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ULTRAVIOLET IRRADIANCE IN METEOROLOGICALLY CONTRASTING SUMMERS OF 1998 AND 1999 IN ESTONIA

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Abstract. Regular monitoring of solar erythemal ultraviolet (UV) irradiance at Tõravere (Estonia) was performed in two years with notably different weather conditions in summer (herein the months May–August). Erythemal UV characteristics were compared and their dependence on meteorological conditions was studied. The erythemal doses over the first half of the summer were similar for both years, but over the second half the dose for 1999 was 28% higher. The strongest affecting factor in both summers was low cloudiness. Its partial correlation with the daily UV doses in the extremely cloudy summer of 1998 (–0.70) was not much higher than in the fine weather summer of 1999 (–0.65) when the noon solar elevation contributed two times more than in cloudy 1998 (about 0.6 and 0.3). The contribution of total ozone was close to zero in 1998 and quite weak (–0.44) in 1999. The daily distributions of erythemal UV index values in case of moderate partial cloudiness often give higher values than in clear sky conditions and the daily doses are higher.

Key words: erythemal UV irradiance, atmospheric total ozone, UV monitoring, low cloudiness, snow cover, UV dose, UV index, albedo.

1. INTRODUCTION

The aim of the UV monitoring is to obtain data about the UV irradiance and doses as well as their interannual and intraseasonal variations. The major climatological quantities of the UV radiation at any site are the doses and irradiance values over the annual cycle and their variances. The year-to-year differences in UV irradiance and doses over the highly regular solar annual cycle are governed by the cloudiness (especially by the amount of low clouds), the atmospheric total ozone, the attenuation by the atmospheric aerosol in the UV region, and by the ground albedo [1–3]. The attenuation by aerosol is dependent on the atmospheric aerosol burden and its optical properties, mainly on aerosol optical depth and single scattering albedo [4]. The attenuation of the ground level

UV radiation by overcast skies with the cloud ceiling above 7 km is estimated to be only about 10%, by clouds with the ceiling between 3 and 7 km up to 50%, and by the lower level clouds up to 80% [5,6]. A high reflectance of snow cover may increase the UV irradiance by up to 20–30% [7,8] as compared to the low albedo of the vegetation. This effect increases with the solar zenith angle. The episodes of snow in late spring are perhaps extraordinary in our conditions. Such events occurred last in late April 1988 and on 11–12 May 1999.

In the Estonian geographical and meteorological situation four months (May–August; below referred to as summer months) are responsible for about 70% of the yearly erythemal dose [9], of which about 50% falls on the six midday hours. Comparing the data recorded in extremely different summers, useful information on the amplitudes of year-to-year differences in erythemal doses and irradiances can be obtained. The units used here for the erythemal dose are minimal erythemal dose (MED) for skin type II (1 MED = 250 CIE weighted J). The erythemal irradiance is expressed in units MED/hour or in UV index [10] units (1 UV index = 2.78 MED/h = 25 CIE weighted mW/m^2). The instrumentation used is described in our publication [9]. The UV monitoring was carried out in close collaboration between the Tartu Observatory and the Estonian Meteorological and Hydrological Institute.

2. METEOROLOGICAL AND TOTAL OZONE CONDITIONS

Here we compare the erythemal UV doses and irradiance over the summer seasons of 1998 and 1999 exhibiting sufficiently different and close to local extremes meteorological conditions. The meteorological data, recorded regularly at the actinometric station of Tartu–Tõravere (about 0.1 km from the site of UV measurements), have been available since 1955, including the low cloud amount separately of the total cloudiness [11] during the daylight time. Both are expressed in tenths and are separated by a stroke in the present text (total cloudiness/low cloudiness). For the total ozone the TOMS data obtained by Nimbus-7 for the period from November 1978 to May 1993 and by other TOMS instruments for more recent years, available through www (http://jwocky.gsfc.nasa.gov/), were used as well as the data of the ground based measurements since 1994 [12]. The integral atmospheric transmittance has been measured at the actinometric station by the direct solar radiation [13]. Its monthly mean values were (respectively in 1998 and 1999) 0.753 and 0.772 in May, 0.764 and 0.745 in June, 0.776 and 0.762 in July, and 0.777 and 0.771 in August. The integral transmittance has no close relationship with the UV transmittance and was not taken into account in correlation studies.

