The thermal plume model

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The model

The original thermal plume model

Hourdin, Couvreux, Menut, JAS, 2002

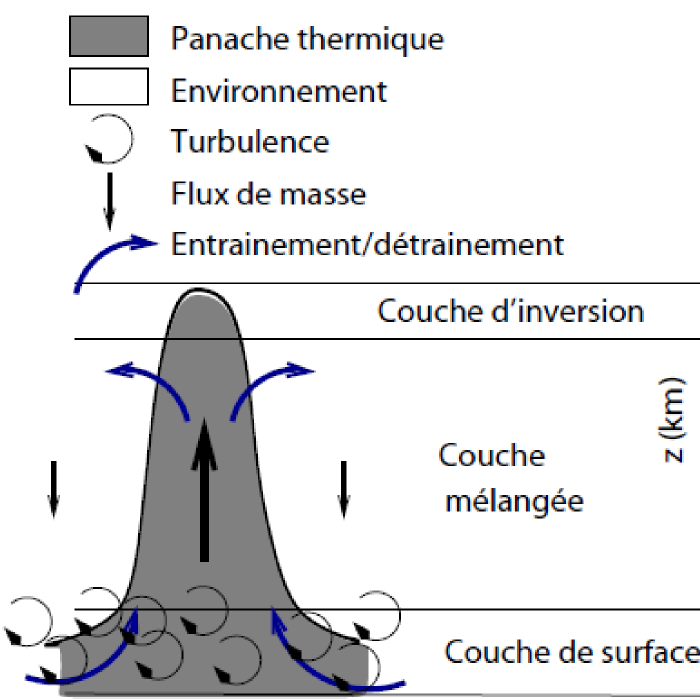
Developed for the dry convective boundary layer

Transport of conserved variables (θl, qt):

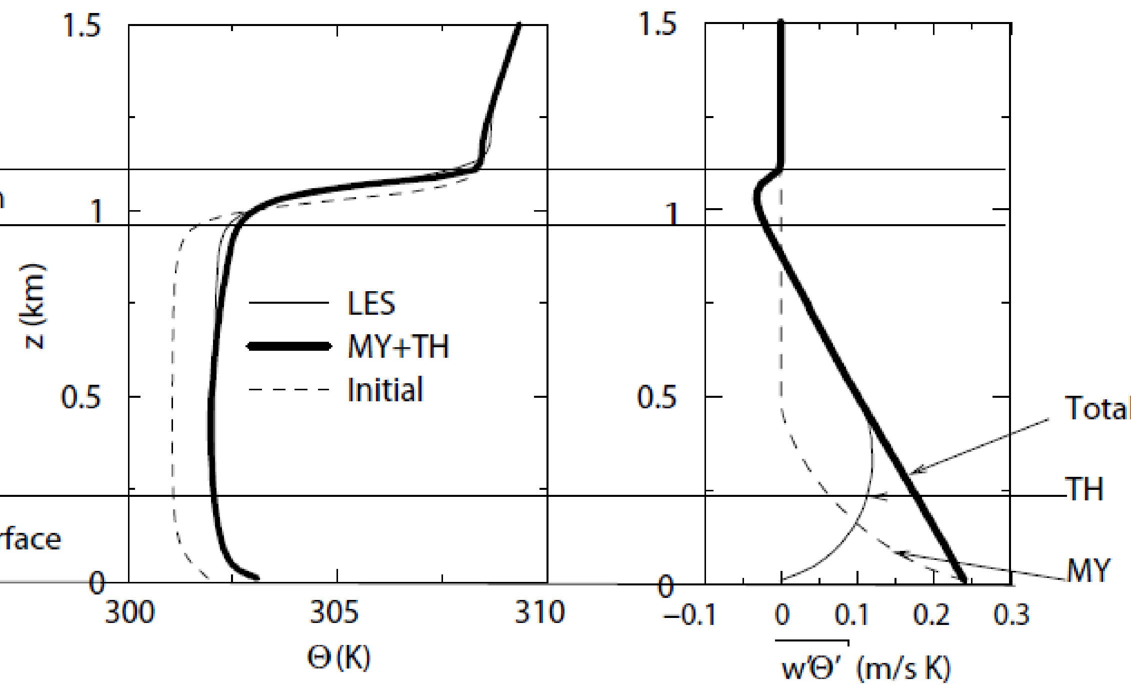
$$\rho \overline{w'\theta'} = -\rho K \frac{\partial \theta}{\partial z} + f(\theta_a - \theta)$$

Turbulent diffusion
Mellor & Yamada (JAS,1974)

Non local transport via thermals
Thermal plume model



Academic dry case (Ayotte & al., 1996)



Model equations

Mellor & Yamada diffusion scheme

Mellor & Yamada, JAS, 1974; Yamada, JAS, 1983

$$K_\phi = lqS_\phi \quad \text{with} \quad q = \sqrt{2e}$$

- Pronostic equation for the turbulent kinetic energy:

$$\frac{1}{2}\frac{\partial q^2}{\partial t} = qlS_m \left\| \frac{\partial \mathbf{v}}{\partial z} \right\|^2 [1 - \omega Ri] - \frac{q^3}{lB_1} + \frac{\partial}{\partial z}\left[lqS_q \frac{\partial q^2/2}{\partial z} \right]$$

- Mechanical production of turbulence
- Effect of stratification
- dissipation
- Vertical turbulent transport of e

Pressure term neglected

- Stability functions: Sm, Sh = f(Ri)

Depend only on large-scale variables

- Mixing length:

$$l = l_0 \frac{\kappa z}{\kappa z + l_0} \quad \text{with} \quad l_0 = 0,2\, \frac{\int_0^\infty zq\,dz}{\int_0^\infty q\,dz}$$

Model equations

Thermal plume model
Hourdin & al., JAS, 2002

Conservation of mass: $$\frac{\partial f}{\partial z} = e - d$$

stationary conditions

Transport of θl, qt, u, v $$\frac{\partial f \psi_u}{\partial z} = e\psi - d\psi_u$$

Conservation of momentum: $$\frac{\partial f w_u}{\partial z} = -d w_u + \alpha g \rho \frac{\theta_{vu} - \theta_v}{\theta_v}$$

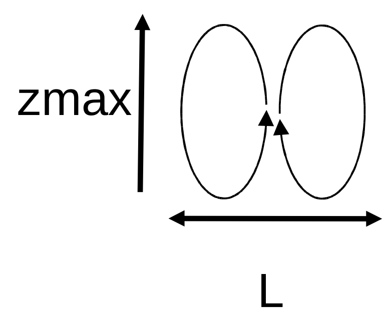
no drag, no friction

Closure: $$\Phi = \frac{w_{max}}{r z_{max} \int_{z=0}^{\infty} \frac{a^{*2}(z) dz}{\rho(z)}}$$

Detrainment:

- plume eroded with a mixing length λ=20m below the inversion
- quadratic decrease of α above

Geometrical considerations based on a 2D roll configuration:



