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Typical distribution of the solar erythemal UV radiation over Slovakia

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Abstract

Maps of the solar erythemal ultraviolet (UV) radiation daily doses were created for every month with horizontal resolution of 500 m at geographical domain 47.15 N–49.86 N×16.94 E–22.81 E covering the territory of Slovakia. Cloud modification factor for the UV radiation (*cmf*$_{UV}$) was modelled utilizing relation between the *cmf* of total and UV radiation.

The maps of the *cmf* factor of the UV radiation were created utilizing measurements of total radiation performed at 9 observatories during 1995–2004 period and the model of *cmf* dependence on altitude. Maps of clear-sky UV radiation daily dose and UV radiation daily dose affected by average cloudiness were constructed for mean monthly total ozone, their upper and lower monthly limits, for two probability levels of snow cover occurrence as criterion for the snow effect incorporation in the model and for 1 day representing typical values of every month. The map-set can be considered as an atlas of the solar erythemal UV radiation over Slovakia.

1 Introduction

Solar UV radiation manifests strong biological effects on life ecosystems. Overexposure to solar UV radiation can exhibit instantly (as e.g., skin erythema), but disturbance of some physiological processes of life organisms can manifest as a consequence of large cumulative doses of the UV radiation (development of skin cancers, change of photosynthetic activity of plants) (WMO, 2003). From the latter point of view, the knowledge on typical UV climate is important.

Determination of the UV climatology using directly ground or satellite measurements is usually impossible due to restricted length of the UV radiation time-series or due to low density of sites with the UV radiation ground measurements. Modelling of the UV radiation and spatial interpolation methods are tools usually applied for the UV climatology estimation.

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Several studies have been performed to determine the UV climatology at different spatial scales – from local studies of UV radiation long-term variability (Lindfors and Vuilleumier, 2005), to regional analyses (Lucini et al., 2006; Meloni et al., 2000) or global UV radiation pattern determination (Herman et al., 1999). Utilizing of the UV-irradiance modelling is possibility how to obtain information on the solar UV radiation at places where measurements are not performed, what is important for map representation of the UV radiation geographical distribution. The UV radiation simulation can also improve the knowledge on its long-term variability in time periods in the past, when no reliable measurements were organized. Total ozone, cloudiness, surface albedo, information on atmospheric turbidity, sunshine duration and total solar radiation are the proxies usually used as an inputs of the models. The UV index and the erythemal UV-radiation daily doses are the parameters most frequently employed for determination of the UV-radiation climatology (Lucini et al., 2006), but there was also an effort to model spectral UV-irradiances (Meloni et al., 2000; Bodeker and McKenzie, 1996). Comparison of UV-radiation models utilizing different input parameters and different approaches to UV radiation modelling at four European places showed, that models involving total radiation as proxy parameter provided the best results (Koepke et al., 2006).

Reliability of the UV-climatologies expressed in map form depends on UV-radiation model quality, on availability of model input parameters and its space distribution (Schmalwieser and Schauberger, 2001) and also on interpolation method utilized for map visualization (Tatalovich, 2006).

The aim of this publication is to create maps of the erythemal UV radiation daily doses typical for the small territory of Slovakia, employing available radiative measurements and meteorological data. UV-radiation climatology expressed in map form can be useful for the future local studies on UV-radiation impact on the biosphere and human beings.

2 Material and methods

2.1 Data

The solar UV radiation has been measured at 5 observatories equipped by the broad-band UV-B radiometers in Slovakia (Table 1). Stability of all instruments has been checked by their comparison with the national standard device periodically since 2002. Relative spectral response and relative angular response was certified by national standard device and by one operational UV-B radiometer located at Skalnaté Pleso only under umbrella of international COST-726 campaign at Davos in 2006.

The UV-radiation climatology was estimated utilizing ancillary data from the 1995–2004 decade. Measurements of total solar radiation performed at 9 stations were utilized by this study (Table 1). The CM-11 pyranometers have been operated at all investigated stations except of Stará Lesná and Skalnaté Pleso equipped with Sontag pyranometers. Stability of all instruments is controlled regularly against the national standard device.

