Processing separately the in-wake and off-wake boundary layers: effect on surface fluxes and low cloud cover in the LMDZ GCM

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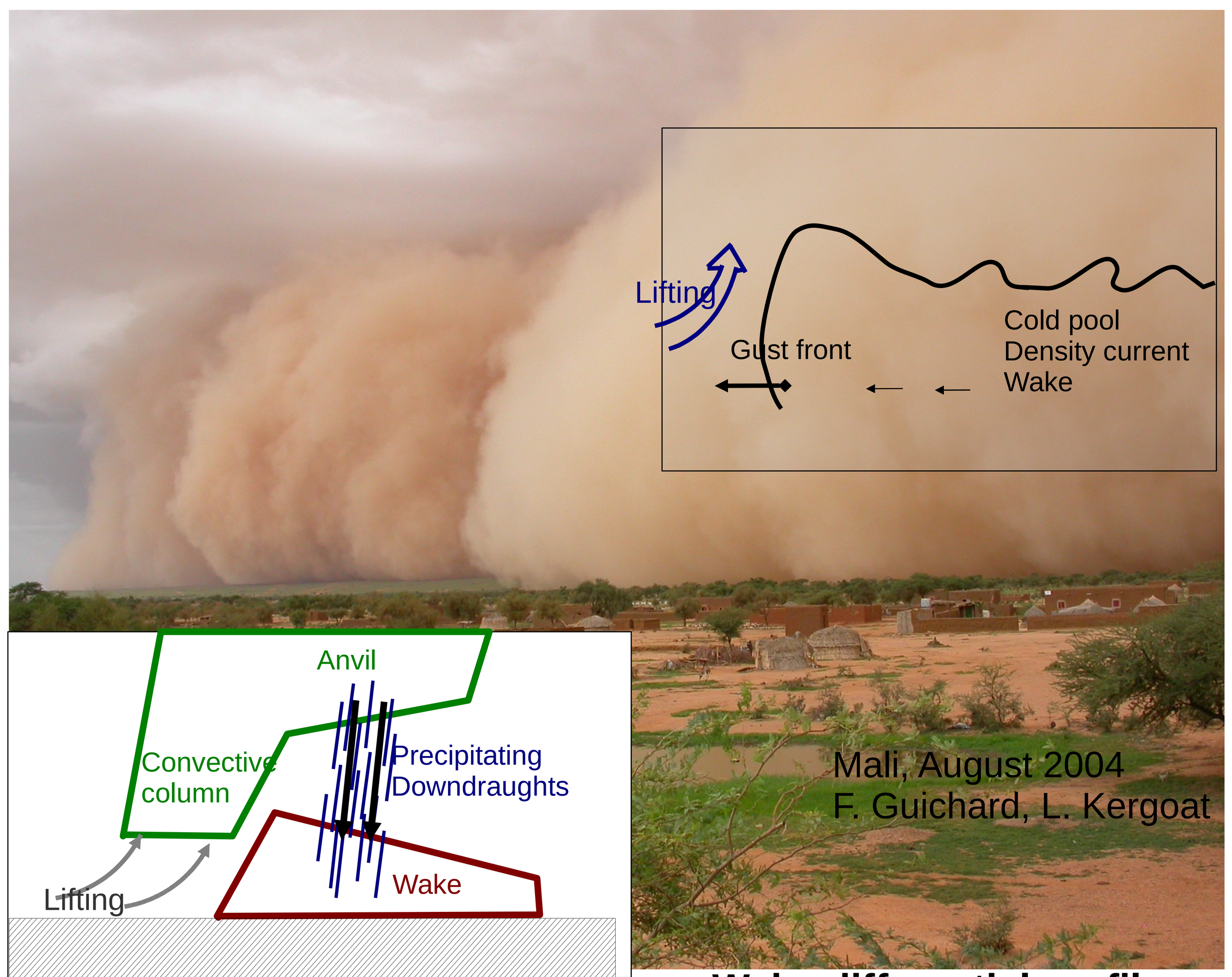
Introduction

In the LMDZ GCM, moist convection is represented by a set of three parametrizations, namely the thermal scheme (representing boundary layer thermals), the wake scheme (representing density currents) and the Emanuel scheme (representing deep convection); the first two parametrizations are coupled with the convective scheme through two variables, the ALE (Available Lifting Energy, used in the convective trigger) and the ALP (Available Lifting Power, used in the convective closure). This set of parametrizations coupled through the ALE/ALP system made it possible to improve largely the simulation of the diurnal cycle of convection over land and of its variability over ocean (Rio et al., 2009, Rio et al., 2012).

