3D Monte-Carlo models and radiative transfer online tools

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1. Introduction

This paper describes two Monte-Carlo radiative transfer models and the results that were obtained for the cases selected for Intercomparison of 3D Radiation Codes. Main construction principles of the horizontally inhomogeneous three-dimensional cloud models developed in RRC "Kurchatov Institute" are discussed. The description of the network software applications for operative online calculations of solar radiative characteristics based upon these models is also presented.

2. Models description

The optical model of the atmosphere for given cases represents a field of horizontally inhomogeneous clouds on a certain altitude. In fact, the cloud field is defined by two-dimensional array $z(x_i,y_j)$ which gives the cloud top altitude. In "Step cloud" and "MMCR cloud" cases $z \equiv$ constant. Spatial distribution of cloud optical thickness is considered as three-dimensional array of extinction coefficient values $\sigma(x,y,z)$. Corresponding values of optical thickness for each cloud pixel are defined as $\tau(x_i, y_j) = \int \sigma(x_i, y_j, z) dz$.

In both models photon trajectories are simulated in concordance with the classical scheme [1]. It consists of algorithms of initial coordinates and direction of photon trajectory selection as well as in simulation of its trajectory as the result of series successive collisions with cloudy drops and underline surface. We use "maximal cross section" method [1] to simulate the photon's motion in stochastic cloudiness.

First model is based on the simple direct simulation of photon trajectories. Each photon trajectory starts on the top of the atmosphere and initial photon weight is equated to the cosine of solar zenith angle. Other horizontal coordinates of start point have uniform distribution on the upper boundary of cloudiness. Fluxes are calculated for each pixel when photon crosses its upper (reflection R), lower (transmittance T) boundaries or is absorbed within this pixel (absorption A). In the estimates of reflectivity (I_u) & transmissivity (I_d) the photon contribution is taken into account only if its trajectory lies within radiation "pencil" when it crosses corresponding pixel boundary. Its full angular width equals 20 degrees for all cases.

Second model is based on conjugated transfer equation using the principle of optical beam reciprocity. A photon trajectory is simulated in opposite direction, i.e. from "receiver" (the place where radiative quantities are estimated) to "source" (along the direction of the Sun rays). Such approach is reasonable if "receiver" is localized and "source" is distributed in space. That is why this method is used for estimations of spatial distributions of radiative quantities.

Radiative characteristic F is calculated in common case as

$$F = \left\langle \sum_{n=0}^{N} Q_n g(\mu) w_0 \exp(-\tau_n) \right\rangle,$$

where n=0..N – the number of a photon collision order with cloudy drops or underline surface for a given trajectory, Q_n - weighting factor accounting for a photon energetic value; $g(\mu)$ - phase function of cloudy scattering or surface reflection; m - cosine of scattering (reflection) angle; w_0 – single scattering albedo or surface albedo; t_n - optical thickness between the point of scattering (reflection) and the top of the atmosphere along direction of the Sun rays. The result is calculated as arithmetic mean among all photon trajectories.

3. Accuracy and computational performance discussion

Table 1 represents the results obtained by the direct simulations as well as reflectivity computations made by conjugated simulations proposed for the first part of 3D radiation codes intercomparison.

The main advantage of the direct model lies in possibility to estimate all required radiative transfer characteristics for one set of photon trajectories. It is pleasure to state satisfactory accuracy of statistical estimates for all radiative quantities. The standard deviation of mean values averaged over the considered area did not exceed the tenth of percent for all estimated quantities. Absolute values of net horizontal flux error were less than 0.005. Maximum errors were observed in reflectivity and transmissivity estimates for single pixels. The errors reached 20-25% when 80 millions trajectories were simulated for the most difficult Landsat case. The execution of this model required almost 48 hours on Pentium II 300 MHz – based computer.

Table 1. Mean values and standard deviations (s) of calculated radiative characteristics

