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Changes in solar radiation and their influence on temperature trend in Estonia (1955–2007)

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[1] On the basis of the data from Tartu-Tõravere Meteorological Station (58°16′N, 26°28′E), changes in solar radiation and temperature in Estonia have been studied for the past half century. Two different periods have become evident in the analyzed time series of solar radiation: a statistically significant decrease in the annual totals of global and direct solar radiation has been detected for the period from 1955 to the beginning of the 1990s, while opposite trends have become evident during more recent years. These changes are in correlation with the changes in the amount of low clouds and in the transparency of cloudless atmosphere (atmospheric aerosol loading). Unlike solar radiation, annual mean temperature has continuously increased during 1955–2007. No time intervals with different slopes have been found in its time series. Because of the relatively short sunshine duration and low Sun elevations, the impact of solar dimming and brightening on the observed warming has turned out to be negligible in the Baltic Sea region.

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1. Introduction

[2] Long-term changes in the Earth's climate are the most serious issue among environmental problems at present. As the solar radiation is the primary energy source for physical processes and phenomena in the atmosphere, a study of long-term records of solar radiation is required. Unfortunately the records of solar radiation for the years before 1950 only exist for a small number of stations: Potsdam (Germany), Stockholm (Sweden), Locarno-Monti (Switzerland), and a few stations in arctic Russia [*Gilgen et al.*, 1998]. Since the 1950s the number of actinometric stations rapidly increased in the world. By the early 1990s the records of solar radiation from numerous stations had been sufficiently long to allow detection in them of statistically significant trends. Authors from several regions reported about tendentious decrease of incoming solar radiation (solar dimming) in the second half of the twentieth century [e.g., *Russak*, 1990; *Stanhill and Moreshet*, 1992; *Liepert et al.*, 1994; *Abakumova et al.*, 1996]. At the turn of the 1980s–1990s the observed decreasing trends underwent conversion. The subsequent solar radiation increase is known as solar brightening [*Wild et al.*, 2005]. The present paper considers the changes in solar radiation reaching the Earth's surface and their possible influence on temperature conditions for Estonia.

2. Description of Data Set

[3] The measurement data analyzed in this study were obtained from the Tartu-Tõravere Meteorological Station of the Estonian Meteorological and Hydrological Institute, a station of the Baseline Surface Radiation Network (BSRN). In Estonia routine fixed time broadband solar radiation measurements started in the outskirts of Tartu (58°21′N, 26°41′E, 76 m a.s.l.) in 1950 (recordings of all components of solar radiation are available since 1955). Tartu, a small town without significant sources of air pollution, had no impact on the quality of actinometric measurements. In 1965, the station was transferred to a rural area, Tõravere, 20 km from Tartu (58°15′N, 26°27′E, 70 m a.s.l.). Simultaneous measurements made at both sites have shown that the data can be considered as a common time series. The station has an observation field with open horizon. As receivers of radiation, Yanishevski thermoelectric instruments were used [*Yanishevsky*, 1957]: for direct solar radiation the actinometer AT-50, for diffuse radiation the pyranometer M-150 with a shadow ring (since 2005 the Kipp&Zonen pyranometer CM-21 with a shadow disc). Global radiation was calculated as the sum of diffuse and direct radiation. All the actinometric receivers were calibrated at least once a month against an etalon actinometer, whose sensitivity has remained unchanged for more than 40 years. As radiation etalons, the Ångström pyrheliometer M-59-8 (until 1996) and the absolute radiometer PMO-6 (from 1996 to the present) were in use in Estonia. Comparison of these standards against the World Radiation Reference in Davos in 1995 and 2000 has shown their stability, the difference from the international standard having not exceeded ±0.1% [*Russak and Kallis*, 2003]. This kind of calibration system as well as the unchanged measurement

