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

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Abstract—We analyze the interrelation between the diurnal intake of UV–B radiation and a number of factors determining the absorption of UV radiation in the atmosphere (total ozone content (TOC), cloud fraction, 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.

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, of concentrations of greenhouse gases that retain the thermal infrared radiation near the Earth's surface. It is noteworthy that multiyear change in the integrated 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/m² in recent years. Authors of [5] gave more exact value of 0.6 ± 0.4 W/m². Despite the constancy of integrated incoming solar irradiance at the top of the atmosphere (solar constant), changes in the flux in the ultraviolet region of the solar spectrum may reach tens of percent [6–9]. Though accounting for just a few percent of the total solar irradiance, 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 is studying intensely the dynamics of the intake of ultraviolet solar radiation (UV radiation) to the Earth's surface and assesses its role in atmospheric processes [11–15].

Analysis of multiyear 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 the Northern Hemisphere. As an example, for cloud-free conditions the zonal average changes in 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 multiyear variations in UV radiation at wavelengths $\lambda = 305$ nm and $\lambda = 325$ nm at 12 stations, located in Canada, Europe, and Japan during 1990–2011 revealed a tendency for a reduction in the intake of 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 $\lambda = 305$ nm and by 0.88% per year at $\lambda = 325$ nm); while in 2006–2011 a deceleration in the growth of UV radiation was noted.

Clouds, albedo of underlying surface, atmospheric aerosol, ozone, and certain other trace gas admixtures can be considered among the main factors influencing the intake of 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 physical-

geographic and climatic features of the 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 may 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 intra-monthly variations, caused by albedo, are 32% in April (6%, on average) and 12−15% in summer months (3%, on average). TOC and clouds influence strongly 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 singled out conventionally in UV radiation reaching the Earth's surface; however, variations of radiation in region B and in the shortwave part of the 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]. The 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 of (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 may increase near the Earth's surface by up to 40% [23].

Clouds have no less effect on the incoming UV−B irradiance. For instance, data in [24] indicate that, for cloud cover of 10, the attenuation of UV−B radiation is 75 ± 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 may 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 snow-covered period, as compared to the snow-free period, the enhancement of integrated 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 near-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 a better understanding and more exact modeling of interrelations between UV−B radiation, ozone, aerosol, and clouds.

The first station for monitoring atmospheric parameters in the near-surface atmospheric layer was created in the framework of the international project for Tropospheric Ozone Research (TOR station) of European Program EUROTRAC in the 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 near-surface air layer at IAO SB RAS TOR station are used to analyze the interrelation of near-surface UV radiation with factors that alter its intensity (TOC, clouds, AOD).

DESCRIPTION OF INITIAL DATA

UV−B radiation had been monitored continuously at IAO SB RAS TOR station [33] from 2002 to 2018. Measurements in the wavelength range of 280−320 nm were carried out using 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 have been monitored using a Brewer MKIV spectrophotometer no. 049 [35, 36].

Hourly ground-based measurements were used to calculate diurnal, monthly, and yearly totals of 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 its increasing tendency: 2003−2010 and 2012−2017. The yearly totals varied within 6.5% over the period of measurements. The annual average intake 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 totals varied from 7 to 16% in different seasons (Fig. 1b). The maximal intake 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 diurnal average outcome 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 diurnal totals of 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 those 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.

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 radiative flux. In turn, a change in ozone content in the atmosphere has an effect on 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 short periods of time and is not always stable over short periods [40]. Nonetheless, the presence of feedback is obvious: the smaller the TOC value is, the larger the fraction of UV−B radiation reaching the Earth's surface.

Independent of the TOC, the intake of 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 diurnal totals of UV−B radiation for each day (Y_i) from multiyear average values for a given time of the day ($Y_{i\mathrm{aver}}$). The result
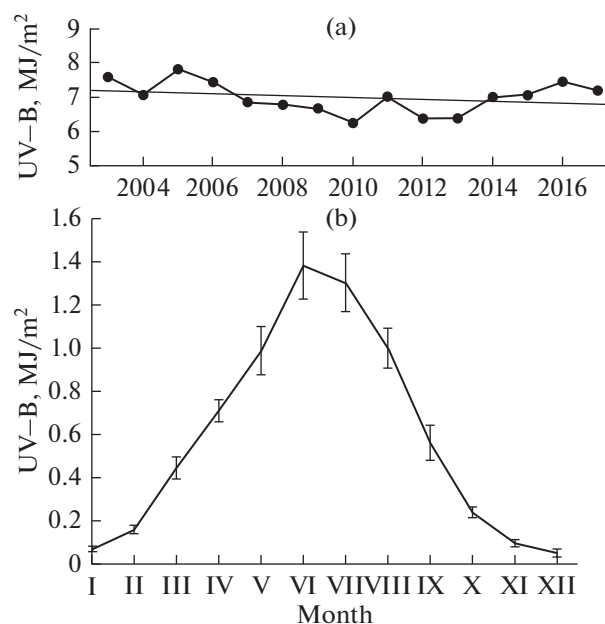

