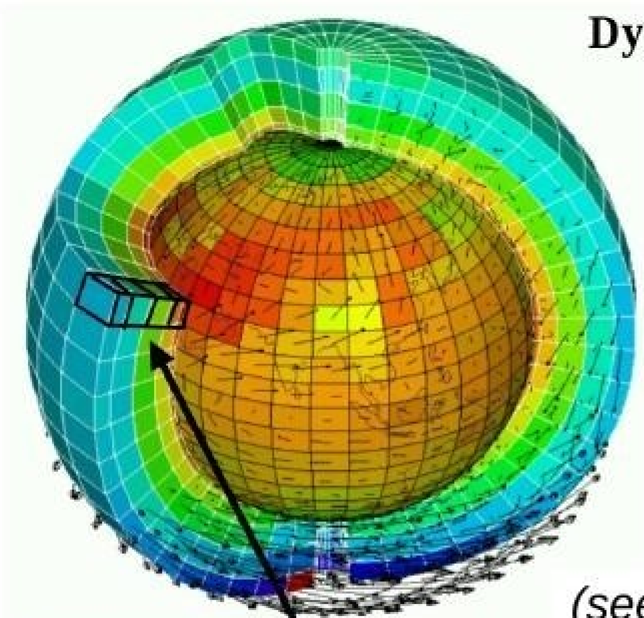
The physical parametrizations in LMDZ

LMDZ Team

Laboratoire de Météorologie Dynamique

December 2019

Quick reminder : general equations



Dynamical core : primitive equations discretized on the sphere

- Mass conservation

  $D\rho/Dt + \rho \,\mathrm{div}\underline{U} = 0$

- Potential temperature conservation

  $D\theta / Dt = Q / Cp \ (p_0/p)^{\kappa}$

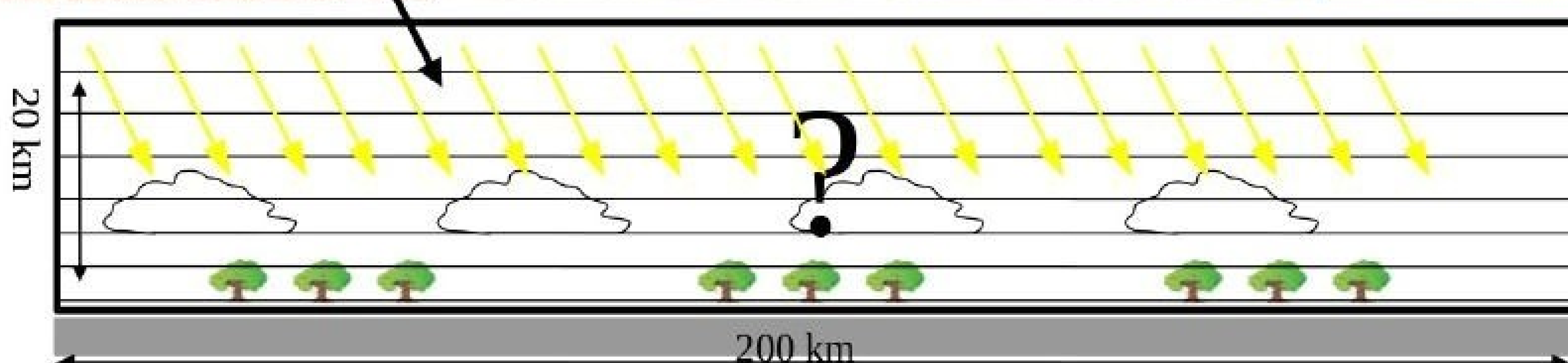
- Momentum conservation

  $D\underline{U}/Dt + (1/\rho)\ \underline{\mathrm{grad}}p - \underline{g} + 2\ \underline{\Omega} \wedge \underline{U} = \underline{F}$

- Secondary components conservation

  $Dq/Dt = Sq$

(see yesterday's presentation by F. Hourdin)



Parameterization = source terms

Atmospheric GCM equations

Primitive equations in pressure coordinates

Momentum equation :

$$\partial_t \vec{v} + \underbrace{(\vec{v}.\vec{\nabla}_p)\vec{v} + \omega \partial_p \vec{v}}_{\text{transport}} + \underbrace{f\vec{k} \times \vec{v}}_{\text{Coriolis}} + \underbrace{\vec{\nabla}_p \Phi}_{\text{gravity}} = \vec{S_v}$$

Continuity equation :

$$\vec{\nabla}_p.\vec{v} + \partial_p \omega = 0$$

Component conservation :

$$\partial_t q + \vec{v}.\vec{\nabla}_p q + \omega \partial_p q = S_q$$

Thermodynamic equation :

$$\partial_t \theta + \vec{v}.\vec{\nabla}_p \theta + \omega \partial_p \theta = \frac{\theta}{c_p T} \dot{Q}_{net}$$

Sources

$\Phi = gz$ geopotential

$\omega = \partial_t p$ vert. velocity

$q =$ specific humidity

$\dot{Q}_{net} =$ heating rate from all diabatic sources

$\vec{S_v}$, S_q and $\dot{Q}_{net}$: source terms determined by the **physical parametrizations** and the **radiative transfer scheme** :

- planetary boundary layer, shallow and deep convection
- scattering and absorption by cloud droplets and crystals
- drag due to topography...

Tendencies

Model tendencies

The integration of a given prognostic variable X $(T, \vec{v}(u,v,w), p, \rho, q_{vap})$ can be written as :

$$X_{t+\Delta t} = X_t + \left(\frac{\partial X}{\partial t}\right)_{\text{dyn}} \Delta t \text{ (dynamical core)} \quad (1)$$

$$+ \left(\frac{\partial X}{\partial t}\right)_{\text{param}} \Delta t \text{ (parameterizations)} \quad (2)$$

Temperature tendencies

Basic facts about parametrizations I

- Each parametrization : (1) works almost independently of the others ; (2) depends on vertical profiles of u, v, w, T, q and on some interface variables with the other parametrizations ; (3) ignores the spatial heterogeneities associated with the other processes (except for some processes in the deep convection scheme).
- The total tendency due to sub-grid processes is the sum of the tendencies due to each process :

$$S_T = (\partial_t T)_\varphi = (\partial_t T)_{\text{eva}} + (\partial_t T)_{\text{lsc}} + (\partial_t T)_{\text{diff turb}} + (\partial_t T)_{\text{conv}} + (\partial_t T)_{\text{wk}} + (\partial_t T)_{\text{Th}} + (\partial_t T)_{\text{ajs}} + (\partial_t T)_{\text{rad}} + (\partial_t T)_{\text{oro}} + (\partial_t T)_{\text{dissip}}$$

Orographic waves

→ Marine Bonazzola

In the model, the total tendency of T for example is $\partial_t T_{\text{dyn}} + \partial_t T_{\text{param}}$ = dtdyn + dtphy, where :

```
dtphy = dteva + dtlsc + dtvdf + dtcon +
        dtwak + dtthe + dtajs +
        (dtswr + dtlwr) + (dtoro + dtlif) + (dtdis + dtec)
```

Output names

→ Not the same as their name in the source code !

physiq_mod.f90

Specific humidity tendencies

Basic facts about parametrizations II

– Similiarly, the total tendency of a given tracer q writes :

$$
\begin{aligned}
S_q \;=\; (\partial_t q)_\varphi \;\; &= (\partial_t q)_{\text{eva}} + (\partial_t q)_{\text{lsc}} + (\partial_t q)_{\text{diff turb}} + (\partial_t q)_{\text{conv}} \\
&+ (\partial_t q)_{\text{wk}} + (\partial_t q)_{\text{Th}} + (\partial_t q)_{\text{ajs}}
\end{aligned}
$$

In the model, the total tendency of q is therefore

$\partial_t q_{\text{dyn}} + \partial_t q_{\text{param}} =$ `dqdyn` + `dqphy`, where :

`dqphy = dqeva + dqlsc + dqvdf + dqcon + dqwak + dqthe + dqajs`

Subroutine structure

physiq_mod.F90 structure - I

Initialization (once) : *conf_phys, phyetat0, phys_output_open*

Beginning *change_srf_frac, solarlong*

Cloud water evap. *reevap*

Vertical diffusion (turbulent mixing) *pbl_surface*

Deep convection *conflx* (Tiedtke) or *concvl* (Emanuel)

Deep convection clouds *clouds_gno*

Density currents (wakes) *calwake*

Strato-cumulus *stratocu_if*

Thermal plumes *calltherm* and *ajsec* (sec = dry)

Large scale clouds *calcratqs*

Large scale and cumulus condensation *fisrtilp*

Diagnostic clouds for Tiedtke *diagcld1*

Aerosols *readaerosol_optic*

Cloud optical parameters *newmicro* or *nuage*

Radiative processes *radlwsw*

In blue : subroutines and instructions modifying state variables

physiq_mod.F90 structure - II

Orographic processes : drag *drag_noro_strato* or *drag_noro*

Orographic processes : lift *lift_noro_strato* or *lift_noro*

Orographic processes : Gravity Waves *hines_gwd* or *GWD_rando*

Axial components of angular momentum and mountain torque : *aaam_bud*

Cosp simulator *phys_cosp*

Tracers *phytrac*

Tracers off-line *phystokenc*

Water and energy transport *transp*

Outputs

Statistics

Output of final state (for restart) *phyredem*

Subroutine structure

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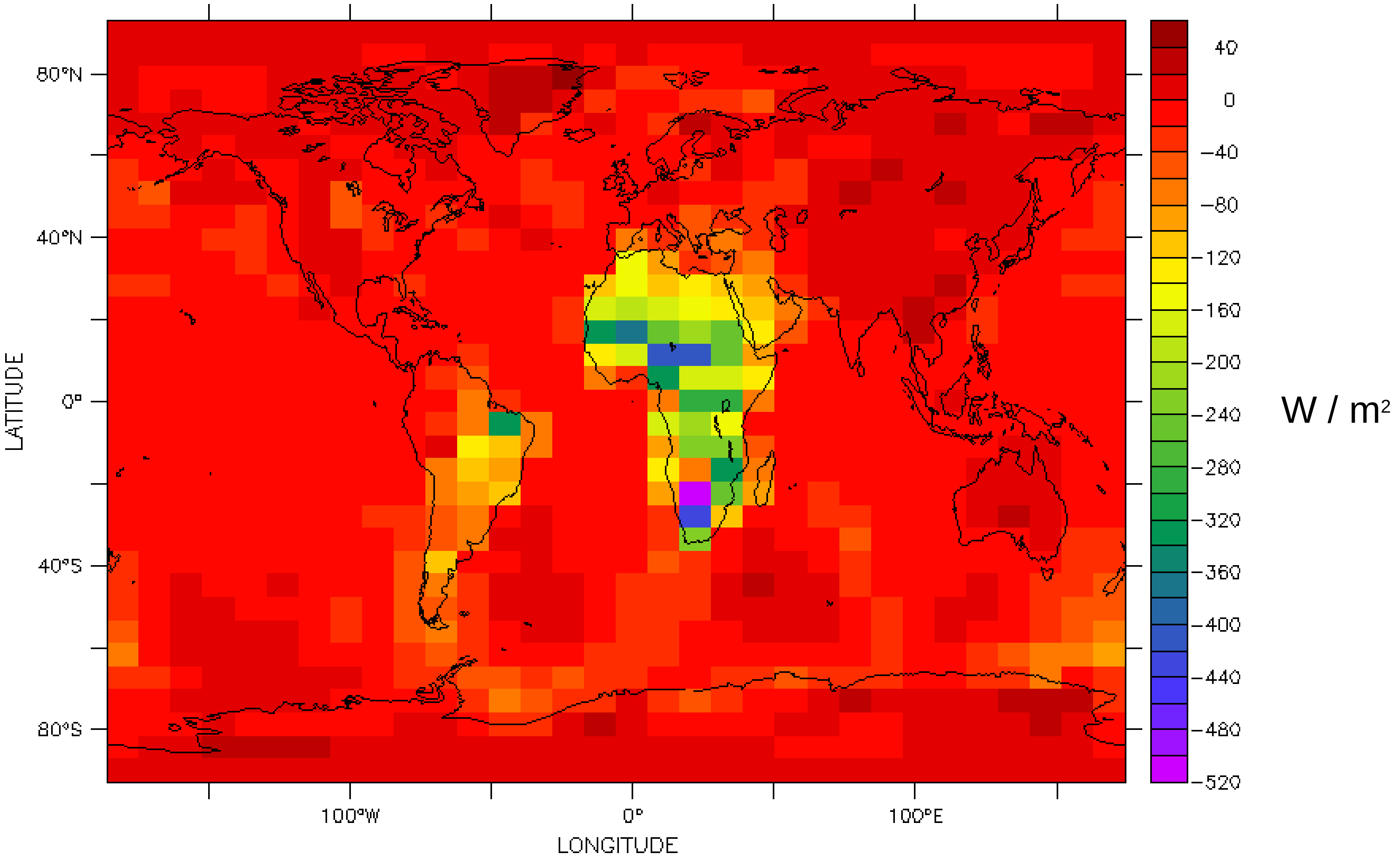
Practice

cd /LMDZ20181204.trunk/modipsl/modeles/LMDZ/BENCH32x32x39 ferret
> use histhf.nc
> shade/l=48 sens
> go land 1

Sensible heat flux at 12h GMT on January 2nd



Turbulent diffusion

Turbulent diffusion

- Turbulent diffusion or "turbulent mixing" : transport by small random movements. Similar to molecular diffusion.

$$Dq/Dt = S_q \quad \text{où} \quad S_q = \frac{\partial}{\partial z}(K_z \frac{\partial q}{\partial z})$$

Downgradient flux

- **Prandtl mixing length** : $K_z = l\ |w|$

  l : characteristic length of the small movements

  w : characteristic velocity

- **Turbulent kinetic energy (TKE)** : $K_z = l\ \sqrt{e}$

$$De/Dt = f(dU/dz, d\theta/dz, e, ...)$$
$$Dl/Dt = ...$$

Shear Bouyancy

Turbulent diffusion

Turbulent diffusion : numerics

Process : Turbulent mixing of moisture (q in kg/kg) and potential enthalpy ($H = C_p\theta$).

$$\left\{\begin{array}{lcl} \frac{dq}{dt} & = & \partial_z\phi_q \\ \phi_q & = & K_z\partial_z q \\ \phi_q|_{\mathrm{srf}} & = & -\mathrm{Evap} \end{array}\right. \qquad \left\{\begin{array}{lcl} \frac{dH}{dt} & = & \partial_z\phi_\theta \\ \phi_\theta & = & K_z\partial_z H \\ \phi_\theta|_{\mathrm{srf}} & = & \phi_{\mathrm{sens}}(\frac{p_0}{p_{\mathrm{srf}}})^\kappa \end{array}\right. \quad (3)$$

(Fluxes positive downward)

$H = C_pT+gz$ = Dry static energy , here conserved

Water (left) and energy (right) conservation Diffusion

(dowgradient flux)

Surface fluxes

Turbulent diffusion is the only one parameterization which « see » the surface

Spatial discretization : (moisture)

$$\left\{\begin{array}{lcl} m_i\partial_t q_i & = & \phi_{q,i+1} - \phi_{q,i} \\ \phi_{q,i} & = & K_i(q_i - q_{i-1}) \\ \phi_{q,1} & = & -\mathrm{Evap} \end{array}\right. \quad (4)$$

Implicit scheme, yields for the first atmospheric layer :

$$\begin{array}{c} q_{1,t+\delta t} = A + B\phi_{q,1}\delta t \\ \phi_{q,1} = K_1(q_{1,t+\delta t} - q_{\mathrm{srf}}) \end{array} \quad (5)$$

First atmospheric layer

A and B are cofficient resulting from solving Eq. (4) over the whole atmosphere.

Eqs. (5) are the mixed boundary conditions for the sub-surface model.