v ~ wmax

No entrainment above the surface layer

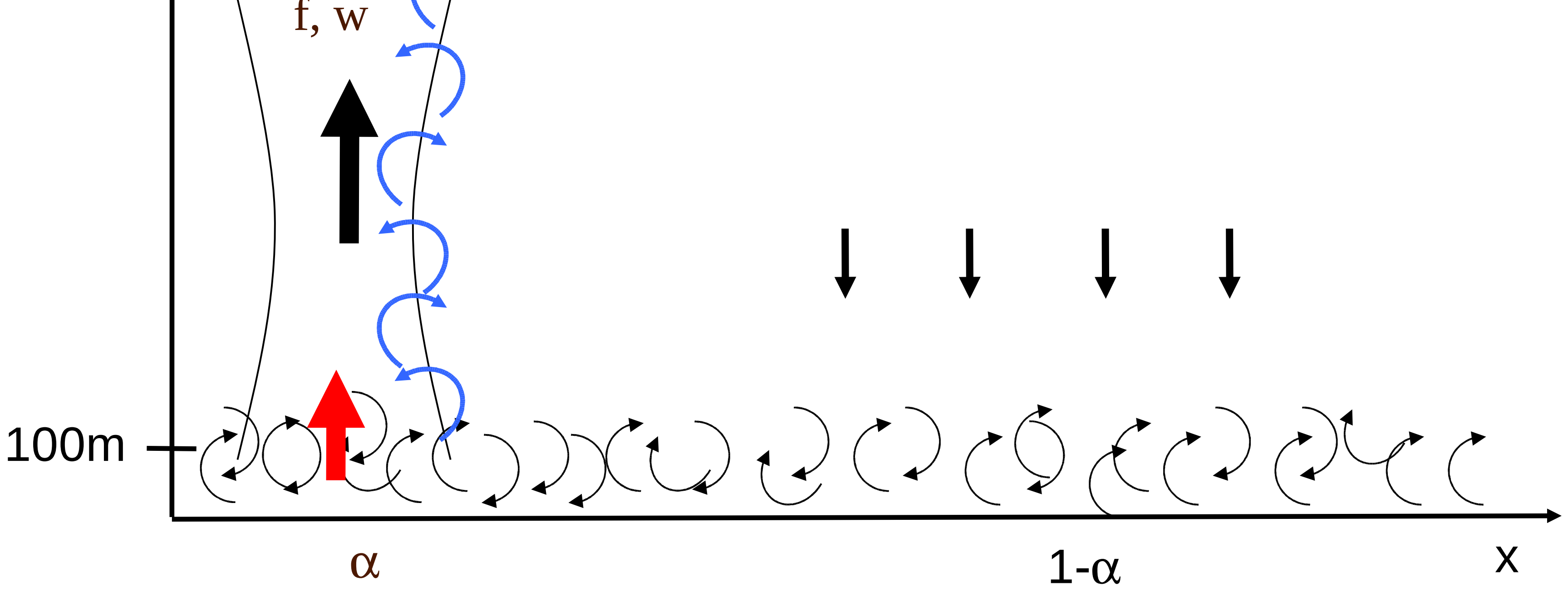
aspect ratio: r = L/zmax = 2

The cloudy thermal plume model

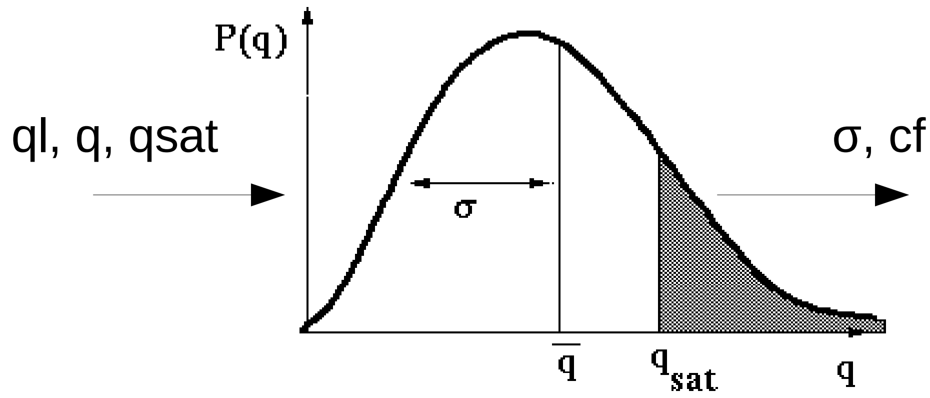
Rio & Hourdin, JAS, 2008

- condensation process within the plume
- entrainment/detrainment
- coupling with a cloud scheme

Internal variables of the scheme:

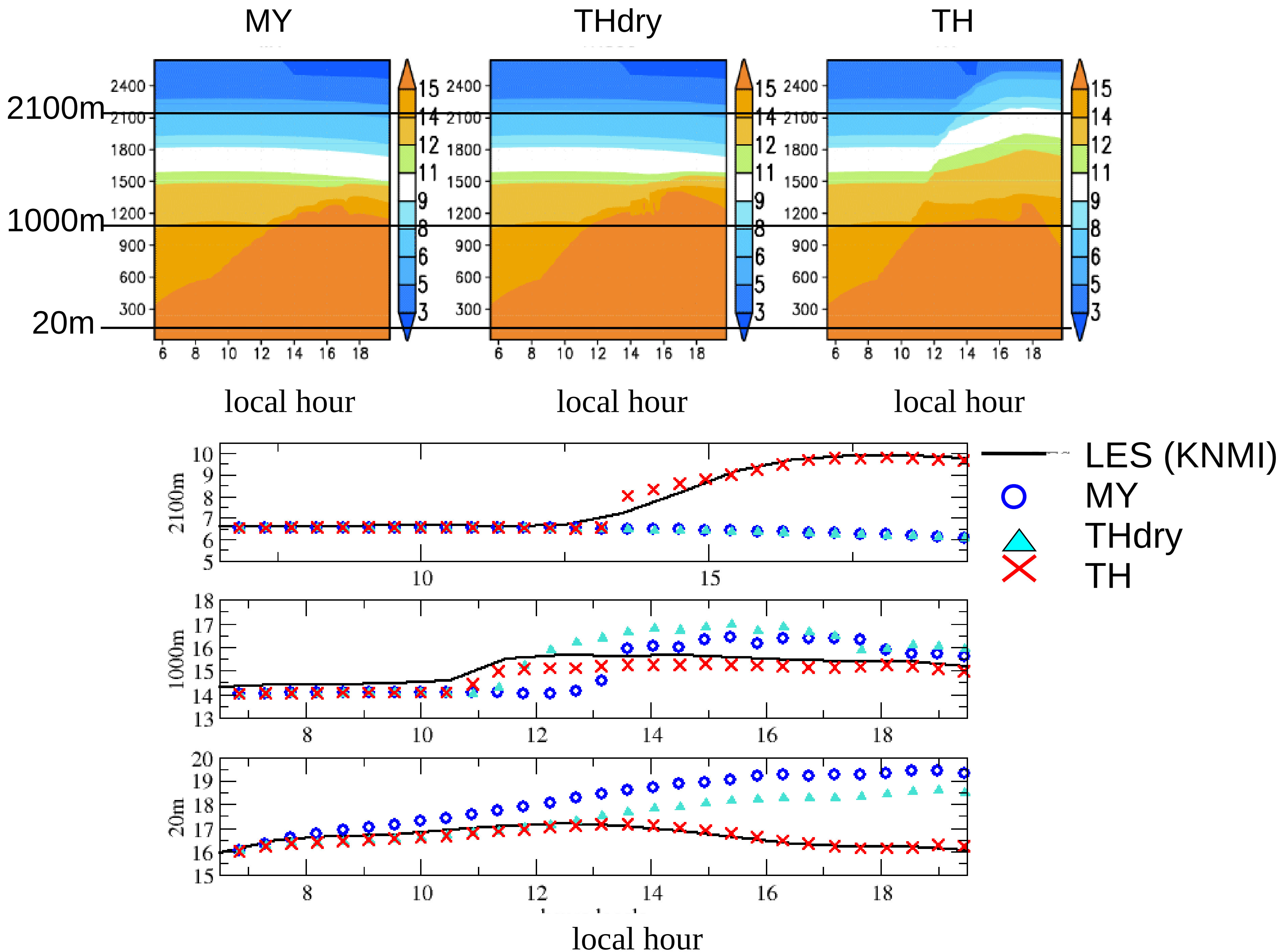


Bony & Emanuel, JAS, 2001



The diurnal cycle of the cloudy boundary layer (ARM case)

Diurnal evolution of total water (g/kg)



