ISSN 1024-8560, Atmospheric and Oceanic Optics, 2020, Vol. 33, No. 6, pp. 638–644.

The Relationship between Ultraviolet Radiation and Meteorological Factors and Atmospheric Turbidity: Part I. Role of Total Ozone Content, Clouds, and Aerosol Optical Depth

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

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

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

Received March 26, 2020; revised March 26, 2020; accepted June 29, 2020

Abstract—We analyze the interrelation between the daily UV–B radiation and a number of factors determining the absorption of UV radiation in the atmosphere (total ozone content (TOC), cloud amount, and aerosol optical depth (AOD)). This is done using a homogeneous time series of measurements of UV–B radiation at the Tropospheric Ozone Research (TOR) station of the Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, from 2003 to 2016, satellite data on TOC, AOD data from the AERONET network, and data on cloud cover from the meteorological site of the Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch, Russian Academy of Sciences. The regression equations are obtained, relating the increment of the diurnal intake of UV-B radiation as a function of the increment of TOC under different cloud conditions and atmospheric transparency.

Keywords: atmosphere, ultraviolet radiation, total ozone content, clouds, variations

DOI: 10.1134/S1024856020060196

INTRODUCTION

How global warming, documented by the Intergovernmental Panel on Climate Change (IPCC), works, requires clarification. The cause of rising air temperature is related by the IPCC to a change in the Earth's radiation budget due to a rapid increase, in the industrial era, in the concentrations of greenhouse gases that retain the thermal infrared radiation near the Earth's surface. It is noteworthy that a long-term change in the total flux of incoming solar radiation is only ~0.1% [1, 2]. At the same time, the Earth's radiation budget is estimated in [3, 4] to have increased from 0.5 to 1.0 W/m^2 in recent years. Authors of [5] gave a more exact value of 0.6 ± 0.4 W/m^2. Despite the constancy of total incoming solar radiation flux at the top of the atmosphere (solar constant), changes in the flux in the ultraviolet region of the solar spectrum can attain tens of percent [6–9]. Though accounting for just a few percent of the total solar flux, this part of the spectrum, being biologically and photochemically active, can act on living organisms on the Earth, as well as on components of the troposphere [10]. Therefore, the world community actively studies the dynamics of the incoming ultraviolet solar radiation (UV radiation) to the Earth's surface and assesses its role in atmospheric processes [11–15].

Analysis of long-term variations in UV radiation showed its global growth in 1979–2008; with the zonal and annual average increase in UV radiation occurring much faster in the Southern than in the Northern Hemisphere. As an example, for cloud-free conditions, the zonal average changes in the radiation at a wavelength of 305 nm were 23% at latitude 50° S and only 9% at 50° N [16]. At the same time, studies of long-term variations in UV radiation at wavelengths λ = 305 and λ = 325 nm at 12 stations, located in Canada, Europe, and Japan during 1990–2011 revealed a trend toward a decrease in the incoming UV radiation [17]. At the same time, it is noted that the period of 1995–2006 was characterized by an increase in UV radiation against the background of the growth in total ozone content (TOC) and a decrease in tropospheric aerosol (UV radiation decreased by 0.94% per year at λ = 305 nm and by 0.88% per year at λ = 325 nm); while a deceleration in the growth of UV radiation was noted in 2006–2011.

Clouds, albedo of underlying surface, atmospheric aerosol, ozone, and certain other trace gas admixtures can be considered among the main factors influencing the incoming UV radiation. The role of TOC significantly increases in the shortwave part of the spectrum of UV radiation [18]. Numerous studies showed that the effect of each of these factors depends on physicalgeographic and climatic features of a region; with this effect being diverse in different spectral intervals. For instance, variations in monthly average UV radiation at $\lambda = 305$ exclusively owing to changes in TOC can exceed 50%, reaching, on average, 35% due to changes in cloud cover [19].

In that work it was also noted that short-term changes in UV radiation at $\lambda = 305$ nm owing to changes in TOC may be larger than 200% (more than 50%, on average). Clouds may cause variations of 150% and larger (35% on the average). Maximal variations within a month, caused by albedo, are 32% in April (6%, on average) and 12–15% in summer months (3%, on average). TOC and clouds strongly influence the variations in UV radiation in summer and fall. TOC exerts the main influence in winter and spring.

The spectral regions B (280–315 nm) and A (315–400 nm) are conventionally singled out in UV radiation reaching the Earth's surface; however, variations in the radiation in region B and in the shortwave part of region A (315–325 nm), reaching the Earth's surface, depend on variations in amounts of ozone, aerosol, and clouds. Variations in aerosol and clouds also influence region A (315–400 nm) [16]. Spectral regions A and B respond identically to the abovementioned factors; therefore, in what follows, by the spectral region B of UV radiation will be meant the wavelength range (280–320 nm), for which we will use the notation UV–B.

