The Role of Surface Albedo in 3D Radiative Effects of Clouds

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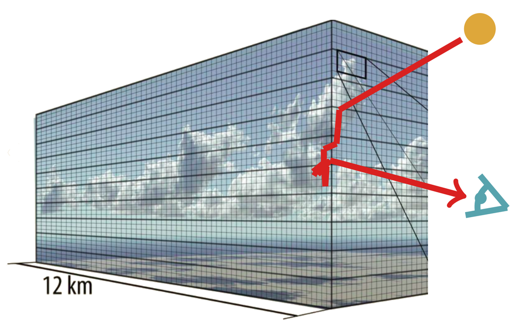
Summary

In the Earth Sciences, the 3D radiative transfer equation is often solved for by Monte Carlo methods. They can, however, be computationally taxing, and that can narrow their range of application and limit their use in explorations of model parameter spaces. A novel family of Monte Carlo algorithms is investigated here in which single simulations provide estimates of both radiative quantities A for a set of parameters $\hat{x}$, as usual, as well as the overarching functional $\mathcal{A}(x)$ that can be evaluated, extremely efficiently, at any x. One such algorithm is developed and demonstrated for horizontally averaged broadband solar radiative fluxes as functions of surface albedo for uniform Lambertian surfaces beneath inhomogeneous cloudy atmospheres. Simulations for a high-resolution synthetic cloud field, at various solar zenith angles, illustrate the potential of the method to gain insights into the nature of 3D radiative effects for complicated atmosphere-surface conditions using information specially derived from the Monte Carlo simulation. For simulations performed with a single surface albedo it is found that as surface albedo increases, 3D radiative effects increase, too, with maxima occurring at middling to large values, and then decrease. By utilizing the derived coefficients that describe $\mathcal{A}(x)$ it was established that these 3D effects stem from differences in fractions of radiation entrapped at successive orders of internal multiple reflections for 1D and 3D transfer.

Leveraging Path-Tracing Monte Carlo Methods

Monte Carlo (MC) methods: input description of the medium π, sample optical paths Γ by simulating radiative processes at the photon scale.

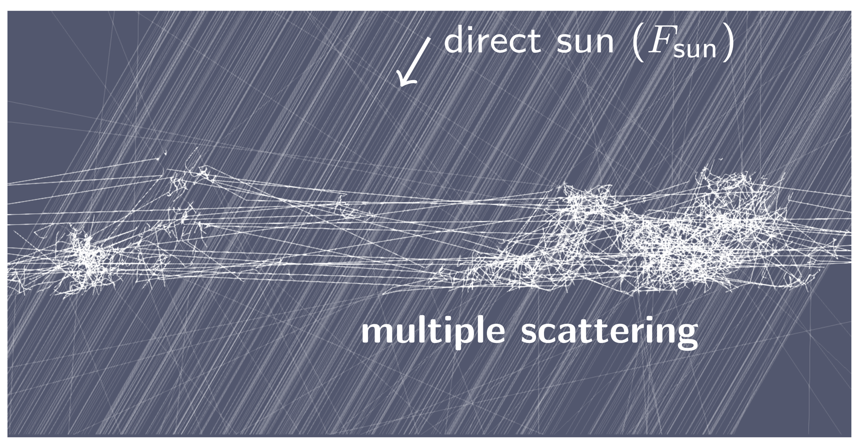


Standard MC: estimate radiative quantity F_π as the mean sampled-path weight.
(e.g. upward flux is the average of reflected path weights F_{sun} and non reflected path weights 0)

Much more information is contained in the sampled paths!
How to extract it? How to synthesize it?

$$F_\pi = \int_{\Omega_\Gamma} \underbrace{d\gamma\, p_\Gamma(\gamma;\pi)}_{\text{probability of path } \gamma} \underbrace{w_\gamma(\pi)}_{\text{path weight}}$$

Proposition $\Rightarrow$ **Symbolic (or Functionalized) MC**:
use the sampled paths to estimate a functional $F(\pi)$
Dunn, 1981; Galtier et al., 2017; Maanane et al., 2020



Solar paths sampled in a heterogeneous cumulus cloud field

Linear Symbolic MC (trivial) $p_\Gamma(\gamma;\pi) \perp \pi$
Path probability is not affected by the parameter
(e.g. π is the amount of incoming solar radiation)

Non-linear Symbolic MC $p_\Gamma(\gamma;\pi) \not\perp \pi$
Path probability is affected by the parameter
(e.g. π is the surface albedo or cloud droplet effective radius)
$\Rightarrow$ use importance sampling to go back to linear, and apply weight-correction *offline*!

$$F(\pi) = \int_{\Omega_\Gamma} d\gamma\, p_\Gamma(\gamma;\hat{\pi})\, w_\gamma(\hat{\pi}) \frac{p_\Gamma(\gamma;\pi)}{p_\Gamma(\gamma;\hat{\pi})}$$

With a single simulation, the radiative fluxes are predicted for any surface albedo!

