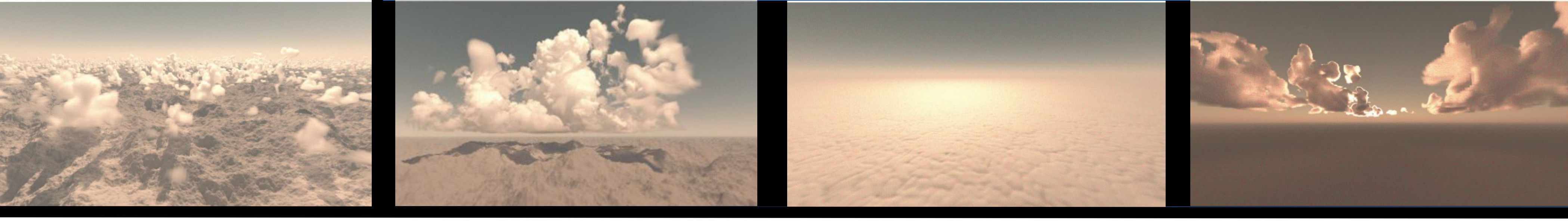
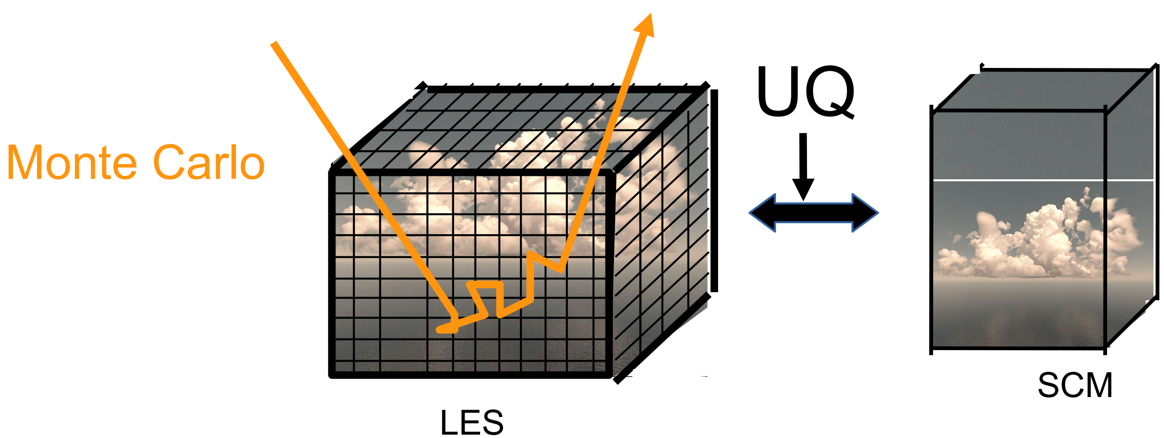


HIGH-resolution simulations to improve and TUNE boundary-layer cloud parameterizations

F Couvreux & F Hourdin

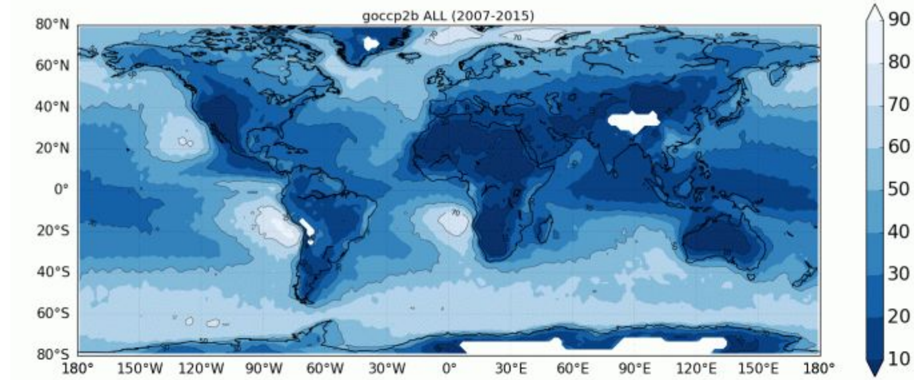
N Villefranque, R Roehrig, C Rio, O Audouin, F Brient… (CNRM & LMD)
D Williamson, V Volodina,… (Exeter University)
R Fournier, S Blanco, V Eymet, V Forest,... (LAPLACE, Mesostar)



Focus on low-level clouds

Key element of climate :

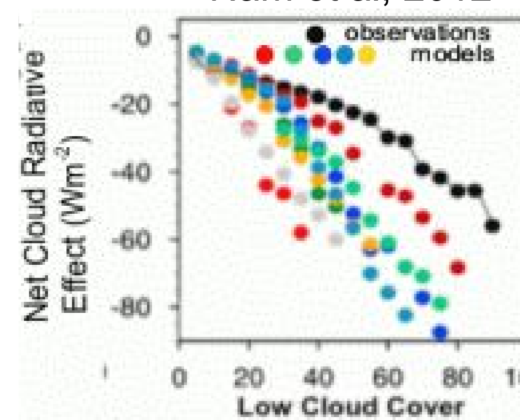
BL clouds obiquitous
Control the Earth radiative budget



Brient et al, JAMES,2019

At the heart of climate uncertainties:

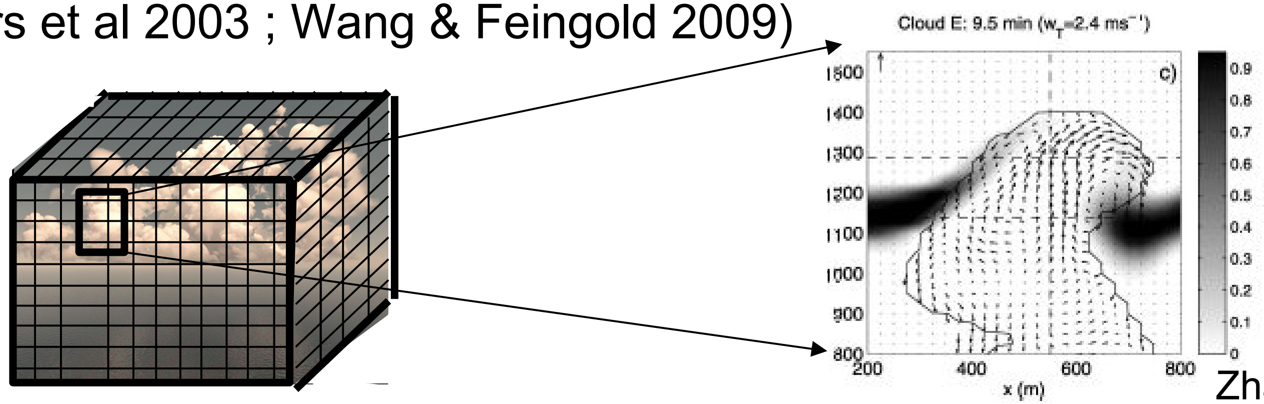
Nam et al, 2012



Parameterized
Still associated to biases (ex too few too bright)
Responsible for spread in projection (Cess et al 89, Bony and Dufresne 2005, Vial et al 2013, Brient et al 2016)

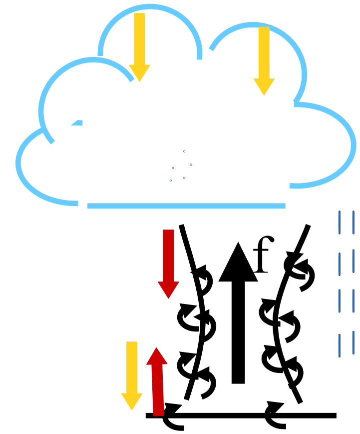
Available references:

Difficult observations by satellite
LES realistically reproduce morphology/thermodynamics of BL clouds (Siebesma and Cuijpers 95 ; Neggers et al 2003 ; Wang & Feingold 2009)



Zhao and Austin, 2005

Improving the cloud representation



Involved several parameterizations

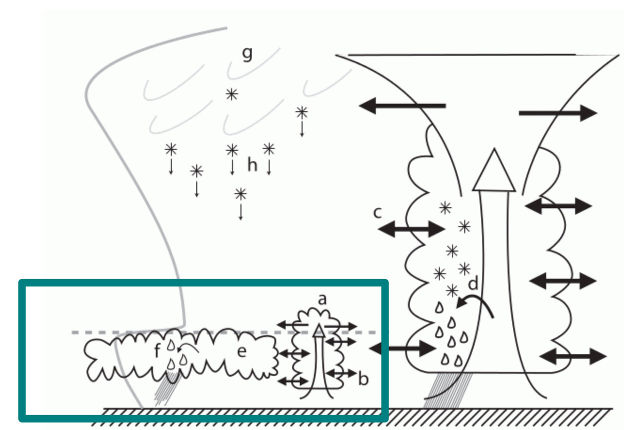
BL clouds=sub-grid processes for most models (NWP, Climate)
Turbulence, convection, cloud scheme, microphysic, radiative scheme

Recent significant progresses

In the parameterizations of cloud and transport (Rio et al 2019)
-turbulence and convection : ex : Eddy-Diffusivity Mass Flux concept
-a better coupling between the cloud scheme and the BL dynamics
In the representation of cloud radiative effects
=> talk R Hogan (Wednesday)

Calibration

Free parameters that must be calibrated
Complicated task, scarcely documented (Hourdin et al 2017)
Often optimization, issue with overtuning (Williamson et al 2015), without much control on impact on parameterization behaviour

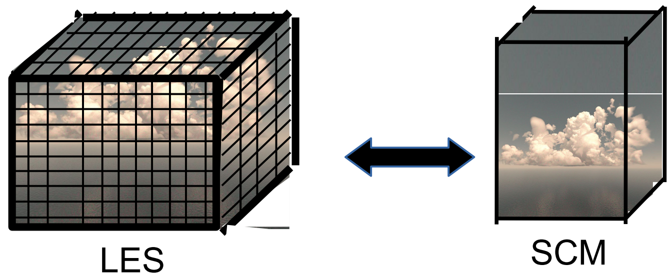


Mauritsen et al, 2012

Objectives

To tackle model development and calibration together in order to be able to disentangle deficiencies due to poor parameter calibration from intrinsic limits rooted in the parameterization formulations

The LES/SCM framework



$\mathbf{y}$ $\quad\quad$ $\mathbf{x_c}$

$$\frac{\partial \boldsymbol{y}}{\partial t} = \mathcal{L}(\boldsymbol{y}) + \mathcal{F}_c(\overline{\boldsymbol{y}}) \quad \longleftrightarrow \quad \frac{\partial \boldsymbol{x}_c}{\partial t} = \sum_{p_{\text{activated}}} \mathcal{P}_p(\boldsymbol{x}_c, \boldsymbol{\lambda}_p) + \mathcal{F}_c(\boldsymbol{x}_c)$$

$$\boldsymbol{x}_c(t=0) = \overline{\boldsymbol{y}}(t=0)$$

Advantages

A fair comparison
Focus on parameterization : no coupling with the large-scale dynamics
A framework largely used for model development and evaluation by GCSS now GASS (Browning 1993 ; Randall et al 1996, GASS, DEPHY)
SCM : cheap, still representative of global modelling (Neggers 2015 ; Gettleman et al 2019)

Objectives

Revisit this framework with new tools and for calibration purposes
To propose a process oriented calibration strategy also using radiative references

Importance of multicases

Construction of a database of cases

- Cover diversity of boundary-layer regimes
- Validate parameterization in different conditions (various coupling, contributions)
- Avoid some error compensation