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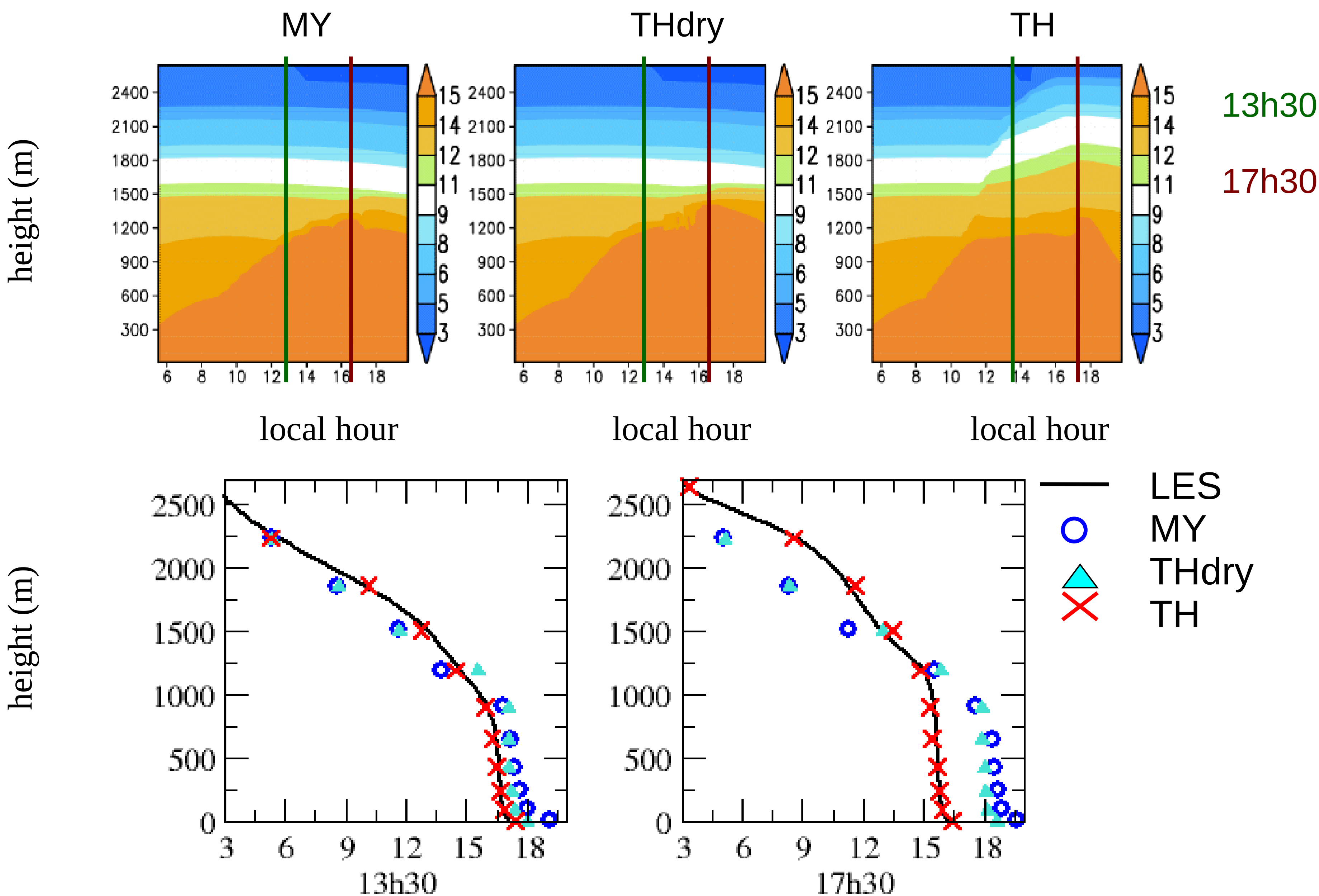
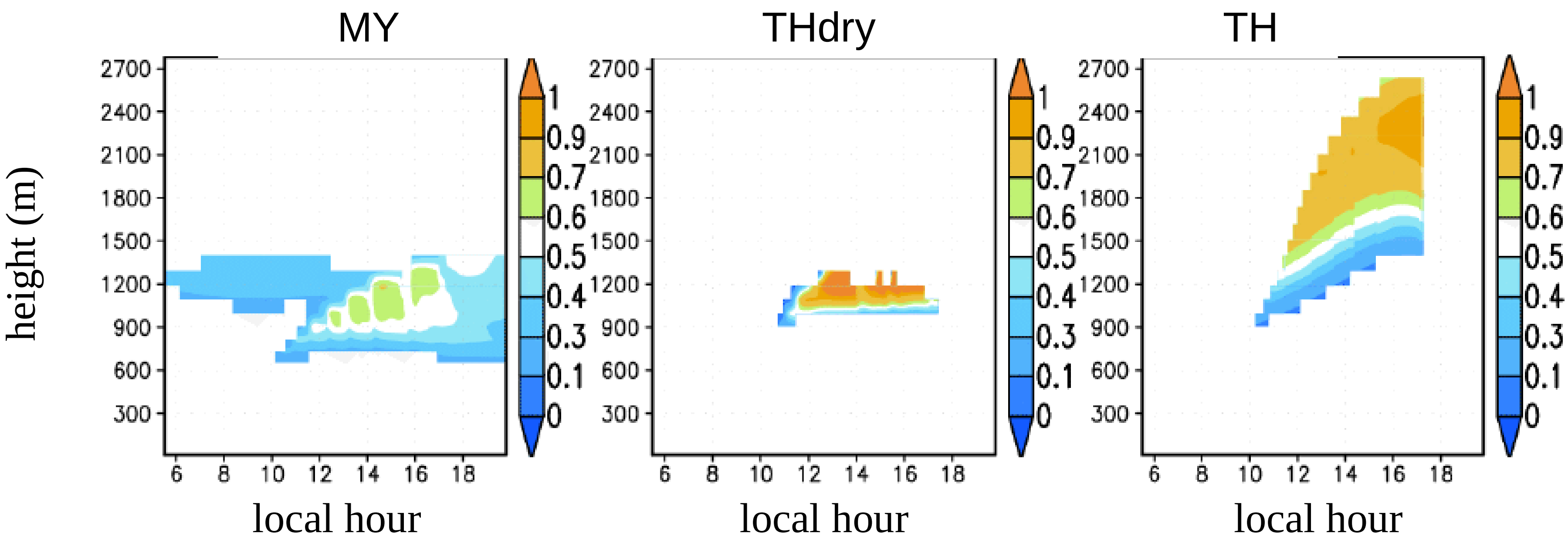
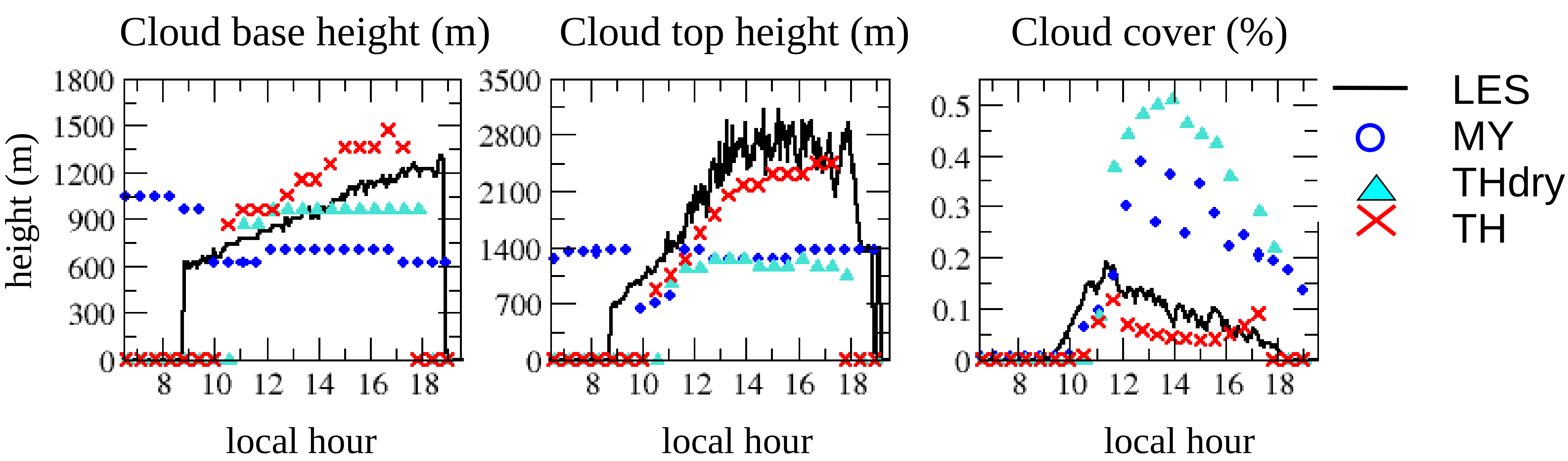


The diurnal cycle of the cloudy boundary layer (ARM case)

Diurnal evolution of cloud water content (g/kg)

