Use of passive-active optical sensing techniques for measuring structural peculiarities of bio-optical characteristics distribution in the upper ocean layer

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One of the problems arising at remote sensing of the ocean is determination of characteristic structures in distribution of bio-optical characteristics of the upper ocean layer. The passive methods of determination of a sea surface color allow us in some cases to solve this problem. However, because of the influence of many factors, the signal-to-noise ratio in these measurements does not allow reliable recognition of such structures. In this paper, fields of chlorophyll A concentration obtained simultaneously from the SeaWiFS satellite and with a shipborne laser fluorimeter in the Tasmanian Sea are statistically processed in parallel. It is shown that characteristic scales in the chlorophyll distribution are observed in both cases, and these scales are connected with the Rossby inner scales.

It is well-known that the information obtained at remote sensing of the ocean by active optical (laser) techniques is in many cases more reliable than that obtained by passive methods. In this connection, the tendency to use the laser techniques in the satellite measurements as calibrating[1–3] in order to increase the accuracy of existing passive methods and to extend their capabilities is justified. Thus, for analysis of the structure of fields of different physical nature and discerning the characteristic structure formations in them using the statistical processing of satellite remote sensing data, it is necessary to conduct similar processing of shipborne measurements for more certain interpretation of the satellite data. This is also true for bio-optical characteristics of the seawater. Structures with characteristic scales of distribution of the seawater bio-optical characteristics are formed due to very complex interaction of hydrophysical, hydrochemical, and hydrobiological processes in the photic ocean layer, and, in turn, cause the corresponding structuring of phytoplankton fields.

In this paper, we present the results of statistical processing of data on the chlorophyll A concentration fields obtained by means of passive sensing of the sea surface color from the SeaWiFS satellite and active sensing from a ship. The statistical analysis was aimed at detection of characteristic structures in distribution of bio-optical characteristics (chlorophyll A) in the upper ocean layer. Formation of characteristic structures in the chlorophyll spatial distribution may be caused by different factors, and the possibility of detecting such structures by remote sensing techniques is needed for solution of a wide variety of problems in oceanography.

For the statistical processing we used the SeaWiFS remote sensing data on the sea surface color[4] and the simultaneous measurements of the chlorophyll A concentration from the training sailing vessel *Nadezhda* with the use of a laser fluorimeter.[5]

The region of the Tasmanian Sea, where the data were obtained, is shown in Fig. 1. The figure also shows a part of the SeaWiFS scanner band dated February 10, 1998. The gray color corresponds to the pixels at which the concentration of chlorophyll A was reconstructed. The rest of the area (white color) in the period of measurements was covered with clouds.

A section of the *Nadezhda* route on February 10, 1998, between 11:00 and 14:00 LT is enclosed in a circle in Fig. 1. The continuous measurements of the fluorescence spectra were conducted with the spatial resolution of 240 m.

The initial data for the processing were the values of the chlorophyll concentration obtained from the SeaWiFS scanner and averaged in roughly 8×8 km squares and the values of the chlorophyll A concentration measured with the shipborne laser fluorimeter (Fig. 2). The region of measurements is shown on an enlarged scale, and the corresponding histogram of the chlorophyll A concentration is build for all squares in the region shown in Fig. 2*a*. The maximum of the distribution falls roughly on 0.4 μg/l concentration. Figure 3 shows the distribution of the chlorophyll A concentration derived from the laser fluorimeter data along the vessel route and the histogram of the chlorophyll concentration constructed on the basis of these measurements. In the latter, we can see two groups of values being characteristic of two clusters of points in Fig. 2*a*. Such a difference between the histograms presented in Figs. 2*b* and 3*b* can be likely explained by the difference in the scales of spatial averaging (although the mean values of the concentrations are close).

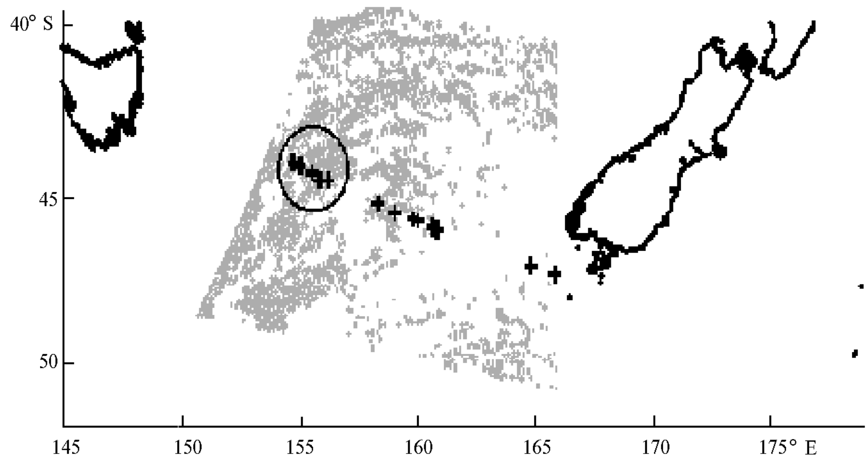

Fig. 1. SeaWiFS picture with the *Nadezhda* route.