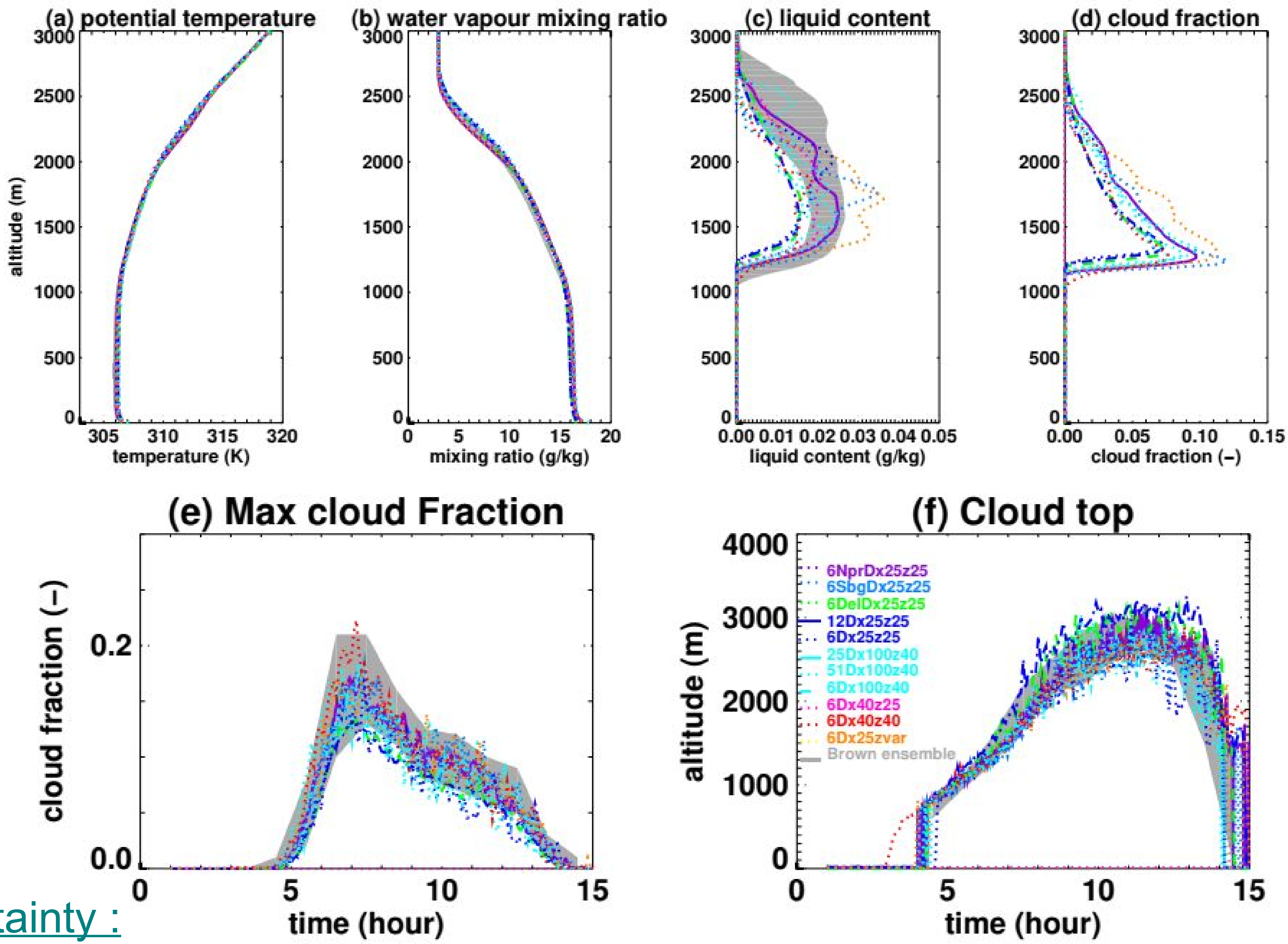
Common format (DEPHY initiative)

Input:
reliability (exact same forcings)
ease the use of multicases (revisit golden cases, add new cases)
Output:
ease the comparison between models
library of references: Ex: a library of the LES realized with Meso-NH http://mesonh.aero.obs-mip.fr/mesonh54/LESDEPHY)

Case name	grid resolution dx=dy, dz (m, m)	Domain Lx=Ly, H (km, km)	Specificity	Radiation	Reference	Observations
Academic cases of dry convective boundary layer						
AYOTTE-1	50, 40	10, 2	Varying inversion (strong/weak capping) and varying cst-in-time surface fluxes	No	Ayotte et al. 1996	No
AYOTTE-2	50, 40	10, 2		No		No
… 6	50, 40	10, 2		No		No
Cases of clear sky continental convective boundary layer						
IHOP	50, 40	10, 5	USA great plains	No	Couvreux et al., 2005	Yes
AMMA	50, 40	10, 5	Semi-arid, West-Africa	No	Canut et al., 2011	Yes
WANGARA	50, 40	10, 5	Semi-arid, Australia	No		Yes
Boundary layer cumulus						
ARM	50, 40	13, 4	Continental shallow, SGP	No	Brown et al., 2002	Yes
BOMEX	50, 40	13, 4	Oceanic shallow, Caraibes	No	Siebesma et al., 2003	Yes
RICO	50, 40	13, 4	Precipitating oceanic, Caraibes	No	Van Zanten et al., 2011	Yes
SCMS	50, 40	13, 4	Continental shallow, Florida	No	Neggers et al, 2002	Yes
CASS	50, 40	13,4	Composite cont. shallow, SGP	No	Zhang et al., 2017	Yes
Marine strato-cumulus clouds						
FIRE	25, 5-15	5, 1.2	Day and Nighttime stratocumulus	Yes	Duynkerke et al. 2004	Yes
DYCOMS2	25, 5-15	5, 1.5	Stratocumulus	Yes	Stevens et al., 2005	Yes
SANDU	35,5-15	9, 3.2	Transition to cumulus, Pacific	Yes	Sandu and Stevens, 2011	Yes
ASTEX	25, 5-15	5, 2	Transition to cumulus, Atlantic	Yes	Van Der Dussen et al., 2013	Yes
GreyZone	250,25-90	100, 5	Transition to cumulus,North Sea	Yes	De Roode et al, in prep	Yes
Stable boundary layer						
GABLS1	?	1000, 500	Academic case	No	Beare et al, 2006	No
GABLS4	1,1	500,200	Antarctica	No	Bazile etal, 2019; Couv et al 2019	Yes
Transition to deep convection						
AMMA	100, 50	100, 20	Niamey, initiation of local storm	No	Couvreux et al., 2012	Yes

Reference LES with uncertainty

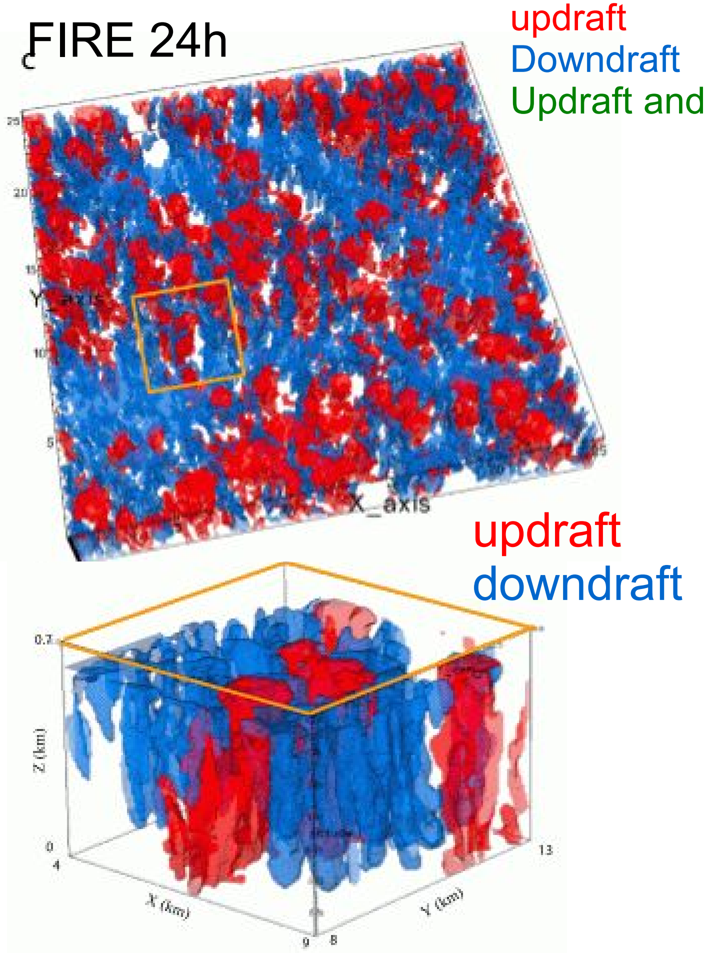
ARMCU

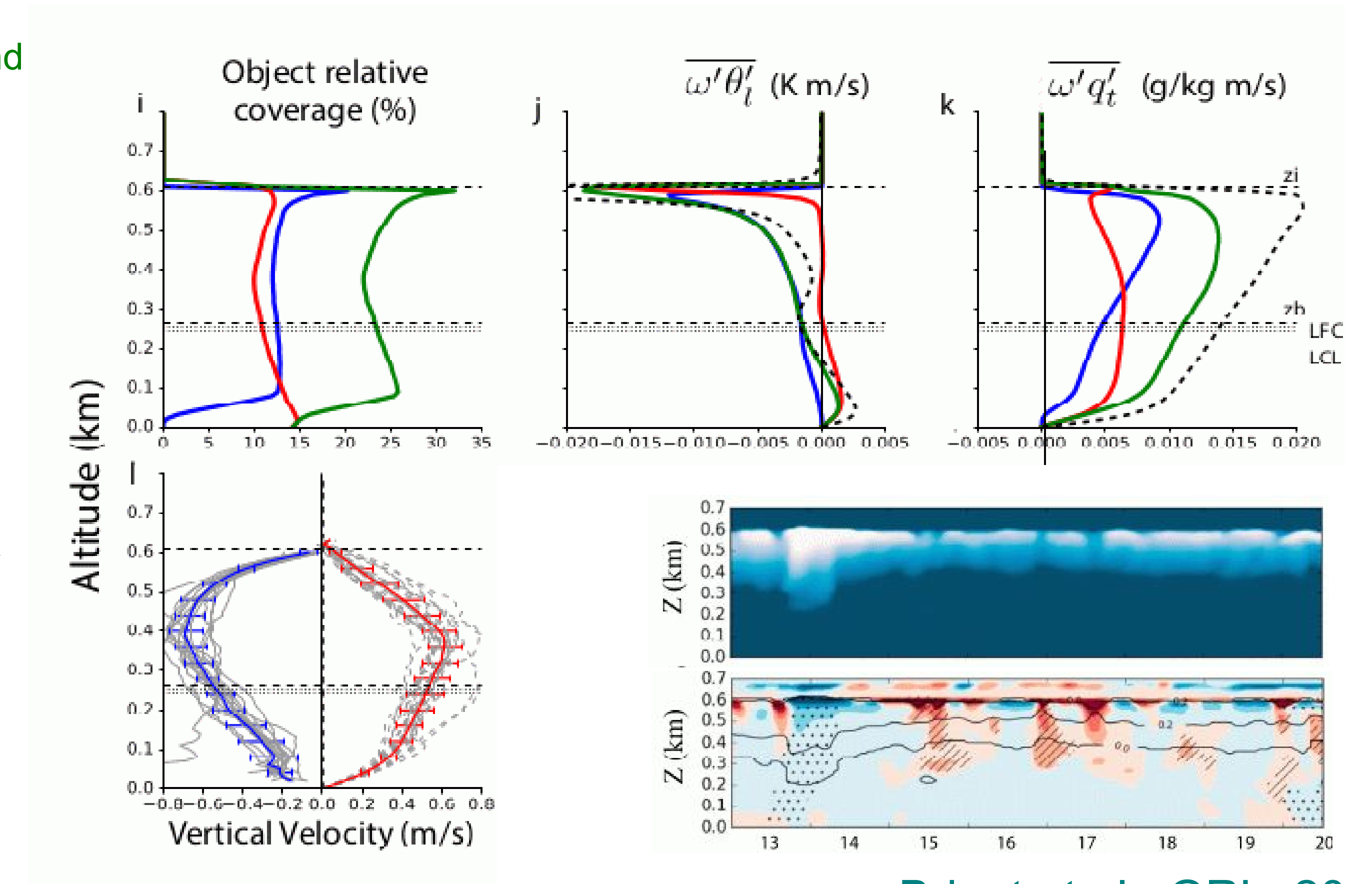


Uncertainty :

- from sensitivity tests (resolution, domain size, turbulence, microphysics) with one given model
- similar range than model intercomparison

Process Analysis in LES





Brient et al., GRL, 2019

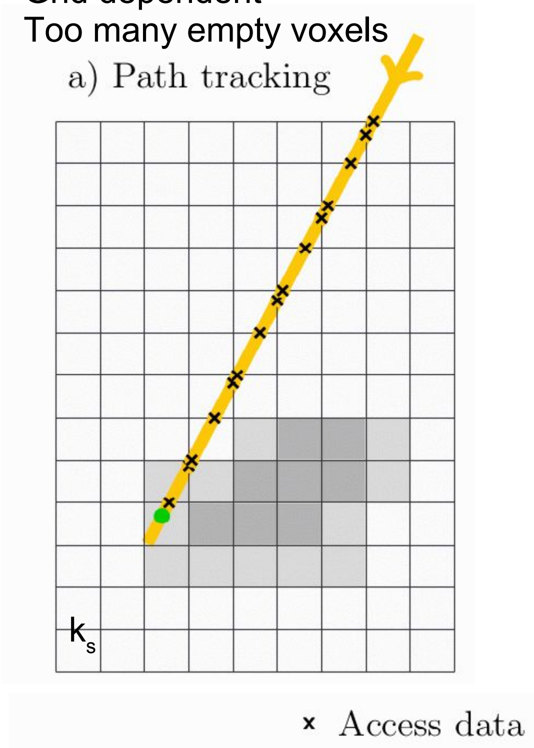
- Boundary-layer coherent structures identified as objects using passive tracers in different LES simulations

- In stratocumulus, both downdrafts and updrafts contribute significantly to heat and moisture transport, although covering only a small fraction of the domain