Model type		Direct												Conjugated	
Case	Exp#	R	s_R	T	s_T	A	s_A	H	s_H	I_d	s_{Id}	I_u	s_{Iu}	I_u	s_{Iu}
1 Step cloud field	1	0.327	0.087	0.673	0.344	N/A	N/A	0.000	0.261	N/A	N/A	0.260	0.165	0.255	0.167
	2	0.580	0.201	0.420	0.075	N/A	N/A	0.000	0.229	0.398	0.164	0.410	0.290	0.406	0.292
	3	0.261	0.069	0.599	0.350	0.141	0.108	0.000	0.178	N/A	N/A	0.204	0.126	0.199	0.127
	4	0.476	0.169	0.325	0.069	0.198	0.175	0.000	0.348	0.314	0.120	0.326	0.230	0.320	0.230
2 MMCR cloud field	1	0.559	0.130	0.441	0.127	N/A	N/A	0.000	0.017	N/A	N/A	0.569	0.171	0.565	0.169
	2	0.698	0.104	0.302	0.092	N/A	N/A	0.000	0.071	0.370	0.115	0.565	0.141	0.563	0.147
	3	0.402	0.054	0.307	0.153	0.291	0.120	0.000	0.050	N/A	N/A	0.394	0.075	0.391	0.074
	4	0.552	0.053	0.200	0.103	0.248	0.090	0.000	0.096	0.251	0.134	0.416	0.076	0.411	0.077
	5	0.757	0.082	0.404	0.096	N/A	N/A	0.000	0.067	0.457	0.114	0.640	0.113	0.639	0.119
	6	0.561	0.130	0.439	0.128	N/A	N/A	0.000	0.014	N/A	N/A	0.639	0.169	0.709	0.171
	7	0.701	0.102	0.298	0.092	N/A	N/A	0.000	0.070	0.361	0.108	0.529	0.136	0.526	0.147
	8	0.760	0.079	0.400	0.097	N/A	N/A	0.000	0.066	0.447	0.109	0.604	0.108	0.600	0.120
3 Landsat cloud field	1	0.304	0.05	0.696	0.427	N/A	N/A	0.000	0.393	N/A	N/A	0.220	0.142	0.216	0.149
	2	0.515	0.118	0.485	0.224	N/A	N/A	0.000	0.225	0.390	0.205	0.337	0.234	0.331	0.246
	3	0.242	0.039	0.628	0.431	0.130	0.124	0.000	0.327	N/A	N/A	0.174	0.109	0.170	0.114
	4	0.424	0.100	0.404	0.222	0.171	0.174	0.000	0.284	0.320	0.181	0.272	0.190	0.266	0.198

The conjugated algorithm is most effectively used for estimates of local radiative transfer characteristics (reflectivity, transmittance) if computations of such characteristics by direct algorithm with zero angular "pencil" are impossible. The difference in the averaging scales causes the difference in the obtained estimates. Note that this difference is more pronounced in the MMCR cloud field case (see Table 1) where C.1 phase function is used. Particularly, the maximal shift between direct and conjugated models in nadir reflectivity estimates is reached for the sixth experiment. Averaging of back scattering peak inherent to C.1 phase function causes underestimation of the main radiative characteristics obtained in this experiment by direct model in comparison with conjugated one.

We should note that the computations for the 3D radiation codes intercomparison required considerable modernization of existing algorithms. Due to obvious reasons the authors tried to minimize necessary changes that is why the problems of calculation efficacy maximizing were out of examination. Satisfactory accuracy of the obtained results (0.1, 0.5% for mean values) and of the calculation time (2-3 days using Intel Pentium Pro 200 MHz and Pentium-II 300 MHz-based workstations) were the basic criteria of the algorithm quality.

Combination of the results obtained by computations of dependent and independent trajectories is applied for calculation of radiance field (Landsat field case) in order to decrease computational time and to keep the satisfactory accuracy. In dependent trajectories computations the sequences of initial parameters for photon trajectories are equal for each pixel. The scheme of dependent trajectories computations is presented on Fig.1.