Distribution of the total solar radiation measurements over the territory of Slovakia is irregular. 5 of 9 instruments are located in small area of the High Tatras mountains in the northern part of Slovakia (Fig. 1). But on the other hand, the altitudes of observatories performing the total solar radiation measurements cover nearly the whole altitude range of investigated geographical area. That is the reason, why dependences on altitude of both UV radiation modification by clouds and snow occurrence were parameterized to depict their spatial distribution.

Daily mean values of the total ozone and monthly climatology were obtained from measurements performed with the Brewer spectrophotometer MKIV at Poprad-Gánovce. It was considered, that total ozone measured at Poprad–Gánovce is representative for whole investigated area. Information on daily snow cover (snow cover thickness) was available for all stations providing global radiation measurements except of Banská Bystrica and Lomnický štít. Digital terrain model DMR500-SK in S-JTSK cartographic projection and resolution of 500 m available at the Internet (http://www.geomodel.sk/sk/download/download.htm) was utilized for the erythemal UV radiation map visualization. The relief altitude at investigated territory varied in range from 50 m a.s.l. to 2650 m a.s.l. Maps of erythemal UV radiation daily doses were created for every month at geographical domain 47.15 N–49.86 N×16.94 E–22.81 E covering the territory of Slovakia.

2.2 Parameterization of UV radiation cloud attenuation

The total solar radiation measurements were used as proxy data for the UV radiation cloud attenuation modelling.

The attenuation of radiation by clouds was expressed by cloud modification factor *cmf*. The *cmf* was defined as a ratio of the radiation measured by any cloudiness condition over the radiation corresponded to clear-sky condition. The attenuation of the UV radiation by clouds cmf_{UV} was modelled as a function of the total solar radiation cloud attenuation cmf_G for 6 categories of the SZA:

$$cmf_{UV} = f(cmf_{G,SZA}). \quad (1)$$

The model of daily values of cmf_{UV} is statistical. Dependence of the cmf_{UV} on the cmf_G was separately expressed by the 2 degree polynomial function for every of the 6 SZA intervals. The value of the SZA related to the time of solar culmination. Regression parameters were determined using data obtained at 4 locations in Europe (Thessaloniki, Davos, Potsdam, Bergen) under the European action COST-726 (Koepke et al., 2006). Clear-sky values of the total and UV radiation for modelling of the cmf_{UV} and cmf_G were calculated by the radiative transfer models. Daily sums of the clear-sky erythemal UV radiation were calculated from irradiances modelled by the TUV (total ultraviolet-visible) radiative transfer model (Madronich, 1993) assuming standard atmospheric conditions, fixed aerosol content (aerosol optical depth of radiation with wavelength λ=340 nm AOD_{340} was set to be 0.4) and its optical characteristics typical for continental aerosol, fixed no-snow surface albedo and for measured total ozone. The weight function for human erythema (McKinlay and Diffey, 1987) was applied on the modelled spectral irradiances. The integration step of 0.5 h was used in summation of modelled irradiances to obtain UV radiation daily doses. Modelled daily doses of clear-sky erythemal UV radiation were corrected if snow was present at any station. Fixed increase of erythemal UV radiation caused by snow reflectivity of 15% was assumed (Pribullová and Chmelík, 2005).

Clear-sky total irradiances were modelled by the libRadtran radiative transfer model (Mayer and Kylling, 2005) for standard atmosphere, no-snow conditions, fixed atmospheric aerosol content expressed by horizontal visibility of 25 km and the *SZA* range of 90°–20°. Daily doses of the clear-sky total radiation were calculated from modelled irradiances for every place with measured total irradiance. The integration time step of 0.5 h was used for calculation of total solar radiation daily doses. If the snow was at any station, correction of the clear-sky total irradiance (SZA dependent increase of total radiation in comparison with no-snow condition was assumed) was performed in accordance with Pribullová and Chmelík (2005) local study conclusions.

