Bilan d'énergie et hétérogénéités dans LMDZOR

F. CHERUY

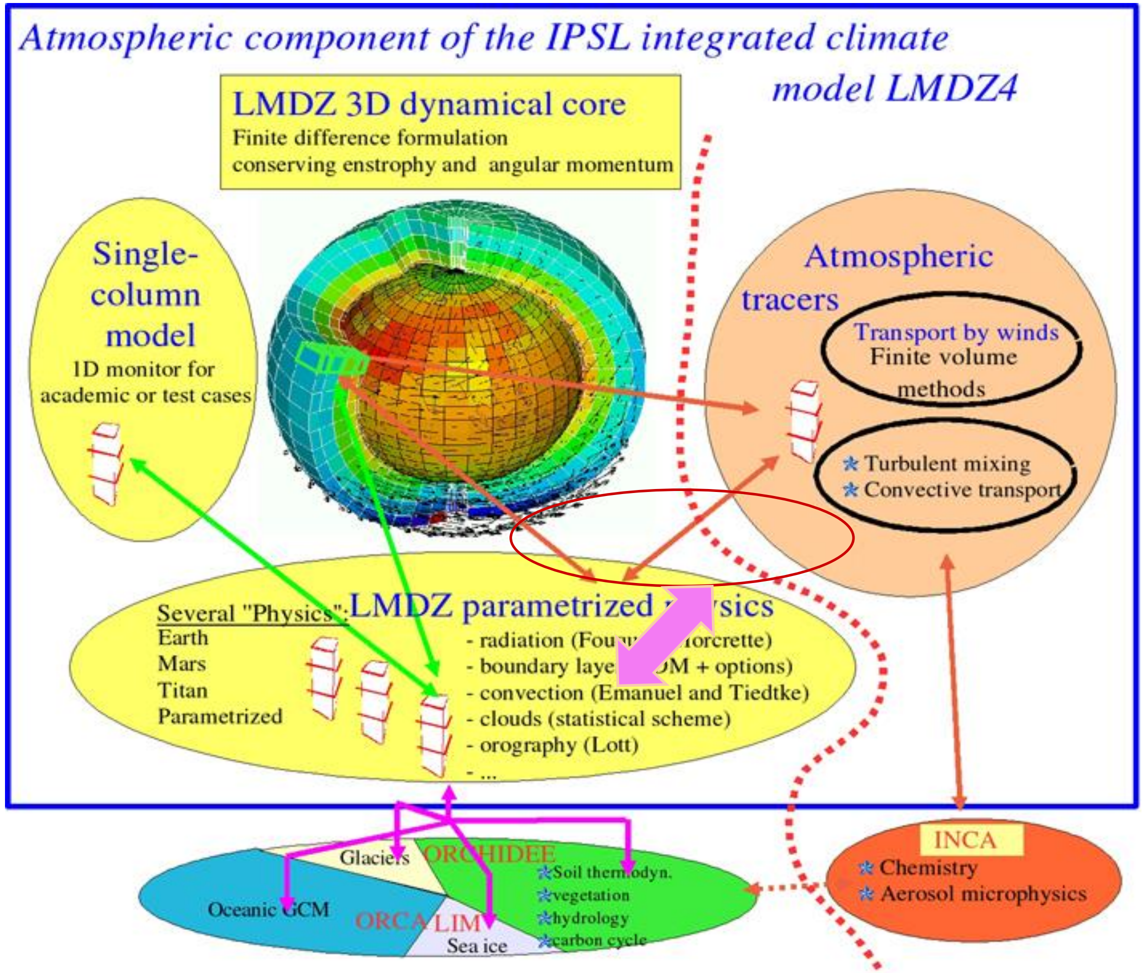
28/03/2022

Atmosphere-surface interactions in IPSL-CM

In LMDZ:
Each surface grid can be decomposed in a Maximum of 4 sub-grid of different type: land (_ter), continental ice (_lic), open ocean (_oce) and sea_ice (_sic)

Radiation at the surface depends on mean surface properties (albedo, emissivity)

Turbulent diffusion depends on local sub-grid properties but each sub-surface sees the same atmosphere