Talk of F Brient Friday Afternoon

References for cloud radiative effect

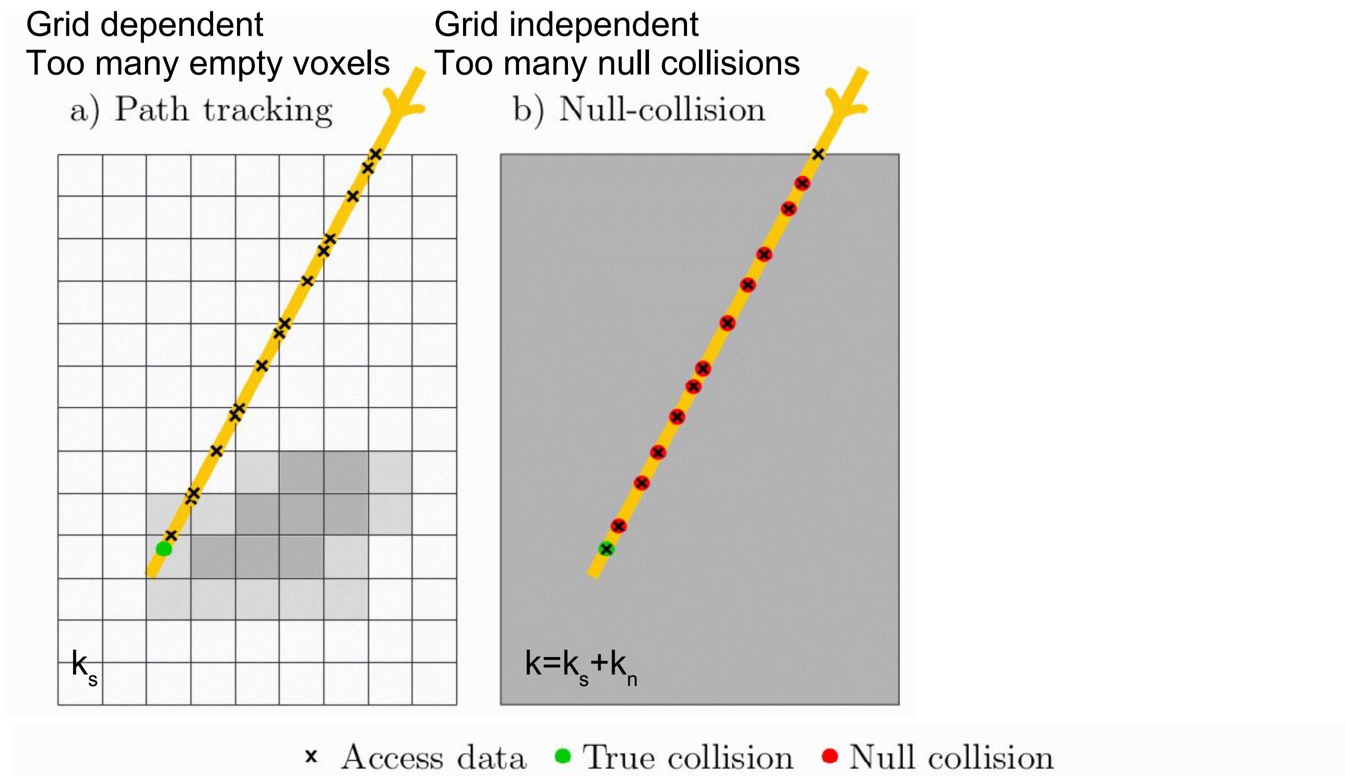
Grid dependent
Too many empty voxels



Monte Carlo methods to compute all types of radiative metrics (local/spatially integrated, monochromatic/ broadband) on LES (despite the increasing amount of data~10[6-9] grids)

Path-tracing library for flexible implementation of Monte-Carlo algorithms in cloudy atmosphere

References for cloud radiative effect



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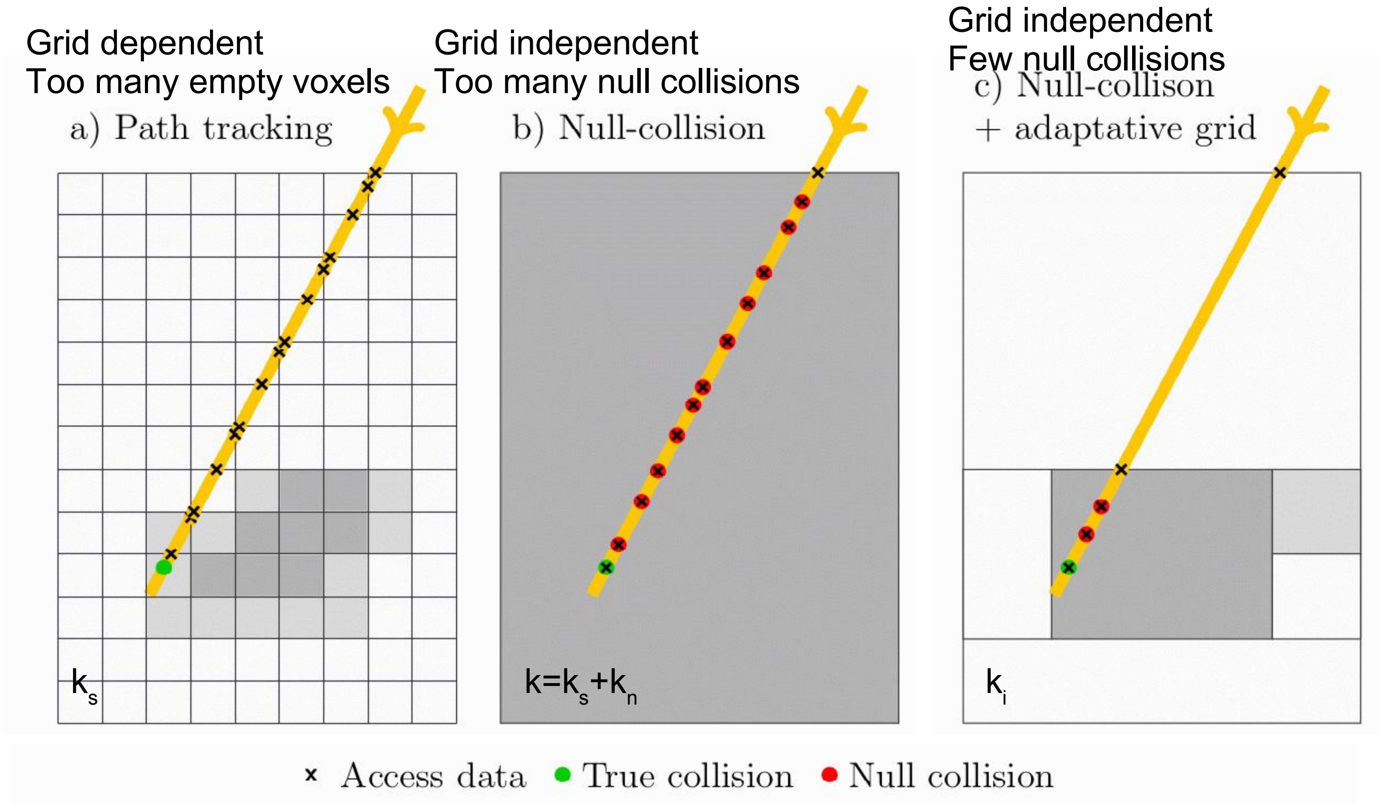
Path-tracing library for flexible implementation of Monte-Carlo algorithms in cloudy atmosphere

Use of null-collision algorithms to by-pass the non-linearity of Beer extinction but not efficient in highly heterogeneous media

References for cloud radiative effect



Villefranque et al, JAMES, 2019

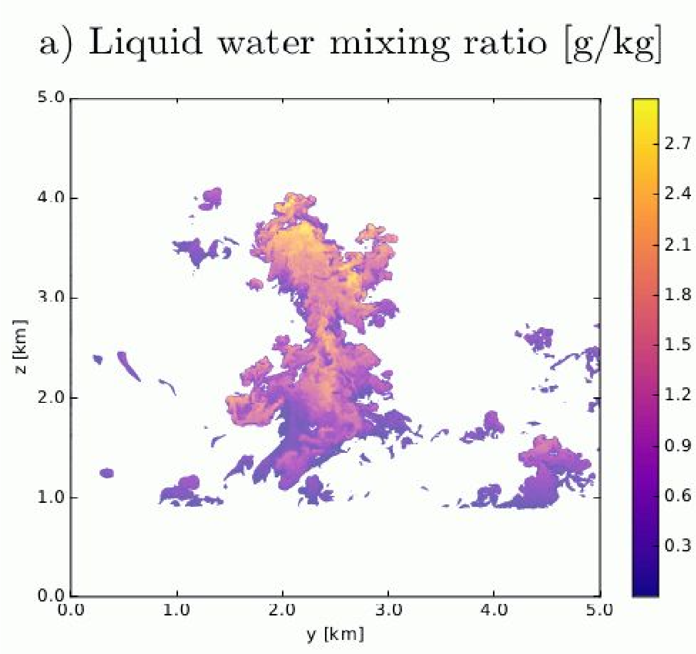
Monte Carlo to compute all types of radiative metrics (local/spatially integrated, monochromatic/ broadband) in LES (with increasing amount of data~$10^{[6-9]}$ grids)

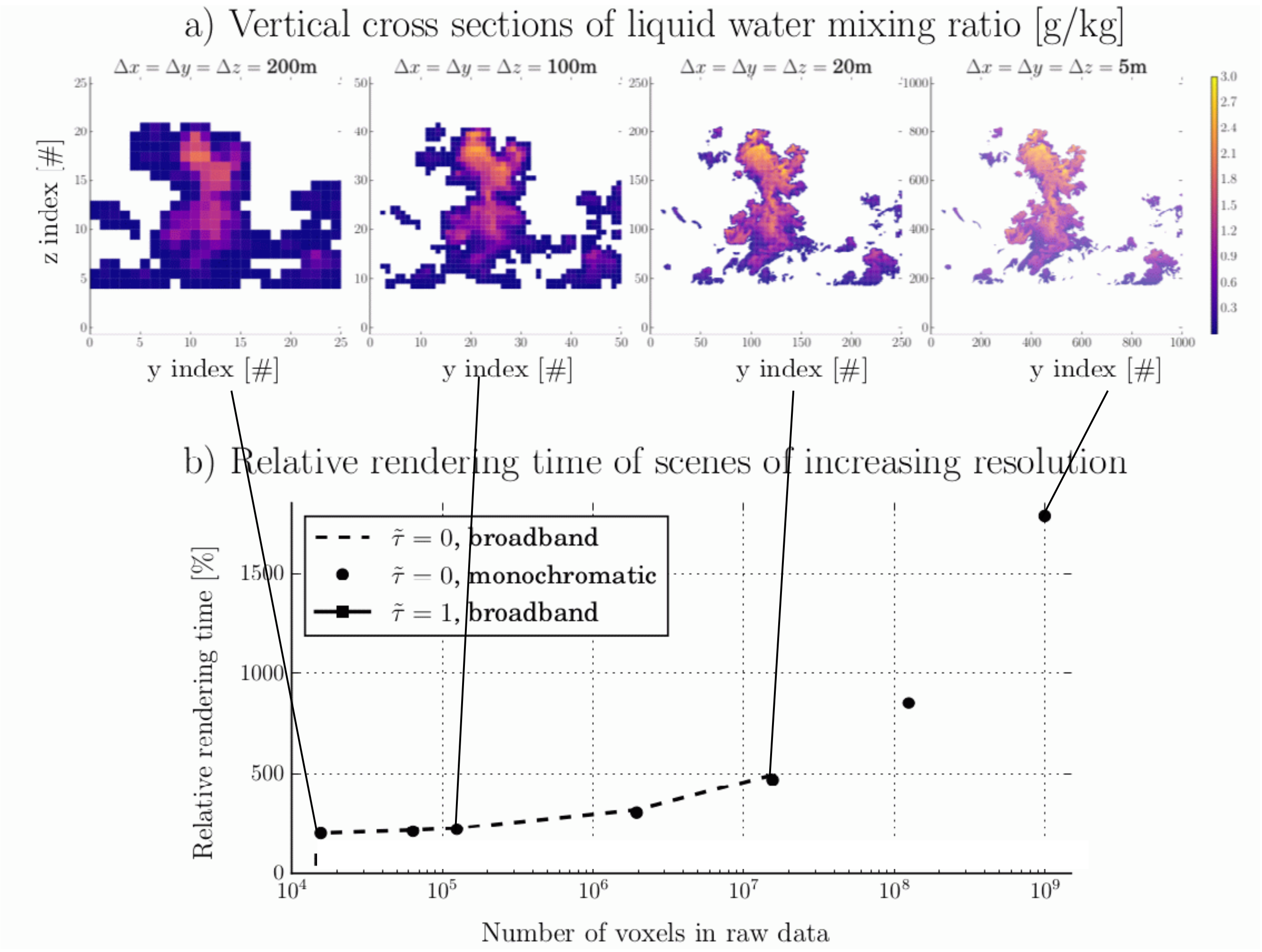
Path-tracing library for flexible implementation of Monte-Carlo algorithms in cloudy atmosphere

Use of null-collision algorithms to by-pass the non-linearity of Beer extinction

Combining null-collision algorithms with recursive hierarchical grids in order to homogeneize the media by subsection (with a condition on optical depth) to accelerate ray-tracing and make them independent of data amount and resolution

