The surface-atmosphere interactions

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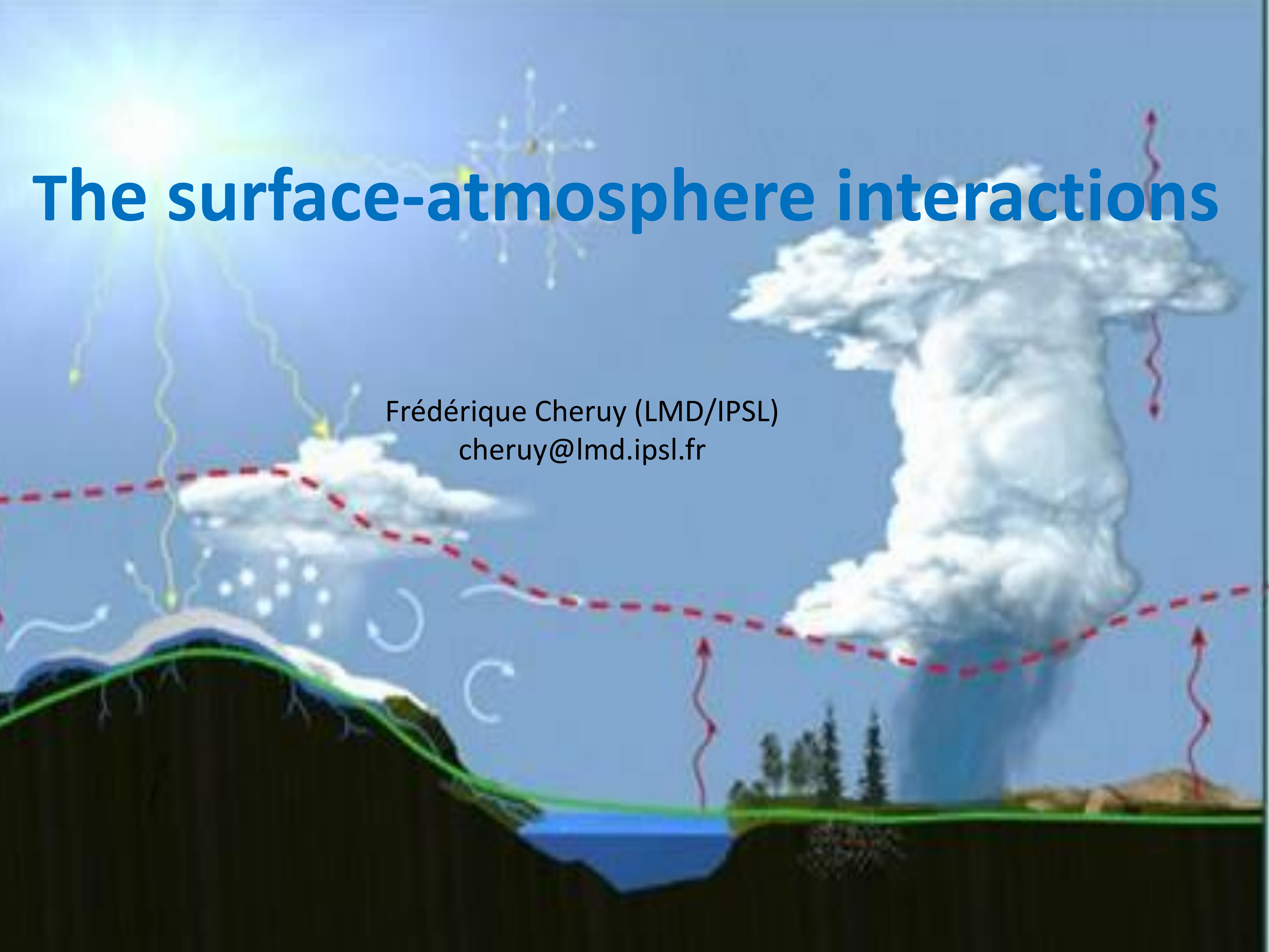

Outline

- Introduction
- Processes involved at the interface
- Turbulent transport
- Some point on the time marching schemes
  (courtesy of E. Millour- LMDZ training)
- Implicit approach, surface temperature and land surface specificities
- Radiation and energy conservation
- The routines in LMDZOR and the calling tree.