Up to now the boundary layer EDMF scheme is called for the average temperature and humidity profile, which leads to various deficiencies:
• Technical problem: the off-wake atmosphere is often absolutely unstable.
•The interaction of cold pools with surface fluxes is not represented.
• The Thermal scheme is strongly inhibited as soon wakes appear, which is incompatible with observation and leads to a lack of low level clouds.

We except that splitting the boundary layer between the wake and the off-wake regions will Bring more reasonable profiles and improve the low level cloud cover.

I – The representation of density currents

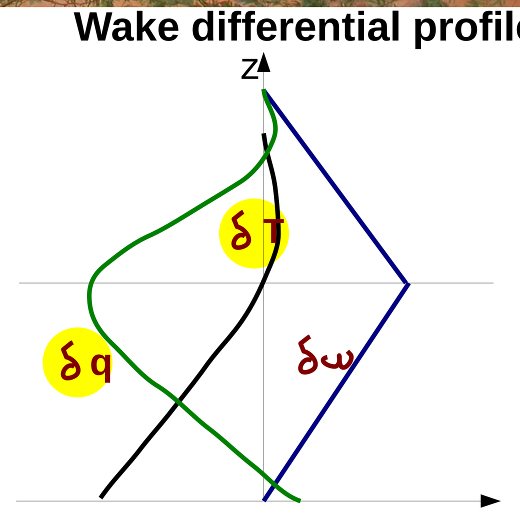


The density current (wake) parametrization

(Grandpeix and Lafore, JAS, 2010 ; Grandpeix et al., JAS 2010)

- Representation of a part of an infinite plane where identical cold pools (radius r, height h) are scattered with an homogeneous density $D_{\rm wk}$.
- State variables : (i) surface fraction covered by the wakes $\sigma_w = \frac{S_w}{S_t}$ ($\sigma_w = \pi r^2 D_{\rm wk}$), (ii) temperature and humidity differences (resp. $\delta\theta(p)$ and $\delta q(p)$) between wake and off-wake regions.
- Spreading speed : C_* such that $C_*^2 \simeq$ WAPE (WAke Potential Energy) ; $WAPE = \int_{p_{top}}^{p_{surf}} R_d \delta T_v \frac{dp}{p}$
- Evolutions of $\delta\theta$ and δq profiles are given by conservation equations of mass, energy and water taking into account vertical advection, turbulence and phase changes.
- Turbulence and phase change terms are assumed to be given by the deep convection scheme.
- $\delta\omega$ profile is linear between the surface and the wake top (no mass exchange through the wake boundary) ; it goes back to 0 linearly between the wake top and an arbitrary altitude (about 4000 m).

Wake differential profiles



Large scale variable tendencies

$$\begin{cases} \partial_t\overline{\theta} = (\partial_t\overline{\theta})_{LS} + \dfrac{Q_R + Q_1^{\rm bl} + Q_1^{\rm cv} + Q_1^{\rm wk}}{C_p} \\ \dfrac{Q_1^{\rm wk}}{C_p} = +(\partial_t\sigma_w - e_w)\,\delta\theta \quad \text{: Spreading \& entrainment} \\ \qquad -\sigma_w(1-\sigma_w)\,\delta\omega\,\partial_p\delta\theta \quad \text{: Differential advection} \end{cases}$$

with similar equations for water vapour.

