RESEARCH PAPER

THE RADIATION RECONSTRUCTION MODEL (VERSION 2) AND ITS APPLICATION FOR ESTIMATING VARIABILITY OF ULTRAVIOLET RADIATION OVER THE 1968–2024 PERIOD IN MOSCOW

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Received: March 11th 2026 / Accepted: April 22nd 2026 / Published: June 30th 2026

https://doi.org/10.24057/2071-9388-2026-4580

ABSTRACT. Solar radiation is a vital component of the climate system, and knowledge of its temporal variation is of great importance. Ultraviolet (UV) radiation, due to its high photon energy, has a strong impact on the biosphere and human health. In this work, a reconstruction model (version 2) for estimating surface solar radiation long-term variability was proposed. It has been configured to assess the variability of erythemal UV radiation and UV-A radiation within the 315–400 nm spectral range. In this version of the model, physical parameterizations of UV radiation with respect to various factors have been refined, and an additional factor, which accounts for nitrogen dioxide influence on UV radiation, has been added. The model was validated against long-term UV measurements at the Moscow State University Meteorological Observatory, which has the longest continuous record of UV observations in the world. The mean RMSE of the differences between model simulations and measurements is on the order of 3% for annual values, which is comparable to the measurement uncertainty. High correlation coefficients (about 0.8) were observed between the modeled and measured values of the UV temporal variability for almost all periods. The analysis of surface UV radiation variability for the 1968–2024 period revealed noticeable UV fluctuations, which were characterized by a minimum in the late 1970s and early 1980s and a maximum after 2010. For erythemal UV radiation, the maximum amplitude of annual changes is about 30%, and for UV-A radiation it is about 19%. Much stronger changes were observed for erythemal UV radiation compared to UV-A radiation owing to the additional influence of ozone variability.

KEYWORDS: Reconstruction model, UV radiation, ozone, aerosol, cloudiness , long-term UV series

CITATION: Chubarova N. Ye. (2026). The Radiation Reconstruction Model (Version 2) And Its Application For Estimating Variability Of Ultraviolet Radiation Over The 1968–2024 Period In Moscow. Geography, Environment, Sustainability, 2 (19), 129-138
https://doi.org/10.24057/2071-9388-2026-4580

ACKNOWLEDGEMENTS: The work was funded by the RSF project No. 25-27-00014.

Conflict of interests: The author reported no potential conflict of interests.

INTRODUCTION

Solar radiation (SR) is an important component of the thermal balance, influencing the geographical distribution of the climatic resources of our planet. Ultraviolet radiation (UVR, 10–400 nm), despite its small energy fraction in the spectrum of solar radiation at the Earth's surface (about 5–10%), has a pronounced biological effect, especially in the UV-B region (280–315 nm), due to the increase in photon energy with decreasing wavelength.

Surface solar energy experiences noticeable seasonal and interannual variations due to the influence of various factors (Liou 2010, WMO 2007). The most important factors are the astronomical ones, mainly a solar angle above the horizon. Geophysical factors also have a significant impact on SR. Depending on the spectral range, gas absorption of solar radiation may play an important role. In the UV range of the spectrum, there are strong absorption bands of ozone. In addition, some other gases (nitrogen dioxide, sulfur dioxide, and a number of organic gas species) also have absorption bands there. In the visible range, relatively weak absorption by ozone and nitrogen dioxide is observed. The infrared spectral region is characterized by strong water vapor absorption bands, as well as by the absorption of a number of other gases like CO2, CH4, and others (Timofeev and Vasiliev 2003). At the same time, the content of the number of gases in the atmosphere is low, and their effect on the actual attenuation of solar radiation may be negligible.

Atmospheric aerosol also has a significant effect on the attenuation of solar radiation. Its properties can exhibit noticeable temporal and spatial variability, especially over recent decades (Zhang et al. 2025). Noticeable changes in aerosol content with a pronounced negative trend have been observed in the Moscow region (Poliukhov et al. 2024). The influence of this factor is particularly pronounced in the UV range of the spectrum due to the prevailing fine aerosol fraction, which increases aerosol optical thickness at shorter wavelengths.

Cloud cover is one of the most important factors affecting solar radiation. Its optical properties are determined by cloud particle size distribution and their aggregate state. Optically thin ice clouds of the upper layer have a weak effect on radiation, while clouds of the lower level noticeably attenuate SR (Abakumova et al. 2008, Calbo et al. 2005). The cloud amount and their spatial structure also play a noticeable role (Chubarova 1998).

Solar radiation has experienced significant interannual changes in the 20th and 21st centuries. Thus, according to the results of global monitoring, a noticeable decrease in surface SR was revealed approximately in the middle of the twentieth century, which was replaced by its growth since the early 1980s (Ohmura 2009, Wild 2009, Long et al. 2009, Wild 2012, Sanchez-Lorenzo et al. 2015, Wild 2016). Since the early 1990s, solar radiation over the European plain has also shown a weak but significant upward trend (The third assessment report 2022, Gorbarenko 2016, Volpert, Chubarova 2021). The causes of these phenomena are mainly related to temporal variations in cloud amount (Abakumova et al. 1996, Stjern et al. 2009, Liepert et al. 2002, Volpert, Chubarova 2021, Gorbarenko 2020, Gorbarenko 2022), variations in atmospheric aerosol (Streets et al., 2009, Wang et al., 2009, Volpert, Chubarova 2021), and gas composition, especially ozone for the UV-B spectral region (Chubarova, Nezval 2000). The indirect influence of cloud-aerosol effects may also be important (Lohmann and Feichter 2005).