Monthly means of the cmf_{UV} factor were calculated for determination of the UV-radiation cloud attenuation climatology at every place with total radiation measurements. As places with available cmf_{UV} values were distributed irregularly over the investigated territory, the dependence of the cmf_{UV} on altitude was fitted to obtain maps of the cmf_{UV} distribution.

2.3 Parameterization of the snow reflectivity effect on UV radiation

To incorporate the snow effect in the UV radiation climatology map visualization, information on the typical space distribution of the snow cover over Slovakia was required. As the stations recording the snow cover were irregularly distributed, the dependence of the snow occurrence on altitude was modelled. Monthly probability of snow occurrence was firstly determined from all available data at every station. The altitude of defined probability of snow occurrence was calculated using the linear interpolation between the altitudes of stations with the snow occurrence probabilities below and above the defined limit. Two probability limits of 50% and 70% were chosen for the determi-

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nation of altitudes above which the snow effect on the UV radiation was incorporated into the model.

2.4 Map visualization

Typical monthly erythemal UV-radiation distribution was obtained by simulation of one day conditions characterized by an appropriate monthly total ozone, cloud attenuation conditions and snow cover distribution. The erythemal UV-radiation map construction was performed in the following steps:

1. The clear-sky daily doses of erythemal UV radiation were calculated by the radiative transfer model TUV for one day of every month. The calculations were performed for fixed continental aerosol content (AOD_{340}=0.4) and 3 categories of the total ozone (monthly average, monthly average± standard deviation from average). The clear-sky daily doses were determined for fixed altitude and geographical coordinates of grid points regularly covering the investigated area (3×4 points).

2. The linear kriging interpolation method (Isaaks and Srivastava, 1989) was applied to recalculate the clear-sky UV radiation to all grid points of digital terrain model (900×500).

3. The clear-sky UV irradiance recalculated for every grid point was then corrected for altitude of every grid. Linear change of the clear-sky erythemal UV radiation with altitude of 15%/1000 m (Pribullová and Chmelík, 2005) was assumed.

4. The correction of the clear-sky UV-radiation daily doses with respect to snow cover was performed at all grid points with altitudes exceeding the limit where snow incidence is observed with both 50% and 70% probabilities.

5. The maps of monthly attenuation of erythemal UV radiation by clouds expressed by the cmf_{UV} were constructed assuming derived dependence of the monthly cmf_{UV} on altitude.

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6. The modelled clear-sky erythemal UV radiation daily doses were multiplied by the cmf_{UV} factor modelled for appropriate altitude and month at every grid point and maps of erythemal UV radiation daily doses reflecting the mean cloudiness effect were created.

Finally 12×3×2 maps were created for clear-sky and cloudy conditions. All maps together can be considered as atlas of the erythemal UV radiation geographical distribution over the territory of Slovakia.

3 Results and discussion

3.1 Attenuation of UV radiation by clouds

The climatology of the erythemal UV-radiation cloud attenuation was determined for every station with available measurements of the total solar radiation. The difference between the annual courses of the monthly cmf_{UV} at the mountain stations and at the valley and low-land stations values was detected.

The lowest cmf_{UV} values ranging between 0.45–0.55 were detected at the mountain stations Lomnický štít, Skalnaté Pleso and Štrbské Pleso in July. Decrease of the cmf_{UV} values to 0.60 was also observed at Stará Lesná and Poprad-Gánovce (located close to the High Tatras mountains) during summer. Convective cloud formation can explain large attenuation of the erythemal UV radiation by clouds in the mountains during the summer.

The highest values of the cmf_{UV} were observed at the mountain stations during winter (December, January). Decrease of the cloud attenuation effect with altitude in winter probably relates to low inverse cloudiness, more frequently formed at valleys and low-lands than at high mountains. Generally, the highest annual amplitude of the cmf_{UV} detected at the mountain stations results from the typical mountain cloudiness regime – intensive convective activity in summer and more frequent clear days in winter.

The valley and low-land stations Hurbanovo, Bratislava, Košice and Banská Bystrica manifested by less significant annual variability of cmf_{UV} (values ranged between 0.65–0.70, except November–January, when the cmf_{UV} dropped to 0.55–0.65).

