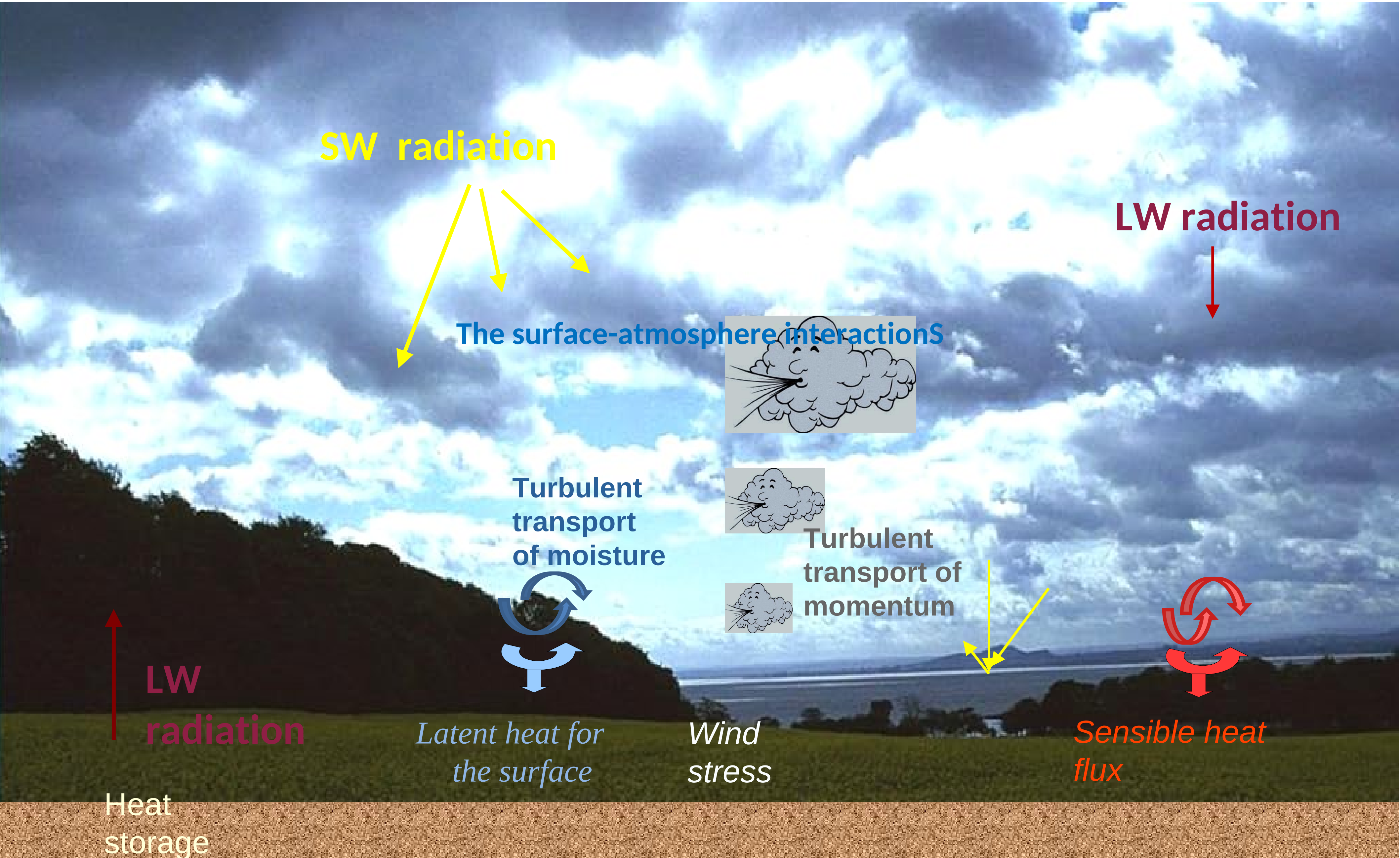
The surface-atmosphere interactions

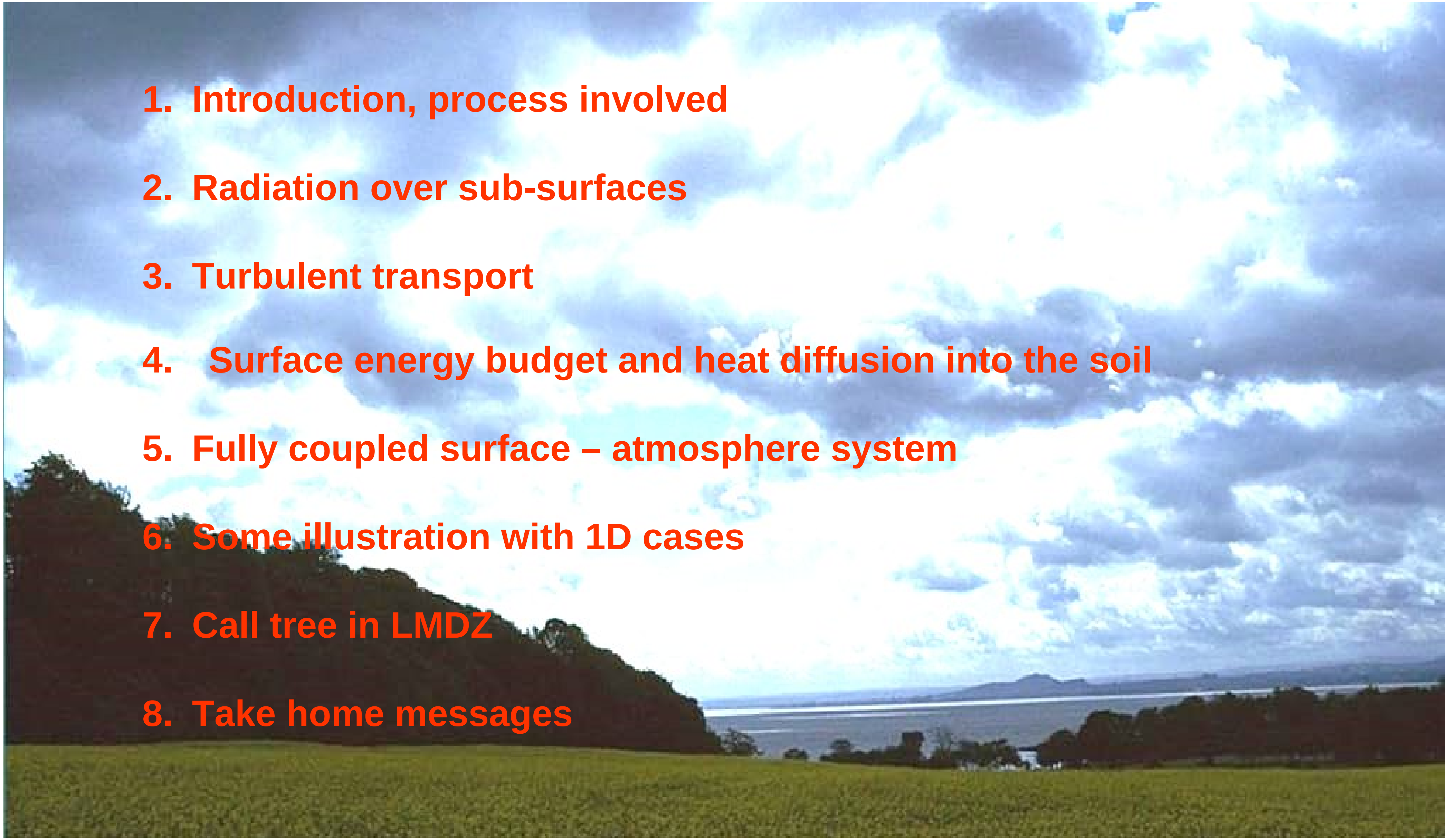
LMDZ Training January 15, 2026

F. Cheruy et al.

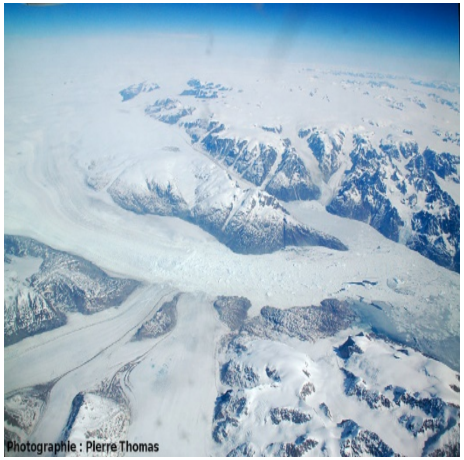


SW radiation
LW radiation
The surface-atmosphere interactionS
Turbulent transport of moisture
Turbulent transport of momentum
LW radiation
Latent heat for the surface
Wind stress
Sensible heat flux
Heat storage

