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## Interannual and Intraseasonal Variations of the Available Solar Radiation

Kalju Eerme  
*Tartu Observatory*  
*Estonia*

### 1. Introduction

The availability of solar radiation is important climate and welfare related environmental factor like temperature or moisture. Living organisms are adapted to the local annual cycles as well as interannual and intraseasonal variations of environmental factors. The importance of appropriate models for global solar radiation has increased in recent decades due to wider use of solar energy applications, including photovoltaic power generation (Šuri et al., 2007, Tiwari and Sodha, 2006). Better understanding of the influence of spectral composition of ground-level solar radiation on terrestrial and aquatic ecosystems has increased the interest in the availability of solar direct irradiance (Lohmann et al., 2006). The annual total does not contain enough information for applications of solar radiation data. Seasonal or even monthly time resolution is often necessary. The annual cycle of availability of solar energy is determined by the annual cycle of noon solar elevation angle, with significant contribution from cloudiness (Tooming, 2002) and atmospheric transparency (Russak, 1990, 2009). Cloud cover at moderate latitudes tends to be thicker and more frequent in late autumn and early winter and less frequent in spring and summer. In the dark half-year not only absolute but also relative availability of solar radiation is smaller.

The attempts of measuring and recording ground-level solar radiation have started about 100 years ago, but usually these activities remained episodic. Most available solar radiation data sets cover significantly shorter time intervals than those of temperature or precipitation. Due to relatively short time series the reasons for variation and regular changes of ground-level solar radiation are still not completely understood.

The present chapter in considering local seasonal and monthly relative availability of solar radiation is based on Estonian solar radiation data. The longest and most complete data set on solar radiation in Estonia has been collected at a typical Estonian rural site at the Tartu-Tõravere Meteorological Station (58°.16'N, 26°.28'E, 70 m a.s.l.). The attempts of recording sunshine duration were made since 1906 (Kallis et. al., 2005). First regular measurements of solar irradiance were performed in late 1930s and continued after 1950 (Ohvril et. al., 2009). Before 1965 the station was based closer to town than its present site. Simultaneous measurements at both sites during one year did not reveal systematic differences. The landscapes at both sites are similar. The Tartu-Tõravere site as well as that before 1965 can be considered typical for Northern Europe. At other geographical regions the contrast

between summer and winter as well as the seasonal impacts of cloud cover and aerosols may be significantly different. Here, the variations of solar ground-level integral global and direct irradiance on seasonal and monthly scales are examined. The continuous record of pyranometer-measured daily global radiation extends back to 1953 and that of pyrhelimeter-measured direct irradiance back to 1955. The study is based on this long-term data set for years 1955-2010 when both quantities are available. The data set is supported by the conventional meteorological data and visual cloud inspection data.

Much of information in meteorological and climatological studies is obtained from measurement data applying statistical methods. The aim of exploratory data analysis (EDA) is to get an insight into the possible processes behind the variations in the collected data. Often the seasonal or monthly data are analyzed for their trends in time. In EDA, mainly the numerical summary measures of collected data sets, characterizing central tendency, spread and symmetry of data samples during their time evolution are used (Wilks, 2006). Quite often the conventional mean is used as a central tendency measure without checking how adequate it is. To get realistic insights into the processes the chosen characteristics must be robust. Robustness means insensitivity to deviations from the assumptions made. Suitability of different central tendency and spread characteristics of the recorded daily sums is compared in the case of skewed probability density distributions and the appropriate characteristics of seasonal and monthly relative solar radiation are found. Major features of variation and trends in the availability of solar radiation in 1955-2010 are studied.

## 2. Daily relative global irradiance $G/G_{clear}$ and relative direct irradiance $I'/I'_{clear}$

The conventionally measured daily energy amounts of global  $G$  and direct solar irradiance  $I'$  falling on a horizontal surface are presented in physical units of MJ/m<sup>2</sup>. For the direct irradiance perpendicular to solar rays, irradiance  $I$  is measured and its values transformed to the horizontal surface  $I'$  are also made available for each day. Until 1996 the Yanishevski AT-50 actinometers and Savinov-Yanishevski M-115 pyranometers were used but were since replaced by the Eppley Labor. Inc. pyrhelimeters and Kipp & Zonen pyranometers. The absolute accuracy of the ventilated Kipp & Zonen pyranometers is about  $\pm 2\%$  and that of the pyrhelimeters  $\pm 1\%$ . In the case of older instruments these uncertainties usually were doubled. In the past intercalibration of sensors was regularly performed in Voeikov Main Geophysical Observatory (St. Petersburg, Russia), whereas now it is done in World Radiation Center (Davos, Switzerland). Between the comparison campaigns, the absolute radiometer PMO-6 No R850405 is used as a secondary standard for regular assurance of the calibration. The previous standard, Ångström pyrhelimeter M-59-8 No. J-1981, has been in use during more than 20 years and the scales of old and new standards have been in agreement with the World Radiation Reference within  $\pm 0.1\%$  (Russak and Kallis, 2003).

The results of statistical treatment of values measured in physical units are illustrative in the case of interannual variations over longer time intervals. Due to the annual cycle even in clear conditions, the summer daily maxima of global solar irradiance at the study site, in absolute scale, are about 17.5 times higher than these of winter minima. The intraseasonal differences of the relative availability of solar radiation are emphasized if the daily values are presented relative to their climatological clear-sky background as the ratios  $G/G_{clear}$  and  $I'/I'_{clear}$ . The daily climatological clear-sky values  $G_{clear}$  and  $I'_{clear}$  are the assumed clear-day values for each calendar day corresponding to the typical conditions of atmospheric

characteristics (Eerme et al., 2006; Eerme et al., 2010). Also they could be defined as those for the assumed dry atmosphere (Eerme et al., 2010). The clear-sky climatological daily sums could be calculated, using radiative transfer codes inserting realistic aerosol optical depth (AOD) data as well as realistic vertical profiles of temperature, water vapor and aerosol content. The clear-sky daily sums could be also interpolated from the observed data corresponding to average typical conditions by selecting the cloudless days proceeding from the recorded daily AOD values. We have used the latter version to avoid systematic differences in scales. The precipitable water vapour variations influence the clear-sky values of  $G_{clear}$  and  $I'_{clear}$  as well but the range of variations of AOD influence is about ten times larger than that of water vapour (Russak et al., 2005).

### 3. Composing of annual cloudless-sky cycles

The interpolated annual cycles of clear-sky daily  $G_{clear}$  and  $I'_{clear}$  for the study site (Eerme et al., 2006) are presented in Fig. 1.

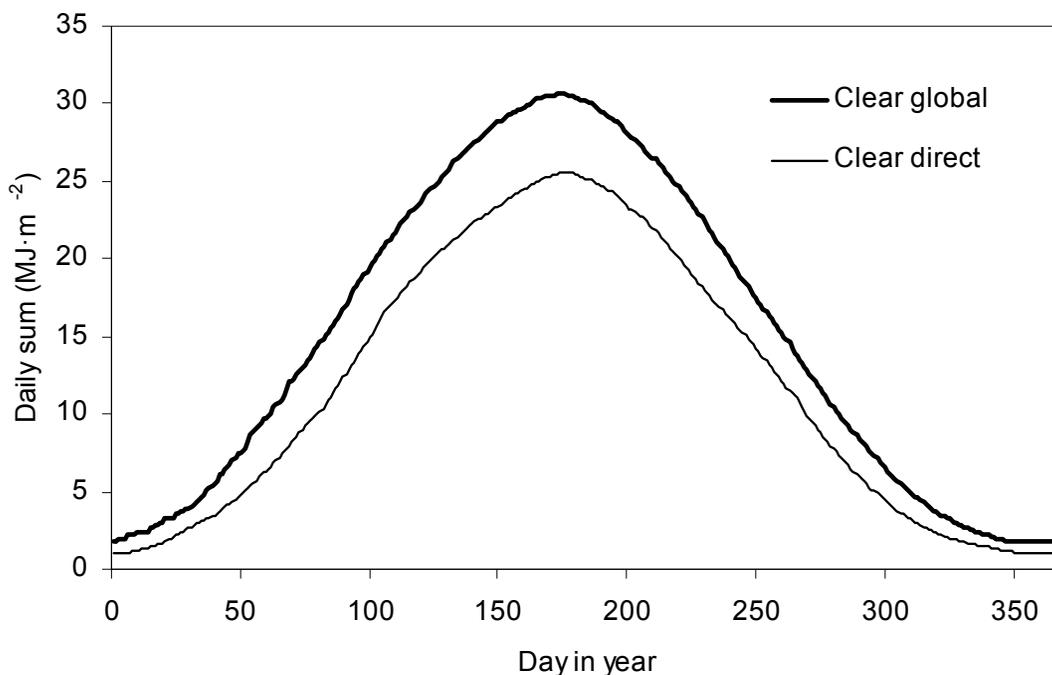


Fig. 1. Graph of the daily global and direct broad-band radiation in MJ m<sup>-2</sup> on cloudless day vs day in the year for Tartu-Tõravere Meteorological Station site

