Comparison of satellite (AVHRR/NOAA) and ground-based measurements of atmospheric aerosol characteristics

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The paper presents some results of a comparative analysis of satellite data and ground-based measurement data on characteristics of aerosol over the territory of Tomsk Region. The goal of analysis was to assess the applicability of data of satellite system AVHRR/NOAA to determination of the characteristics of atmospheric aerosol and smokes of forest fires. The results of research show good potentialities of using data collected with AVHRR/NOAA for operative monitoring of atmospheric aerosol characteristics and for estimating the atmospheric optical condition over the Western Siberian regions from space.

Introduction

In recent decade the efforts on planning and conducting large-scale field experiments in the area of physics and chemistry of the atmosphere have been markedly increased. One of the main goals of these investigations is compiling of a more complete data set on the global and regional regularities in the spatiotemporal variations of the characteristics of tropospheric aerosol, including the aerosol of anthropogenic origin, whose source are forest fires. The investigation of aerosol characteristics and its effect on the radiation budget in the atmosphere is among most promising investigations of the International Global Atmospheric Chemistry (IGAC, http://www.igac.unh.edu) project being a key part of the International Geospheric–Biospheric Program (IGBP, http://www.igbp.kva.se). In this project we pointed out the necessity of a combined use of spaceborne, airborne, and ground-based instrumentation to measure the aerosol characteristics of the atmosphere for achieving the tasks of the project.

By rough estimates of specialists, every year the area of forest fires covers, on the average, about 8 to 10 million hectares, and the annual quantity of aerosol, emitted to the atmosphere by forest fires, is about 130 million tons.[1] Taking into account the aerosol effect on the principal biochemical cycles (in particular, on the global hydrocarbon budget), the problem of forest fire monitoring and investigating the impact of forest fires on the composition and optical properties of the atmosphere is of vital importance. A complex solution of this problem calls for the use of remote techniques of investigation with the use of satellite data. The solution of this problem is one of the strategic goals of new International Program on Global Observation for Forest and Land Cover Dynamics (GOFC–GOLD, http://www.fao.org/gtos/gofc–gold).

By now, the experience has been gained in the world in using satellite systems for monitoring of atmospheric aerosol and smokes of forest fires (see, for example, Refs. 2–6). However, in Russia, where annually a great number of large forest fires occur, practically no large-scale operative space monitoring of aerosol and smokes is performed. This fact requires speeding up further work in this area.

Primary goals of the research

Many-year experience has been gained at the Institute of Atmospheric Optics (IAO) SB RAS in performing theoretical and experimental (ground-based and airborne) investigations of atmospheric aerosol. The results of these investigations have been published in literature in Russia and abroad. There are vast data arrays compiled on the aerosol and meteorological characteristics of the atmosphere, which can be used for validation and further development of the techniques of space monitoring of atmospheric aerosol. The description of investigation results, databases, and references can be found at Internet site of IAO (http://www.iao.ru). Since spring of 1998 at the Institute of Atmospheric Optics has performed regular monitoring of the Tomsk region using a “ScanEx” Station of Digital Satellite Signal Detection in five spectral channels ($\lambda = 0.63$; 0.84; 1.6; 3.75; 10.8; 12.0 μm) of the AVHRR/NOAA (Advanced Very High Resolution Radiometer, National Oceanic and Atmospheric Administration USA) satellite system. These conditions have opened up new opportunities for supplementary studies of atmospheric aerosol characteristics (including smokes of forest fires) for the Western Siberian region based on the complex analysis of data of regular ground-based measurements of aerosol characteristics and digital satellite data in the visible and infrared spectral ranges.

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The goal of this work is assessment of fundamental potentialities of using the AVHRR/NOAA system in Tomsk region to obtain quantitative characteristics of the atmospheric aerosol and smokes of forest fires. For this purpose, a comparative analysis was carried out of satellite data (AVHRR channel 1) with the data of the ground-based measurements of such aerosol characteristics, as aerosol optical thickness (AOT), the aerosol number density (cm^{-3}), the scattering coefficient at a wavelength $\lambda = 0.52$ μm (km^{-1}), mass soot content ($\mu\text{g/m}^3$) for the period from May to September 1999. The ground-based observations have been conducted in Tomsk and at a distance of 70 km from Tomsk on the bank of Ob River near Kireevsk settlement.

