Temporal variations of downward solar radiation, aerosol optical thickness and cloudiness over North of the European part of Russia based on surface data records (during 40 years)

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Abstract. The results of the analysis of temporal changes in the aerosol optical thickness of the atmosphere, the factor of turbidity, cloudiness and incoming solar radiation near the Earth's surface in the north of the European Territory of Russia (ETR) based on observations of the Roshydromet actinometric network for 1976―2014 are presented. Trends of synchronous changes in the above parameters have been revealed, both for the entire observation period and in the post-volcanic period (1995―2014). Under conditions of the aerosol optical thickness (AOT) decreasing (an increasing of the transparency of the atmosphere) for average cloudiness, a neutral time dependence of the incoming radiation is observed. Comparison with the results at actinometric stations in the south of ETR was carried out.

1. Introduction
Solar short-wave radiation arriving at the Earth's surface is the main component of the radiation balance in the surface layer of the atmosphere and an important factor influencing climatic processes [1-3]. Variations in the incoming solar radiation cause changes in other components of the radiation (and heat) balance of the underlying surface and are obviously the object of climate monitoring. For example, in works [4-10], data on changes in the total incoming radiation in Europe, China, India, Africa, and North America have been analyzed. At the same time, it was found that until the mid-1980s, it decreased by 0.07—0.03 W/m² per year; in subsequent years, an increase of 0.08—0.02 W/m² per year was noted for 75% of stations [11]. At a quarter of the stations (part of China and India), since the mid-1980s, the total radiation continued to decrease by 0.08 W/m² per year. The background station Mauna Loa showed a neutral course of total radiation over time. In [11], it was assumed that until the mid-1980s, the ubiquitous decrease in the incoming total solar radiation Q was due to rapid industrial growth, accompanied by powerful industrial emissions. 1980 to 2000 The observed increase in Q is associated with the introduction of technologies for cleaning emissions in developed countries of Europe and America and the partial transfer of production to Asia (India and China). The last decade has been characterized by a decrease in Q in India and in parts of China, reflecting industrial growth. In publications [11-13], the trends of changes in total solar radiation are summarized according to the data of ground-based observing systems BSRN (BASELINE SURFACE
RADIATION NETWORK) and AERONET (AEROSOL ROBOTIC NETWORK). The tendencies (sign) and rates of change in the flux of incoming solar radiation are the same both in cloudy and cloudless conditions, which indicates the possible role of aerosol in changes in total radiation. Atmospheric aerosol is constantly considered as a factor influencing solar radiation in the atmosphere. The scattering aerosol weakens due to the reflection of the solar radiation arriving at the upper boundary of the aerosol layer, causing local and sometimes regional cooling of the lower layers of the atmosphere; the absorbing aerosol causes heating of the aerosol layer itself, which leads to the subsequent heating of the surface atmospheric air due to mixing.

Most reliable way to obtain information about the AOT (aerosol optical thickness) of the atmosphere is through the combined use of satellite and ground-based observations. The data of actinometric observations carried out on the Roshydromet network can be used to obtain additional and regular information on the spatial and temporal AOT variability. Such information is necessary primarily for improving models of optically active atmospheric components and increasing the reliability of calculations of radiation transfer in the atmosphere. Russia is characterized in IPCC reports and in publications [1-2, 14-15] as a territory of decreasing AOT in the direction from south to north and is a kind of "white" spot; AOT estimates based on ground-based network observations are an advantageous supplement to the data from AOT satellite monitoring over Russia [16]. The merit of these estimates is the length of the considered series of actinometric observations (40 years), the versatility of the measurement technique and the processing of results for all stations, as well as the vast coverage area of the Russia, which is little considered, but large in area. Atmospheric aerosol is constantly considered as a factor influencing solar radiation in the atmosphere. The scattering aerosol weakens due to the reflection of the solar radiation arriving at the upper boundary of the aerosol layer, causing local and sometimes regional cooling of the lower layers of the atmosphere; the absorbing aerosol causes heating of the aerosol layer itself, which leads to the subsequent heating of the surface atmospheric air due to mixing.

2. Results: the AOT changes over the Russian Federation, based on the data from 75 stations

Actinometric observations performed at the network of Roshydromet stations provide an information basis for monitoring the components of the radiation balance, cloudiness, transparency aerosol optical thickness (AOT) of the atmosphere [14-15, 17-19]. In these studies, the AOT was estimated using a technique developed by specialists from the Meteorological Observatory of Moscow State University [20]. A typical picture of the change in the annual AOT values in the period 1961-2013 gives the presented in Fig. 1 for the northern station Ust-Vym (62.2 ° N, 50.4 ° E), which clearly shows the AOT responses to stratospheric disturbances caused by the consequences of the four powerful volcanic eruptions: Agung (8 ° S, 116 ° E) – 1963, Fuego (14 ° N, 91 ° W) – 1974, El Chichon (17 ° N, 93 ° W) – 1982, Pinatubo (15 ° N, 120 ° W) – 1991. Obviously, there is also a fairly stable decrease in the AOT value since 1995.

