3D Radiative Transfer in Cloudy Atmospheres

What is it, why do we need it, how can we model it?

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CNRM, CNRS/Météo France, Toulouse, France

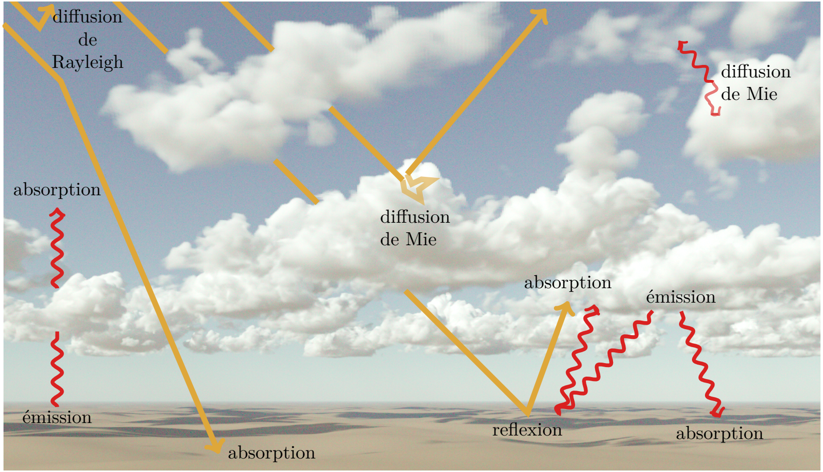
2016-19: PhD student at Centre National de Recherches Météorologiques in Toulouse
2021-22: EarthCare postdoc at LMD (Paris), remotely with Howard, Jason and Zhipeng
Nov-Feb: CCCma visit, Victoria BC

Simulated cloud field (ARM-Cumulus at 8 m resolution) rendered using a Monte Carlo path-tracing model (htrdr, Villefranque et al. 2019)

Radiation (solar and thermal) is obviously important for climate... global energy balance and circulations

The Radiative Transfer Equation (RTE, Chandrasekhar, 1960)

- Radiance is preserved along a straight line in the absence of matter to interact with
- Variation of radiance along a line = absorption (-), in and out scattering (+ and -), emission (+)



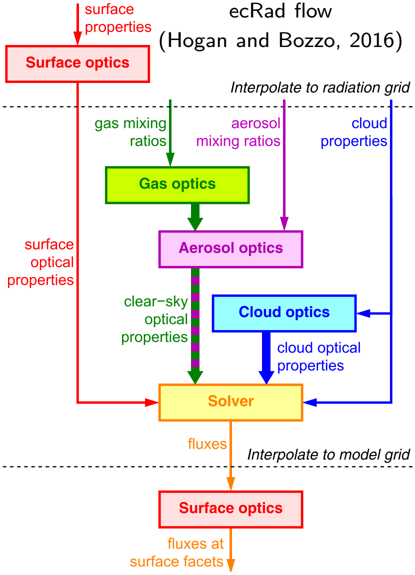
Energy balance in infinitesimal line of sight, Eulerian approach, classical form of RTE

Follow a "photon" throughout the atmosphere, Lagrangian approach, integral form of RTE

Concept of *light path*, Monte Carlo methods

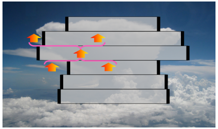
How does this translate to the cloud field scale???

Solving radiative transfer in large scale atmospheric models

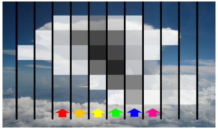


Optics: from particle type, size and concentration ...
to extinction coefficient, single scattering albedo, phase function at each wavelength

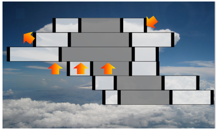
Solver: the radiative transfer model *at the cloud field scale*
Main issue: geometrically complex subgrid clouds



