Tools & methods to evaluate the 3D radiative effects of shallow cumulus clouds

The effect of cloud water horizontal distribution on the shortwave albedo and transmittance

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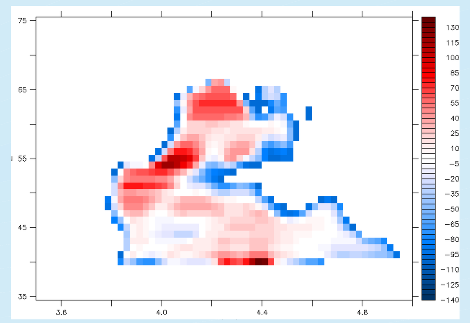
1 - Clouds in models and observations

The representation of **clouds** is a challenge for weather forecast and climate models.

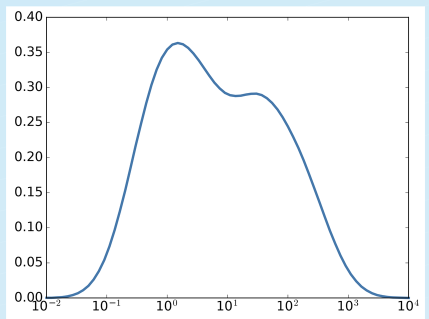
The importance of **3D interactions between clouds and radiation** lead to the development of new parametrizations in NWP and global models.

Still, some 3D characteristics, such as the **horizontal distribution** of cloud liquid water content in a cloud field, are hardly represented into the radiation schemes.

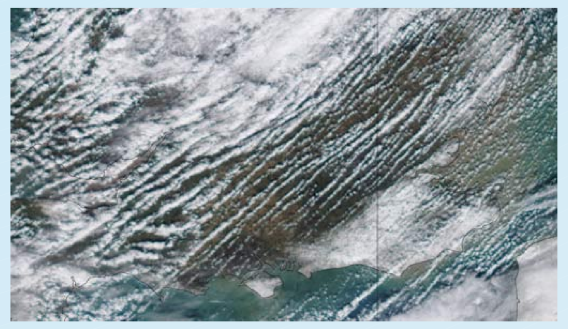
Nevertheless, we know and observe that :
Clouds are highly inhomogeneous (~75 % variability) : **microscale variability**
In a cumulus field, LWC varies from one cloud to another : **macroscale variability**
The morphology of cumulus fields varies around the globe : **mesoscale variability**



Deviation from average q_l in a cloud [%] (LES with CNRM & LA model MesoNH)



Log distribution of mean LWP [g/m²] of clouds in a LES cumulus field



Cumulus clouds forming cloud streets (blog.metoffice.gov.uk)

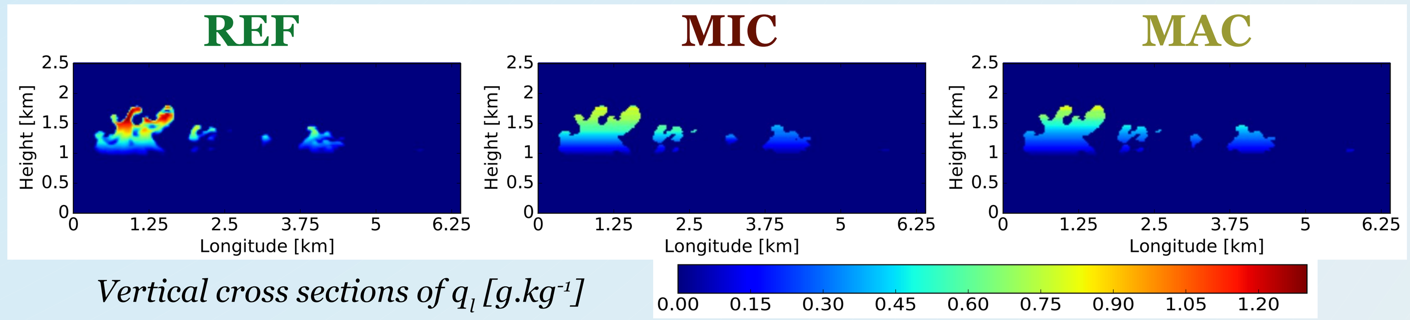
How can we determine the impacts of these types of horizontal variability on the SW total albedo and transmittance ?

