Estimate of Horizontal Cloud Inhomogeneity Effect on Solar Radiative Fluxes for Conditions of Winter Zvenigorod Experiment

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Introduction

Study of physical phenomena determining large-scale dynamical and energetic processes in the atmosphere requires quite full account of mechanism of cloud-radiation interaction, the main regulator of radiative energy exchange. This necessitates the creation of new simple shortwave and longwave flux calculation techniques that describe the radiative transfer in the real atmosphere as accurately as possible, and yet are quite efficient. These calculation techniques can be tested either by integrated radiation experiments or against benchmark calculations made as part of these international projects such as during Intercomparison of Radiation Codes used in Climate Models (Fouquart et al. 1991) and current Intercomparison of three-dimensional (3D) Radiation Codes (Cahalan 2000).

In the present work, the broadband fluxes of solar radiation are calculated using two different approaches. The purpose is

- to compare the results obtained by these methods; and

- to estimate the horizontal cloud inhomogeneity effect, caused by stochastic geometry of real cloud fields, on upward and downward fluxes of solar radiation using winter Zvenigorod Cloud-Aerosol-Radiation Experiment (ZCAREX-99) data.

Calculation Techniques

Method A. The method, developed for horizontally homogeneous cloudy atmosphere (Gorchakova 2000), includes multiple reflections from clouds and earth's surface, Rayleigh scattering, scattering and absorption by cloud and aerosol particles as well as absorption by atmospheric gases H_2O, CO_2, O_2, and O_3. The entire solar spectrum (0.2µm to 4.0 µm) is divided into eight intervals, within each of which the optical characteristics of cloud-aerosol atmosphere are assumed to be constant. Absorption by atmospheric gases (H_2O, CO_2, and O_2) was calculated using integral transmission function (ITF)

(Podol'skaya and Neelova 1997). The "mean photon path" method was utilized to compute the gaseous absorption in the scattering aerosol atmosphere with clouds (Tarasova 1997). Absorption of O_3 was calculated by the method of Liou (1992) according to parameterization suggested by Lacis and Hansen (1974).

Method B. The effects of stochastic cloud geometry on solar radiative transfer in the atmosphere are treated using Poisson model of broken clouds as proposed by Titov (1990). In addition to traditional optical and geometrical cloud parameters, also used as input parameter is the aspect ratio $\gamma = H/D$, where H is geometrical thickness, D is the characteristic horizontal size of cloud elements (the values $\gamma << 1$ correspond to calculations in horizontally homogeneous cloud model). The mean broadband fluxes are calculated by Monte Carlo method, developed to solve the system of closed equations for mean intensity in statistically homogeneous broken clouds by Titov and Zhuravleva (1997). The absorption of solar radiation by water vapor and carbon dioxide is accounted for by means of transmission function as given in Golubitskii and Moskalenko (1968) with the spectral resolution $\Delta\nu \approx 10\text{-}20\ cm^{-1}$.

Since most solar radiation is absorbed by ozone in the atmosphere for $z > H^* = 14$ km, at this stage of problem solution we will use the following simplified scheme: (i) in calculation of downward radiative fluxes at levels $z > H^*$ the ozone absorption is treated with Lacis (1974) parameterization; (ii) in layer $z < H^*$ the ozone absorption is neglected; and (iii) the upward fluxes are calculated only at levels $z < H^*$.

Each of these approaches has a number of advantages. For instance, Method À is less expensive and can be used efficiently to calculate radiative fluxes in cases where atmospheric situation is close to horizontal homogeneity. Method B can be used to estimate the effects, caused by real horizontally inhomogeneous clouds, on radiative fluxes, both in entire shortwave range and in the narrower spectral intervals. With the availability of the two different radiation calculation techniques, we can much better interpret field data.