Homogeneous max-overlap + 2-stream
e.g. Morcrette and Fouquart 1986



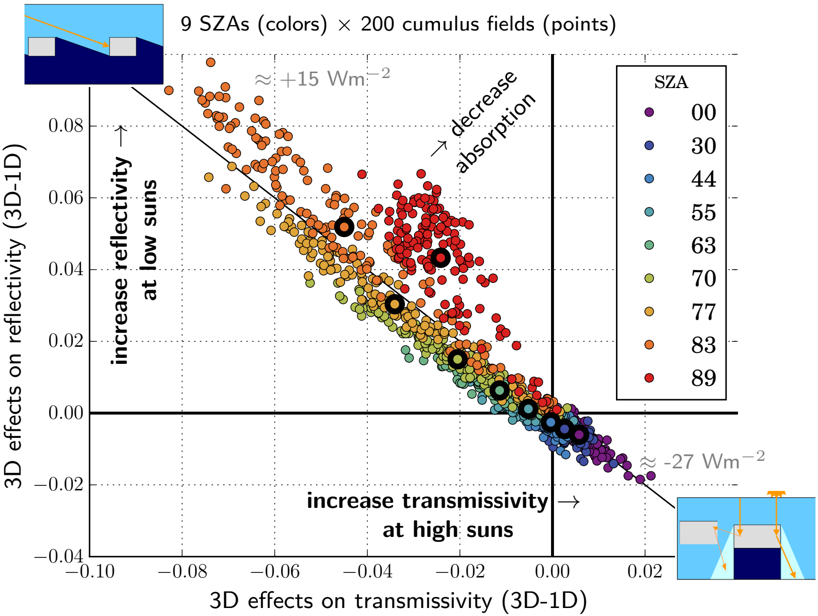
Stochastic sampling cloud heterogeneity + 2-stream (= McICA)
Barker et al. 2002, Pincus et al. 2003
Current standard



Modified 2-stream (TripleClouds and SPARTACUS)
Shonk and Hogan 2008, Hogan et al. 2016, 2019

ICA = Independent Columns Approximation
= one 1D RT calculation per column, then averaged
ICA versus 3D transport? ⇒ 3D effects

Change in radiation due to 3D effects, horizontally averaged, as a function of solar zenith angle



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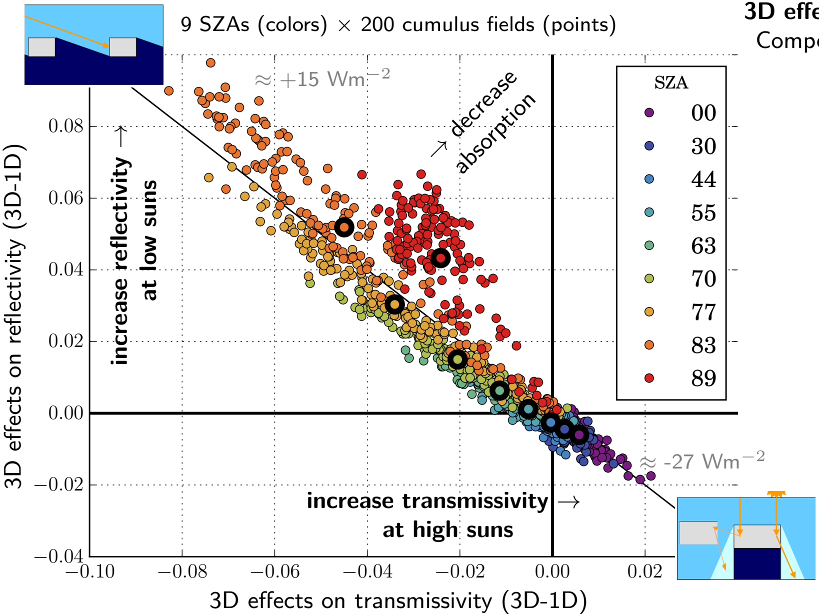
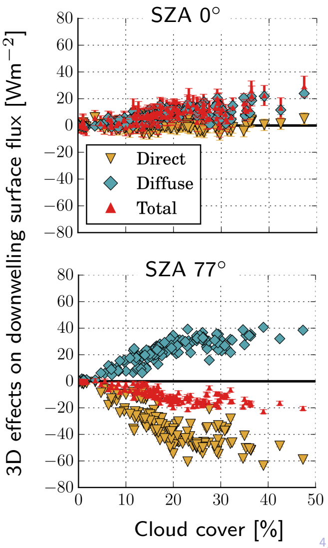