The averaged low cloudiness for four summer months (May–August) was extremely high in 1998 and relatively low in 1999. The 45-year average low cloud amount for these months is 4.0 tenths. In 1998 the corresponding value was the highest – 5.6. Similar values (5.4) were recorded in the summers of 1987 and

1990. The average amount of low clouds in the summer of 1999 was slightly lower than the longtime mean – 3.7. During the 1990s it was smaller only in 1992 (3.5) and equal in 1997 (3.7). The smallest summer amounts of low clouds during the last 45 years were recorded in the summers of 1972 (3.05) and 1975 (2.9). In 1998 the low cloud amount coincided with the longtime mean only in May and was significantly higher during the next three months. In 1999 it exceeded the longtime mean value only in August (4.6 vs 4.2). The average low cloud amount for two midsummer months June and July was lower than the 1999 value only in three summers (1972, 1975, and 1992) and equal in other three summers (1964, 1980, and 1988). The variance of low cloud amount was found to be not much affected by the different dynamical stability of the atmosphere in 1998 and 1999 as the standard deviations for the interval May–August were 2.8 tenths in 1998 and 2.5 tenths in 1999.

The average total ozone value for 1979–99, based mostly on the TOMS data, was 348 DU (Dobson unit = 10^{-3} atm cm) for May–August. In 1998 it was the highest on record, equalling 370 DU. The second highest value of 368 DU was recorded in 1981. The summer average total ozone was 346 DU in 1999, which is close to the 20-year mean, mostly due to a comparatively high (393 DU) value in May. The extreme lowest summertime mean total ozone values were recorded in the summers a year after the major volcanic eruptions at El Chichon in 1983 (334 DU) and Mt. Pinatubo in 1992 (333 DU). Taking separately the monthly mean values of both years 1998 and 1999, one can see that in May these were very close to each other (395 and 393 DU). The mean June value of 1998 (361 DU) was slightly higher than the 20-year mean (355 DU) and that of 1999 belonged to the two lowest ones (331 DU). The values for both July (369 DU) and August (355 DU) 1998 set a record and those of 1999 (332 and 327 DU) were not far from normal (341 and 321 DU). In both summers the monthly averaged total ozone during three months from June to August has been almost at a constant level. In the summers of 1979–92 a nearly linear decrease in the total ozone mean level about 20 DU per month has usually been observed. In some cases the mean level persisted for two months, mostly in June and July, but never for three months. The atmospheric conditions in 1999 were much more stable than in 1998. The upper tropospheric pressure field changed extremely slowly as compared to the rapid zonal movement in 1998. Due to the weak synoptic-scale variance of the upper level pressure, the standard deviation of the total ozone during June–August 1999 (12.3 DU) was nearly halved as compared to the same time interval of 1998 (23.7 DU).

The summer of 1999 was similar to the summer of 1992 when the low cloud amount was similarly distributed on an average. It was 0.4 tenths higher in August and 0.9 tenths lower in June. The differences in May and July were small. The yearly mean total ozone was the lowest in the 20-year record in 1992 as a consequence of Mt. Pinatubo 1991 major eruption [14–16]. The monthly mean values of 1992 were the most different from those of 1999 in May (356 and 393 DU) and August (303 and 327 DU). The June mean total ozone in 1992 was

10 DU higher than in 1999 and the July mean values were almost equal. On the basis of these total ozone and low cloudiness data the erythemal doses in the summer of 1992 could be expected higher than in the summer of 1999. Taking into account the distributions of low clouds and total ozone in another "good summer" of 1988, the erythemal doses might be close to those of the summer of 1999. In the summer of 1980 with the similar low cloud amount the TOMS total ozone was higher than in 1999 during the whole summer. For the 1970s we do not possess any reliable data about total ozone. For 1964 published monthly mean smoothed values of ground based network observations of total ozone are available [17]. On the basis of these and the low cloud data the erythemal dose in the summer of 1964 might be similar to that of 1999. So, the summer erythemal doses of 1999 can be at least among the five largest and the doses of 1998 close to the very lowest in the last 45 years. The difference of summer erythemal doses of these two years can be taken as an approximation of the amplitude of variance of summer erythemal UV doses over Estonia.