Turbulent diffusion

Turbulent diffusion : numerics

Process : Turbulent mixing of moisture (q in kg/kg) and potential enthalpy ($H = C_p\theta$).

$$\begin{cases} \frac{dq}{dt} = \partial_z \phi_q \\ \phi_q = K_z \partial_z q \\ \phi_q|_{srf} = -\text{Evap} \end{cases} \quad \begin{cases} \frac{dH}{dt} = \partial_z \phi_\theta \\ \phi_\theta = K_z \partial_z H \\ \phi_\theta|_{srf} = \phi_{sens}(\frac{p_0}{p_{srf}})^\kappa \end{cases} \quad \text{(Fluxes positive downward)} \tag{3}$$

Spatial discretization : (moisture)

$$\begin{cases} m_i \partial_t q_i = \phi_{q,i+1} - \phi_{q,i} \\ \phi_{q,i} = K_i(q_i - q_{i-1}) \\ \phi_{q,1} = -\text{Evap} \end{cases} \tag{4}$$

Implicit scheme, yields for the first atmospheric layer :

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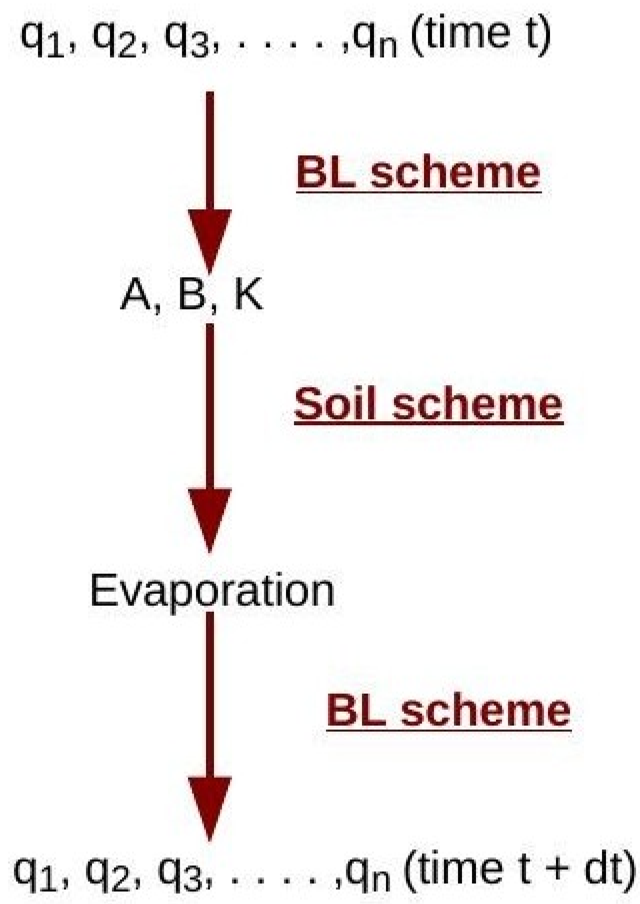


Turbulent diffusion : practice

Vertical diffusion

Subroutine : pbl_surface

Tendencies :

dtvdf, dqvdf, duvdf, dvvdf

Other variables

- sens : sensible heat flux at the surface (positive upward)
- evap : water vapour flux at the surface (positive upward)
- flat : latent heat flux at the surface (positive downward)
- taux, tauy : wind stress at the surface

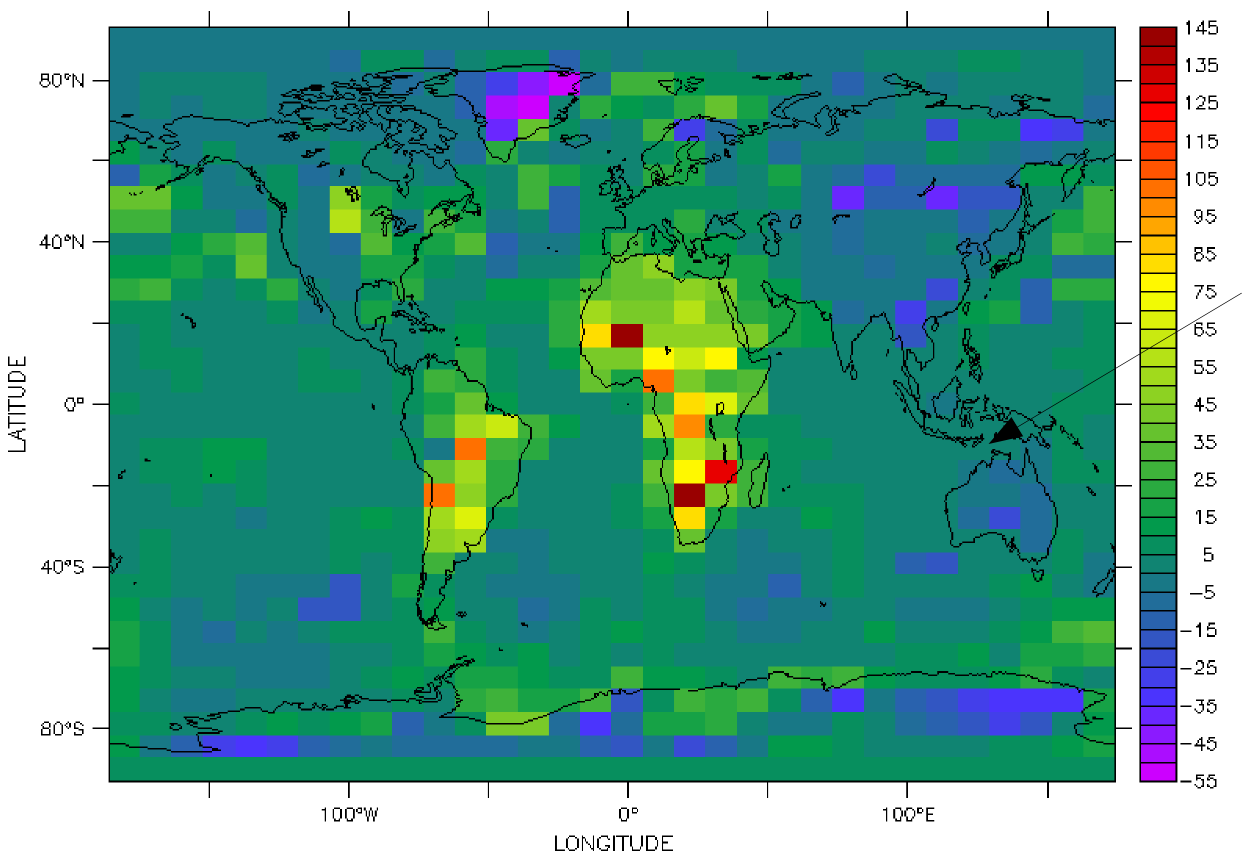
ferret

> use histhf.ns

> shade/l=48 dtvdf[k=@max]*86400

> go land 1

Then choose a relevant location like for example :
x=20/y=-10



DTVDF*86400

1D case study
TWP-ICE

→ My plots in the following

Turbulent diffusion : practice

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ferret

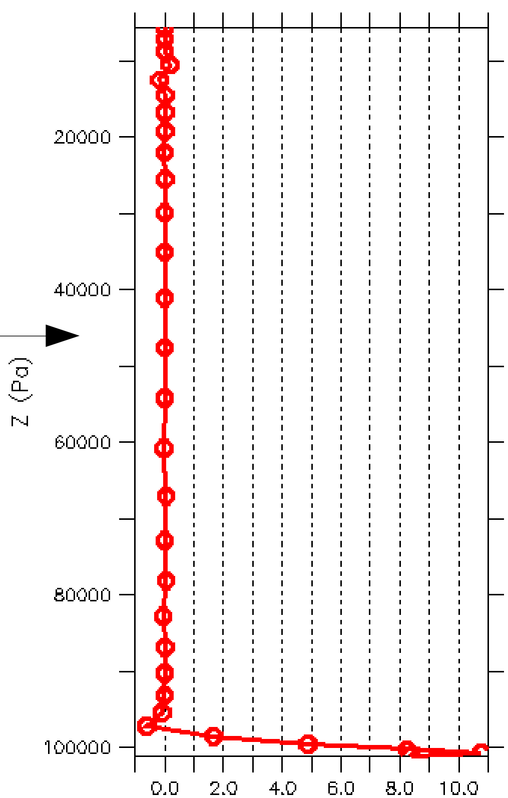
> use histhf.nc

>plot/l=48/thick=3/x=…/y=…/k=10:39 dtvdf*86400

>plot/l=48/thick=3/x=…/y=.../k=10:39 dqvdf*86400*1000

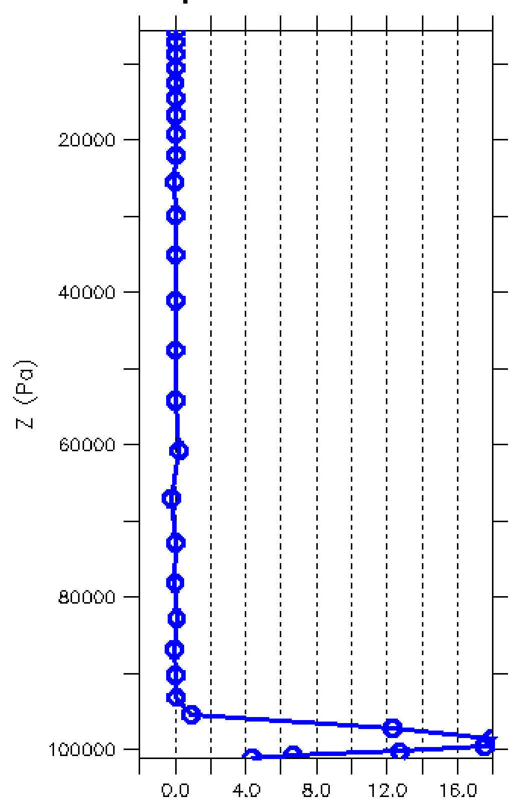
TWPICE case

dtvdf*86400



K/day

dqvdf*86400*1000



g/(kg.day)

Turbulent diffusion : practice

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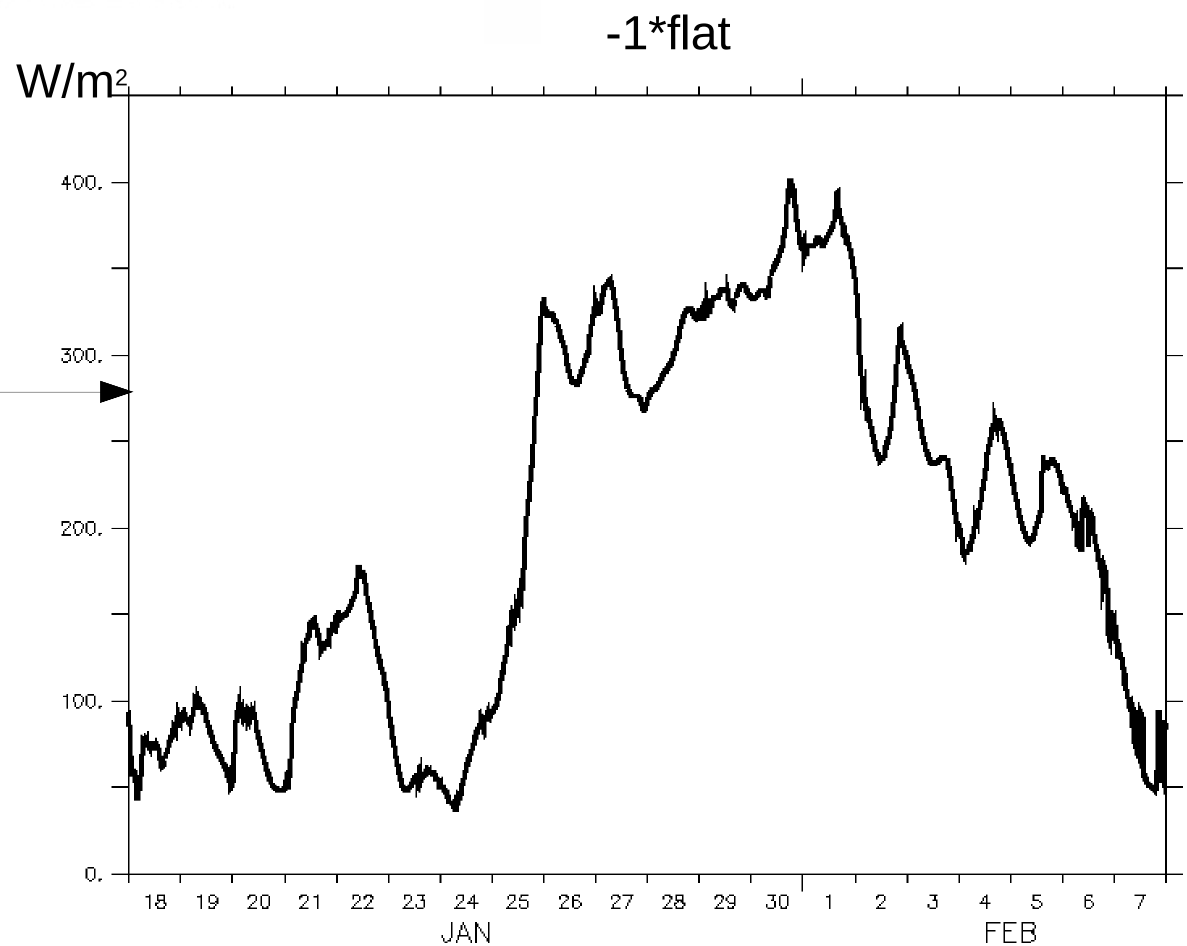
ferret