References for cloud radiative effect

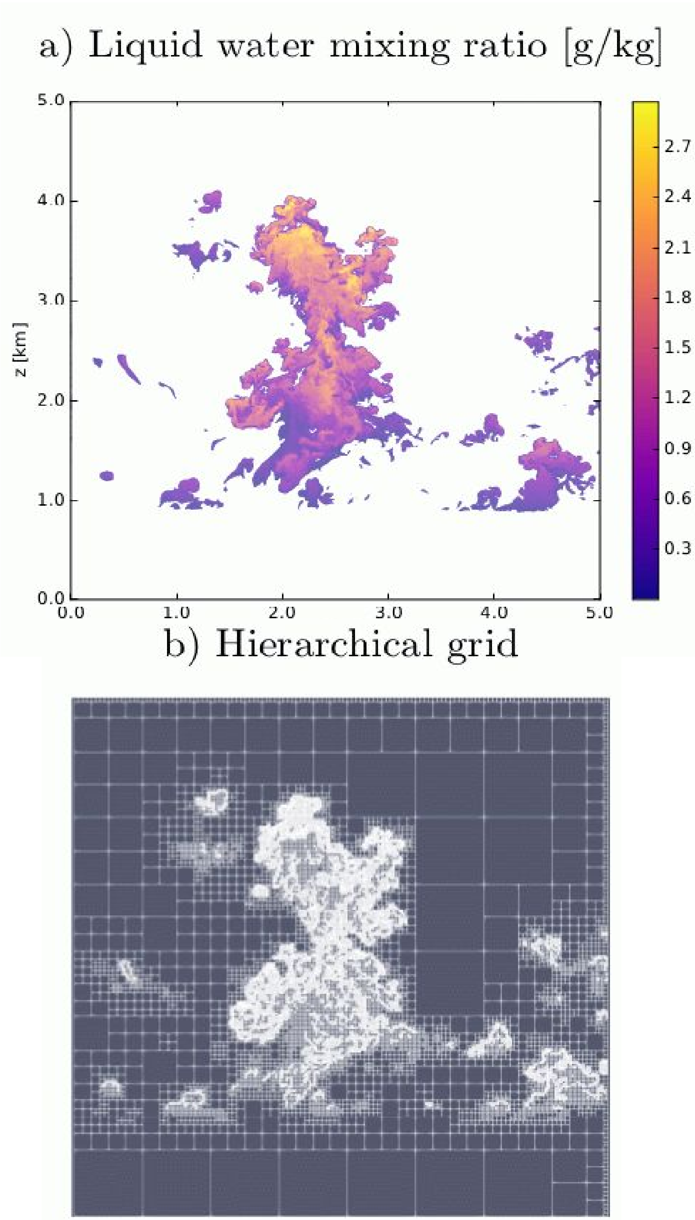




LES of congestus, Dx=5m
Strauss et al, 2021

Villefranque et al., JAMES, 2019

References for cloud radiative effect



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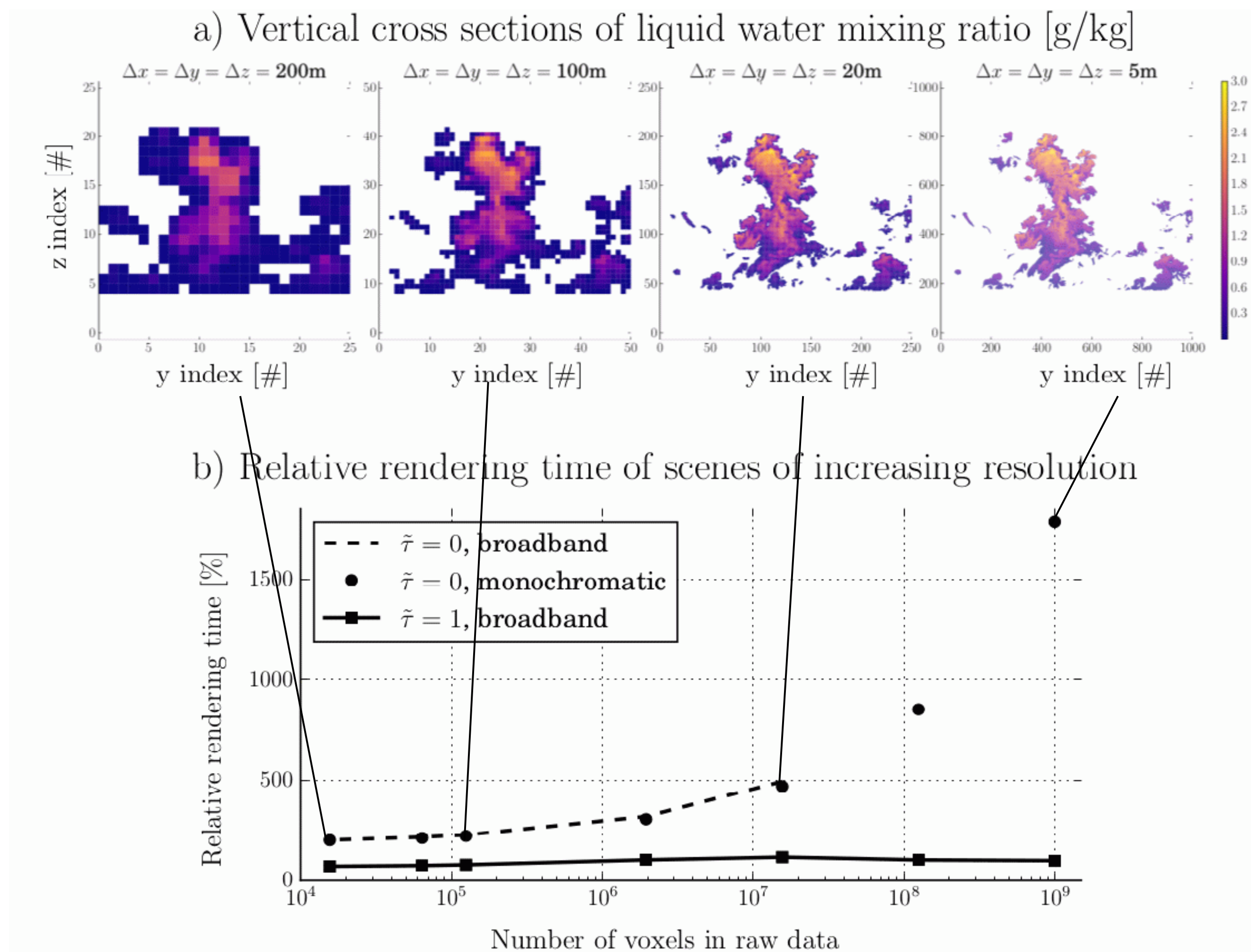


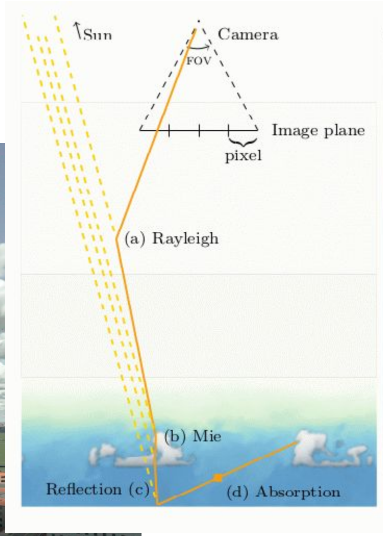
Insensitivity to the complexity of the input data

A code freely available

[Tutorial on the tool Wednesday Morning]

Villefranque et al., JAMES, 2019

Synthetic images of clouds

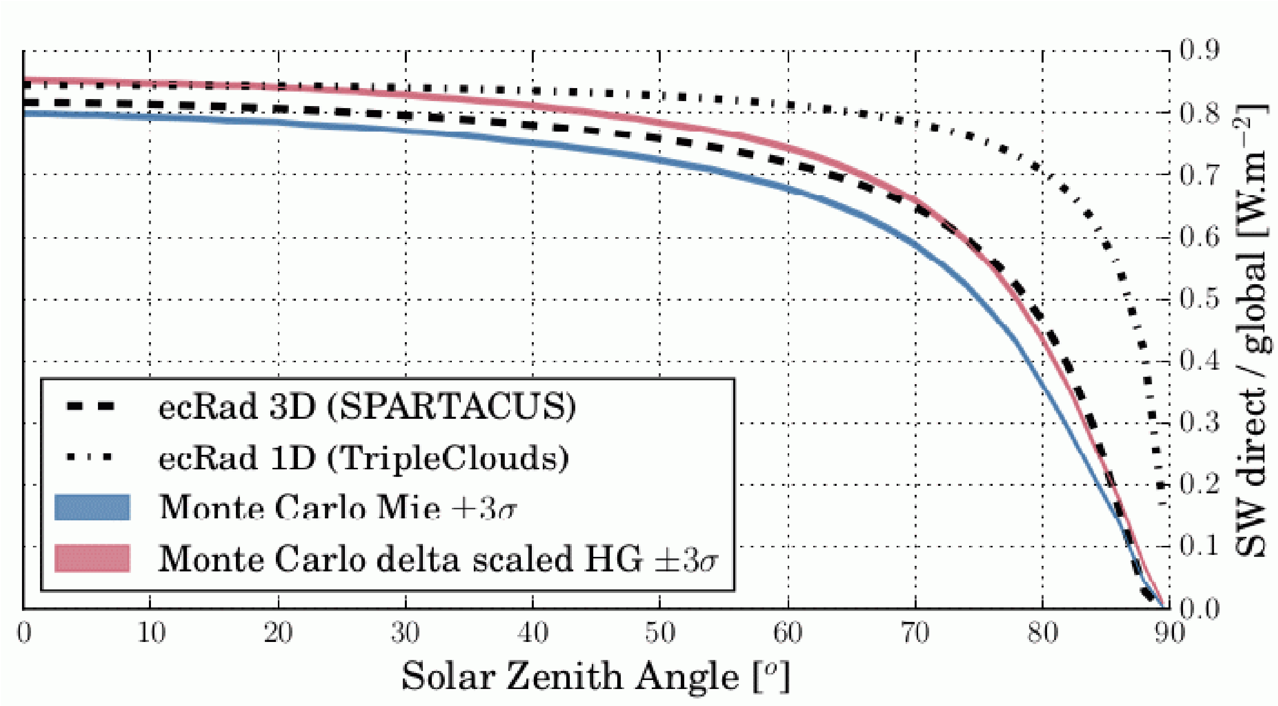


Joulin et al, 2020

- 3 Monte-carlo backward computation for the responsivity spectra of the human eye for each pixel of the camera
- Can deal with complexity of surface and atmosphere

https://www.lmd.jussieu.fr/~nvillefranque/pages/galerie.html

References for radiative development

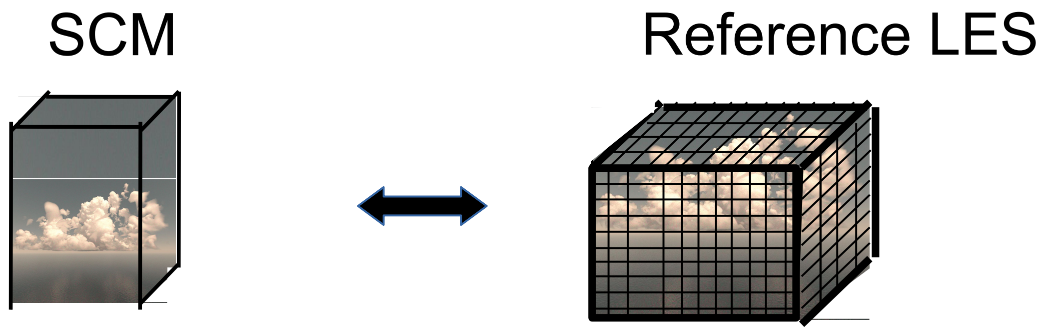


Villefranque et al., JAMES, 2019

- New process-oriented diagnostic to evaluate radiative parameterizations: statistic analysis of photon paths, direct/diffuse partitionning

- Possible to study the sensitivity to various assumptions classically made in the 2-stream radiative scheme (ex optical properties, phase functions, ...)

