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Some Theoretical and Applied Aspects of the Oceanic Bioluminescence Registration from Space

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Abstract

The analysis of the surface bioluminescence in the World Ocean registration problems for the purposes of its regions ecological express-monitoring and evaluation of the plankton algae spatial distribution at night time by the existing space systems has been proposed. The connection of the plankton community characteristics with a bioluminescent potential (BP) in the euphotic layer and a possibility to evaluate BP according to bioluminescence intensity in the near-surface layer of 0 - 10 m has been demonstrated. It has been shown that with complete correspondence with the vertical structure in the plankton community at the dark time bioluminescence intensity in 0 - 10 m layer exceeds the same in 60 - 70 m layer for one and a half orders and practically determines BP in 0 - 100 m layer. Peculiarities of the plankton organisms light emission, important for the oceanic bioluminescence registration with the space means of observation are under discussion. Equation for calculation of the measured by the space device sea luminescence level and volume of the bioluminescence intensity in the surface layer of the World Ocean, which can be registered due to modern technical means of the space systems has been corrected. The conclusion has been done that on the base of the space data about spatial and temporal phytoplankton distribution and bioluminescence "*in situ*" measurements it is possible to create regional algorithms for transition from numerical estimations of the phytoplankton (chlorophyll "a") to the day time bioluminescent potential and solution of inverse tasks at night time.

Keywords

Plankton, Sea Bioluminescence, Space Systems

1. Introduction

The tasks of making more effective and operative control of marine environment condition demanded together with traditional modes of monitoring to use methods of operative oceanography, including remote sounding of marine surface [1]-[8]. Remote methods have great advantage if compared with contact measurements methods, as they can be conducted with the help of the space means and aircrafts and contain express-information about the state of the plankton community at the near-surface layer on great water areas. Today they know already numerous successful experiments on usage of the space measurements for express evaluation of the spatial and temporal dynamics in the surface layer water color, wind waves kinetics, distribution of chlorophyll "a", mineral suspension and organic substance solution, pollution sources in different regions etc. [9]-[16]. Remote methods of operative oceanography play for sure a decisive role in biological and ecological investigations of the World Ocean in the 21st century [1].

In comparison with obvious successes in the studies of the mentioned above ocean physical and biological characteristics by the methods of the space sounding achievements in the studies by such methods of the near-surface sea waters bioluminescence are quite moderate. But they could increase considerably an effect of using ocean space monitoring, making it more functional and for a time of the twenty-four hours regime. That is why theoretical basing and demonstration of the oceanic bioluminescence space registration real possibilities with the purpose of considerable increase in effective usage of the modern means for operative monitoring of the ocean surface and making its functional load higher are the main objectives of the given work.

2. Materials and Methods

Bioluminescence—an organism electro-magnetic irradiation in the visible spectrum field—is an important element of the World ocean pelagic communities functioning [17] [18] [19] [20]. The studies of bioluminescence characteristics and elucidation of their connection with the plankton habitants characteristics are being conducted in different countries for about 70 years [19] [21]. For this period, great material has been accumulated, which permitted together with colleagues from different countries to create a base of the World Ocean bioluminescence data [22] [23].

This database permitted to determine interconnections between bioluminescence intensity and the plankton community indices, gradients of temperature and salinity and to trace spatial-temporal bioluminescence field changeability at the regional and synoptic scale, to reveal physical and biological factors, causing these changeability, to evaluate an influence of the anthropogenic press on the biota functional condition etc. [21] [24] [25].

Intensity of bioluminescence was measured using the IBSS-made bathyphotometers [8] [19] with multiple vertical (10 - 30) profiling of the upper 100-metre

layer, with 3 minute intervals between soundings. A special device was employed, which limited the astronomical component of luminescence and provided a constant level of mechanical stimulation of bioluminescents. Profiles were conducted with a speed of 1 m sec^{-1}. Measurements of bioluminescence of plankton organisms began 2 hours after sunset. This permitted the exclusion of the influence of daylight on the rhythm of light emission of plankton bioluminescents and their vertical migration. Together with bioluminescence measurements, temperature of the studied layer, speed of drift of the vessel, force and direction of wind were taken.