2- Simulating cloud fields

High resolution atmospheric simulations (Large Eddy Simulations) of cumulus clouds with MesoNH

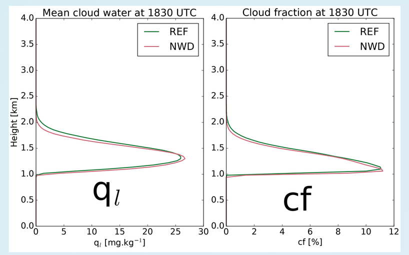
ARM Cumulus : continental case, from *Brown et al., 2002, QJRMS*
Domain 51.2 x 51.2 x 4 km³ ; Resolution $\Delta x = \Delta y = 100$m, $\Delta z = 40$m

To study the effect of micro and macroscale variability
For each cell (i,j,k) of cloud γ of **REF**, replace $q_l^{i,j,k}$ by $<q_l^{i,j,k}>$ with
MIC : <.> = average over cloudy cells of cloud γ at level k
MAC : <.> = average over all cloudy cells at level k

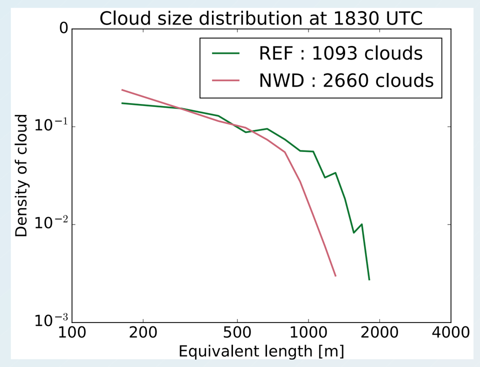


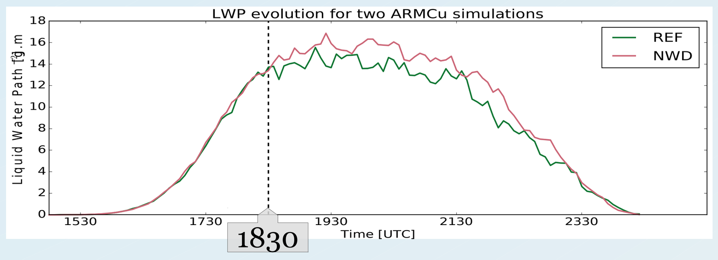
Vertical cross sections of q_l [g.kg⁻¹]

To study the effect of mesoscale variability
Horizontal wind forcings : **REF** : u_{frc} = 10 m/s , **NWD** : u_{frc} = 0 m/s



At 1830 UTC, **REF** and **NWD** present the same average characteristics and total cloud cover...





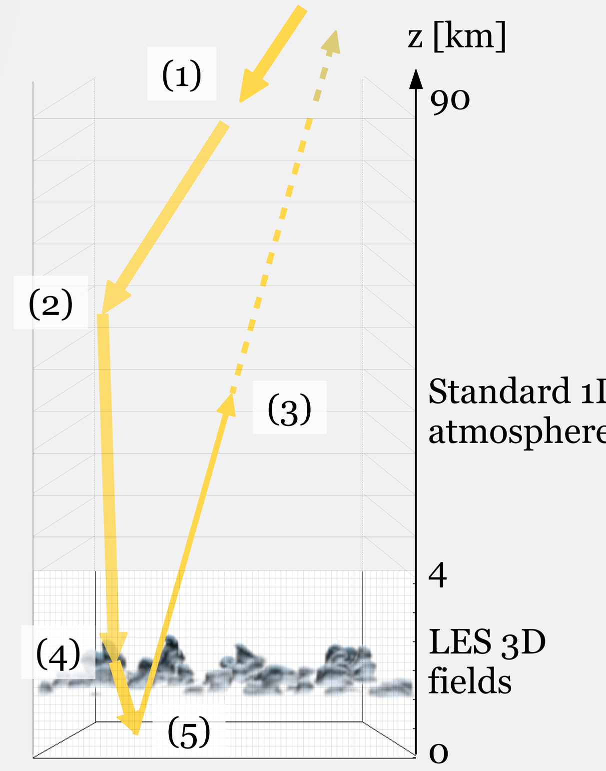
... but not the same number of clouds and size distributions.