3. ERYTHEMAL DOSES AND UV INDEX VALUES

The monthly erythemal doses for 1998 are presented in [9] and for both 1998 and 1999 in Table 1. The erythemal UV doses for the whole summer are most sensitive to the low cloud amounts and atmospheric total ozone values at times close to the summer solstice when the midday solar elevation is the highest and changes are slow. For improving awareness about UV irradiation the full daily doses do not seem to be the best characteristic as people prefer the midday hours for lying in the sunshine and all hazards of overexposure occur during these hours. The best medical characteristic of UV radiation from this point of view is the noon value in MED/hour or the UV index. Besides the full daily dose the dose for six midday hours could be used. The values of this dose during the summer months of 1998 and 1999 are presented in Figs. 1 and 2 together with the daily total ozone and low cloudiness data. In clear skies or in skies partly covered with upper level clouds the midday six-hour contribution was 70–73% and in nearly overcast by low clouds conditions around 65% of the daily erythemal dose. A comparison of the whole summer erythemal doses of two years was performed on a ten-day basis. Table 2 presents the ten-day mean low cloud amounts in tenths, the ten-day mean total ozone values in DU, and the ten-day mean daily erythemal doses in MED for skin type II. The ratios of ten-day doses are illustrated in Fig. 3. For 30 days before and after the summer solstice the ten-day mean low cloud amounts as well as the mean total ozone values were significantly higher in 1998 than in 1999. The erythemal doses over these ten-day periods in 1998 were correspondingly lower, with the exception of 2–11 June when the values of both governing factors were lower in 1999 but the UV dose was nearly equal to that of 1998. The greatest difference was observed for the second ten-day period after the solstice when the ten-day dose of 1999 was 64% higher than that of 1998.

Table 1. Monthly doses of erythemal UV radiation in 1998 and 1999

Month	1998 Dose, MED	1999 Dose, MED
January	8.07	8.87
February	27.69	30.01
March	97.00	88.47
April	165.12	154.75
May	307.42	282.79
June	335.27	402.72
July	322.08	421.60
August	220.69	280.98
September	143.87	165.42
October	58.07	39.69
November	16.79	14.21
December	6.02	5.70

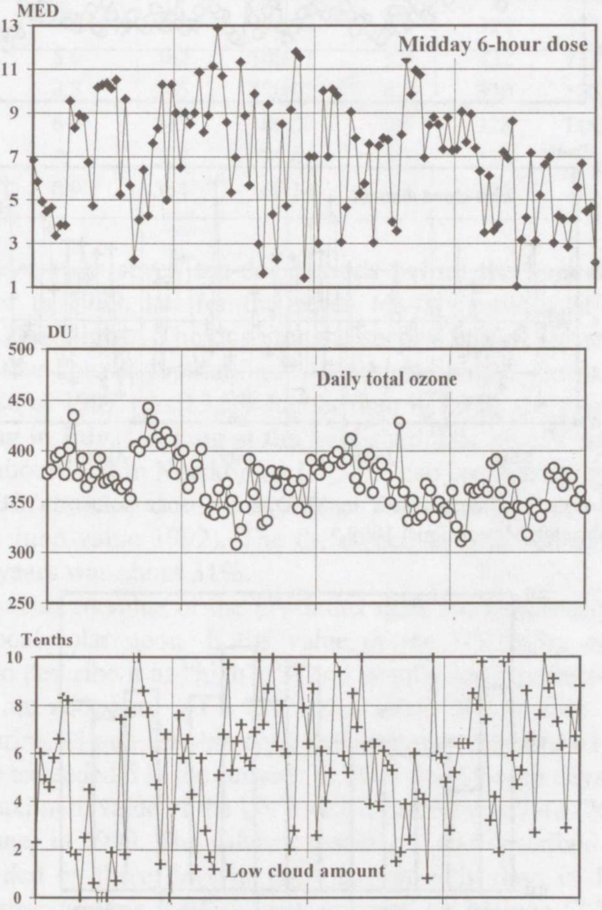

Fig. 1. Midday six-hour erythemal doses in MED, total ozone values in DU, and low cloud amounts in tenths through May–August 1998.

