Clouds

LMDz Training – December 2020

J-B Madeleine, C. Rio 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

Radiative forcing

LW radiative forcing

Positive : clouds reduce the LW outgoing radiation

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

SW radiative forcing

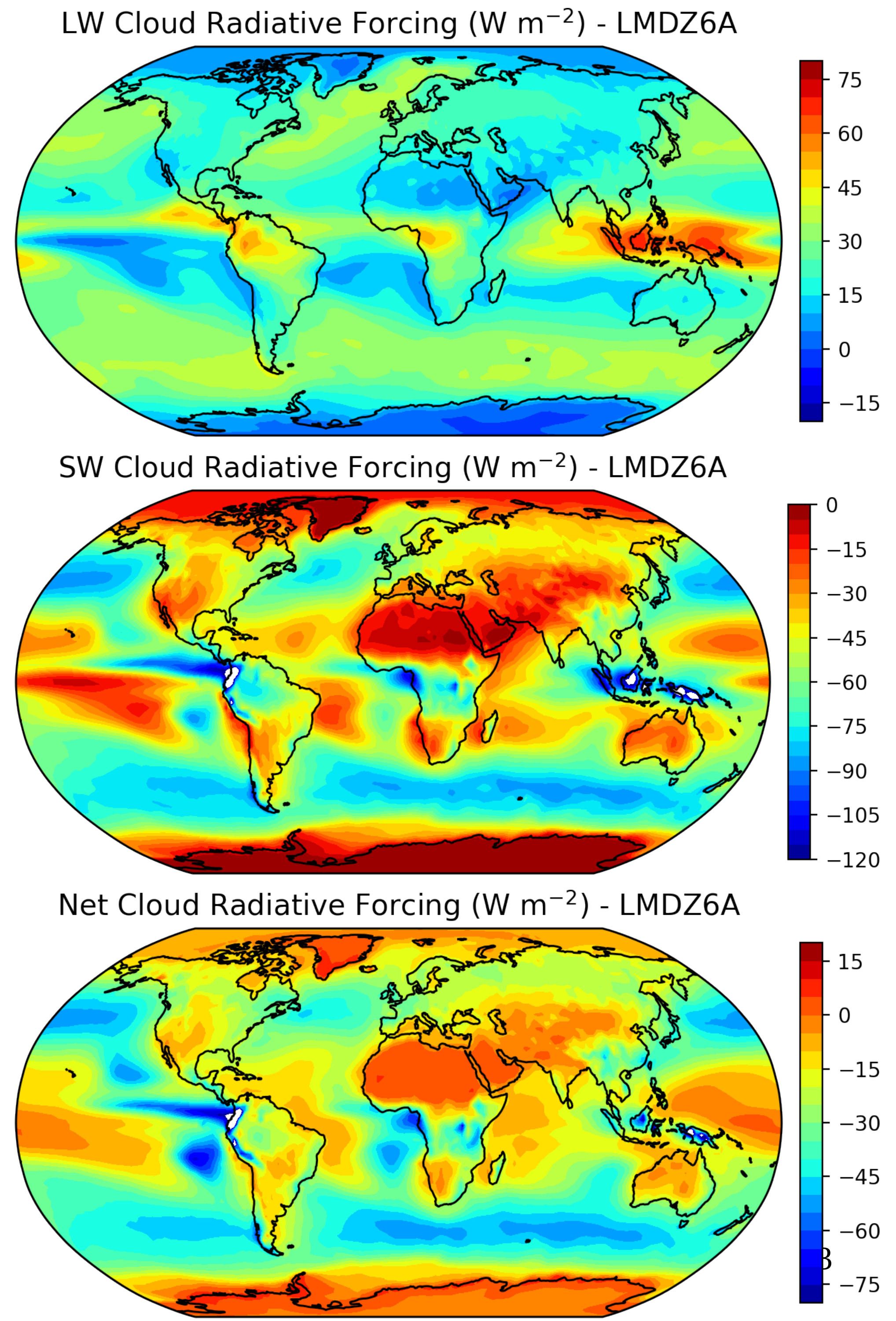
Negative : clouds reflect the incoming SW radiation

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

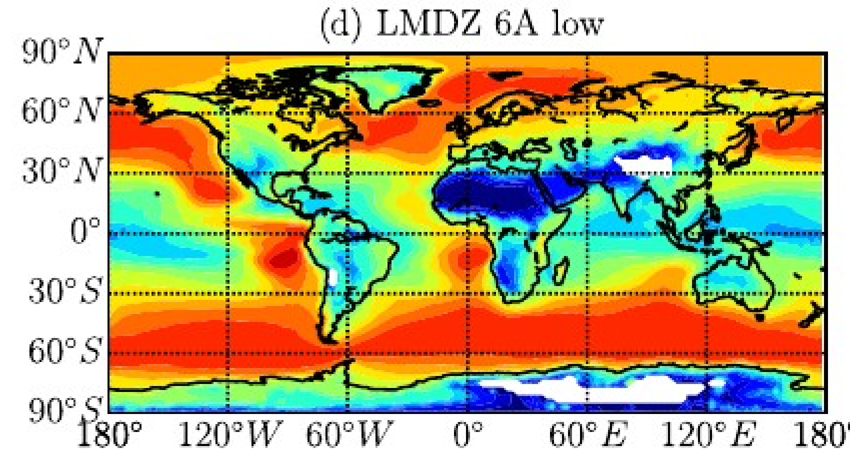
cldh : High-level cloud **cover**
cldm : Mid-level cloud **cover**
cldl : Low-level cloud **cover**
cldt : Total cloud **cover**

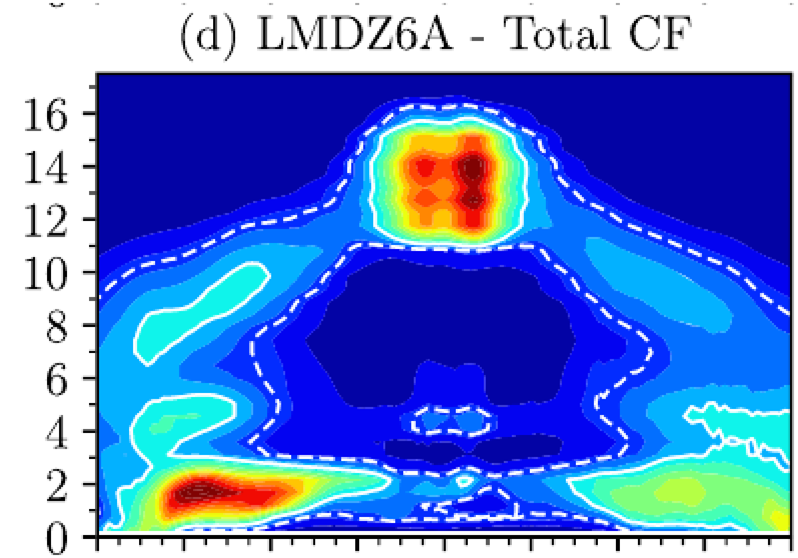
low-level clouds = below 680 hPa or ~3 km
mid-level clouds = between 680 and 440 hPa
high-level clouds = above 440 hPa or ~6.5 km

lwp (kg/m2) : long_name : Cloud liquid water path
iwp (kg/m2) : long_name : Cloud ice water path
cldq (kg/m2) : Cloud total water path (lwp+iwp)

lwcon (kg/kg) : 3D cloud liquid water content
iwcon (kg/kg) : 3D cloud ice water content
rneb : 3D cloud **fraction**

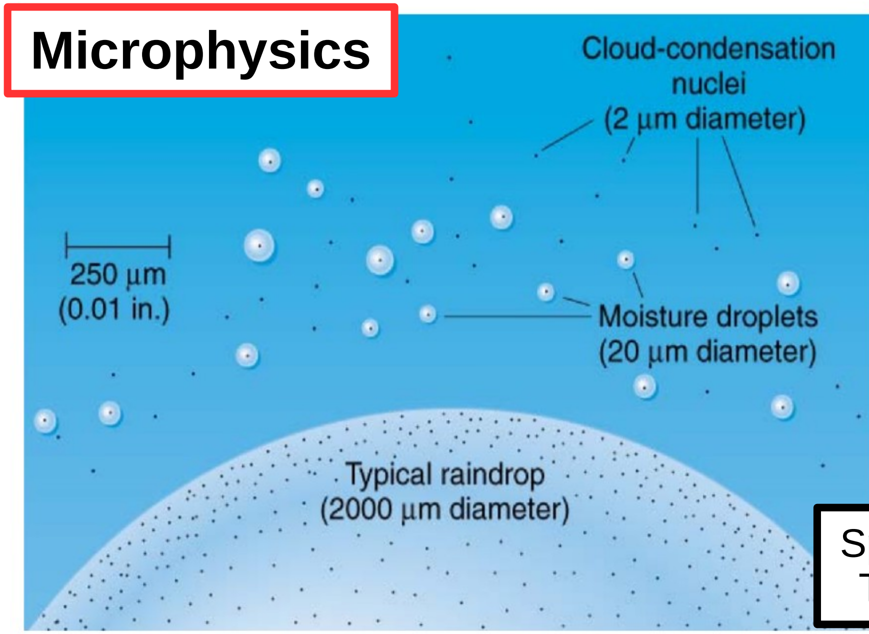
pr_lsc_l (kg/m2/s) : 3D rain mass fluxes (lsc or con)
pr_lsc_i (kg/m2/s) : 3D snow mass fluxes (lsc or con)
rain_fall (kg/m2/s) : surface rainfall (plul+pluc)
snow (kg/m2/s) = surface snowfall