3- Solving radiative transfer

A full 3D SW Monte Carlo code to compute the 3D albedo and transmittance of a 3D cumulus field : the SCART code

Close to the physic of transport :
→ **Exact resolution of the 3D radiative transfer equation**
→ **Shortwave spectral integration**
→ **Emission** at TOA with given SZA and sampled wavelength (1)
→ **Atmospheric effects** : Rayleigh scattering (2) and absorption (3) by gas
→ **Mie** scattering and absorption by droplets (4) for a given size distribution
→ **Ground reflections** (5) following a BRDF

Numerical properties :
→ **Highly parallelized**
As each path is independent from the others
→ **Based on tools from image rendering**
With libraries developed by Meso-Star
→ **Data / model orthogonality**
Even if the data is often meshed, the paths and media are continuous.
→ **Maximum cross section**
Add fictive particles (purely forward scatterers) to simulate a homogeneous media
→ **Statistical errors computed**
One of the advantages of the MC method : estimate a quantity and its variance at the same time



Schematic representation of one Monte Carlo path, traced in a cloudy atmosphere : it ends when an absorption occurs or when the TOA is reached

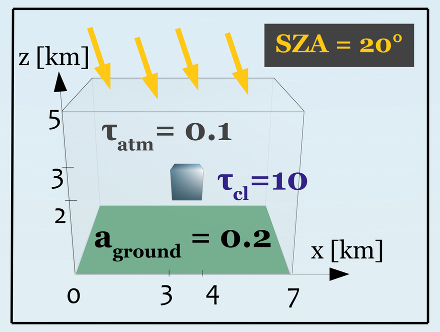
Data :
→ Cloud field : LES MesoNH
→ Gas properties : RRTM *
→ Mie model : Mishchenko **

* The gas properties were not directly taken from RRTM but from the ECRAD code that uses them, thanks to R. Hogan (ECMWF, Reading, UK), V. Eymet (Meso-Star, Toulouse, France) and Q. Libois (CNRM, Toulouse, France).
** The code is based on the book [1] and was first developed by M. Mishchenko before it was modified by J. Dauchet (Institut Pascal, Clermont-Ferrand, France).

Simultaneous estimation of downward, upward, net fluxes, their **standard deviations** and their **sensitivities** to multiple **microphysical parameters** (parameters of the particles size distributions, refraction indexes, single scattering albedos...)

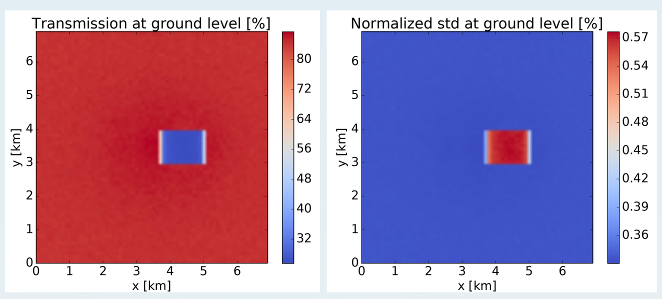
A first validation of SCART

Test case design is inspired from IPRT case C2 : Cubic cloud.



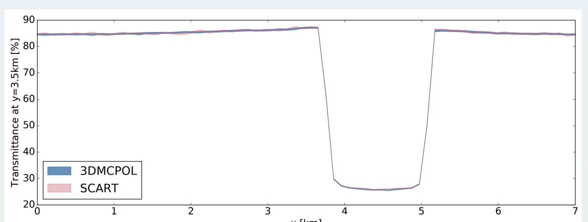
→ SCART albedo & transmittance were compared to 3DMCPOL thanks to Céline Cornet (LOA, Lille, France)
→ Cloud phase function : Henyey-Greenstein with g=0.85
→ Single scattering albedo for cloud & atmosphere : ω = 1

Transmittance and normalized standard deviation maps :



490M of paths simulated. Scattering by atmospheric molecules and cloud droplets. Reflections at the BOA. Pixel at reflection position records contribution to local transmittance.