A process-based calibration tool



History matching with iterative refocusing (Williamson et al 2013)

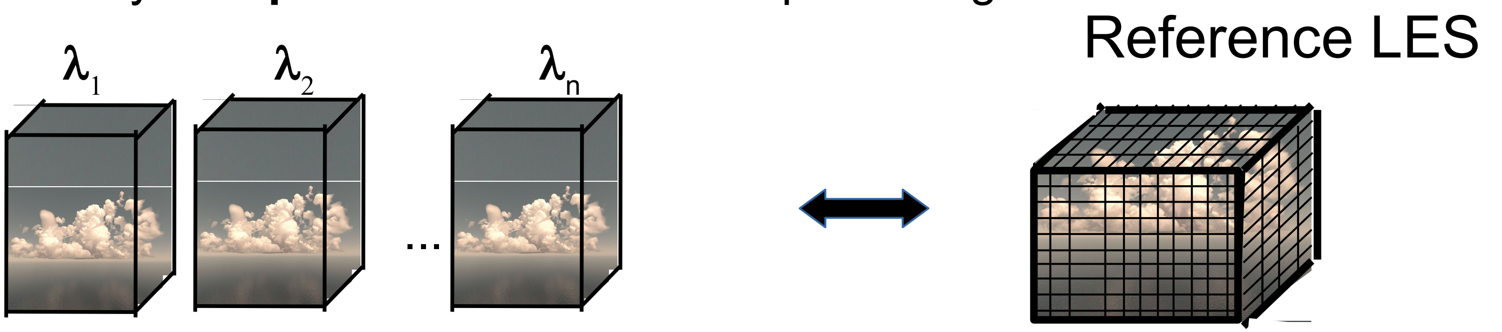
- Machine learning approaches for tuning (UQ)

To define the sub-space of the <u>parameter values</u> for which <u>SCM</u> matches <u>LES</u> on <u>selected metrics</u> for <u>a series of cases</u> within a given <u>uncertainty</u>

A process-based calibration tool

Selection of **metrics** [can combine different cases and metrics]

Identify **free parameters** and their a-priori ranges



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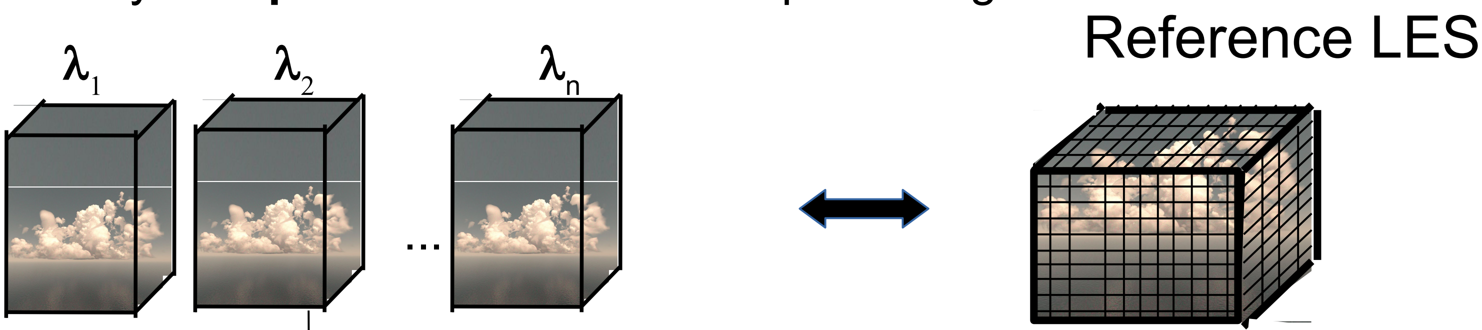

SCM metrics = training dataset

emulator

metrics for any λ ± uncertainty

History matching with iterative refocusing (Williamson et al 2013)

- Machine learning approaches for tuning (UQ)
- Extensive exploration of parameter space with emulator

A process-based calibration tool

Selection of **metrics** [can combine different cases and metrics]

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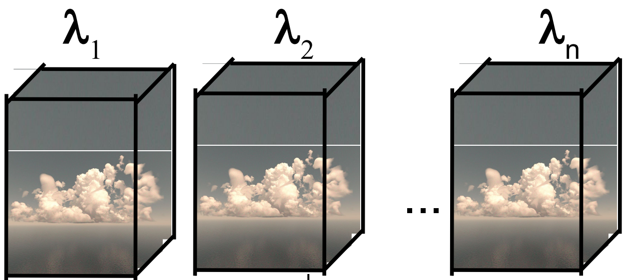
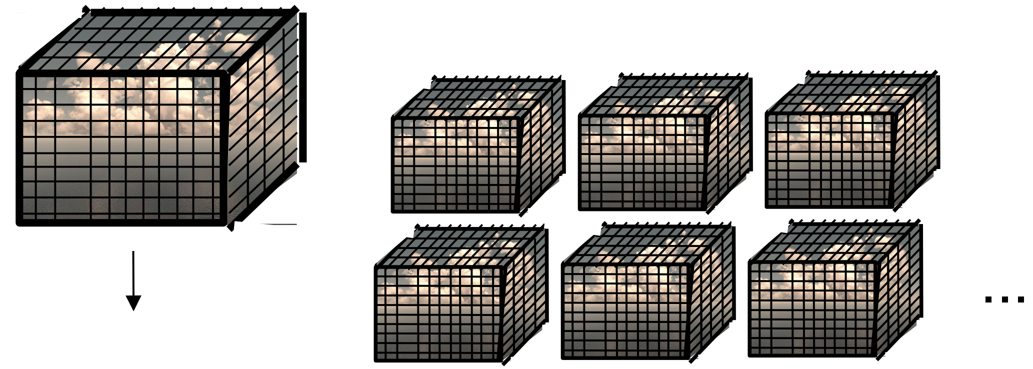


Reference LES



SCM metrics = training dataset

emulator

metrics for any λ ± uncertainty

Reference metrics ± uncertainty

structural error

Discard **impossible values of parameters**

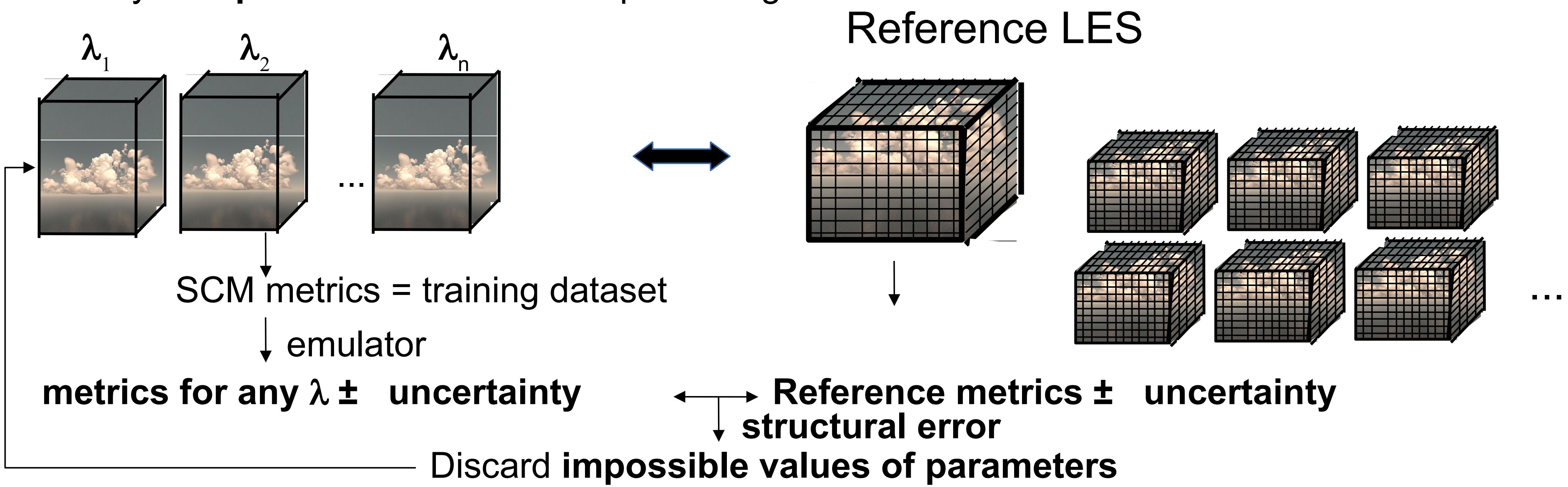
History matching with iterative refocusing (Williamson et al 2013)

- Machine learning approaches for tuning (UQ)
- Extensive exploration of parameter space with emulator
- Taking into account different sources of uncertainties : a/observation error, b/ emulator error and c/ an error tolerance or structural error to avoid error compensation

A process-based calibration tool

Selection of **metrics** [can combine different cases and metrics]

Identify **free parameters** and their a-priori ranges



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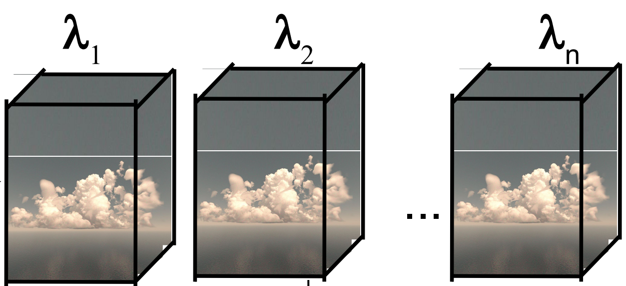
- Removing progressively implausible values

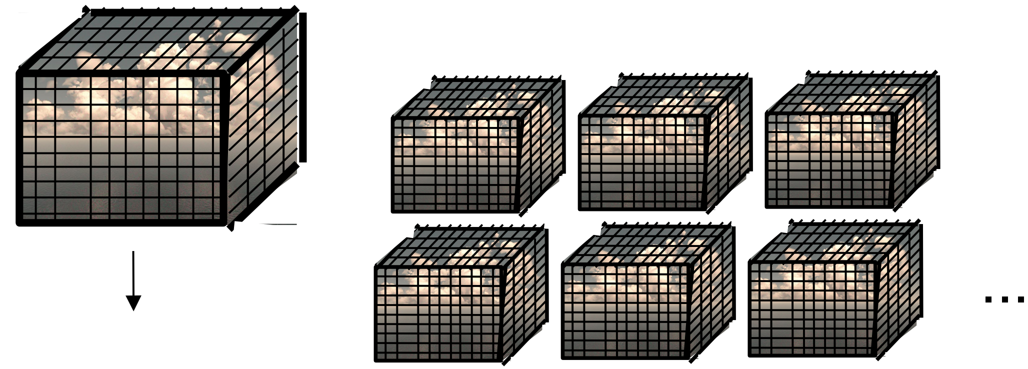
A process-based calibration tool

Selection of **metrics** [can combine different cases and metrics]

Identify **free parameters** and their a-priori ranges



Reference LES



SCM metrics = training dataset

emulator

metrics for any λ ± uncertainty

Reference metrics ± uncertainty

Discard **impossible values of parameters**

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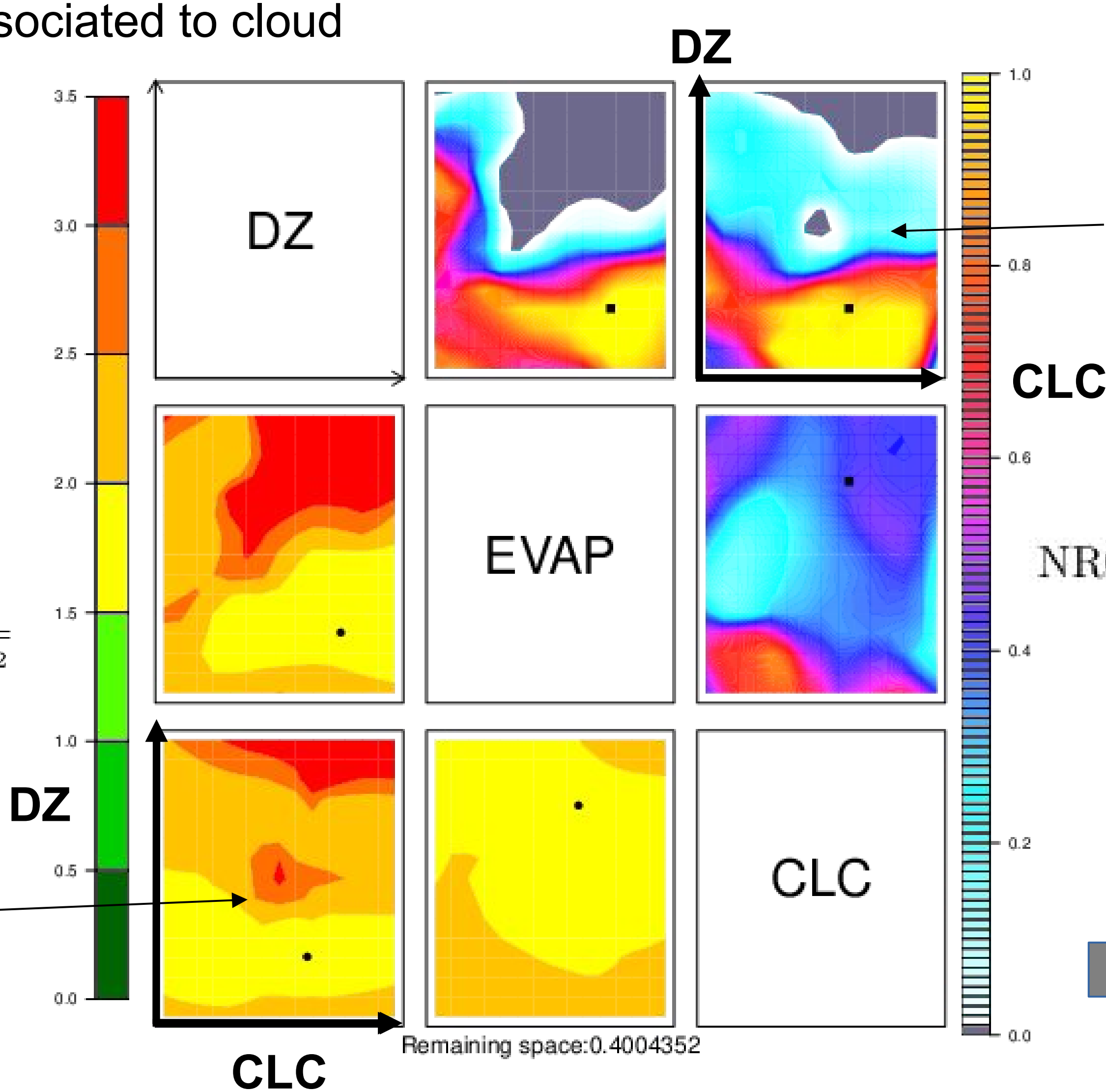
- Removing progressively implausible values