Notable long-term trends have also been observed for surface UV radiation (Krzyścin J et al. 2025, den Outer et al. 2010, Čížková, K. et al. 2018, McKenzie et al. 1999, etc.). It should be noted that spatial and temporal variations in UV radiation near the Earth's surface are very significant due to strong variations in geophysical parameters (Wang et al. 2013, Zubov et al. 2025). In addition to the ozone reduction, the decreases in cloud amount and aerosol loading play a significant role in the positive trends of UV radiation observed after the mid-1990s over northern mid-latitudes (Bais et al. 2014).

In order to quantify the interannual changes in surface SR and UVR in different geographical conditions, different reconstruction models are usually used (Kaurola et al. 2000, Krzyscin et al. 2004, Chubarova 2008, Lindfors et al. 2007, etc.). Reconstruction models are the tools that are applied to assess the long-term variability in SR and UVR when direct measurements are unavailable. These models have evolved from simple empirical formulas to the complex account of the physical processes, with additional use of reanalysis data. With the help of these models, it is possible to estimate the influence of a particular geophysical factor and quantify its contribution to the variability of solar radiation.

For example, the most advanced studies of long-term UVR trends (WMO 2007) rely on these reconstructed datasets, which allow separation of the effects of ozone depletion and assess the effects of cloud and aerosol variability on ultraviolet radiation near the surface (WMO 2007, Herman 2010). These models have played a crucial role in assessing long-term trends in UV radiation and identifying their causes. However, not all geophysical factors were taken into account in these models, and some of the dependencies have to be improved. Note that modern machine learning methods, with their high efficiency, do not allow such analyses to be done.

In this paper, an improved version of the reconstruction model is proposed, which has been configured for the evaluation of surface UV radiation changes, taking into account new factors and refining previously obtained parameterizations in the first version of the UV reconstruction model, presented in (Chubarova 2008). This version of the model can also be used for other spectral ranges after appropriate additional correction. The emphasis on the study of UV radiation is related to its strong influence on the biosphere and the connection of UV radiation with climate change (Bernhard et al. 2023, Barnes et al. 2022). The assessment of long-term changes in UV radiation is especially important, since many biological and health effects depend on the dose of ultraviolet radiation accumulated over a long period. Therefore, the assessment of possible UV changes in previous decades is very essential.

DATA AND METHOD DESCRIPTION

The development of the new version of the UV reconstruction model was based on the results of model calculations and some parameters retrieved from the UV measurements at the Moscow State University Meteorological Observatory (MSU MO) (55.7ºN, 37.5ºE).

For calculations, the TUV (Tropospheric Ultraviolet Visible) radiation model with the 8-stream discrete ordinate method (Madronich and Flocke 1998) was applied in the study. This radiative model produces the smallest errors in calculating UV radiation (less than one percent). The radiative simulations were performed in the range of 280–400 nm with a resolution of 1 nm. The vertical distribution of the model included 80 layers at 1 km resolution. We used model simulations mainly for the estimation of several physical parameters, which cannot be obtained from measurements.

Various datasets were applied as the input parameters for the reconstruction model. In particular, the data of total ozone content from the Central Aerological Observatory (CAO) available via the archive of the Voeikov Main Geophysical Observatory (VMGO) were used to assess ozone content before 1979, and for the later period, the NASA satellite measurements (TOMS, EARTH Probe, OMI) were used. In the absence of satellite measurements during the 1993–1996 period, we again used the ground-based ozone data from the CAO. Studies have shown that the differences between satellite and ground-based measurements lie within a few percent (Piacentini et al. 2002), which is satisfactory accuracy for their application in the reconstruction model.

For characterizing the aerosol attenuation, the aerosol optical thickness (AOT) at 340 nm was applied. These data were available from the AERONET data at Moscow State University for the 2002–2021 period. For other periods, we converted the estimates of AOT at 550 nm from the measurements of direct short-wave radiation and atmospheric moisture content (Tarasova, Yarkho 1991) to AOT at 340 nm using the climatic values of the Angstrom parameter from AERONET climatology in Moscow. It should be noted that there is a satisfactory agreement between the values of aerosol optical thickness in the visible range of the spectrum obtained from direct AERONET measurements and the AOT values calculated using the method described in (Tarasova, Yarkho 1991).

Satellite data on NO_2 content measured by the OMI instrument (Burrows et al. 1998) were used to account for the effects of nitrogen dioxide on UV radiation. In the analysis, the period from 2005 to 2024 was considered, as no reliable NO_2 data were available before that time. When calculating for longer periods, it was assumed that NO_2 values for the previous period corresponded to the mean values observed in 2005 and 2006, and they did not change.

Such an approach is justified because restrictions on gasoline quality in Moscow were introduced only in 2005. It should be noted that accounting for the NO_2 content is especially important in urban conditions similar to those of the Moscow metropolitan area, where its concentrations are relatively high.