Simultaneously, the information and methodical bases were formed of the regional system for assessment of the optical condition of the atmosphere using satellite data, which is being created for the purpose of operative determination of the aerosol optical characteristics and atmospheric correction of data of space-based monitoring of the underlying surface.

Results

At the initial stage of solving the problem presented in the paper an imitation numerical simulation was performed, using LOWTRAN-7 (Ref. 7) program, of the upwelling radiation fluxes in the first ($\lambda = 0.63$ μm) and second ($\lambda = 0.84$ μm) channels of the AVHRR/NOAA system for a wide range of optical and geometric conditions of observations. One of the main goals of the calculations performed was compiling the database for a satellite system created for high-speed space-based monitoring of atmospheric aerosol and atmospheric optical conditions. According to the results of numerical simulation we have investigated the dependences of intensities of scattered (J_{sct}) and reflected (J_{rfl}) solar radiation fluxes on the geometry of satellite observations (angle of scanning, sun elevation, relative azimuth), albedo of the underlying surface (US), meteorological parameters of the atmosphere, and characteristics of the near-ground aerosol. Figures 1 and 2 show some results of numerical simulation, where the intensity values are normalized in percent by the value of solar constant in the corresponding spectral ranges.

Figure 1 shows for the first channel of the AVHRR system the dependences of intensities of scattered J_{sct} and reflected J_{rfl} solar radiation fluxes (the albedo $A = 0.1$) on the geometry of sun position with the availability of aerosol (rural type[7]) in the surface layer at the meteorological visual range being equal to 10 km.

As one would expect, the intensity of reflected radiation increases smoothly with increasing the angular sun height (H_υ). In this case J_{rfl} does not depend on the relative azimuth of observation (φ), which is a projection on the plane formed by vectors satellite–sun and satellite–observation point. At the same time the scattered radiation intensity J_{sct} has the following distinctive properties: (a) J_{sct} depends on the relative observation azimuth (φ); (b) at small values of $\varphi < 50°$ and $H_\upsilon \approx 10–20°$ the local maximum of J_{sct} is formed.

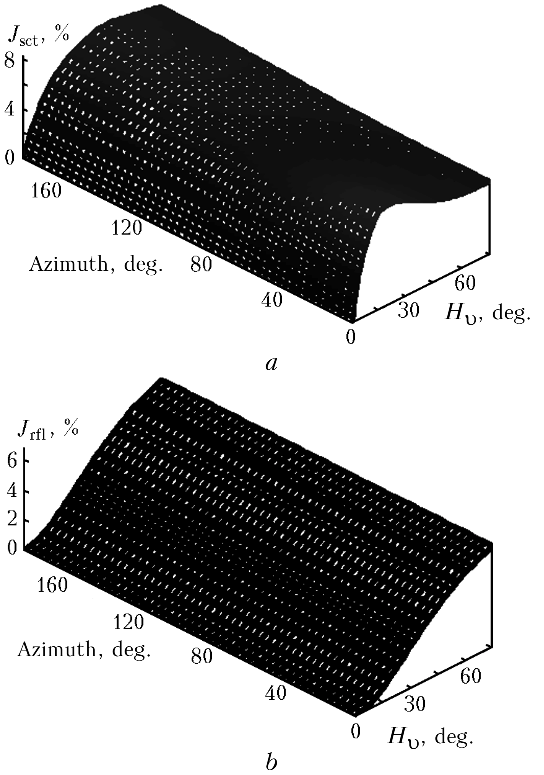

Fig. 1. Intensities of scattered (*a*) and reflected (*b*) solar radiation fluxes depending on the geometry of observations. Channel 1 AVHRR/NOAA ($\lambda = 0.63$ μm), rural aerosol (MVR = 10 km).

Figure 2 shows for AVHRR channels 1 and 2 the dependences of the scattered solar radiation flux intensity for two values of the scanning angles of the instrument axis ($\theta = 20°$ and $40°$), two values of relative azimuth ($\varphi = 0$ and $180°$), and two values of the meteorological visibility range (20 and 2 km). Data of numerical simulation enable us to refine the peculiarities in the behavior of J_{sct} and to draw the following conclusions.

1. Dependences of J_{sct} on the optical and geometric observation parameters are of close qualitative character for channels 1 and 2 of the AVHRR system.
2. The amplitude of local maximum increases together with the scanning angle (θ) of the instrument axis.
3. The local maximum is more pronounced at the values of the meteorological visibility range being equal to 10–15 km.

