TEMPORAL AND SPATIAL VARIABILITY OF FIELDS OF THE OPTICAL AND AEROSOL CHARACTERISTICS IN THE ATMOSPHERE

I. OPTICAL CHARACTERISTICS OF THE ATMOSPHERE

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The paper describes the results of application of the normalized span method to an analysis of temporal series of observations of the atmospheric optical thickness and its aerosol component in the visible and near-IR ranges. The values of the Hurst exponent are shown to differ significantly from $H = 0.5$, *which points to nonrandom character of the formation of atmospheric radiation regime. The revealed coincidence of the* H *values for the atmospheric optical thickness and its aerosol component confirms the determining role of aerosols in this process and the identity of the mechanisms governing the variation of the examined parameters. The daily variation of aerosol component of atmospheric optical thickness is found to be principally different under enhanced volcanic activity and standard conditions.*

In recent years in an analysis of time series the so-called method of normalized span has received wide acceptance. Using this method, the results of observations of such parameters as the index of solar activity (for example, the Wolf number), roughness elevations of the sea surface, thickness of annual rings of trees, thickness of sediments, long-term time variations of river discharges, and some meteorological parameters[1,2] (average daily and instantaneous temperatures, air humidity, wind speed and direction, and so on) were analyzed. One of the main reasons why the special attention is attracted to the results obtained on the basis of the normalized span method is connected with the prospects for the development of new fairly simple and reliable prognostic schemes.

It has been this fact that prompted us to process several samples of the results of optical and aerosol observations being at our disposal. It should be noted that this analysis was not made previously. This is mainly caused by a limited number of such data arrays that are not very accessible. The regularities discussed below are by far preliminary and should be carefully checked and verified further. However, their establishment even in some particular cases studied by us is of indisputable interest.

The random variable $x(t)$ observed during the period t is characterized by its mean value

$$\xi(t) = \frac{1}{t}\sum_{i} x(\tau_i) \tag{1}$$

and by the standard deviation

$$S(t) = \left\{\frac{1}{t}\sum_{i}\,[x(\tau_i)^2 - \xi(t)^2]\right\}^{1/2}, \tag{2}$$

where τ_i are the observation times.

Defining the span of the variable $x(t)$ for the period t as

$$R(t) = \max x(t) - \min x(t), \tag{3}$$

the relation

$$R(t)/S(t) \sim t^H \tag{4}$$

can be written. The parameter $R(t)/S(t)$ is called the normalized span.

It can easily be shown[3] that for a random process with independent values of $x(t)$ and finite variance, $H = 0.5$.

However, as early as the 50–60s Hurst[1] who had analyzed the time dependence of the normalized span and formulated the empirical law demonstrated that for many natural processes $H = 0.72 \pm 0.08$.

In this connection, Eq. (4) was called the Hurst law and the exponent H – the Hurst constant. (In Ref. 1, the designations K and H were used; the modern name of the constant was introduced by Mandelbrot.[4])

The conclusion drawn by Hurst was confirmed by numerous further investigations.[2] Table I presents the results of analysis of some observations of meteorological and hydrological characteristics. In all cases, the values of H differ greatly from 0.5 (for the

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simplest model of random process – to flip a coin – $H = 0.5$).

Already Hurst posed the question about the reason for this difference. He proposed that the values H shifted due to the existence of numerous interconnections for natural processes and the effect of "memory" of a sort. Thus the river discharge whose regularities were predominantly studied by Hurst, was determined not only by the liquid water content during observations, but also by the regional synoptic conditions, the state of ground water in the river basin for a long preceding period, and so on.[1]

TABLE I. The values of the Hurst exponent H for some natural processes.[1]

Hydrometeorological characteristics		Observation period (year)	Number		Mean	Variance
			Stations	Cycles		
Water discharge	Water discharge	10–100	39	94	0.72	0.091
	from the river Rhone	1080	1	66	0.77	0.055
Level of rivers and lakes		44–176	4	13	0.71	0.082
Level of precipitation		24–214	39	173	0.70	0.088
Sediments	Lake Saki	50–2000	1	114	0.69	0.064
	Lakes Maugham and Timiscaming	50–1200	2	90	0.77	0.094
	Lakes Corinti and Hailey	50–650	2	54	0.77	0.098
Meteorological parameters	Temperature	29–60	18	120	0.68	0.087
	Pressure	29–96	8	28	0.63	0.070
	The number of solar spots	38–190	1	15	0.75	0.056
	Thickness of annual rings of trees	50–900	5	105	0.79	0.076
Mean for individual characteristic	Water exchange		83	346	0.72	0.08
	Sediments		5	258	0.74	0.09
	Meteorological parameters		32	268	0.72	0.08
Total mean		10–2000	120	872	0.726	0.082

