Digging into the 3D Radiative Effects of Shallow Cumulus Clouds:
Tools and Methods to Further Understand them and Evaluate their Representations in Atmospheric Models

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Introduction & Objectives

- Cloud processes impact weather and dominate climate sensitivity
- Accurately representing cloud-radiation interactions in atmospheric models has been identified as a challenging task for models at all resolutions
- One of the strong yet common approximations is to propagate light on the vertical only (1D) instead of propagating it in all three dimensions (3D)

We present **3D tools** (1.) developed as libraries allowing to easily implement different Monte Carlo (MC) codes that can be used to answer various scientific questions:

- **Provide the community with benchmark 3D radiation calculations** (2.)
- **Better understand & document the 3D radiative effects of clouds** (3.)
- **Help develop & evaluate parameterizations of 3D radiative effects** (4.)

2. Validation and benchmark

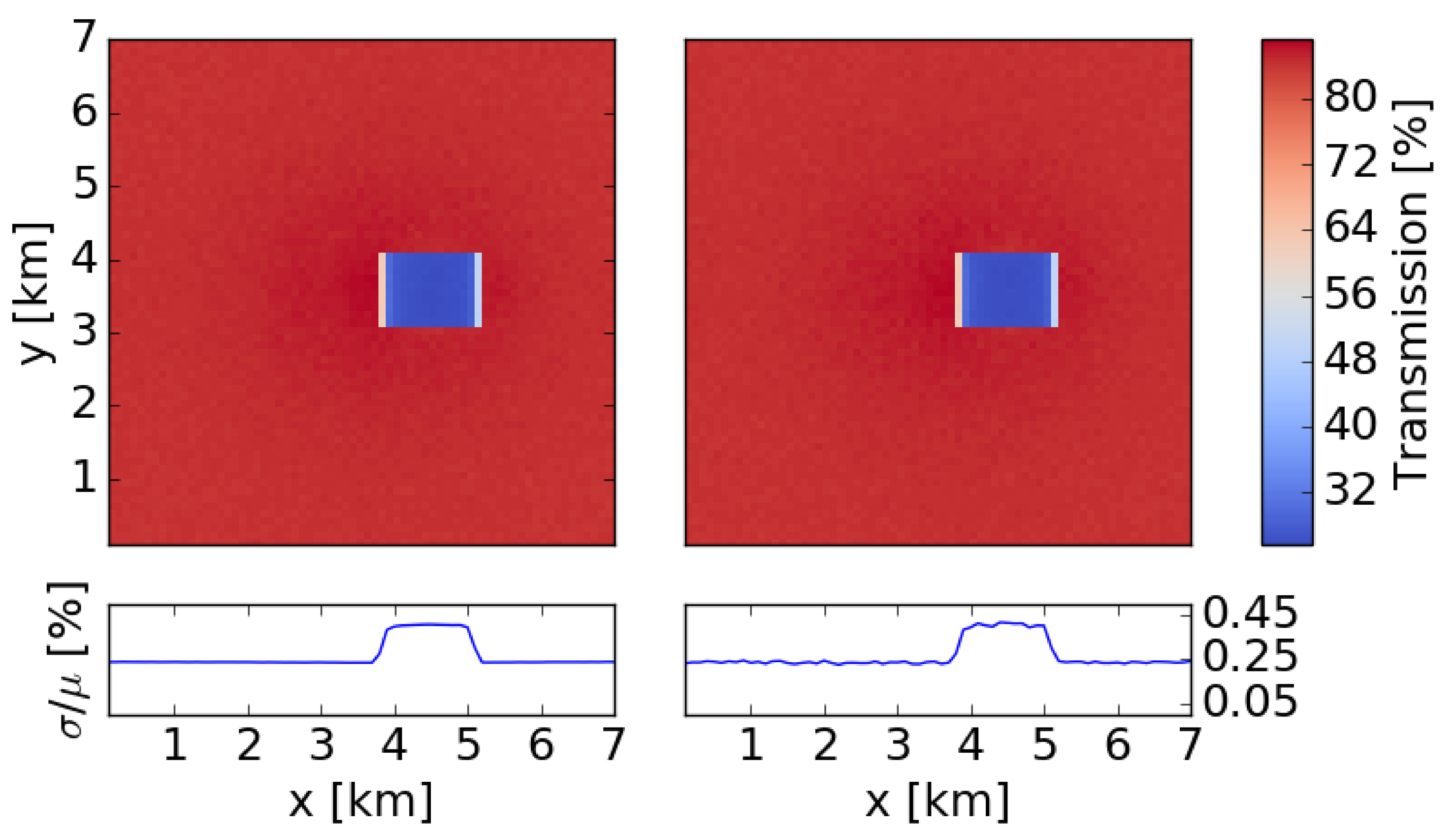

Figure: Surface transmission map (top) and relative standard deviation at y=3.5km (bottom) below cubic cloud in atmosphere, sun at 20^o (IPRT case 2, Emde et al. 2018), for two MC models: (left) SW forward S-CART and (right) 3DMCPOL (Cornet et al. 2010), for N=980M realizations.

We compare our tools against published results to ensure validity. We will therefore be able to provide benchmark radiation computations to the community, in particular as a metric to tune the parameterizations of clouds or radiation in low-resolution models.

