SPECIFIC FEATURES OF MANY-YEAR VARIABILITY OF SOLAR RADIATION CHARACTERISTICS OVER WEST SIBERIAN REGION

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In this paper we discuss some regularities of the variation of incoming radiation characteristics based on the data of actinometric stations nearest to Tomsk. It is shown that the general feature of the period from 1959 to 1994 for the region under study is the tendencies toward the increase of the sunshine duration and scattered radiation as well as toward a decrease in the direct solar radiation influx. Together with the trend component, typical is the presence of low-frequency fluctuations due to the change of cloudiness regime. Some individual features of the many-year variability, statistical characteristics, and estimation calculations performed indicate in favor of a gradual increase of the aerosol turbidity of the atmosphere in the region under study (more clearly, in its southern part) and, furthermore, of the gaseous pollution in two regions.

INTRODUCTION

The Institute of Atmospheric Optics is well known for its numerous investigations into the basic problems of atmospheric optics and influence of various factors on the light propagation through the atmosphere. At the same time, before 1992 practically no experimental studies of solar radiation fluxes have been performed at the Institute. However, verification of the radiation models of the cloudy atmosphere developed[1] as well as a number of new research programs and complex experiments have required arrangement of the radiation measurements, and G.A. Titov has played an important role in this activity. Professor Titov was a coordinator of the "Monitoring of Ultraviolet, Visible, and Infrared Radiation Fluxes" subproject as a part of the "Climate and Ecological Monitoring of Siberia" Program.[2] He made a valuable contribution to the development of corresponding studies and, in particular, appearance of the study presented in this paper.

In connection with the radiation measurements to be carried out in Tomsk, it was interesting to analyze, based on the data of nearby actinometric stations, the many-year variability of incoming solar radiation to reveal specific features characteristic of the West Siberia, being a typical region of boreal climatic zone.

When studying the influence of various factors on the formation of radiation regime over the particular area under study, the problem should be solved on distinguishing between the global and local factors of the solar radiation influx variability.

Generalizations on the problem of many-year radiation variations have been drawn based on the data of the USSR actinometric network.[3–9] Together with the importance of the resume of these studies, it should be noted that, because of the variety of interactions in the climatic system, there remain contradictions and hypothetical character in the explanation of interannual variations and trends. Among the basic hypotheses on the “influence,B the following ones are usually being mentioned: the cycles of solar activity, volcanic eruptions, variations of the solar constant, instability of the general circulation of the atmosphere, El Niño phenomenon, change of the anthropogenic impact, and others. Regarding the radiation characteristics, the difficulty of the interpretation results from the lack of continuous series of observations what is essential when isolating the intersecular variability. The most complete analysis of many-year variations of solar radiation until 1970 has been performed by Pivovarova.[3] Characteristics of the trends during the last decades (since 1960 until 1987) have been considered based on the data of 160 actinometric stations throughout CIS.[4] Among the basic conclusions of Ref. 4 we can isolate a decrease of annual sums of the total solar radiation (negative trends in 94% of cases) and direct solar radiation (97% of cases) as well as an increase in the scattered radiation (60% of cases).

The aim of this study is to explain general and specific features of long-term variability of solar radiation characteristics over only one selected region, but on the base of a continuous series of observations (36 years). In so doing, we have also made use of many-year data on sunshine duration (SSD) and assessments of the influence of atmospheric turbidity. We used the results of observations at six actinometric stations: Aleksandrovskoe, Ogurtsovo (Novosibirsk), Eniseisk, Blagoveshchenka, Kuzedeevo, Omsk, as well as data on SSD obtained in Tomsk.[10,11] Geographical locations of these observation sites are shown in Fig. 1.