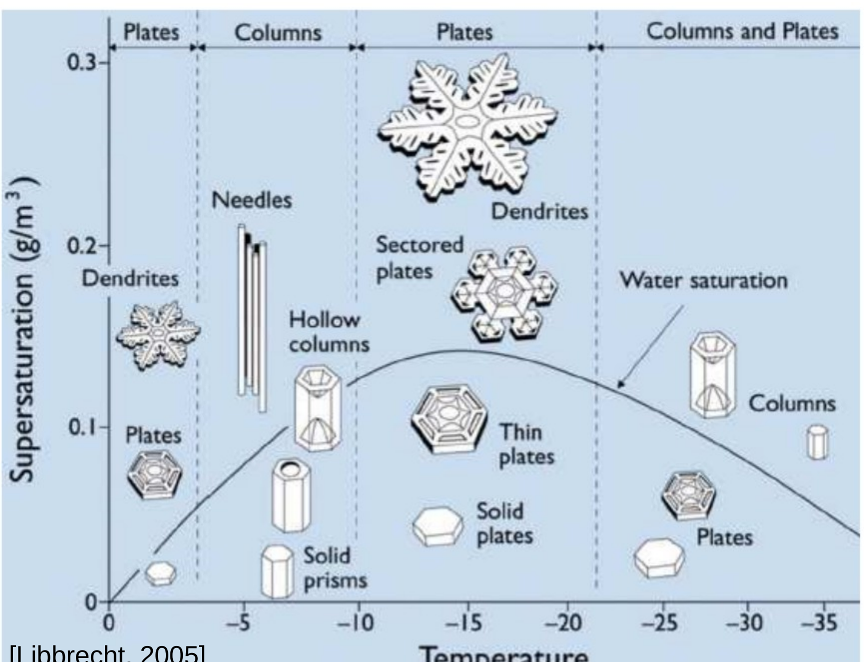


Modeling clouds : a challenge

Microphysics

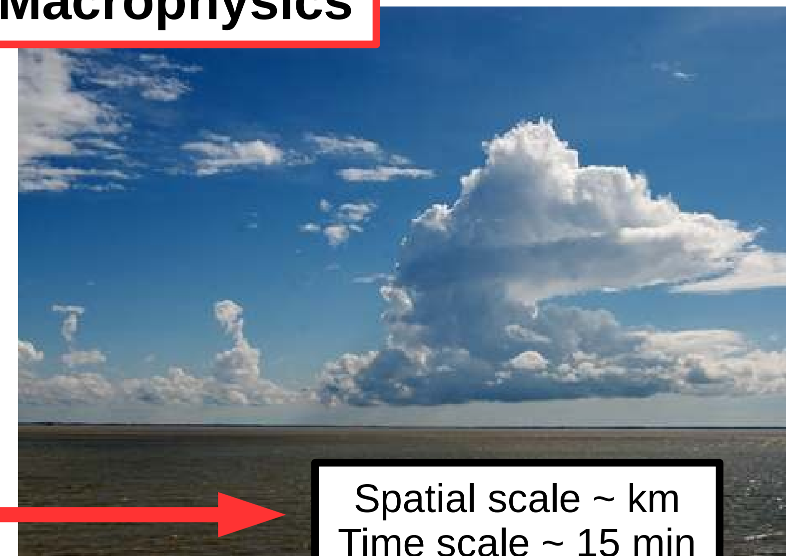


Spatial scale ~ µm
Time scale ~ 1 s

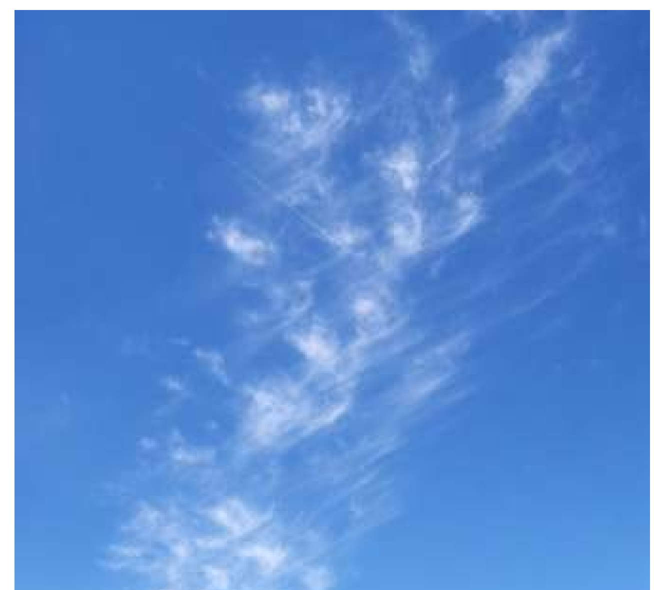


[Libbrecht, 2005]

Macrophysics



Spatial scale ~ km
Time scale ~ 15 min



Fundamental process

- Clausius-Clapeyron equation :

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

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

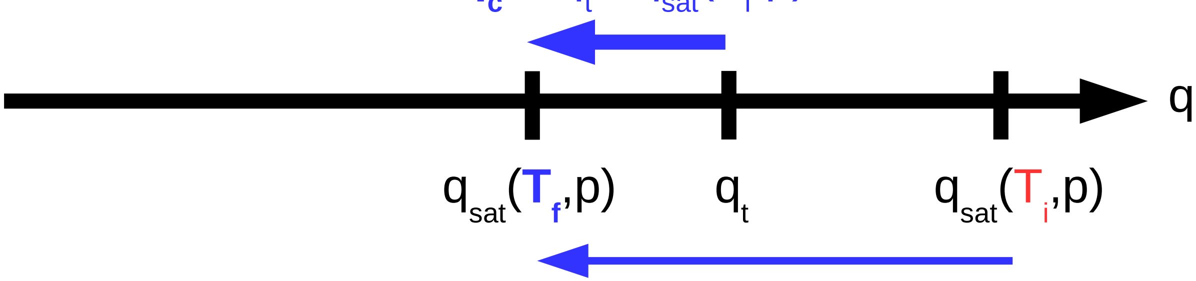
- Saturation mass mixing ratio :

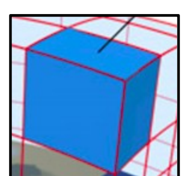
$$q_{sat}(T,p) \simeq 0.622\,\frac{e_{sat}(T)}{p}$$

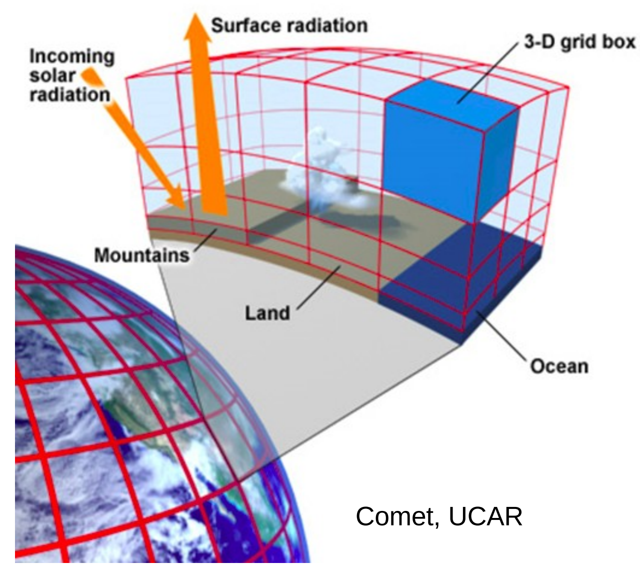
, where $e_{sat}(T)$ grows exponentially with temperature

- Clouds form when an air parcel is cooled :