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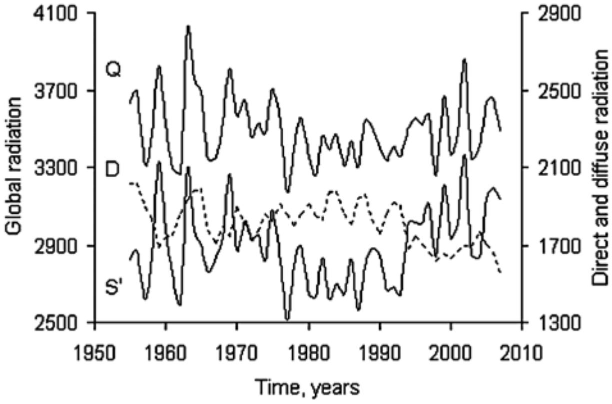

Figure 1. Time series (1955–2007) of the annual totals of global (Q), diffuse (D), and direct radiation incident on a horizontal surface (S') at Tartu-Tõravere. Unit is MJ m^{-2}.

methods permit avoidance of systematic errors in actinometric data and have allowed the monitoring of long-term changes in radiation in Estonia during the last half century.

3. Solar Radiation

[4] Two different periods can be distinguished in the time series of solar radiation in Estonia. A significant decrease from the 1950s until the turn of the 1980s and 1990s is characteristic of the annual totals of global Q and direct solar radiation incident on a horizontal surface S' (solar dimming) (Figure 1).

[5] Statistical significance p of the trends has been estimated by means of the Student's t-parameter. Only the trends of significance level $p \leq 0.05$ have been taken into account in our subsequent analysis.

[6] According to linear approximation, the decrease per decade amounted to 1.7% ($p = 0.02$) for Q, and 3.8% ($p = 0.02$) for S' during 1955–1992. The records of global and direct radiation were rather similar and the corresponding absolute decreases were close (about 60 MJ m^{-2} per decade). In both time series significant trends were found for March and September only (in March about 20 MJ m^{-2} per decade, in September about 14 MJ m^{-2} per decade, $p < 0.01$). No significant trend was found in the time series of diffuse radiation during these years.

[7] Since the early 1990s both global and direct radiation have increased (solar brightening). At the same time a decreasing tendency was characteristic for diffuse radiation. Although, these changes are obvious, the period is too short for a statistical analysis.

[8] Because of the geographical position of Estonia close to the Baltic Sea and on the path of cyclones moving from the Atlantic Ocean to the east, cloudiness, especially optically thick low cloudiness, should be considered as the most important factor regulating incoming solar radiation. In the dimming period a significant increase ($p = 0.05$) by 0.5 tenths has been detected in the time series of annual mean low cloudiness (Figure 2). The annual course of cloud amount is similar to that of the North Atlantic oscillation (NAO) index, the measure of the intensity of the westerly (zonal) circulation. This index is calculated as the difference of the standardized sea-level pressure anomalies between Ponta Delgadas (Azores) and Reykjavik (Iceland). The data of NAO index are available at www.cpc.noaa.gov/data/teledoc/nao.shtml. In winter, from December to March, the correlation between the monthly mean amount of low clouds and NAO index is significant (correlation coefficients $R = 0.38–0.51$). In the years 1955–1992 significant increasing trends ($p < 0.01$) for low cloudiness were found in March and September, by 2.2 and 1.5 tenths, respectively.

[9] Besides cloudiness, solar radiation depends on the transparency of cloudless atmosphere. As a transparency parameter, the Bouguer atmospheric transparency coefficient P_m has been used in the present study. It can be calculated from the formula

$$P_m = (S_m/S_\mathrm{o})^{1/m}, \tag{1}$$

derived from the well-known Bouguer-Lambert law. Here S_m denotes the broadband beam flux density at normal incidence in cloud-free atmosphere at relative optical air mass m, reduced to the Earth-Sun mean distance. The solar constant $S_\mathrm{o} = 1.367$ kW m^{-2}. To eliminate the dependence of P_m on solar elevation caused by the Forbes effect, all their values were reduced to optical air mass $m = 2$ by the method presented by *Myurk and Okhvril* [1990]. The atmospheric transparency was calculated at Tartu-Tõravere for the period 1950–2007.