The surface-atmosphere interactions



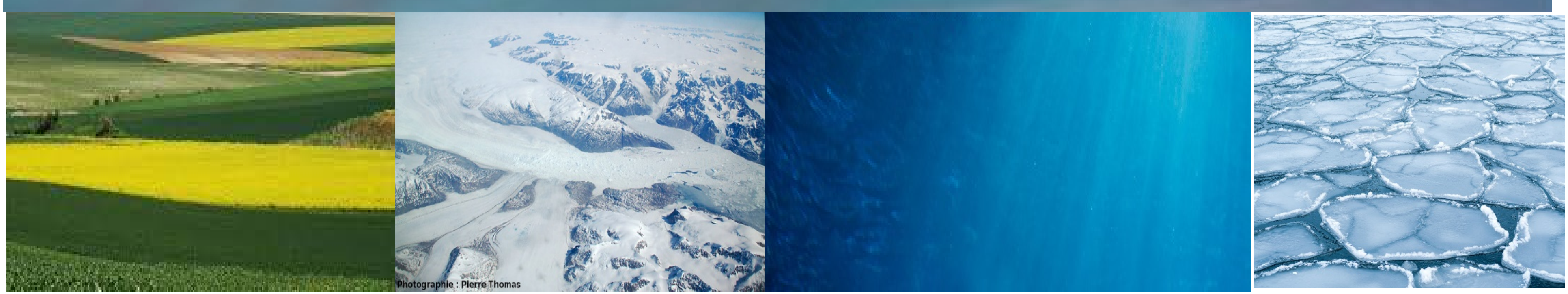
1. Introduction, process involved
2. Radiation over sub-surfaces
3. Turbulent transport
4. Surface energy budget and heat diffusion into the soil
5. Fully coupled surface – atmosphere system
6. Some illustration with 1D cases
7. Call tree in LMDZ
8. Take home messages


Photographie : Pierre Thomas

Turbulent diffusion depends on local sub-grid properties (roughness)

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

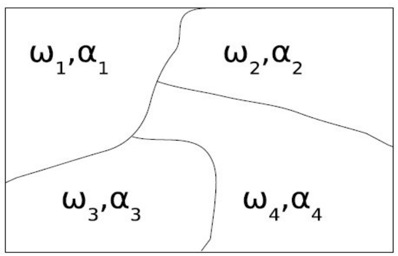
In LMDZ : 4 sub-surfaces : land, land-ice, ocean, sea-ice



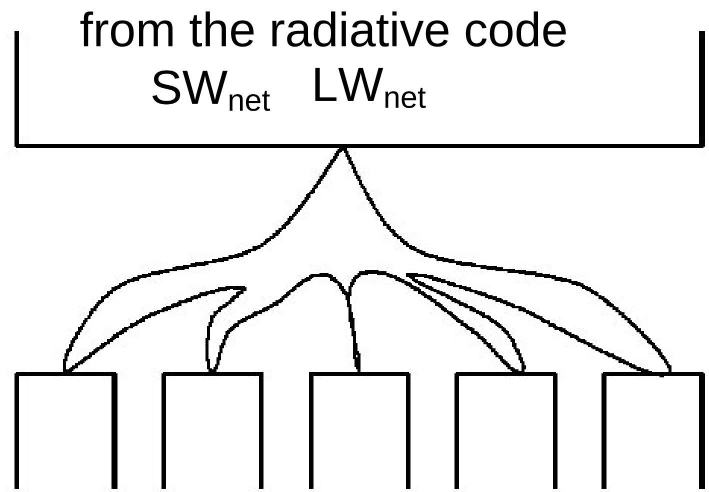
Split the the SW radiation on sub-surfaces

Each grid cell is divided into several sub-areas or ``sub-surfaces" of fractions

$$\sum_i \omega_i = 1$$



One atmospheric column
covers all the sub-surface



$\alpha oce, \epsilon oce$ ….. $\alpha land, \epsilon land$…..

Split the the SW radiation on sub-surfaces

The grid average net flux SW_{net} has been computed previously by the radiative code

We need to (1) conserve energy and (2) take into account the value α_i of the local albedo of the sub-surface i

$$SW_{dn} = \frac{SW_{net}}{(1-\alpha)}$$

[redacted]

$$SW_{net}^{i} = (1-\alpha_i) SW_{dn} = \frac{(1-\alpha_i)}{(1-\alpha)} SW_{net}$$

$$\sum_i \omega_i SW_{net}^{i} = SW_{net}$$

The grid average net flux SW_{net} has been computed previously by the radiative code

We need to (1) conserve energy and (2) take into account the value of the surface temperature (emissivity) of the sub-surface i

$$LW^i_{net}(T^i_s) = \epsilon_i(LW_{dn} - \sigma(T^i_s)^4)$$

$$T^{i4}_s \approx T^4_s + 4T^3_s(T - T^i_s)$$

$$LW^i_{net}(T^i_s) \approx \epsilon_i(LW_{dn} - \sigma T^4_s) - 4\epsilon_i\sigma T^3_s(T^i_s - T_s)$$

$$\epsilon = \sum_i \omega_i\epsilon_i$$

$$\mathrm{LW}_{net}(T_s) = \epsilon(LW_{dn} - \sigma(T^i_s)^4) - 4\sigma T^3_s \sum \omega_i\epsilon_i(T^i_s - T_s)$$

Energy conservation

$$4\sigma T^3_s \sum \omega_i\epsilon_i(T^i_s - T_s) = 0$$

$$T_s = \frac{\sum \omega_i\epsilon_i T^i_s}{\epsilon}$$

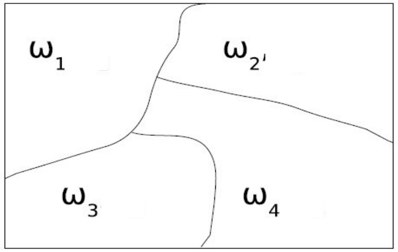
Due to radiative code limitation, in LMDZ, we always must have $\varepsilon_i = 1$

,

Each grid cell is divided into several sub-areas or ``sub-surfaces" of fractions

$$\sum_i \omega_i = 1$$

In the timestep :one PBL over **each** sub-surface



Z_{oh}^{i} Z_{om}^{i}

Vertical turbulent diffusion for moisture, heat , momentum

Time evolution of a variable X due to turbulent transport as the divergence of the turbulent flux:

$$\begin{cases} \frac{\partial X}{\partial t} & = -\frac{1}{\rho} \frac{\partial \Phi}{\partial z} \\ \Phi & = -\overline{w'X'} = -\rho k_z \frac{\partial X}{\partial z} \end{cases} \quad \text{with}$$

k_z : the vertical turbulent diffusion coefficient for X

in the atmosphere

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho} \frac{\partial [-\rho k_z \frac{\partial X}{\partial z}]}{\partial z}$$

Numerical world

Vertical discretization :

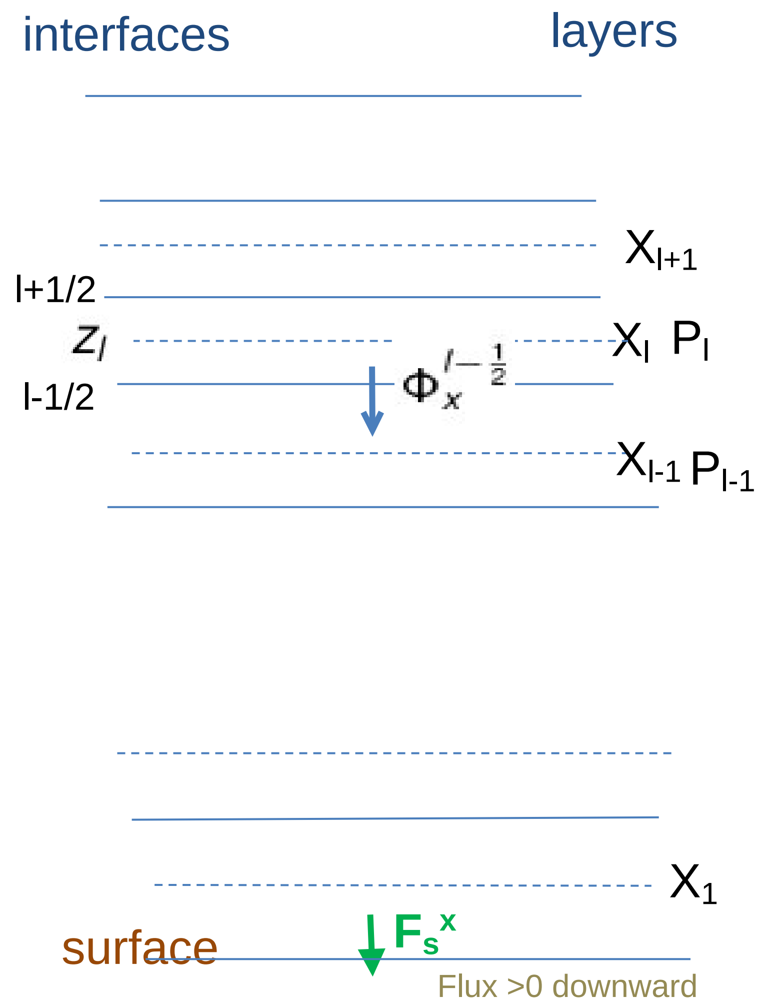
$$\Phi_x^{l-\frac{1}{2}} = -\rho_{l-\frac{1}{2}} k_{l-\frac{1}{2}} \frac{(X_l - X_{l-1})}{z_l - z_{l-1}} = -K_{l-\frac{1}{2}}(X_l - X_{l-1})$$

$$\frac{\partial X_l}{\partial t} = -\frac{1}{m_l}(K_{l-\frac{1}{2}}(X_l - X_{l-1}) - K_{l+\frac{1}{2}}(X_{l+1} - X_l))$$

