SIMULATION OF THE UPWARD GOING FLUX OF THERMAL RADIATION SCATTERED BY AEROSOL

PART I. FLUX INTENSITY

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In this paper we consider some results of simulation of the upward going flux of thermal radiation of the "atmosphere–underlying surface" system. The aerosol effect on the intensity and structure of the flux of scattered thermal radiation is studied over a wide range of optical and geometric conditions of observations using the Monte Carlo method and several approximate techniques.

1. INTRODUCTION

The underlying surface temperature determination within the accuracy not worse than 0.5–1.0° using remote sensing data obtained in 3.5–4 and 8–13 μm ranges is caused by the necessity to perform a correction of measurement data for the influence of the atmosphere. As a rule, when developing operative algorithms,[1] the problem of account for aerosol extinction distorting effect is set aside, or simplest modifications of these algorithms[2] or appropriate radiation models, e.g. "conservative" scattering model,[3] are used for the solution of this problem.

Despite of a positive experience of using regular algorithms of atmospheric correction of results of remote measurement of oceanic surface temperature using NOAA satellites, the problem of correct and reliable account for aerosol extinction and scattering effects under conditions of strongly turbid atmosphere is still open. So, to improve the accuracy and reliability of algorithms for atmospheric correction, it is necessary to study in more detail the mechanism of forming the upward fluxes of thermal radiation of the atmosphere and underlying surface scattered by aerosol.

The effect of boundary aerosol layer on the intensity and structure of scattered thermal flux for the case of a spatially homogeneous Lambertian surface is investigated in this paper. In addition, the estimation of accuracy of approximate models of single and conservative radiation scattering is carried out.

2. BASIC CHARACTERISTICS OF SIMULATION

The thermal radiance and radiative temperature of the "atmosphere–underlying surface" (A–US) system are the basic characteristics to be simulated.

$$J_\lambda = J^{0}_{\lambda} + J^{\mathrm{MS}}_{\lambda} ,$$

$$J^{0}_{\lambda} = B_\lambda[T_{\mathrm{S}}]\,\tau(0) + \int\limits_0^H [1-\omega_0(h)]\, B_\lambda[T(h)]\,\frac{\partial\tau(h)}{\partial h}\,dh ,$$

$$T^{\mathrm{MS}}_{\lambda} = B^{-1}_{\lambda}[\,J_\lambda\,] ,\quad T^{0}_{\lambda} = B^{-1}_{\lambda}[\,J^{0}_{\lambda}\,],$$

where J_λ is the radiance, T_λ is the radiative temperature, $B_\lambda[T_\lambda]$ is the Planck function, $B^{-1}_{\lambda}[J_\lambda]$ is the inverse Planck function, $\tau(h)$ is the atmospheric transmittance from its upper boundary (H) down to altitude h, ω_0 is the single scattering albedo, $J^{\mathrm{MS}}_{\lambda}$ is upward scattered radiance (MS denotes "multiple scattering"), T_{S} is the underlying surface temperature, and $T(h)$ is the atmospheric temperature at altitude h.

To evaluate the value of $J^{\mathrm{MS}}_{\lambda}$, we used one of the algorithms of the Monte Carlo method, namely, the direct simulation of the conjugate trajectories,[4] the separation of contributions from surface and the atmosphere as well as from single scattering was made as a part of this procedure. The error of ${}^{\mathrm{MS}}_{\lambda}$ value determination using the Monte Carlo method was about 0.02 degree.

Values of temperature corrections $\Delta T^{\mathrm{MS}}_{\lambda} = T^{\mathrm{MS}}_{\lambda} - T^{0}_{\lambda}$ and $\Delta T^{\mathrm{SS}}_{\lambda} = T^{\mathrm{SS}}_{\lambda} - T^{0}_{\lambda}$ (SS denotes "single scattering") as well as the corresponding values of $\Delta T^{\mathrm{MS}}_{\lambda}(\mathrm{atm})$ and $\Delta T^{\mathrm{SS}}_{\lambda}(\mathrm{atm})$, which correspond to atmospheric contribution, were computed at the final stage.

