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Variations and tendencies of cloud, aerosol and solar radiation in the past decades over East of the Asian Part of Russia based on surface and satellite data records

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Abstract. The results of studies of atmospheric aerosol over the territory of Russia are of great interest from the point of view of environmental and climatic problems. The article presents the results of the spatial-temporal variability of aerosol optical thickness (AOT) over the Asian Part (AP) of the Russian Federation in recent decades. The Database (DB) “Aerosol optical thickness of the atmosphere from satellite and ground-based observations” created by the authors was used. The presented trends in AOT changes (annual values, summer values) and statistical estimates of real empirical series show that there is a good agreement between the annual values of AOT for satellite and ground-based values, for monthly values the discrepancy has more value. Based on observational and reanalysis data, the interannual variability of the average annual and average summer values of the total radiation flux coming to the surface was studied. The empirical typification of interannual changes in the intra-annual course of the cloud cover values (%) over the considered time interval was carried out. The analysis was performed for the Tiksi Arctic station and for the Yakutsk, Ussuriysk, Irkutsk and Yekaterinburg stations located in the AP of the Russian Federation. Introduction

1. Introduction

A special IPCC report “Global warming” (2018) indicates a warming of 1.5 °C [1] in the middle of the century, which leads to possible dramatic consequences in the environment, in particular, an increase in the number of forest and grass fires and pollution by absorbing and dispersing aerosols of vulnerable and as critical for the Earth’s climate as the Arctic [2-5]. Aerosol optical thickness of the atmosphere (AOT) is an important parameter in assessing climate changes: changes in the temperature of the underlying surface and changes in the total solar radiation [6-8]. The Russian Arctic covers a vast territory and is poorly equipped with monitoring stations for climatically important atmospheric parameters: surface impurities, aerosol optical thickness of the atmosphere (AOT), cloud cover and incoming radiation. In this regard, observations at the Tiksi International Arctic Observatory provide unique information on the radiation - climatic parameters of the Arctic atmosphere. At the same time, we consider it relevant to conduct a comparative and cumulative analysis of climatically significant factors (aerosol, clouds) according to independent ground-based observations (AERONET and ACTINOMETRY), satellite (MODIS) estimates and other methods (reanalysis) for the diagnosis of average values, variations and trends at available time intervals 10 -15 years. As part of the above task, the article analyzes the changes in seasonal and annual values of AOT, cloud cover and incoming radiation for the Tiksi Arctic station and for several stations in the Asian Part of Russia as a comparison: using both the AERONET network ground-based data series and the corresponding



MODIS satellite data. We have evaluated the comparability, variations of average values and trends of temporary changes. We add that the works on the analysis of satellite data sharing capabilities (MODIS) and synchronous ground-based observations (AERONET and ACTINOMETRY) are actively carried out at this stage of the development of international and domestic research [9-12]. At the same time, regional features of changes in interrelated factors are revealed: aerosol, cloudiness and incoming radiation [1-3], as well as these changes are analyzed and modeled. In particular, the variability of AOT and clouds is used to simulate the time evolution and regional changes in radiation effects in the atmosphere, radiation effects on the Earth's surface [13-16].

2. Research objective

- 1) According to satellite, ground-based network observations and reanalysis data, we plan to study changes in seasonal and annual values of AOT, cloudiness and incoming radiation in the atmosphere over the Asian part of Russia over the past decades for several stations, and also to consider the characteristic features of changes in aerosol and cloudiness. The database "Aerosol optical thickness of the atmosphere according to satellite and ground-based observations" will be used [11].
- 2) Then we plan to evaluate the systematic trends in AOT changes (annual and summer values) and statistical estimates of real empirical series.
- 3) We will compare the AOT values obtained from synchronous satellite and network ground-based observations.
- 4) Based on measurements at the Tiksi station and reanalysis data, we will study the interannual variability of the average annual and average summer values of AOT, cloud cover and the total flux of solar incoming radiation. We will compare the interannual changes on Tiksi with two reference stations in the east of the Russian Federation: Yakutsk and Ussuriysk. All stated goals are within the framework of studies already conducted by the Russian authors [17-23] and their colleagues abroad, for example [24-25].