COUPLING BETWEEN ATMOSPHERE AND SURFACE

Processes involved

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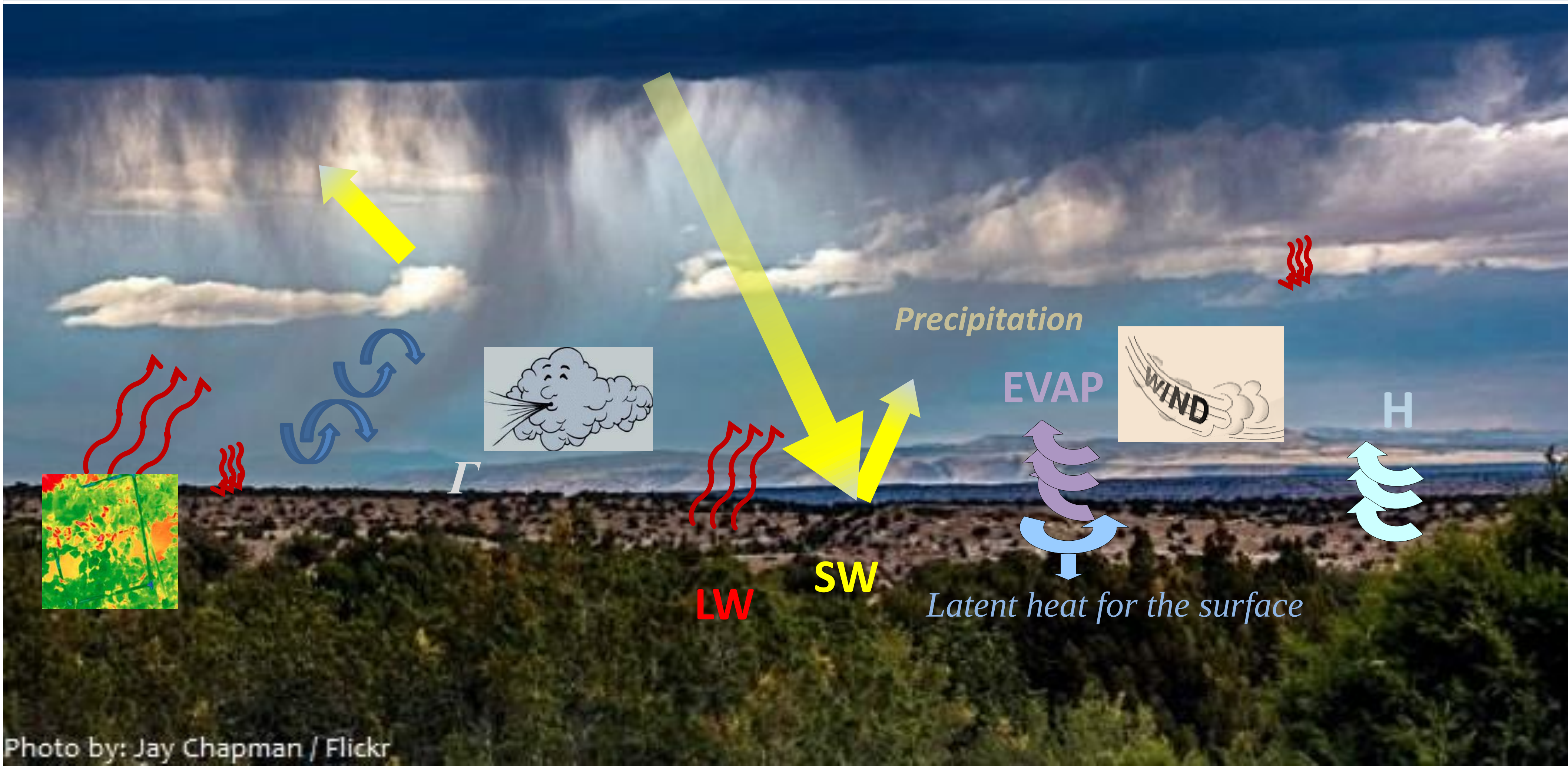


The **atmosphere and the surface are coupled** through *turbulence* (in boundary layer) and *radiatio*
(SW and LW).