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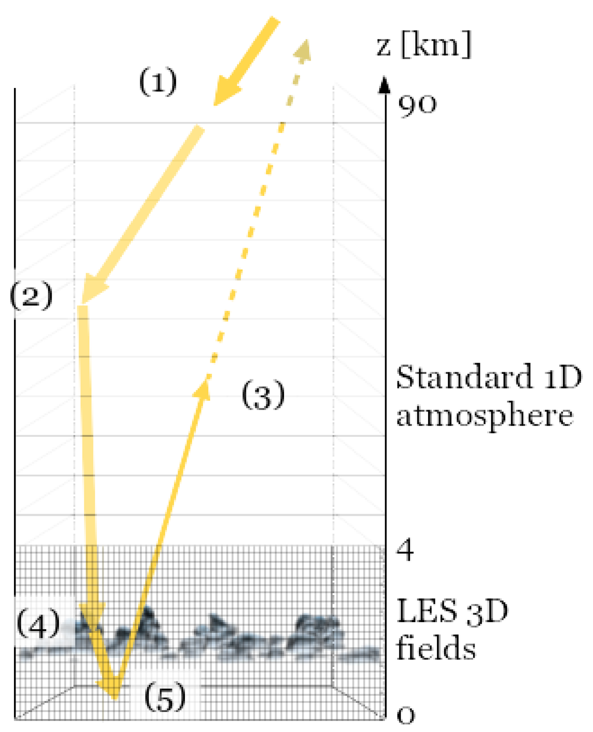
1. The Star Cloudy Atmosphere Radiative Transfer (S-CART): a set of elementary MC tools

We use and develop **state-of-the-art tools**, necessary in atmospheric Monte Carlo models: random sampling, ray-tracing, parallel integration, efficient treatment of **complex heterogeneities**, optimized large data volume structuring and access... We use **Large Eddy Simulation** (LES) outputs as inputs to **Monte Carlo** codes based on the S-CART tools. Other inputs are optical properties of gas (absorption profiles at various wavelengths + Rayleigh) and clouds (from Mie theory). Various options allow to compute multiple metrics and their variances. One originality is to simultaneously compute the **derivative of the metrics** with respect to optical or microphysical parameters.

Figure: A shortwave (SW) forward Monte Carlo (MC) code and how to compute derivatives:



(1) Emission at TOA, wavelength sampling
(2) Rayleigh scattering
(3) Partial absorption (RRTMG)
(4) Mie scattering (Mishchenko)
(5) Ground reflexion (BRDF)

Simultaneous derivative-based sensitivity!

$$T(x) = \int_\gamma P_\Gamma(\gamma;\Pi)\,\{w(\gamma)\}\,\mathrm{d}\gamma$$

$$\Rightarrow \partial_\Pi T(x) = \int_\gamma \partial_\Pi P_\Gamma(\gamma;\Pi)\,\{w(\gamma)\}\,\mathrm{d}\gamma$$

$$\Rightarrow \partial_\Pi T(x) = \int_\gamma P_\Gamma(\gamma;\Pi)\left\{\frac{\partial_\Pi P_\Gamma(\gamma;\Pi)}{P_\Gamma(\gamma;\Pi)} w(\gamma)\right\}\mathrm{d}\gamma$$