This character of changes in annual AOT is typical for most stations. Average long-term and extreme values of annual AOD, and estimates of trends for the territory of Russia as a whole for three periods (based on data from 75 stations) are presented in table 1.

The mean AOT value for the analyzed dataset is 0.15 and varies from 0.26 to 0.09, which is consistent with the range of spatial changes in AOT (0.30—0.05) for the Russia according to the IPCC reports. The spatial distribution of AOT over the territory of Russia is consistent with the modeling results presented in the IPCC reports. Over the territory of Russia AOT decreases from the southwest to the northeast. Since 1995 year, at most stations, the process of “cleaning” the atmosphere from aerosol has been manifested. Thus, for the Russia the trend of AOT changes is negative; the absolute values of the rate of AOT changes over 10 years vary from (- 0.06) in the south to (+ 0.01) in the north. The relative trend is on average (- 13%) for 10 years.
Figure 1. An example of long-term changes in the annual values of aerosol optical thickness (AOT) and their deviations from the average \( d (\%) = 100\% \left( AOT_i - AOT_{av} \right) / AOT_{av} \) at Ust-Vym station for the period 1961—2014 (base period adopted by WMO, 1961-1990).

Table 1. Average annual AOT and their changes in the indicated years by the ground-based measurements over the Russian Federation (75 stations).

| Time interval | AOT      | Trends of AOT (for 10 years) |
|---------------|----------|------------------------------|
|               | Average | Maximal | Minimal | Average | Maximal | Minimal |
| 1976-2014     | 0,15    | 0,26    | 0,09    | -0,03   | 0,01    | -0,06   |
| 1976-1994     | 0,18    | 0,26    | 0,12    | -0,02   | 0,02    | -0,11   |
| 1995-2014     | 0,11    | 0,20    | 0,06    | -0,02   | 0,05    | -0,12   |

3. Analysis of changes in AOT, cloud cover and incoming radiation for the north of the ETR

Analysis of data on atmospheric turbidity and trends in its change in the northern polar region makes it possible to obtain additional data on the state of the atmosphere in this region, which is most important from the point of view of its influence on the Earth's climate [21]. Our paper presents the results of changes in AOT and total solar radiation \( Q \) for stations in the Russian north in the ETR. To characterize the conditions of the European sector of the Arctic, we used data on the stations of the Northern UGMS: Bugrino, Kotkino, Arkhangelsk, Kargopol, Eletskaya, Ust-Vym, Irael for the period 1961-2013, as well as data from Umba and Apatity stations located on the Kola Peninsula since 1976. In the north of the ETR (in the region north of 62° N), reliable AOT values can be obtained for the period from March to October. The region as a whole is characterized by high transparency. The
annual variation of the AOT in the north of the ETR has a spring maximum in April and a second less pronounced summer maximum in July. Differences are observed in the annual course of AOT for two observation periods: for a 30-year period (1976-2005) and a period of relatively high transparency (1994-2013), which average 16%. The average over a 30-year period under real and “undisturbed” conditions diverge within 8%. The data series for "undisturbed" conditions are formed by removing from the real observation series 2 years following the years of powerful volcanic eruptions El Chichon (1982 year) and Pinatubo (1991 year). To characterize long-term changes in turbidity, we analyzed the series of annual values of AOT and turbidity factor $T_2$ for the period 1976-2013. Turbidity factor $T_2$ was calculated using standard methods. The linear approximation of the time course indicates a decrease in the atmospheric turbidity, while during the last 5 years both the rate of change in AOT and the sign of changes have been steadily retained. At the same time, the statistical significance of the trends in $T_2$ and AOT changes for “undisturbed” conditions increases in comparison with real conditions.

**Figure 2.** Change in the annual values of the turbidity factor $T_2$ (●) and the aerosol optical thickness of the atmosphere AOT (○) in the North of the ETR during the period 1976-2014 (a) and the period 1994-2013 (b).
Long-term changes in the annual values of $T_2$ and AOT for the north of the ETR are presented in figure 2 (a, b). The duration of the period of relatively high transparency of the atmosphere over the territory of Russia is currently 20 years. Changes in $T_2$ and AOT occurring within this period in the north of the ETR indicate that conditions of relatively high atmospheric transparency remain.

Generally, long-term changes in AOT both throughout the period under consideration and in the last 20 years are negative, with a low rate of change (several % per year). Nevertheless, the relatively long length of the time series and the annual averaging of daily observations allow us to conclude that the rate of change in AOT has retained its magnitude and sign in recent years.

Figure 3 shows the temporal changes in the total solar radiation for the Umba station. There are insignificant and small positive (for average annual daily values) and negative (for average July daily values) tendencies of changes. The results were obtained for practically unchanged (with annual averaging) cloud conditions. Figure 4 shows the tendencies of changes in the coverage of the sky with clouds (annual values) for the stations Umba (1), Tsimlyansk (2). The degree of coverage of the sky with clouds was downloaded through a specialized server https://giovanni.gsfc.nasa.gov/giovanni, monthly values were used "cloud fraction from cloud mask", TERRA / MODIS.