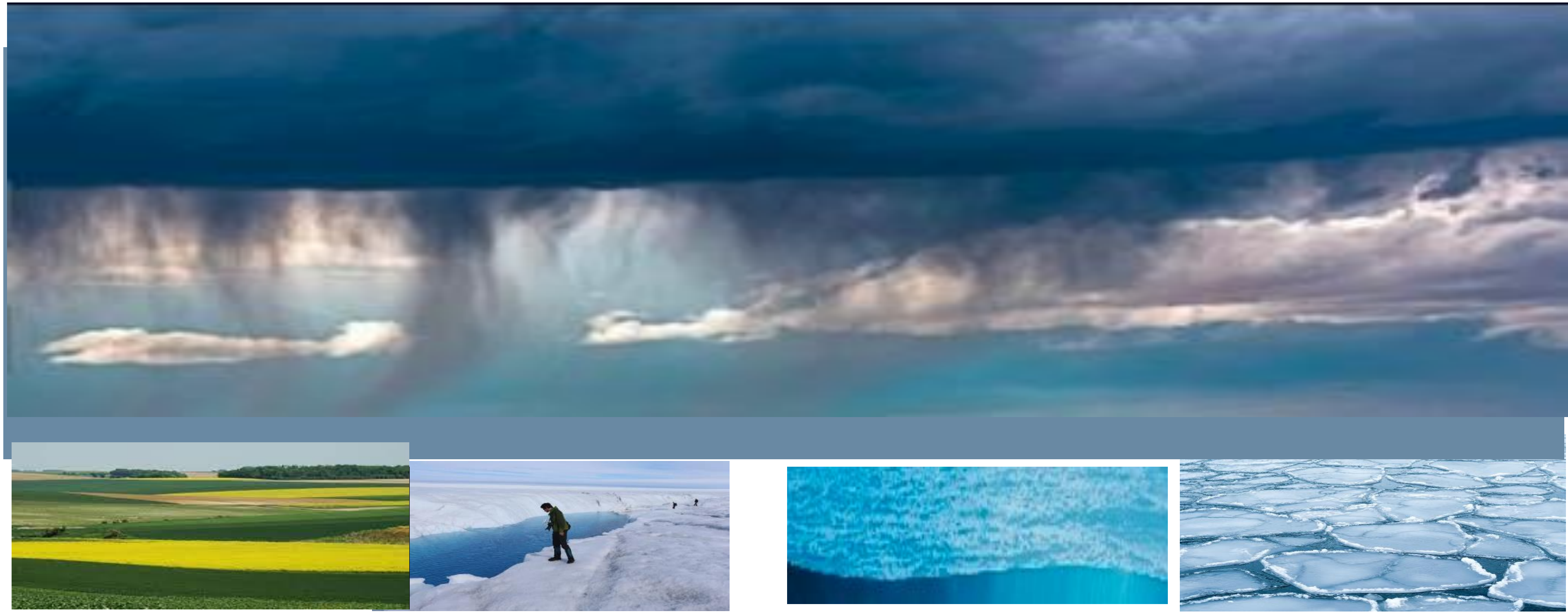
Surface impacts atmosphere via orography, roughness, albedo, emissivity

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 and atmosphere



4/3 sub-surfaces types

Albedo, emissivity , rugosity

Radiation , turbulent fluxes

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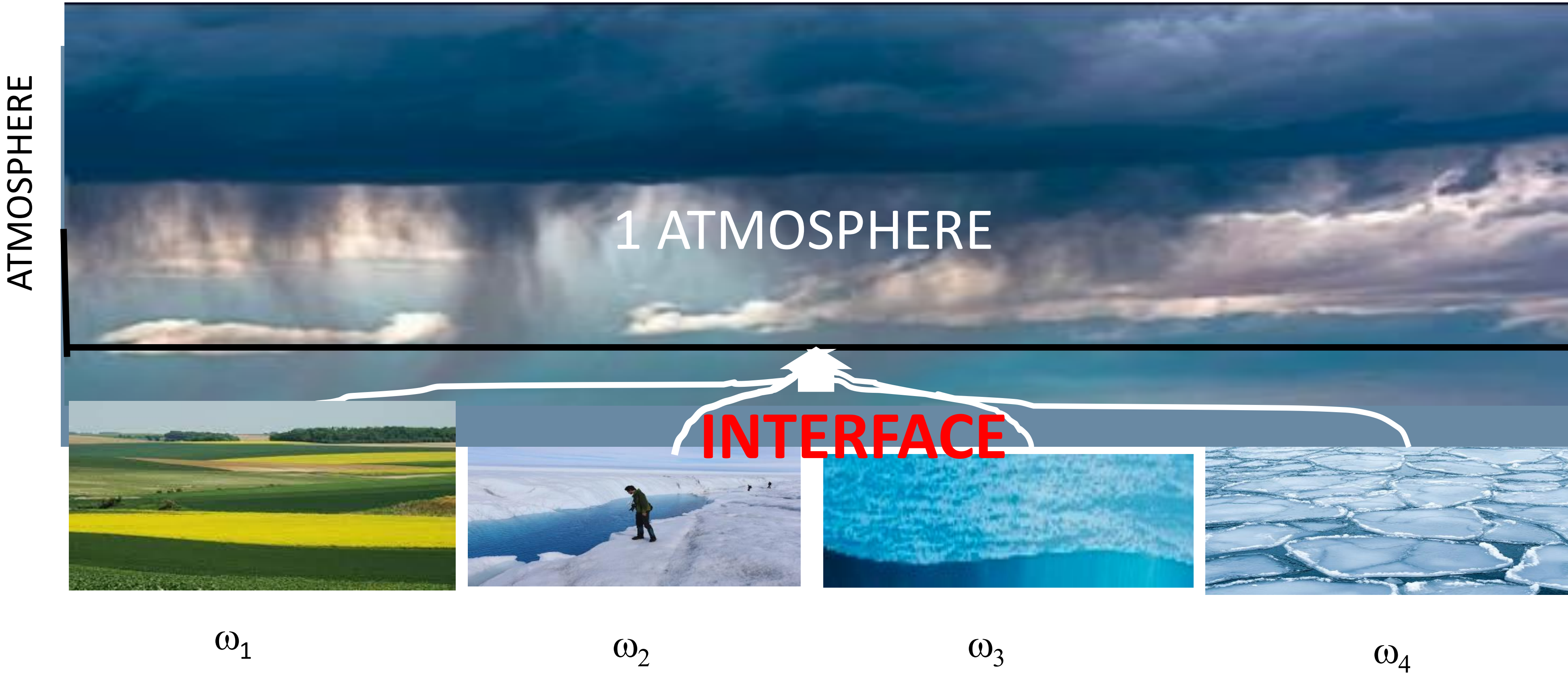
4 sub-surfaces types

