PROBLEMS AND PROSPECTS FOR AN ASSESSMENT OF GLOBAL OCEAN BIOPRODUCTIVITY FROM SATELLITE DATA

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Totality of the processes affecting the spectral brightness of upwelling radiation recorded by a satellite sensor is considered. The problems are formulated whose solution is necessary for an assessment of global ocean bioproductivity.

A primary productivity of the global ocean can be evaluated only with the use of satellite observations, because only they are capable of carrying out synoptic survey of the global ocean. However, such an assessment is impossible only on the basis of satellite observations without data of shipborne and other measurements, special subsatellite experiments for monitoring of the obtained satellite data, and check of the developed calculational algorithms. It is advisable to consider two problems independently: (1) identification of the ocean regions with different primary productivity or, in a more general formulation, the studies of the relative spatiotemporal variability of the primary productivity of the global ocean and (2) qualitative assessment of the primary productivity of various regions in different seasons and on their basis the study of carbon fluxes from the atmosphere to the ocean, which is of prime importance for the prediction of the CO_2 content in the atmosphere and of the associated global climate changes. The evidence for the successful solution of the first problem by means of satellite observations is the data of the American coastal–zone color scanner (CZCS) which has been used onboard Nimbus–7 since 1978 up to 1986. Much information has been acquired about the color of the ocean.[1] Charts, presented in Ref. 1, show a distribution of the concentration of the phytoplankton pigments in tentative colors in various regions of the global ocean (in some charts even seasonal and monthly trends have been indicated). Twenty color grades were used for the concentration increasing from < 0.05 to 30 mg/m^3. Such a large number of grades indicates only the sensitivity of the measuring and data processing systems rather than the real accuracy of the determination of the pigment concentrations. In addition to the random error, the assessment of the pigment concentrations from the CZCS data has a systematic error, i.e., the pigment concentration is underestimated when it is smaller than 1 mg/m^3 (on average by about 20%), and overestimated (on average by 150%) when it is larger than 1 mg/m^3 (see Ref. 2).

In the fall of 1993 NASA schedules the launch of the new Sea–WiFS (Sea–Viewing Wide Field Sensor) scanner of the ocean color representing a much more refined detector of the second generation. The new detector will cover the entire global ocean surface every two days with a spatial resolution of 4.4 km and in required cases of 1.1 km. The accuracy of measuring the absolute spectral brightness of the upwelling radiation is better than 5% while that of the relative measurements is better than 1% (see Ref. 3). The expected accuracy a of chlorophyll determination for the water of the first type is 35% when the optical properties of the sea water are primarily determined by the phytoplankton; the errors substantially increase for the water of the second type when the nonorgarnic suspension and yellow matter play a significant role. The accuracy of the assessment of primary productivity from the satellite data was the subject of a special study.[2]

Figure 1 shows the scheme of the total combination of phenomena which affect the shapes of the signal recorded from the satellite. As can be seen from the figure, the chain of acting factors is rather long. The content of the phytoplankton and suspended particles, determining the light scattering and absorption by the sea water, depends on the primary productivity and the scattering and absorption determine the spectral brightness of the radiation emanating from the water column. Then the radiation reflected from the surface and scattered in the atmosphere, the so–called atmospheric haze, is added. The contribution of the above–indicated factors to the brightness being measured differs in magnitude in different spectral regions. However, the contribution of the atmospheric haze predominates throughout the spectrum: usually it is more than 90% everywhere. The difference between the brightness of the water with different chlorophyll concentrations can change by several times near the surface, but it is manifested only in the shortwave spectral region and is less than 20% in the satellite observations.

We identify four aspects in the examined problem:

(1) data acquisition from a satellite with high accuracy over a wide spectral region,

(2) determination of the spectral brightness of the radiation emanating from the water column from the satellite data referred to as the problem of the correction for the contribution of the atmosphere (here the contribution of the radiation reflected from the surface is also taken into account[4],)

(3) calculation of bio–optical characteristics of the subsurface layer with the use of the obtained values of brightness, and

(4) calculation of the primary and new productions, annual, seasonal, and monthly charting, and estimates of the global production and CO_2 fluxes.

Let us consider each of these problems in order.

1) Four spectral intervals centered at 443, 520, 550, and 670 nm were used in the CZCS. Eight intervals are planned for use in the Sea–WiFS: six of them have 20–nm bandwidth in the visible range (centered at 412, 443, 490, 510, 555, and 670 nm), and two wider intervals are in the IR range (745–785 and 845–885 nm). The accuracy of measurements, as has already been noted, is rather high: better than 1% for the relative variations and better than 5% for the absolute values. One of the main drawbacks of the CZCS –– the lack of the permanent control of the detector sensitivity –– has been taken into account: the calibration over the Sun and the Moon is provided monthly in the Sea–WiFS. Moreover, the periodic test and intercalibrations over the subsatellite measurements is provided.