[10] Short-time (1–2 years) deviations in the time series of P_2 can often be linked to volcanic eruptions. Also extensive forest fires can reduce atmospheric transparency to a high degree. Extraordinarily high atmospheric turbidity was observed in Estonia in 1984 and in 1992, resulting from the eruptions of El Chichón (1982) and Mount Pinatubo (1991). Then the annual mean flux densities of direct solar radiation were 82 and 78% of the average over 1950–1981, respectively.

[11] As with solar radiation, two different periods can be selected in multiyear series of atmospheric transparency. A distinct decreasing trend lasted from 1950 till the mid-1980s, during which the decline amounted to 3.9% ($p < 0.01$). A reversal in transparency was found in the late 1980s and early 1990s (Figure 3).

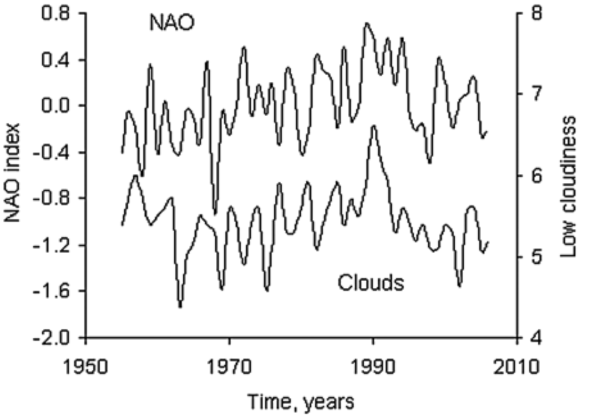

Figure 2. Time series of annual mean low cloudiness (in tenths) at Tartu-Tõravere, and NAO index, 1955–2007.

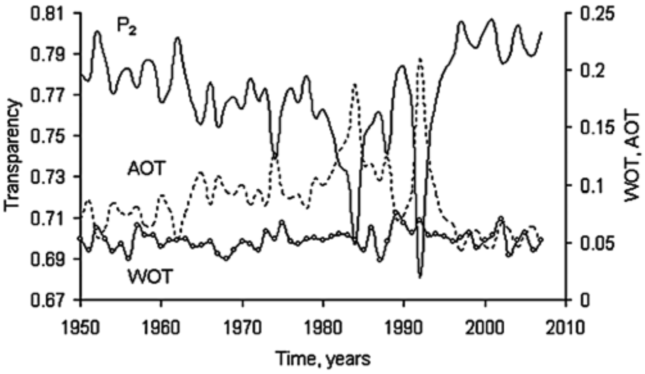

Figure 3. Time series of the annual mean atmospheric transparency P_2, optical thicknesses of water vapor (WOT) and aerosol (AOT) at Tartu-Tõravere, 1950–2007.

[12] Extinction of solar radiation under clear sky conditions can be considered as caused by permanent gaseous components of the atmosphere (ideal atmosphere), water vapor and aerosol. Optical thickness of ideal atmosphere can be easily calculated. Optical thickness of water vapor, WOT, was calculated using the *Gueymard*'s [1998] formula modified by *Okulov* [2003]. Having evaluated transmittances for ideal atmosphere and water vapor, the residual transmittance is that of aerosol (Figure 3). During the solar dimming period the optical thickness of aerosol increased essentially, while that of water vapor remained practically stable. The observed increase in aerosol optical thickness coincides with the period of extensive development of industry, energy and transport, also with numerous volcanic eruptions. Considerable part of air pollution in Estonia originates from far-off sources.

[13] At the turn of the 1980s and 1990s the trends described above reversed their directions: direct and global radiation, atmospheric transparency began to increase (brightening), while diffuse radiation, low cloudiness, the NAO index and aerosol optical thickness to decrease. This permits us to suppose that some changes had taken place in the atmospheric processes.

