Solar radiation as a synchronizing factor of circadian and ultradian biological rhythms of planktonic communities

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Abstract. The change in the intensity of glow of organisms in the coastal waters of the Crimea was considered. It is shown that the synchronizing factor for circadian and ultradian biological rhythms of planktonic communities is the change in the intensity of solar radiation when changing light and dark times of the day. The parameters of the main biological rhythms of planktonic communities, leading to a change in the glow intensity of planktonic communities, were found out by the method of decomposition in a Fourier series. It is shown that the change in the glow intensity of organisms with a period of 14 hours characterizes the circadian rhythms of the light and dark periods. Changes with a period of 4.7 and 2.8 hours are due to the ultradian endogenous rhythms of the plankton community, associated with the intensity of division of phytoplankton cells and the rate of their consumption by zooplankton. Calculations showed that the correlation coefficients between the measured values of the glow intensity of organisms and the calculated ones, taking into account the influence of the three main biological rhythms, is r = 0.906, which confirms the correctness of the accepted assumes.

1. Introduction

In the seas located in temperate latitudes, including the Black Sea, the intensity of the glow of aquatic organisms is an important factor in the functioning of the plankton community and is subject to periodic circadian and ultradian changes [1–8].

The biological rhythms of organisms are synchronized by external cyclic processes, while the change in the intensity of solar radiation is the most important of the external factors. However, it should be borne in mind that, in addition to the cyclical effect of solar radiation, external rhythms for any organism are cyclical changes in the activity of the behavior of other living beings in the community, determined, first of all, by their ultradian endogenous rhythms.

Bioluminescent organisms are active participants in the biological processes of the pelagic zone, and therefore the intensity of the glow of aquatic organisms is a very important informational characteristic of the vital processes of marine communities [1, 9–12]. To study the concentration, spatial and temporal distribution of aquatic communities in natural habitat conditions without disturbing the structure of pelagic communities (in situ), which include bioluminescent organisms, rapid assessment methods based on the use of high-speed biophysical measuring complexes can be applied [13–15].
The distribution of bioluminescent aquatic organisms in the habitat and the processes of their life are influenced by biotic factors (age, sex, reproduction, migration, etc.) and abiotic factors (degree of illumination of the habitat, temperature and salinity, current, availability of food, etc.) [16–18].

As the analysis of the scientific literature data shows, in the life cycles of most species of aquatic organisms inhabit the pelagic zone, several processes, repeating at certain intervals time, can be distinguished, which are circadian or ultradian rhythms [2, 3, 5, 19, 20].

In particular, endogenous rhythms are manifested in many physiological processes of microalgae: nutrition, respiration, growth, formation of pigments, etc. [8, 10, 19]. It is known that most physiological and biochemical processes change during the daily. Some of the processes are activated during the dark period, others during the day. The daily change of day and night, fixed by phytoplankton due to the work of phytochrome and cryptochrome like photoreceptors, makes it possible for phytoplankton to accurately distribute light-dependent and dark processes (in particular, growth and reproduction) in time [16, 21, 22].

Recently, methods for studying life processes occurring in biological systems, based on measuring the parameters of physical fields that arise in the process of life of biological systems, in particular, marine communities, have become more and more widespread [6, 8, 18]. At the same time, the use of biophysical devices makes it possible to study the life processes of pelagic communities in natural conditions in real time (in situ) without disrupting the structure and interspecific relationships of aquatic organisms [13–15, 23]. If the processing of the amplitude-temporal variability of the glow intensity created by the pelagic communities is carried out using analytical, mathematical and statistical methods of information processing, then it becomes possible not only to reveal the biological rhythms of pelagic communities, but also to evaluate their parameters and consider the features of interspecific relationships.

The aim of this work is to study the influence of factors synchronizing circadian and ultradian biological rhythms of planktonic communities directly in the environment (in situ) and to determine the parameters of these rhythms.

2. Materials and methods
The material for the study was the data obtained at diurnal stations during the cruises of the R/V "Professor Vodyanitsky" along the southwestern shelf of the Crimea. To study the temporal variability of the spatial and vertical distribution of the intensity of glow of organisms in the upper 100-m layer, we used the method of multiple bathyphotometric sounding of the water column with using the measuring hydrobiophysical complex “Salpa-M” [15]. Every hour, 10 soundings were carried out with an interval of 2 min. During the analysis of temporal changes in the intensity of glow of organisms, the values averaged over each hour were used. The measurement interval for vertical sounding was 1 m.

Vertical sounding of the intensity of the glow of the pelagic communities was carried out in the depth range of 0–60 m. Further, the range of depths with a high level of intensity of glow of organisms was determined. For this, when analyzing the results obtained, the range of depths at which measurements were made was divided into five-meter layers. Then a 5-meter layer was found with the maximum value of the glow intensity of organisms, and then a range of depths was found in which the intensity of glow of aquatic organisms exceeded the level of 0.5 of the maximum. Thus, a range of depths with a high level of intensity of the glow of pelagic communities was identified. This turned out to be a depth range from 0 to 35 m. Further researches were carried out for this layer.

