Clouds

LMDz Training – December 2021

J-B Madeleine and the LMDz team

For more detail, see Madeleine et al. 2020
https://doi.org/10.1029/2020MS002046


Picture by Oleg Artemyev taken from the ISS

Picture by Thomas Pesquet taken from the ISS

Radiative forcing

LW radiative forcing

Positive : clouds reduce the LW outgoing radiation

Annual mean : +29 W m^{-2}

SW radiative forcing

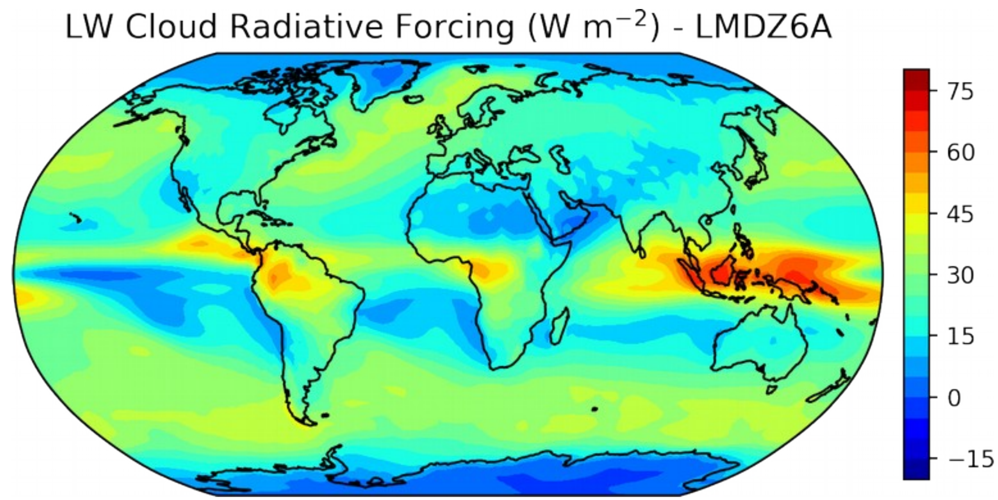
Negative : clouds reflect the incoming SW radiation

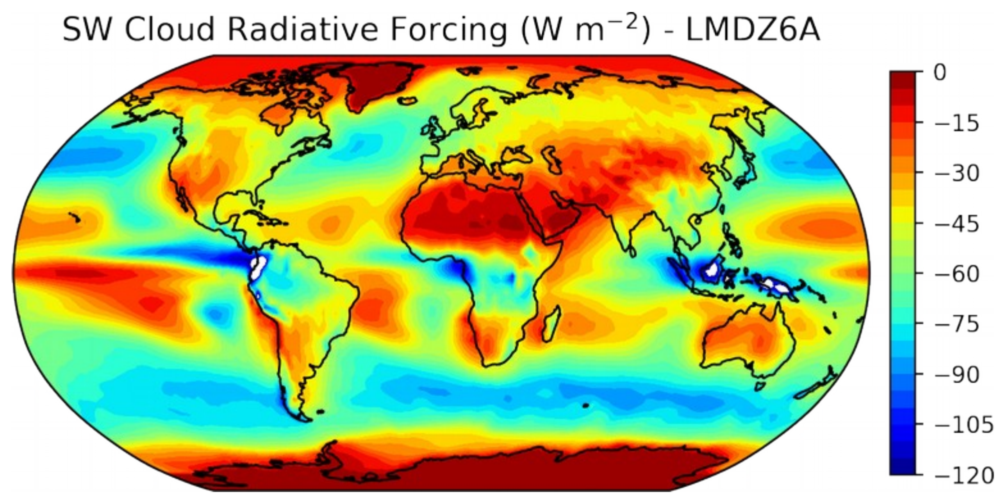
Annual mean : -47 W m^{-2}

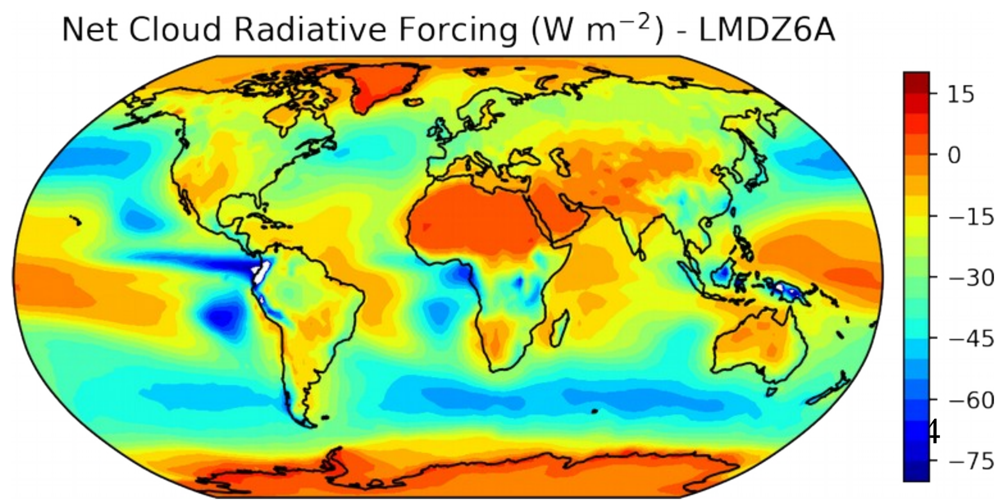
Net forcing : **Cooling**

Annual mean : -18 W m^{-2}

« The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation »
5th IPCC report







Visualize clouds in LMDZ

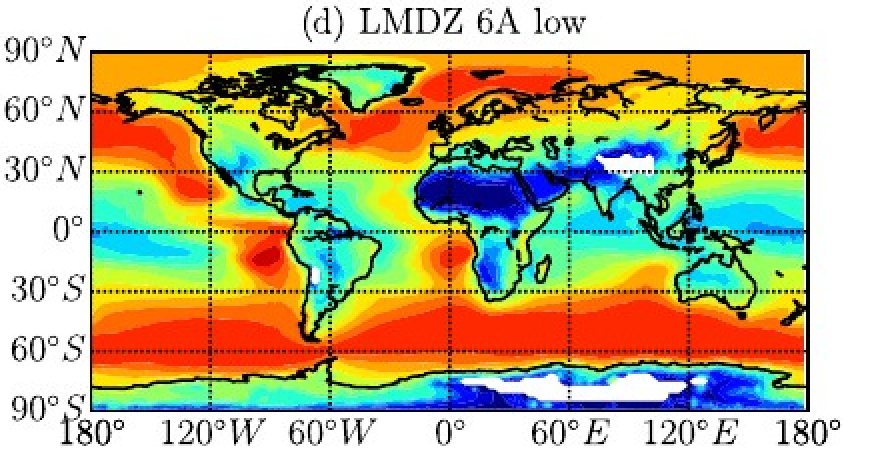
prw (2D) : Precipitable water (kg/m^2)
pluc/plul (2D) : Convective/lsc rainfall (kg/m^2/s)
snow (2D) = surface snowfall (kg/m^2/s)
lwp (2D) : Cloud liquid water path (kg/m^2)
iwp (2D) : Cloud ice water path (kg/m^2)

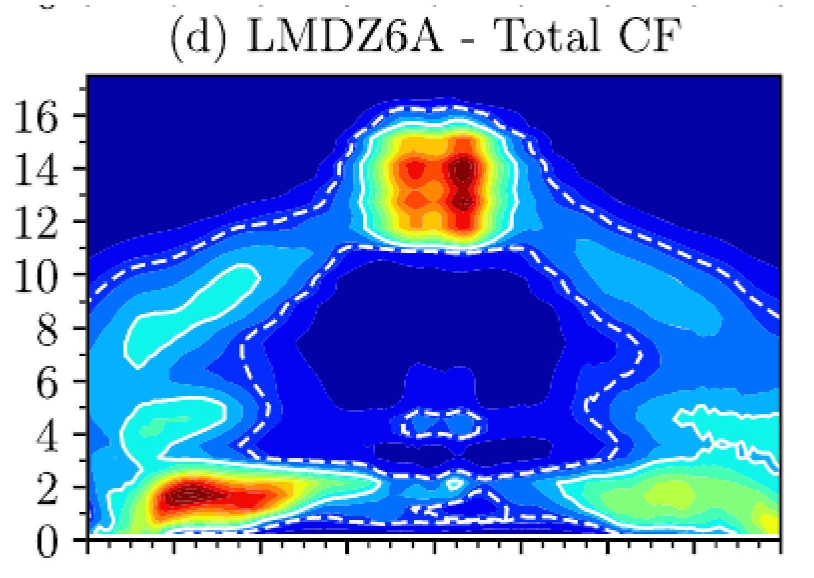
ovap (3D) : water vapor content (kg/kg)
oliq (3D) : cloud liquid water content (kg/kg)
ocond (3D) : cloud liq+ice water content (kg/kg)

pr_lsc_l (3D) : lsc rain mass fluxes (kg/m^2/s)
pr_lsc_i (3D) : lsc snow mass fluxes (kg/m^2/s)

rneb (3D) : cloud **fraction** (%)
cldh (2D) : High-level cloud **cover** (%)
cldm (2D) : Mid-level cloud **cover** (%)
cldl (2D) : Low-level cloud **cover** (%)
cldt (2D) : Total cloud **cover** (%)

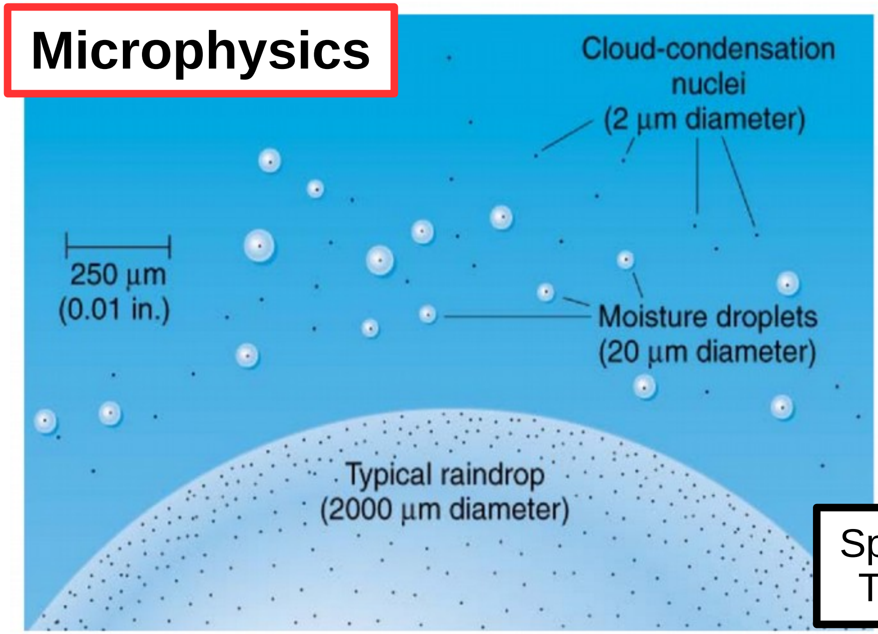
low-level clouds = below 680 hPa or ~3 km
mid-level clouds = between 680 and 440 hPa
high-level clouds = above 440 hPa or ~6.5 km