Fig. 1. (a) Interannual variations and (b) annual behavior of income of UV−B radiation in Tomsk.

was normalized by multiyear average values for a given day of the season over a period of time considered. The deviations were calculated from the formula

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

Thus, we obtained two multiyear (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 for 2011 shows relative deviations of TOC and diurnal totals of UV−B radiation from multiyear average values.

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 $\Delta UV{-}B$ radiation changes (in percent) in response to the total ozone content increase by 1%. The coefficient b represents a percentage increase in daily totals of UV−B-radiation relative to multiyear 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 study period, total and low-level clouds show a tendency to increase. We estimated the joint effect of clouds and the AOD on the diurnal intake of 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.
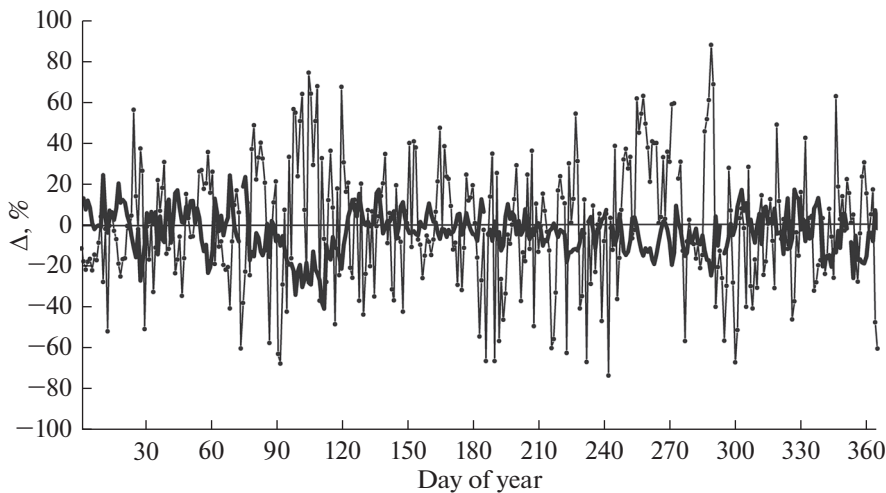
Fig. 2. Deviation of UV−B radiation (semi-bold line) and TOC (thin line) in 2011 from multiyear average values.

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

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

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

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

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

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

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

| Year	r	$a \pm \text{Se}(a)$	$b \pm \text{Se}(b)$
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; and $\text{Se}(a)$ and $\text{Se}(b)$ are standard errors of the regression coefficients a, b.

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

Then, from each of the five datasets above, we selected days with $AOD_{500} \leq 0.15$ ("clean 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 clean atmosphere. The correlation coefficients are significant with confidence no lower than 99% in all datasets. Despite the considerable dispersion of values relative to regression line (in Fig. 3), we can see quite a significant negative correlation, for which $r = -0.47$ under clear-sky conditions ($N_{total} \leq 2$) and −0.56 for the clean atmosphere, while for the cloudy sky ($8 < N_{total} \leq 10$) 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 after processing 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 $AOD_{500} \leq 0.15$ (Table 2).