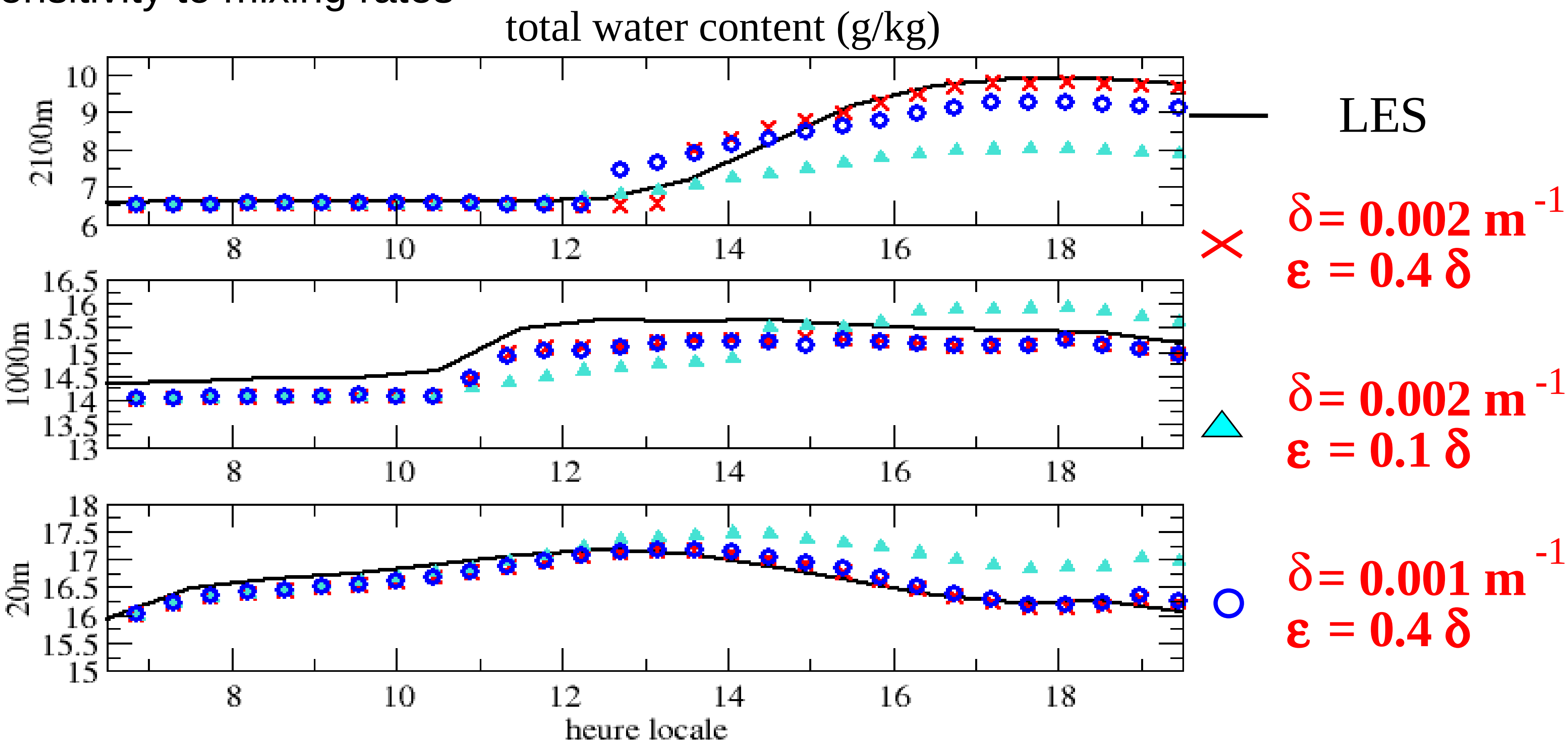


Diurnal evolution of cloud characteristics

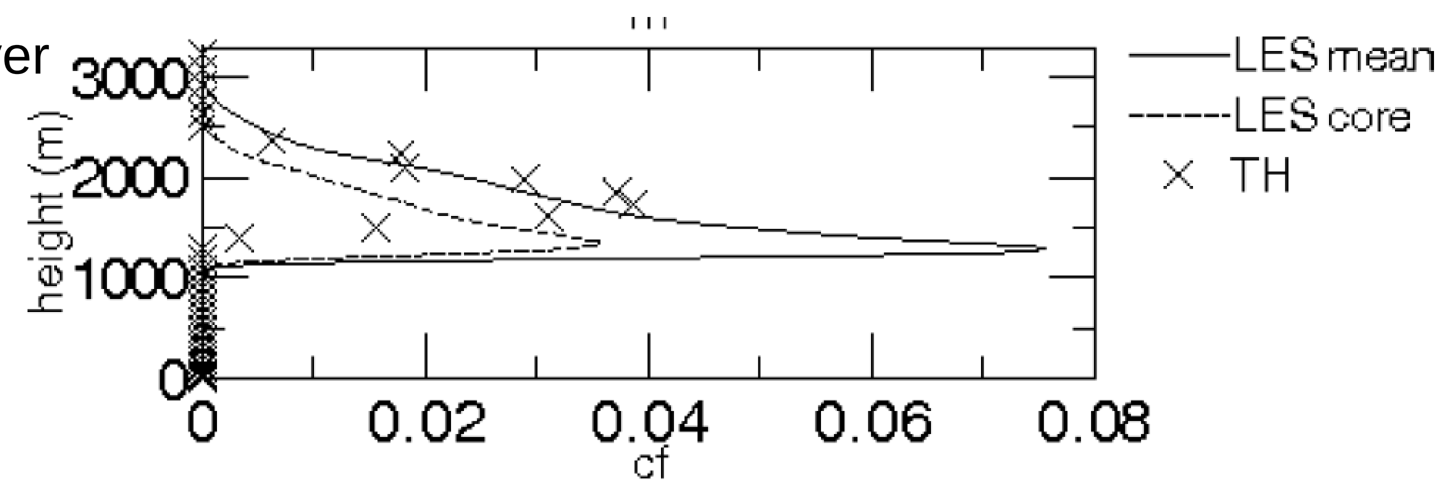


Main limitations of the scheme

Sensitivity to mixing rates



The diagnosed cloud cover



Latest developments

Formulation of mixing rates and w equation

Rio & al., BLM, 2010

Equation for the vertical velocity

$$\frac{\partial f w_u}{\partial z} = -\mathrm{d}w_u + \alpha\rho\Gamma$$

with

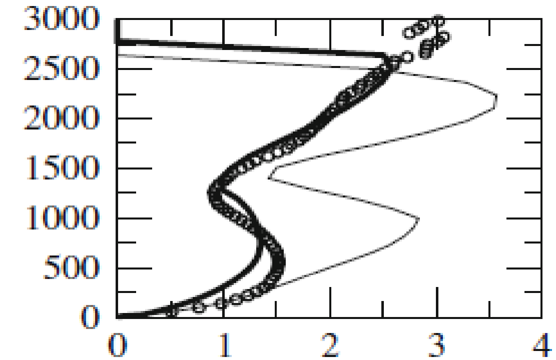
$$\Gamma = a_1 B - b w_u^2$$

drag ($b w_u^2$)

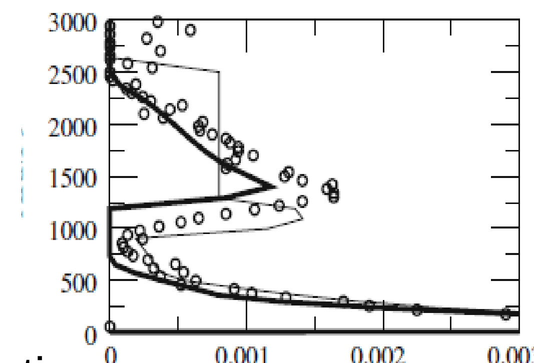
Impact of pressure perturbations (a_1)

o LES —— TH ▬▬ TH new

vertical velocity (m/s)



entrainment rate (1/m)



Formulation of mixing rates

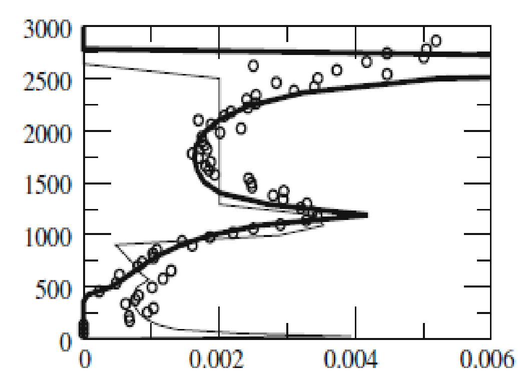
$$\varepsilon = \max\left(0, \frac{1}{1+\beta_1}\left(a_1 \frac{B}{w_u^2} - b\right)\right)$$

Impact of acceleration/deceleration ($\frac{B}{w_u^2}$)

$$\delta = \max\left(0, -\frac{a_1\beta_1}{1+\beta_1}\frac{B}{w_u^2} + c\left(\frac{\Delta r_t / r_t}{w_u^2}\right)^d\right)$$

detrainment favoured in a dry environment

detrainment rate (1/m)