A change in the concentration of stratospheric ozone under calm conditions leads to variations in the intensity of UV–B radiation near the Earth's surface by 5–25% [20, 21]. When stratospheric ozone depressions, or the so-called ozone "holes," occur [22], the intensity of UV–B radiation can increase near the Earth's surface by up to 40% [23].

Clouds have no less effect on the incoming UV–B radiation. For instance, data in [24] indicate that, for cloud amount equal to 10, the attenuation of UV–B radiation is $75 \pm 10\%$, on average.

As regards atmospheric aerosol, its contribution to absorption of UV–B radiation is as small as10% under cloud-free conditions over background regions [25, 26]. The situation rapidly changes when the concentration of aerosol particles increases. For instance, when aerosol-rich air masses came from the Sahara to the territory of Spain, the aerosol optical depth (AOD) increased to 1.76, and attenuation of radiation at $\lambda =$ 320 nm reached 50% [27]. Studies in Beijing showed that absorption of UV radiation can reach 50% under conditions of strong pollution for visibility ranges shorter than 2500 m [28]. For comparison: in Moscow during summer 2010 in the period of strongest pollution by smoke from fires, the maximal losses were 64% for the total radiation (300–4500 nm) and 91% for UV radiation (300–380 nm) at $AOD_{500} = 6.4$ [29].

A significant contributor to variations in the intensity of UV–B radiation is the albedo of the underlying surface. Surface-reflected radiation is scattered on air molecules and aerosol particles in different directions and, in particular, in the backward direction, adding to recorded UV–B radiation. In the period when snow is lying, as compared to the snow-free period, the enhancement of total radiation is 4.5%, on average [30, and even larger, up to 22%, in the ultraviolet region of spectrum [31].

Despite many studies, the spatiotemporal variations and the value and direction of changes in surface UV–B radiation are still poorly understood. Therefore, correct measurements of spectral intensity of UV–B radiation and the main factors determining its level on the Earth's surface are very important for better understanding and more exact simulation of interrelations between UV–B radiation, ozone, aerosol, and clouds.

The first station for monitoring atmospheric parameters in the surface air layer was created within the international project for Tropospheric Ozone Research (TOR station) of European Program EUROTRAC in V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS) [32]. The station is located in Tomsk Akademgorodok and has coordinates (56°28′ N, 85°03′ E). Continuous automatic measurements at the station had been initiated in late December 1992 and continue into the present. The structural scheme of the TOR station as of 2018 was described in detail in [33].

In this work, data from continuous monitoring of atmospheric parameters in the surface air layer at IAO SB RAS TOR station are used to analyze the interrelation of the surface UV radiation with factors which change its intensity (TOC, clouds, and AOD).

DESCRIPTION OF INITIAL DATA

UV–B radiation had been continuously monitored at IAO SB RAS TOR station [33] from 2002 to 2018. Measurements in the wavelength range 280–320 nm were carried out using a UVB-1 ultraviolet pyranometer (Yankee Environmental Systems, Inc., United States). The error of the pyranometer measurements is < 5%, the time constant is 0.1 s. Later, the measurements were suspended for technical reasons. The principle of the pyranometer operation, method of measurements, and procedure for data recording were considered in our works [34, 35]. In parallel, from fall 2003 to July 2016, the spectral characteristics of UV–B radiation were monitored using Brewer MKIV spectrophotometer no. 049 [35, 36].

Hourly ground-based measurements were used to calculate daily, monthly, and yearly UV–B radiation. A decreasing tendency of UV–B radiation in Tomsk (the relative value of the trend, calculated similar to [37], is −5.9%, Fig. 1a) is revealed over the measurement period.

At the same time, we can single out two periods, when UV–B radiation decreased or showed signs of increasing tendency: 2003–2010 and 2012–2017. The yearly UV–B radiation varied within 6.5% over the period of measurements. The annual average income had been 6.98 ± 0.46 MJ/m^2. The maximum (7.8 MJ/m^2) was recorded in 2005, and minimum (6.2 MJ/m^2) in 2010. The variation coefficient of monthly UV–B radiation varied from 7 to 16% in different seasons (Fig. 1b). The maximal income of UV–B radiation (1.38 ± 0.15 MJ/m^2) was noted in June, and the minimal (0.05 ± 0.02 MJ/m^2) in December. The daily average income had been 0.019 ± 0.015 MJ/m^2, with a maximum of 0.046 ± 0.005 MJ/m^2 in June.

The variability factors of daily UV–B radiation reaching the Earth's surface were analyzed using AOD_{500} data obtained from ground-based measurements of direct radiation by the AERONET CE-318 photometer in Tomsk [38]. We used the processing level 2.0 data. A detailed method of AERONET data processing and filtering was described in [39]. The results of satellite monitoring of ozone content in atmospheric column by Atmospheric Infrared Sounder (AIRS) instruments are taken from http://giovanni.gsfc.nasa.gov. We additionally employed hourly observations of the cloud cover in the daytime at the meteorological site in the Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch, Russian Academy of Sciences.