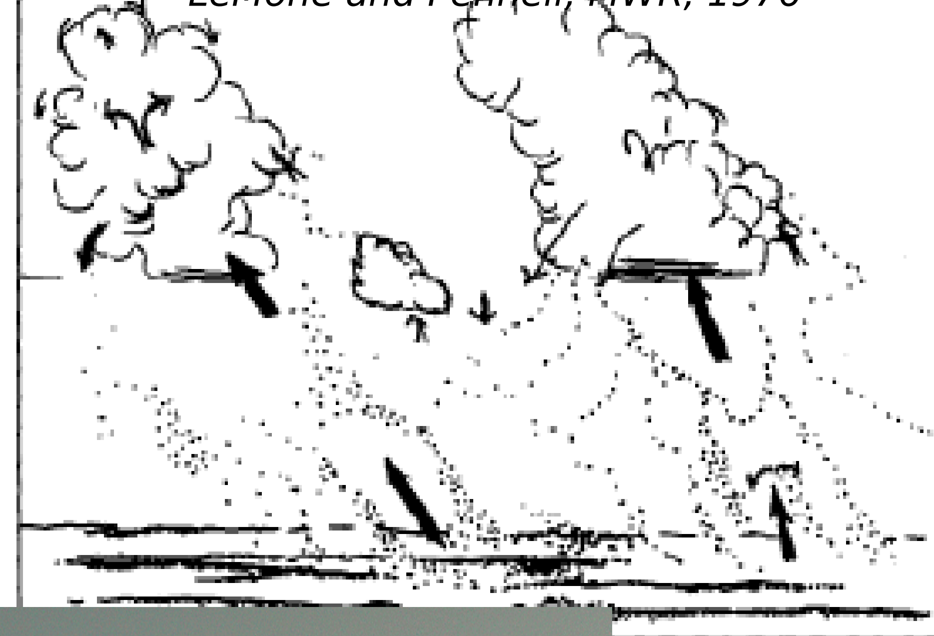
> use histhf.nc

> plot/thick=3/x=…/y=… -1*flat

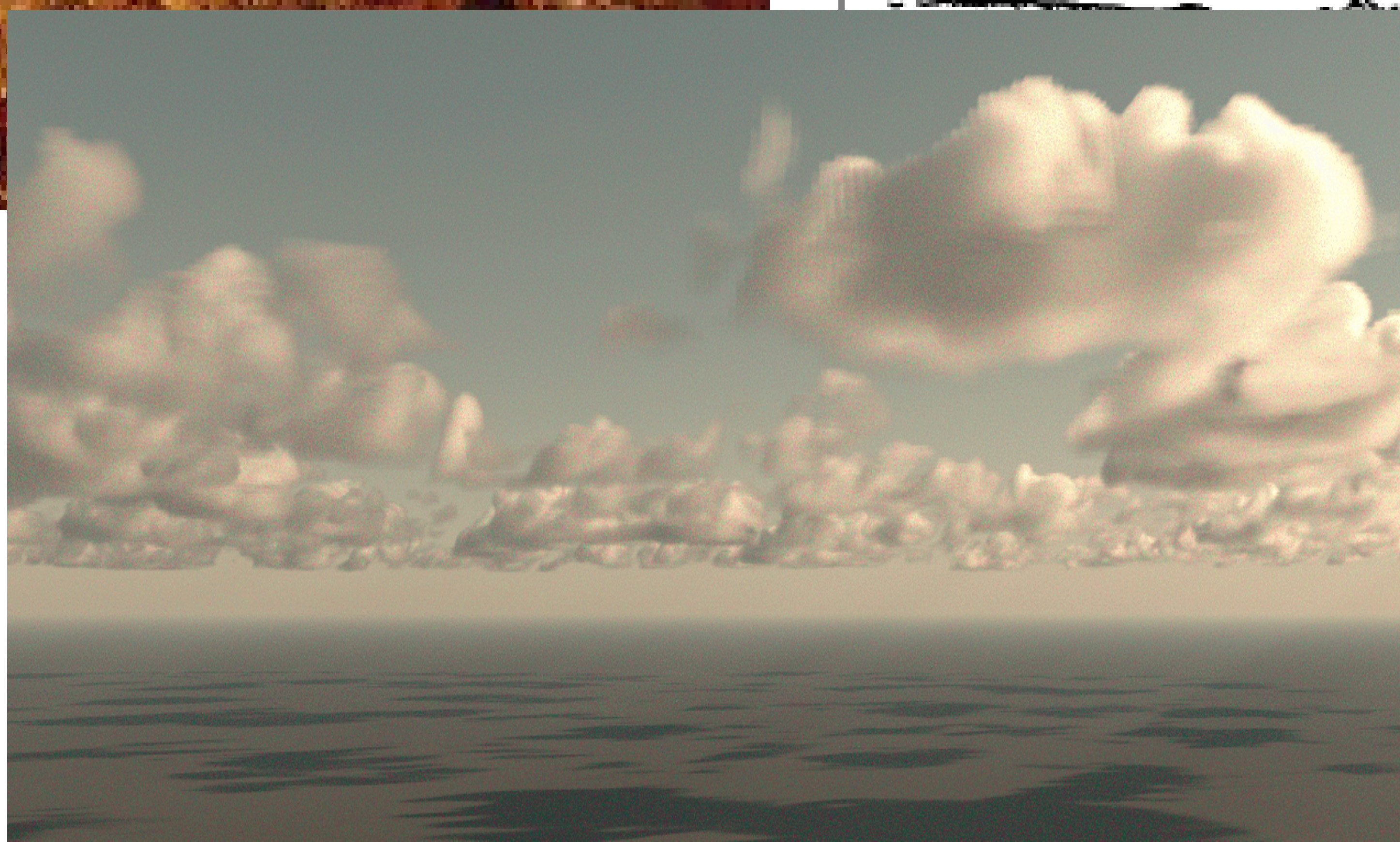
> plot/thick=3/x=…/y=… -1*sens

TWPICE case



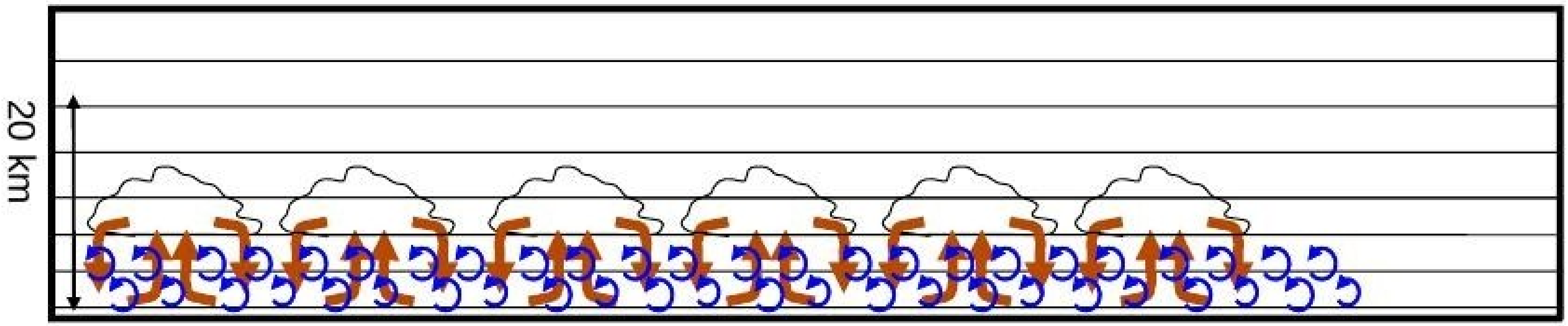


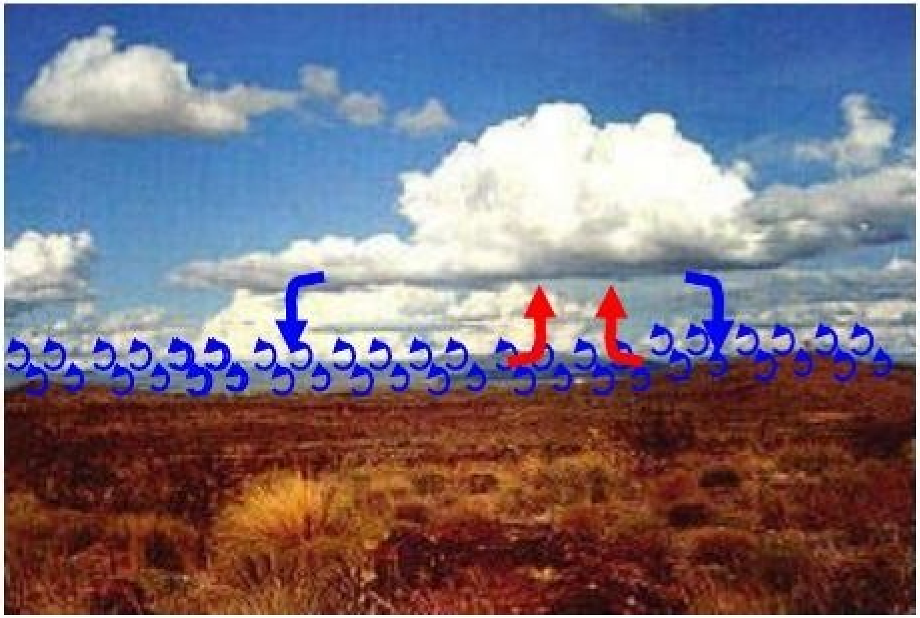
LeMone and Pennell; MWR, 1976



Thermals

In a model column there are structures
of boundary layer scale

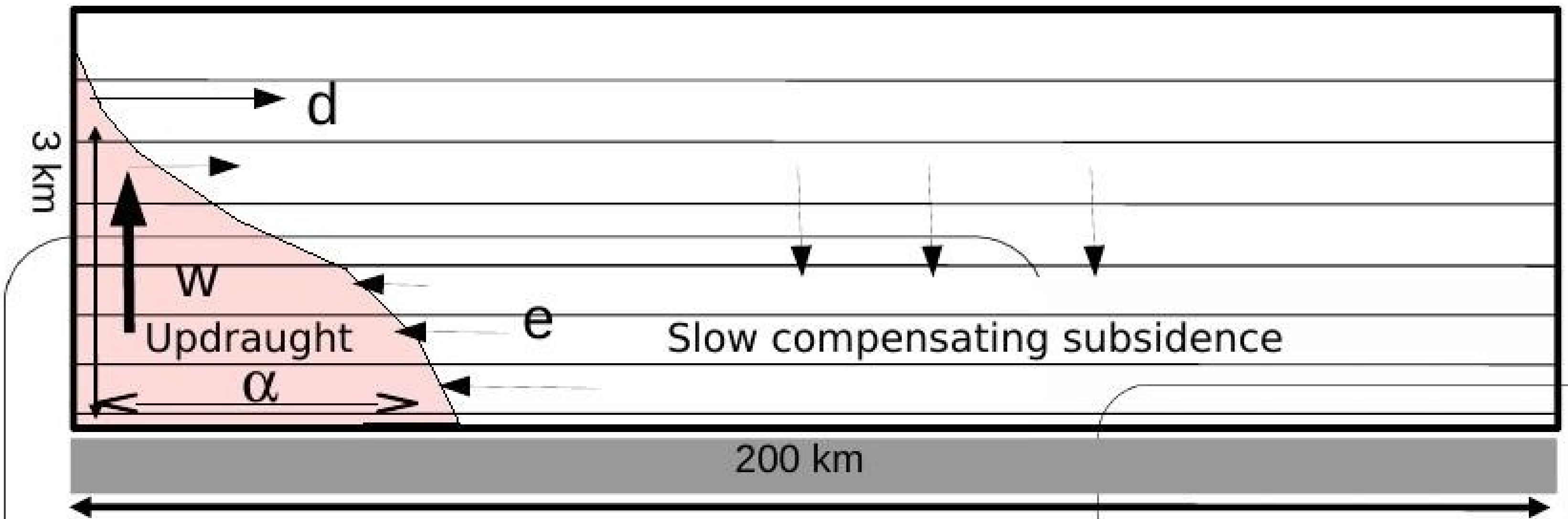




"The Thermal Model":
Each column is split in two parts: Ascending air from the surface and subsiding air around it.

The model represents a mean plume (the thermal) and a mean cloud.

Thermals



Internal variables of the parametrization :

- w = mean vertical velocity of ascending plumes
- α = fractionnal area covered by the updraughts
- e = lateral input rate of air into the plume (entrainment)
- d = output rate of air from the plume (detrainment)
- q_a = concentration of constituant q in the updraughts

Source term for the explicit equations :

$$S_q = -\frac{1}{\rho}\frac{\partial}{\partial z}\overline{\rho w' q'} = \frac{1}{\rho}\frac{\partial}{\partial z}\left[\rho K_z \frac{\partial q}{\partial z}\right] - \frac{1}{\rho}\frac{\partial}{\partial z}[f(q_a - q)]$$

Turbulent Diffusion

Transport by the thermal plume model

- **Mass conservation**

$$\frac{\partial f}{\partial z} = e - d \quad \text{where} \quad f = \alpha \rho w$$

- **Mass conservation of constituent q**

$$\frac{\partial f q_a}{\partial z} = eq - dq_a$$

- **Equation of movement**

$$\frac{\partial f w}{\partial z} = -dw + \alpha \rho B$$

- **where B is the buoyancy :**

$$B = g\frac{\theta_{va} - \theta_v}{\theta_v}$$

- **and the complex part lies in the expression of e and d :**

$$e = f\, max\left(0, \frac{\beta}{1+\beta}\left(a_1 \frac{B}{w^2} - b\right)\right)$$

$$d = \ldots$$

Etc ...

Thermals : practice

Thermals and dry adjustment

Subroutine : calltherm

Tendencies :

dtthe, dqthe,duthe, dvthe

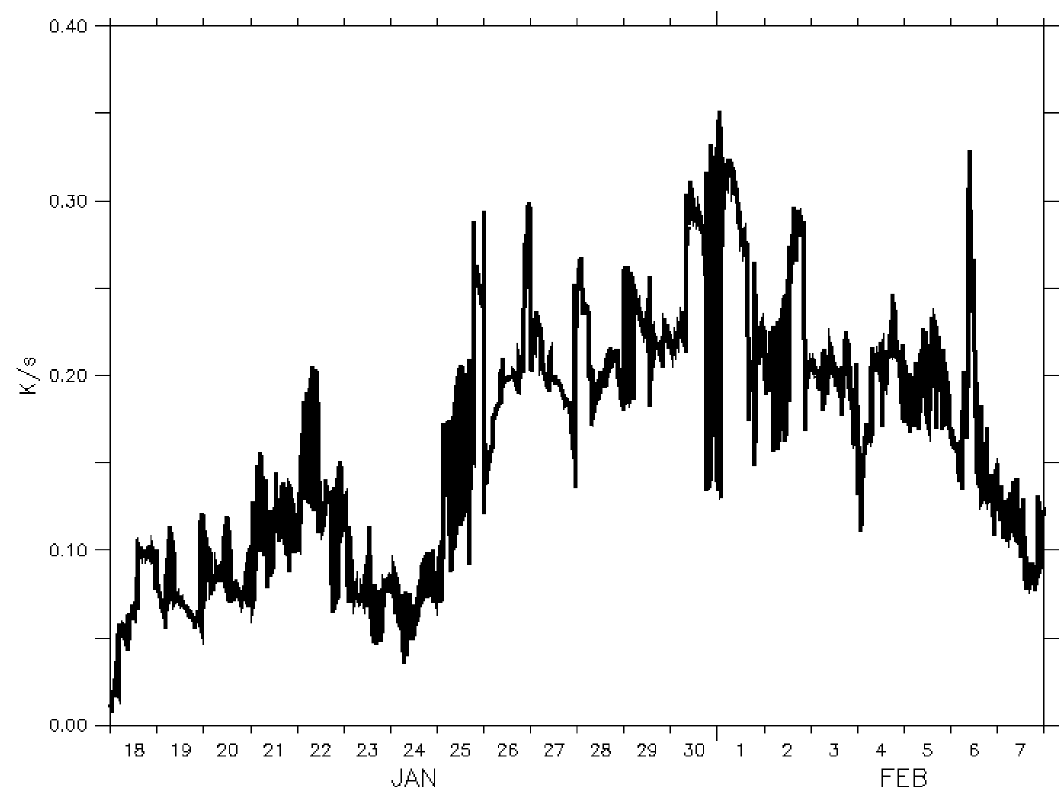
Other variables

- dtajs : temperature tendency due to the sole dry adjustment
- dqajs : humidity tendency due to the sole dry adjustment
- a_th : fractional area of thermal plumes
- d_th : detrainment
- e_th : entrainment
- f_th : mass flux
- w_th : vertical velocity in the thermal plume (m/s, positive upward)
- q_th : total water content in the thermal plume
- zmax_th : altitude of the top of the thermal plume (m)
- f0_th : Thermal closure mass flux (kg/m².s)

TWPICE case

ferret
> use histhf.nc
> plot/thick=3/x=…/y=… f0_th

f0_th



Thermal closure mass flux (K/s) kg/(m².s)

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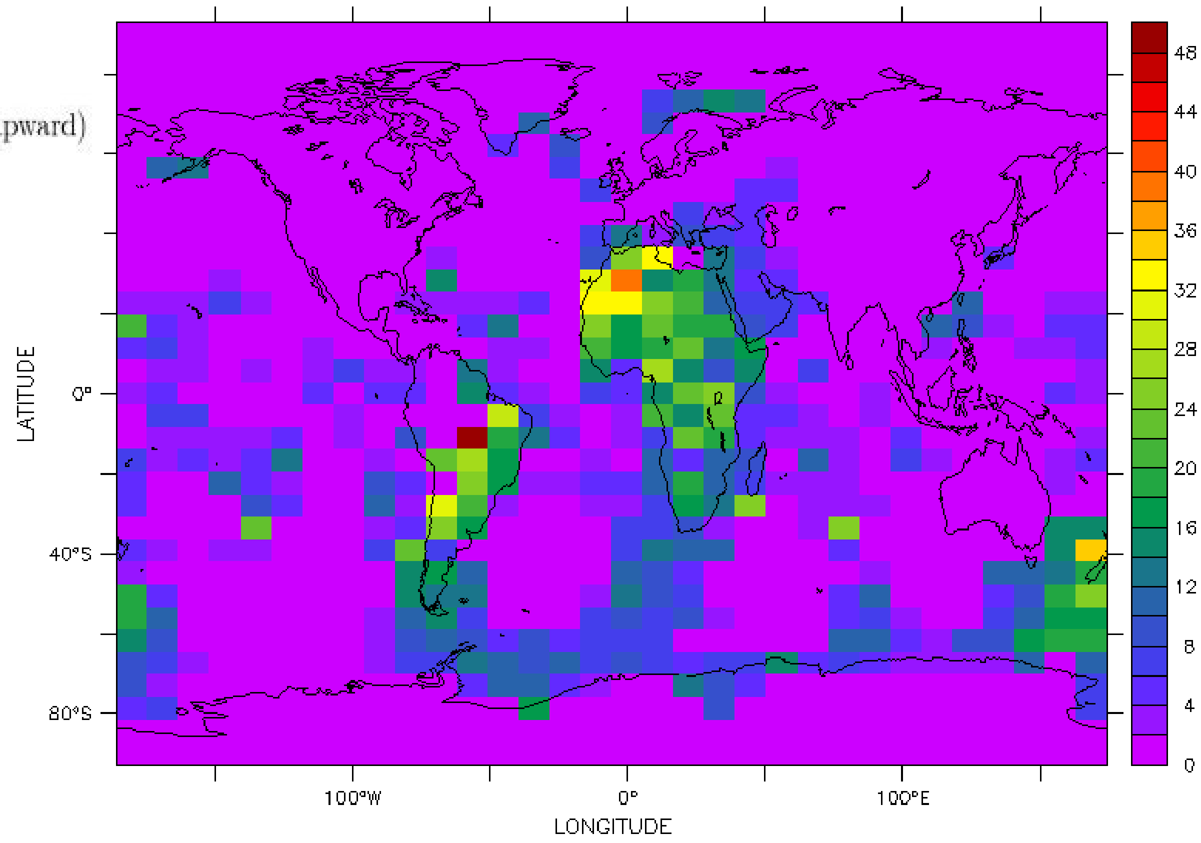
> shade/l=48 dtthe[k=@max]*86400
> go land 1



DTTHE[K=@MAX]*86400

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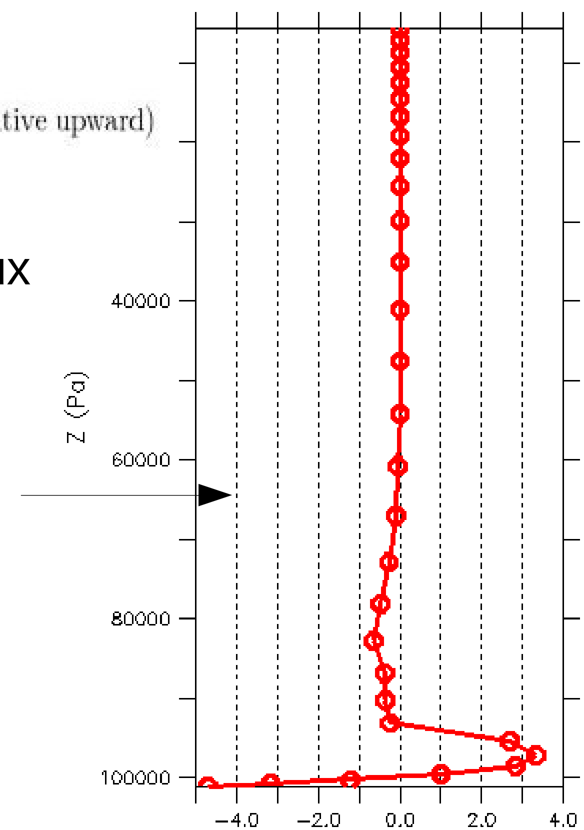
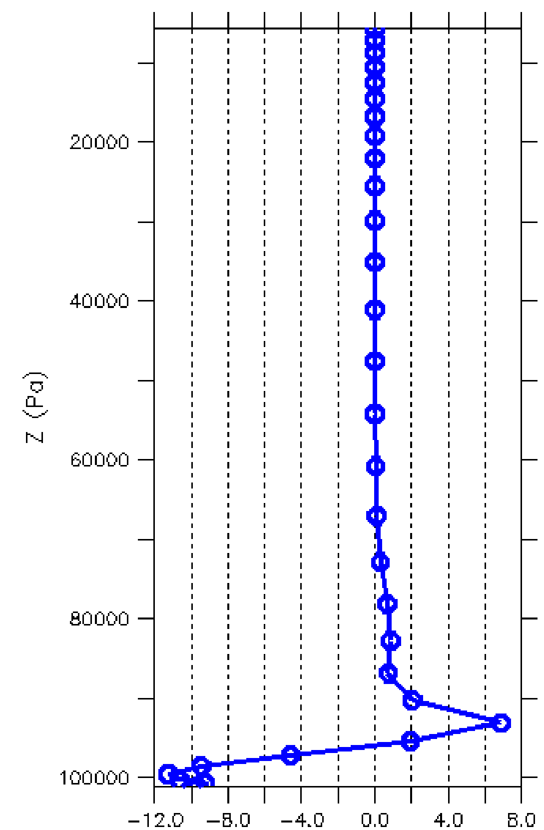
dtthe*86400