Higher transmittance near the edges of the cloud.
Highest relative uncertainties are below the cloud.

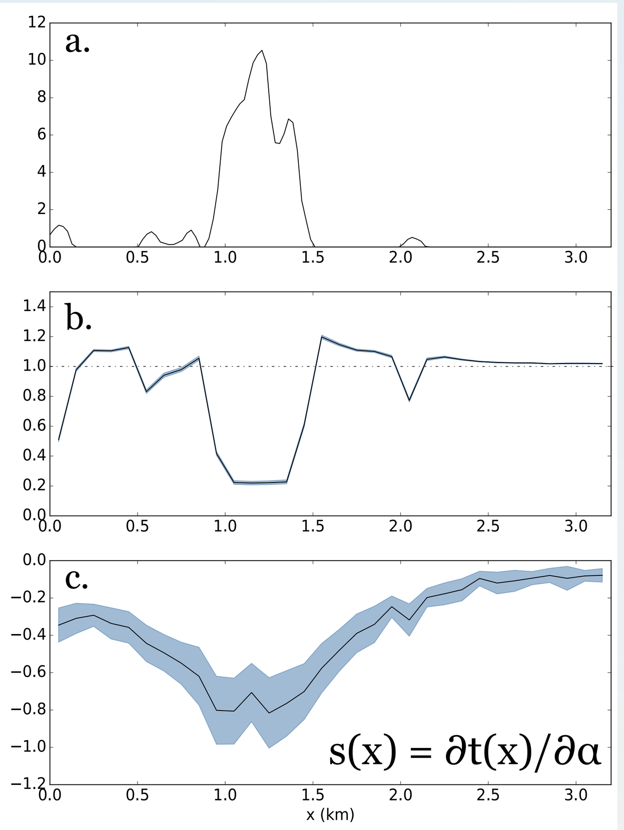


Transmission at y=3.5km, 3DMCPOL compared to SCART, +/- one standard deviation.

An example of sensitivity computation

a. Zenithal optical depth cross section in a LES cumulus field at y = y^{cs}
b. Transmittance t on the y^{cs} line under a cloud at SZA 0°
c. **Sensitivity s** to the absorption to extinction ratio **α=1-ω**, at ω=0.99
Results plotted with their 99.7% confidence interval (± 3 σ)

→ **Higher confidence for transmission than sensitivity**



Optical depth ~ 10 → shallow cumulus
3 shallow clouds and 1 deeper
Clear sky after 2.2km

Transmittance is lowest under cloud
Cloud side effect (leakage) where t > 1
t → 1 far from the clouds
(computation without atmospheric effects)

What is t(x) when α is increased by 10% ?
$\Delta t(x) \approx s(x)\Delta\alpha$ with $\Delta\alpha = 0.1\ \alpha = 0.001$
For example at x = 1km, $\Delta t(x) \approx -0.008$
→ Under the cloud, transmission decreases by ~ 0.4% when absorption rises by 10%

Radiation in 3D cloud scenes : summary & perspectives

Horizontal variability of cloud liquid water as a 3D characteristic of clouds
How to study the impact of a 3D characteristic on radiative quantities such as SW albedo and transmittance ?

Cloud fields
→ Simulation of realistic shallow cumulus cloud scenes with the LES model MesoNH
→ Modification of LES fields to cancel the horizontal variability of a cloud field at different scales
→ Modification of wind to get two scenes with same 1D cloud profiles (q_l, cf) and different cloud populations

Radiation
→ A new Monte Carlo code to compute SW radiative transfer in cloudy atmosphere
→ Based on open source libraries developed by Meso-Star, using state-of-the-art image rendering tools
→ Simultaneous computation of the quantity, its variance and its sensitivity to microphysical parameters

That methodology...
→ can be used to compute benchmark radiative results, particularly useful to tune NWP and global models
→ can help to improve our understanding of 3D radiation and therefore develop better parametrizations
→ can be applied to different cloud scenes, shallow cumulus, stratocumulus, transitions and deeper clouds
→ can be used to evaluate the 3D effects of clouds on radiative fluxes and heating rates

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