Selection of cloudless days was based on the daily sums of direct irradiance and sunshine duration with inclusion of the hourly values, if necessary, and on the cloud visual inspection data. The used data enabled us to confirm that the solar disk was not obscured by clouds but did not exclude a possibility of appearance non-obscuring clouds during the day. Such small cloud amounts have minor or practically no influence on the recorded daily values of solar radiation. The effect of variation of the distance between the Earth and the Sun is considered in the data. The smoothed annual cycles have been composed, using a moving average of 5 to 10 days with balanced positive and negative deviations of the AOD from its seasonal climatological value. For the period before 2002 the AOD values for broad-band

solar radiation prepared by Russak (Russak, 2006; Russak et al., 2005, 2007) have been used. The data for years 1983-1985 and 1992-1995 were excluded for reason of containing significantly higher values from El Chichon and Pinatubo major eruptions than the usual contribution of large values. Major volcanic eruptions can be considered as stochastic natural fluctuations of atmospheric conditions in time scales of the performed study. The variations of global volcanic activity appear at much lower frequencies than the studied variations of available solar radiation.

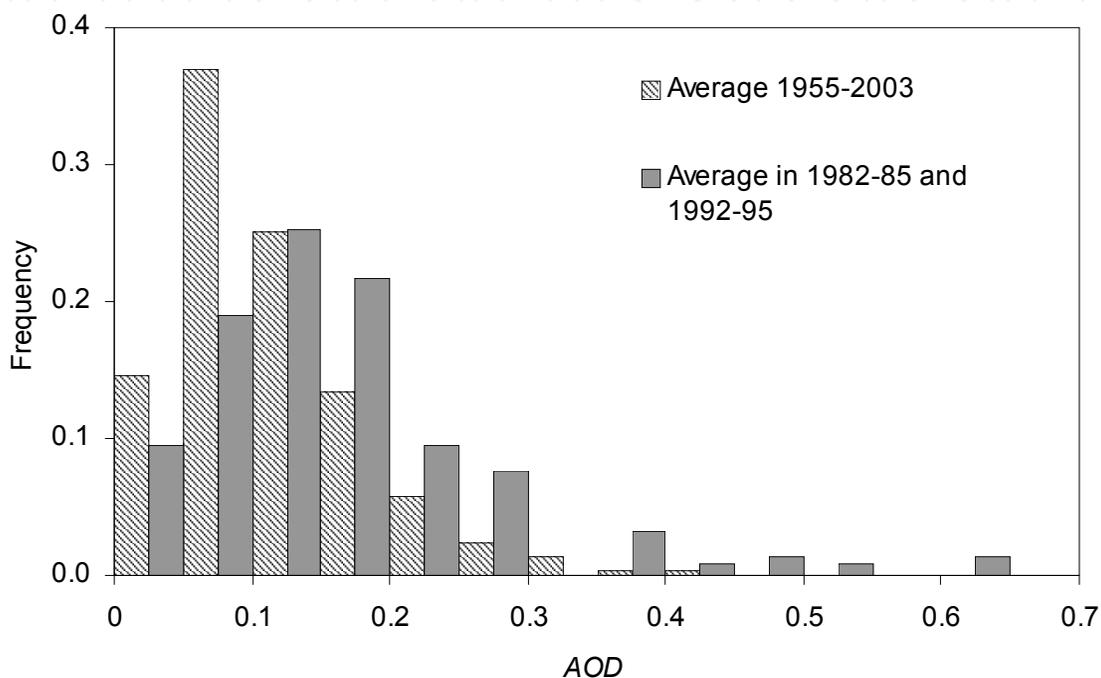


Fig. 2. Probability density distributions of broadband aerosol optical depth in 1955-2003 in normal conditions and in volcanically disturbed atmosphere in 1983-1985 and 1992-1995

Fig. 2. illustrates the distribution of broad-band AOD in summer half-year in normal and volcanically disturbed conditions. Since February 2002 the AERONET Cimel-318a sun-photometer (<http://aeronet.gsfc.nasa.gov>) operates at Tartu-Tõravere Meteorological Station. The cloud corrected AOD data at level 2.0 are used. Reliable relationship was established between the broadband AOD and AERONET AOD at 500 nm (Teral et al., 2004). The summer half-year distribution of AOD at 500 nm is presented in Fig. 3. The major part of AOD data are recorded in April to September. In February and November as well as often in October and March the amount of data is too small for statistical conclusions. In December and January almost no data have been recorded due to very low noon solar elevation. Thus, in November to February the cycles of  $G_{clear}$  and  $I'_{clear}$  are less reliable than in March to October. It should be mentioned that at the study site about 80 % of global solar radiation and 87 % of direct irradiance are received during the bright period of the year from spring equinox to autumnal equinox. The average contribution, from the period November to February, to the annual amount of global irradiance is around 5.9 % and that of direct irradiance around 3.3 %.

The cloudless days exhibiting large deviations of  $G_{clear}$  and  $I'_{clear}$  from the current normal value were excluded. The seasonal probability density distributions (see Fig. 2 and Fig. 3) of the AOD are skewed with a sharp maximum at small values and long tail of large values (Eerme et al., 2006). In the case of such distribution the conventional mean is not an appropriate measure of central tendency because it is shifted toward larger values than the major body of distribution. Median coincides with the peak of distribution much better and its value is about 20-30 % less than the conventional mean. However, median does not consider the differences in both wings of distribution. In the cases of equal median the distribution of values in wings may be substantially different.

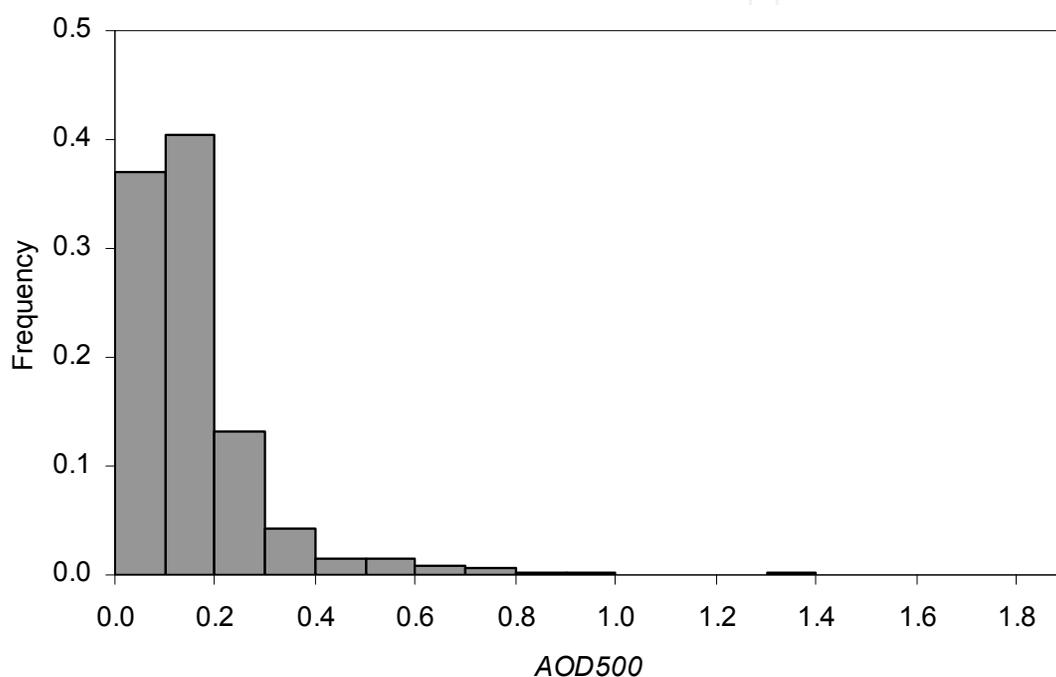


Fig. 3. Probability density distribution of AERONET measured AOD in summer half-year at 500 nm in 2002-2010

