COMBINED-SIGNAL MODEL IN PROBLEMS OF INTERPRETATION OF PHOTOMETRIC MEASUREMENTS OF CLOUD FIELDS

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It is shown for the example of the analysis of the conditions of observation that the effect of the variability of the vertical and horizontal dimensions of the elements of a cloud field on the brightness of the cloud and cloud-free zenith must be taken into account separately. Estimates are obtained for the probability of the presence of a cloud along the line of sight from the results of photometric measurements (daytime).

Information, contained in the brightness field of the downwards propagating solar radiation, about the structure of the cloud field is especially valuable for determining the conditions for and supporting the operation of ground-based optical systems.

Theoretical and experimental works on the investigation of the brightness of the downwards propagating solar radiation employ a model that essentially consists of combining random fields or processes.[1–3] In particular, the two-component process of fluctuations of the observed monochromatic brightness $B_{ob}(t)$ can be written in the form

$$B_{ob}(t) = q(t)B_1(t) + [1 - q(t)]B_0(t), \qquad (1)$$

where $B_1(t)$ and $B_0(t)$ are the fluctuations of the brightness of the cloud and the break in the cloud layer; $q(t)$ is a unit step function that switches on the states of the process and assumes two values (corresponding to the number of states): 1, if a cloud is observed, and 0 otherwise. The average value of the stationary process (1) is described by the linear dependence[3]

$$\overline{B_{ob}} = p\,(\overline{B_1} - \overline{B_0}) + \overline{B_0}\ , \qquad (2)$$

where the overbar denotes averaging with respect to the parameter t and p is the average value of the process $q(t)$, and is equal to $P[q(t) = 1]$.[1] The variance of the process (1) can be represented as a quadratic polynomial of p:

$$\sigma^2_{ob} = -p^2(\overline{B_1} - \overline{B_0})^2 + p\,[(\overline{B_1^2} - \overline{B_0^2}) - 2(\overline{B_1} - \overline{B_0})\overline{B_0}] + \sigma^2_0\ . \qquad (3)$$

In practice this model is difficult to use because of its nonstationarity, which is manifested in trends of the average values and the variances of the brightness. The nonstationary nature of the process arises for several reasons. First of all, the observed processes occur against the background of determinate changes in the brightness field which are associated with the change in the visible position of the sun. In addition, the nonstationariness in the form $B_{ob}(t)$ and $\sigma^2_{ob}(t)$ can arise owing to time dependence of 1 (or several) parameters appearing in Eqs. (2) and (3): $p(t)$, $B_1(t)$, $B_0(t)$. These dependences can be caused by the spatial nonuniformity of the cloud field. In Ref. 2 it is pointed out that a stationary cloud field as a whole can be described by the average characteristics — the probability for the presence of a cloud p and the horizontal dimensions of the cloud L_1 and the cloud break L_0. If an observer, located under the cloud layer, moving with velocity B, records the temporal fluctuations of the monochromatic brightness of the radiation with the help of a narrow-angle detector, oriented in a constant direction, then the relations (1)–(3) describe the processes observed in the sections of the cloud field. The switching of the states of the process on the section of the cloud field can be described by a random phototelegraph signal $q(t)$ with the parameters p (the probability of a definite state) and λ (the frequency of the Poisson flux of switching points distributed on the time axis t). It is not difficult to find a relation between these parameters, the horizontal dimensions of the elements of the cloud field $\overline{L_1}$ and $\overline{L_2}$ and the velocity of the cloud field $\overline{V}$:

$$p = \overline{L_1}/(\overline{L_1} + \overline{L_0}), \qquad \lambda = \overline{V}(1/\overline{L_1} + 1/\overline{L_0}). \qquad (4)$$

The dependence on the times $\overline{L_1}(t)$, $\overline{L_0}(t)$ or $\overline{V}(t)$ causes the process $q(t)$ and therefore the observed process (1) to be nonstationary.

The amplitudes of the signals of the processes $B_1(t)$ and $B_0(t)$ depend nonlinearly on the vertical dimensions of the elements of the field associated with their optical thickness.[4] The variation of the average optical thicknesses of the elements of the cloud field will cause the ratio of the average values of the brightnesses $\overline{B_1}$ and $\overline{B_2}$ in Eqs. (2) and (3) to vary and will affect the stationariness of the proc-

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ess $B_{ob}(t)$, even if the cloud field is uniform in the horizontal direction and $\bar{V}$ is constant.