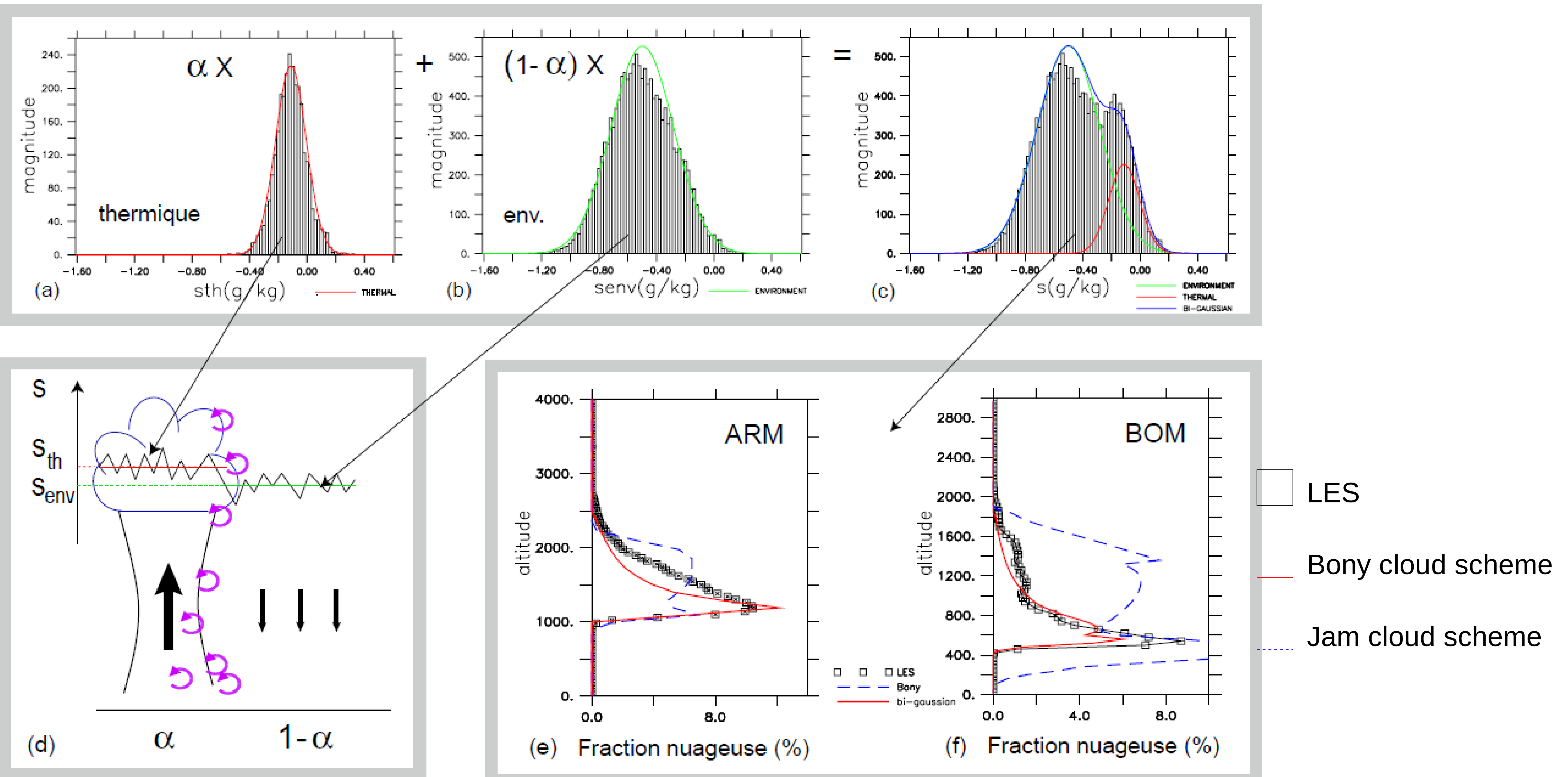
Coupling with a new diagnostic cloud scheme

Jam & al., in preparation for BLM

- Bi-gaussian distribution of the saturation deficit s
- 5 parameters: α, sth, senv given by the model

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

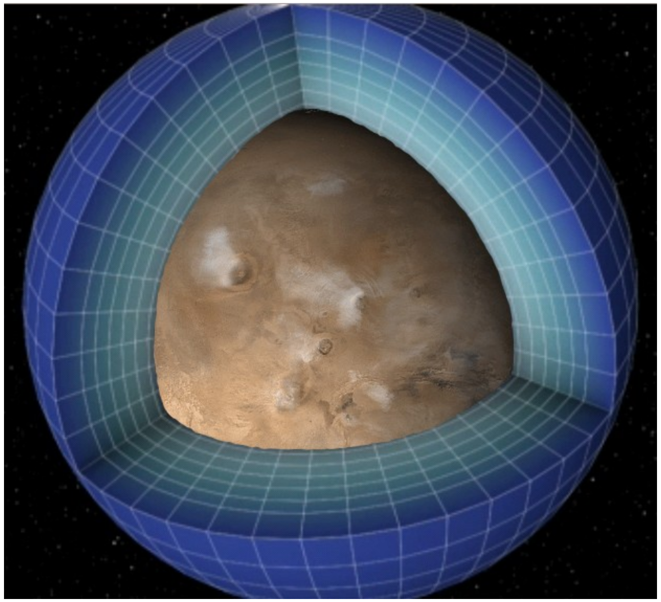
$$\sigma_{s,th} = c_{th} \times \left(\frac{\alpha}{1-\alpha}\right)^{-\frac{1}{2}} \times (\overline{s}_{th} - \overline{s}_{env}) + b \times \overline{q}_{t_{th}}$$