The model of conservative scattering[2] (CS) was used to calculate the thermal radiance and radiative temperature of the A–US system along with Monte Carlo method. In accordance with this model

$$J^{\mathrm{CS}}_{\lambda} = B_\lambda[T_{\mathrm{S}}]\,\tau(0) + \int\limits_0^H B_\lambda[T(h)]\,\frac{\partial\tau(h)}{\partial h}\,dh ,$$

$$T^{\mathrm{CS}}_{\lambda} = B^{-1}_{\lambda}[\,J^{\mathrm{CS}}_{\lambda}\,] .$$

To estimate the effect of aerosol upon the radiative temperature, we calculated

$$\mathrm{d}\,T_{\mathrm{aer}} = T^{\mathrm{mol}}_{\lambda} - T^{\mathrm{MS}}_{\lambda} ,$$

where $T^{\mathrm{mol}}_{\lambda}(\mathrm{atm})$ is the radiative temperature of the A–US system in the case of purely molecular atmosphere. To estimate the accuracy of the approximate models of single and conservative scattering, we calculated the values

$$\mathrm{d}\,T_{\mathrm{CS}} = T^{\mathrm{MS}}_{\lambda} - T^{\mathrm{CS}}_{\lambda} ,$$

$$\mathrm{d}\,T_{\mathrm{SS}} = T^{\mathrm{MS}}_{\lambda} - T^{\mathrm{CS}}_{\lambda} ,$$

and also $\mathrm{d}T_{\mathrm{SS}}(\mathrm{atm})$.

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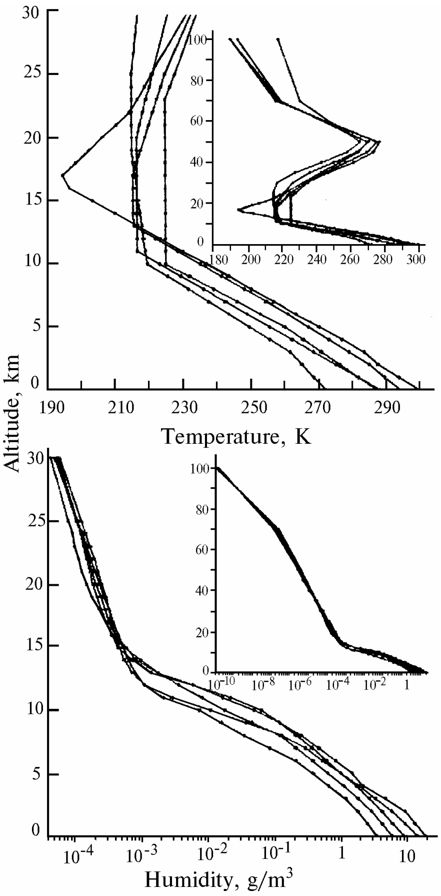

FIG. 1. Vertical profiles of temperature and humidity for various meteorological models of atmosphere.

3. OPTICAL AND GEOMETRIC CONDITIONS USED IN SIMULATION

Simulation was carried out under the following optical and geometric conditions: spectral ranges of 3.55–3.95 μm (λ = 3.75 μm) and 10.3–11.3 μm (λ = 10.8 μm), angles of observation φ = 0 and 45°, altitude of observation of 800 km, the atmosphere was considered spherically symmetric and vertically inhomogeneous. Meteorological models of the atmosphere included the tropics, midlatitudinal summer and winter, the arctic summer, and the standard US–1976 model. (Figure 1 presents vertical profiles of temperature and humidity for these models).

The aerosol models included the maritime, rural, and urban types of aerosol in boundary atmospheric layer of 0–2 km (visibility range S_M = 2–50 km) and background content of aerosol in the troposphere and the stratosphere. Underlying surface was assumed spatially homogeneous, Lambertian, and emitting as a black body within the temperature range T_S = 272.2–299.7 K depending on the atmospheric model used.

