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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Solar Radiation Measurements at the Fonovaya Observatory: Part II: Results from 2021 Measurements

B. D. Belan[a], *, G. A. Ivlev[a], **, A. V. Kozlov[a], D. A. Pestunov[a], T. K. Sklyadneva[a], and A. V. Fofonov[a]

[a] *V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, 634055 Russia*

**e-mail: bbd@iao.ru*

***e-mail: ivlev@iao.ru*

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Abstract—Ground-based measurements at the Fonovaya Observatory in 2021 are used to analyze the variations in solar radiation in the wavelength ranges 0.285–2.8, 0.280–0.400, and 0.280–0.315 μm. The calculations of the radiation balance and albedo of the underlying surface are presented. The diurnal radiation balance is shown to be -1.20 ± 1.18 MJ/m^2 during the period of stable snow cover, from November to March, and $+8.83 \pm 4.49$ MJ/m^2 in the snow-free period, from May to September. The diurnal solar radiation absorption by the Earth's surface is estimated to not exceed 2 MJ/m^2 during the period of stable snow cover, from December to March, and to vary from 10 to 25 MJ/m^2 in summer.

Keywords: atmosphere, radiation, albedo, radiation balance

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INTRODUCTION

The Second Assessment Report on Climate Changes and their Consequences for the territory of the Russian Federation suggests [1] that the main feature of the modern climate changes is global warming in the late twentieth century–early twenty-first century. Observations indicate that the average increasing rate of increase in the air temperature on the globe has been 0.166°C/10 year over 1976–2012. In [1], it is also noted that the period following 1976 is characterized by more intense warming, in both Russia-averaged time series of annual average anomalies, and in global time series, with the rate of increase on the territory of Russian Federation (0.43°C/10 years) being almost a factor of two larger than on the global scale.

The incoming solar radiation and the level of longwave emission are among the most important factors influencing the climate and, in particular, the surface air temperature.

The analysis of long-term variations in the total solar radiation at more than 400 stations around the world [2] indicates that the total solar radiation shows an increase from 1920 to the early 1960s, followed by its decrease until 1980s; the solar radiative influx again started growing since early 1990s, with its temperature sensitivity to the radiation changes being 0.05–0.06 K/(W m^{-2}). The analysis of long-term variations in shortwave solar radiation measured at 180 actinometric stations in Europe [3] showed the presence of two well-defined periods: a decrease from 1964 to 1989 and an increase from 1990 to 2010. Interestingly, the total radiation is noted to increase at 123 out of 130 European stations from 1990 to 2010. At the same time, in [4] it is revealed that a vast area with weakly negative trends of incoming radiation had formed in 1986–2010 on the Asian territory of Russia. This is most strongly manifested in mid-Siberia and in the south of Western Siberia. According to monitoring data for 1996–2016, the sunshine duration and the annual total incoming radiation decreased in Tomsk (a relative value of the trend had been −2.5%) [5, 6]. It is noteworthy that no temperature decrease was observed [6].

The climate system is quite complex and contains many feedforwards and feedbacks; therefore, the measurements aimed at identifying the roles of individual factors influencing the weather and climate should be complex. Considering that the warming rate in Russia is still larger than elsewhere on the planet, strong attention should be paid to development of the national network of stations monitoring the radiation characteristics and the state of the atmosphere in the surface layer.

V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Science, monitors atmospheric parameters in the surface air layer at 11 sites located on the territory of Western Siberia. The instrumental basis of the observation sites and certain results were described in [7–9]. One of the best equipped sites is the Fonovaya Observatory located on the eastern bank of the Ob River 60 km west of Tomsk (56°25′ N, 84°04′ E) [9]. Since July 2016, the total solar radiation has been monitored at the Observatory with a Kipp&Zonen pyranometer CM3 that measures the solar radiative flux in the wavelength range λ = 0.305–2.8 μm. Since April 2019, we have initiated the measurements of photosynthetically active radiation (PAR) with a PQS1 sensor (Kipp&Zonen). In November 2020, the radiation measurement unit was extended to include still another group of instruments (pyranometers SMP10, SUV-B, and SUV5 and radiometer CNR4). The specifications of instruments and methodological aspects of measurements are described in the first part of this paper [10].

Here, we analyze the measurements of solar radiation, radiation balance (*B*), and albedo (*A*) of the underlying surface at the Fonovaya Observatory in 2021.