$q_c = q_t - q_{sat}(T_f,p)$

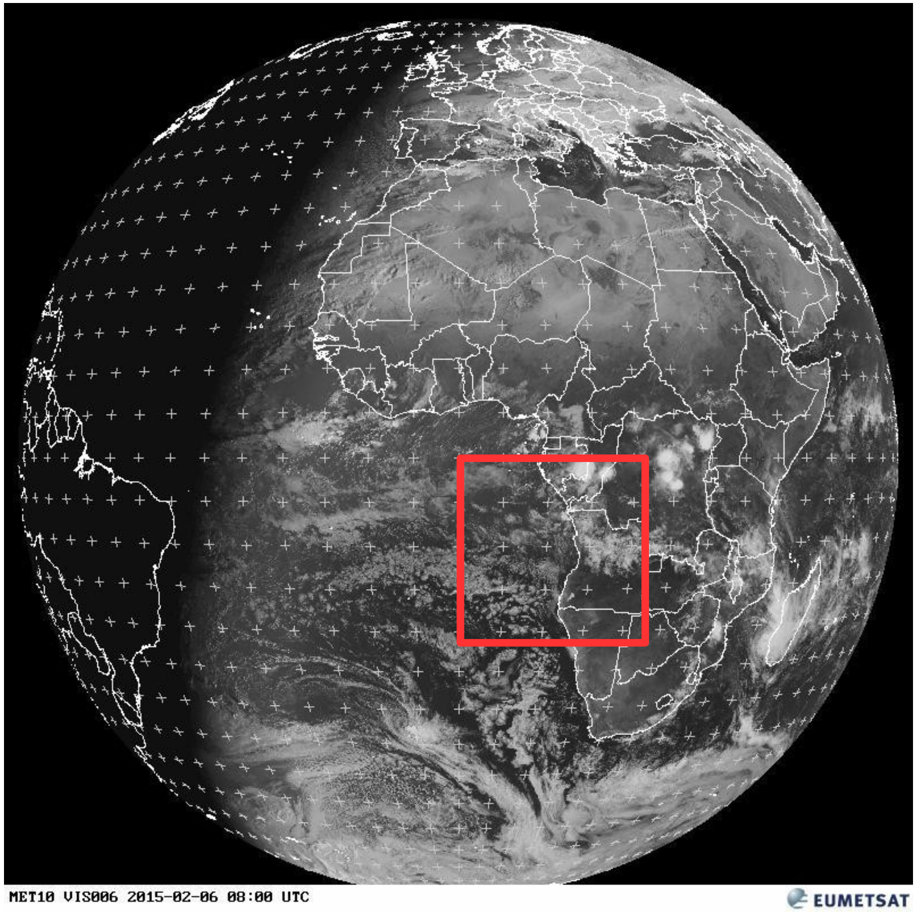


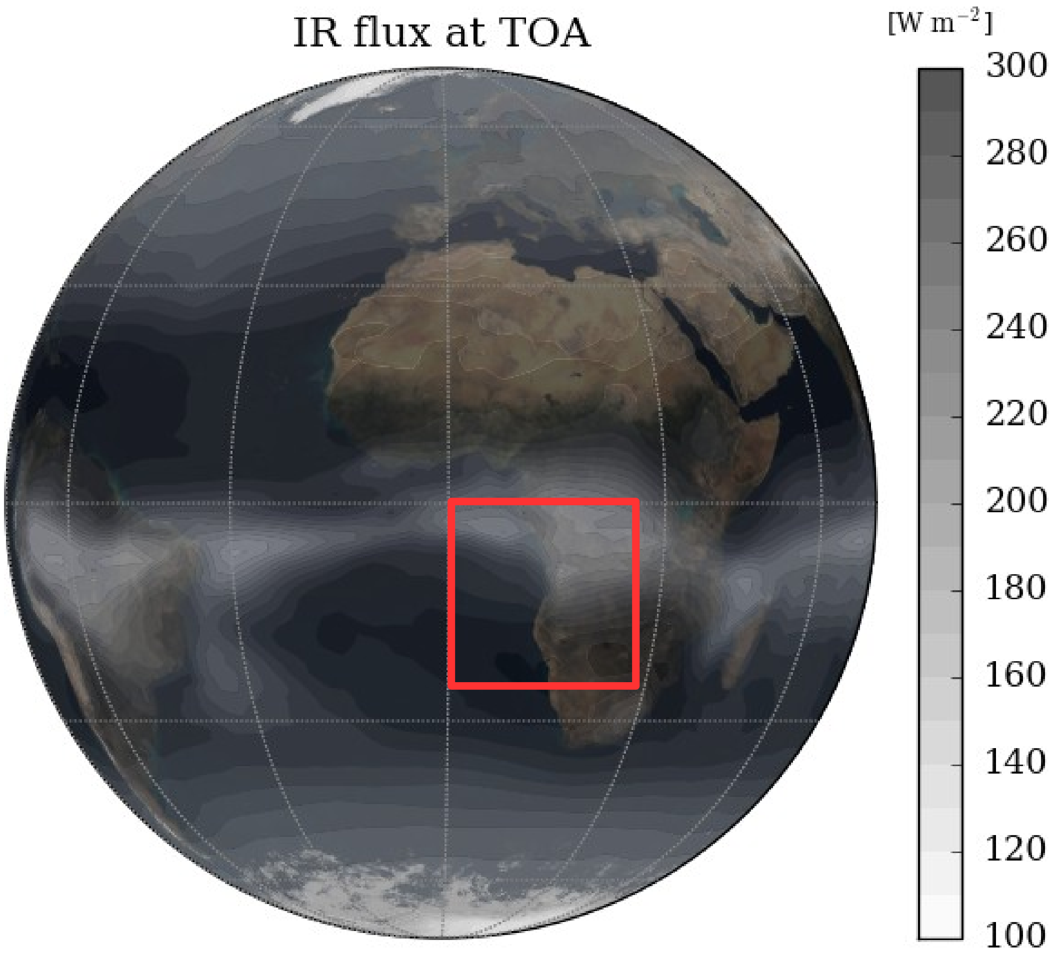
- But clouds do not look like that : 



Comet, UCAR

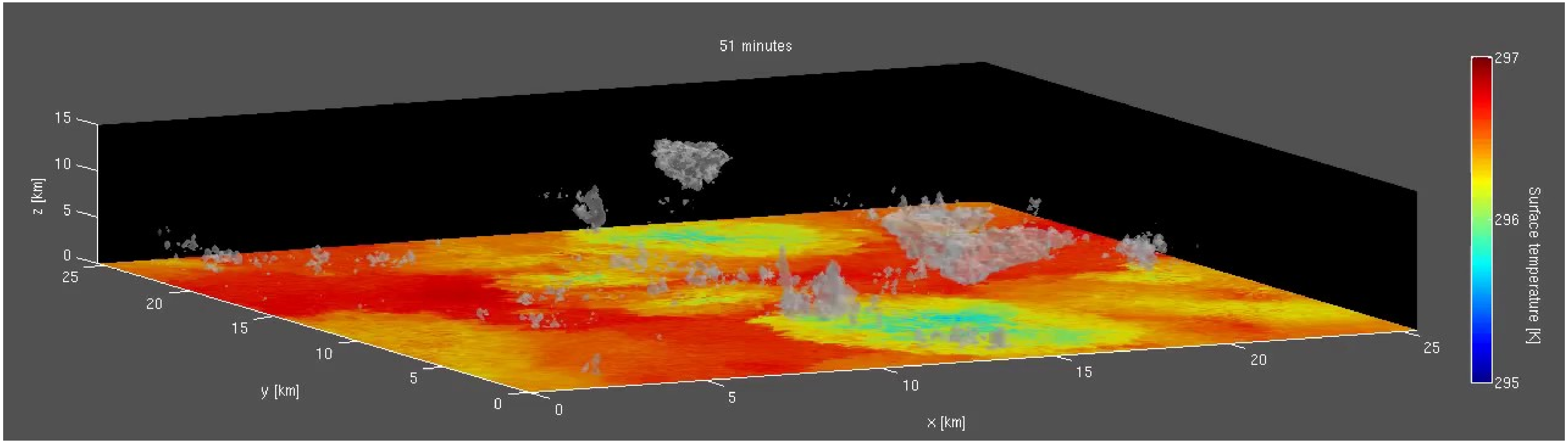
A wide variety of processes





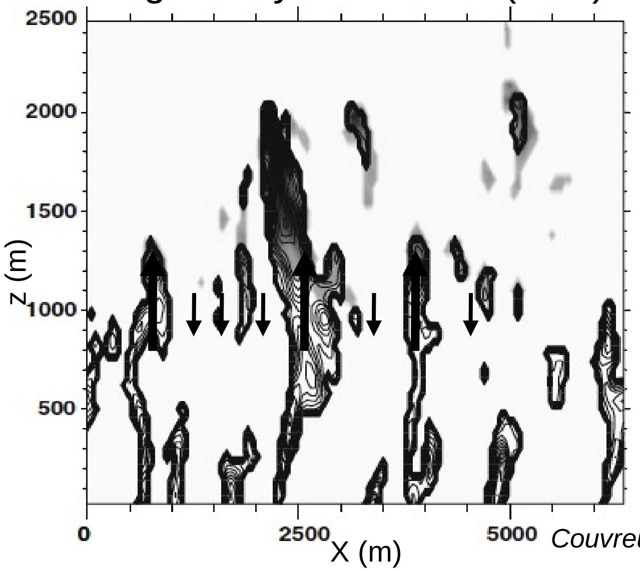
[IPSL Climate Model / 144x142 horizontal resolution]