Implemented in scart `gitlab.com/najdavlf/scart_project`

Illustration on homogeneous slabs

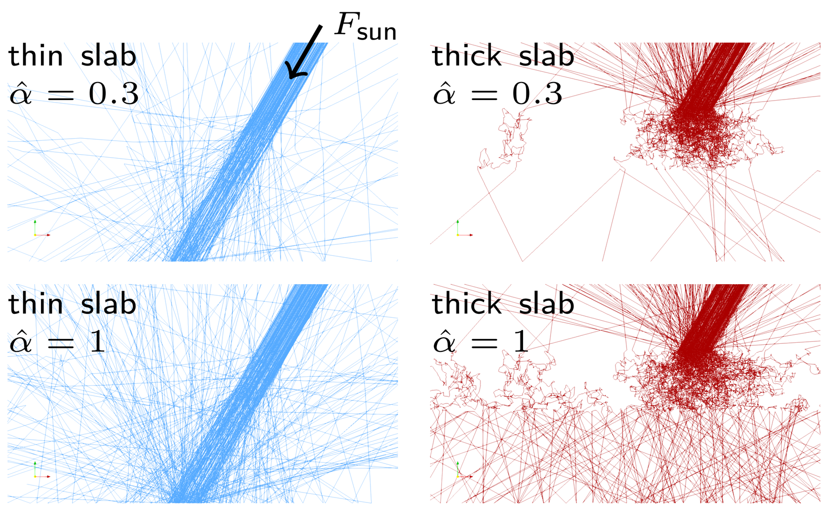
1. Write the radiative transfer equation with $\hat{\alpha}$ an arbitrary value for α

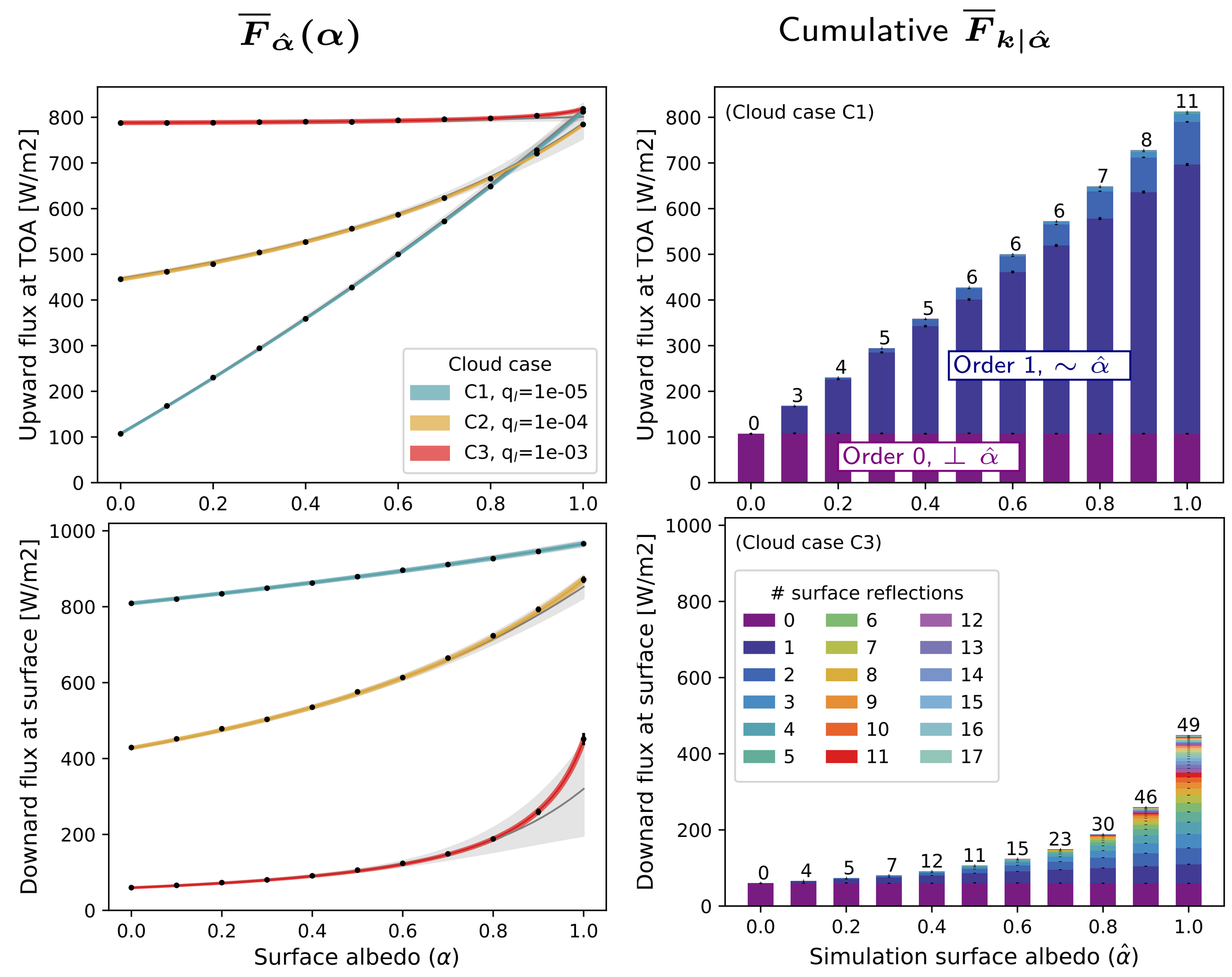
$$F(\alpha) = \sum_{k=0}^{\infty} F_{k|\hat{\alpha}} \left(\frac{\alpha}{\hat{\alpha}}\right)^k$$

