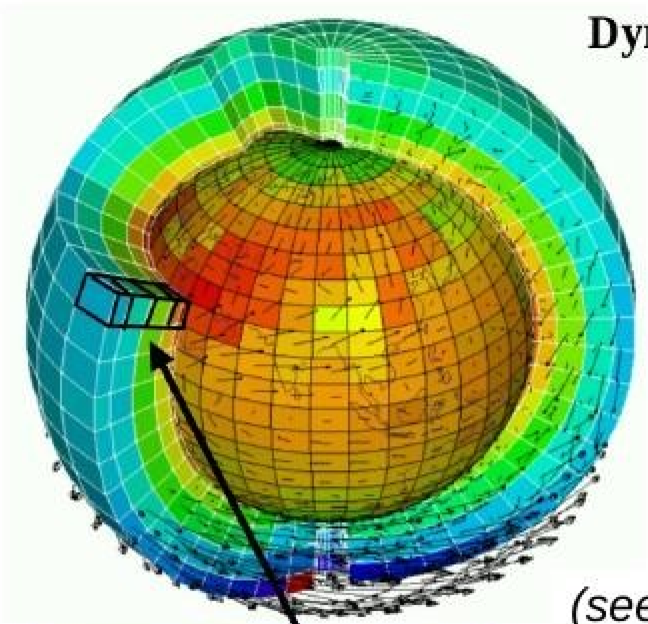
The physical parametrizations in LMDZ

LMDZ Team

Laboratoire de Météorologie Dynamique

December 2018

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

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

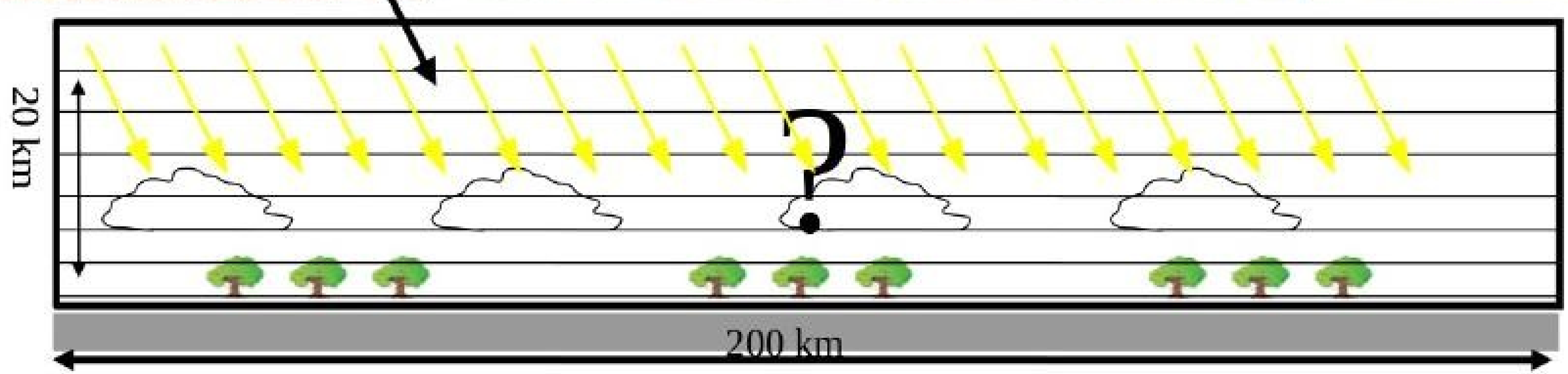
- Momentum conservation

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

- 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 :

$$\partial_t \vec{v} + (\vec{v}.\vec{\nabla}_p)\vec{v} + \omega\partial_p\vec{v} + f\vec{k} \times \vec{v} + \vec{\nabla}_p\Phi = \vec{S_v}$$

transport Coriolis gravity

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 :

$$S_q = (\partial_t q)_\varphi = (\partial_t q)_{\rm eva} + (\partial_t q)_{\rm lsc} + (\partial_t q)_{\rm diff\ turb} + (\partial_t q)_{\rm conv} + (\partial_t q)_{\rm wk} + (\partial_t q)_{\rm Th} + (\partial_t q)_{\rm ajs}$$

In the model, the total tendency of q is therefore

$\partial_t q_{\rm dyn} + \partial_t q_{\rm param} =$ `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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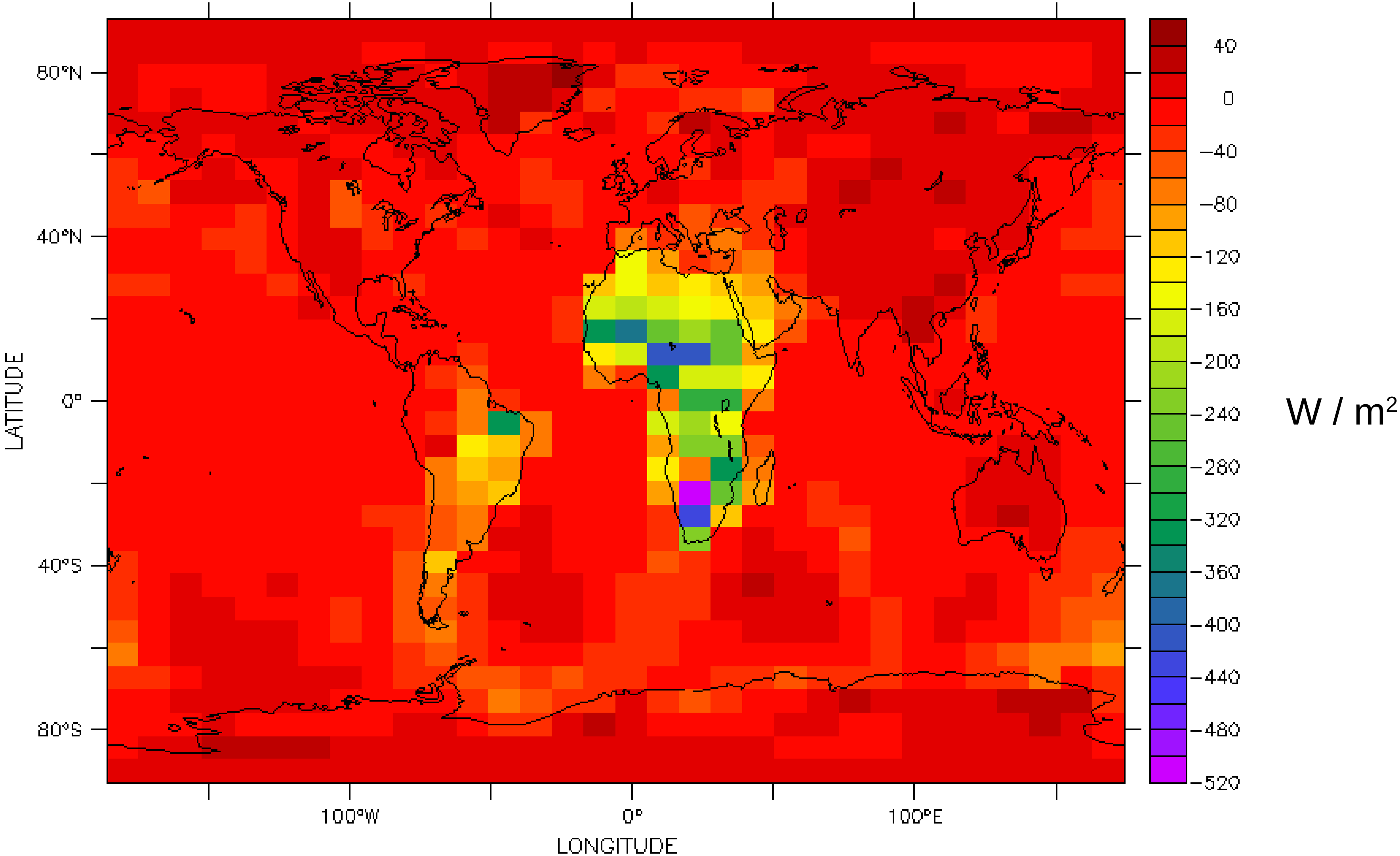
Practice

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 ($H = C_p\theta$).

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

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

(Fluxes positive downward)

Water (left) and energy (right) conservation

Diffusion (dowgradient flux)

Surface fluxes

Spatial discretization : (moisture)

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

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

Implicit scheme, yields for the first atmospheric layer :

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

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 ($H = C_p\theta$).

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

Spatial discretization : (moisture)

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

Implicit scheme, yields for the first atmospheric layer :

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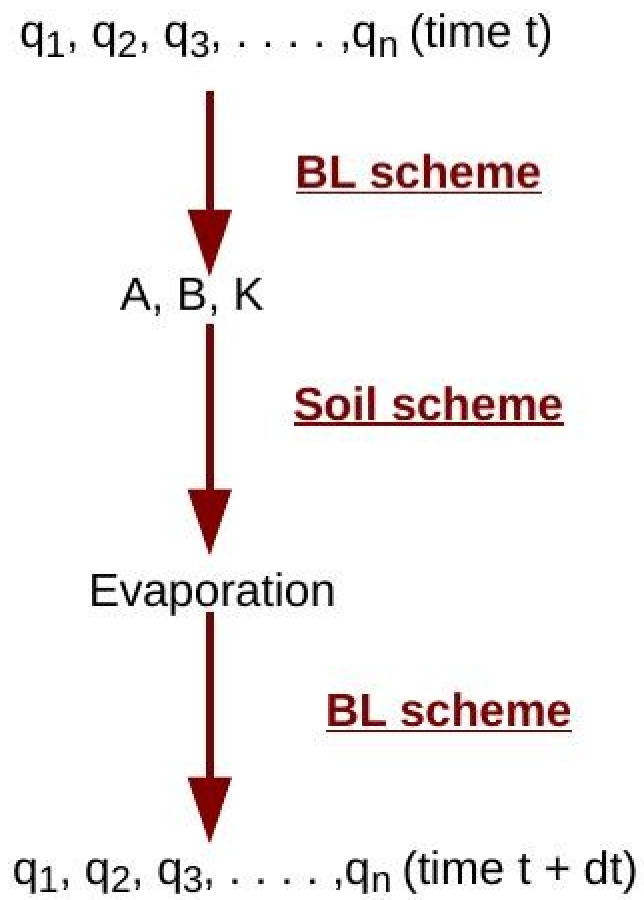


Turbulent diffusion : practice

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)

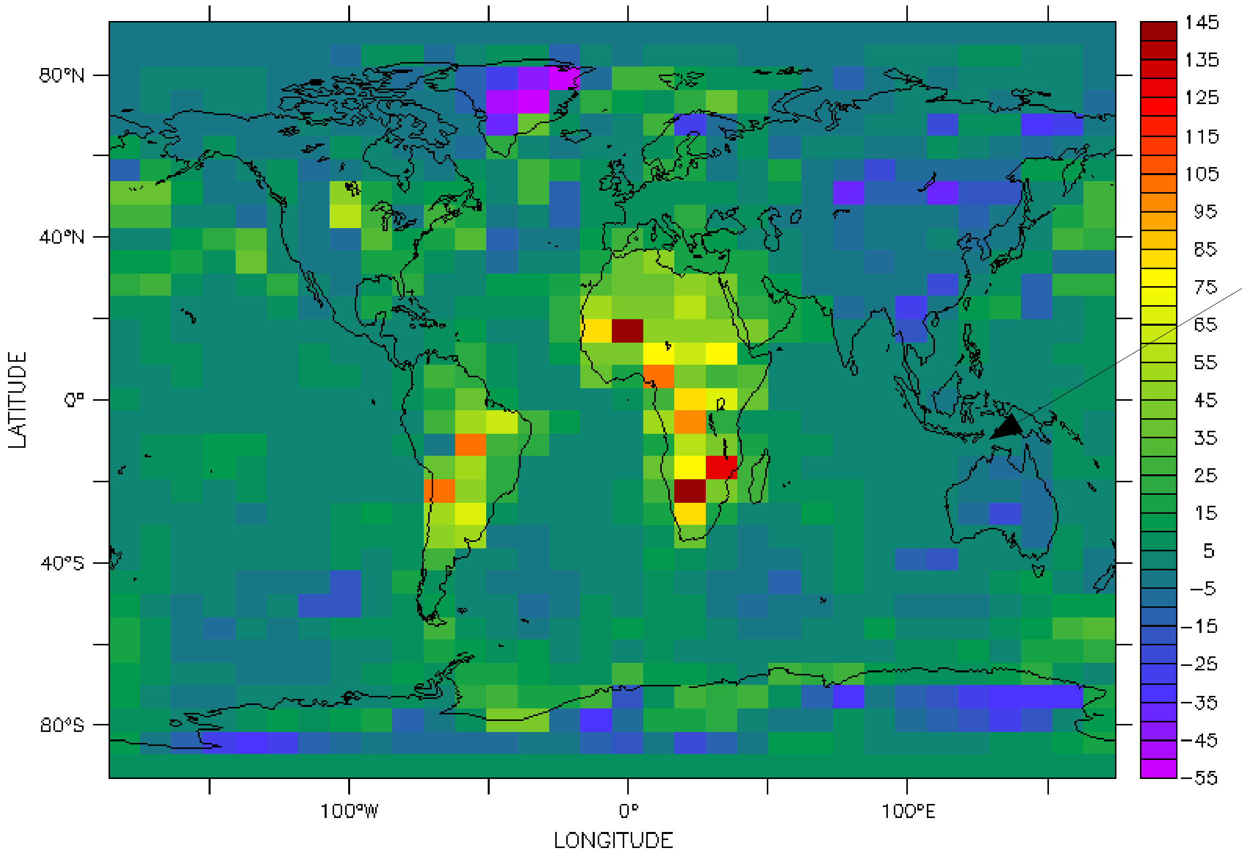
– flat : latent heat flux at the surface (positive downward)