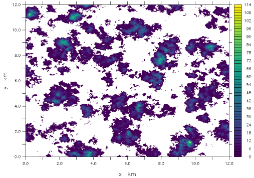
3D effects increase with cloud cover

Competing direct and diffuse effects

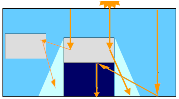


Change in radiation due to 3D effects, horizontally averaged, as a function of surface albedo

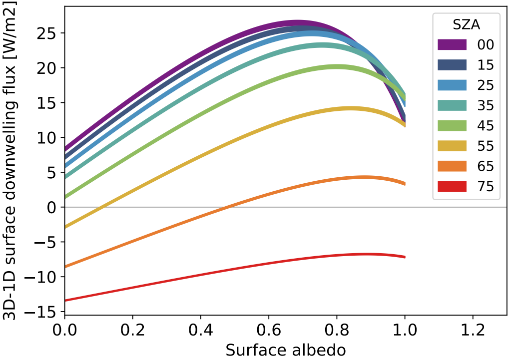
Cloud field optical depth



paths in cumulus



3D effects at surface



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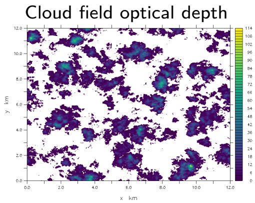
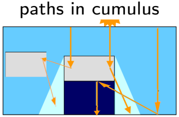
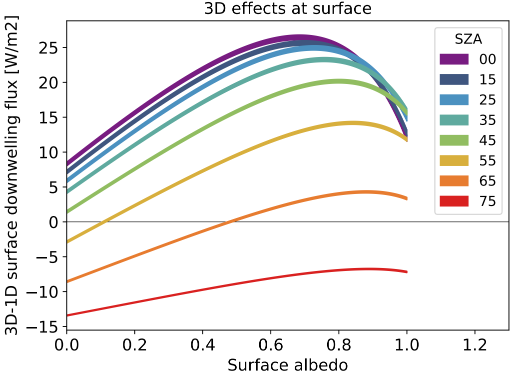
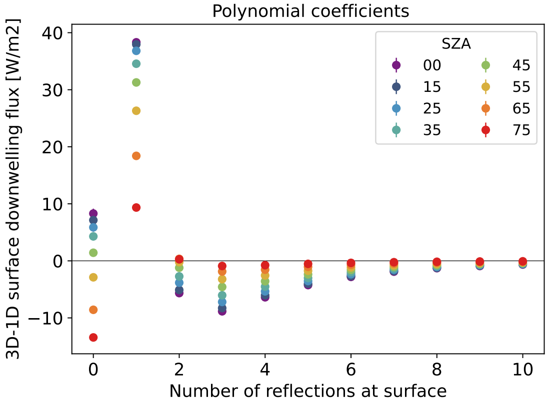
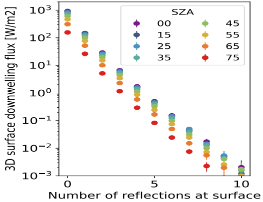
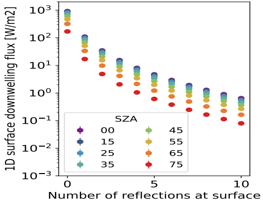






