Model physics part II
Convective and large-scale clouds

LMDz Training – January 2024
J-B Madeleine and the LMDZ team

Picture by Oleg Artemyev taken from the ISS

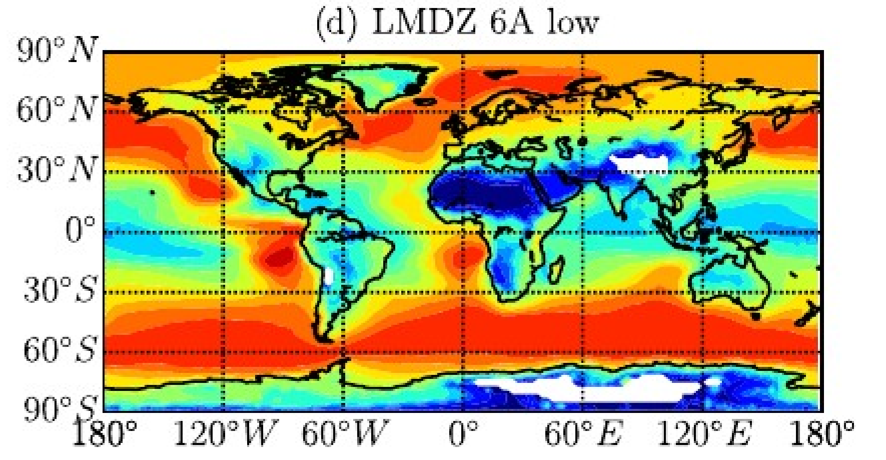
Picture by Thomas Pesquet taken from the ISS

Some useful animations :

- Satellite animation using the SEVIRI instrument :
  http://pmm.nasa.gov/education/videos/water-vapor-animation
- Animations of updrafts and triggering of deep convection over the mountains of Arizona :
  https://animations.atmos.uw.edu, 15.1 and 16.5
- Animation of the cloud field in high resolution LMDZ simulations :
  https://lmdz.lmd.jussieu.fr/pub/Training/Presentations/LMDZ_animation-highres.mp4

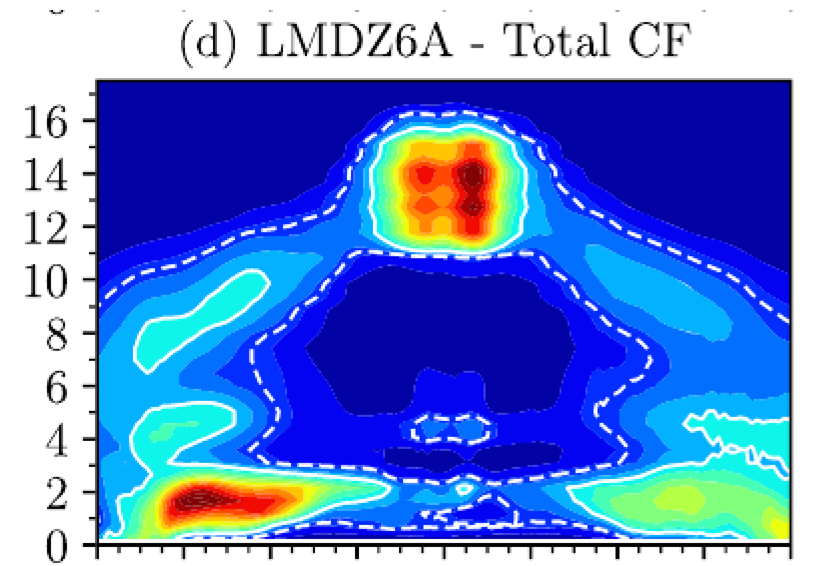
How to visualize clouds in LMDZ

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)

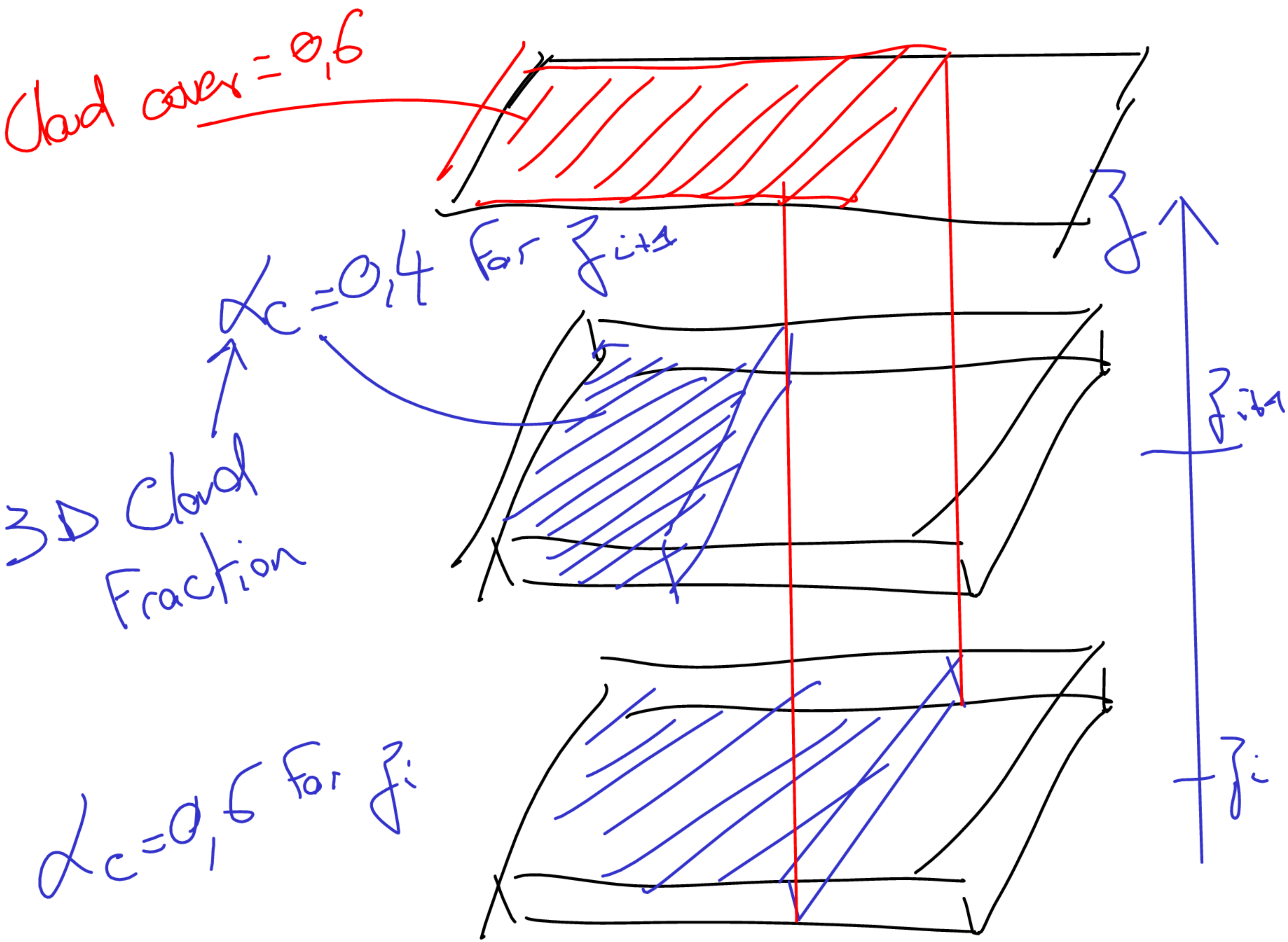
pr_lsc_l (3D) : lsc rain mass fluxes ($kg/m^2/s$)
pr_lsc_i (3D) : lsc snow mass fluxes ($kg/m^2/s$)



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** (%)

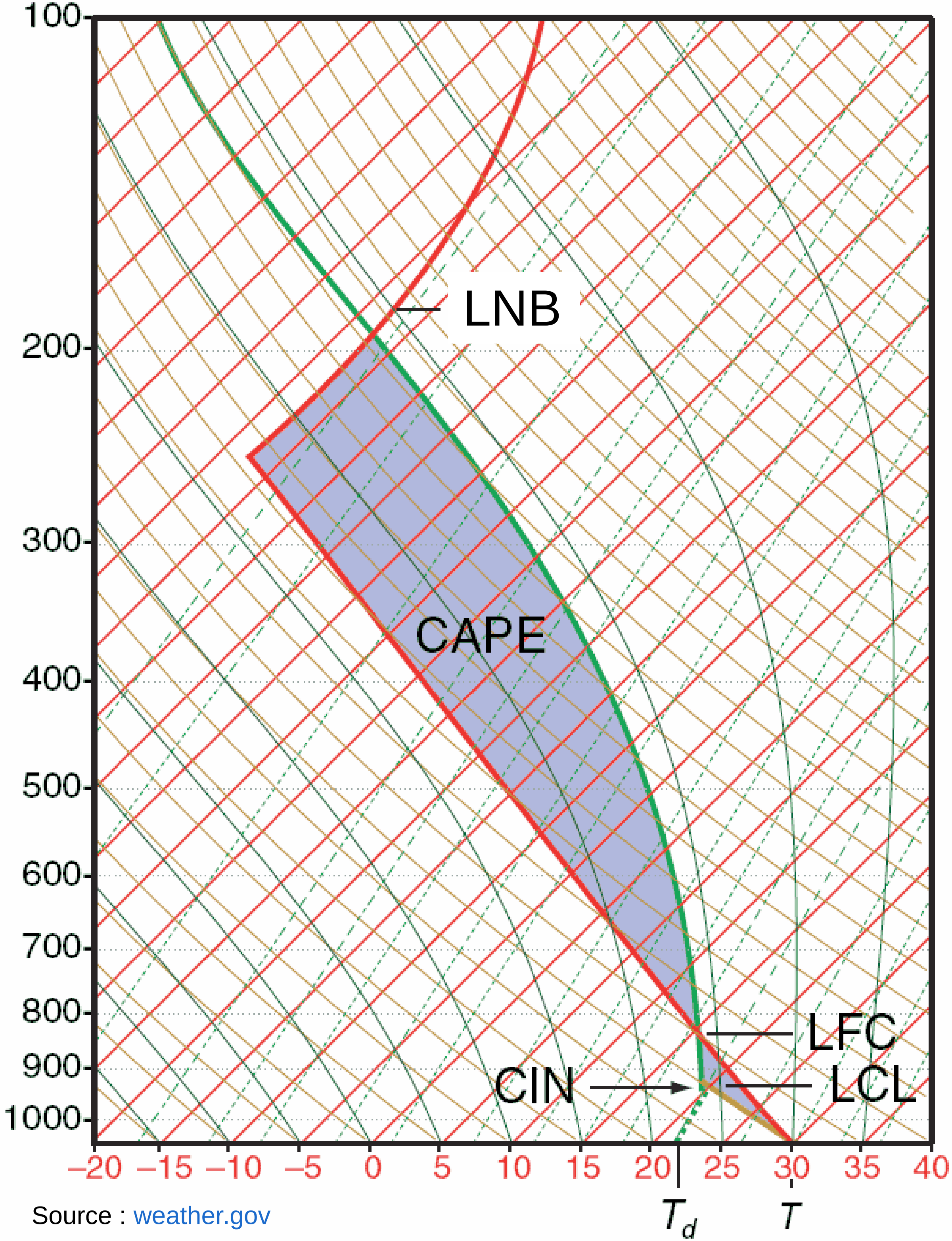
low-level clouds = below 680 hPa or ~3 km
mid-level clouds = between 680 and 440 hPa
high-level clouds = above 440 hPa or ~6.5 km