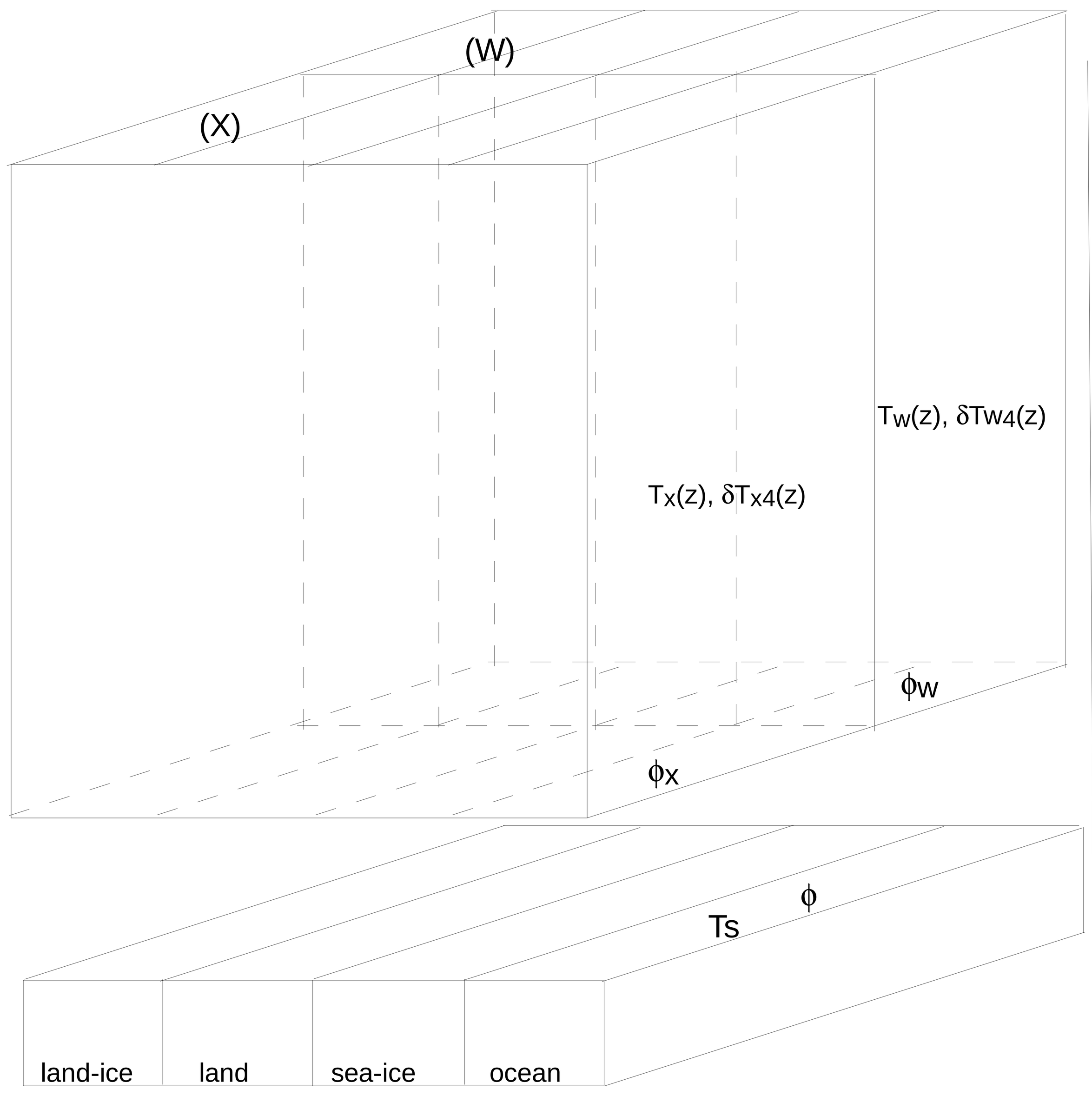
Wake variable tendencies

$$\begin{cases} \partial_t\delta\theta = -\overline{\omega}\,\partial_p\delta\theta + \dfrac{\delta Q_1^{\rm cv} + \delta Q_1^{\rm wk}}{C_p} - \dfrac{k_{\rm gw}}{\tau_{\rm gw}}\,\delta\theta \\ \qquad \text{where } \tau_{\rm gw} = \frac{\sqrt{\sqrt{\sigma_w}(1-\sqrt{\sigma_w})}}{4Nz\sqrt{D_{\rm wk}}} \\ \qquad \text{is the damping time by gravity waves} \\ \dfrac{\delta Q_1^{\rm wk}}{C_p} = -\dfrac{e_w}{\sigma_w}\,\delta\theta \quad \text{: Entraînement} \\ \qquad -\delta\omega\,\partial_p\overline{\theta} \quad \text{: differential advection of } \overline{\theta} \\ \qquad -(1-2\sigma_w)\,\delta\omega\,\partial_p\delta\theta \quad \text{: differential advection of } \delta\theta \end{cases}$$

