Lecture 22.

Methods for solving the radiative transfer equation with multiple scattering. Part 4: Monte Carlo method. Radiative transfer methods for inhomogeneous clouds.

Objectives:

1. Monte Carlo method.

2. Examples of radiative transfer methods for inhomogeneous clouds: 1D with a cloud fraction, independent column approximation (ICA), and SHDOM.

Required reading:

L02: 6.7

Additional/Advanced reading:

I3RC community Monte Carlo model: http://code.google.com/p/i3rc-monte-carlo-model/

The International Intercomparison of 3D Radiation Codes (I3RC): http://i3rc.gsfc.nasa.gov/

Cahalan, R. F., et al., 2005: The International Intercomparison of 3D Radiation Codes (I3RC): Bringing together the most advanced radiative transfer tools for cloudy atmospheres. Bull. Amer. Meteor. Soc. **86** (9), 1275-1293.

Marshak A. and A.Davis (Eds.), 3D Radiative Transfer in Cloudy Atmospheres Springer-Verlag Berlin, 2004.

Davis, A. B., and A. Marshak, 2009: Solar Radiation Transport in the Cloudy Atmosphere: A 3D Perspective on Observations and Climate Impacts. Reports on Progress in Phys.. (Submitted) http://128.183.102.137/publications/fulltext/DavisMarshak_final_RPP.pdf

1. Monte Carlo method.

- ✓ The absorption and scattering processes in the atmosphere can be considered as stochastic processes.

Recall that energy of one photon is hc/λ , where h = 6.626×10^{-34} J s

Solar flux at the top of the atmosphere at 550 nm = 2.55×10^{15} photons cm^{-2} s^{-1}

Thus, the radiative field can be predicted by statistical analysis of traveling photons.

The scattering phase function can be interpreted as a probability function for the redistribution of photons in different directions.

The single scattering albedo ω_0 can be interpreted as the probability that a photon will be scattered, given an extinction event.

NOTE: 1- ω_0 is called **co-albedo** and can be considered as the probability of absorption per extinction event.

The concept of the Monte Carlo method is to simulate photon propagation in an optically effective medium as a random process.

<u>Generation of random numbers</u>:

Using a random number generator (a numerical algorithm), the random numbers, ***rn***, between 0 and 1 with a probability distribution function ***PDF*** can be generated.

Using this ***rn***, we can generate another set of random numbers as

$$rx = -\ln(rn)$$

with ***PDF = exp(-rx)*** and ***rx*** between 0 and infinity.

Let's consider a homogeneous medium characterized by the extinction coefficient β_{ext}, single scattering albedo ω_0 and phase function $P(\mu, \mu')$.

<u>Monte Carlo method simulates the trajectories of individual photons according to the following scheme:</u>

(1) Determine starting position x_0 and direction (μ,φ) of a photon

(2) Generate a photon path length (using random numbers ***rx***)

$$x = rx$$

(3) Calculate a new photon position (x_0+x) called the event point (or collision point)

(4) Analyze what can happen with the photon at this event point by generating the random number ***rn*** and comparing it with ω_0

if $rn > \omega_0$ => the photon is absorbed => go to (1) for a new photon.