It is particularly remarkable that in the model experiments taking into account the prehistory of the process (note that the original simplest version of such model experiment – numerical cards – has been developed and realized already by Hurst himself) for sufficiently long time series there is a tendency for $H \to 0.5$, but for the natural processes this is not observed in most cases.[1,2] It should be noted that in case of numerical simulation of random processes an asymptotic tendency to $H = 0.5$ is usually observed for very long series ($N \approx 10^5$–10^6). In this case, it is impossible to estimate anyhow exactly the reliability of the values of H obtained from samples of measurements of limited lengths. In this connection, the Hurst law that establishes the difference of H from 0.5 for natural processes is considered an empirical law. A true reason for obtaining biased estimates of H when studying the natural processes has not been elucidated up to now. It is assumed that the original explanation[1] is valid.

This fact, namely, the difference of H from 0.5 found for natural processes some researchers explained by their fractal structure. It has been argued on occasion that the fractal structure is a common characteristic of natural processes and their main difference from the anthropogenic processes that are characterized by strict (geometrical) relations or are random.

It seems to us that such a conclusion, being predominantly of common physical and philosophical significance, should be more carefully warranted and theoretically explained. However, of particular interest is the fact itself of establishing definite regularities in time variations of different natural processes even in cases in which their nature has not yet been understood. This interest is also caused by the development of new prognostic systems describing the evolution of processes in the environment and even in the social relations.

A rigorous theoretical basis for such feasibility (as well as for a true nature of this phenomenon) is lacking; more likely, the analogy with the process of generalized Brownian motion studied by Mandelbrot acts here. Having introduced in Ref. 4 a concept of generalized Brownian motion, he showed that the particle position is described by a fractal structure with the dimension $D = 2 - H$. In Refs. 4 and 5 that are now regarded as classical, the conditions of the fractal systems formation and the methods of their description have been formulated.

For the classical Brownian motion ($H = 0.5$) the correlation between the former (at $t < 0$) and future ($t > 0$) increments of the coordinates is absent while for the generalized Brownian motion the correlation function for the future increments $B_H(t)$ with the former ones $B_H(-t)$ has the finite nonzero value

$$C(t) = \langle -B_H(-t)\; B_H(t)\rangle / \langle B_H^2(t)\rangle = 2^{2H-1} - 1 . \tag{5}$$

When $H \neq 1/2$, it turns out that $C(t) \neq 0$ for arbitrary t.

For $H > 1/2$ the observed tendency retains, namely, if over the past period of time the positive increments of the measurable parameters were observed, then over a period of time comparable with the observation period the parameter will increase. And vice versa, the former tendency to the decrease means, on average, the further decrease of the parameter. This feature of preservation of the tendency of the process evolution is called persistence.

The case with $H < 1/2$ is characterized by antipersistence, namely, the former increase of the parameter means its future decrease and the tendency to the former decrease of the parameter makes its future probable increase.

The behavior of the time series described by Eq. (5) contradicts the properties of statistical series and physical systems that are strictly proved or usually assumed by virtue of their practical evidence. As a rule, the statistical independence of terms of the series is assumed for large periods of time and (or) space, which is a significant component of the concepts on thermal equilibrium.

The persistence (antipersistence) can be used to make a simple and reliable prediction of the further evolution of the process under observation based on the data of its history that, as noted above, explains largely the principal concern to such investigations in recent years.

As mentioned above, in an analysis of various natural processes the lengths of samples, as a rule, are limited. This makes difficult the estimate of reliability of the determined values of the Hurst exponent H. These problems are dramatized by the fact that, for example, hydrometeorological characteristics undergo significant seasonal and diurnal variations. This results in the considerable increase of the spread of points on the plot of the dependence of the normalized span on the time and in the detection of quasiperiodic variations that distort significantly the sought-after dependence. If the physical nature of the process being studied and its regularities are well understood, it is possible to introduce the corresponding corrections, but in most cases this procedure can affect significantly the results of analysis.