LIST OF MEASURED RADIATION CHARACTERISTICS

Data from radiation measurement unit at the Fonovaya Observatory were used to analyze the variations in radiation characteristics of the atmosphere in the background region in 2021. Measurements of the total solar radiation (λ = 0.285–2.800 μm) are carried out with the pyranometer SMP10; the total UV radiation in the wavelength region λ = 0.280–0.400 μm, with the pyranometer SUV5, and the total UV-B radiation (λ = 0.280–0.315 μm), with the pyranometer SUV-B. From here on, the term “total radiation” or “Q” is taken to mean the total solar radiation, term “UV radiation” to mean the total ultraviolet radiation, and term “UV-B radiation” to mean the total UV-B radiation.

Using the radiometer CNR4, we initiated the measurements of the total Q and the reflected shortwave R_{sw} radiation, as well as the Earth’s surface radiation E_s and longwave counterradiation of the atmosphere E_a in the wavelength ranges 0.3–2.800 and 4.5–42000 μm, respectively.

SOLAR RADIATION

The measurements were used to calculate diurnal totals of Q, UV, and UV-B radiation. Annual variations in the diurnal solar radiation for three wavelength ranges are presented in Table 1. Diurnal totals of solar radiation during the year varied from maximal values in May–July to minimal in December. In winter months, the daily average solar radiation did not exceed Q = 5.5 MJ/m^2, UV radiation = 0.3 MJ/m^2, and UV-B radiation = 1.3×10^{-3} MJ/m^2. In spring, as solar elevation increases, the diurnal solar radiation grows (Q = 14.6 ± 7.0 MJ/m^2, UV radiation = 0.8 ± 0.3 MJ/m^2, UV-B radiation = $1.0 \times 10^{-2} \pm 0.5 \times 10^{-2}$ MJ/m^2). As compared to winter, in summer period (June–August), the diurnal total and UV radiation increase by about a factor of five, while UV-B radiation, by more than a factor of 10. In this season, the coefficient of variation (V) of diurnal totals varied in the range 25–38%. The maximal diurnal solar radiation was recorded on June 5, 2021: Q = 31.0 MJ/m^2, UV radiation = 1.6 MJ/m^2, and UV-B radiation = 2.4×10^{-2} MJ/m^2. During fall, the variability ranges of diurnal totals of Q, UV and UV-B radiation had been 0.40–18.28, 0.03–0.92, and 0.10×10^{-3}–1.55×10^{-2} MJ/m^2, respectively.

The monthly average percentage of diurnal variations in the UV radiation in the total radiation was from 5 to 8%; and the percentage of UV-B radiation, 0.01–0.1% depending on the season.

In addition to the SMP10 pyranometer measurements of the total radiation, the CM3 pyranometer measurements of the total radiation in the wavelength range λ = 0.305–2.800 μm have been carried out on the territory of the Fonovaya Observatory since 2016. In January 2019, the same radiation sensor was also installed at the basic experimental complex (BEC) located in the eastern suburb of Tomsk. Both CM3 sensors are installed at the same altitude; and the parameters they measure are fixed simultaneously. The Q measurements at these two sites were compared. In 2021, the yearly solar radiation was 1.6% greater at Fonovaya than at BEC (3865 MJ/m^2 at Fonovaya versus 3801 MJ/m^2 at BEC). A similar result was also obtained for 2020: yearly solar radiation at Fonovaya was 2.8% greater (3921 MJ/m^2 at Fonovaya versus 3812 MJ/m^2 at BEC). Table 2 presents the deviations of monthly totals of the total radiation at BEC (Q_{BEC}) from those at Fonovaya ($Q_{\text{background}}$) for different periods; they were calculated from the formula

$$\Delta Q = (Q_{\text{background}} - Q_{\text{BEC}}) / Q_{\text{background}} \times 100\%.$$

From Table 2 it can be seen that the difference in the monthly incoming total radiation is not constant throughout the year. Clouds are one of the main commonly recognized factors influencing the incoming solar radiation. Possibly, it is cloud parameters and higher atmospheric transparency in the region of Fonovaya Observatory that determined greater solar radiation in almost all months of the year as compared to the region of BEC. Meanwhile, the monthly totals of Q in the region of BEC show a stable tendency to exceed those in the region of Fonovaya in October–November 2021 and 2019 and in November 2020. We think that this may be because the Fonovaya Observatory is located at the bank of the Ob River. This large body of water free of ice can influence the reduction of the atmospheric transparency in autumn.