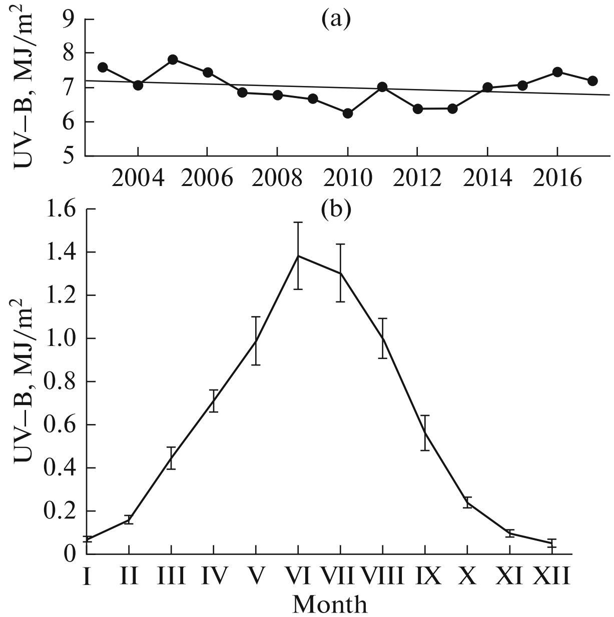

Fig. 1. (a) Interannual variations and (b) annual behavior of incoming UV–B radiation in Tomsk.

RESULTS

The total ozone content is determined mainly by its stratospheric portion. The TOC level may be influenced by a wealth of factors and, in particular, by circulation processes in the atmosphere; the strongest TOC variations in the Northern Hemisphere are caused by the orientation of the Earth's rotation axis relative to the solar radiation flux. In turn, a change in ozone content in the atmosphere affects the fraction of UV radiative flux entering the lower troposphere from the top of the atmosphere. Measurements of UV–B radiation and their comparison with TOC variations showed that their interrelation is readily traced over long periods of time and is not always stable over short periods [40]. Nonetheless, the presence of feedback is obvious: the smaller the TOC value, the larger the fraction of UV–B radiation reaching the Earth's surface.

Independent of the TOC, the incoming UV–B radiation at the measurement site shows a pronounced annual behavior with a maximum in the summer period and a minimum during winter. To eliminate the effect of annual behavior on the estimate of the interrelation between their variations, we compared deviations of the average TOC values and daily UV–B radiation for each day (Y_i) from long-term average values for a given time of the day ($Y_{i\text{aver}}$). The result was normalized to long-term average values for a given day of a season over a period of time considered. The deviations were calculated by the formula

$$\Delta I = (Y_i - Y_{i\text{aver}})/Y_{i\text{aver}} \times 100\%.$$

Thus, we obtained two long-term (2003–2016) time series of daily deviations ΔTOC_i and $\Delta UV–B_i$, as well as the time series of deviations for each year. As an example, Figure 2 shows relative deviations of TOC and daily UV–B radiation from the long-term average values for 2011.

The ΔTOC_i and $\Delta UV\text{-}B_i$ time series, thus obtained, are found to show a significant inverse correlation dependence, both for separate years and for the entire period of observations (Table 1). The correlations were maximal in 2011 with the coefficient $r = -0.42$, and minimal in 2006 ($r = -0.22$). All correlation coefficients in Table 1 are significant with 99% confidence probability.

The coefficient a shows how ΔUV–B radiation changes (in percent) in response to the total ozone content increase by 1%. The coefficient b represents a percentage increase in daily UV–B-radiation relative to long-term average values.

Previously [41], we showed that clouds in daylight hours of observations are absent in less than 9% of cases; and in the other cases cloud structures are observed. In the period under study, total and low-level clouds show a tendency to increase. We estimated the joint effect of clouds and the AOD on the daily UV–B radiation for a varying TOC. For this, the total dataset was processed to compile a few subsets, sorted with respect to the cloud cover in daytime. Ultimately,

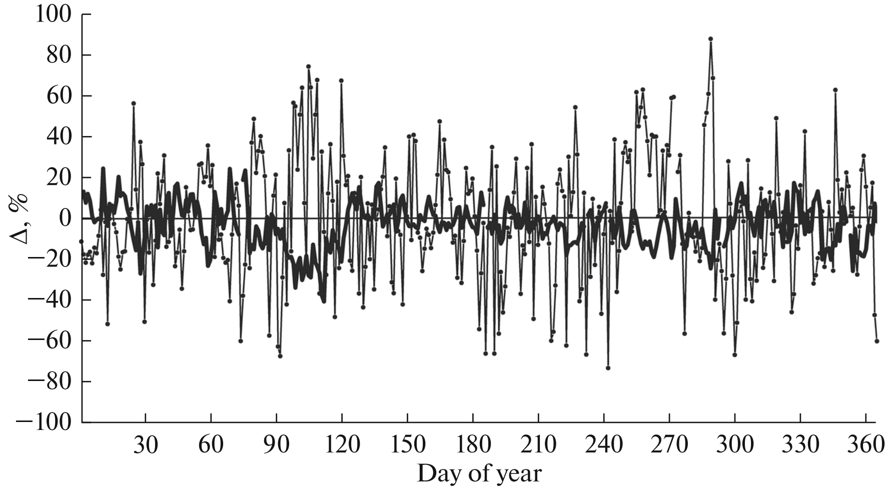

Fig. 2. Deviation of UV–B radiation (semi-bold line) and TOC (thin line) in 2011 from the long-term average values.

