Lower oxygen boundary of the plankton bioluminescence distribution in marine environment

V.V. Zavoruev

Institute of Computational Modeling
Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk

Received September 16, 2005

We have analyzed the vertical intensity profiles of the plankton bioluminescence and oxygen concentration in the Black Sea and in the Pacific Ocean nearby the east coast of America. Location of the depth maximum of the plankton bioluminescence is established between the isooxygens of 0.35 and 0.20 ml/l. At oxygen concentration in water lower than 0.10–0.20 ml/l, the plankton bioluminescence was not detected.

Investigation of the ocean's light field is of great fundamental and applied significance. Light distribution in water depends on many physical, chemical, and biological factors. The marine plankton not only absorbs and scatters solar radiation, but also is capable to radiate light quanta in the visible spectral range. The bioluminescence phenomenon manifests itself everywhere in the world ocean. The *in situ* luminescence intensity of the marine organisms depends on temperature, salinity, biogenic concentration, and intensity of solar radiation penetrating into water.[1,2] Only fragmentary data on the oxygen concentration influence on the bioluminescence intensity distribution in the marine environment are available.[2]

In this paper, we analyze the vertical intensity structure of the plankton bioluminescence in the oceanic waters characterized by the oxygen deficit.

The study was carried out during the 38th and 44th cruises of the research vessel *Dmitry Mendeleev*. The purpose of complex expeditions was to study the functioning and state of pelagium in the Black Sea and the eastern part of the Pacific Ocean. Complex researches of hydrophysical, hydrochemical, and biological parameters were carried out. The routes were chosen so that to obtain comparative characteristics of the pelagian ecosystem in all main regions.

The Central American measurement profile originated in a point with the coordinates of 08°57′N, 90°00′W (station No. 3498) and finished at 17°07′N, 102°54′W (station No. 3504). Stations are numerated according to the logbook of the research vessel *Dmitry Mendeleev*. The profile laid off along the coast of Central America covered waters with the deep minimum in the oxygen concentration.

The measurement procedure and the equipment complex are described in Ref. 3.

In summer, bioluminescence in the Black Sea is determined by *N. miliaris*.[4] Vertical profiles of the plankton bioluminescence have two maxima (Fig. 1).

The upper maximum of the plankton luminescence was always detected under the isothermal layer. On the entire sea area, its position coincides with the maximal density gradient or with the so-called seasonal pycnocline (Table 1).

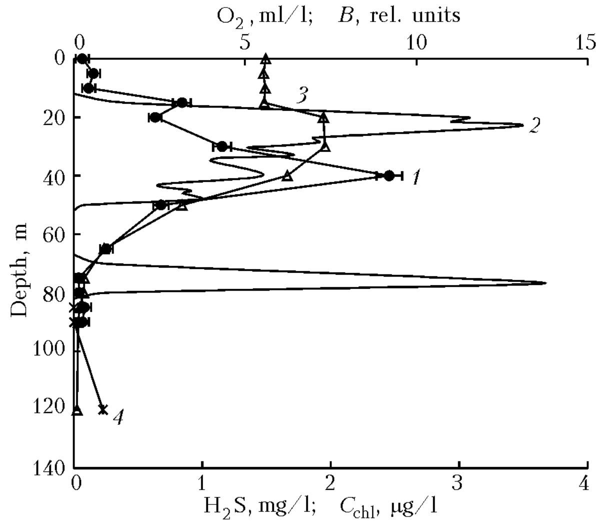

Fig. 1. Vertical profiles of the chlorophyll concentration C_{chl} (*1*), plankton bioluminescence *B* (*2*), oxygen concentration (*3*), and hydrogen sulfide concentration (*4*) in August, 1989, at the station with coordinates 43°28′N, 34°00′E.