– 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

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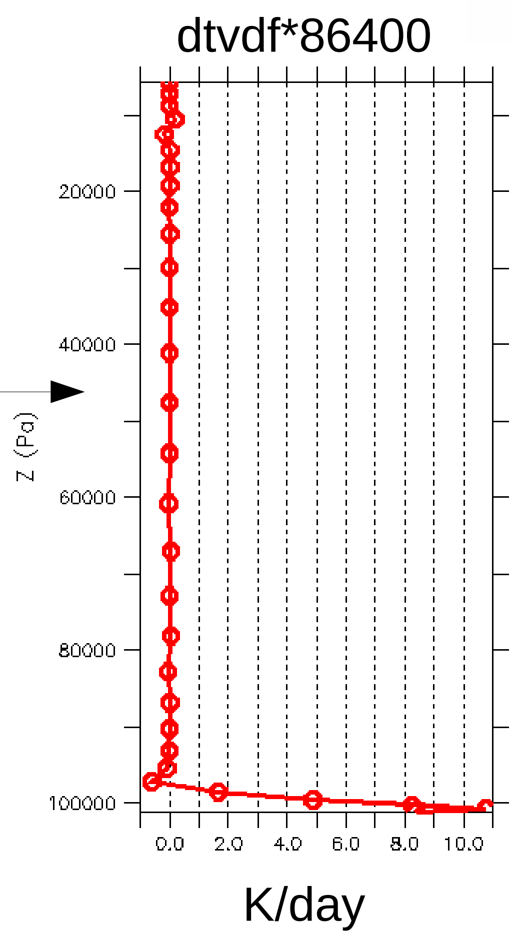
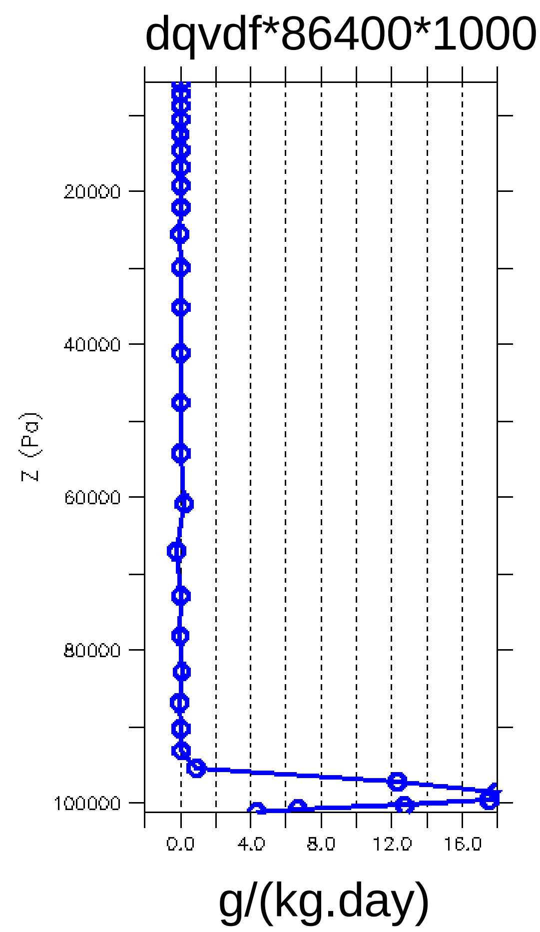
> use histhf.nc

> 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





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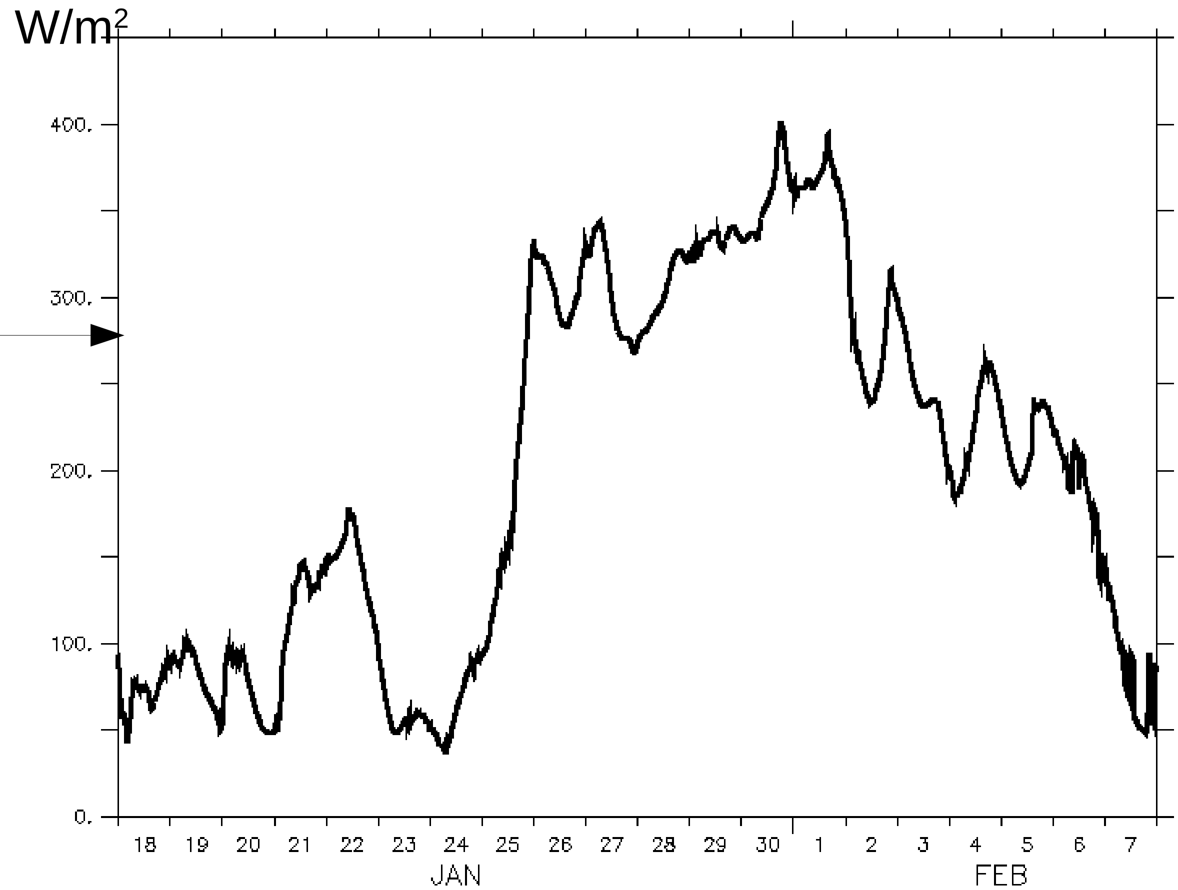
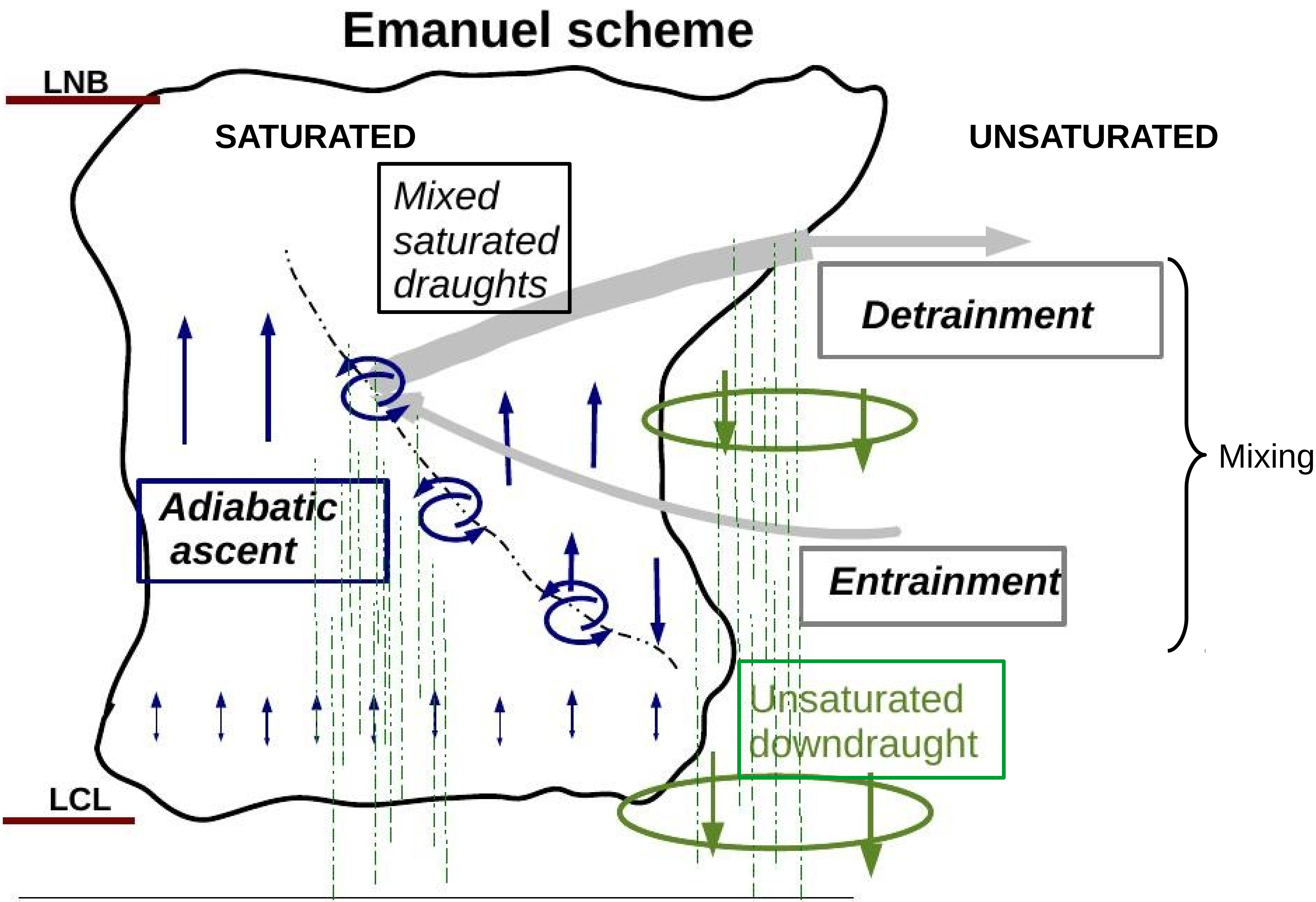
> use histhf.nc
> plot/thick=3/x=…/y=… -1*flat
> plot/thick=3/x=…/y=… -1*sens

-1*flat

TWPICE case



Deep convection : Emanuel scheme



Deep convection : practice

Deep convection

Subroutine : concvl

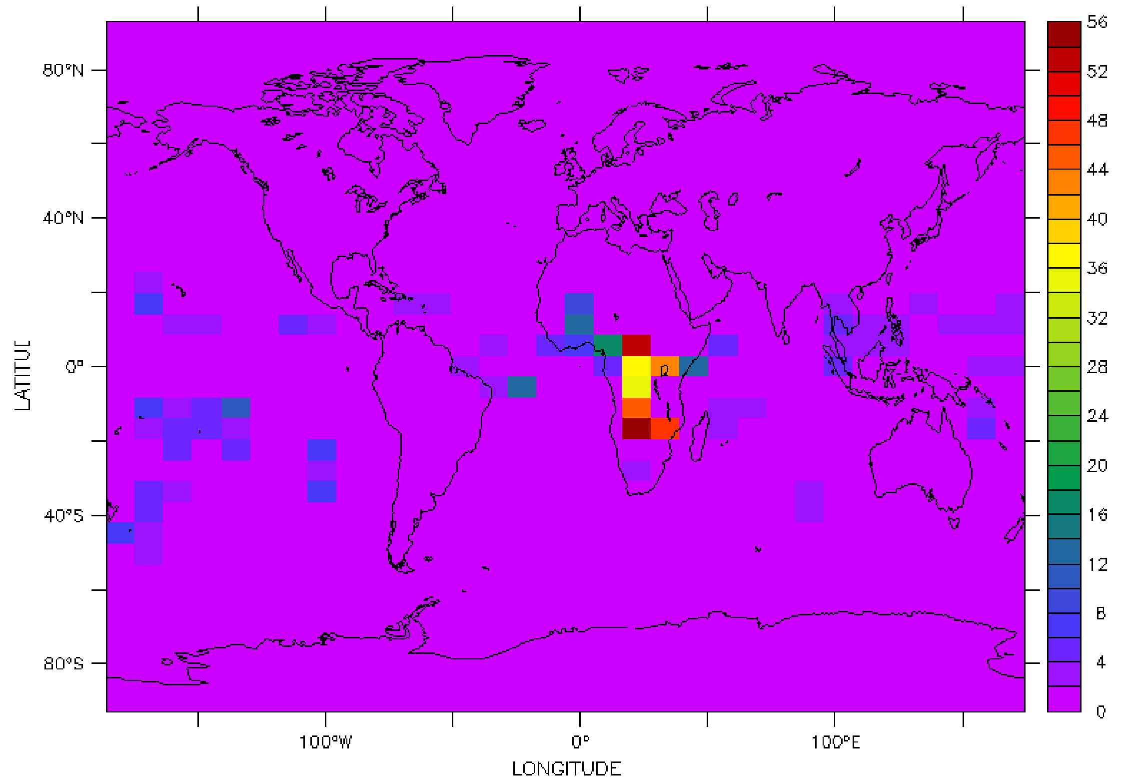
Tendencies :

