Short Abstract for the I3RC workshop, Tucson, Arizona, November 15–17, 2000

I3RC phase 2 results from the MYSTIC Monte Carlo model

Bernhard Mayer

Deutsches Zentrum für Luft und Raumfahrt (DLR), Oberpfaffenhofen, Germany.

Model description

MYSTIC[1] is a forward photon tracing method, allowing the calculation of fluxes and intensities in three-dimensional atmospheres including a complex lower boundary with inhomogeneous surface albedo and topography [*Mayer*, 1999]. Compared to *Mayer* [1999], the following features have been added to MYSTIC and its driver, libRadtran (http://www.libradtran.org):

(1) **Radiances** are calculated either by cone sampling, as in phase 1, or by summing the escape probabilities at each scattering point (see e.g. *O'Hirok and Gautier* [1999]; *Marshak et al.* [1999]). The latter method generally reduces the statistical noise and removes the systematic uncertainty introduced by the non–zero opening angle of the sampling cone. In I3RC phase 1, larger deviations of MYSTIC from the average occurred only in one instance: case 2, experiment 6. Here, the sharp peak of the C1 phase function in the backward direction caused a systematic underestimation of the nadir reflectivity of about 3% by the cone sampling method. Using the new method, the bias was removed completely. For I3RC phase 2, all radiances were calculated using the escape probability method.

Due to the large dynamic range of the scattering funcion, "hot spots" may occur, that is, locations where the scattering direction accidentally coincides with the forward peak. These "hot spots" can be avoided either by tracing many photons (often more than feasible), or by truncating the phase function. Two model versions were used for I3RC phase 2: DZLR1, where the phase function was used as is, without changes; and DZLR2, where the forward peak was truncated by replacing the scattering function by a linear function $a + b \cdot \mu$ in the range $\mu = 0.99 \ldots 1.0$, conserving the integral $\int_{0.99}^{1} p(\mu) d\mu$. The truncation was only applied to the escape probabilities, while the photon scattering was still calculated using the unchanged phase function. The effect of this truncation method is similar to the averaging by cone sampling but less pronounced, as only a fraction of the photons is affected. The difference between DZLR1 and DZLR2 is clearly visible in remote sensing experiment 1 where a large fraction of the radiance is photons scattered backwards in the cloud top and then scattered in the forward direction towards the receiver. Here, the mean reflectivity calculated by DZLR2 is too low by 1% (case4) and 2% (case5) compared to DZLR1. In most other cases, the mean reflectivities calculated by DZLR1 and DZLR2 agree within the statistical uncertainty of the model.

[1]MYSTIC: Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres.

(2) MYSTIC was extended to allow different **cloud phase functions** for each grid cell, as requested for the remote sensing experiments 11 – 15 and for all heating rate experiments. The following method allows a continuous variation of the phase function, that is, a different effective radius for each grid box: Scattering by clouds, molecules, and aerosols is handled separately in MYSTIC. In a first step, the type of scattering (Rayleigh, aerosol, or cloud) is determined, and in a second step, the scattering direction is sampled randomly from the phase function of the respective scatterer. Cloud scattering directions are calculated by random sampling from the inverse cumulative probability distribution $\mu(P)$ which is tabulated every 0.5μm effective radius (using the original input provided for I3RC phase 2). For interstitial radii, the scattering angle μ is linearely interpolated between the two adjacent values of the effective radius. Thus it is possible to use different phase functions for each grid cell and at the same time keeping the memory requirements and computational time reasonable. The most demanding experiments, integrated shortwave heating rates, still run easily on a PC with 256 MBytes of RAM.

(3) To calculate integrated **shortwave fluxes and heating rates**, the correlated–k parameterizations of *Kato et al.* [1999] and *Fu and Liou* [1992] were introduced into libRadtran. The I3RC phase 2 calculations were done using the 32 bands of *Kato et al.* [1999]. Considering all weighting points and treating overlapping bands with multi–dimensional correlated–k, a total of 575 monochromatic calculations is required to get integrated shortwave quantities. The photons are distributed over these 575 subbands in a way to minimize the uncertainty of the integrated transmittance. With this method, the computation time for shortwave quantities is comparable to that of monochromatic calculations with the same uncertainty.

For the broadband calculations, the spectral dependences of extinction coefficient, single scattering albedo, and phase function for aerosols and clouds were calculated using a slightly modified version of Frank Evans' cloudprp (with an increased number of terms in the Legendre expansion and, for the aerosol scattering function, an increased upper limit for the radius in the size distribution).

(4) **Non–Lambertian surface albedo** can be considered according to the BRDF parameterization by *Rahman et al.* [1993] (RPV). The implementation requires a small lookup table of the albedo as a funtion of incidence angle. Albedos larger than 1 produced by the RPV formula for low incidence angles where cut at 1.

(5) A preliminary implementation of **thermal emission** has been realized. Forward tracing of statistically emitted

Table 1. MYSTIC calculations for I3RC2, phase 2, case 4.