Turbulent diffusion (pbl_surface, LMDZ)

Change of a variable X with the time due to the turbulent transport (continuity) :

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial \Phi}{\partial z}$$

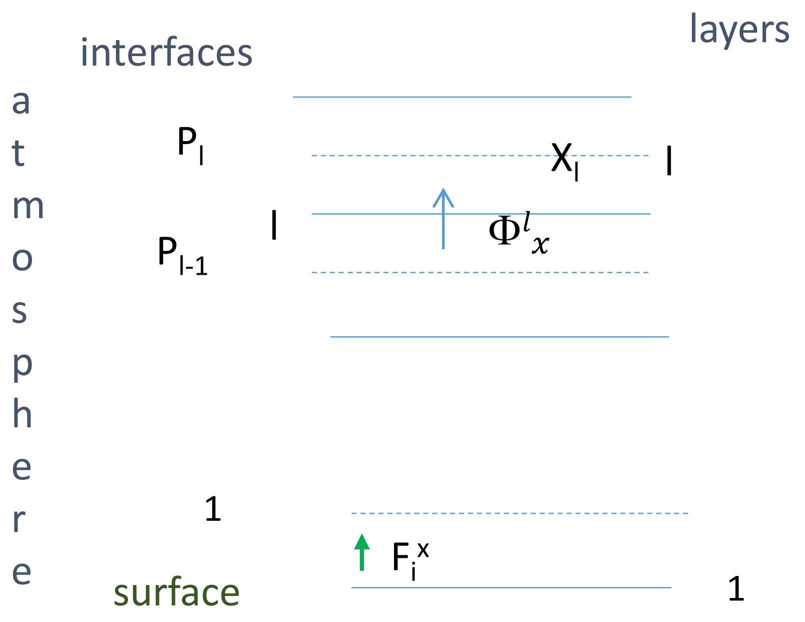
$$\Phi = -\rho k_z \frac{\partial X}{\partial z}$$

$\Phi^l = -K_l\,(X_l - X_{l-1})$ (vertical discretization)

From turbulent diffusion scheme
(pbl in LMDZ)

4 Flux F^x_i actuellement

$\delta P = (P_{l-1} - P_l) = \rho g \delta z = m_l g$



X= specific humidity, enthalpie

Solving the tridiagonal system for each sub_surface

downhill

$$C_n^X = \frac{X_n^0 \delta P_n}{\delta P_n + R_n^X}$$

$$D_n^X = \frac{R_n^X}{\delta P_n + R_n^X}$$

$$C_l^X = \frac{X_l^0 \delta P_l + R_{l+1}^X C_{l+1}^X}{\delta P_l + R_l^X + R_{l+1}^X (1 - D_{l+1}^X)}$$

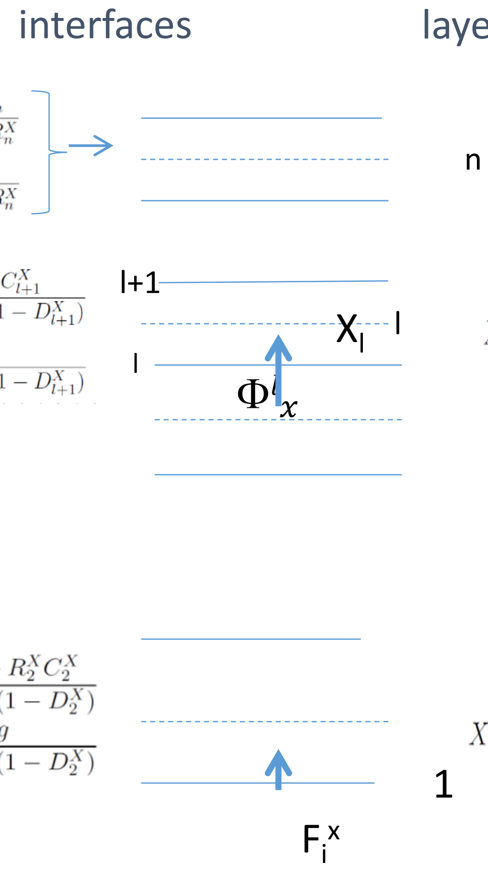
$$D_l^X = \frac{R_l^X}{\delta P_l + R_l^X + R_{l+1}^X (1 - D_{l+1}^X)}$$

depend only on properties in the layers above and the variables at the previous time step.

