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Atmospheric aerosol variability in Estonia calculated from solar radiation measurements

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ABSTRACT

Direct solar radiation data obtained during 1955–1994 at the Tõravere Actinometric Station (Estonia) have been used to study the long-term variations of the atmospheric aerosol. In a linear approximation, the optical thickness of atmospheric aerosol averaged over months from April to August has increased by 73% at Tõravere during the last 40 years. The aerosol loading of the atmosphere depends on wind direction, the southern and southeastern winds being the main carriers of aerosol. During the last decade, the increase in the optical thickness of aerosol in the case of W-, NW- and N-winds has slowed down. This is most likely caused by a reduction in the SO_2 emission in Western and Central Europe as well as in Finland. In April, the advection of aerosol is greatest from the NE-direction. We suppose that this effect points to the possibility of aerosol transfer to Estonia through the Arctic regions.

1. Introduction

In the 20th century, changes in the composition of the atmosphere have become evident. An increase in aerosol loading of the atmosphere has had an essential rôle to play in this process. Increased aerosol has influenced solar radiation transfer through the atmosphere and thereby the energy balance of the atmosphere and the ground surface. Several ways exist of how to obtain information on atmospheric aerosol. Besides direct samplings of aerosol from aircraft, and the measuring of aerosol profiles by modern photometers aboard satellites, the use of the data extracted from routine actinometric measurements in hundreds of actinometric stations throughout the world should be considered as a source of study on the long-term changes in aerosol loading over various geographical regions. 318 actinometric stations were active in Europe (the Soviet Union excluded) in 1989, and among these, the direct solar radiation was measured in 108 stations (Catalogue, 1989). On the territory of the former Soviet Union, the recording of solar radiation started before 1960 in 160 actinometric stations (Zhitorchuk et al., 1994). In spite of several shortcomings, such as low accuracy, the use of solar radiation data obtained from the extensive world radiation network allows us to monitor, over decades, changes in atmospheric composition in different climatic conditions. The use of routine actinometric measurements for studying the air pollution and its long-term changes should be considered as an essential complimentary source of information on the composition of the atmosphere.

In this work, data from direct solar radiation obtained at Tõravere Actinometric Station of the Estonian Meteorological and Hydrological Institute (Estonia, 58.3°N, 26.5°E), have served as a data base for studying changes in the composition of the atmosphere. This station is situated in a rural area, where local atmospheric pollution sources are absent.

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2. Trends in time series of solar radiation

Our earlier analysis of the annual totals of global and direct solar radiation incident on a horizontal surface has shown a certain decreasing tendency in Estonia during recent decades (Russak, 1990). During 1955 to 1993, the decrease in global radiation amounts to 6.7% (significance level $p=99\%$), and for direct radiation to 14.9% ($p>99\%$).

In the Baltic Sea region, solar radiation transfer is influenced most by cloudiness (at Tõravere the actual annual mean sunshine duration reaches only 36% of the maximum possible duration). Our analysis of the time series for mean annual cloudiness for 1964–1986 showed an increase of 11% ($p>95\%$) in the low-level cloudiness (Russak, 1990). As another factor influencing the changes in radiation transfer, optical properties of the cloudless atmosphere must be considered. For 1955–1986, a significant decrease of 5.7% ($p>99\%$) was detected in the time series of the mean annual Bouguer transparency cofficient (Russak, 1990).

The analysis of hourly totals of direct solar radiation in cloudless atmosphere has allowed us to assess the optical thickness of atmospheric aerosol and its variability for 1955–1994. Because of the higher probability of the occurrence of cloudless hours, only data for the months from April to August have been studied. The hourly observations of cloudiness at the actinometric station were used to select the cloudless hours.

To eliminate the dependence of measured solar radiation on the elevation of the sun, the ratio of the hourly totals of direct solar radiation measured in cloudless atmosphere to the corresponding totals in the ideal atmosphere was introduced. The term "ideal atmosphere" denotes such an atmosphere, where water vapour and aerosol are absent (Sivkov, 1968).

Direct solar radiation on the ground can be expressed as:

$$S_m = S_o \, e^{-m\tau(i)} \, e^{-m\tau(a)} \, e^{-m\tau(w)} . \quad (1)$$

Here, S_m denotes direct solar radiation on the surface, S_o the solar constant, m optical air mass, $\tau(i)$ optical thickness of the ideal atmosphere, $\tau(a)$ optical thickness caused by aerosol, $\tau(w)$ optical thickness caused by water vapour.