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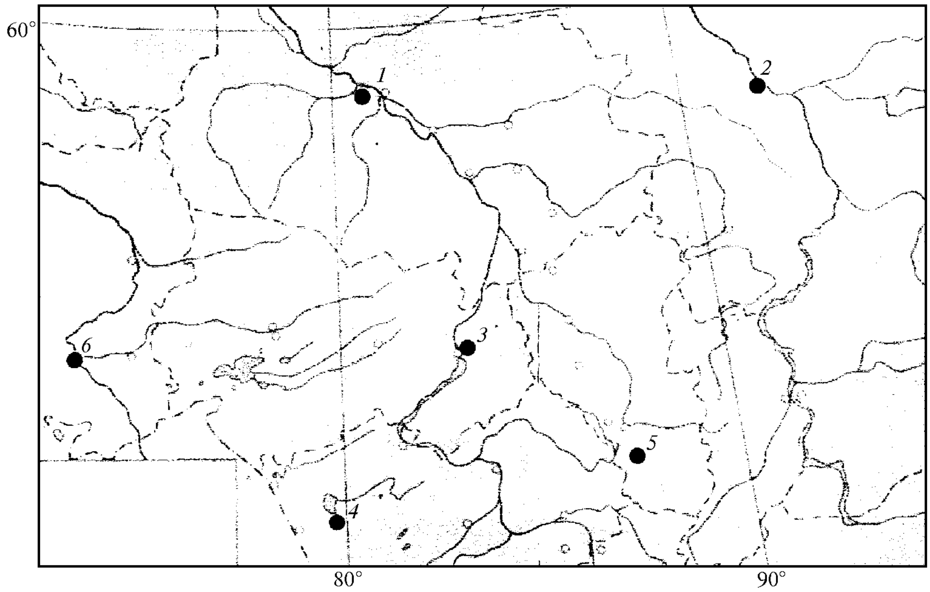

FIG. 1. The map of the West Siberian region and observation sites: Aleksandrovskoe (1), Eniseisk (2), Ogurtsovo (3), Blagoveshchenka (4), Kuzedeevo (5), Omsk (6).

1. MANY-YEAR TRENDS

Annual sum variations and linear trends of the total (Q), direct (S), and scattered (D) solar radiation as well as the SSD (S_s) are shown in Fig. 2. The trend was calculated, following Ref. 4, using approximations of series by linear functions:

$$x = \alpha_0 + \alpha_1\, t; \quad \beta_x = \frac{10\ \alpha_1}{\bar{x}}\ 100\%, \tag{1}$$

where x is the current value of the series component; α_0 and α_1 are the coefficients calculated using the method of least squares; t is the serial number; β_x is the relative intensity of trend (%) that defines the rate of its variations during a decade (see Table I). It should be noted that observational series for Eniseisk and Omsk are shorter than others, therefore in some cases certain differences with the characteristics at other stations can occur.

Significance of the trend was evaluated according to the Student criterion as described in Ref. 12. To achieve compact and simple presentation, the statistically significant trends with the confidence of 90% are marked with bold type, and those with 95% confidence are additionally underlined.

The simplest of the characteristics considered (SSD) is primarily determined by cloudiness, while being dependent on the atmospheric transparency only in exceptional cases (in the presence of fogs and mists). As follows from Fig. 2, the tendency of increase in the annual sum S_s is typical of the SSD and more pronounced in Tomsk and Kuzedeevo regions. Of course, significance of the trend at some stations is insufficient, but the tendency is the same. Therefore, a common feature for this region during the last 36 years was, to a certain degree, the gradual decrease of cloudiness and, as a result, an increase of SSD.

TABLE I. Relative intensity of the trend (β, %) for several regions (denotes short-period observation series; bold-type values denote significant trends (90% level); bold-type and underlined values correspond to the more than 95% confidence level).*

β_x	Period	Aleksandrovskoe	Eniseisk*	Ogurtsovo	Blagoveshchenka	Kuzedeevo	Omsk* (S_s – Tomsk)
β_{S_s}	Year	**2.33**	–	0.26	0.70	**3.78**	**4.02**
	Summer	**4.51**	–	1.35	0.02	**4.39**	**3.98**
	Winter	**−6.34**	–	−3.70	−9.28	0.61	6.64
β_S	Year	−1.68	−5.24	**−2.61**	**−6.79**	**−6.26**	**−7.93**
	Summer	2.82	−6.40	−0.34	**−4.67**	**−5.87**	**−5.31**
	Winter	−13.16	10.27	−7.60	**−15.78**	**−9.05**	−4.14
β_D	Year	1.35	**8.19**	**4.74**	**2.05**	**−4.95**	**8.14**
	Summer	0.91	**11.02**	**3.31**	1.33	**−3.51**	**6.86**
	Winter	0.83	−7.80	**7.04**	−0.11	**−7.85**	**7.72**
β_Q	Year	−0.15	1.95	1.01	**−2.77**	**−5.61**	−0.02
	Summer	1.97	1.76	1.22	**1.99**	**−4.85**	0.03
	Winter	−3.59	−2.94	2.13	**−5.74**	**−8.25**	3.69