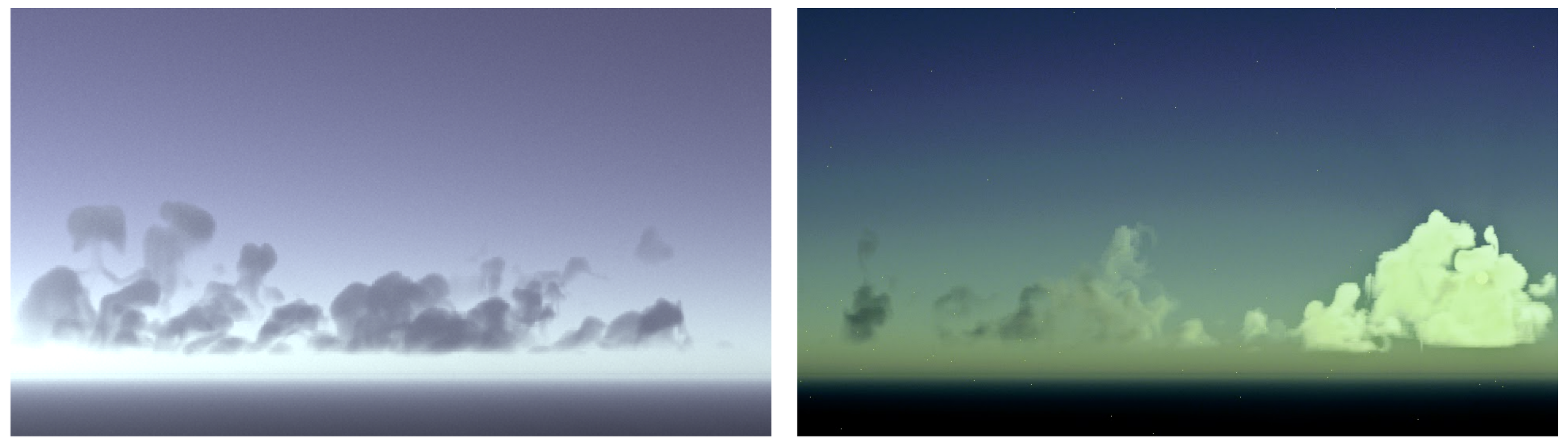


Figure: **LES fields** (8th hour of the ARM-Cumulus case of Brown et al. 2002, simulated with the Meso-NH model (Lac et al. 2018)), **rendered by a SW reverse MC based on S-CART tools**. **Different advection schemes** have been used for momentum in the LES model : centered 2nd order + leap frog (left) and centered 4th order + Runge Kutta 4 (right). Visualizing the cloud field allows to assess realism of the models, e.g. 2nd order advection scheme is more diffusive than the 4th order scheme.

Optimized treatment of complex heterogeneity based on **maximum cross section** and techniques from video games, motion picture & film industries.

Philosophy of the S-CART tools: efficiency, modularity, freedom

Facilitate the development of specific MC codes (SW/LW, direct/reverse) needed to tackle different scientific questions