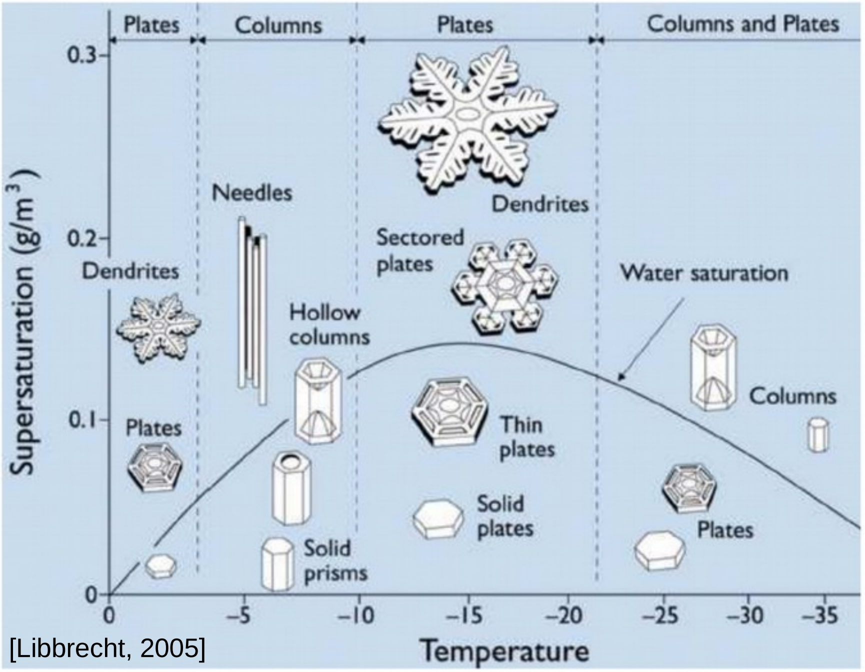


Modeling clouds : a challenge

Microphysics

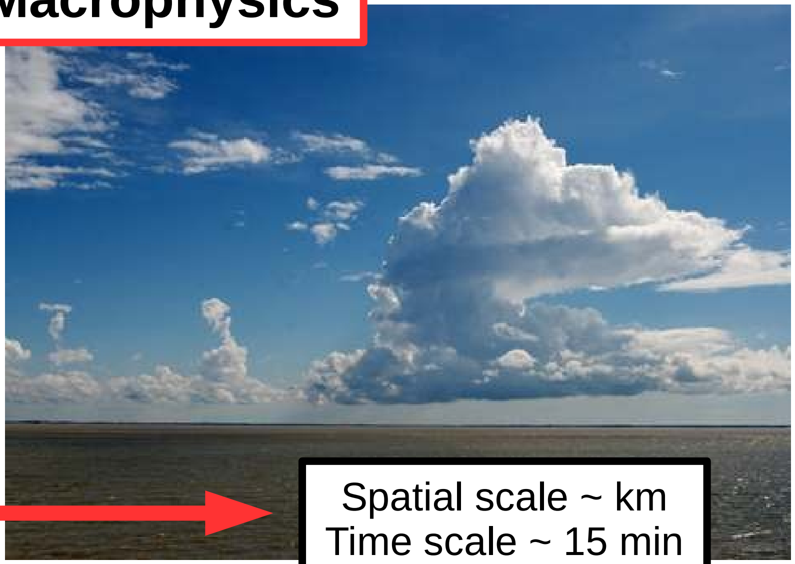


Spatial scale ~ µm
Time scale ~ 1 s



[Libbrecht, 2005]

Macrophysics



Spatial scale ~ km
Time scale ~ 15 min

Fundamental process

- Clausius-Clapeyron equation :

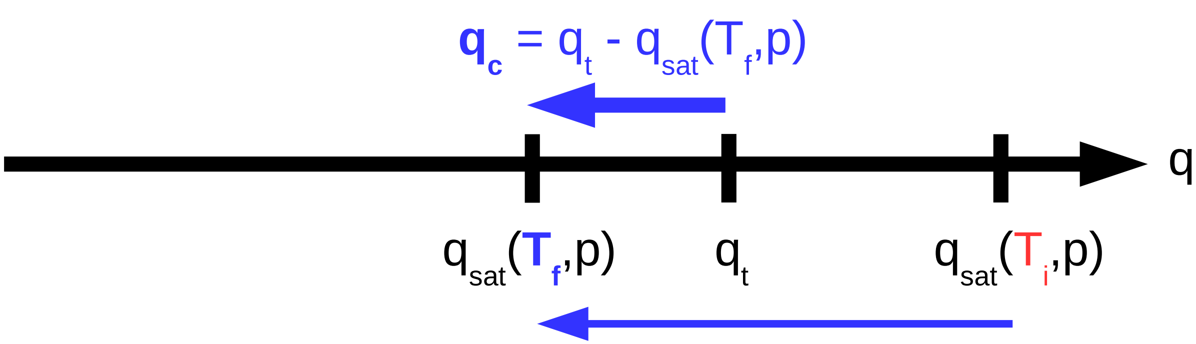
$$\frac{1}{e_{\text{sat}}}\frac{\mathrm{d}e_{\text{sat}}}{\mathrm{d}T} = \frac{L}{R_{\text{vap}}T^2}$$

T	0°C	20°C
e_{sat}	6.1 hPa	23.4 hPa
q_{sat}	3.7 g kg^{-1}	14.4 g kg^{-1}

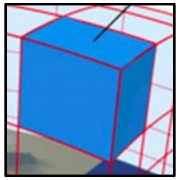
- Saturation mass mixing ratio :

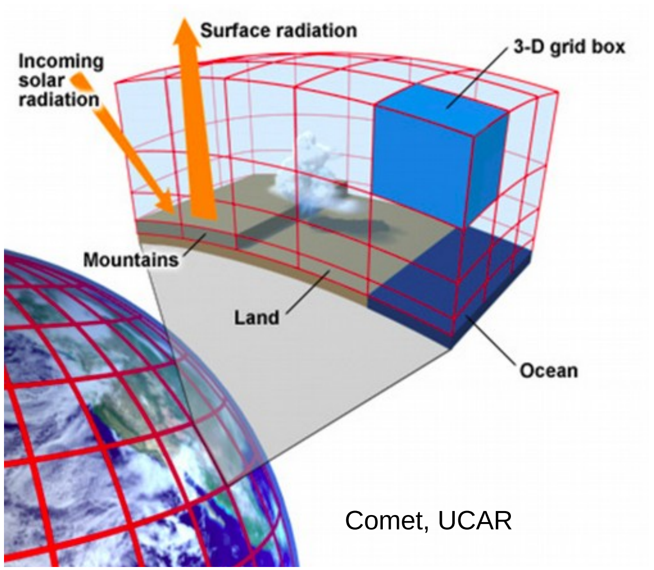
$q_{sat}(T,p) \simeq 0.622\,\dfrac{e_{sat}(T)}{p}$, where $e_{sat}(T)$ grows exponentially with temperature

- Clouds form when an air parcel is cooled :



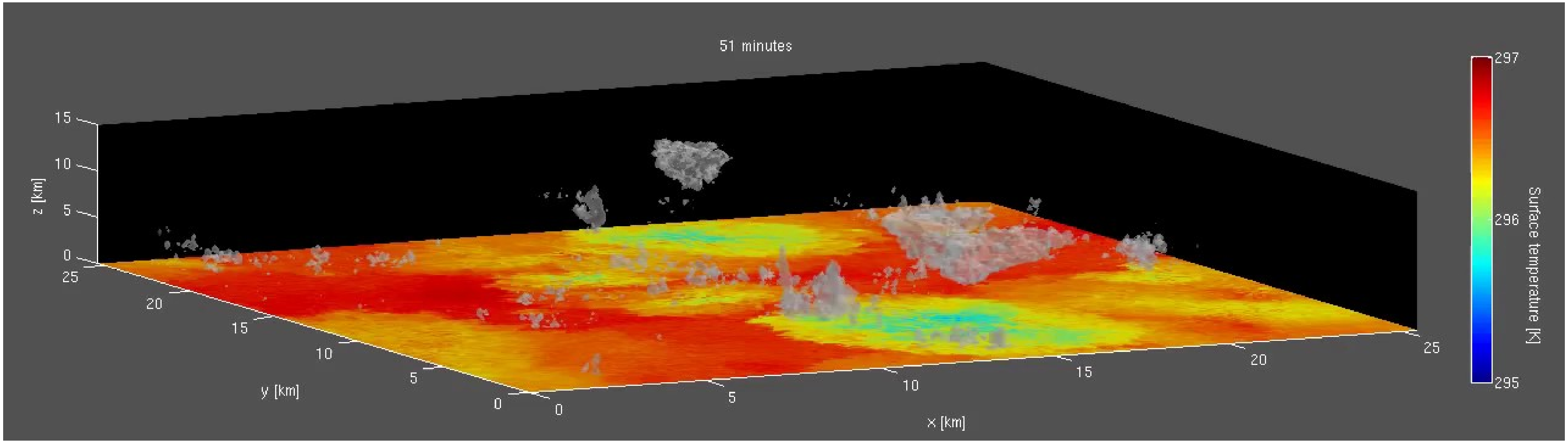
- But clouds do not look like that :





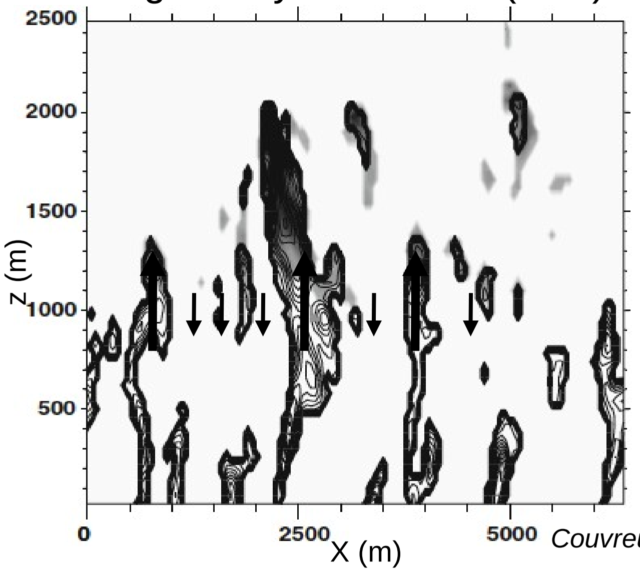
Comet, UCAR

Many processes in one grid cell



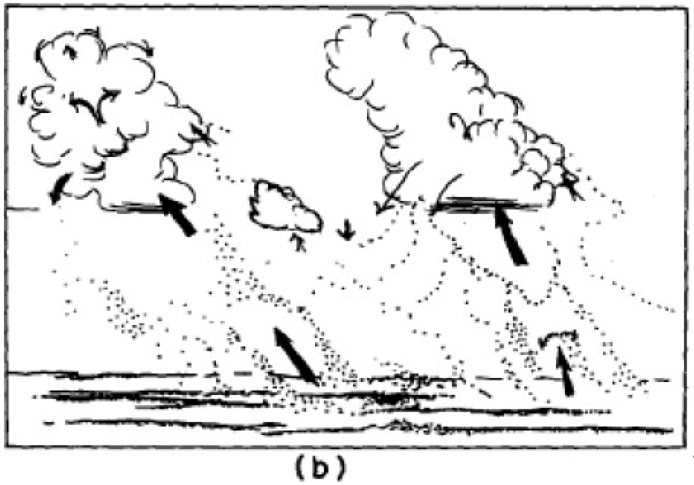
Around 8 hours of simulation by a **Cloud Resolving Model (CRM)** – C. Muller, LMD

Thermals in a
Large-Eddy Simulation (LES)



Couvreux et al., BLM, 2010

Conditional sampling of thermals based on a tracer emitted at the surface.