The values of the spatial surface albedo, A, were also used as an input parameter in the model. In the UV region, it was set to 0.02 for the warm period, and for the cold snow period, this value was assumed to be 0.4. This is lower than the local snow surface albedo due to the influence of dark trees and buildings, in accordance with the TOMS MLER data (Chubarova et al. 2002). During the transition periods, we applied the degree of snow coverage coefficient, which is a standard characteristic measured at meteorological stations.

For obtaining the data on cloud amount, we used hourly visual cloud observations at the MSU MO for the 1968-2024 period. UV cloud transmission at different cloud amounts was estimated from long-wave UV measurements (Chubarova 1998). To simulate the UV effects due to cloud optical thickness (COT), the hourly measurements of global shortwave radiation in the absence of direct radiation were used with the additional correction for the UV spectral region.

Validation of the UV reconstruction model was carried out using long-wave UV observations since1968 at the MSU MO (Chubarova, Nezval 2000), which are the longest series of UV radiation measurements in the world. The long-wave UV measurements were carried out using UV pyranometers (Vysotsky et al. 1982) and some other instruments, which were calibrated for the same 300–380 nm spectral region. However, this is not a standard spectral range. Therefore, for this study, the measurements were converted to the standard UV-A region (315–400 nm). For this purpose, the parameterization has been obtained, based on TUV model simulations in both the 300–380 nm and 315–400 nm spectral regions with different geophysical input parameters. Additionally, we compared the obtained results with the direct evaluation of the difference between UV radiation within the 300–380 nm and 315–400 nm ranges during the international UV Filter Radiometer comparison 2017 campaign at the PMOD/WRC, Switzerland in 2017 (Hülsen, Gröbner 2018). The two dependencies show good agreement with a difference of approximately 2%. The entire dataset before 2021 was corrected, using the obtained parameterization. Since 2021, direct UV-A observations have been a part of measurements of a new radiation RAD-MSU (BSRN) complex, which has been in operation at the MSU MO. As a result, for the 1968–2024 period, the long-term homogeneous series of UV-A radiation measurements were obtained.

The results of the model reconstruction of erythemal UV radiation (UVery) were also tested. Erythemal UV radiation is a biologically active UV radiation that causes erythema (skin redness) and is characterized by a specific spectral erythemal sensitivity. Testing the quality of UVery reconstruction has been carried out since 1999, when regular measurements of erythemal UV radiation began at Moscow State University (Chubarova 2002, Zhdanova et al. 2014). Since 2021, erythemal UV radiation has been measured as a part of the monitoring program of the new radiative RAD-MSU (BSRN) complex. The entire UVery dataset has been calibrated against the instrument, which was in turn tested during the international UV Filter Radiometer comparison in 2017 at the PMOD/WRC, Switzerland. Hourly UVery data were corrected for solar elevation and ozone according to the standard procedure (Hülsen, Gröbner 2018). In addition, the quality of UV measurements was tested by comparisons with model estimations in clear sky conditions. The analysis has shown a satisfactory agreement between measurements and model data.

RESULTS

Description of the UV radiation reconstruction model

The proposed reconstruction model is intended to assess the long-term variability of surface solar radiation due to various geophysical factors. The version of the model is a further development of the UV reconstruction model described in Chubarova (2008), however, the new version includes new factors, refinements, and new physical parameterizations. An additive approach is used, in which the effect of each factor is assessed separately with the exception of those, which assessment requires accounting for mutual influence.

The interannual variability of solar UV radiation (V_i) per month, season, or year can be written as the sum of UV relative changes caused by variations in total ozone content (*v1*), changes in nitrogen dioxide content (*v2*), variations in aerosol optical thickness (*v3*), changes in UV transmission due to cloud cover (*v4*), and variations in cloud optical thickness (*v5*) as shown in Eq. (1):

$$V_i = \sum_j \Big[W_j(h)\Big(v1_{i,j}([O3]) + v2_{i,j}([NO2]) + v3_{i,j}(AOT, Pclear) + v4(CQ, A) + v5_{i,j}(OT, Pov, A)\Big)\Big] I \sum_j W_j(h) \quad (1)$$

where the index *i* corresponds to the year number, and the index *j* corresponds to the month number; *[O3]* is the total ozone content; *[NO2]* is the nitrogen dioxide content; *AOT* and *OT* are the optical thickness of aerosols and clouds; Pclear and Pov are the frequencies of clear and cloudy days; *CQ* is the cloud *UV* transmission for different cloud amounts; and *A* is the spatial surface albedo.

The equation also takes into account the weighting function W_j, which has a power-law relationship with solar angle $W_j(h)=h^b$, where b is the coefficient obtained from model calculations; it decreases with increasing wavelength. According to model simulations for erythemal UV radiation, *b* = 2, and for UV-A radiation, *b* = 1.3. In the further analysis, the influence of each geophysical factor in the new model version will be described.