Couvreux et al, 2020

Tutorial on the tool
Tuesday Afternoon

One example with LMDZ

Revisiting the CMIP6 tuning of LMDZ6A model on 1D cases (ARMCU/RICO/SANDU) by comparison with LES
Varying 3 parameters associated with EDMF+ cloud scheme
Targeting 8 metrics associated to cloud



Fraction of the Not Ruled Out Yet (NROY) points when varying EVAP

$$\mathrm{NROY}_f^1 = \{\boldsymbol{\lambda} \mid I_f(\boldsymbol{\lambda}) < T\}$$

$$I_f(\check{\lambda}) = \frac{|r_f - \mathbf{E}[f(\check{\lambda})]|}{\sqrt{\sigma_{r,f}^2 + \sigma_{d,f}^2 + \sigma_f(\check{\lambda})^2}}$$

Minimum value of the Implausibility when varying EVAP

Ruled out : values of (CLC,DZ) excluded whatever the value of EVAP)

Wave #1

Hourdin et al, 2020

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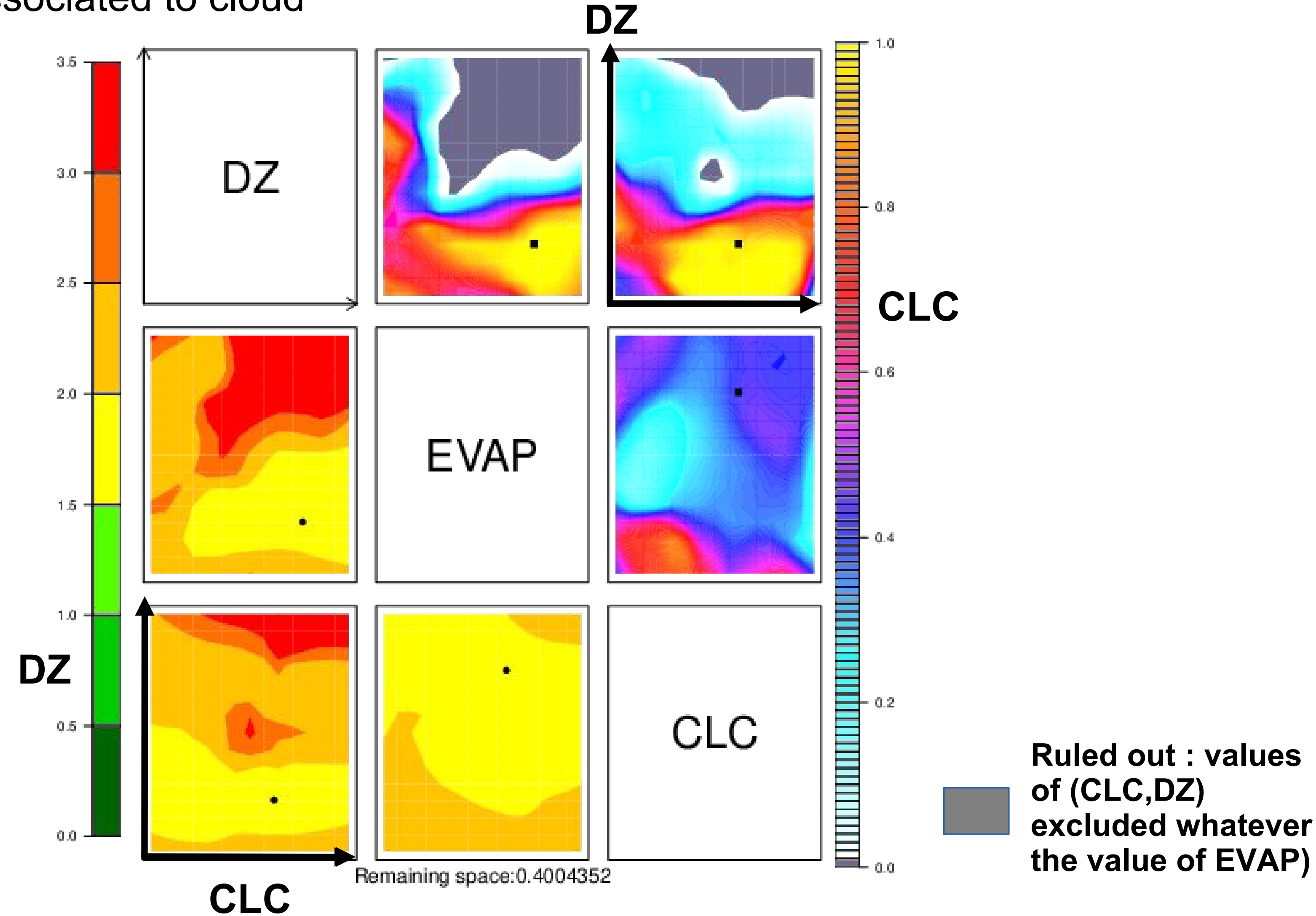

Wave #1

Hourdin et al, 2020

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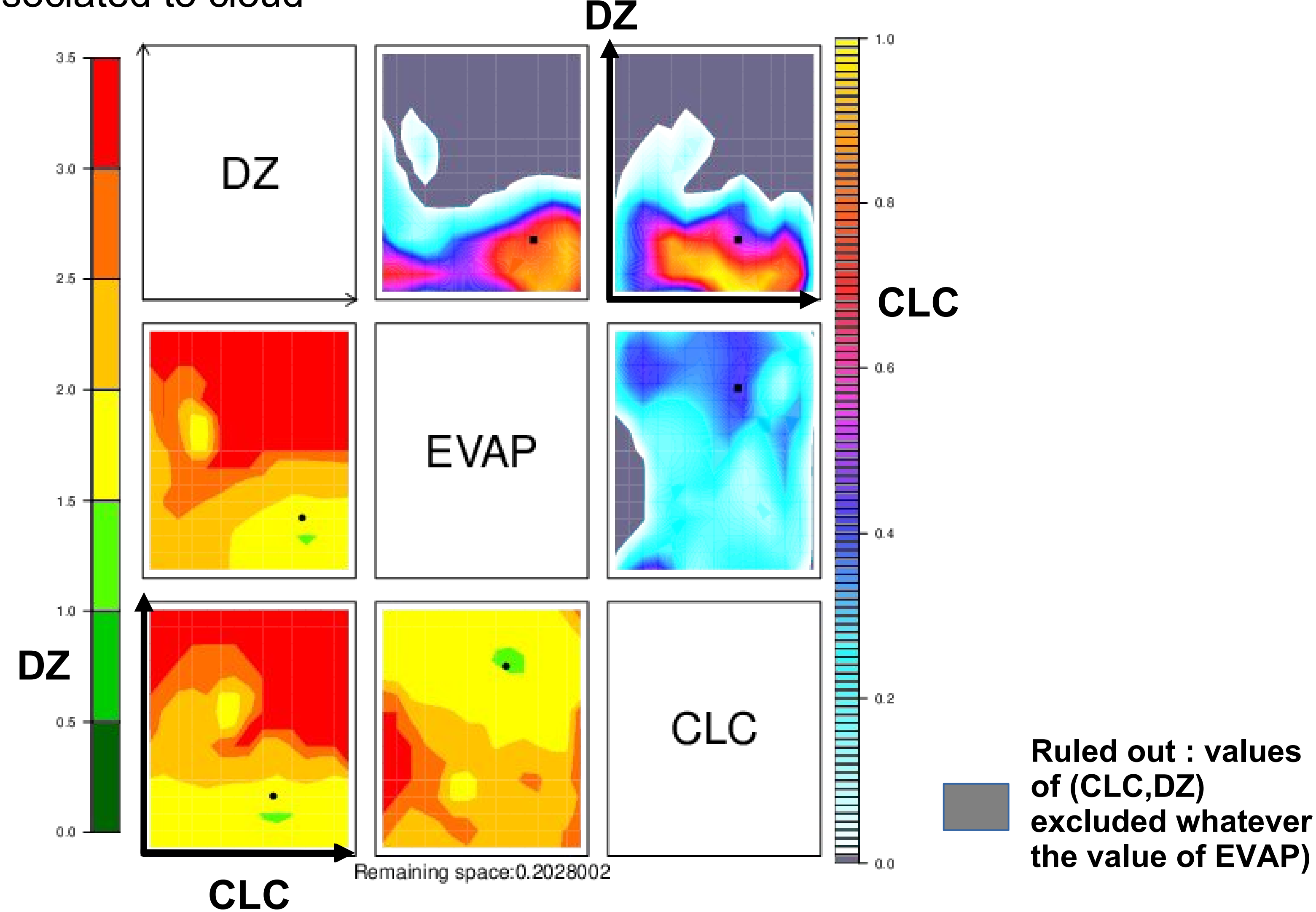
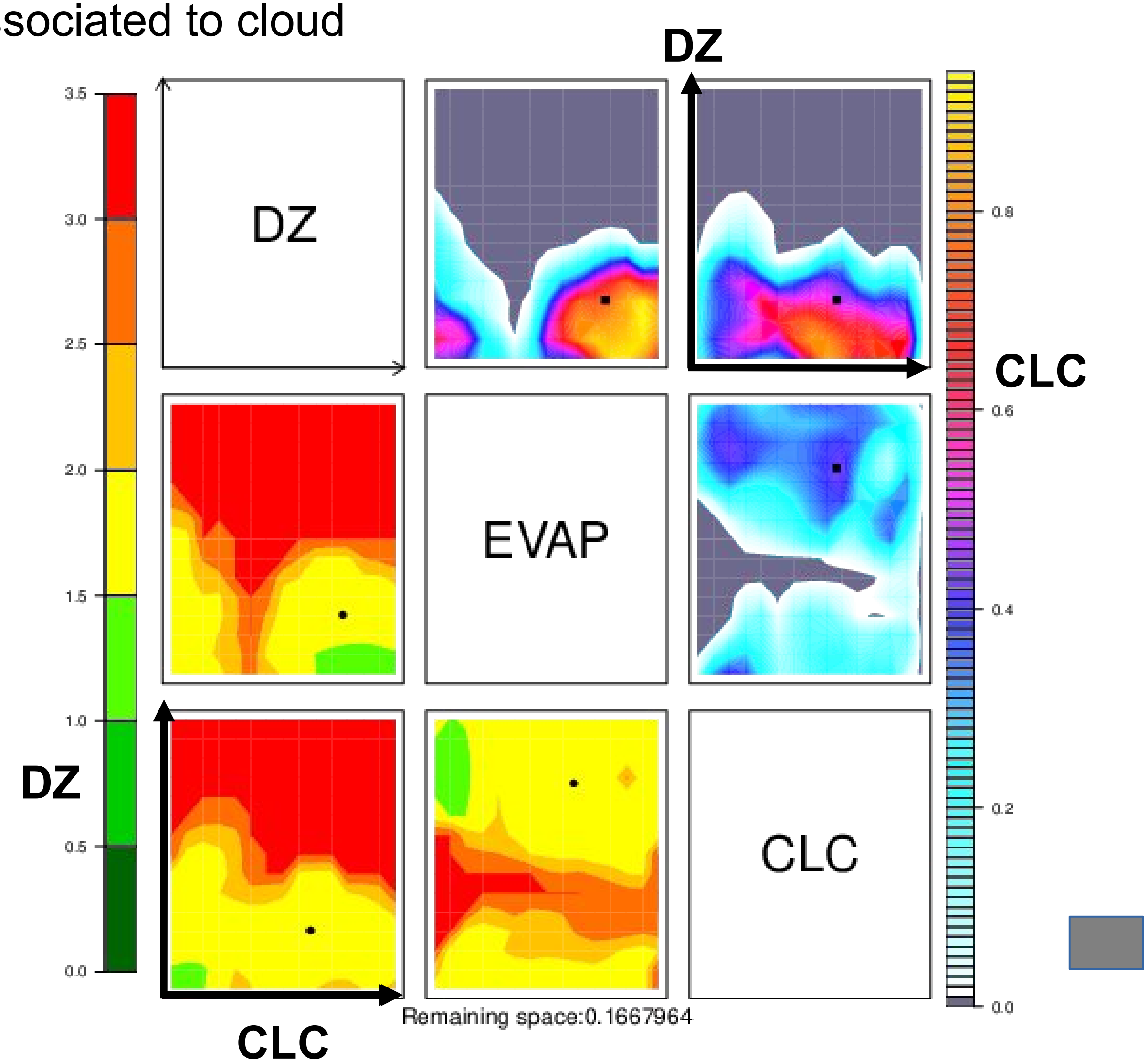


Wave #2

Hourdin et al, 2020

One example with LMDZ

Revisiting the CMIP6 tuning of LMDZ6A model on 1D cases (ARMCU/RICO/SANDU) by comparison with LES
Varying 3 parameters associated with EDMF+ cloud scheme
Targeting 8 metrics associated to cloud