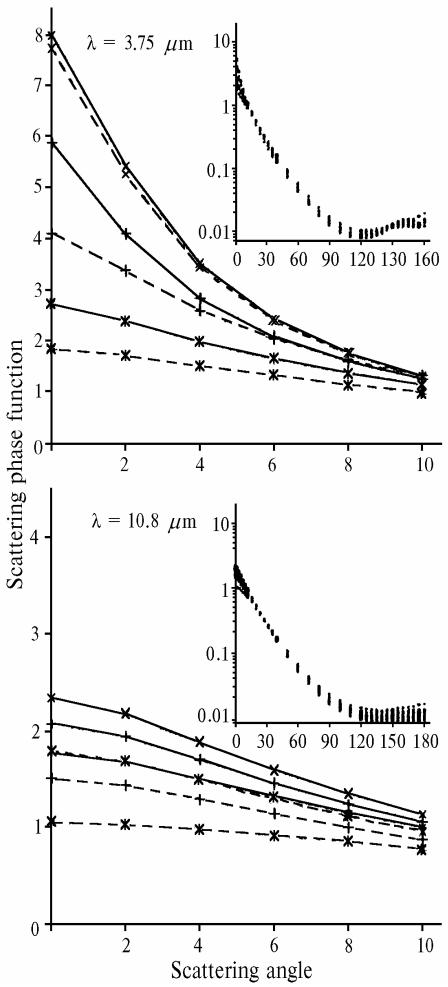

FIG. 2. Angular dependence of scattering phase function and the range of its variability for the following types of aerosol: rural (+), maritime (∗), and urban(×).

Figure 2 presents the angular dependence of scattering phase function and the range of its variability for each of the three aerosol types. Table I contains the data on the aerosol scattering to aerosol extinction ratio.

Vertical profiles of meteorological parameters of the atmosphere as well as the coefficients of molecular and aerosol extinction (scattering) were obtained from the data compiled in the LOWTRAN–7 complex.[5]

4. SIMULATION RESULTS

Results of simulation are presented in Figs. 3–6 and in Tables II–IV.

Figure 3 illustrates the aerosol effect on the radiative temperature of A–US system (dT_{aer} value) under various observation conditions. Figure 4 shows the temperature corrections as function of optical thickness of aerosol.

TABLE I. Range of variability of the aerosol scattering to aerosol extinction ratio.

Aerosol type	Meteorological models				
	Tropics	Midlatitudinal summer	Midlatitudinal winter	Arctic summer	US - 1976
	λ = 3.75 μm				
Rural	0.8667	0.8534	0.8609	0.8632	0.8596
	0.9153	0.9128	0.9150	0.9144	0.9114
Maritime	0.9561	0.9581	0.9581	0.9564	0.9597
	0.9724	0.9753	0.9734	0.9738	0.9794
Urban	0.5364	0.4902	0.5067	0.5132	0.4641
	0.5440	0.5048	0.5327	0.5252	0.4663
	λ = 10.8 μm				
Rural	0.5176	0.5465	0.5542	0.5412	0.5896
	0.5775	0.6022	0.5861	0.5896	0.6147
Maritime	0.4876	0.5588	0.5283	0.5091	0.6562
	0.5234	0.5778	0.5401	0.5496	0.7284
Urban	0.3548	0.3646	0.3804	0.3723	0.3750
	0.3951	0.4046	0.3984	0.3999	0.4126