Time discretization

$$m_l \frac{X_l^{t+\delta t} - X_l^t}{\delta t} = -(K_{l-\frac{1}{2}}(X_l^? - X_{l-1}^?) - K_{l+\frac{1}{2}}(X_{l+1}^? - X_l^?))$$

$$m_1 \frac{X_1^{t+\delta t} - X_1^t}{\delta t} = K_{\frac{3}{2}}(X_2^? - X_1^?) - F_s^{x?}$$



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

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Time discretization : implicit

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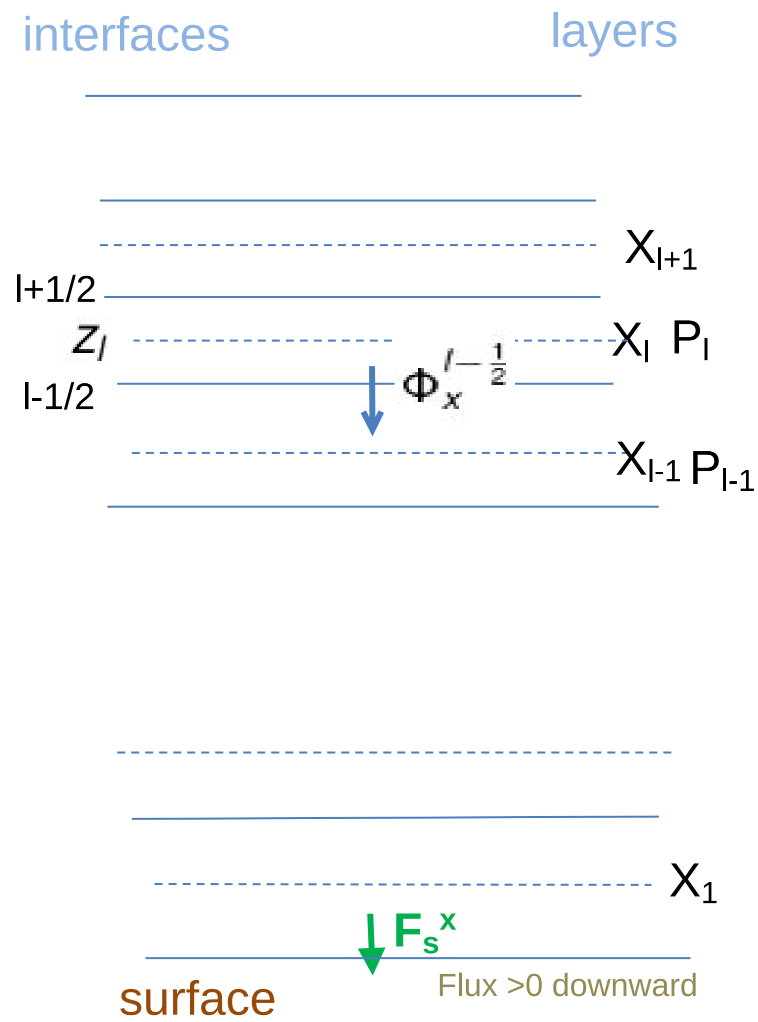
$$-K_{l-\frac{1}{2}} X_{l-1}^{t+\delta t} + (\frac{m}{\delta t} + K_{l+\frac{1}{2}} + K_{l-\frac{1}{2}}) X_l^{t+\delta t} - K_{l+\frac{1}{2}} X_{l+1}^{t+\delta t} = \frac{m_l}{\delta t} X_l^t$$

$$m_1 \frac{X_1^{t+\delta t} - X_1^t}{\delta t} = k_{\frac{3}{2}}(X_2^{t+\delta t} - X_1^{t+\delta t}) - F_s^{x,t+\delta t}$$



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Tri-diagonal system with implicit boundary condition

$$-K_{l-\frac{1}{2}} X_{l-1}^{t+\delta t} + (\frac{m}{\delta t} + K_{l+\frac{1}{2}} + K_{l-\frac{1}{2}}) X_l^{t+\delta t} - K_{l+\frac{1}{2}} X_{l+1}^{t+\delta t} = \frac{m_l}{\delta t} X_l^t$$

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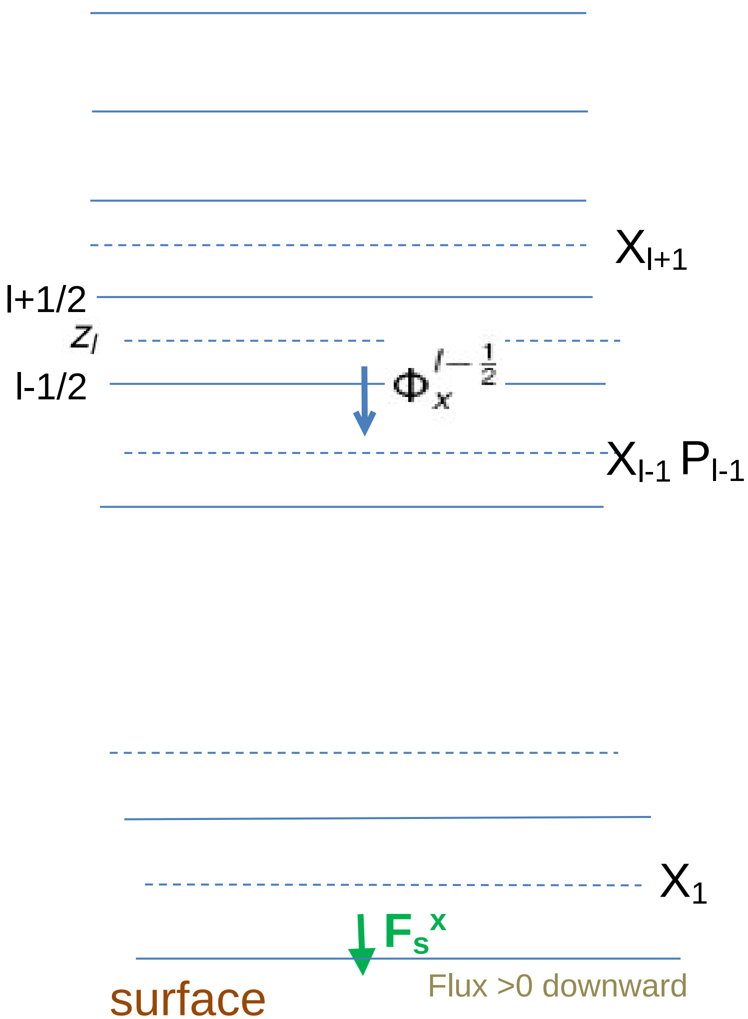

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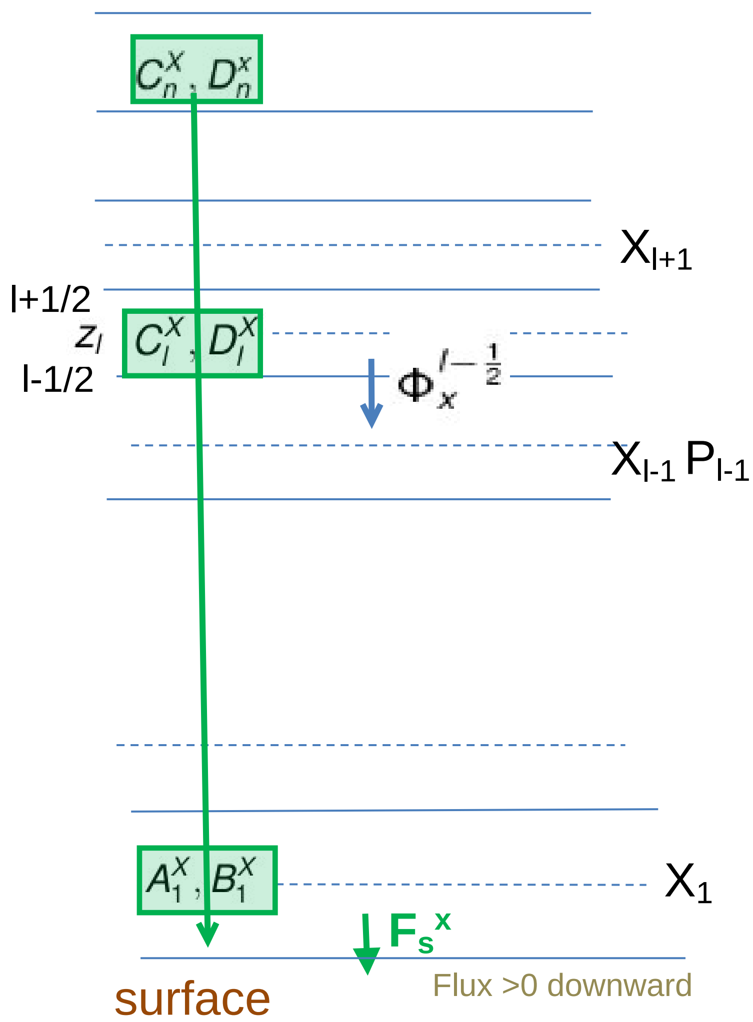
LU decomposition

Forward substitution : C_l^X, D_l^X depend only on properties in the layers above and the variables at the previous time step.