DO NOT MIX UP CLOUD FRACTION AND CLOUD COVER ;-)



Convective clouds

For more detail, see Grandpeix et al., 2004 :
https://doi.org/10.1256/qj.03.144
as well as Rio et al., 2009 :
https://doi.org/10.1029/2008GL036779



Source : weather.gov

Theory

Main variables shown on a skew-T diagram :

Red profile : Environment
Green profile : Adiabatic ascent

LCL : Lifted Condensation Level
LFC : Level of Free Convection

CIN : Convective INhibition
CAPE : Convective Available Potential Energy

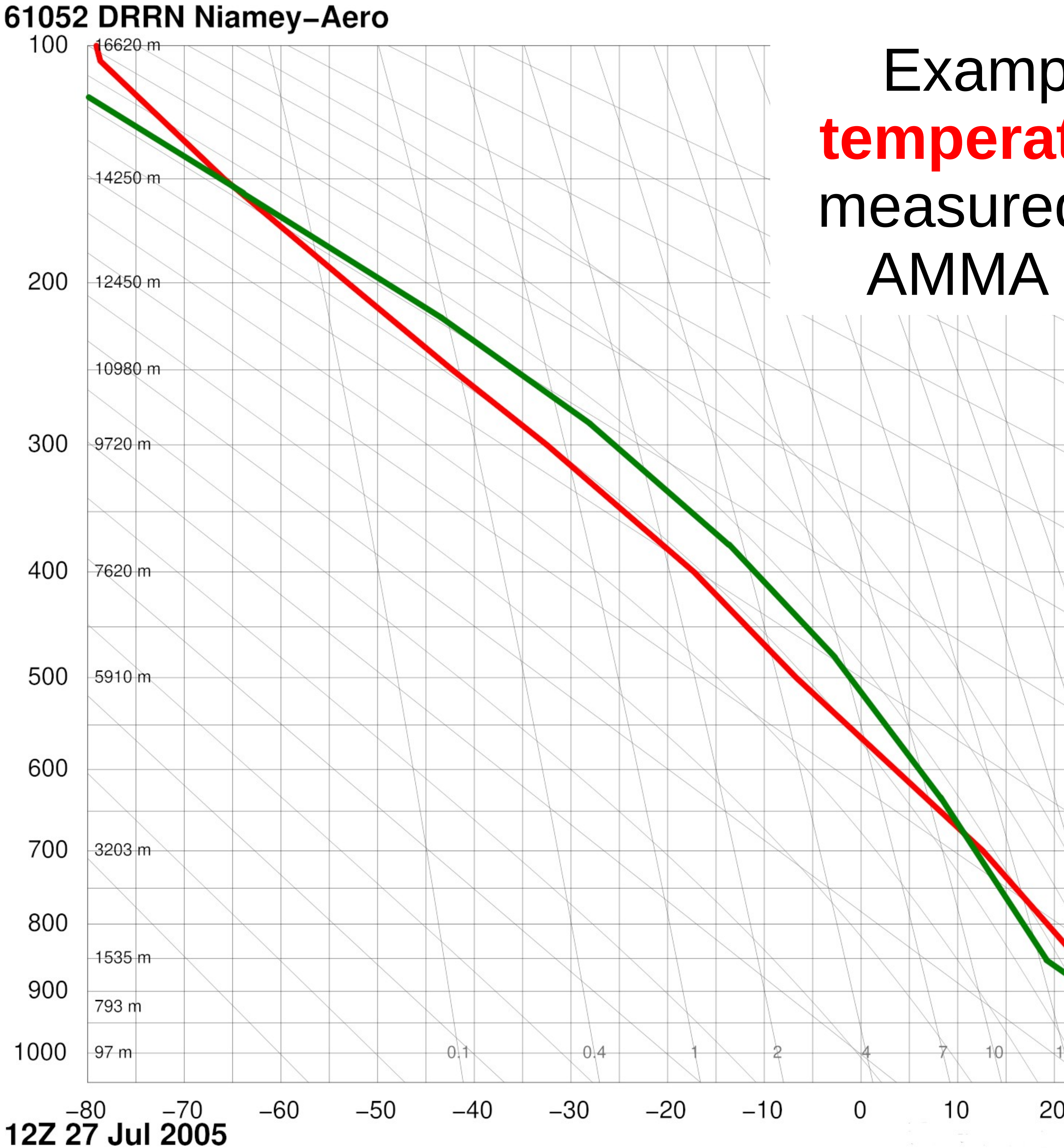
CAPE = (J/kg) $\displaystyle\int_{z_{LFC}}^{z_{LNB}} \boxed{g(\frac{T}{T_{env}} - 1)} \cdot dz$

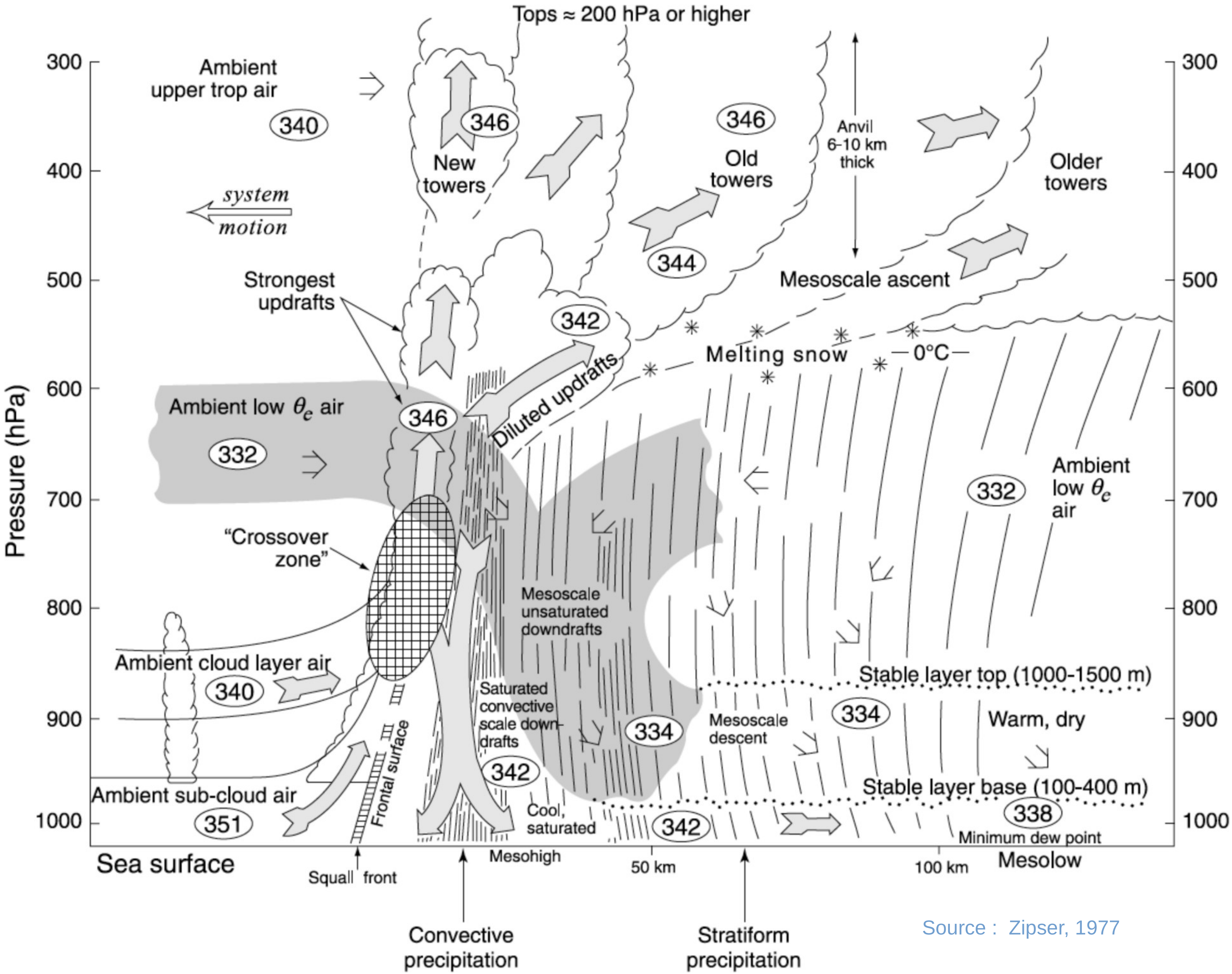
Buoyancy (N/kg)

$E_c = \frac{1}{2} \cdot w^2$ and therefore :

$$\boxed{\text{CAPE} = \Delta_{LFC \rightarrow LNB} E_c}$$

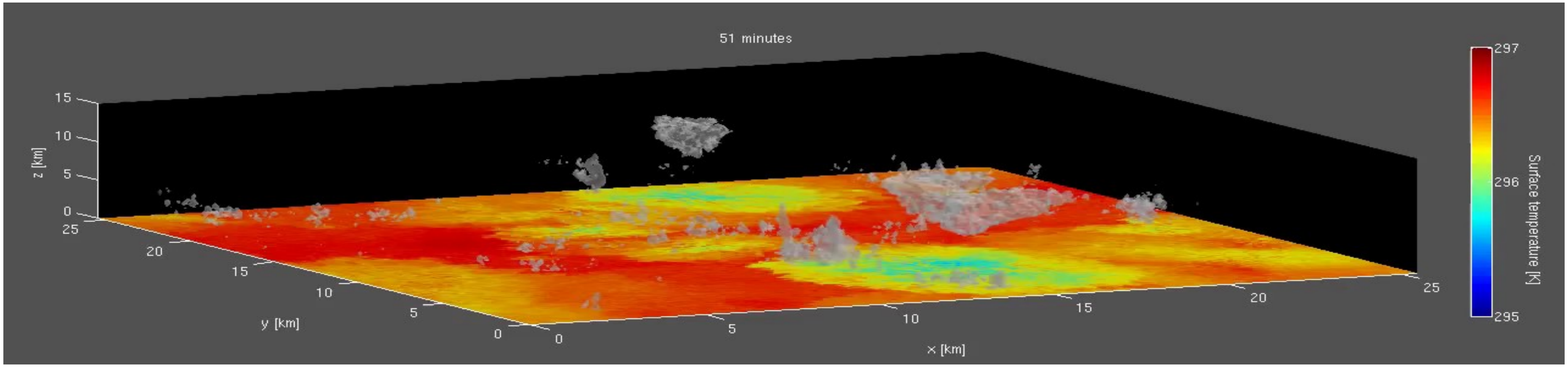
Example of **real temperature profile** measured during the AMMA campaign