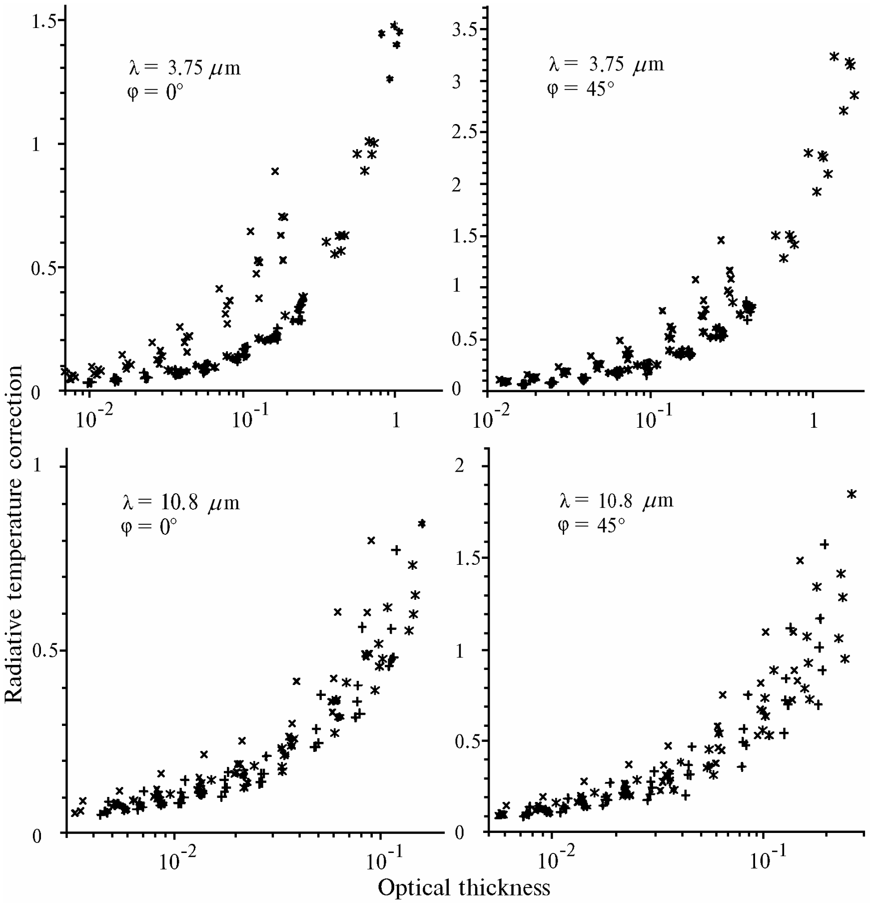

FIG. 3. Aerosol effect ($\mathrm{d}\,T_{\mathrm{aer}}$) *on radiative temperature at various observational conditions for rural* (+), *maritime* ($*$), *and urban* ($\times$) *aerosol.*

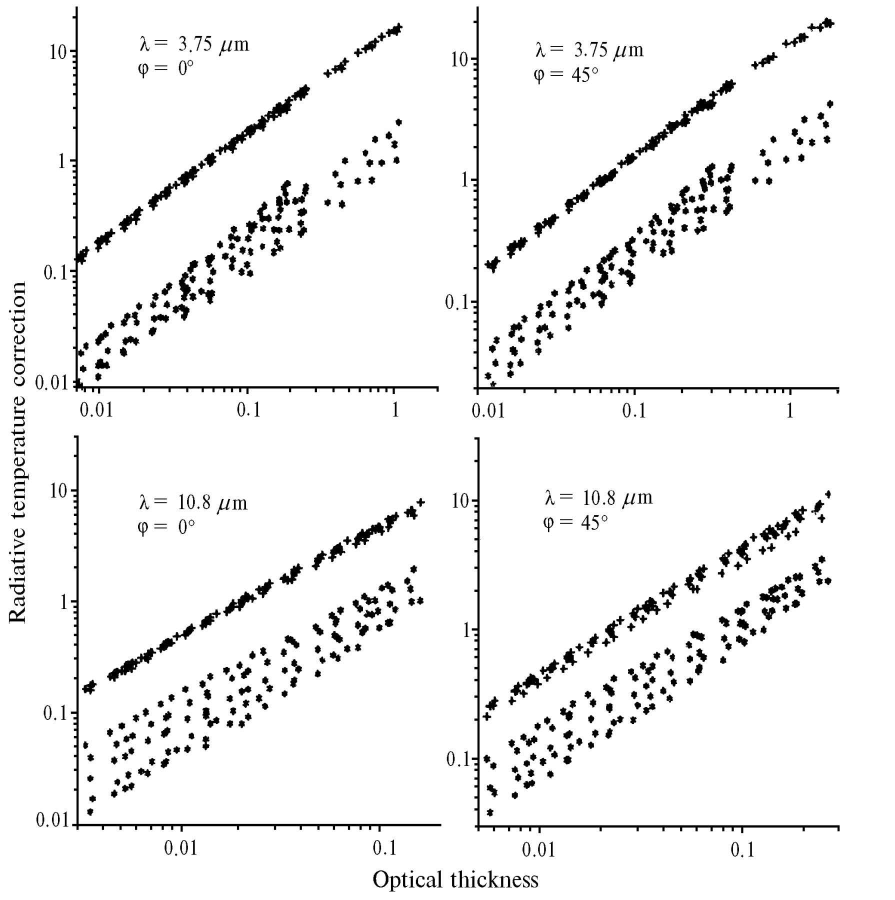

FIG. 4. Temperature corrections $\Delta T_\lambda^{\mathrm{MS}}$ (+) *and* $\Delta T_\lambda^{\mathrm{MS}}$(atm) (∗) *as functions of optical thickness of aerosol* τ_{sct} (*due to scattering*).