We shall illustrate what we have said above for the specific example of the analysis of the observations of the brightness of the zenith, performed in May 1987 with the help of a stellar-solar photometer[5] (the field of view is equal to 5 angular minutes and the working wavelength is equal to 0.69 μm). On one of the days, in the first realization in the bottom and middle troposphere above the point of observation the axis of the pressure trough was found. By 7 h local time a Sc cloud cover formed. A 10-point cloud cover remained up to 11 h and by 15 h it dispersed. The height of the lower edge of the cloud cover varied from 700 to 1600 m and its velocity was estimated to be 6 m/sec.

On the next day (the second realization) the observations were performed under conditions of the trailing part of the pressure trough. Above the 1500 m level advection of moist air occurred and after 13 h clouds were observed to appear near the horizon. In both cases parts of realizations from 9.35 to 13.55 were used in the analysis.

The analysis of the result consisted of several stages. First, corrections were introduced for the spectral sensitivity of the photometer. For this, under the conditions of high transmission observations of an exoatmospheri'c source with a tabulated spectrum were performed.[6] In order to take into account the effect of different factors the realization was divided into nonoverlapping sections (lines), each with a duration of approximately 626 sec; this corresponded on the average to 3.8 km in the linear scale. For each line with the running number j it was assumed that the realization was stationary, i.e., the relations (2) and (3) were satisfied. As pointed out in Ref. 2, for processes of the type (1) in problems of classification an amplitude detector can be used. To formulate the deciding rule the results of exponential smoothing $\tilde{B}(\tilde{t})$ of "cloud-free" sample and the rms deviations $\tilde{\sigma}$ of the instantaneous readings from the smoothed readings were used here. The final rule was as follows: if $B_{ob}(t) > \tilde{B}(\tilde{t}) + k\tilde{\sigma}$, then $B_{ob}(t) = B_1(t)$ and $q(t) = 1$, "cloud". Otherwise, if $B_{ob}(t) \le \tilde{B}(\tilde{t}) + k\tilde{\sigma}$, then $B_{ob}(t) = B_0(t)$ and $q(t) = 0$, "no cloud," where $k = 1, 2, 3$; the "no cloud" class corresponds to estimates of meteorological data "with no clouds, high humidity is observed". Actually, this is an amplitude detector with a variable threshold, and Eq. (5) is the analog of the rule, proposed in Ref. 7, for adopting a solution in the presence of a cloud cover, based on the average value of the brightness in a fixed angular direction of the clear sky for a given position of the sun.

It follows from analysis of the conditions of observation that in the first realization the trend in the brightness must be caused primarily by the changes in the thickness of the cloud layer, the probability for the presence of a cloud in the direction of viewing, and the position of the sun. Indeed, from 9.35 to 11.50 the change in the thickness of the continuous cloud layer ($p = 1$) had an overall tendency to decrease, and as a result the level of the observed brightness increased, and this was accompanied by a tendency for the brightness of the cloud-free zenith to increase in connection with the change in the position of the sun (the points 1, ..., 12 in Fig. 1a). From 11.50 to 13.55 against the background of the change in the thickness of the layer the overall quaintity of clouds decreased and the level of observed brightness decreased; this was partially compensated by an increase in brightness owing to the change in the visible position of the sun (the points 13, ..., 23 in Fig. 1a). In the second realization the level of the observed brightness increased owing to the fact that the effects of the change in the position of the sun coincided with advection of moist air.

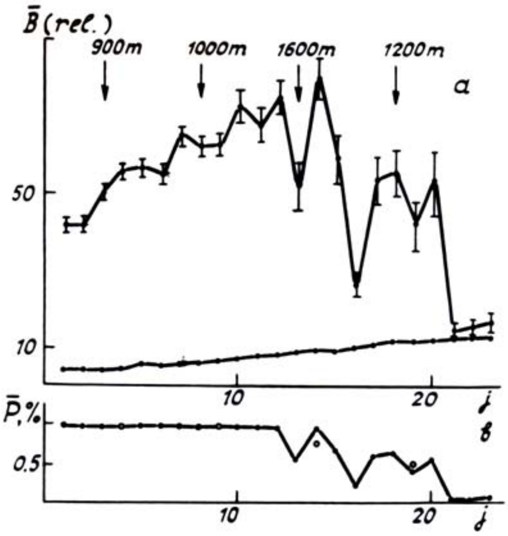

FIG. 1. The time averages of the observed brightness of the zenith and the probability for the presence of clouds: a) the top curve corresponds to the presence of cloud; the error ranges in the estimation of the average and the height of the bottom edge of the cloud cover are indicated; the bottom curve corresponds to no clouds (on the scale of the figure the error in the estimate is negligibly small); b) estimates of the probability for the presence of clouds in the zenith from the results of photometric observations (dots) and the overall amount of clouds based on the data from the meteorological service (circles).