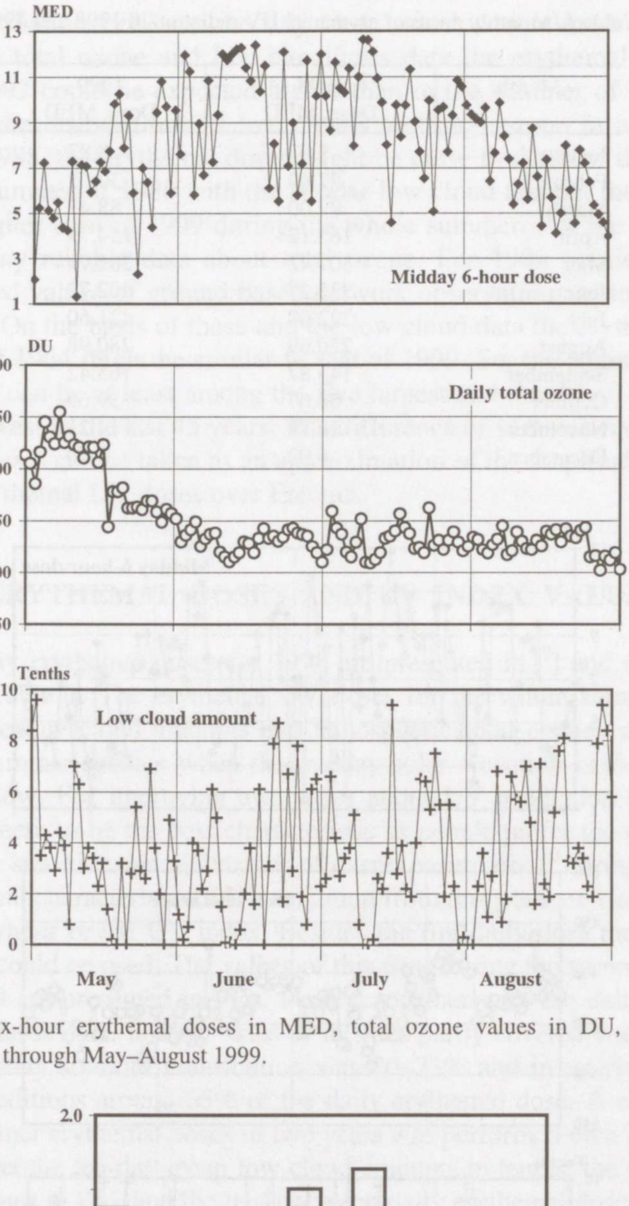

Fig. 2. Midday six-hour erythemal doses in MED, total ozone values in DU, and low cloud amounts in tenths through May–August 1999.

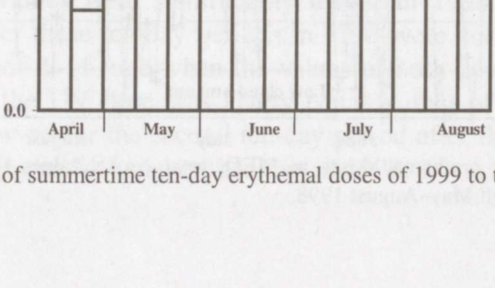

Fig. 3. Ratios of summertime ten-day erythemal doses of 1999 to those of 1998.

Table 2. Midday six-hour erythemal doses over ten-day periods before and after the summer solstice

	1998			1999			UV dose
	Mean low cloud amount, tenths	Mean total ozone, DU	Ten-day UV dose, MED	Mean low cloud amount, tenths	Mean total ozone, DU	Ten-day UV dose, MED	1999/1998
13–22 April	7	414	40.65	2.9	378	55.83	1.37
23 April–2 May	2.2	384	86.14	5.3	374	58.11	0.67
3–12 May	4.5	388	81.67	4	424	74.92	0.92
13–22 May	2.5	377	118.19	2	392	107.02	0.91
23 May–1 June	5.9	409	102.52	4.5	359	102.82	1.00
2–11 June	4.2	366	132.82	2.6	332	133.59	1.01
12–21 June	7.1	355	101.68	2.5	326	152.84	1.50
22 June–1 July	6.8	369	96.09	4.5	331	122.55	1.28
2–11 July	6.6	390	93.13	2.9	329	152.53	1.64
12–21 July	5.6	382	100.61	3.3	332	131.42	1.31
22–31 July	4.5	345	120.02	4.1	330	120.08	1.00
1–10 August	6.6	349	86.58	2.5	328	116.59	1.35
11–20 August	6	352	71.4	5.1	332	82.31	1.15
21–30 August	6.9	364	60.14	4.4	326	76.86	1.28

The total dose over seven ten-day periods before the summer solstice was only 3% higher in 1999, but for the seven ten-day periods after the summer solstice it was 28% higher. The dose for the second half of the summer of 1998 was 7% lower than for the first half and 17% higher in the summer of 1999. The four-month dose in 1999 was 15.5% higher than in 1998, the greatest difference (31%) occurring in July. Looking at the published data on UV measurements in our close neighbourhood in Norrköping [18], one can see that the greatest year-to-year difference in monthly doses was 2 times (between the very low June value 1991 and high June value 1992). The difference in four summer month doses between these years was about 31%.

The daily maximum value of the UV index does not necessarily coincide with the value at local solar noon. If the value of the UV index exceeds 5, it is recommended to describe it as "high" [19] and usually some protective measures to avoid sunburn are necessary. At a UV index value of 5 a dose 1 MED can be accumulated during 33 min for skin type II. There were counted 61 days when the UV index value exceeded 5 in the summer of 1998 and 89 such days in the summer of 1999. The maximum value of the UV index recorded was 7.42 (26 June) in 1998 and 7.64 (17 June) in 1999. The values exceeding 7 and described as "very high" [19] were recorded on three days in 1998 and on eight days in 1999. The next highest values after 17 June in 1999 were recorded on 30 June (7.59) and 24 July (7.61). None of the days showing an extremely high UV index was clear. The sun was mostly cloud-free but on an average even more than half of skies were covered with cirrus and cumulus clouds. In the closest to the solstice clear days (total cloud amount smaller by 1 tenth) on 19 June and 28 June the UV index maximum values were 6.26 and 6.32. On fully clear days 10 July and 11 July these were 6.85 and 6.82 due to better atmospheric transparency. So, in a partly cloudy fine weather the erythemal irradiance can often be enhanced by about 10–20%.