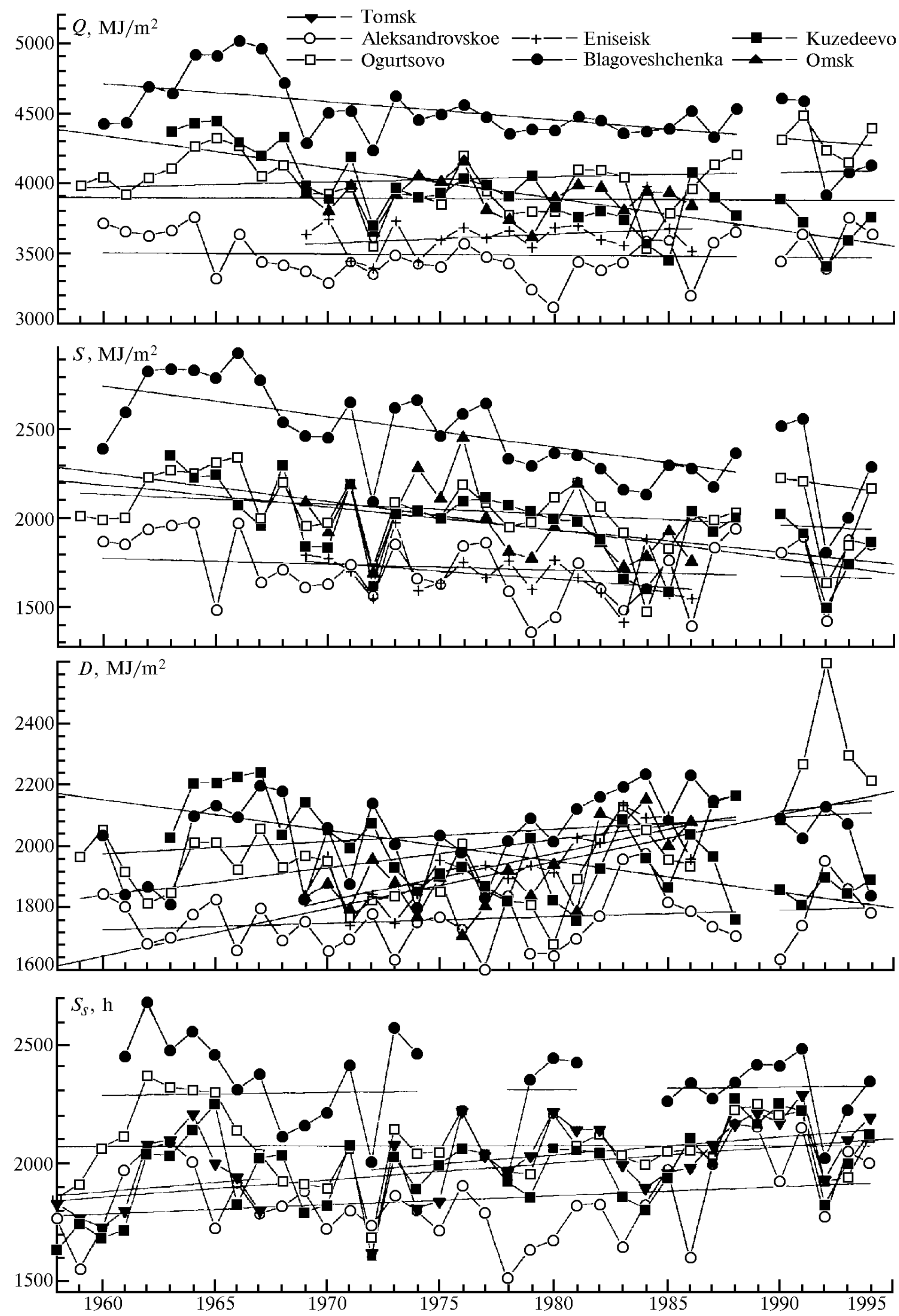

FIG. 2. Annual sums and linear trend of SSD and radiation characteristics: S, D, and Q.