Thus, one of the main objects being considered is the result of measurements of the atmospheric optical thickness. Due to the variation of the zenith distance of the sun during the day, the thickness varies regularly, and one of the possible ways for solving the problem is the reduction of all analyzed data to one solar zenith distance (when publishing the results of such measurements, the values of the optical thickness are usually given for the vertical atmospheric column). But simultaneously with the variation of the atmospheric mass, the atmospheric stratification and concentrations of some radiation-attenuating gases and aerosols may vary. It is hardly probable to propose a universal method for taking into account these variations of the atmospheric state. Attempts to correct the measurements may lead to unpredictable consequences. Therefore, when analyzing the measurements of atmospheric transmittance, we used the data obtained during noon hours for slightly varying and practically identical air masses.

Another complicated problem when interpreting the data obtained by this analysis is connected with the fact that in practice in many cases the Hurst constants differ on different time scales. As noted above, it is impossible to evaluate strictly the reliability of the H values obtained for samples of short lengths and it is possible that in some cases this effect is caused by insufficient body of data. However, it often appears that the observed variations of the dependence character are caused by the objective differences in the nature of the process being studied for different time periods.

The measurements of the atmospheric optical characteristics (spectral and integral) – the atmospheric transmittance and optical thickness and its components – have been the focus of attention for atmospheric optics and actinometry and have received wide acceptance. The actinometric (integral) measurements are mass in character. There also exist large arrays of data of spectral measurements, especially in the short-wave spectral range.

Figure 1*a* shows the results of processing by the normalized span method of a part of the experimental data array[6,7] on the spectral atmospheric optical thickness and coefficients of atmospheric and aerosol extinction determined on the basis of these data.

The measurements published in Refs. 6 and 7 refer to the entire atmospheric column and cover the spectral range from 2 to 15 μm; the data presented here refer to the wavelength $\lambda = 2.2$ μm. It is of interest to note that the values of the normalized span of the coefficients of aerosol and atmospheric extinction lie on one curve. It seems that this fact can be considered as one more verification of the importance of aerosol extinction for the formation of the atmospheric optical characteristics. The value $H = 0.78 \pm 0.04$ obtained in analysis testifies that the values of the total atmospheric $\alpha_{\text{ext}}(t)$ and aerosol $\alpha_{\text{aer}}(t)$ extinction are interdependent. It seems that such a conclusion cannot be considered entirely unexpected, because the values of these coefficients under conditions of the real atmosphere cannot vary instantaneously and "remember" prehistory over the preceding period. Based on the data of Fig. 1*a*, this period may change from several hours to several days.

Figure 1*b* shows the results of corresponding processing of a small part of the experimental data array[8] being at our disposal. The extinction components were separated by the methods described in Ref. 9 (it is self-evident that we should check the correctness of the dependence illustrated by the curves in Fig. 1*b* for the aerosol extinction coefficients determined by the method of extinction component separation described in Ref. 8). It should be noted that in analysis of the data providing the basis for the construction of the dependence illustrated by Fig. 1, definite cyclicity with periods from several hours to 3–5 days is revealed. The body of data being analyzed is too limited to argue for confident detection of such periodicity (in this connection, the corresponding data are not considered here in detail), but the fact itself of revealing these variations is not surprising, because analogous effects were frequently observed during microphysical and optical measurements.[10] They are usually interpreted as manifestations of difference in the air masses changing due to the impact of synoptic processes.