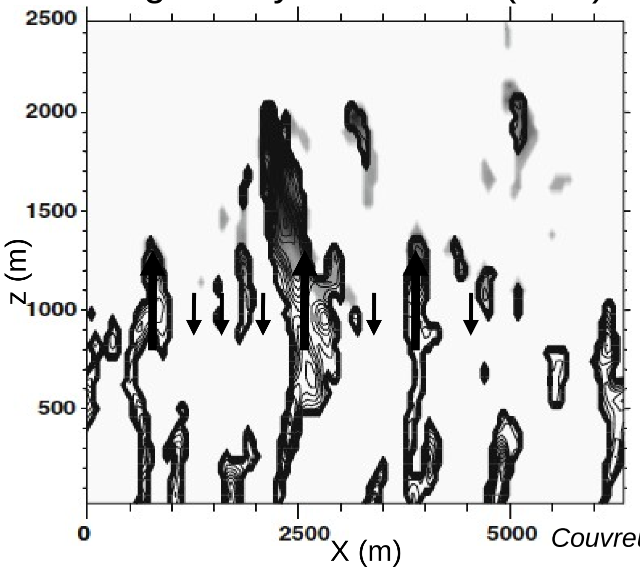
Source : Zipser, 1977

Many processes in one grid cell



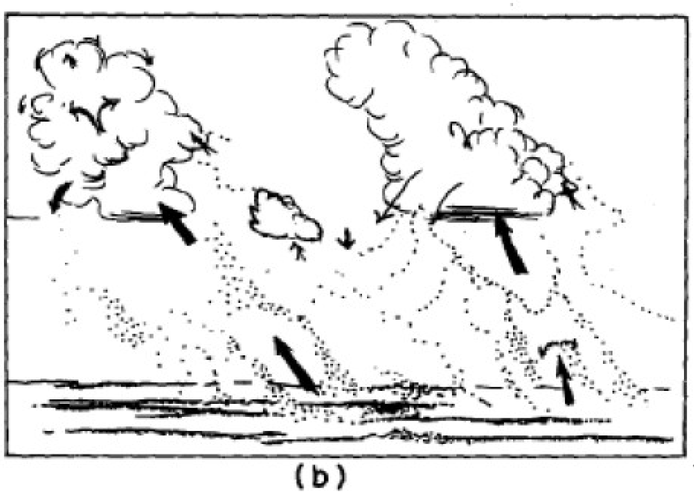
Around 8 hours of simulation by a **Cloud Resolving Model (CRM)** – C. Muller, LMD

Thermals in a
Large-Eddy Simulation (LES)



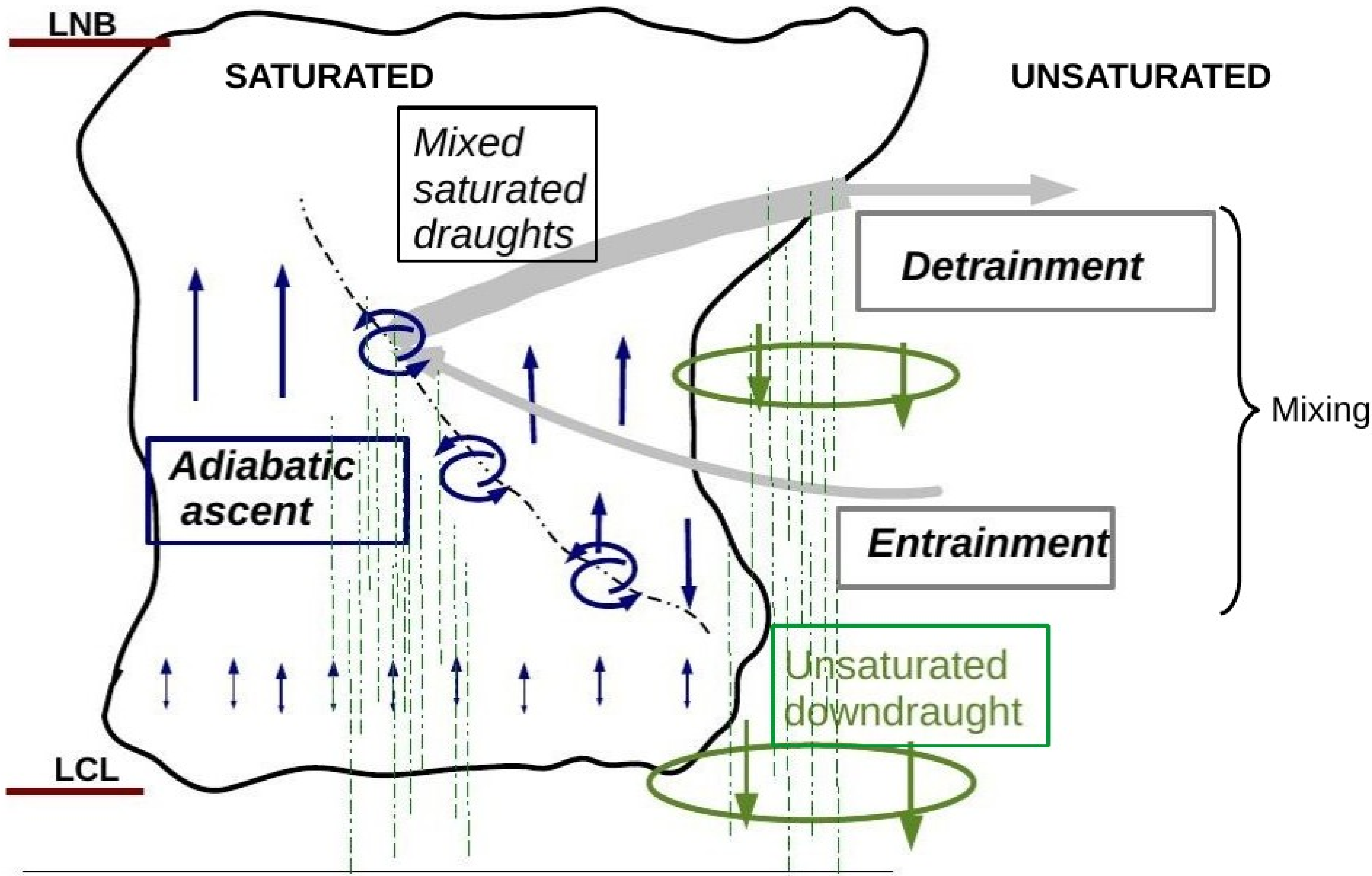
Couvreux et al., BLM, 2010

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



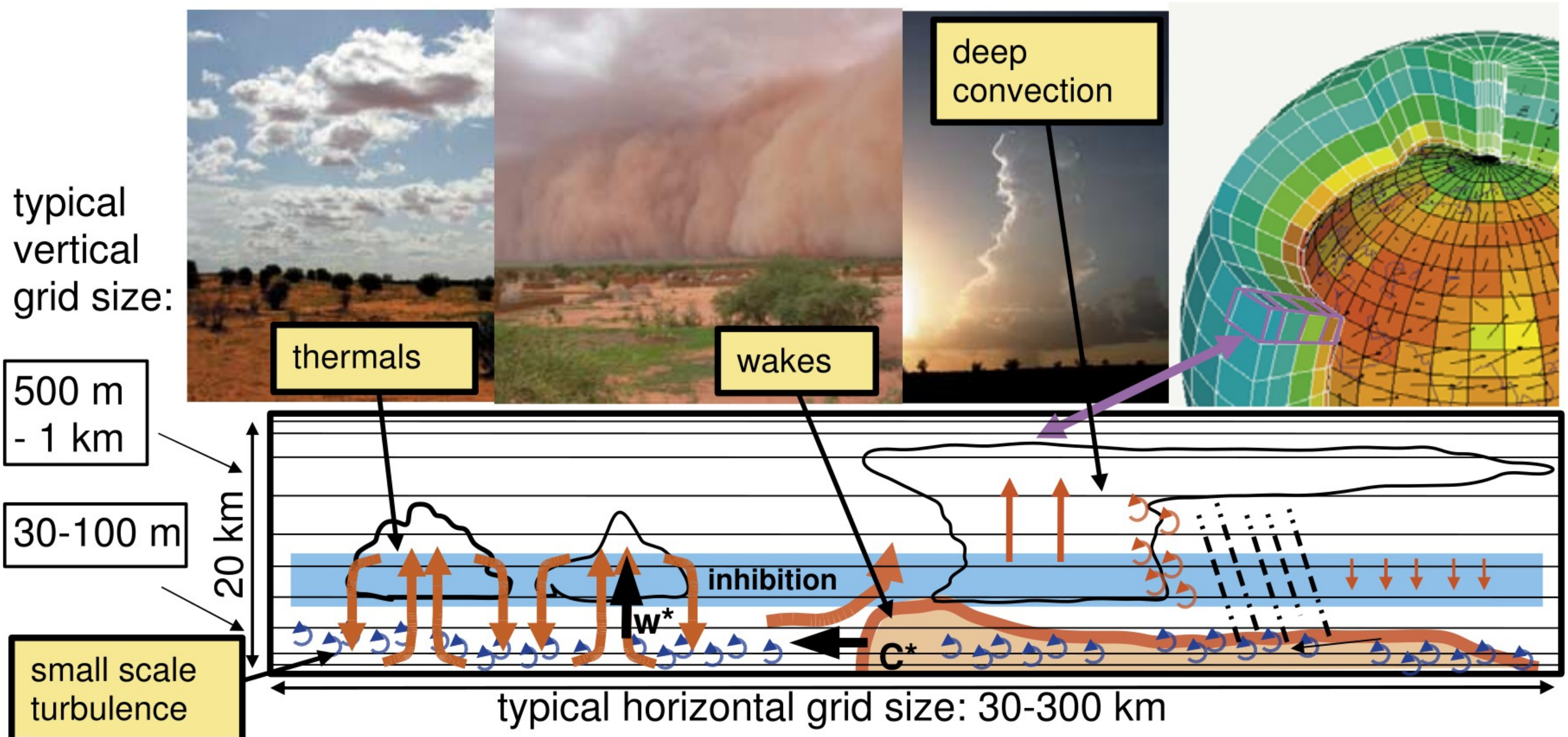
Lemone et Pennell, MWR, 1976

Emanuel scheme (1991)



LMDZ framework

Source : Rio et al., 2009



$$\mathrm{ALE}^{\mathrm{th}} = w_*^2/2$$

$$\mathrm{ALE}^{\mathrm{wk}} \simeq C_*^2$$

Deep convection is triggered if :

- $\max(\mathrm{ALE}^{\mathrm{th}}, \mathrm{ALE}^{\mathrm{wk}}) > |\mathrm{CIN}|$
- at least one cloud reaches a given threshold size (stochastic triggering scheme, Rochetin et al., 2014)

Fundamental process

- Clausius-Clapeyron equation :

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

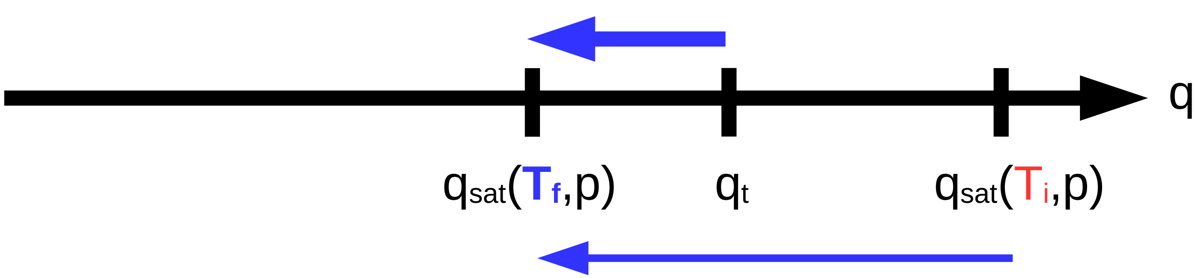
T	0°C	20°C
e_{sat}	6.1 hPa	23.4 hPa
q_{sat}	$3.7\ \text{g kg}^{-1}$	$14.4\ \text{g kg}^{-1}$