Many processes in one grid cell



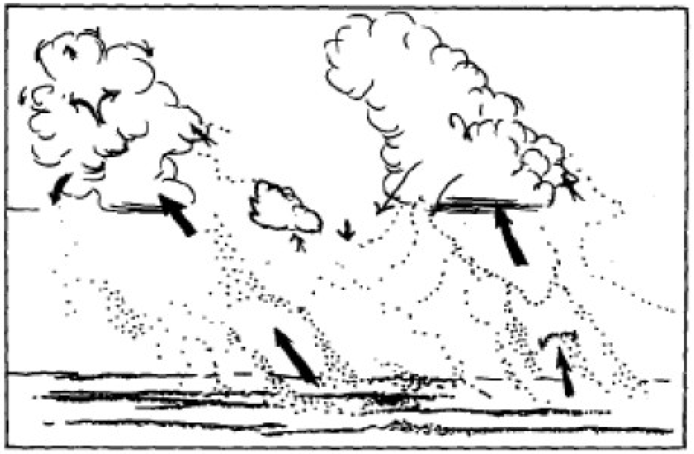
Around 8 hours of simulation by a **Cloud Resolving Model (CRM)** – C. Muller, LMD

Thermals in a
Large-Eddy Simulation (LES)



Couvreux et al., BLM, 2010

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

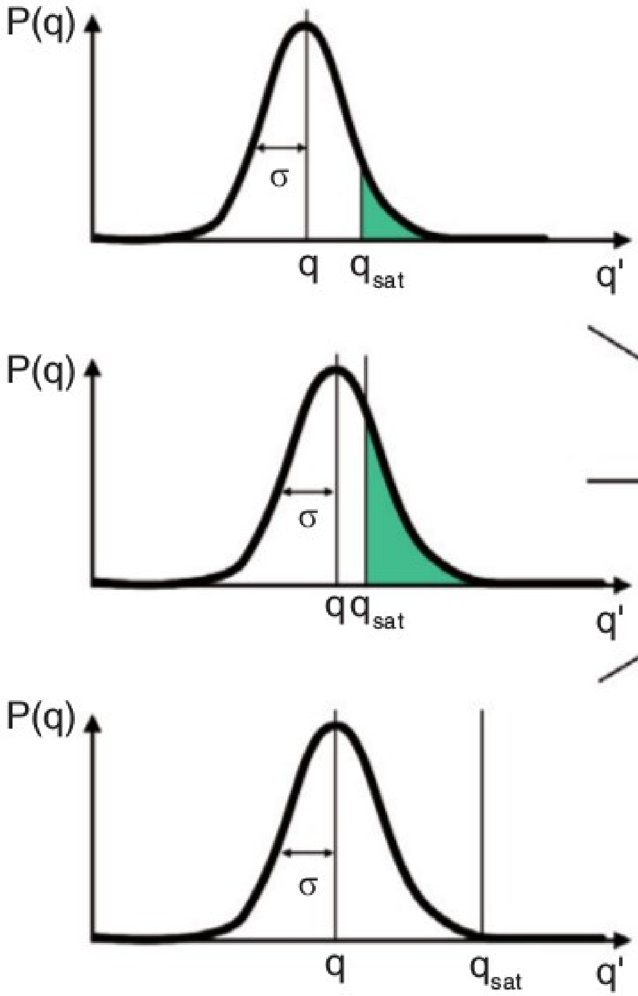


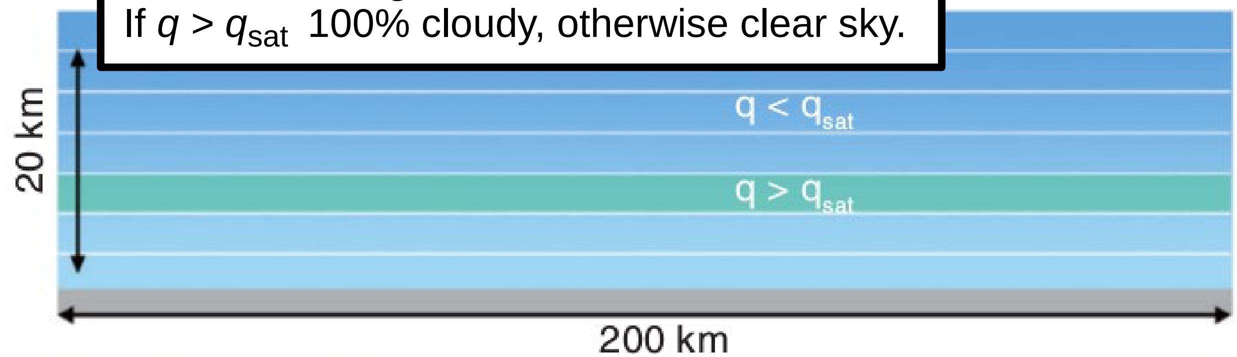
(b)

Lemone et Pennell, MWR, 1976

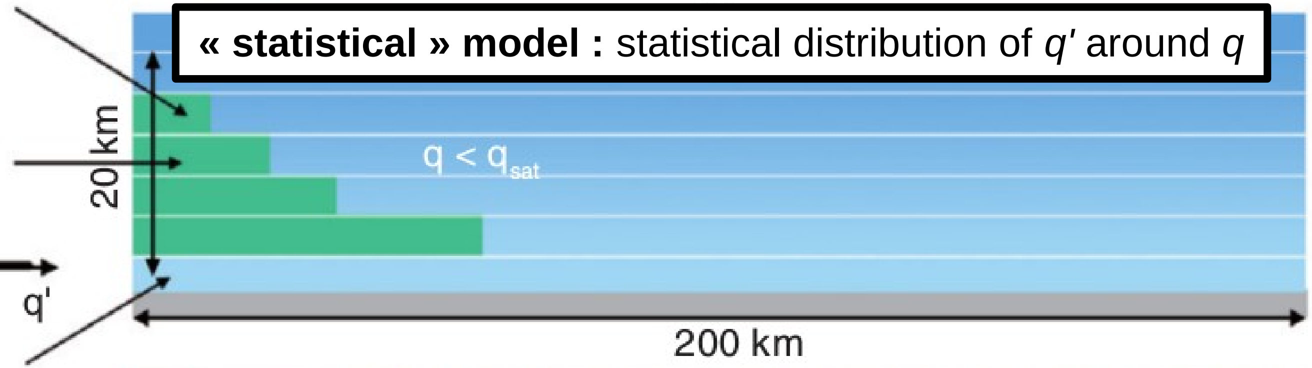
Statistical cloud scheme

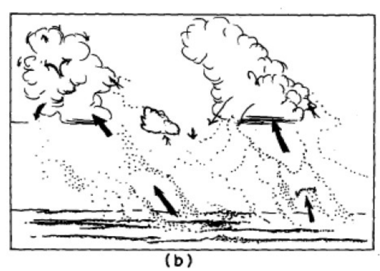
« all or nothing » model :
If $q > q_{sat}$ 100% cloudy, otherwise clear sky.

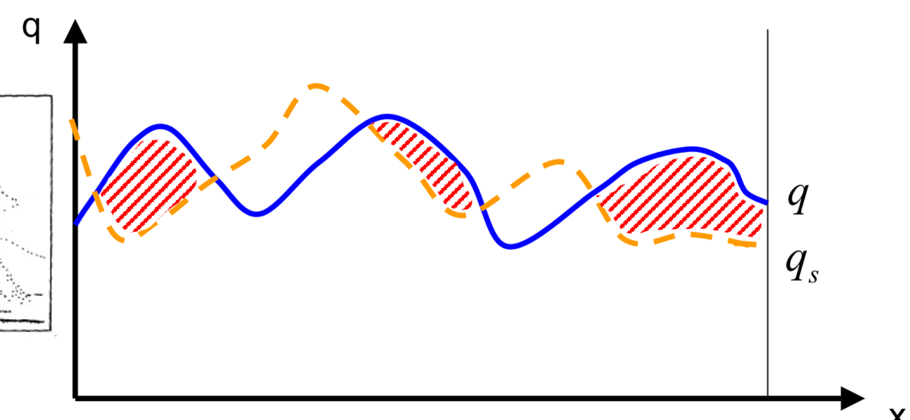




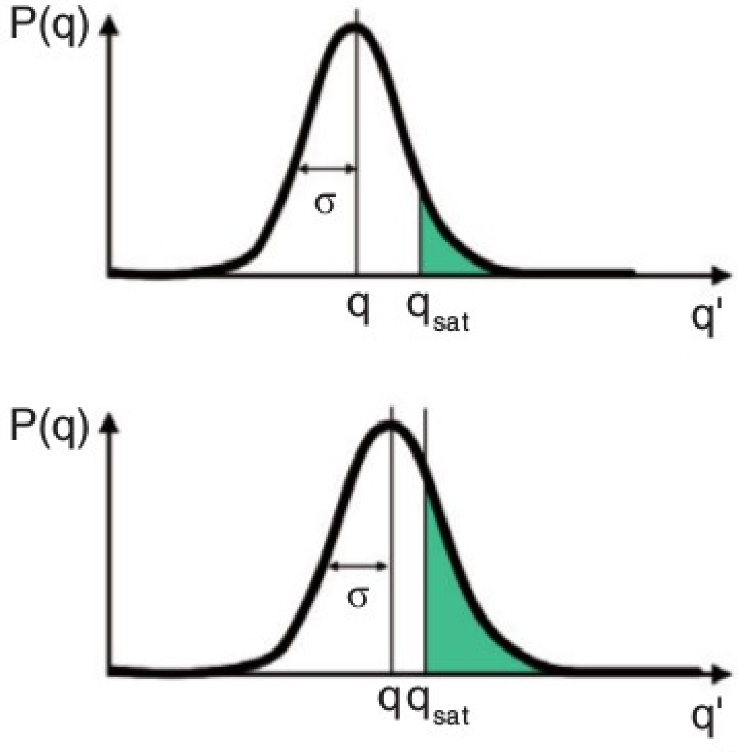
« statistical » model : statistical distribution of q' around q