3. Empirical data

The article used both original experimental data, for example, AOT values obtained by the estimation method based on network actinometrical observations [19, 20], and standard AOT monthly values available on the AERONET network (AEROSOL ROBOTIC NETWORK), (<http://aeronet.gsfc.nasa.gov/>), as well as satellite monthly AOT values and monthly cloud cover (Terra / MODIS: Moderate Resolution Imaging, MOD08_M3 v6.1, <http://modis.gsfc.nasa.gov/>). For additional data validation and comparability, the database "Aerosol optical thickness of the atmosphere from satellite and ground-based observations" [11], 2018, State Registration Certificate No. 2018620215 in the Federal Service for Intellectual Property was used. The database is intended to carry out work on the assessment and analysis of temporary changes in AOT in the Russian Federation, to assess the comparability of different types of AOT monitoring, and was formed as part of the project "Study of the consistency of data from ground-based and satellite monitoring of transparency, aerosol optical thickness of the atmosphere not in Russia". The MERRA-2 reanalysis data for INCIDENT SHORTWAVE LAND (M2NMNXLQ v.512.4, MERRA-2 Model, Monthly, 0.5x0.625 °) were used to determine the average monthly values of the total incoming radiation. In all cases the download has been carried out through the Giovanni server <https://giovanni.gsfc.nasa.gov/giovanni>.

Table 1. Five observation stations in the Asian Part of Russia (APR), hose data are used in the work

	Years	Latitude (°N)	Longitude (°E)
Ussuriysk	2008-2015	43.8	131.95
Irkutsk	2005-2016	52.3	104.31
Yekaterinburg	2002-2016	56.9	60.61
Yakutsk	2004-2016	62.0	129.7
Tiksi	2004-2016	71.6	128.9

4. Results and analysis

So, we analyze the interannual variations in the annual and seasonal values of AOT, cloud cover (cloud cover in%), the total solar radiation incoming to the underlying surface based on the satellite and ground-based observations at several stations in the Asian territory of Russia (APR), indicated in Table 1. Note that three stations in Table 1 are built quasi-uniformly in east longitude (130°) from north to south: Tiksi (71.6, 128.9), Yakutsk (62.0, 129.7), Ussuriysk (43.8, 131.95), which potentially allows trace latitudinal of considered atmospheric parameters.

4.1. Aerosol optical thickness of the atmosphere (AOT)

The characteristics of AOT variability, namely, average annual values and their variations, are presented in Table 2 and in Figure 1. Analysis shows that data discrepancy between the satellite (MODIS) and ground-based (AERONET) international network is 0.01 - 0.03 absolute AOT units, i.e., about 5-10%. At the same time, local variability (standard deviations from the mean) and temporal (trends of interannual changes) are close with satellite and ground-based determination and are 0.03-0.07 and 0.02-0.05 absolute AOT units, respectively. In general, it can be determined that for the conditionally “northern” stations Tiksi and Yakutsk there is a more variable “aerosol weather”. The trends in interannual changes in average AOT are well reproduced by both MODIS and AERONET data: from 3% per year (0.05 for 10 years) for the “northern” Yakutsk station to (-3%) per year (-0.07 for 10 years) for the conditionally “southern” station Ussuriysk. Clear evidence of the negative and positive trends in AOT changes is also shown in Figure 1. Two reservations about the results should be given. At this stage of the review, we leave aside the data of the Russian actinometric network, which give a dropdown result in the estimates and that the estimates of the reliability of the obtained interannual changes are low and are not yet presented up to the accumulation of a larger amount of data.