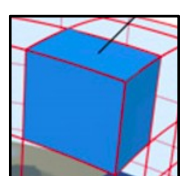
- Saturation mass mixing ratio :

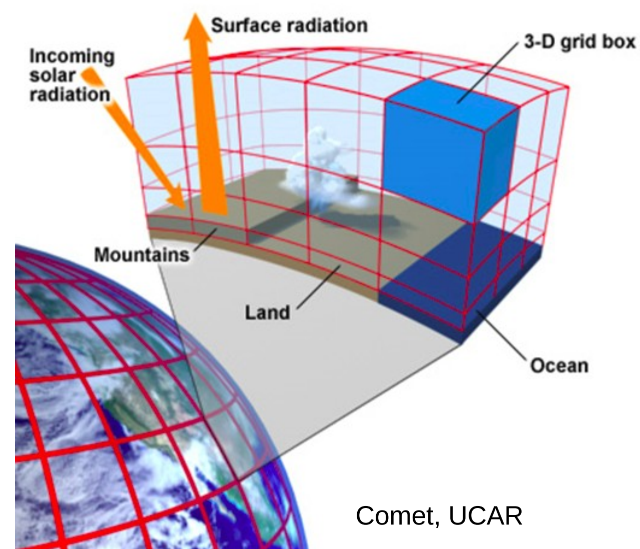
$q_{sat}(T,p) \simeq 0.622\,\frac{e_{sat}(T)}{p}$, where $e_{sat}(T)$ grows exponentially with temperature

- Clouds form when an air parcel is cooled :

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



- But clouds do not look like that : 

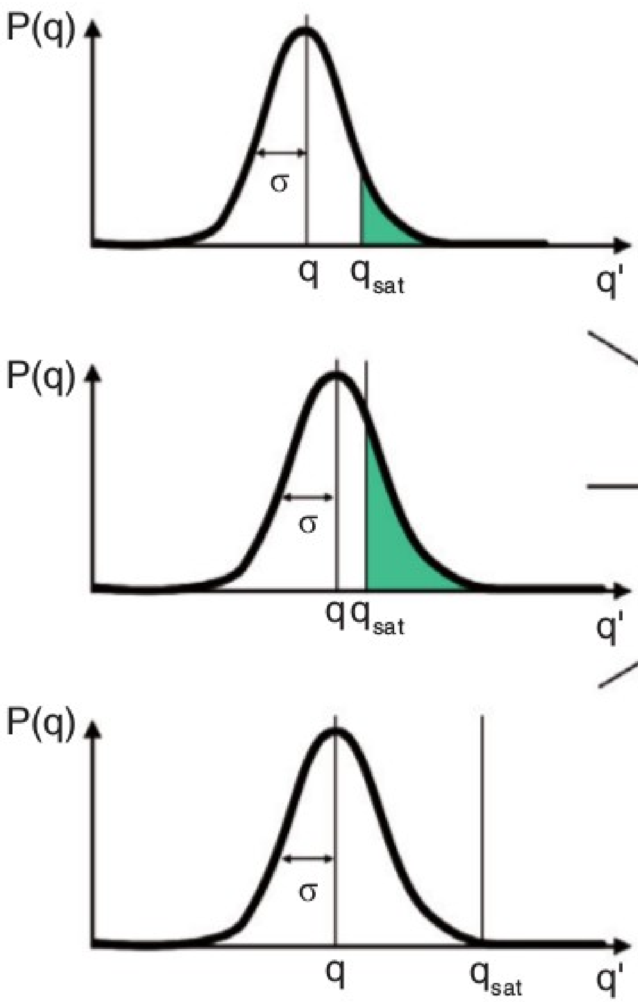


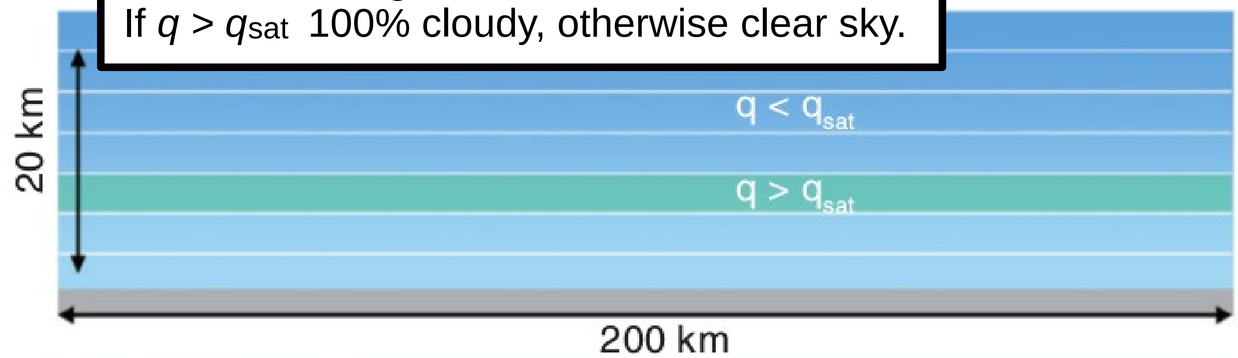
Comet, UCAR

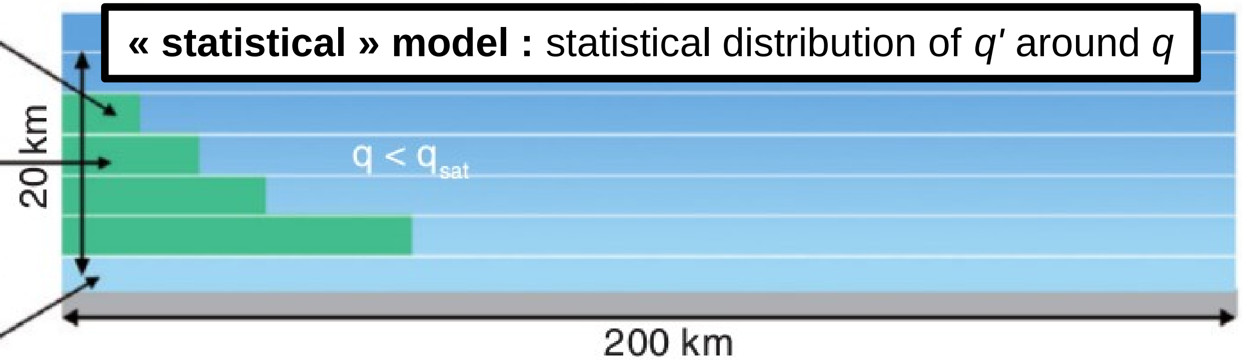
Statistical cloud scheme 1/2

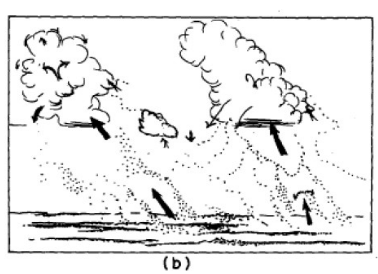
« all or nothing » model :
If $q > q_{sat}$ 100% cloudy, otherwise clear sky.

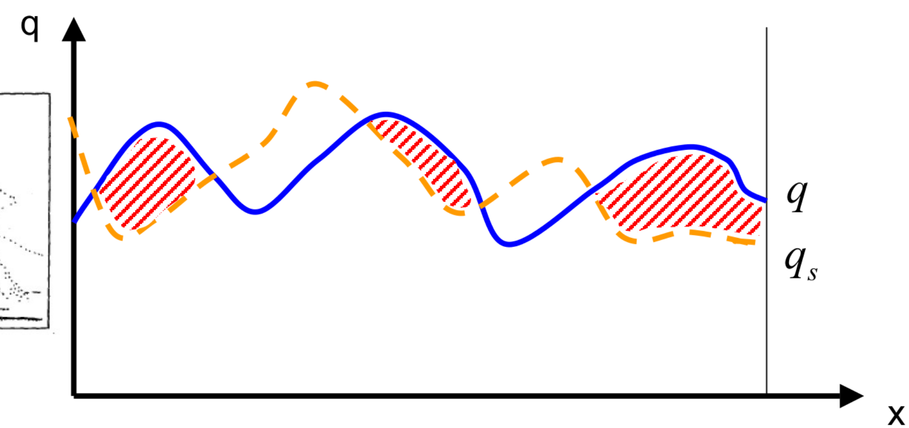
« statistical » model : statistical distribution of q' around q



