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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Variability of Sunlight Duration in Tomsk in 1961–2018

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Abstract—Variations in the sunlight duration (SLD) in Tomsk are analyzed for the period from 1961 to 2018 and separately for 1961–1990 and 1981–2010. Data on clouds and total solar radiation obtained at the TOR-station of IAO SB RAS in 1996–2018 are used. The actual long-term monthly mean SLD ranges from 44 h in December to 317 h in June–July. The analysis of the long-term variation in SLD shows its increase from 1961 to 1989 and its decrease starting from 1999 due to an increase in the low cloud cover and high frequency of continuous clouds. The SLD in Tomsk in the modern period has increased relative to the historical period. Regression equations between SLD and the total solar radiation (Q) are derived.

Keywords: atmosphere, duration, radiation, regression, sunlight

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INTRODUCTION

Solar radiation is the source of energy for almost all natural processes on Earth, one of the main climate-forming factors, and the renewable energy resource of the planet [1–3]. Therefore, studies are being carried out on incoming solar radiation both across the globe [4–7] and in individual regions [8–12]. As a result of these studies, global patterns of the Earth's radiation budget variability and its regional features are ascertained. The latter require further study, which is especially relevant in the changing climate [13, 14].

Potential solar energy resources for the Tomsk region (TR) were assessed in [15] based on measurements at meteorological and actinometric stations until 1970. It was shown that the frequency of clear sky (the cloud amount is 0–2) did not exceed 10% from October to March and 20–26% in other months, and the frequency of cloudy sky (the cloud amount is 8–10) was 51–79%. The average sunlight duration (SLD) varied from 1514 to 1846 h, and the actual annual SLD was 35–41% of the possible SLD (SLD is a period of the day when the Sun is above the horizon, not covered by clouds, fog, mist, etc., and its direct rays illuminate the surface).

During the year, the monthly total radiation maximum under clear sky falls in June, when Sun's altitude is the highest. Based on the above results, three zones with different potential solar energy resources were identified in the TR: zone I with a resource of 1100–1200 kWh/m^2; zone II with 1000–1100 kWh/m^2, and zone III with 900–1000 kWh/m^2. In recent decades, new trends in changes in the radiation parameters of the atmosphere have been outlined; therefore, it is advisable to carry out studies with the use of more recent data.

The Tomsk region is located in the temperate latitudes of the Northern hemisphere, in close proximity to the geographical center of Asia. This circumstance has a decisive effect on the formation of its climate. The TR climate is transitional from the temperate continental of the East European Plain to the sharply continental of the East Siberia. The long extent of the TR from south to north causes significant changes in the time of sunrise and sunset and in the daylight duration during the year. Since 1991, the number of actinometric stations in this territory has significantly decreased. However, SLD measurements are carried out at many remaining meteorological stations. The correlation between the SLD and the solar radiation [16] allows one to use these data to calculate the sums of total radiation taking into account the latitude, Sun declination, and cloud amount in areas not provided with actinometric observations.

In this work, we analyze a change in the SLD in Tomsk from 1961 to 2018 and derive the regression equations between the SLD and the total solar radiation (Q).

SOURCE DATA

The information from the World Data Center (http://meteo.ru/data) on the SLD for 1961–2018, as well as for the periods 1961–1990 and 1981–2010, recommended by WMO as historical and current base periods for calculating the "historical" and "current"

Table 1. Possible SLD in Tomsk (56°29′52″ N, 84°58′28″ E)

Parameter	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Possible SLD	7 h 28 min	9 h 31 min	11 h 43 min	14 h 10 min	16 h 21 min	17 h 42 min	17 h 10 min	15 h 13 min	12 h 51 min	10 h 10 min	8 h 14 min	6 h 53 min
Sunrise	09:46	08:49	07:38	06:16	05:07	04:30	04:51	05:49	06:51	07:51	08:58	09:49
Sunset	17:14	18:21	19:22	20:26	21:28	22:12	22:02	21:03	19:42	18:22	17:13	16:42
Sun altitude, deg	128	20.9	31.8	43.7	52.8	57.3	55.6	48.2	37.1	25.6	15.6	10.7

norms of meteorological parameters, is involved. The cloud data are used to analyze the SLD variability, and the data on the total solar radiation measured at the TOR station of the V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS) [17], in 1996–2018 are used for the regression analysis.