Phytoplankton was sampled with a rosette of 10-l water bottles, fixed 1 m higher than the bathyphotometer, from intense bioluminescence layers and standard horizons. The water samples were filtered with 0.45 μm pore diameter filters, after which the numbers of testaceous dinophyte algae were counted. These dinoflagellates are the most important bioluminescence component of marine phytoplankton [21]. Means of data of bioluminescence intensity and average number of dinoflagellates, for the layer 0 - 100 m, were calculated and coefficients of correlation and linear regressions ($Y = bX + a$) of the dependence "bioluminescence intensity (Y) – number of dinoflagellates (X)" determined.

These materials made a base for a conception we accepted about possibility to register oceanic bioluminescence with the help of the space systems that we give in this article.

3. Results

Earlier we have shown that bioluminescence intensity in tropic waters was closely connected with values of plankton biomass and fluorescence of chlorophyll "a" [26] (**Figure 1**). To compare the trends of these characteristics we used our own data and published materials of other researchers [13] [18] [22] [26]. The most obvious under visual comparison of these fields in Atlantic Ocean is the fact that bioluminescence trends similar the trends of the mesozooplankton biomass and chlorophyll "a" fluorescence (**Figure 1**). This proves prevailing contribution of the given plankton fractions into bioluminescence field formation, which is confirmed by close correlative links of bioluminescence with biomass and abundance of plankton and first of all of dinophyte algae [19].

Such level of connection is observed everywhere, including such peculiar in thermochaline parameters of water masses regions as Black and Marmara seas, which is seen from materials of the stations fulfilled in 35 and 53 cruises of R/V "Professor Vodyanitsky" and in the cruise of Turkish R/V "Bilim" (**Table 1**). The given in the **Table 1** magnitudes of correlation coefficients ($p < 0.05$) and equations of linear regression coincide with the same for the other regions of the World ocean [19]. This important for comparison of the space data on spatial and temporal distribution of phytoplankton and bioluminescence, working out an algorithm for conversion numerical phytoplankton evaluations (chlorophyll "a") to the bioluminescent potential and for solution of inverse task.

4. Discussion

The efforts in measuring bioluminescence by the remote methods were undertaken many times, including those with laser exciting [27] [28] [29]. The essence of these methods is simple: mounted on the airplane or space carrier lidar emit an impulse of coherent radiation in optic range, which gets into water and while distributing it excites bioluminescence. Bioluminescence light signal through water surface and atmosphere gets to accepting device—photomultiplier (PMP), then on after transformation signal is placed into board computer for storage and further processing.

The most complete theoretical grounds for possibility of remote registration of the surface layer bioluminescence is given in the work [30]. The author calculated energetic characteristics of the bioluminescence light field at the planned height over the ocean surface. On the base of the literature data he gave