The increase of SSD had to result in an increase of the annual sums S, other conditions being the same. However, in reality, a negative trend was observed at all stations. Moreover, a decrease in S is more significant in the southern regions with a well-developed industry. At the same time, it should be noted that scattered radiation has increased during the same period (except for the region nearby Kuzedeevo in the highlands to the south of Novokuznetsk).

It is characteristic of the many-year variability of the total solar radiation that its tendencies are very nonuniform over the region under study. Thus, in the northern part of the region the opposite effects of S and D radiation cancel each other and, as a result, there were no significant variation of the total solar radiation there. We can say about a significant trend only in the cases of Blagoveshchenka and Kuzedeevo stations. During this period marked decrease of the total radiation influx was observed in these regions. For example, the parameter Q in Kuzedeevo region has varied from ~ 4400 MJ/m^2 in the late fifties down to 3600 MJ/m^2 in the mid nineties and became comparable with that in the most northern region – Aleksandrovskoe. It would be logical to connect the differences in trends and the above-mentioned contradiction between the behavior of S and S_s with some specifically local features in variations of aerosol and gas composition of the atmosphere. An attempt of making such an explanation will be presented below, but first let us consider other regularities of the solar radiation variations.

2. LOW-FREQUENCY FLUCTUATIONS

Together with specific features of solar radiation variability in several regions, we can note some general local minima – short periods of an abrupt decrease in SSD. More evidently this manifests itself in the values averaged for each station and normalized to the mean (see Fig. 3). In this case, local features of the SSD variation are smoothed, while the general features of a region become better distinguishable. The main minima in the SSD behavior were observed in 1960, 1972, 1978, and 1992, and the less pronounced one was observed in 1975. Such a behavior of the SSD was an evident consequence of the presence of analogous minima in the annual sums of Q and S (see Fig. 2) and the maxima for the scattered radiation. It is more difficult to reveal the sources of short-duration decrease of the radiation or increase of cloudiness during the above-mentioned years. In any case, no direct influence of the volcanic eruptions, for example, has been revealed. As follows from Fig. 3, which presents the dates of most powerful volcanic eruptions, only in one case a decrease in S_s, Q, and S was observed one year after the Mt. Pinatubo eruption. It should be explained that the conclusion drawn does not contradict the evident influence of volcanic and anthropogenic activity on the direct solar radiation at clear sky[3,7,8] that depends only on the atmospheric transmittance. The situation is quite different in the cases with actual annual and monthly sums of direct solar radiation and, especially, the Q and D radiation. In this case the cloudiness plays the foreground role in variations of the radiation influx, while the influence of turbidity characteristics of the atmosphere is masked. Surely, this does not exclude a more complicated influence of volcanoes via possible changes in the general circulation and other processes.