It is important to note that the SLD is affected by changes in the cloud regime and atmospheric transparency (in addition to astronomical factors) in real conditions. Therefore, based on the SLD measurement data, the relative SLD is calculated as a percentage ratio of the SLD observed to the possible SLD. The SLD maximum is determined by astronomical factors (the Sun declination and angle and the geographical latitude of an observation site) and characterizes possible SLD; it is an indicator of sunshine for any region. Table 1 shows the values of possible SLD in Tomsk on the 15th day of each month, which we use in the analysis. During the year, the possible monthly SLD varies from 214 h in December to 525 h in June–July. Although the main factor of the annual variation in the SLD is the daylight duration, the features of the actual variation are largely caused by the cloud regime.

As has been previously shown [18], the percentage of clear sky in the daytime does not exceed 9% in Tomsk. Clouds are observed in other times: low clouds in 56% of cases, middle clouds in 49% of cases, and high clouds 74% of cases. Regardless of the season, the most common are middle (*As* + *Ac*) and high (*Ci* + *Cs* + *Cc*) clouds. The frequency of other clouds shows a pronounced seasonal dependence: the maximum of towering clouds (54%) falls in the summer period when convective processes are predominant, while (*St* + *Sc*) clouds occur most often in the fall (27%). In September–November, the frequency of continuous low clouds is 31%.

RESULTS

The SLD measurement processing results are presented in Table 2 for different time periods. One can see that the long-term average monthly SLD varies from 44 h in December to 317 h in June–July. The cloudiest month in Tomsk is December: the average relative SLD is 21%, the minimal SLD are 10 h (1998) and 13 h (2015), and the maximal SLD is 109 h (2005). January is the next month in order of cloudiness: the minimal SLD is 19 h (1966), the maximum is 151 h (2016), and the relative SLD is 30%. The coefficient of SLD variation in December–January (42–44%) is maximal over the year. The period from April to August is the sunniest in Tomsk: the average SLD attains 53–60%, and the maximum, 75–80% of the possible SLD; the maximal SLD (433 h) was recorded in July 1981, and minimal (318 h), in April 1990.

Cloudiness is the main factor of interannual changes in the SLD. Figure 1 shows long-term changes in the annual SLD and cloudiness.

As can be seen from Fig. 1, the SLD increased until 1989, and the opposite trend has been observed since 1999. The SLD in Tomsk has currently increased relative to the historical period. The annual average SLDs in 1996–2018 were 5% higher than the historical

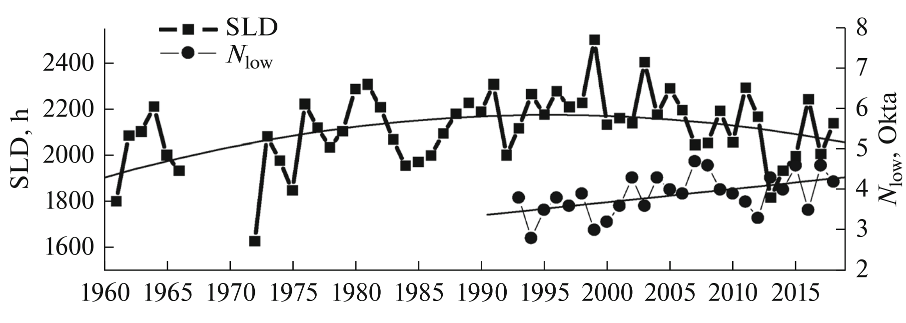

Fig. 1. Long-term changes in the low cloud amount and annual SLD.