The effect of total ozone on UV

The relative changes of UV radiation *(dQoz/Qoz_mean)* against its mean value to variations in total ozone content against its mean value *d[O3]/[O3mean]*, *v1*, are estimated by taking into account the radiation amplification factor *Rx(h)*, which depends on the solar angle h and spectral range considered (Eq. 2):

$$v1_{i,j} = \frac{dQoz_{i,j}}{Qoz\_mean} = Rx(h^j)\left[\frac{d[O3]i,j}{[O3]mean}\right] \quad (2)$$

For erythemal UV radiation at $h = 40°$, *Rx(h)* is -1.1, which is consistent with Andrady et al. (2010). However, due to the shift of the effective wavelength with a change in solar angle, this value may noticeably vary. Therefore, the new version of the model takes into account the *Rx* dependence on solar angle. The following parameterization was estimated using modeling for the range h = 5–90⁰ (Eq. 3):

$$Rx(h) = -0.0000019\,h^3 + 0.000387\,h^2 - \\ -0.0246h - 0.68305,\ R^2 = 0.997 \quad (3)$$

For the UV-A region, the *Rx* value is small (Rx_{UVA} = -0.02), because ozone absorption is very weak there.

The application of *Rx* dependence on solar angle significantly changed the estimation of UVery variability due to ozone during winter months, when solar angle is small. For example, in December, the estimated UVery variability due to ozone has changed by up to 6% compared to the previous version of the model due to changing Rx from -1.1 to -0.89 at a solar angle of about 10°. For annual values, the difference of UVery variability was within 1% compared to the first version of the model.

Overall, the ozone factor contributed to maximum UVery annual variations of up to 15% for the 1968-2024 period with a standard deviation of 3.5%. For UV-A radiation, the ozone effect is very small with a maximum annual variability of up to 0.2%.

The effect of nitrogen dioxide on UV

The account of nitrogen dioxide [NO²] influence on UV radiation (v2) was carried out according to the model dependence of relative UV sensitivity to changes in NO² content per 1 matm.cm obtained in (Chubarova 2006). Using this relative UV sensitivity, we can estimate $v2_{i,j}$ (Eq. 4):

$$v2_{i,j} = \frac{dQNO2_{i,j}}{QNO2mean} = [NO2]_i\left(A \times ln\left(h_j\right) - B\right) - \\ -[NO2]_{mean}\left(A \times ln\left(h_j\right) - B\right),\ R^2 = 0.99 \quad (4)$$

According to the model calculations, the coefficients *A* and *B* for UVery are equal to *A* = 0.0083 and *B* = 0.0431, respectively, while for the UV-A region, these coefficients are the following: *A* = 0.0138 and *B* = 0.074. The difference in the *A* coefficients demonstrates a stronger UV-A dependence on NO_2 content. This happens since there is an increase in NO_2 absorption coefficients with wavelength in the UV range. Similarly, the influence of other small gas species with absorption bands in the UV range, such as SO_2, HCHO, etc., can be accounted for by using a similar scheme. However, their concentrations in Moscow are very low and do not have a significant impact on the interannual UV variations, while the influence of NO_2 on UV in urban environments can be noticeable.

According to the satellite OMI data, the mean NO_2 content during the 2005–2024 period was equal to 0.57 matm.cm and was characterized by a noticeable negative linear trend of 0.05 matm.cm per 10 years (with correlation coefficient r = 0.68). The observed NO_2 variations led to small annual changes of 0.2% in erythemal UV radiation and of 0.4% in UV-A radiation. However, for winter months with low solar angles, the effects are more pronounced. For example, in December, variations reach 0.5% and 0.8%, respectively, for UVery and UV-A radiation. Despite the noticeable negative trend in NO_2 content, these changes have a limited impact on the temporal fluctuations of UV radiation in Moscow.

The effect of aerosol on UV

The relative changes in UV radiation due to aerosols (v3) were estimated with a new scheme, taking into account the effects of surface albedo and a more accurate assessment of aerosol attenuation. These values were calculated using the parameterization obtained from accurate model simulations with account of AOT, single scattering albedo SSA = 0.92, Angstrom parameter *α*, and solar angle h as well as the frequency of days during a month, when it is possible to estimate AOT (*Pclear)*. The parameterization is the following (Eq. 5):

$$v3_{i,j} = \frac{Pclear_{i,j}dQaer_{i,j}}{Qaer_{mean}} = Pclear_{i,j}\left(AOT_{550,i,j}\left(\frac{550}{340}\right)^{a^i} - \\ -AOT_{550mean,i,j}\left(\frac{550}{340}\right)^{a^i}\right)\left\{\left(0.42\frac{1}{\sin h_j} + 0.93\right)SSA + \\ + \left(-0.49\frac{1}{\sin h_j} - 0.97\right)\right\},\ R^2 = 0.99 \quad (5)$$

Note that in summer, mean *Pclear* is equal to 47%, while in some years, it can reach 97%. In winter, mean *Pclear* is only 10% with the maximum of 53% in some years. The decrease in this frequency in winter leads to a much smaller effect of aerosol.

The new aerosol scheme in the reconstruction model has significantly changed the assessment of its impact on UV radiation since the old scheme used only an empirical relationship between UV radiation and aerosol optical thickness. The maximum UV variability due to aerosols reaches only 3%, with a standard deviation of 0.6%. The application of the new aerosol scheme provided a slightly reduced positive UV trend compared to the old aerosol scheme. However, the overall trend of increasing UV radiation in recent years due to the decrease in aerosol has not been affected. This negative AOT trend has been revealed according to the AERONET measurements during the recent decades (Poliukhov et al. 2023).