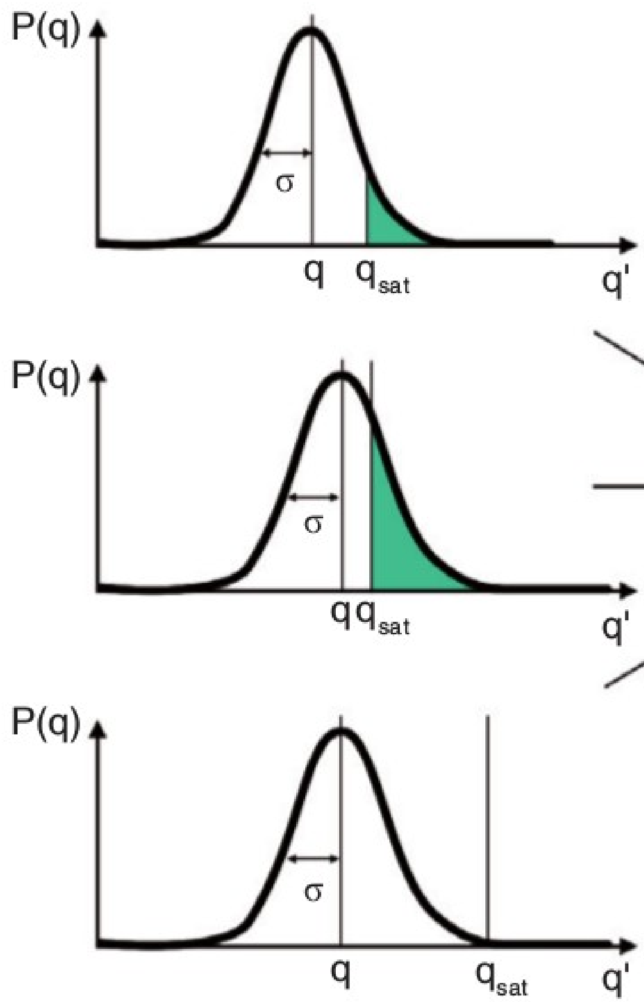


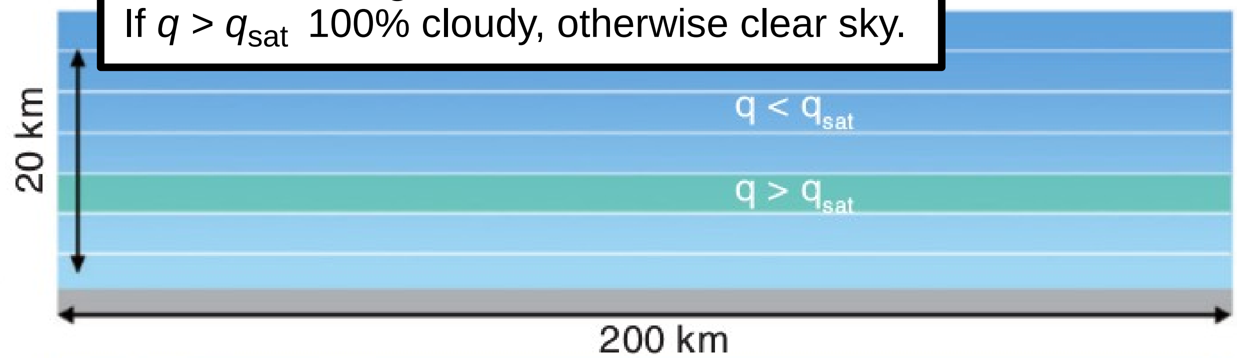
(b)

Lemone et Pennell, MWR, 1976

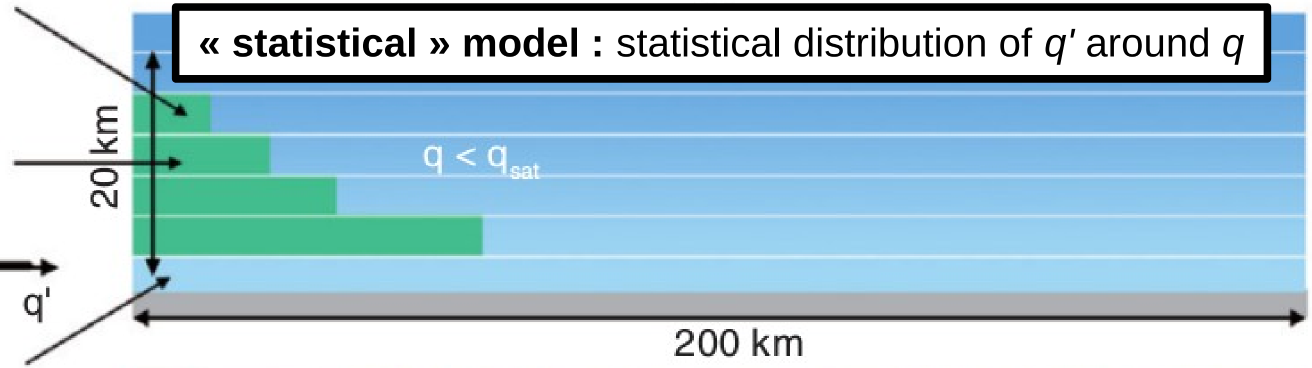
Statistical cloud scheme

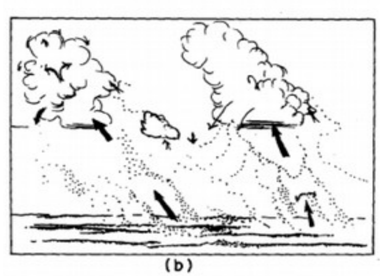
« all or nothing » model :
If $q > q_{sat}$ 100% cloudy, otherwise clear sky.

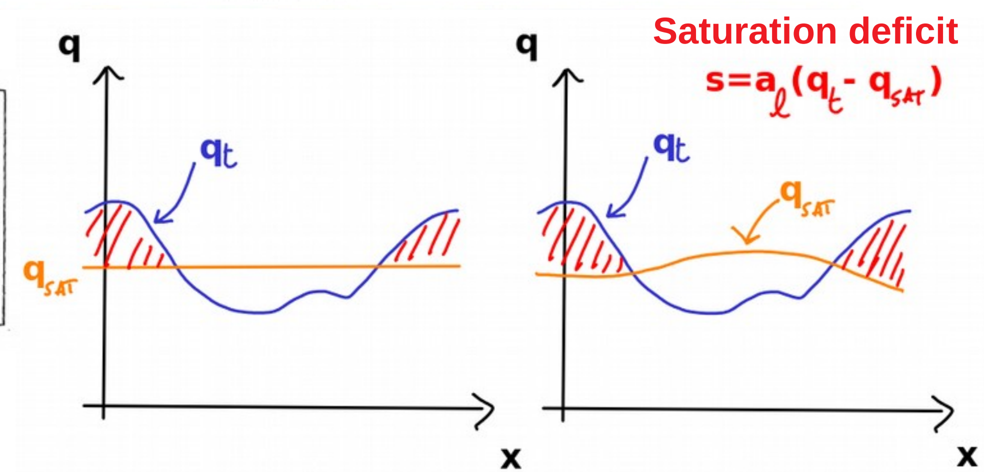




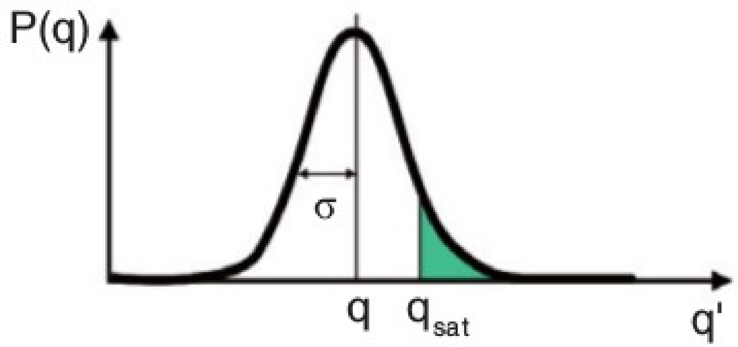
« statistical » model : statistical distribution of q' around q

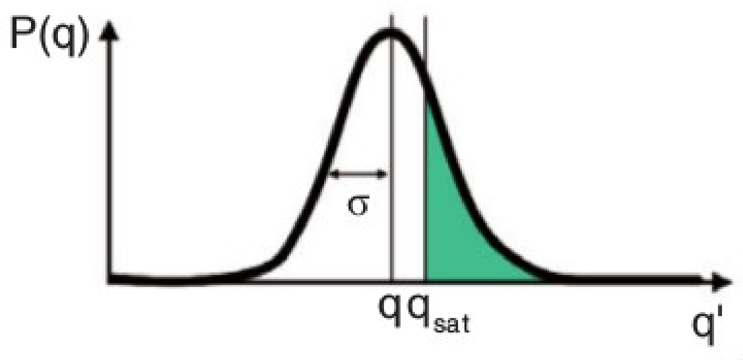






Statistical cloud scheme 2/2





The goal of a cloud scheme is therefore to compute q_c^{in} and the cloud fraction based on the different physical parameterizations.