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

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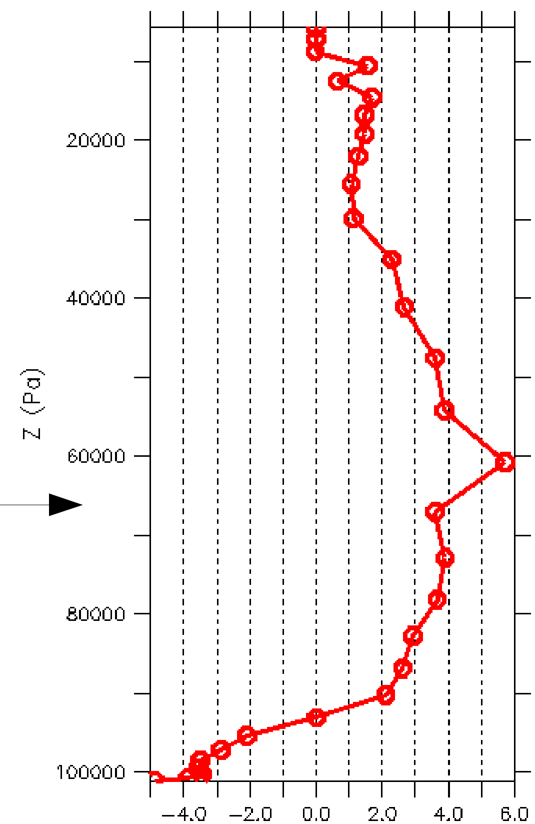
> plot/l=48/thick=3/x=…/y=…/k=10:39 dtcon*86400

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

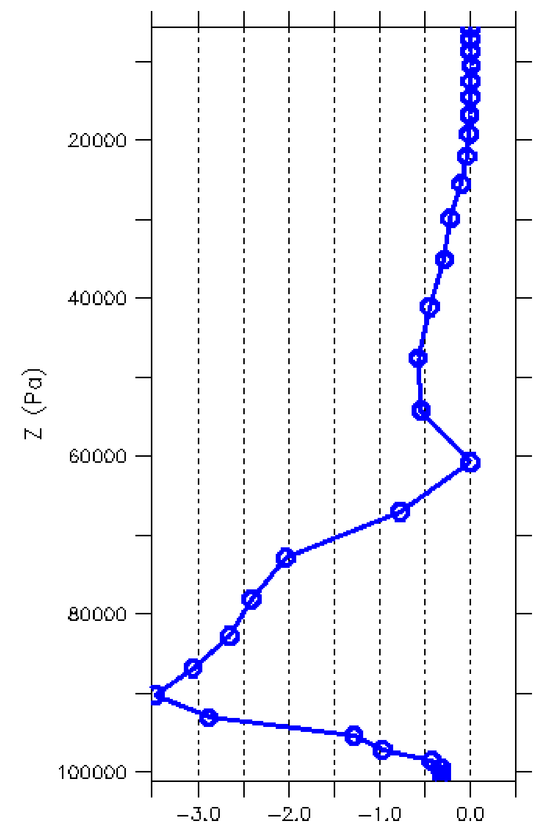
TWPICE case →

dtcon*86400



K/day

dqcon*86400*1000



g/(kg.day)

Deep convection : practice

Deep convection

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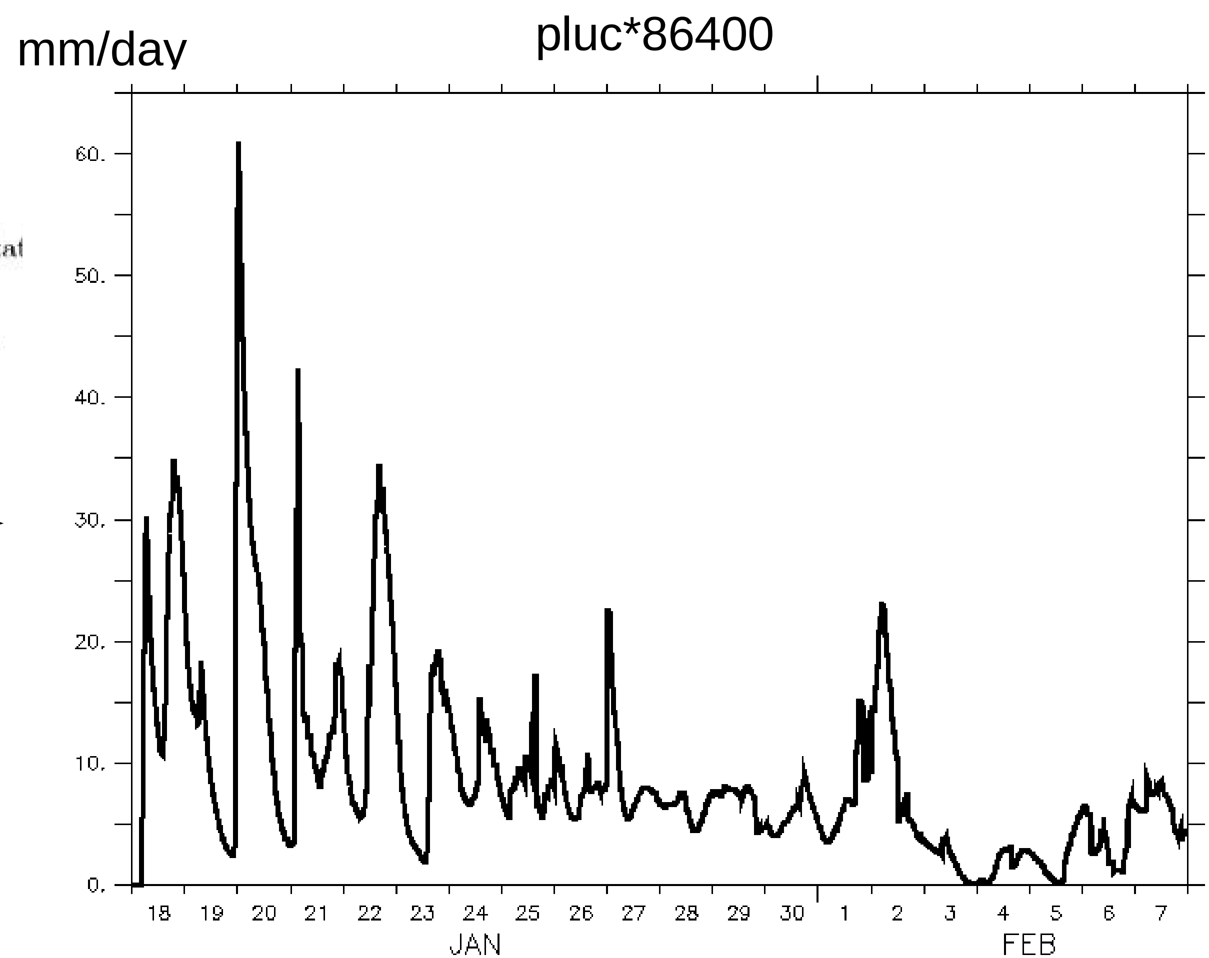
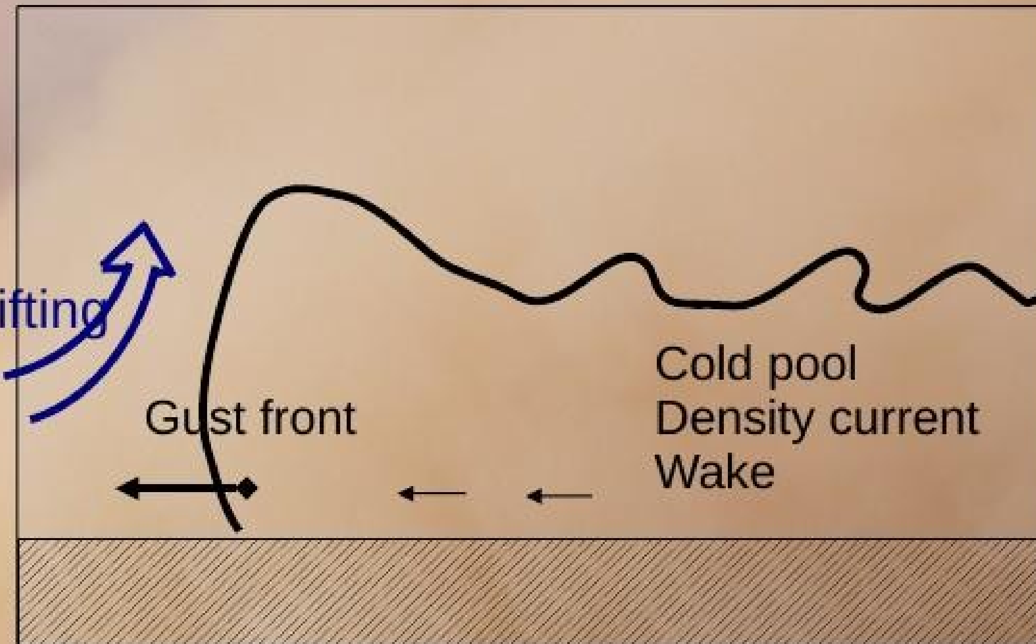
TWPICE case →



What drives deep convection : triggering and closure

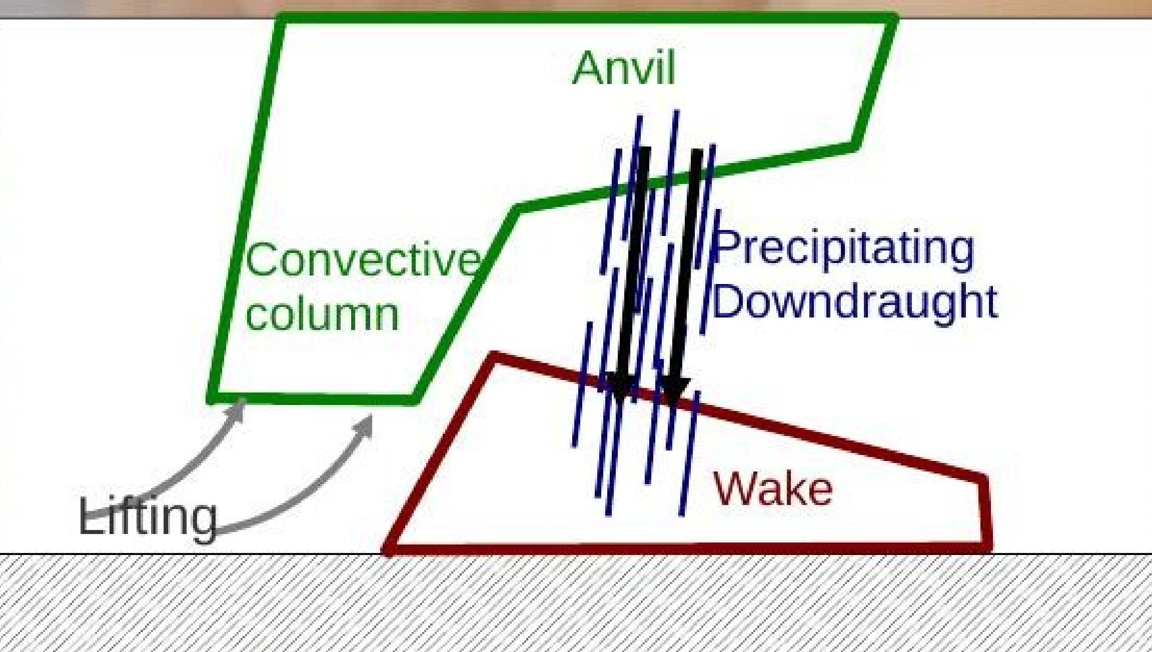


Triggering

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

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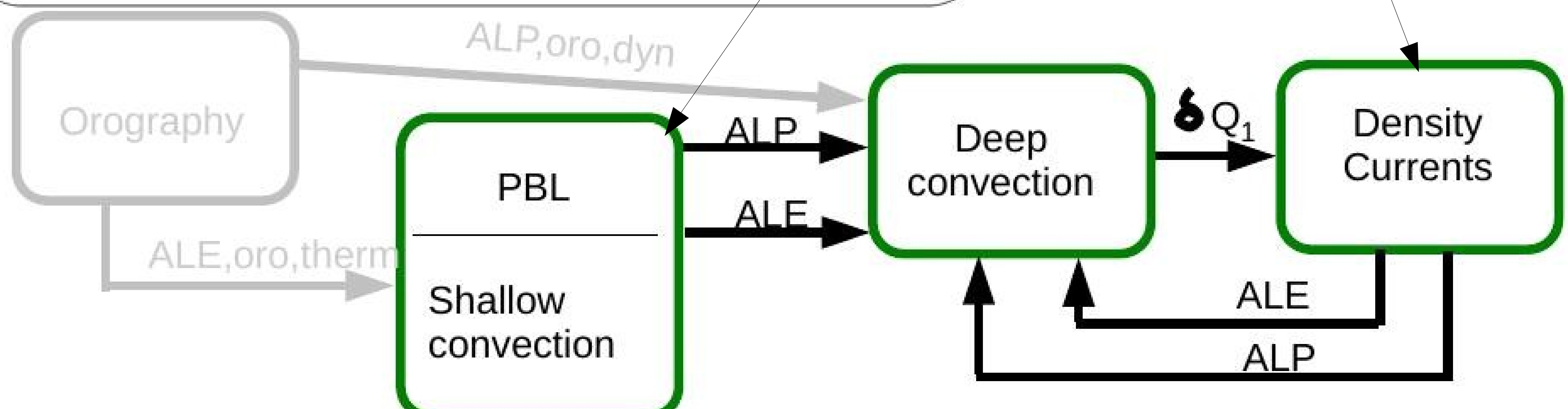
The deep convection scheme is then coupled to 2 PBL processes :