Water vapour equations are similar except for the gravity wave term :

$$(\partial_t\delta q_v)_{\rm gw} = -\frac{k_{\rm gw}}{\tau_{\rm gw}}\,\delta\theta\;\frac{\partial_z[\overline{q_v} + (1-2\sigma_w)\delta q_v]}{\partial_z[\overline{\theta} + (1-2\sigma_w)\delta\theta]}$$

2 -The splitting of the boundary layer



Four sub-surfaces x Two atmospheric profiles ==> Eight atmospheric columns

Surface-Atmosphere coupling

(Equations for heat ; similar equations hold for moisture)

The wakes are supposed to move rapidly above the various sub-surfaces so that surface temperature is homogeneous over each subsurface.

Interface variables for the atmosphere :
- ϕ_i^w , surface heat flux between sub-surface (i) and wake atmospheric column.
- ϕ_i^x , surface heat flux between sub-surface (i) and off-wake atmospheric column.

Interface variables for sub-surface (i) :
- T_i^a at begining of time-step, a temperature such that the surface flux ϕ_i is related to the surface temperature $T_{s,i}$ by $\phi_i = K_i C_p\,(T_i^a - T_{s,i})$.
- K_i : exchange coefficient at the surface.
- Coefficients A_i and B_i such that the linear relationship between T_i^a and ϕ_i implied by the atmospheric column reads $T_i^a = (1/C_p)(A_i + B_i\phi_i\Delta t)$.

Surface-Atmosphere coupling 2

Model equations

In each column (w,i) and (x,i), the atmospheric model yields a linear relation between temperature T_1 at first level and surface flux ϕ :

$$\begin{cases} T_{1,i}^w = \dfrac{1}{C_p}\,(A_i^w + B_i^w\phi_i^w\Delta t) \\ T_{1,i}^x = \dfrac{1}{C_p}\,(A_i^x + B_i^x\phi_i^x\Delta t) \end{cases} \qquad (1)$$

At each interface (w,i) and (x,i), surface exchange laws yield :

$$\begin{cases} \phi_i^w = K_i^w(T_{1,i}^w - T_{s,i}) \\ \phi_i^x = K_i^x(T_{1,i}^x - T_{s,i}) \end{cases} \qquad (2)$$

Coupling with sub-surface :

$$\begin{cases} \phi_i = \sigma_w\phi_i^w + (1-\sigma_w)\phi_i^x = \phi_i^x + \sigma_w\delta\phi_i \\ T_i^a = \dfrac{1}{C_p}(A_i + B_i\phi_i\Delta t) \\ \phi_i = K_i C_p\,(T_i^a - T_{s,i}) \end{cases} \qquad (3)$$

(for any variable y : $\delta y = y^w - y^x$)

Surface-Atmosphere coupling 3

Solving

From atmosphere to sub-surfaces :

$$\begin{cases} K_i = K_i^x + \sigma^w\,\delta K_i \\ T_i^a = T_{1,i}^x + \sigma^w\dfrac{K_i^w\,\delta T_{1,i}}{K_i} \end{cases} \qquad (4)$$

$$\begin{cases} K_i^{'w} = \dfrac{K_i^w}{1 - B_i^w K_i^w\Delta t} \\ K_i^{'x} = \dfrac{K_i^x}{1 - B_i^x K_i^x\Delta t} \end{cases} \qquad (5)$$