Proposed by British statistician Bowley and popularised in the classic book by Tukey (Tukey, 1977), trimean takes into consideration the distribution in wings through inclusion of the 0.25 and 0.75 quartiles. In calculating trimean these values are considered with single and median with double weight. For AOD as well as for later  $G/G_{clear}$ , three central tendency measures – conventional mean, median and trimean, have been calculated and compared. We have a reason to consider trimean as the most appropriate measure for central tendency of skewed distributions.

#### 4. Probability density distributions of daily $G/G_{clear}$ and measures of their central tendency and spread

The daily ratios of  $G/G_{clear}$  were studied statistically within four conventional seasons of the year. The winter season extends from Dec 22 to March 20, the spring season from March 21 to June 20, the summer season from June 21 to Sept 22 and the autumnal season from Sept

23 to Dec 21. The summer, half-year which includes both spring and summer seasons was also studied separately. Similar study was performed on monthly level. The maximum, mean and minimum values of calculated central tendency measures for relative global irradiance in all seasons are presented in Table 1. Also the spread characteristics, StDevTri and StDevMed, were calculated relative to the trimean and median like the conventional standard deviation (StDev) is calculated relative to the mean (Wilks, 2006). For almost all seasons and months the StDevTri is the smallest and StDevMed tends to be the largest.

Quantity	Winter	Spring	Summer	Autumn	Summer half-year
$G/G_{clear}$					
Mean	0.568	0.658	0.652	0.467	0.650
Median	0.530	0.653	0.646	0.412	0.675
Trimean	0.552	0.656	0.648	0.429	0.668
Min	0.406	0.563	0.567	0.371	0.586
Max	0.767	0.771	0.768	0.605	0.748
$I/I'_{clear}$					
Mean	0.306	0.425	0.400	0.230	0.412
Min	0.163	0.249	0.283	0.090	0.305
Max	0.521	0.601	0.557	0.378	0.542

Table 1. Seasonal central tendency measures of the relative global irradiance  $G/G_{clear}$  and relative direct irradiance  $I/I'_{clear}$  in 1955–2010

The seasonal and monthly probability density distributions of daily  $G/G_{clear}$  for every year were studied for their symmetry and deviation from the Gaussian distribution. The seasonal as well as monthly probability density distributions in most cases were flatter than the Gaussian distribution and skewed. Sharper distributions appeared less frequently. Both the negatively and positively skewed ones were found. In dark half-year the monthly and seasonal probability density distributions tend to be positively and in bright half-year negatively skewed. Median and trimean of distributions in separate years tend to be larger than conventional mean in the prevailing sunny conditions. In cloudy conditions, on the contrary, conventional mean tends to be larger than median and trimean. The difference between median and mean is usually larger than that between trimean and mean. Year-to-year variation of the ratios, Mean/Trimean and Mean/Median within seasons of the dark half-year was significantly larger than in the summer half-year.

In cloudy dark half-year, when small values of  $G/G_{clear}$  dominate, a few sunny days appearing in a month may cause positive skewness of distribution and enlarge the value of the conventional mean. The biases between mean and trimean, and between mean and median may exceed 20 %, while the majority of  $G/G_{clear}$  are very small values. In the months of bright half-year, a few very small values due to heavily cloudy days shift the conventional mean toward lower value. The annual monthly values of mean, median and trimean of  $G/G_{clear}$  and their year-to-year variation were studied. The seasonal and half-yearly differences between trimean, median and conventional mean are small because during the long periods different situations are encountered, and the distribution becomes more symmetric than it is for shorter intervals. Using the conventional mean as a reference

leads to underestimation of the contrast between the winter and summer months availability of solar irradiance.

The ratio of Mean/Trimean of  $G/G_{clear}$  is positively correlated to the skewness of distribution during a whole year. The monthly coefficients of linear correlation vary between 0.55 and 0.88. In September to February the ratio, Mean/Trimean is positively correlated with the kurtosis of distribution, and in March to August the correlation was negative. In March to August the main tendency and the spread measures were negatively correlated. The monthly coefficients varied between  $-0.20$  and  $-0.65$ . It means that instead of large values of  $G/G_{clear}$  dominating, the contribution of large deviations is small. In October to December positive correlation, with coefficients 0.60 and 0.65 respectively were obtained. It means that the probability of large deviations increases with increasing contribution of relatively small values.

### 5. Year-to-year variations of half-yearly, seasonal and monthly availability of global irradiance

The annual availability of solar radiation at the latitude of study was determined by the contribution of summer half-year since the contribution of winter half-year was only about 20 %. At the same time the interannual variations tend to be larger in winter months. The variation in every summer half-yearly total, during the 56 years considered remains within  $\pm 10\%$  about the average, except for the two extremely sunny years 1963 and 2002, when the totals exceeded the average by 15 % and reached 75 % of the climatological cloudless-sky value.

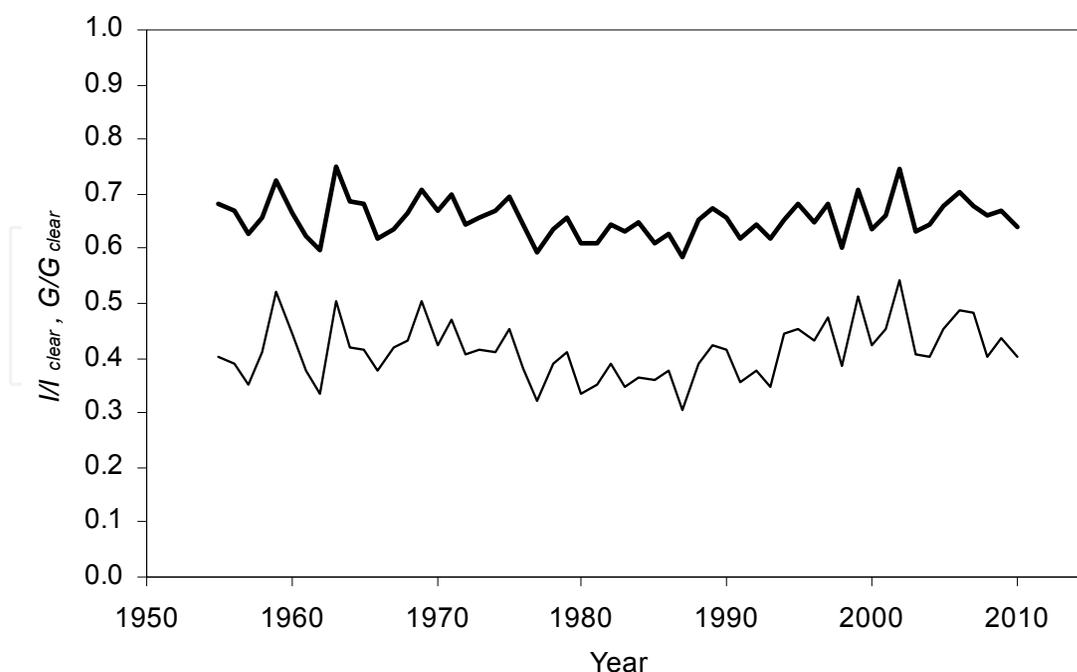


Fig. 4. Time series of summer half-year average  $G/G_{clear}$  (above) and  $I/I_{clear}$  (below) in 1955-2010

In most years, the deviations from the mean are significantly less than 10 %. For the summer half-yearly totals, the difference between conventional mean and trimean is about 0.3 % and that between conventional mean and median about 0.6 %. The conventional mean could be considered here as acceptable as the measure of the general trend. The year-to-year variations are most strongly correlated with cloudiness. The coefficients of linear correlation of the average  $G/G_{clear}$  with the average total cloud amount, low cloud amount and the number of overcast days in all seasons have been around  $-0.80$ . The linear correlation between the summer half-yearly sums of relative global and relative direct irradiance is equal to 0.90, which is much higher than that for the winter half-year, when it is only 0.60, indicating larger contribution from the direct radiation to the variation of global irradiance at higher solar elevations and snow-free conditions. At the seasonal level the correlation was the highest, 0.96, in summer, and somewhat lower, 0.92, in spring when the ground albedo was not stable.