Albedo, emissivity , rugosity

Radiation , turbulent fluxes



$$\sum \omega_i = 1$$

4 sub-surfaces types

Albedo, emissivity , rugosity

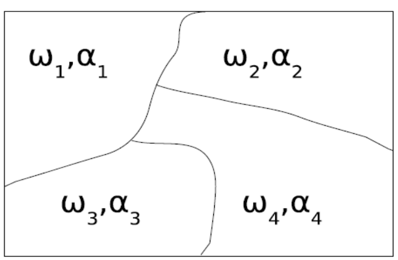
Radiation , turbulent fluxes

Coupling between atmospheric column(s) and sub-surfaces

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

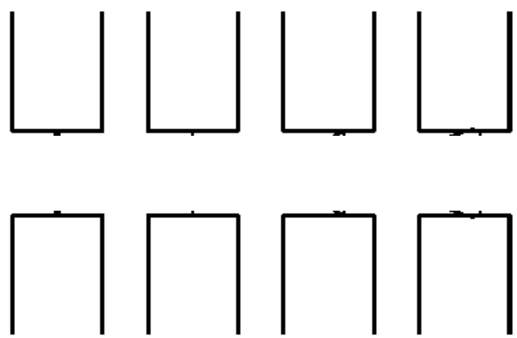
Sub-surfaces

$$\sum_i \omega_i = 1$$



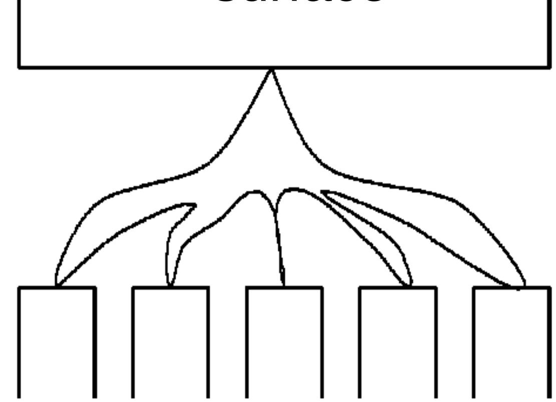
Turbulent flux

One PBL over **each** sub-surface

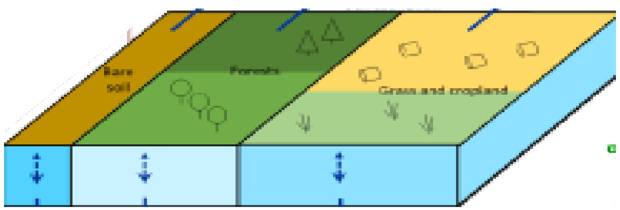


Radiative flux

One column **covers all** the sub-surface



INTERFACE



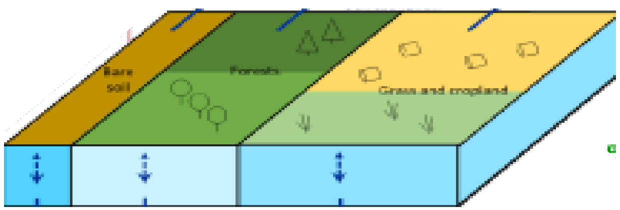
Processes involved at the interface

Radiation = $LW_{up} + LW_{dn} + SW_{up} + SW_{dn}$

Turbulent flux : $H_{(sensible)} + L_{(Latent)}$

Soil heat conduction : G

INTERFACE



Processes involved at the interface

Forcing

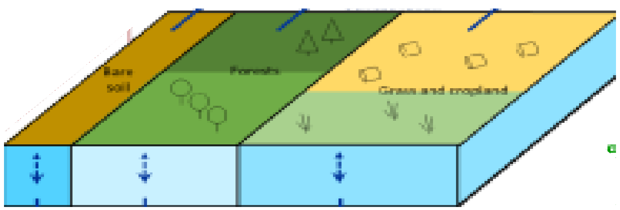
Radiation = $LW_{up} + LW_{dn} + SW_{up} + SW_{dn}$

Turbulent flux : $H_{(sensible)} + L_{(Latent)}$

Soil heat conduction : G

Response (Turbulent flux, Soil heat conduction)

INTERFACE



Processes involved at the interface

Forcing

Radiation = $LW_{up} + LW_{dn} + SW_{up} + SW_{dn}$

Passive response (depends only on T_s)