Direct solar radiation in the ideal atmosphere can be determined by the following, proposed by Sivkov (1968):

$$S_{m(i)} = S_o \, (1.04–0.160 \, m^{0.5}), \quad (2)$$

where $S_{m(i)}$ denotes direct solar radiation in the case of the ideal atmosphere at the air mass m.

Long-term changes in the time series for the ratio $S_m/S_{m(i)}$ express changes in direct solar radiation in a cloudless atmosphere caused by water vapour and aerosol. An analysis of this data set shows a decreasing trend during the last 40 years at Tõravere. According to a linear approximation, direct solar radiation, averaged over April to August, has decreased by 10.1% ($p>99\%$) in cloudless hours (Fig. 1). Changes in solar radiation were different from month to month. Significant trends became evident in April and August when the decrease was 16.6% ($p>99\%$) and 20.1% ($p>95\%$), respectively.

3. Changes in the atmospheric water vapour and aerosol

The next step in our investigation consisted of separating optical thicknesses of aerosol and water vapour. Because no sounding of the atmosphere had been carried out at Tõravere, the atmospheric water content had to be estimated indirectly. The long-term mean monthly values of the water content for Tõravere, W_0, were taken from the Atlas (1984). The water content for every day used by

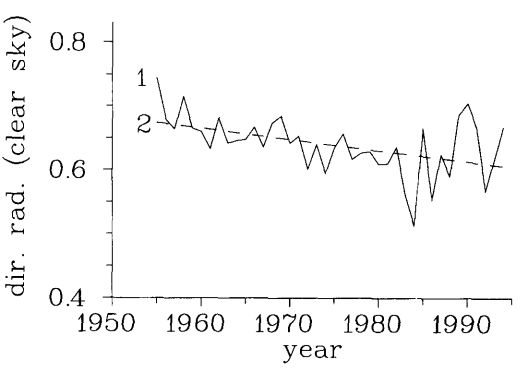

Fig. 1. Time series (1) and linear approximation (2) of direct solar radiation in cloudless atmosphere averaged from April to August at Tõravere (in relative units).

us was deduced from the formula

$$W = W_0\, e/e_0\,, \tag{3}$$

where e_0 denotes long-term monthly mean water vapour pressure for an analysed month at Tõravere, e water vapour pressure measured simultaneously as radiation. To calculate the optical thickness of water vapour, the following formula, presented by Pivovarova (1977), was used:

$$\Delta S_w = 0.184(mW)^{0.27}\,, \tag{4}$$

where ΔS_w expresses the extinction of direct solar radiation caused by water vapour.

A later analysis of the time series of the optical thickness of water vapour in the atmosphere has indicated its relative stability. A significant increase in the content of water vapour has been noticable only for August (an increase by 4.1%, $p = 96\%$). This increase may be due to an increase in precipitation there in August. As shown by Kivi and Russak (1990), the amount of precipitation increased by 85% ($p = 95\%$) at Tõravere in August during 1955–1989. However, this substantial increase in precipitation should not be considered as a serious change in the precipitation regime. As shown by Jaagus (1992), the time series of precipitation for Estonia reveals some periodicity. Therefore, an increase in precipitation over the years 1955–1989 should be interpreted rather as a phase in this cyclicity, which might be caused by changes in the atmospheric circulation in the Baltic Sea region. In all the studied months, the mean rôle of water vapour in the atmospheric optical thickness remained smaller than that of aerosol. The optical thickness of aerosol averaged over April, May, June, July and August shows an obviously increasing trend at Tõravere (Fig. 2). Its growth during last 40 years amounted to 0.069 (73%), $p > 99\%$. From 1955 to the early 1980s, the aerosol optical thickness at Tõravere was increasing more-or-less uniformly. During the last decade, a few high peaks have occurred due most probably to powerful volcanic eruptions. We assume that the high values of aerosol optical thickness in 1983, and especially in 1984, resulted from the influence of the El Chichon eruption in Mexico in April 1982. The influence of the eruption of Mt. Pinatubo in June 1991 on the Philippines was of a somewhat different nature. In 1992, aerosol optical thickness had already reached a high value at Tõravere. Thereafter a decrease set in.

