Fluorescent and bioluminescent fields in surface waters of the Pacific Ocean

V.V. Zavoruev

Institute of Computer Simulation,
Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk

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Bioluminescence and fluorescence fields in surface waters of the Pacific Ocean have been investigated, along with simultaneous measurements of water temperature. As the temperature rose, bioluminescence increased and fluorescence decreased in 85% cases. As the temperature decreased, fluorescence increased. It is important that the change in luminescence either preceded a temperature front or succeeded it. The scales of inhomogeneities in phytoplankton fluorescence were 30–60 km, and the fluorescence peaks exceeded, on the average, the background level by approximately 35%. Inhomogeneities of the bioluminescence field achieved 100 km and exceeded the background by ten and more times.

Introduction

The suspended matter in seawater consists of particles of organic and inorganic origin. The living component is represented by small plankton organisms, among which the phytoplankton is the most mass representative in the surface waters of the pelagic zone of seas and oceans. Photosynthesizing organisms contain chlorophyll, which fluoresces in the red and far red portion of the visible spectrum under the exposure to natural or artificial radiation.[1] The chlorophyll concentration and the fluorescence intensity are connected by a proportional dependence.[2] The amount of chlorophyll in surface waters of the pelagic zone of the Pacific Ocean varies from 0.2 to > 2 μg/l (Ref. 3). More than 90% of this pigment is contained in diatoms, which are incapable of independent motion and therefore can be considered as a suspended matter. Thus, from measurements of the chlorophyll fluorescence field, we can estimate the scale of inhomogeneities in the distribution of the living suspended matter in the Pacific Ocean.

It is believed that the composition of the marine plankton usually includes organisms capable of emitting radiation in the green part of the spectrum.[4] The main sources of radiation in the upper layers of marine ecosystems are Dinoflagellates and Radiolaria.[5] They form the bioluminescent field in the World Ocean. Dinoflagellates and Radiolaria can also be considered as suspended matter, because they have no motor apparatus. The distribution of the luminescent suspended matter can be estimated from the bioluminescence intensity.[4]

At vertical sensing in the Black Sea, it was shown that simultaneous recording of bioluminescence and fluorescence gives more adequate idea on the distribution of suspended matter than their separate usage.[6] However, this approach was not used for open-path investigations. In this connection, the aim of this paper was to determine the scales of inhomogeneities in the distribution of the living suspended matter in surface water of the Pacific Ocean at simultaneous measurement of fluorescence and bioluminescence field in many-kilometer sections.

Methods

The instrumental system developed and used in the 38th voyage of *Dmitrii Mendeleev* research vessel (RV) included a bioluminescence sensor placed in a flow-though light-tight chamber. Through a specialized trunk, this chamber was fixed under the vessel bottom, along with a temperature sensor and a pump lifting water to the laboratory.[4] The laboratory housed recording instrumentation and a flow-through fluorometer.[7] The delay in measurement of fluorescence from the time of measurement of the bioluminescent signal was 10 s. At a 12-knot speed, the vessel covered roughly 60 m. This error is negligible when measuring inhomogeneities of luminescent fields larger than 1 km.

At oceanic stations, to obtain additional information on luminescent fields, vertical profiles of the fluorescence and bioluminescence were studied. The intensity of plankton luminescence was measured with a Romashka-3 probe, which is capable of measuring bioluminescence both during day- and nighttime, since it is equipped with a special dimmer to cut off the astronomic light.[4] In addition, water samples from the levels at the depths from 0 to 200 m were collected with a Romashka-3 bathyphotometer to measure phytoplankton fluorescence.

Temperature fronts were separated by the technique described in Ref. 8.