Comparison of Calculation Techniques

Both of the methods outlined above were used to calculate the upward ($F^{\uparrow}$) and downward ($F^{\downarrow}$) fluxes of solar radiation, based on Zvenigorod Cloud-Aerosol-Radiation Experiment (ZCAREX-99) data (Golitsyn et al. 2000). The calculation results presented below are obtained for atmospheric situation observed on February 5, 1999:

- overcast low-level Sc clouds occupied the layer 0.6 km to 1 km
- because water phase of clouds was not determined during the experiment, liquid water clouds were assumed with (liquid water path [LWP]) LWP = 35.3 gm^{-2} and effective cloud droplet size r_{eff} = 10 μm
- the vertical profiles of pressure, temperature, and water vapor are obtained using data of meteorological, aerological, lidar, and satellite measurements

- solar zenith angle $\xi_{\oplus} = 76.95°$
- we used as aerosol model the continental aerosol model as recommended in WCP-112 (WCP-112, 1986)
- it was assumed that the surface albedo $A_s = 0.4$.

Table 1 summarizes results of calculations of upward and downward fluxes of solar radiation at different atmospheric levels; as seen, agreement is quite good. The small, about 3 to 4 Wm^{-2}, differences may be, e.g., due to use of different methods of accounting for the spectral features of optical characteristics of clouds and atmospheric gases, as well as because Method A and Method B employ different methods of solution of transfer equation.

Table 1. Upward and downward fluxes (Wm^{-2}), calculated by Method A and Method Â for overcast and clear-sky conditions (February 5, 1999).

	Clear Sky				Clouds			
	$F^{\uparrow}$		$F^{\downarrow}$		$F^{\uparrow}$		$F^{\downarrow}$	
z, km	**Method A**	**Method B**	**Method A**	**Method B**	**Method A**	**Method B**	**Method A**	**Method B**
100	308.23	308.23	115.95	-	308.23	308.23	157.69	-
20	290.43	289.24	116.46	-	290.45	289.24	158.57	-
13.8	283.05	281.72	116.51	118.88	283.11	281.1	158.82	162.37
8.8	263.68	264.12	103.56	105.16	264.31	264.57	146.42	150.38
2.8	231.57	229.38	90.72	91.88	233.13	231.62	133.14	137.23
2	224.27	222.73	88.41	89.46	226.24	223.54	131.29	135.10
1	198.08	196.36	78.40	79.60	200.90	198.16	123.41	126.73
0.6	188.34	186.38	74.72	75.10	99.63	98.05	39.01	39.55
0	175.66	174.90	70.26	69.96	96.42	94.89	38.57	37.96

Horizontal Inhomogeneity Effect

As is well known, the radiative characteristics of the cloudy atmosphere, calculated without (F_{PP} and with (F_{3D}) account of horizontal inhomogeneity of real clouds, may substantially differ. Based on numerical experiments, Titov and Zuev (1995) showed that, when surface albedo $A_s = 0$ the radiative fluxes in the clouds are determined primarily by solar zenith angle. For instance, at $\xi_{\oplus} \approx 0$ the upward fluxes under horizontally homogeneous cloud conditions are related to those for random cloud fields by the inequality $F_{PP}^{\uparrow} > F_{3D}^{\uparrow}$; whereas for $\xi_{\oplus} \geq 30°$ the sign of the inequality changes for the opposite one, $F_{PP}^{\uparrow} < F_{3D}^{\uparrow}$.

Switching to $A_s > 0$ case (winter conditions, snow cover), the boundary conditions of the problem change, since surface-reflected radiation can be considered as a diffuse source illuminating the bottom of the atmosphere. The radiative transfer equation is additive with respect to source function; therefore, the vertical profiles of fluxes F in this case are sums of two functions where

- the first summand is proportional to F, calculated assuming that top of the atmosphere is illuminated by unidirectional source of radiation and $A_s = 0$

- the second summand is dominated by diffuse source located at height z = 0. Obviously, the power and angular structure of this source depend on magnitude and angular structure of downward radiation at level z = 0 and law of surface reflection. We note that the radiative fluxes produced by this diffuse source are proportional (by mean-value theorem) to fluxes calculated for a certain solar zenith angle $\xi_{\oplus}$ and $A_s = 0$.