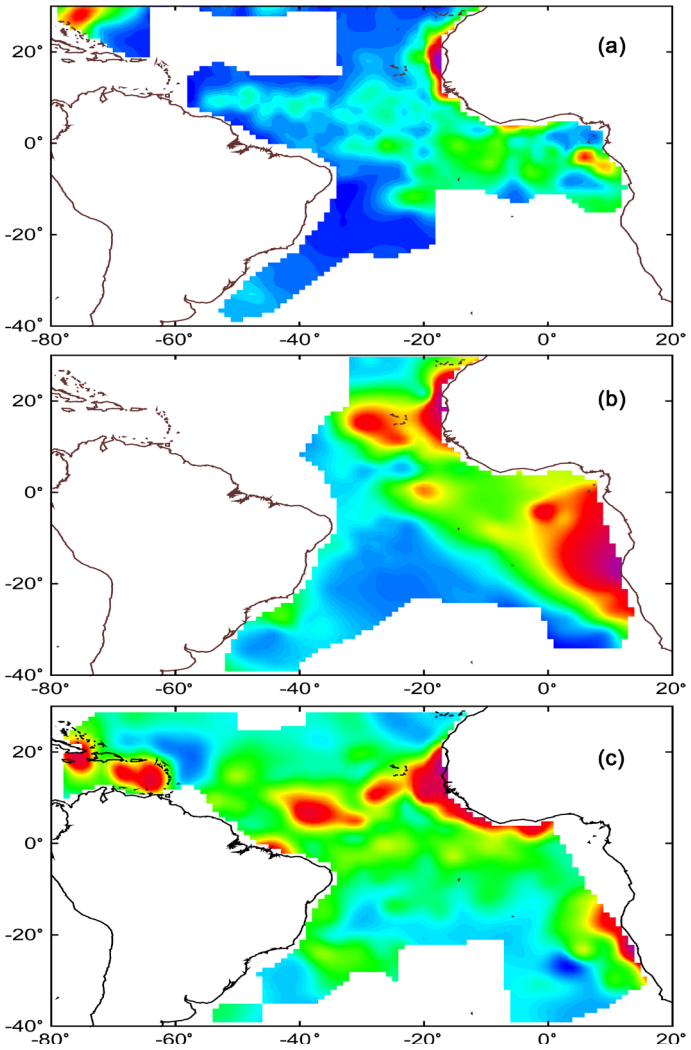

Figure 1. The Atlantic ocean bioluminescent field (b) and plankton community components: (a) phytoplankton (chlorophyll "a" and mesozooplankton (c). Increase in parameters volumes corresponds to the spectrum color gamma (from blue to red) color gamma (from Piontkovski, Tokarev, Bitukov, Williams & Kiefer, 1997).

Table 1. Correlation between bioluminescence and number of the total phytoplankton at the stations in the Black (4824, Bs2) and Marmara (Ms5s) seas.

Region	Bearings	Horizon (m)	Bioluminescence intensity (10^{-12} W·cm^{-2}·l^{-1})	Phytoplankton abundance (cell·l^{-1})	Equation of regression and correlation coefficient (r)
4824 (The Black sea)	44.16 N.Lat. 31.51 O.Lon.	1	927	918,621	У = 277.2 + 0.028x r = 0.851
		5	2729	951,420	
		10	2191	930,240	
		15	2809	987,698	
		20	2797	988,950	
		25	1971	897,600	
		30	1628	307,000	
		35	1840	104,000	
		40	191	82,498	
		45	0	40,258	
		50	0	40,800	
Bs2 (The Black Sea)	41.57 N.Lat. 29.36 O.Lon.	1	3000	308,101	У = −143.1 + 0.069x r = 0.759
		10	2223	414,552	
		15	3099	378,033	
		20	3423	429,894	
		25	3852	250,818	
		30	2604	70,359	
		40	147	85,443	
		50	39	51,008	
		60	48	64,078	
		70	45	67,660	
		85	36	45,600	
Ms5c (Marmara sea)	40.46 N.Lat. 29.05 O.Lon.	1	1899	308,177	У = 217.4 + 0.064x r = 0.77
		10	1980	487,711	
		15	1410	72,140	
		20	3	51,805	
		25	0.5	25,802	
		40	0.5	30,604	
		45	0.5	39,201	
		50	0.5	55,200	
		55	0.5	43,851	

estimation of voluminous density of the bioluminescent sources for different types of organisms. Having solved corresponding tasks of theoretical optics

(transfer of radiation) he evaluated relation bioluminescent signal-astronomic background under the given threshold sensitivity of the registering device.

But to our opinion, the authors of this paper had not taken into consideration a number circumstance, to a great extent determining possibilities of the bioluminescence field space registration. First of all to the contrary to hydro-optic field described by physical laws of energy transfer, characteristics of bioluminescence (intensity, scattering indicatrix, weakening during distribution, etc.) depend on the action of many factors, first of all, biological: composition of organisms, which generate light flashes of different duration and amplitude; their physiological state; endogenous and exogenous luminescence diurnal rhythms; spatial anisotropy of light emitting organs etc., not elucidated in many aspects by the present time.

The second disputable data are given when analyzing the data on energetic characteristics of bioluminescents light emission. For example, energy of the flash of mass plankton bioluminescent in the Black sea *Noctiluca scintillans* (Macartney) Kofoid & Swezy is taken in calculations as 0.1×10^{-6} W·cm^{-2} (3.0×10^{6} phot·s^{-1}). But it is known that luminescence intensity in plankton bioluminescents depends on development stage, season, day time, functional state and can change for several orders of magnitudes [21] [24]. For example, in *N. scintillans* flash amplitude can change from 1.0×10^{-7} W·cm^{-2} (3.0×10^{6} phot·s^{-1}) to 1.0×10^{-3} W·cm^{-2} (3.15×10^{10} phot·s^{-1}), *i.e.* for 3 - 4 orders [21].