K/day

dqthe*86400*1000



g/(kg.day)

Large scale condensation & evaporation

Représentation des nuages

q : concentration en vapeur d'eau

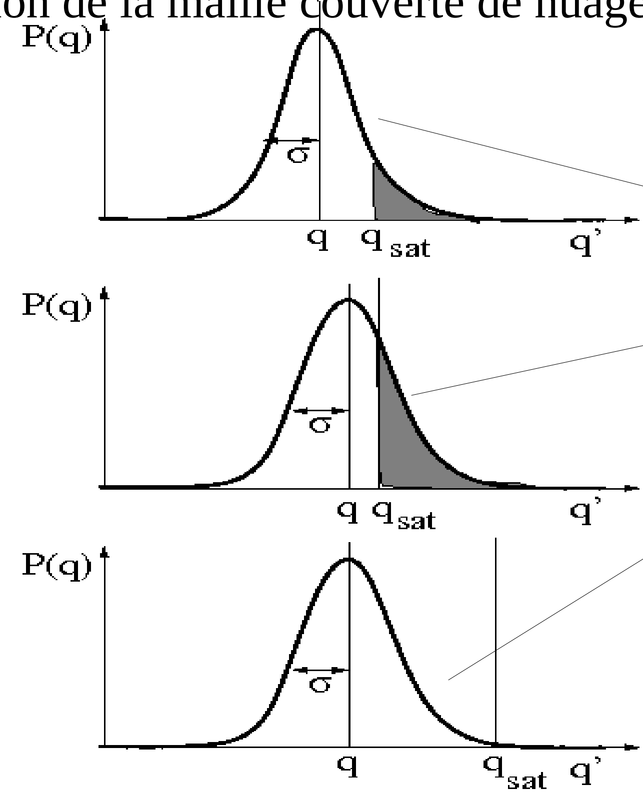
q_{sat} : concentration maximum à saturation

Si $q > q_{sat}$:

→ la vapeur d'eau condense = nuage

On connait q et q_{sat} à l'échelle de la maille

→ Fraction de la maille couverte de nuages ?



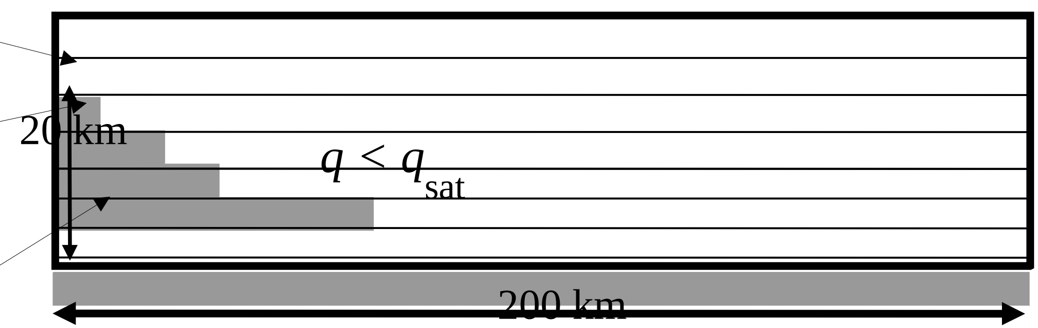
Paramétrisation simple : gaussienne σ / q = 20%

Modèle « tout ou rien » :

Si $q > q_{sat}$ maille nuageuse, sinon ciel clair.

Modèle « statistique » :

On suppose une distribution statistique de q' dans la maille autour de q



Intervient dans ***Q***

→ condensation

→ prise en compte des nuages dans le code radiatifs

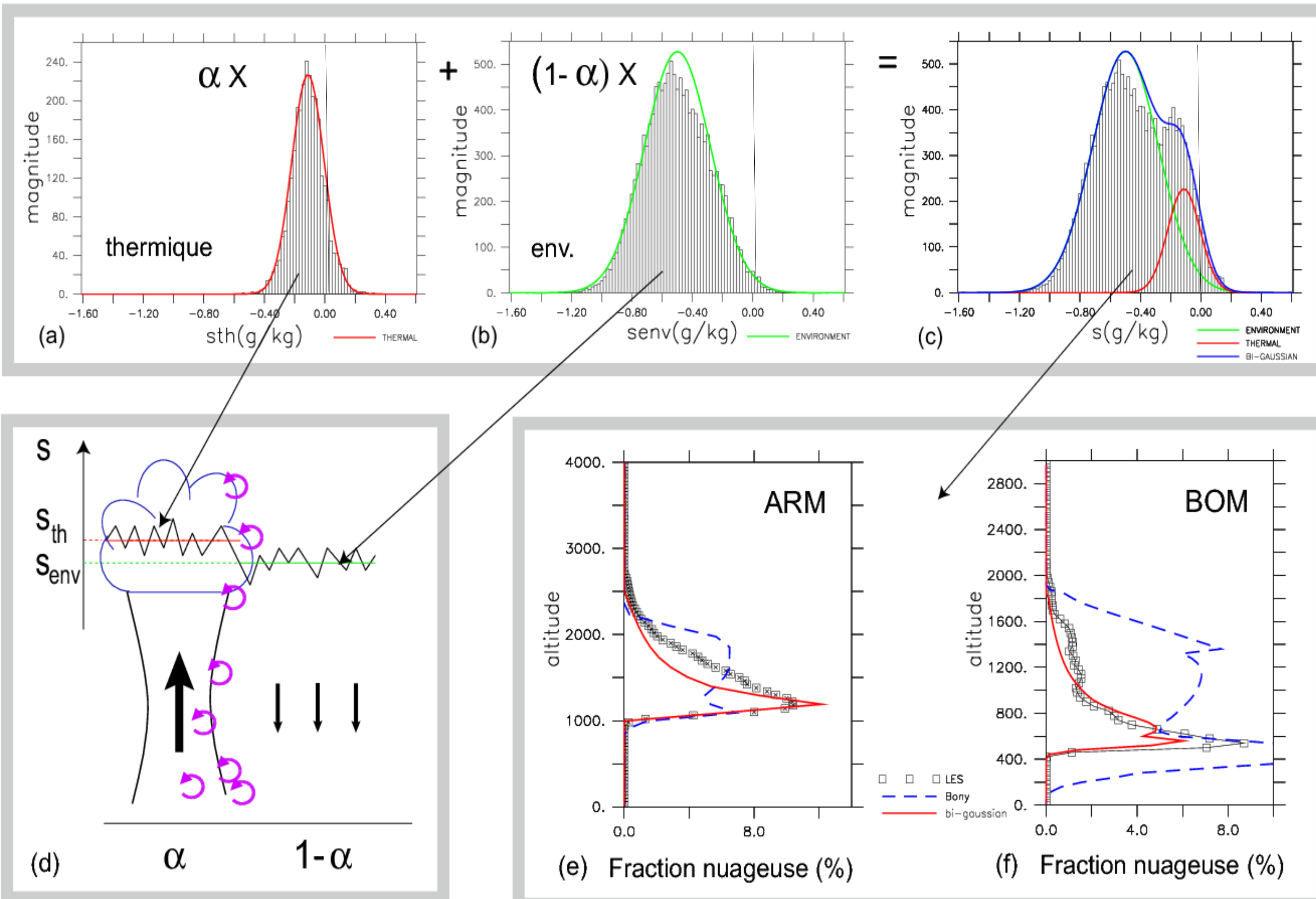
Large scale condensation & evaporation

Nouvelle paramétrisation de nuages couplée aux thermiques :

Utilisation d'une PDF bi-gaussienne pour la distribution d'eau totale sous nuageuse

Une gaussienne pour les panaches thermiques et une pour l'environnement

Comparaison des distributions prédites par ce schéma avec les distributions des LES



Large scale condensation & evaporation : practice

Large scale condensation (evap & lsc)

Subroutines : reevap & fisrtilp

Tendencies :

dteva, dqeva : tendencies due to cloud water evaporation

dtlsc, dqlsc : tendencies due to cloud water condensation

Total tendencies are the sums of the evaporation and condensation tendencies.

Other variables

- plul : so called "large scale" or "stratiform" precipitation ; encompasses both stratiform precipitation and boundary layer cumulus precipitation.
- rneb : cloud cover
- pr_lsc_l : vertical profile of large scale liquid precipitation
- pr_lsc_i : vertical profile of large scale ice precipitation

```
ferret
> use histhf.ns
> shade/l=48 dtlsc[k=@max]*86400
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```
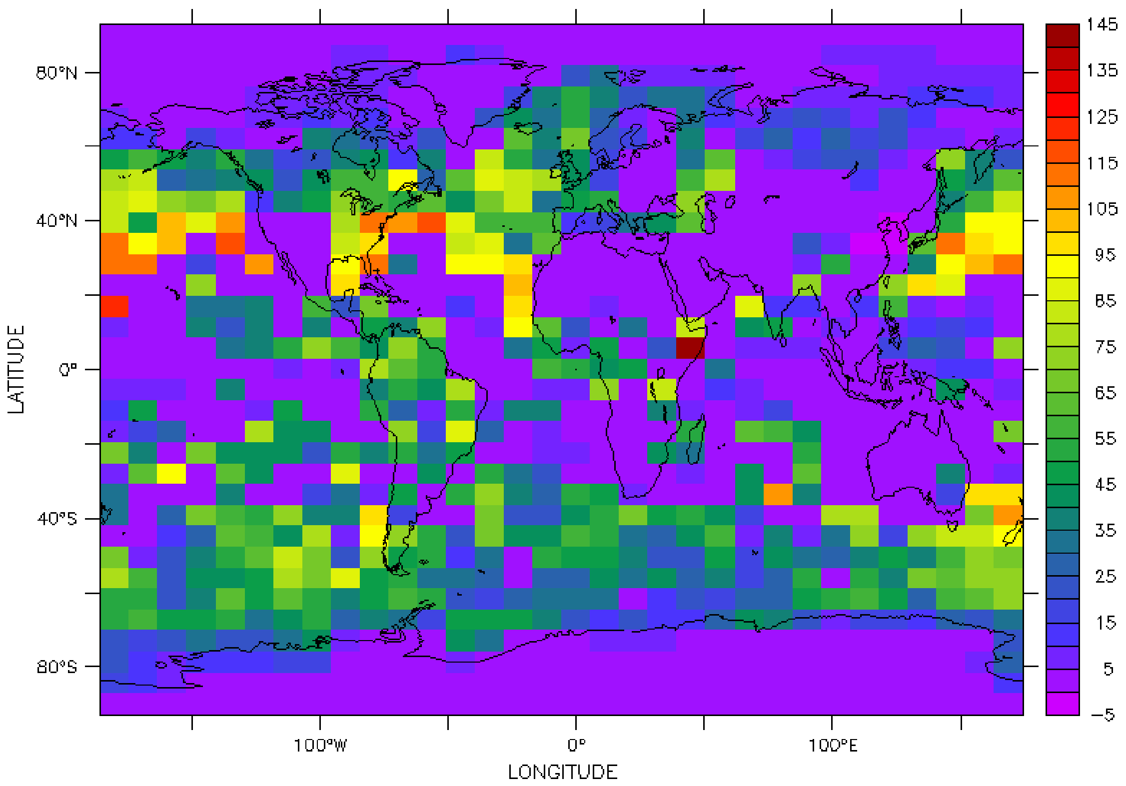
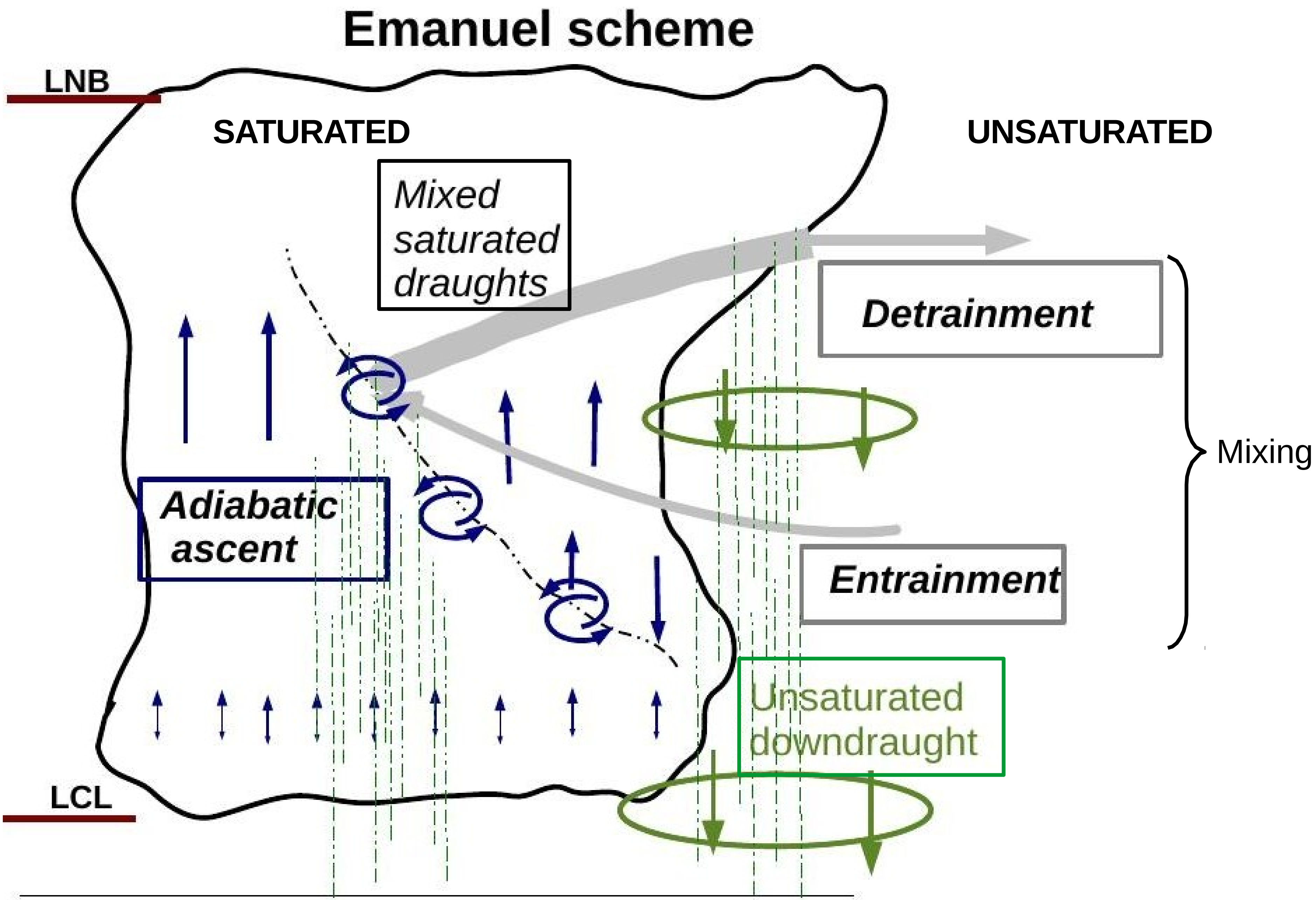



DTLSC[K=@MAX]*86400+DTEVA[K=@MAX]*86400

Deep convection : Emanuel scheme



Deep convection : practice

Deep convection

Subroutine : concvl

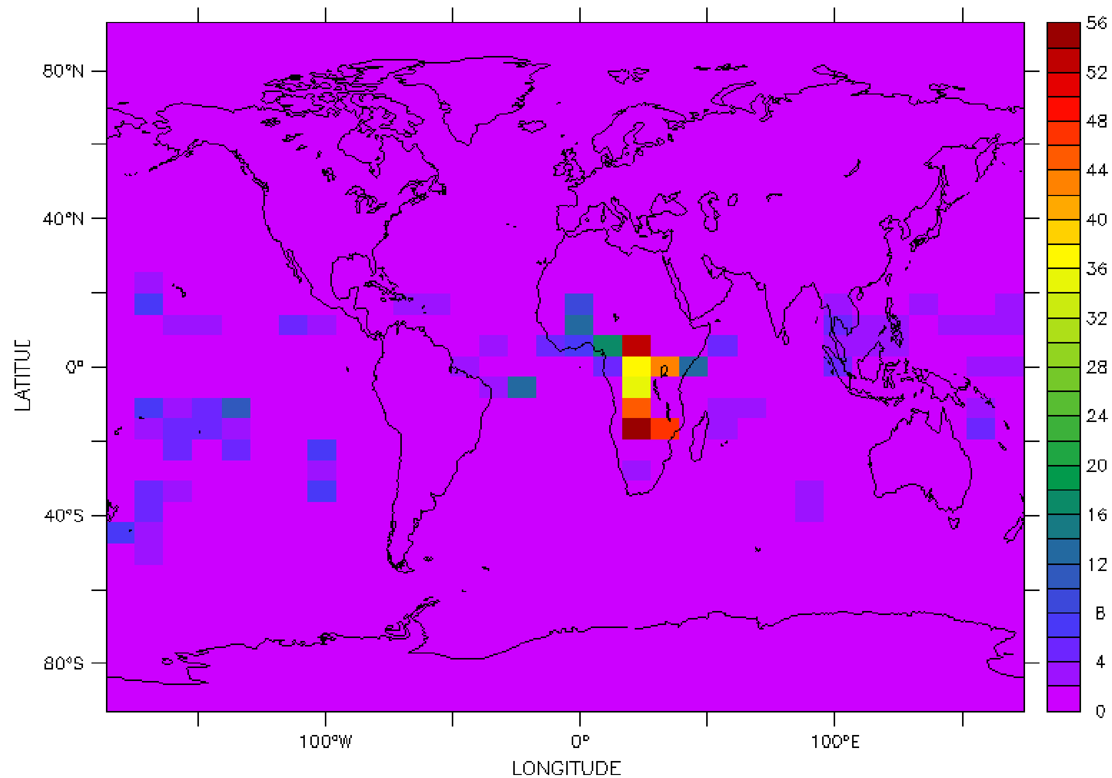
Tendencies :

dtcon, dqcon, ducon, dvcon

Other variables

- pluc : convective precipitation at the surface
- ftd : temperature tendency due to the sole unsaturated downdraughts
- fqd : moisture tendency due to the sole unsaturated downdraughts
- clwcon : condensed water of convective clouds ("in cloud" condensed water content)
- Ma : mass flux of the adiabatic ascent
- upwd : mass flux of the saturated updraughts
- dnwd : mass flux of the saturated downdraughts
- dnwd0 : mass flux of the unsaturated downdraught (precipitating downdraught)
- pr_con_l : vertical profile of convective liquid precipitation
- pr_con_i : vertical profile of convective ice precipitation