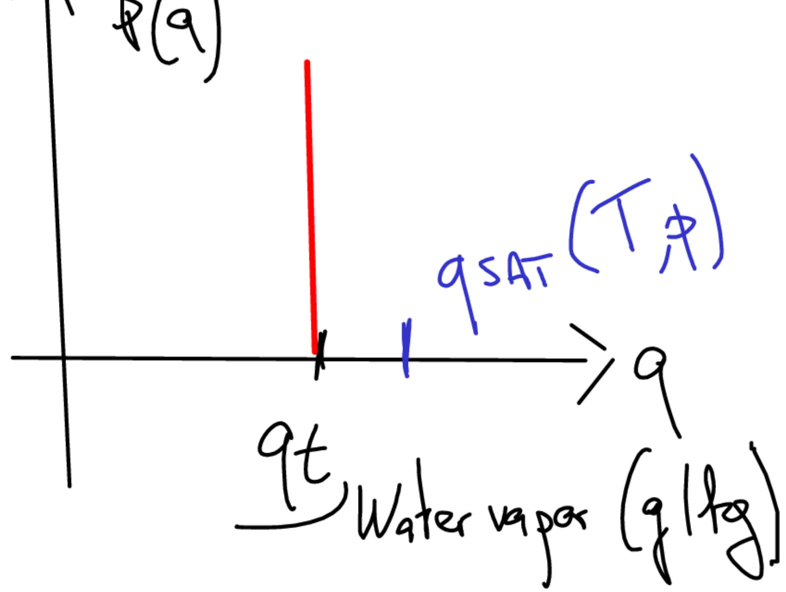




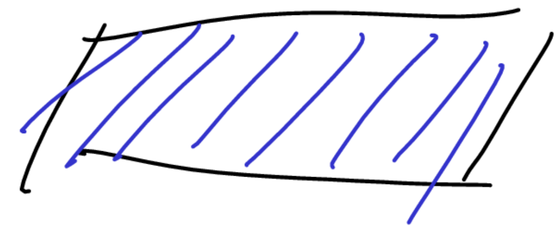




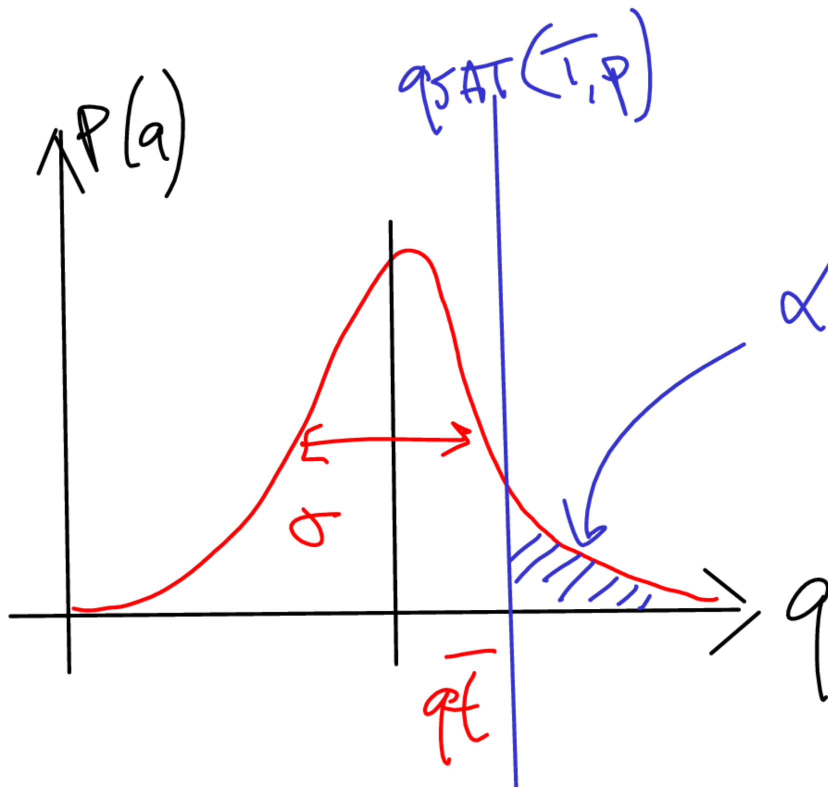
ALL OR NOTHING MODEL



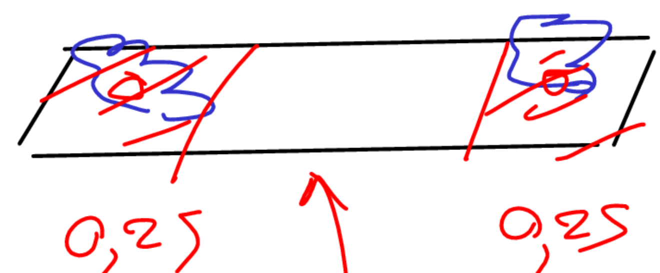
$\alpha_c = 1$ Cloud fraction



STATISTICAL CLOUD SCHEME

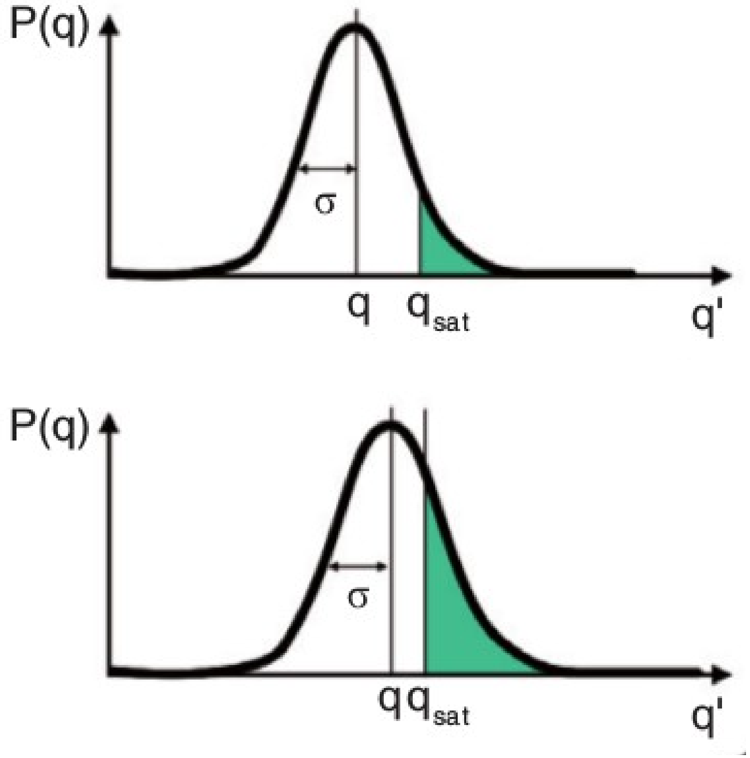


$$\alpha_c = \int_{q_{SAT}}^{\infty} p(q)\, dq$$



NO DIFFERENCE IN THE MODEL

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 :

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

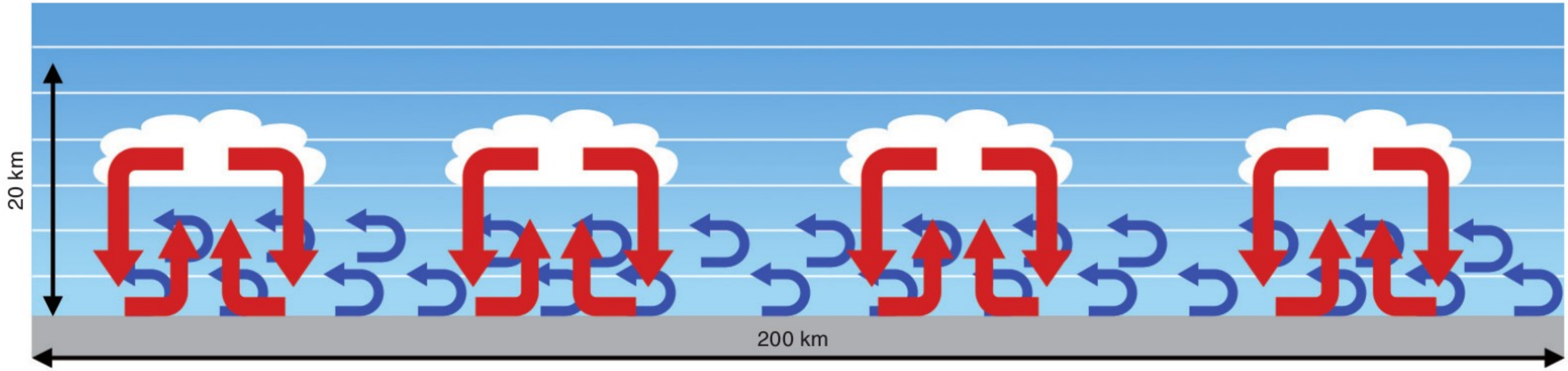
Cloud fraction :

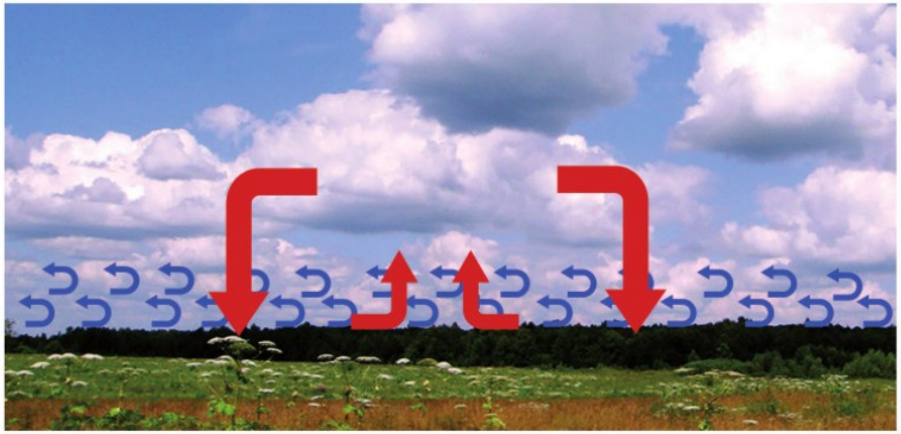
$$\alpha_c = \int_{q_{sat}}^{\infty} P(q) dq$$

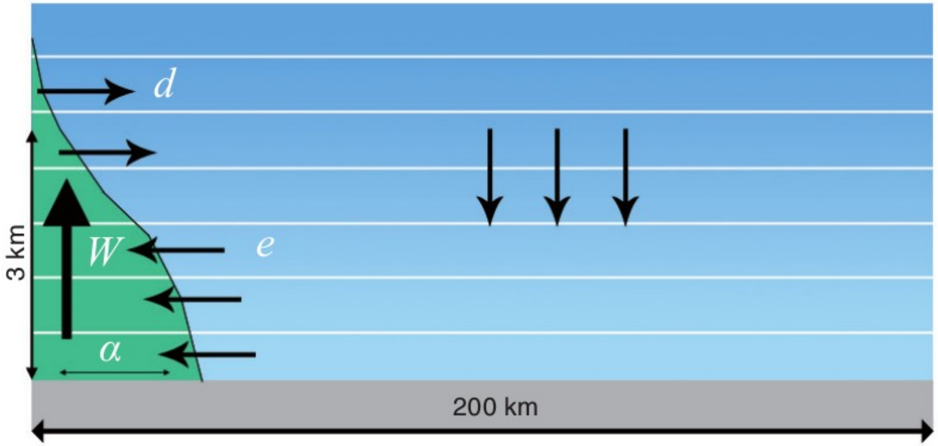
In-cloud condensed water content :

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

Shallow convection 1/2







Shallow convection 2/2

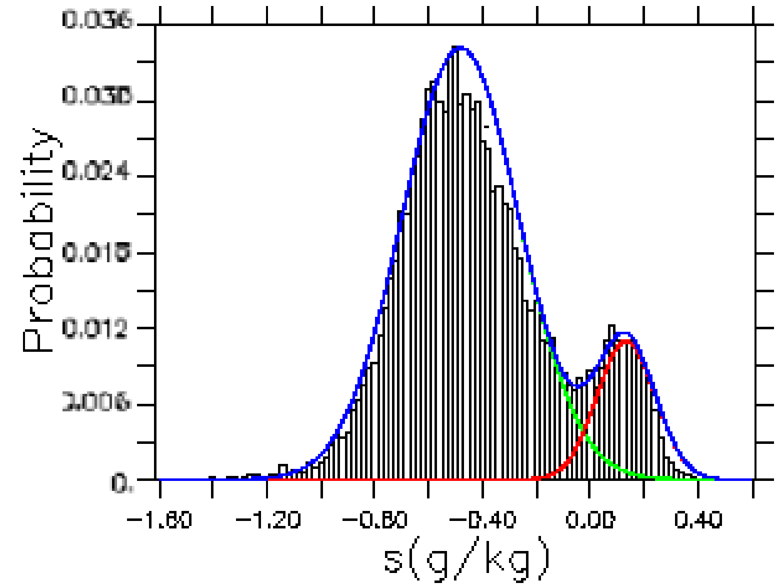
Bi-Gaussian distribution of saturation deficit s:

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

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 :