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 :

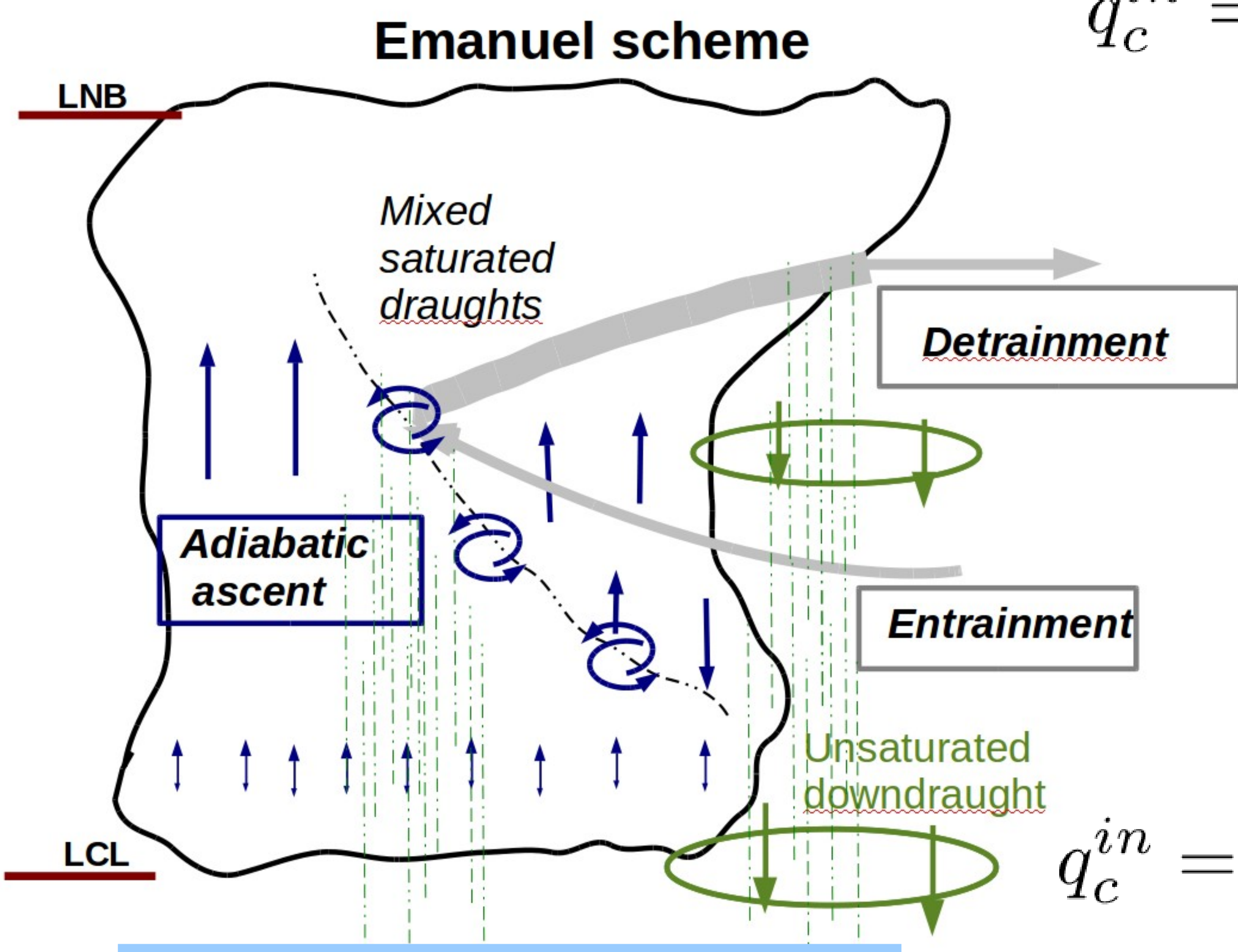
$$q_c^{in} = \frac{q_c}{\alpha_c}$$

Architecture of the cloud scheme

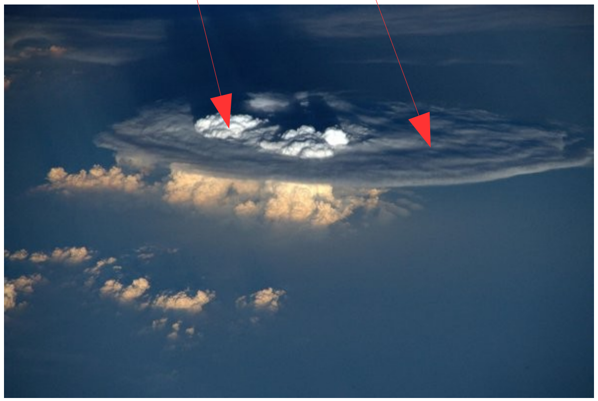
Procedure / Subsection	Input variables	Other outputs
	↺ Updated variables	
2.1. Evaporation	$\theta\ q_v\ q_l\ q_i$	
	↺ $\theta\ q_t\ (q_l = q_i = 0)$	
2.2. Local turbulent mixing	$\theta\ q_t$	
	↺ $\theta\ q_t$	
2.3. Deep convection	$\theta\ q_t\ ALE\ ALP$	$q_c^{in,cv}$ $P_{l,i}^{cv}\ d\theta_{dw}^{cv}\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



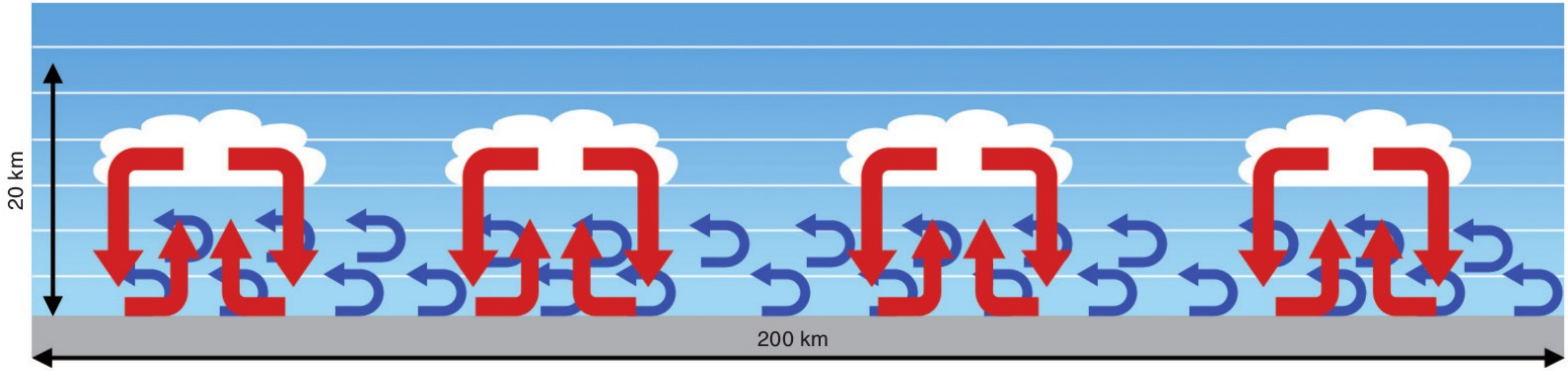
$$q_c^{in} = \frac{\sigma_a \; q_{ca} + \sigma_m \; q_{cm}}{\sigma_a + \sigma_m}$$