[14] The improvement of atmospheric transparency during the last 15–20 years can be explained by the establishment of strict requirements against air pollution as well as by an economical decline in the former socialist countries. The maximum emission of SO_2 in Europe per annum was reached in the middle of the 1970s. During the following 15 years it decreased by about a third. In comparison with the northwestern and some central parts of Europe, where a reduction had already started in the 1970s, there was a time lag of about 10 years in the southern and eastern parts of Europe [*Mylona*, 1996]. During the period 1990–2003, the emission of SO_2 decreased in Estonia by 63%, NO_x by 48% and emission of volatile organic compounds by 43% (these data are available at http://www.keskkonnainfo.ee/publications/105_PDF.pdf). In the Czech Republic, an important source of anthropogenic aerosol in Central Europe, the emission of SO_2 was reduced by 86% and that of NO_x by 55% in 1989–2000 [*Hejkrlik*, 2002].

[15] These observed changes in the time series of P_2 are not of local character. Similar trends have also been found at another station in Estonia, Tiirikoja (situated about 70 km from Tartu-Tõravere), and in Moscow [*Okulov et al.*, 2001].

4. Temperature

[16] Global warming is a well-known fact. However, the reasons for the observed temperature rise are not yet clear: is it a result of human activities or only a phase of natural variability of climate?

[17] Different rates of warming in different regions of the world [*Schönwiese et al.*, 1994; *Klein Tank et al.*, 2005] indicate that the main factors forming the temperature conditions would also differ between regions. In the following we try to assess to what extent the observed temperature trends can be connected with the changes in solar radiation in Estonia (the Baltic Sea region).

[18] A certain upward trend was detected for the annual mean temperature in Estonia in the second half of the twentieth century. According to a linear approximation the rise of temperature made 1.8°C at Tartu-Tõravere during the period 1955–2007 ($p < 0.01$). This increase was about 2 times faster than that for global land mean temperature (available at http://www.cru.uea.ac.uk/cru/data/temperature/crutem3gl.txt). The warming was not uniform throughout a year. On the significance level $p < 0.01$ we found increases in March and April only (Figure 4). The rise of temperature was by 3.9° and 3.6°C, respectively.

[19] On the significance level $p = 0.05$ the rise of temperature was 3.4°C in January. Somewhat smaller was the warming in July (1.6°C) and August (1.3°C), both on the level $p = 0.04$.

[20] Numerous papers [e.g., *Barrie et al.*, 1976; *Michaels and Stooksbury*, 1992; *Tegen et al.*, 2000; *Coakley*, 2005] describe the observed decline in solar radiation as a factor having noticeable masking effect on the greenhouse warming. *Wild et al.* [2007] reported a more rapid increase of the mean land surface temperature after the decrease in solar radiation was reversed.

[21] In Estonia linear correlation between monthly totals of global radiation and mean monthly temperatures is relatively high and statistically significant for most of the

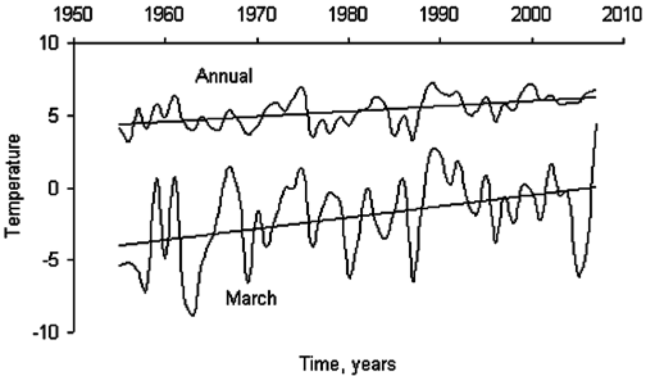

Figure 4. Annual and monthly mean (March) temperature series and their linear trends at Tartu-Tõravere, 1955–2007. Unit is °C.