In these realizations it was found that the temporal trends could be approximated by linear equations. The rank correlation τ (Ref. 8) for overlapping time intervals of realizations with and without clouds (indices 1 and 0, respectively) were calculated as a criterion for the linear trend. From 9.35 to 11.50 $\tau_1 = 0.6$ and $\tau_0 = 0.99$ ($\sigma_\tau = 0.03$ in both cases). From 11.50 to 13.55 $\tau_1 = -0.31$ and $\tau_0 = 0.96$

($\sigma_\tau = 0.04$). The use of trend criteria and additional information about the conditions of observation made it possible to take into account the effect of the position of the sun, the thickness of the layer, and the probability for the presence of a cloud in each line of information and to formulate the arrays $B_{1j}(t)$, $B_{0j}(t)$, and $q_j(t)$, where j is the running number of the row. After obvious transformations of (2) the instantaneous values of the probabilities $\hat{p}_j$ were estimated using the values of $\overline{B_{1j}}$, $\overline{B_{0j}}$, and $\overline{B_{obj}}$. The estimates of the probability obtained as average values of the process $q_j(t)$ were identical to the estimates made from the expression (2). The correlation coefficient between the estimates of the probability and the corresponding values of $\overline{B_{obj}}$ is equal to 0.93±0.03 (with a probability of 95%); this confirms that the linear dependence (2) is valid.

For comparison, Fig. 1b shows the estimates of the probability for the presence of a cloud at the zenith and the overall amount of clouds based on data from the meteorological service.

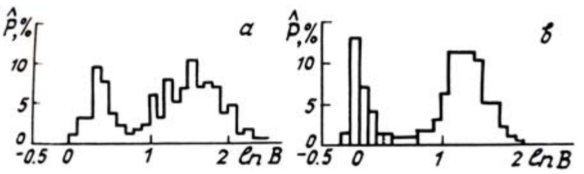

FIG. 2. Histograms of the distribution of photometric readings from the zenith with clouds before (a) and after (b) corrections were introduced for the dependence on the positions of the sun, the height of the bottom edge of the cloud cover, and the spectral sensitivity of the photometer.

For processes of the type (1) the signal amplitudes must satisfy a uniform distribution of the form $f_p(B) = pf_1(B) + (1 - p)f_0(B)$. Figure 2 shows empirical histograms of the observed values of the brightness calculated for the entire sample before (Fig. 2a) and after (Fig. 2b) corrections for the dependence on the position of the sun and the spectral sensitivity of the photometer. The two modes of the distribution correspond to the most likely values of the brightness of the clouds and the break in the cloud cover; the difference between them is significant at the level 0.01.

Conclusions. The spatial nonuniformity of the cloud field is manifested in the temporal trends of the observed values of the brightness in the direction of observation (zenith). In order to make the proper corrections for the trends additional information about the conditions of the observation is required, in particular, about the height of the bottom edge of the cloud cover, the thickness and velocity of the layer, and the coordinates of the angular position of the sun and the probability for the presence of clouds in the line sight. Information about some of these factors can be obtained from photometric measurements. For example, the probability for the presence of clouds at the zenith can be determined, if aside from the observed values of the brightness the brightness of the cloud-free zenith is known (here it is assumed that the brightness of the break in the cloud layer approaches in the limit the brightness of the clear sky for the same coordinates of the point of observation and position of the sun). The effect of the variability of the vertical and horizontal dimensions of the elements of the cloud field must be taken into account separately. For example, for the situation discussed (Sc cloud cover) the change in the cloud point from 10 to 1-2 and the height of the bottom edge from 900 to 1600 m was manifested as a trend in the values of the brightness opposite to the main trend. After corrections were introduced for the effect of the altitude of the bottom edge and the position of the sun a high value was obtained for the sample linear correlation coefficient between the values of the brightness and the probability for the presence of a cloud on the line of sight through the cloud layer.

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