In the time series of yearly averages of  $G/G_{clear}$  and  $I/I'_{clear}$  in the summer half-year (Fig.4), a remarkable feature is observed: an interval of reduced values in the years 1976–1993, when 15 out of 18 values were lower than the 1955–2010 average. The period of low values was more contrasting in terms of direct than global irradiance. Searchers of linear trends could easily find a dimming trend between the 1960s and the mid-1980s and a brightening trend from the middle of the 1980s. Similar behaviour of annual totals from late 1950s and early 1960s has been obtained also in other sites of Northern Europe and European Russia (Wild et al., 2005; Chubarova, 2007). The finding of approximately 35-year periodicity of alternation of cloudy and bright conditions in Western Europe was attributed to sir Francis Bacon who declared it in first decade of 17th century. Later it was forgotten and found again in several cases. The dimming and following brightening presented in Fig. 4 is rather a manifestation of this periodicity. A little more than one full period is presented.

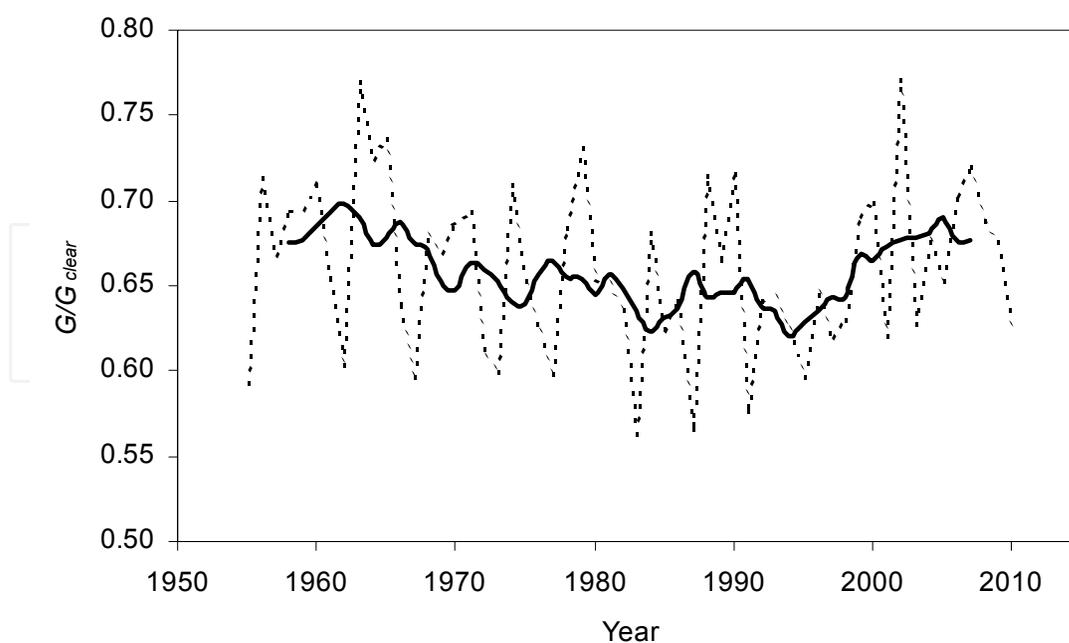


Fig. 5. Long-term variation of  $G/G_{clear}$  with year in spring, 1955–2010: Annual values and 7-year moving average

Considering the spring and summer seasons separately, some significant differences in the long-term behaviour of the available solar irradiance become evident. The smooth line representing 7-year moving average of interannual variation of  $G/G_{clear}$  in the spring season exhibits maxima around 1965 and 2000 and minima between 1980 and 1985 as well as around 1995 (Fig. 5).

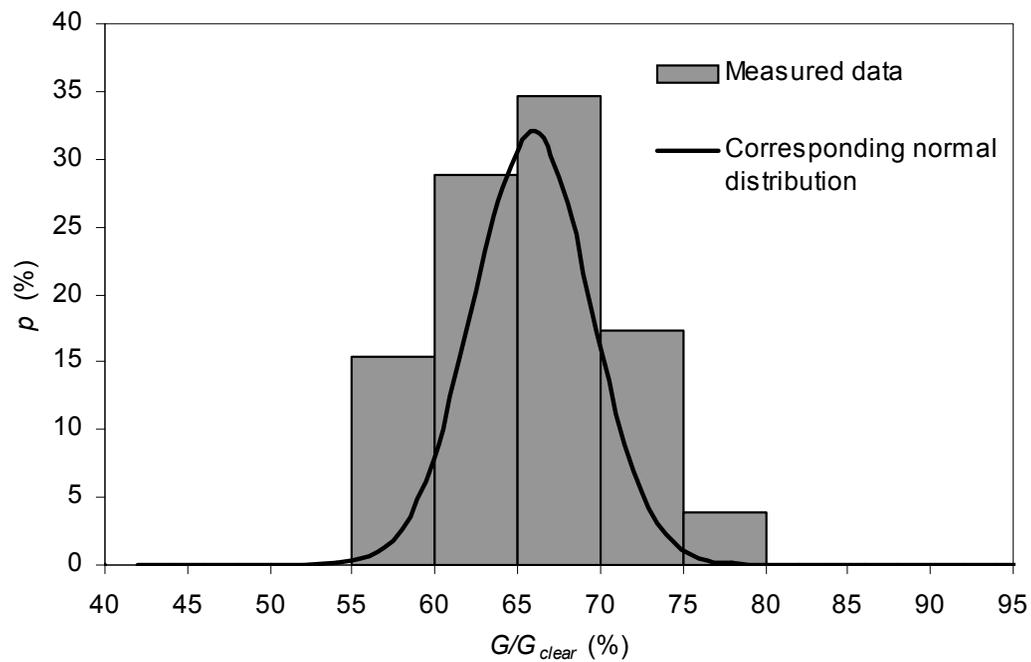


Fig. 6. Probability density histogram of  $G/G_{clear}$  in spring season

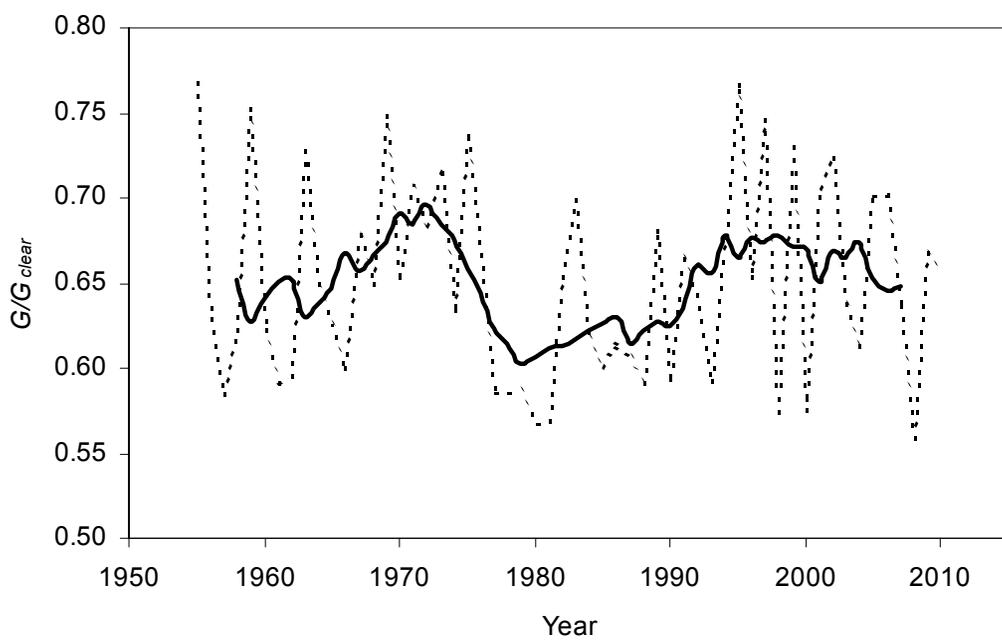


Fig. 7. Long-term variation of  $G/G_{clear}$  with year in summer, 1955-2010: Annual values and 7-year moving average