we obtained five datasets with different amounts of total clouds (N_{total}):

$$\text{I: } N_{total} \le 2 \, (411 \text{ days}),$$

$$\text{II: } 2 < N_{total} \le 4 \, (238 \text{ days}),$$

$$\text{III: } 4 < N_{total} \le 6 \, (326 \text{ days}),$$

$$\text{IV: } 6 < N_{total} \le 8 \, (582 \text{ days}),$$

$$\text{V: } 8 < N_{total} \le 10 \, (3351 \text{ days}).$$

Table 1. The correlation coefficients between ΔTOC_i and $\Delta UV{-}B_i$

Year	r	$a \pm Se(a)$	$b \pm Se(b)$
2003	−0.26	−0.86 ± 0.34	4.91 ± 3.06
2004	−0.24	−0.90 ± 0.39	9.57 ± 3.98
2005	−0.31	−1.46 ± 0.46	21.86 ± 4.05
2006	−0.22	−0.87 ± 0.41	12.60 ± 4.01
2007	−0.34	−1.11 ± 0.33	−4.91 ± 2.94
2008	−0.28	−0.87 ± 0.32	−7.28 ± 3.29
2009	−0.33	−1.10 ± 0.33	−3.29 ± 3.11
2010	−0.30	−0.72 ± 0.25	−6.31 ± 3.10
2011	−0.42	−1.15 ± 0.26	−2.51 ± 2.85
2012	−0.25	−0.80 ± 0.32	−8.81 ± 3.17
2013	−0.26	−0.70 ± 0.27	−7.35 ± 3.05
2014	−0.34	−0.96 ± 0.28	−3.56 ± 2.92
2015	−0.40	−1.19 ± 0.29	−2.62 ± 2.95
2016	−0.41	−1.18 ± 0.27	4.59 ± 3.16
2003–2016	−0.28	−0.93 ± 0.10	0.63 ± 0.98

a, b are coefficients of the linear regression equation $Y = aX + b$, where X is the corresponding ΔTOC_i value, and Y is equal to a predicted $\Delta UV{-}B_i$ value for a given X; Se(a) and Se(b) are the standard errors of the regression coefficients a, b.

As an example, Figs. 3a and 3b show the dependence of the deviation $\Delta UV{-}B_i$ on ΔTOC_i for clear-sky ($N_{total} \le 2$) and cloudy ($8 < N_{total} \le 10$) days.

Then, from each of the five datasets, we selected days with $AOD_{500} \le 0.15$ ("clear atmosphere"): 172 days for I, 78 days for II, 126 days for III, 217 days for IV, and 503 days for V. In Figs. 3c and 3d, we can see how the situation changes when we consider days with only the clear atmosphere. The correlation coefficients are significant with confidence no lower than 99% in all the datasets. Despite the considerable dispersion of values relative to the regression line (in Fig. 3), we can see quite a significant negative correlation, for which $r = -0.47$ under clear-sky conditions ($N_{total} \le 2$) and −0.56 for the clear atmosphere, while for the cloudy sky ($8 < N_{total} \le 10$) the correlation coefficients are much lower and equal to −0.25 and −0.38.

After processing the data in five datasets compiled taking into account the cloud cover and disregarding the AOD and in five datasets taking into account the AOD, we identified the dependences of $\Delta UV{-}B_i$ on ΔTOC_i for each cloud cover range without accounting for AOD and with $AOD_{500} \le 0.15$ (Table 2).

From Fig. 3 and Table 2 it follows that under the conditions of the transparent atmosphere and minimal cloud amount the average deviation of UV–B radiation with respect to all deviations of daily UV–B radiation analyzed in this work is 31.2%. Thus, the data presented in Table 2 can then be used to determine the cloud effect on the decrease in the increment of daily UV–B radiation relative to the cloud-free and transparent atmosphere ($N_{total} \le 2$, $AOD_{500} \le 0.15$). The attenuation will be 0.7% for cloud cover $2 < N_{total} \le 4$; 2.8% for $4 < N_{total} \le 6$; 12.0% for $6 < N_{total} \le 8$; and 28.7% for $8 < N_{total} \le 10$.