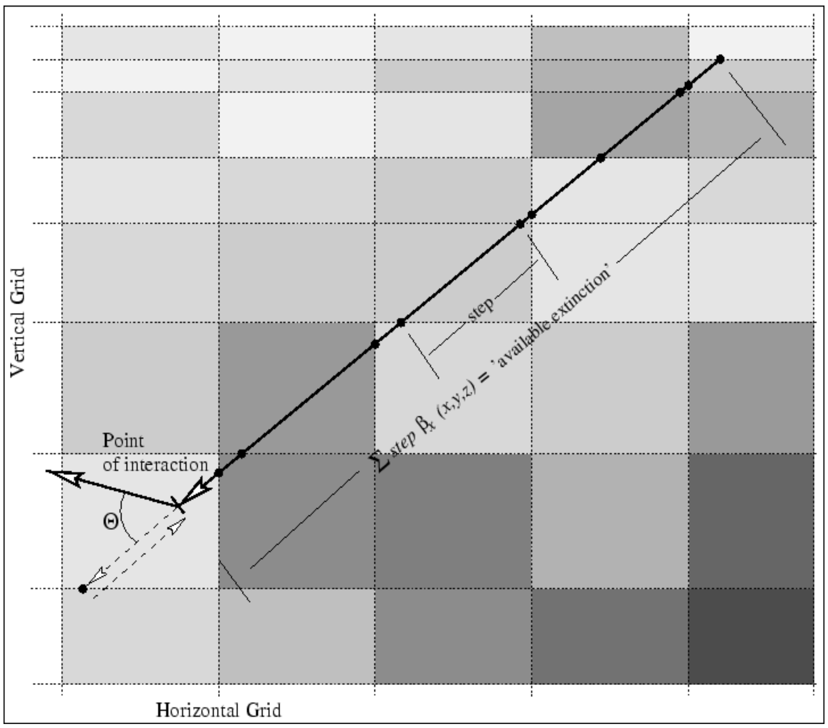
if $rn < \omega_0$ => the photon is scattered => go to (5)

(5) Find a new direction for the scattered photon using the phase function to calculate the cumulative probability function to relate the scattering angle to a random number.

(6) Then repeat starting with (3) until the all photons are analyzed.

- ✓ Monte Carlo requires about 10^6 –10^9 photons to produce statistically reliable results.
- ✓ **Backward Monte Carlo method**: starts with the photon at the point of interest and traces back to the source.

Let's consider the inhomogeneous atmosphere. We can split it into the homogeneous grids.



Point of interaction (or event point)

$$rx = \sum_{step} step \quad \beta_{ext} \ (x, y, z)$$

where ***step*** = step-size in each grid

***l* =1/β$_{\mathbf{ext}}$** is called **free path-length**.

$$\frac{I}{I_0} = \exp(-\tau) = \exp(-\beta_{ext} x) = \exp(-x/l) \qquad [22.1]$$

2. Radiative transfer techniques for inhomogeneous clouds.

Clouds exhibit high variability in space (x, y, z) => one-dimensional radiative transfer has limited applications