Table 2. Average annual AOT and their changes in the indicated years by satellite and ground-based observations at the ATR of the Russian Federation (GMS – ground actinometrical data from [11])

	MODIS AOT (standard deviation)	AERONET AOT (standard deviation)	GMS AOT (standard deviation)	MODIS variation 10 yy. Variation% during 1 y.	AERONET variation 10 yy. Variation% during 1 y.	GMS variation 10 yy. Variation% during 1 y.
Ussuriysk (2008-2015)	0.25 (0.03)	0.26 (0.04)	0.22 (0.02)	-0.03 -1%	-0.07 -3%	-0.01 -0.5%
Irkutsk (2005-2016)	0.14 (0.03)	0.15 (0.04)	0.15 (0.04)	0 0	+0.05 +3%	+0.03 +2%
Yekaterinburg (2002-2016)	0.19 (0.04)	0.16 (0.02)	0.12 (0.02)	-0.01 -0.5%	-0.04 -2%	-0.02 -2%
Yakutsk (2004-2016)	0.18 (0.07)	0.15 (0.05)	0.09 (0.02)	+0.05 +3%	+0.06 +3%	-0.02 -2%
Tiksi (summer 2004- 2016)	0.19 (0.06)	-----	-----	+0.02 +1%	-----	-----

4.2. Spatio-temporal changes in cloud cover, characteristics of interannual and intra-annual variations

Figure 2 shows the interannual changes in the seasonal cloud cover (degree of coverage of the sky in %) for three stations, ranged by 130 east longitude from north to south. Note that for Tiksi station there are no data from November to January of each year. Figure 2 clearly demonstrate the different nature of the intra-annual cloud cover at the conditionally northern (Tiksi and Yakutsk) and conditionally southern (Ussuriysk) stations. For the former, the maximum cloudiness is stably observed in September-October, and for the latter -- in October, the minimum cloudiness is stably observed, and the distributed maximums of cloudiness are observed in July and March. This indicates the circulatory nature of the formation of seasonal changes in the cloud cover associated with the transfer of air masses in the region [26-28]. The interannual changes in cloudiness for annual and summer values are shown

in Figure 3. Note that the total average values for annual and summer values are close and make up 75-78%, 59-55%, 66-69%, respectively, from north to south. At the same time, trends are practically not detected or are small.

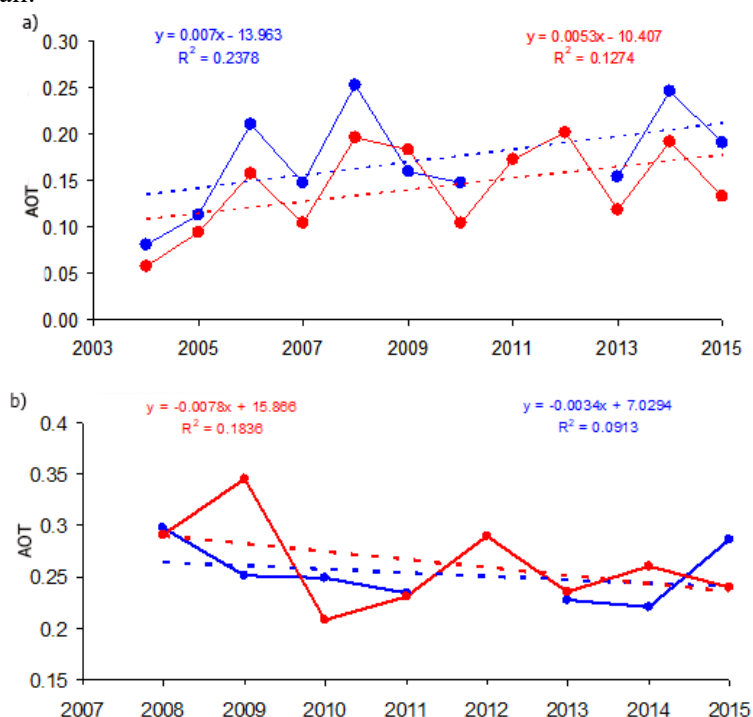


Figure 1. Interannual variability of AOT for Yakutsk (a), Ussuriysk (b) over 130 °east longitude of APR; for MODIS (blue) and AERONET (red) values