Mean total water content :

$$\bar{q} = \int_0^\infty q \; P(q) \; dq$$

Domain-averaged condensed water content :

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat}) P(q) dq$$

Cloud fraction :

$$\alpha_c = \int_{q_{sat}}^{\infty} P(q) dq$$

In-cloud condensed water content :

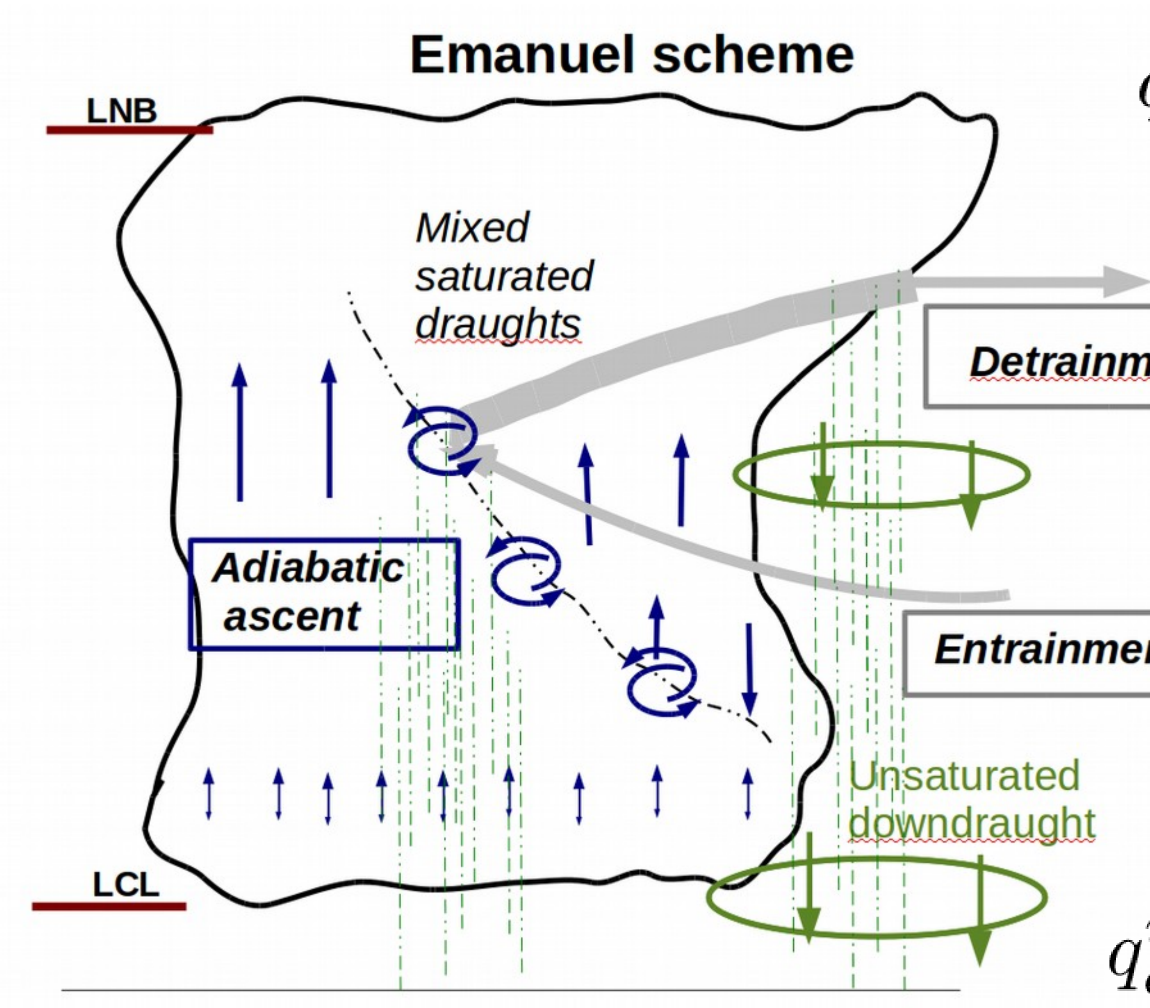
$$q_c^{in} = \frac{q_c}{\alpha_c}$$

Architecture of the cloud scheme

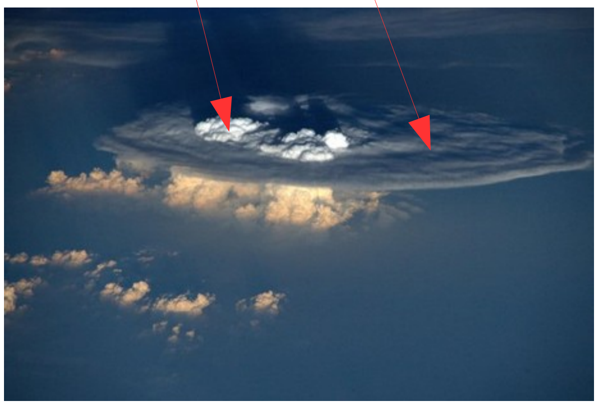
Procedure / Subsection	Input variables	Other outputs
	$\circlearrowleft$ Updated variables	
2.1. Evaporation	$\theta\ q_v\ q_l\ q_i$	
	$\circlearrowleft$ $\theta\ q_t\ (q_l = q_i = 0)$	
2.2. Local turbulent mixing	$\theta\ q_t$	
	$\circlearrowleft$ $\theta\ q_t$	
2.3. Deep convection	$\theta\ q_t\ ALE\ ALP$	$q_c^{in,cv}\ P_{l,i}^{cv}\ d\theta_{dw}^{cv}\ dq_{t,dw}^{cv}$
	$\circlearrowleft$ $\theta\ q_t$	
2.4. Deep convection PDF	$q_t\ q_c^{in,cv}$	α_c^{cv}
2.5. Cold pools (wakes)	$\theta\ q_t\ d\theta_{dw}^{cv}\ dq_{t,dw}^{cv}$	$ALE^{wk}\ ALP^{wk}\ \theta_{env}^{wk}\ q_{t,env}^{wk}$
	$\circlearrowleft$ $\theta\ q_t$	
2.6. Shallow convection	$\theta_{env}^{wk}\ q_{t,env}^{wk}$	$(s_{th}\ \sigma_{th}\ s_{env}\ \sigma_{env})^{th}\ ALE^{th}\ ALP^{th}$
	$\circlearrowleft$ $\theta\ q_t$	
2.7. Large-scale condensation	$\theta\ q_t\ (s_{th}\ \sigma_{th}\ s_{env}\ \sigma_{env})^{th}$	$q_c^{in,lsc}\ \alpha_c^{lsc}\ P_{l,i}^{lsc}$
	$\circlearrowleft$ $\theta\ q_v\ q_l\ q_i$	
2.8. Radiative transfer	$q_c^{in,lsc}\ \alpha_c^{lsc}\ q_c^{in,cv}\ \alpha_c^{cv}$	
	$\circlearrowleft$ θ	

CAREFUL : clouds are evaporated/sublimated at the beginning of each time step (~15 min), but vapor, droplets and crystals are prognostic variables. In other words, **clouds can move but can't last for more than one timestep** (meaning that for example, crystals can't grow over multiple timesteps).

1. Deep convection



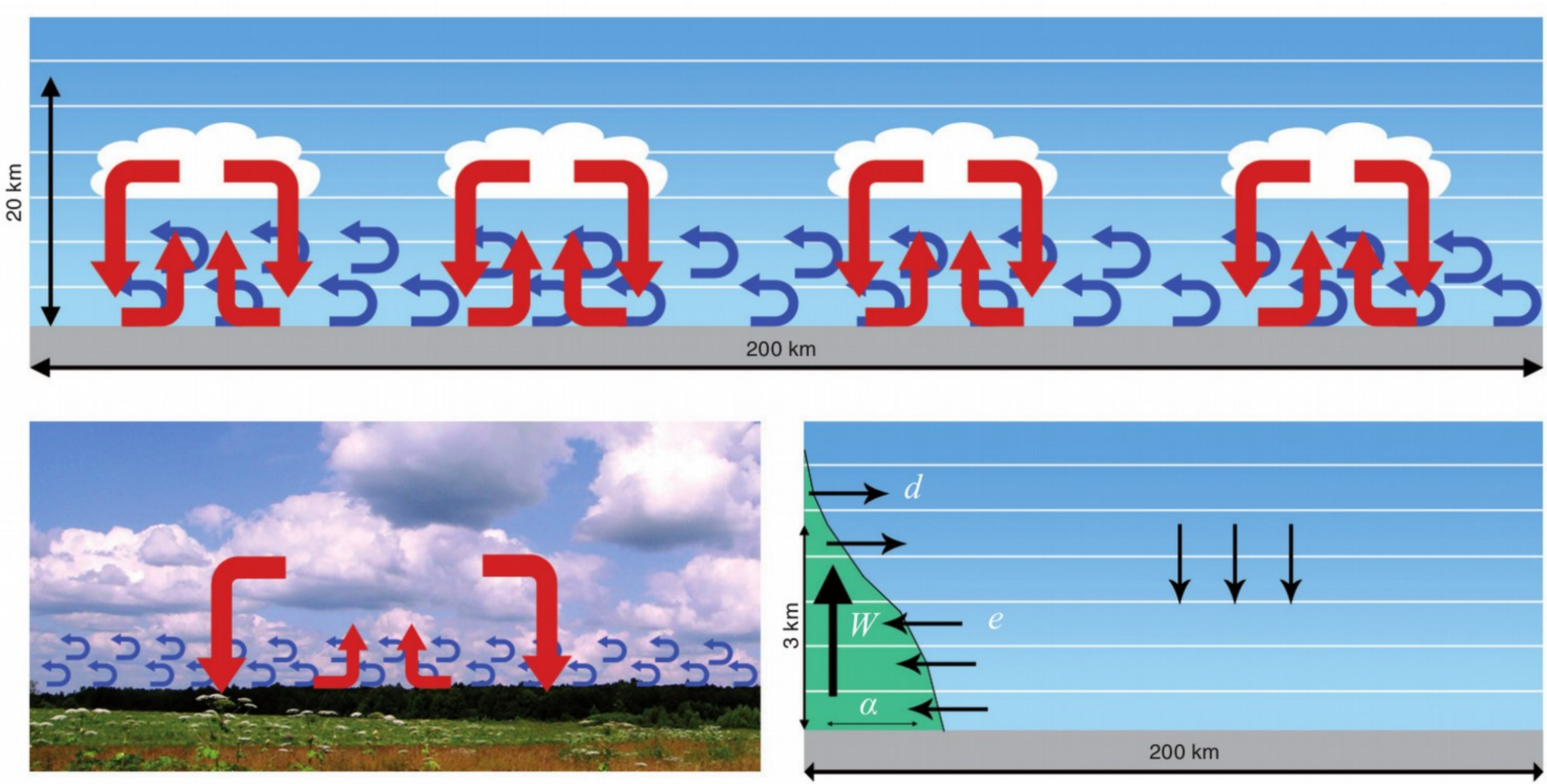
$$q_c^{in} = \frac{\sigma_a\, q_{ca} + \sigma_m\, q_{cm}}{\sigma_a + \sigma_m}$$



$$q_c^{in} = \frac{\dfrac{M_a}{\rho\, w_a}\, q_{ca} + \dfrac{\tau\, M_t\, g}{\delta p}\, q_{cm}}{\dfrac{M_a}{\rho\, w_a} + \dfrac{\tau\, M_t\, g}{\delta p}}$$

q_c^{in} is computed by the deep convection scheme and $\bar{q}$ is known → cloud fraction is found

2. Shallow convection 1/2



2. Shallow convection 2/2

Bi-Gaussian distribution of saturation deficit s:

$$Q(s) = (1-\alpha_{th}) f(s,\, s_{env},\, \sigma_{env}) + \alpha_{th} f(s,\, s_{th},\, \sigma_{th})$$