A 7-year moving average turned out to be effective for smoothing the short-term variations and emphasizing the expected trends. This has also been approved in the case of other Estonian meteorological and hydrological data (Järvet and Jaagus, 1996).

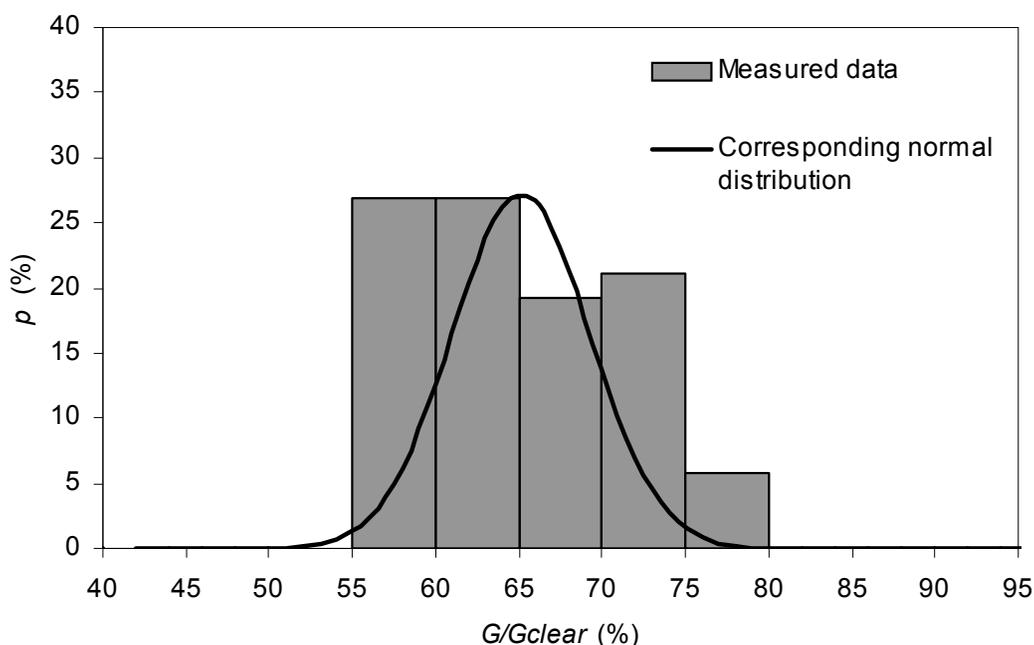


Fig. 8. Probability density histogram of  $G/G_{clear}$  in summer season

The probability density distribution of  $G/G_{clear}$  for the spring of years 1955–2010 (Fig. 6) is symmetric and the values were close to the average with the highest frequency. The major part, 65%, of the annual values occurred between 0.60 and 0.70; 20% were above 0.70 and 15% were below 0.60. The observations by several authors of the long-term dimming trend up to the middle of the 1980s and those of the following brightening trend (Che et al., 2005; Wild et al., 2005; Sanchez-Lorenzo et al., 2007) were generally in agreement with the  $G/G_{clear}$  observed in the spring.

In the summer, the distribution was less symmetric and the amounts of very large and small values were about 27% for both. In summer periods of large and small values of  $G/G_{clear}$  (Fig. 7) were revealed. Large values dominated in 1966–1975 and more so from 1994. No obvious long-term trend of dimming or brightening was found. Up to the late 1960s each fourth summer was sunny. During the mentioned bright periods, approximately each second summer was sunny. The probability density distribution of summer  $G/G_{clear}$  shown in Fig. 8 does not fit the normal distribution and exhibits rather bimodal nature. This suggests that the existence of two different regimes associated with mean wet or dry summers (D'Andrea et al., 2006), being partly driven by soil moisture, may be the reason of such distribution observed in Estonia, and presumably in other parts of Northern Europe. Such behaviour is expected to result from multiple equilibria in the continental water balance containing the contributions of large scale weather patterns as well as of the local soil water contents. The spring and summer mean  $G/G_{clear}$  are poorly correlated with each other.

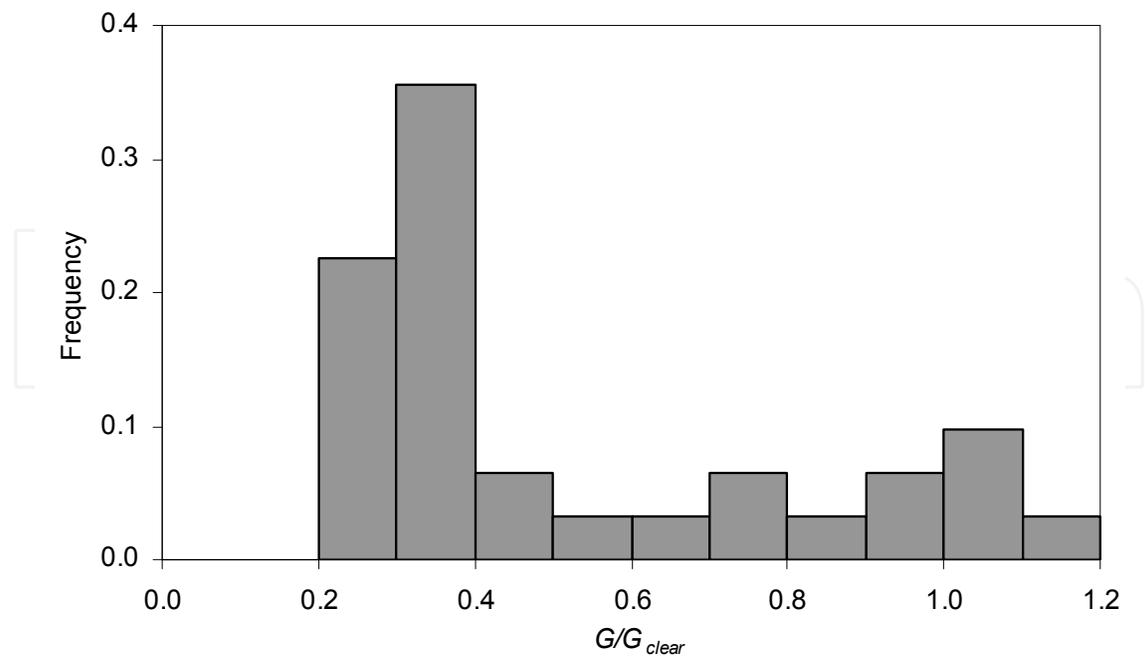


Fig. 9. Typical histogram of monthly distribution of relative daily sum of global irradiance  $G/G_{clear}$  in dark half-year

At the site, the daily mean of global irradiance in the summer half-year is approximately 0.65 of its climatological cloudless-sky value. It is almost equal to that of spring and summer. In two extremely fine weather years of 1963 and 2002, its value reached 0.75 of the clear-sky value. In three most cloudy summer half-years the value remained slightly below 0.60 of the climatological clear-sky value.