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

$$X_1 = A_1^X + B_1^X F_s^x \delta t$$



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$$F_s^{x,t+\delta t}$$

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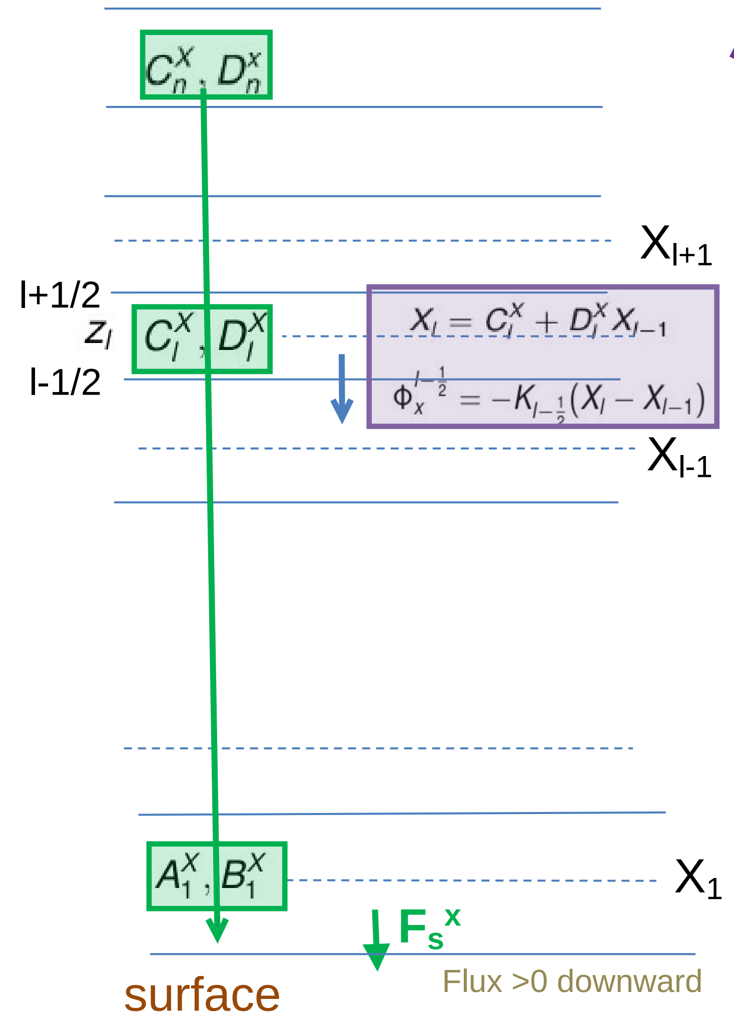

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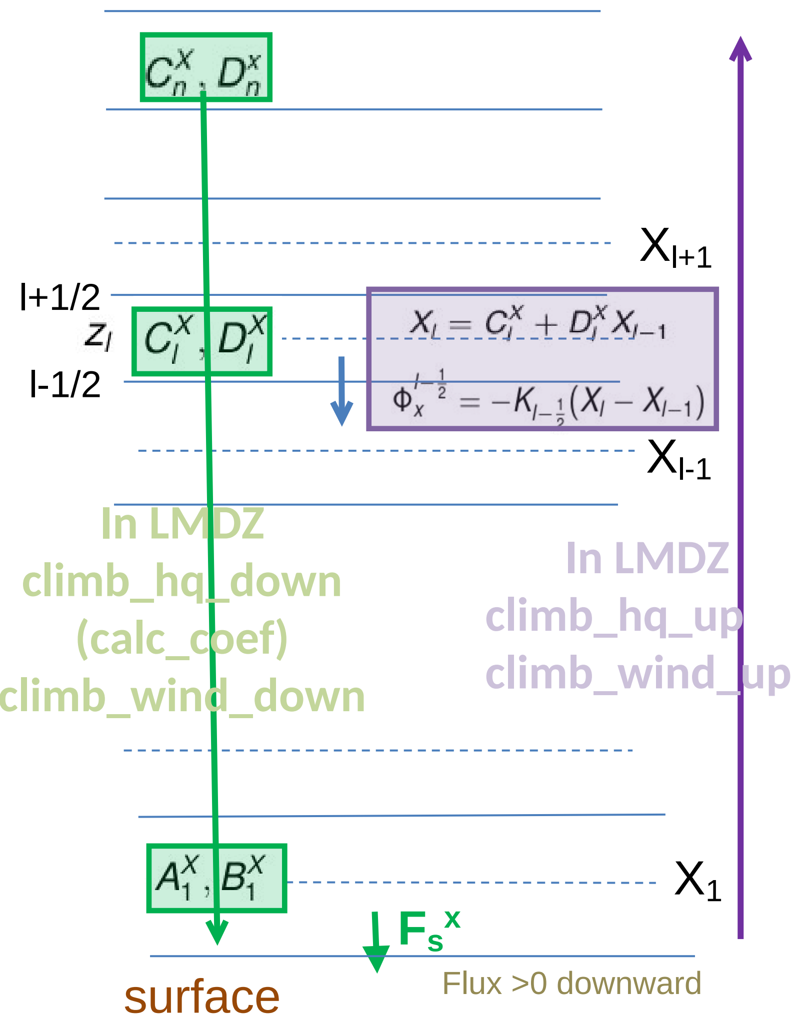

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backward substitution $X_l = C_l^X + D_l^X X_{l-1}$ $\quad X_1 = A_1^X + B_1^X F_s^{x^{t+\delta t}} \delta t$

depend only on atmosphere

Surface layer : constant flux (empirical, 10%),scale variables

$u_*^2 = \frac{\tau}{\rho} = -\overline{u'w'}$, friction velocity (velocity scale)

$\theta^* = -\frac{\overline{w'\theta'}}{u_*} = \frac{H}{\rho c_p u_*}, \quad q^* = -\frac{\overline{w'q'}}{u_*}$

MOST, flux-gradient (Neutral)

$$\frac{\partial u}{\partial z}\frac{\kappa z}{u_*} = 1 \qquad \frac{\partial \Theta}{\partial z}\frac{\kappa z}{\Theta_*} = 1$$

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$$\frac{\partial u}{\partial z}\frac{\kappa z}{u_*} = 1 \qquad \frac{\partial \Theta}{\partial z}\frac{\kappa z}{\Theta_*} = 1$$

$$\int_{u_o}^{u_1} \partial u = \int_{z_o}^{z_1} \frac{u_*}{\kappa z}\,\mathrm{d}z \qquad \int_{\Theta_s}^{\Theta_1} \partial \Theta = \int_{z_o}^{z_1} \frac{\kappa \Theta_*}{z}\,\mathrm{d}z$$

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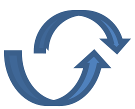
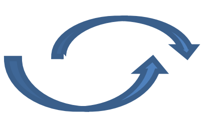


$$\int_{u_o}^{u_1} \partial u = \int_{z_o}^{z_1} \frac{u_*}{\kappa z}\,\mathrm{d}z \qquad \int_{\Theta_s}^{\Theta_1} \partial \Theta = \int_{z_o}^{z_1} \frac{\kappa \Theta_*}{z}\,\mathrm{d}z$$

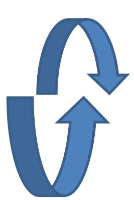
$$u_1 - u_0 = \frac{u_*}{\kappa}\ln\frac{z_1}{z_0} \qquad \Theta_* = (\Theta_1 - \Theta_s)\frac{\kappa}{\ln\frac{z_1}{z_{0_\Theta}}}$$

$$\rho u_*^2 = \tau = \rho u_1^2 \frac{\kappa^2}{\ln\frac{z_1}{z_0}\ln\frac{z_1}{z_0}} = \rho C_d u_1^2$$

$$H = \rho C_p \kappa^2 \frac{u_1}{\ln\frac{z_1}{z_{0_\Theta}}\ln\frac{z_1}{z_{0_u}}}(\Theta_1 - \Theta_s)$$



stable



instable

$$H = \rho C_p \kappa^2 \frac{u_1}{\ln\frac{z_1}{z_{0_\Theta}}\ln\frac{z_1}{z_{0_u}}} F_{stab(R_i, z_0)}(\Theta_1 - \Theta_s)$$