3. Sensitivity

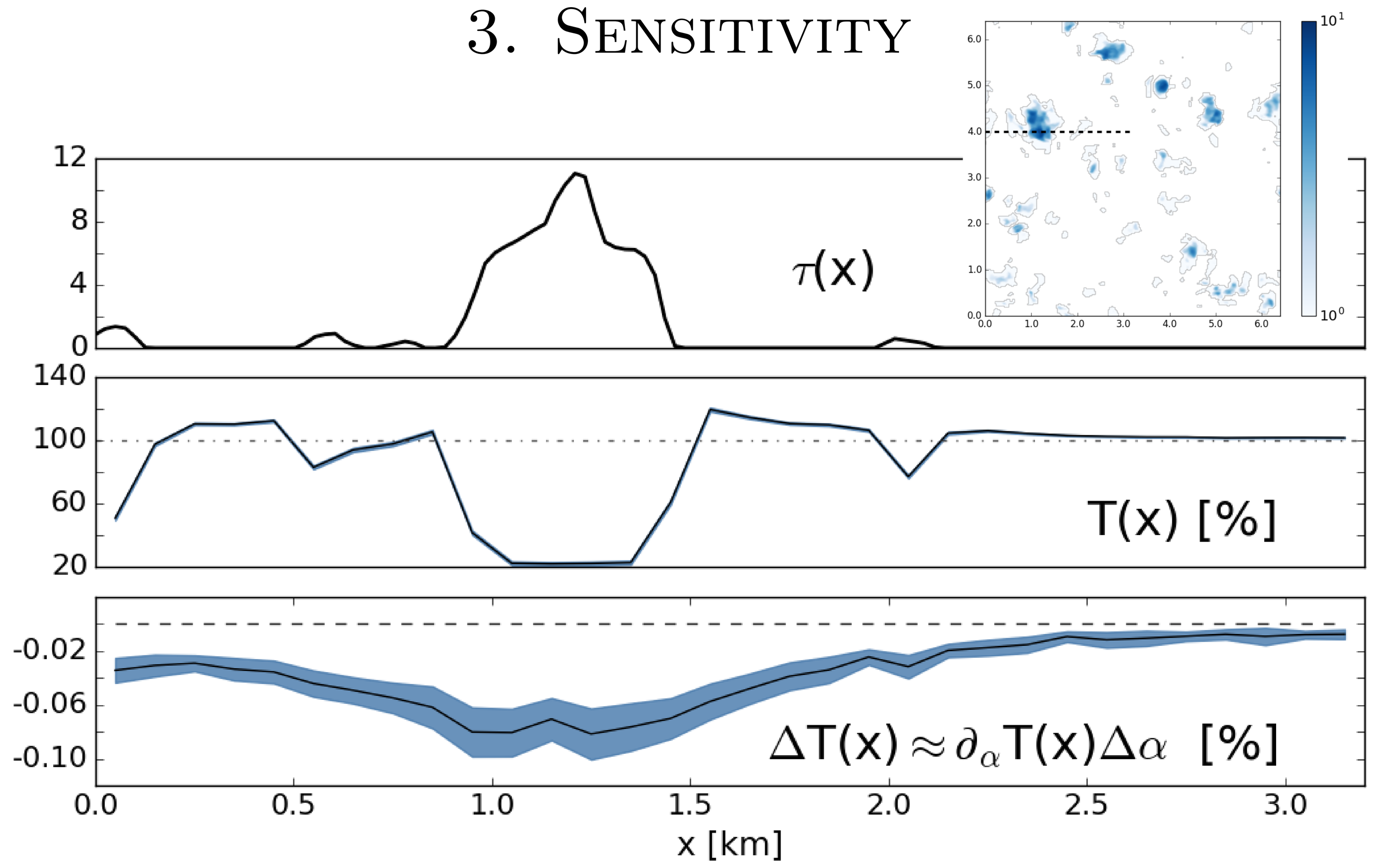


Figure: Solar transmission at the surface (T) and its response (ΔT) to a 10% perturbation of the absorption-to-extinction ratio ($\Delta\alpha$) under cumulus clouds of optical depth τ, in vacuum, simulated by S-CART SW reverse MC. Impact of $\Delta\alpha$ perturbation is greater under the cloud but non-zero in clear sky.

Transmission greater than 100% in clear sky regions near the clouds = photons scattered through cloud edges. In the sensitivity plot: if the rate of absorption were 10% higher (at the detriment of the scattering rate), the transmission would be lower, even in clear sky $\Rightarrow$ scattering is responsible for transmission being $>$ 100%.