By virtue of aforesaid, the profiles of fluxes for $A_s > 0$ and those at $A_s = 0$ may substantially differ; and the horizontal cloud inhomogeneity effect on mean radiative fluxes will be smoothed out, to some degree, by surface reflections. Quantitatively, the magnitude of this factor will be determined by input model parameters: solar zenith angle, aspect ratio, cloud fraction, and surface albedo.

Let us estimate the influence of effects, caused by the random cloud geometry, on $F^{\uparrow(\downarrow)}$ using data on atmospheric parameters observed during ZCAREX on February 5, 1999. Since overcast clouds were observed on that day, we will consider the changes that could take place under conditions of partial cloudiness provided the vertical and horizontal cloud sizes are comparable. The calculations presented below were made for two aspect ratios ($\gamma = 0.5$ and $\gamma = 2$) and cloud fractions in the range $0.3 \le N \le 0.8$ using Method B.

Figure 1 presents the mean upward and downward fluxes as functions of cloud fraction and aspect ratio γ. The maximum differences between F_{pp} and F_{3D} occur for intermediate cloud fractions $N \approx 0.5$ to 0.6 and increase with growing γ, from ≈10 to12 Wm^{-2} at $\gamma = 0.5$ to ≈ 17 to 20 Wm^{-2} at $\gamma = 2$.

Figure 2 shows the vertical profiles $F^{\uparrow}_{PP}(z)$ and $F^{\uparrow}_{3D}(z)$ ($0 \le z \le H^* = 14$ km) for $N = 0.5$ and $0 \le \gamma \le 2$. Since above-cloud atmosphere has relatively small optical depth, the flux difference, caused by the random cloud field geometry, varies little with height from cloud top up to $H^* = 14$ km.

Conclusion

Comparison of broadband fluxes of solar radiation, calculated by different methods using ZCAREX99 data, has shown that they agree quite well. The flux discrepancy is within variations due to use of different methods of accounting for spectral features of atmospheric gases, and to use of different optical cloud characteristics such as scattering phase functions.

Calculations of broadband fluxes of solar radiation, made using winter ZCAREX99 data, have shown that the horizontal cloud inhomogeneity effect is quite weak. The effects caused by the random cloud field geometry decrease for high albedo of underlying surface with snow cover ($A_3 = 0.4$).

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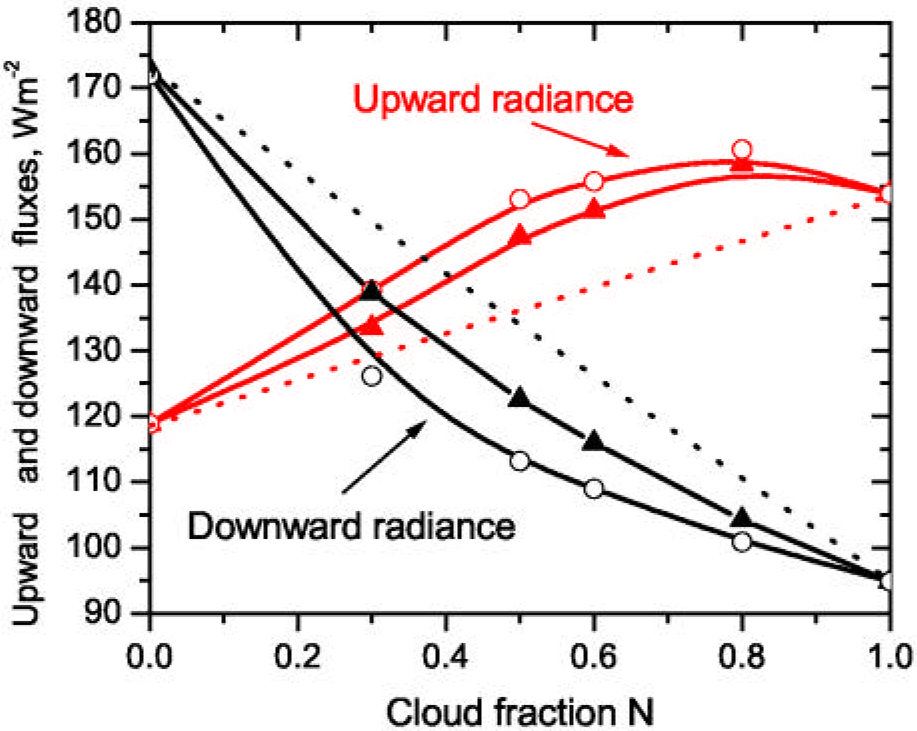