ALBEDO OF UNDERLYING SURFACE

Data from the CNR4 radiometer were used to calculate the albedo of underlying surface

$$A = (R_{sw}/Q) \times 100\%.$$

Table 1. Statistical values of the diurnal totals of radiation parameters of the atmosphere in 2021

Parameter	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Q, MJ/m^2												
Average	2.70	5.55	8.36	15.99	19.41	18.89	21.65	14.94	8.82	5.61	1.46	1.13
Min	1.14	1.27	3.15	3.21	6.13	6.49	5.60	3.75	1.50	1.00	0.37	0.49
Max	5.14	10.26	13.07	24.41	28.26	31.00	29.14	21.64	18.28	11.12	3.40	2.33
Standard deviation	1.04	2.59	2.89	6.06	6.37	7.16	5.48	5.24	4.74	2.91	0.76	0.55
V, %	38	46	35	38	33	38	25	35	54	52	52	49
UV radiation, MJ/m^2												
Average	0.12	0.29	0.57	0.84	1.02	1.04	1.16	0.82	0.49	0.31	0.11	0.07
Min	0.06	0.10	0.29	0.25	0.41	0.45	0.41	0.29	0.12	0.08	0.03	0.04
Max	0.17	0.58	0.81	1.23	1.43	1.58	1.49	1.12	0.92	0.56	0.21	0.14
Standard deviation	0.02	0.16	0.16	0.27	0.28	0.33	0.24	0.23	0.21	0.13	0.04	0.03
V, %	17	55	28	32	27	32	21	28	43	42	36	43
UV-B radiation × 10^2, MJ/m^2												
Average	0.04	0.13	0.46	0.97	1.57	1.72	2.01	1.38	0.68	0.28	0.05	0.02
Min	0.02	0.03	0.21	0.33	0.65	0.62	0.60	0.48	0.14	0.06	0.01	0.01
Max	0.07	0.29	0.75	1.60	2.40	2.62	2.63	1.93	1.55	0.54	0.14	0.14
Standard deviation	0.02	0.06	0.17	0.36	0.50	0.56	0.44	0.41	0.37	0.14	0.03	0.01
V, %	50	46	37	37	32	33	22	30	54	50	60	50
B, MJ/m^2												
Average	–0.91	–1.59	–1.26	4.27	9.91	10.18	12.68	8.63	3.49	0.49	–1.30	–1.08
Min	–3.38	–3.98	–3.62	–1.36	3.39	3.40	3.18	2.44	0.22	–1.74	–4.14	–3.40
Max	1.91	0.10	1.12	10.64	15.11	16.87	16.98	13.18	8.97	2.55	0.08	0.80
Standard deviation	1.36	1.07	1.09	3.80	3.46	3.93	3.62	3.11	2.26	1.31	1.08	1.02
V, %	184	67	87	89	35	37	29	36	65	267	83	94
A, %												
Average	75	80	82	47	20	23	19	21	23	22	78	82
Min	66	71	76	15	13	20	14	18	17	15	59	58
Max	87	90	87	81	22	29	25	24	30	26	91	95
Standard deviation	6.5	5.0	2.9	22.5	2.0	1.6	3.0	1.9	2.3	2.6	9.4	8.3
V, %	9	6	4	48	10	7	16	9	10	12	12	10

Table 2. Difference in monthly totals of total radiation between Fonovaya and BEC ΔQ, %

Year	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2021	–0.4	0.6	5.2	–3.0	5.2	–1.3	3.3	4.5	3.8	–5.1	–10.8	2.7
2020	5.5	0.2	8.6	–0.8	5.1	5.0	3.6	–2.3	4.1	2.8	–9.5	4.2
2019	–	0.1	9.2	2.8	1.8	1.9	5.5	4.3	–4.8	–6.4	–2.4	4.6

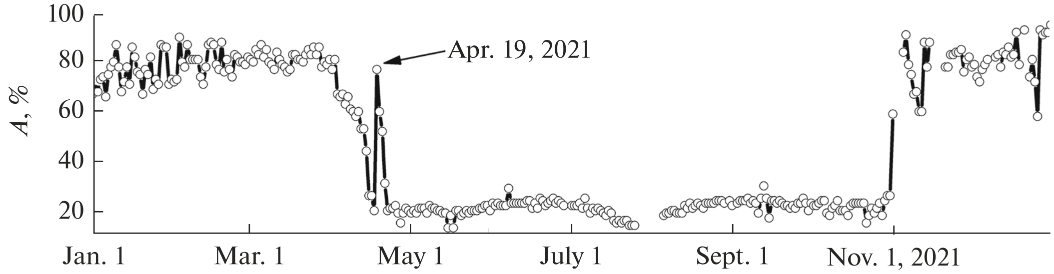

Fig. 1. Annual behavior of the albedo of underlying surface.