If the AOD is disregarded, under the conditions of minimal clouds the average deviation of UV–B radia-

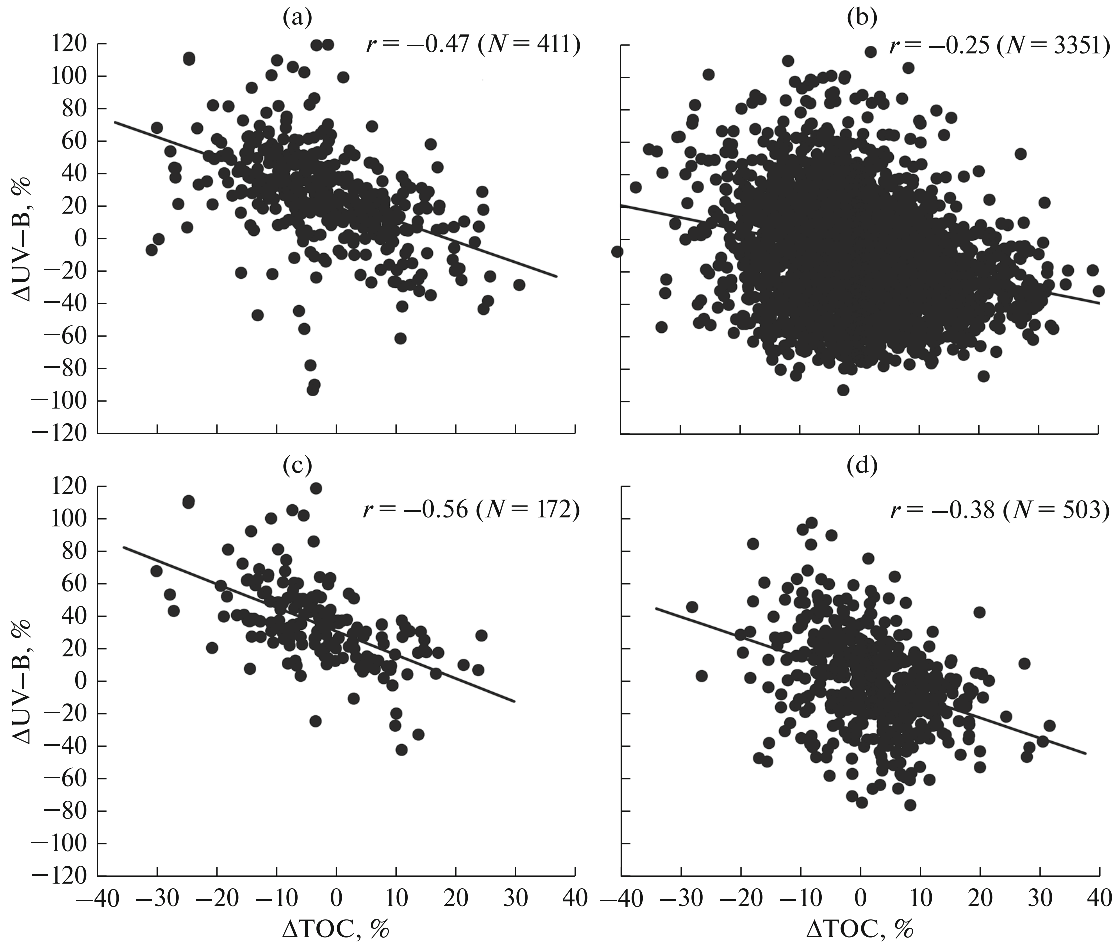

Fig. 3. Regression plot of ΔUV–B$_i$ versus ΔTOC$_i$ for clear-sky and cloudy days: (a) $N_{total} \leq 2$; (b) $8 < N_{total} \leq 10$; (c) $N_{total} \leq 2$, $AOD_{500} \leq 0.15$; (d) $8 < N_{total} \leq 10$, $AOD_{500} \leq 0.15$; the correlation coefficient is calculated using N points for the 0.99 confidence level.

Table 2. Dependences of ΔUV–B$_i$ on ΔTOC$_i$ for different cloud amount and AODs with 0.99 confidence level

Total cloud amount	$a \pm$ Se(a)	$b \pm$ Se(b)	r	N
$N_{total} \leq 2$	−1.29 ± 0.52	23.8 ± 5.69	−0.47	411
$2 < N_{total} \leq 4$	−1.58 ± 0.30	23.6 ± 2.91	−0.56	238
$4 < N_{total} \leq 6$	−1.24 ± 0.29	21.7 ± 2.58	−0.42	326
$6 < N_{total} \leq 8$	−1.36 ± 0.21	14.9 ± 2.1	−0.46	582
$8 < N_{total} \leq 10$	−0.75 ± 0.10	−8.4 ± 1.03	−0.25	3351
$N_{total} \leq 6$	−1.35 ± 0.16	23.0 ± 1.56	−0.48	974
		$AOD_{500} \leq 0.15$		
$N_{total} \leq 2$	−1.45 ± 0.33	31.2 ± 3.37	−0.56	172
$2 < N_{total} \leq 4$	−1.88 ± 0.56	30.5 ± 4.56	−0.61	78
$4 < N_{total} \leq 6$	−1.63 ± 0.57	28.4 ± 4.43	−0.45	126
$6 < N_{total} \leq 8$	−1.64 ± 0.37	19.2 ± 3.24	−0.52	217
$8 < N_{total} \leq 10$	−1.25 ± 0.27	2.5 ± 2.42	−0.38	503
$N_{total} \leq 6$	−1.59 ± 0.25	30.1 ± 2.32	−0.54	376