The same regularity has been revealed earlier; however, it was explained in the following way: "In summer the basic bioluminescent is *Noctiluca*. The variation of fat content is typical of it; therefore, a specific weight of the organism varies. Thus, *Noctiluca* passively moves vertically, delaying in those layers where its buoyancy appears neutral. More often, this takes place in the temperature jump layer. Just there the increased concentration of this organism is observed. In the layer of the temperature jump, the bioluminescence field intensity achieves its maximum."[5] Later, this view of the bioluminescence upper maximum and the luminous organisms dominating in it has not changed. "It is necessary to note, that in the jump layer the optimum conditions for habitation of organisms are sometimes created.

Table 1. Thickness (m) of isothermal water layer (H_z), position of oxygen boundary at the level of 0.25 ml/l (O_2), of upper (B_{up}) and lower (B_{low}) bioluminescence maxima, the depth of the hydrosulfide (H_2S) zone

Coordinates	Sea areas	Date	O_2	H_2S	H_z	B_{up}	B_{low}
43°20′N	Central	07.29	90	115	10	10–15	70–75
32°25′E		09.05	90	100	20	25–30	80–85
43°28′N	Central	08.02	80	100	15	20–25	75–77
34°00′E		09.04	90	100	15	15–20	75–80
43°20′N	Central	08.07	95	119	15	15–20	75–90
36°11′E		09.03	95	120	15	15–20	75–80
42°11′N	Southwest	07.23	125	169	7	10–15	115–120
28°40′E	part	08.25	130	140	15	15–20	125–130
44°34′N	Northwest						
30°57′E	part	07.27			12	10–20	
44°27′N	Northeast						
37°55′E	part	08.04	165	150	20	20–30	135–140
41°25′N	Southeast						
38°12′E	part	08.29	130	90	15	15–20	110–115

The data of biological sampling testify that *Noctiluca* – the basic source of bioluminescence flashes in the Black Sea – forms agglomerations all over the jump zone, both above and under the thermocline layer."[6]

In the Black Sea nearby the chemocline, the basic bioluminescent organism year-round is *N. miliaris*. It follows from numerous researches devoted to studies of vertical structure of the Black Sea plankton and bioluminescent fields.[6–9]

The data are available[10] on attribution of the plankton agglomerations in the Black Sea to a rather narrow and constant range of the conditional density σ_t equal to 15.0–16.1. Really, the luminescence depth maximum was attributed to the water layer, in which the values of σ_t fell in the above-stated range. However, this layer is wide enough relative to the width of the bioluminescence peak. Since most well known bioluminescence reactions are oxygen-dependent, it is reasonable to assume that the lower maximum position of the plankton luminescence is determined by the oxygen concentration. Figure 2 demonstrates the isooxygens, between which the lower maximum of the plankton bioluminescence is detected. At oxygen concentrations in water below 0.10–0.15 ml/l the *Noctiluca* bioluminescence is not found. The number of *N. miliaris* is equal to zero 10–15 m below the depth of luminescence peak.

Computations of hydrological parameter gradients carried out for all stations in the pelagic region of the Black Sea in July–August, have shown the absence of their extrema at depths of detection of plankton luminescence minima. Possibly, the bioluminescent habitat is determined by the lower limit of oxygen consumption necessary for their functioning.

Each species of the aquatic organisms has its lower oxygen limit. Main factor limiting the habitation depth of the Black Sea organisms is not a hydrogen sulfide but the oxygen deficit in the stratified pycnocline waters. The combination of these two hydrological factors serves as a natural biological limit dividing the system into layers of "aerobiosis" and "chemobiosis."[10]