The daily average albedos were calculated for zenith angles smaller than 85°.

In variations in A during 2021 we can identify two periods (Fig. 1 and Table 1): with stable snow cover (January–March and November–December) and without snow (May–October). In the period with a stable snow cover, the surface albedo varied in the range 58–95% depending on the state of snow cover (fresh, packed, or dirty snow). The coefficient of variation in the surface albedo is 4–12% in this period. In period from May to October, $A = 13–30\%$ ($V = 7–16\%$).

In April, we could observe a rapid short-term albedo growth ($V = 48\%$) due to a change in surface properties followed by a decrease and return to initial values. After the underlying surface gradually changed in the first half of April, A decreased from 70 to 26% (total snow melt). On April 18, 2021, it was raining, and the rainfall amount was 4 mm ($A = 20\%$); while on April 19, it was snowing, and surface albedo rapidly increased to 77%. Then, snow was melting and the albedo decreased to $A = 21\%$ by April 24.

RADIATION BALANCE

The radiation balance of the underlying surface [11]:

$$B = (Q - R_{sw}) - E_{eff} = Q(1 - A) - E_{eff},$$

where $Q(1 - A)$ is the absorbed radiation (shortwave balance B_{sw}); $E_{eff} = (E_s - E_a)$ is the effective terrestrial radiation (longwave balance B_{lw}) characterizing heat loss by the Earth's surface.

The radiation balance may be either positive or negative depending on the relationship between the absorbed radiation and effective terrestrial radiation. The value and sign of B determine the thermal states of the Earth's surface and surface air layer [12].

Studying the oscillations of the radiation balance and its components is of great interest in the time of global climate change. Analysis of long-term variations in radiative fluxes based on observations at the Meteorological Observatory of Moscow State University over 60 years showed that the absorbed radiation, the effective emission, the counterradiation of the atmosphere, and the radiation balance of the Earth's surface tend to increase [13–15]. The radiation balance has started to strongly increase since the mid-1990s. The rate of increase in the yearly B values is two times larger in the modern period than throughout the observation period since 1954 [14, 15]. Since the mid-1990s, the growth of longwave fluxes is noted, and a strong tendency towards an increase in the counterradiation of the atmosphere is revealed [14, 15], indicating a growing contribution of longwave fluxes to the increase in the radiation balance.

Our CNR4 radiometer observations allowed us to obtain the annual behaviors of B, B_{sw}, and B_{lw} in 2021 on the territory of the Fonovaya Observatory (Fig. 2, Table 1). When snow cover was stable, from January to March and from November to December 2021, B_{sw} = 27.96 ± 19.03 W/m^2, B_{lw} = −25.75 ± 18.31 W/m^2; while from April 7 to October 18, 2021, B_{sw} = 223.58 ± 102.06 W/m^2, B_{lw} = −49.85 ± 22.59 W/m^2. The absolute B_{lw} value is two times smaller in the period of stable snow cover than without snow. The shortwave balance is a factor of eight larger in the spring-summer-fall period than in winter. Variations in the effective terrestrial radiation are the largest from March to April and from October to November, during snow melting and formation of snow cover, after redistribution between fractions of shortwave and longwave parts of the total balance, which is consistent with the conclusions in [16].

The patterns of variations in the radiation balance are determined by different factors that influence its main components. At night, the radiation balance is determined only by the effective terrestrial radiation, which depends only on surface temperature, clouds, and stratification of the atmosphere. In daytime, the main factors that determine the radiation balance are the solar elevation, clouds, and albedo of the underlying surface [11].