One mode for thermals : s_{th}, σ_{th}

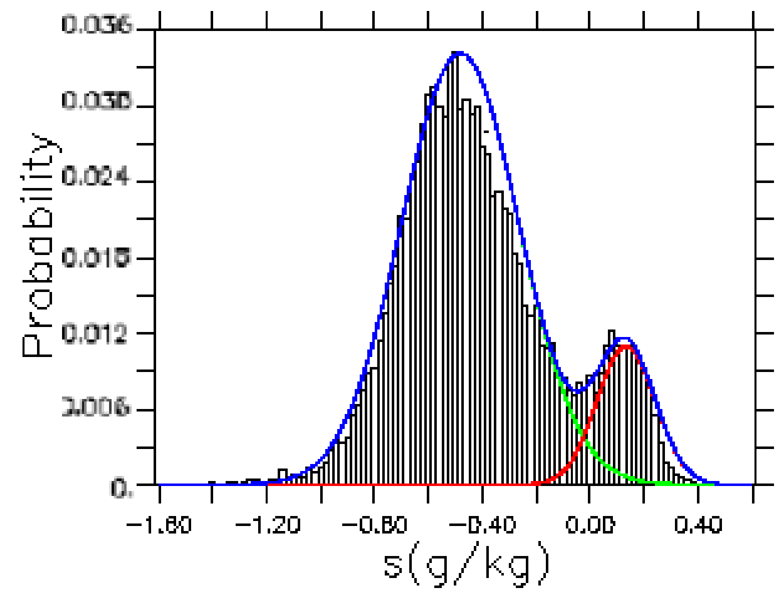
One mode for their environment : s_{env}, σ_{env}

S_{env}, s_{th}, and α are given by the shallow convection scheme, and the distribution's variances are parameterized following :

$$\sigma_{\mathrm{s,env}} = c_{\mathrm{env}} \frac{\alpha^{\frac{1}{2}}}{1-\alpha} (\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\, \overline{q}_{t_{\mathrm{env}}}$$

$$\sigma_{\mathrm{s,th}} = c_{\mathrm{th}}\, \alpha^{-\frac{1}{2}} (\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\, \overline{q}_{t_{\mathrm{th}}}$$

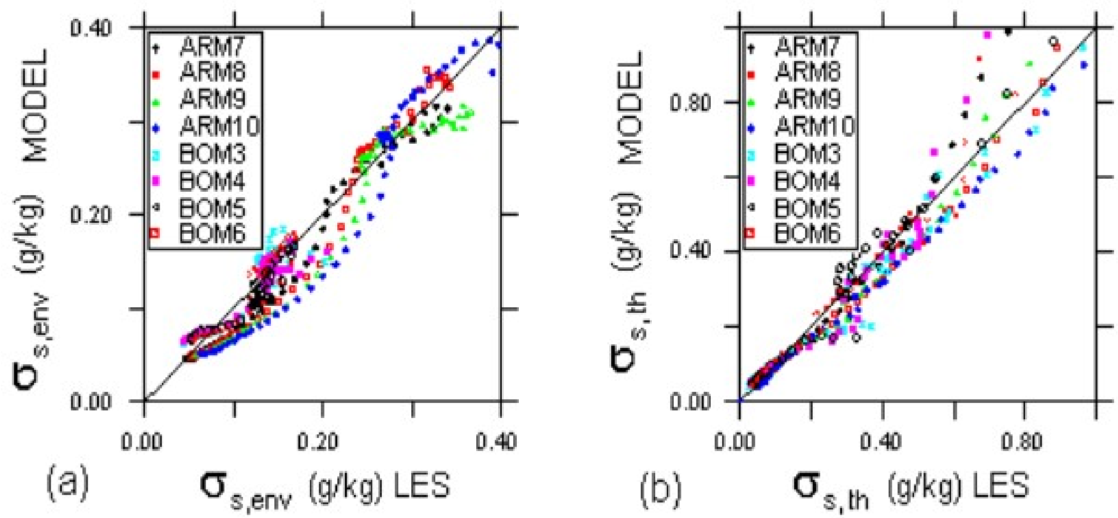
[Jam & al., BLM, 2013]

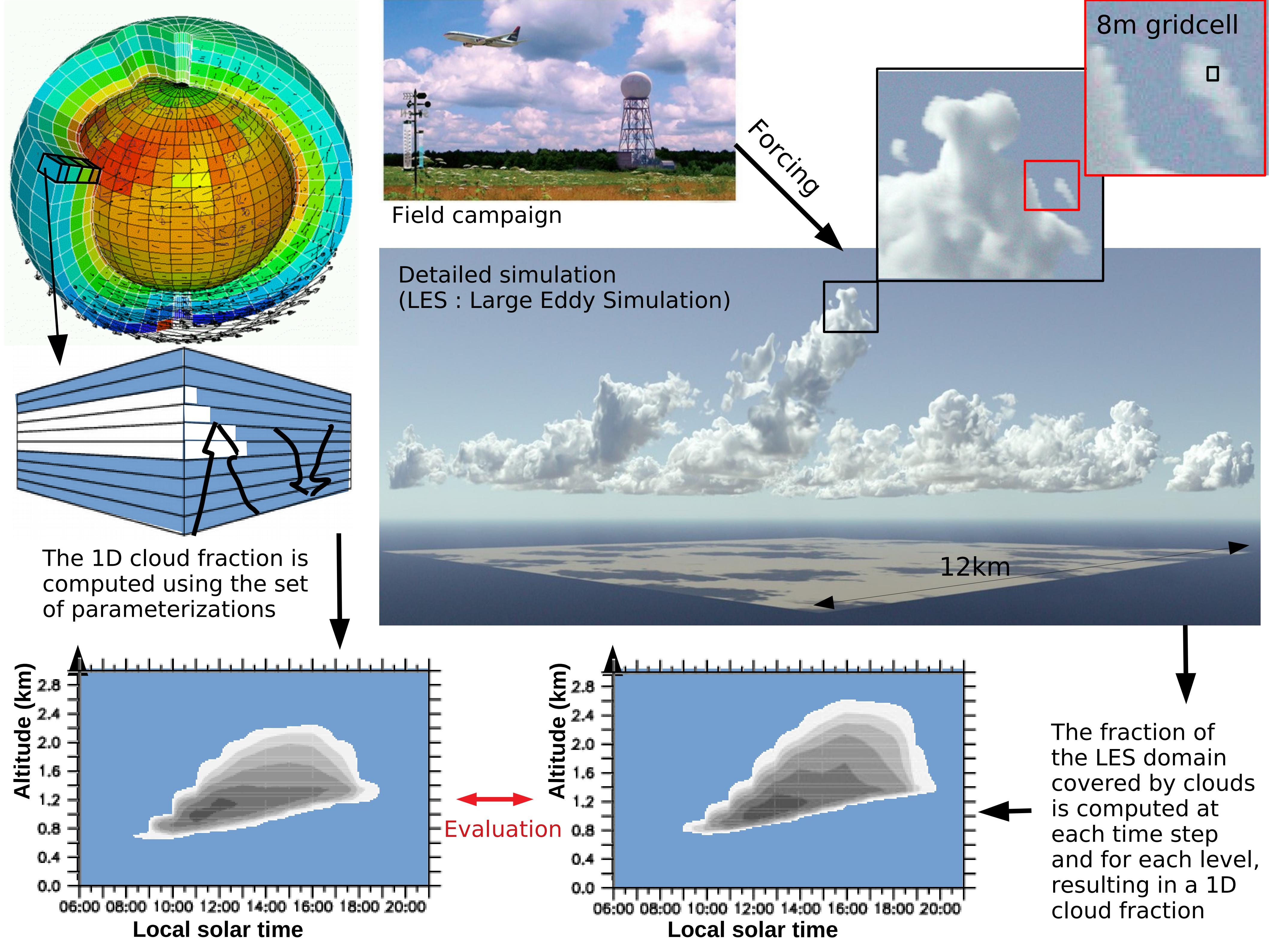


q_c^{in} and the cloud fraction can be computed following :

$$q_c^{in} = \int_0^{\infty} s\, Q(s)\, ds \qquad \alpha_c = \int_0^{\infty} Q(s)\, ds$$

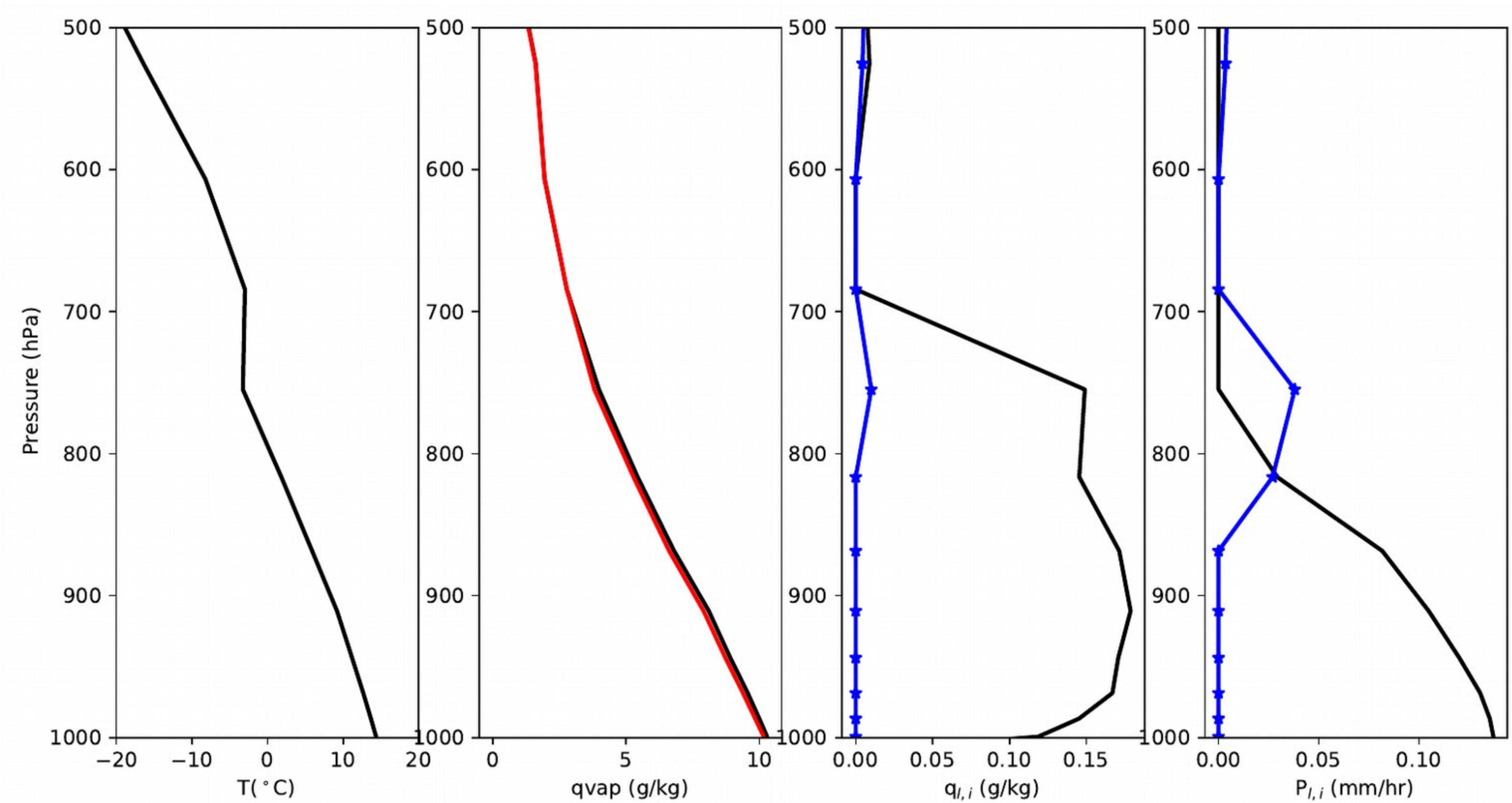
[Jam & al., BLM, 2013]