The empirical probability distributions of the daily erythemal doses over months in both summers are presented in Fig. 4. None of them corresponds to the normal distribution. It means that the major governing processes through summer are not stochastic. In May as well as in August 1998 the distributions were highly bimodal. In May both the total ozone and low cloud amount values occurred to be high approximately at the same time during the first and the last ten days and low to moderate in the middle ten days. The coefficient of linear correlation between these two major factors influencing the erythemal dose was 0.55 in May 1998. For the whole summer it was close to zero, i.e. the total ozone is independent of low cloud amount and vice versa. In August two synoptic-scale wavelike periods of low to high values in total ozone were observed, the higher amounts of low clouds tending to occur at high total ozone values resulting in bimodal distribution of daily doses as in May. The distributions of daily doses in June and July 1998 were closer to unimodal but had significant negative asymmetry because of the comparatively large amount of low values. The distribution, especially in July, contains a high amount of values not very strongly attenuated by the partial cloudiness. In 1999 the distributions of daily doses were more symmetric in May and August. In May the weak modes of both of the very low and very high values are represented, but most of the values correspond to the low cloud amounts around 3–4 tenths. The distribution of daily doses in June 1999 is bimodal (slightly resembling the one for a harmonic process) with about one-third of the highest values, comparatively high contribution of the moderate values, and no values lower than 10 MED, often met in 1998. The asymmetric unimodal distribution for July 1999 is shifted towards higher values as compared to July 1998.

The multiple linear regression between the daily erythemal doses UVD as well as the midday six-hour doses UVD6 and the three major influencing factors (noon solar elevation S in degrees, low cloudiness C in tenths, and total ozone X in Dobson units) was calculated for both summers separately. The following regression equations

$$\mathrm{UVD} = -8.04 + 0.44\mathrm{S} - 0.99\mathrm{C} + 0.02\mathrm{X},$$

$$\mathrm{UVD6} = -1.97 + 0.26\mathrm{S} - 0.70\mathrm{C} - 0.002\mathrm{X}$$

were found for the summer of 1998 and

$$\mathrm{UVD} = 5.13 + 0.42\mathrm{S} - 0.70\mathrm{C} - 0.04\mathrm{X},$$

$$\mathrm{UVD6} = 6.69 + 0.25\mathrm{S} - 0.52\mathrm{C} - 0.028\mathrm{X}$$

for the summer of 1999. The multiple linear regression coefficients in the case of full daily doses were 0.78 for 1998 and 0.87 for 1999. For six midday hours the values were not much smaller (0.77 for 1998 and 0.84 for 1999). The coefficients of the regression equation are of high confidence level (P-values except for the coefficient of total ozone in 1998 are close to zero). The lower coefficient for 1998 can be explained by the higher contribution of the cloud optical thickness variations which were not taken into account.