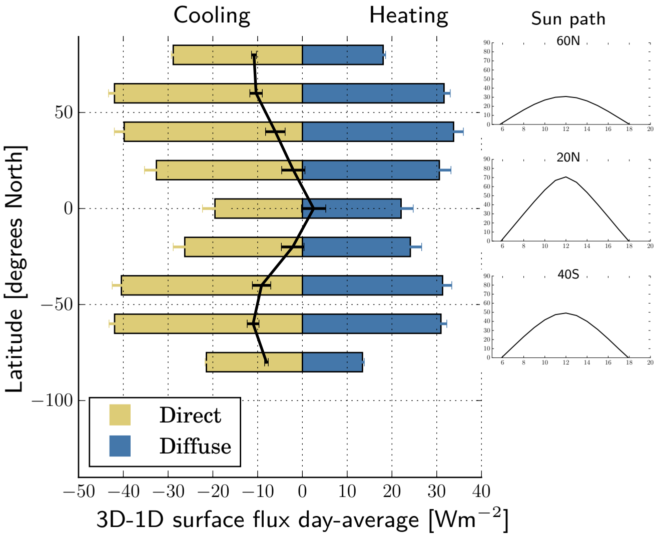






Day-averaged errors due to 3D effects, horizontally averaged, as a function of latitude (21st Sept)

Idealized experiment with one static cloud field
Each path starts at a different time of the day



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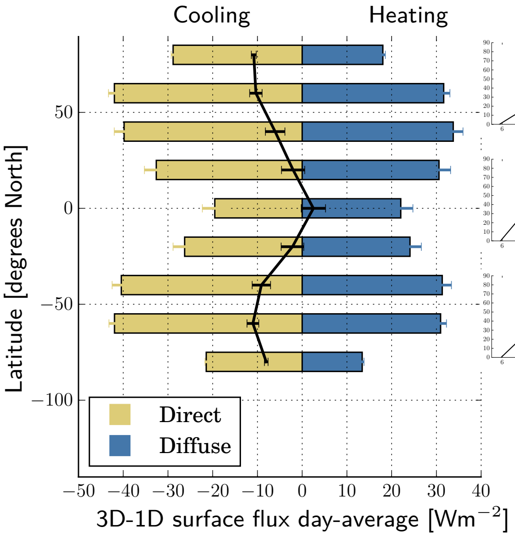
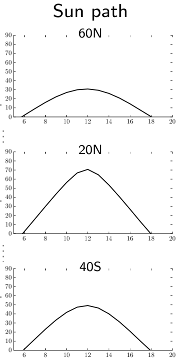
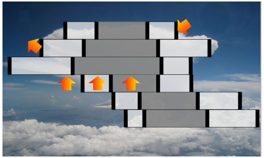




Summary

- 3D effects in the solar, depend on SZA, cloud field properties, surface albedo
- Larger surface albedo, enhances entrapment, more light to the surface... ocean/continent contrasts
- Do not systematically average out over the day... latitudinal contrasts

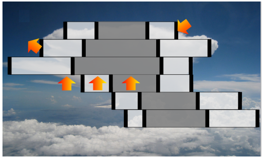
⇒ **Impacts on climate?**



- 3 regions per layer = 2 cloudy (1 thin, 1 thick) + 1 clear
- Overlap of fractional clouds = exponential-random

- TripleClouds = transfers between overlapping regions of distinct layers
- **SPARTACUS = TripleClouds + transfers between regions in a given layer**

The SPeedy Algorithm for Radiative TrAnsfer through CloUd Sides (Hogan, Shonk, Schäfer, et al. 2013-16-19)