The mean annual cmf_{UV} values ranged from 0.61 at Štrbské Pleso to 0.68 at Hurbanovo. An increase of the monthly cmf_{UV} with altitude was determined in period October –January. A decrease of the cmf_{UV} with altitude was found from May to August. The dependence of the cmf_{UV} on altitude is less significant during September, November, February and in March, when the range of the cmf_{UV} values is small (0.68–0.75 in March) and UV radiation cloud attenuation is nearly uniform over the whole investigated area.

The dependence of the cmf_{UV} on altitude was modelled to determine its geographical pattern. The 2 degree polynomial function was used to express dependence of the cmf_{UV} on altitude. The stations Banská Bystrica and Lomnický štít were excluded from the fitted vertical profile from October to June due to missing information on snow. The quality of modelled dependence is summarized in Table 2.

The lowest correlation coefficient between modelled and measured data was determined in February, March, October and November, when the cmf_{UV} did not depend on altitude significantly. The relative RMS error is also large for January and July (5.0–5.4%), in spite of relatively high correlation coefficients between measured and modelled values. The vertical profile of the cmf_{UV} can not be expressed using the simple polynomial function in some months (July, January). The lowest values of the cmf_{UV} observed from April to August at Skalnaté Pleso could partly relate to non-ideal horizon and shadow effect manifesting at this place in summer.

3.2 Snow climatology

The snow occurrence probability for every month was calculated as a ratio of number of days with snow over number of all days. Two limit cases of the snow incidence probability of 50% and 70% were investigated.

The probability of the snow incidence below 50% and 70% was detected at all stations from June to October and from May to October, respectively. The snow incidence exceeding probability of 50% was found for the station Hurbanovo (representing the lowest parts of the Danubian low-land) only in January. In May, the snow probability above 50% was still detected at Skalnaté Pleso. Snow incidence was assumed for whole investigated territory only in January.

The altitudes of defined snow incidence probability represented the limits for incorporation of the snow effect on the erythemal UV radiation. The erythemal UV-radiation values are enhanced by the snow reflectivity at inhabited areas with altitude around 1000 m a.s.l. in April. The snow cover is above populated areas in May, but the people present at the peak ski-resorts in the Tatras mountains can be affected by the enhanced erythemal UV-radiation values due to snow.

3.3 Maps of erythemal UV radiation

The maps of erythemal UV-radiation created as result of the modelling and spatial visualization methods provide information on its range and spatial distribution over investigated territory of Slovakia.

The decrease of the erythemal UV radiation with increasing geographical latitude was expected for the area with homogeneous surface with uniform altitude. Maps of clear-sky erythemal UV-radiation daily dose did not follow the expected pattern. As high elevated places are concentrated in the north and central parts of Slovakia, the highest monthly values of the erythemal UV radiation were detected at these mountain peaks for clear-sky conditions, especially for the lower limits of the total ozone and snow cover presence simulated at high altitudes. The daily doses of the erythemal UV radiation ranging between 4 and 7 kJ.m^{-2} were detected at the peaks of the Tatra mountains from May to July by the cloudless sky and for total ozone ranging ±standard deviation from its monthly average. Well expressed increase of the erythemal UV radiation with altitude is documented in Fig. 2 for the clear-sky condition in May and July.

The range of the erythemal UV radiation values decreased after incorporation of the cloud effect on the modelled UV radiation (Fig. 3). Increase of the erythemal UV

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radiation influenced by mean cloudiness with altitude was still detected from November to May, when vertical increase of the cmf_{UV} factor was detected. But the geographical distribution of the UV radiation did not copy the relief as by the clear-sky conditions.

The spatial distribution of the erythemal UV radiation attenuated by average cloudiness did not follow the relief model from May to September. As can be seen in Fig. 3 for July, the highest erythemal UV-radiation daily doses (of 3 $kJ.m^{-2}$) were detected at the southern parts of the Danube and the East-Slovak low-lands. The erythemal UV-radiation daily doses about 2 $kJ.m^{-2}$ were found in the northern part of Slovakia with no significant differences between valleys and lower mountain positions.