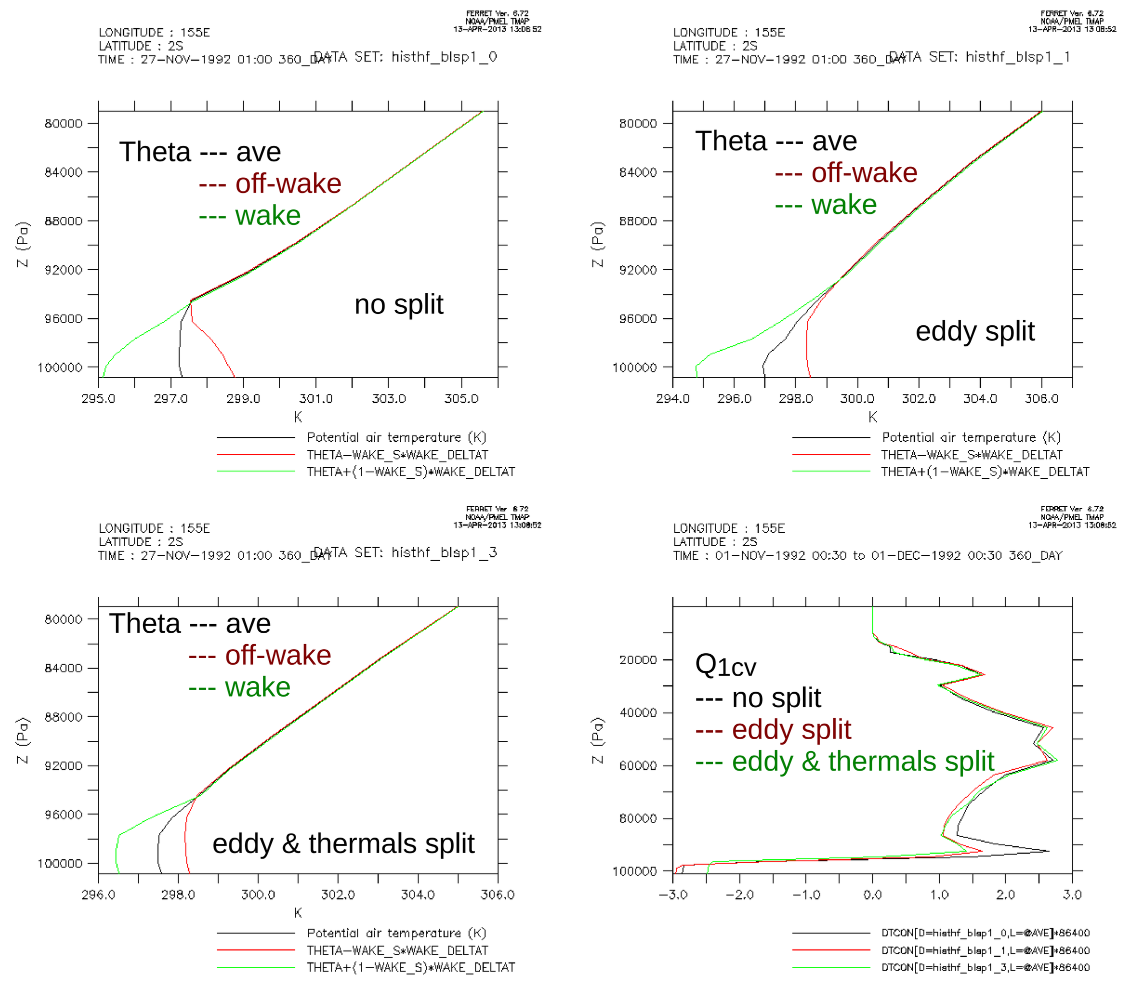
$$\begin{cases} K_i' = K_i^{'x} + \sigma^w\,\delta K_i' \\ A_i = A_i^x + \sigma^w\dfrac{K_i^{'w}\,\delta A_i^w}{K_i'} \end{cases} \qquad (6)$$

$$B_i = B_i^x + \sigma^w B_i^x\frac{\delta K_i}{K_i}\left(1 + \frac{K_i^{'w}}{K_i'}\right) + \sigma^w\frac{K_i^{'w}K_i'}{K_i'K_i}\delta B_i \qquad (7)$$