In LMDZ
climb_hq_down
climb_wind_down

$$A_1^X = \frac{X_1^0 \delta P_1 + R_2^X C_2^X}{\delta P_1 + R_2^X (1 - D_2^X)}$$

$$B_1^X = \frac{-g}{\delta P_1 + R_2^X (1 - D_2^X)}$$



$$X_l = C_l^X + D_l^X X_{l-1}$$

?

$$X_1 = A_1^X + B_1^X F_1^X \delta t$$

X= wind, enthalpie, specific humidity, tracers

Once F_1^x (flux of water mass, heat between the surface and the atmosphere) is known, the X_i can be computed from the first layer to the top of the PBL for each sub-surface

Case of the continental surface

- Surface energy budget

$$SW_{net} + LW_{net} + F + L + \Phi_0 = 0$$

$$SW_{net} + LW_d \underline{- \varepsilon\sigma T_s^4 + F + L + \Phi_0} = 0$$

depends on Ts

$$L = \beta\rho V C_d (q_1 - q_s(T_s))$$

$$F = \rho V C_d (T_1 - T_s)$$

- Heat conduction in the soil: diffusion equation :

$$\Phi_T = -\lambda \frac{\partial T}{\partial z}$$

$$\frac{\partial T}{\partial t} = -\frac{1}{C} \frac{\partial \Phi_T}{\partial z}$$

Boundary conditions:

✓ bottom : $\Phi = 0$
✓ top: Continuity of the fluxes and the temperature between sub-surface and atmosphere

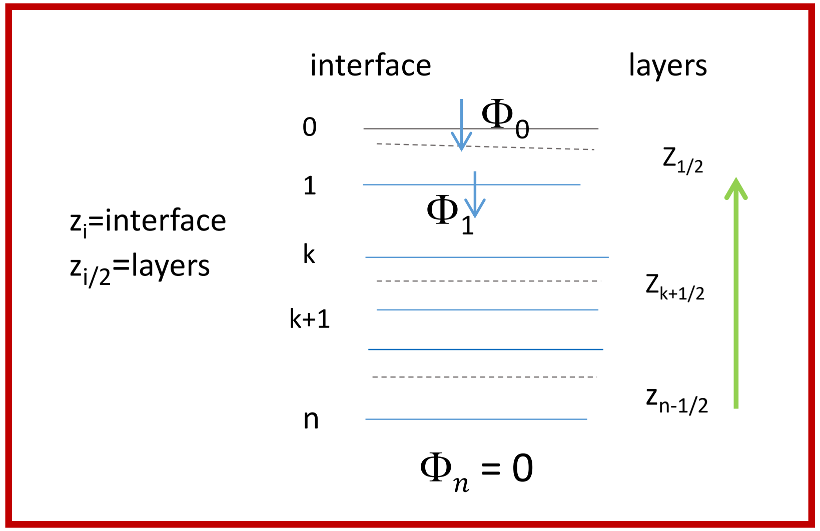
- Heat conduction : Diffusion equation

$$\Phi_T = -\lambda \frac{\partial T}{\partial z} \quad ; \quad \frac{\partial T}{\partial t} = -\frac{1}{C}\frac{\partial \Phi_T}{\partial z}$$

We obtain by recurrence (same as for atmosphere)

- **Top: Continuity between sub-surface and atmosphere**

$$C_{p\ 1/2} \frac{T^t_{1/2} - T_{1/2}}{\delta t} = \frac{1}{z_1 - z_0}\left[\lambda_1 \frac{T^t_{3/2} - T^t_{1/2}}{z_{3/2} - z_{1/2}}\right] + Rad + \sum F^{\downarrow}(T^t_S) - \varepsilon\sigma(T^t_S)^4 \qquad T^t_{3/2} = \alpha^t_1\, T^t_{\frac{1}{2}} + \beta^t_1$$



- Intermediate layers

$$T^t_{k+1/2} = \alpha^t_k\, T^t_{k-1/2} + \beta^t_k$$

At t, α_k and β_κ depend on $T_{k1/2}$ at the previous time step they can be computed with a recurrence relationship from one layer to the other.