Table 2. Statistical characteristics of the monthly SLD in Tomsk

Parameter	Month												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
1961–2018													
SLD, h	69	108	180	226	272	317	317	256	170	93	55	44	2115
V, %	42	25	21	15	17	14	13	17	24	28	34	44	7
SLD_{min}, h	19	53	102	144	167	223	194	165	79	36	27	10	1626
(year)	(1966)	(2014)	(2001)	(1985)	(2013)	(1995)	(2016)	(1978)	(1992)	(1972)	(1966)	(1998)	(1972)
SLD_{max}, h	151	166	277	318	387	433	420	334	266	153	116	109	2500
(year)	(2016)	(1996)	(1998)	(1990)	(1999)	(1981)	(1998)	(1995)	(2016)	(1981)	(1981)	(2005)	(1999)
SLD, %	30	41	49	53	54	60	60	55	44	29	22	21	47
SLD_{min}, %	8	20	28	34	33	42	37	35	21	11	11	5	36
SLD_{max}, %	65	63	76	75	77	82	80	72	69	48	46	51	56
1961–1990													
SLD, h	57	104	169	224	258	314	316	256	173	87	52	41	2064
d, %	−17	−4	−6	−1	−5	−1	0	0	2	−7	−6	−9	−2
SLD, %	25	39	46	53	51	60	60	55	45	27	21	19	46
Δ, %	−5	−2	−3	0	−3	−1	0	0	1	−2	−1	−2	−1
1981–2010													
SLD, h	71	113	188	226	289	319	321	269	165	100	60	48	2170
d, %	4	5	5	0	6	1	2	5	−3	7	9	8	3
SLD, %	31	43	52	53	57	61	61	58	43	31	24	22	48
Δ, %	1	2	2	0	3	0	1	3	−1	2	2	2	1
1996–2018													
K	0.86	0.72	0.78	0.82	0.84	0.81	0.76	0.83	0.93	0.76	0.71	0.81	0.55

d is the relative difference between the SLD in individual periods (1961–1990 and 1981–2010) and the full period (1961–2018) of observations with respect to the SLD of the full period; Δ is the corresponding difference between the SLD of individual and full periods; *V* is the variation coefficient; *K* is the correlation coefficient between the SLD values and the monthly total radiation.

norm. However, no significant growth of the SLD relative to the current base period is observed [18]. Figure 1 also shows the annual average low cloud amount from 1996 to 2018. The trends in these two parameters are opposite. The decrease in SLD since 1999 is due to an increase in the low cloud amount and a high frequency of continuous clouds (up to 30%). The same effect was noted in other works [19–21].

The increase in the cloud frequency is probably due to the feedbacks postulated by M. Kulmala et al. [22–24]. The essence of the postulate is that an increase in the CO_2 concentration increases the temperature and plant productivity, which stimulates the emission of volatile organic compounds and increases the cloud condensation nuclei concentration and cloudiness. This hypothesis of partly confirmed by work [25].

The correlation between SLD and solar radiation allows the use of SLD data in calculation of the total solar radiation. Earlier [16], techniques for estimating the monthly total solar radiation from observations in 1960–1980 using the absolute SLD and taking into account the altitude of the midday sun were developed. The authors of [15] derived the multiple regression equation for three variables which connect the annual total radiation, latitude, and the annual SLD; the annual total radiation error did not exceed 3–4% for the Tomsk region. Since new trends in variations in the radiation and meteorological parameters of the atmosphere appeared in recent decades [26–28], we have compared the monthly total radiation measured at the TOR station of IAO SB RAS and the SLD for Tomsk in 1996–2018 (23 cases). A quantitative correlation between these parameters in this period is revealed (Table 3). Figure 2 shows, for example, the relationship between the SLD and the monthly total radiation in September.

Regression equations with coefficients *a* and *b* were derived in [29] for daily and monthly *Q* and SLD for Moscow based on observations at the Meteorological Observatory of Moscow State University from 1955 to

Table 3. Coefficients in the regression equation $Q = a\text{SLD} + b$ for monthly Q and SLD

Coefficient	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
a	0.402	0.455	0.689	1.230	1.260	1.085	0.847	1.028	0.967	0.688	0.519	0.342
b	45.37	104.55	191.04	153.22	201.85	273.74	335.46	208.97	120.66	75.85	41.24	30.09
R^2	0.861	0.722	0.784	0.820	0.844	0.807	0.756	0.829	0.929	0.763	0.708	0.808

Coefficient a shows how much the total radiation income increases with a change in the SLD per unit time; b is the monthly total radiation under the cloudy sky (i.e., the sum of scattered radiation).