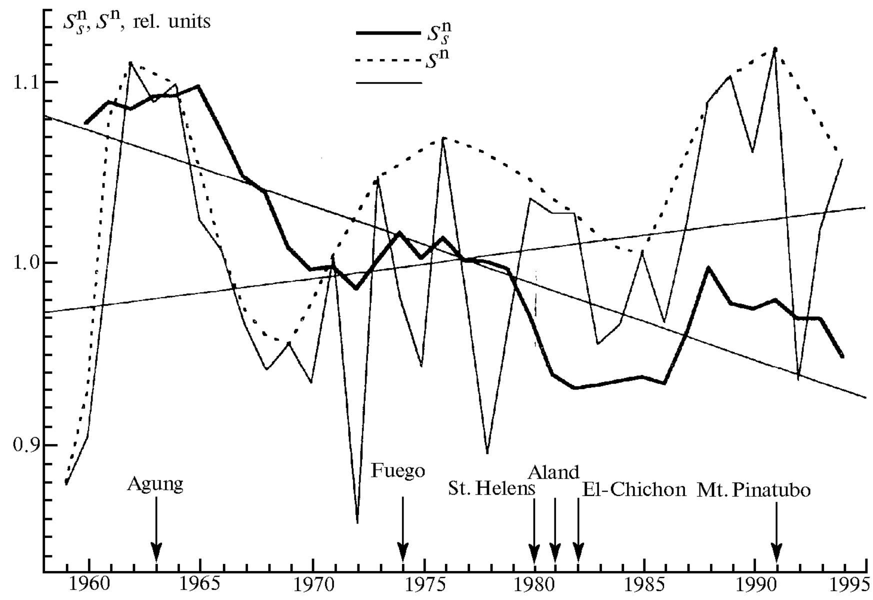

FIG. 3. Relative variation of SSD and direct solar radiation averaged for the region under study. (Arrows show the most powerful volcanic eruptions.)

We can reveal another one low-frequency component in the many-year behavior of S_s (three waves with maxima in 1962, 1976, and 1991), if we exclude the short-period minima and plot the envelope curve (see Fig. 3, dotted curve). Similar fluctuations with the periods of 10 to 16 years appear in the radiation characteristics. We can isolate the low-frequency component using the method of moving average. As an example, in Fig. 3 we present relative variation of the direct solar radiation in the region under study resulting from calculation of the normalized values of S for every observation site, followed by determination of the relevant mean behavior with applying the moving average (7-year long window). As can be seen from this figure, the long-period waves and the tendency toward a decrease in S are the common features for this region.

Earlier, Pivovarova has analyzed this problem and revealed a relation of the radiation fluctuations to the change in the general circulation (zonal and meridional transport).[3] Therefore, there is a reason to suppose that in the years later on the long-period fluctuations and irregular "short-period" decreases in S, Q, and S_s, as well as an increase of D were connected with the disturbances in the general circulation and corresponding variations of the cloudiness regime in the atmosphere.

The presence of low-frequency waves, we have discussed above, makes difficult the correct isolation of the trend at the insufficient series of observation data. In this connection, the negative trend of Q and S calculated in Ref. 4 seems to be far overestimated. The end of the period analyzed (1987) is in the minimum of the low-frequency wave before the next increase in the radiation characteristics. Therefore, negative trends of Q revealed in Ref. 4 can be, to a considerable degree, a result of the processing technique used, but not of the natural origin. In our case we discuss a longer observation series (including the third wave), and the estimations made are more realistic.

3. SEASONAL FEATURES

In order to estimate seasonal differences in variation of the solar radiation for the last forty years, we have analyzed sums for summer (June to August) and winter (December to February) seasons (see Table I). Without going into details, below we will describe the most general features.

Let us first note that specific weight of the SSD value and radiation influx in winter is essentially weakened due to astronomic factors such as lower sun's altitude and day-time duration as compared to those in summer. The above feature of radiation characteristics manifests itself in the trends, as well as in low-frequency fluctuations. As a consequence, in most cases (various regions and radiation characteristics) the interannual behavior of summer sums agrees with the annual ones and, in fact, determines the latter. The manifestation of this fact is more characteristic of Q and S_s. As an example of these differences we can present data on the mean values of three-month sums of Q at Aleksandrovskoe station: 1631.5 MJ/m^2 in summer and 167.9 MJ/m^2 in winter.

The tendency of the many-year variation of SSD during different seasons has a common regularity for the region under study. Typical for all the stations are an increase of S_s (decrease of cloudiness) in summer time and, as a rule, its decrease in winter time that reduces the positive trend in the annual sums.

Behavior of the direct solar radiation is practically identical at all stations in both seasons – S gradually decreases. Therefore, this tendency can be considered as a general feature for the entire region and main seasons.

The many-year winter-time variation of scattered radiation at different stations is contradictory. Apparently, local features of variations of the atmospheric transmittance and albedo are the factors that mainly influence the behavior of D radiation in winter. A trend of the scattered radiation in summer is positive (except Kuzedeevo), that define analogous behavior of the annual sums of D.