It is not quite clear also in the paper, whether author took into consideration difference in spectral characteristics of the registering space devices and spectral composition of the bioluminescence field in the region of measurements. But as we have shown difference in the bioluminescence field spectral characteristics and those of the board registering devices, regional specificity of the plankton bioluminescents species composition and time (season, ontogenetic) changeability of their light emission spectral characteristics predetermine considerable difference in the amplitude indices of the registered characteristics [21] [31].

A number of questions are caused by the used method of bioluminescence registration with the help of satellites. Really first attempts to stimulate bioluminescence by the source of coherent light with wave length 560 + 39 nm revealed discrepancies in the results obtained. In particular, it is not clear whether organism luminescence (*Pyrocystis lunula* Schütt, F. (1896)) is a reaction to laser impulse or excitement takes place due to ultrasound, appearing under interaction of laser ray with water and resulting in heating and heat widening of environment in the field of taking up the penetrating radiation [32].

It is necessary also to mark that under satellite registration of the bioluminescence in the World Ocean coastal zone there occur many additional complexities. For example, sea water in a number of regions contains soluble non-organic and organic substances, including oil hydrocarbons, as well as it undergo influence of the acid rains which change processes of solution, heat exchange, indices of its albedo etc. That is why penetrating into water laser ray stimulates not only

bioluminescence but also causes fluorescence of these pollutions. Such "pollutant fluorescence" has wide spectrum (400 - 750 nm) with two maximums of radiation, close to 440 and 580 nm, which can shift depending on the type of pollutants and their concentration, remaining practically constant under any length of excitement wave. As pigments of the phytoplankton are also fluorescent this creates considerable obstacle for using proved methodics of the satellite ocean sounding for studying bioluminescence.

The first remote observation of the spontaneous surface oceanic bioluminescence at 15,400 km^2 square has been fulfilled in Indian Ocean by American meteorology satellite from the height of 800 km in a regime of "postponed time" [33]. Luminescence was observed during three nights and the authors consider that only bacteria are able to create such low – level spontaneous light emission, as they emit light constantly and their luminescence can continue during many days [31].

It is known that bioluminescence intensity of characteristic for the given region bacteria *Vibrio harveyi* Johnson and Shunk, 1936 makes 10^{-3} phot·s^{-1}·cl^{-1}, and maximum of the spectral emission—490 nm with half-width of emission of 70 nm [34]. As a detector of light emission in the satellite used PMP with optic range of 470 - 950 nm. For better visual contrast between surface bioluminescence and surrounding light background satellite data were processed with a program, permitting to register minimal signal of a level 1.8×10^{-4} W·m^{-2}·$ster^{-1}$. Then a share of the registered light emission of "milk sea" (due to non-coincidence of the bioluminescence emission spectrum and spectral sensitivity of the light detector of satellite) could be determined by formula [33]:

$$F = \frac{\int_{\lambda=0}^{\infty} B_\lambda T_\lambda \theta \Phi_\lambda d_\lambda}{\int_{\lambda=0}^{\infty} \Phi_\lambda d_\lambda} \quad (1)$$

where: B_λ—spectrum of bacteria luminescence;

Φ_λ—spectral characteristic of luminescence sensor;

T_λ—spectral coefficient of atmosphere radiation;

θ—angle of the satellite optical system vision;

Evaluation of bacteria colony minimal population (C_{min}·cl·m^{-2}) at the level of minimal signal C_{min}·1.8×10^{-4} W·m^{-2}·$ster^{-1}$ was made on the base of equation [33]:

$$C_{\min} = \pi L_{\min} \frac{2\lambda}{hcw} \quad (2)$$

where: λ—length of luminescence wave;

h—Plank constant;

c—light rate in vacuum;

w—level of photon emitted by cell.