From Fig. 3 and Table 2 it follows that under the conditions of the transparent atmosphere and minimal cloud cover the average deviation of UV−B radiation with respect to all deviations of daily totals of 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 daytime totals of UV−B radiation relative to the cloud-free and transparent atmosphere ($N_{total} \leq 2$, $AOD_{500} \leq 0.15$). The attenuation will be 0.7% for cloud cover $2 < N_{total} \leq 4$; 2.8% for $4 < N_{total} \leq 6$; 12.0% for $6 < N_{total} \leq 8$; and 28.7% for $8 < N_{total} \leq 10$.
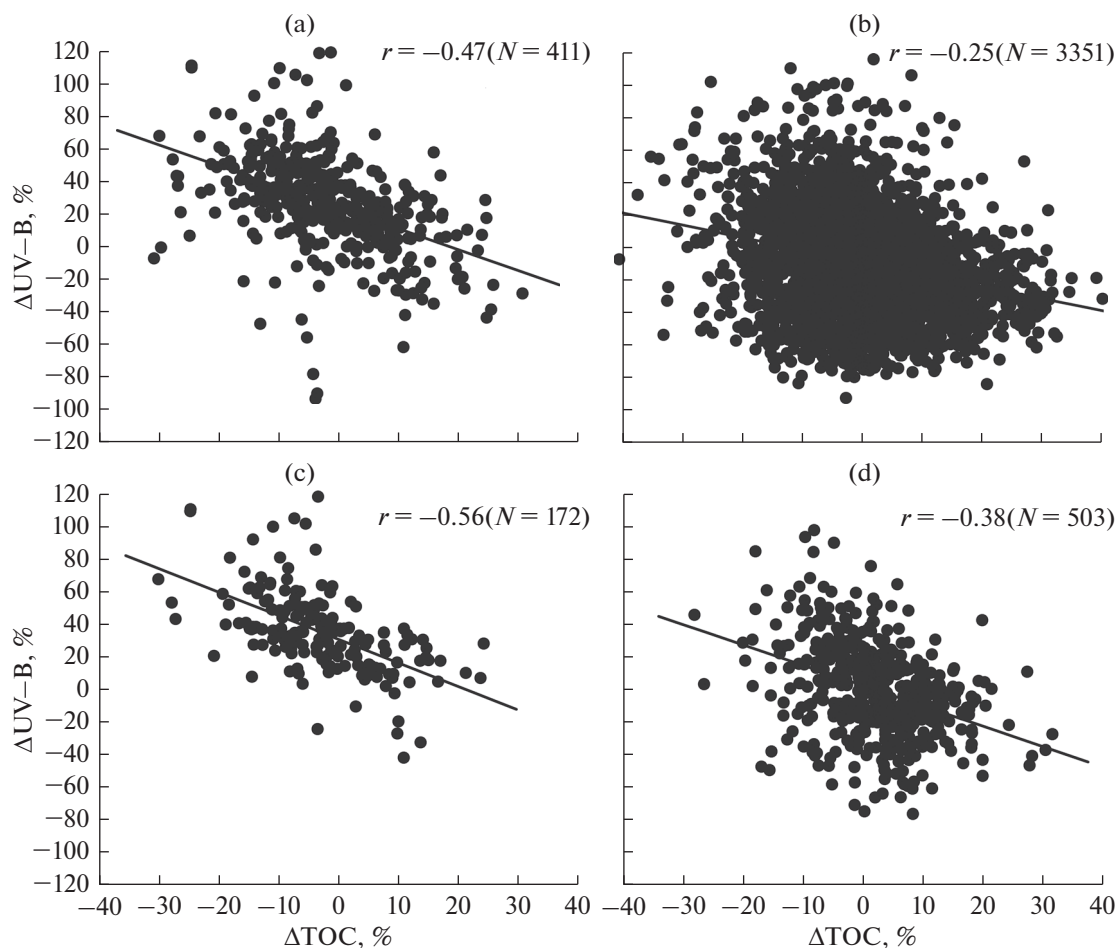
Fig. 3. Regression plot of $\Delta UV{-}B_i$ versus ΔTOC_i for clear-sky and cloudy days: (a) $N_{total} \leq 2$; (b) $8 < N_{total} \leq 10$; (c) $N_{total} \leq 2$, $AOD_{500} \leq 0.15$; (d) $8 < N_{total} \leq 10$, $AOD_{500} \leq 0.15$; the correlation coefficient is calculated using N points for the 0.99 confidence level.

Table 2. Dependences of $\Delta UV{-}B_i$ on ΔTOC_i for different cloud cover and AODs with 0.99 confidence level

Amount of total clouds	$a \pm Se(a)$	$b \pm Se(b)$	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

If the AOD is disregarded, under the conditions of minimal clouds the average deviation of UV−B radiation with respect to all deviations of daytime totals of UV−B radiation is 23.8%. Data in Table 2 make it possible to determine the effect 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 clean conditions is from 4.3 to 10.9% for the corresponding cloud conditions.

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

CONCLUSIONS

Multiyear variations in the diurnal intake of 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 in the Institute of Atmo-

spheric Optics, Siberian Branch, Russian Academy of Sciences, in 2003–2016. We can drew 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 short-wave radiation by 1.45%, on average.

The average contribution of the AOD to variations in the diurnal intake is from 4.3 to 10.9%, depending on the cloud cover.

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

In the studies, no account was taken of the data on surface albedo, which can also contribute appreciably to variations in dependence of values of UV–B radiation on the TOC.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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