Field campaign
Forcing
8m gridcell
Detailed simulation
(LES : Large Eddy Simulation)
12km
The 1D cloud fraction is
computed using the set
of parameterizations
Altitude (km)
Local solar time
Evaluation
The fraction of
the LES domain
covered by clouds
is computed at
each time step
and for each level,
resulting in a 1D
cloud fraction

3. Large scale condensation

Temperature, water vapor, clouds and precipitation over one timestep



1 REEVAPORATION **2** CLOUD FORMATION **3** PRECIPITATION

3. Large scale condensation

- Rain/snow is partly evaporated in the grid below (parameter controlling the evaporation rate) :

$$\frac{\partial P}{\partial z} = \beta[1 - q/q_{sat}]\sqrt{P}$$

1 **REEVAPORATION**

2 **CLOUD FORMATION**

If there is no shallow convection

q_c^{in} and the cloud fraction can be computed following :

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat}) P(q) dq \qquad \alpha_c = \int_{q_{sat}}^{\infty} P(q) dq$$

Log-normal distribution of total water q_t using a prescribed variance $\sigma = \xi q_t$

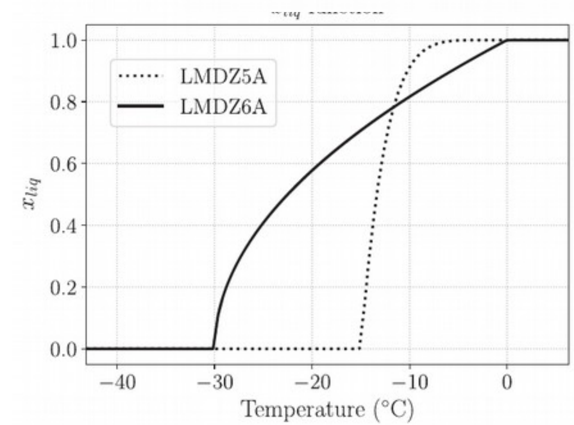
If there is shallow convection

q_c^{in} and the cloud fraction can be computed following :

$$q_c^{in} = \int_0^{\infty} s\, Q(s)\, ds \qquad \alpha_c = \int_0^{\infty} Q(s)\, ds$$

In both cases, cloud phase is parameterized using a simple function of temperature :

$$x_{liq} = \left(\frac{T - T_{min}}{T_{max} - T_{min}}\right)^n$$



3. Large scale condensation

3 **PRECIPITATION**

- A fraction of the condensate falls as rain (parameters controlling the maximum water content of clouds and the auto-conversion rate) :

$$\frac{dq_{lw}}{dt} = -\frac{q_{lw}}{\tau_{convers}}\left[1 - e^{-(q_{lw}/clw)^2}\right]$$

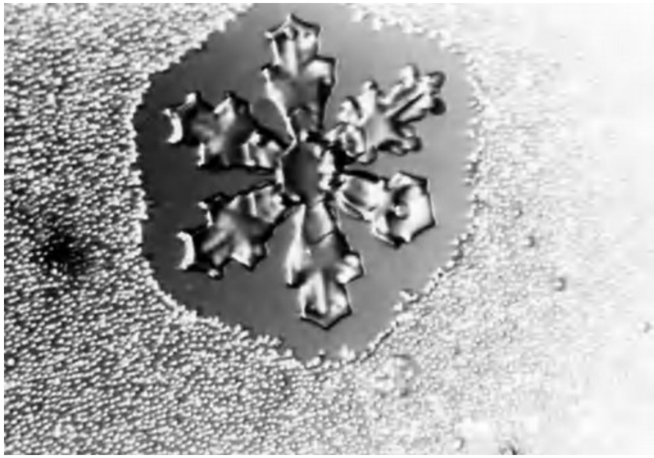
- Another fraction is converted to snow following :
- This fraction depends on the same temperature function as clouds → rain can be created below freezing
- When this occurs, the resulting liquid precipitation **is converted to ice.**
- When freezing, rain releases latent heat, which can potentially bring the temperature back to above freezing. If this is the case, a small amount of rain remains liquid to stay below freezing.

$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

$$w_{iw} = \gamma_{iw} w_0$$

$$w_0 = 3.29(\rho q_{iw})^{0.16}$$

Growth of an ice crystal at the expense of surrounding supercooled water drops [Wallace, 2005]



Tuning parameters

$$\frac{\partial P}{\partial z} = \beta[1 - q/q_{sat}]\sqrt{P}$$

coef_eva=0.0001

$$\frac{dq_{lw}}{dt} = -\frac{q_{lw}}{\tau_{convers}}\left[1 - e^{-(q_{lw}/clw)^2}\right]$$

cld_lc_lsc=0.00065
cld_tau_lsc=900

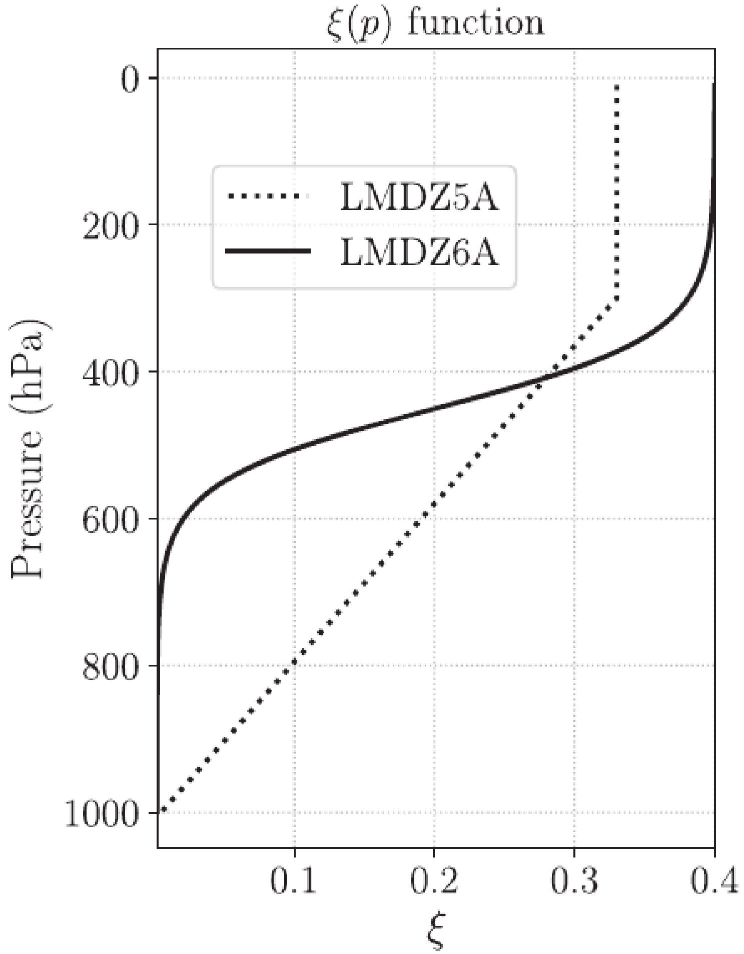
$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

$$w_{iw} = \gamma_{iw} w_0$$

ffallv_lsc=0.8

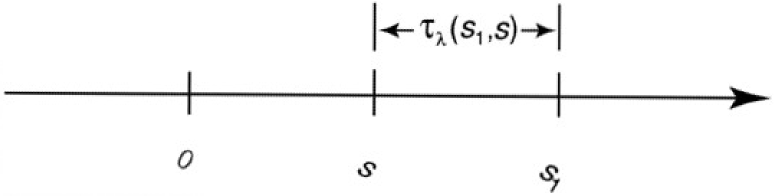
$$\sigma = \xi q_t$$

ratqsp0=45000
ratqsdp=10000
ratqsbas=0.002
ratqshaut=0.4



Radiative transfer

Radiative transfer equation :



$$-\mu\frac{\partial I_\lambda}{\partial \tau_\lambda}(\tau_\lambda,\mu,\Phi) = -I_\lambda(\tau_\lambda,\mu,\Phi) + S_\lambda(\tau_\lambda,\mu,\Phi)$$

$$+\frac{w_{0_\lambda}}{4\pi}\int_0^{2\pi}\int_{-1}^{1} P_\lambda(\mu,\mu',\Phi,\Phi')I_\lambda(\tau_\lambda,\mu',\Phi')d\mu' d\Phi'$$

Solving the radiative transfer equation requires :

- $\boldsymbol{q_{rad}}$ to compute the optical depth ;
- **Cloud droplet and crystal sizes** to compute the optical properties ;
- The cloud fraction **α** to compute the heating rates in the clear-sky (1-α) and cloudy (α) columns.

$$q_{rad} = q_c^{in,\,cv}\alpha_c^{cv} + q_c^{in,\,lsc}\alpha_c^{lsc}$$

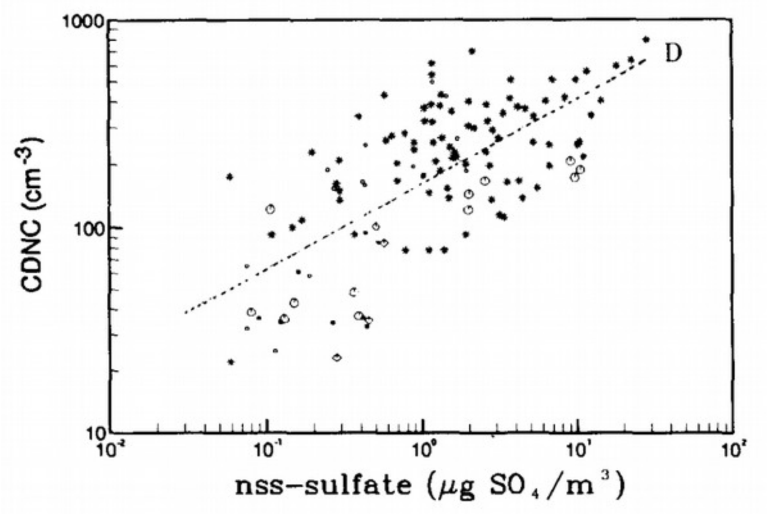
$$\alpha_c = \min\left(\alpha_c^{cv} + \alpha_c^{lsc},\ 1\right)$$

Optical properties of liquid clouds

(see O. Boucher's talk)

$$\mathrm{CDNC} = 10^{1.3 + 0.2\log(m_{\mathrm{aer}})}$$

Link cloud droplet number concentration to soluble aerosol mass concentration (Boucher and Lohmann, Tellus, 1995)



N = CDNC

$$r_3 = \left(\frac{l\,\rho_{\mathrm{air}}}{(4/3)\,\pi\rho_{\mathrm{water}}\,N} \right)^{1/3}$$

$$r_{\mathrm{e}} = \frac{\int r^3 n(r)\,\mathrm{d}r}{\int r^2 n(r)\,\mathrm{d}r}$$

$$r_{\mathrm{e}} = 1.1\ r_3$$

Size-dependent computation of cloud optical properties (Fouquart [1988] in the SW, Smith and Shi [1992] in the LW)

Optical properties of ice clouds

Optical properties are computed using Ebert and Curry [1992], based on the computed crystal sizes.