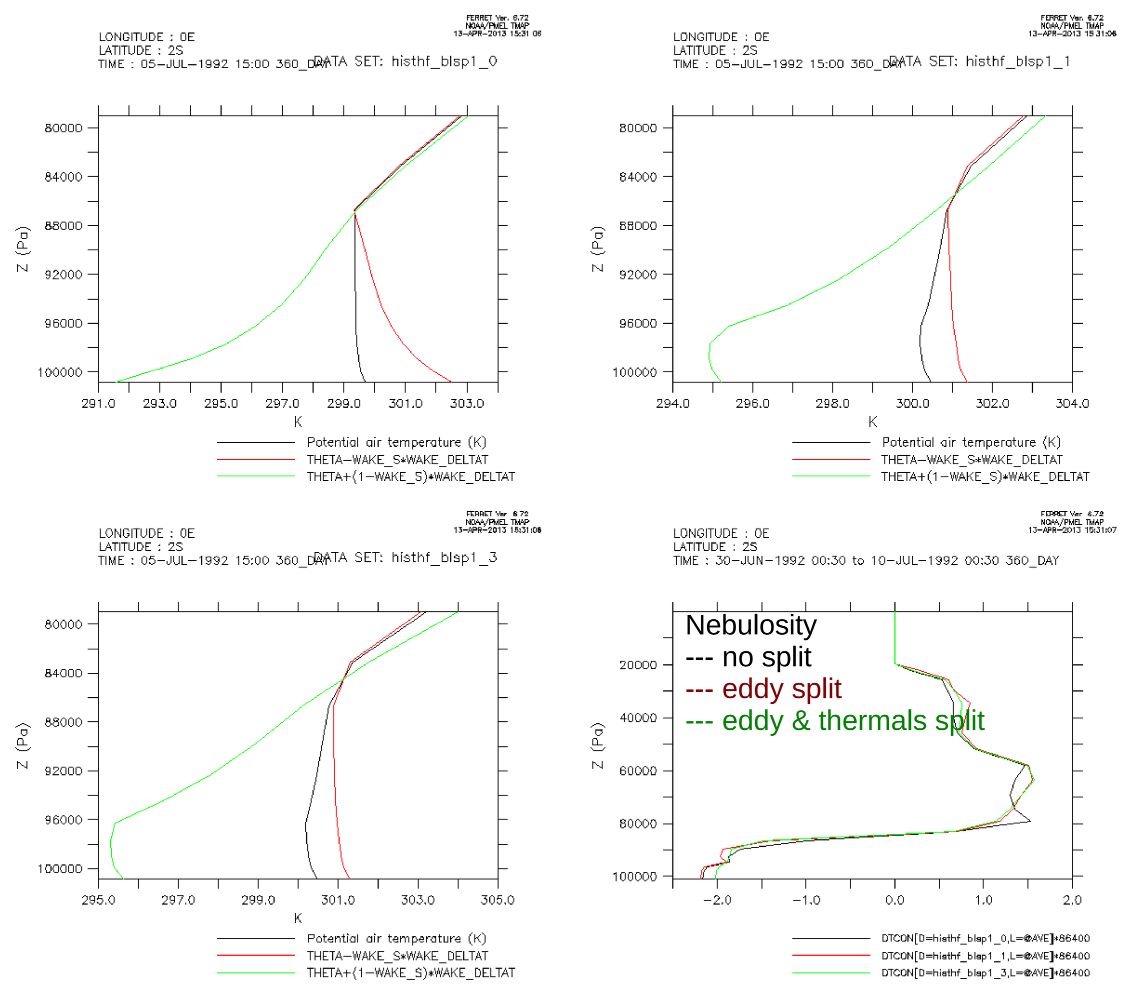
From sub-surfaces to atmosphere :

$$\begin{cases} \delta\phi_i = \dfrac{K_i^{'w}K_i^{'x}\delta A_i + \phi_i\delta K_i'}{K_i'} \\ \phi_i^w = \phi_i + (1-\sigma^w)\delta\phi_i \\ \phi_i^x = \phi_i - \sigma^w\delta\phi_i \end{cases} \qquad (8)$$

