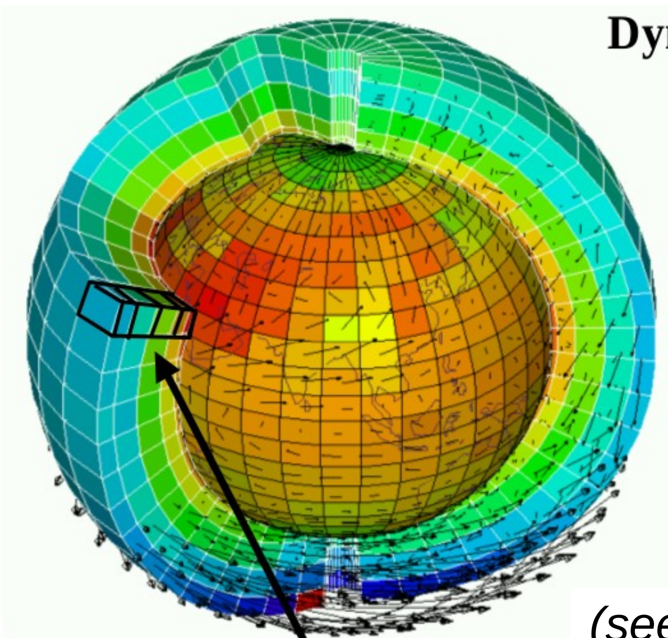
The physical parametrizations in LMDZ

LMDZ Team

Laboratoire de Météorologie Dynamique

December 2017

Quick reminder : general equations



Dynamical core : primitive equations discretized on the sphere

- Mass conservation

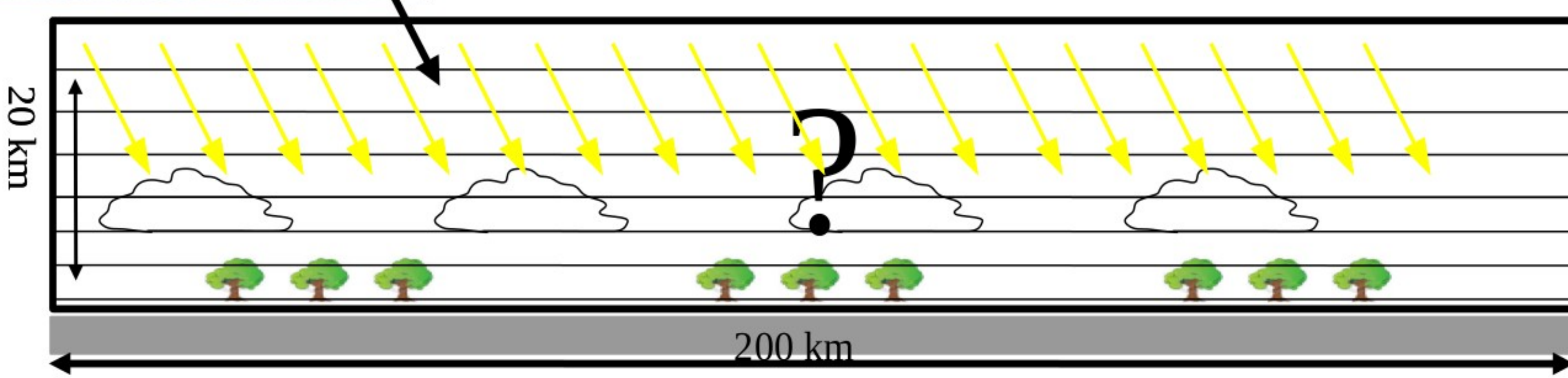
  $D\rho/Dt + \rho\,\mathrm{div}\underline{U} = 0$
- Potential temperature conservation

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



Atmospheric GCM equations

Primitive equations in pressure coordinates

Momentum equation :

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

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 :

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

$\Phi = gz$ 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. . .

Model tendencies

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

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

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

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 :