We calculated the diurnal totals of the radiation balance (Fig. 2b and Table 1). The ΣB_d values are negative (average ΣB_d = (−0.91) − (−1.59) MJ/m^2) in the period with a stable snow cover of the underlying surface, and they are positive (average ΣB_d = 0.49–12.68 MJ/m^2) without snow. For the comparison: in Moscow in 1994–2007, the long-term average diurnal totals of radiation balance varied from −0.42 MJ/m^2 in Novem-

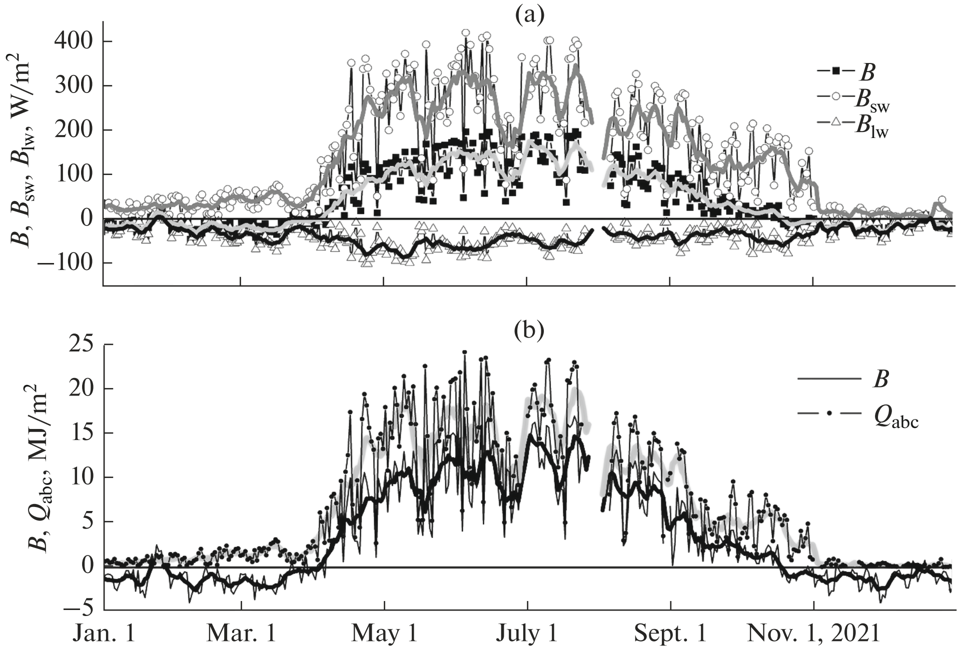

Fig. 2. (a) Daily averages of the total (B), shortwave (B_{sw}), and longwave (B_{lw}) radiation balances and seven-point averages (light-gray, gray, and black lines, respectively); (b) diurnal radiation balance B_d and solar radiation absorbed by the Earth's surface (Q_{abs}) per day, as well as the seven-point average radiation balance (black line) and seven-point average absorbed solar radiation (light-gray line).

ber to 1.01 MJ/m^2 in March; and they varied from 3.70 to 10.14 MJ/m^2 in the warm period [13].

The diurnal totals of the radiation balance strongly vary as functions of weather conditions and the state of the underlying surface. The coefficient of variation is large throughout the year, and the variations are maximal (267%) in October and minimal (29%) in July.

In spring 2021, the diurnal radiation balance changed from negative to positive values on April 7 (B = 2.05 MJ/m^2), 10 days before the snow cover

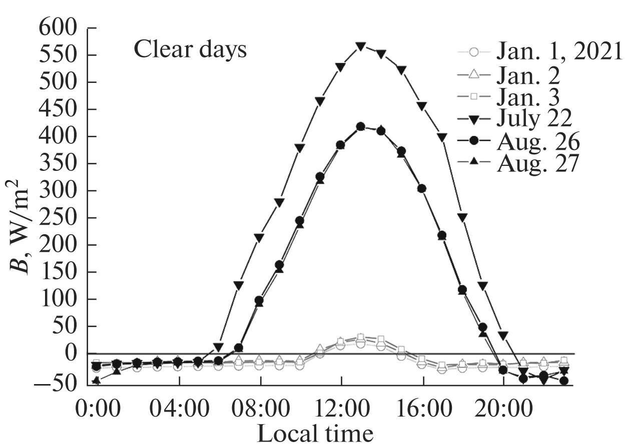

Fig. 3. Diurnal behavior of the radiation balance under the clear-sky conditions.

became unstable. In fall, the radiation balance had reversed its sign to negative on October 18 (B = −0.07 MJ/m^2), 14 days before the snow cover became stable. Data in [17] indicate that zero crossings of the ΣB_c values on the territory of Russia are observed, on average, after March 13 and October 24.

We estimated the amount of solar radiation absorbed by the Earth's surface ($Q_{abs} = Q - R_{sw}$). In the period of stable snow cover, the diurnal absorption of solar radiation by the Earth's surface did not exceed 2 MJ/m^2 (Fig. 2b). As snow gradually melts in the spring period, the daily amount of absorbed solar radiation increases to 15 MJ/m^2. The Q_{abs} value varies in the ranges 10–25 MJ/m^2 in summer and 2–10 MJ/m^2 in the fall.