The annual course of the erythemal UV radiation can be seen in Fig. 4 for all observatories equipped with the UV-radiometers. The erythemal UV radiation modelled by clear sky and under average cloudiness is presented for these stations. The modelled values were obtained by interpolation from maps for coordinates of every station. The mapped values were compared with monthly means of the measured UV radiation calculated from the period 2002–2004. A good agreement between the monthly mean of measured erythemal UV radiation and the modelled values (assuming monthly mean of both the total ozone and the cmf_{UV} and the surface covered by snow from altitudes with snow incidence probability of 50%) is documented in Fig. 4.

The largest differences between modelled and measured erythemal UV-radiation daily doses about 20% were detected at all stations in February and March, when the cmf_{UV} factor did not manifest significant dependence on altitude. The best agreement between measured and modelled values of UV- radiation daily doses was determined in Bratislava and at Poprad-Gánovce, where the relative difference between modelled and measured values did not exceed 10% for the whole year, except of the period January–March. The summer values of the erythemal UV radiation were overestimated by the model at stations Stará Lesná and Skalnaté Pleso. These stations are strongly affected by convective clouds in the summer. Differences between the total ozone, cloudiness and snow presence during the periods 2002–2004 and 1995–2004, model error and interpolation error can contribute to discrepancies between modelled and measured mean values of erythemal UV-radiation.

4 Conclusions

The high resolution maps of erythemal UV radiation daily dose were created for one day of every month characterized by typical (monthly average of the cloud modification effect, average total ozone) and the extreme phenomena (clear-sky condition, upper and lower limits of the total ozone, lower and higher limits of snow incidence probability) affecting the erythemal UV radiation. The erythemal UV radiation was modelled over the small Slovak territory characterized by diverse relief.

The cloud effect on the erythemal UV radiation was simulated by statistical modelling of the erythemal UV-radiation cloud attenuation dependence on the total radiation and on the solar zenith angle. Results of the local studies on the snow and altitude influence on the total and erythemal UV radiation under clear-sky conditions performed in the High Tatras mountains (Pribullová and Chmelík, 2005) were used for implementation of vertical gradient of the UV radiation and also for incorporation of the snow reflectance effect on the UV and total radiation. The total ozone measured at Poprad-Gánovce was assumed to be representative for the whole investigated territory. The modelling was performed with assumption of fixed aerosol content. 10-years climatology of the total ozone, total solar radiation and snow cover was used for determination of typical pattern of the erythemal UV radiation distribution over investigated territory. The dependence of both the UV radiation cloud modification and the snow probability occurrence on altitude was modelled for visualization of the erythemal UV-radiation in the maps.

The cloud attenuation of the erythemal UV radiation varied from 50% in the summer to 20%–25% in December–January in the High Tatras mountains. The low variability of the UV-radiation cloud modification was detected at the low-lands. The erythemal UV-radiation cloud attenuation ranged between 30% and 35% for the whole year at low-lands, except of December and January when reduction of the UV radiation increased

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to 40%–45%. The 10-years climatology of the snow cover showed, that except of winter months, when the SZA is large, the probability of snow presence of 70% was detected at inhabited altitudes about 1000 m a.s.l. in April. The increase of the erythemal UV-radiation caused by high snow reflectivity is also probable at altitudes above 1600 m a.s.l., where some ski-resorts provide their activities, in May.

The maps of the erythemal UV-radiation distribution show, that the highest daily doses of 4–7 kJ.m^{-2} can be detected at the peaks of the High Tatra mountains under clear-sky conditions from May to July. The erythemal UV radiation is reduced by clouds to values of 3 kJ.m^{-2} at low-lands and at the highest Tatra's mountain peaks in summer. The daily doses of about 2 kJ.m^{-2} were detected at the rest of Slovak territory in the summer. The resulting map-set of the erythemal UV radiation modelled for average and limit conditions can be considered as atlas of the erythemal UV radiation over Slovakia. The maps will be available on the internet site of the Geophysical Institute (http://www.ta3.sk/gfu/interes.htm).