2. Estimate $F_{k|\hat{\alpha}}$ as the mean weight of the paths that have been reflected k times (as in e.g. Barker and Davies 1992)

$$F_{k|\hat{\alpha}} \approx \overline{\boldsymbol{F}}_{\boldsymbol{k|\hat{\alpha}}} = \frac{1}{N_{k|\hat{\alpha}}} \sum_{i=1}^{N_{k|\hat{\alpha}}} w_{i,k}$$

3. Evaluate $\overline{\boldsymbol{F}}_{\hat{\alpha}}(\boldsymbol{\alpha}) = \sum_{k=0}^{K_{\max}} \overline{F}_{k|\hat{\alpha}} \left(\frac{\alpha}{\hat{\alpha}}\right)^k$





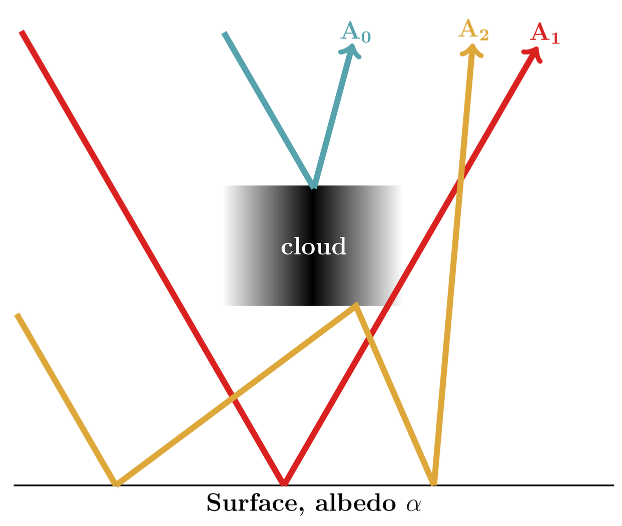
● = one standard MC simulation

— = one Symbolic MC simulation (colored $\Rightarrow \hat{\alpha} = 1$; gray $\Rightarrow \hat{\alpha} = 0.3$)

In practice

- Sort paths into categories (number of reflections)
- Estimate partial fluxes F_k (reflected k times)
- They are the coefficients of the polynomial function ...