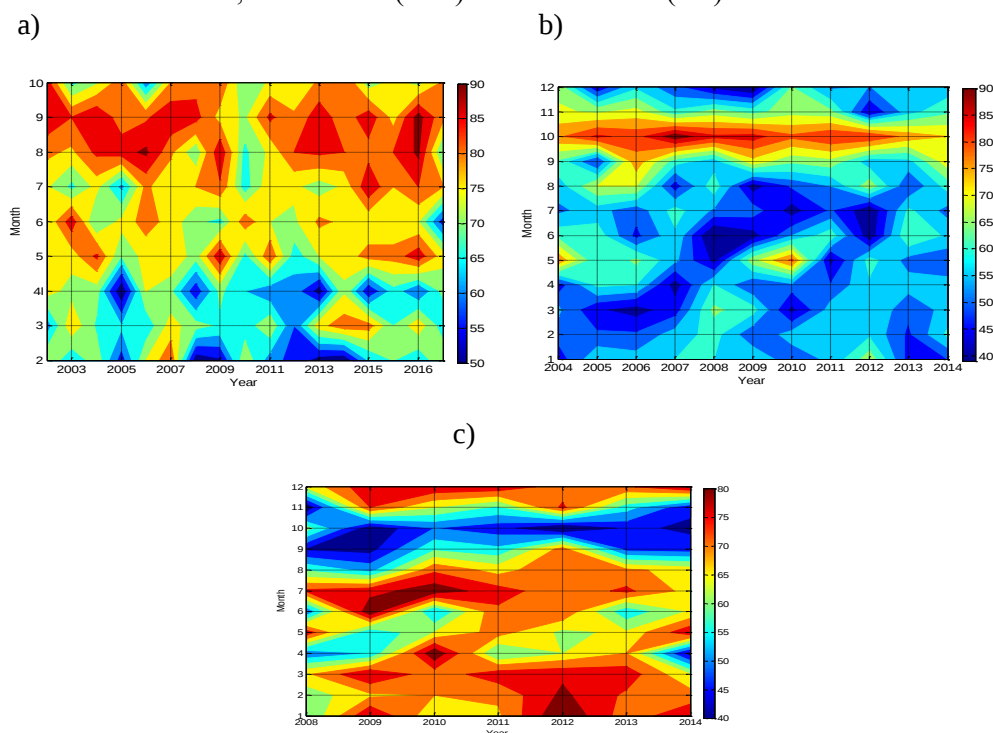
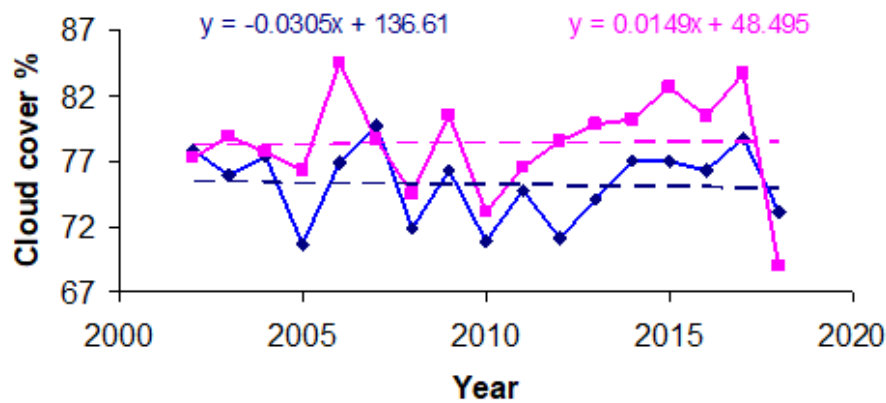
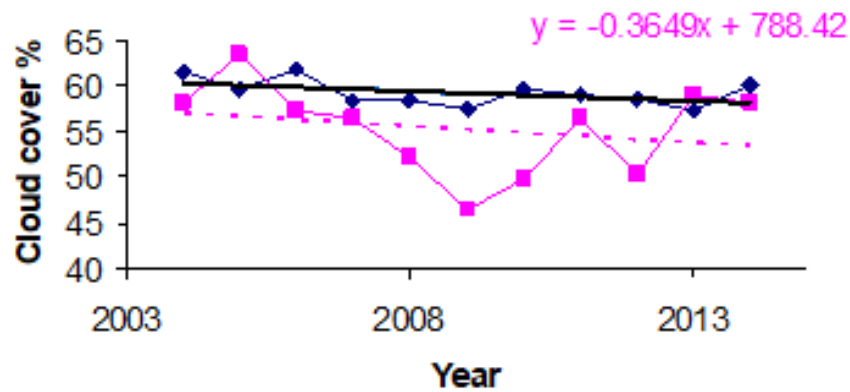