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2) The correction of the CZCS data for the contribution of the atmosphere in Ref. 4 was based on several rather serious restrictions. First, the atmosphere was considered to be cloudless; second, it was assumed that the ocean surface is flat and free of foam and the receiver operates outside the sun's glitter patten (the satellite sensor could be tilted to avoid the speculary reflected solar radiation). There was one more essential assumption about the existence of the clear water sections with the pigment concentration less than 25 mg/m^3. For them the normalized brightness of the radiation emanating from the water column was taken to be constant at wavelengths of 520, 550, and 670 nm (at a wavelength of 670 nm it was zero). Angström's coefficient in the spectral dependence of the aerosol atmospheric thickness was estimated from the experimental data for these wavelengths, the obtained value was taken for the entire area of the analyzed image and was used to calculate the brightness of the atmospheric haze at a wavelength of 443 nm. The other assumptions were also used, in particular, that the aerosol scattering phase function is independent of the wavelength.

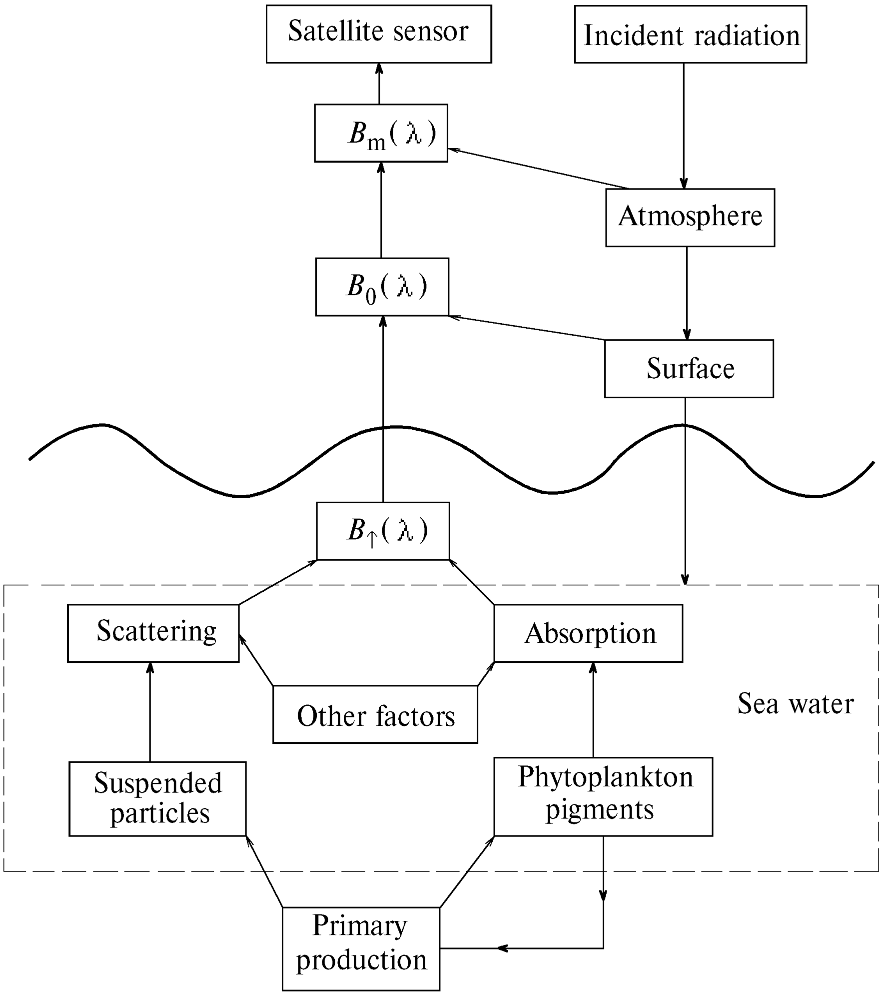

FIG. 1. The total combination of factors affecting the shape of the signal recorded by the satellite color scanner. $B_i(\lambda)$, $B_0(\lambda)$, *and* $B_m(\lambda)$ *are the spectral brightnesses of upwelling radiation under the water surface, above it, and at the top of the atmosphere.*

Two assumptions essentially restrict the possible application of the experimental data. These are the assumptions that the atmosphere is cloudless and the ocean is black in the red spectral region. They are wrong when the wind–driven waves and the foam are presented. The foam makes the contribution to radiation which is comparable with the contribution of the radiation emanating from the water column even when the foamy surface makes only 0.5% of the total one (see Ref. 5). The elaboration of the methods of taking into account of the contribution of radiation reflected from foam is one of the most important problems for the future studies and it is necessary to study in detail the characteristics of the foamy formations for which the accurate data are unavailable today. The other most important problem is taking into account the effect of broken cloudiness (the continuous cloudiness is an insuperable obstacle).