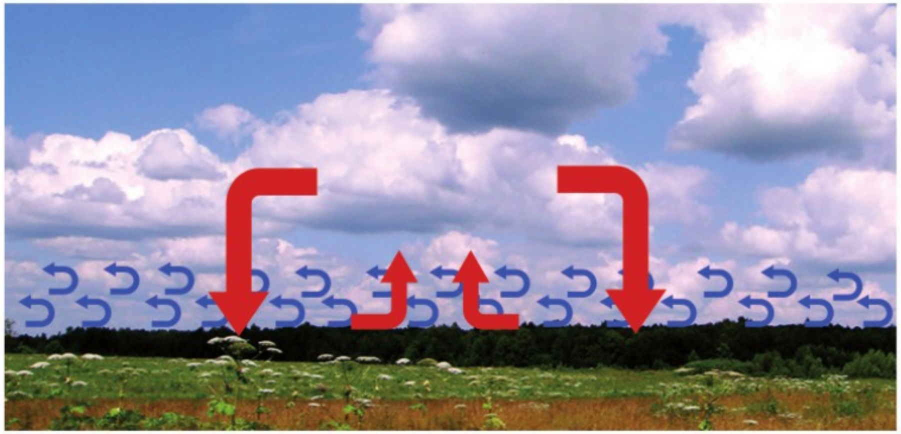


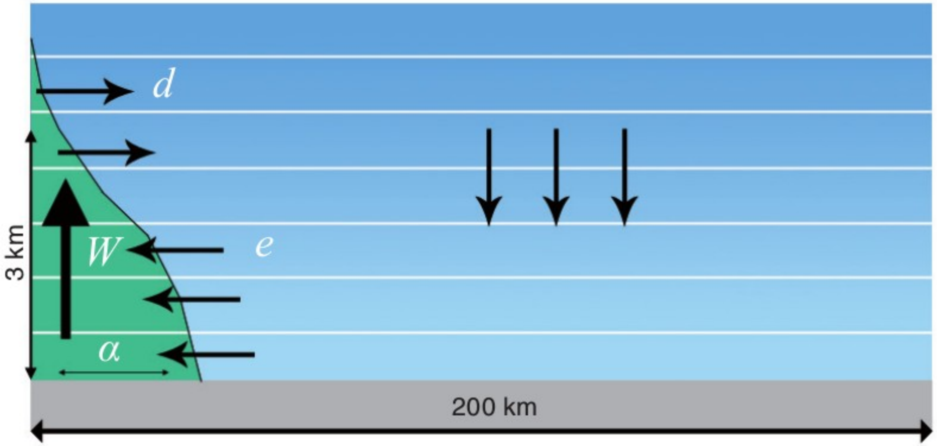
$$q_c^{in} = \frac{\frac{M_a}{\rho \; w_a} \, q_{ca} + \frac{\tau \; M_t \; g}{\delta p} \, q_{cm}}{\frac{M_a}{\rho \; w_a} + \frac{\tau \; M_t \; g}{\delta p}}$$

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

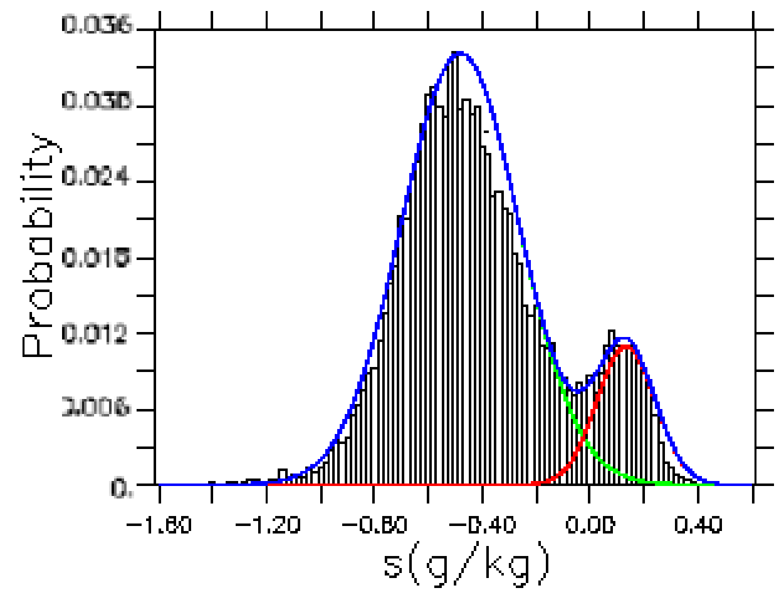
Bi-Gaussian distribution of saturation deficit s:

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

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

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

[Jam & al., BLM, 2013]



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

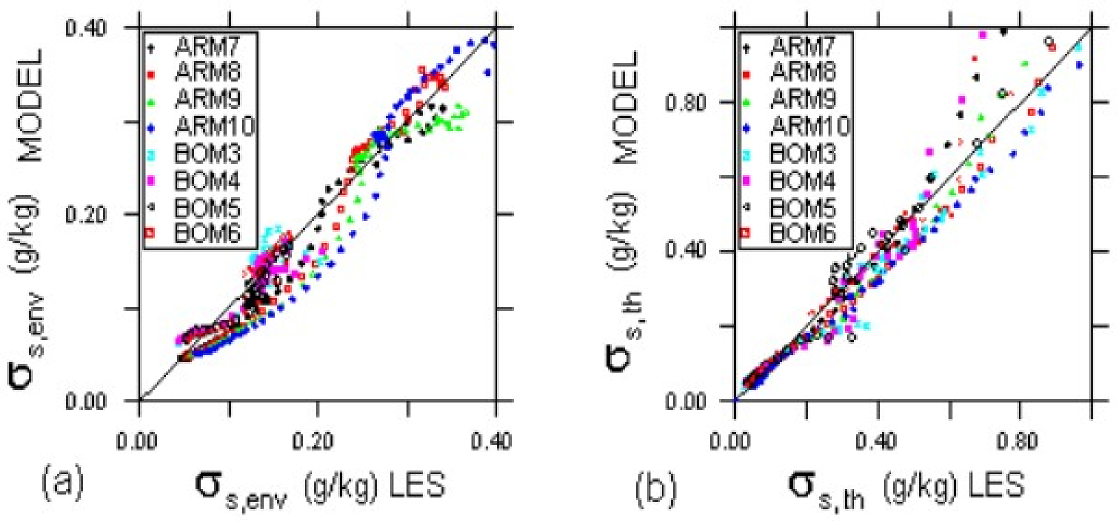
$$\sigma_{s,\mathrm{env}} = c_{\mathrm{env}} \frac{\alpha^{\frac{1}{2}}}{1-\alpha} (\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\, \overline{q}_{t_{\mathrm{env}}}$$

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

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

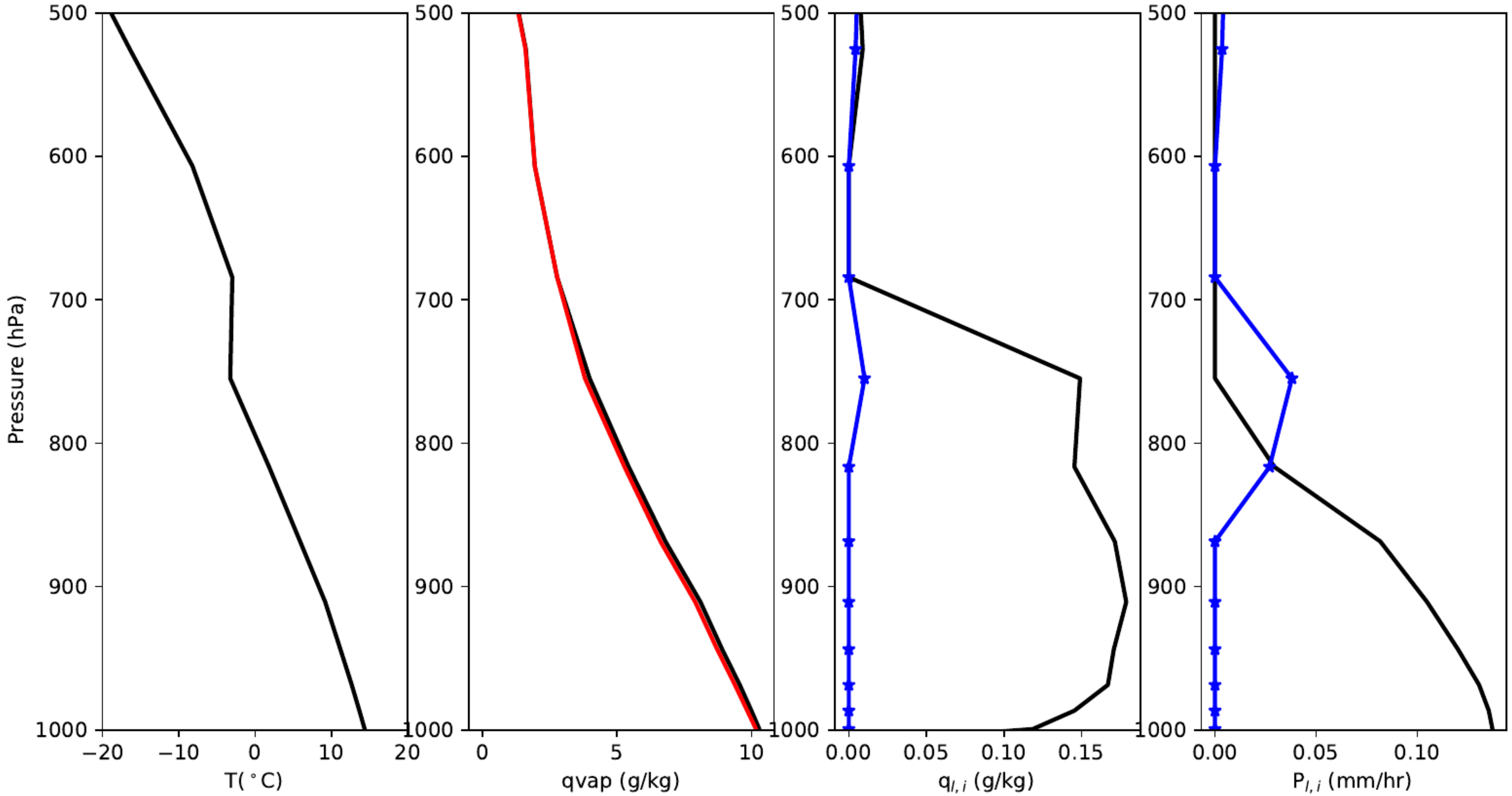
$$q_c^{in} = \int_0^{\infty} s\, Q(s)\, ds \qquad \alpha_c = \int_0^{\infty} Q(s)\, ds$$