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Table 1. Stations utilized for determination of erythemal UV-radiation climatology in Slovakia, their abbreviations, geographical coordinates and time periods with available total solar radiation (G) measurements, UV radiation measurements (UV) and information on snow cover.

Station	Latitude [N]	Longitude [E]	Altitude [m a.s.l.]	G	UV	snow
Hurbanovo (HU)	47.87	18.20	135	1995–2004	no	1995–2004
Bratislava (BA)	48.17	17.12	292	1995–2004	2002–2004	1995–2004
Košice (KE)	48.70	21.27	230	1995–2004	2002–2004	1995–2004
Banská Bystrica (BB)	48.73	19.12	427	1986–1993	no	no
Poprad-Gánovce (GA)	49.03	20.32	703	1995–2004	2002–2004	1995–2004
Stará Lesná(SL)	49.10	20.28	810	1995–2004	2002–2004	1995–2004
Štrbské Pleso (StP)	49.12	20.07	1387	1995–2004	no	1995–2004
Skalnaté Pleso (SP)	49.18	20.23	1778	1995–2004	2002–2004	1995–2004
Lomnický štít (LS)	49.20	20.22	2635	1984–1992	no	no

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Table 2. Correlation coefficient *r* between measured and modelled values of the cmf_{UV} and the relative RMS error of the modelled cmf_{UV} dependence on altitude.

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.921	0.208	0.204	0.886	0.989	0.949	0.943	0.943	0.846	0.549	0.358	0.798
RMS [%]	5.4	4.6	7.8	2.9	1.2	4.1	5.0	3.7	4.0	4.1	6.0	7.9

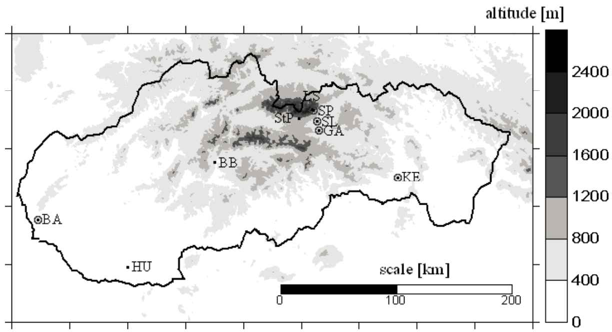

Fig. 1. Investigated territory with surface altitude and border of Slovakia. The places with measurements of total solar radiation are designed by black dots, places with UV radiation measurements are labelled by rings. The abbreviations of observatories relate to Table 1.

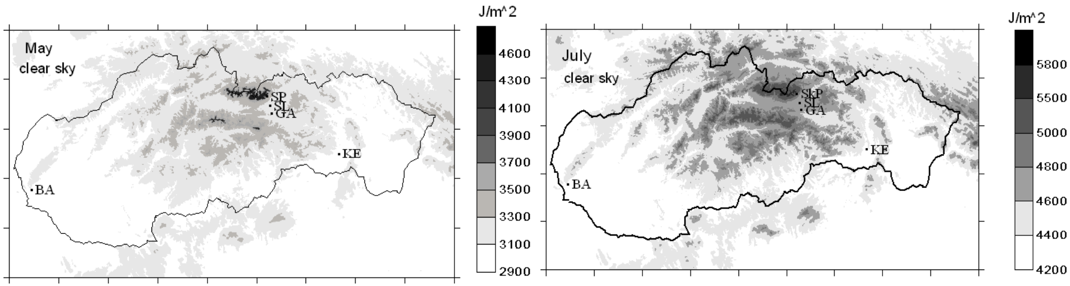

Fig. 2. Modelled clear-sky erythemal UV-radiation daily doses for May and for July. The clear-sky UV radiation daily doses were calculated for the first day of month and corresponding monthly average values of the total ozone and appropriate snow conditions (the surface covered by snow was assumed from altitudes with snow incidence probability of 50%).