Table 1. Correlation Coefficients Between Monthly Values of Temperature and Global Radiation and Temperature and NAO Index at Tartu-Tõravere in 1955–2007[a]

Month	$R(t,Q)$	$R(t,\mathrm{NAO})$
January	**−0.745**	**0.651**
February	**−0.789**	**0.628**
March	**−0.774**	**0.704**
April	−0.026	0.165
May	**0.401**	0.182
June	**0.552**	**0.376**
July	**0.666**	0.223
August	**0.693**	0.322
September	0.324	0.158
October	−0.217	0.322
November	**−0.738**	0.200
December	**−0.686**	**0.523**
Annual	−0.020	**0.473**

[a]Temperature and global radiation, $R(t,Q)$; temperature and NAO index, $R(t,\mathrm{NAO})$. Coefficients on significance level $p < 0.01$ are in bold.

months (Table 1). In winter, from November to March, the correlation is negative. This does not express a direct impact of solar radiation on temperature. It should be considered that the temperature is measured throughout 24 hours while the solar radiation in daytime only. Prevailing optically thick clouds reduce the solar radiation (during daylight), also the radiative cooling (day and night), whereas under clear sky conditions they would both increase. In winter on higher latitudes daylight is short and solar elevation low. For example, in the winter solstice at Tartu-Tõravere the light time lasts about 6 hours and the maximum solar elevation reaches only 8.3°. From December to March global radiation makes only 13% of its annual total. In these conditions the incoming solar radiation is not able to compensate for the outgoing infrared radiation and the share of solar radiation in the formation of temperature conditions is negligible in Estonia in the cold season.

[22] Positive significant correlation between solar radiation and temperature was found from May to August only. Then the dispersion of the monthly totals of global radiation can explain 16–48% of the variance in the monthly mean temperature.

[23] We could not detect any periods with different slopes in the temperature trend, the increase being relatively uniform in Estonia at about 0.35°C per decade. This is probably due to the peculiarities of the weather in the Baltic Sea region, where the short duration of sunshine (annual duration being only about 36% of its potential value in Estonia) does not allow the presence of solar radiation to have significant direct effect on the temperature trend. In March–April, the months of the greatest observed warming, the impact of solar radiation on temperature is inconspicuous.

[24] In the Baltic Sea region atmospheric circulation is the main factor regulating temperature conditions. In winter, from December to March, correlation between temperature and the NAO index is significant ($R = 0.52–0.70$, $p < 0.01$). Changes in the aerosol content in the atmosphere may here have an impact on the warming process, mainly through the advection of air masses whose physical parameters were formed in lower latitudes, where the solar radiation plays a more essential role. It is possible that changes in incoming solar radiation caused by changes in aerosol can also, in their turn, influence the character of atmospheric circulation and thereby the cloudiness conditions in Estonia.

[25] Correlation coefficients between temperature and solar radiation, also between temperature and NAO index are presented in Table 1.

[26] According to prevailing opinion the global warming is caused by an enhancement of the greenhouse effect, which manifests itself as an increase in the downward flux of the atmospheric thermal radiation. Because the latter has been measured at Tartu-Tõravere since 2003 only, changes in the greenhouse effect were assessed by the use of the data on the long-wave component of net radiation. It was calculated from net radiation, measured during 1962–1997 by a Yanishevsky net radiometer M-10 [*Yanishevsky*, 1957] and in 1997–2001 by a Reemann net radiometer GB-1 [*Russak and Kallis*, 2003]. In the time series of both net and net long-wave radiation, continuous increasing trends (about 53 and 75 MJ m^{-2} per decade, respectively, $p < 0.01$) have been detected during this approximately 40-year period (Figure 5). Such an increase of net long-wave radiation can be caused either by a reduction in upward thermal radiation or by an increase in atmospheric infrared radiation. The first alternative is improbable because of increased ground temperature. Therefore the observed growth of net long-wave radiation should be interpreted as growth of atmospheric radiation, i.e., enhancement of the greenhouse effect.

[27] Statistically significant changes in analyzed characteristics are presented in Table 2.