The effect of cloud amount on UV

The UV variability due to cloud amount (v4) was obtained by using the estimates of effective UV cloud transmittance. First, this characteristic at zero albedo (*A=0*) was calculated as $CQ_{A=0}$=*Q/Q*, where *Q* is the global UV radiation in the presence of clouds, and *Q0* is the UV radiation in their absence at the same other parameters and zero surface albedo.

The $CQ_{A=0}$ is defined as a combination of relative cloud amount frequency, weighted by the cloud transmittance in the UV range (Eq. 6):

$$CQ_{A=0} = \sum_{Nl=0}^{10}\left(\{P(Nl) - P(Nl, N=10)\}\right) \\ CQ_{A=0}(Nl) + P(Nl, N=10) \\ CQ_{A=0}(Nl)\,CQ_{up} \quad (6)$$

Here, *P(Nl)* is the frequency of the most dense lower-level cloud amount *Nl* at different total cloud cover amounts *N* for a given month; *P(Nl, N = 10)* is the frequency of total cloud amount *N* = 10 when lower-level cloud amount is different. The UV transmittance at different lower-level cloud amount $CQ_{A=0}$*(Nl)* and at overcast upper-level clouds are determined according to long-term measurements (Chubarova 1998). This equation is based on the assumption that upper- and middle-level clouds affect the UV transmittance only when *N* = 10. Hence, this method independently considers the UV transmittance by optically dense lower-level clouds and thin upper-level clouds.

When the surface albedo is high, the effects of multiple reflection between the surface and the atmosphere should be taken into account.

For cloudy conditions, the multiple reflection coefficient *R* is defined as follows (Eq. 7):

$$R = r0(1-N) + N \times (r0 + k \times OT) \quad (7)$$

Here, *r0* is the coefficient of multiple reflection between a surface with different albedo and a cloudless atmosphere, *N* is the cloud amount, and *OT* is the cloud optical thickness. The efficiency of multiple reflection in a cloudy atmosphere is determined by the coefficient k. According to model calculations, this value is equal to 0.58.

The coefficient of multiple reflection in clear sky conditions, *r0*, is determined by the properties of the atmosphere and has different relationships with various atmospheric parameters, depending on the spectral range. According to model calculations for UV-A radiation, the coefficient of multiple reflection, *r0*, is determined by AOT at 550 nm, while for erythemal radiation *r0* is determined by the total ozone content [O3].

Based on model calculations, the following parameterizations of the *r0* coefficients for UVery and UV-A radiation are as follows (Eqs. 8–9):

$$r0(UVery) = -0.000081 \times [O3] + 0.39667,\ R^2 = 0.93 \quad (8)$$

$$r0(UV-A) = 0.0247AOT550 + 0.3124,\ R^2 = 0.94 \quad (9)$$

The multiple reflection coefficient *R* in cloudy conditions is assumed to be proportional to the radiative loss due to clouds (Eq. 10):

$$R = r0 + k\left(1 - CQ_{A=0}\right) \quad (10)$$

Accordingly, we represent UV radiation at surface albedo *A* for cloudless and cloudy conditions as Eqs. 11–12:

$$Q_A = Q_{A=0} / (1 - r0\,A) \quad (11)$$

$$Q_A = Q_{A=0} / (1 - R\,A) \quad (12)$$

As a result, the UV cloud transmittance at surface albedo *A* can be estimated as Eq. 13:

$$CQ_A = CQ_{A=0}(1 - Ar0) / \left(1 - A\left(r0 + k\left(1 - CQ_{A=0}\right)\right)\right) \quad (13)$$

The CQ_A value is used in the calculation of UV variability due to UV cloud transmission $v4_{i,j}$ (Eq. 14):

$$v4_{i,j} = \frac{dCQ_{Ai,j}}{CQ_A mean} \quad (14)$$

This updated scheme for estimating UV variability due to cloud amount at different surface albedo also led to the changes with a maximum range of 0.6% compared to the old scheme. The spectral features of R also have an impact on the difference in the changes of UVery and UV-A radiation due to different types of dependencies for r0 (see Eq. 8 and Eq. 9). The range of variability lies within 3.2% for annual values. However, for the summer period, when surface albedo does not change, the range of variability is significantly lower, approximately 1.8%.

Overall, cloud amount is one of the most significant factors affecting the interannual variability of solar radiation. Over the period from 1968 to 2024, the maximum range of UV variability was approximately 18%, with a standard deviation around 4.5%.

The effect of the cloud optical thickness on UV

The radiative attenuation due to the optical thickness of clouds (v5) was calculated in conditions of the full absence of direct solar radiation S, i.e., in conditions of a continuous dense extended cloud cover. Variations in effective radius of cloud particles were not taken into account, since they are negligible compared to the effects of cloud optical thickness (Liou 2010). In addition, frequency of cases with optically dense extended cloudiness, *Pov*, was taken into account. This approach allows a user to estimate the contribution due to variations in cloud optical thickness ($v5_{i,j}$) according to Eq. 15:

$$v5_{i,j} = \frac{Pov_{i,j} dCQ_A(S=0)_{i,j}}{CQ_A(S=0)\,mean} \quad (15)$$

In this case, UV cloud transmissions were calculated using cloud transmissions of the entire short-wavelength range, following the previously obtained parameterization (Chubarova et al., 2018).