The monthly trimean values of  $G/G_{clear}$  presented in Table 2, varied over wide range. The ratio of maximal to minimal value varied from about 3.4 in December to 1.6 in June. The lowest values in November and December were about 0.20, while the highest was recorded in March and was about to 0.99.

Typical histogram of monthly distribution in dark half-year is presented in Fig 9. Sharp high value was recorded during the prevailing thick cloudiness. In November, about 50 % and in December and January about 25 % of the distributions were sharper than the Gaussian. In bright half-year the distribution was flatter than the Gaussian. In summer months sharp distributions may occur in the extremely fine weather conditions. Typical histogram of monthly distribution in bright half-year is shown in Fig 10.

In Table 3, the monthly average together with maximum and minimum values of the ratio Mean/Trimean are presented as well as the coefficients of linear correlation of this ratio with the kurtosis and skewness of distribution.

Variations in spread characteristics have been largest in StDevMed, but only moderately larger than those in two other spread characteristics. For all the months except November, the StDevTri in most cases happened to be the smallest. The ratio StDev/StDevTri exhibits sharper and more symmetric distributions than the ratio of StDevMed/StDevTri. Its values remained in the range between 0.98 and 1.02 with a very few exceptions lower than 0.98 and

only one exception above 1.02 out of 648. The distribution of the ratio  $StDevMed/StDevTri$  exhibits only one case of value below 0.98, but the tail often reaches the range between 1.06 and 1.10.

Month	$G_{clear}$ MJ · m <sup>-2</sup>	$G/G_{clear}$ trimean			$I'_{clear}$ MJ · m <sup>-2</sup>	$I'/I'_{clear}$		
		Min	Mean	Max		Min	Mean	Max
Jan	87.0	0.251	0.484	0.726	50.6	0.038	0.184	0.389
Feb	184.9	0.304	0.554	0.773	117.8	0.108	0.262	0.522
March	416.5	0.350	0.640	0.989	291.1	0.095	0.365	0.756
Apr	626.1	0.390	0.634	0.851	491.7	0.117	0.373	0.625
May	830.4	0.465	0.700	0.899	675.0	0.244	0.451	0.765
June	904.9	0.528	0.693	0.852	748.6	0.222	0.435	0.630
July	878.7	0.484	0.687	0.889	732.9	0.199	0.424	0.696
Aug	698.8	0.428	0.662	0.878	566.7	0.153	0.405	0.739
Sept	458.4	0.384	0.593	0.774	366.7	0.114	0.323	0.597
Oct	263.0	0.271	0.447	0.760	188.7	0.070	0.248	0.519
Nov	113.4	0.200	0.345	0.646	73.2	0.020	0.130	0.355
Dec	58.5	0.208	0.442	0.705	36.2	0.028	0.144	0.307

Table 2. The monthly values of assumed normal  $G_{clear}$  in physical units and recorded minimal, mean and maximal values of the trimean of monthly relative global  $G/G_{clear}$ . Monthly assumed normal  $I'_{clear}$  and recorded minimal, mean and maximal values of  $I'/I'_{clear}$  in 1955-2010

## 6. Year-to-year variations of seasonal and monthly direct irradiance

The major contribution to the values of  $G/G_{clear}$  came from the variations of the relative direct irradiance  $I'/I'_{clear}$ . In all seasons and months, overcast days occurred when no direct irradiance was recorded. In late autumn and early winter majority of days were overcast. In December of one of the years under study, sunshine was available only in one day out of 31. In such situations it is impossible to study the probability density distributions of  $I'/I'_{clear}$  like it was done for the global irradiance  $G/G_{clear}$ . The monthly and seasonal values of  $I'/I'_{clear}$  presented in Table 1 and Table 2 were obtained by dividing the recorded sum of  $I'$  by the integrated  $I'_{clear}$  for the same period.

The sunniest season during the study was spring, when 0.43 of the direct irradiance relative to the assumed clear sky conditions was available on average. Similarly during autumn, darkest period, less than 0.25 was available. For the whole summer half-year, the  $I'/I'_{clear}$  was 0.41 on average. The range of interannual variations has been the largest in autumnal period

when the largest value exceeds about four times the smallest one. In the winter period this ratio was close to three, and in spring and summer it was close to two. The monthly  $I'/I'_{clear}$  varied from its overall maximum 0.765, encountered in one May to overall minimum 0.02 encountered in one November. The typical monthly values have been between 0.40 and 0.45 in the brightest months, May to August, and between 0.135 and 0.185 in the darkest ones, November to January. The range of interannual variations of monthly  $I'/I'_{clear}$  was the smallest in June as it was for  $G/G_{clear}$ .

Month	Ratio Mean/Tri			Correl of Mean/Tri		Correl. of Kurt Skew	% of Posit Skew
	Max	Mean	Min	Kurtosis	Skewness		
Jan	1.28	1.085	0.97	0.68	0.81	0.83	90
Feb	1.23	1.045	0.93	0.57	0.88	0.64	69
March	1.25	0.995	0.88	-0.15	0.62	-0.25	52.4
Apr	1.09	0.985	0.90	-0.30	0.82	-0.56	26
May	1.10	0.97	0.90	-0.24	0.75	-0.62	12
June	1.03	0.97	0.92	-0.28	0.75	-0.68	9.5
July	1.03	0.975	0.90	-0.03	0.59	-0.73	4.8
Aug	1.03	0.975	0.93	-0.22	0.64	-0.77	11.9
Sept	1.11	1.005	0.92	0.45	0.84	0.49	47.6
Oct	1.41	1.07	0.91	0.30	0.67	0.72	81
Nov	1.34	1.14	1.00	0.44	0.69	0.91	100
Dec	1.32	1.095	0.97	0.28	0.55	0.91	100

Table 3. Monthly ratios Mean/Tri of  $G/G_{clear}$  (first 3 columns) and their linear correlation with kurtosis and skewness of the distribution of daily values  $G/G_{clear}$  (columns 4 and 5); linear correlation of kurtosis and skewness (column 6) and percent of positively skewed distributions (column 7)

Sunshine duration was recorded in more sites than direct irradiance, and the records often covered longer time intervals. Due to this advantage, sunshine duration has been used as a proxy for reconstruction of global irradiance (Ångström, 1924; Zekai, 1998; 2001; Cancillo et al., 2005) and also direct irradiance (Power, 2001). Direct irradiance is a more appropriate measure of potential sunshine effects than sunshine duration because sunshine episodes prefer certain solar elevation ranges. In May to September frequent convective clouds reduce available sunshine during noon hours when the solar elevation is high and the monthly relative direct irradiance is usually about 75-80 % of relative sunshine duration at the study site.

## 7. Year to year variation of seasonal and monthly totals and trends

At the study site the summer half-year of 1955-2010 contributed 80 % of the annual global irradiance, about 87 % of direct irradiance and about 75 % of sunshine duration on average.

In the dark winter period the amplitude of variations was larger before year 1977, including the extreme lowest value recorded in 1961 and the extreme highest one in 1963.