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

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)
```

Basic facts about parametrizations II

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

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

In the model, the total tendency of q is therefore

$\partial_t q_{\mathrm{dyn}} + \partial_t q_{\mathrm{param}} = \texttt{dqdyn} + \texttt{dqphy}$, where :

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

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*

Turbulent diffusion

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

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

- **Prandtl mixing length** : $K_z = l\,|w|$
  l : characteristic length of the small movements
  w : characteristic velocity
- **Turbulent kinetic energy (TKE)** : $K_z = l\,\sqrt{e}$

$$\begin{aligned} De/Dt &= f(dU/dz, d\theta/dz, e, ...) \\ Dl/Dt &= ... \end{aligned}$$

Turbulent diffusion : numerics

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

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

Spatial discretization : (moisture)

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

Implicit scheme, yields for the first atmospheric layer :

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

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.

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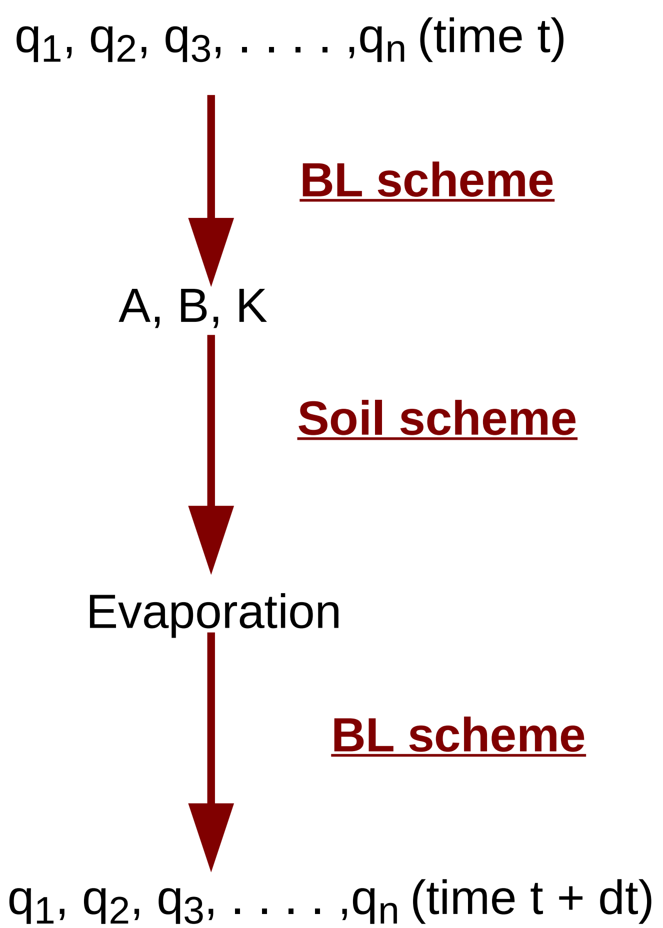


Vertical diffusion

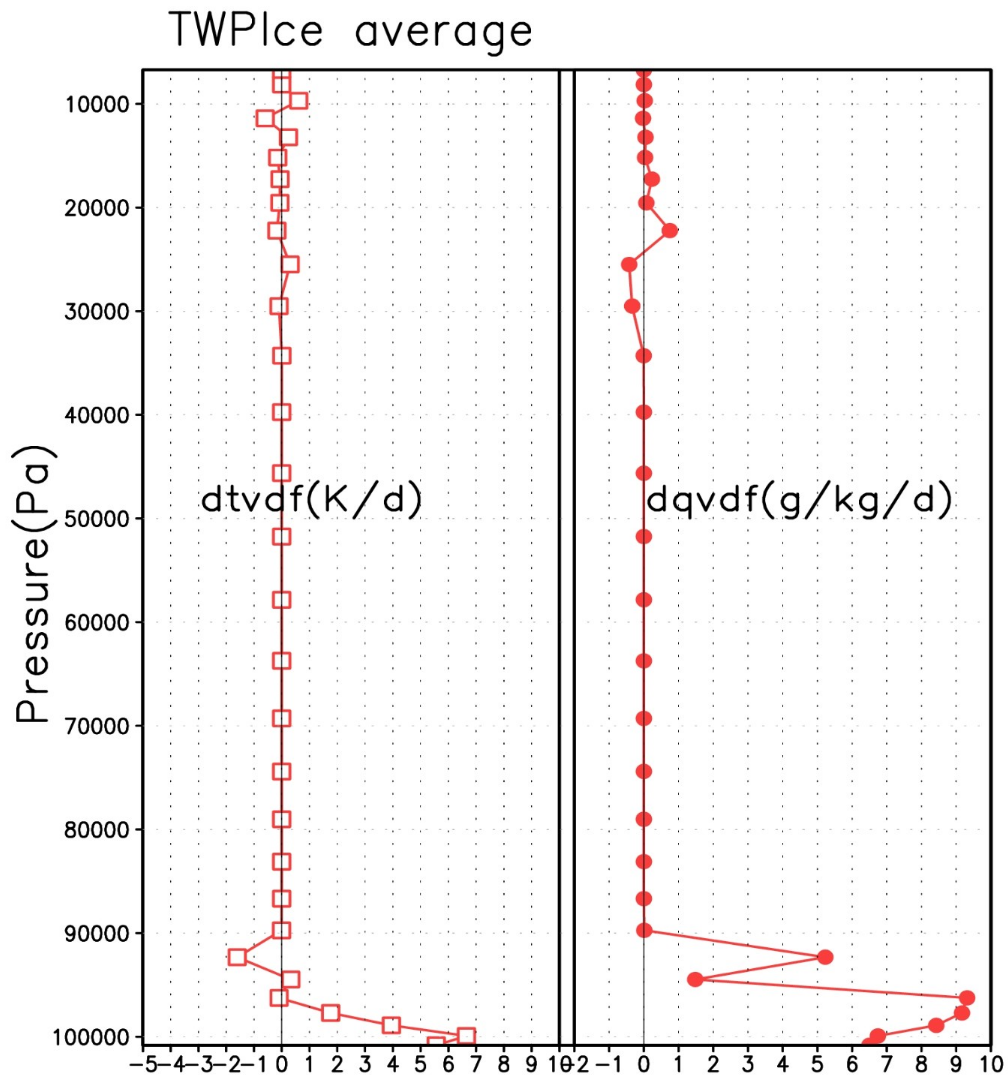
Subroutine : pbl_surface

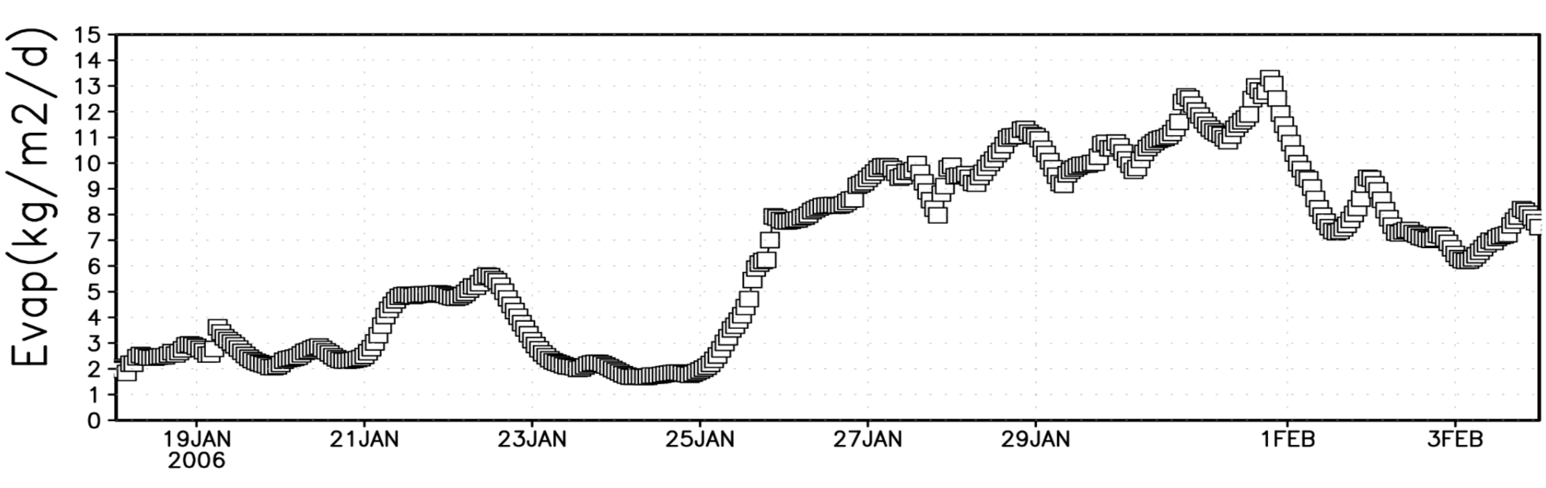
Tendencies :

dtvdf, dqvdf, duvdf, dvvdf

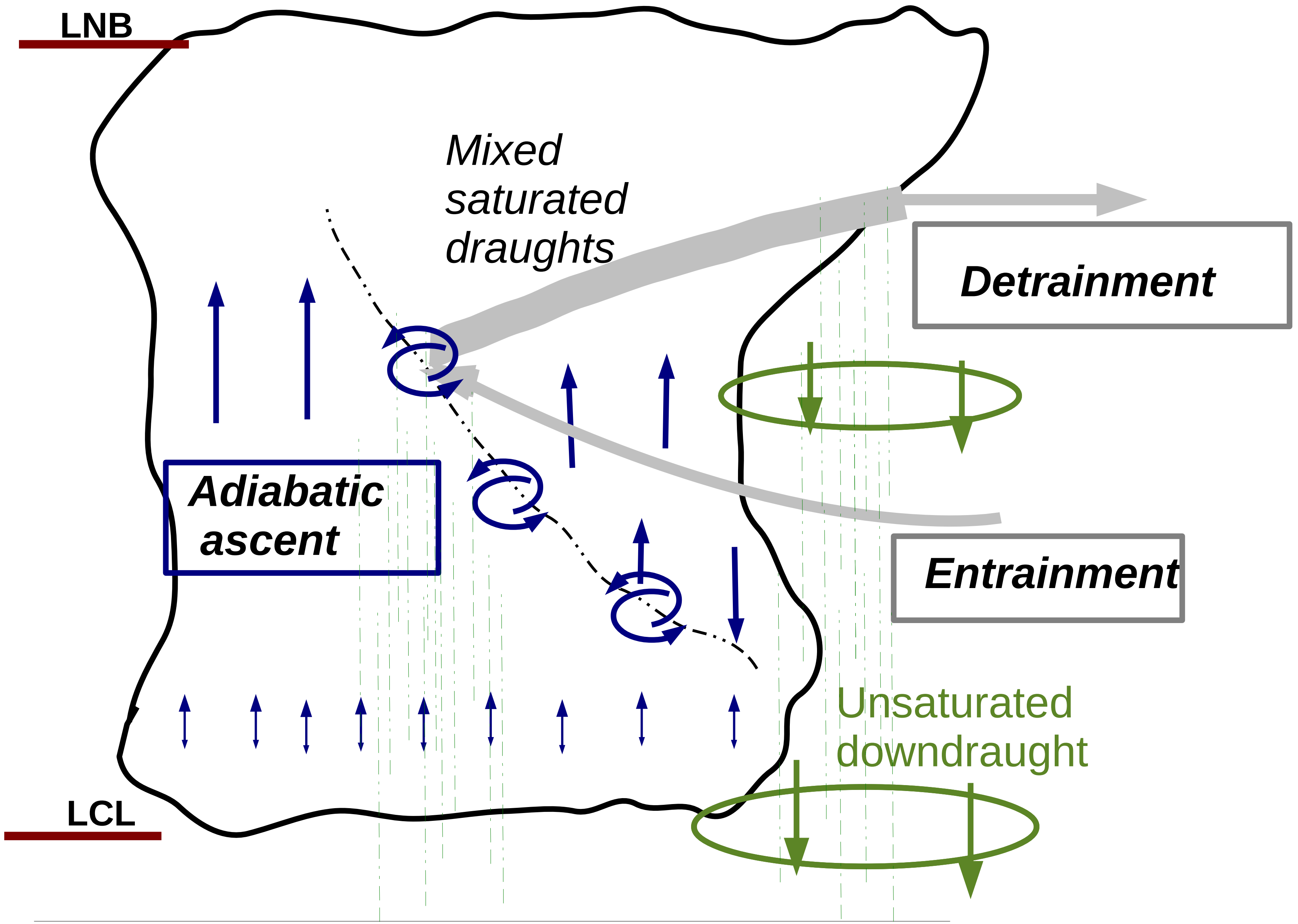
Other variables

- 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





Emanuel scheme



Deep convection

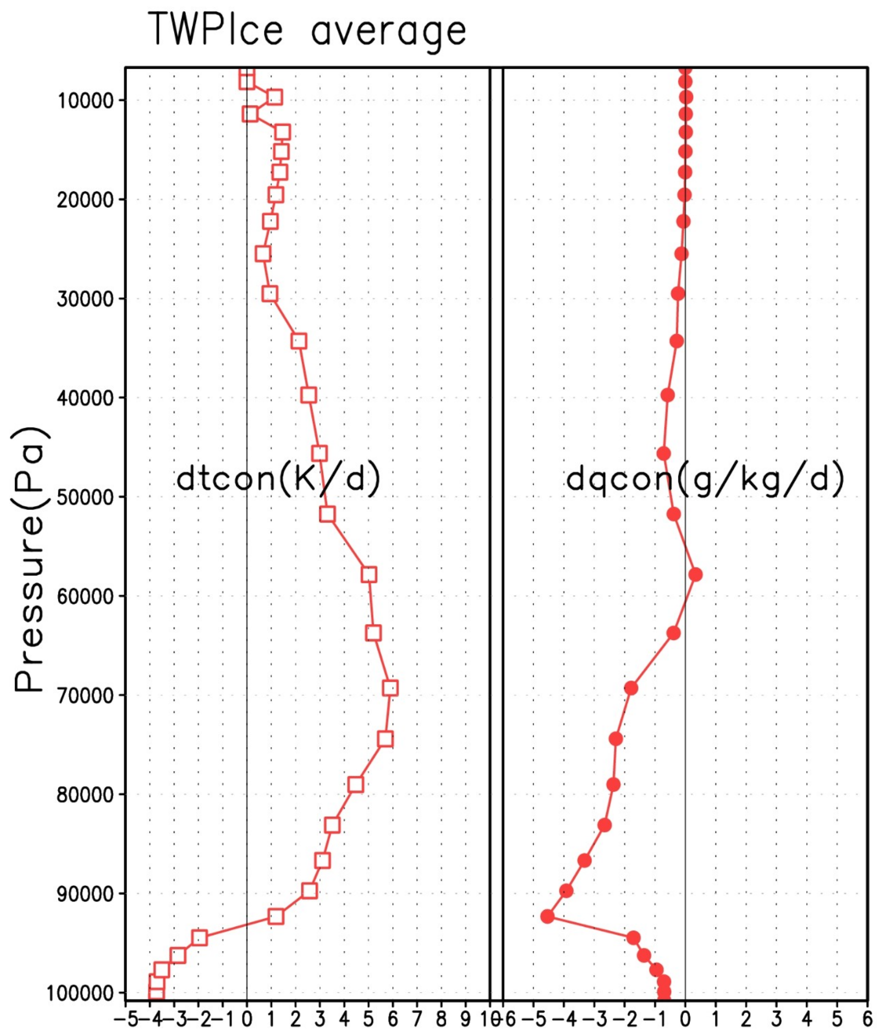
Subroutine : concvl

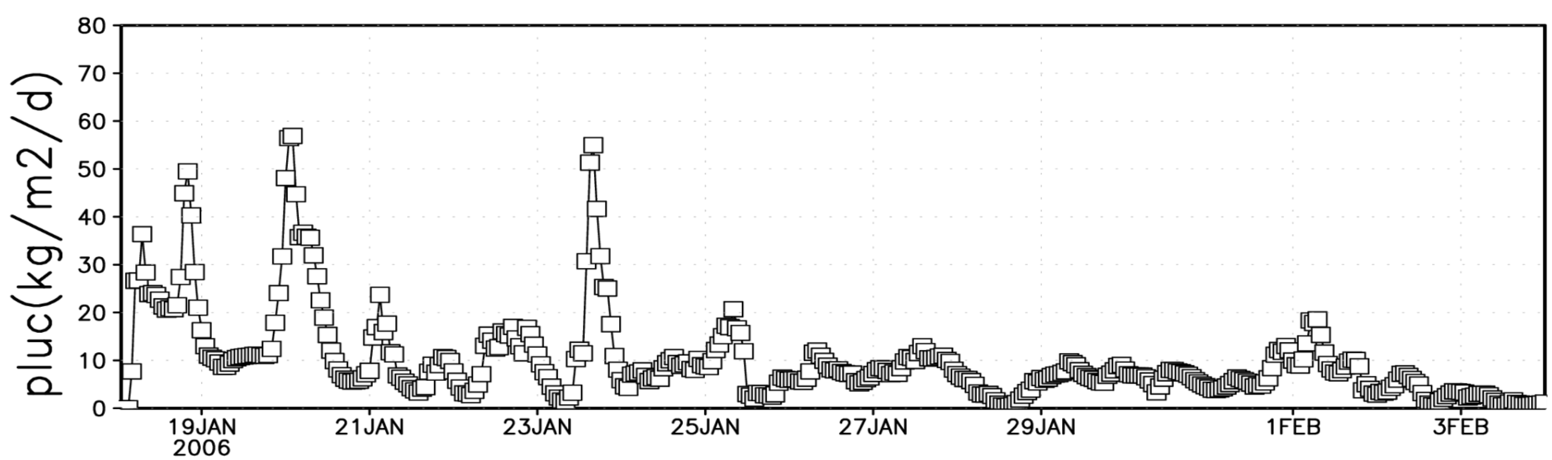
Tendencies :

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





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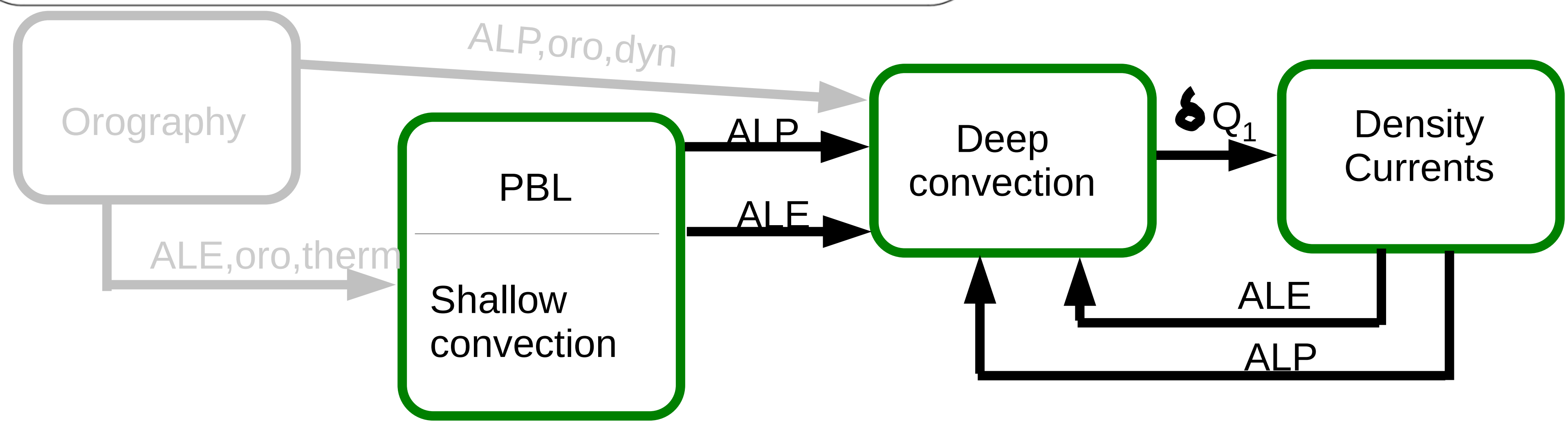
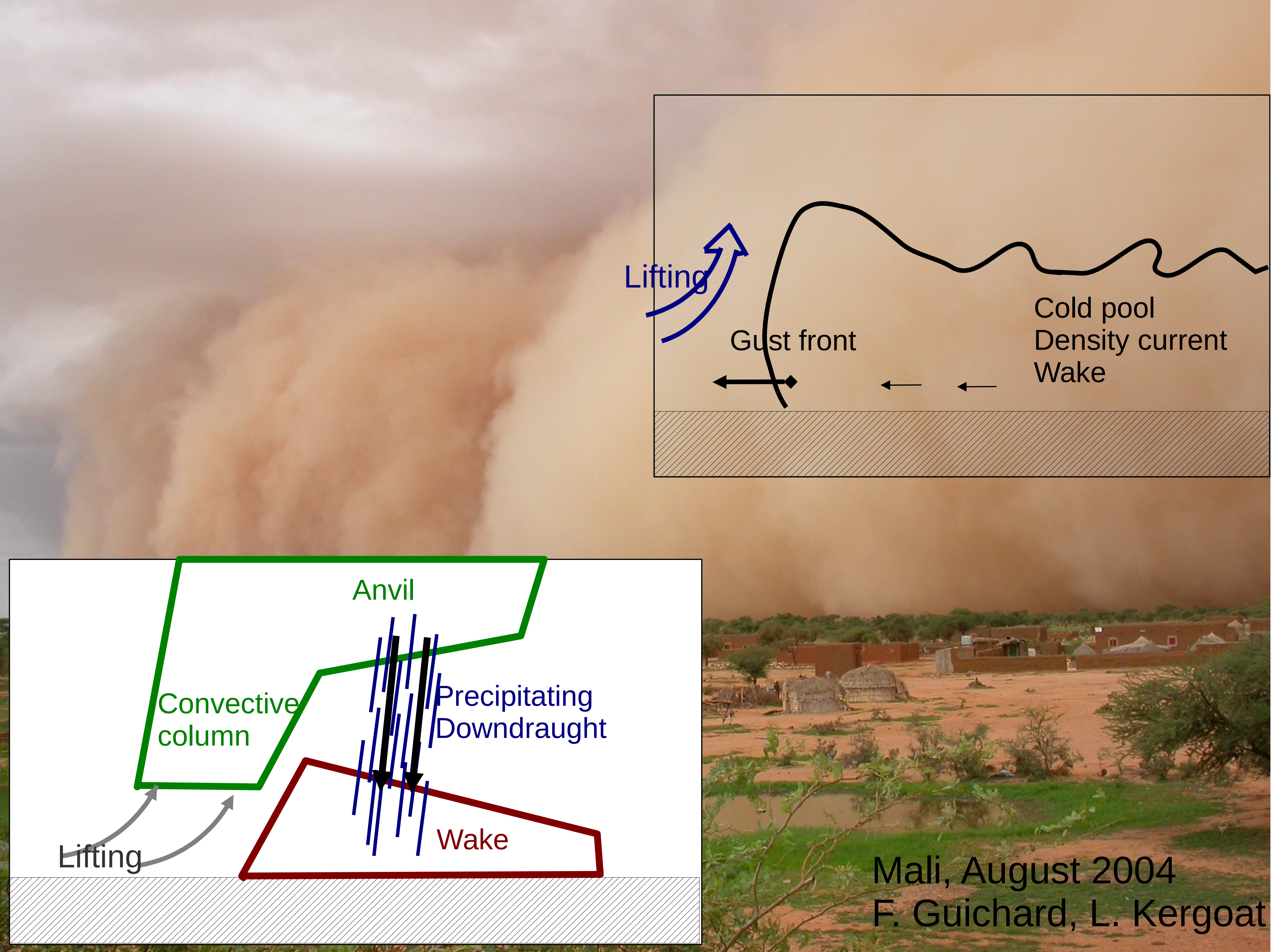
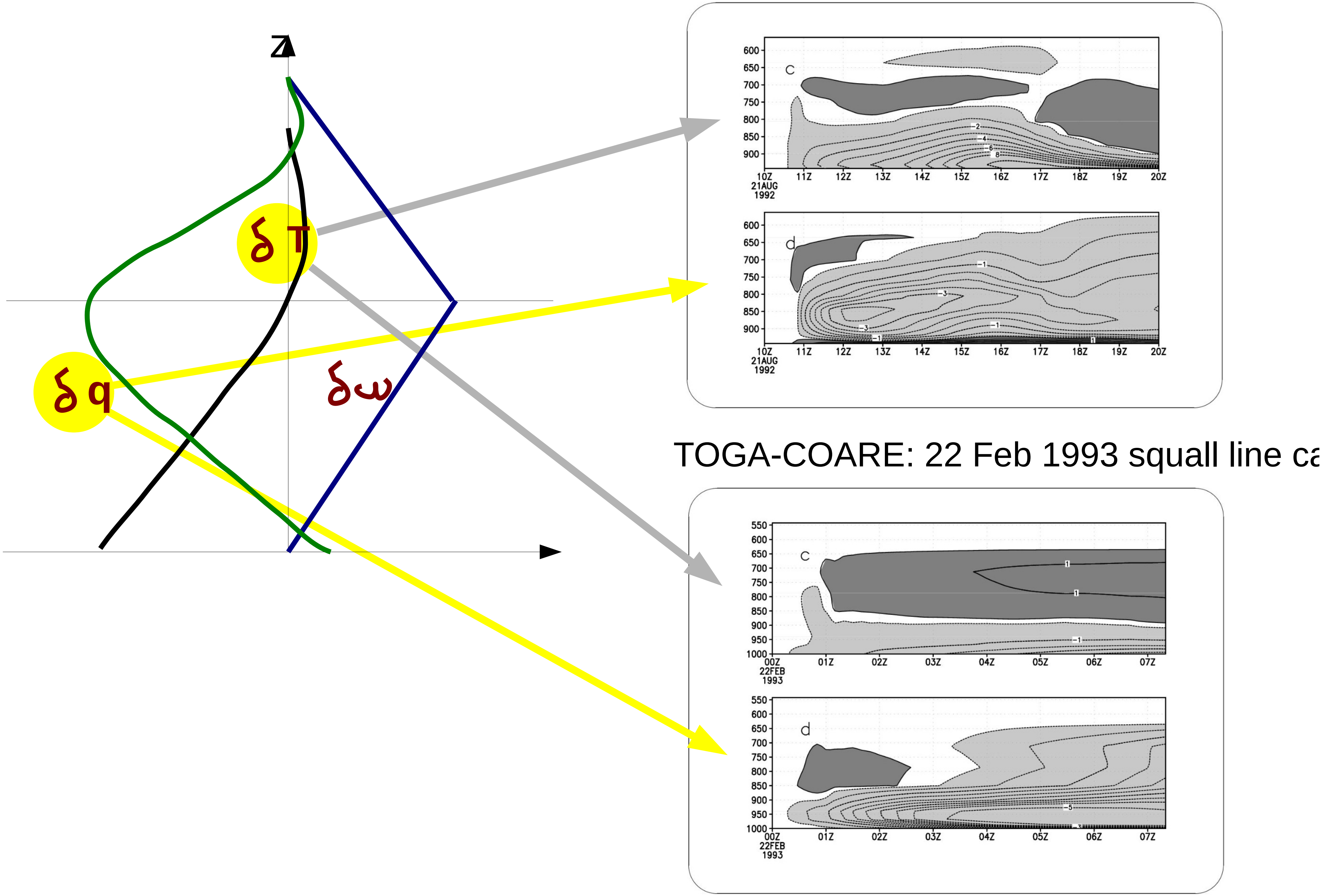



Lifting
Gust front
Cold pool
Density current
Wake
Anvil
Convective
column
Precipitating
Downdraught
Wake
Lifting
Mali, August 2004
F. Guichard, L. Kergoat

Simulated wake properties

HAPEX92: 21 Aug 1992 squall line case



Cold pools (wakes)

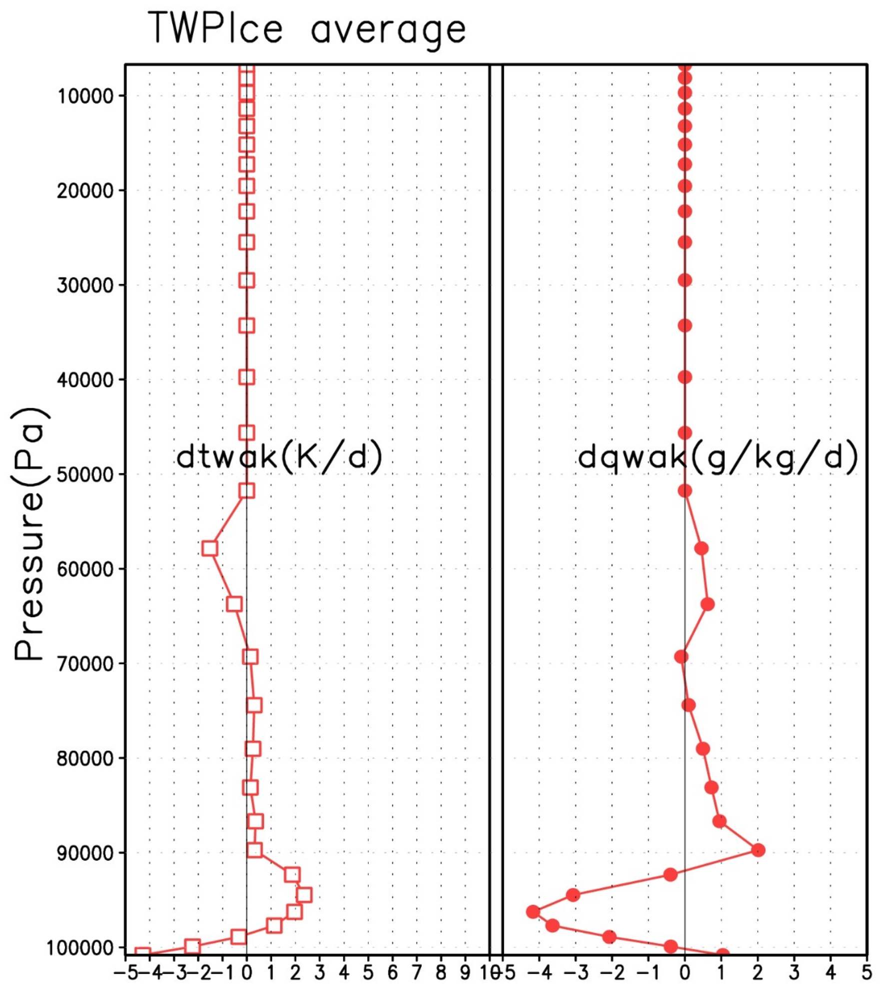
Subroutine : calwake

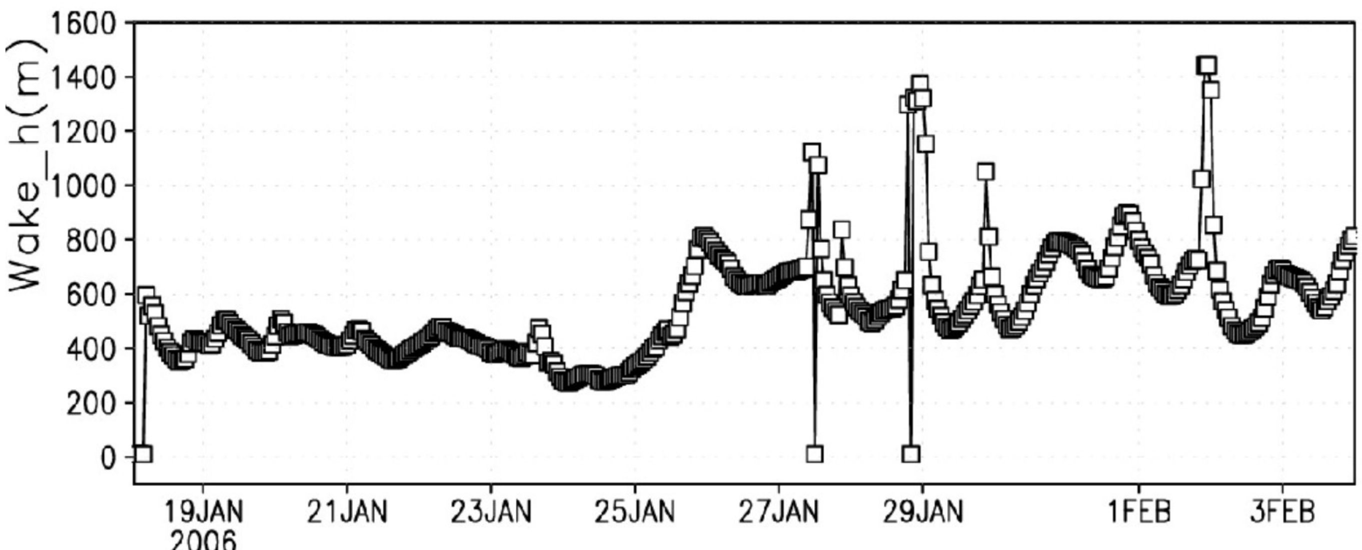
Tendencies :

dtwak, dqwak

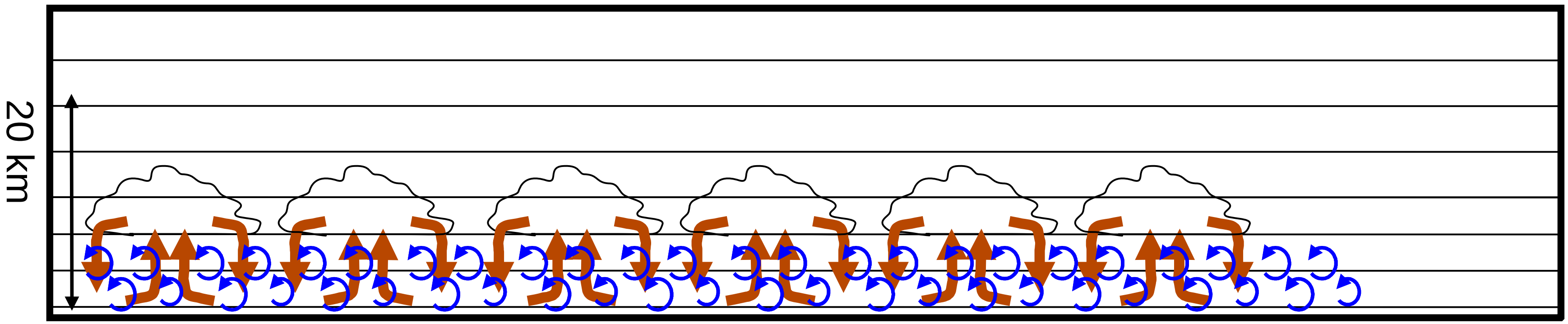
Other variables

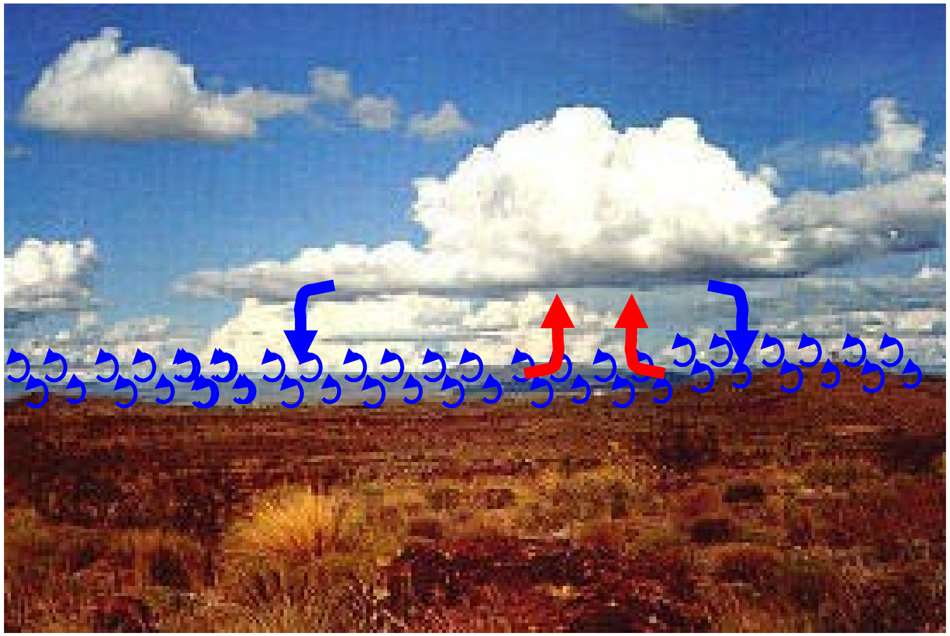
- Alp_wk : lifting power due to cold pools
- Ale_wk : lifting energy due to cold pools
- wake_s : fractional area of cold pools
- wake_h : cold pool height
- wape : WAke Potential Energy