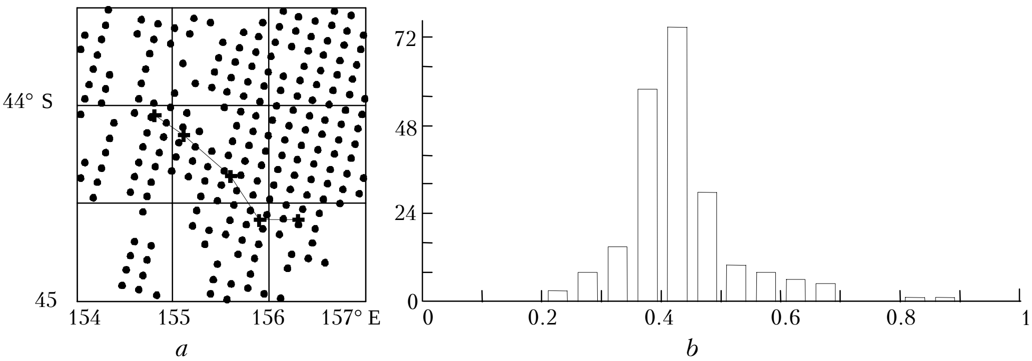

Fig. 2. Region of measurements (*a*) and histogram of chlorophyll concentration (*b*); the chlorophyll concentration, in μg/l, is plotted as horizontal, and the number of measurements with this concentrations is plotted as vertical.

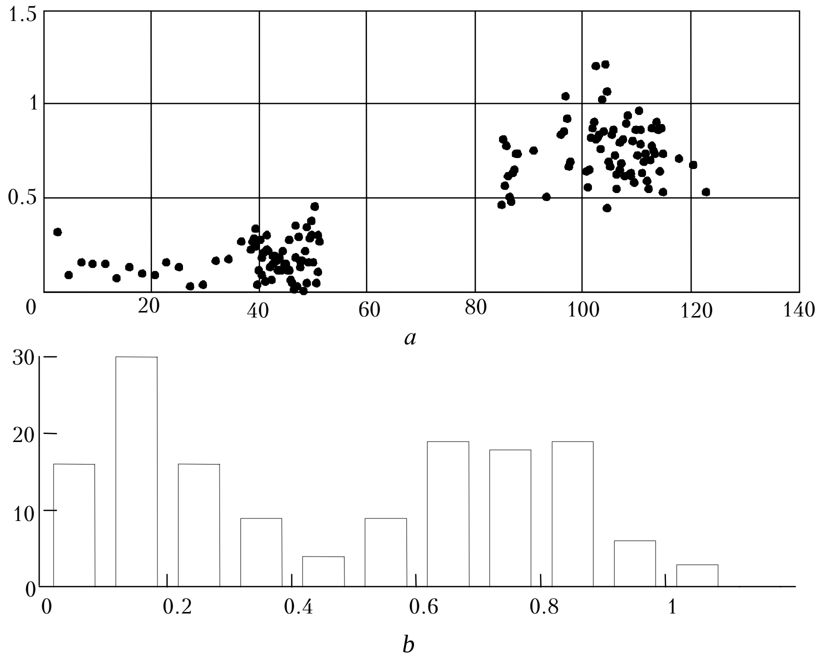

Fig. 3. The chlorophyll concentration measured with laser fluorimeter (*a*) (concentration, in μg/l, is plotted as vertical, and the distance along the vessel route, in km, is plotted as horizontal); histogram of chlorophyll concentration (*b*) (axes are the same as in Fig. 2*b*).

The statistical characteristics were estimated using the well-known algorithms. Here we only underline some important, in our opinion, methodical peculiarities connected with the limited length of the samples, spatiotemporal variability of the data, and their errors. The correlation functions were calculated via statistical estimates of the structure functions. This method is preferable in the case of approximate homogeneity of a random field and possible systematic errors in measurements.[6,7] In this case, averaging is performed for overlapping gradations of distances between the measurement points (and gradations of the angle for the anisotropic field). This allows us to increase the number of averaging intervals and decrease the variance at smoothing or approximation of the correlation functions.

It is very interesting to compare the behavior of the correlation functions obtained for the two arrays of the measured data. The shape of the correlation functions allows one to determine the characteristic scale of structures in the distribution of the chlorophyll A concentration.[8]

Figure 4 shows the correlation functions of the chlorophyll concentration for the fluorimetric measurements from the vessel (Fig. 4*a*) and for the concentrations obtained by processing the space picture shown in Fig. 2*a* (Fig. 4*b*). The values of the chlorophyll A concentration inside a 35-km long section of the route strongly correlate (the value of the correlation function drops down to 0.7 of its maximum value at the distance about 35 km). The values of the empirical structure and correlation functions obtained at small distances, upon extrapolation to the zero distance can be used in estimation of accuracy of the initial data and errors connected with inhomogeneity and small-scale processes. Thus, from the satellite data shown in Fig. 2*a* we can find the signal-to-noise ratio (roughly equal to 2) using Fig. 4. This ratio for the laser fluorimetry data presented in Fig. 3*a* is about 10.