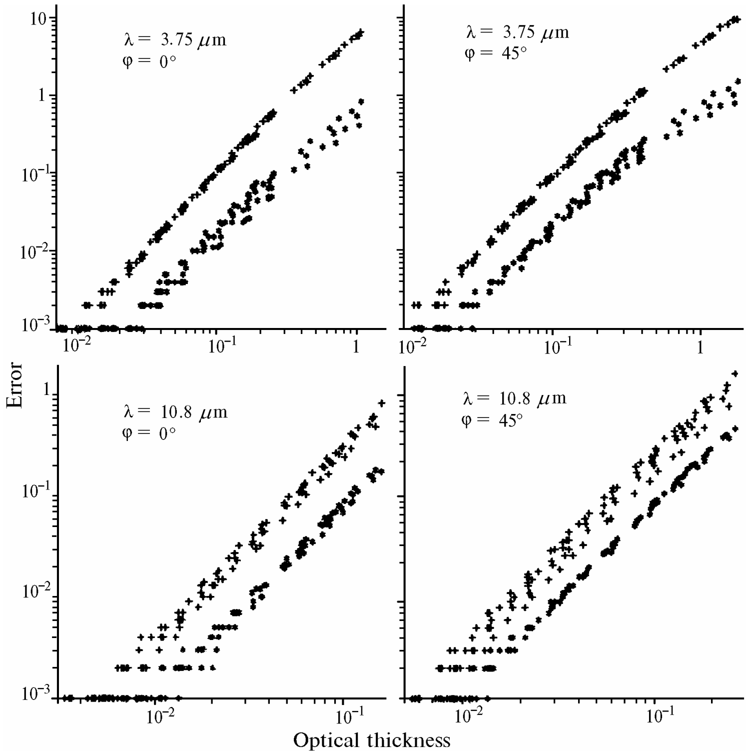

FIG. 5. Error of radiative temperature calculation using single scattering approximation: d T_{SS} (+) *and* d T_{SS}(atm) (∗).

Figures 5 and 6 and Table II present the data on radiative temperature calculation error, when using approximate models of single and conservative scattering in comparison with the multiple scattering model. Table III lists the minimum values of the visibility range, at which use of single scattering model provides the calculational accuracy in radiative temperature not worse than 0.5–1°.

Table IV contains the data on seasonal variations of temperature corrections depending on the observational conditions as well as the minimum values of S_M, for which the range of these variations is less than 1–2°.

The analysis of data obtained yields the following conclusions:

1. The account for distorting effect of aerosol is advantageous only at low values of S_M. Thus, for the accuracy of radiative temperature calculation to be $\delta T_\lambda = 0.5°$ the range of these values must be $S_M < 5$–10 km and for $\delta T_\lambda = 1.0°$ $S_M < 2$–5 km (see Fig. 3 and Table III).

2. The contribution from surface into the intensity of upward going flux of scattered radiation dominates regardless of the conditions of observation. The contribution from the atmosphere reaches 0.5–1.0° only at visibility range $S_M < 2$–5 km (see Fig. 4).

3. The temperature corrections increase smoothly when optical thickness of aerosol (due to scattering) increases for all optical and geometric conditions under consideration (see Fig. 4).

4. When simulating the process of thermal radiation transfer, the account for multiple photon collisions with aerosol particles is necessary only at $S_M < 3$–5 km (see Fig. 5 and Table III). In so doing the error of calculation of atmospheric contribution ΔT_λ(atm) does not exceed 0.5°. The only exception is the case of maritime aerosol ($\lambda = 3.75$ μm), when the single scattering approximation is sufficient only at $S_M > 8$–16 km as well as, when calculating the atmospheric contribution, at $S_M > 2$–7 km.

5. Despite a wide variability of meteorological parameters of the atmosphere and underlying surface temperature (see Figs. 1 and 2 and Table I) the seasonal variations of ΔT_λ^{MS} do not exceed 2.0° at $\lambda = 3.75$ μm and 3.2° at $\lambda = 10.8$ μm (see Table IV). In such a way, at the visibility range $S_M > 4$ km the error, when approximating T_λ^{MS} as the season–averaged value, does not exceed ±1.0° as well as at $S_M > 7$ km the error is not greater than ±0.5°.