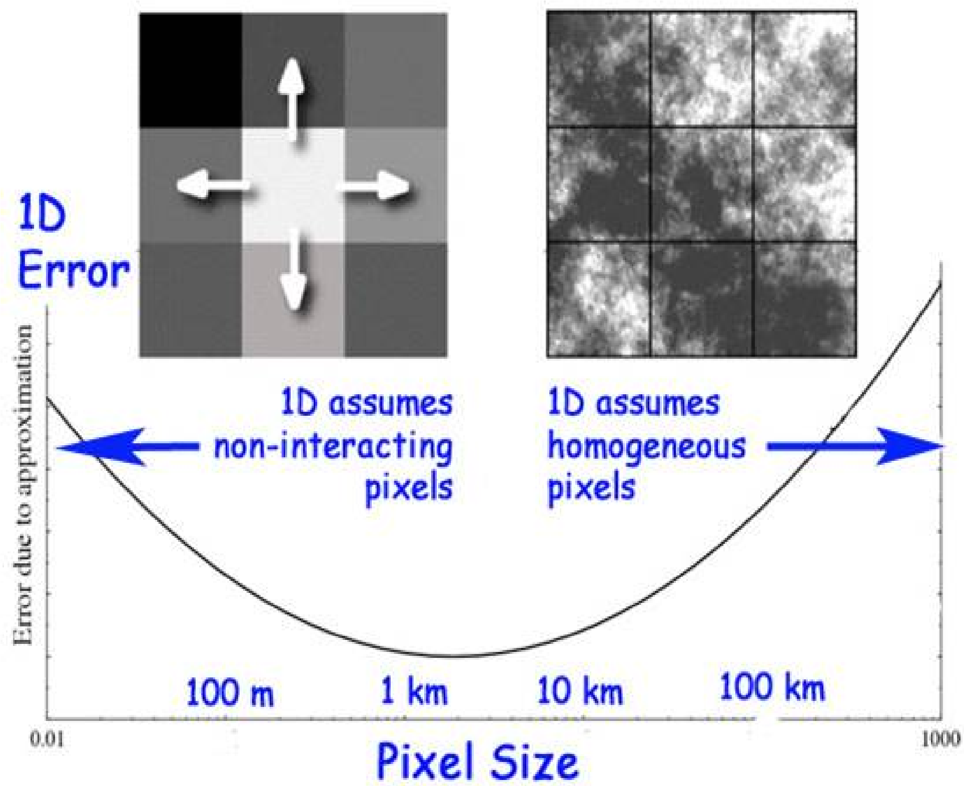


Figure 22.1 Illustration of the sources of errors in one-dimensional radiative transfer in cloudy conditions (Wiscombe et al.).

How to treat the inhomogeneity of clouds:

The simplest method: **introduce a cloud fraction f_{cl}**

(f_{cl} is commonly reported from meteorological observations)

$$I = f_{cl} I_{cl} + (1 - f_{cl}) I_{clear}$$

where I_{cl} is the intensity calculated with one-dimensional cloud, and I_{clear} is the intensity of clear sky.