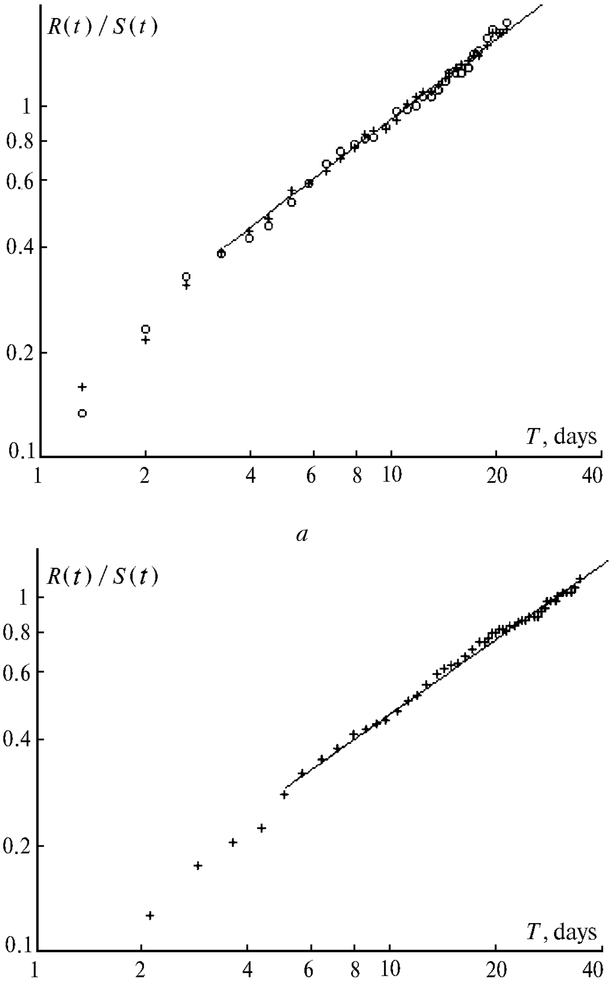


FIG. 1. Time dependence of the normalized span of coefficients of total atmospheric (small circles) and aerosol (small crosses) extinction. Experimental data were taken from Refs. 6 and 7 (a) and 8 (b)

Figure 2 shows the results of analogous processing of pyroheliometric measurements of the spectral transmission of atmospheric column[11] (as in the preceding case, the data are shown here for $\lambda = 2.2$ μm). In this case, the Hurst exponent differs essentially from $H = 0.5$ typical of random process.

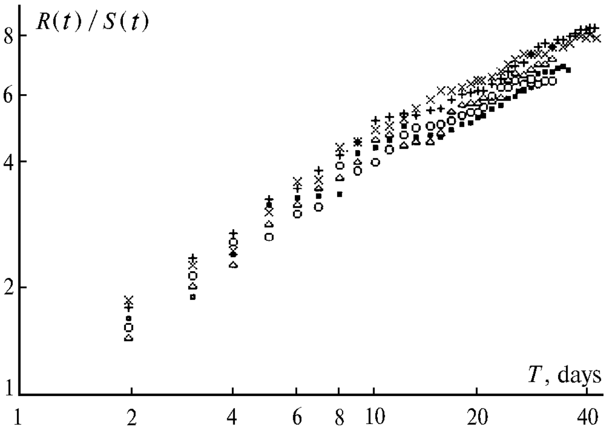


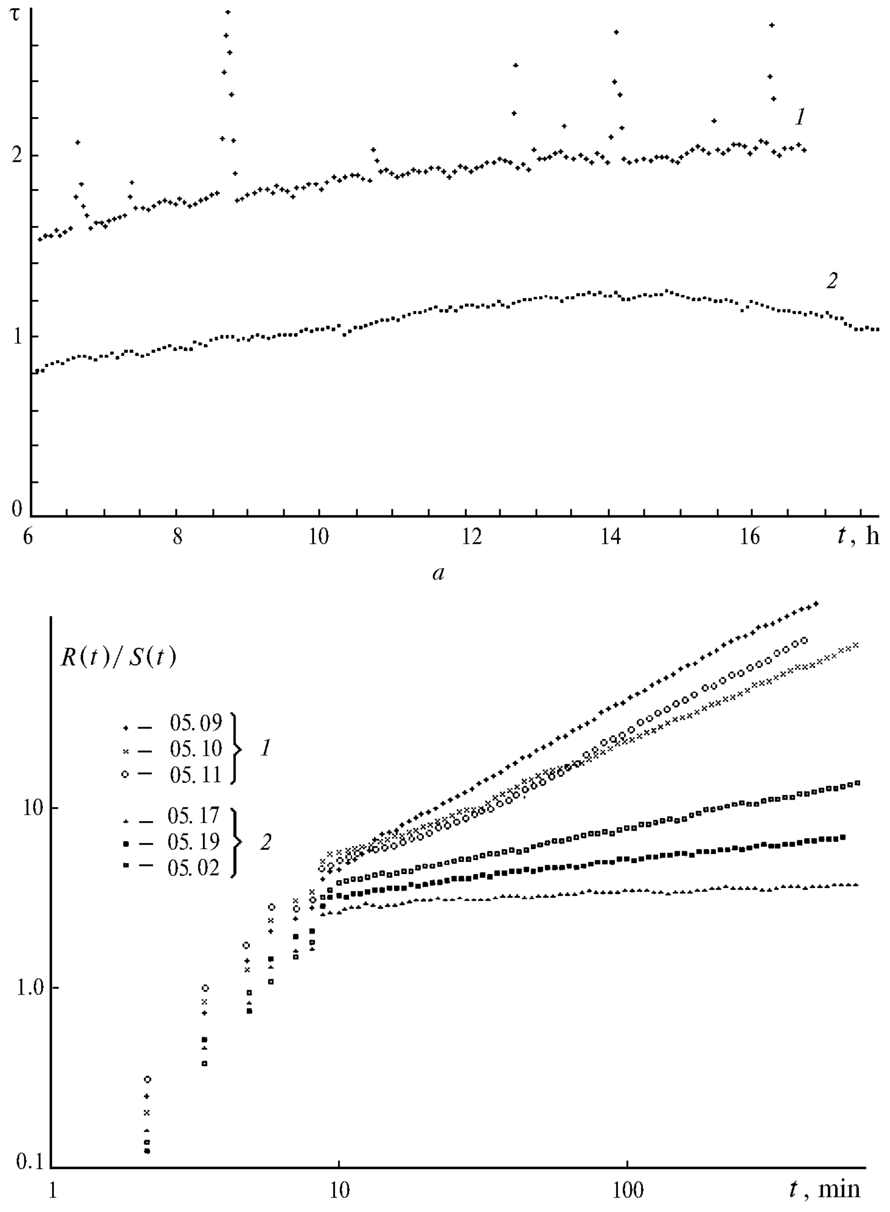
FIG. 2. Time dependence of the normalized span. The experimental data of Smithsonian Institute[11] (pyroheliometric measurements of spectral transmittance of the atmospheric column). Different symbols indicate different years of observation.