- **Bottom** : $\Phi_n = 0$ $\qquad T^t_{n-1/2} = \alpha^t_{n-1}\, T^t_{n-\frac{3}{2}} + \beta^t_{n-1}$

- Heat conduction : Diffusion equation

$$\Phi_T = -\lambda \frac{\partial T}{\partial z} \;;\; \frac{\partial T}{\partial t} = -\frac{1}{C}\frac{\partial \Phi_T}{\partial z}$$

- Top: Continuity between sub-surface and atmosphere

(1) $$C^t_{p_{1/2}} \frac{T^t_{1/2} - T_{1/2}}{\delta t} = \frac{1}{z_1 - z_0}\left[\lambda_1 \frac{T^t_{3/2} - T^t_{1/2}}{z_{3/2} - z_{1/2}}\right] + \sum F^{\downarrow}(T^t_S) - \varepsilon\sigma(T^t_S)^4$$

(2) $$T^t_{3/2} = \alpha^t_1 \, T^t_{\frac{1}{2}} + \beta^t_1$$

Ts is extrapolated as a function of $T^t_{\frac{1}{2}}$ taking advantage of (2)

(very thin layers, and continuity of the temperature - Hourdin 1993))

$$C' * \frac{T^t_S - T^0_S}{\delta t} = G' * + SW_{net} + LWd + \sum F^{\downarrow}(T^t_S) - \varepsilon\sigma(T^t_S)^4$$

Case of the continental surface

- Surface energy budget

$$SW_{net} + LW_{net} + F_s + L + \Phi_0 = 0$$

$$SW_{net} + LW_d - \varepsilon\sigma T_s^4 + F_s + L + \Phi_0 = 0$$

depends on Ts

Aridity factor

$$L = \beta\rho V C_d (q_1 - q_s(T_s))$$

$$F_s = \rho V C_d (H_1 - H_s)$$

H=enthalpy

$$F^t_{s,H} = A^1{}_H + B^1{}_H F^t_{s,H} \partial t$$ *Turbulent diffusion Atmosphere*

$$F^t_{s,H} = \frac{1}{zikt}(H^t_1 - H^t_s) \qquad \frac{1}{zikt} = \rho|\vec{v}|C_d$$

Bulk formulation

C_d^x drag coefficient (Monin Obukhov, constant flux in the surface layer) depends on

- roughness lenghts (gustiness, vegetation),
- Richardson number (boundary layer stability)
- Formulation depends on the sub-surface type

$$F^t_{s,H} = \frac{1}{zikt}(A^1_H + B^1_H . F^t_{s,H}\delta t - H^t_s)$$

$$F^t_{s,H} = \frac{1}{zikt}\left[\frac{(A^1_H - H^{t-\delta t}_s)}{1 - \frac{1}{zikt}B^1_H\delta t} - \frac{(H^t_s - H^{t-\delta t}_s)}{1 - \frac{1}{zikt}B^1_H\delta t}\right]$$

$$F^t_{s,H} = sensfl_{old} - sensfl_{sns}(T^t_s - T^{t-\delta t}_s)$$

$$F^t_{s,q} = L\rho|\overrightarrow{v}|C_d\beta(q^t_1 - q_{sat}(T^t_s))$$

$$q_{sat}(T^t_s) = q_{sat}(T^{t-\delta t}_s) + \left.\frac{\partial q_{sat}}{\partial t}\right|_{(T=T^{t-\delta t}_s)}(T^t_s - T^{t-\delta t}_s)$$

$$q^t_1 = A^1_q + B^1_q.F^t_{s,q}\delta t$$

$$F^t_{s,q} = \frac{1}{zikt}\beta(A^1_q + B^1_q.F^t_{s,q}\delta t - q_{sat}(T^{t-\delta t}_s) + \left.\frac{\partial q_{sat}}{\partial t}\right|_{(T=T^{t-\delta t}_s)}(T^t_s - T^{t-\delta t}_s))$$