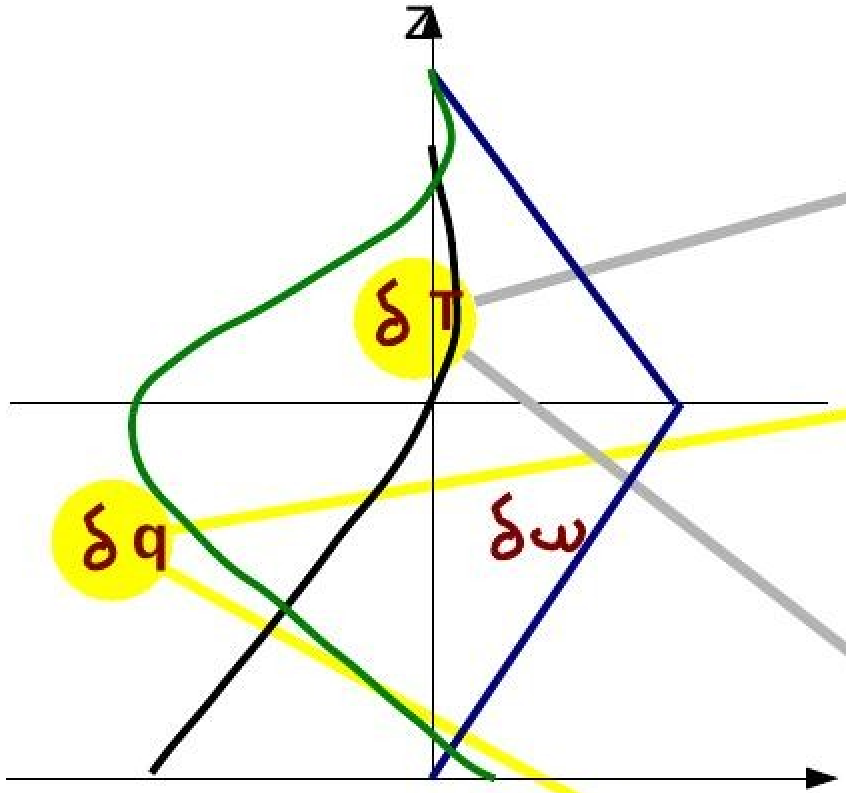
1. Thermals

2. Density currents (or wakes or cold pools)

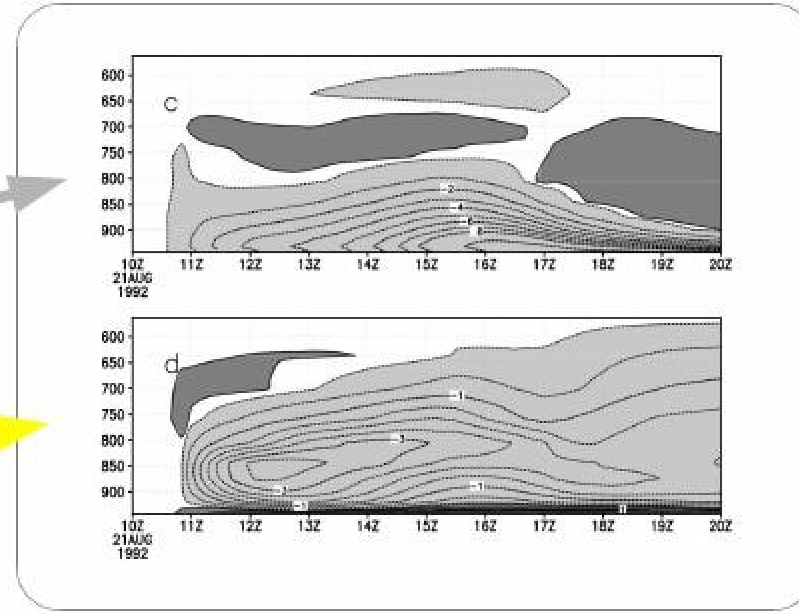


Density currents

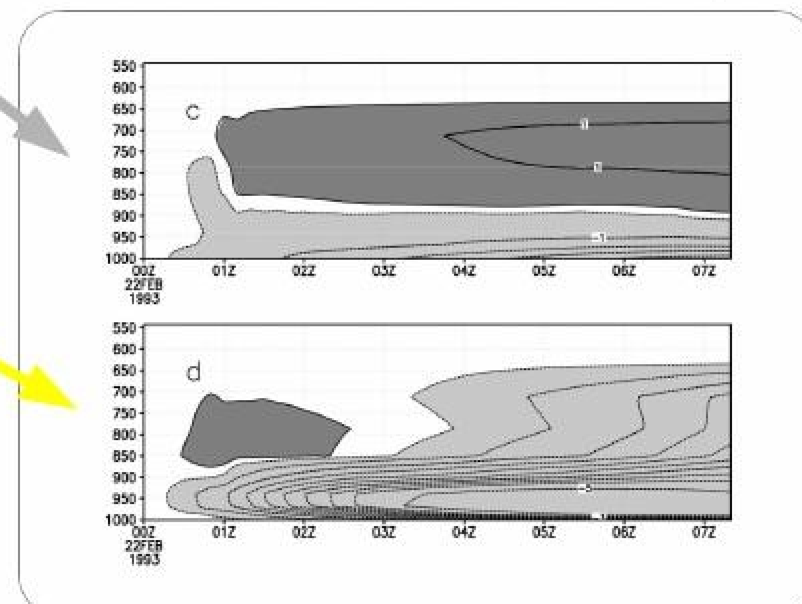
Simulated wake properties



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

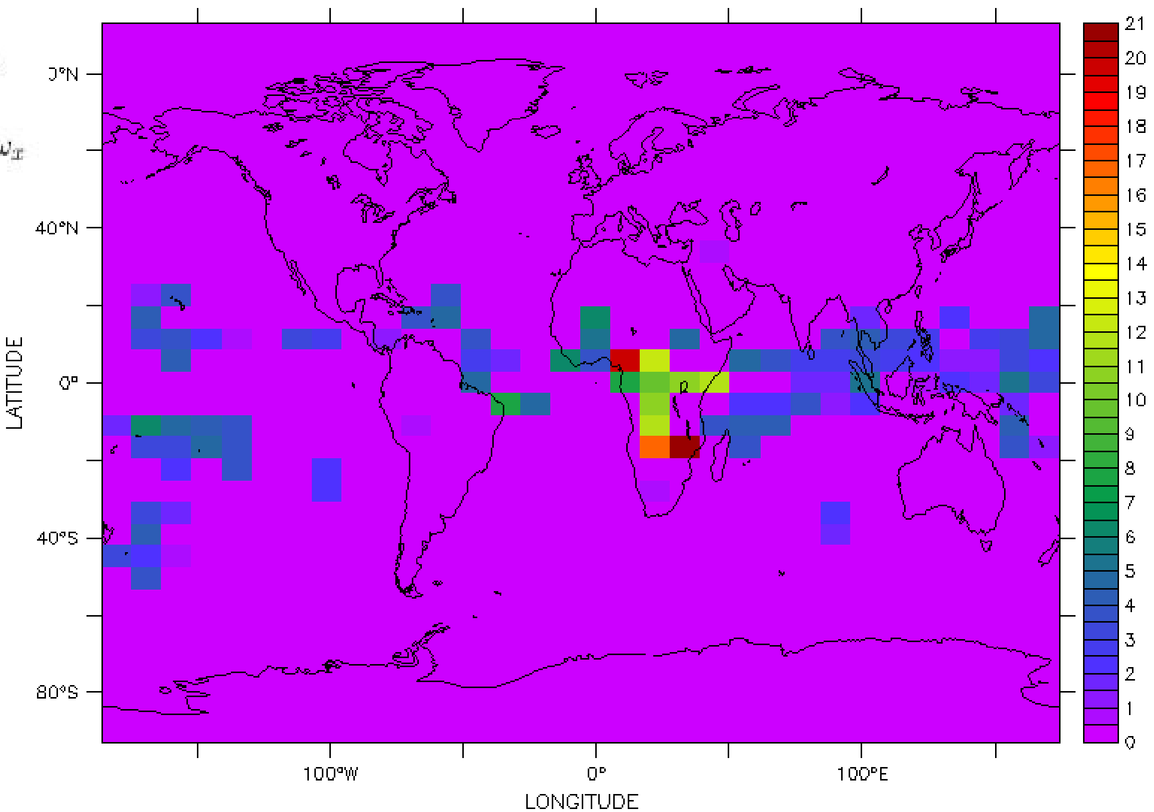
Tendencies :