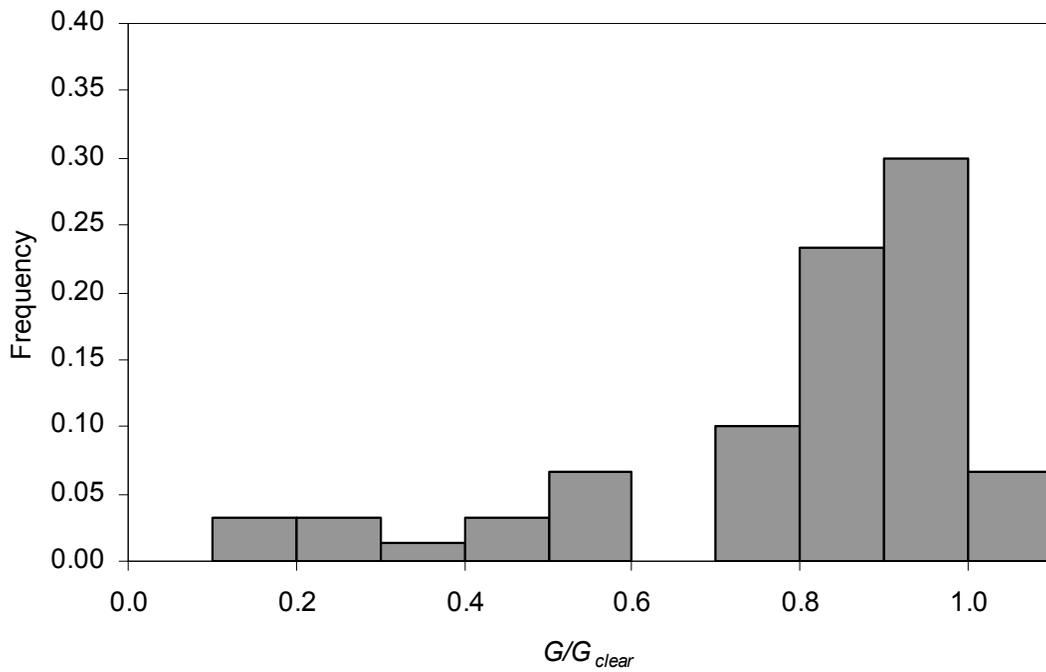


Fig. 10. Typical histogram of monthly distribution of relative daily sum of global irradiance  $G/G_{clear}$  in bright half-year

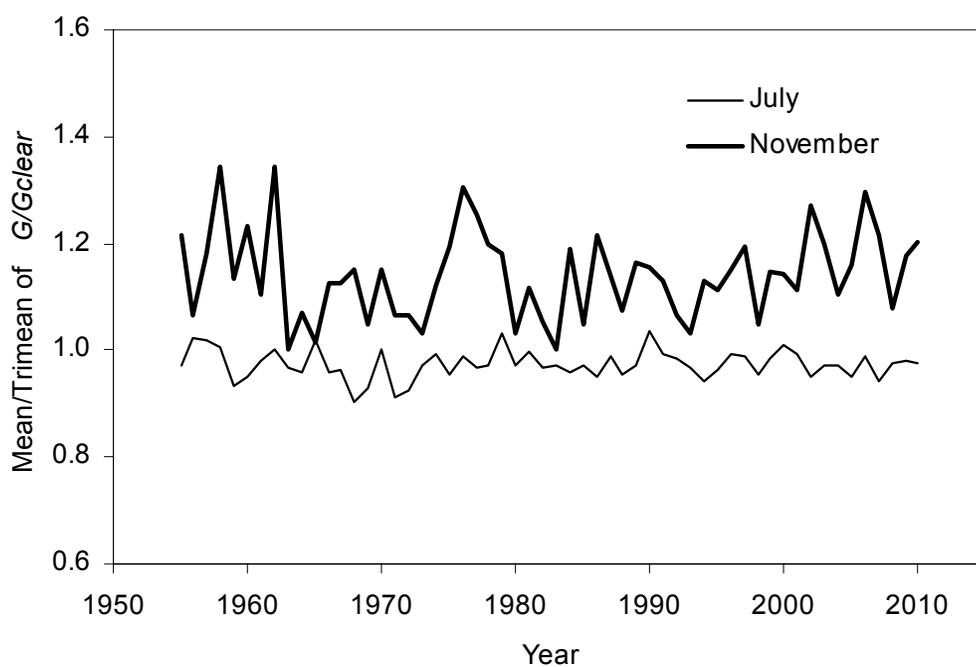


Fig. 11. Time evolution of the ratio Mean/Trimean of  $G/G_{clear}$  in July and in November 1955-2010

Often linear trends are used for characterizing the tendencies of variation in time. We have no reason to expect some overall trend of increase or decrease in  $G/G_{\text{clear}}$  during the whole observed time interval of 1955-2010 in any month. However, there were shorter intervals manifesting quite linear tendency of brightening or dimming. Atmosphere is essentially a non-linear system exhibiting quasiperiodic and nonsymmetric variability in different timescales. Ascending and descending branches of those cycles could be successfully approximated by linear trends.

Month	Mean	Trimean	Median	Time interval
Jan	-0.00416	-0.00454	-0.00418	1963-2008
Feb	0.00299	0.00348	0.00405	1955-1986
March	-0.00599	-0.00691	-0.00755	1955-1995
Apr	-0.00250	-0.00220	-0.00205	1955-1984
	0.00320	0.00454	0.00563	1985-2010
May	0.00090	0.00113	0.00139	1955-2010
June	-0.00109	-0.00117	-0.00123	1955-2010
July	0.00028	0.00138	0.00228	1955-1978
	0.00257	0.00288	0.00329	1979-2010
Aug	-0.01095	-0.01092	-0.01046	1995-2010
Sept	-0.00295	-0.00362	-0.00368	1955-1994
Oct	0.00213	0.00309	0.00353	1955-1989
	-0.00433	-0.00523	-0.00598	1985-2010

Table 4. Slopes of linear trends of  $G/G_{\text{clear}}$  by the conventional mean, trimean and median during time intervals allowing linear approximation

Usually the slopes of calculated linear trend in  $G/G_{\text{clear}}$ , both positive and negative, happened to be larger for the trimean and median than for the conventional mean. A sample of estimated linear trends in all the three general trends measures for time intervals, manifesting the trends most evidently is presented in Table 4. The time evolutions of the ratio of Mean/Trimean in summer and winter months are different. In Fig. 11 the time evolutions of the ratio for relatively sunny month, July and cloudy month, November are presented. In November to March the dimming trends prevail at the site in all months and negative slopes for trimean and median are larger than those for the conventional mean. In January there appeared an overall positive tendency in the ratio Mean/Trimean in 1967-2008. Relatively large positive peaks of the ratio have been encountered in separate years with an increasing frequency after 1988. As was noticed above, those large values of ratio appear when  $G/G_{\text{clear}}$  values were small, presenting sharp and strong positive skewed distribution. In February they were about two times smaller than those in January,

manifesting also overall negative trend. During the last two decades, on the average, the ratios Mean/Trimean were larger, and the values of all three central trend measures of  $G/G_{\text{clear}}$  were smaller than before.