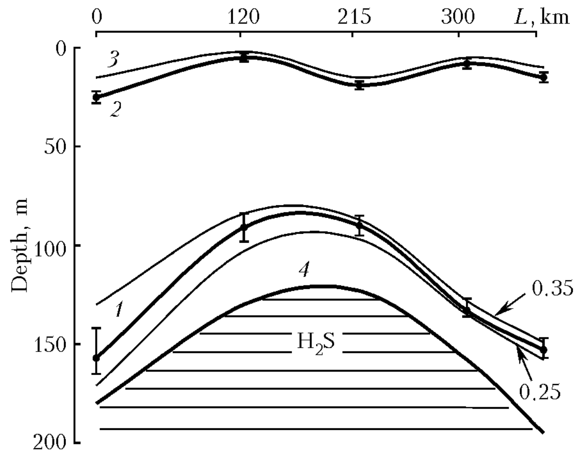

Fig. 2. Detection depth of the bioluminescence maxima along the Gelendzhik–Sinop profile (east halistasis) at daytime in August, 1989: the deep bioluminescence maximum (*1*); the bioluminescence maximum in the photic layer (*2*); the upper thermocline boundary (*3*). Values 0.25 and 0.35 correspond to the oxygen concentration in ml/l. The hydrosulfide zone boundary (*4*) corresponds to concentration of 0.1 ml/l.

According to criterion of separation of a frontal zone[11] in the vertical profile of oxygen concentration, the frontal characteristics are not found at the depths of location of the lower plankton luminescence maximum. However, taking into account the oxygen physiological minimum of organisms necessary in the *in vivo* reaction for emission of light quanta, the frontal zone criterion can be expressed as

$$\frac{\Gamma_{ic}}{\Gamma_{ic} - \Gamma_{cr}} \geq 10, \quad (1)$$

where Γ_{ic} is the gradient of oxygen concentration in the ith water layer located between the surface and the depth of the O_2 minimal content; Γ_{cr} is the gradient at the depth of the maximal bioluminescence.

As a rule, a necessary condition for formation of the depth plankton agglomerations is the pycnocline characteristic of waters, though this condition is not necessary for explanation of maximal zooplankton abundance in great depths of seas and oceans. It is a well-known fact that the mesoplankton migrates vertically down to great depths, forming agglomerations in layers of the oxygen minimum.[12] For example, nearby Peru coasts the maximum biomass quantity of *Euphausia inermis* was found in a depth of about 500 m with oxygen concentration of 0.15–0.18 ml/l (Ref. 13). Any gradients of hydrological parameters, significant in size, were not revealed in these depths. In this case, it is possible to distinguish the frontal zone causing the zooplankton agglomeration using formula (1) for the gradient computation in the vertical profile of the oxygen distribution. In this view, explanation of the depth of the plankton bioluminescence maximum location seems quite realistic in terms of frontal characteristics, at which the physiological features of the luminous organisms are taken into account.

Thus, in the Black Sea, the oxygen concentration lower than 0.15 ml/l prevents the plankton bioluminescence manifestation.

It is well known that the water salinity in the Black Sea is less almost by half, than in the world ocean, and the oxygen deficit is created there due to its "eating" by the hydrogen sulfide. Therefore, the detected lower oxygen boundary of bioluminescence could be typical only for the Black Sea plankton. To clarify the same regularity in oceanic waters, we have analyzed the experimental data on the bioluminescent field structure in the pelagic region of the Eastern Pacific, which is characterized by the presence of a deep-sea oxygen minimum layer covering extensive water areas. In some parts, it lays in a depth of 500–800 m, rising in others up to 80–100 m (Ref. 14). Moreover, the origin of the oxygen minimum is caused by hydrodynamics of oceanic waters, rather than by chemical interaction with sulfide as it takes place in meromictic basins.[15]

The plankton bioluminescence distribution in the Central American profile is shown in Fig. 3.

The luminescence maximum coincided with the halocline. A feature of the luminescence field in the profile was the presence at all stations of the depth maximum comparable to the upper peak in the bioluminescence intensity. Three peaks were distinguished at the station No. 3499. Like in the Black Sea, the depth maximum of the plankton luminescence was found there nearby the oxygen minimum and was limited by isooxygens of 0.2 and 0.3 ml/l. The depth of the plankton bioluminescence maximal intensity detection coincided with the frontal zone position computed for oxygen by formula (1).

It should be noted that the oxygen deficit is observed in deep waters of the Indian Ocean. Researches of the bioluminescence vertical profiles in the Arabian Sea have shown that the luminescence is completely absent in depths of 300–400 m, where the oxygen concentration makes 0.10–0.20 ml/l (Ref. 2).