which can then be evaluated for any surface albedo

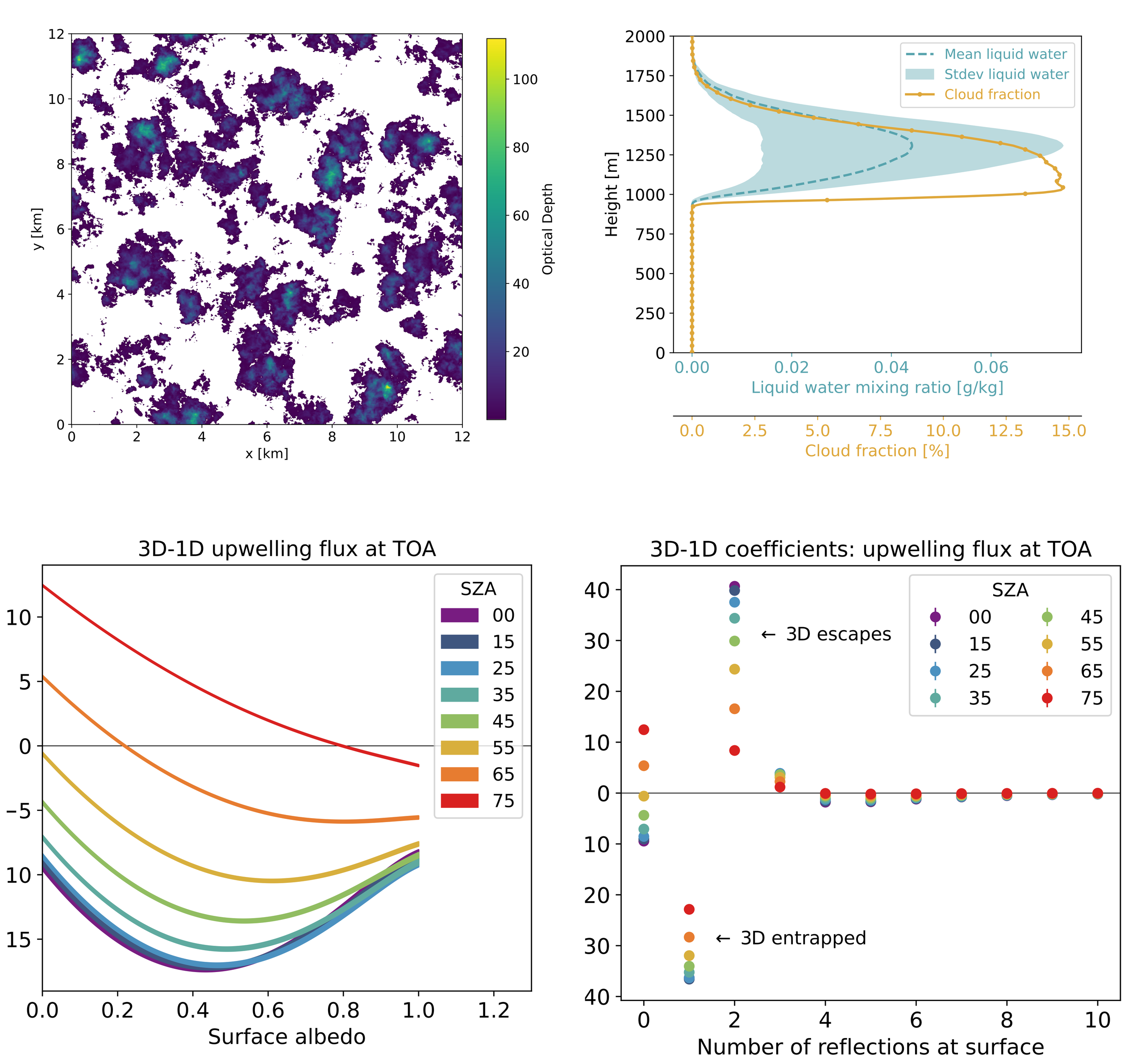


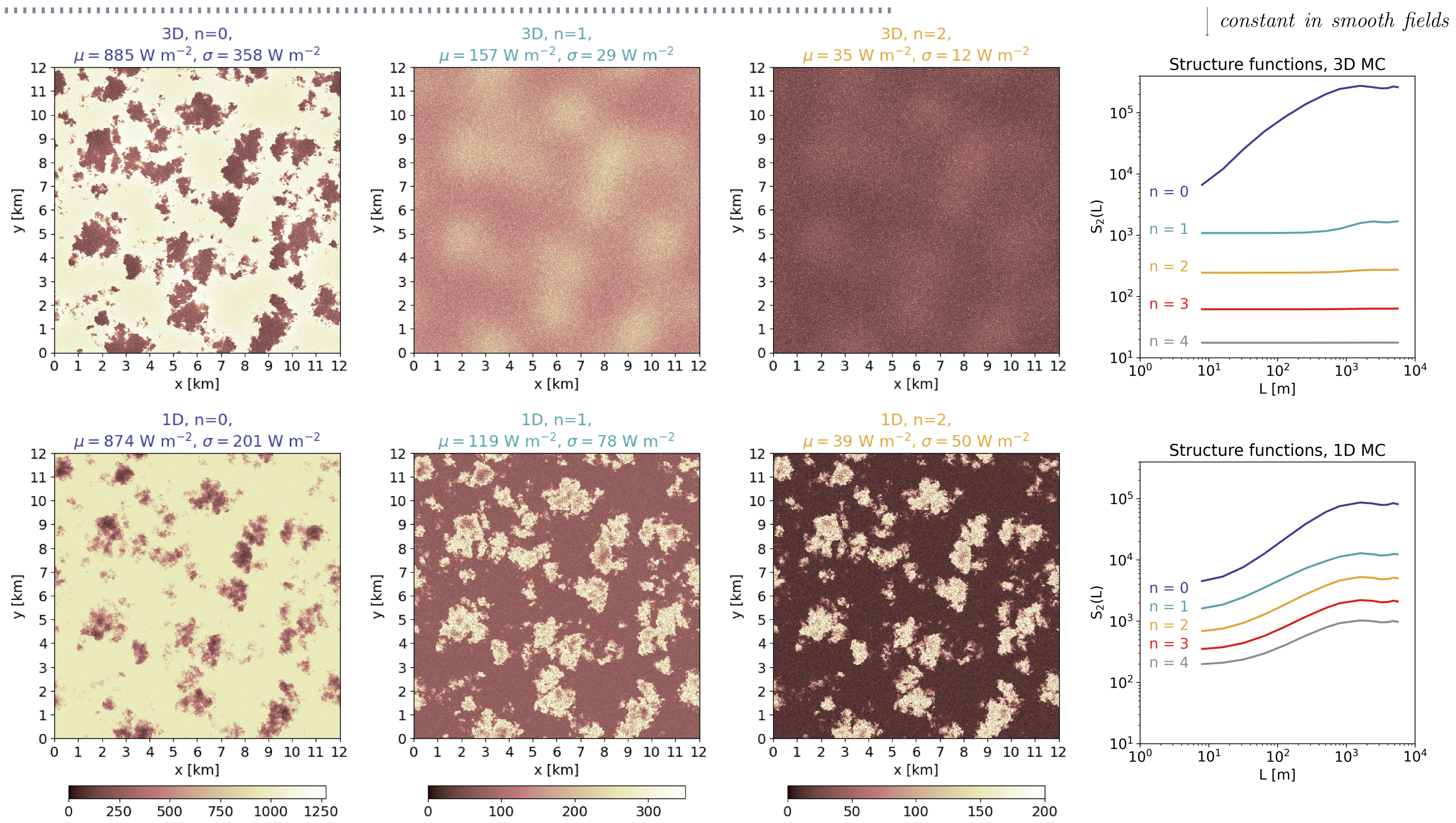
Using a large α in the simulation allows to sample longer paths
$\Rightarrow$ better estimate of highly non-linear functions

Role of surface albedo in 3D radiative effects of cumulus clouds: entrapment enhancement

$$S_2(L \equiv k\Delta x) = \frac{1}{N_x^2} \sum_{i=1}^{N_x} \sum_{j=1}^{N_x} \frac{(A[i,j]-A[i+k,j])^2 + (A[i,j]-A[i,j+k])^2}{2}$$

constant in smooth fields





Villefranque et al., 2023, *A Functionalized Monte Carlo 3D Radiative Transfer Model: Radiative Effects of Clouds Over Reflecting Surfaces*, accepted in JAMES. doi:10.1029/2023MS003674
Galtier et al., 2017, *A symbolic approach for the identification of radiative properties*, in JQSRT. doi:10.1016/j.jqsrt.2017.03.026
Dunn, 1981, *Inverse Monte Carlo analysis*, in JCP. doi: 10.1016/0021-9991(81)90085-1

Maps produced with **htrdr** software
https://www.meso-star.com/projects/htrdr/htrdr.html