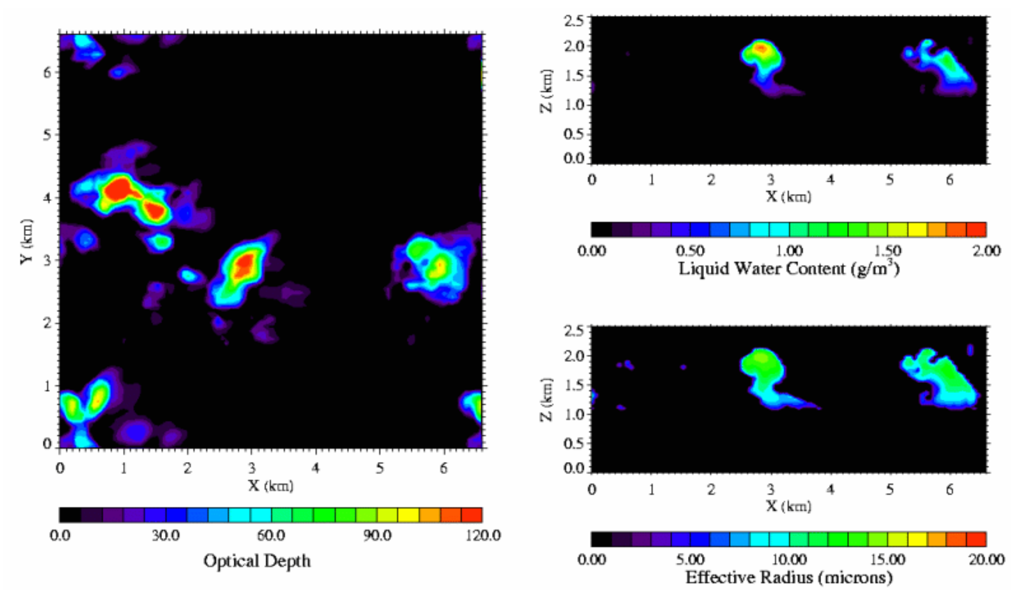
But the problem is that

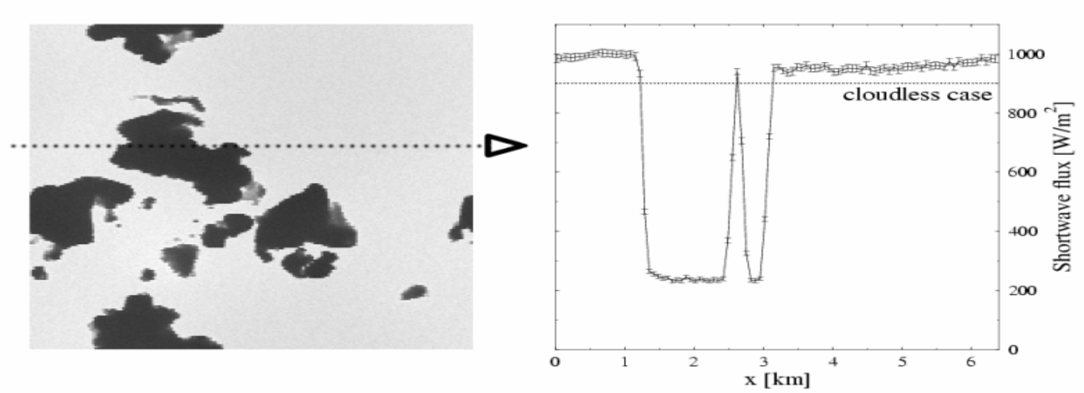
$$f_{cl}(observed) \neq f_{cl}(radiative)$$

Another problem is cloud overlap.

Independent Column Approximation (ICA)

- ✓ ICA is computational efficient technique to calculate the radiative transfer accounting for the cloud inhomogeneity. A cloud is subdivided into columns, plane-parallel radiative transfer is applied to each column, and the overall radiative transfer effect is the summation from the individual columns. Thus, ICA calculates the domain-averaged radiative properties.
- ✓ ICA requires the probability distribution of optical depth PDF (τ) in the cloudy part of the scene, instead of just the mean optical depth.
- ✓ ICA concept is well suitable for GCM models, but does not work well in the remote sensing of cloud properties.
- ✓ Modification of ICA, NICA (nonlocal independent column approximation) has been proposed to account for 'radiative smoothing' effect (i.e., the tendency of horizontal photon transport to smooth the radiative field predicted by ICA.





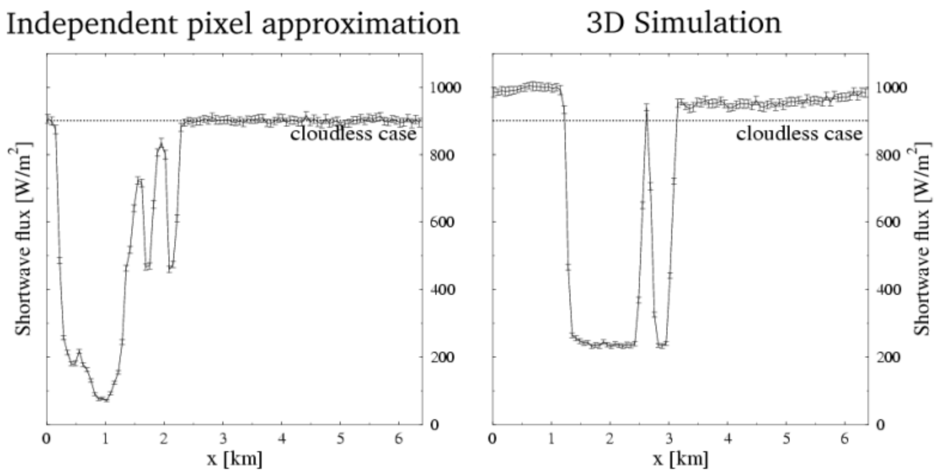


Figure 22.2 Solar flux (0.2µm - 4µm) at the Earth's surface calculated with ICA and Monte Carlo for the cloud field shown on the upper panels. The sun is shining from the left, solar zenith angle is 30°. The right image shows a cross section along the dotted line (Mayer et al).

NOTE:

- ✓ The 3D shadows do not appear below the clouds, but of course offset into the direction of the direct solar beam.
- ✓ The 3D radiation field outside the cloud shadows is enhanced compared to the one-dimensional approximation.
- ✓ The 3D flux inside the cloud shadows is considerably enhanced compared to the independent pixel approximation by more than a factor of 2. This is caused by sidewards scattering of radiation under the cloud.