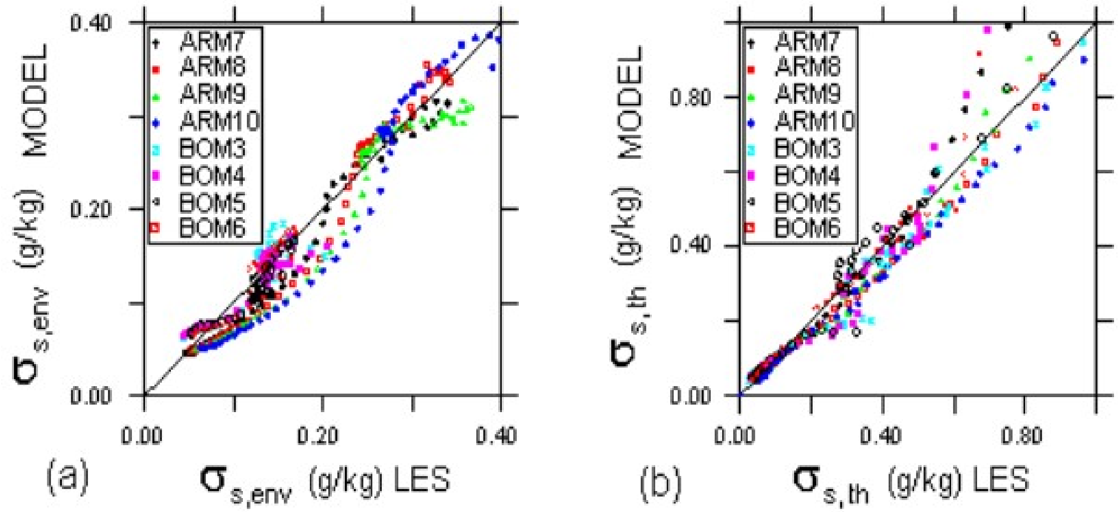
$$\sigma_{\mathrm{s,env}} = c_{\mathrm{env}} \frac{\alpha^{\frac{1}{2}}}{1-\alpha} (\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\, \overline{q}_{t_{\mathrm{env}}}$$

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

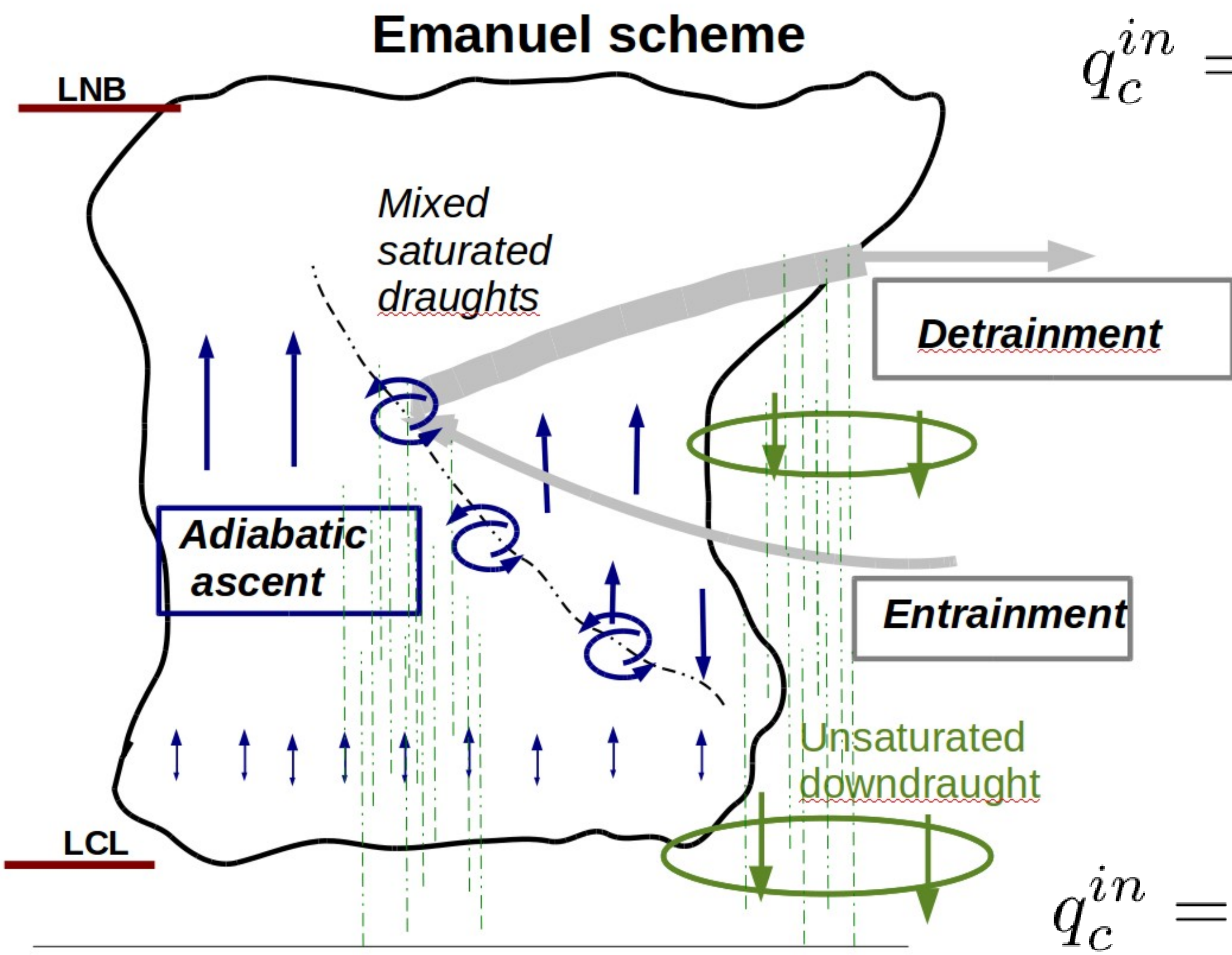
q_c^{in} and the cloud fraction can be computed following :

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

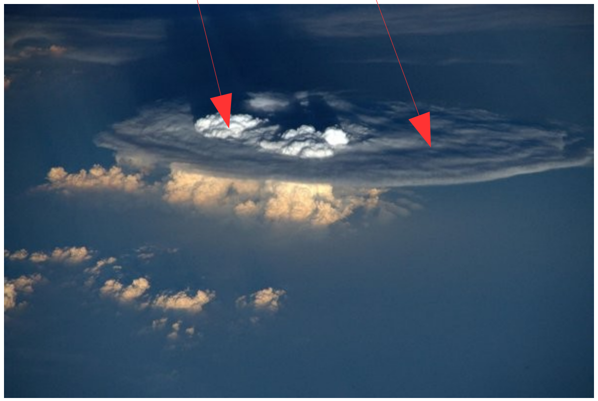
[Jam & al., BLM, 2013]



Deep convection cloud scheme



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



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

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

Large-scale clouds

For more detail, see Madeleine et al. 2020 :
https://doi.org/10.1029/2020MS002046
You can also have a look at the data, available at :
https://zenodo.org/record/3942031

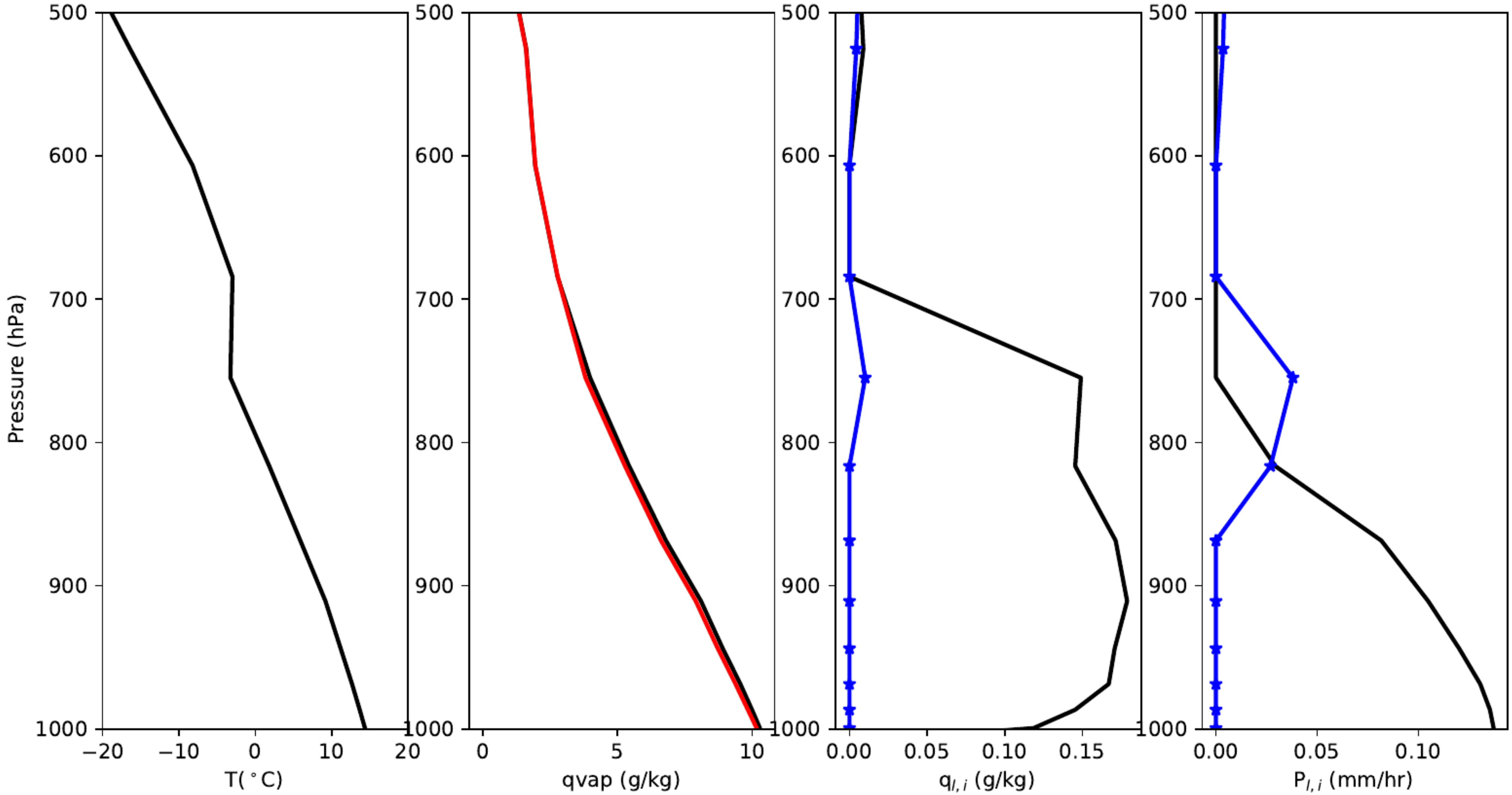
Architecture of the physical scheme

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).

Large scale condensation 1/3

Temperature, water vapor, clouds and precipitation over one timestep



1 REEVAPORATION 2 CLOUD FORMATION 3 PRECIPITATION

Large scale condensation 2/3

- 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 :

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

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

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

If there is shallow convection

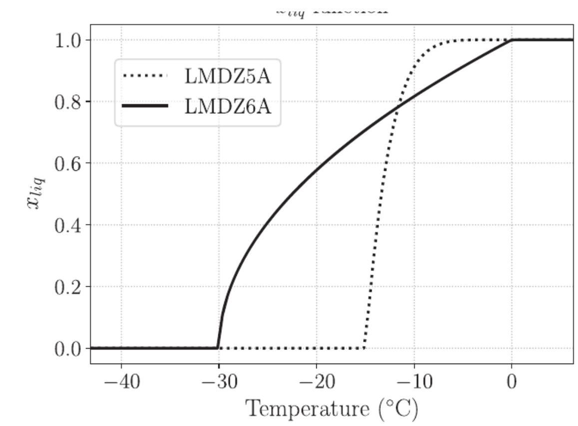
q_c^{in} and the cloud fraction can be computed following :

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

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

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

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



Large scale condensation 3/3

3 **PRECIPITATION**

- A fraction of the condensate falls as rain (parameters controlling the maximum water content of clouds and the auto-conversion rate)
- For clouds, it corresponds to a sink term written as :

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

[Kessler 1969, Sundqvist 1988]

- Another fraction is converted to snow ; the corresponding sink term for ice clouds depends on the divergence of the ice crystal mass flux :

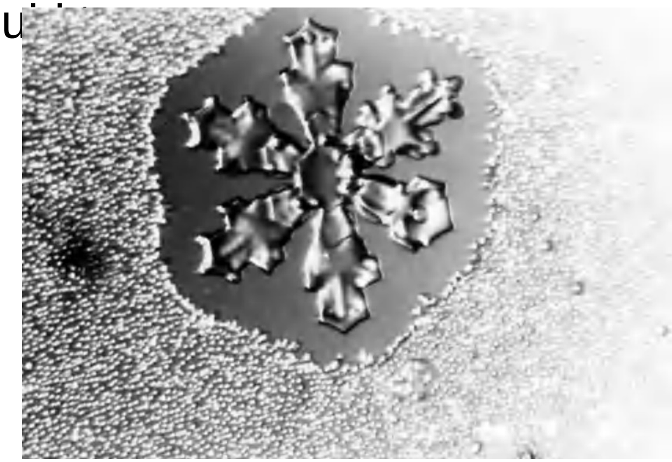
$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

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

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

[Heymsfield, 1977; Heymsfield & Donner, 1990]

- 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 liqu[illegible] stay below freezing.