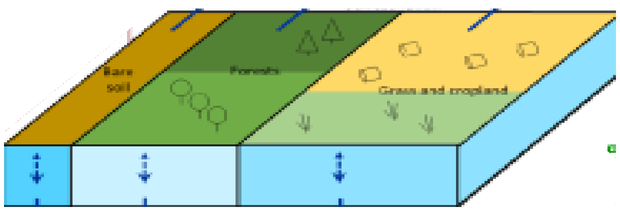
Turbulent flux : $H_{(sensible)} + L_{(Latent)}$

Soil heat conduction : G

Response

Radiation = $H_{(sensible)} + L_{(Latent)} + G$

INTERFACE



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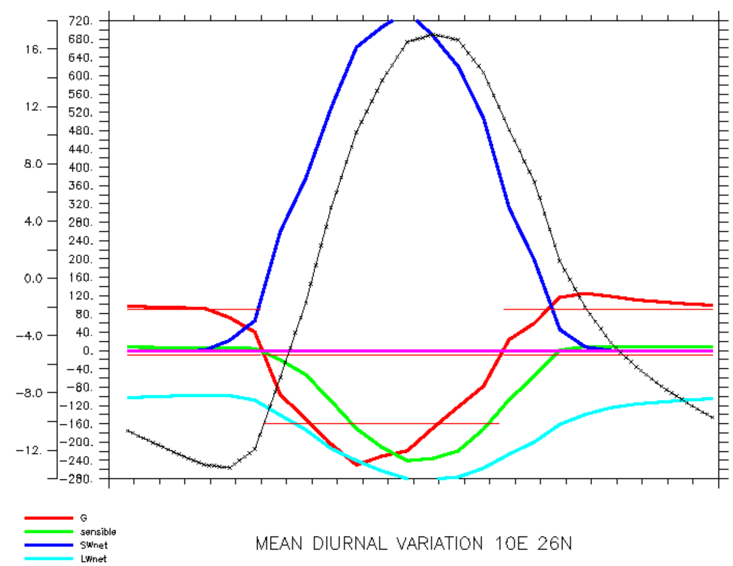
} **Response**

Radiation = $H_{(sensible)}$ + $L_{(Latent)}$ + G



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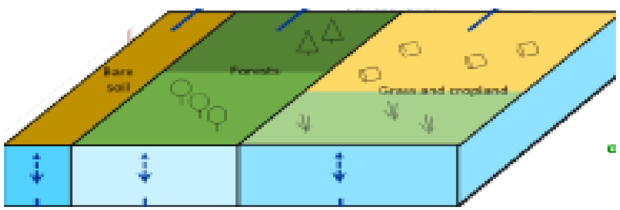


Processes involved at the interface

Forcing

Radiation = LW_{up} + LW_{dn} + SW_{up} + SW_{dn}

(depends only on T_s)

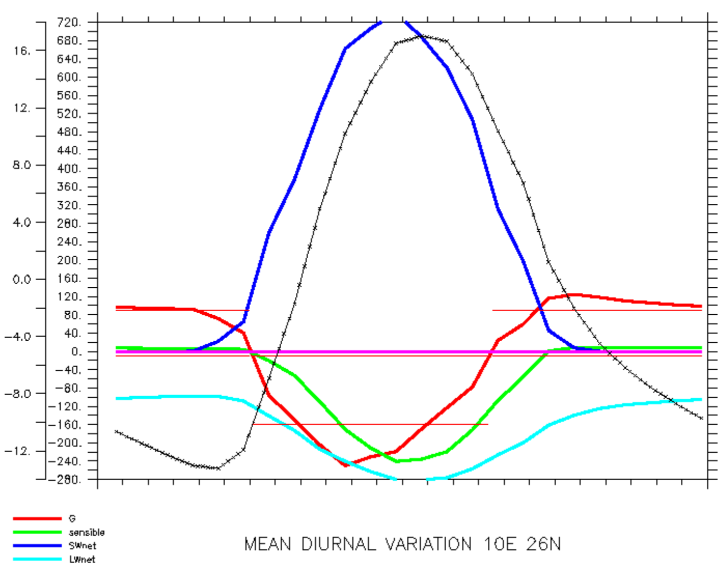
Turbulent flux : $H_{(sensible)}$ + $L_{(Latent)}$