tion with respect to all deviations of daily UV–B radiation is 23.8%. Data in Table 2 make it possible to determine the effect of real AOD conditions with respect to ideal conditions ($AOD_{500} \leq 0.15$). The attenuation will be 7.4% for cloud amount $N_{total} \leq 2$; 6.9% for $2 < N_{total} \leq 4$; 6.7% for $4 < N_{total} \leq 6$; 4.3% for $6 < N_{total} \leq 8$; and 10.9% for $8 < N_{total} \leq 10$. Thus, the average attenuating effect of the AOD, which we actually noted, versus clear conditions is from 4.3 to 10.9% for the corresponding cloud conditions.

Our results are consistent with those in [19, 20, 25].

CONCLUSIONS

Long-term variations in the daily UV–B radiation and factors determining these variations were analyzed based on a homogeneous time series from measurements at the Tropospheric Ozone Research (TOR) station of Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, in 2003–2016. We can draw the following conclusions.

Under the conditions of the clear-sky and transparent atmosphere ($N_{total} \leq 2$, $AOD_{500} \leq 0.15$) an increase in the TOC by 1% leads to decrease in shortwave radiation by 1.45%, on average.

The average contribution of the AOD to variations in the daily UV–B radiation is from 4.3 to 10.9%, depending on the cloud amount.

If we consider that the daily average UV–B radiation under clear-sky conditions is 31.2% higher than the total average values, clouds may reduce the increment of UV–B radiation by 0.7–28.7% on the average, depending on the cloud amount.

In the studies, we ignore the surface albedo, which can also appreciably contribute to variations in dependence of UV–B radiation on the TOC.

ACKNOWLEDGMENTS

The authors thank organizers of the websites https://aeronet.gsfc.nasa.gov, http://giovanni.gsfc.nasa.gov for compiling information and providing the possibility for its free use.