The use of a new scheme for describing the effect of optically dense clouds compared to the old scheme results in differences of approximately 0.3–0.4%. The maximum interannual differences in UV variability due to this factor are approximately 4%, with a standard deviation of 0.7%. The results of the comparisons between the new and the old model version are presented in Table 1.

The reconstruction model was tested against long-term UV-A measurements for the 1968–2024 period and against UVery measurements for the 1999–2024 period. The assessment of the uncertainties of the UV reconstruction model should account for the existence of the UV measurement errors, which equal approximately 5% according to the instrument certificates[1].

Table 2 shows the estimates of correlation coefficients and RMSE between measurements and model estimates of UV variability. It can be seen that the model generally reproduces relative variability of UV radiation over the years. During the warm season, when the accuracy of input parameters is high, the correlation coefficient between the model and measured values is approximately 0.83. For annual values, the correlation coefficients are slightly lower (0.79 and 0.76, respectively, for UV-A and UVery, see Table 2), which can be attributed to both the increased uncertainty of the albedo effect and the increased measurement errors during the cold season. The mean RMSE estimates are

Table 1. The comparisons of UV relative changes caused by variations in different geophysical factors between the new version 2 and the old model version for UVery and UV-A radiation (given in parentheses), expressed in terms of relative variability (%)

	Ozone impact (v1,%)	NO_2 impact (v2,%)	Aerosol impact (v3,%)	Effective cloud amount impact (v4,%)	Cloud optical thickness impact (v5,%)
Maximum range of difference	1% (-*)	A new factor	2.5% (2%)	0.6%(0.6%)	0.3% (0.4%)
Standard deviation	0.2% (-*)		0.6% (0.5%)	0.13% (0.14%)	0.06% (0.08%)

Comments: * – since another spectral region was used, hence, the comparison is not meaningful.

[1] https://www.kippzonen.com/

approximately 3.1%, which is lower than the measurement errors of approximately 5%.

Therefore, we can conclude that the reconstruction model (version 2) satisfactorily reproduces the interannual variability of UV radiation.

Regarding monthly UV variability, it can be seen that the correlation coefficient significantly increases in the spring and summer months, and the RMSE is approximately equal to the measurement errors. However, in January, the RMSE increases, reaching 11% and 17.9% for UV-A and erythemal UV radiation, respectively. This can be partly attributed to the uncertainties of measurements due to the problems with stability of sensor temperature during the cold season, especially in the first years of measurements, when there were particularly significant differences in erythemal UV radiation. Additionally, the model may not account for the more complex effects of three-dimensional re-reflection in conditions of broken clouds and high surface albedo, which can also contribute to the increase of uncertainty. Nevertheless, the model generally explains more than 60–80% of the observed variability of UV radiation in most months and seasons. It should be noted that only physically determined dependencies have been applied in the model with no additional correction factors.

Variability of surface UV radiation in Moscow according to the reconstruction model

We analyzed the main features in UV variability in the Moscow region using the proposed reconstruction model. Figure 1 shows the interannual variability of annual UV-A and UVery values for the 1968–2024 period. This variability of both UV-A and UVery radiation has revealed a pronounced minimum in the late 1970s and early 1980s, which was followed by an increase that has been decelerating in recent years. The amplitude of UVery variability (around 30%) is significantly higher than that of UV-A radiation (19%) mainly due to the additional strong influence of ozone on UVery. The differences in the interannual variability between UV-A and UVery radiation vary from -9% to +7%.

The observed UVery trends are in good agreement with the reconstructed UVery data for Central and Eastern Europe (Krzyscin et al. 2004), which also show a significant decrease in the late 1970s and an increase in the 1990s. This confirms the regional nature of the observed variability of UV radiation.

The maximum positive deviation of erythemal UV radiation (+13%) was seen in 2011, when mini ozone holes were observed in spring over northern and eastern Europe (Bernhard et al., 2013) and directly over Moscow. The lower ozone values were also registered in summer. The parallel increase in UV-A radiation in 2011 indicates that this increase was also influenced by other factors, primarily the decrease in cloud cover. This is in agreement with (Bernhard et al. 2013), where it was pointed out that the strong increase in UV in Scandinavian countries was explained by both ozone and cloud decrease. A detailed analysis of the causes of UV variations will be presented in a separate paper. In recent years, after 2011, there has been no significant trend in the erythemal UV radiation. However, the UVery level is approximately 5–8% higher than the average value over the 1968–2024 period.

Fig. 2 presents the interannual variability of UV-A and erythemal UV radiation according to the reconstruction model for the central months of the seasons. One can see different trends in UV radiation for different months of the year. In winter, there is a decrease in UV radiation for both spectral ranges, while in April, July, and October there is a pronounced statistically significant UV increase. The positive trends in April and July are higher for erythemal UV radiation (3–4% per 10 years) compared to UV-A radiation (2% per 10 years).