```
ferret
> use histhf.ns
> shade/l=48 dtcon[k=@max]*86400
> go land 1
```



DTCON[K=@MAX]*86400

Deep convection : practice

Deep convection

Subroutine : concvl

Tendencies :

dtcon, dqcon, ducon, dvcon

Other variables

- pluc : convective precipitation at the surface
- ftd : temperature tendency due to the sole unsaturated downdraughts
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ferret

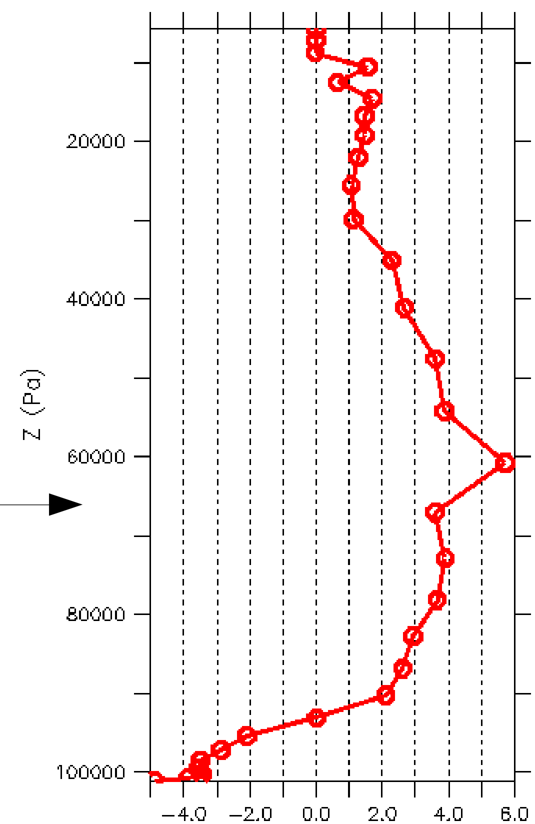
> use histhf.nc

>plot/l=48/thick=3/x=…/y=…/k=10:39 dtcon*86400

>plot/l=48/thick=3/x=…/y=.../k=10:39 dqcon*86400*1000

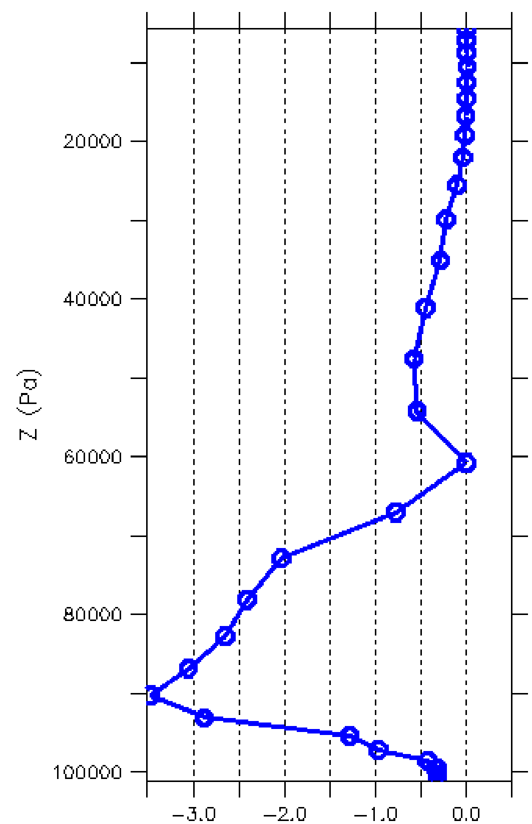
TWPICE case →

dtcon*86400



K/day

dqcon*86400*1000



g/(kg.day)

Deep convection : practice

Deep convection

Subroutine : concvl

Tendencies :

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Other variables

- pluc : convective precipitation at the surface
- ftd : temperature tendency due to the sole unsaturated downdraughts
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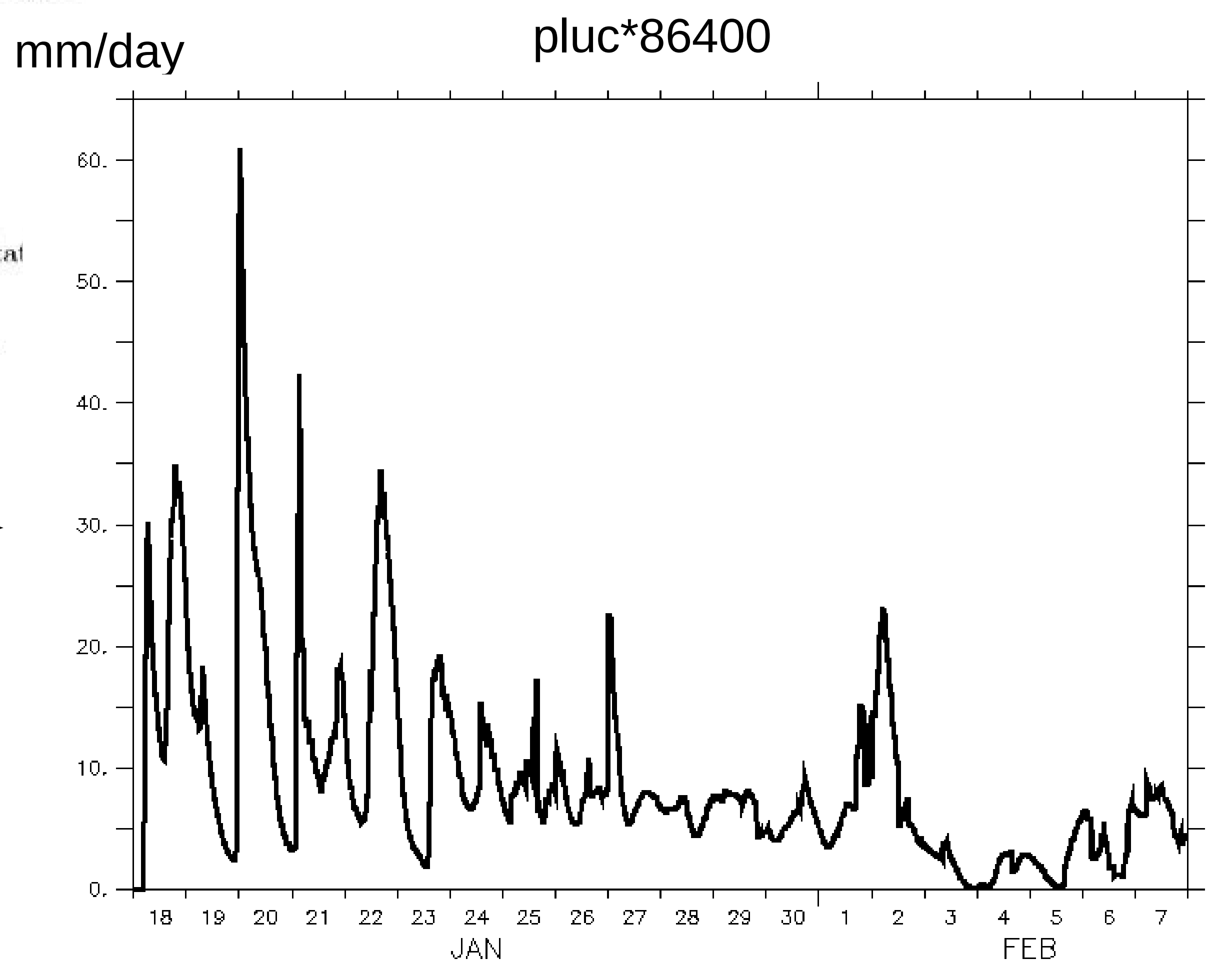
- dnwd0 : mass flux of the unsaturated downdraught (precipitat downdraught)
- pr_con_l : vertical profile of convective liquid precipitation
- pr_con_i : vertical profile of convective ice precipitation

ferret
> use histhf.nc
> plot/thick=3/x=…/y=… pluc*86400

TWPICE case →

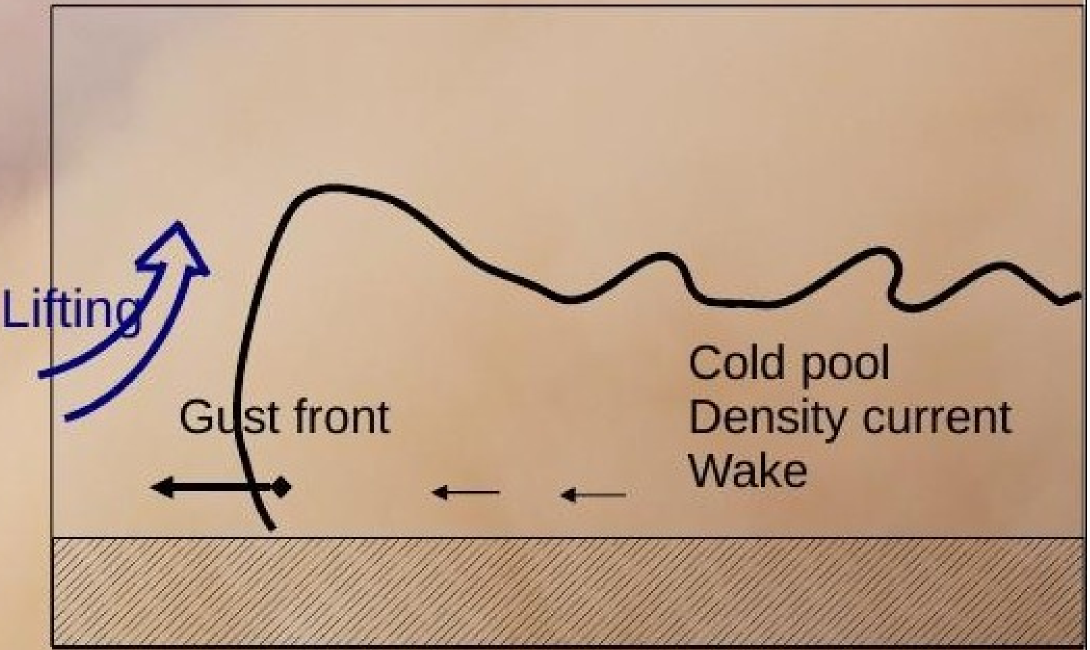


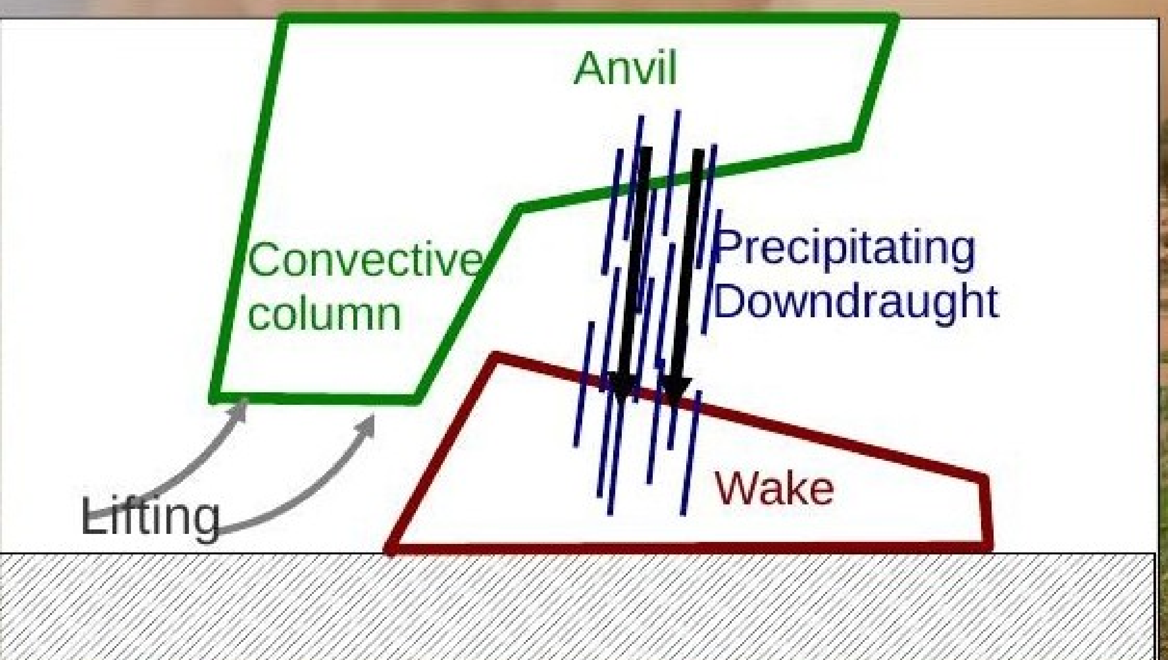
What drives deep convection : triggering and closure

Triggering

ALE = Available Lifting Energy $ALE = 0.5\, W_{max,PBL}^2$

Triggering criteria if ALE > |CIN| then Emanuel scheme is activated





Closure