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
```



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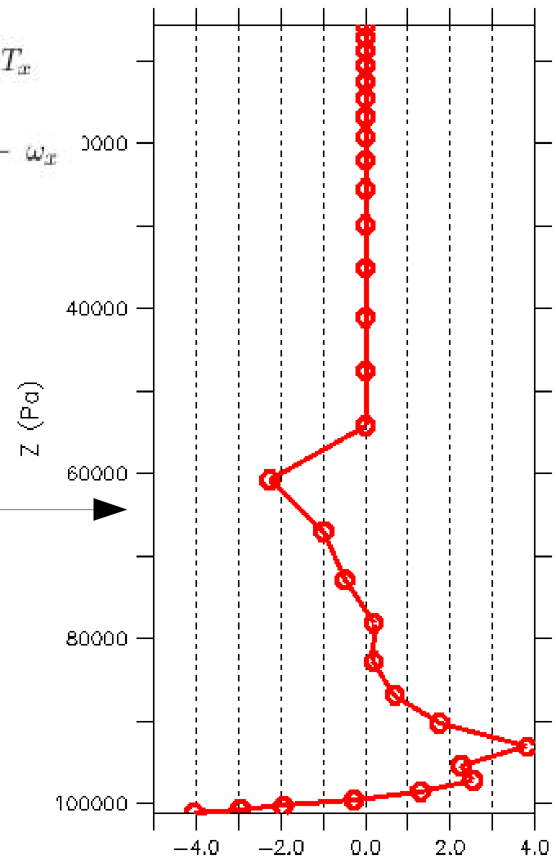
> plot/l=48/thick=3/x=…/y=…/k=10:39 dtwak*86400
> plot/l=48/thick=3/x=…/y=.../k=10:39 dqwak*86400*1000

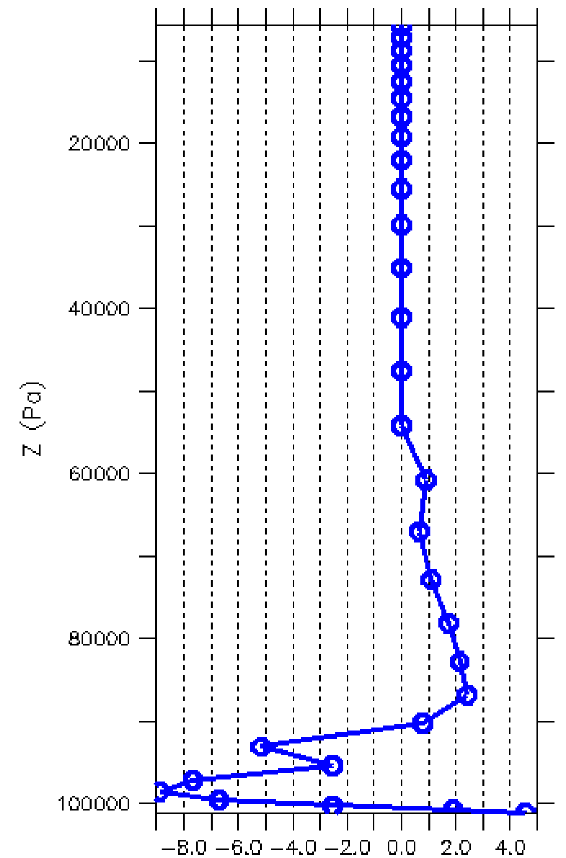
TWPICE case →

dtwak*86400



K/day

dqwak*86400*1000



g/(kg.day)

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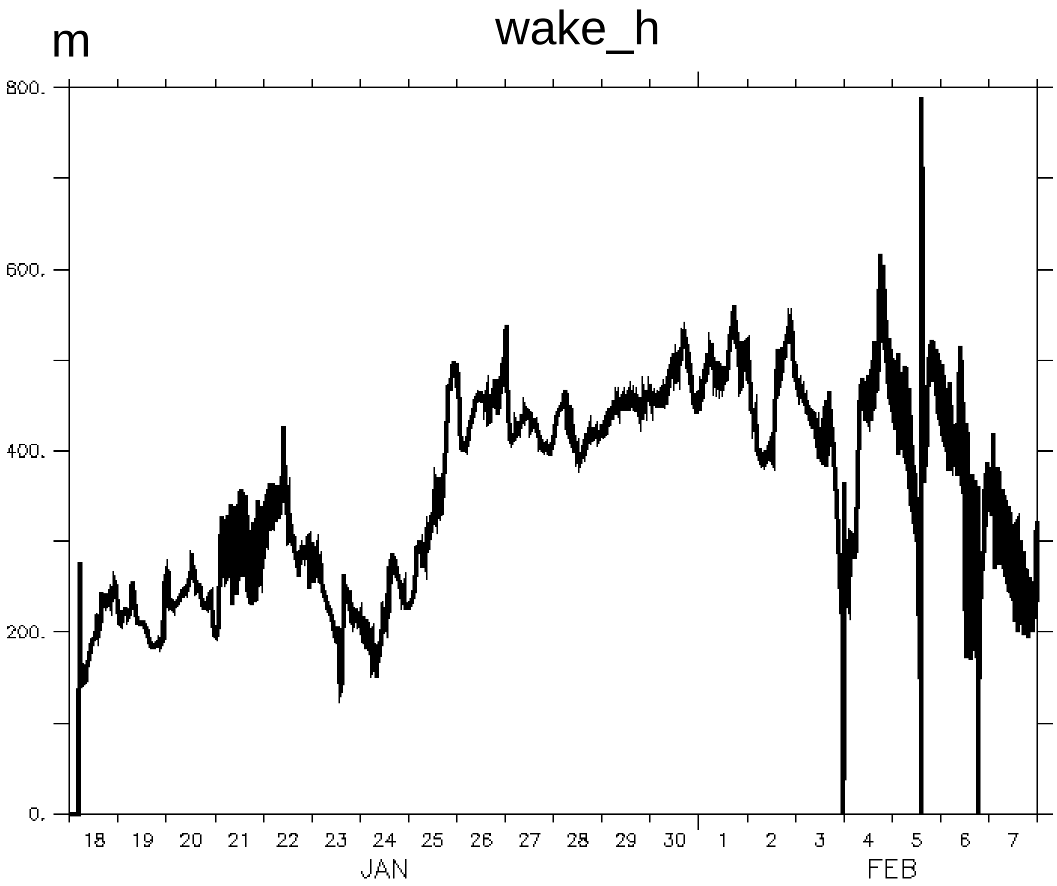
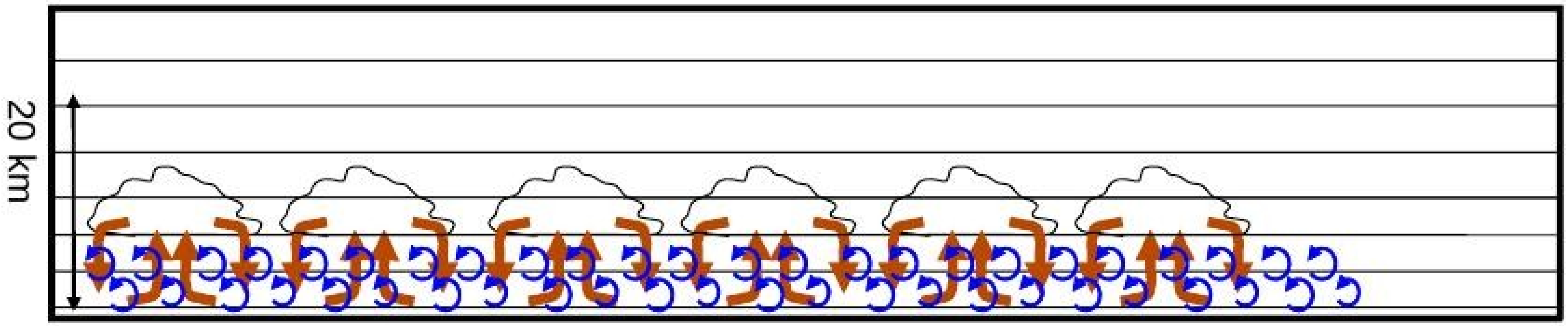
ferret
> use histhf.nc
> plot/thick=3/x=…/y=… wake_h

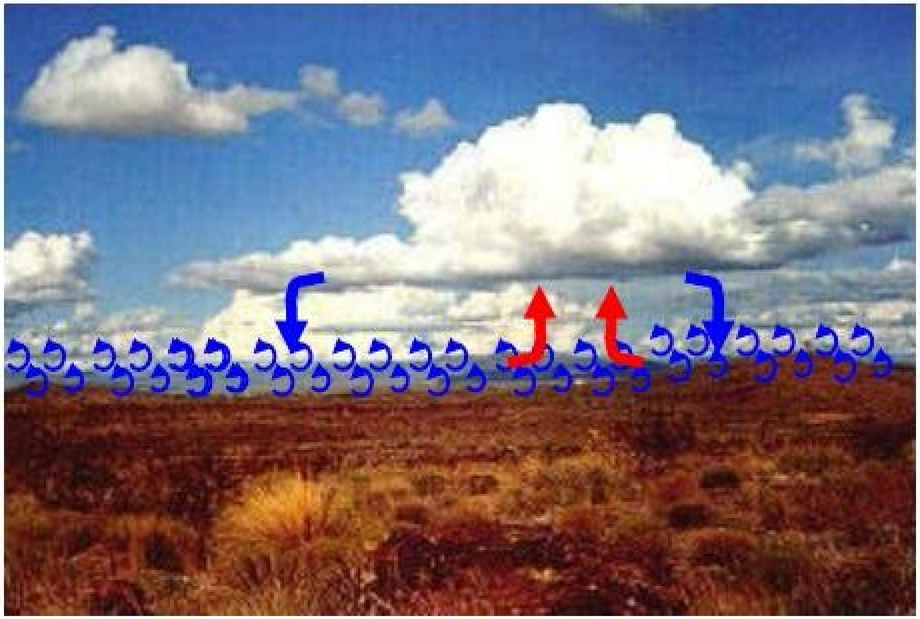
TWPICE case



Thermals

In a model column there are structures of boundary layer scale

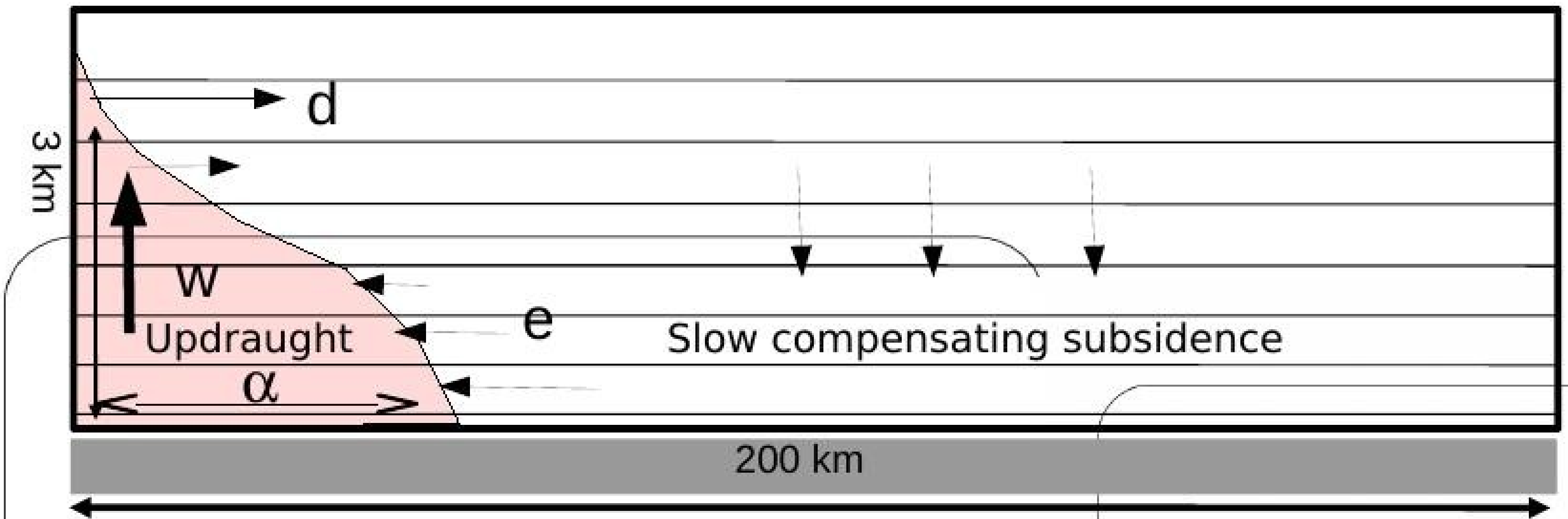




"The Thermal Model":
Each column is split in two parts: Ascending air from the surface and subsiding air around it.

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 :**

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