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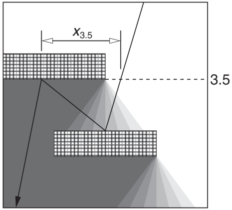
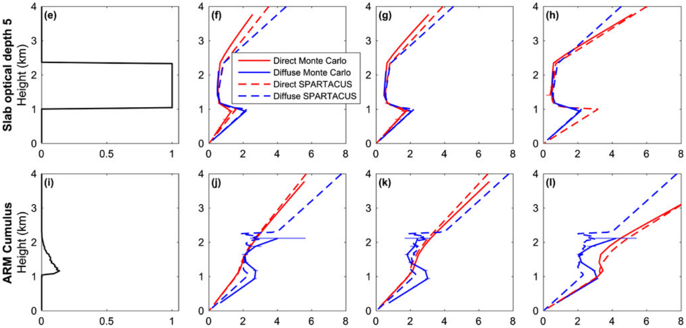
The model was originally designed to represent transfers "through cloud sides"
But "entrapment" does not necessarily involve cloud sides! ⇒ Hogan, Fielding, Barker, Villefranque & Schäfer, 2019

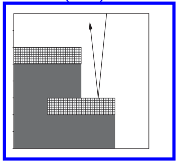




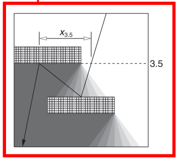
Cloud fraction   Mean horizontal distance between crossings, x [km]

SPARTACUS with entrapment, results

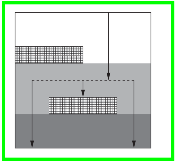
Zero (1D)

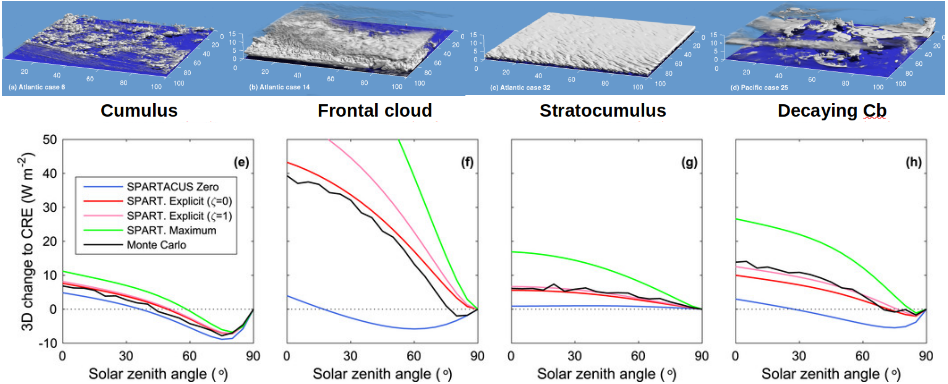


Explicit



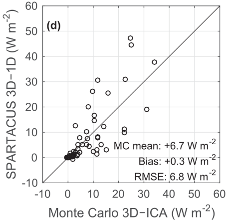
Maximum





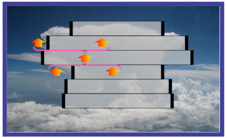
- SPARTACUS with explicit entrapment matches Monte Carlo simulations well on average
- Very important for multi-layered cloud scenes!

More sophisticated parameterization... more free parameters...



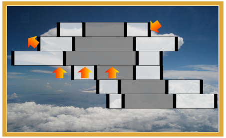
Calibrating SPARTACUS with High-Tune:Explorer (Couvreux, Hourdin, Villefranque, et al. 2020-21)

1D RT in max-overlap homogeneous clouds



FSD=0, $z_0=\infty$, $C_s=\infty$

3D RT in exp-overlap heterogeneous clouds



FSD, z_0, C_s from LES

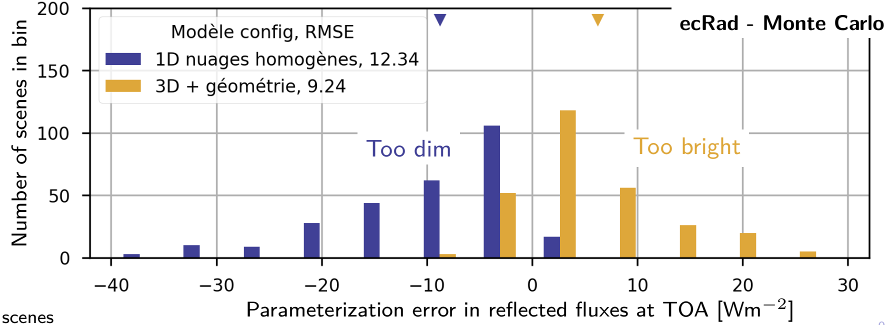
FSD = Relative horizontal heterogeneity of in-cloud water, smaller FSD $\Rightarrow$ more opaque $\Rightarrow$ brighter