Soil heat conduction : G

Response

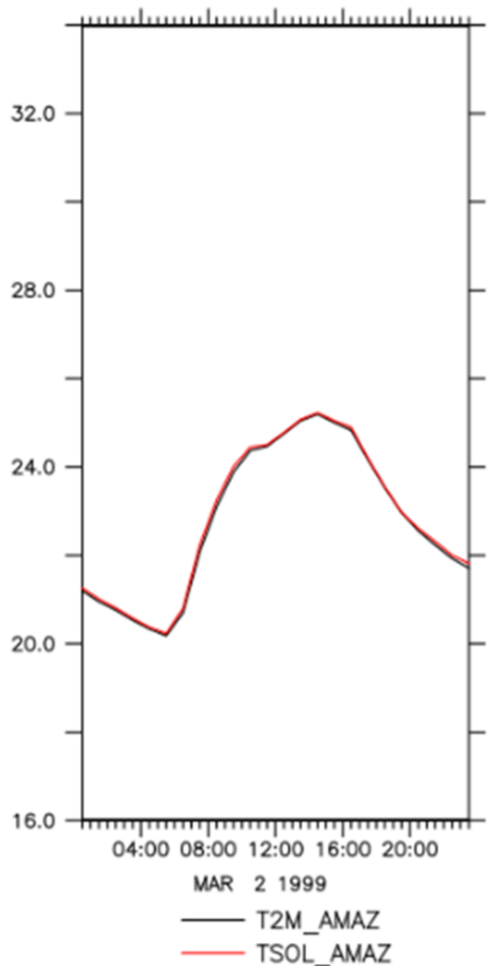
depends on Ts and air values

depends on Ts

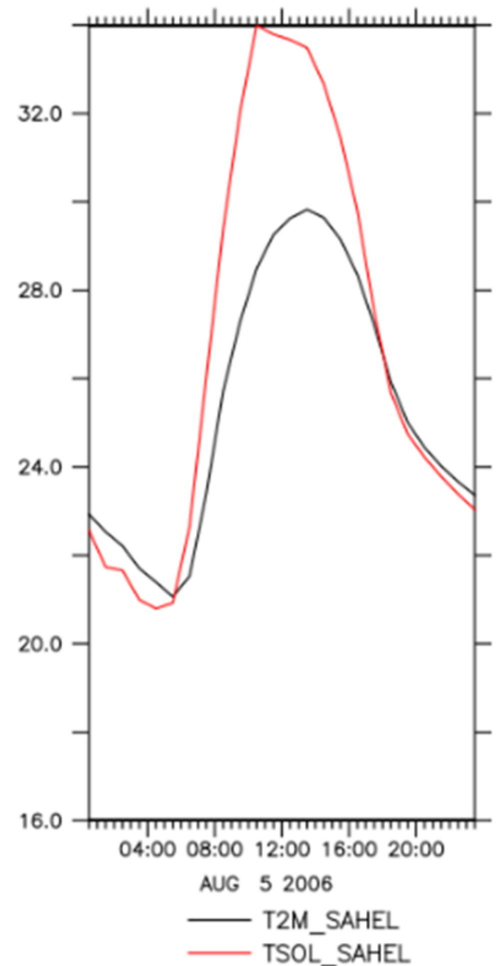


Radiation = $H_{(sensible)}$ + $L_{(Latent)}$ + G

Amazonie



Sahel



February
Moist soil
Low albedo
High value of z0

June
Dry soil
High albedo
Low value of z0

TURBULENT TRANSPORT

Change of a variable X with the time due to the turbulent transport

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial \Phi}{\partial z} \quad \text{(continuity)} \qquad \Phi = -\rho k_z \frac{\partial X}{\partial z}$$

$$\Phi = \overline{w'X'}$$

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho k_z \frac{\partial X}{\partial z}\right)$$

$$k_z = l^2 \frac{\partial \|v\|}{\partial z} = l\left|\overline{w'}\right| \quad \text{Prandl}$$

In the boundary layer: *l* = f(TKE) - Mellor Yamada in LMDZ

Near the surface : l ~ κ z

TURBULENT TRANSPORT : Surface Layer

Near the surface : $l \sim \kappa z$

MOST $u_*^2 = \frac{\tau}{\rho} = -\overline{u'w'}$, $\theta^* = -\frac{\overline{w'\theta'}}{u_*} = -\frac{H}{\rho c_p u_*}$, $q^* = -\frac{\overline{w'q'}}{u_*}$

Neutral case $\frac{\partial u}{\partial z}\frac{\kappa z}{u_*} = 1$ $\frac{\partial \theta}{\partial z}\frac{\kappa z}{\theta_*} = 1$

$\frac{\partial u}{\partial z} = U_* / \kappa z$

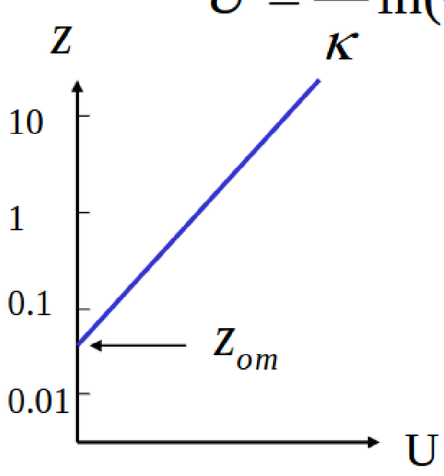
$H = -\rho c_p u_* \theta^* = \rho c_p l^2 \frac{\partial \|v\|}{\partial z}\frac{\partial \theta}{\partial z}$

$H = \rho c_p u_* \kappa z \frac{\partial \theta}{\partial z}$

$\int_{z0}^{z} \partial u = \frac{U_*}{\kappa}\int_{z0}^{z}\frac{\partial z}{z} = \frac{U_*}{\kappa}\ln(\frac{z}{z_0})$