ALP = Available Lifting Power $ALP = 0.5\, s\, W_{PBL}^3$

Cloud base mass flux $M_b = f\,(ALP)$

Mali, August 2004
F. Guichard, L. Kergoat

What drives deep convection : triggering and closure

Deep convection

Subroutine : concvl

Tendencies :

dtcon, dqcon, ducon, dvcon

Other variables

- pluc : convective precipitation at the surface
- ftd : temperature tendency due to the sole unsaturated downdraughts
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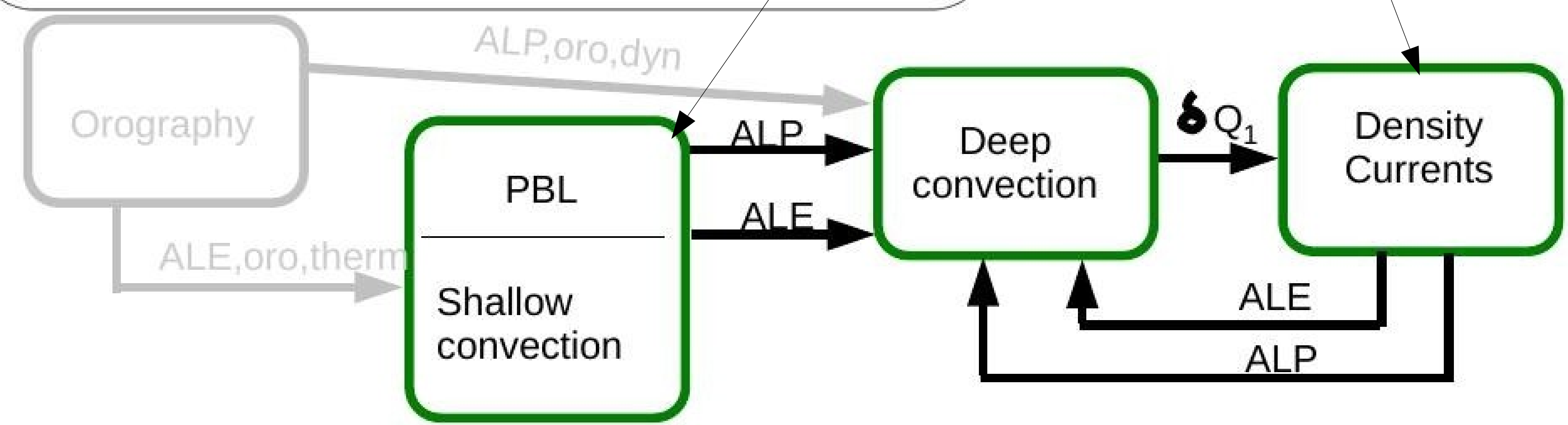
- pr_con_l : vertical profile of convective liquid precipitation
- pr_con_i : vertical profile of convective ice precipitation

The deep convection scheme is then coupled to 2 PBL processes :

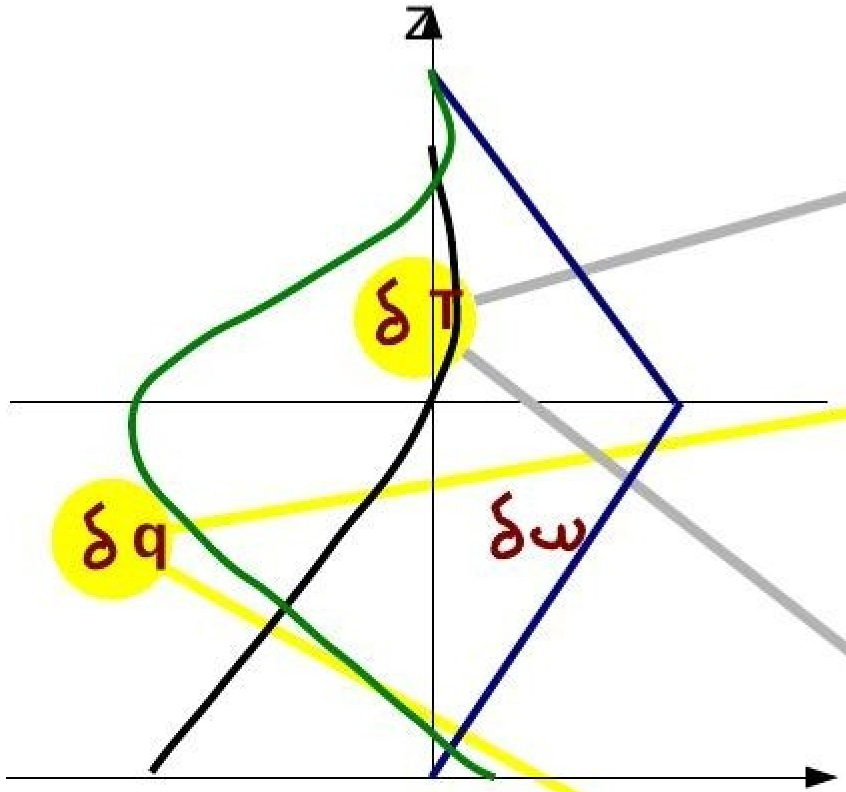
1. Thermals

2.Density currents (or wakes or cold pools)

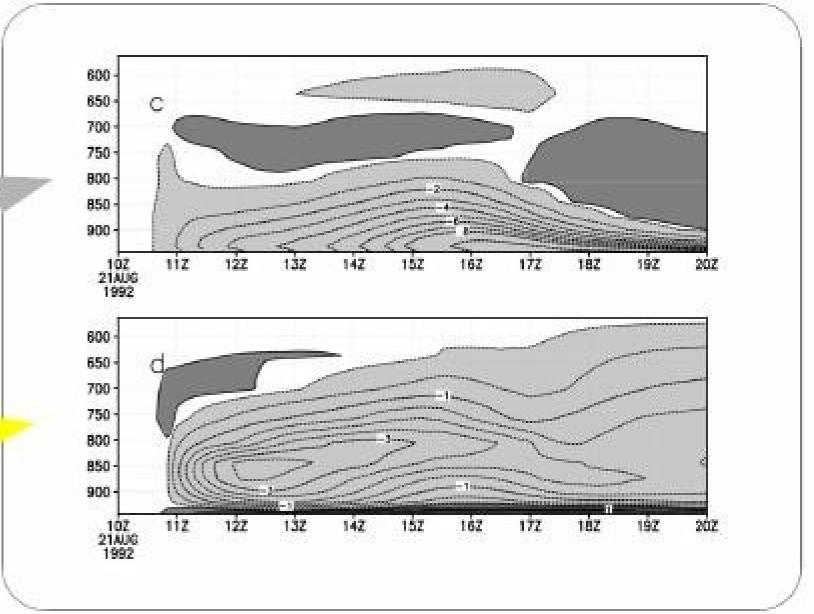


Density currents

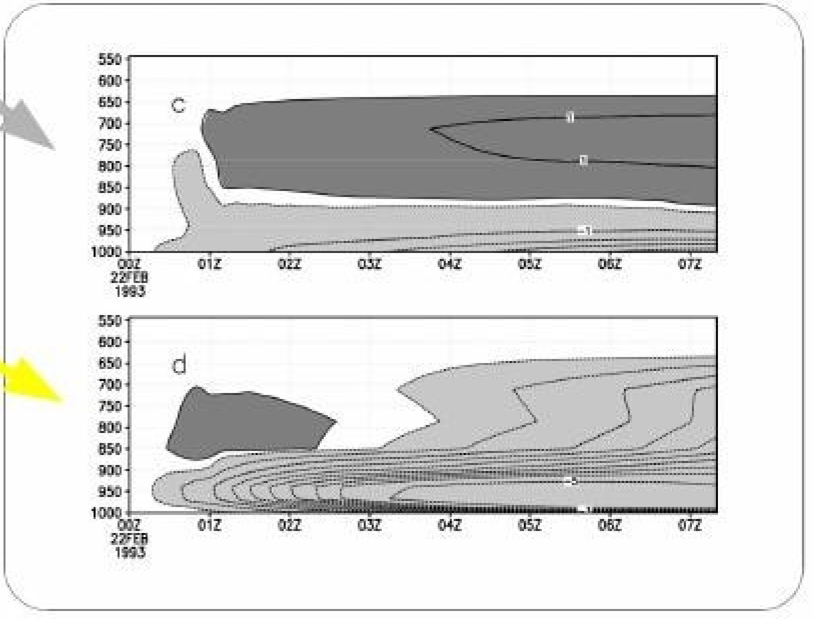
Simulated wake properties



HAPEX92: 21 Aug 1992 squall line case



TOGA-COARE: 22 Feb 1993 squall line ca



Prognostic variables expressed like this :

Delta A = A_w - A_x

Density currents : practice

Cold pools (wakes)

Subroutine : calwake

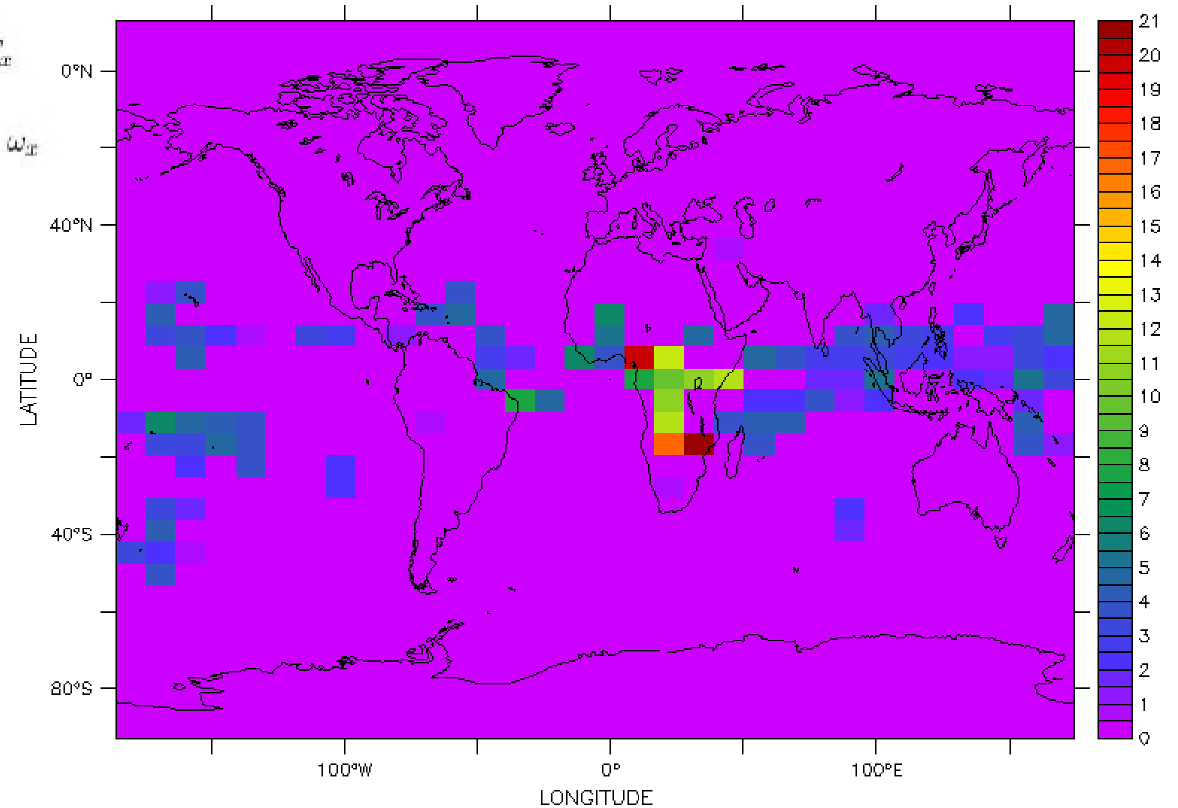
Tendencies :

dtwak, dqwak

Other variables

- Alp_wk : lifting power due to cold pools
- Ale_wk : lifting energy due to cold pools
- wake_s : fractional area of cold pools
- wake_h : cold pool height
- wape : WAke Potential Energy
- wake_deltat : vertical profile of temperature difference $T_w - T_x$
- wake_deltaq : vertical profile of humidity difference $q_w - q_x$
- wake_omg : vertical profile of vertical velocity difference $\omega_w - \omega_x$