Similar conclusions can be drawn from the results of numerical simulation, obtained for aerosol of a different type (urban aerosol[7]).

To achieve the main goal of the research, the processing of satellite measurements J_{sat} (albedo) was performed presenting the intensity values of the upwelling radiation flux at the top of the atmosphere normalized in percent by the value of solar constant in the appropriate spectral ranges.

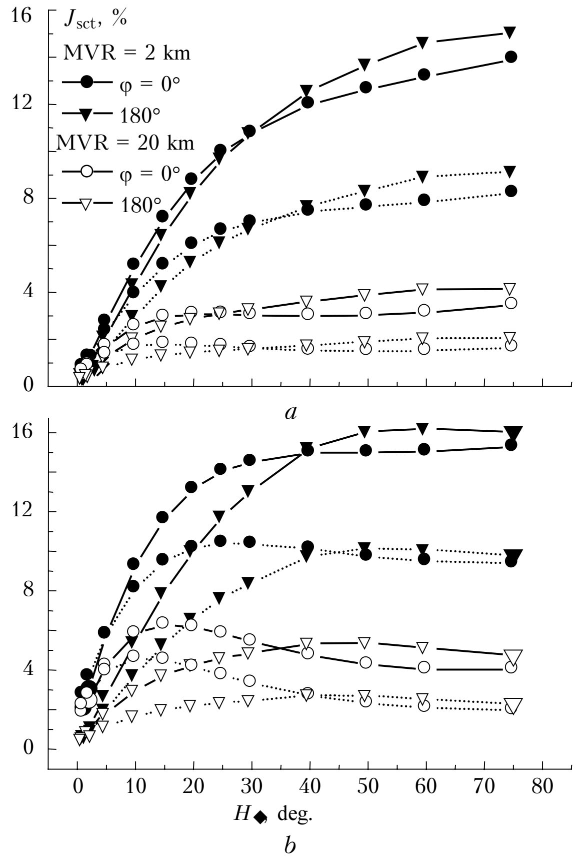

Fig. 2. The influence of geometry of observations and MVR on the intensity of the scattered solar radiation flux in channels of AVHRR/NOAA: channel 1 (solid curves), channel 2 (dashed curves). Scanning angle θ = 20° (*a*) and 40° (*b*).

The value J_{sat} can be expressed as follows:

$$J_{sat} = J_{sct} + J_{rfl} = J_{sct} + AJ_{\uparrow},$$

where J_{sct} and J_{rfl} are the intensities of solar radiation fluxes scattered by the atmosphere and reflected by the underlying surface; A is albedo of the underlying surface; $J_{\uparrow}$ is the intensity of solar radiation flux reflected from the “mirror” underlying surface ($A \approx 1.0$).

The processing of satellite data included the following stages.

(1) Calibration, geographic referencing, and data vizualization, rejection of cloud photographs.

(2) The calculation, for each satellite photograph, of the “molecular” (conditions of the atmosphere without aerosol) values of intensities of scattered and reflected from the “mirror” underlying surface solar radiation fluxes (J^0_{sct} and $J^0_{\uparrow}$) based on the meteorological information for the time of space monitoring and on the parameters of the observation geometry.

(3) Statistical analysis of spatiotemporal variability of satellite data in the vicinity of points of ground-based measurements to prepare for visible channels of the AVHRR charts of albedo of the underlying surface $A(x, y)$.

The statistical analysis of time series of satellite photographs and the construction of charts of albedo of the underlying surface involves the following basic ideas:

- selection of images with no clouds corresponding to conditions of high atmospheric transmittance (for control we used the results of ground-based measurements of aerosol characteristics);
- the calculation of albedo values

$$A(x, y) = (J_{sat}(x, y) - J^0_{sct})/J^0_{\uparrow};$$

- search for optimal, for aerosol space-based monitoring, spots on the underlying surface characterized by low albedo and spatial quasihomogeneity (that enables one to minimize the effect of underlying surface and errors in geographic referencing on the interpretation of satellite measurements);
- assessment of seasonal and interannual variability of the underlying surface albedo.