The samples used to obtain the results illustrated by the plots from Figs. 1 and 2 were limited in length. In all cases they did not exceed several tens (30–50) of points. Using samples of such lengths, it is difficult to evaluate objectively the reliability of the Hurst exponents. To obtain more significant estimates, the results of actinometric measurements were processed performed in the region of Colima (Mexico) in May–June 1995 with participation of one of the authors.

The directly transmitted solar radiation was measured with the Apply actinometer (UV spectral range) every minute. Thus, about 650–700 readings were obtained in the daytime. The values of the atmospheric optical thickness and its aerosol component were calculated on the basis of the measurements. The data for 12 observation days were analyzed by the normalized span method.

During the measurements the periodic increase of volcanic activity was observed. In Fig. 3*a*, where the measurements are shown for typical days of the period being studied, a clear-cut distinction can be seen between the days with the enhanced volcanic activity and standard conditions. In the first case, against the background, on average, of slightly higher values of optical thickness intense spikes are observed (sometimes a short-time increase by a factor of 1.5–2 is observed).

Figure 3*b* shows the plots of time dependence of the normalized span (note that as distinct from Figs. 1 and 2, Fig. 3*b* is purely illustrative in character; for $t > 10$ min the curves were drawn based on the corresponding conventional symbols that referred to individual observation days and demonstrated the character of the obtained dependences). Taking into account practically complete coincidence of the results for atmospheric extinction and its aerosol component, the curves are shown only for the aerosol component of the optical thickness.



b

FIG. 3. Curves of daytime variations of aerosol component of the atmospheric optical thickness (a) and the corresponding dependences of the normalized span (b) typical of the days with the increased volcanic activity (1) and standard conditions (2).

All the days with the increased volcanic activity can be combined into one group for which the Hurst exponents vary within the range $H \approx 0.60–0.83$, while under the standard conditions $H \le 0.3$.

After superficial analysis of the results obtained, one may assume that they are contradictory, namely, individual samples yield different values of the Hurst exponent. However, taking into account the above-mentioned effect of diurnal and seasonal variations on the Hurst exponent estimates, we believe that different processes are manifested here, characterized by radically different time scales: if the data of Refs. 6, 7, 8, and 10 (see Figs. 1 and 2) refer to the variations of the atmospheric optical thickness due to the change of air masses on which, probably, seasonal variations of the atmospheric aerosol state are superimposed, for the data shown in Fig. 3 the diurnal variations are most important (days under standard conditions) or aperiodic external impacts (volcanic emissions).

Of special interest, in our opinion, is the sharp difference between the values of the Hurst exponent H for the periods of increased volcanic activity and under standard conditions. Most likely this effect is related with the principal difference of the main aerosol sources and spatial distribution of atmospheric aerosols during these periods.

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