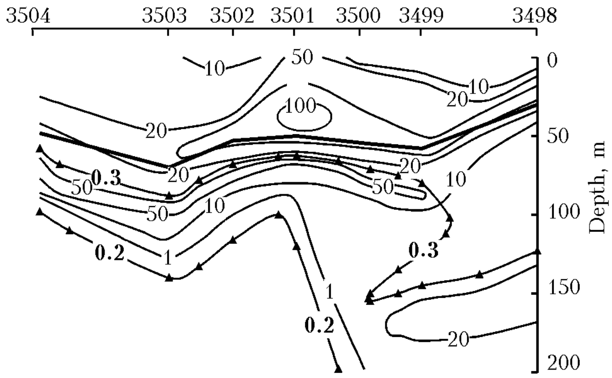

Fig. 3. Distribution of the bioluminescence intensity in the Central-American profile. The solid bold line shows the halocline position. Figures 0.2 and 0.3 denote isolines of the corresponding oxygen concentration in ml/l. The station numbers are shown on abscissa proportionally to the distance between them.

Thus, the influence of oxygen concentration on vertical distribution of bioluminescence intensity is recognized. The lower boundary of the plankton luminescence in the oceanic ecosystems is an isooxygen of 0.2 ml/l.

References

1. P.J. Herring, *Bioluminescence in Action* (Academic Press, London, 1978), 667 pp.
2. I.I. Gitelzon, L.A. Levin, R.N. Utyushev, O.A. Cherepanova, J.V. Chugunov, *Bioluminescence in Ocean* (Gidrometeoizdat, St. Petersburg, 1992), 283 pp.
3. V.V. Zavoruev, Atmos. Oceanic. Opt. **16**, No. 1, 72–76 (2003).
4. E.P. Bityukov and L.M. Khlystova, in: *Sea Biology* (Naukova Dumka, Kiev, 1975), Issue 34, pp. 100–109.
5. E.P. Bityukov, V.P. Rybasov, and V.G. Sheida, Oceanology **2**, No. 6, 1089–1099 (1967).
6. V.A. Urdenko, L.A. Zemlyanaya, and V.L. Vladimirova, Gidrobiol. Zh. **14**, No. 2, 17–23 (1979).
7. L.G. Koval, *Zoo and Necrozooplankton of the Black Sea* (Naukova Dumka, Kiev, 1984), 128 pp.
8. E.P. Bityukov, V.I. Vasilenko, I.M. Serikova, and J.I. Tokarev, Ecologiya morya, Issue **46**, 19–24 (1996).
9. M.E. Vinogradov, Zh. Obshchei Biol. **58**, No. 3, 43–60 (1997).
10. M.E. Vinogradov, Dokl. Akad. Nauk SSSR **306**, No. 3, 717–721 (1989).
11. K.N. Fedorov, *Physical Nature and Structure of Ocean Fronts* (Gidrometeoizdat, Leningrad, 1983), 296 pp.
12. I.A. Kiselev, *Plankton of Seas and Continental Water Bodies. 2. Distribution, Seasonal Dynamics, Nourishment and Significance* (Nauka, Leningrad, 1980), 440 pp.
13. M.V. Flint and E.G. Kolosova, in: *Ecosystems of Eastern Boundary Currents and Central Parts of the Pacific Ocean* (Nauka, Moscow, 1990), pp. 213–230.
14. P.A. Stunzhas, A.N. Gusarova, and P.N. Makkaveev, in: *Ecosystems of Eastern Boundary Currents and Central Parts of the Pacific Ocean* (Nauka, Moscow, 1990), pp. 47–68.
15. O.K. Bordovsky, A.N. Gusarova, J.P. Nalbandov, P.A. Stunzhas, L.N. Propp, in: *Frontal Zones of the Southeast Part of the Pacific Ocean. Biology, Physics, Chemistry* (Nauka, Moscow, 1984), pp. 64–76.