(4) The calculation of aerosol characteristics based on satellite data for optimal areas of the underlying surface

$$J_{aer}(x, y) = J_{sat}(x, y) - J^0_{sct} - A(x, y, \theta, H_\upsilon)\, J^0_{\uparrow}$$

and conducting of a comparative analysis of satellite data J_{aer} and data of ground-based measurements on atmospheric aerosol characteristics. It should be noted that in calculating J_{aer} the influence of geometry on albedo of the underlying surface was approximately taken into account using the expression $A(x, y, \theta, H_\upsilon) = A(x, y) \cdot g(\theta, H_\upsilon)$, where the type and parameters of the function $g(\theta, H_\upsilon)$ were selected based on the data given in Refs. 8 and 9.

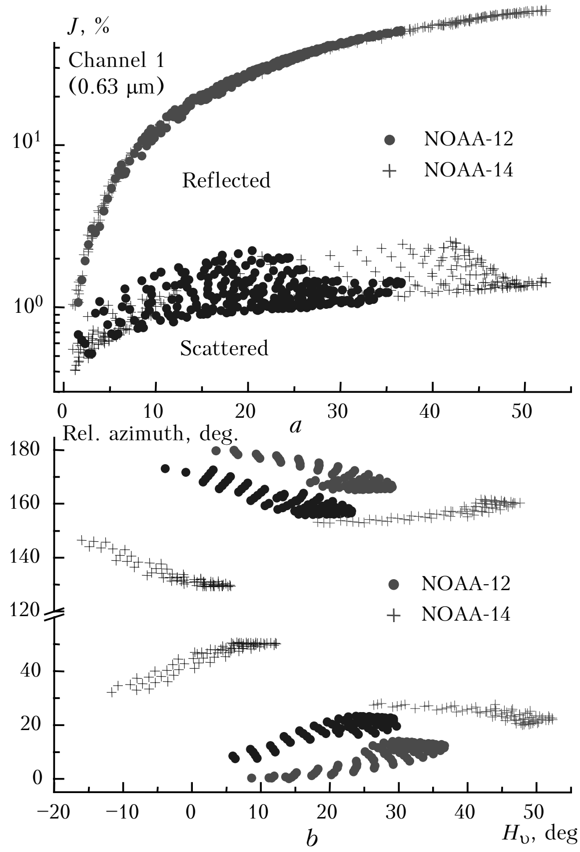

Fig. 3. Calculated results on the intensities of solar radiation fluxes scattered and reflected from the underlying surface under conditions of transparent atmosphere in the vicinity of Tomsk (*a*). Geometry of solar position during spaceborne measurements (*b*).

Consider now the results obtained at the stages of the above-mentioned processing of satellite measurements.

Illustration of the results obtained at the stage 2 is given in Fig. 3.

In this figure the calculated data are given on the values $J^0_{\rm sct}$ and $J^0_\uparrow$ for the channel 1 of AVHRR and data on the sun position geometry (H_υ and φ) during spaceborne measurements, which was used for calculating these values. Figure 3 is supplemented with Table 1 with statistical data on the intensities $J_{\rm sct}$ and $J^0_\uparrow$ for channels 1 and 2 of AVHRR and two types of satellites.

The results obtained at the stage 3 are shown in Fig. 4. Here the charts are shown for the channel 1 AVHRR of the satellite NOAA-14 of the albedo $A(x, y)$ of two areas of the underlying surface of the size of 0.6° in latitude and 1° in longitude (≈ 67 × 74 km) in the vicinity of points of ground-based measurements. The charts were obtained in July 1999. To assess the interannual variability of these data analogous charts were constructed for July 1998. Analysis of July charts of the US albedo for 1998 and 1999 makes it possible to draw a conclusion about their good identity.

Thus the divergence of values of $A(x, y)$ is about 5–10%. Figure 4 along with the charts of $A(x, y)$ shows the charts of characteristics of space inhomogeneity of the albedo $\delta A(x, y)$ – rms deviation of values $A(x, y)$ in the vicinity of 7 × 7 pixels. Data shown in Fig. 4 make it possible to isolate in the charts spatially homogeneous US areas with $\delta A(x, y) < 0.04$ of a sufficient size. The results, obtained at this stage, demonstrate a possibility of making up seasonal charts of albedo based on the satellite images of regional catalogs with the areas optimal for space monitoring of the aerosol.