4. STATISTICS AND CORRELATION

Additional information on the specific features of radiation regime can be obtained from the statistical characteristics that are given in Table II. It can be seen that behavior of the mean, maximum, and minimum values of S_s, S, D, and Q has clear latitude dependence – a decrease in the values from the south to the north. Violation of a rule is observed only at Kuzedeevo station, where the values of all characteristics are too low, being comparable with the ones observed at more northern station of Ogurtsovo. This fact has been noted in earlier period (before 1964, in Ref. 9) and was related to the specific conditions of the mountain area.

TABLE II. Statistics of the annual sums of radiation (MJ/m^2) *and SSD* (hours). *(* is for short-period series).*

Station, parameter	Mean	min	max	RMS	V, %
Aleksandrovskoe:					
Q	3495	3114	3767	159	4.54
S	1727	1369	1985	178	10.33
D	1769	1608	1985	93	5.28
S_s	1858	1519	2180	169	9.12
*Eniseisk:					
Q	3629	3400	3990	132	3.64
S	1686	1427	1982	130	7.73
D	1943	1746	2140	108	5.56
Ogurtsovo:					
Q	4042	3545	4499	215	5.31
S	2050	1484	2345	185	9.01
D	1991	1684	2603	177	8.88
S_s	2087	1691	2369	143	6.87
Blagoveshchenka:					
Q	4506	4082	5024	223	4.95
S	2459	1943	2927	245	9.95
D	2047	1798	2240	131	6.39
S_s	2684	1937	2684	249	9.27
Kuzedeevo:					
Q	3941	3426	4451	264	6.69
S	1965	1515	2349	207	10.53
D	1975	1769	2244	133	6.75
S_s	1988	1614	2278	165	8.29
*Omsk:					
Q	3896	3622	4166	135	3.46
S	1980	1691	2453	205	10.36
D	1916	1712	2158	125	6.53
Tomsk: S_s	2017	1627	2304	168	8.32

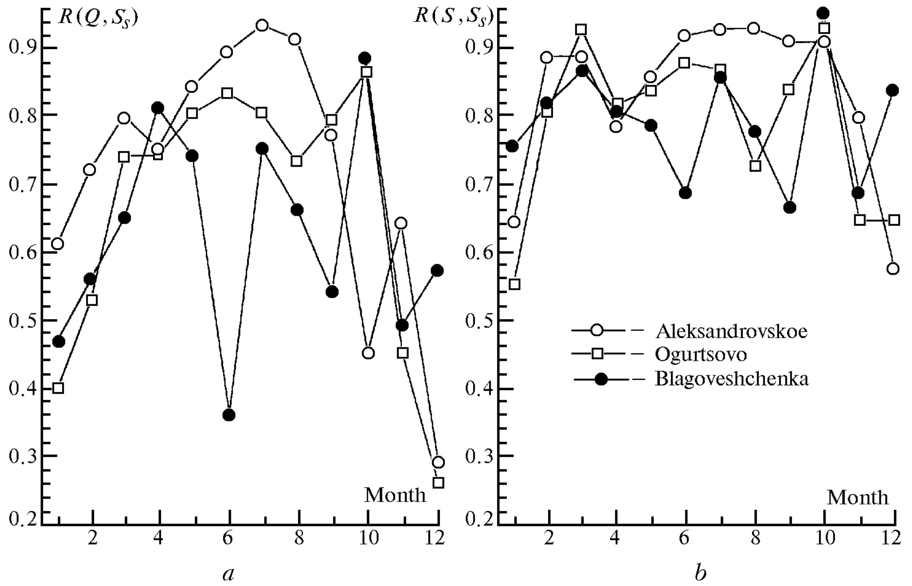

FIG. 4. Coefficients of S_s correlation with total (a) and direct (b) solar radiation.

To a certain degree, the latitude dependence manifests itself in the standard deviation. Therefore, to estimate variability of the values characteristic of several regions, it would be more correct to compare relative values such as the coefficient of variations V. As can be seen from Table II, maximum variations (about 10%) are characteristic of the direct solar radiation (for SSD those are slightly lower). Total solar radiation is characterized by low variability ($V \approx 5\%$). However, it is more important to underline a significant difference in variations (especially, of Q and D) between rural (Aleksandrovskoe and Eniseisk) and urban areas (Kuzedeevo in Kuzbass, Blagoveshchenka between Pavlodar and Barnaul, and Ogurtsovo near Novosibirsk). For example, coefficients of variation of total solar radiation V_Q are from 3.6 to 4.5% in the rural areas and from 5 to 10.5% in the regions with well-developed industry.