- wake_deltat : vertical profile of temperature difference $T_w - T_x$
- wake_deltaq : vertical profile of humidity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





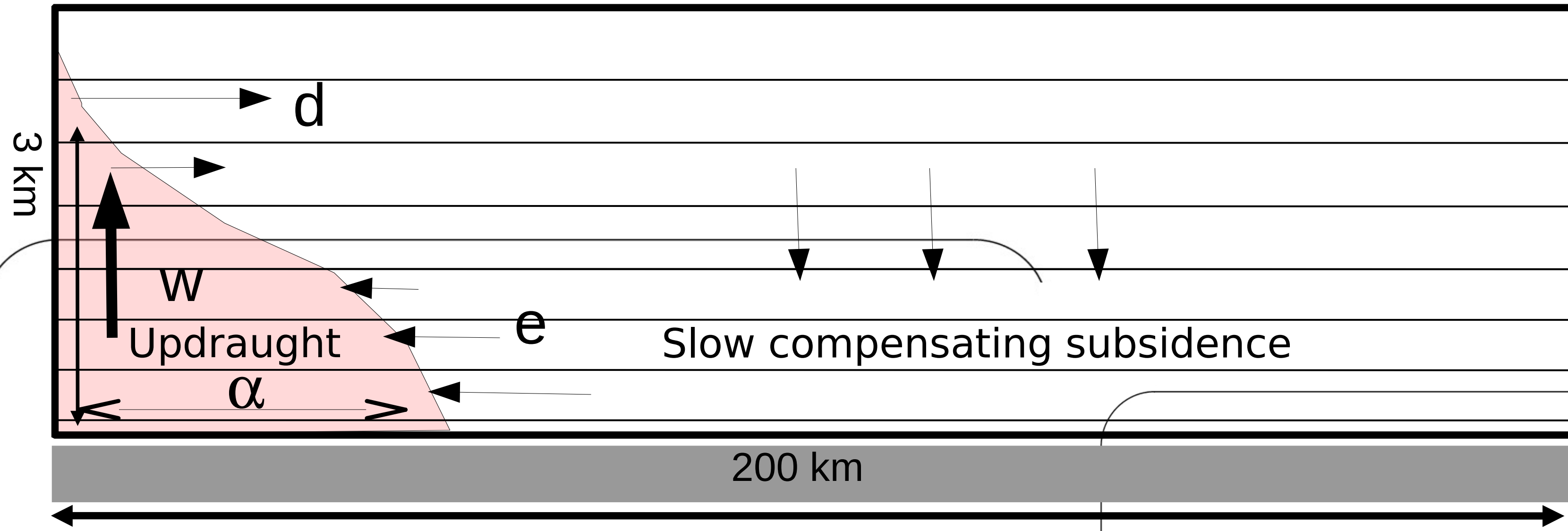
In a model column there are structures of boundary layer scale





"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.



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 :**

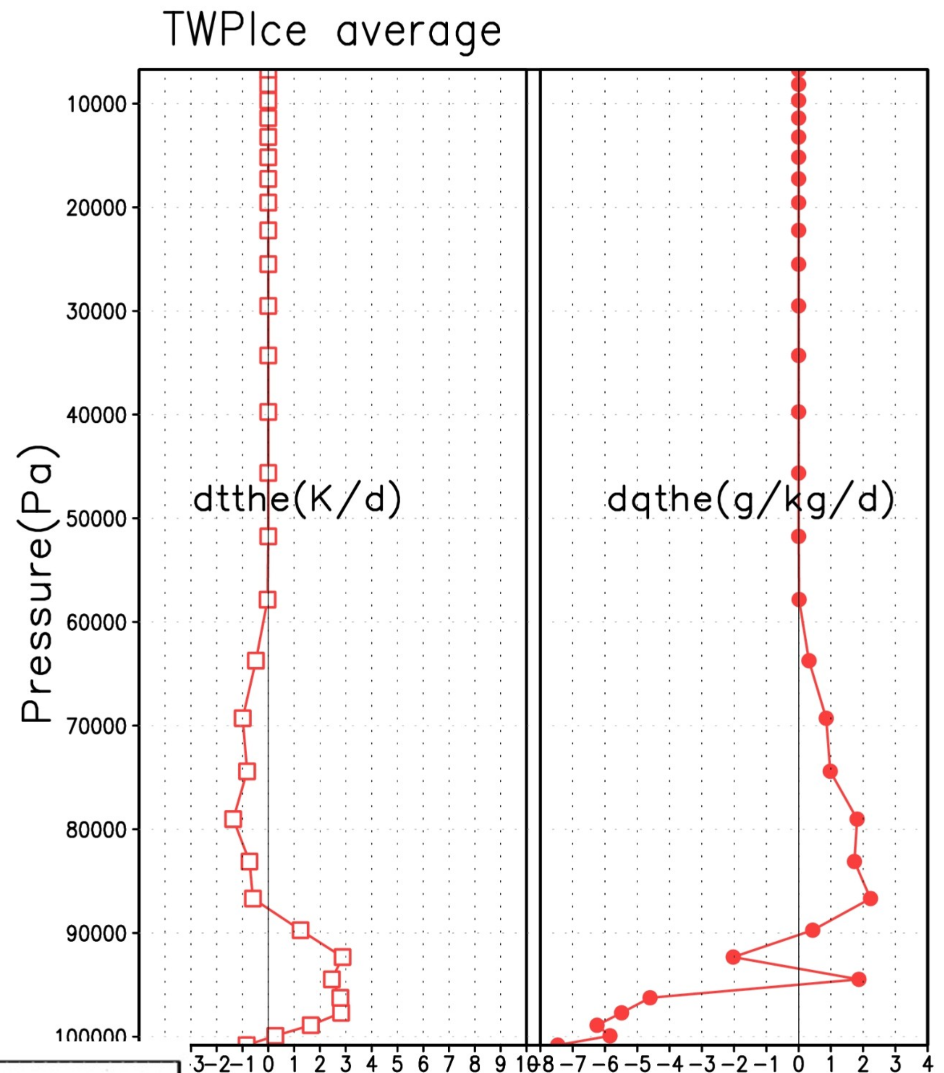
$$B = g\frac{\theta_{va} - \theta_v}{\theta_v}$$

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

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

$$d = ...$$

Etc ...



Thermals and dry adjustment

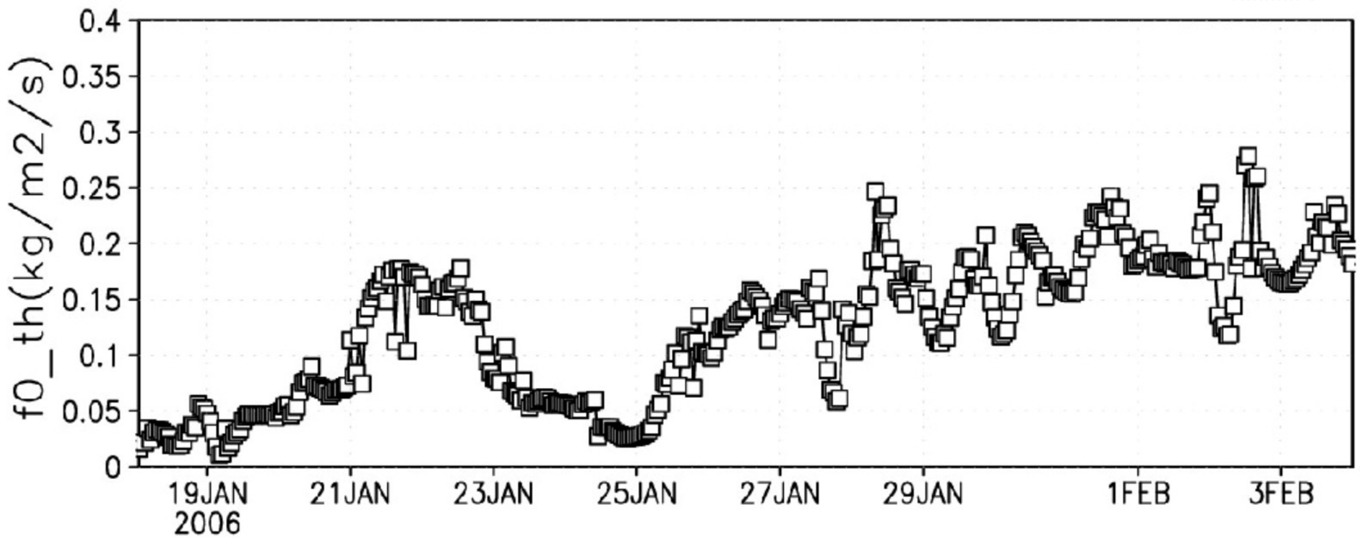
Subroutine : calltherm

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)



Large scale condensation (evap & lsc)

Subroutines : reevap & fisrtilp

Tendencies :

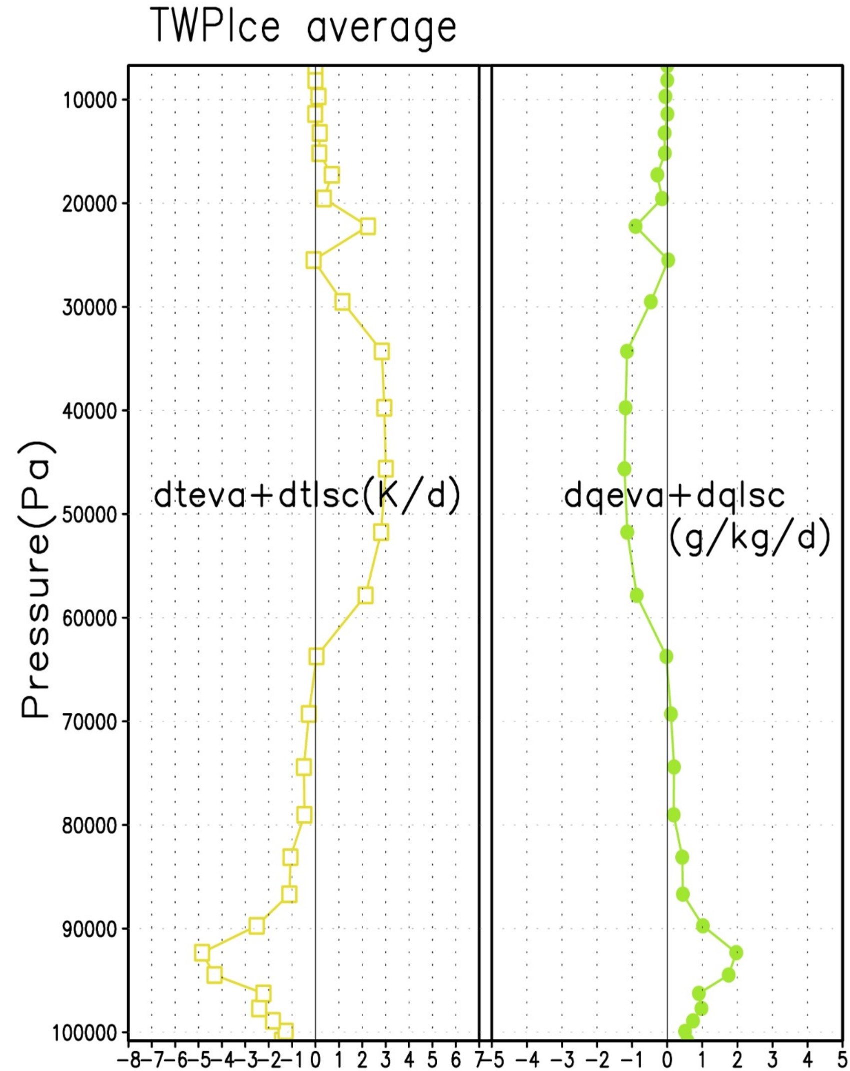
dteva, dqeva : tendencies due to cloud water evaporation

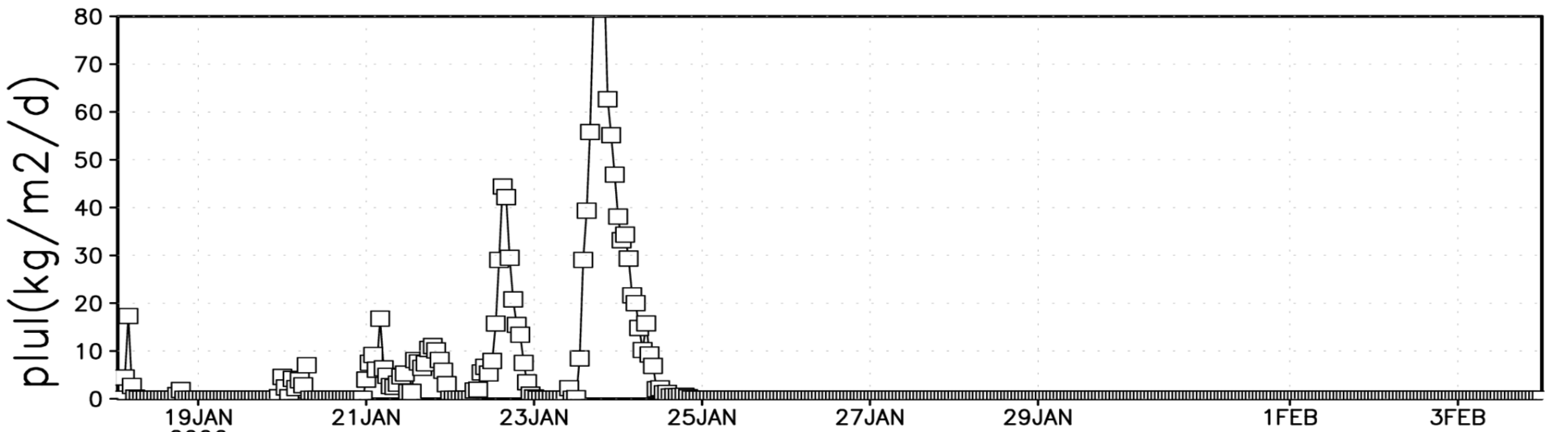
dtlsc, dqlsc : tendencies due to cloud water condensation

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





Radiation I

Subroutine : radlwsw

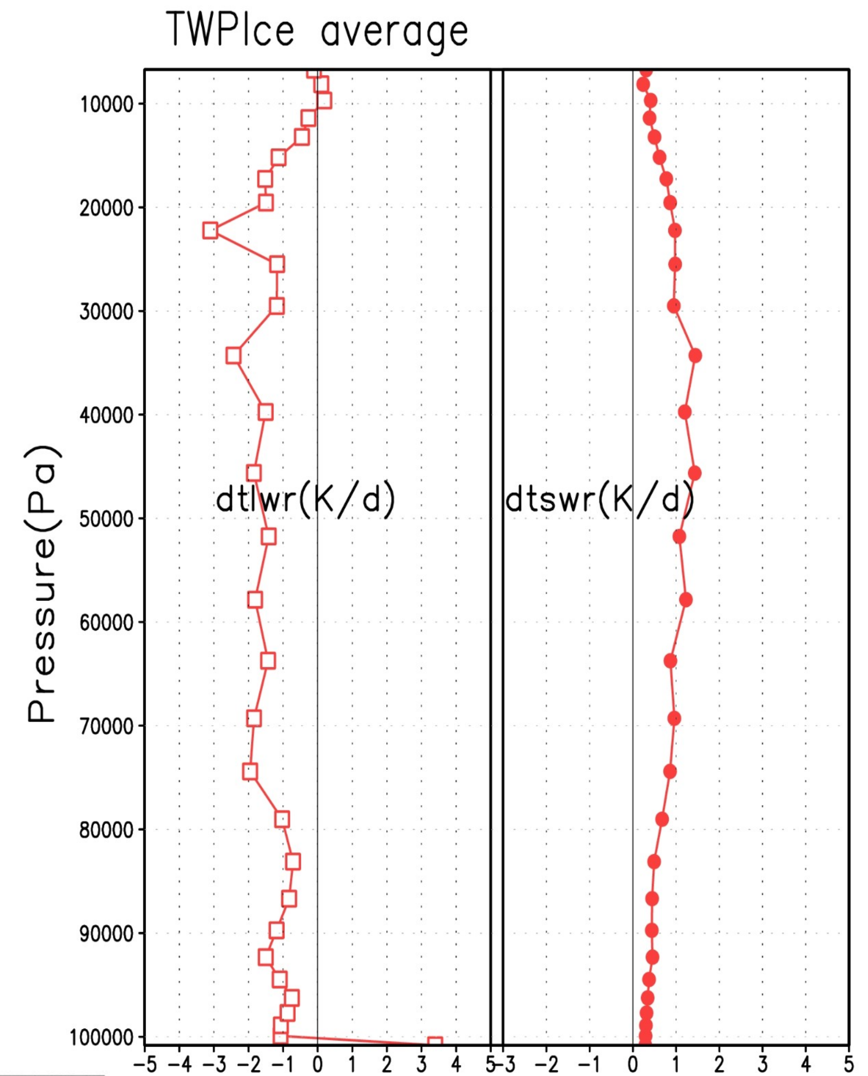
Tendencies :

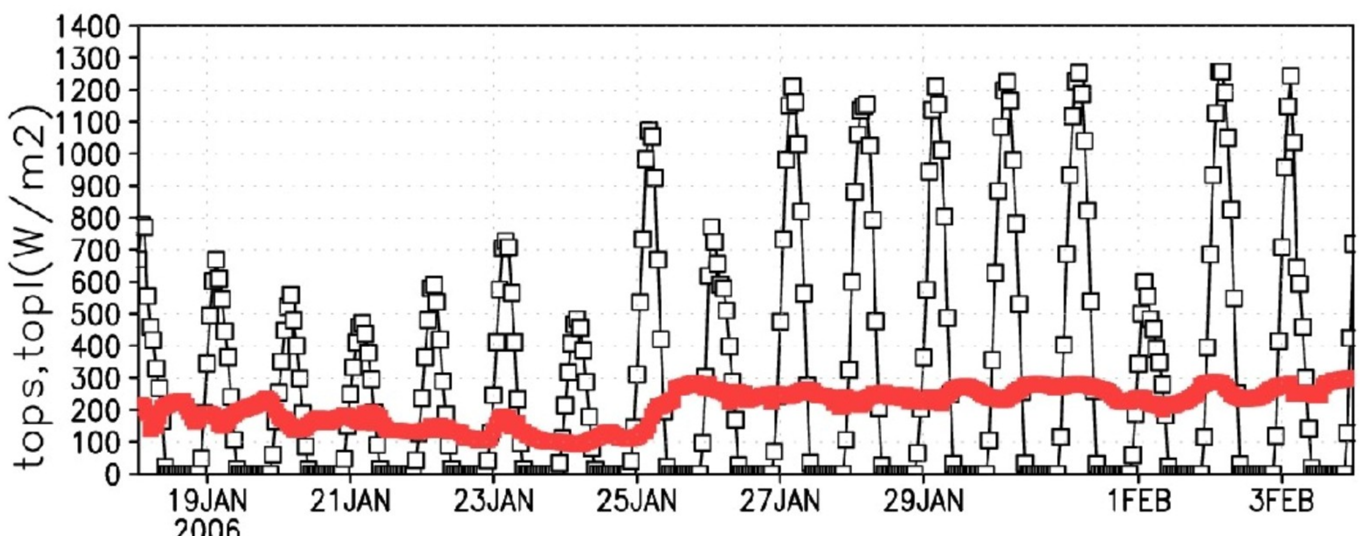
dtswr, dtlwr Temperature tendencies due to solar radiation (SW = short wave) and thermal infra-red (LW = long wave)