5. Conclusions

[28] Using solar radiation and air temperature data gathered at Tartu-Tõravere meteorological station (58°15′N, 26°28′E, Estonia) for the period 1955–2007, long-term changes in their time series and the impact of solar dimming and brightening on warming were studied. In Estonia, as in several regions of the world, significant decrease and subsequent increase in solar radiation has been detected during the past half century. These trends are most likely caused here by changes in cloudiness resulting from variations in atmospheric circulation, and changes in aerosol content in the atmosphere. Because of the geographical position (Estonia lies on the path of cyclones moving from

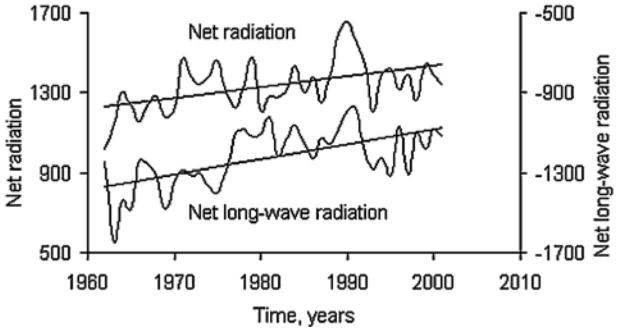

Figure 5. Time series of annual totals of net and net long-wave radiation at Tartu-Tõravere in 1961–2002, and their linear approximations. Unit is MJ m^{-2}.

Table 2. Statistically Significant ($p \leq 0.05$) Changes in Direct, Global, Net, and Net Long-Wave Radiation, NAO Index, Low Cloudiness, Atmospheric Transparency, and Temperature[a]

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	A
							1955–1992						
S'			**−74**						**−51**				**−248**
Q			**−88**						**−54**				**−232**
NAO	1.4	**1.6**	**1.7**										**0.6**
m			**2.2**						1.5				0.5
							1950–1982						
P_2				−5.1	**−6.0**	**−6.3**				−4.2	−3.8		**−3.9**
							1962–2001						
B	**29**	**30**						36	**18**	13		16	**208**
B_L	**34**	**26**				**48**	**50**	**50**	**52**		**26**		**293**
							1955–2007						
t	3.4		**3.9**	**3.6**			1.6	1.3					**1.8**

[a] Direct radiation, S'; global radiation, Q; net radiation, B; net long-wave radiation, B_L; all are in MJ m^{-2}. Low cloudiness, m (in tenths); atmospheric transparency, P_2 (in %); temperature, t (in °C). I–XII denote January–December; A is annual. Changes on the level $p \leq 0.01$ are in bold.

the Atlantic Ocean to the east), cloudiness, especially optically thick low cloudiness, should be considered as the most important factor regulating incoming solar radiation. In the dimming period a significant increase by 0.5 tenths has been detected in the time series of the annual mean low cloudiness. Its annual course is similar to that of the North Atlantic Oscillation (NAO) index, the measure of the intensity of the westerly (zonal) circulation. In winter, from December to March, the correlation between the monthly mean amount of low clouds and the NAO index is significant. Both the intensity of westerly circulation and low cloudiness, decreased in the years of solar brightening. Besides cloudiness, solar radiation depends on the transparency of cloudless atmosphere. During the solar dimming period the optical thickness of aerosol increased essentially and reversed to decrease in the late 1980s and early 1990s. However, in comparison with cloudiness, the role of atmospheric transparency is less important in the formation of solar radiation conditions in the Baltic Sea region.

[29] During the period 1955–2007 the general temperature trend was on the increase, but there were no time intervals in which the warming accelerated significantly. In the months when trends in solar radiation were statistically significant, correlation between global radiation and temperature was practically absent. In the higher geographical latitudes, owing to low Sun elevations and short sunshine duration, solar radiation is less important in the formation of temperature conditions and therefore the masking effect of atmospheric aerosol content on the greenhouse warming has been inconspicuous. In Estonia solar radiation is able to increase temperature from May to August only.

[30] Atmospheric aerosol may have indirect impact on the warming process in the Baltic Sea region, mainly through the advection of air masses whose physical parameters were formed in lower latitudes, where the solar radiation plays a more essential role. It is possible that changes in atmospheric aerosol content can influence the character of atmospheric circulation and thereby cloudiness conditions in Estonia. An increased amount of aerosol should also be considered as an additional supply of condensation nuclei in the atmosphere.

[31] **Acknowledgments.** The research was supported by the Estonian Science Foundation grant 7347.

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