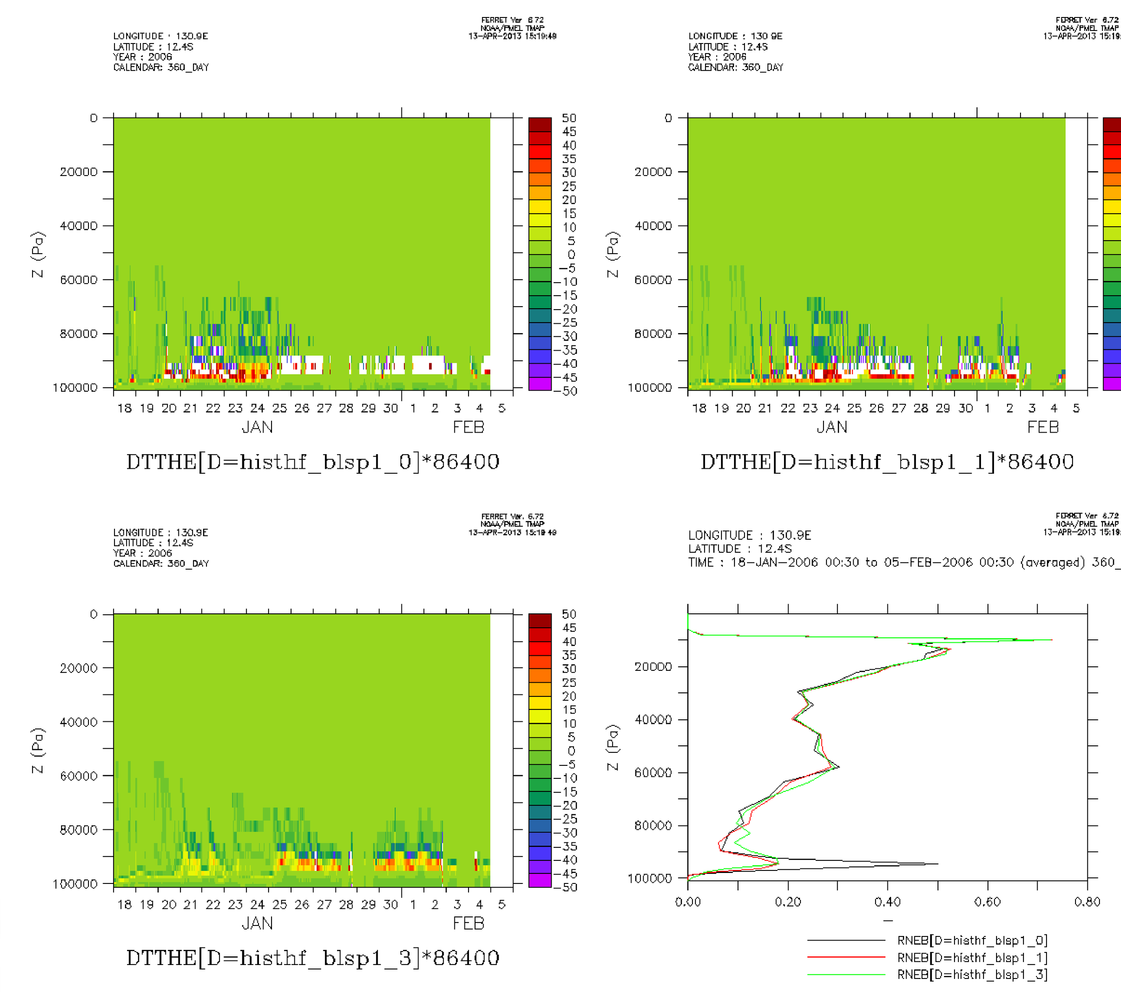
3 -TOGA-COARE 1D simulations



4 – Radiative-Convective Equilibrium 1D simulations (Semi-arid conditions)



5 -TWPICE 1D simulations



Conclusion

•Vertical temperature profiles are now reasonable.

•Thermals are changed, but not quite as expected: they are Deeper, but they are less active (contrary to Expectations).
=> A spurious very high nebulosity at very low level Disappears