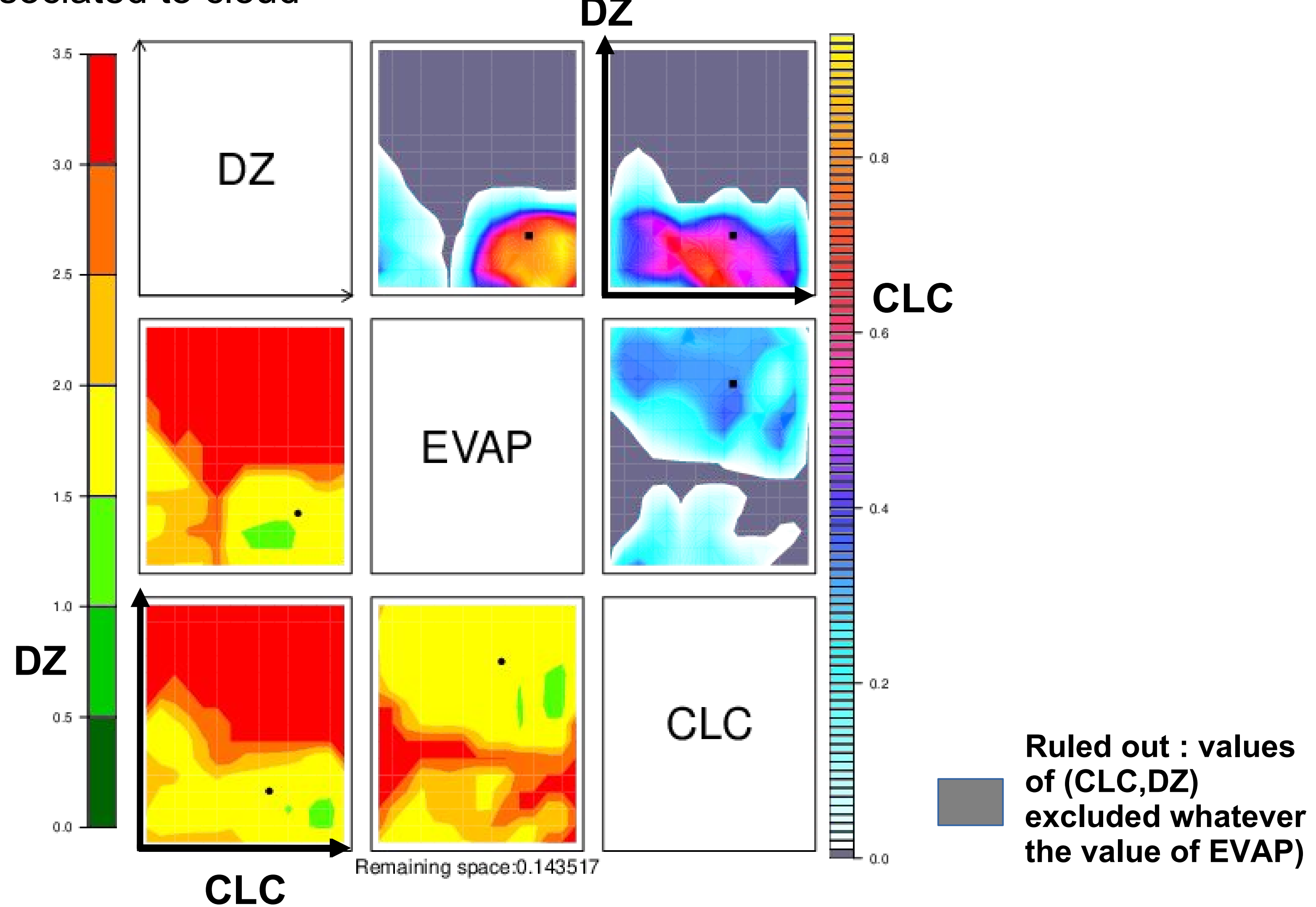
Ruled out : values of (CLC,DZ) excluded whatever the value of EVAP)

Wave #3

Hourdin et al, 2020

One example with LMDZ

Revisiting the CMIP6 tuning of LMDZ6A model on 1D cases (ARMCU/RICO/SANDU) by comparison with LES
Varying 3 parameters associated with EDMF+ cloud scheme
Targeting 8 metrics associated to cloud

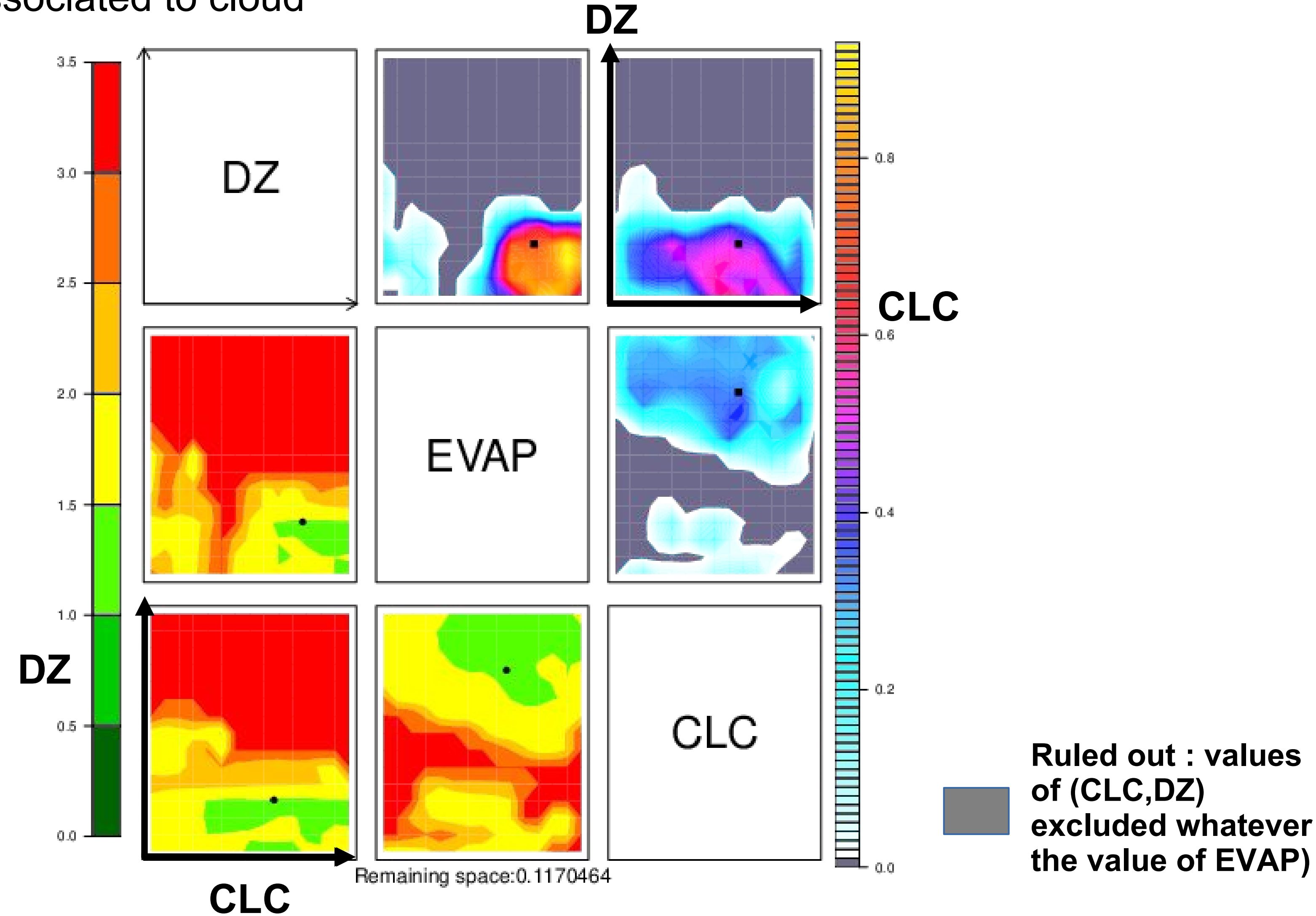


Wave #4

Hourdin et al, 2020

One example with LMDZ

Revisiting the CMIP6 tuning of LMDZ6A model on 1D cases (ARMCU/RICO/SANDU) by comparison with LES
Varying 3 parameters associated with EDMF+ cloud scheme
Targeting 8 metrics associated to cloud

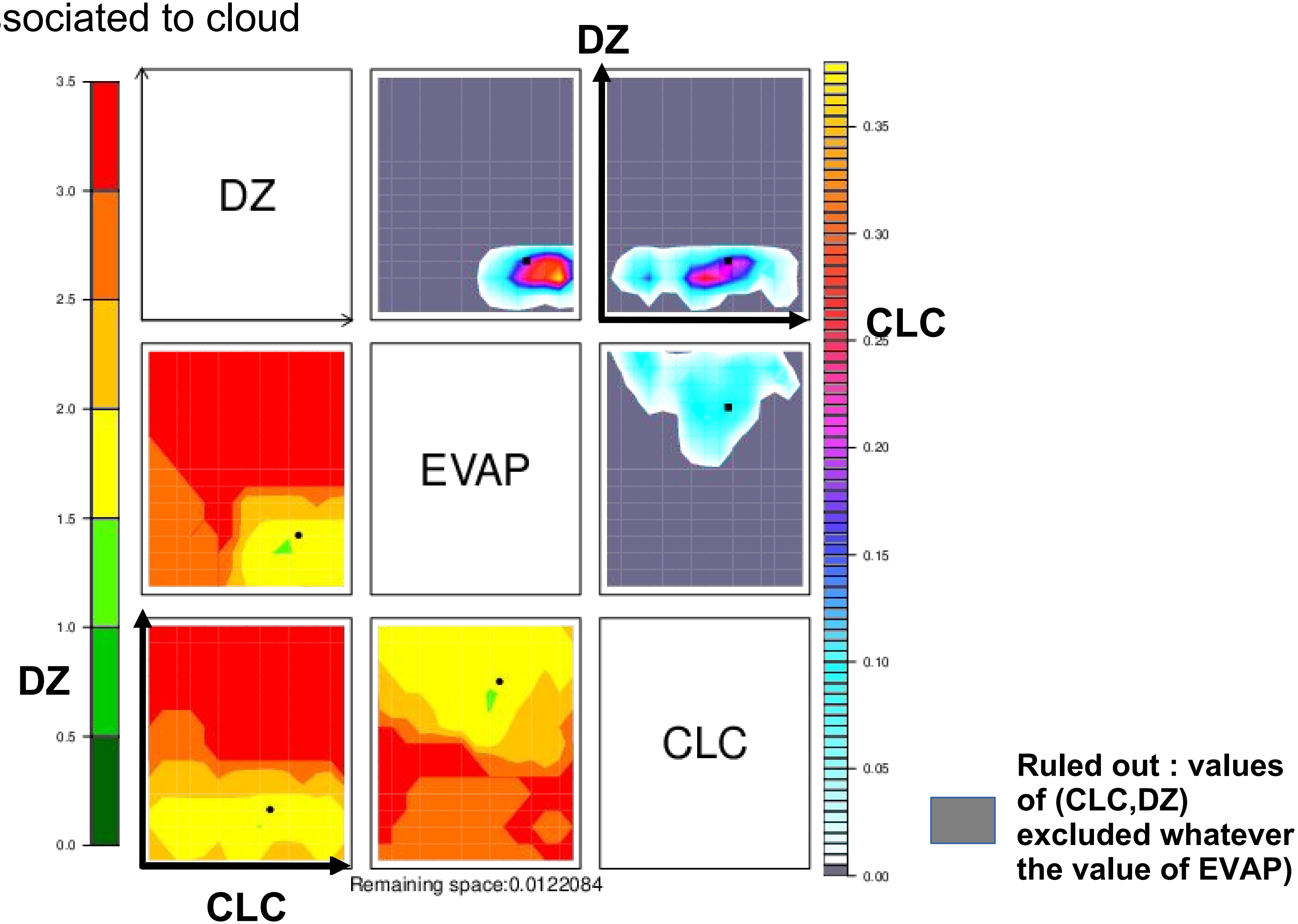


Wave #5

Hourdin et al, 2020

One example with LMDZ

Revisiting the CMIP6 tuning of LMDZ6A model on 1D cases (ARMCU/RICO/SANDU) by comparison with LES
Varying 3 parameters associated with EDMF+ cloud scheme
Targeting 8 metrics associated to cloud