FUNDING

This work was supported by the Russian Foundation for Basic Research (grant no. 19-05-50024). The work was carried out using the infrastructure of the Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences created and run within State Assignment no. AAAA-A17-117021310142-5, including the Center for Collective Use Atmosphere.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. J. Lean, "The Sun's variable radiation and its relevance for Earth," Ann. Rev. Astron. Astrophys. **35**, 33–67 (1997).
2. B. Pittock, "Can solar variations in the Earth's climate?," Clim. Change **96** (4), 483–487 (2009).
3. V. A. Golovko, "Energy aspects of the Earth climate variation: Sight from Space," Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli Kosmosa **9** (5), 140–154 (2012).
4. K. E. Trenberth, J. T. Fasullo, and M. A. Balmaseda, "Earth's energy imbalance," J. Climate **27** (9), 3129–3144 (2014).
5. G. L. Stephens and T. L'Ecuyer, "The Earth's energy balance," Atmos. Res. **166**, 195–203 (2015).
6. D. W. Tarasik, V. E. Fioletov, D. I. Wardle, J. B. Kerr, L. J. B. McArthur, and C. A. McLinden, "Climatology and Trends of Surface UV Radiation," Atmos. Ocean. **41** (2), 121–138 (2003).
7. S. K. Solanki, N. A. Krivova, and J. D. Haigh, "Solar irradiance variability and climate," Ann. Rev. Astron. Astrophys. **51**, 311–351 (2013).
8. O. Coddington, J. L. Lean, P. Pilewskie, M. Snow, and D. Lindholm, "A solar irradiance climate data and record," Bull. Am. Meteorol. Soc. **97** (7), 1265–1282 (2016).
9. A. Sanchez-Lorenzo, A. Enriquez-Alonso, M. Wild, J. Trentmann, S. M. Vicento-Serrano, A. Sanchez-Romero, R. Posselt, and M. Z. Hakuda, "Trends in downward surface solar radiation from satellites and ground observations over Europe during 1983–2010," Remote Sens. Environ. **189**, 108–117 (2017).
10. A. Andrady, P. J. Aucamp, A. T. Austin, A. F. Bais, C. L. Ballare, P. W. Barnes, G. H. Bernhard, L. O. Bjorn, J. F. Bornman, D. J. Erickson, F. R. de Gruijl, D.-P. Hader, M. Ilyas, J. Longstreth, R. M. Lucas, S. Madronich, R. L. McKenzie, R. Neale, M. Norval, K. K. Pandey, N. Paul, H. H. Redhwi, S. A. Robinson, K. Rose, M. Shao, R. P. Sinha, K. R. Solomon, B. Sulzberger, Y. Takizawa, A. Torikai, K. Tourpali, C. E. Williamson, S. R. Wilson, S.-A. Wangberg, R. C. Worrest, A. R. Young, and R. G. Zepp, "Environmental effects of ozone depletion and its interactions with climate change: Progress report, 2015," Photochem. Photobiol. Sci. **15** (2), 141–174 (2016).
11. N. E. Chubarova, "Monitoring of biologically active UV radiation in the Moscow region," Izv., Atmos. Ocean. Phys. **38** (3), 312–322 (2002).
12. A. De Miguel, R. Roman, J. Bilbao, and D. Mateos, "Evolution of erythemal and total shortwave solar radiation in Valladolid, Spain: Effect of atmospheric factors," J. Atmos. Sol.-Terr. Phys. **73** (5-6), 578–586 (2011).
13. C. S. Zerefos, K. Toupali, K. Eleftheratos, S. Kazadzis, C. Meleti, U. Feister, T. Koskela, and A. Heikkila, "Evidence of a possible turning point in solar UV-B over Canada, Europe and Japan," Atmos. Chem. Phys. **12** (5), 2469–2477 (2012).
14. M. I. Nakhaev, L. B. Anan'ev, N. S. Ivanova, A. M. Zvyagintsev, I. N. Kuznetsova, and I. Yu. Shalygina, "UV irradiance, UV index, and their forecast," Tr. Gidrometeorol. Nauchno-Issled. Tsentra Ros. Federatsii, Is. **351**, P. 173–187 (2014).
15. Yu. M. Timofeev and E. M. Shul'gina, "Russian investigations in the field of atmospheric radiation in 2011–2014," Izv., Atmos. Ocean. Phys. **52** (5), 467–482 (2016).
16. J. R. Herman, "Global increase UV irradiance during the past 30 year (1979–2008) estimated from satellite data," J. Geophys. Res. D **115** (2010). https://doi.org/10.1029/2009JD012219
17. E. Ezhova, I. Ylivinkka, J. Kuusk, K. Komsaare, M. Vana, A. Krasnova, S. Noe, M. Arshinov, B. Belan, S. Park, J. Lavric, M. Heimann, P. Kolari, T. Petäjä, P. Hari, T. Vesälä, J. Bäck, U. Rannik, V.-M. Kerminen, and M. Kulmala, "Direct effect of aerosols on solar radiation and gross primary production in boreal forest," Atmos. Chem. Phys. **18** (24), 17863–17881 (2018).
18. *Scientific Assessment of Ozone Depletion. Report WMO N 50* (WMO, 2006).
19. S. Simic, P. Weihs, A. Vacek, H. Kromp-Kolb, and M. Fitzka, "Spectral UV measurements in Austria from

1994–2006: Investigations of shot- and long-term changes," Atmos. Chem. Phys. **8** (23), 7033–7043 (2008).