As follows from the graphs shown in figure 5, the relationship between the aerosol content in the atmosphere (more precisely, AOT) and the incoming solar radiation flux is not observed in the presented time interval. However, for pronounced abrupt changes in AOT (powerful volcanic eruptions El Chichon – 1982 y. and Pinatubo – 1991 y.), negative anomalies of total radiation $Q$ are expressed in the next 1-2 year after the entry and formation of the stratospheric aerosol layer. The norm is calculated for 1981-2001 in accordance with the recommendations made in the Assessment Report on the peculiarities of the climate in the territory of the Russian Federation [22].

![Figure 3](image_url)

**Figure 3.** Long-term changes in total radiation (1 - mean annual daily values, 2 - mean July daily values) for Umba station (66.7 ° N; 34.3 ° E).
Figure 4. Trends in cloud coverage (annual values) for stations Umba (1), Tsimlyansk (2).

Table 2 shows the absolute and relative anomalies of \( Q \) and AOT, as well as their average values for the "volcanic" 1976-1994 and "post-volcanic" 1995-2013 periods. The rate is calculated as average values for 1981-2001. AOT is characterized by positive anomalies of 10% in the period 1976-1994 and negative anomalies of 40% for the 1995 period. At the same time, the total radiation in the north of the EPR is characterized by a "correct" tendency of \( Q \) changes: positive AOT anomalies correspond to negative values of \( Q \) anomalies and, conversely, for the last 20 years.

**Table 2.** Anomalies and average values of AOT and \( Q \).

| Time interval | Anomalies of AOT Umba | Average values AOT Umba | Anomalies of AOT Tsimlyansk | Average values AOT Tsimlyansk | Anomalies of \( Q \) (W/m\(^2\)) Umba | Average values \( Q \) (W/m\(^2\)) Tsimlyansk | Anomalies of \( Q \) (W/m\(^2\)) Tsimlyansk | Average value \( Q \) (W/m\(^2\)) Tsimlyansk |
|---------------|-----------------------|-------------------------|-----------------------------|-----------------------------|--------------------------------------|---------------------------------------------|--------------------------------------------|---------------------------------------------|
| 1976 - 1994   | 0.01 10               | 0.15 15                 | 0.25 -4                     | 229 0                       | 0 0                                  | 365                                         |                                  |
| 1995 - 2013   | -0.07 -45             | 0.08 -40                | 0.13 4                      | 237 1                       | 0 0                                  | 366                                         |                                  |
| 1976 - 2013   | 0.13                  | 0.19                    | 233 365                     |                                  |                                      |                                              |                                  |

In the south of the EPR, the annual \( Q \) values have a neutral time course, despite the pronounced negative AOD anomalies in the last 20 years, which is possibly related to the cloudiness trends in the
southern region and (or) the more pronounced influence of the cloud factor on the incoming solar radiation flux.

The obtained estimates of interannual changes in the AOT and Q series, as well as their annual variation, are consistent with the data of [23 - 24], in which the analysis of data on the total incoming radiation and integral transparency of the atmosphere at the Russian Arctic stations was carried out and the nature of long-term, interannual, and seasonal changes to these parameters was presented. In these works, it was shown that for more than 50 years of observations of the total radiation, no statistically significant trends in the change in its annual sums were observed in both polar regions, as well as the fact that in the polar regions the manifestation of powerful volcanic eruptions in the AOT atmosphere is expressed, solar radiation for one and a half years or more after the eruption. In the spring, the AOT of the atmosphere is formed under the influence of the transfer of anthropogenic emissions to the Arctic from sources located in the temperate latitudes of the Northern Hemisphere.

Figure 5. Anomalies of the annual values of the total radiation Q (a) and corresponding AOT anomalies (b) for Umba station. Quadratic approximation of the trend line has been carried out.
5. Conclusion
Quantitative estimates of changes in the aerosol optical thickness of the atmosphere and incoming solar radiation are presented based on the data of observations of the Russian actinometric network over 40 years for several stations in the north and south of the ETR. For AOT, there are quite pronounced anomalies, positive (1976-1994) and negative (after 1994). Negative AOD anomalies in the last 20 years are caused both by the absence of large volcanic eruptions with a global manifestation and increasing the AOT of stratospheric aerosol, and by the regional manifestation of a decrease in anthropogenic emissions on the territory of Russia. For the incoming radiation fluxes, a neutral time dependence is observed under the conditions of aerosol "clearing" of the atmosphere and average cloudiness. At the same time, in 1–2 years, following the powerful volcanic eruptions of El Chichon and Pinatubo, stable negative anomalies of the annual average daily value of incoming radiation $Q$ of 20 W/m$^2$ are observed relative to the norm calculated for 1981–2001.

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