3. Results and discussion
Figure 1 shows the found average data in the bioluminescence intensity of organisms and their standard deviations. It can be seen that in the bioluminescence intensity of organisms is subject to fluctuations. First, with the onset of darkness, an increase in the intensity of the glow of organisms is observed, which decreases (falls) by morning. Second, there is a change in the glow intensity of plankton communities during the night time. So, at 19:00, 23-24:00 and at 03:00, an increase in the
glow intensity of the inhabitants of the pelagic zone is observed, and at 20:00, as well as by 1:00 am and by 6:00 am, a decrease in the bioluminescence intensity of aquatic communities is observed.

![Figure 1. Diurnal changes in the intensity of bioluminescence of planktonic communities.](image)

The synchronizing factor that gives a start to the dark processes is the change of light and dark times of the day. As a result, the processes of increase and decrease in the intensity of the bioluminescence of organisms are repeated at the same time every dark time of the day. This fact gives reason to consider them periodically repeating processes and therefore the discrete Fourier transform is applicable to them [24–26].

However, the observed decrease in the glow intensity of organisms by 20 o'clock and by 1 o'clock indicates that, in addition to the circadian rhythm, synchronized by the alternation of the light and dark periods of the day, some other ultradian rhythms that also affect the changes in the bioluminescence intensity of the plankton community. The periods of these rhythms will be searched using the discrete Fourier transform [24–26].

Let us apply the discrete Fourier transform to the found changes in the intensity of bioluminescence of planktonic communities (Fig. 1). This will allow us to represent changes in the intensity of luminescence of aquatic organisms in the form of a finite number of harmonic functions (spectral components), differing in periods and amplitudes, and giving an idea of the circadian and ultradian rhythms existing in aquatic systems. The Fourier series can be represented in the following form [24–26].

\[
I(t) = a_0 + \sum_{n=1}^{N/2} A_n \sin \left( \frac{2\pi n \phi}{T} + \phi_n \right)
\]

(1)

where \( I(t) \) – is the glow intensity of plankton community at time \( t \), \( a_0 = \frac{1}{N} \sum_{i=1}^{N} x_i(t) \) – is a constant value or zero harmonic, \( x_i(t) \) – time series of experimentally measured values of bioluminescence intensity, \( N \) – is the number of points of the experimental measure time series, \( N/2 \) – is the number of harmonics of a Fourier series, \( A_n \) – is the amplitude of the \( n \)-th harmonic, \( n=1, 2, \ldots, N/2 \) – is the number of harmonics, \( T \) – is the period of the first harmonic, \( \phi_n \) – is the initial phase of the \( n \)-th harmonic.

As a result of Fourier series expansion of the initial time series of bioluminescence intensity values of aquatic communities (Fig. 1), it was found that the first, third and fifth harmonic components have the highest amplitudes. The amplitudes of these harmonic components are respectively equal: 931, 725 and 656 pW cm\(^{-2}\)l\(^{-1}\).
changes in the glow intensity of planktonic communities is mainly determined by its amplitude. The larger the amplitude of the harmonic, the more significant its contribution and, accordingly, on the contrary, the contribution of harmonics with small amplitudes is insignificant. As a result, it can be considered that the first, third, and fifth harmonics are significant and make the main contribution to changes in the glow intensity of aquatic communities. We will neglect the influence of the second, fourth, sixth and seventh harmonics in modeling biological processes, considering their amplitudes to be small.

For the three basic harmonic oscillations, it was obtained:
- the period of the first (main) harmonic oscillation is equal to the length of the time series – 14 hours, it characterizes the circadian rhythm of changes in the intensity of the bioluminescence of aquatic communities;
- the period of the third harmonic oscillation is – 4.7 hours;
- the period of the fifth harmonic oscillation is – 2.8 hours.

In this case, the processes that form the main harmonic oscillation with a period of 14 hours are responsible for slow changes in the bioluminescence intensity of planktonic communities and characterize the circadian rhythm, and the processes that form the third and fifth harmonic oscillations are responsible for the rapid changes that characterize ultradian biological rhythms (Figure 2).

\[
y_1(t) = 930.6 \cdot \sin(0.449t - 1.3882); \\
y_3(t) = 725.1 \cdot \sin(1.337t - 0.5482); \\
y_5(t) = 655.7 \cdot \sin(2.244t - 1.5252). 
\]

Taking into account the principle of superposition and taking into account the accepted assumptions regarding the smallness of the amplitudes of the second, fourth, sixth and seventh harmonic components, the intensity of the glow of aquatic communities at night on the South-Western shelf of Crimea can be calculated by the formula:

\[
I_{\text{pac}}(t) = a_0 + y_1(t) + y_3(t) + y_5(t),
\]
Analysis of the literature has shown that one of the factors of the daily change in the intensity of the glow of marine organisms is the change in the intensity of solar radiation. Analysis of the values of the intensity of daytime and nighttime bioluminescence of plankton at different depths showed that the glow of aquatic communities at night is much higher than during the day [4, 6, 7]. Yu.N. Tokarev noted [6] that, due to changes in illumination during the day, the intensity of bioluminescence in the dark and during the day changes by a factor of 30–100. As a result, it can be established that in our studies the first harmonic characterizes the process of increasing the intensity of the bioluminescence of organisms during the dark time of the day and falling in the morning hours. This biological rhythm is due to the change and duration of the light and dark periods. From expression (2) for \( y_1(t) \) it can be seen that the amplitude of the first harmonic component is equal to 931 pW cm\(^{-2}\) t\(^{-1}\), which characterizes its contribution to the change in the bioluminescence intensity of the hydrobionic community during the dark time of the day.