Sensible heat flux

$$H = C_p\Theta = C_p T(\frac{P}{P_o})^{\kappa}$$

$$\begin{cases} F_s^{H,t+\delta t} = \rho|\vec{v}|C_d(H_1^{t+\delta t} - H_s^{t+\delta t}) \\ H_1^{t+\delta t} = A_1^{H,t} + B_1^{H,t} F_s^{H,t+\delta t}\delta t \end{cases}$$

$$F_s^{H,t+\delta t} = \frac{A_1^{H,t}}{\frac{1}{\rho|\vec{v}|C_d} - B_1^{H,t}\delta t} - \frac{\rho|\vec{v}|C_d}{\frac{1}{\rho|\vec{v}|C_d} - B_1^{H,t}\delta t} H_s^{t+\delta t}$$

$$F_s^{H,t+\delta t} = M_H^t + N_H^t T_s^{t+\delta t}$$

$$C_{d,h} = \rho C_p \kappa^2 \frac{1}{\ln\frac{z_1}{z_{0_\Theta}} \ln\frac{z_1}{z_{0_u}}} F_{stab(R_i, z_0)}$$

Latent heat flux

$$\begin{cases} L_s^{q,t+\delta t} = \rho|\vec{v}|\beta C_d(q_1^{t+\delta t} - q_{sat}(T_s^{t+\delta t})) \\ q_1^{t+\delta t} = A_1^{q,t} + B_1^{q,t} L_s^{q,t+\delta t}\delta t \end{cases}$$

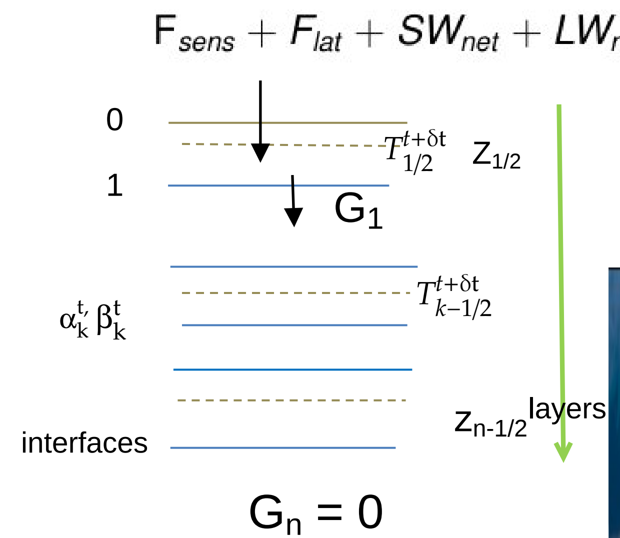
$$q_{sat}(T_s^{t+\delta t}) = q_{sat}(T_s) + \frac{\partial q_{sat}}{\partial T}|_{T_s^t}(T_s^{t+\delta t} - T_s^t)$$

$$L_s^{q,t+\delta t} = M_q^t + N_q^t T_s^{t+\delta t}$$

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

Heat conduction (1) $\begin{cases} \frac{\partial T}{\partial t} = -\frac{1}{c}\frac{\partial G}{\partial z} \\ G = -\lambda \frac{\partial T}{\partial z} \end{cases} \longrightarrow \frac{\partial T}{\partial t} = -\frac{1}{c}\frac{\partial[-\lambda \frac{\partial T}{\partial z}]}{\partial z}$



- Discretization of (1) in space and time

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

- (1) for the first interface : energy conservation

$$\Phi_1 = -\lambda_1 \frac{(T_{\frac{3}{2}} - T_{\frac{1}{2}})}{(z_{\frac{3}{2}} - z_{\frac{1}{2}})}$$

$$c_p \frac{T^{t+\delta t}_{1/2} - T^t_{1/2}}{\delta t} = \frac{1}{(z_1 - z_0)}[\lambda_1 \frac{(T^{t+\delta t}_{3/2} - T^{t+\delta t}_{1/2})}{(z_{3/2} - z_{1/2})} + F^{t+\delta t}_{sens} + F^{t+\delta t}_{lat} + SW_{net} + LW_d - \epsilon\sigma {T^{t+\delta t}_s}^4]$$

Heat conduction (1)

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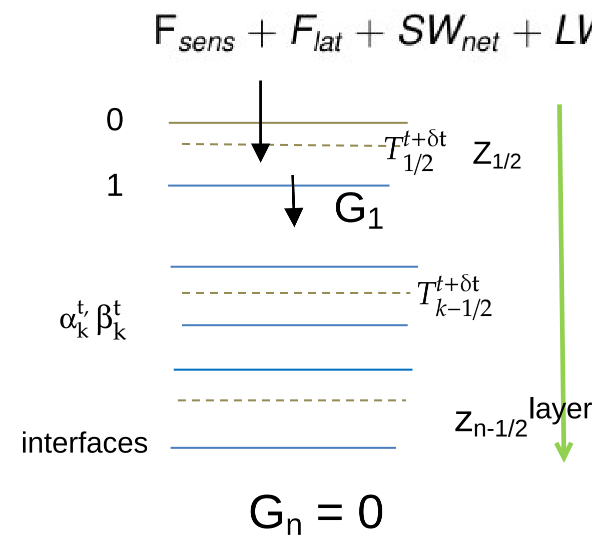

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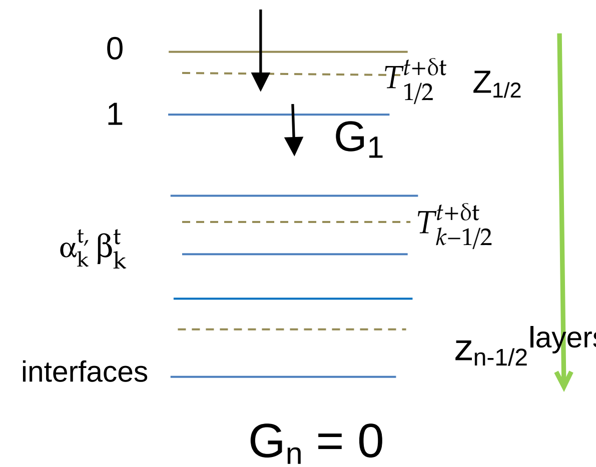
$$F_s^{H,t+\delta t} = M_H^t + N_H^t T_s^{t+\delta t} \qquad L_s^{q,t+\delta t} = M_q^t + N_q^t T_s^{t+\delta t}$$

Heat conduction (1) $\begin{cases} \frac{\partial T}{\partial t} = -\frac{1}{c}\frac{\partial G}{\partial z} \\ G = -\lambda \frac{\partial T}{\partial z} \end{cases} \longrightarrow \frac{\partial T}{\partial t} = -\frac{1}{c}\frac{\partial[-\lambda \frac{\partial T}{\partial z}]}{\partial z}$

$F_{sens} + F_{lat} + SW_{net} + LW_{net}$



- **Discretization of (1) in space and time** (implicit)

$$T_{k+1/2}^{t+\delta t} = \alpha_k^t \, T_{k-1/2}^{t+\delta t} + \beta_k^t \qquad (R_k)$$

- **(1) for the first interface : energy conservation**

$$\Phi_1 = -\lambda_1 \frac{(T_{\frac{3}{2}} - T_{\frac{1}{2}})}{(z_{\frac{3}{2}} - z_{\frac{1}{2}})}$$