peqBcoef dans Orchidee

$$F^t_{s,q} = \frac{\frac{1}{zikt}\beta(A^1_q - q_{sat}(T^{t-\delta t}_s))}{(1 - \frac{1}{zikt}\beta B^1_q\delta t)} - \frac{\frac{1}{zikt}\beta\left.\frac{\partial q_{sat}}{\partial t}\right|_{(T=T^{t-\delta t}_s)}}{(1 - \frac{1}{zikt}\beta B^1_q\delta t)}(T^t_s - T^{t-\delta t}_s)$$

peqAcoef dans Orchidee

Case of the continental surface

$$C' * \frac{T_S^t - T_S^0}{\delta t} = G' * + SW_{net} + LWd + \sum F^{\downarrow}(T_S^t) - \varepsilon\sigma(T_S^t)^4$$

Solved using the sensitivity of the flux to the surface temperature to calculate the flux at the new time-step

$$F_{s,H}^t = sensfl_{old} - sensfl_{sns}(T_s^t - T_s^{t-\delta t})$$

$$\sigma * T_s^{t-\delta t^4} - 4\varepsilon\sigma T_s^{t-\delta t^3}(T_s^t - T_s^{t-\delta t})$$

$$F^t_{s,q} = flat_{old} - flat_{sens}(T^t_s - T^{t-\delta t}_s)$$

Case of the continental surface

$$C' * \frac{T_S^t - T_S^0}{\delta t} = G' * + SW_{net} + LWd + \sum F^{\downarrow}(T_S^t) - \varepsilon\sigma(T_S^t)^4$$

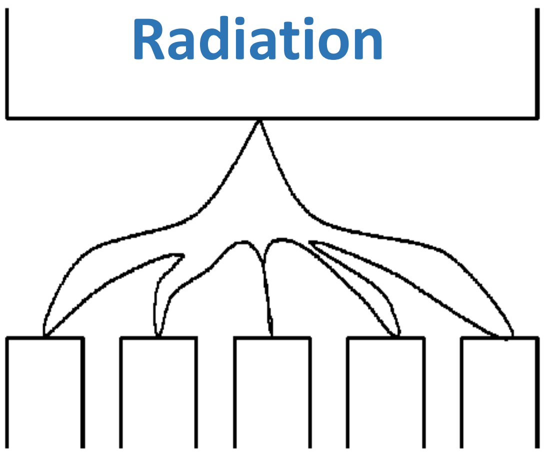
Solved using the sensitivity of the flux to the surface temperature to calculate the flux at the new time-step

$$F^t_{s,H} = sensfl_{old} - sensfl_{sns}(T^t_s - T^{t-\delta t}_s)$$

$$\sigma * {T^{t-\delta t}_s}^4 - 4\varepsilon\sigma {T^{t-\delta t}_s}^3 (T^t_s - T^{t-\delta t}_s)$$

$$F^t_{s,q} = flat_{old} - flat_{sens}(T^t_s - T^{t-\delta t}_s)$$

1 column covers all the sub-surfaces



Derivation of local sub-surface **net longwave radiation** from grid average net longwave radiation

The net longwave (LW) radiation $\bar{\Psi}^L$ has been computed by the radiative code for each grid cell. How to split it depending on the sub-surfaces local properties and ensuring energy conservation?

If the downward longwave flux $F_\downarrow$ is uniform within each grid, the net LW flux for a sub-surface i may be written as:

$$\psi_i^L(T_i) = \epsilon_i \left(F_\downarrow - \sigma T_i^4\right) \quad (1)$$

where T_i is the surface temperature of sub-surface i and ϵ_i its emissivity. A linearization around the mean temperature $\bar{T}$ gives:

$$\psi_i^L(T_i) \approx \epsilon_i \left(F_\downarrow - \sigma \bar{T}^4\right) - 4\epsilon_i \sigma \bar{T}^3 (T_i - \bar{T}) \quad (2)$$

To conserve the energy, the following relationship must be true:

$$\sum_i \omega_i \psi_i^L = \bar{\Psi}^L \quad (3)$$

Using Eq. 2 gives

$$\sum_i \omega_i \psi_i^L = \bar{\epsilon} \left(F_\downarrow - \sigma \bar{T}^4\right) - 4\sigma \bar{T}^3 \sum_i \omega_i \epsilon_i \left(T_i - \bar{T}\right) \quad (4)$$

where $\bar{\epsilon} = \sum_i \omega_i \epsilon_i$ is the mean emissity.