Figure 2. Interannual variability of the intra-annual cloud cover (%) for Tiksi (a), Yakutsk (b), Ussuriysk (c) over 130 °east longitude of APR

a)



b)



c)

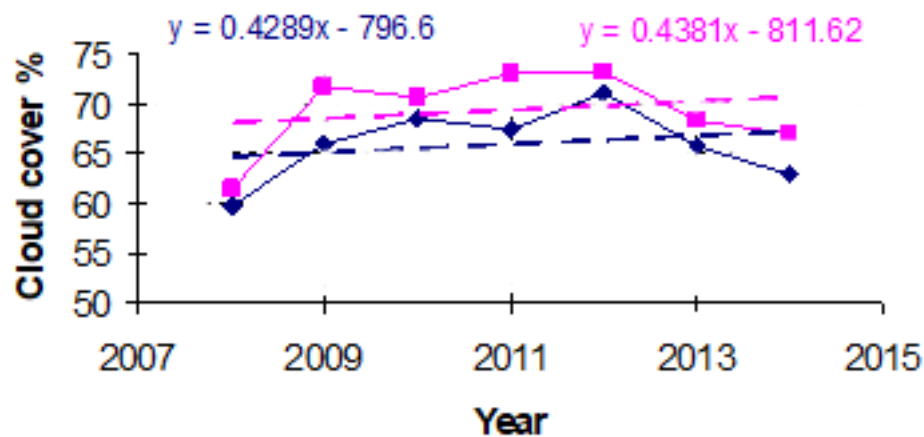


Figure 3. Interannual variability of cloud cover (%) for Tiksi (a), Yakutsk (b), Ussuriysk (c) over 130 °east longitude of APR; for year (blue) and summer (pink) values

4.3. Incoming solar radiation: range of variations and trends

Table 3 presents the average summer values of the total flux of solar radiation, as well as the range of variations of these values for 3 stations 130° of the eastern meridian: Ussuriysk, Yakutsk, Tiksi. The choice of the summer season is due to the lack of data at the Arctic station throughout the year.

Table 3. Average summer values of AOT and incoming radiation, as well as their changes during indicated years from satellite and ground-based observations on the APR

	MODIS AOT (standard deviation)	AERONET AOT (standard deviation)	MODIS Variation 10 years. variation% 1 year	AERONET variation years variation% 1 year	Incoming radiation (range of values)	Incoming radiation variation 10 years
Ussuriysk (2008-2015)	0.22 (0.03)	0.29 (0.07)	-0.04 -2%	-0.12 -4%	246 (258-235)	+0.2 W/M ²
Yakutsk (2004-2016)	0.18 (0.06)	0.16 (0.05)	+0.11 +6%	+0.08 +5%	224 (242-212)	+4 W/M ²
Tiksi (2004-2016)	0.19 (0.06)	-----	+0.02 +1%	-----	177 (189-163)	-0.4 W/M ²