Etc ...

Thermals : practice

Thermals and dry adjustment

Subroutine : calltherm

Tendencies :

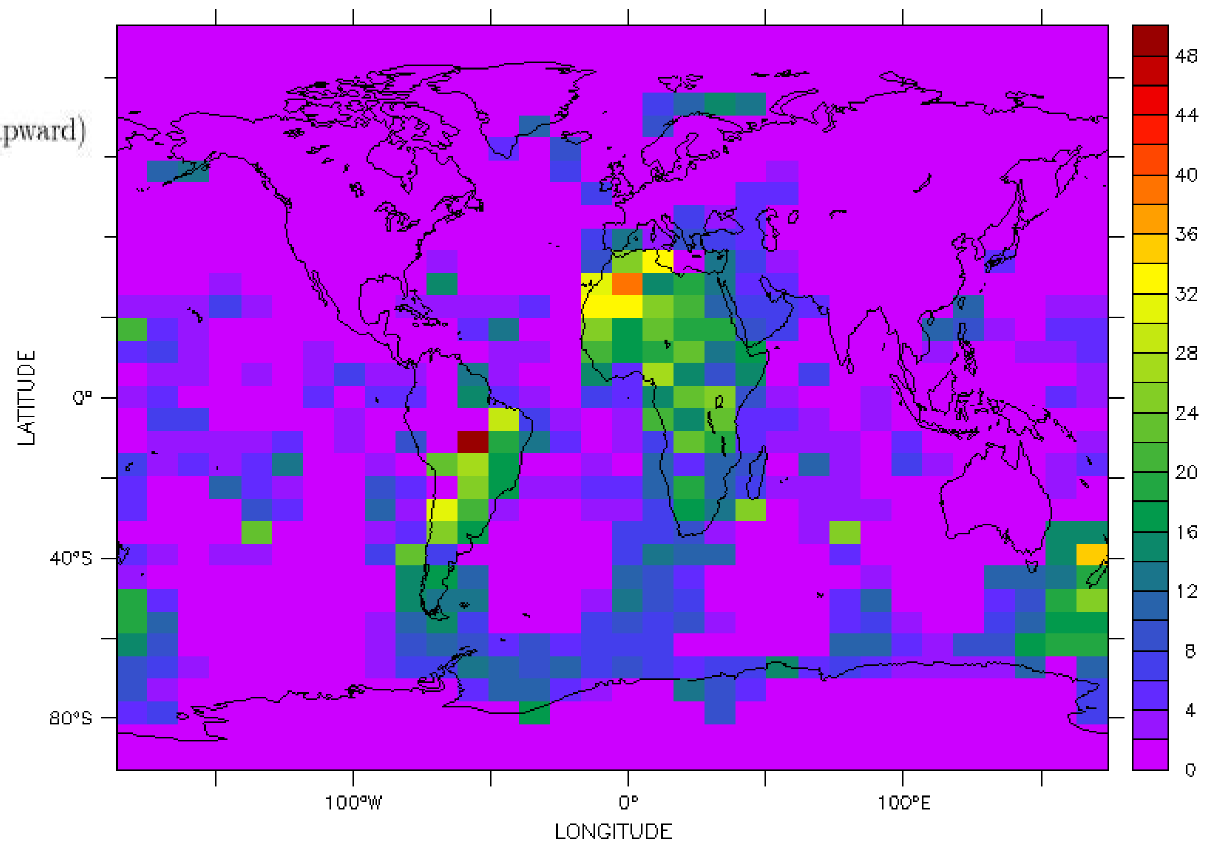
dtthe, dqthe,duthe, dvthe

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)

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



DTTHE[K=@MAX]*86400

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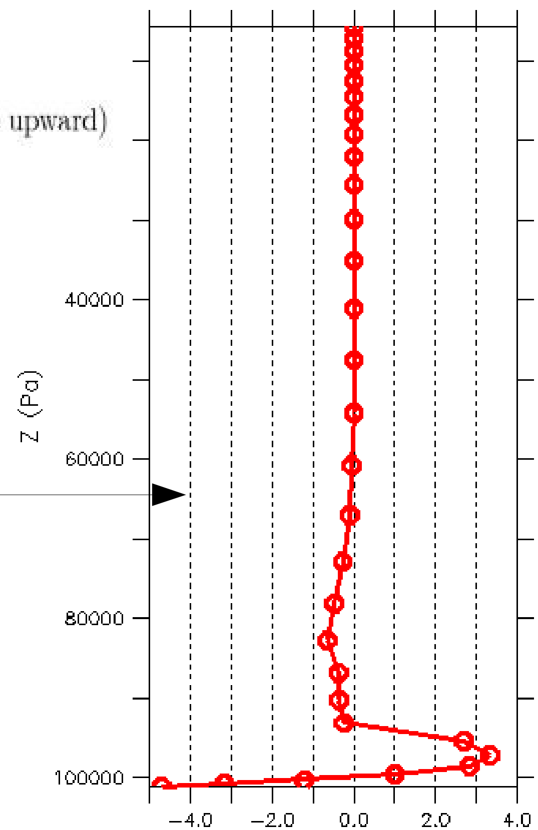
ferret
> use histhf.nc
> plot/l=48/thick=3/x=…/y=…/k=10:39 dtthe*86400
> plot/l=48/thick=3/x=…/y=.../k=10:39 dqthe*86400*1000

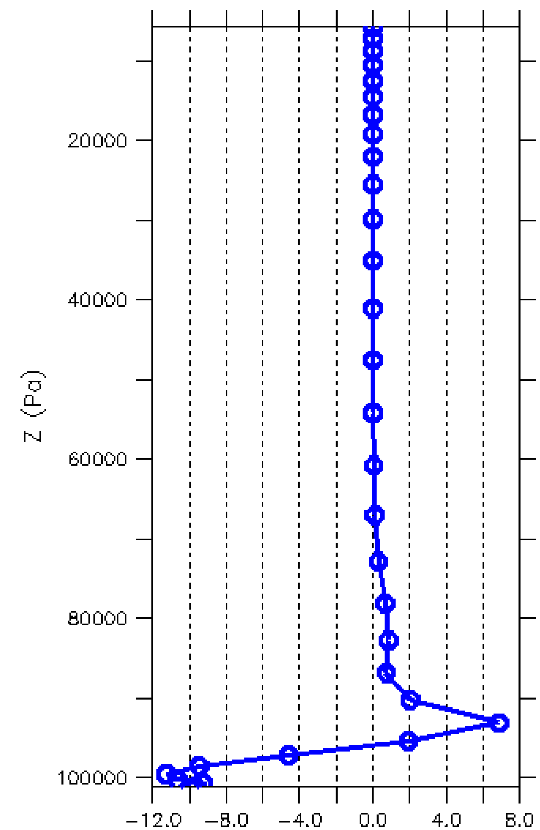
TWPICE case

dtthe*86400



K/day

dqthe*86400*1000



g/(kg.day)

Thermals : practice

Thermals and dry adjustment

Subroutine : calltherm

Tendencies :

dtthe, dqthe,duthe, dvthe

Other variables

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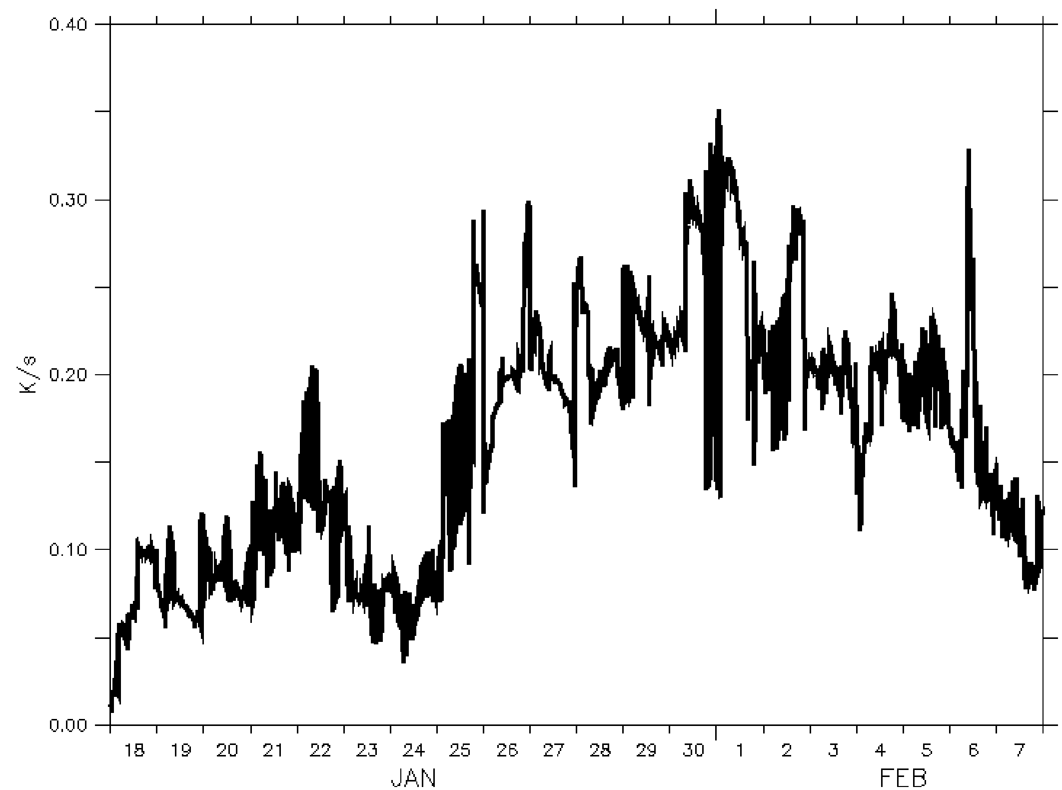
ferret
> use histhf.nc
> plot/thick=3/x=…/y=… f0_th

TWPICE case →

f0_th



Thermal closure mass flux kg/(m².s)