Derivation of local sub-surface **net longwave radiation** from grid average net longwave radiation

$$\sum_i \omega_i \psi_i^L = \bar{\epsilon}\left(F_\downarrow - \sigma \bar{T}^4\right) - 4\sigma \bar{T}^3 \sum_i \omega_i \epsilon_i \left(T_i - \bar{T}\right) \tag{4}$$

where $\bar{\epsilon} = \sum_i \omega_i \epsilon_i$ is the mean emissivity. The second term on the right hand side is zero if

$$\bar{T} = \frac{\sum_i \omega_i \epsilon_i T_i}{\bar{\epsilon}} \tag{5}$$

To ensure energy conservation, we need in addition to verify:

$$\bar{\Psi}^L = \bar{\epsilon}\left(F_\downarrow - \sigma \bar{T}^4\right) \tag{6}$$

Which is consistent with the definition of the net LW flux at the surface. We rewrite now Eq. 2 as:

$$\psi_i^L(T_i) \approx \epsilon_i \left(F_\downarrow - \sigma \bar{T}^4\right) - 4\epsilon_i \sigma \bar{T}^3 (T_i - \bar{T})$$

$$\psi_i^L(T_i) \approx \frac{\epsilon_i}{\bar{\epsilon}} \bar{\Psi}^L - 4\epsilon_i \sigma \bar{T}^3 (T_i - \bar{T}) \tag{7}$$

Due to radiative code limitation, in LMDZ, we always must have $\varepsilon_i = 1$

Energy conservation: the radiation is computed by the atmospheric model,

Derivation of local sub-surface **net solar radiation** from grid average net solar radiation

The grid average net flux Ψ_s at surface has been computed for each grid point by the radiative code.

We want (1) to conserve energy and (2) to take into account the value of the local albedo αi of the sub-surface.

We compute the downward SW radiation as

$$F_{\downarrow}^{s} = \frac{\Psi_s}{(1-\alpha)}$$

with the mean albedo

$$\alpha = \sum_i \omega_i \alpha_i$$

$$\psi_i^s = (1-\alpha_i) F_{\downarrow}^{s}$$

For each sub-surface i, the absorbed solar radiation reads:

$$\psi_i^s = \frac{(1-\alpha_i)}{(1-\alpha)} \bar{\Psi}^s$$

One may verify that this procedure ensure energy conservation, i.e.

$$\sum_i \omega_i \psi_i^s = \Psi_s$$

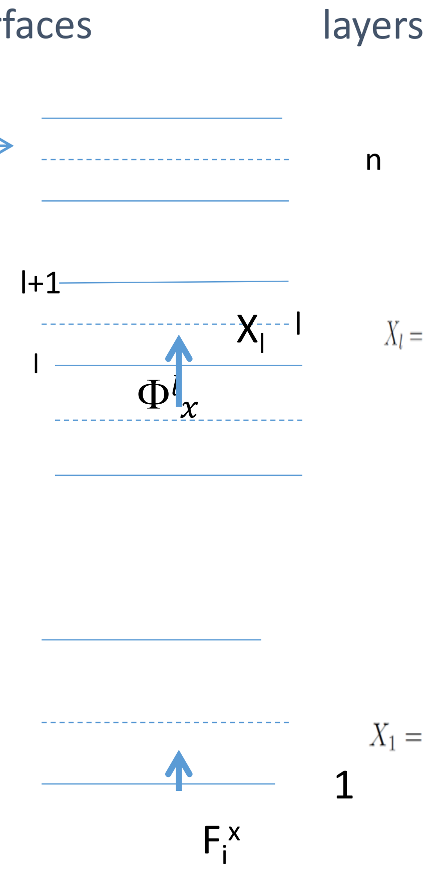
Solving the tridiagonal system for each sub_surface

downhill

$$C_n^X = \frac{X_n^0 \delta P_n}{\delta P_n + R_n^X}$$
$$D_n^X = \frac{R_n^X}{\delta P_n + R_n^X}$$

depend only on properties in the layers above and the variables at the previous time step.