Fig.3 shows UV variability over the year and over the warm (May-September) period, which demonstrates a consistency of their UV changes. The correlation coefficients

Table 2. The correlation coefficients and Root Mean Square Errors (RMSE) between the results of the UV reconstruction model and measurements for the year, warm season, and central months of the seasons

	Spectral range	Period	Correlation coefficient	RMSE
Year	UV-A	1968–2024	0.79	3.10%
	UVery	1999–2024	0.76	3.10%
Warm period (May–September)	UV-A	1968–2024	0.83	3.20%
	UVery	1999–2024	0.83	3.10%
January	UV-A	1968–2024	0.73	11.00%
	UVery	1999–2024	0.50	17.90%
April	UV-A	1968–2024	0.83	5.60%
	UVery	1999–2024	0.85	5.40%
July	UV-A	1968–2024	0.86	4.80%
	UVery	1999–2024	0.90	4.40%
October	UV-A	1968–2024	0.88	7.90%
	UVery	1999–2024	0.82	8.70%

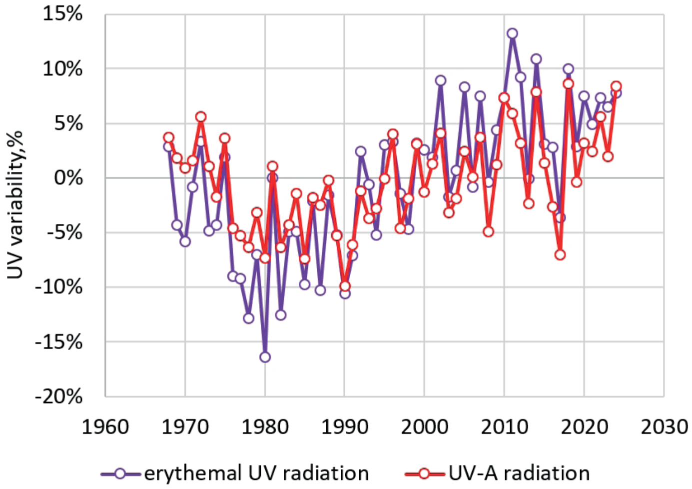

Fig. 1. Variability of annual UV-A and erythemal UV radiation in Moscow according to the reconstruction model (version 2) for the 1968–2024 period. The data are normalized over the 1968–2024 period

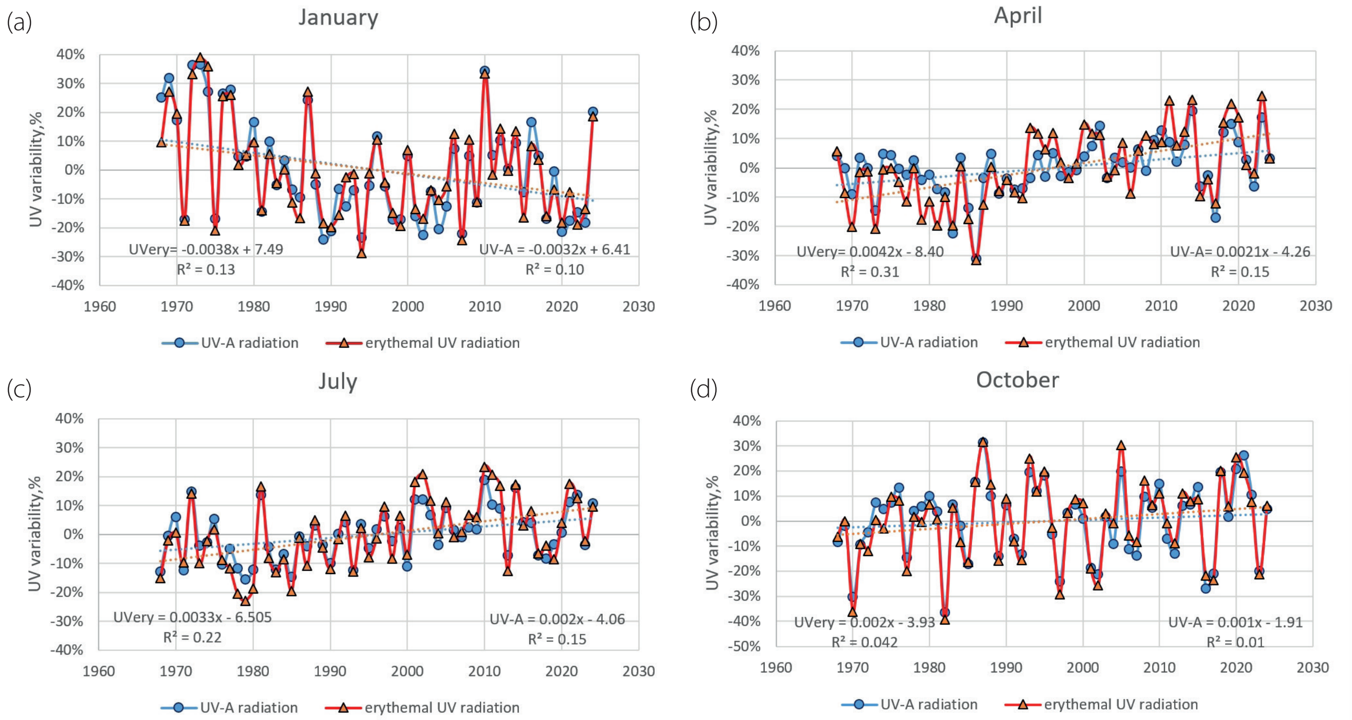

Fig. 2. Interannual variability of UV-A and erythemal UV radiation according to the reconstruction model for January (a), April (b), July (c), and October (d). The dotted lines show the linear trends for these periods

between them for erythemal and UV-A radiation are 0.97 and 0.9, respectively. The close relationship between the annual values and values during the warm season is determined by a high fraction of UV radiation during the warm season, reaching 70% for UV-A radiation and 78% for UVery due to higher solar angles in the warm period. Therefore, the higher errors of the reconstruction model during the winter season do not significantly affect the estimates of variability of annual values.