Large scale condensation & evaporation : practice

Large scale condensation (evap & lsc)

Subroutines : reevap & fisrtilp

Tendencies :

dteva, dqeva : tendencies due to cloud water evaporation

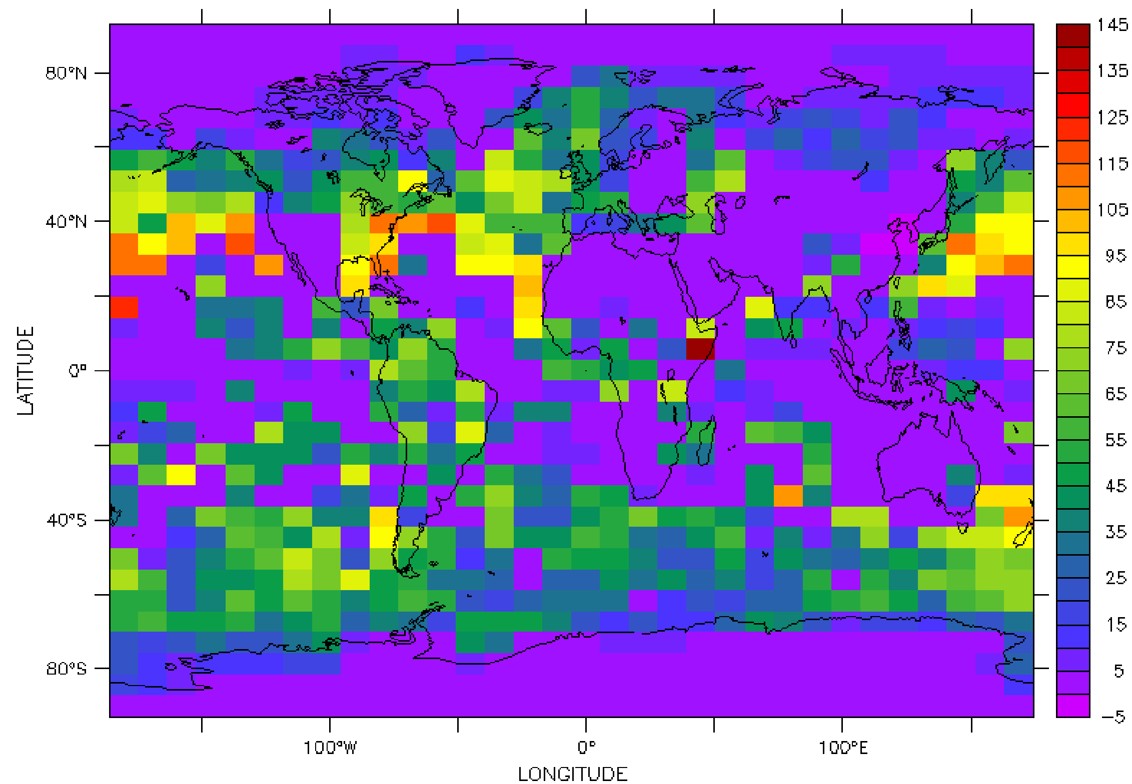
dtlsc, dqlsc : tendencies due to cloud water condensation

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
> go land 1



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

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Large scale condensation (evap & lsc)

Subroutines : reevap & fisrtilp

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ferret

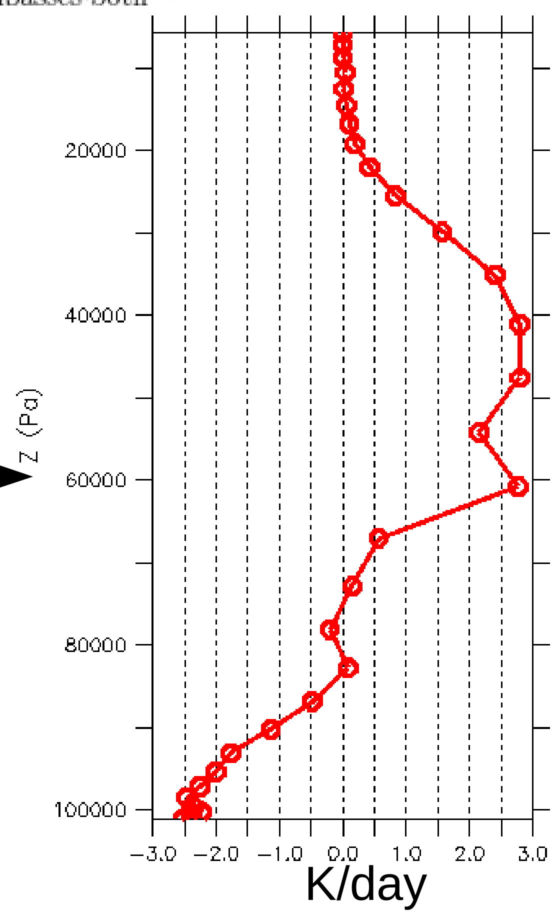
> use histhf.nc

> plot/l=48/thick=3/x=…/y=…/k=10:39 (dtlsc+dteva)*86400

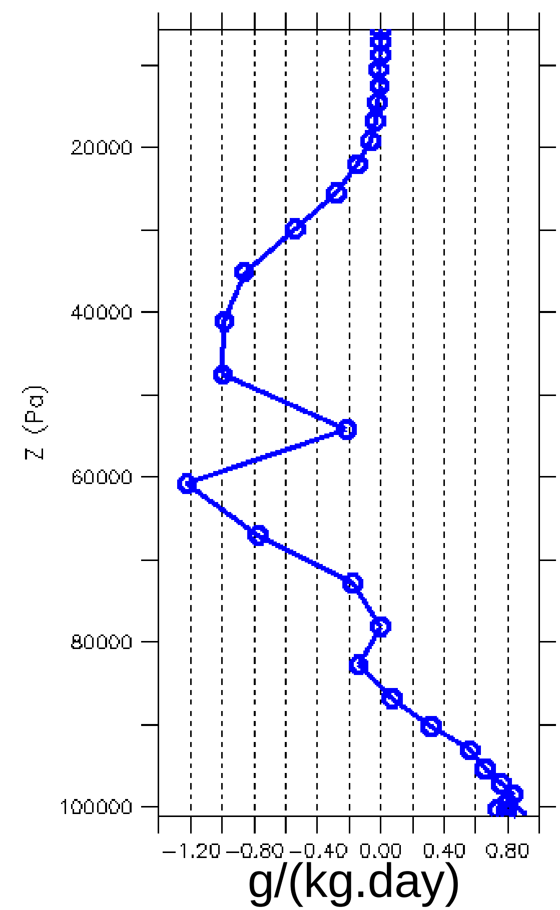
> plot/l=48/thick=3/x=…/y=.../k=10:39 (dqlsc+dqeva)*86400*1000

TWPICE case

(dtlsc+dteva)*
86400



(dqlsc+dqeva)
*86400*1000



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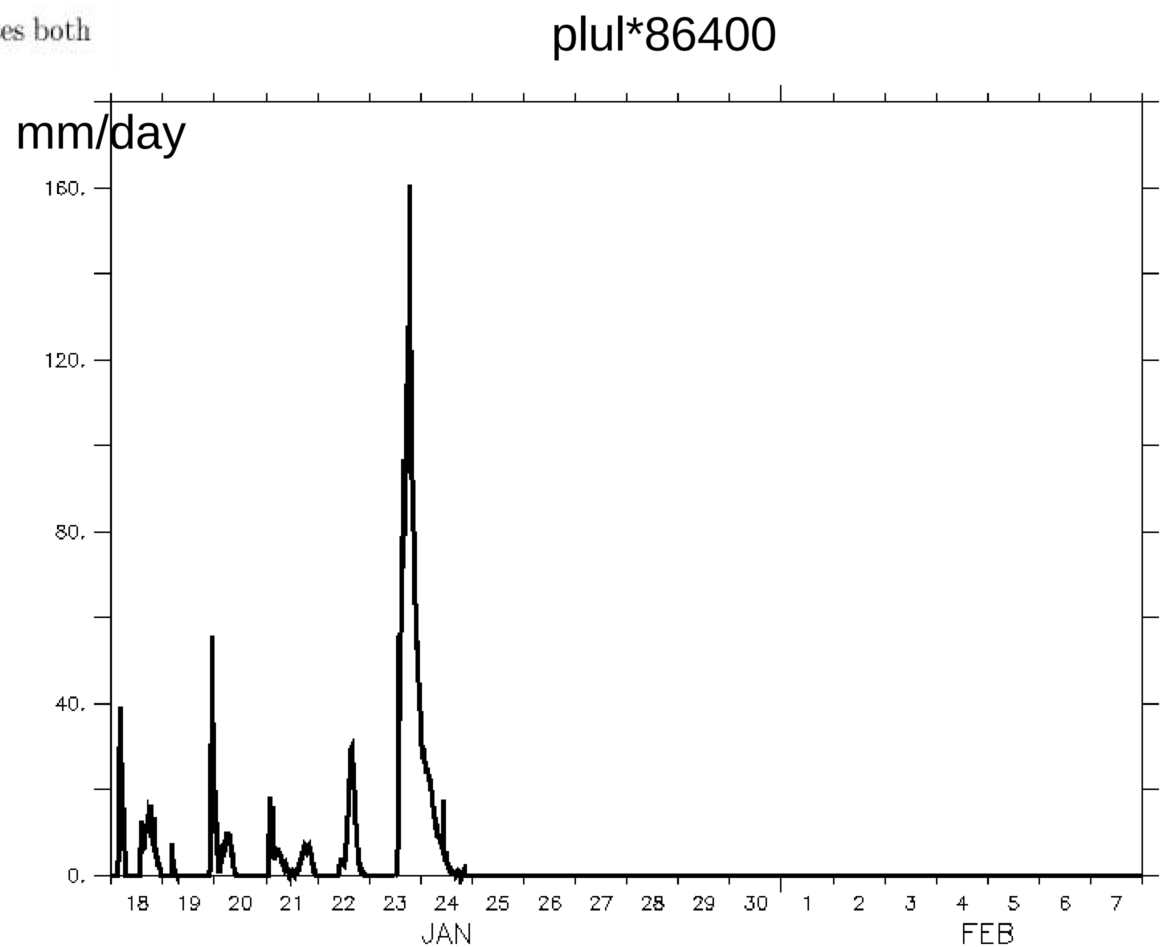