$\int_{z0}^{z} \partial \theta = \frac{H}{\rho c_p u_* \kappa}\ln\left(\frac{z}{z_{0h}}\right)$

$$U = \frac{u_*}{\kappa}\ln(\frac{z}{z_{om}})$$



$\tau = \frac{\rho\kappa^2}{\ln\left(\frac{z}{z_0}\right)^2} u^2$

$H = \kappa^2 \frac{\rho c_p \, u(z)(\theta_z - \theta_s)}{\ln\left(\frac{z}{z_{0h}}\right)\ln\left(\frac{z}{z_0}\right)}$

$\tau = \frac{\rho\kappa^2}{\ln\left(\frac{z}{z_0}\right)^2} u^2 f_{stab\_m}$

$H = f_{stab\_h}\, \kappa^2 \frac{\rho c_p \, u(z)(\theta_z - \theta_s)}{\ln\left(\frac{z}{z_{0h}}\right)\ln\left(\frac{z}{z_0}\right)}$

TURBULENT TRANSPORT

Discretization

(pbl_surface, LMDZ)

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

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho k_z \frac{\partial X}{\partial z}\right)$$

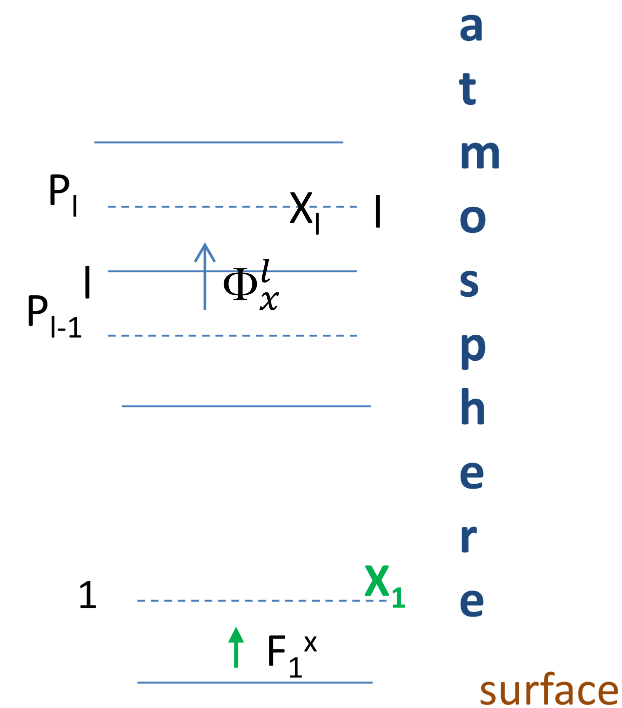
$$F_1^q = \beta \rho V C_{d,q} \left(q_1 - q_s(T_s)\right)$$

$$F_1^h = \rho V C_{d,h} \left(T_1 - T_s\right)$$

$$F_1^u = \rho V C_{d,m} \left(u_1 - u_o\right)$$

$$C_{dm} = \kappa^2 / \left(\ln\left(\frac{z}{z0m}\right) * \ln\left(\frac{z}{z0m}\right)\right) * Fstab$$

$$C_{dh} = \kappa^2 / \left(\ln\left(\frac{z}{z0m}\right) * \ln\left(\frac{z}{z0h}\right)\right) * Fstab$$



X= specific humidity, enthalpie, momentum

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

TURBULENT TRANSPORT

Discretization
(pbl_surface, LMDZ)

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

$$\frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho k_z \frac{\partial X}{\partial z}\right)$$

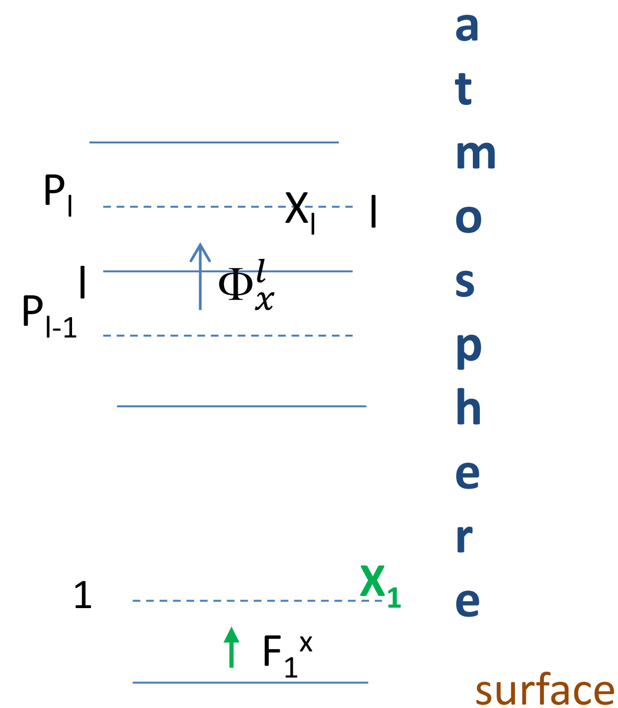
$$F_1^q = \beta \rho V C_{d,q} (q_1 - q_s(T_s))$$