Applications

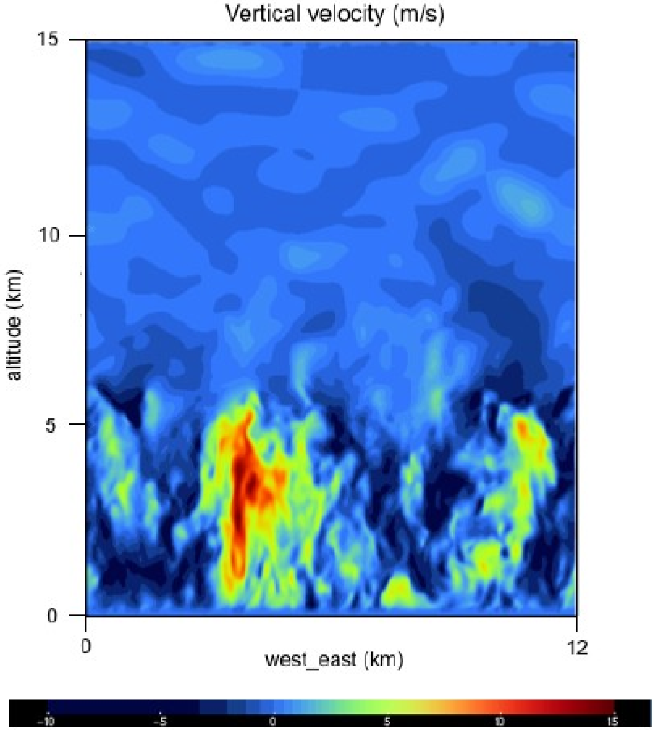
The thermal plume model sent to Mars

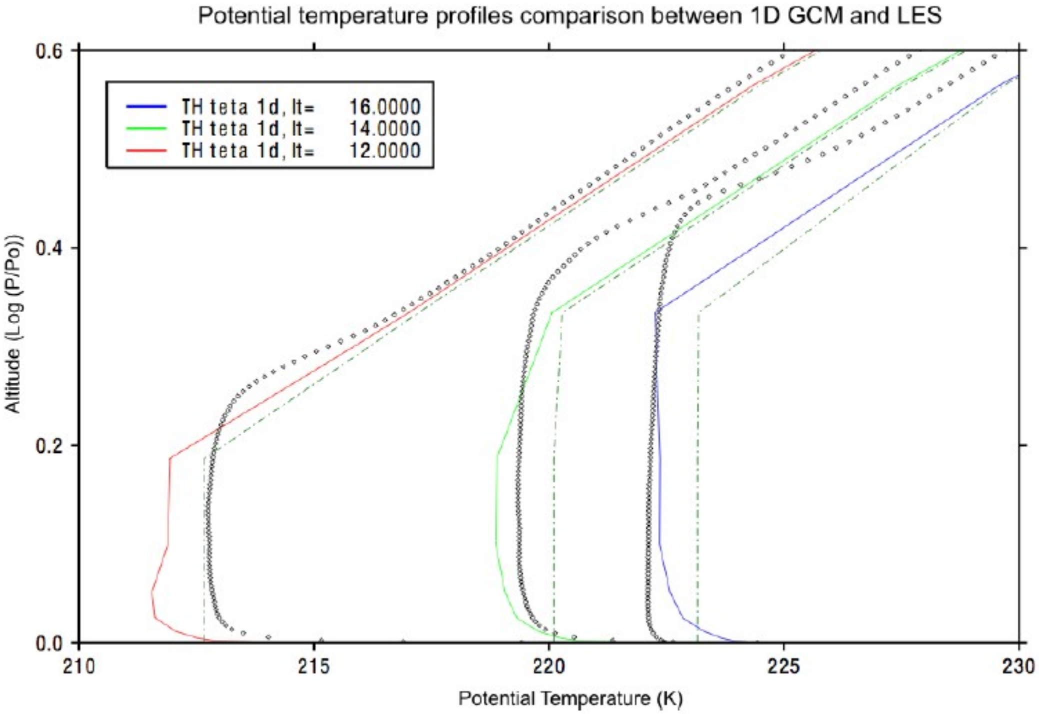
A. Colaïtis & al., work in progress



Martian GCM version of LMDZ

LES simulation



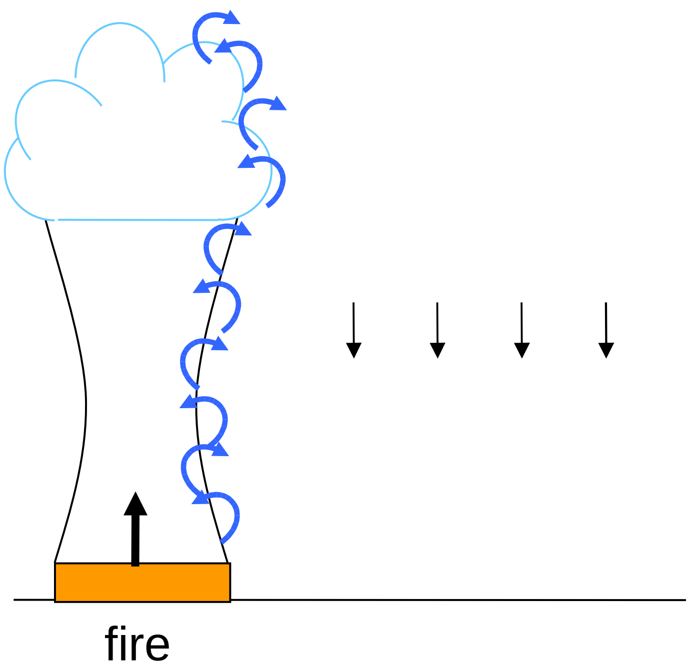


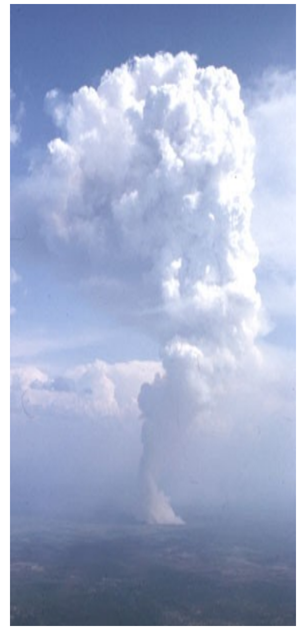
- coherent updrafts and
- coherent downdrafts within the Martian boundary layer

The pyro-thermal plume model

Rio & al., ACP, 2010

Adaptation of the thermal plume model to the representation of the vertical transport of aerosols and gas by pyro-plumes generated by fires.

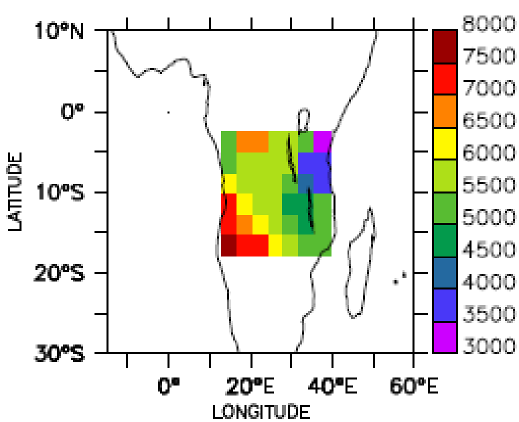




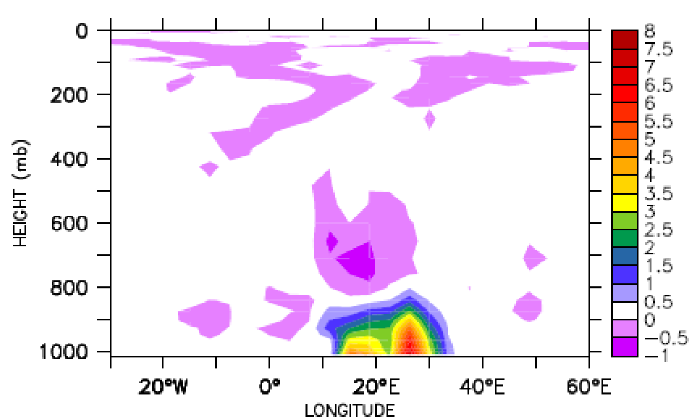
$$\theta_0' = \left(\frac{\left(\frac{F}{\rho C_p}\right)^2 \theta_{ve}}{3/2gh}\right)^{1/3}$$

$$A = \frac{F * \frac{S}{Aire}}{C_p \theta_0'}$$

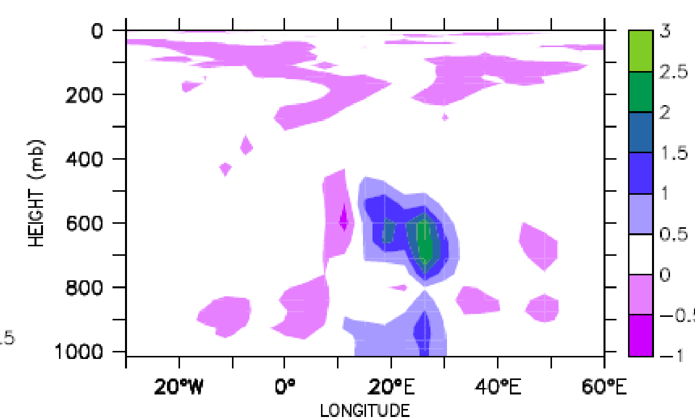
Injection height (m)



Diurnal Tropospheric Excess of CO2 (ppmv)