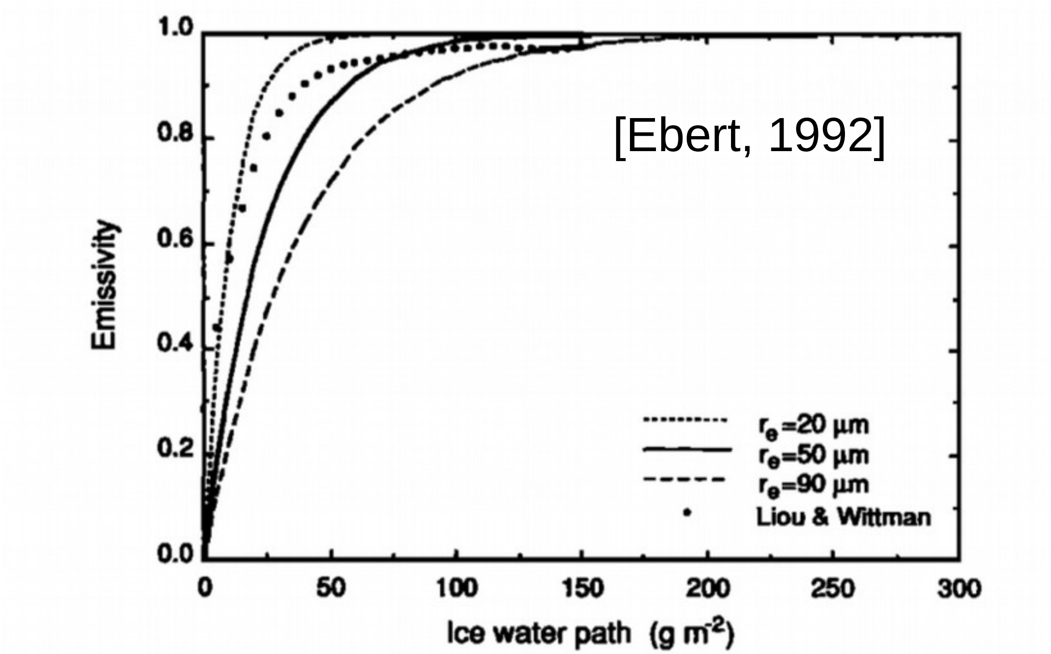
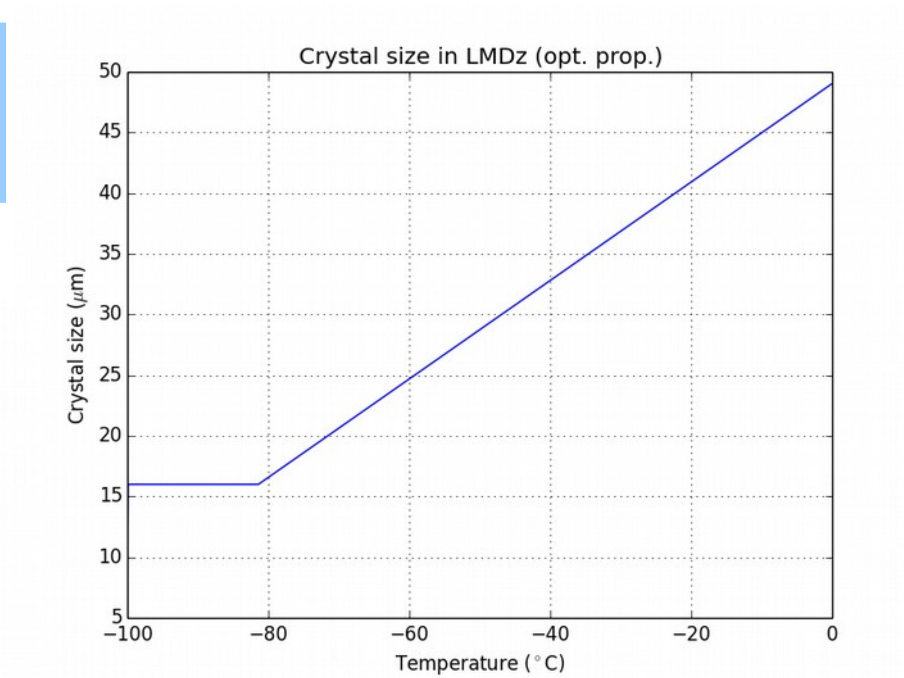
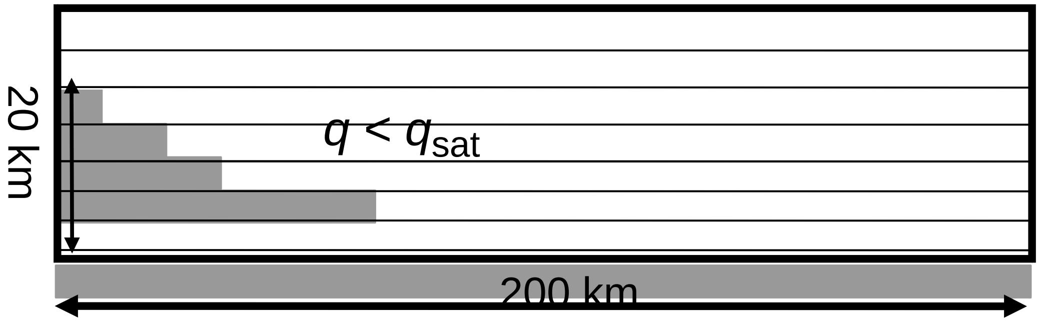


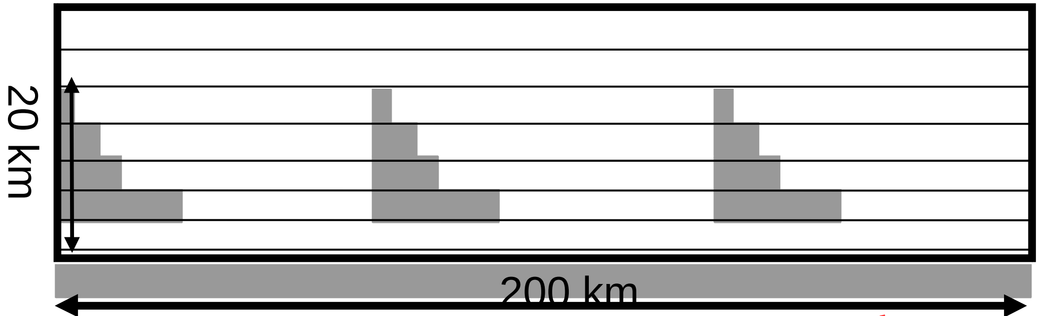
Fig. 5. Cirrus infrared emissivity for r_e = 20, 50, and 90 μm as a function of ice water path. The solid circles represent values computed using the parameterization of *Liou and Wittman* [1979].



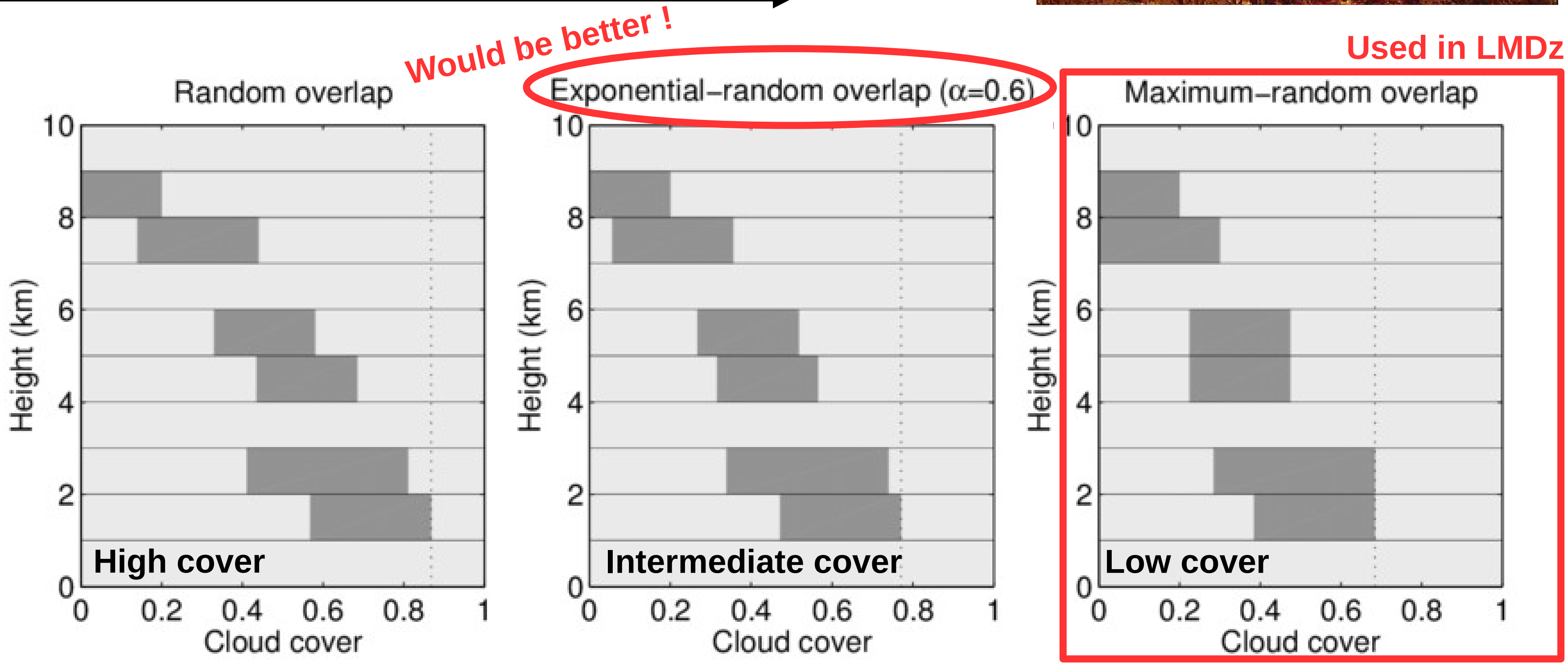
Crystal sizes follow
$r = 0.71T + 61.29$ in µm
[Iacobellis et Somerville 2000]
with r_{min} ~ 10 µm (tuneable)
for T < -81.4°C *[Heymsfield et al. 1986]*

CF versus height is known, but radiation also needs to know the total cloud **cover ;** we therefore parameterize the **cloud overlap**



