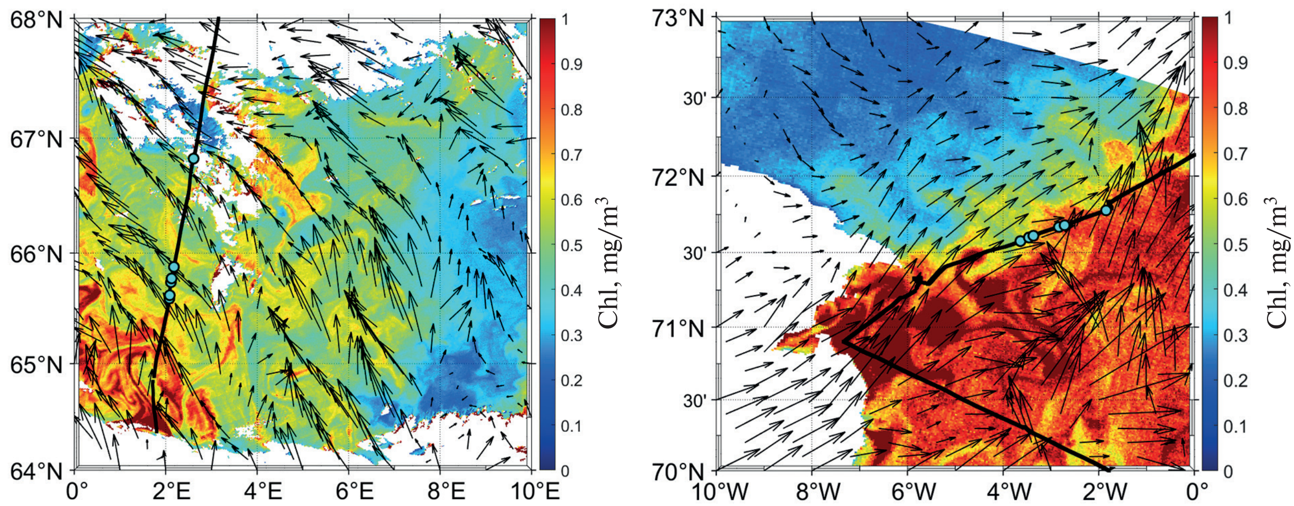

Fig. 3. Current map according to reanalysis data (black arrows) averaged a day before shipboard measurements and satellite concentration of Chl (in color) according to MODIS data (left: MODIS/Aqua, August 5, 2020, 12:10 UTC; right: MODIS/Terra, August 16, 2020, 11:35 UTC). Cyan circles indicate areas with significant negative R values, white areas correspond to the lack of data due to clouds or places being out of image. Left: area of track 6 (5.08.2020), right: area of track 7 (09.08.2020). The maximum length of the arrows corresponds to 0.4 m/s