Using the correlation function given in Fig. 4*b*, we can find the correlation radius of the chlorophyll A field as measured from space. The value equal to 0.7 of the correlation function maximum is achieved at the distance about 25–30 km between the centers of squares. This result, on the whole, is in a good agreement with that obtained from the plot shown in Fig. 4*a*.

Figure 5 shows a 2D correlation function reconstructed from the SeaWiFS data. Analysis of this function allows us to tell about anisotropy of the chlorophyll field on the scales larger than 20 km. Thus, the isolines of the function values remain symmetric up to the distance about 20 km, then circles markedly transform into ellipses. As this takes place, the orientation of the long axes of the correlation ellipses at the distances of 50–60 km roughly coincides with the direction of the vessel movement (wind direction). The scales about 20–30 km are typical of the upper ocean layer in summer in mid-latitudes of the both hemispheres. They correspond to the well-known Rossby scale, which determines the characteristic size of synoptic variability of hydrological characteristics of the upper quasi-homogeneous layer.

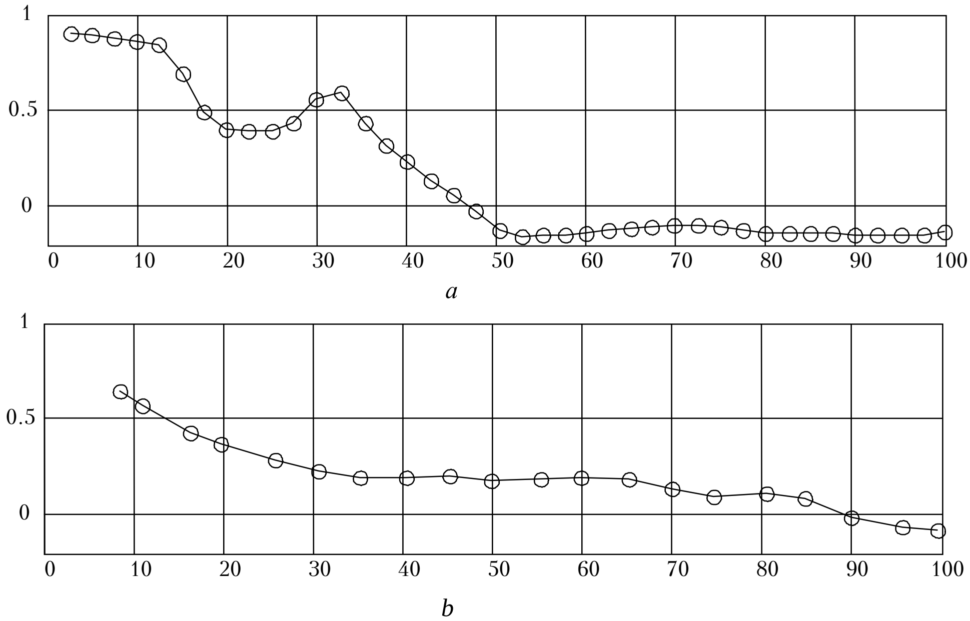

Fig. 4. Correlation functions of fluorimetric (*a*) and satellite (*b*) measurements; the distance, in km, is plotted as horizontal, and the value of the correlation functions is plotted as vertical.

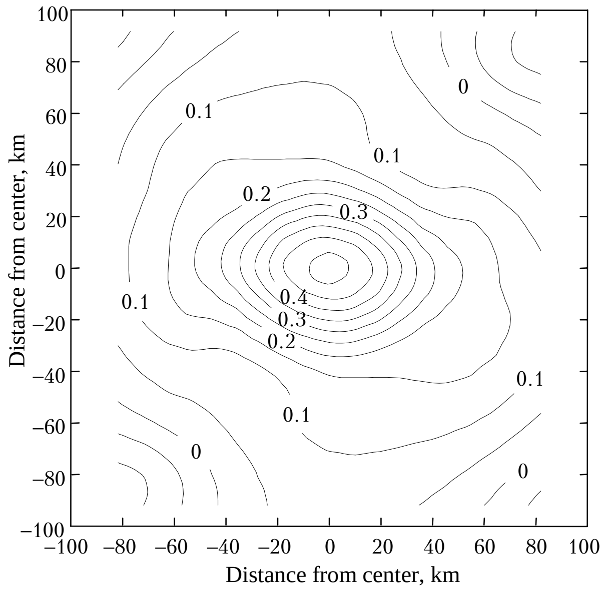

Fig. 5. Two-dimensional correlation function for the satellite data.

The behavior of the 2D correlation function of the chlorophyll field represents the isotropy of different hydrophysical fields in the ocean at small distances, well-known from the data on their statistical structure, as well as appearance of anisotropy (correlation ellipses) on the scales exceeding synoptic ones.

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