It is well known that Q and S radiations are in a close relation with the cloud fraction and SSD (Refs. 3, 13, and 14). Analysis of cross-correlation coefficients of the monthly sums of Q, S, and S_s (Fig. 4) has confirmed the presence of interrelationship with maximum values during warm season. However, another conclusion is more interesting, which is not so trivial. An important feature is that high correlation occurs (except for October) for the “backgroundB station of Aleksandrovskoe in comparison with other regions. Evidently, this is a result of additional and higher fluctuations of the atmospheric transmittance (non-correlated with S_s) in the urban areas. This fact, together with the above-mentioned ones, allows us to draw an evident conclusion that some general and individual regularities of the radiation variation are related to variations of the air pollution of both natural and anthropogenic origin.

5. INFLUENCE OF THE ATMOSPHERIC TRANSMITTANCE

Let us consider what variations of the atmospheric turbidity factors (aerosol, contaminating gases) could cause the differences in the dynamics of radiation regimes over individual regions. Unfortunately, short-period series (about 20 years) of data on aerosol optical thickness (AOT) and practical absence of relevant observations in the region under study do not enable, in this case, to use the results obtained (the only station that observes the AOT is situated in Omsk – at the boundary of the region under study). As to the contaminating gases, from the viewpoint of duration and regularity of observations, the situation is much worse. Therefore, let us use indirect estimations. The ratio of direct solar radiation to the scattered radiation measured at particular Sun elevation angles under clear sky is often used as an indicator of AOT variation and, consequently, of the atmospheric transmittance. It is practically impossible to show interrelationship between the transmittance and more complex characteristics, such as diurnal and annual sums of the radiation in a strictly analytic form, because too many factors are needed to be taken into account in that case. At the same time, from the standpoint of general considerations it is clear that, if we consider a simple case without seasonal and diurnal redistribution of the cloudiness or turbidity characteristics, then the sums of direct solar radiation are in proportion to SSD as well as to the aerosol and gas components of the atmospheric transmittance: $S \sim T_a T_g S_s$. If we take into account the tendency toward an increase in the scattered radiation at the increasing cloud fraction[13–15] (except for the case of overcast) and scattering by aerosols and the inverse absorption dependence, using analogous approach, we obtain another approximate expression: $D \sim T_g/(T_a S_s)$. So for the ratio and product of S by D we can write the following:

$$S/D \sim (T_a S_s)^2, \quad (2)$$

$$S D \sim T_g^2 . \quad (3)$$

Moreover, the former expression characterizes the integrated effect of the cloudiness and aerosol scattering, while the latter describes only the absorption by the atmosphere. In order to compensate for the influence of cloudiness, it is necessary to normalize equation (2) to the value of S_s.

Let us note that in this case it is not principle what kind of the functional dependence occurs (moreover, these equations have been derived based on the qualitative reasoning). It is more important that we can judge the influence of transmittance components T_a and T_g on the radiation based on ratio between the sums of S and D radiation.

To trace the tendency of scattering and absorption variation at different sites from year to year, let us carry out normalization to the radiation characteristics occurring in the initial period (1959). Then we obtain two relative values of γ, which can be considered as qualitative indicators of the variation of the atmospheric pollution:

$$\gamma_{scat} = \frac{[S/D\, S_s]_i}{[S/D\, S_s]_{1959}} = f(T_a), \quad (4)$$

$$\gamma_{abs} = \frac{[S\, D]_i}{[S\, D]_{1959}} = f(T_g). \quad (5)$$

Thus, omitting mathematical details of the functional relation $f(T)$, we can assume that a decrease (or increase) of γ parameters indicates the same tendency in variation of the atmospheric transmittance components.