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





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)

In the model, this would be **(- sens)**

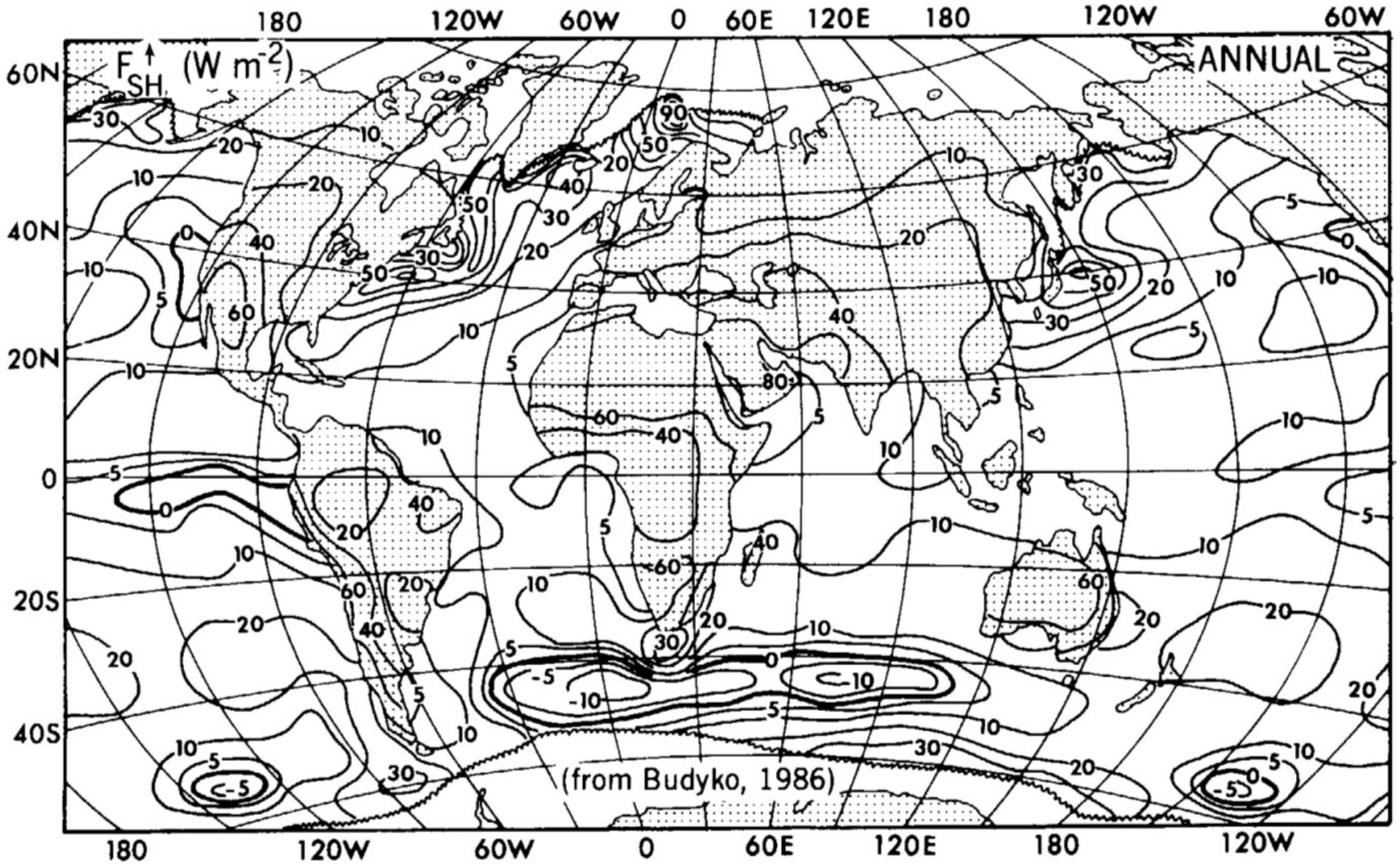


FIGURE 10.8. Global distribution of the sensible heat flux from the earth's surface into the atmosphere in W m^{-2} for annual-mean conditions after Budyko (1986).

hines_gwd

⇒ Parametrization of the momentum flux deposition due to a broad band spectrum of gravity waves.

Sources d'ondes de gravité : Convective, fronts, relief.

Wave mean flow interaction equations :

$$\frac{\partial \bar{u}_g}{\partial t} - f_0 \bar{v} = -\frac{1}{\rho_0}\frac{\partial}{\partial y}\left(\rho_0 \overline{u'_g v'_g}\right)$$

$$\frac{\partial \bar{T}}{\partial t} + N^2 \frac{H}{R}\bar{w} = -\frac{1}{\rho_0}\frac{\partial}{\partial y}\left(\rho_0 \overline{v'_g T'}\right) + \frac{\bar{J}}{c_p}$$

Transformed Eulerian mean Equations :

$$\frac{\partial \bar{u}_g}{\partial t} - f_0 \bar{v}^* = \frac{1}{\rho_0}\vec{\nabla}\cdot\vec{F} + \bar{X}$$

$$\frac{\partial \bar{T}}{\partial t} + N^2 \frac{H}{R}\bar{w}^* = \frac{\bar{J}}{c_p}$$

Avec $(\bar{v}^*, \bar{w}^*)$: "residual mean circulation"

$$\bar{v}^* = \bar{v} - \frac{1}{\rho_0}\frac{R}{H}\frac{\partial}{\partial z}\left(\rho_0 \frac{\overline{v'_g T'}}{N^2}\right)$$

$$\bar{w}^* = \bar{w} + \frac{1}{\rho_0}\frac{R}{H}\frac{\partial}{\partial y}\left(\rho_0 \frac{\overline{v'_g T'}}{N^2}\right)$$