Results and discussion

As known, temperature fronts affect the plankton distribution.[9,10] Therefore, luminescent characteristics of water were considered in relation to variation of temperature gradients. The continuous record of

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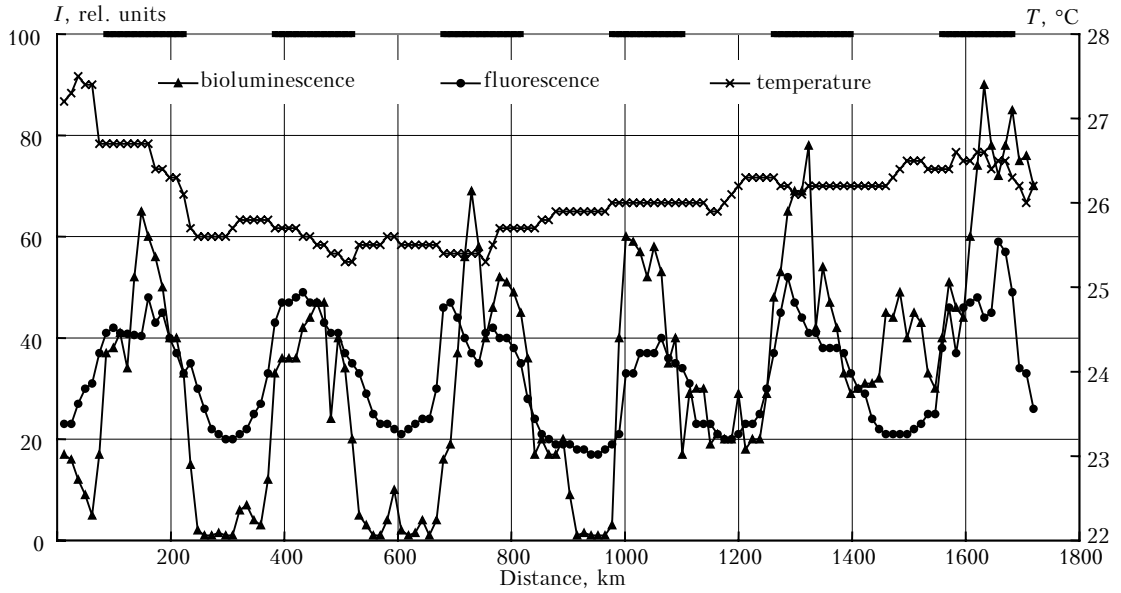

Fig. 1. Variation of bioluminescence, fluorescence, and temperature in the equatorial part of the Pacific Ocean in the section between 02°10′N, 111°04′W and 08°41′S, 84°05′W. Solid bars on the top indicate nighttime.

temperature, fluorescence, and bioluminescence of the surface seawater in the equatorial part of the Pacific Ocean for six days of the vessel voyage is depicted in Fig. 1. The common tendency of temperature variation was characterized by the decrease from 27.6 to 25.7°C along a 500-km long path and then by gradual growth up to 26.8°C at the following more than 1000-km long path. Against the background of the smooth temperature variation, rather sharp changes by, on the average, 0.2–0.3°C at small spatial intervals were observed. These changes were just temperature fronts of the ocean surface water.

Interpretation of luminescence extrema in the front areas turned out to be a complicated problem. The main difficulty was in the diurnal rhythm of bioluminescence and fluorescence, which, as known, depends on the duration and intensity of the solar illumination.[2,11,12] In nighttime, the plankton luminescence was higher than at the solar illumination. For the first three days, the difference between the mean daytime and mean nighttime bioluminescence was almost two orders of magnitude. In the following days, this difference decreased down to 3 to 5 times. The bioluminescence intensity at the section was 10^{-10}–$5.7 \cdot 10^{-8}$ W/cm^2. Diurnal variations of the fluorescence intensity in day- and nighttime were 2–3 times, which well agreed with the data of other authors.[11,13] The common feature of luminescent signals was the time of beginning of an increase or a decrease in the luminescent intensity at the transition from day to night.

It is clear that if a temperature front fell on the sunrise or sunset period, then it was almost impossible to interpret the luminescent signal variation: whether it is connected with its diurnal rhythm or with a change in the plankton concentration. The way out of this situation was to consider variations of the fluorescence and bioluminescence in the regions of temperature fronts found either in daytime or at night. Variation of luminescence in the front regions was ambiguous. In 85% of cases, bioluminescence increased at a temperature rise, while fluorescence decreased. At a temperature drop, to the contrary, fluorescence increased and bioluminescence decreased. It is characteristic that variation of luminescence either preceded a temperature front or succeeded it.