Estimations made on the basis of calculated values of γ_{scat} (Fig. 5) indicates the tendency to decrease in T_a (or increase of AOT), including the practically background station of Aleksandrovskoe. Such a behavior of aerosol component accounts for the decrease of direct solar radiation influx, as well as for an increase of scattered radiation, thus removing contradictions between time behavior of S_s and S (a decrease of T_a is found to be more important for S than an increase of SSD). Let us also notice that the tendency of increasing aerosol scattering is a general feature for the region (it is not improbable that it is of a global character).

From the behavior of the second parameter, γ_{abs}, it follows that variations observed at Aleksandrovskoe and Ogurtsovo stations are not very large, but those observed at Blagoveshchenka and Kuzedeevo stations showed a significant increase of the absorption of solar radiation. The latter circumstance well agrees with the enhanced anthropogenic influence of the Kuzbass industrial zone. The data of ecological airborne surveys of the atmosphere performed over Pavlodar–Blagoveshchenka and Kemerovo regions also confirm this fact. It is interesting to note that a decrease in the transmittance owing to the absorption in Blagoveshchenka and especially Kuzedeevo well accounts for the causes of negative trends in the scattered and total solar radiation (see Table I and Fig. 2). At the increase of only aerosol component T_a, the pattern would be different – decrease of S, increase of D, and inessential variation of the total solar radiation.

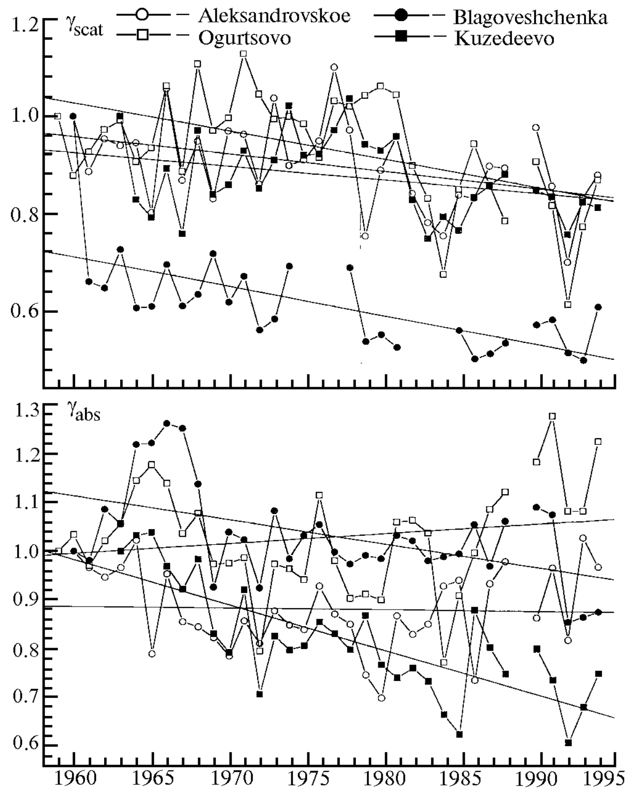

FIG. 5. The many-year variability of γ_{scat} and γ_{abs} parameters for four stations of the region.

CONCLUSIONS

Analysis of the many-year variation of the radiation characteristics of the atmosphere made based on the data collected over West Siberia enables us to draw the following conclusions:

1. During the period under study (1959–1994) the following general tendencies have been revealed:

– an increase of the annual sums of SSD owing to a decrease in the cloud fraction in summer (in winter the opposite tendency was observed);

– an increase of scattered radiation and decrease of direct solar radiation under the influence of the enhanced aerosol turbidity of the atmosphere.

2. The general regularity is irregular short-period decreases of the annual sums of S_s, S, and Q (but increase of D), as well as the low-frequency fluctuations with714-year period, which are caused by

the change of the atmospheric circulation regime and cloudiness.

3. Estimations of γ_{scat} and γ_{abs} as well as some other indirect factors explain local features of the radiation regime by differences in the aerosol–gas contamination:

– variations of the total solar radiation influx due to the aerosol over Aleksandrovskoe and Ogurtsovo regions were inessential (direct solar radiation has decreased, when the scattered one has increased).

– essential increase of the absorption component T_g of transmittance over Blagoveshchenka and Kuzedeevo resulted in an additional decrease of S and changed the tendency in the behavior of D, that resulted in a general decrease in the solar radiation influx.

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