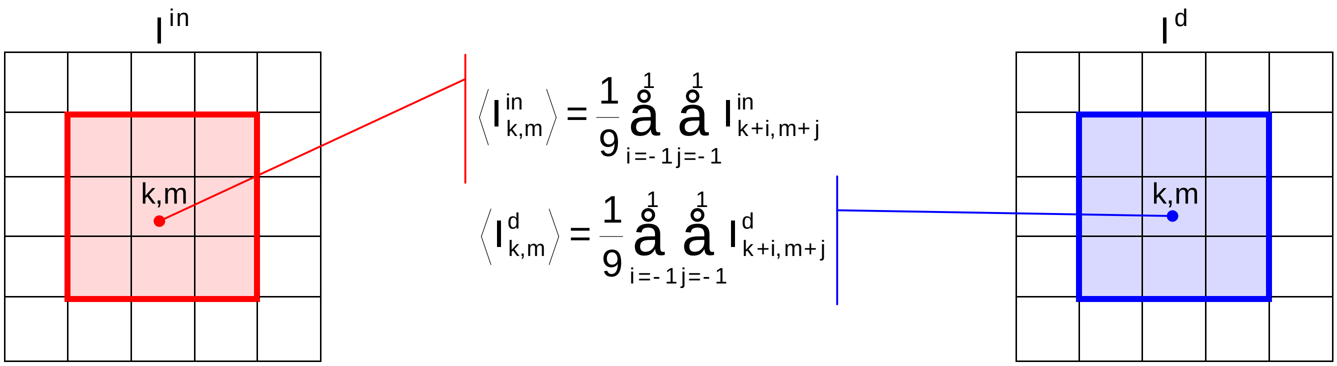

Fig. 1. Array of radiance estimations for Landsat cloud field

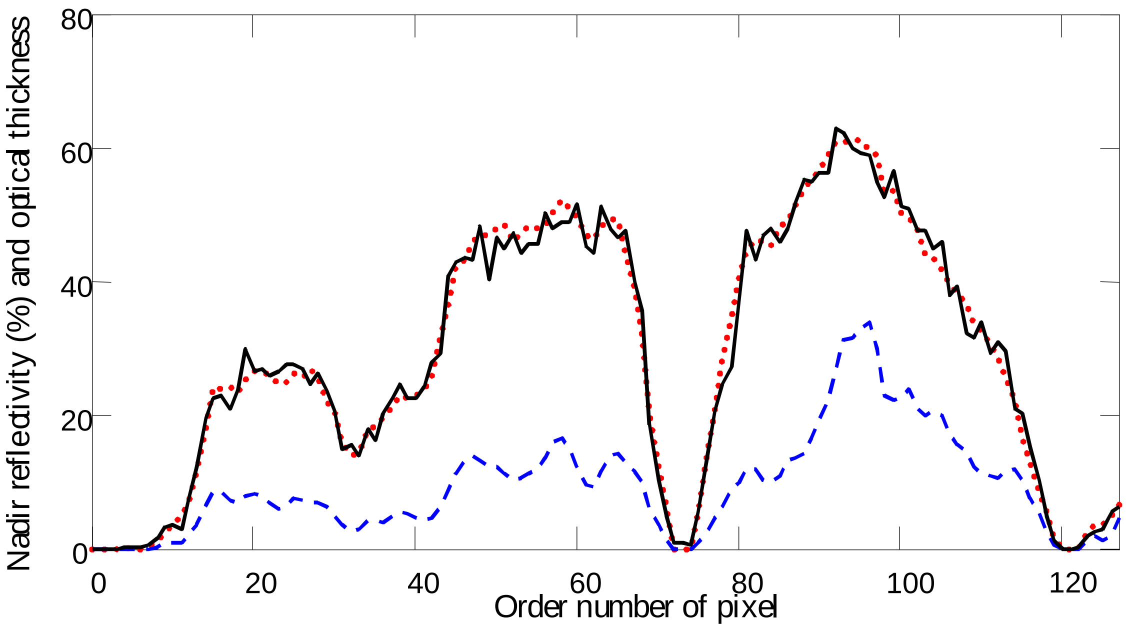

Fig. 2. Profiles of nadir reflectivity (in percents) and optical thickness (case 3#4, 55th line).

75 000 conjugated independent trajectories, errors » 2.5%;

4 000 (2 000+2 000) combined trajectories, errors » 5%;

optical thickness.

Fig.1 shows that mean radiances for both dependent and independent trajectories computations are estimated with accounting for radiance values of neighboring pixels. Radiance in a given pixel $I^c_{k,m}$ is calculated as a sum of radiance obtained by dependent trajectories computations $I^d_{k,m}$ and residual $\Delta_{k,m}$ between mean radiances for dependent and independent trajectories respectively

$I^c_{k,m} = I^d_{k,m} + \Delta_{k,m}$, where $\Delta_{k,m} = \langle I^{in}_{k,m} \rangle - \langle I^d_{k,m} \rangle$.

Satisfactory accuracy of the results remaining in such approach allows to reduce the number of simulated photons. Thus, Fig.2 shows the results of independent trajectories calculation where number of photons equals 75000 per pixel and combination of results obtained by incorporation of dependent and independent trajectories computations where number of photons is equal to 4000 (per 2000 photons respectively) per pixel. While the time of calculation greatly reduced, the error in radiance distribution increased insignificantly, namely it doubled (5% in comparison with 2.5%). Note, that if the mentioned above algorithm doesn't provide accuracy improvement the error of computations would be equal to $2.5\% \times (\sqrt{75000/4000}) \approx 10.8\%$.

4. Network software applications for operative calculations of solar radiative characteristics in different atmosphere conditions

Modern methods for operative estimation of solar radiative fluxes using satellite images are based upon the interpolations of reference radiances and fluxes pre-calculated for the plane-parallel cloud layer model. Drawbacks of the method application to broken-cloud conditions are well known and were reported by many authors. At the same time recent progress in computing facilities enables to extend the above interpolation approach to horizontally inhomogeneous 3D cloud models.