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

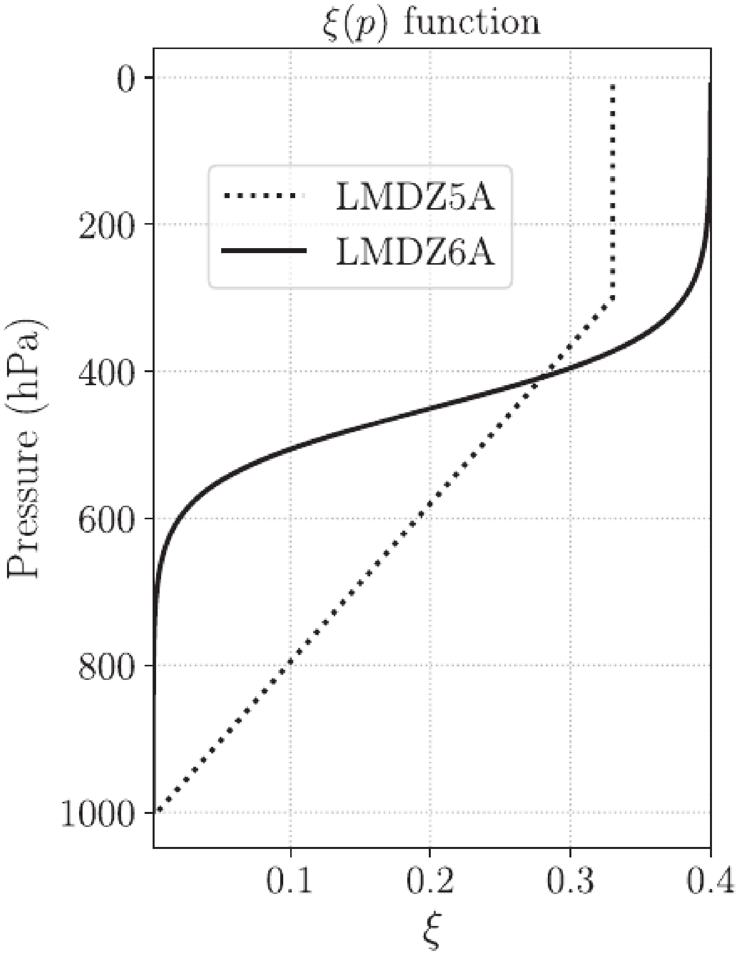
$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

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

ffallv_lsc=0.8

$$\sigma = \xi q_t$$

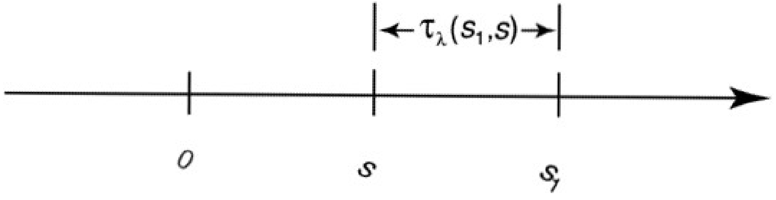
ratqsp0=45000
ratqsdp=10000
ratqsbas=0.002
ratqshaut=0.4



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.

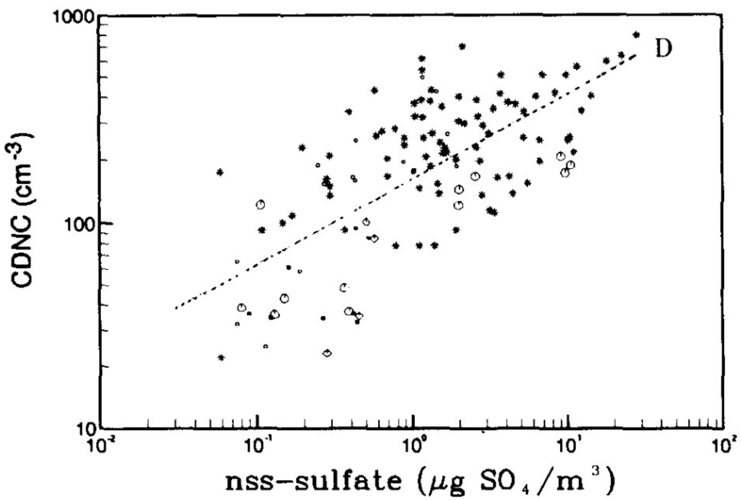
$$q_{rad} = q_c^{in,\,cv}\alpha_c^{cv} + q_c^{in,\,lsc}\alpha_c^{lsc}$$

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

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.

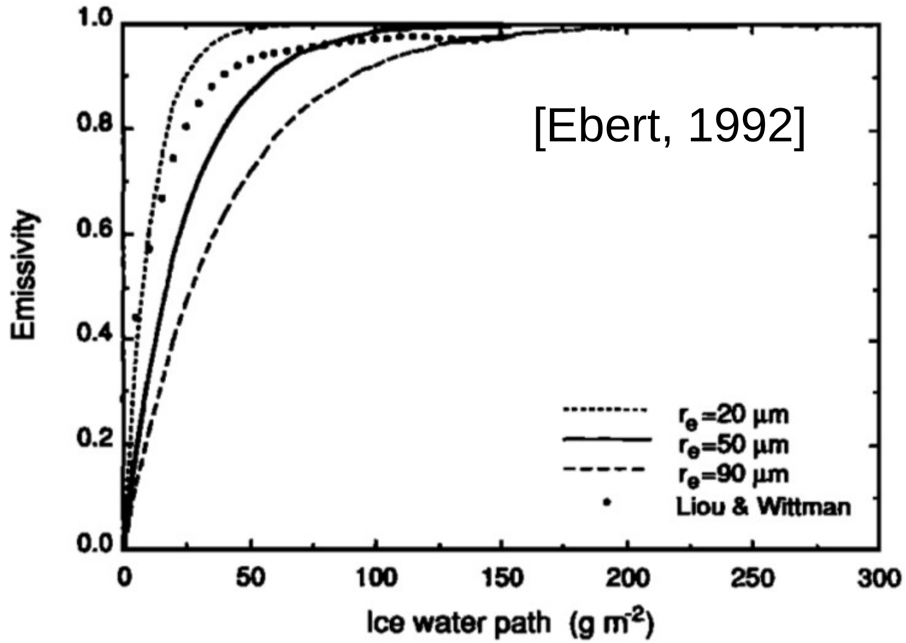
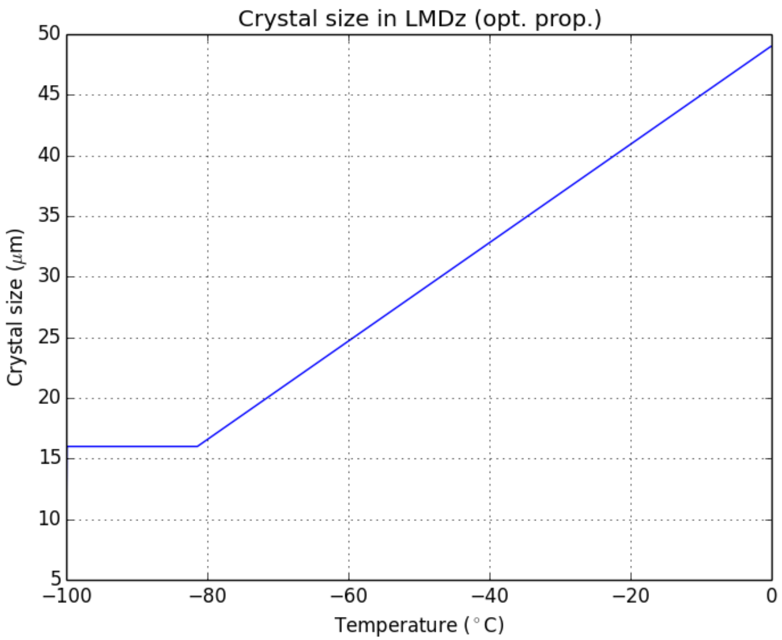
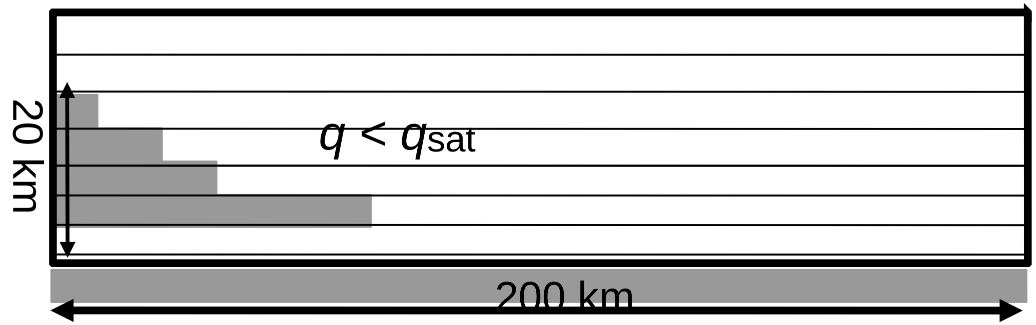


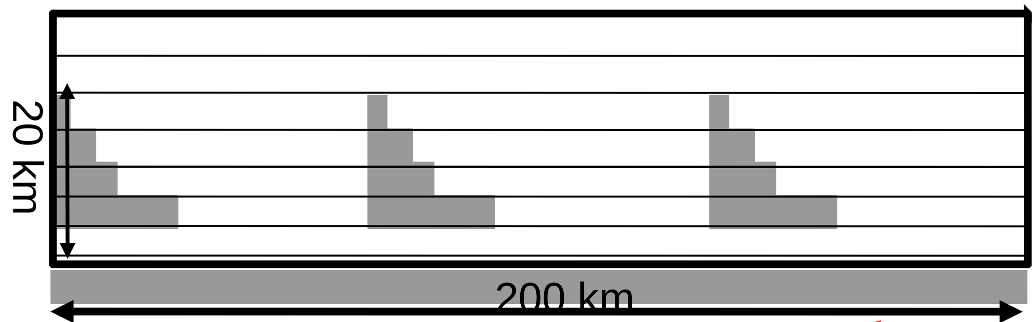
Fig. 5. Cirrus infrared emissivity for r_e = 20, 50, and 90 μm as a function of ice water path. The solid circles represent values computed using the parameterization of *Liou and Wittman* [1979].