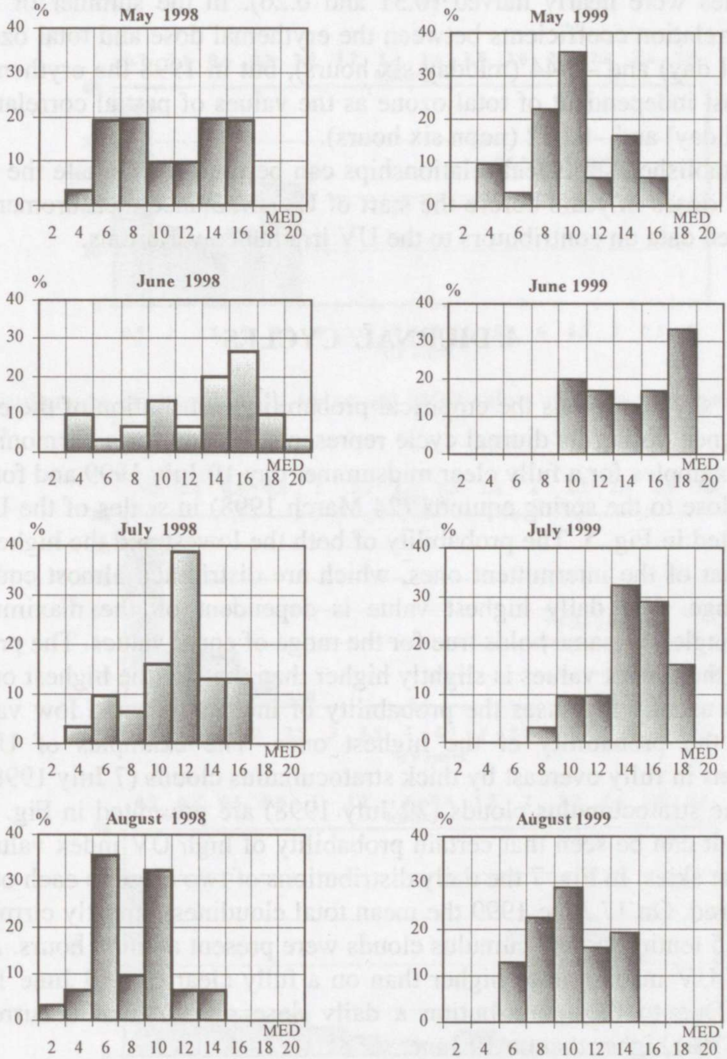

Fig. 4. Distributions of daily erythemal doses by summer months in 1998 and 1999.

The calculated correlation matrixes show that in all cases the erythemal doses are most affected by the low cloud amount. In the extremely cloudy summer of 1998 this partial correlation coefficient was –0.70 for the whole day doses and –0.72 for the midday six-hour doses. In the fine weather summer of 1999 the low clouds contributions were both nearly equal (–0.65) and smaller than in 1998. The relative contributions of other two major factors were significantly dependent on the low cloud amount. In the fine weather summer of 1999 the partial correlation of noon solar elevation was 0.62 for the daily erythemal doses and 0.56 for the midday six-hour doses. In the extremely cloudy summer of 1998 these values were nearly halved (0.31 and 0.26). In the summer of 1999 the partial correlation coefficients between the erythemal dose and total ozone were –0.43 (full day) and –0.44 (midday six hours), but in 1998 the erythemal doses were almost independent of total ozone as the values of partial correlation were 0.007 (full day) and –0.032 (noon six hours).

The established statistical relationships can be used to estimate the climatological UV doses in years before the start of UV irradiance measurements, using the recorded data on contributors to the UV irradiance variations.

4. DIURNAL CYCLES

In clear sky conditions the empirical probability distribution of the erythemal UV irradiance during its diurnal cycle represents the one for a harmonic regular process. Examples for a fully clear midsummer day 10 July 1999 and for a day at the time close to the spring equinox (24 March 1998) in scales of the UV index are presented in Fig. 5. The probability of both the lowest and the highest values exceeds that of the intermittent ones, which are distributed almost equally in a certain range. The daily highest value is dependent on the maximum solar elevation angle, the same holds true for the range of equal values. The probability of finding the lowest values is slightly higher than that for the highest ones. Low cloudiness usually increases the probability of intermittent and low values and decreases the probability of the highest ones. The examples of UV index distributions in fully overcast by thick stratocumulus clouds (7 July 1998) and by less opaque stratocumulus clouds (29 July 1998) are presented in Fig. 6. In the latter case it can be seen that certain probability of high UV index values exists for overcast skies. In Fig. 7 the daily distributions of two close to each other days are compared. On 17 June 1999 the mean total cloudiness (mostly cirrus) over a day was 6.5 tenths and the cumulus clouds were present at noon hours. A certain amount of UV index values higher than on a fully clear day 19 June 1999 was recorded. Due to this contribution a daily dose on 17 June occurred to be 1.1 MED (7%) higher that on 19 June.

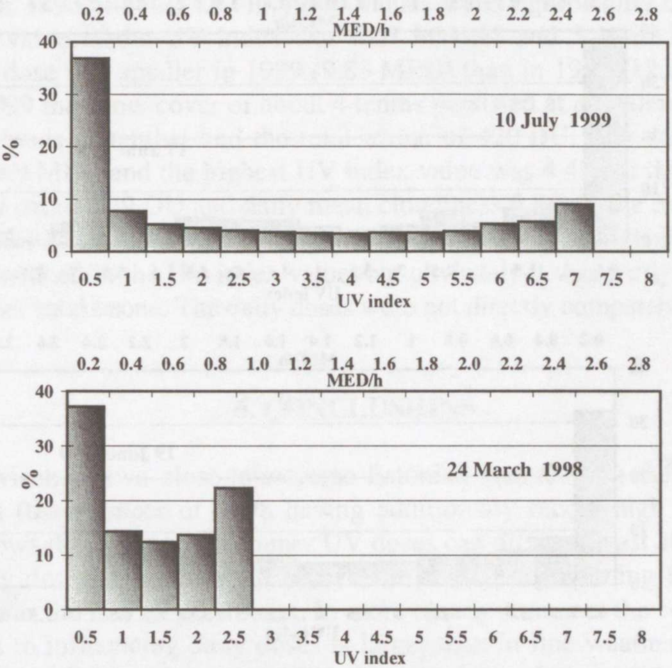

Fig. 5. Distributions of clear day UV index and MED values in cases of different solar noon elevations.