$\mathbf{z_0}$ = Overlap decorrelation length scale, smaller z_0 $\Rightarrow$ larger cloud cover $\Rightarrow$ brighter

$\mathbf{C_s}$ = Cloud effective scale, smaller C_s $\Rightarrow$ more 3D effects $\Rightarrow$ dimmer at high suns, brighter at low suns

35 cloud fields × 8 SZAs = 280 scenes

ecRad evaluation



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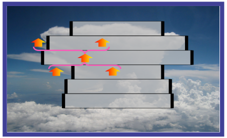

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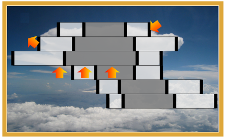
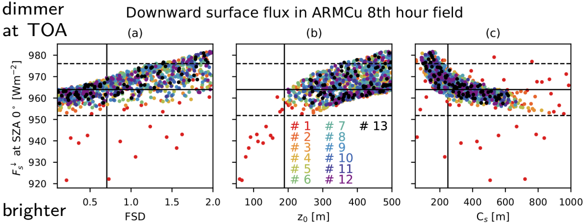


FSD, z_0, C_s from LES

dimmer at TOA



brighter at TOA

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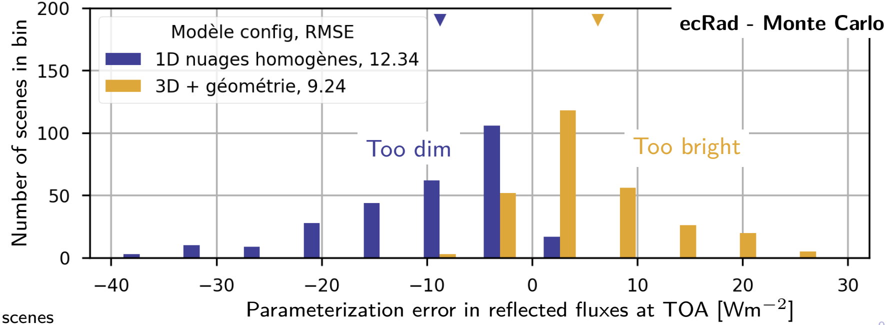

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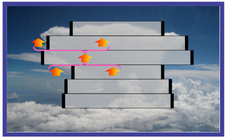

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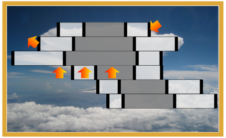

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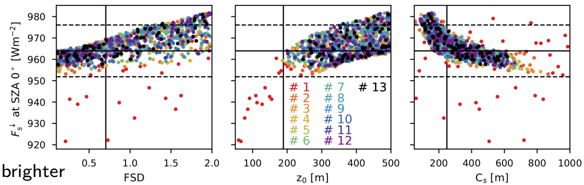
dimmer at TOA

Downward surface flux in ARMCu 8th hour field



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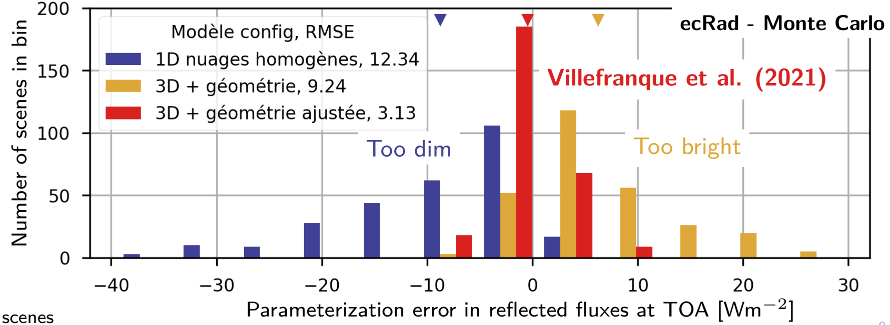
ecRad evaluation & **tuning** FSD = 1.079, z_0=436 m, C_s=155 m