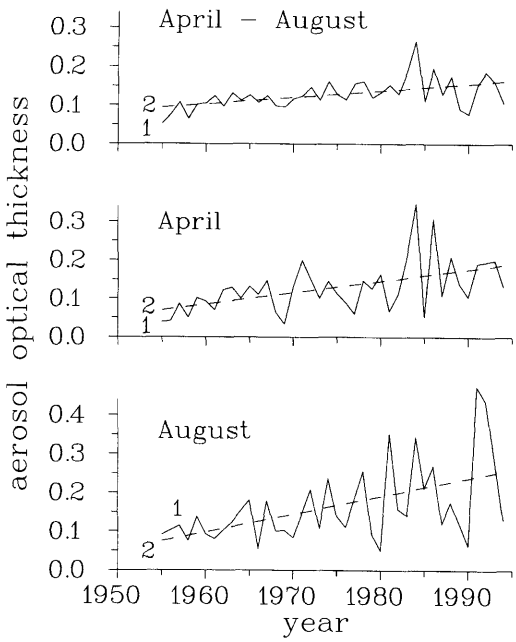

Fig. 2. Time series (1) and linear approximations (2) of aerosol optical thickness at Tõravere, 1955–1994, calculated from direct solar radiation measurements.

The increase in aerosol optical thickness varied from month to month. Statistically significant trends have been found only for April and August. In April, the increase was 0.117 or 167% ($p > 99\%$) (Fig. 2). The peak in 1983 and 1984 should be related to the El Chichon eruption products in the stratosphere. Unfortunately, we cannot say anything about the influence of the eruption of Mt. Pinatubo on the optical thickness in April, because there were no cloudless hours at Tõravere in this month in 1982.

In August, the growth of the monthly mean aerosol optical thickness during the last 40 years was 0.180 or 238% ($p > 97\%$) (Fig. 2). A relatively large interannual variability in this run was most probably caused by the interannual variability of rainfalls, the latter serving as a cleaning factor of the troposphere (in August, showers are characteristic for Estonia and, therefore, the duration and amount of precipitation varies essentially from year to year). The highest values of the monthly mean aerosol optical thickness in August over the period under study were observed in 1991 and

1992, which may be related to the Pinatubo eruption.

4. The dependence of aerosol optical thickness on wind directions

Since, at Tõravere and in its nearest surroundings, sources of anthropogenic air pollution are absent, we supposedly are concerned with the aerosol mostly transported there from more-or-less distant sources of pollution. Hence, the aerosol concentration in the atmosphere must depend on wind directions. The dependence of the averaged optical thickness over April-August 1955–1994 on wind directions is presented in Fig. 3 as a wind rose. The southern winds are the main carriers of aerosol; SE-winds also play an essential rôle. The smallest amount of aerosol is usually carried over Tõravere by NW-winds.

The increase in aerosol optical thickness has become evident for all wind directions during the years under study. The greatest increase averaged from April to August has been observed in the case of S-winds, the smallest in the case of N-winds (Fig. 4). The dynamics of the increase in aerosol content has been found to depend on the wind direction. In the case of W-, NW-, and N-winds, the aerosol advection has fallen during recent decades; in the case of the winds blowing from other directions, the strong increase has been found to have continued (Table 1). This result seems to reflect a drop in the SO_2 emission in Europe in the last decade. Arends et al. (1994) and Ryaboshapko et al. (1994) have shown that in Western and Central Europe, sulphur emission reached its maximum in the late 1970s, and after that, a rather sharp fall was observed. In Finland, sulphur emission has also continously increased since the 1950s, until the oil crisis in 1973–1974 (Tähtinen et al., 1993). Anthropogenic sulphur emission from the Soviet Union reached its maximum in the mid-70s. After this, emission remained practically stable (Ryaboshapko et al., 1994).

The rôle of different wind directions in April is somewhat different. In this month, NE-winds are the main carriers of aerosol and their rôle is comparable to the rôle of E- and SE-winds (Fig. 3). At this point, we would like to note that during the 40 years under study, this effect has strengthened (Fig. 4).

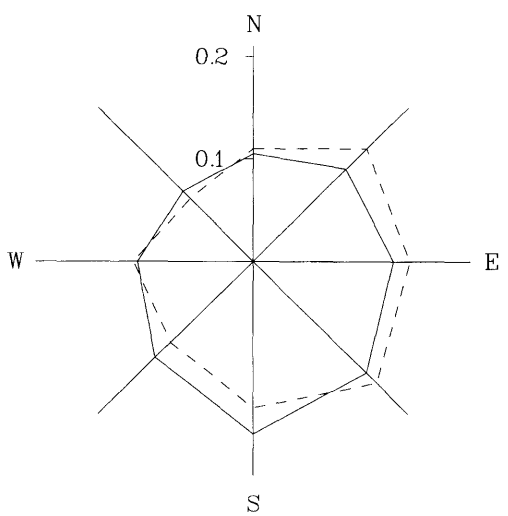

Fig. 3. The dependence of mean aerosol optical thickness on wind direction at Tõravere, 1955–1994. Solid line denotes April–August; dashed line, April.