ferret
> use histhf.nc
> plot/l=48/thick=3/x=…/y=… plul*86400

TWPICE case →



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

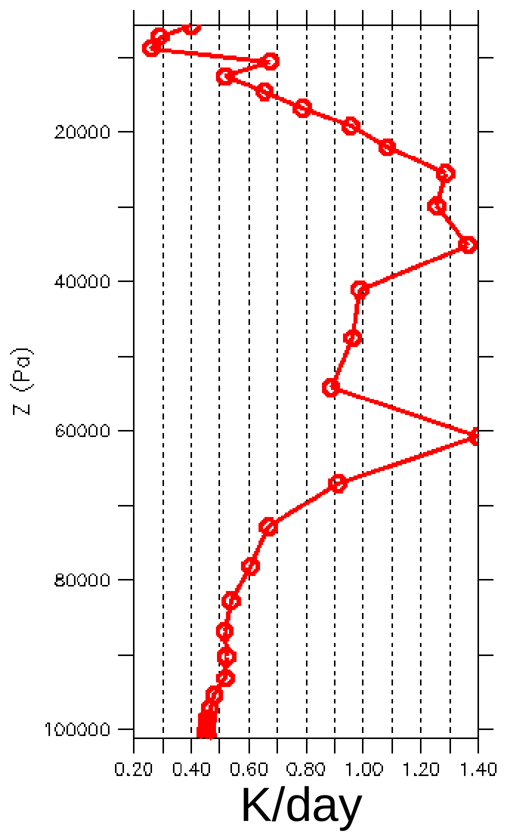
> use histhf.nc

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

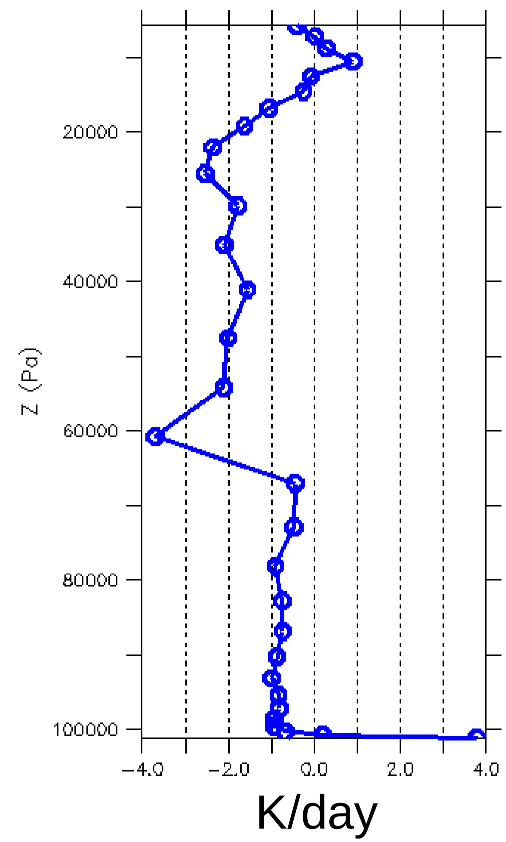
> plot/thick=3/k=10:39 (dtswr[x=@ave,y=-30:30@ave,l=@ave])*86400

TWPICE case →

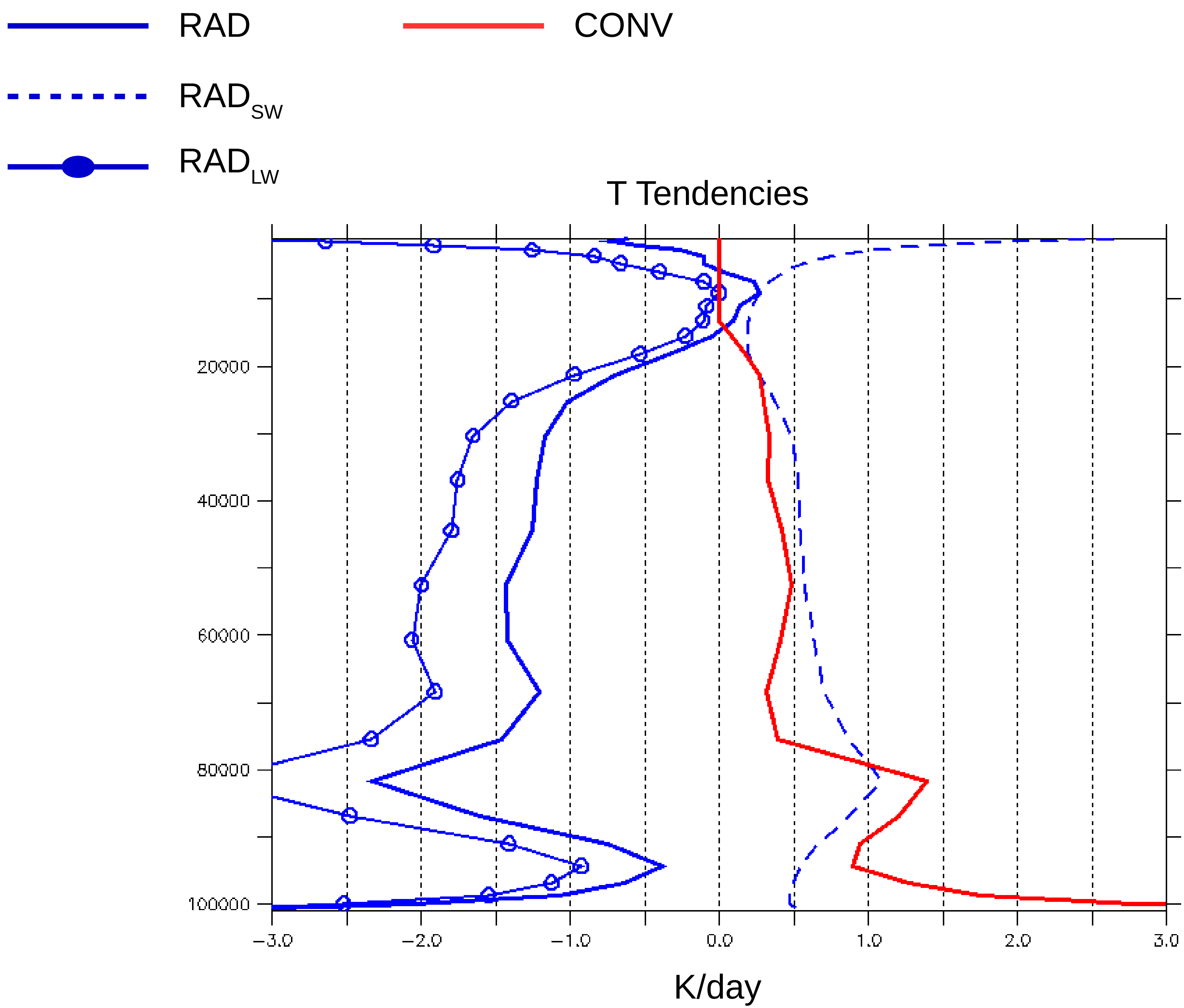
dtswr*86400



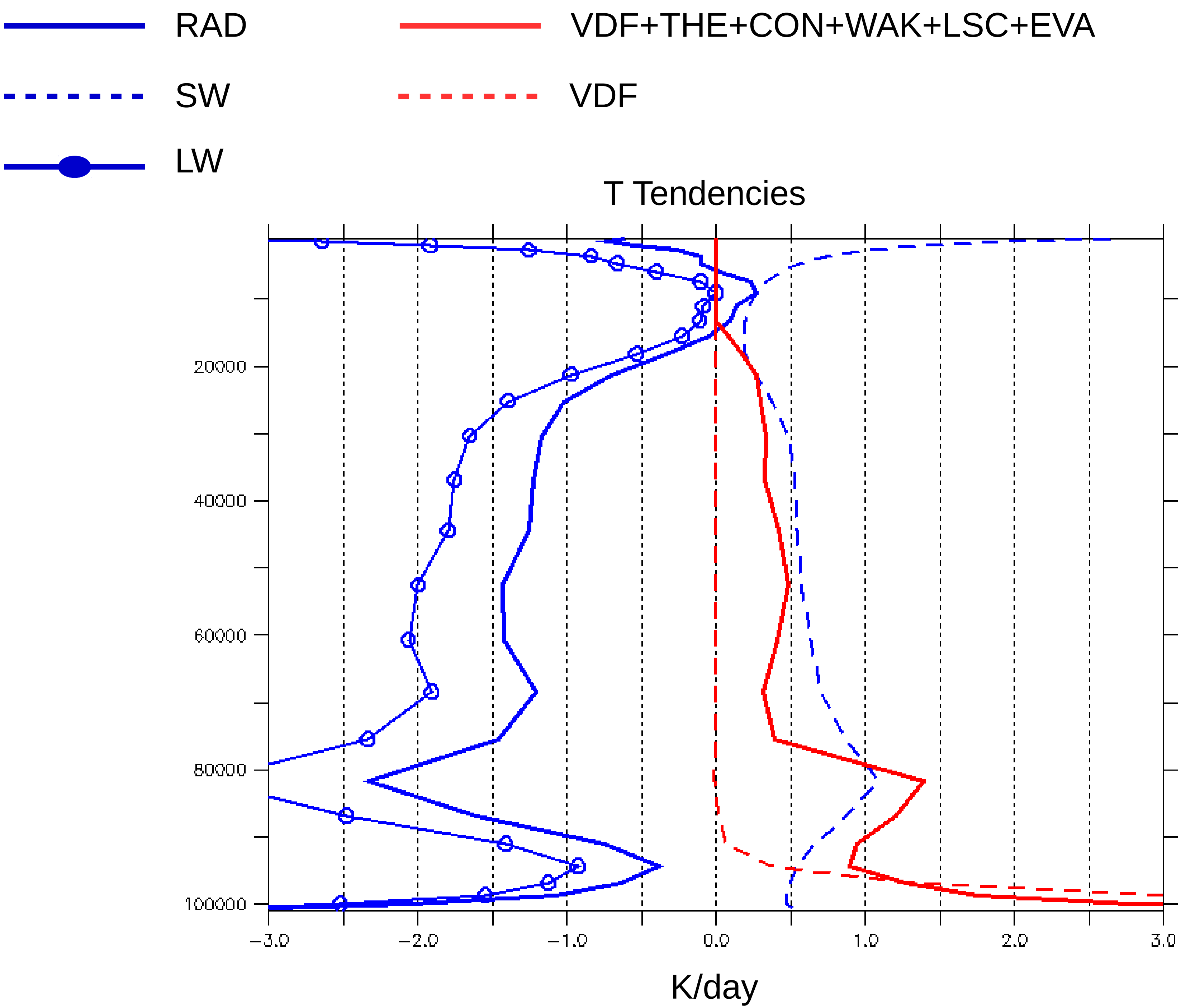
dtlwr*86400



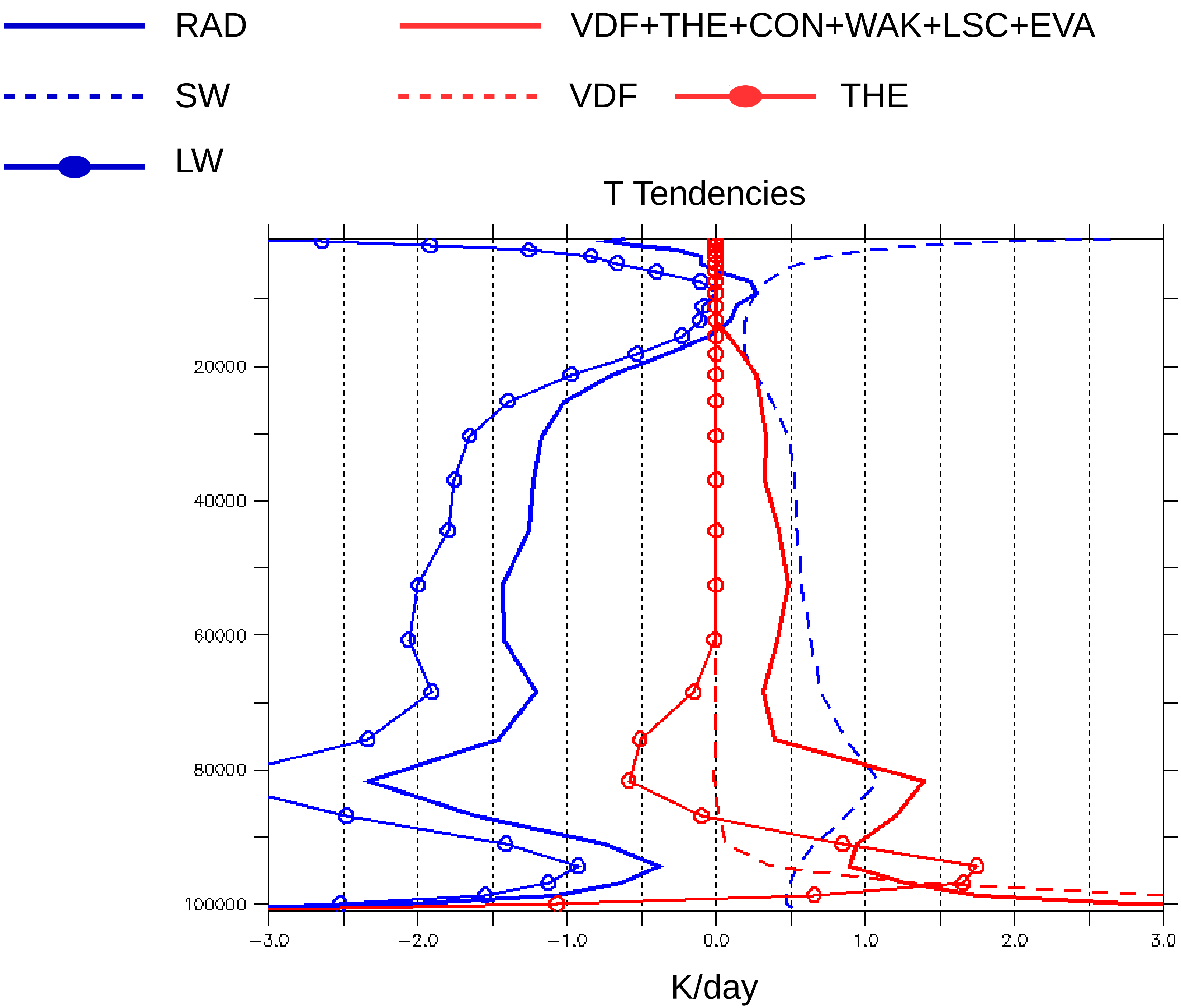
Radiative-Convective Equilibrium over the tropical belt



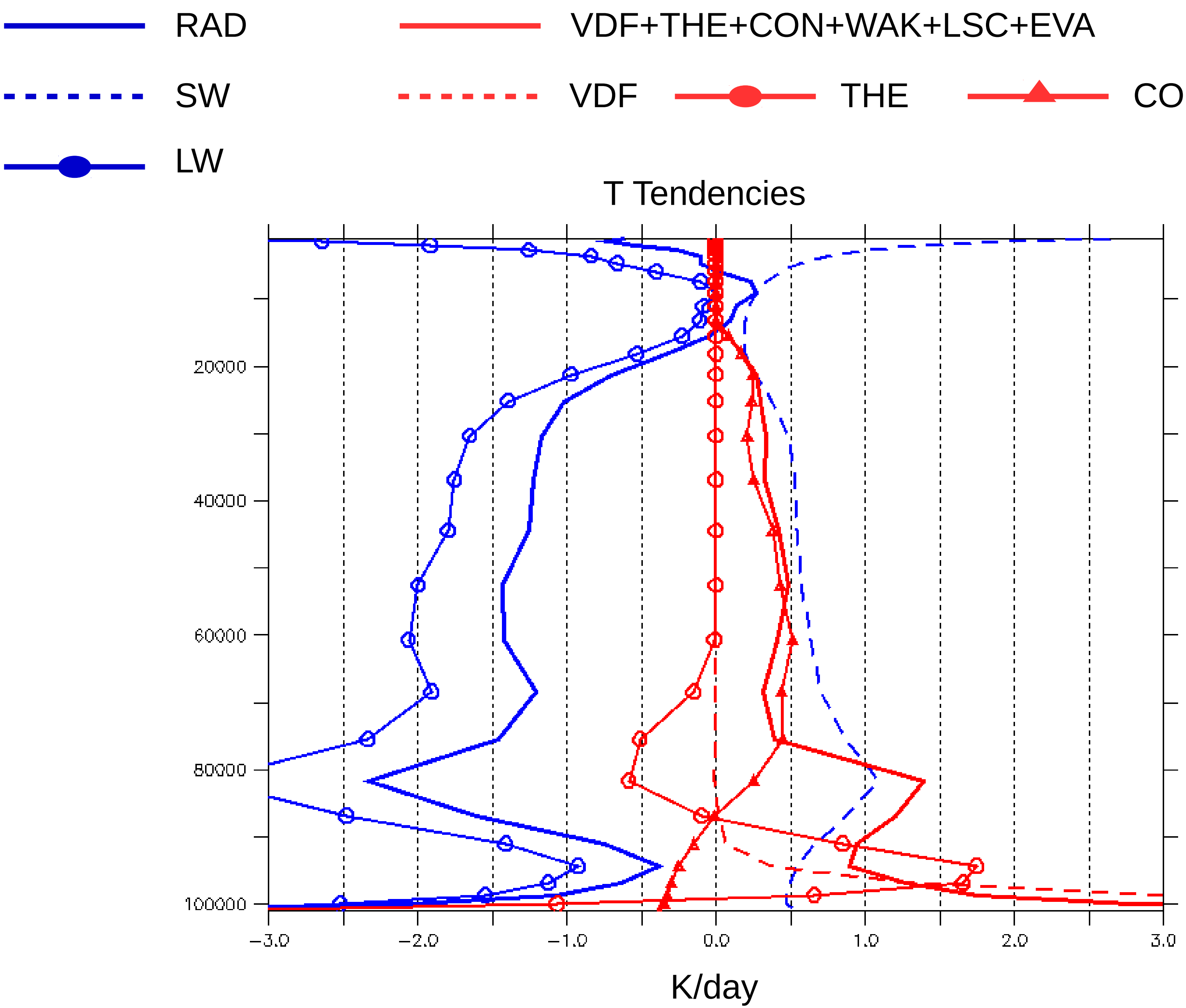
Radiative-Convective Equilibrium over the tropical belt



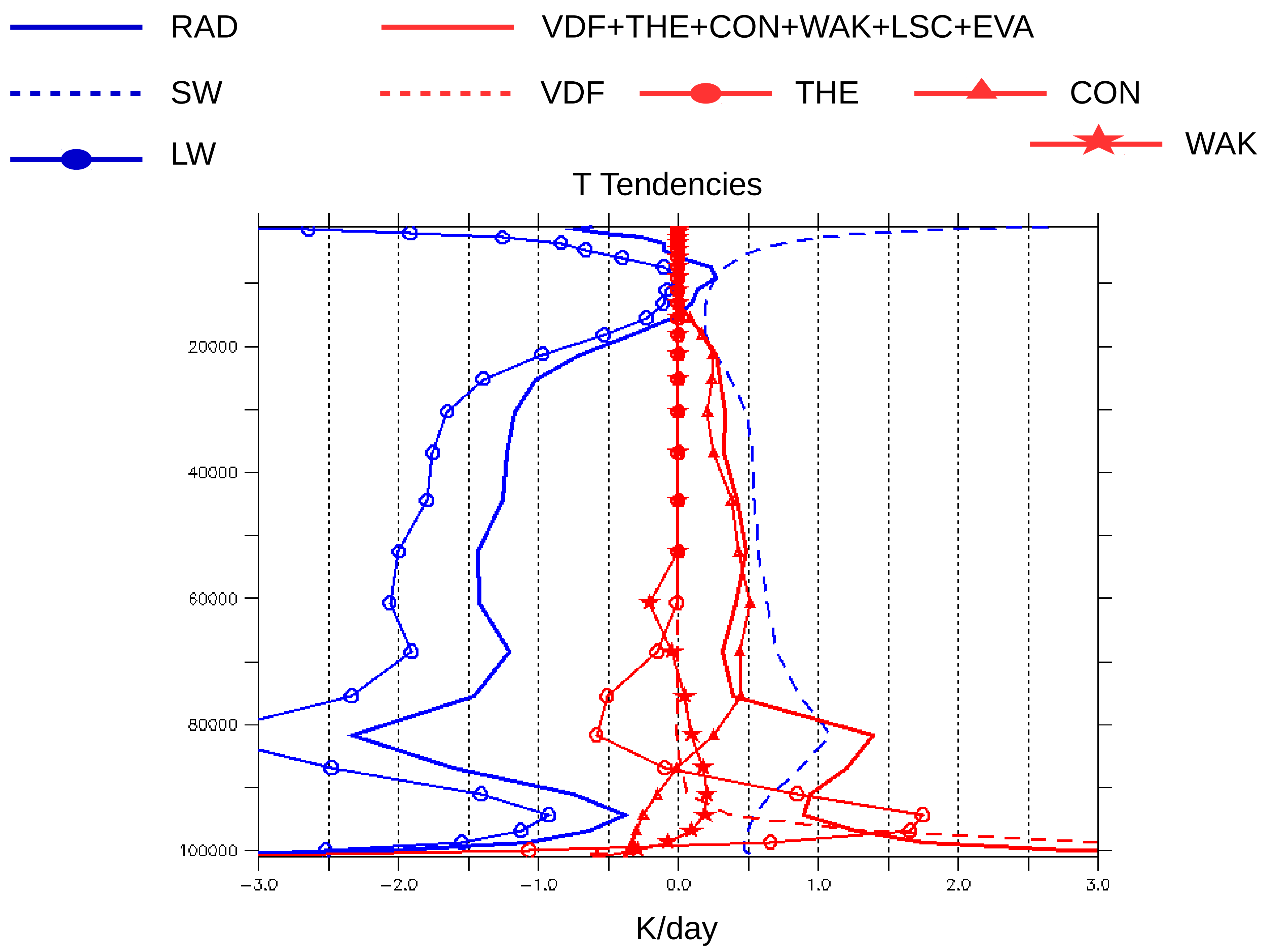
Radiative-Convective Equilibrium over the tropical belt



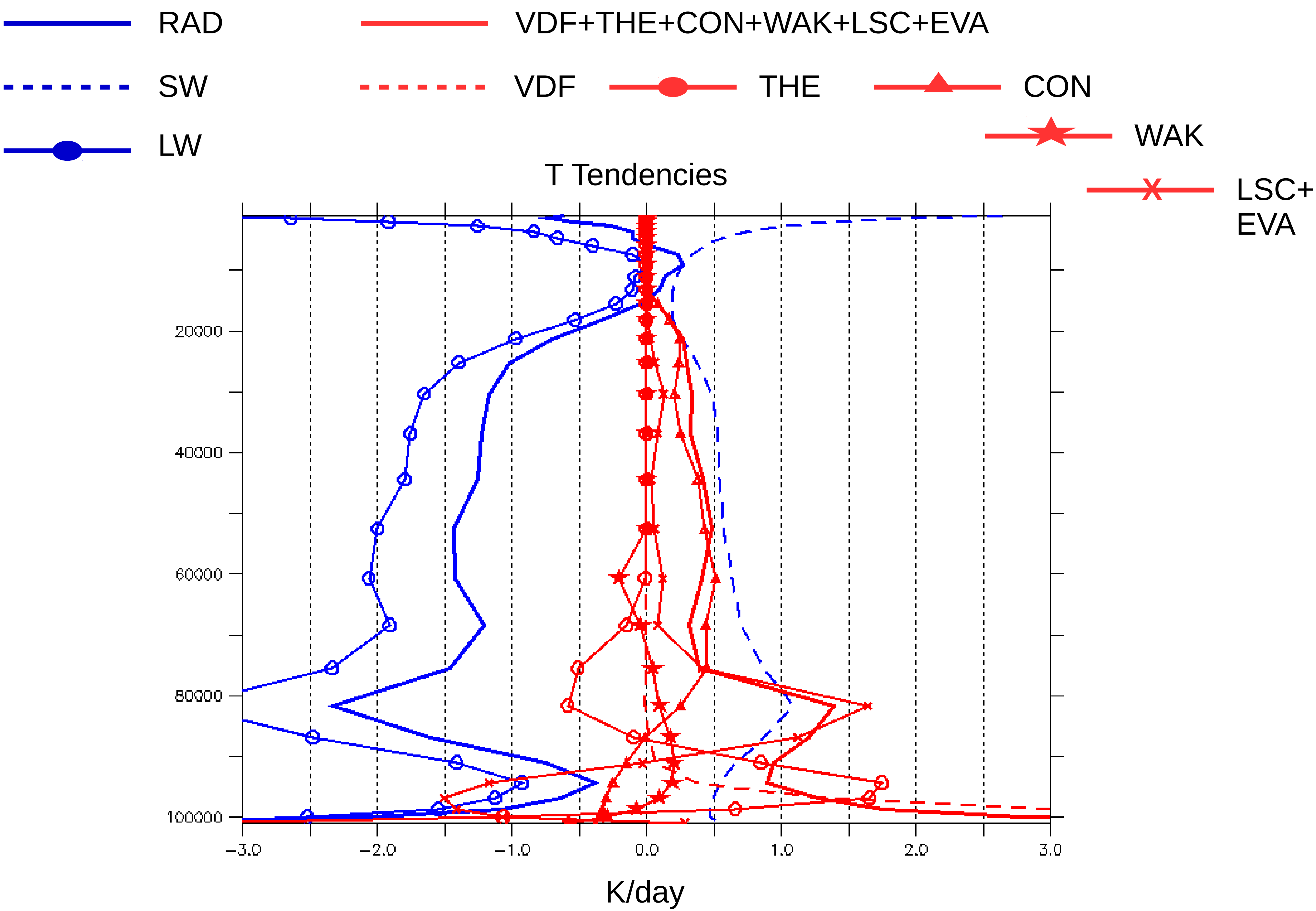
Radiative-Convective Equilibrium over the tropical belt



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 !