DISCUSSION AND CONCLUSIONS

An improved version of the solar radiation reconstruction model (version 2) has been proposed. This model has been configured to assess the variability of surface ultraviolet radiation in different spectral ranges. All model blocks have been modified, and a new block has been added. The application of the dependence between the radiation amplification factor due to ozone and solar angle has provided a much more accurate description of the winter UVery variations compared to those in the old version of the model. The account of the NO_2 impact on the UV variability was added. The changes in NO2 content provide UV response of a maximum of 0.5-0.8% in winter months. The aerosol block of the model was also modified: instead of an empirical equation, a model parameterization taking into account the optical aerosol properties has been used. This has slightly adjusted the trend of UV radiation due to aerosol. The coefficients of multiple reflection for UVery and UV-A radiation have been refined. In clear sky conditions, their values were shown to be determined by ozone for erythemal UV radiation and by aerosol for UV-A radiation. The estimates of UV variability due to cloudiness also have been refined.

Testing the model against measurement data from the Meteorological Observatory of Moscow State University has shown satisfactory results. The mean RMSE values are around 3% for annual values, which is comparable to the measurement errors themselves, especially during the first years of the UV monitoring period. The correlation coefficients between the model and measured values of UV variability are high (around 0.8), especially during the warm season, when the model uncertainties associated with surface albedo are lower. At the same time, the variability

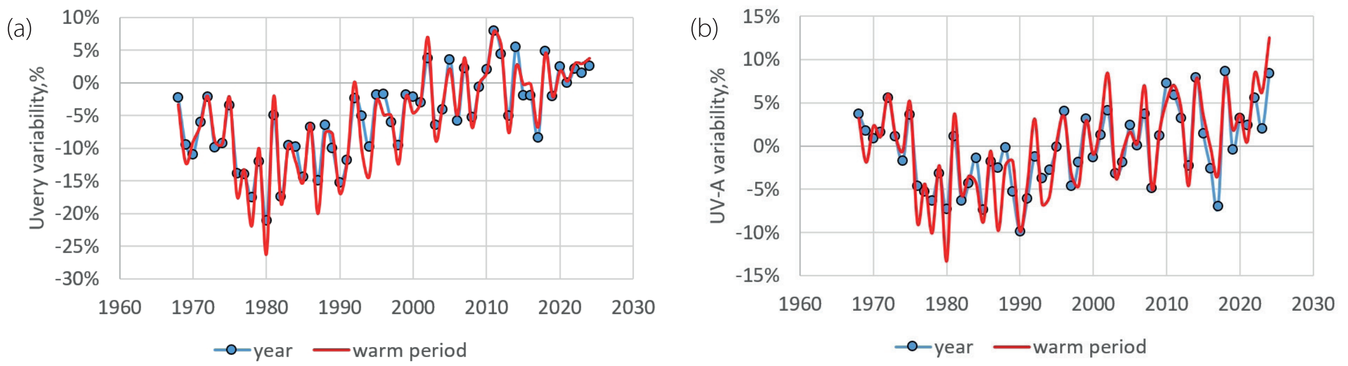

Fig. 3. Variability of UVery (A) and UV-A (B) radiation over the year and over the warm (May–September) period according to the reconstruction model in Moscow for the 1968–2024 period

of UV radiation during the warm season largely determines its annual variability, as evidenced by the corresponding high correlation coefficients between these series. The values in brackets should be changed to (around 0.9-0.97)

The previous version of the UV reconstruction model provides a similar order of the correlation coefficients for different seasons, except winter (R = 0.4 in the previous model vs. R = 0.55 in the new one). The new model has a better agreement due to a better account of cloud optical thickness and the *Rx* dependence on solar angle. However, the limit for further model improvement is set by the quality of the measured data with the uncertainty of approximately 5%, particularly during the cold season when air temperatures are negative.

The analysis of surface UV radiation variability over this period has revealed noticeable changes with a minimum in the late 1970s and early 1980s and a maximum after 2010. Moreover, the variations are more pronounced for erythemal UV radiation mainly due to an additional consideration of ozone variability. At the same time, there are multidirectional UV changes in different months of the year: in January, the trend is negative, while in April, July, and October, it is positive. The positive trends in April and July are higher for erythemal UV radiation (3–4% per 10 years) compared to UV-A radiation (2% per 10 years).

Thus, the new version of the reconstruction model has enabled identification of the general features of long-term UV variability for two spectral regions and their differences. For the Moscow region the spectral differences are mainly expressed in a significantly lower UV-A changes with maximum amplitude of 19%, compared to the 30% amplitude of erythemal UV radiation.

The proposed reconstruction model can also be used for assessing the variability of solar radiation in other spectral regions after tuning several coefficients.

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