[Jam & al., BLM, 2013]



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 shallow convection

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

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

If there is no shallow convection

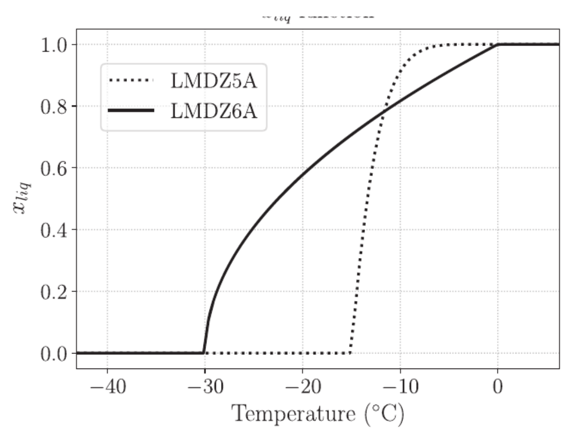
q_c^{in} and the cloud fraction can be computed following :

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

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

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

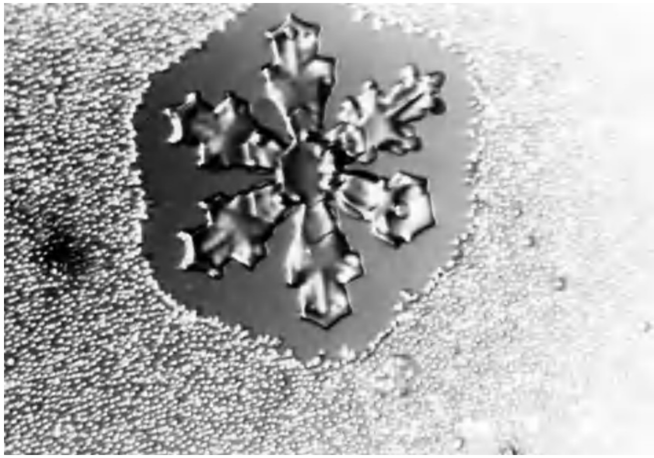
3 **PRECIPITATION**

- 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.

$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$
$$w_{iw} = \gamma_{iw} w_0$$
$$w_0 = 3.29(\rho q_{iw})^{0.16}$$

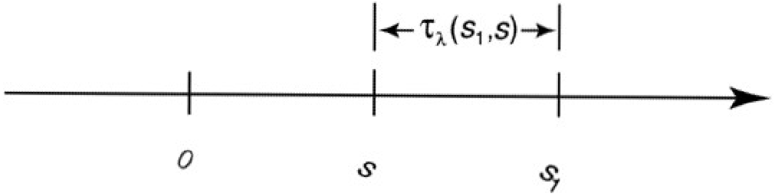


Growth of an ice crystal at the expense of surrounding supercooled water drops [Wallace, 2005]

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.

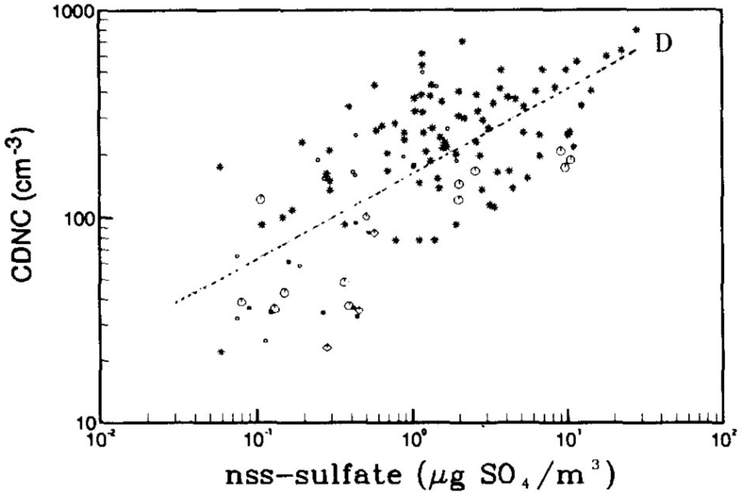
$$q_{rad} = q_c^{in,\,cv}\alpha_c^{cv} + q_c^{in,\,lsc}\alpha_c^{lsc}$$

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

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.

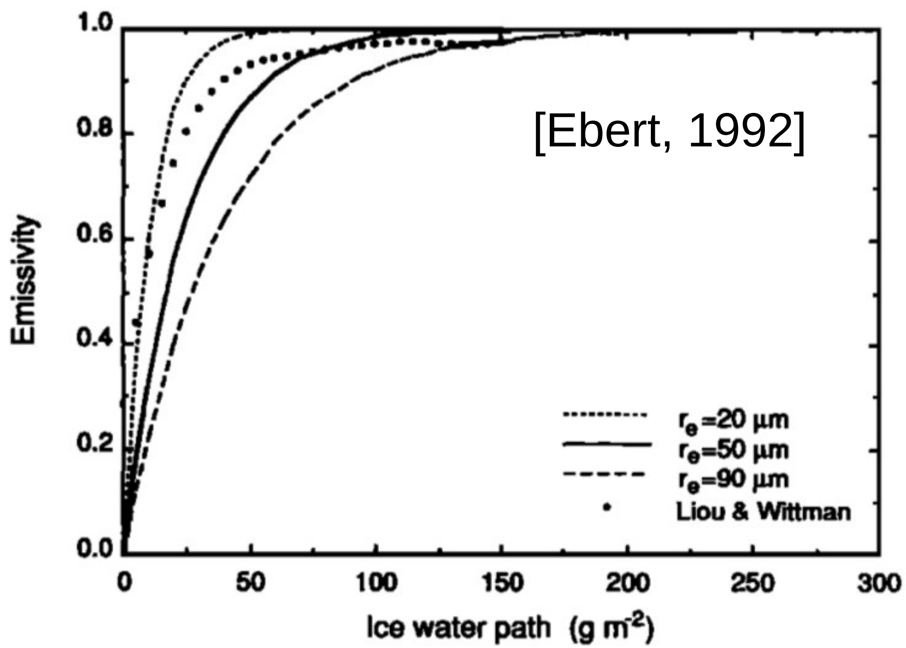
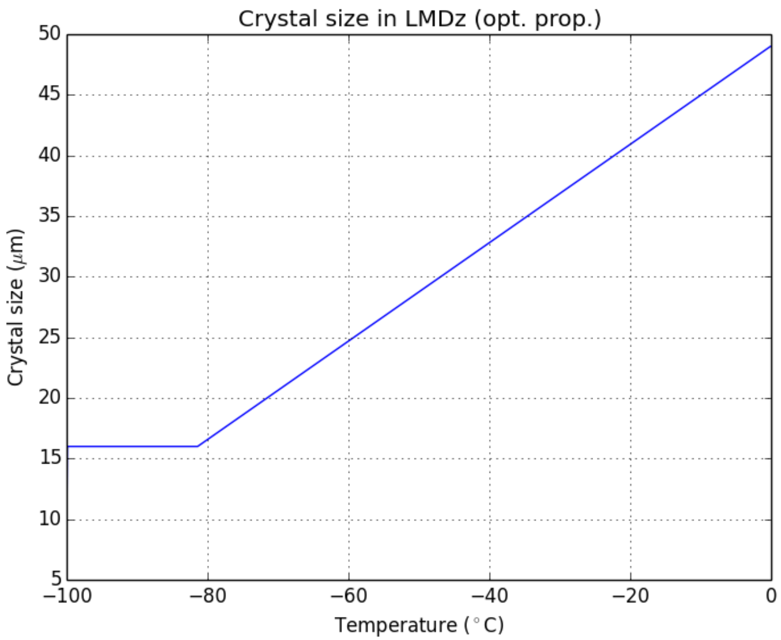