Wave #10

Hourdin et al, 2020

One example with LMDZ

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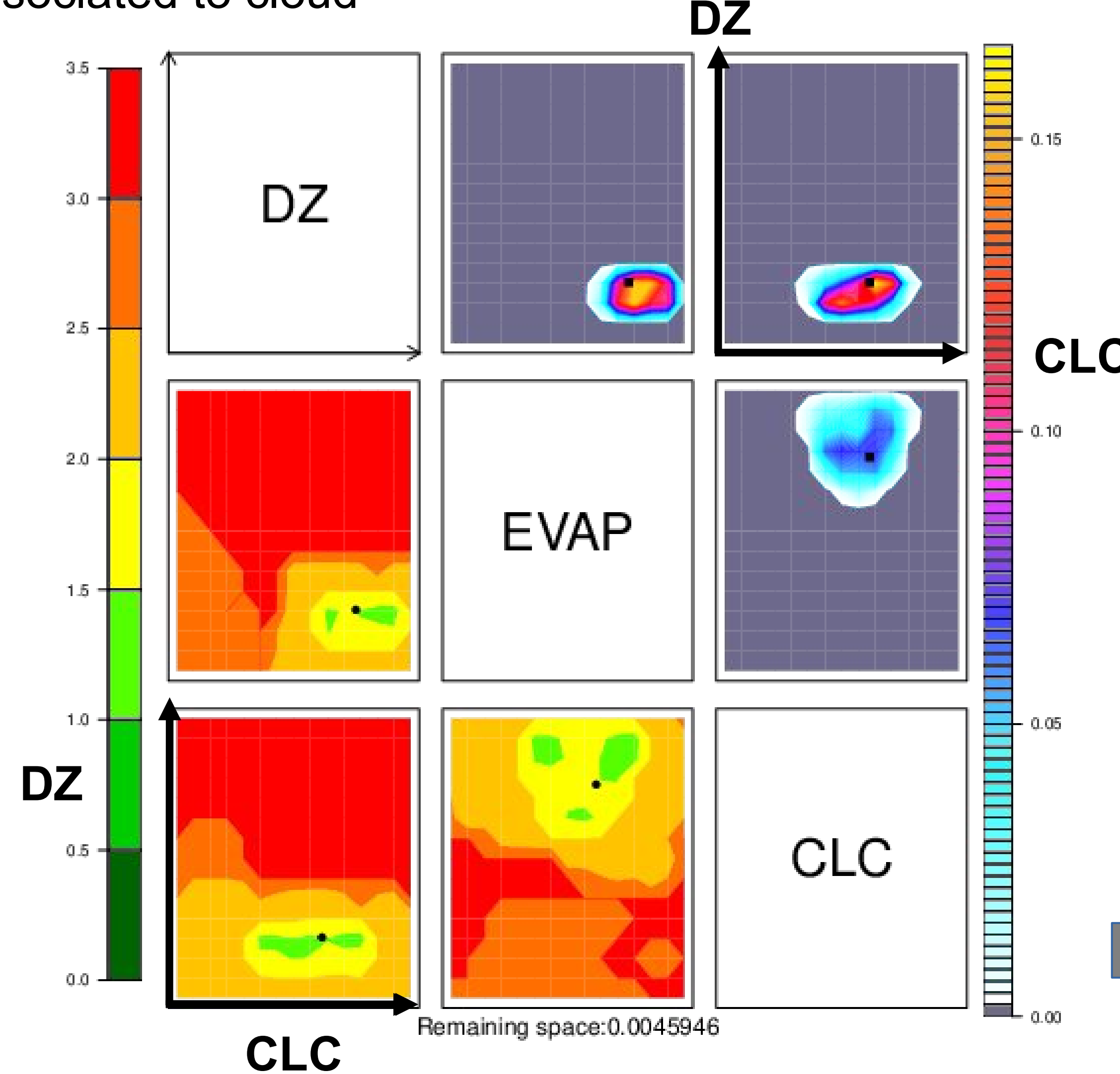


Ruled out : values of (CLC,DZ) excluded whatever the value of EVAP)

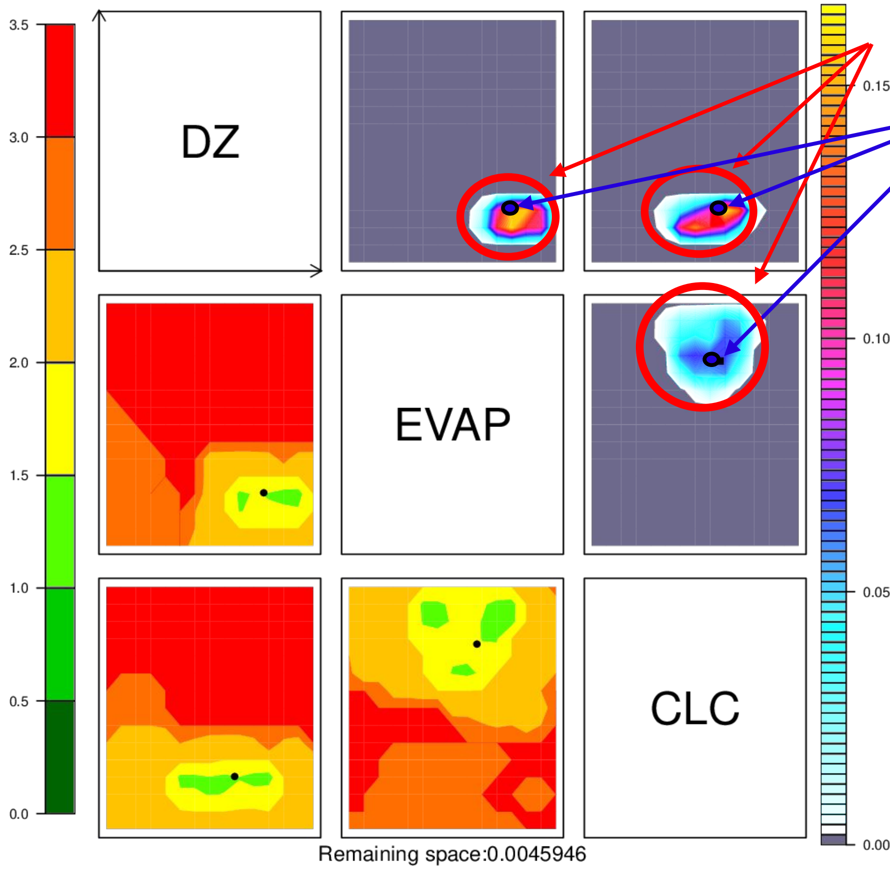
Wave #20

Hourdin et al, 2020

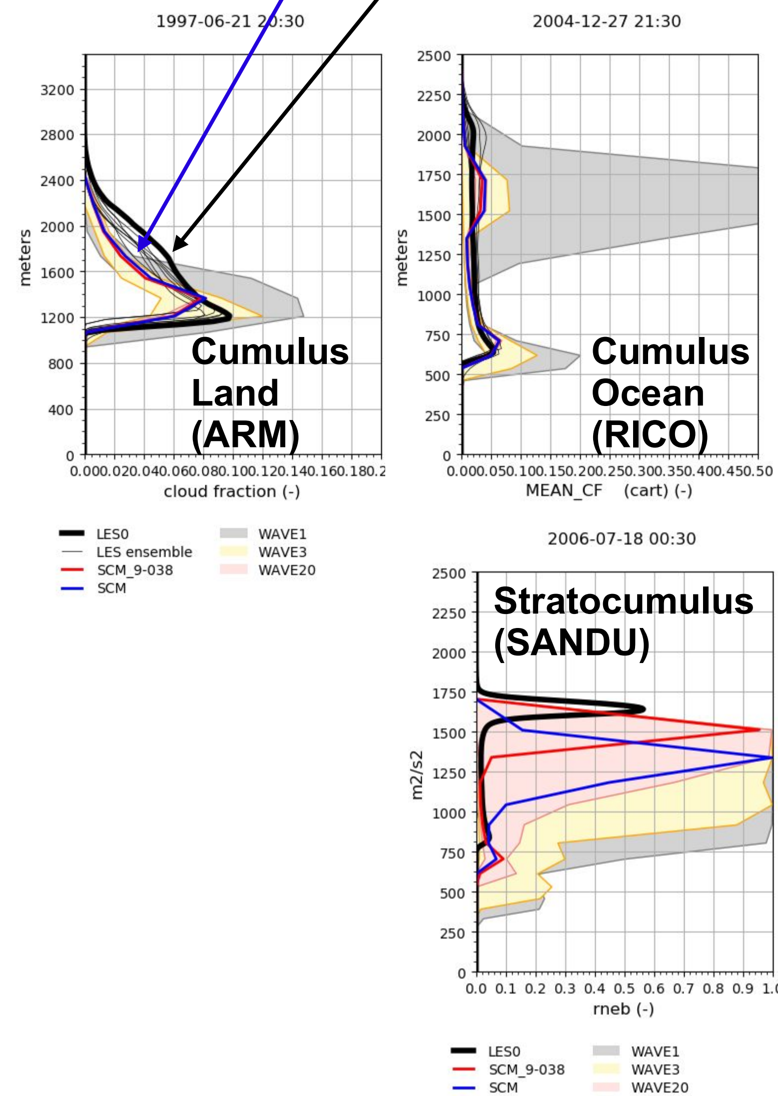
One example with LMDZ

Not Ruled Out Yet (NROY) space after 20 waves in 1D

Retained value for the LMDZ6A (by hand) tuning



Reference : LES

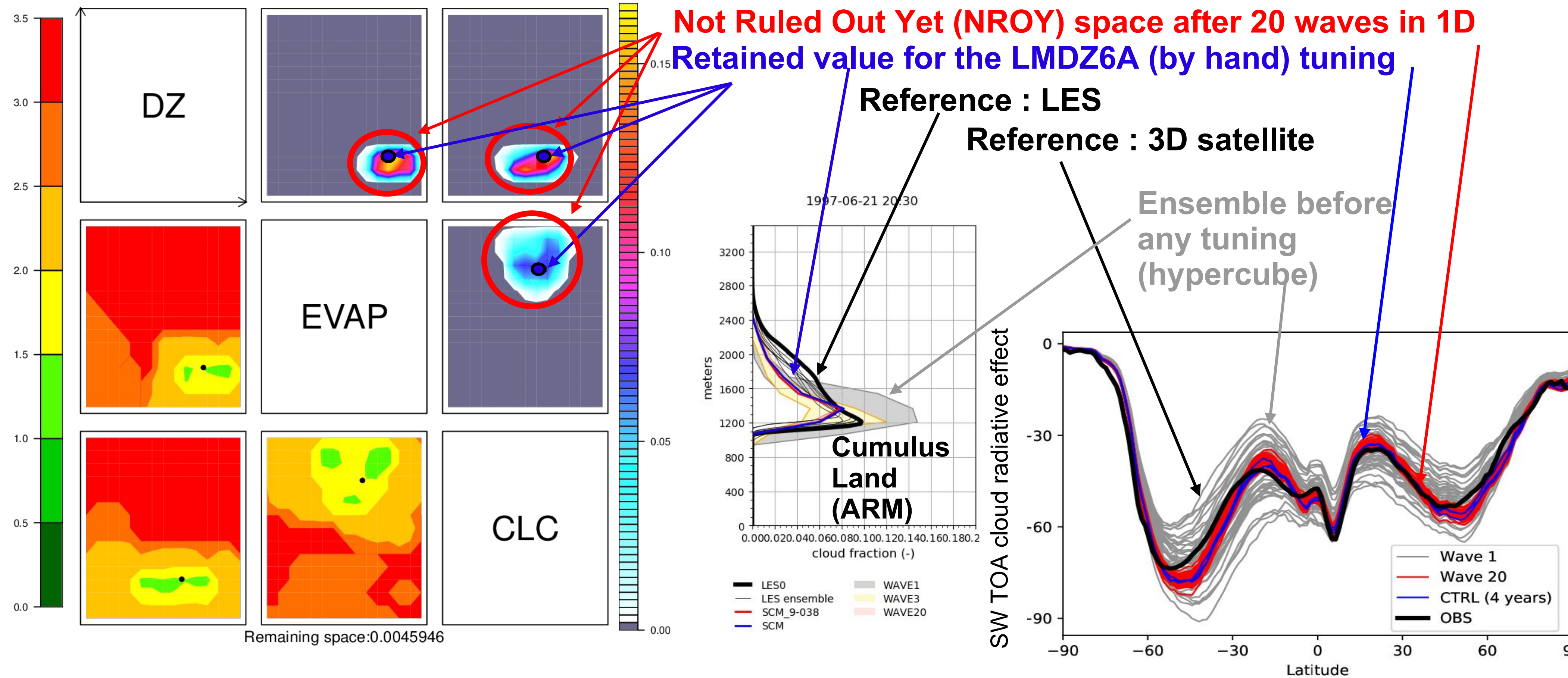


Enveloppe
Vague 1
Vague 3
Vague 20

LES0
LES ensemble
SCM_9-038
SCM

Hourdin et al, 2020

One example with LMDZ



The SCM/LES tuning allows

1) to choose parameters that guarantee a good simulation of cloudy scenes
2) to adjust for a large part the radiative effects of clouds in the 3D GCM
3) guarantees that the GCM tuning is compatible with process-scale representation

Hourdin et al, 2020

Other applications

- Calibration of the stable boundary layer (Audouin et al, JAMES, 2021) :

  Focusing on the turbulence parameterizations on ARPEGE-Climat on an extremely stable case
  Deficiencies due to calibration

- Assessing calibration issues and limit of convective parameterization:

  Is it possible to find a calibration of the convective parameterization suitable for shallow and deep convection ?
  => talk of R Roehrig Tuesday Morning

- A useful tool during the development of a parameterization :

  => talk of L Touze-Peiffer (Tuesday Morning)
  => talk of L d'Alencon (Friday Afternoon)

- Can also be applied to a given parameterization used offline (Villefranque et al, JAMES, 2021) :

  with radiative references obtained by Monte-Carlo methods
  => talk of N Villefranque (Wednesday Afternoon)

Conclusions

- Multi-disciplinarity crucial to obtain the two breakthroughs

Uncertainty Quantification community => process-based calibration tool
Physicians & computer sciences => radiative reference insensitive of the LES complexity

- Radiative tool

Produce synthetic images of 3D LES cloudy scenes
Radiative references useful for development/evaluation/calibration of parameterizations (radiative + coupling with other parameterizations)

- Tuning tool

Harness machine learning to improve physical parameterizations
Further exploit the LES/SCM comparison and the diversity of multicases
Easy to use with the common DEPHY format
Must be associated to a modeller expertise
Towards a well defined tuning strategy with solid physical (emphasis on processes) and statistical (UQ) basis
A key ingregient in the process of parameterization development

Some references

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