6. When using the approximate models to account for distorting effect of aerosol, in most cases the model of conservative scattering provides the smallest error of calculation (see Table II and Fig. 6). The use of this model is only inefficient for the case of maritime aerosol at $S_M \cong 2$–10 km in the 3.5–4 μm range, because the error of T_λ calculation on the basis of conservative scattering model in this case may exceed the contribution from aerosol. In this case the model of multiple scattering should be necessary used.

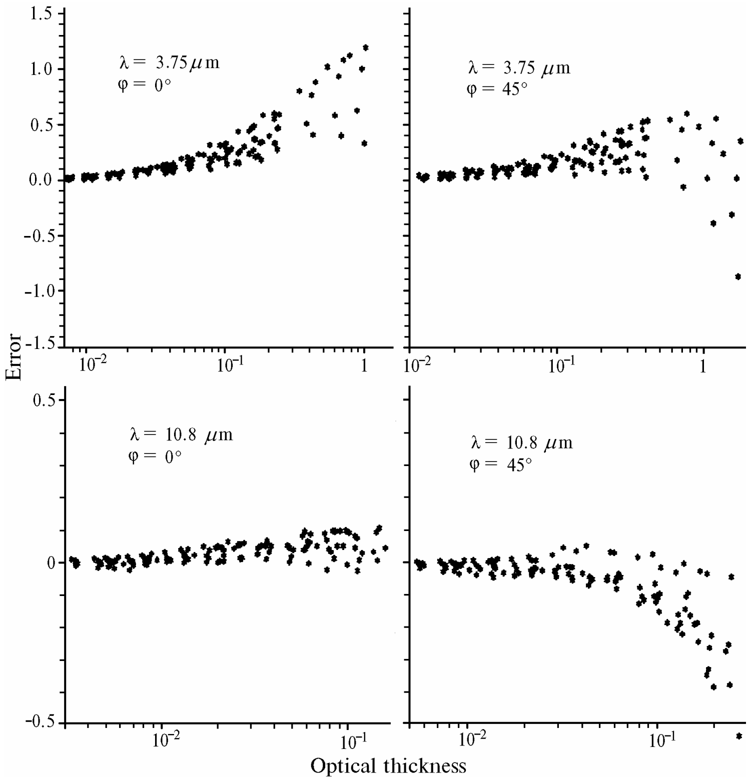

FIG. 6. Error of radiative temperature calculation using model of conservative scattering (dT_{CS}).

Summarizing the above said, let us formulate the main conclusions of this study.

1. When modeling the process of thermal radiation transfer the effects of multiple scattering can be neglected at the optical thickness being less than 0.24–0.40.

2. In practice the contribution from aerosol scattering into the upward going flux can be calculated quite accurate using a simple approximation (e.g., with a power or polynomial series) of the dependence of temperature corrections on optical thickness of aerosol.

3. If the surface can be considered to be spatially homogeneous and Lambertian, for the most optical and geometric situations the free radiance of A–US system can be calculated with a reasonable accuracy using an approximate model of conservative scattering.

TABLE II. Error of radiative temperature calculation using models of single and conservative scattering