We failed to find a direct relation between the temperature and fluorescence. Earlier it was shown that fluorescence flares up in marine ecosystems at the places of decreased thickness of the upper mixed layer, where the way from the source of nutrients (deep water) to the photic zone is short.[14] The existence of extrema beyond the temperature front confirms the conclusion that factors favoring and supporting hydrological gradients do not affect considerably the phytoplankton distribution.[11] The population of marine phytoplankton reacts to changes in the environment with some delay, as was confirmed by investigations in Lake Baikal.[15]

Mesoscale inhomogeneities of the increased luminescence of phytoplankton chlorophyll were 30–60 km, and the excess of the averaged fluorescence peak over the background was about 35%. Inhomogeneities of the bioluminescence field achieved 100 km in size and exceeded the background by 10 and more times.

Once more, the determination of the scales of inhomogeneities in luminescent fields was performed at a 1000-km section along 30°N latitude in the central part of the Pacific Ocean when crossing the 180th meridian (Fig. 2).

Temperature fronts in this section were more pronounced than on the equator. A bioluminescent signal in the surface water was not observed even at night, because of the absence of luminescent organisms in the upper water layer. This was confirmed by measurements of the vertical profiles of bioluminescence in daytime and

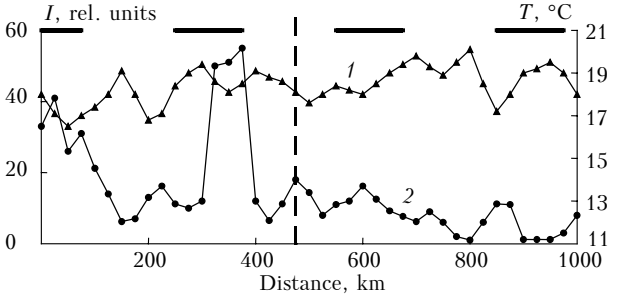

Fig. 2. Variation of temperature (*1*) and fluorescence (*2*) in the Pacific Ocean when crossing the 180th meridian (vertical dashed line on the plot) along the 30°N latitude. Solid bars on the top indicate nighttime.

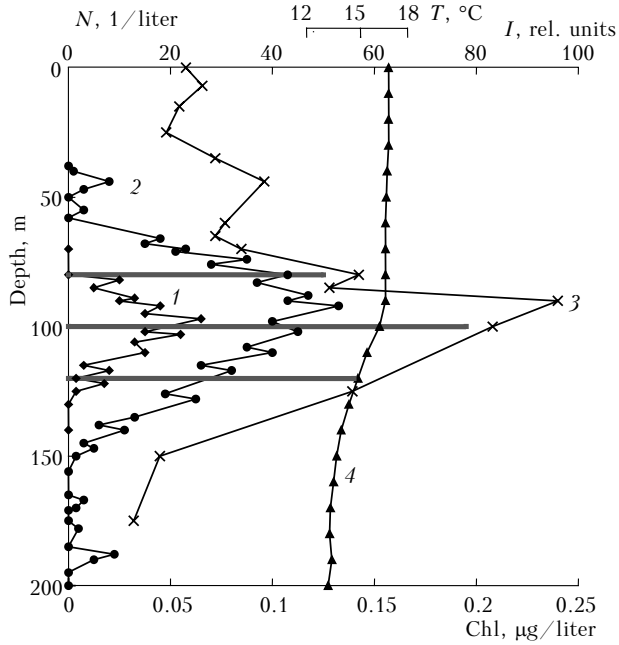

Fig. 3. Vertical distribution of hydrobiological parameters in the Pacific Ocean at the station No. 3536 (30°04′01″N, 153°43′01″W) on April 08 of 1987: bioluminescence intensity (*1* and *2*) in daytime (08:00) and nighttime (20:00), chlorophyll concentration (*3*), temperature (*4*). Horizontal bars indicate the population of small zooplankton.