It is very important to extrapolate the contributions of the atmospheric haze determined in the red wavelength region to the short–wave region with reasonable accuracy.

To improve this accuracy, it would be desirable to use statistic estimates of spectral dependences of the aerosol thickness under various conditions of observation, but they are few in number for the marine atmosphere. It is necessary to sharply intensify the acquisition of data on the optical characteristics of the marine atmosphere.

3) The basic problem in the determination of the bio–optical characteristics of the subsurface layer is the elaboration of the general algorithm and subsequent differentiation of its parameters under various ocean conditions. The presently accepted classification into case one and case two seems to be too tentative; the general algorithm must be developed with the parameters adjustable to various oceanic conditions.

4) The fourth part of the problem is the determination of the primary productivity from the satellite data. It is least understood now. The satellite observations can yield information only about rather thin subsurface layer whose thickness does not exceed 20–30 m. One can determine the total pigment content from these data since according to the estimate performed by Morel[6] the correlation coefficient between the above–indicated values is equal to 0.934 when the pigment concentration in the subsurface layer varies by more than a factor of 10^3 from 0.01 to 20 mg/m^3. These estimates were obtained at 3500 stations even for the stratified water.[6]

There are various models used to calculate the primary productivity: simple empirical and more intricate semi–analytical. The models developed by Ryther and Yentsch,[3] Bannister,[8] Platt, and Sathyendranath,[9] and Balch et al.[10,11] are well known. The algorithm for the calculation of the primary productivity from the satellite data has been developed by Pelevin and Koblentz–Mishke at the Institute of Oceanology. Some of these models (not all) yield good results, if the values of the input parameters are known. But these parameters are unknown when using the satellite data and the results turn out to be inadequate.[2] The intercomparison[2] of the results calculated with the use of various models and the results of direct determinations of the primary production showed that the surface production could be determined with reasonable accuracy, but all the considered models yielded unsatisfactory results for the net production. It is interesting that the most intricate model yields the worst results.[9] Apparently the reason is the multistep calculations with insufficiently accurate knowledge of the input parameters. In such a situation it is quite possible that the simple semi–empirical algorithms with a few number of the parameters may be more effective.

The algorithm P_m^b/K proposed in Ref. 8 (see also Refs. 12 and 13) appears to be the most promising, in which P_m^b is the maximum assimilative number and can be estimated from the satellite data on the surface temperature. The accuracy of such an estimate of P_m^b shows promise to be improved (compared to Ref. 2) on the basis of the serious oceanological analysis.[14] Now there is a good chance for such an analysis: first, there are data of the CZCS and AVHRR high–resolution radiometer and second, there are data of the shipborne measurements.

The most important condition for the successful solution of the problem of application of the satellite data is the performance of the integrated subsatellite experiments and the supplementary measurements from onboard the ships, buoys, and aircrafts. The NASA program of the Sea–WiFS operation includes a large number of shipborne measurements[15] of the spectral irradiance at the surface and at the various depths in the water column, the spectral brightness of the upwelling radiation under water, other optical parameters, the spectral atmospheric transparency, the wind velocity and the state of the sea surface, the depth profiles of the temperature and salinity; determination of the concentration of the phytoplankton pigments, the suspension, the stained organic substance, the net primary production, the new production, the losses due to eating away, and so on. For performing these investigations it is expedient to use large ships, which the Institute of Oceanology and some other Institutes have and which are capable to take onboard the ship 60–75 experts, that makes it possible to carry out the above–indicated measurements simultaneously. An example of such integrated investigations is the mission of the 23–rd voyage of the scientific–research ship *Vityaz'*, whose main problem was the validation of the results of satellite observations based on data of shipborne measurements.[16]

Subject–oriented shipborne studies in combination with measurements from the anchored and drifting buoys and airborne measurements will allow one, at least partially, to fill the gaps inevitably appearing in the satellite information primarily because of the cloudiness. It is important to choose the regions for the performance of such experiments. The preliminary serious analysis is also required, in particular, based on the CZCS data. These data are valuable because they show the spatiotemporal location of the maximum gradients of biological characteristics, while ignorance of the peak character of production processes, as was noted in Ref. 17, may be one of the possible reasons of underestimating the net production of the global ocean. These regions should be studied most thoroughly.

In the nearest decade the sufficient amount of satellite data on the ocean color will probably appear. The launching of the American–Japanese satellite with the OCTS color and temperature sensor is scheduled for 1995, while of the third modification of the MODIS–N spectro–radiometer –– for 1998 (see Ref. 18). The problem is to retrieve the most complete and accurate information about the ocean from these data.

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