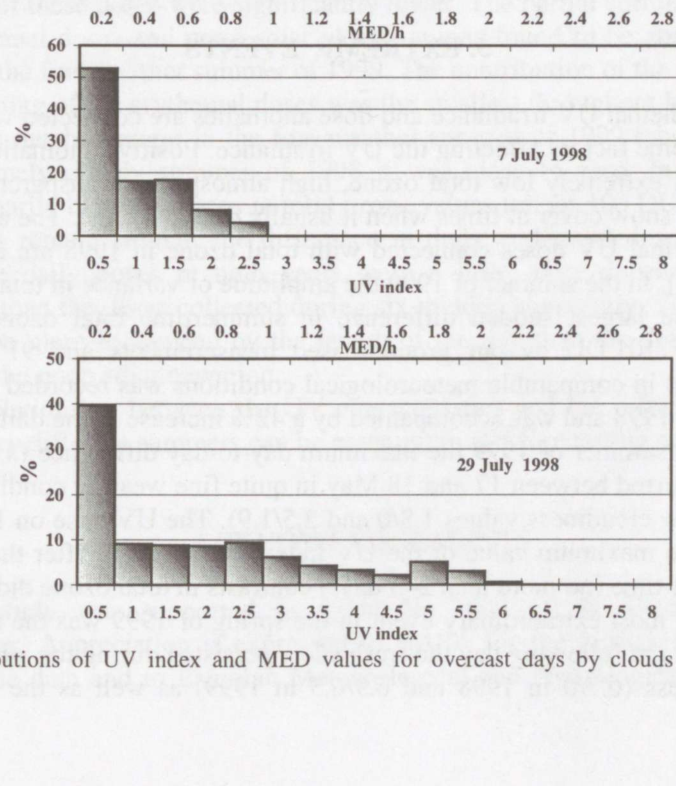

Fig. 6. Distributions of UV index and MED values for overcast days by clouds with different transmission.

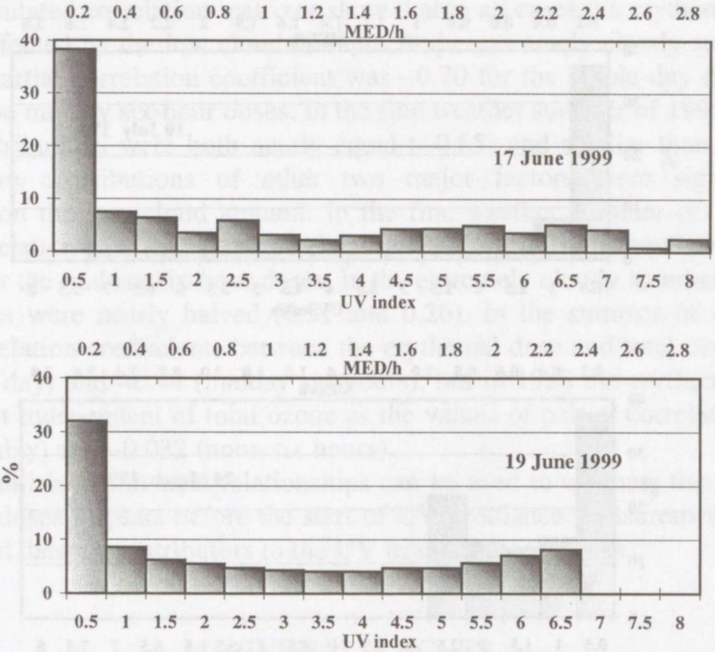

Fig. 7. Comparison of the distributions of UV index and MED values for a day with moderate cirrus and cumulus clouds 17 June 1999 and a clear day 19 June 1999.