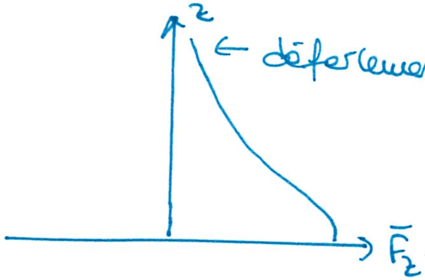
$\vec{F}$ flux d'Eliassen-Palm $\quad \vec{F} = \vec{c_g}\cdot A$

Pour Ondes de gravité :

- Niveau critique de déferlement : $|\hat{\omega}| = |\omega - ku| \to 0$
  $\hat{\omega}$ fréquence intrinsèque
- sign $(\bar{F}_z)$ = − sign $(\hat{\omega})$

$\hat{\omega} < 0$, $k > 0$ } $\hat{c}_\varphi < 0 \quad \bar{F}_z > 0$

Propagation de la Phase vers l'Ouest

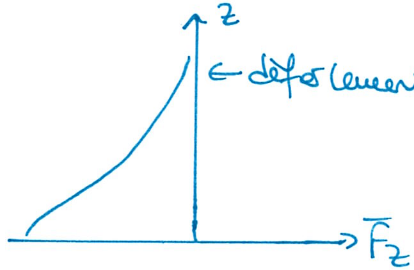


$\frac{d\bar{F}_z}{dz} < 0 \Rightarrow \frac{\partial \bar{u}}{\partial t} < 0$

Freine le vent moyen

$\hat{\omega} > 0$, $k > 0$; $\hat{c}_\varphi > 0 \quad \bar{F}_z < 0$

Propagation de la Phase vers l'Est



$\frac{d\bar{F}_z}{dz} > 0 \Rightarrow \frac{\partial \bar{u}}{\partial t} > 0$

Accélère le vent moyen

⇒ Quasi-Biennal Oscillation

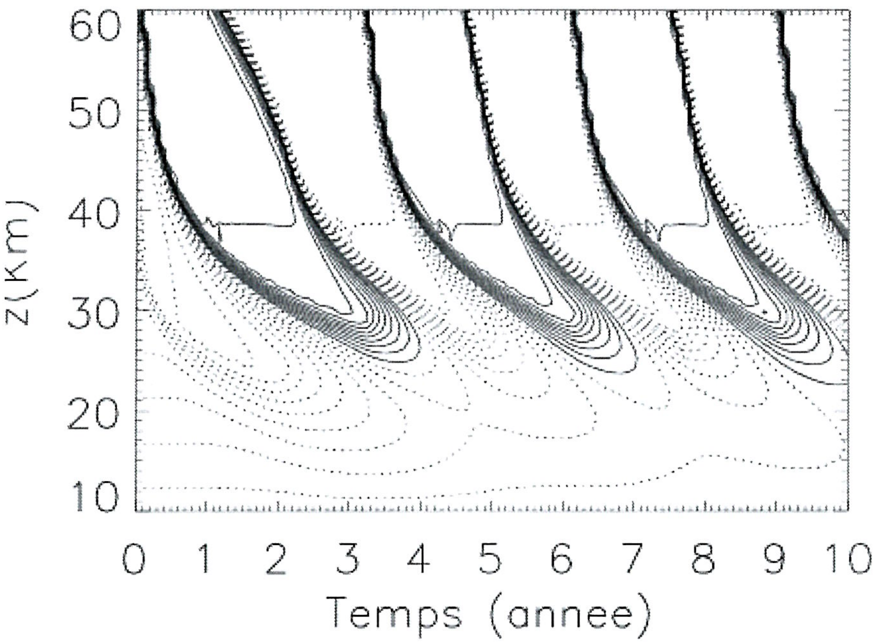
Altitude de déferlement des ondes de gravité :

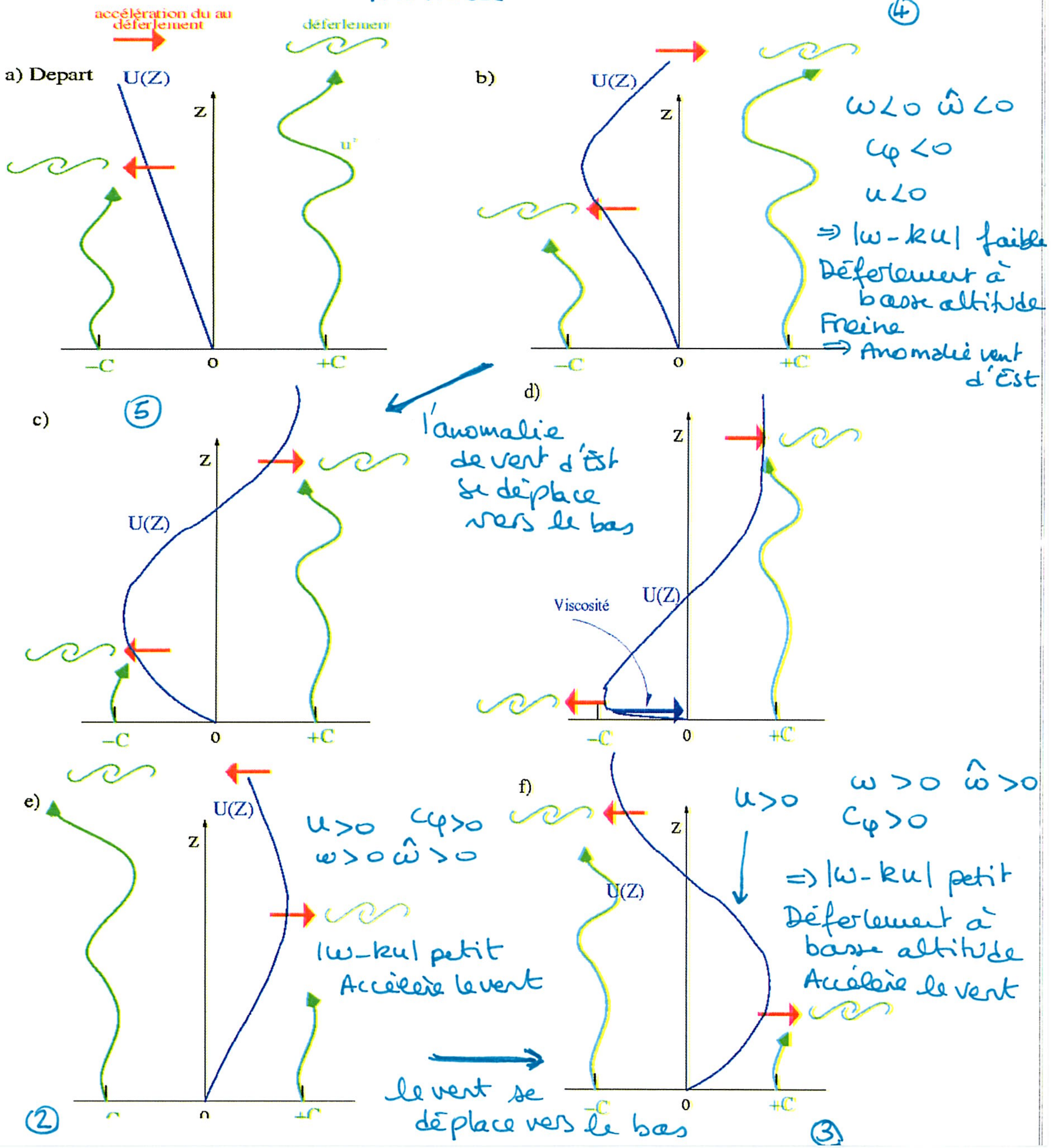
$$z = 2H \ln\left(\frac{|\omega - ku|}{|m|\, w_0}\right)$$

- $\hat{\omega} > 0$ Accélère le vent moyen
- $\hat{\omega} < 0$ Freine le vent moyen

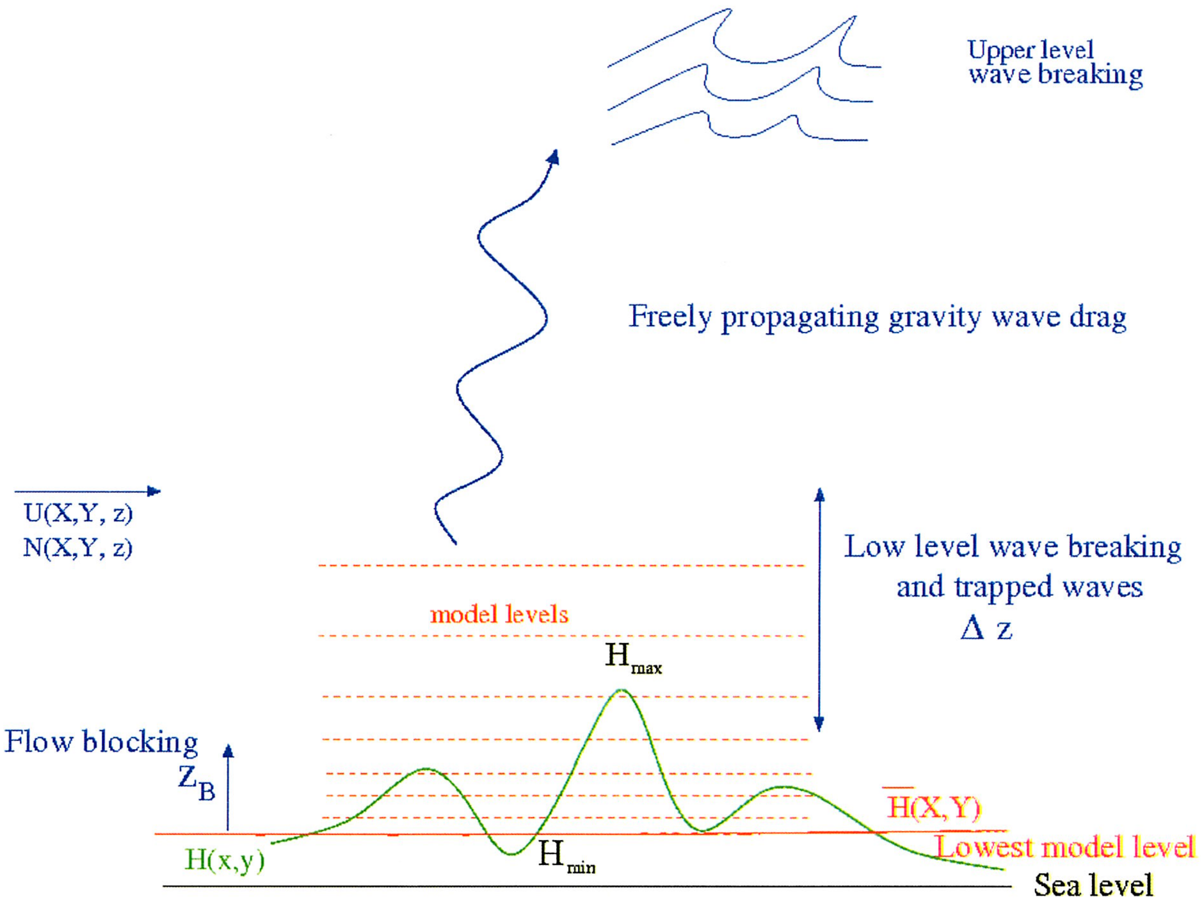
① $\omega > 0$ $\hat{\omega} > 0$ $c_\varphi > 0$
$u < 0 \Rightarrow |\omega - ku|$ grand
Pénétration de l'onde à haute Altitude

$\bar{u}$ (m/s)





drag_noro

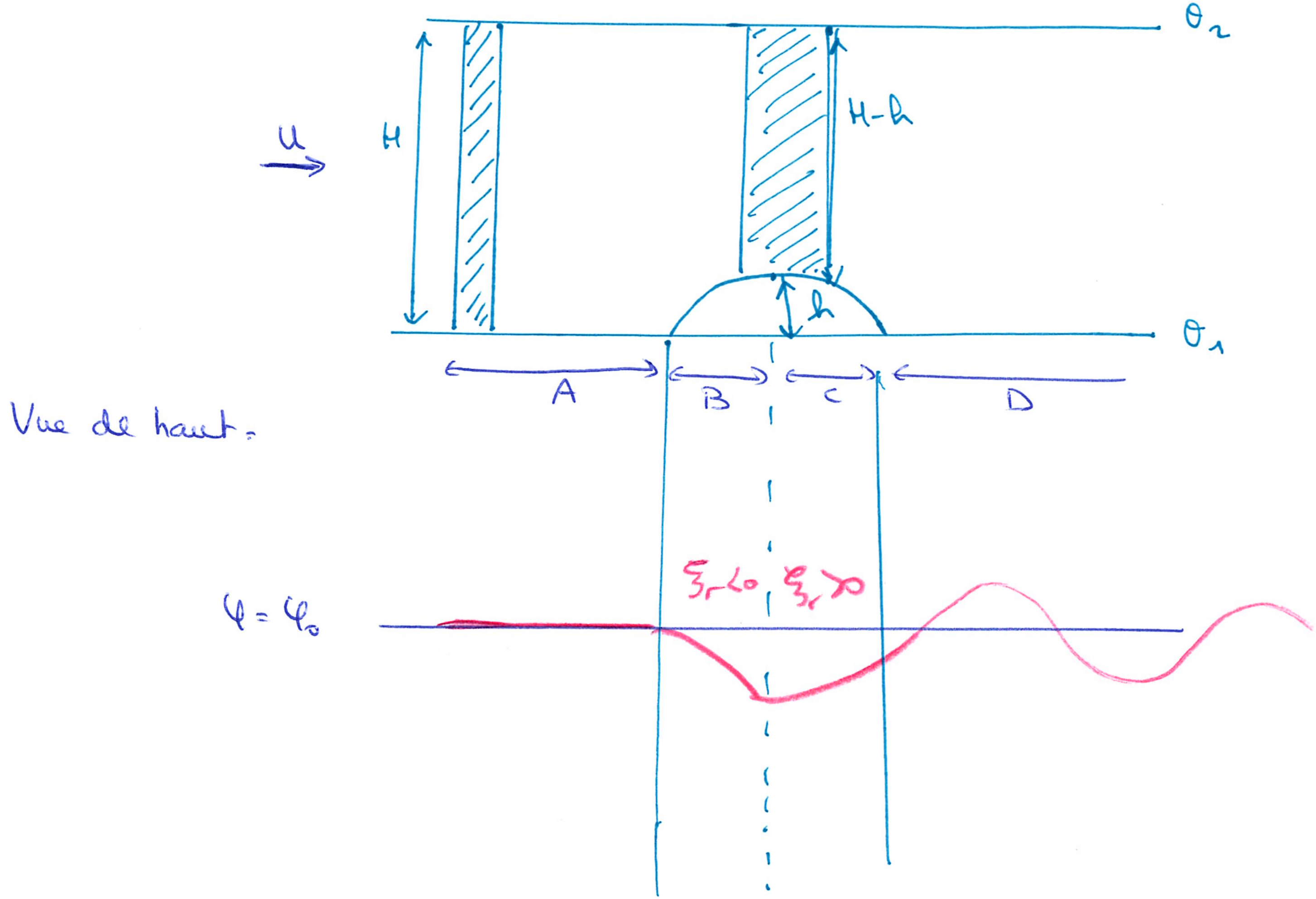