Exp.	# of ph.	Speed [ph./s]	Time [hrs]	DZLR1 Δ x / x [%] [a]	DZLR2 Δ x / x [%] [a,b]
HR 1	200,000,000	4,824	11.5	0.003	–
HR 2	200,000,000	3,385	16.4	0.003	–
HR 5	250,000,000	3,405	20.4	0.006	–
HR 6	250,000,000	2,606	26.6	0.006	–
RS 1	100,000,000	2,604	10.7	0.161	0.039
RS 2	100,000,000	2,096	13.3	0.194	0.042
RS 3	100,000,000	2,680	10.4	0.044	0.032
RS 4	100,000,000	1,923	14.4	0.042	0.039
RS 6	25,000,000	624	11.1	0.279	0.040
RS 7	25,000,000	488	14.2	0.315	0.099
RS 8	25,000,000	640	10.8	0.073	0.038
RS 9	100,000,000	512	54.2	0.048	0.042
RS 11	25,000,000	164	42.4	0.133	0.135
RS 12	25,000,000	124	56.1	0.200	0.132
RS 13	25,000,000	168	41.5	0.060	0.072
RS 14	25,000,000	128	54.4	0.128	0.100

[a] x = *downward flux* for heating rate experiments (HR), x = *nadir reflectivity* for remote sensing experiments (RS); Δx is the standard deviation of the average.
[b] For experiments 1,2,3,4, and 9, a factor of two less photons were traced with DZLR2 but the uncertainties were corrected by multiplying them with $1/\sqrt(2)$.

photons, however, can be a very time–consuming process because the emission is largest at high optical thicknesses where also the absorption is large. A reasonable implementation would probably require backward tracing.

I3RC phase 2 model runs

Table 1 gives an overview over the MYSTIC results submitted so far. All experiments except the thermal emission and the independent pixel approximation were processed for both cloud cases. A total of 4 billion photons was traced in 1300 hours computational time. From the table it is obvious that the computational speed is lower for intensities than for fluxes, due to the time-consuming calculation of the escape probabilities. For the same reason, the computation time increases nearly linearely with the number of radiance directions: compare experiments RS 1–4 (1 direction), RS 6–9 (4 directions), and RS 11–14 (13 directions). As noted above, the computation time required for integrated shortwave flux is comparable to that of a monochromatic calculation: compare the monochromatic experiments HR 1 and 2 with the broadband calculations HR 5 and 6. Only the high accuracy results were submitted. For a variety of examples, the uncertainty always decreased with the inverse square root of the number of photons traced, and hence approximately with the inverse square root of the computational time.

The calculations were done on a Pentium III, 600 MHz, 256 MByte Linux Box, similar to the I3RC machine. All computation times submitted were determined on this machine and they are generally within 20% compared to the computation times on the I3RC machine.

Conclusions

I3RC triggered a lot of model development and improvement for libRadtran/MYSTIC and was a very valuable exercise therefore. While MYSTIC is probably not the fastest model, together with its driver libRadtran it may be one of the most general and easy-to-use codes. All calculations were done with the same code, operated with a short, human-readable, input file.

Acknowledgments. I would like to thank the I3RC team, in particular Lazaros Oreopoulos and Frank Evans who created the model experiments and did a great job in defining this huge set of input conditions in an non-ambiguous and complete way. My attendance of the Tucson workshop was made possible by travel support by the I3RC project.

References

Fu, Q., and K. Liou, On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres, *Journal of the Atmospheric Sciences*, *49*, 2139–2156, 1992.

Kato, S., T. Ackerman, J. Mather, and E. Clothiaux, The k-distribution method and correlated-k approximation for a shortwave radiative transfer model, *J. Quant. Spectrosc. Radiat. Transfer*, *62*, 109–121, 1999.

Marshak, S., A. Davis, L. Oreopoulos, and T. Varnai, Error estimation in the Monte Carlo method for calculating solar radiances; Illustration with cloud models based on Landsat measurements, in *I3RC workshop, Tucson, Arizona, November 17-19, 1999*, 1999.

Mayer, B., I3RC phase 1 results from the MYSTIC Monte Carlo model, in *I3RC workshop, Tucson, Arizona, November 17-19, 1999*, 1999.

O'Hirok, W., and C. Gautier, Santa Barbara Three-Dimensional (SB3D) Radiative Transfer Model, in *I3RC workshop, Tucson, Arizona, November 17-19, 1999*, 1999.

Rahman, H., M. Verstraete, and B. Pinty, Coupled surface-atmosphere reflectance (CSAR) model. 2. Semiempirical surface model usable with NOAA advanced very high resolution radiometer data, *Journal of Geophysical Research*, *98*, 20,791–20,801, 1993.

Bernhard Mayer, Deutsches Zentrum für Luft- and Raumfahrt (DLR), Oberpfaffenhofen, 82234 Wessling, Germany (e-mail: bernhard.mayer@dlr.de)

This preprint was prepared with AGU's LaTeX macros v4, with the extension package 'AGU++' by P. W. Daly, version 1.6b from 1999/08/19.