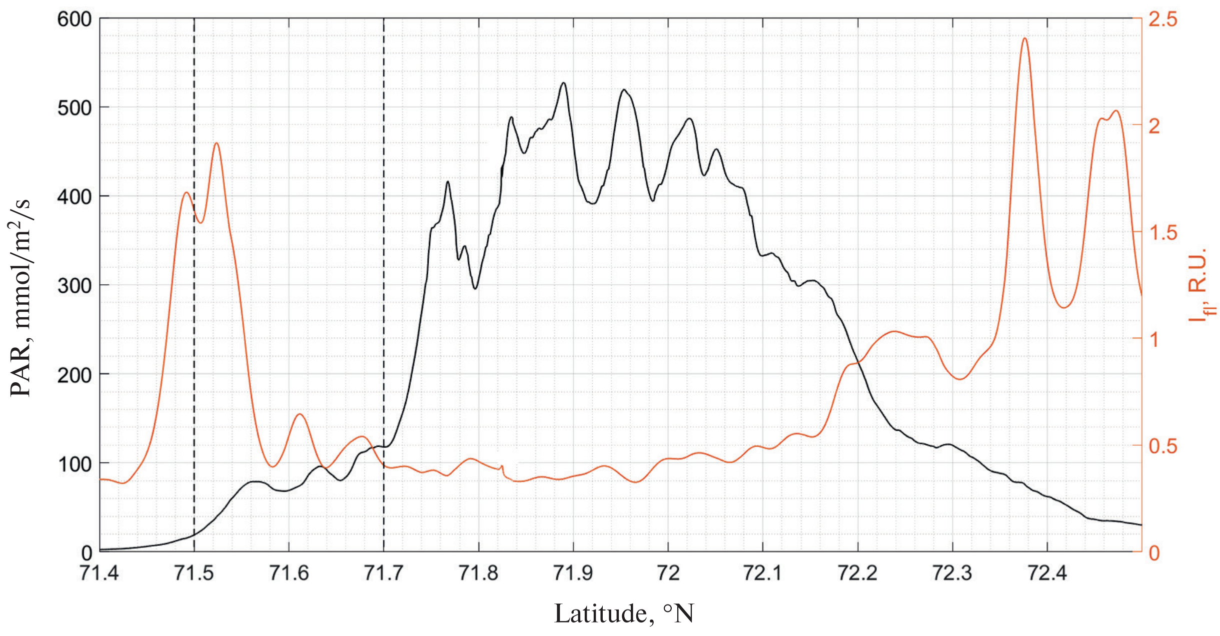

Fig. 4. The distributions of the PAR and Chl fluorescence intensity values along the R/V track according to shipboard measurements on August 9, 2020. The area highlighted by vertical lines corresponds to the region 7 with negative correlation (Fig. 2)

graph by vertical lines. Decreased fluorescence signal near 71.5°N corresponds to an increase in the PAR level recorded at the beginning of daylight hours. In addition, positive divergence values in this area indicate the rise of waters to the surface. In this case, phytoplankton cells fall into more illuminated layers, which additionally enhances the effect of photoadaptation, contributing to an even greater suppression of the fluorescence intensity level [19]. Thus, the cause that determines a significant negative correlation in this section of the route may be the flux of photosynthetically active radiation, the influence of which can overlap the opposite contribution of surface currents that increase Chl fluorescence. It is also interesting to note that the Chl fluorescence intensity peaks were recorded in the dark time of the day. Additional phytoplankton information is required for a detailed analysis of the effects of PAR on I_{fl}.

The relationship between the values of the studied characteristics in sections 8 and 9 is explained by an increase in the Chl concentration due to advection of water masses.

5. Conclusions

Examples of the influence of water dynamics on the spatial distribution of Chl fluorescence intensity in the surface layer of the Barents and Norwegian Seas were studied. This influence consists of many factors, so it is sometimes difficult to single out the dominant one from them. We used the method of sliding correlations applied to the data of shipboard continuous measurements of the chlorophyll fluorescence intensity along the vessel route, reanalysis data, and satellite data of MODIS ocean color scanners on the Chl concentration. Areas with positive and negative correlations between the surface currents divergence values and the Chl fluorescence intensities were registered. The existence of areas with a positive correlation is explained by an increase in the concentration of phytoplankton in the surface layer of water due to an increase in the intensity of the rise of both the algae themselves and the biogenic elements necessary for their development. With a decrease in the intensity of surface water rise, a corresponding decrease in the Chl fluorescence intensity is observed. A negative correlation can be formed under the influence of additional factors, such as the advection of water masses differing in Chl content and the diurnal variation of PAR values. It should be noted that it was not possible to register the effect of water dynamics on the spatial distribution of the Chl fluorescence intensity on most sections of the vessel route. This may be due to a number of reasons, the most probable of which should be considered the homogeneity of the spatial distribution of bio-optical characteristics over most of the route. When continuing research, it is advisable to consider other parameters — the seawater beam attenuation coefficient and the curl of the velocity field.

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