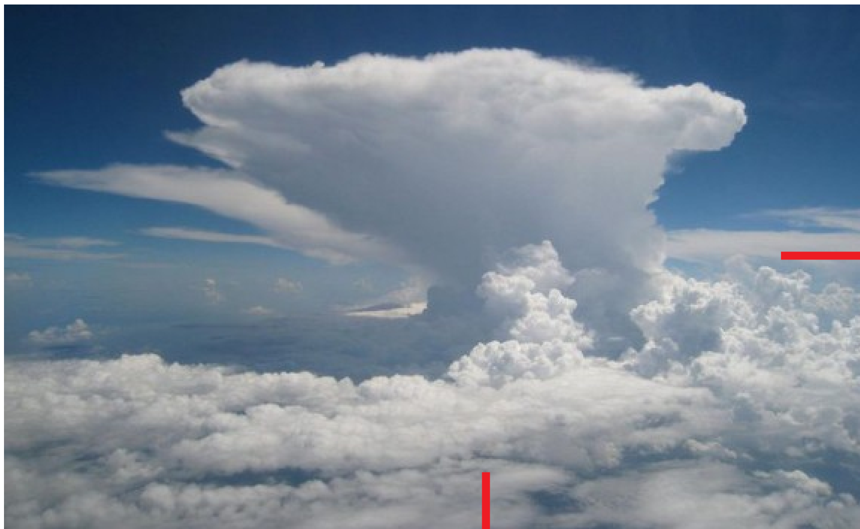


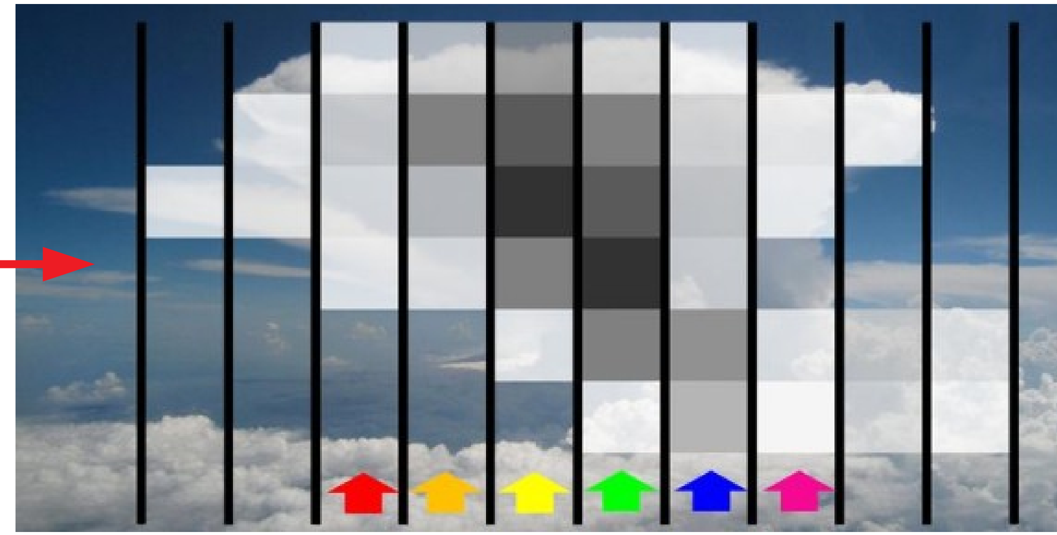
For the GCM, these two scenes are identical ;



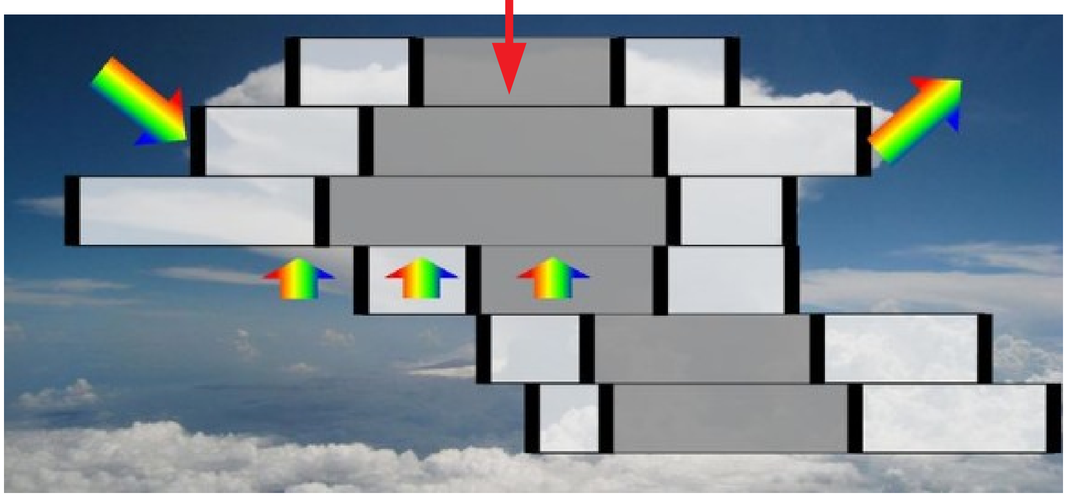
[Radiation parameterization and clouds, Hogan, 2009]

Subgrid scale heterogeneity and 3D effects : **ecRad (ECMWF)**





Monte-Carlo Independent Column Approx.
(McICA, Pincus et al. 2005)



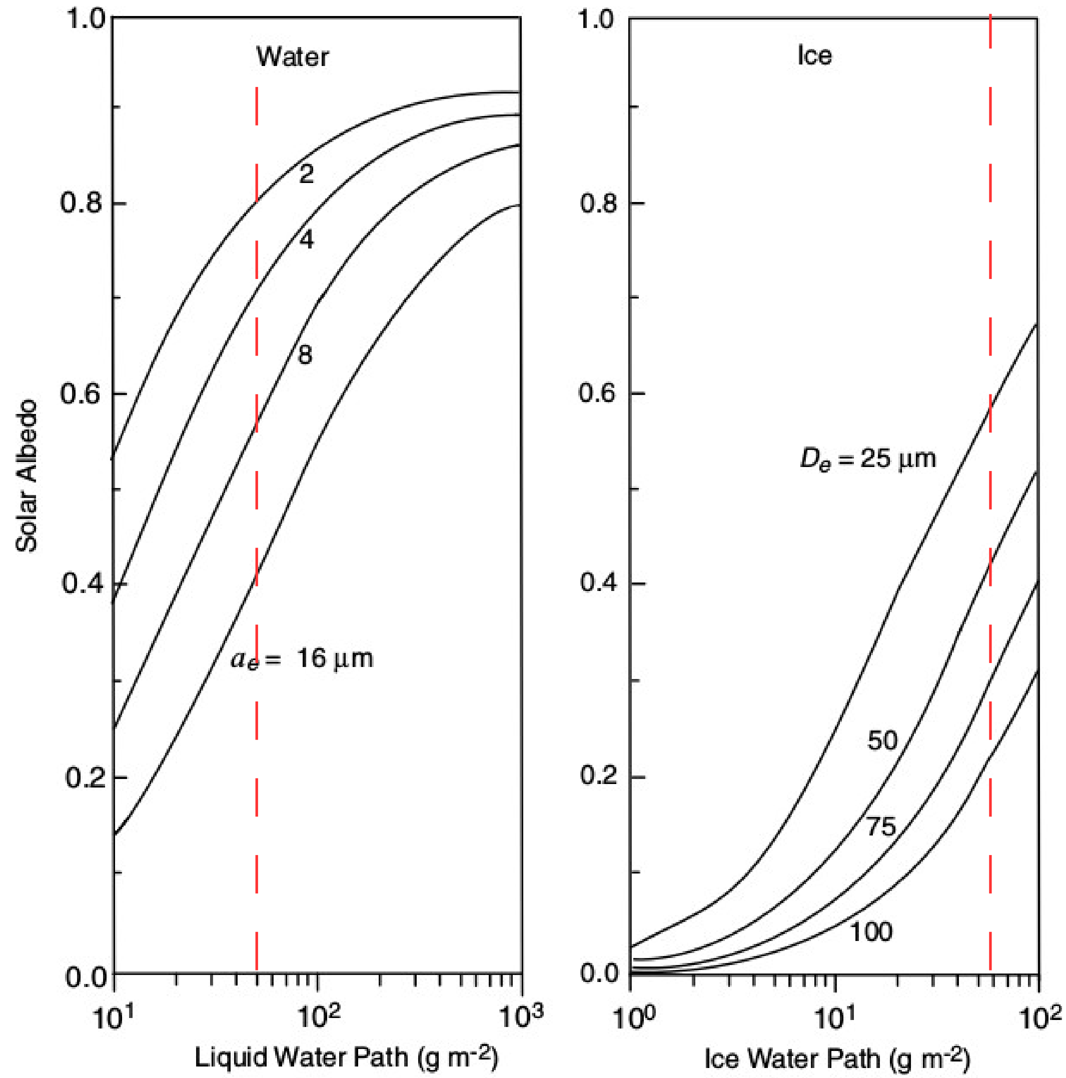
- Takes into account cloud sizes but also horizontal radiative transfer in the case of SPARTACUS
- Cloud sizes must be parameterized along with cloud fraction and opacity

SPARTACUS (Hogan et al., 2016)
Accounts for 3D effects

Welcome to the LMDz team !

Importance of cloud phase

- Clouds reflect sunlight (negative forcing, cooling) and emit in the infrared (positive forcing, warming) ;
- For the same water content, liquid clouds reflect more sunlight than ice clouds ;
- <u>For liquid clouds :</u> if the cloud water content increases, there is a negative forcing (reflection dominates) ;
- <u>For ice clouds :</u> if the cloud water content increases, the forcing depends on the size of the crystals.



[Liou 2002]

Précision sur les sorties

- L'eau nuageuse que voit le rayonnement n'est pas la même que l'eau nuageuse utilisée dans la physique et la dynamique. Lors de la conversion en précipitation dans fisrtilp, c'est une moyenne de l'eau restante dans le nuage PENDANT la précipitation qui est stockée dans radliq pour le rayonnement, et non l'eau restante À LA FIN du pas de temps, qui elle est utilisée dans la physique et advectée par la dynamique. (C'est un choix qui peut être discuté.) Du coup, il est facile de se perdre et de voir des incohérences dans les sorties entre l'eau qui sort du rayonnement et celle qui sort de la physique.
- Pour résumer, sont écrites ci-dessous les variables qui sont égales avec entre parenthèses le nom de la routine correspondante ou "netcdf" quand il s'agit des sorties :
- Rayonnement : xflwc(newmicro) + xfiwc(newmicro) = cldliq(physiq) = radliq(fisrt) = lwcon(netcdf) + iwcon(netcdf)
- Physique / dynamique : ql_seri(physiq) + qs_seri(physiq) = ocond(netcdf)
- Attention cependant : radliq(fisrt) /= ocond(netcdf) autrement dit : lwcon(netcdf) + iwcon(netcdf) /= ocond(netcdf) (ce qui n'est pas du tout évident)
- Si on enlève la moyenne faite par fisrtilp lors de la conversion en précipitation, on obtient bien l'égalité entre l'ensemble des variables. Ci-contre un exemple de profils des différentes variables. Cette moyenne tend à augmenter l'eau nuageuse transmise au rayonnement. Comme il s'agit d'une moyenne sur le pas de temps plutôt qu'une eau restante à la fin du pas de temps, elle tend donc, a priori, à faire des nuages plus brillants. Cette moyenne remonte à Le Treut et Li (1991), où le pas de temps physique du modèle était d'une demi-heure contre 15 min actuellement.