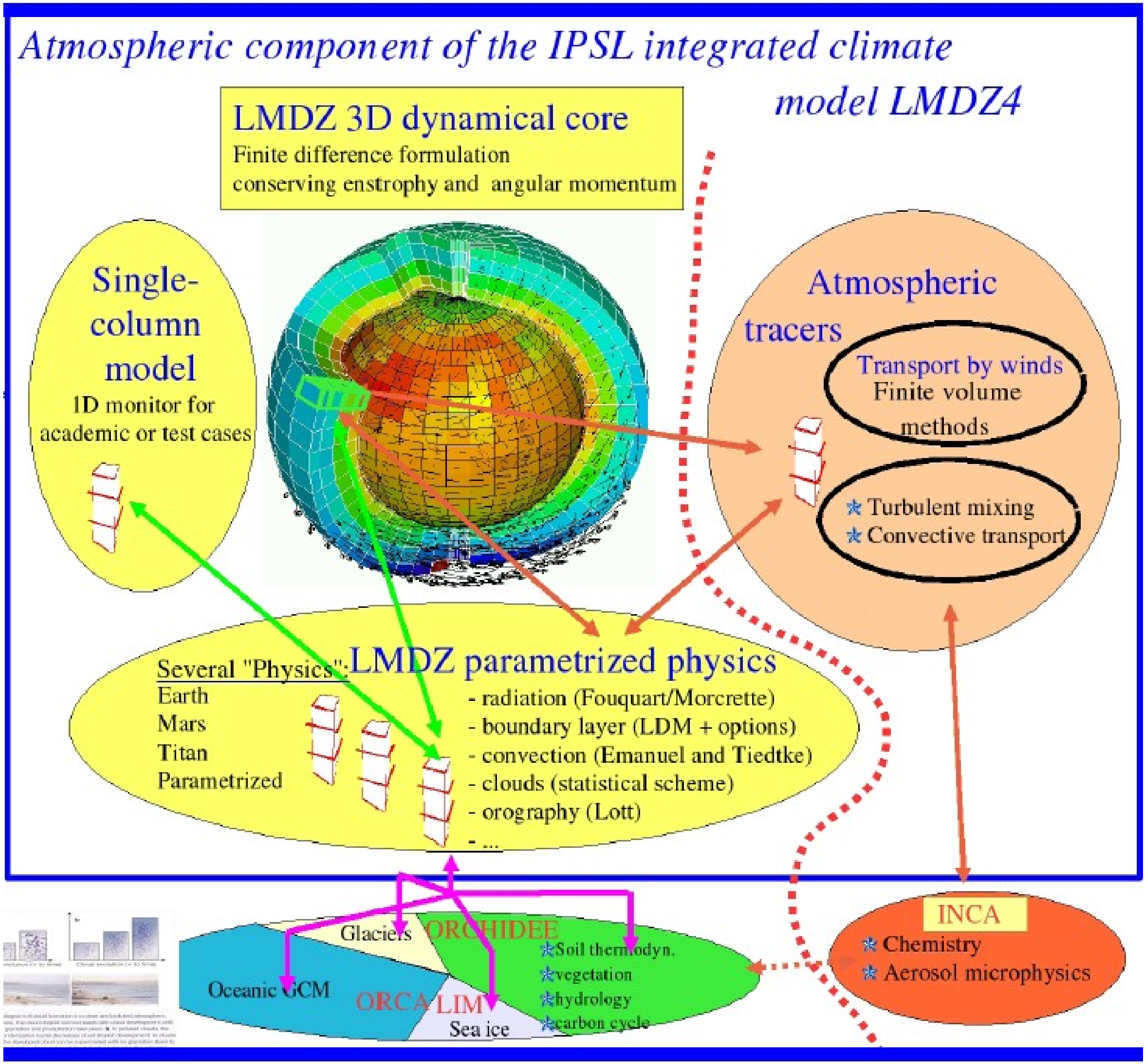


without pyro-plumes



with pyro-plumes

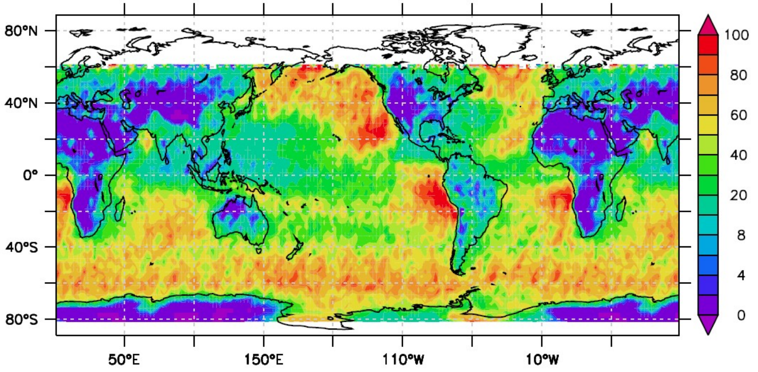
The thermal plume model implemented in the IPSLCM5b coupled model

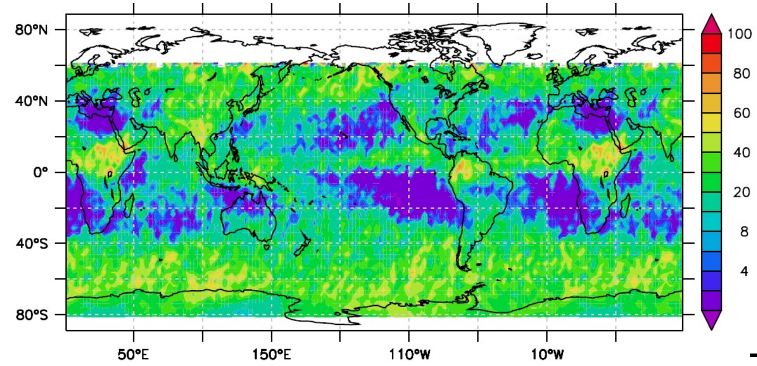


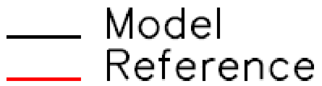
Low and Middle clouds (forced run)

Low clouds (%) | Middle clouds (%)