Table 4. Comparison of measured and calculated monthly total solar radiation

Parameter	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1996–2018												
Q_1	79.7	156.7	319.2	435.7	556.0	621.0	599.0	469.6	284.2	143.2	71.8	47.4
Q_2	56.7	138.2	281.1	422.5	548.0	622.1	596.7	479.3	315.1	170.3	70.3	27.7
d, %	29	12	12	3	1	0	0	−2	−11	−19	2	42
2018												
Q_1	90.4	164.0	324.3	382.9	415.5	582.9	606.7	491.5	268.9	152.3	69.0	66.7
Q_2	67.8	147.3	284.4	366.8	432.4	613.8	632.3	504.4	316.9	185.9	59.5	51.4
d, %	25	10	12	4	−4	−5	−4	−3	−18	−22	14	23

$d = (Q_1 - Q_2)/Q_1 \times 100\%$, Q_1 are the measured and Q_2 are the calculated data.

2017, as well as a formula for the monthly total integral radiation at any site and at any time of the year, which takes into account the dependence of the coefficients a and b on the Sun altitude at apparent noon under the assumption that the average cloud parameters change little in space:

$$Q_{\text{month}} = (\sin h + 0.37)\text{SLD} + 373.3\sin h - 55,$$

where SLD is the average SLD over the period under study; h is the midday Sun altitude on the 15th of the month.

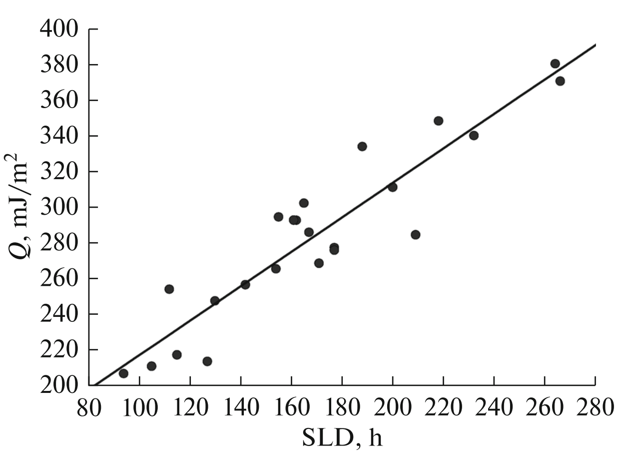

Fig. 2. SLD–monthly total radiation dependence.

The comparison between the total radiation values observed and calculated by this formula for 1996–2018 for Tomsk showed that the differences between them are less than 5% from April to August and increase to 40% in the winter months (Table 4).

If we use the ratios for each specific month to calculate the total radiation, then the differences in the winter months are reduced and make up from 10 to 25%. Table 4 includes, for example, the calculations for 2018. Thus, in the Tomsk region, the formula suggested in [29] can be used only in the spring–summer period, when the frequency of the cloudy weather is insignificant and the probability of the partly sunny weather is high.

CONCLUSIONS

The study showed that the possible monthly SLD in the Tomsk region can vary from 214 h in December to 525 h in June–July. The actual long-term average monthly SLD varies from 44 h in December to 317 h in June–July. The coefficient of SLD variation in December–January (42–44%) is maximal over the year. The sunniest period in Tomsk is from April to August. In this time, the average SLD attains 53–60%, and maximal, 75–80% of the possible SLD. The maximal SLD (433 h) was recorded in July 1981, and minimal (318 h), in April 1990.

The analysis of the long-term variation in the SLD showed its increase from 1961 to 1989 and decrease since 1999 due to an increase in the low cloud amount and a high frequency of continuous clouds (up to 30%).

The SLD has been currently increased in Tomsk as compared to the historical period. The average annual SLDs for 1996–2018 are 5% higher than the historical norm.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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