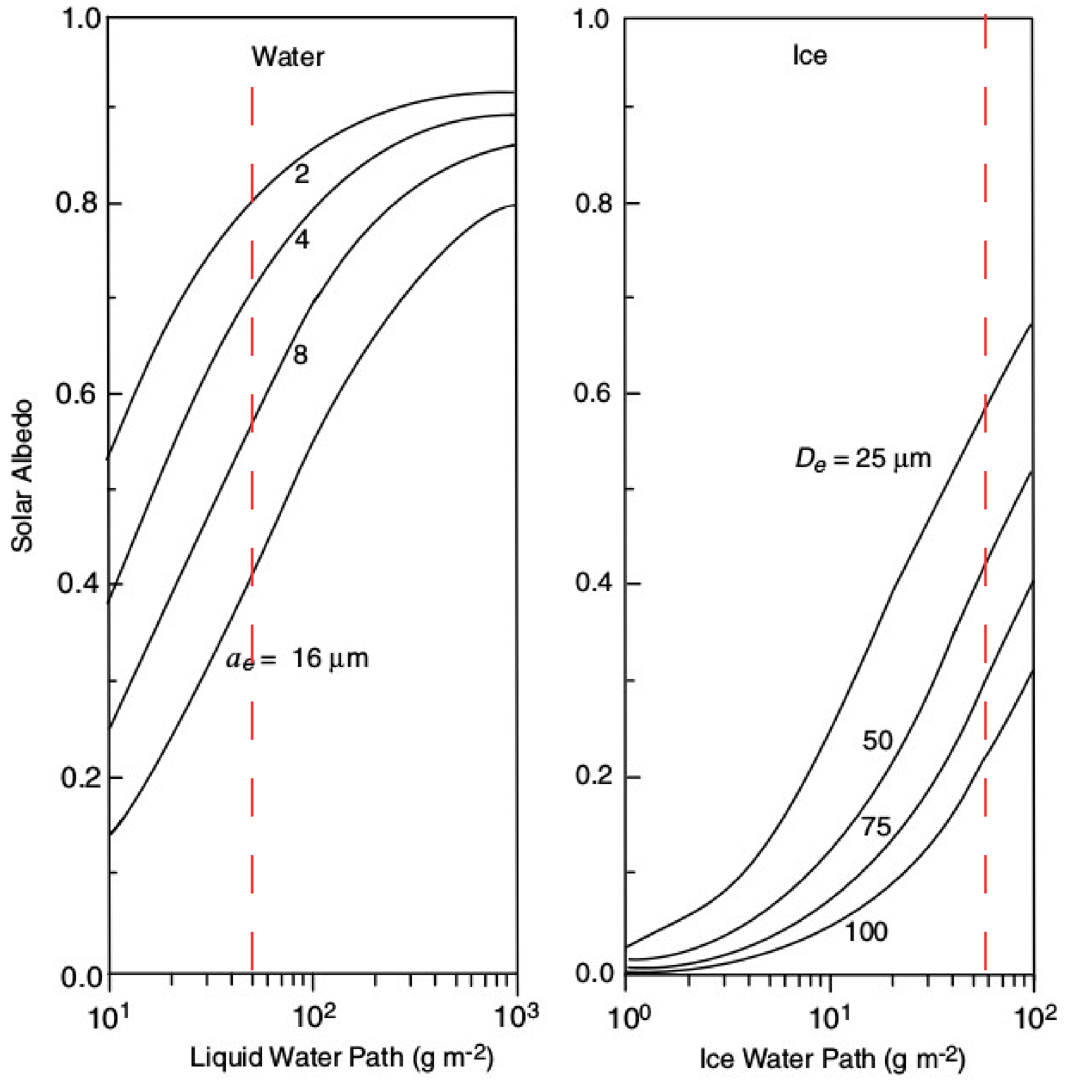
Fig. 5. Cirrus infrared emissivity for r_e = 20, 50, and 90 µm as a function of ice water path. The solid circles represent values computed using the parameterization of *Liou and Wittman* [1979].



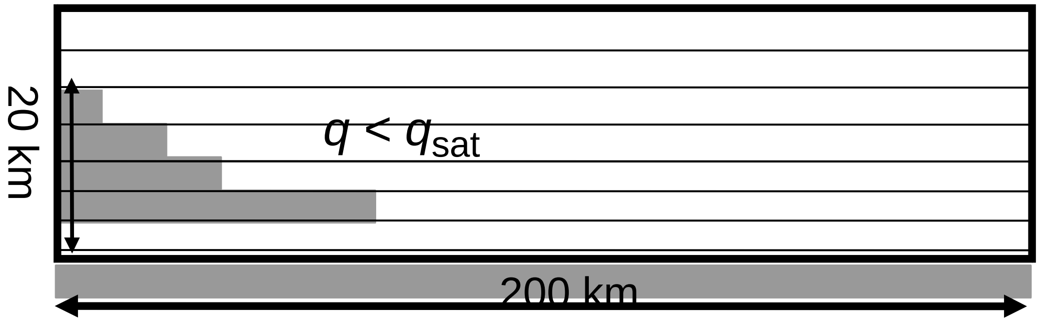
Crystal sizes follow
r = 0.71T + 61.29 in µm
[Iacobellis et Somerville 2000]
with r_{min} ~ 10 µm (tuneable)
for T < -81.4°C *[Heymsfield et al. 1986]*

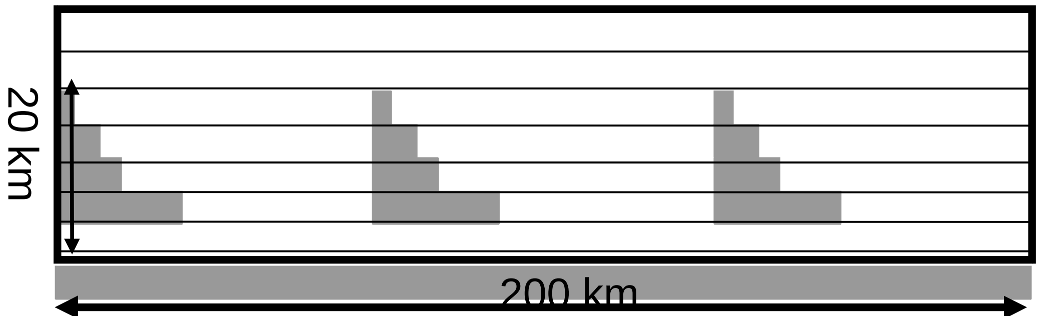
Importance of cloud phase

- 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]

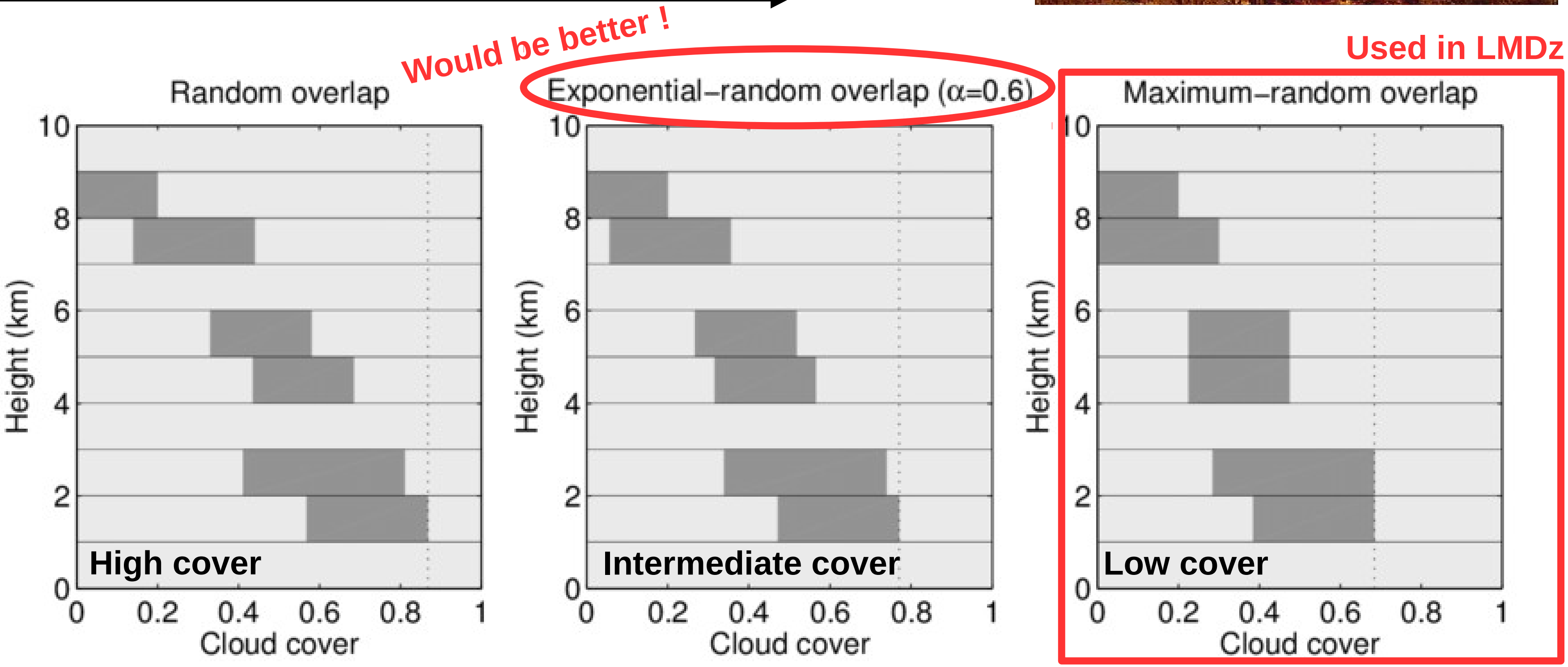




CF versus height is known, but radiation also needs to know the total cloud **cover ;** we therefore parameterize the **cloud overlap**

LMDz : Maximum random overlap

For the GCM, these two scenes are identical ;



[Radiation parameterization and clouds, Hogan, 2009]

Welcome to the LMDz team !