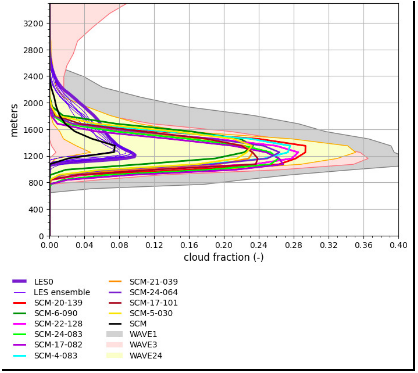


More ongoing work at LMD!

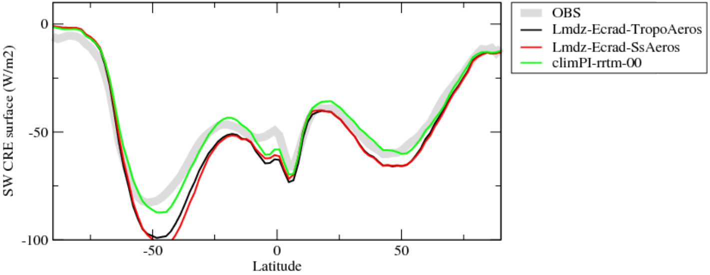
- Maëlle Coulon Decorzens, PhD student tuning/radiation

  Most GCMs tune cloud parameters targetting radiative metrics
  Compensating errors? Investigate this in the SCM/LES framework →
  LMDZ SCM + offline SPARTACUS, target MC references

ARMCu 8th hour, LES vs tuned SCM



- ecRad online in LMDZ, led by Abderrahmane Idelkadi



  Change in climate due to inclusion of 3D effects specifically?
  Tuning + feedbacks

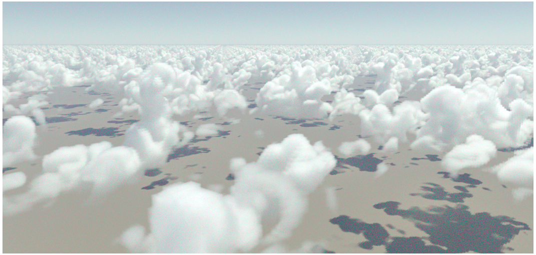
The future of 3D radiative transfer in GCMs?

• 2-stream based models: efficient and very powerful for learning because need to summarize our understanding of what are the processes that matter and how they work at the cloud field scale...
But what if an entire process is missing (eg entrapment, LW issues in high clouds)?

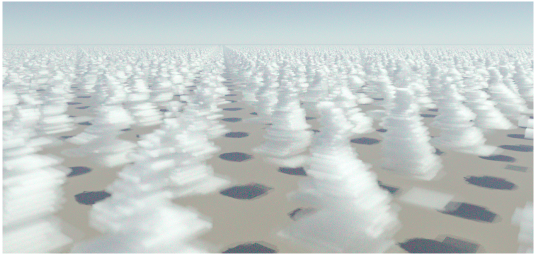
• Monte Carlo methods allow much more than accurate solving radiation: flexibility, creativity, looking at the paths, accessing the processes... **Could they also be suitable for parameterization?**
$\Rightarrow$ Idea investigated in Barker et al., 2016: stochastic generation of 3D cloud fields + MC solver.