The reason for the appearance of high-frequency oscillations (third and fifth harmonic) with a period of 4.7 and 2.8 hours are biological processes associated with the quantitative development of phytoplankton during the day and relationships in the food chain of the inhabitants of the pelagic zone.

In a enough plenty of works devoted to the development of phytoplankton [5, 19, 20, 27, 28], it was noted that the number and biomass of phytoplankton organisms in the pelagic zone depends, first of all, on the rate of cell division and on the intensity of their consumption by zooplankton. In the work of S.A. Piontkovsky and T.S. Petipa [29], devoted to the study of diurnal changes in the intensity of feeding in the copepodite Acartia (Acartiura) clausi (Giesbrecht, 1889), it was shown that the intensity of feeding at night and during the day in crustaceans of different ages is different, which is associated with their different ability to the intensity of migration. With an increase in the intensity of migration of crustaceans, which is observed at night, the intensity of their feeding increases. For example, sexually mature males and females outside the breeding period, as well as Acartia clausi stage V migrate more actively than other stages, making large movements in depth, and adhering to deeper water layers in the daytime. At night, rising from the deep-water layers to the surface, these groups of crustaceans feed with a much higher intensity compared to other groups. Younger copepodites and nauplii, on the contrary, make small movements in depth, the amplitude of their migrations is small, they constantly inhabit the uppermost layers of water and feed with the greatest intensity during the daytime. The existence of different daily intensities and rhythms of feeding is probably due to the different adaptability of age groups to solar radiation. It was also noted in [29] that males survive worse under high solar radiation than under low solar illumination.

The type of food consumed by zooplankton also affects the ultradian rhythm of feeding intensity. For example, the complete process of the passage of food through the intestines by all age stages of Acartia clausi, as well as in many other species of copepods, with a predominance of phytoplankton in food, lasts an average of 3 hours, and with additional animal food, the duration of the digestion process increases on average to 5 hours \[29\]. Consequently, the periods of increase in the intensity of feeding of crustaceans depend on the type of food and are near to three or five hours.

There are different opinions regarding the rate of cell division of planktonic organisms during the day. The study of the rate of cell division of the Black Sea phytoplankton in cultures was carried out by L.A. Lanskaya [27]. As a result of her research, she came to the conclusion [27] that the division of most species of dinoflagellates occurs around the clock, but the maximum number of dividing cells occurs in the evening hours (18-19) and at night. A.V. Kovalev [30] and N.G. Stolbova et al. [31] also allocated night hours for maximum reproduction of planktonic algae.

The noted features of phytoplankton cell division during the dark time of the day suggest that the increase in the glow intensity of aquatic communities observed in our studies at 19:00, 23-24:00, and by 3:00 a.m. is the result of the prevalence of the rate of division of luminous cells of dinoflagellates over the intensity of their eating by zooplankton in this time.
The cyclical nature of the variability of the bioluminescence intensity of aquatic communities with amplitudes of 725 and 656 pW cm\(^{-2}\)l\(^{-1}\) and, respectively, periods of 4.7 and 2.8 hours, indicates that the third and fifth spectral components of the Fourier series expansion are significant and are due to ultradian endogenous diurnal rhythms of the inhabitants of the pelagic.

The calculations showed that the correlation coefficient between the theoretical, calculated from the three largest harmonics (equations (2) and (3)), and the measured values of the change in the bioluminescence intensity of aquatic organisms is \(r = 0.906\). This indicates that the changes described by the combined influence of the first, third, and fifth spectral components characterize quite well the processes that cause changes in the bioluminescence intensity of the plankton community in the dark period of day and confirms the correctness of the assumptions made. At the same time, the change in solar radiation is a synchronizing factor that gives rise to both circadian and ultradian biological rhythms of the plankton community.

4. Conclusion

It is shown that the circadian and ultradian biological rhythms of the inhabitants of the pelagic zone with periods of 14 hours, 4.7 and 2.8 hours have an effect on changes in the intensity of the luminescence of aquatic communities at night. These rhythms are synchronized by the change in the intensity of solar radiation when changing the light and dark time of the day. These biological rhythms lead to periodic changes in the intensity of glow created by pelagic communities with amplitudes of 931, 725 and 656 pW cm\(^{-2}\)l\(^{-1}\). The correlation coefficient between the measured values and those calculated from the three found harmonic components is \(r = 0.906\), which confirms the correctness of the accepted assumptions.

5. References

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