Upper level
wave breaking
Freely propagating gravity wave drag
U(X,Y, z)
N(X,Y, z)
Low level wave breaking
and trapped waves
Δ z
model levels
H max
Flow blocking
Z B
H(X,Y)
Lowest model level
H(x,y)
H min
Sea level

lift_noro

Au cours d'un mouvement adiabatique on conserve la vorticité potentielle :

$PV = \frac{1}{\rho} \xi_a \frac{\partial \theta}{\partial z}$ avec $\xi_a = f + \xi_r$



- En A :

$PV = \frac{f_0}{\rho} \frac{(\theta_2 - \theta_1)}{H}$ $\xi_r = 0$ $\xi_a = f_0$

- En B :

$\frac{\partial \theta}{\partial z} \nearrow$ Donc $\xi_a \searrow$

$\Rightarrow \xi_r < 0$

Déviation vers le Sud $(v < 0)$

- En C :

$\frac{\partial \theta}{\partial z} \searrow$ Donc $\xi_a \nearrow$ $\xi_r > 0$

Déviation vers le Nord

- En D :

$\frac{\partial \theta}{\partial z}$ retrouve sa valeur initiale

$\frac{\partial \theta}{\partial z} = \frac{\theta_2 - \theta_1}{H}$ $\xi_a = f_0$

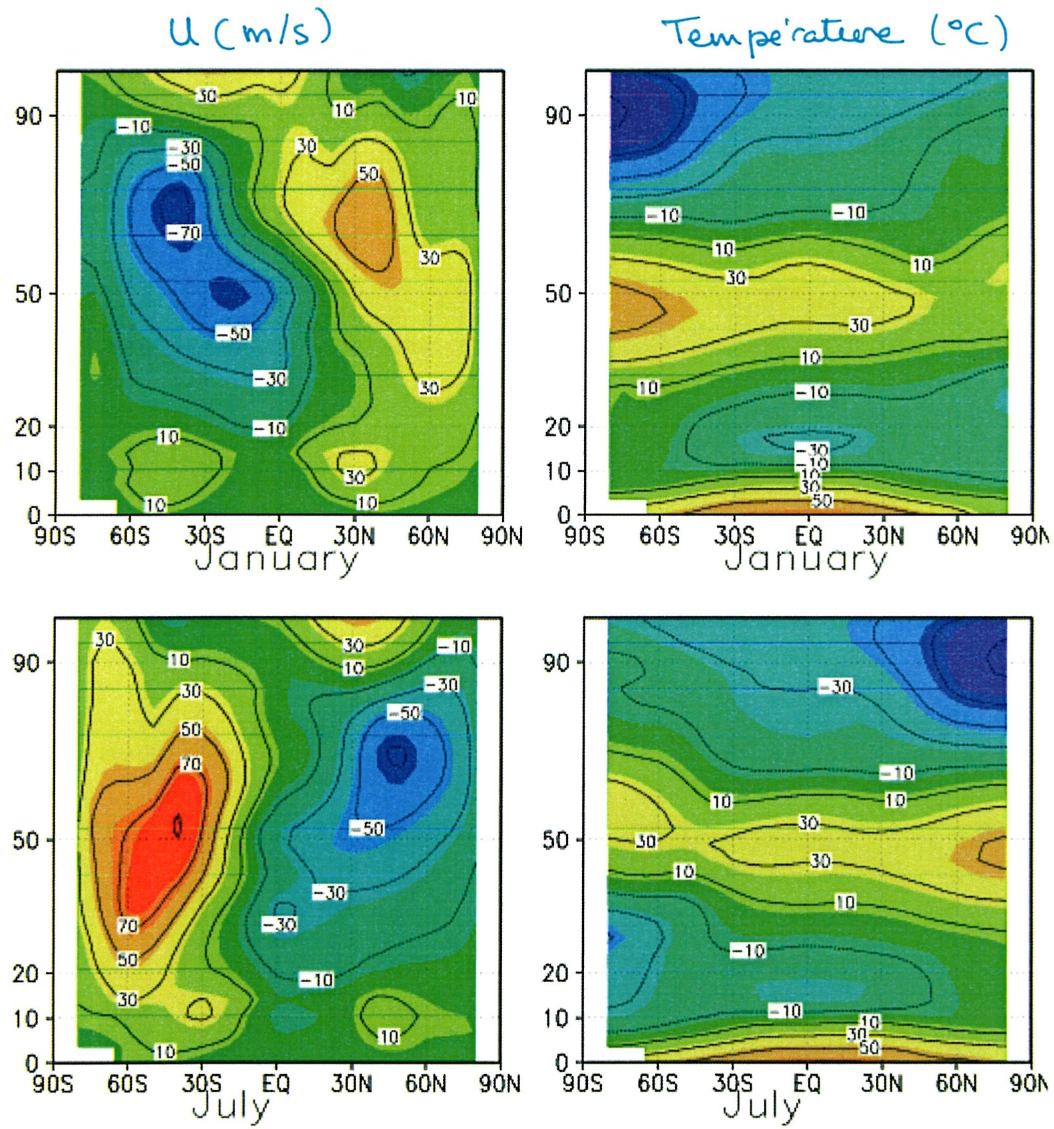
Mais quand la colonne atteint la latitude φ_0 elle vient du sud ⇒ trajectoire oblique.

La colonne traverse le parallèle.

Au Nord $f = f_0 + \beta y$ $\xi_r = -\beta y$

⇒ on retourne vers le Sud.

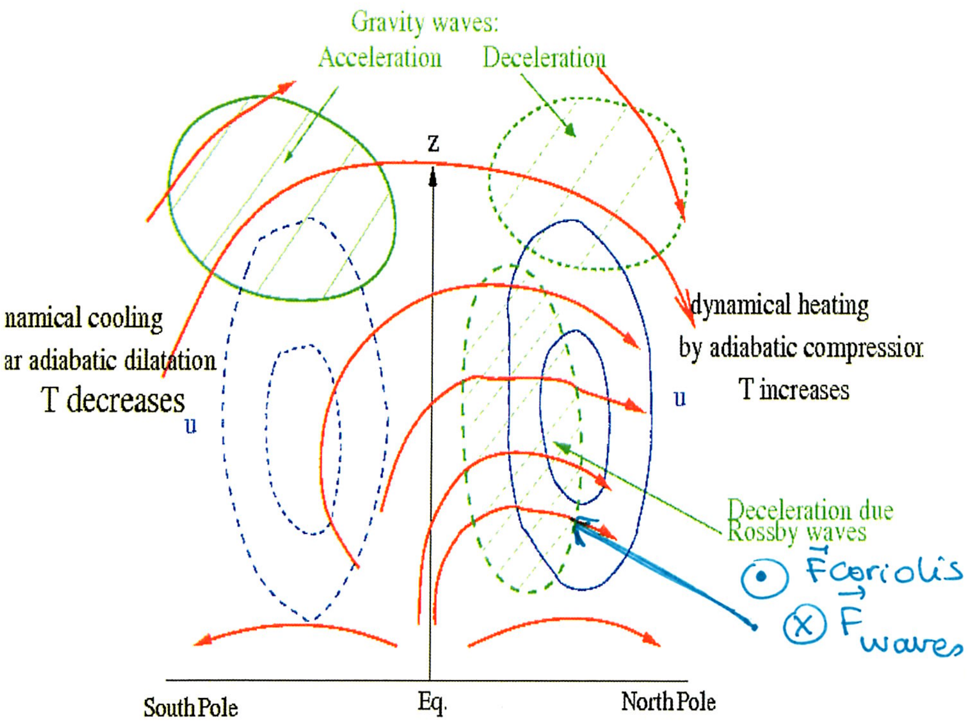
Etc.



⇒ Importance des ondes de Rossby stationnaires créées par le relief pour la circulation stratosphérique.

- A 50 km max de Température au Pôle d'Été
- En Janvier $u > 0$ ds l'Hem Nord
  $u < 0$ ds l'Hem Sud