$$C_l^X = \frac{X_l^0 \delta P_l + R_{l+1}^X C_{l+1}^X}{\delta P_l + R_l^X + R_{l+1}^X (1 - D_{l+1}^X)}$$
$$D_l^X = \frac{R_l^X}{\delta P_l + R_l^X + R_{l+1}^X (1 - D_{l+1}^X)}$$



$$X_l = C_l^X + D_l^X X_{l-1}$$

In LMDZ
climb_hq_down
climb_wind_down

$$A_1^X = \frac{X_1^0 \delta P_1 + R_2^X C_2^X}{\delta P_1 + R_2^X (1 - D_2^X)}$$
$$B_1^X = \frac{-g}{\delta P_1 + R_2^X (1 - D_2^X)}$$

?

$$X_1 = A_1^X + B_1^X F_1^X \delta t$$

X= wind, enthalpie, specific humidity, tracers

Once F_1^x (flux of water mass, heat between the surface and the atmosphere) is known, the X_i can be computed from the first layer to the top of the PBL for each sub-surface

The tendencies for X_i : ($X^t_i - X^{t-\delta t}_i$) for each sub-surface weighted by the fraction occupied by the sub-surface in the grid-mesh are then summed to obtain the trend due to the vertical diffusion over the grid-mesh

Call tree

In subroutine PHYSIQ
loop over time steps
CALL change_srf_frac : Update fraction of the sub-surfaces (pctsrf)
....
CALL pbl_surface Main subroutine for the interface with surface

- Calculate net radiation at sub-surface
- *Loop over the sub-surfaces nsrf*
  - Compress variables (Consider only one surface type and only the points for which the fraction for this sub-surface in not zero)
  - CALL cdrag: coefficients for turbulent diffusion at surface (cdragh and cdragm)
  - CALL coef_diff_turb: coef. turbulent dif. in the atmosphere (ycoefm et ycoefm.)
  - CALL climb_hq_down downhill for enthalpy H and humidity Q
  - CALL climb_wind_down downhill for wind (U and V)
  - CALL surface models for the various surface types: **surf_land**, **surf_landice**, **surf_ocean** **or** **surf_seaice**.
  - **Each surface model computes:**
    - evaporation, latent heat flux, sensible heat flux
    - surface temperature, albedo (emissivity), roughness lengths
  - CALL climb_hq_up : compute new values of enthalpy H and humidity Q
  - CALL climb_wind_up : compute new values of wind (U and V)
  - Uncompress variables : (some variables are per unit of sub-surface fraction, some are per unit of grid surface fraction)
  - Cumulate in global variables after weighting by sub-surface fractions
  - Surface diagnostics : (T, q, wind are evaluated at a reference level (2m) owing to an interpolation scheme based on the MO laws).
- *End Loop over the sub-surfaces*
- Calculate the mean values over all sub-surfaces for some variables

End pbl-surface

Atmosphere/surface coupling in LMDZOR

LMDZ (phylmd)

Planetary boundary layer and surface modules

pbl_surface

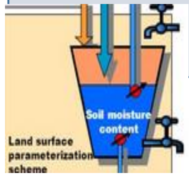
(A_q , $B_{q,}$ A_H , $B_{B,}$ $C_{dh,}$, A_u , $B_{u,}$ A_v , B_v , C_{dh}, T_1, $q_{1,}$ u_1,$v_{1,}$ $LW_{net,}$ $LW_{down,}$ Sw_{net})