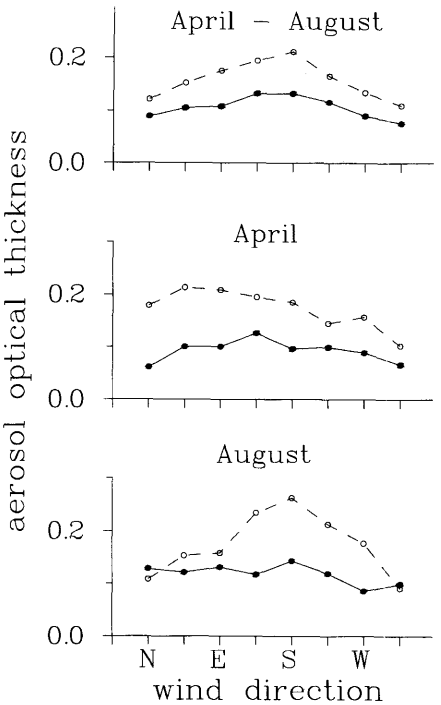

Fig. 4. Dependence of aerosol optical thickness on wind direction in different subperiods. Solid line refers to the period 1955–1967, dashed line, 1981–1994.

Table 1. *Optical thickness of atmospheric aerosol at Tõravere averaged from April to August over different periods*

Period	N	NE	E	SE	S	SW	W	NW
1955–67	0.089	0.105	0.108	0.132	0.132	0.116	0.090	0.076
1968–80	0.106	0.126	0.124	0.153	0.165	0.123	0.112	0.105
1981–94	0.121	0.152	0.175	0.194	0.211	0.165	0.134	0.110

As for this direction, the following NE anthropogenic aerosol sources must be considered (Fig. 5).

(a) The Leningrad District (Russia), where the Slantsy Thermal Power Plant is an essential source of SO_2 influencing Estonia.

(b) An industrial area in the NE-Estonia (about 140 km from Tõravere), where two big thermal power plants produce energy by burning oil-shale up to 22 Mt yearly (Liblik and Rätsep, 1993).

(c) The industrial area of the Kola Peninsula (Russia).

(d) The Arctic, which is of special interest. Several authors, e.g. Rodionov and Marshunova (1992), Kondratyev and Johannessen (1993), have noted that the dominating type of atmospheric circulation in winter leads to the advection of aerosol from moderate latitudes into the Arctic, whereas an essential part of this may return to moderate latitudes. Due to specific weather conditions in the Arctic in winter, such as frequent inversions, accumulation of air pollutants has become evident there. Therefore, we suppose that in Spring, when increasing solar radiation favours photochemical processes in the atmosphere, the advection of aerosol from the Arctic to moderate latitudes should be more intensive. If this hypothesis is confirmed, it could help to explain the peculiarities of aerosol advection in April.

In August, the increase in aerosol optical thickness has been found to be greatest with S-winds.

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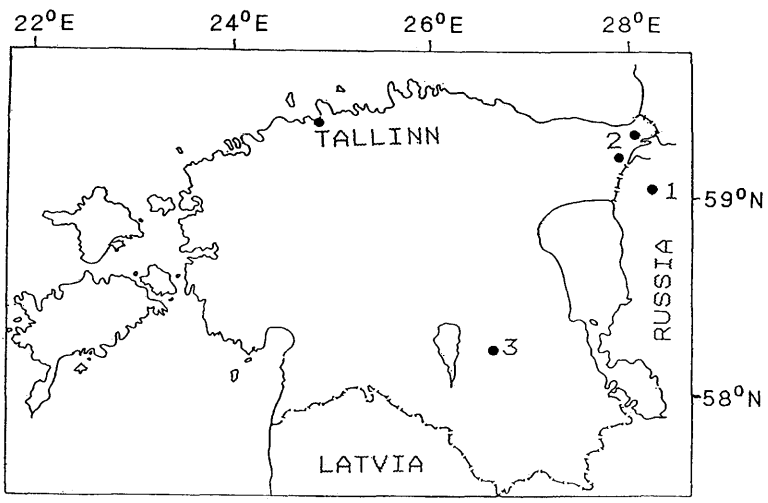

Fig. 5. Schematic map indicating the locations of the Slantsy Thermal Power Plant (1), the industrial area in NE Estonia (2), and Tõravere (3).

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