Figure 3 shows daily variations in the radiation balance under different underlying surface states. Clear days were selected to eliminate the cloud effect. We used the observations from Kozhevnikovo weather station (no. 29532, http://pogodaiklimat.ru) located ~20 km from the Fonovaya Observatory.

The radiation balance grows with increasing solar elevation under the conditions of a stable snow cover on clear days (Fig. 3); however, no difference is noted between pre- and afternoon values, and no difference in the time of the balance transition through zero in the morning and evening hours. At night, with no clouds, the radiation balance of the snow-covered surface is smaller in absolute value than that of the grass-

Table 3. Average absolute amplitude of the diurnal variations in the intensity of the radiation balance, W/m^2, positive daily average total of the radiation balance B_+, and negative daily average total of the radiation balance B_-, MJ/m^2

Parameter	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Δ	41.95	48.55	69.10	275.53	416.56	451.69	484.89	380.51	245.67	182.65	10.80	9.62
B_+	0.25	0.18	0.51	5.92	11.15	11.98	13.44	9.48	4.99	2.49	0	0
B_-	−1.05	−1.77	−1.77	−1.66	−1.13	−1.13	−0.90	−0.86	−1.18	−2.01	−1.31	−1.08

covered surface. However, this is not true for monthly average nighttime values of the radiation balance in January and July (Table 3).

To estimate the energy resources it is necessary to know the values of the radiation balance for day and night separately. Table 3 presents the absolute values of diurnal amplitude of the radiation balance, as well the positive (at daytime) and negative (at night) daily average totals of the radiation balance.

The annual behavior of the monthly total of radiation balance mainly echoes that of the total radiation. Its value is positive from April to October with the maximum (B = 369 MJ/m^2) in July. In 2021, the yearly total of the radiation balance had been 1280 MJ/m^2, or 34% of the total radiation. These data well agree with the results obtained by other authors. The authors of work [18] indicate that the radiation balance, on an annual average basis, varies in the range 1122–1441 MJ/m^2 in Tomsk oblast, increasing from north (Aleksandrovskoye) to south (Tomsk). The yearly total of the radiation balance is 32–37% of the total radiation. In Moscow, the average value B = 1295 MJ/m^2 (1958–2007), and the coefficient of variation is 9% [13]. The authors of work [13] also note that the yearly totals of B rapidly increase in Moscow from 1994 to 2007 (by 23% over 13 years) and the increase in the radiation balance in the last decade continues [15].

CONCLUSIONS

Based on measurements carried out in 2021 with the use of the radiation measurement unit of the measurement complex at the Fonovaya Observatory, we obtained the statistical values of the diurnal totals of the radiation parameters of the atmosphere.

Analysis of measurements of solar radiation in different wavelength ranges made it possible to estimate the variations in solar radiation in the background region of Western Siberia. In winter period, from December to February, the diurnal solar radiation did not exceed 7.3 (λ = 0.285–2.800 μm), 0.4 (λ = 0.280–0.400 μm), and 1.4 × 10^{-3} MJ/m^2 (λ = 0.280–0.315 μm). In summer, the diurnal total and UV radiation increase by almost a factor of five (Q = 18.9 ± 6.6 MJ/m^2, UV radiation = 1.0 ± 0.3 MJ/m^2), and the diurnal UV-B radiation, by a factor of 10 (1.7 × 10^{-2} ± 0.5 × 10^{-2} MJ/m^2).

We carried out the calculations and made the first estimates of how the radiation balance varies in the background region. It was found that the diurnal radiation balance B = −1.20 ± 1.18 MJ/m^2 from November to March under stable snow cover, and B = 8.83 ± 4.49 MJ/m^2 in the snow-free period from May to September. In spring 2021, the diurnal radiation balance changed from negative to positive values on April 7 (B = 2.05 MJ/m^2). In the fall, a change from positive to negative values was noted on October 18 (B = −0.07 MJ/m^2). We obtained monthly average values of the radiation balance for daytime and nighttime.

It is shown that the diurnal absorption of solar radiation did not exceed 2 MJ/m^2 in the period with a stable snow cover from December to March and it varied from 10 to 25 MJ/m^2 in summer.

It is found that, during 2021, A = 58–95% in January–March and November–December (with a stable snow cover), and A = 13–30% from May to October (snow-free period).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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