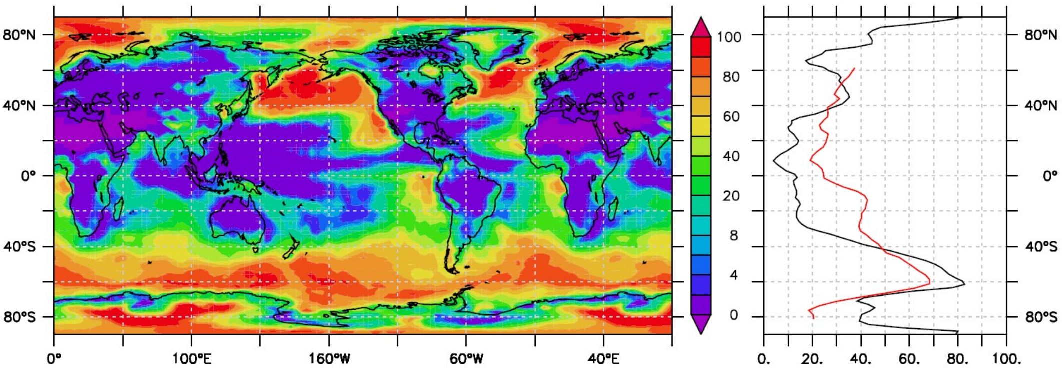
CALIPSO

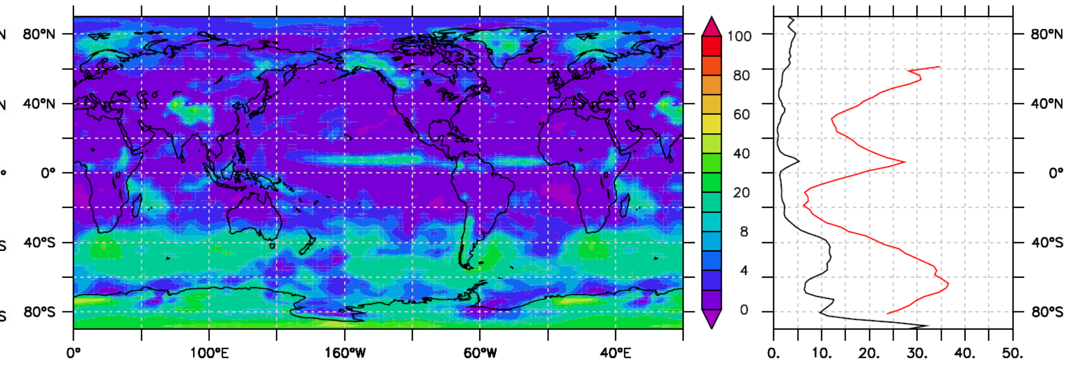




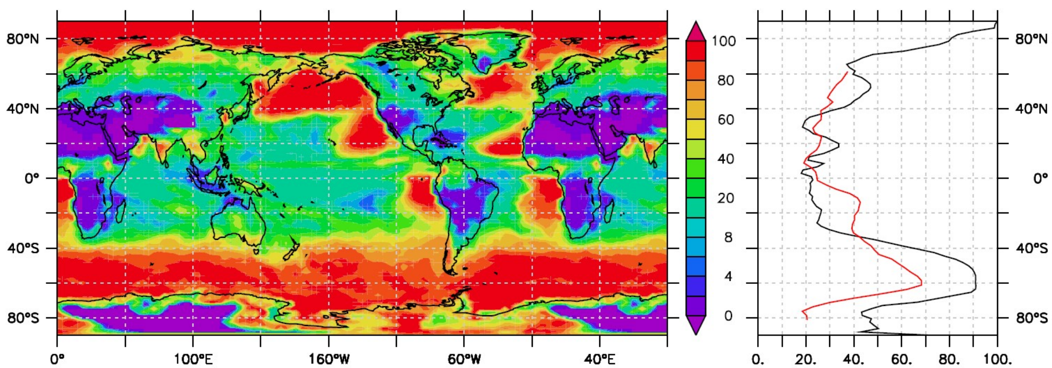


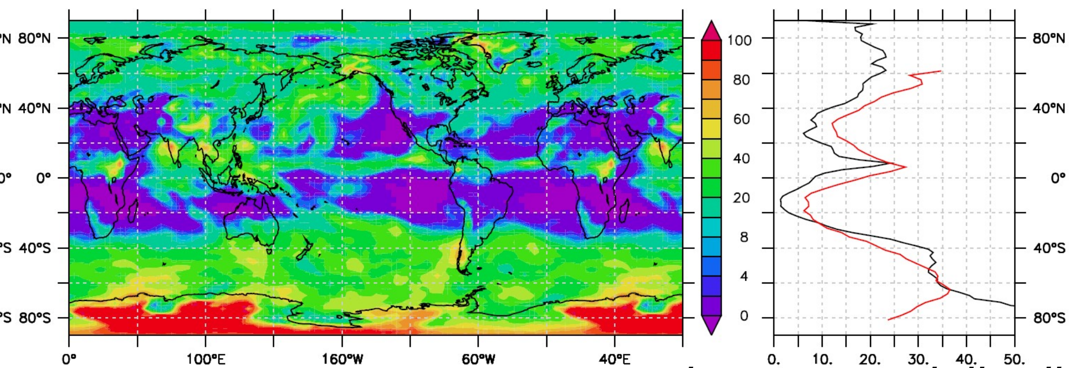
LMDZ AR5a





LMDZ AR5b



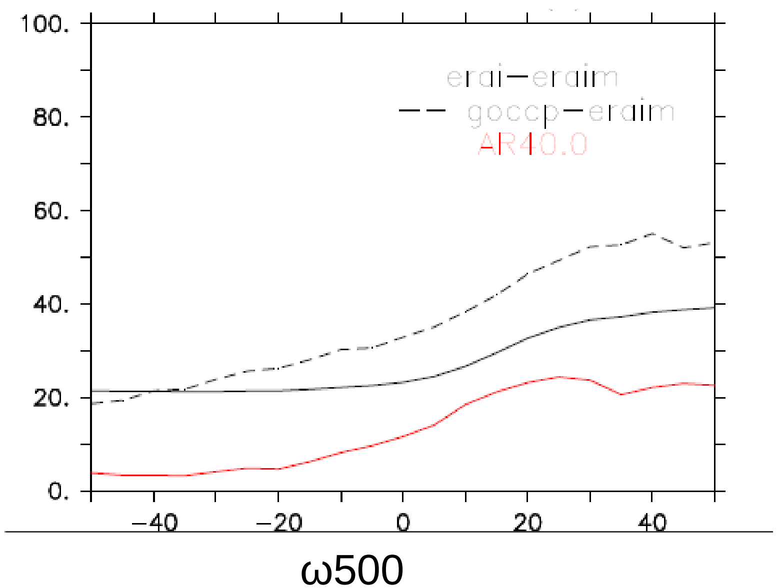


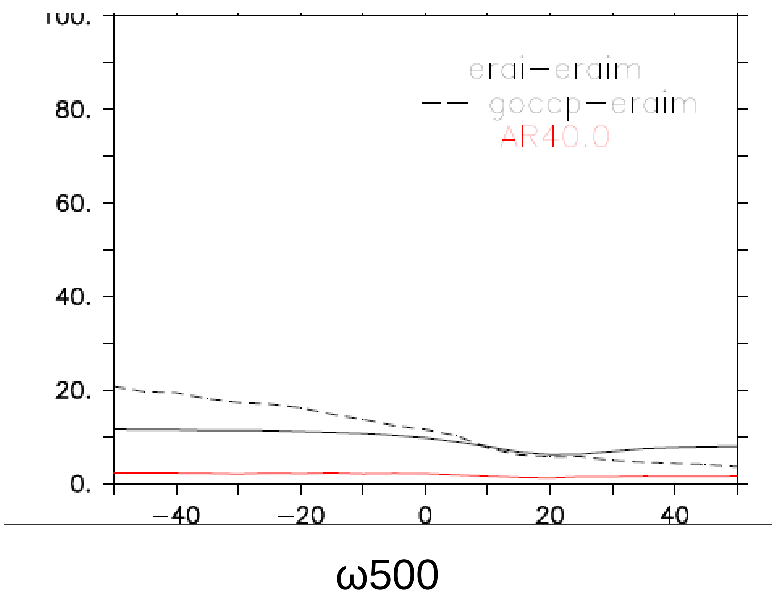
Figures: A. Idelkadi

Low and Middle clouds (forced run)

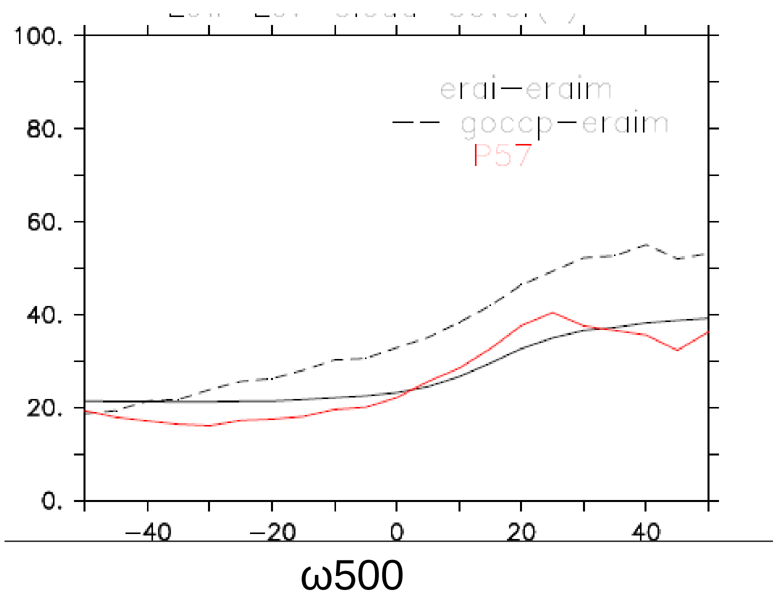
Low clouds (%) | Middle clouds (%)

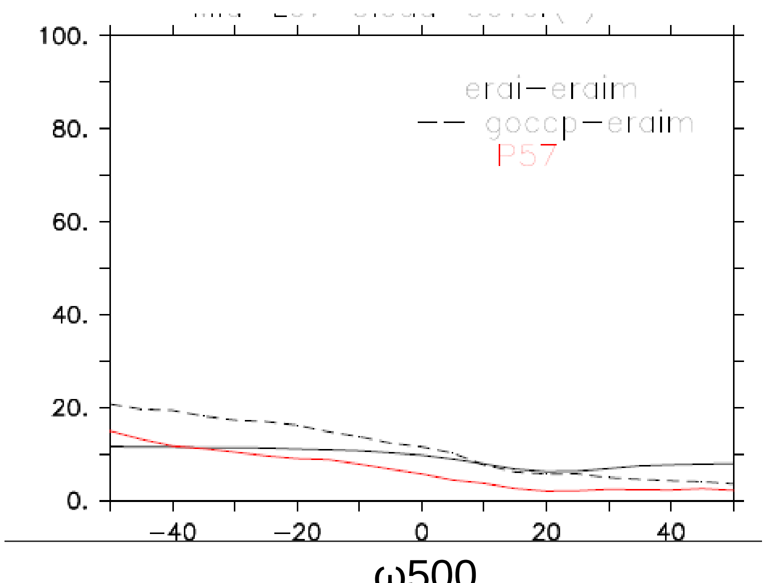
LMDZ AR5a





LMDZ AR5b





Figures: A. Idelkadi

Concluding remarks

Encouraging results:
- Diurnal cycle of the cloudy boundary layer over land and ocean
- Progressive understanding and improving of the model

Numerous applications:
- Martian thermals
- pyro-convection
- climate modelling
- gas species transport ...

Remaining issues:

Scheme components:
- representation of stratocumulus clouds: transport of TKE
- specification of detrainment
- specification of entrainment in the surface layer
- w equation

Interactions with other components:
- coupling with the diffusion scheme
- coupling with the cloud scheme
- coupling with the deep convection scheme