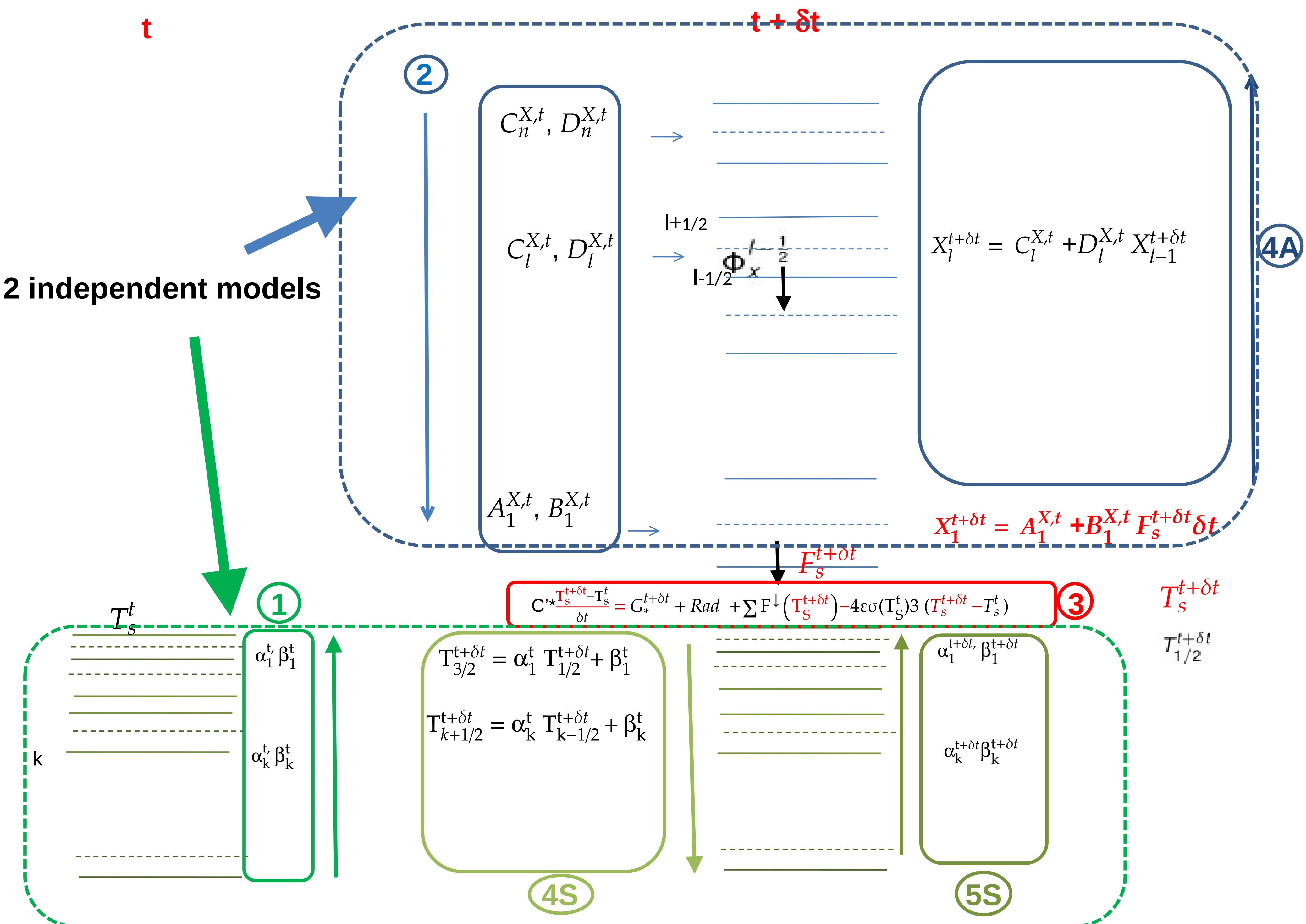
$$c_p \frac{T_{1/2}^{t+\delta t} - T_{1/2}^{t}}{\delta t} = \frac{1}{(z_1 - z_0)}\left[\lambda_1 \frac{(T_{3/2}^{t+\delta t} - T_{1/2}^{t+\delta t})}{(z_{3/2} - z_{1/2})} + F_{sens}^{t+\delta t} + F_{lat}^{t+\delta t} + SW_{net} + LW_d - \epsilon\sigma T_s^{t+\delta t^4}\right]$$

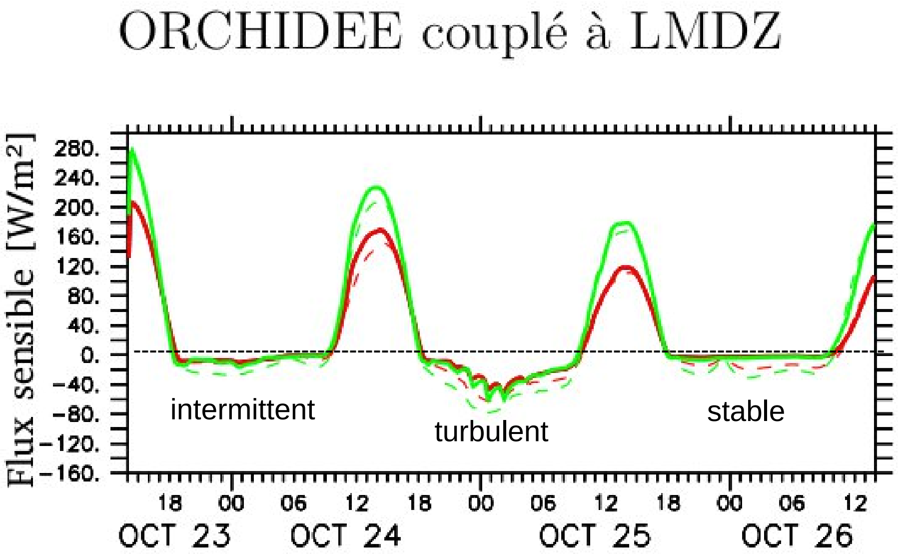
$$F_s^{H,t+\delta t} = M_H^t + N_H^t T_s^{t+\delta t} \qquad L_s^{q,t+\delta t} = M_q^t + N_q^t T_s^{t+\delta t}$$

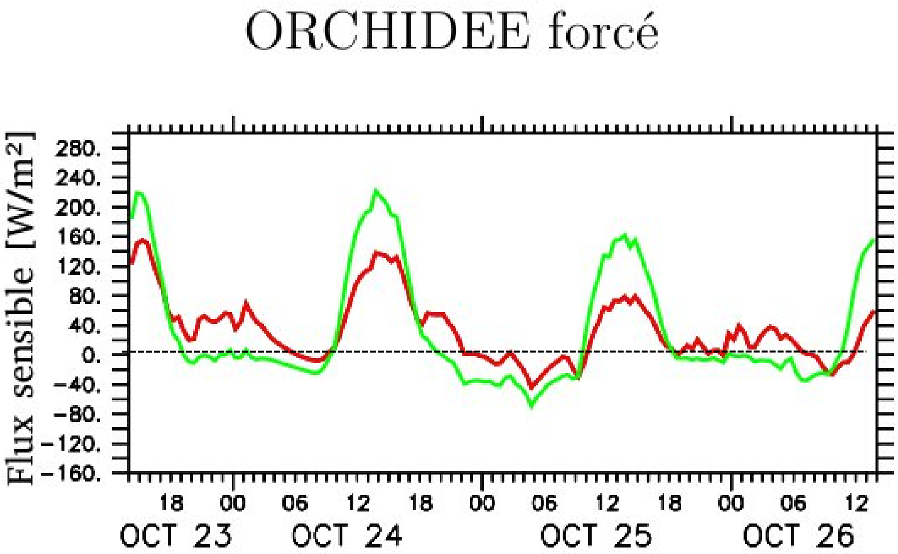
- **Temperature continuity : T_s extrapolated from soil temperature**

$$C'^{*}\frac{T_s^{t+\delta t} - T_s^t}{\delta t} = G_*^{t+\delta t} + Rad + \sum F^{\downarrow}\left(T_S^{t+\delta t}\right) - 4\varepsilon\sigma (T_S^t)^3 \, (T_s^{t+\delta t} - T_s^t)$$