Note that maximum spatial resolution of modern instruments applied in particular for global cloud monitoring (such as AVHRR/NOAA, Imager/GOES, MVIRI/Meteosat, SEVIRI/MSG) comes to 1-3 km depending on viewing angle. The specific linear dimensions of the broken clouds and cloud discontinuities observed from satellites at full cloud coverage are approximately of the same scale. Hence, in order to develop the cloud geometrical structure model eligible in the above context it is required to consider the cloud parameter retrievals averaged over the area that includes about tens of such single clouds. Cloud parameters that can not be directly derived from the satellite measurements should be incorporated into the model by synergetic use of data available from other instruments and/or statistical estimates for the specified geographical region.

In this context the model of broken cloud geometrical structure was developed. It is characterized by normal random field being horizontally isotropic and limited from the bottom at definite atmosphere level. The parameters of field correlation function are determined depending on cloud amount, mean diameter and thickness of clouds. Such models are widely used in estimations of multi-directional clear line of sight and provide a satisfactory agreement between model calculations and direct observations. The particular implementation of the above method is described in [2,3,4].

The detailed radiative transfer description for horizontally inhomogeneous 3D cloud models requires considerable amount of computer time that makes such software practically useless for the needs of getting the fast results. Due to this fact it is necessary to develop the network software applications for online operative calculation of main solar radiative characteristics by user-defined atmosphere parameters.

Interpolations on mesh points of fluxes and radiances pre-calculated using direct 3D Monte-Carlo method are applied for reducing of the computation time. Calculations of the mesh points are made considering all main solar radiation transfer effects for mentioned above horizontally inhomogeneous 3D cloud models developed in RRC "Kurchatov Institute". Mesh points were obtained with high spectral resolution in the 0.2-5 mm spectral band for different cloud amounts, extinction coefficients and solar zenith angles.

To simulate the photon's trajectory in cloudiness, instead of "maximal cross section" method, the so called "step-by-step" method was used, where the photon free path between two collisions in stochastic cloudiness is calculated while photon is moving with small steps along the chosen direction. The accumulation of scattering and absorption thickness along the trajectory is made on each step, i.e. optical thickness accumulated on previous steps is increased on step length multiplied by cloud or aerosol extinction coefficient depending upon photon's location. The step length is approximately 2-3 times smaller then the cloud model grid spacing. The obtained results show that the accuracy of radiative characteristics estimates equals 3-4% and the time of computations halves as compared to "maximal cross section" method. Table 2 represents the results of the mean solar characteristics calculated using "step-by-step" method for Landsat case with broken clouds.

Table 2. Mean values and standard deviations (s) for "step-by-step" method

Case	Exp#	R	s_R	T	s_T	A	s_A	H	s_H	I_u	s_{Iu}	I_d	s_{Id}
3	1	0.298	0.048	0.702	0.420	N/A	N/A	0.000	0.393	N/A	N/A	0.216	0.140
Landsat	2	0.510	0.114	0.490	0.224	N/A	N/A	0.000	0.224	0.389	0.204	0.333	0.231
cloud	3	0.240	0.037	0.635	0.429	0.125	0.116	0.000	0.108	N/A	N/A	0.172	0.109
field	4	0.423	0.097	0.412	0.222	0.165	0.164	0.000	0.278	0.322	0.181	0.271	0.190

One can see that the results are in a good agreement with Table 1. "Step-by-step" method was applied for calculation of mean spectral solar radiative fluxes and radiances in different cloud conditions. Thus the database of mesh values was pre-calculated for 111 wave lengths bands and is used for the fast estimates of radiative characteristics by derived from satellites cloud parameters. The database mesh points were obtained for:

7 cloud amounts from 0 to 1;

6 cloud extinction coefficients from 1 to 80 km^{-1};

5 sun zenith angles cosines from 0.25 to 0.85;

5 values of spectral (for the 111 bands) surface albedo.

Cloud amount in conjunction with solar and satellite angular coordinates and cloudy extinction coefficient are used as input parameters to pre-calculated database of solar radiance angular distributions and solar fluxes vertical profiles. Radiative fluxes are calculated using this database for user-defined spectral band on the base of linear interpolations for cloud amount, extinction coefficient and angles for a given geometry of satellite observation.

Nowadays this software for the fast online calculation of spectral radiative characteristics and vertical profiles of solar fluxes is available via Internet (http://www-litms.imp.kiae.ru, online tools).

References

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