Aerosol type	S_M	φ = 0°				φ = 45°			
		mol – MS	MS – CS	MS – SS total	MS – SS atmosphere	mol – MS	MS – CS	MS – SS total	MS – SS atmosphere
λ = 3.75 μm									
Maritime	2	1.474	1.189	6.584	0.829	3.229	0.869	9.644	1.557
	5	0.625	0.879	1.762	0.256	1.505	0.597	3.102	0.629
	10	0.378	0.587	0.601	0.099	0.852	0.533	1.154	0.274
	23	0.174	0.328	0.114	0.023	0.391	0.336	0.233	0.066
Rural	2	0.361	0.598	0.569	0.090	0.863	0.523	1.127	0.254
	5	0.175	0.308	0.119	0.022	0.373	0.353	0.264	0.067
	10	0.107	0.206	0.036	0.007	0.259	0.207	0.084	0.022
	23	0.072	0.095	0.007	0.001	0.124	0.127	0.014	0.004
Urban	2	0.883	0.363	0.319	0.075	1.460	0.353	0.599	0.192
	5	0.410	0.227	0.073	0.017	0.771	0.195	0.143	0.044
	10	0.257	0.141	0.021	0.005	0.487	0.125	0.046	0.013
	23	0.144	0.076	0.004	0.001	0.236	0.089	0.009	0.003
λ = 10.8 μm									
Maritime	2	0.843	0.102	0.810	0.179	1.847	0.537	1.631	0.469
	5	0.409	0.085	0.170	0.037	0.885	0.188	0.376	0.106
	10	0.235	0.058	0.052	0.012	0.537	0.084	0.120	0.034
	23	0.143	0.040	0.009	0.003	0.284	0.041	0.018	0.006
Rural	2	0.769	0.078	0.467	0.119	1.572	0.390	0.947	0.294
	5	0.374	0.051	0.097	0.024	0.746	0.129	0.217	0.062
	10	0.206	0.031	0.005	0.002	0.462	0.072	0.068	0.020
	23	0.153	0.013	0.006	0.002	0.268	0.042	0.011	0.004
Urban	2	0.795	0.094	0.262	0.069	1.480	0.165	0.535	0.187
	5	0.412	0.065	0.054	0.013	0.747	0.062	0.122	0.038
	10	0.249	0.048	0.017	0.005	0.471	0.044	0.037	0.012
	23	0.161	0.021	0.003	0.001	0.277	0.036	0.007	0.002

Note: In the table we use the following abbreviations: case of molecular atmosphere (mol), multiple scattering (MS), single scattering (SS), and conservative scattering (CS) models.

TABLE III. Minimum values of S_M for two different values of accuracy of radiative temperature calculations (model of single scattering).

Aerosol type	Accuracy K	φ = 0°		φ = 45°	
		Total	Atmosphere	Total	Atmosphere
λ = 3.75 μm					
Maritime	1.0	7.5 – 5.5	< 2	11.1 – 8.7	3.3 – 2.1
	0.5	11.5 – 8.6	3.1 – 2.1	16.4 – 13.0	6.5 – 3.0
Rural	1.0	< 2	< 2	2.2 – 2.1	< 2
	0.5	2.2 – 2.0	< 2	3.5 – 3.2	< 2
Urban	1.0	< 2	< 2	< 2	< 2
	0.5	< 2	< 2	2.3 – 2.0	< 2
λ = 10.8 μm					
Maritime	1.0	< 2	< 2	2.8 – 2.0	< 2
	0.5	2.7 – 2.0	< 2	4.4 – 2.6	< 2
Rural	1.0	< 2	< 2	< 2	< 2
	0.5	< 2	< 2	3.1 – 2.0	< 2
Urban	1.0	< 2	< 2	< 2	< 2
	0.5	< 2	< 2	2.2 – 2.0	< 2

TABLE IV. Minimum values of S_M *for two different ranges of seasonal variations of radiative temperature together with maximum value of seasonal variations of temperature.*

Aerosol type	Range of variations	φ = 0°		φ = 45°	
		Total	Atmosphere	Total	Atmosphere
λ = 3.75 μm					
Maritime	2.0	< 2	< 2	2.7 – 2.0	< 2
	1.0	3.3 – 2.4	2.5 – 2.1	4.4 – 3.3	6.0 – 4.4
	Maximum variations, K	1.238	1.152	2.040	1.951
Rural	2.0	< 2	< 2	< 2	< 2
	1.0	< 2	< 2	< 2	< 2
	Maximum variations, K	0.426	0.287	0.604	0.586
Urban	2.0	< 2	< 2	< 2	< 2
	1.0	< 2	< 2	< 2	< 2
	Maximum variations, K	0.272	0.188	0.283	0.322
λ = 10.8 μm					
Maritime	2.0	< 2	< 2	3.5 – 3.0	< 2
	1.0	2.8 – 2.4	2.3 – 2.0	6.9 – 6.0	3.2 – 2.7
	Maximum variations, K	1.335	1.031	3.195	1.299
Rural	2.0	< 2	< 2	2.3 – 2.1	< 2
	1.0	< 2	< 2	5.0 – 4.6	2.2 – 2.0
	Maximum variations, K	0.849	0.777	2.124	1.008
Urban	2.0	< 2	< 2	< 2	< 2
	1.0	< 2	< 2	3.7 – 3.3	< 2
	Maximum variations, K	0.648	0.551	1.615	0.623

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