One diffusion equation from the top of the PBL to the bottom of the soil



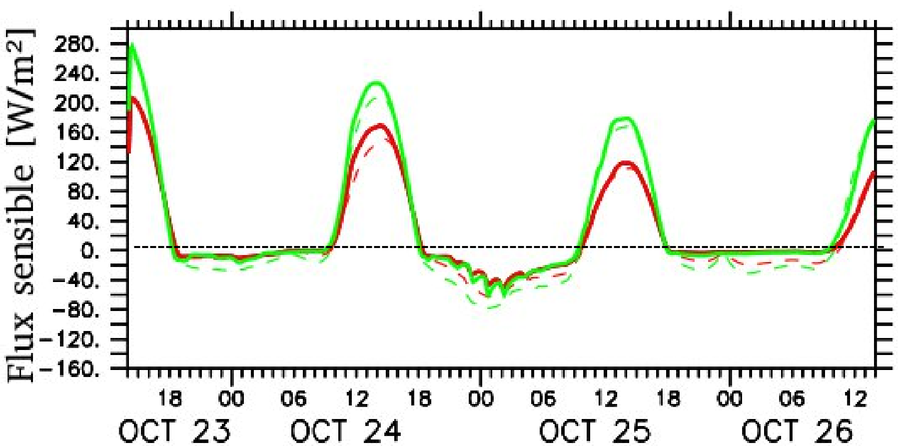




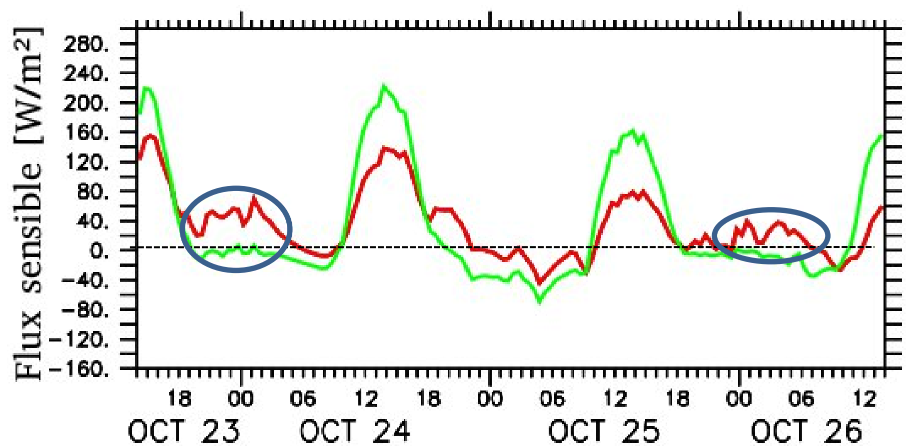
PhD S. Ait Mesbah

Dice 1D case, Best et al.,2025

ORCHIDEE couplé à LMDZ



ORCHIDEE forcé

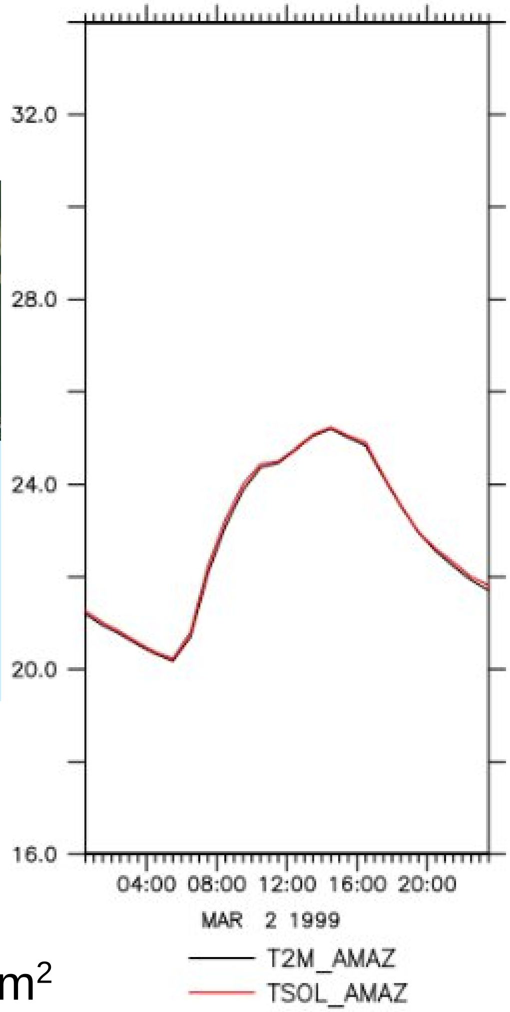


PhD S. Ait Mesbah

Dice 1D case

Same physics : different local conditions

Amazonie

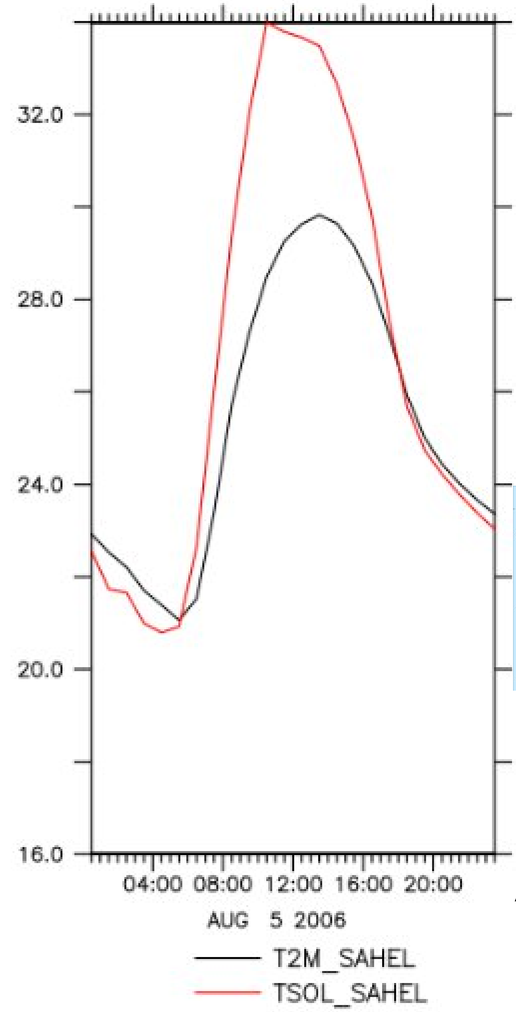


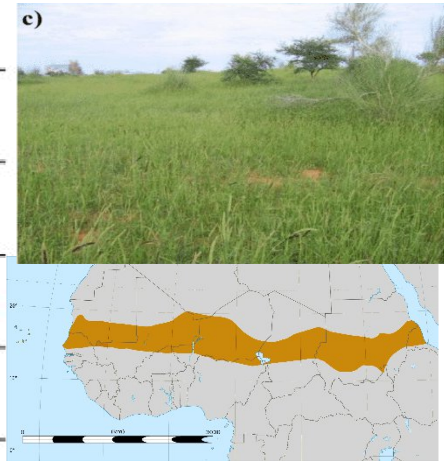
Albedo 0.12

Z_0 =1.8m

Soil moisture:50kg/m^2

Sahel





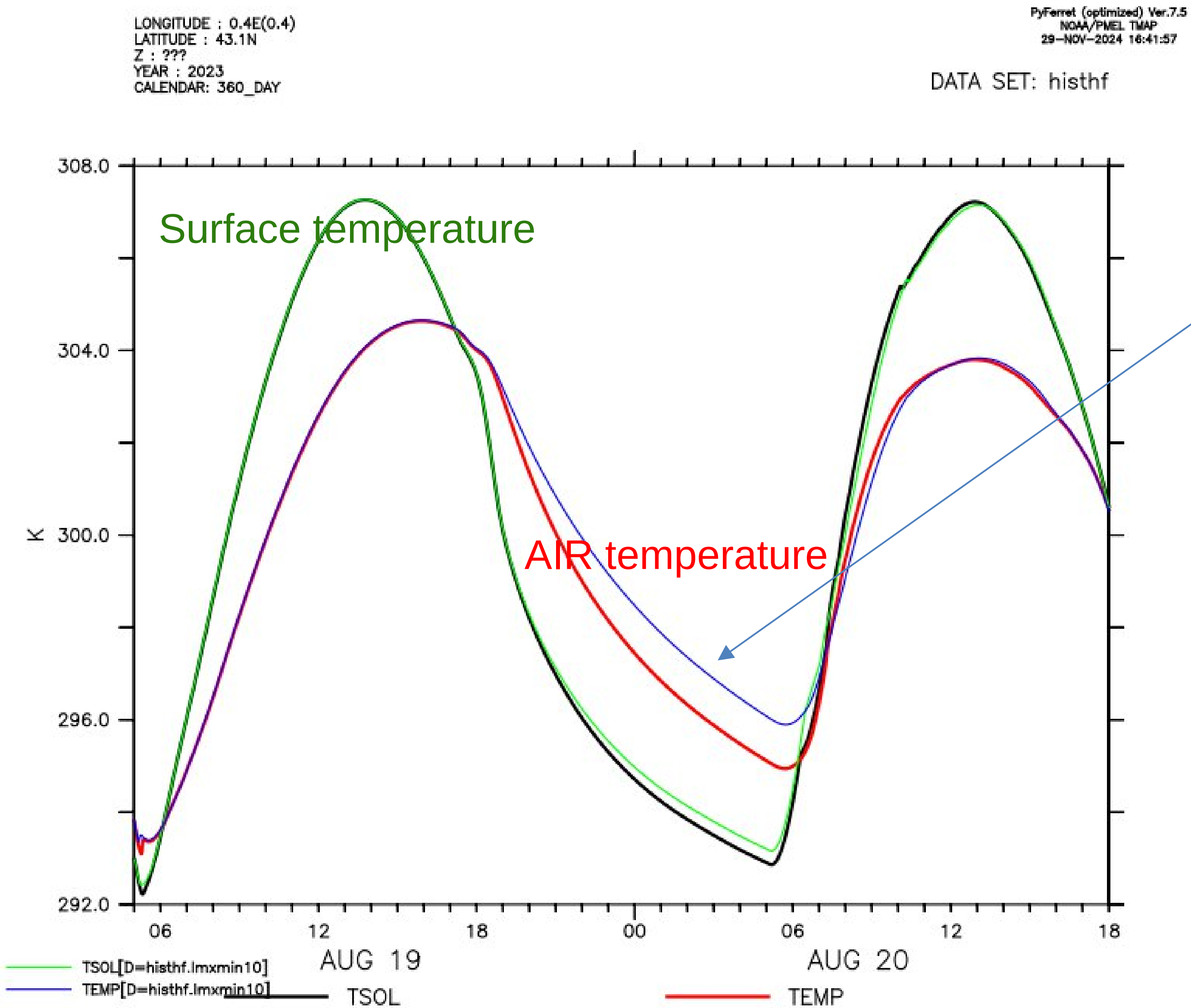
Albedo=0.26

Z_0 =0.01m

Soil moisture:25kg/m^2

Thanks :Rachida El Ouaraini and Bouchra Sadiki,UM6P 2022

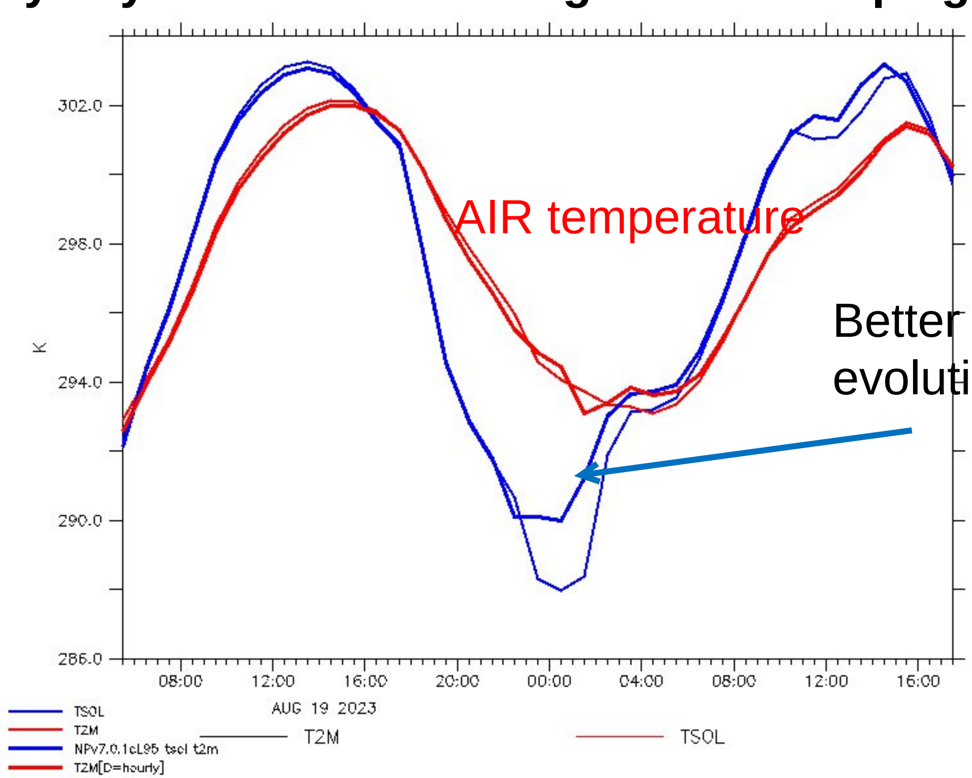
2 clear sky days in summer during MOSAI campaign in Lannemezan (Near Pyrénées)



Same physics authorizing less decoupling between land surface and atmosphere

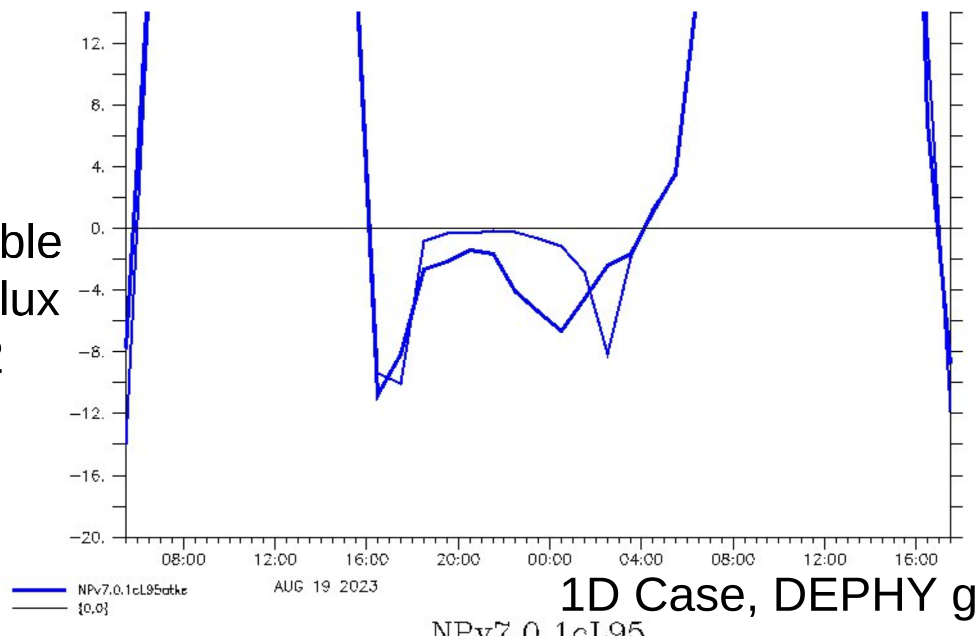
1D Case, DEPHY group, A. Maison et al., 2026 in prep ;

2 clear sky days in summer during MOSAI campaign in Lannemezan (Near Pyrénées)



Better numerical treatment of the evolution equation of tke (Vignon et al.,2024)

Sensible heat flux W/m2



1D Case, DEPHY group, A. Maison et al., 2026 in prep ;

Atmosphere/surface coupling in LMDZOR

LMDZ (phylmd)

Planetary boundary layer
and surface modules

pbl_surface

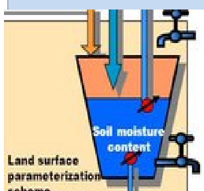
$(A_q , B_q, A_H , B_B, C_{dh},, A_u , B_u, A_v , B_v , C_{dh}, T_1, q_1, u_1, v_1, LW_{net}, LW_{down}, Sw_{net})$

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

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 = y)

surf_land_orchidee

LW_{dwn}, SW_{net}, LW_{net}, T_1, q_1, $cdrag_h$, u_1,v_1

A_q , B_q, A_H , B_B, rain, snow)

fluxsens, fluxlat, albedo, ε, tsurf_new, z0

intersurf **ORCHIDEE (sechiba)**

petA_orc,petB_orc,peqA_orc,peqB_orc,swet, swnet,lwdown, cdrag

Water and Energy budget (surface and soil)

diffuco (z0, albedo , emissivity) E

enerbil fluxsens ,fluxlat, tsurf_new

thermosoil G, ztsol

Hydrol: hydrology – diffusion scheme

Atmosphere/surface coupling in LMDZOR

LMDZ (phylmd)

Planetary boundary layer and surface modules

pbl_surface

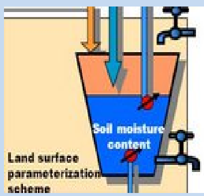