5. EXTREME EVENTS

The erythemal UV irradiance and dose anomalies are connected with extreme values of some factors affecting the UV irradiance. Positive anomalies appear in the cases of extremely low total ozone, high atmospheric transparency, and the presence of snow cover at times when it usually does not exist. The anomalies in daily erythemal UV doses connected with total ozone in 1998 are described in our paper [9]. In the summer of 1999 the amplitude of variance in total ozone was smaller. The largest sudden difference in summertime total ozone values (a decrease of 101 DU by our ground-based measurements and 91 DU by the TOMS data) in comparable meteorological conditions was recorded between 20 and 22 July 1998 and was accompanied by a 42% increase in the daily erythemal dose. In the summer of 1999 the maximum day-to-day difference (a decrease of 79 DU) occurred between 17 and 18 May in quite fine weather conditions (mean total and low cloudiness values 1.8/0 and 2.5/1.9). The UV dose on 18 May was 28% and the maximum value of the UV index 25% higher. After that event the largest short-time (no more than 2–3 days) contrasts in total ozone did not exceed 46 DU. The most extraordinary event in the spring of 1999 was the snowfall on 10 May. On the following day the fresh snow persisted during the whole day but the cloudiness (6.7/0 in 1998 and 6.9/6.3 in 1999) as well as the total ozone

(364 DU in 1998 and 423 DU in 1999) values were significantly different. The maximum value of the UV index was 5.07 in 1998 and 5.56 in 1999, but the erythemal dose was smaller in 1999 (9.83 MED) than in 1998 (12.11 MED). On 12 May 1999 the snow cover of about 4 tenths persisted at a moderate amount of cumulus clouds (3 tenths) and the total ozone of 420 DU. The daily erythemal dose was 9.9 MED and the highest UV index value was 4.49. At the same day in 1998 (total ozone 379 DU and daily mean cloudiness 5.8/2.5) the erythemal dose was 11.6 MED and the UV index was 4.67. The effect of the high albedo of fresh snow was noticed in the UV index value, but obviously it was partly compensated by the higher total ozone. The daily doses were not directly comparable.

6. CONCLUSIONS

Comparison of two close-to-extreme Estonian summers on the basis of low cloudiness (the summer of 1998 having additionally record-high average total ozone) shows that the whole summer UV doses can differ at least about 15% and the ten-day doses more than 1.5 times. The strongest governing factor in both summers was the low cloud amount. In more cloudy summers the contribution of cloudiness to influencing daily doses is larger than in fine weather summers. In the extremely cloudy summer of 1998 the partial correlation of daily UV doses with the low cloud amount was not much higher than in the fine weather summer of 1999, but the relative contributions of solar elevation and total ozone to the variation of these doses were significantly lower. The partial correlation between the erythemal doses and noon solar elevation was found to be about two times higher in the fine weather summer of 1999. The contribution of the total ozone to the governing of the erythemal doses was the smallest throughout both summers, but it was much stronger in the fine weather summer of 1999 (about –0.44). In the extremely cloudy summer of 1998 it was close to zero. In the cases of extraordinarily big differences in total ozone values (about 100 DU), while other conditions remain similar, the difference in daily erythemal doses can exceed 40%. The daily doses in both years were a little more dependent on solar elevation than the doses collected during six midday hours only. The daily doses seem to be more influenced by the length of the day than the doses of midday hours by the noon solar elevation.

The relationship between the UV characteristics and the influencing factors during very different summers can be essential in UV forecasting activities.

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ULTRAVIOLETTKIIRGUS METEOROLOOGILISELT KONTRASTSETEL SUVEDEL 1998 JA 1999 EESTIS

Kalju EERME, Uno VEISMANN ja Rutt KOPPEL

Päikese erüteemse ultraviolettkiirguse monitooringu andmed Tõravere kohta katavad seni kaht märkimisväärselt erineva suvise (siin mai–august) ilmastikuga aastat. On käsitletud erüteemse ultraviolettkiirguse karakteristikute sõltuvust meteoroloogilistest tingimustest. Suve esimese poole erüteemne doos oli mõlemal aastal sarnane. Suve teisel poolel osutus 1999. aasta doos 28% suuremaks. Mõlemal suvel sõltusid päevased doosid kõige enam madalate pilvede hulgast. Ekstreemselt pilvisel 1998. aasta suvel ei olnud ultraviolettkiirguse osakorrelatsioon madala pilvisusega (kordaja –0,70) mitte eriti palju kõrgem kui ilusate ilmadega 1999. aasta suvel (–0,65). Päikese maksimaalne kõrgus horisondist andis viimasel aga erüteemse doosi kaks korda kõrgema osakorrelatsiooni (kordajad vastavalt 0,6 ja 0,3). Osooni koguhulga panus erüteemse doosi muutlikkusse osutus pilvisel 1998. aasta suvel peaaegu nulliks ja oli ka 1999. aasta suvel küllaltki väike (–0,44). Ultraviolettindeksi päevased jaotustihedused sisaldavad mõõduka kiud- ja rünkpilvisuse korral rohkem suuri väärtusi kui selge ilmaga ja suuremad tulevad ka päevased erüteemsed doosid.