```
ferret
> use histhf.ns
> shade/l=48 dtwak[k=@max]*86400
> go land 1
```



DTWAK[K=@MAX]*86400

Density currents : practice

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Subroutine : calwake

Tendencies :

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ferret

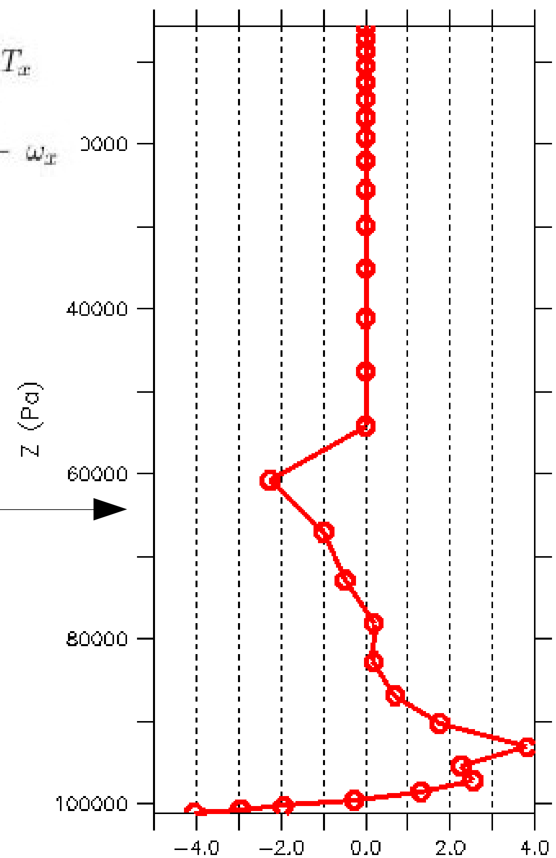
> use histhf.nc

>plot/l=48/thick=3/x=…/y=…/k=10:39 dtwak*86400

>plot/l=48/thick=3/x=…/y=…/k=10:39 dqwak*86400*1000

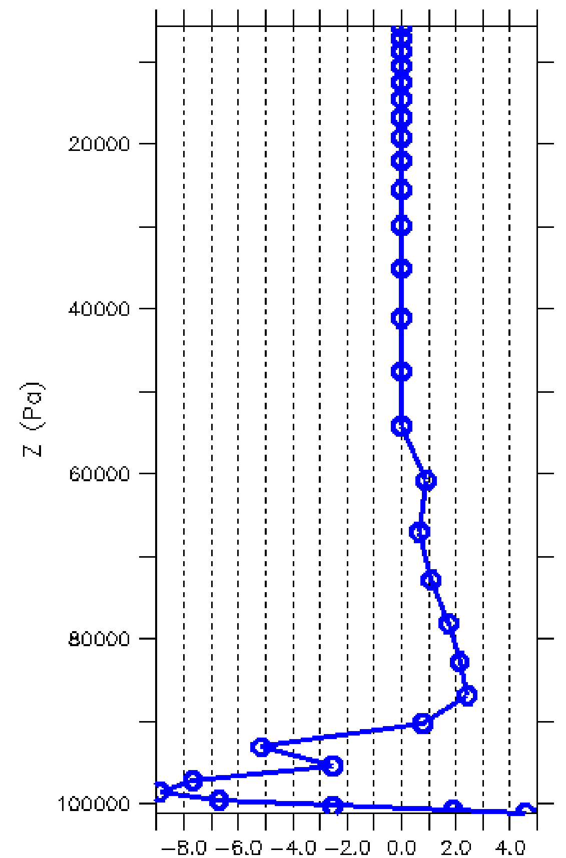
TWPICE case →

dtwak*86400



K/day

dqwak*86400*1000



g/(kg.day)

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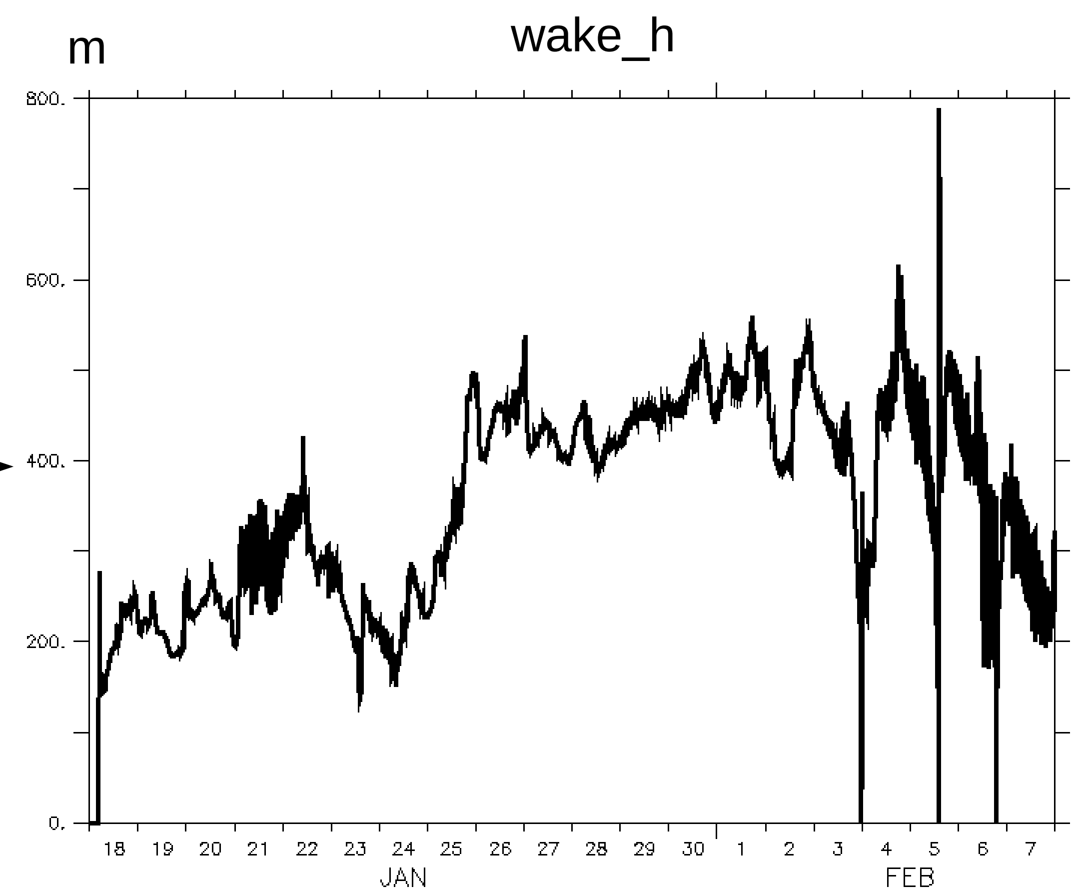
ferret
> use histhf.nc
> plot/thick=3/x=…/y=… wake_h

TWPICE case →



Large scale condensation & evaporation : practice

Large scale condensation (evap & lsc)

Subroutines : reevap & fisrtilp

Tendencies :

dteva, dqeva : tendencies due to cloud water evaporation

dtlsc, dqlsc : tendencies due to cloud water condensation

Total tendencies are the sums of the evaporation and condensation tendencies.

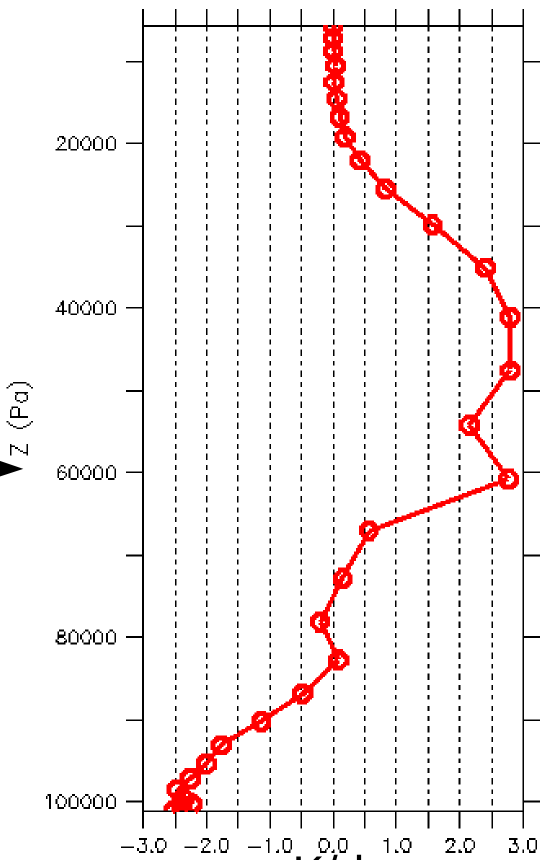
Other variables

- plul : so called "large scale" or "stratiform" precipitation ; encompasses both stratiform precipitation and boundary layer cumulus precipitatic
- rneb : cloud cover
- pr_lsc_l : vertical profile of large scale liquid precipitation
- pr_lsc_i : vertical profile of large scale ice precipitation

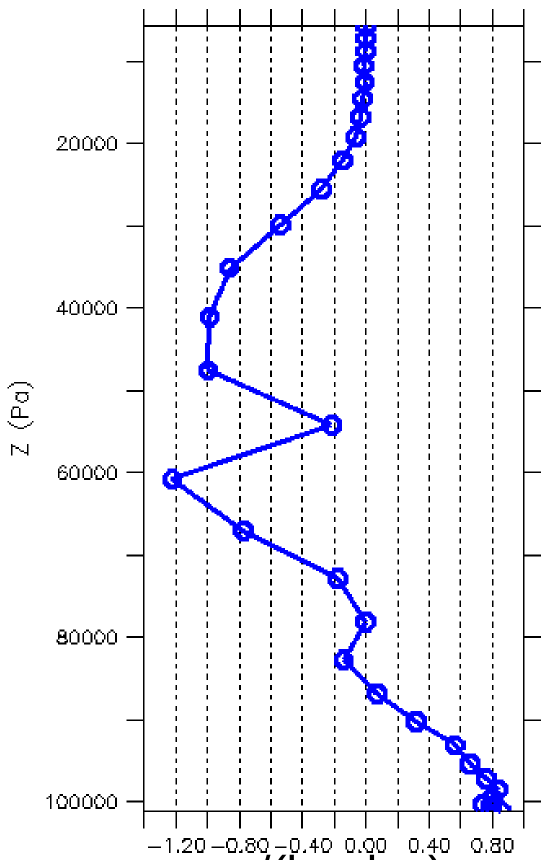
ferret
> use histhf.nc
>plot/l=48/thick=3/x=…/y=…/k=10:39 (dtlsc+dteva)*86400
>plot/l=48/thick=3/x=…/y=.../k=10:39 (dqlsc+dqeva)*86400*1000

TWPICE case

(dtlsc+dteva)* 86400



(dqlsc+dqeva) *86400*1000



Large scale condensation & evaporation : practice

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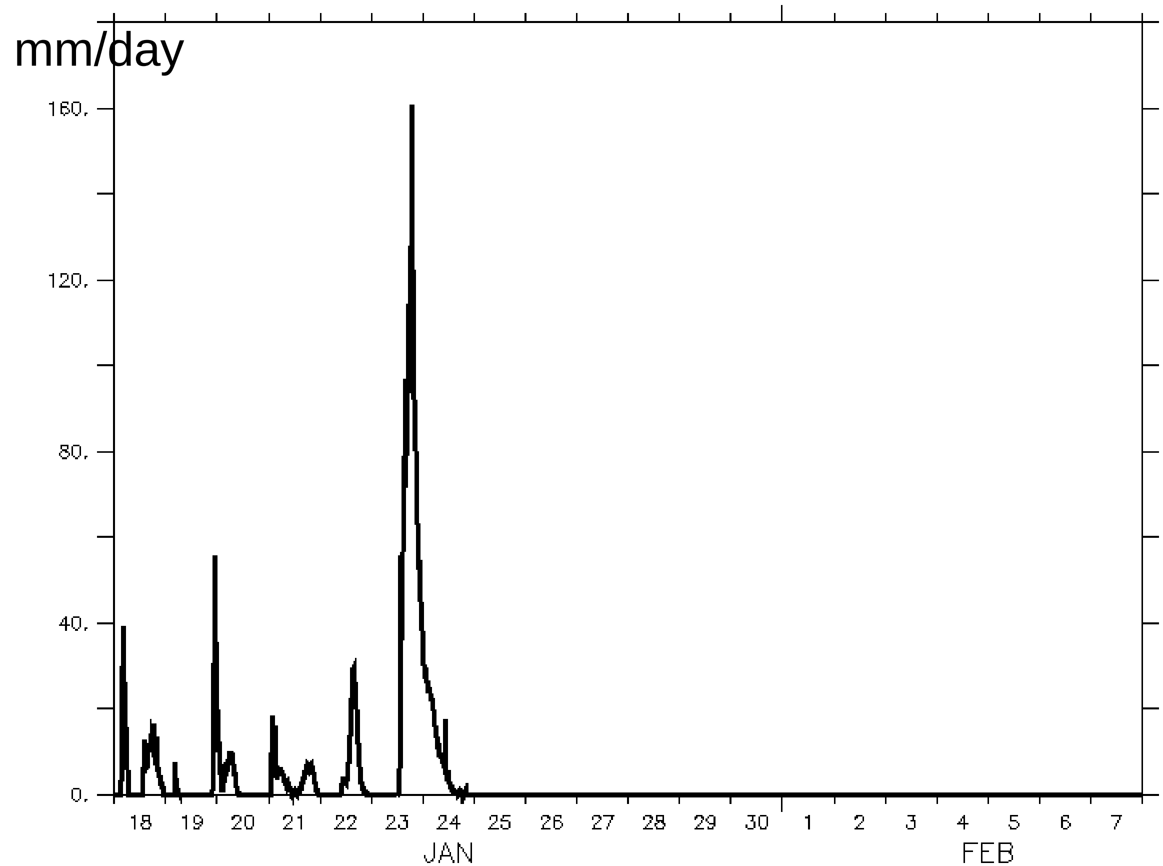
ferret

> use histhf.nc

> plot/l=48/thick=3/x=…/y=… plul*86400

TWPICE case →

plul*86400



Radiation : practice over the tropical belt

Radiation I

Subroutine : radlwsw

Tendencies :

dtswr, dtlwr Temperature tendencies due to solar radiation (SW = short wave) and thermal infra-red (LW = long wave)