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**

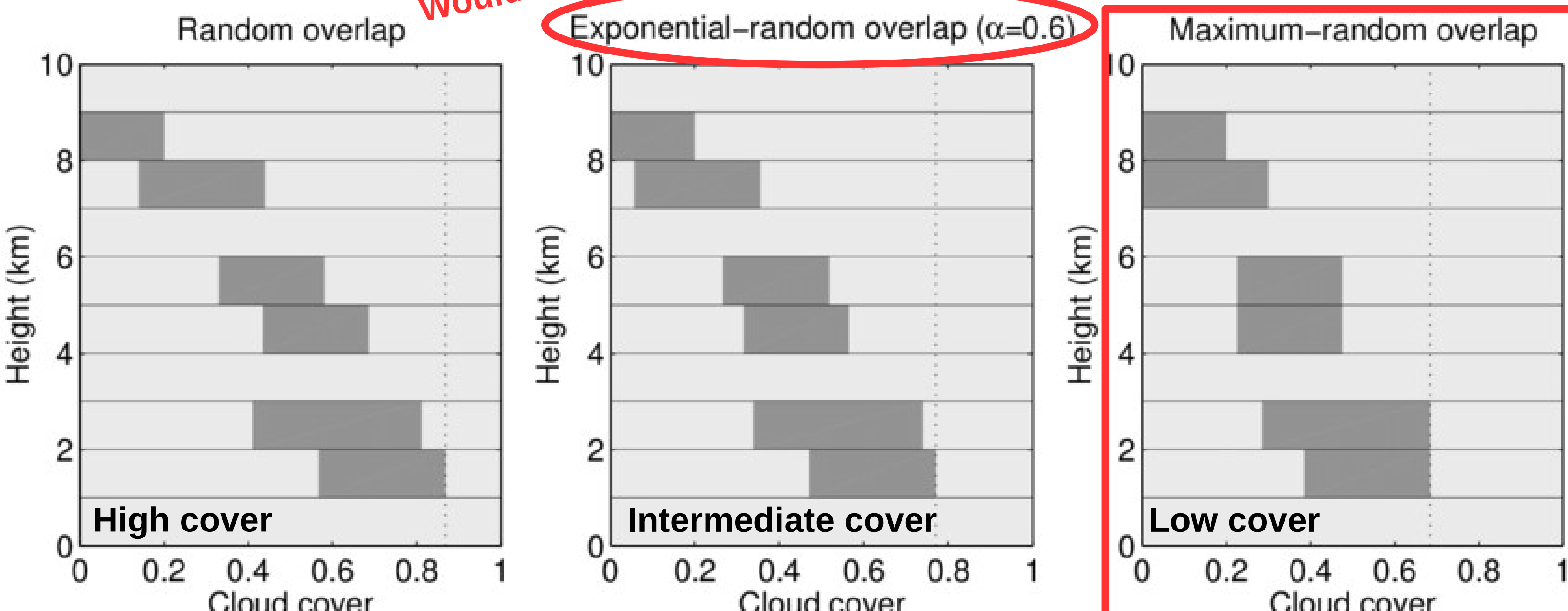




For the GCM, these two scenes are identical ;

Would be better !

Used in LMDz



[Radiation parameterization and clouds, Hogan, 2009]

Radiative forcing

LW radiative forcing

Positive : clouds reduce the LW outgoing radiation

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

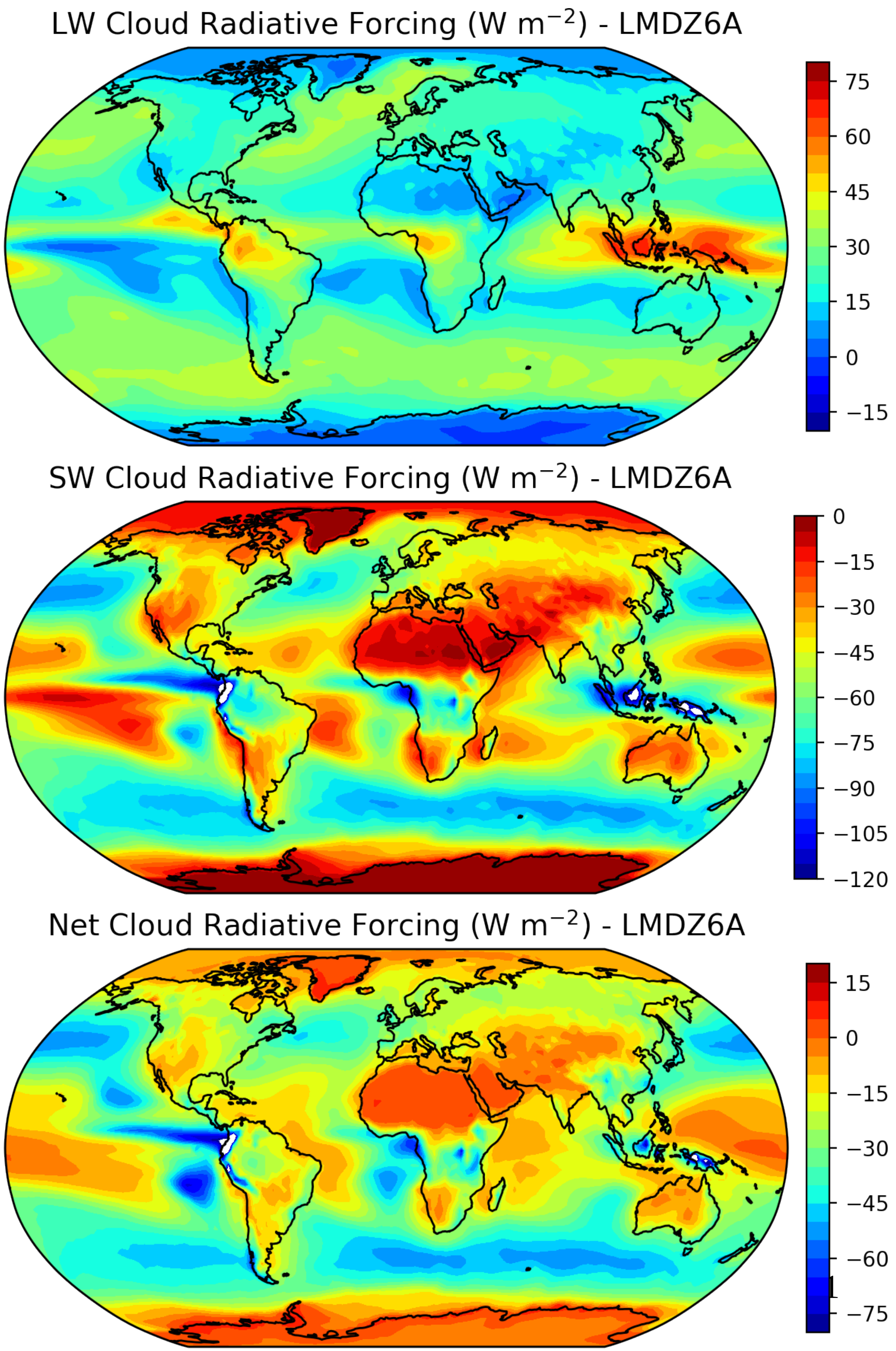
SW radiative forcing

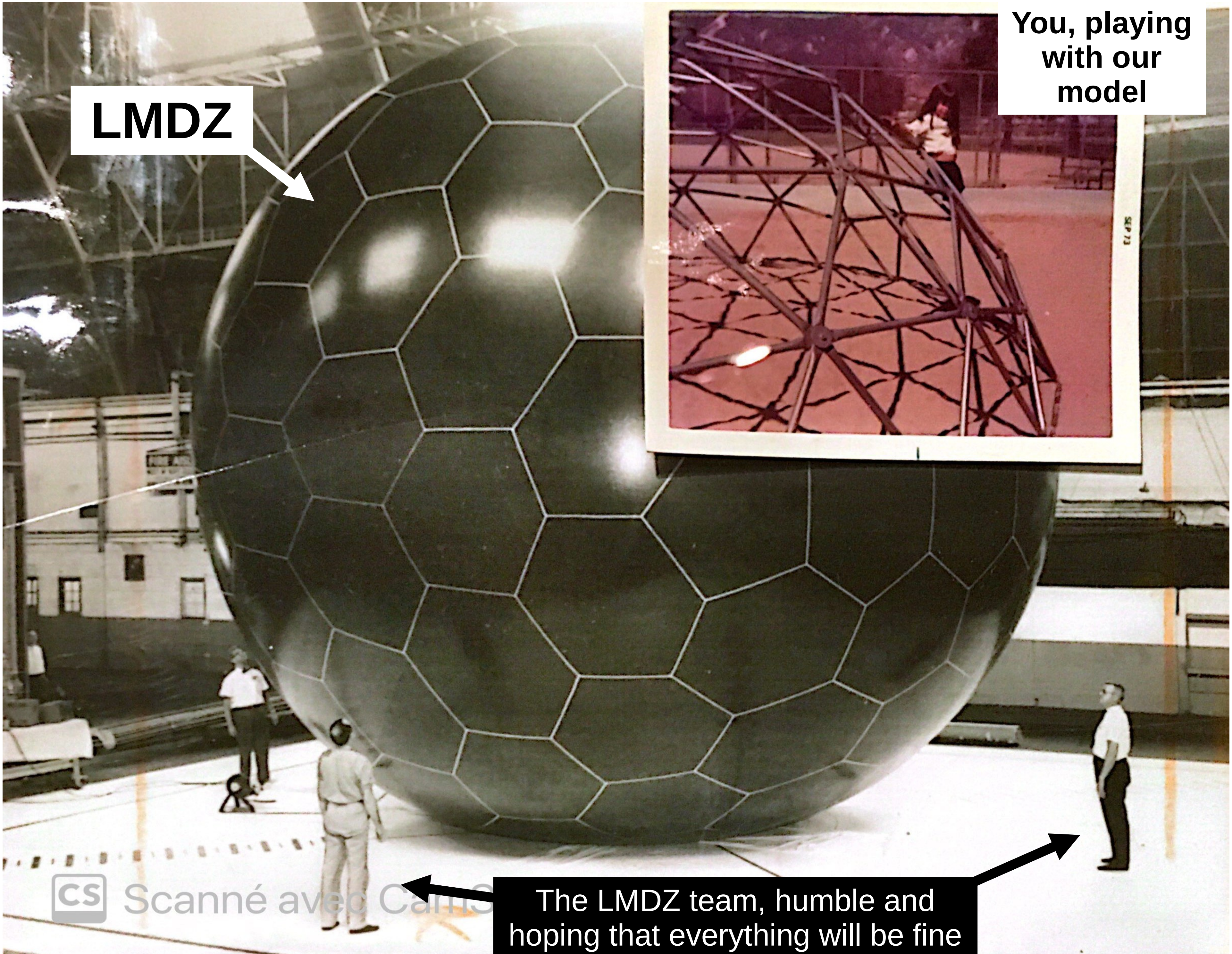
Negative : clouds reflect the incoming SW radiation

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

Net forcing : **Cooling**

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




LMDZ
You, playing with our model
The LMDZ team, humble and hoping that everything will be fine