On the base of formulas (1) and (2) for registration of minimal bioluminescence by the satellite light detector they have determined bacteria cells concentration,

which must correspond to $C_{min} = 2.8 \times 10^8$ cl·cm^{-2}. Considering given above light energy (W) of one bacteria bioluminescent signal under modern technical possibilities of space devices can be registered if its minimal level exceeds $F_{min} = W \cdot C_{min} = 2.8 \times 10^{15}$ phot·s^{-1}·m^{-2} [33]. But to our opinion one should consider some conditionality of such suppositions, as such low levels of light emission with duration of bioluminescence many times exceeding 1c are characteristic for spontaneous bioluminescence ("glow") of dinoflagellates [31]. Moreover formula (1) for calculation of a share of the registered luminescence of "milk sea" is not quite correct. And besides, even under condition that in the given region surface luminescence is generated exclusively by bacteria, on the base of the given in the works [30] [33] prerequisites and boundary conditions it must look like the following:

$$F = \frac{\int_{\lambda=0}^{\infty} B_\lambda T_\lambda(\theta)\Phi_\lambda d_\lambda}{\int_{\lambda=0}^{\infty} B_\lambda d_\lambda} \quad (3)$$

In such case concentration of bacterial cells, corresponding to minimal level of the bioluminescent signal in 1.8×10^{-4} W·m^{-2}·ster^{-1} will considerable differ (to the side of increase) from the given in the work of American colleagues [33].

Having analyzed the given in the database "The database on the bioluminescence field of the World Ocean" materials and having compared them with the given in the works [23] and [33] threshold sensitivity of the satellite sensors we give in **Table 2** regions of the World Ocean where surface bioluminescence just today can be correctly measured. And their bioluminescence field energy is given in two sizes, most widely used in literature sources: W·cm^{-2}·l^{-1} and phot·s^{-1}·l^{-1}. Transition coefficient (from 10^{-12} W·cm^{-2}·l^{-1} to phot·s^{-1}·l^{-1}) has been received by us under intercalibration of the hydrobiophysical complex "Salpa" and American apparatus "Hidex" in 1996 during international expedition on board R/V "Bilim" (Turkey) in the Black and Marmara seas [16].

Thus, today on the base of the space data on spatial and temporal phytoplankton distribution and synchronous measurements "*in situ*" of bioluminescence it is possible to create regional algorhythms of transition from quantitative evaluations of phytoplankton (chlorophyll "a") to bioluminescent potential at the day time and solution of inverse tasks at night. The materials of above mentioned database on the World Ocean bioluminescence and successful examples of working out regional algorhythms for transition satellite measurements of chlorophyll "a" to biological and ecological parameters of the euphotic layer for White, Okhotsk and Black seas can serve as ground for this [10] [35].

5. Conclusions

1) The level of the World Ocean surface layer bioluminescence, which can be registered with modern technical possibilities of space systems, has been determined.

Table 2. The World Ocean regions with a level of surface bioluminescence, enough for registration by modern space systems.

Bioluminescence intensity (10^{-12} W·cm^{-2}·l^{-1})	Bioluminescence intensity ($\times 10^{15}$ phot·m^{-3}·s^{-1})	Region	Bearings
2500.00	3.75	Mediterranean	35.05 N.Lat.; 04.54 W.Lon.
2200.00	3.3	Atlantic Ocean	35.40 N.Lat.; 6.50 W.Lon.
2000.00	3.0		12.39 N.Lat.; 36.6 W.Lon.
4500.00	6.75	Black sea	41.25 N.Lat.; 29.21 O.Lon.
3500.00	5.25	Mediterranean	36.05 N.Lat.; 07.07 W.Lon.
2700.00	4.05		36.43 N.Lat.; 18.46 W.Lon.
5000.00	7.5	Black sea	42.56 N.Lat.; 31.09 O.Lon.
5500.00	8.25	Atlantic Ocean	25.02 S.Lat.; 05.27 W.Lon.
2100.00	3.15		36.25 S.Lat.; 18.10 W.Lon.
2500.00	3.75	Black sea	44.22 N.Lat.; 34.25 O.Lon.
4500.00	6.75		44.15 N.Lat.; 33.30 O.Lon.
2700.00	4.05	Atlantic Ocean	43.20 N.Lat.; 36.2 W.Lon.
3000.00	4.5	Black sea	45.00 N.Lat.; 31.45 O.Lon.
4500.00	6.75		44.16 N.Lat.; 31.51 O.Lon.
10,000.00	15.0		44.06 N.Lat.; 36.19 O.Lon.
4000.00	6.0		41.34 N.Lat.; 29.20 O.Lon.

2) On the base of the space data on the spatial and temporal phytoplankton distribution and bioluminescence measurements "*in situ*", it is possible to create regional algorhythms for reversing from quantitative evaluations of phytoplankton (chlorophyll "a") to bioluminescent potential at the day time and solution of inverse tasks at night.

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