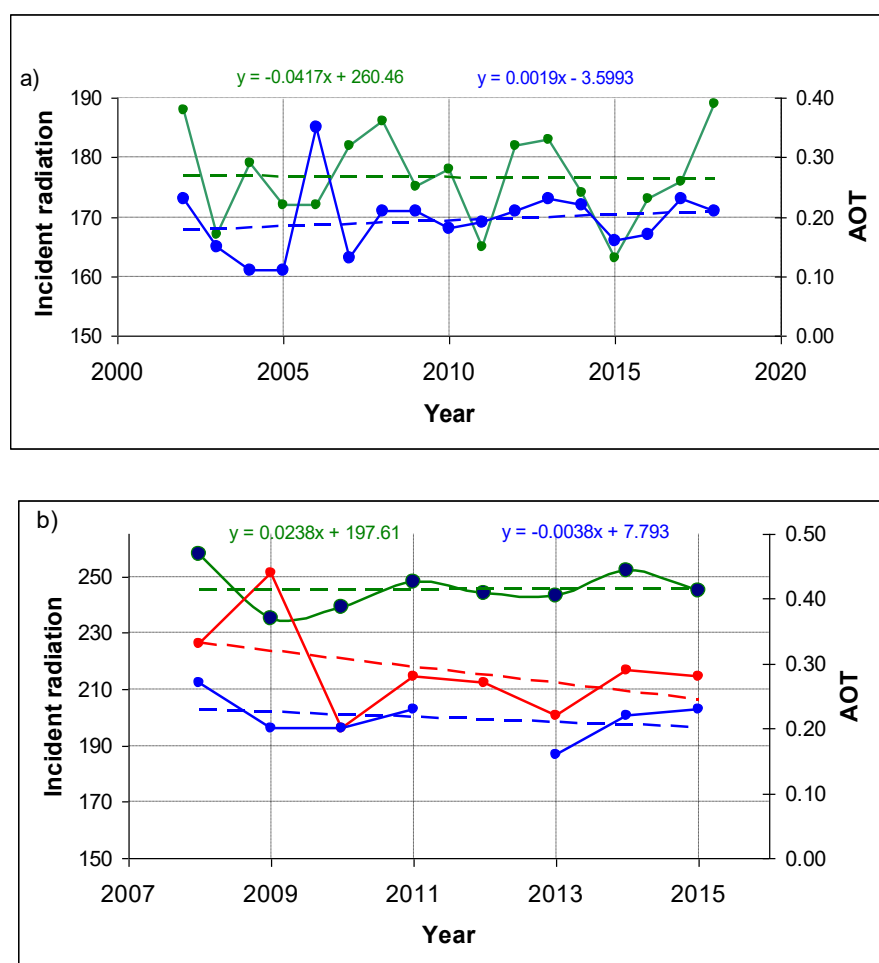


Figure 4. Interannual variability of summer AOT (blue and red) and summer incident radiation (green) for Tiksi (a) and Ussuriysk (b) over 130° east longitude of APR; MODIS (blue), AERONET (red) and reanalysis MERRA (green)

For the northern and southern stations the trends of the incoming radiation are minimal and make up shares of the one W/m^2 assigned to the 10-year interval (see also Figure 4). I would like to note that there is a possible agreement between the signs of a positive (or negative) change in incoming radiation and a negative (or positive) change in AOT. For both of these stations, a neutral interannual variation in the mean cloud point is observed (Figure 3). Data for Yakutsk fall outside this agreement; it is possible that interannual changes in the cloud cover play a paramount role for this station (Figure 3). In conclusion, we point out the results of comparing the estimates given in the work with important similar estimates in previous studies [3, 10, 14, 15, 29-31]. The values of AOT trends presented and obtained by us for Yakutsk are in excellent agreement with those obtained for both annual and seasonal summer AOT values. More extensive and detailed comparisons of our estimates for temporary long-term changes in AOT with the data [10, 15, 31] show their mutual agreement both in sign and magnitude. As a rule, monotonic changes in AOT over a 10-year interval are a few hundredths of absolute units of AOT with a predominance of a negative trend. Estimates of the interannual changes in the incoming radiation for the Russian territory [14] in the decades after 1990 are $(-2) - (-1) \text{ W/m}^2$ over 10 years or not observed at all [3]. For Europe [15, 26, 27], the characteristic values are $(+3) - (-4) \text{ W/m}^2$.

5. Conclusion

In this publication, we tracked the interannual variations in the seasonal and annual values of AOT, cloudiness and incoming radiation at several observation stations over the Asian Part of Russia. To assess the indicated atmospheric parameters satellite (MODIS) and ground (AERONET) observation arrays were used, as well as reanalysis data. The main estimates are presented in the article in numerical and graphical form. The values of the indicated atmospheric factors, determined by satellite and ground-based scans among themselves, are compared. An attempt was made to range the observed average annual and seasonal values of AOT, cloud cover and incoming solar radiation flux, as well as their intra-annual changes in latitude along the 130 meridians. The comparison of the obtained trends with the data in previous publications was carried out.

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