Table 1. Statistical data on the intensities $J_{\rm sct}$ and $J^0_\uparrow$ of the scattered and reflected from the underlying surface solar fluxes

Channel	Radiation type %	Mean	RMS	Regression error	Max
		NOAA-12			
1	$J^0_\uparrow$	28.958	11.723	0.709	51.271
	$J^0_{\rm sct}$	1.235	0.308	0.302	2.233
2	$J^0_\uparrow$	26.800	10.450	1.421	46.230
	$J^0_{\rm sct}$	0.487	0.119	0.119	0.885
		NOAA-14			
1	$J^0_\uparrow$	38.127	25.051	0.993	68.720
	$J^0_{\rm sct}$	1.298	0.511	0.347	2.556
2	$J^0_\uparrow$	33.476	21.625	1.951	63.535
	$J^0_{\rm sct}$	0.483	0.149	0.121	0.910

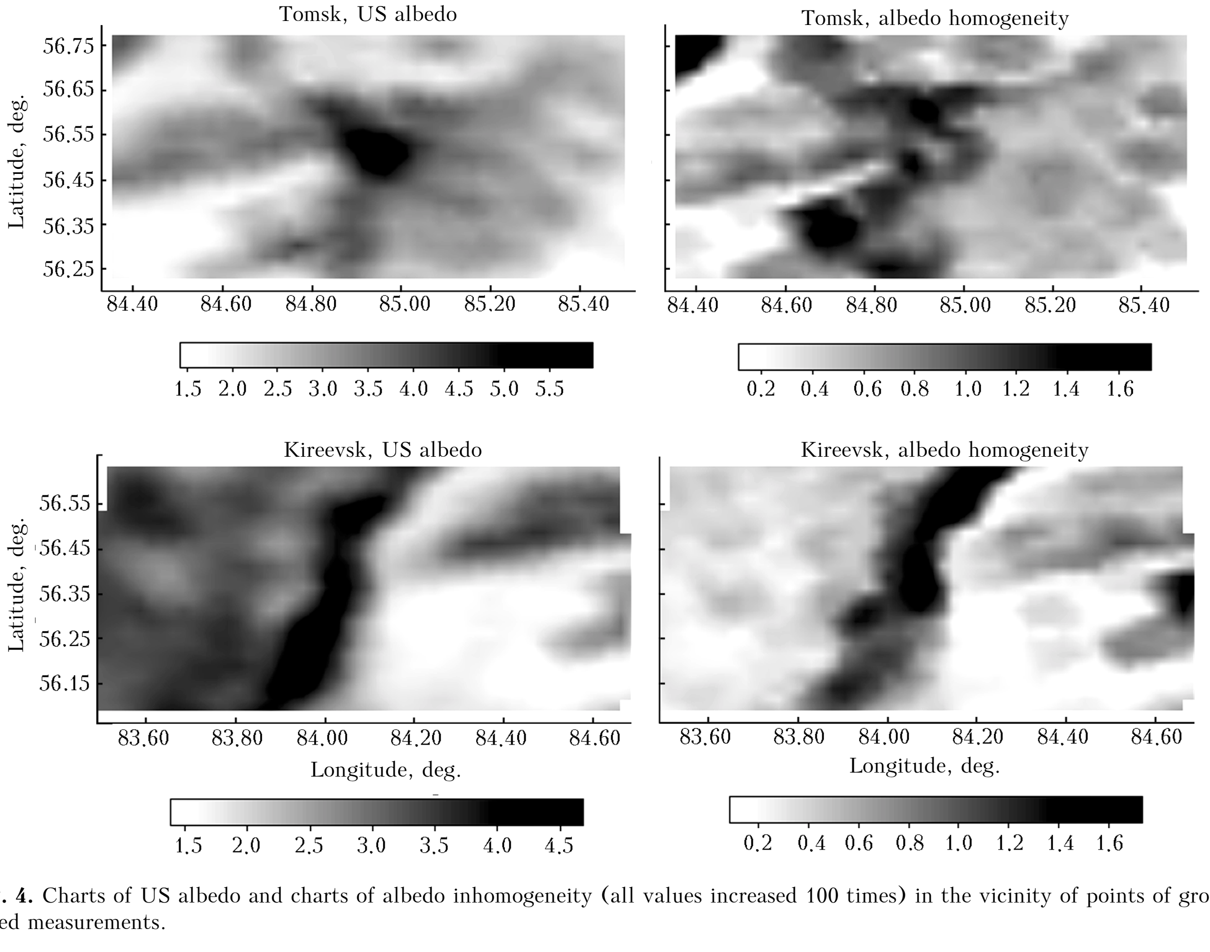

Fig. 4. Charts of US albedo and charts of albedo inhomogeneity (all values increased 100 times) in the vicinity of points of ground-based measurements.