Figure 1. Mean upward (z = 13.8 km) and downward (z = 0) fluxes for different cloud fractions and aspect ratios. Calculations are made for horizontally-homogeneous cloud conditions (dotted lines) and using Poisson cloud model (solid lines) for aspect ratio $\gamma = 0.5$ (solid triangles) and $\gamma = 2.0$ (open circles). Surface albedo $A_s = 0.4$; solar zenith angle $\xi_\oplus = 76.95°$.

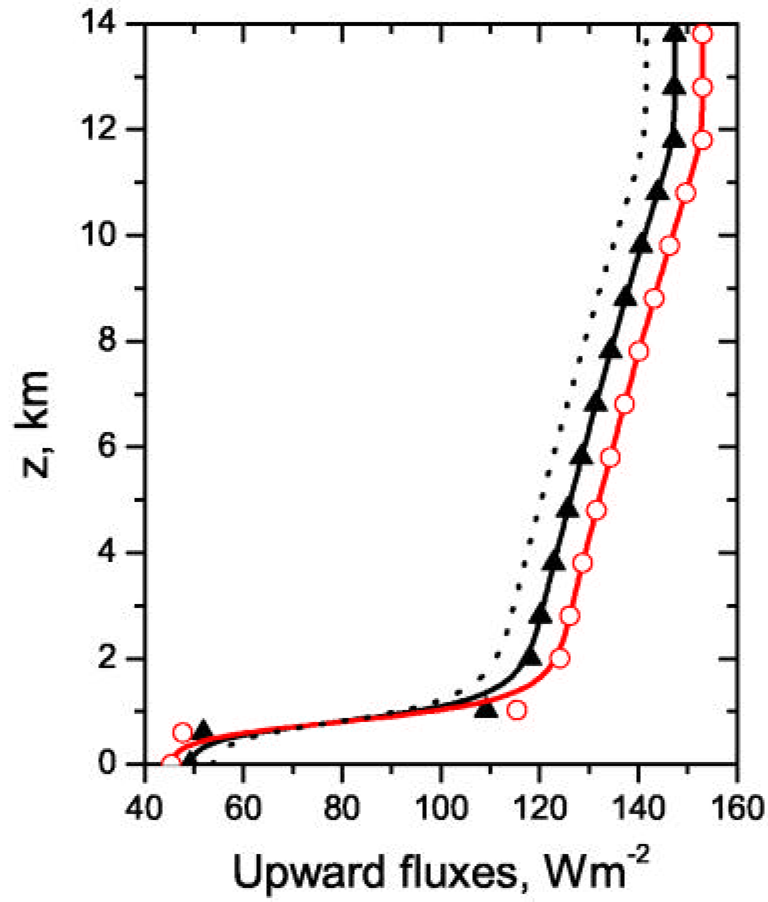

Figure 2. Vertical profiles of upward fluxes calculated with (solid lines) and without (dotted lines) account of random cloud geometry for cloud fraction $N = 0.5$; aspect ratio $\gamma = 0.5$ (solid triangles) and $\gamma = 2.0$ (open circles); surface albedo $A_s = 0.4$; solar zenith angle $\xi_{\oplus} = 76.95°$.