20. B. Petkov, V. Vitale, C. Tomasi, M. Mazzolo, C. Lanconelli, A. Lupi, and M. Busetto, "Variations in total ozone column and biologically effective solar UV exposure doses in Bologna, Italy during the period 2005–2010," In. J. Biometeorol. **58** (1), 31–39 (2014).
21. M. Anton, A. Cazoria, D. Mateos, M. J. Costa, F. J. Olmo, and L. Alados-Arboledas, "Sensitivity of UV erythemal radiation to total ozone changes under different sky conditions: Results for Granada, Spain," Photohem. Photobiol. **92** (1), 215–219 (2016).
22. R. R. Garsia, "Atmospheric science: An Artic ozone hole?," Nature **478** (7370), 462–463 (2011).
23. P. Gies, A. Klekociuk, M. Tully, S. Henderson, J. Javorniczky, K. King, L. Lemus-Deschamps, and J. Makin, "Low ozone over Australia in August 2011 and its impact on solar ultraviolet radiation levels," Photohem. Photobiol. **89** (4), 984–994 (2013).
24. A. M. El-Nouby and E. A. Ahmed, "Comparative analysis of cloud effects on ultraviolet-B and broadband solar radiation: Dependence on cloud amount and solar zenith angle," Atmos. Res **168**, 149–157 (2016).
25. V. De Bock, H. de Backer, R. van Malderen, A. Mangold, and A. Delcloo, "Relations between erythemal UV dose, global solar radiation, total ozone column and aerosol optical depth at Uccle, Belgium," Atmos. Chem. Phys. **14** (22), 12251–12270 (2014).
26. I. Fountoulakis, A. F. Bais, K. Fragkos, C. Meleti, K. Tourpali, and M. M. Zempila, "Short- and long-term variability of spectral solar UV irradiance at Thessaloniki, Greece: Effects of changes in aerosols, total ozone and clouds," Atmos. Chem. Phys. **16** (4), 2493–2505 (2016).
27. M. Anton, M. Sorribas, Y. Bennouna, J. M. Vilaplana, V. E. Cachorro, J. Grobner, and L. Alados-Arboledas, "Effects of an extreme desert dust event on the spectral ultraviolet irradiance at El Arenosillo (Spain)," J. Geophys. Res. D **117** (2012). https://doi.org/10.1029/2011JD016645
28. J. L. An, Y. S. Wang, X. Li, Y. Sun, and S. H. Shen, "Relationship between surface UV radiation and air pollution in Beijing (in Chinese)," Environ Sci. **29** (4), P. 1054–1058 (2008).
29. N. Chubarova, Ye. Nezval, M. Sviridenkov, A. Smirnov, and I. Slutsker, "Smoke aerosol and its rediative effects during extreme fire event over central Russia in summer 2010," Atmos. Meas. Tech. **5** (3), 557–568 (2012).
30. C. Di Biagio, A. di Sarra, P. Eriksen, S. E. Ascanius, G. Muscari, and B. Holben, "Effect of surface albedo, water vapour, and atmospheric aerosols on the cloud-free shortwave radiative budget in the Arctic," Clim. Dyn. **39** (3-4), 953–969 (2012).
31. S. Simic, M. Fitzka, A. Schmalwieser, P. Weihs, and J. Hadzimustafic, "Factors affecting UV irradiance at selected wavelengths at Hoher Sonnblick," Atmos. Res. **101** (4), 869–878 (2011).
32. M. Yu. Arshinov, B. D. Belan, V. V. Zuev, V. E. Zuev, V. K. Kovalevskii, A. V. Ligotskii, V. E. Meleshkin, M. V. Panchenko, E. V. Pokrovskii, A. N. Rogov, D. V. Simonenkov, and G. N. Tolmachev, "TOR-station for monitoring of atmospheric parameters," Atmos. Ocean. Opt. **7** (8), 580–584 (1994).
33. D. K. Davydov, B. D. Belan, P. N. Antokhin, O. Yu. Antokhina, V. V. Antonovich, V. G. Arshinova, M. Yu. Arshinov, A. Yu. Akhlestin, S. B. Belan, N. V. Dudorova, G. A. Ivlev, A. V. Kozlov, D. A. Pestunov, T. M. Rasskazchikova, D. E. Savkin, D. V. Simonenkov, T. K. Sklyadneva, G. N. Tolmachev, A. Z. Fazliev, and A. V. Fofonov, "Monitoring of atmospheric parameters: 25 Years of the Tropospheric Ozone Research Station of the Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences," Atmos. Ocean. Opt. **32** (2), 180–192 (2019).
34. B. D. Belan, G. A. Ivlev, and T. K. Sklyadneva, "Many-year monitoring of total and UV (B) radiation in Tomsk city," Opt. Atmos. Okeana **25** (1), 61–65 (2012).
35. B. D. Belan, G. A. Ivlev, and T. K. Sklyadneva, "Long-term monitoring of total and UV-B radiation in Tomsk," Atmos. Ocean. Opt. **25** (4), 281–285 (2012).
36. B. D. Belan, G. A, Ivlev, and T. K. Sklyadneva, "Variations of UV-B radiation in Tomsk in 2003–2007," Atmos. Ocean. Opt. **21** (7), 535–539 (2008).
37. Yu. V. Zhitorchuk, V. V. Stadnik, and I. N. Shamina, "Study of linear trends in time series of solar radiation," Izv. RAN. Fiz. Atmos. Okeana. **30** (3), 389–391 (1994).
38. https://aeronet.gsfc.nasa.gov. Cited February 26, 2020.
39. D. M. Giles, A. Sinyuk, M. G. Sorokin, J. S. Schafer, A. Smirnov, I. Slutsker, T. F. Eck, B. N. Holben, J. R. Lewis, J. R. Campbell, E. J. Welton, S. V. Korkin, and A. I. Lyapustin, "Advancements in the Aerosol Robotic Network (AERONET) Version 3 database—automated near-real-time quality control algorithm with improved cloud screening for sun photometer aerosol optical depth (AOD) measurements," Atmos. Meas. Tech. **12**, 169–209 (2019).
40. G. R. Casale, D. Meloni, S. Palmieri, and A. M. Siani, "Solar UV-B irradiance and total ozone in Italy: Fluctuations and trends," J. Geophys. Res. D **105** (4), 4895–4901 (2000).
41. T. K. Sklyadneva, T. M. Rasskazchikova, V. G. Arshinova, and M. Yu. Arshinov, "Changes in radiation and meteorological parameters of the atmosphere from observation data in Tomsk," Opt. Atmos. Okeana **31** (4), 288–293 (2018).

Translated by O. Bazhenov