• Ongoing work: *what miminal assumption do we need to make on cloud geometry to estimate cloud radiative effect to within x%?*

Original cumulus cloud field from LES



Generated. "Mean cloud" assumption, CRE $\approx \pm 10\%$



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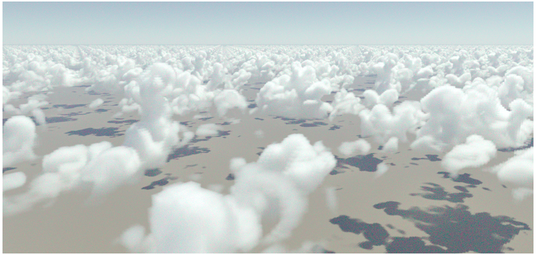

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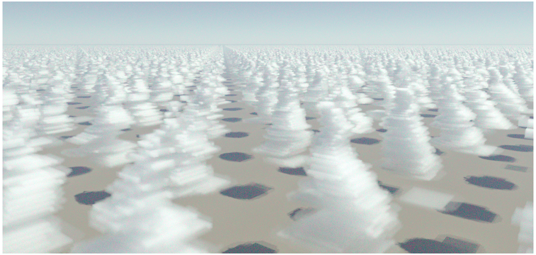

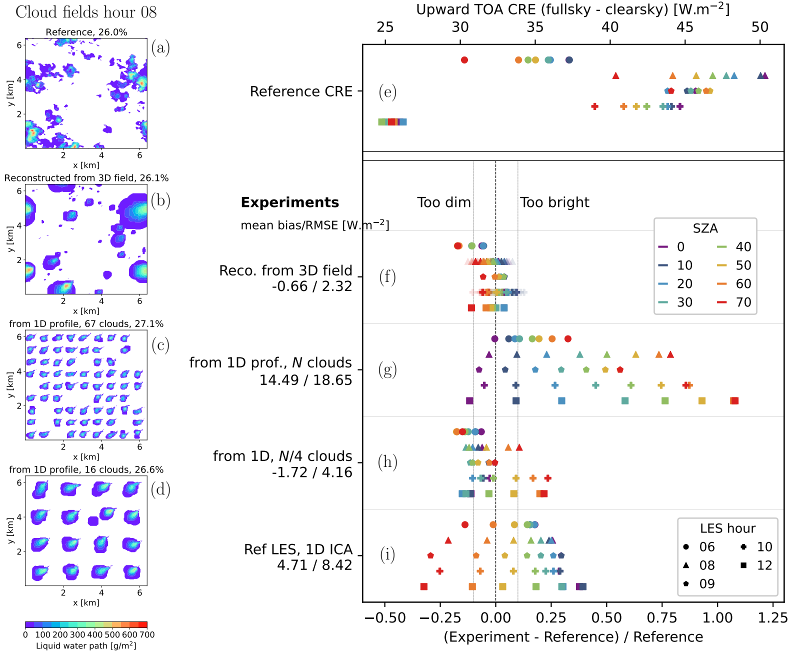

Cloud fields hour 08
Reference, 26.0%
(a)
Reconstructed from 3D field, 26.1%
(b)
from 1D profile, 67 clouds, 27.1%
(c)
from 1D profile, 16 clouds, 26.6%
(d)
x [km]
y [km]
0 100 200 300 400 500 600 700
Liquid water path [g/m^2]
Upward TOA CRE (fullsky - clearsky) [W.m^{-2}]
25 30 35 40 45 50
Reference CRE
(e)
Experiments
mean bias/RMSE [W.m^{-2}]
Too dim
Too bright
Reco. from 3D field
-0.66 / 2.32
(f)
from 1D prof., N clouds
14.49 / 18.65
(g)
from 1D, N/4 clouds
-1.72 / 4.16
(h)
Ref LES, 1D ICA
4.71 / 8.42
(i)
SZA
0 10 20 30 40 50 60 70
LES hour
06 08 09 10 12
−0.50 −0.25 0.00 0.25 0.50 0.75 1.00 1.25
(Experiment - Reference) / Reference