Barker, et al., Assessing 1D Atmospheric Solar Radiative Transfer Models: Interpretation and Handling of Unresolved Clouds. Journal of Climate, vol. 16, Issue 16, pp.2676-2699, 2003.

The Monte Carlo Independent Column Approximation (McICA):

combines IAC and Monte Carlo (incorporated into the ECMWF forecasting model)

Spherical Harmonic Discrete Ordinate Method (SHDOM):

(developed by F. Evans, http://nit.colorado.edu/~evans/shdom.html)

- ✓ SHDOM is a highly efficient and flexible 3D atmospheric radiative transfer model.
- ✓ SHDOM uses an iterative process to compute the source function (including the scattering integral) on a grid of points in space. The angular part of the source function is represented with a spherical harmonic expansion.
- ✓ SHDOM can compute unpolarized, monochromatic and broadband (with a k-distribution), shortwave and longwave radiative fluxes. The medium properties (extinction, phase function, etc.) are specified at each grid point, and the surface albedo may vary as well.

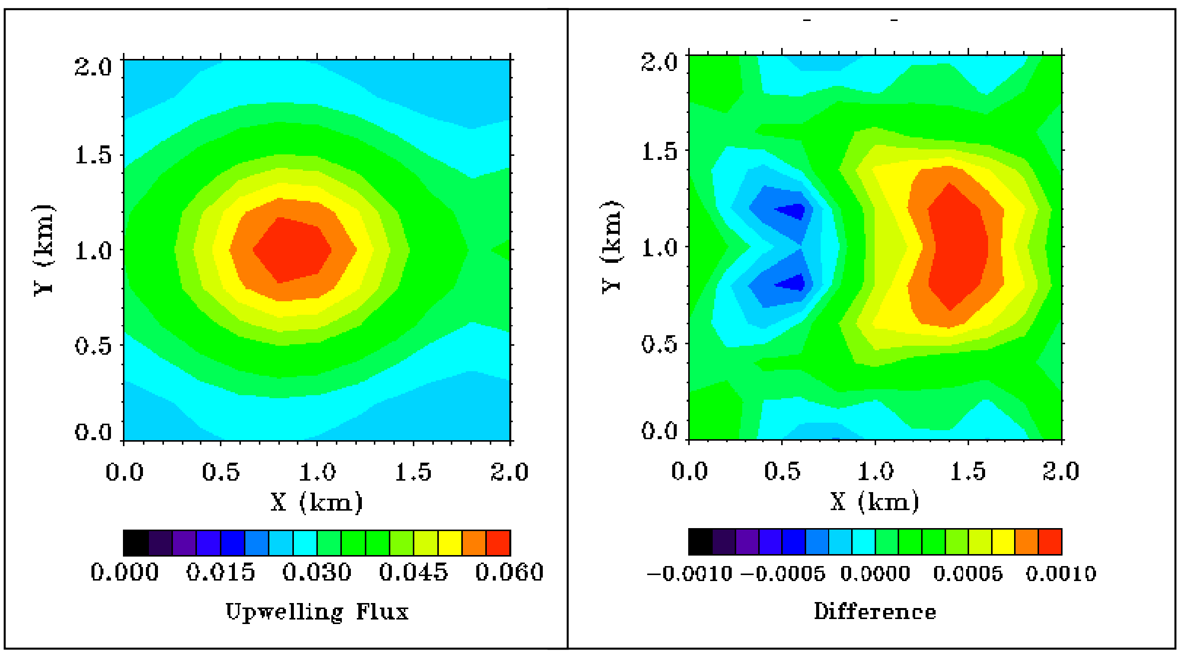


Figure 22.3 Comparison of Monte Carlo and SHDOM methods: differences (SHDOM-MC) in radiative fluxes (at 1.65 μm) reflected by the inhomogeneous cloud (Evans et al.)