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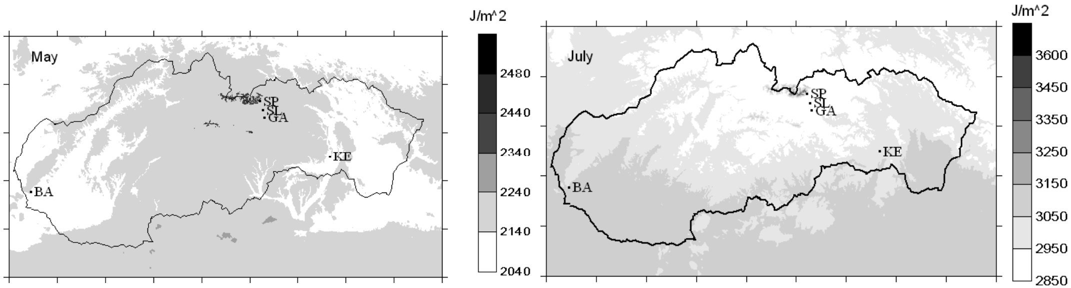

Fig. 3. Modelled erythemal UV-radiation daily doses for May and for July assuming mean attenuation by clouds. The UV radiation daily doses were calculated for the first day of month and corresponded monthly average values of the total ozone, the cmf_{UV} and appropriate snow conditions (the surface covered by snow was assumed from altitudes with snow incidence probability of 50%).

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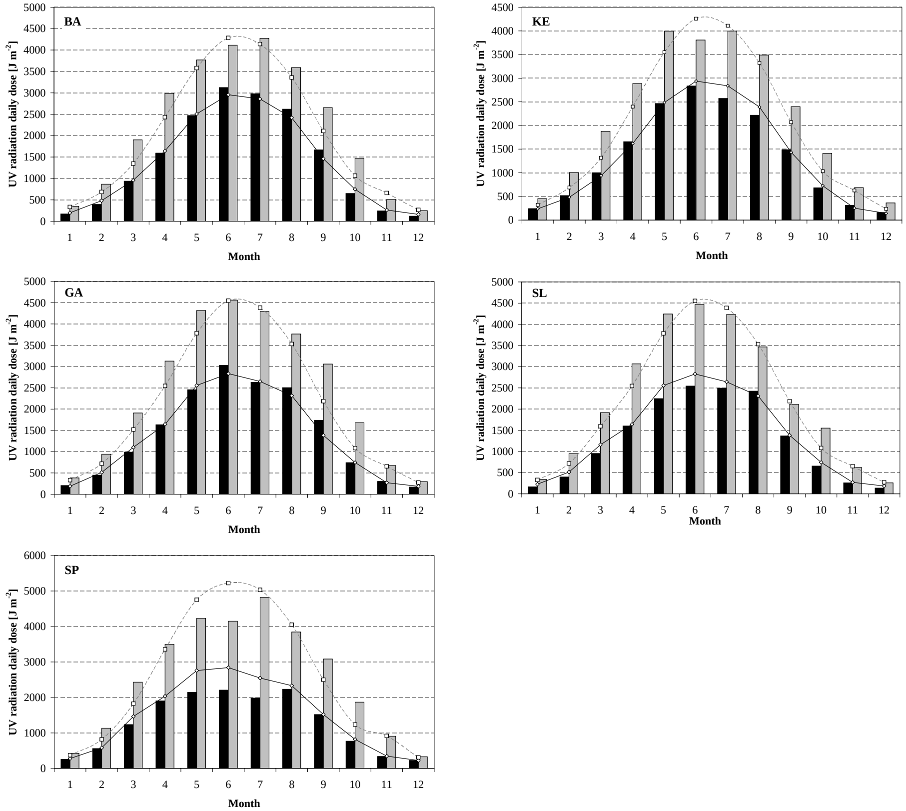

Fig. 4. Monthly mean values of the erythemal UV radiation calculated from measured data at stations equipped by the UV- radiometers (abbreviations in Table 1) for the 2002–2004 period (black columns), the modelled clear-sky erythemal UV radiation (grey squares) and the erythemal UV radiation attenuated by mean cloudiness (white diamonds). The erythemal UV radiation was modelled for average total ozone and typical snow conditions (the surface covered by snow was assumed from altitudes with snow incidence probability of 50%).

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