AcoefH, AcoefQ, BcoefH, BcoefQ cdragh,lwdown,swnet

,

(is_ter, ok_veget = n)

surf_land_bucket



(soil.F90: soil T, heat capacity, conduction,

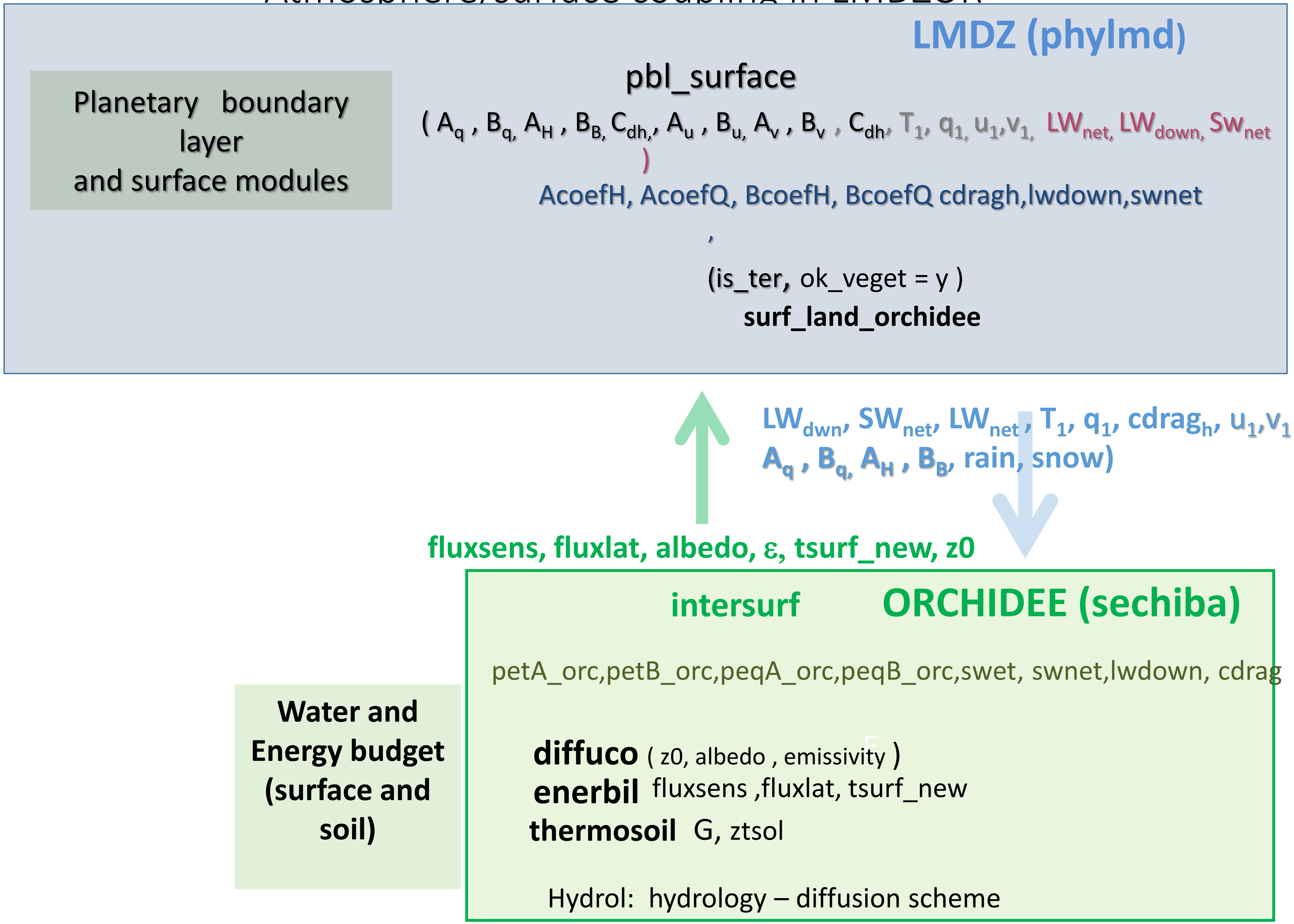
calcul_flux : sens,flat,tsurf_new

Hydro= water budget (snow, precip, Evap)

(is_ter, ok_veget = y)

surf_land_orchidee

Atmosphere/surface coupling in LMDZOR



- Rugosité moyenne sur la maille

Drag neutre par PFT (von Karman constant, hauteur de la premiere couche, z0).

-z0 prescrit par PFT (fonction hauteur et rapport z0h/z0m prescrit)

-calculé en fonction LAI, rapport z0h/z0m = fonction B

Inversion du drag moyen sur les PFT > rugosité moyenne.