nighttime at several stations situated at 30°N. For example, at the station with the coordinates 30°04′01″N, 153°43′01″W, plankton luminescence even in nighttime began from the depth of 40 m (Fig. 3). The maximum of bioluminescence was located at the depth of 100 m. The zooplankton population and phytoplankton chlorophyll concentration reached their maxima at this level as well. Judging from the shape of the vertical bioluminescence profiles with their numerous extrema and taking into account the zooplankton population, we can state that the depth luminescence in the central part of the Pacific Ocean is caused by zooplankton. Zooplankton accumulations were observed in the thermocline zone. If the phytoplankton contributed to bioluminescence, then luminescence would be observed in nighttime at the depth down to 35 m from the surface, since the chlorophyll content in the water layer was 0.05 μg/l, and this value is only five times as low as its maximum content at 100 m. This conclusion follows from the hydrobiological situation, which was observed in the region of Peru upwelling. Luminescence, whose intensity correlated with the chlorophyll concentration, was observed there in nighttime in the upper water layer (Fig. 4). In daytime, bioluminescence was absent in the surface water, because of photoinhibition of chemical reactions leading to emission of quanta in the green portion of the spectrum.[4]

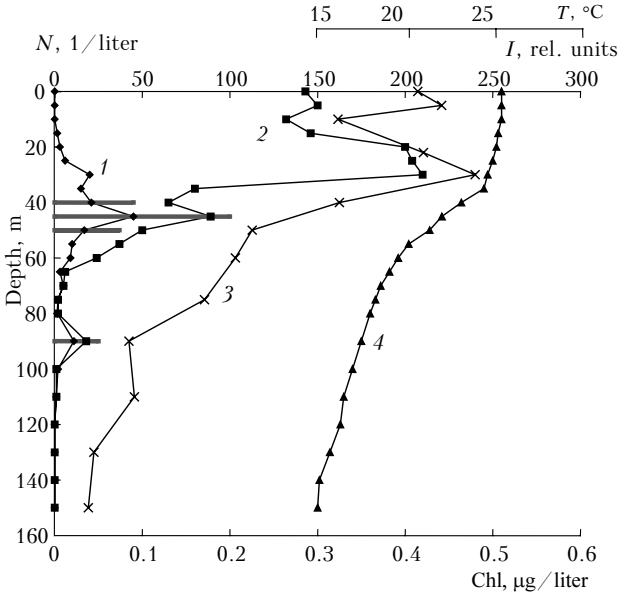

Fig. 4. Vertical distribution of hydrobiological parameters in the Pacific Ocean at the station No. 3485 (07°58′09″S, 80°45′07″W) on February 10, 1987: bioluminescence intensity (*1* and *2*) in daytime (08:00) and nighttime (20:00), chlorophyll concentration (*3*), temperature (*4*). Horizontal bars indicate the population of small zooplankton.

It should be noted, if coming back to the data shown in Fig. 2, that, unlike the diurnal behavior of fluorescence in the equatorial region, the fluorescence intensity at 30°N in the Pacific Ocean did not obey the diurnal solar rhythm. A more clear correlation with temperature variation was observed. As temperature dropped down, fluorescence increased with some delay. Inhomogeneities were clearly pronounced in the Western Hemisphere and their size was about 100 km.

Conclusions

1. Variations of the bioluminescence and fluorescence intensity of the surface seawater in the equatorial part of the Pacific Ocean obey the diurnal rhythm. The mean bioluminescence intensity in daytime is 3 to 100 times lower than in nighttime, and that of fluorescence is 2 to 3 times lower. In April in the 30°N region of the Pacific Ocean, no diurnal rhythm of fluorescence was observed.

2. Inhomogeneities of the fluorescence fields achieved 60 km in the equatorial part of the Pacific Ocean and 100 km

in the 30°N region. In the equatorial zone, the plankton luminescence intensity achieved $5.7 \cdot 10^{-8}$ W/cm^2, and inhomogeneities of the bioluminescence fields had the size up to 100 km. The bioluminescence intensity in April in the surface seawater of the northern part of the central Pacific Ocean was lower than the threshold sensitivity of a luminescence sensor – 10^{-11} W/cm^2.

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