- Le gradient de Température n'est pas aussi fort que s'il était déterminé radiativement uniquement.

En Janvier :



⇒ Diminution du gradient horizontal de Température obtenu par les termes radiatifs.

Relation de dispersion des ondes de Rossby :

$$c - u_0 = \frac{-\beta}{k^2 + l^2 + \frac{f_0^2}{N^2}\left(m^2 + \frac{1}{4H^2}\right)}$$

ondes stationnaires : $c = 0 \Rightarrow u_0 > 0$

$$m^2 = \frac{N^2}{f_0^2}\left[\frac{\beta}{u_0} - (k^2 + l^2)\right] - \frac{1}{4H^2}$$

Propagation verticale des ondes de Rossby pour $m^2 > 0$

$\Rightarrow$ $\boxed{0 < u_0 < u_c}$

z

$u = u_c$ $\quad \vec{F} = 0$

$0 < u < u_c$ $\quad \uparrow \vec{F} = \vec{c_g} A$

$\Big\}\ \frac{\partial F_z}{\partial z} < 0$

En Janvier ds HN

$u > 0 \Rightarrow$ propagation verticale jusqu'à z tq $u = u_c$

TEM équation : $\frac{\partial \bar{u}}{\partial t} - f_0 \bar{v}^* = \frac{1}{\rho_0} \vec{\nabla} \cdot \vec{F}$

$\frac{\partial F_z}{\partial z} < 0 \Rightarrow$ freinage

Stationnaire : $-f_0 \bar{v}^* = \frac{1}{\rho_0} \vec{\nabla} \cdot \vec{F}$

Orography

Subroutines : drag_noro (or drag_noro_strato)
& lift_noro (or lift_noro_strato)

Tendencies :
dtoro, duoro, dvoro : tendencies of temperature and velocity due to the drag
dtlif, dulif, dvlif : tendencies of temperature and velocity due to the lift

Total tendencies are the sums of the drag and lift tendencies.