Figure 5 shows the results obtained at the final (fourth) stage of processing the satellite measurement data.

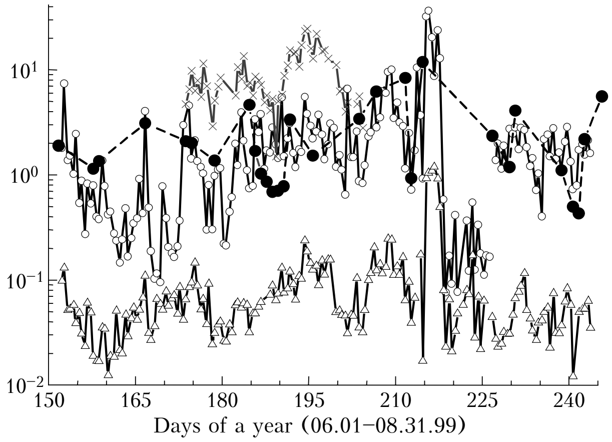

Fig. 5. Time dependence of J_{aer} from satellite data and ground-based measurements of aerosol characteristics: aerosol number density, cm^{-3} (—○—); the scattering coefficient ($\lambda = 0.52$ μm), km^{-1} (—△—); AOT ($\lambda = 0.63$ μm) (—×—). J_{aer} ($\lambda = 0.63$ μm), % (--●--).

Figure 5 shows the data of ground-based measurements of aerosol characteristics and the value of J_{aer} (channel 1, NOAA-14) for one of the optimal parts of the underlying surface in the vicinity of Tomsk during the period from 1st June 1999 to 31st August 1999. Analysis of these results enables us to note a good agreement between time dependence revealed from satellite data and data of ground-based measurements.

Table 2. Correlation coefficients R_{sat} and R_{aer} between ground-based measurements of aerosol characteristics and satellite data J_{sat} and J_{aer} (N is the sampling volume); statistical properties of the aerosol characteristics are also given

Aerosol characteristics	R_{sat}	R_{aer}	N	Mean	RMS	Max
	Tomsk					
AOT	0.53	0.95	12	0.085	0.036	0.153
Number concentration, cm^{-3}	0.63	0.77	47	1.982	1.611	9.615
Scattering coefficient, km^{-1}	0.52	0.64	37	0.094	0.076	0.314
Soot content, $\mu\text{g/m}^3$	0.05	0.39	37	0.904	0.747	3.441
	Kireevsk					
AOT	0.89	0.91	10	0.251	0.192	0.609

Figure 5 is supplemented by Table 2, where the correlation coefficients R_{aer} are given between satellite data J_{aer} and data of ground-based measurements of aerosol characteristics. In Table 2 for each aerosol characteristics its statistical data are given (mean sample values, rms deviation, and maximal values). Analysis of Table 2 makes it possible to draw a conclusion about the presence of positive correlation between the satellite data and ground-based measurements. However it should be noted that the correlation coefficient between J_{aer} and the soot content is significantly less than for other characteristics.

In addition, the correlation coefficients R_{sat} are given between the ground-based measurements of aerosol characteristics and the "initial" satellite data J_{sat}. Comparison of R_{sat} and R_{aer} enables us to note, for the case of measurements in Tomsk, the marked difference ($R_{\text{aer}} > R_{\text{sat}}$ by 0.12–0.42) that reflects a satisfactory efficiency of determination from satellite measurements of aerosol contribution using a described procedure of processing the data of space-based monitoring.

A potential error of reconstruction of AOT (as the most adequate value J_{aer}) is, on the average, about 10% for the channel 1 of the AVHRR system that is in a good agreement with the results from Refs. 3 and 5.

Conclusion

The results of investigations make it possible to draw a conclusion about good potential possibility of using the AVHRR/NOAA satellite system in the regions of Western Siberia for space monitoring of atmospheric aerosol characteristics (including forest fire smokes) and routine assessment of optical condition of the atmosphere for the purpose of atmospheric correction of satellite data. For practical realization of these possibilities there is a need for further development of methods of interpretation of satellite measurements adapted to regional conditions of observations and preparation of regional catalogs of charts of albedo of the underlying surface.

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