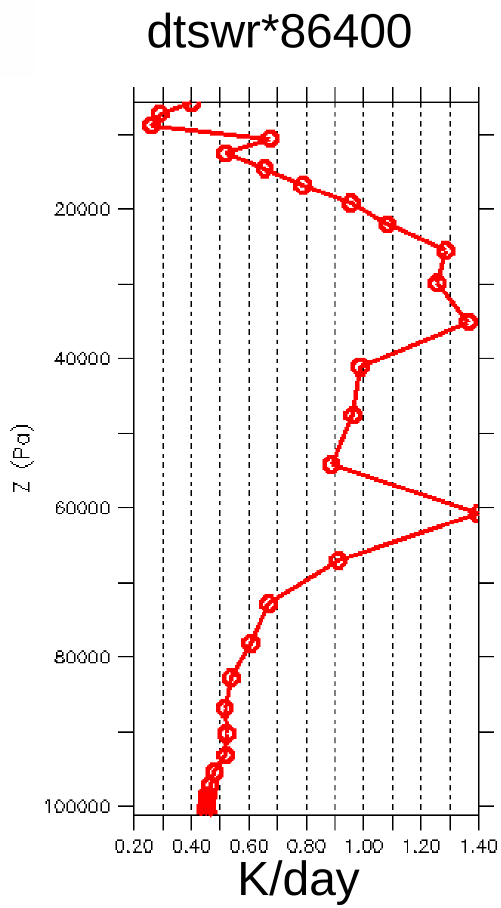
The total radiative tendency is the sum of the SW and LW tendencies.

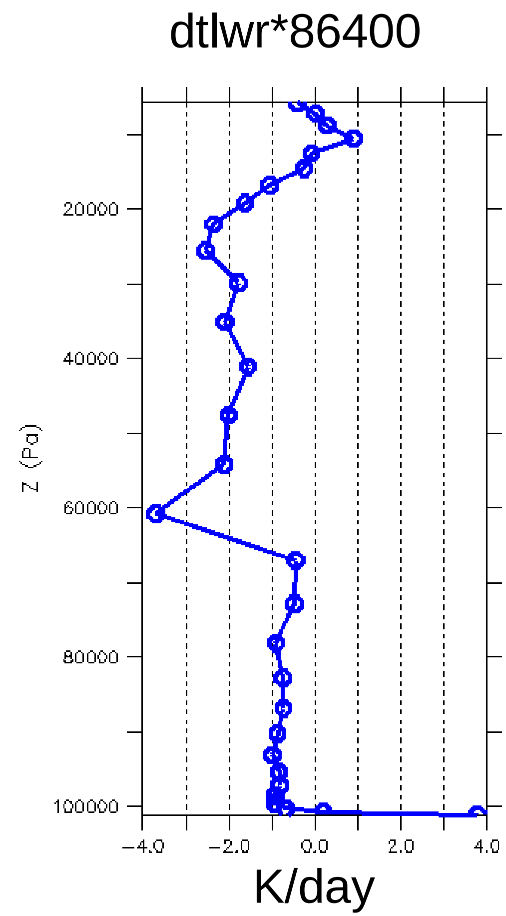
Other variables

- dtsw0 : clear sky SW tendency
- dtlw0 : clear sky LW tendency
- tops : net solar radiation at top of atmosphere (positive downward)
- topl : net infra-red radiation at top of atmosphere (positive upward)
- tops0, topl0 : same for clear sky
- sols : net solar radiation at surface (positive downward)
- soll : net infra-red radiation at surface (positive downward)
- sols0, soll0 : same for clear sky

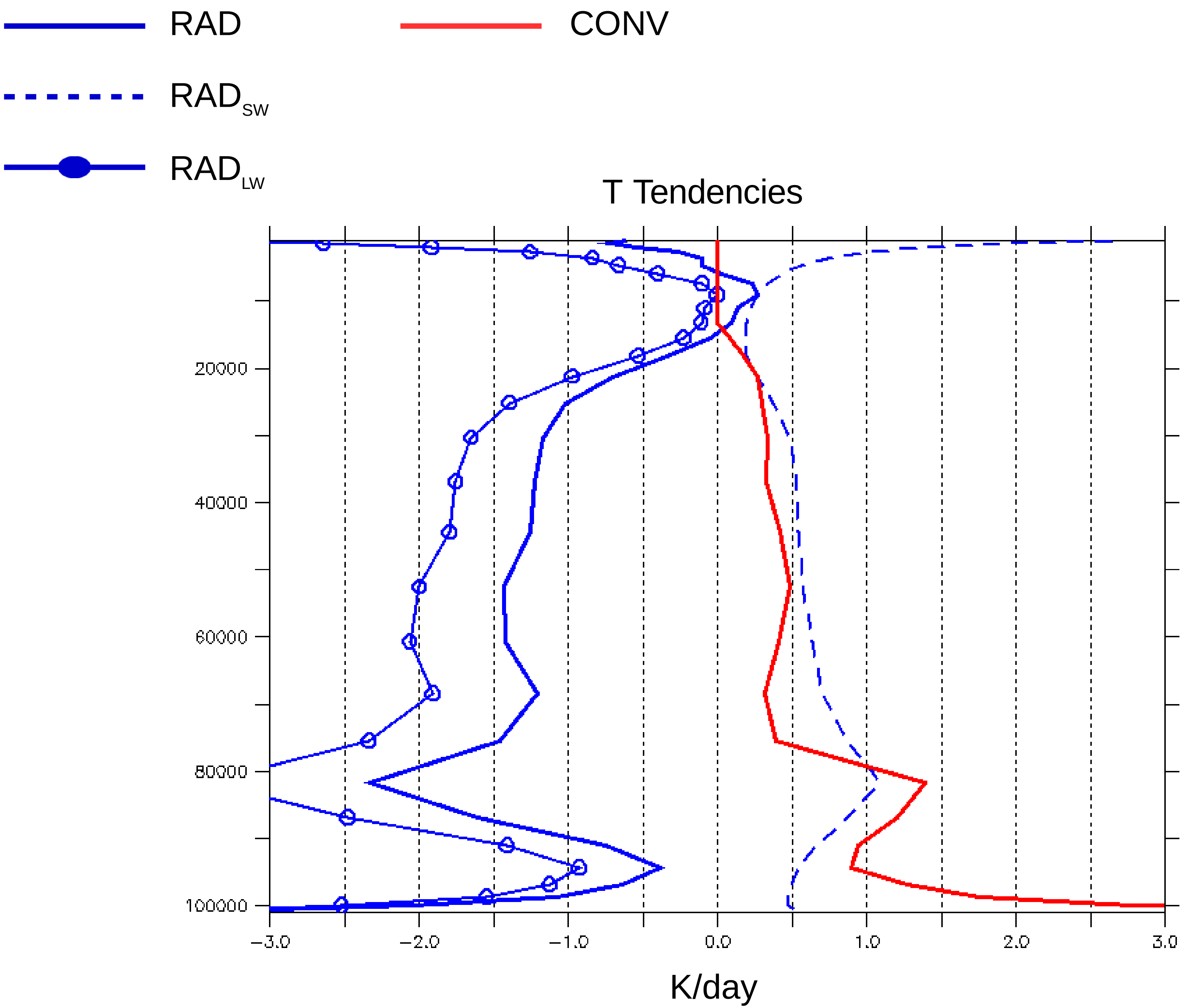
```
ferret
> use histhf.nc
>plot/thick=3/k=10:39 (dtswr[x=@ave,y=-30:30@ave,l=@ave])*86400
> plot/thick=3/k=10:39 (dtswr[x=@ave,y=-30:30@ave,l=@ave])*86400
```

TWPICE case →

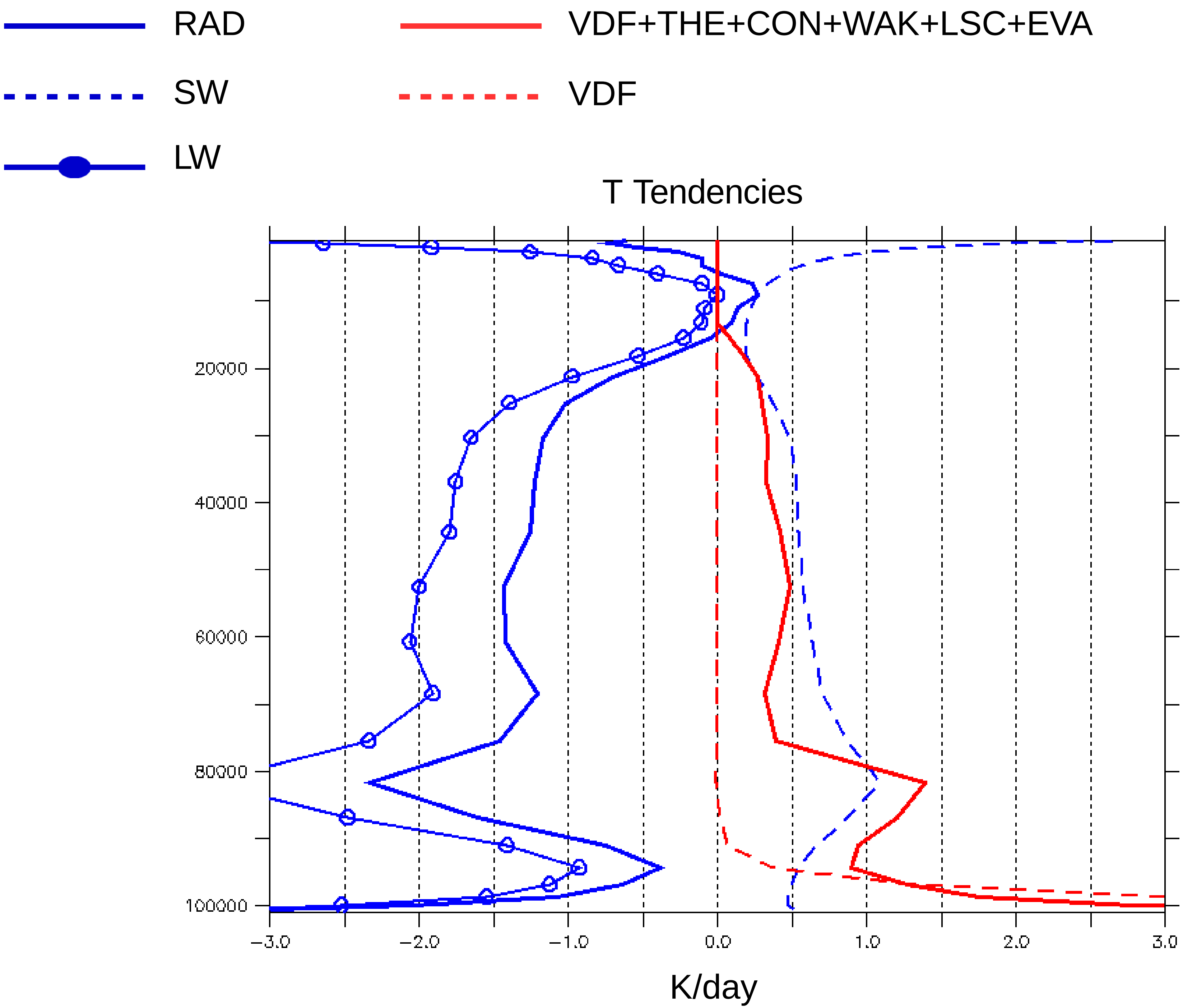




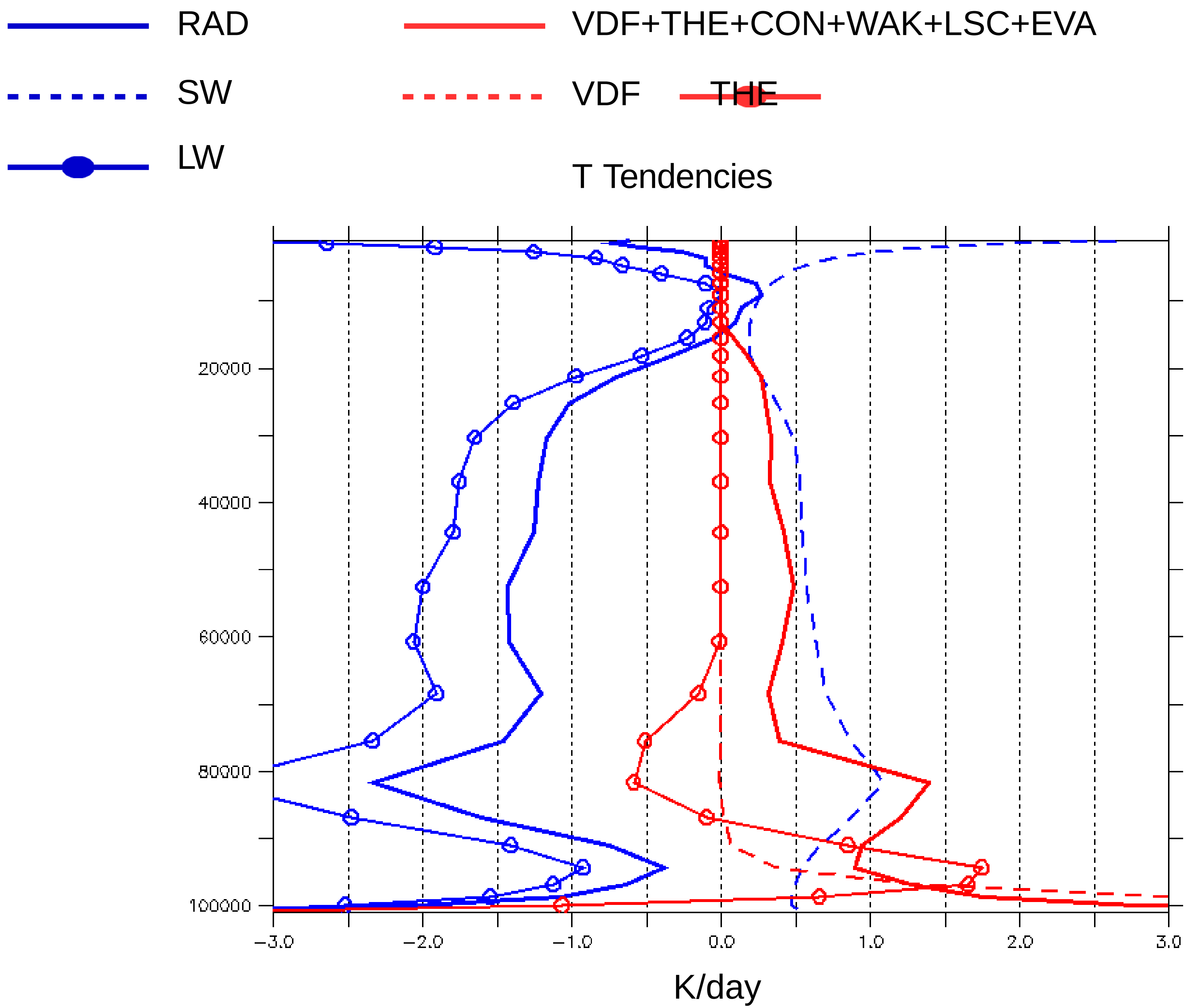
Radiative-Convective Equilibrium over the tropical belt



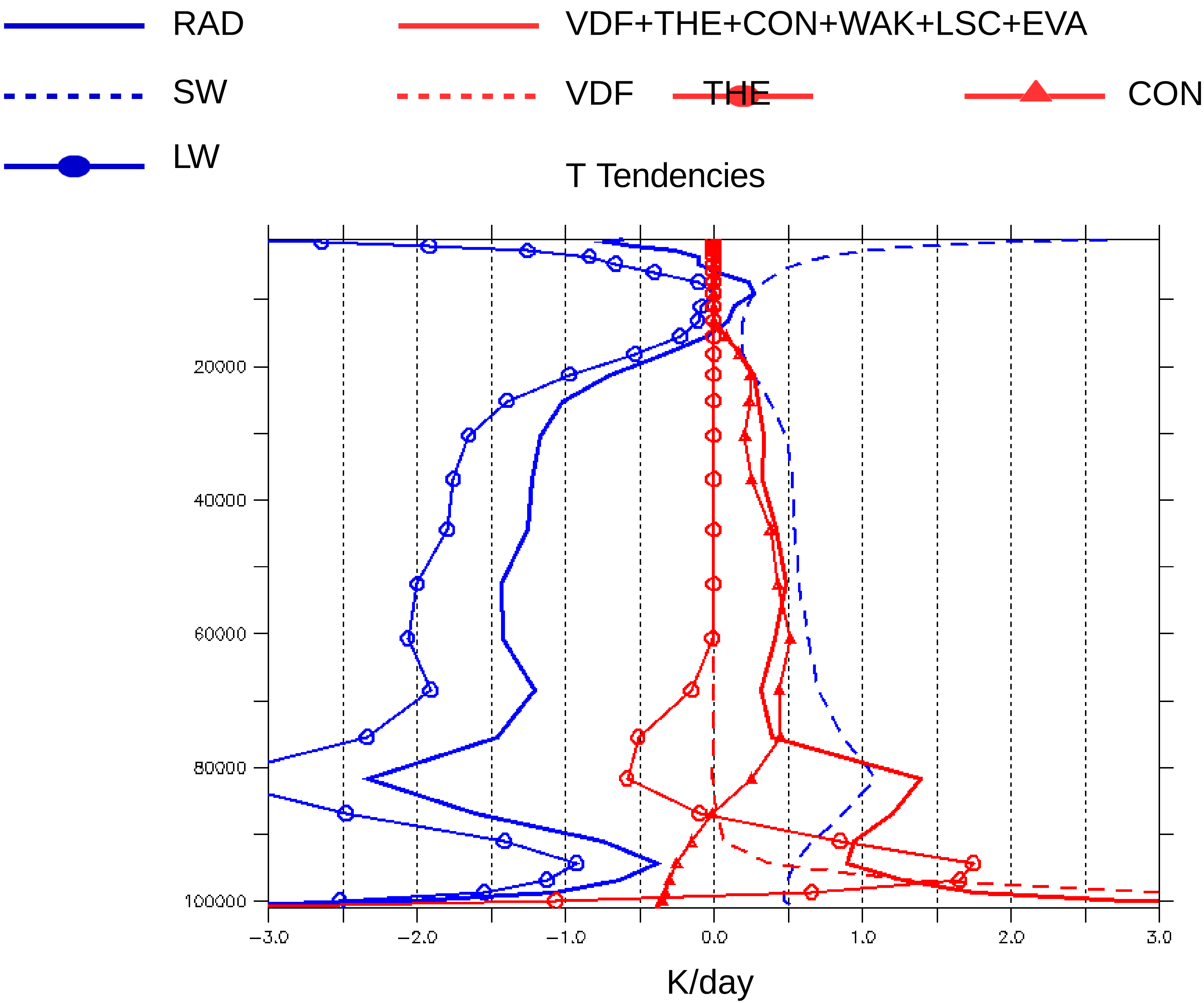
Radiative-Convective Equilibrium over the tropical belt



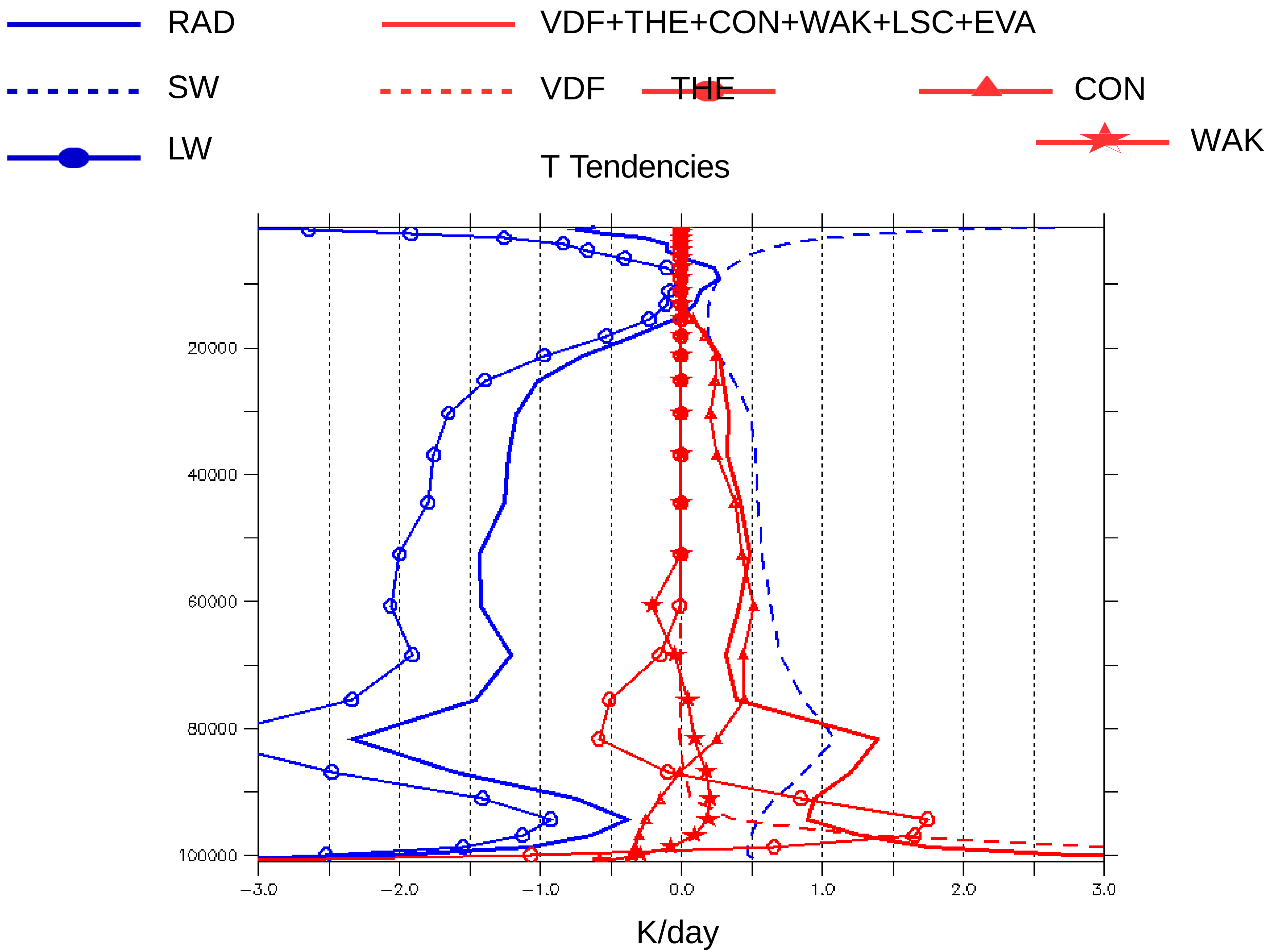
Radiative-Convective Equilibrium over the tropical belt



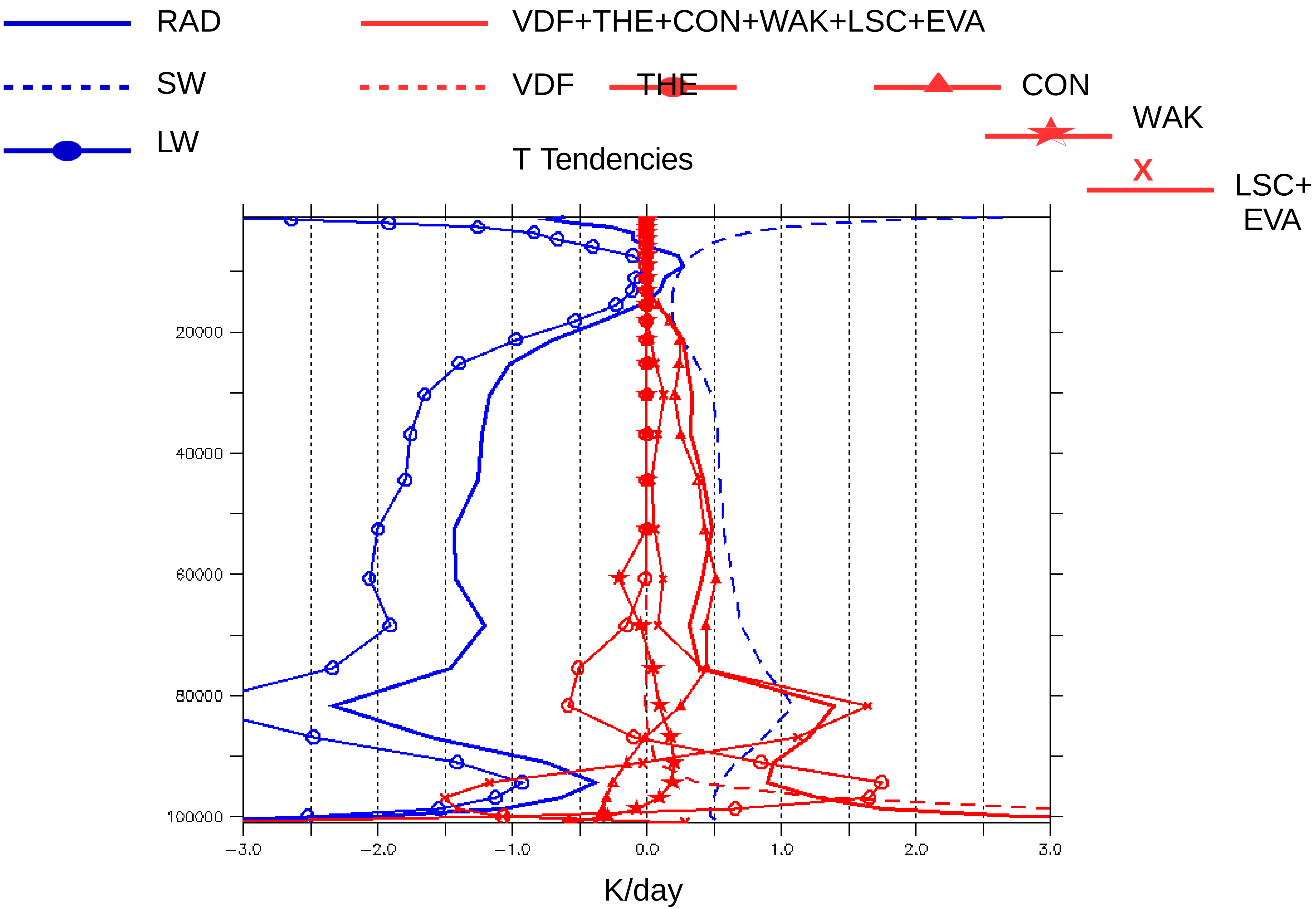
Radiative-Convective Equilibrium over the tropical belt



Radiative-Convective Equilibrium over the tropical belt



Radiative-Convective Equilibrium over the tropical belt



Energy budgets

Radiation II : Energy budget

Energy budget at the top of the atmosphere :

`nettop = tops-topl = (SWdn-SWup) - (LWup-LWdn)`

Energy input (received solar energy minus reflected solar and emitted LW energy)
Positive in the tropics, negative at the poles

Surface energy budget (from the atmosphere to the surface) :

`bils = soll + sols + sens + flat`

`soll = lwdnsfc-lwupsfc` (same for `sols`)

`flat` : latent heat flux (from the atmosphere to the surface)
Negative when there is surface evaporation

`sens` : sensible heat flux (from the atmosphere to the surface)
Positive when the atmosphere heats the surface (polar regions)
Negative when the atmosphere is heated by the surface (continents & oceans)

Try to do it !