4. Evaluate parameterizations

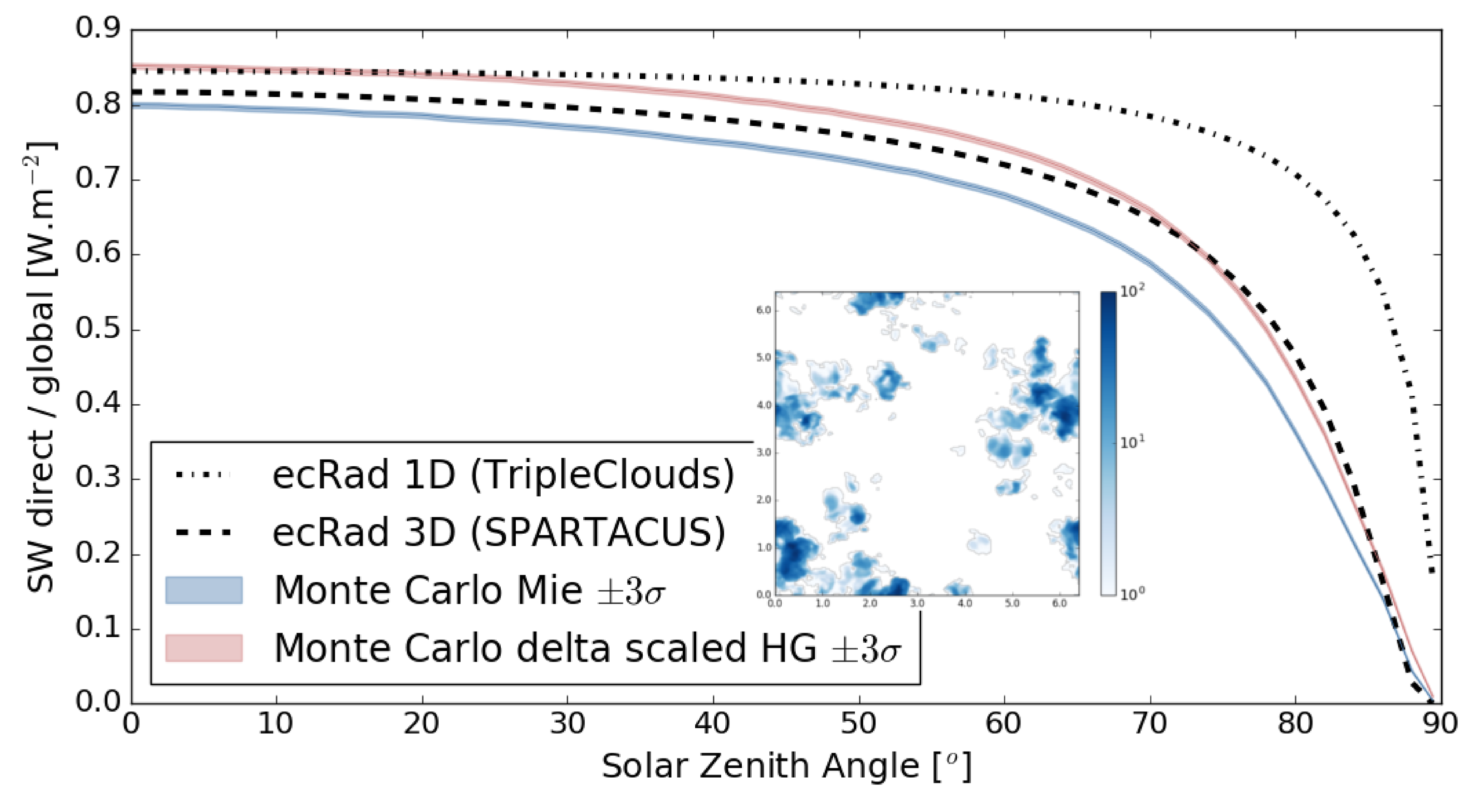


Figure: SW direct-to-global ratio at the surface as a function of solar zenith angle. Comparison between 2-stream radiation scheme, ecRad (Hogan & Bozzo 2018), with and without 3D effects, and S-CART based forward MC on a LES field from ARM-Cumulus (zenith optical depth also shown).

The partition of solar fluxes into direct and diffuse is relevant to a number of applications (solar energy, vegetation). We show evidence of its dependency on 3D radiative effects of clouds. SPARTACUS (Schaefer et al. 2016) is able to represent them accurately. Delta scaling: forward scattering is treated as direct, as in most 2-stream schemes.