(A_q , $B_{q,}$ A_H , $B_{B,}$ $C_{dh,}$, A_u , $B_{u,}$ A_v , B_v , C_{dh}, T_1, $q_{1,}$ u_1,$v_{1,}$ $LW_{net,}$ $LW_{down,}$ SW_{net})

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

LW_{dwn}, SW_{net}, LW_{net}, T_1, q_1, $cdrag_h$, u_1,v_1

A_q , $B_{q,}$ A_H , B_B, rain, snow)

fluxsens, fluxlat, albedo, ε, tsurf_new, z0

intersurf ORCHIDEE (sechiba)

petA_orc,petB_orc,peqA_orc,peqB_orc,swet, swnet,lwdown, cdrag

Water and Energy budget (surface and soil)

diffuco (z0, albedo , emissivity) E

enerbil fluxsens ,fluxlat, tsurf_new

thermosoil G, ztsol

Hydrol: hydrology – diffusion scheme

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, momentum
- 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

Take home messages

- Atmosphere and surfaces are coupled through turbulent diffusion and radiation
- Different sub-surface are considered (albedo, emissivity, rugosity) for ocean, land, land-ice, sea ice but only one atmosphere is above.
- For each sub-surface one solves a unique diffusion equation from the top of the PBL to the bottom of the soil with an implicit scheme. The surface energy budget allows to find the boundary conditions
- Priority is given to the energy conservation
- The coupling matters : surface forced simulations can produce irrealistic surface fluxes, local surface condition strongly impact near surface variables
- « screen » variables - T2m, q2m, wind10m are not prognostic variables (interpolation)

- Technical note **:** Description of the interface with the surface and the computation of the turbulent diffusion in LMDZ (J.L.Dufresne and J. Ghattas) https://forge.ipsl.jussieu.fr/orchidee/attachment/wiki/Documentation/CouplingLMDZ/Dufresne,%20Ghattas%20-%202009_Coupling-ORC-LMDZ.pdf
- Thèse F. Hourdin 1993 (section 3.3.3 and annexes) web page F. Hourdin
- Wang F., F. Cheruy, J.L. Dufresne, 2016: The improvement of soil thermodynamics and its effects on land surface meteorology in the IPSL climate model. Geosci. Model Dev., 9, 363–381, 2016 www.geosci-model-dev.net/9/363/2016/
- Cheruy et al.,2020 Improved near surface continental climate in IPSL-CM6A-LR by combined evolutions of atmospheric and land surface physics https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019MS002005