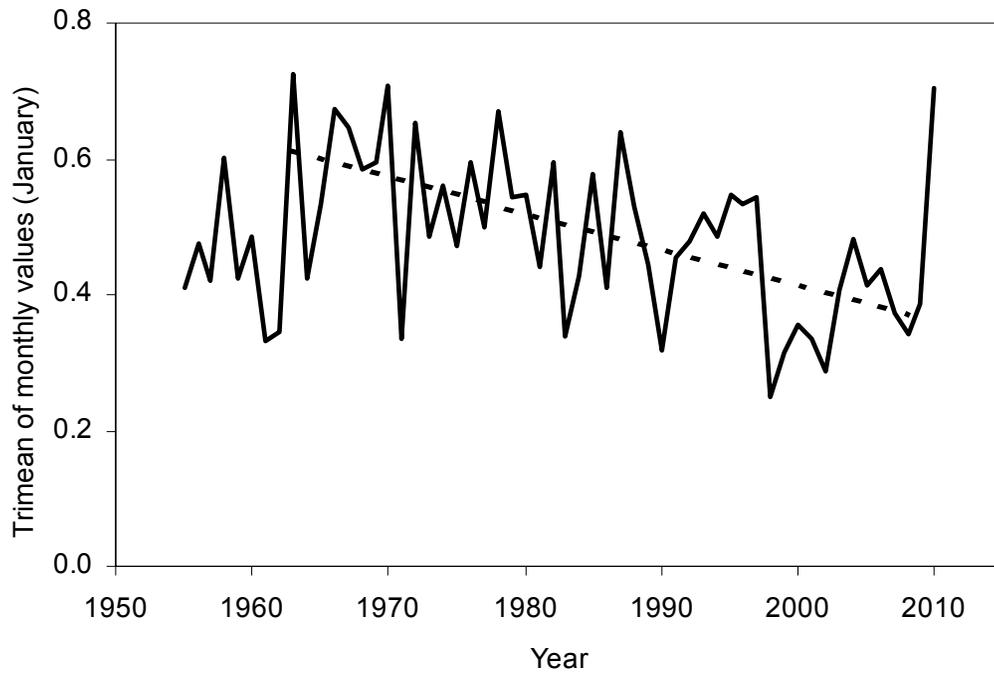


Fig. 12. Trend of dimming for January in 1963-2008

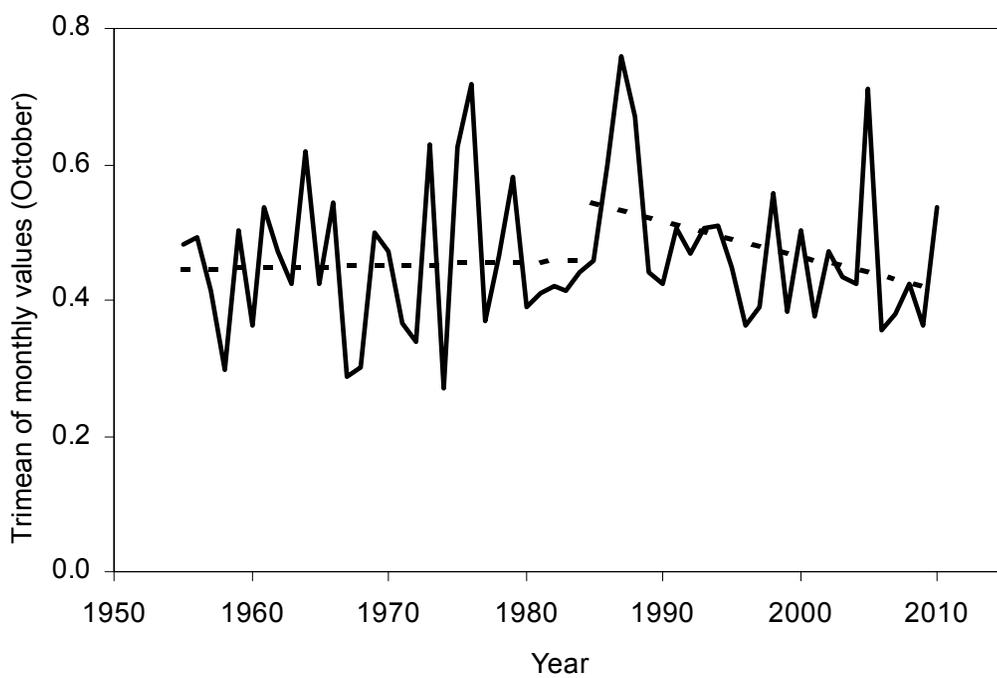


Fig. 13. Switching from brightening to dimming trend in October

In March, a dimming trend was obvious in 1955-1995 and in April of 1955 – 1977 the trend also appeared, but then has changed to the brightening in 1977-1995. In May to August small positive trends in  $G/G_{\text{clear}}$  were observed. In June the positive trend in 1955-1973 has changed to negative in 1973-2003. July and August exhibit small overall positive trends due to the more frequent fine weather conditions since 1994. In September the trend of dimming in 1955-1992, has changed to the brightening later. In October quite significant tendency of brightening has changed to more strong dimming during the last two decades (see Fig. 13). In November, the dimming tendency was observed during the whole observation period. The negative slope of the trend has increased significantly after 1983. In December, similar increase of the linear dimming trend happened around 1977.

## 8. Conclusion

The relative availability of solar radiation at moderate and subpolar latitudes manifests no significant correlation between seasons. The weather regimes often change significantly during each of the conventional four seasons. The annual available amount of solar energy at these latitudes depends on the contributions of spring and summer seasons. For solar radiation applications study of the interannual variations and trends on the seasonal and even on the monthly level is necessary. Detailed data on interannual variation of the available solar energy within seasonal and often even monthly limits are useful for estimation of the biospheric responses, local potential for recreation services as well as for food and clean energy production.

The results obtained at one Estonian site could be considered as an example manifesting that the variations and trends of the relative availability of solar radiation may be substantially different in different seasons and months. Statistical analysis of trends and interannual variations needs at first finding the most appropriate general trend measures based on the probability density distributions of daily amounts of relative global irradiance within selected time intervals. In the case of symmetric distributions the conventional mean is a good measure but in the case of skewed distributions using of it leads to distorted interseasonal proportions and trends.

Using conventional mean instead of more robust trimean, leads to overestimation of the monthly general trend of  $G/G_{\text{clear}}$  in October to February by 4.5 % to 14% on average, depending on the month. In cases of thick clouds domination in separate years, the values of monthly mean may be by 30-40 % larger than trimean and median. In some cases the values of conventional mean were found to be up to 10 % lower than the trimean and median. In bright half-year, April to August, the conventional mean was consistently about 2.5 % lower than the trimean, and using it leads to some underestimation of central tendency in  $G/G_{\text{clear}}$ . Using conventional mean as a measure of monthly central tendencies is related to apparent reduction of the contrast between relative solar energy supply in summer and winter.

Monthly relative availabilities of broadband solar irradiance at the study site and presumably also in its wider neighbourhood varied in wide ranges. The ranges of variations were smaller in months of summer half-year and larger in autumnal and winter seasons. The average availability of global irradiance in summer half-year, and separately in spring and summer seasons, was 0.65 and that of direct irradiance 0.41 of the assumed normal

cloudless weather amount. In spring the relative availability of direct irradiance has been to some extent larger than in summer and its interannual variation smaller.

Slopes of the linear trends were found to be smallest in the case of using conventional mean as a central tendency measure. It leads to underestimation of the dimming and brightening trends in the cases when linear approximation is appropriate for their description. In summer months, in most cases, small brightening trends were found. In June it changed to rather a dimming trend around 1973. In winter months there appears an overall dimming tendency of  $G/G_{\text{clear}}$  in recent two decades. Using the conventional mean leads to underestimation of that trend by up to 20-30 % as compared to the version calculated on the basis of trimean.

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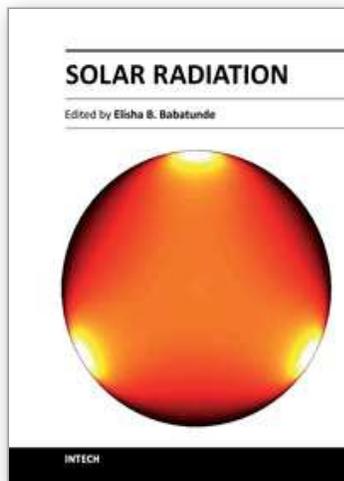
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Edited by Prof. Elisha B. Babatunde

ISBN 978-953-51-0384-4

Hard cover, 484 pages

**Publisher** InTech

**Published online** 21, March, 2012

**Published in print edition** March, 2012

The book contains fundamentals of solar radiation, its ecological impacts, applications, especially in agriculture, architecture, thermal and electric energy. Chapters are written by numerous experienced scientists in the field from various parts of the world. Apart from chapter one which is the introductory chapter of the book, that gives a general topic insight of the book, there are 24 more chapters that cover various fields of solar radiation. These fields include: Measurements and Analysis of Solar Radiation, Agricultural Application / Bio-effect, Architectural Application, Electricity Generation Application and Thermal Energy Application. This book aims to provide a clear scientific insight on Solar Radiation to scientist and students.

### **How to reference**

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Kalju Eerme (2012). Interannual and Intraseasonal Variations of the Available Solar Radiation, Solar Radiation, Prof. Elisha B. Babatunde (Ed.), ISBN: 978-953-51-0384-4, InTech, Available from:  
<http://www.intechopen.com/books/solar-radiation/interannual-and-intraseasonal-variations-of-the-available-solar-radiation>

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### **InTech China**

Unit 405, Office Block, Hotel Equatorial Shanghai  
No.65, Yan An Road (West), Shanghai, 200040, China  
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

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