$$F_1^h = \rho V C_{d,h} (T_1 - T_s)$$

$$F_1^u = \rho V C_{d,m} (u_1 - u_o)$$

$$C_{dm} = \kappa^2 / (\ln(\frac{z}{z0m}) * \ln(\frac{z}{z0m})) * Fstab$$

$$C_{dh} = \kappa^2 / (\ln(\frac{z}{z0m}) * \ln(\frac{z}{z0h})) * Fstab$$



Spatio-temporal boundary-value problem

X= specific humidity, enthalpie, momentum

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

Time marching schemes

- **The big picture**: you want to solve

$$\frac{df(t)}{dt} = R(f,t)$$
$$f(t=0) = f_0$$

from a known initial condition at time t=0 to time t=...

- So it is all about using a time marching scheme, built on Taylor expansion for evaluation of the time derivative, and choosing at which time level $t=n.\delta t$ the right hand side term R[f(t),t] is to be evaluated :

$$f(t_0+\delta t) = f(t_0) + \frac{\delta t}{1!}f'(t_0) + \frac{(\delta t)^2}{2!}f''(t_0) + \ldots$$

Time marching schemes

- Explicit Euler scheme (1st order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1} - f_n}{\delta t} \\ R(f,t) &\simeq R(f(t_n), t_n) \end{aligned}$$

- Implicit Euler scheme (1st order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1} - f_n}{\delta t} \\ R(f,t) &\simeq R(f(t_{n+1}), t_{n+1}) \end{aligned}$$

- Crank-Nicholson scheme (2nd order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1} - f_n}{\delta t} \\ R(f,t) &\simeq \frac{R(f(t_{n+1}), t_{n+1}) + R(f(t_n), t_n)}{2} \end{aligned}$$

Time marching schemes

- Illustrative example, on a decay equation (known solution!)

$$\frac{dq(t)}{dt} = -\frac{1}{\tau}q(t) \longrightarrow q(t) = q_0 e^{-\frac{t}{\tau}}$$

- Building Euler explicit (E) & implicit (I) schemes:

$$\begin{aligned} \frac{dq(t)}{dt} &= -\frac{1}{\tau}q(t) \\ \Rightarrow \frac{q^{n+1}-q^n}{\delta t} &\simeq -\frac{1}{\tau}q^n \qquad \text{(E.E.)} \\ \Leftrightarrow q^{n+1}-q^n &= -\frac{\delta t}{\tau}q^n \\ \Leftrightarrow q^{n+1} &= \left[1-\frac{\delta t}{\tau}\right]q^n \end{aligned}$$

CFL condition dt/tau<2

$$\begin{aligned} \frac{dq(t)}{dt} &= -\frac{1}{\tau}q(t) \\ \Rightarrow \frac{q^{n+1}-q^n}{\delta t} &\simeq -\frac{1}{\tau}q^{n+1} \qquad \text{(E.I.)} \\ \Leftrightarrow q^{n+1}-q^n &= -\frac{\delta t}{\tau}q^{n+1} \\ \Leftrightarrow \frac{\tau+\delta t}{\tau}q^{n+1} &= q^n \\ \Leftrightarrow q^{n+1} &= \frac{1}{1+\frac{\delta t}{\tau}}q^n \end{aligned}$$

Courtesy of E. Millour

Side note about explicit or implicit time marching schemes

Even when solving linear spatio-temporal boundary-value problems, e.g.:

$$\frac{dA}{dt} = \kappa \frac{\partial^2 A}{\partial x^2} \qquad \frac{\partial X}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho k_z \frac{\partial X}{\partial z}\right)$$

The explicit Euler approach leads to a straightforward expression for grid point values (but with stability constraints) :

$$\frac{A_i^{k+1} - A_i^k}{\delta t} = \frac{\kappa}{h^2}\left[A_{i-1}^k - 2A_i^k + A_{i+1}^k\right]$$

Whereas the implicit Euler approach leads to a (tridiagonal) system of equations to solve:

$$\frac{A_i^{k+1} - A_i^k}{\delta t} = \frac{\kappa}{h^2}\left[A_{i-1}^{k+1} - 2A_i^{k+1} + A_{i+1}^{k+1}\right]$$

Courtesy of E. Millour

=> requires more computations, but may be necessary if time-stepping constrains require using large time steps.

Side note about tridiagonal system solving

When needing to solve a tridiagonal system of the form:

T.x=y , T tridiagonal matrix, x & y vectors

Rather than invert T (costly!) to generate T^{-1} (dense matrix) and then compute $x=T^{-1}.y$ (matrix-vector product)

Use the LU decomposition (Gaussian elimination) of T to split the problem into two very simple sub-problems:

1) L.U=T , L and U are bidiagonal (lower/upper) matrices

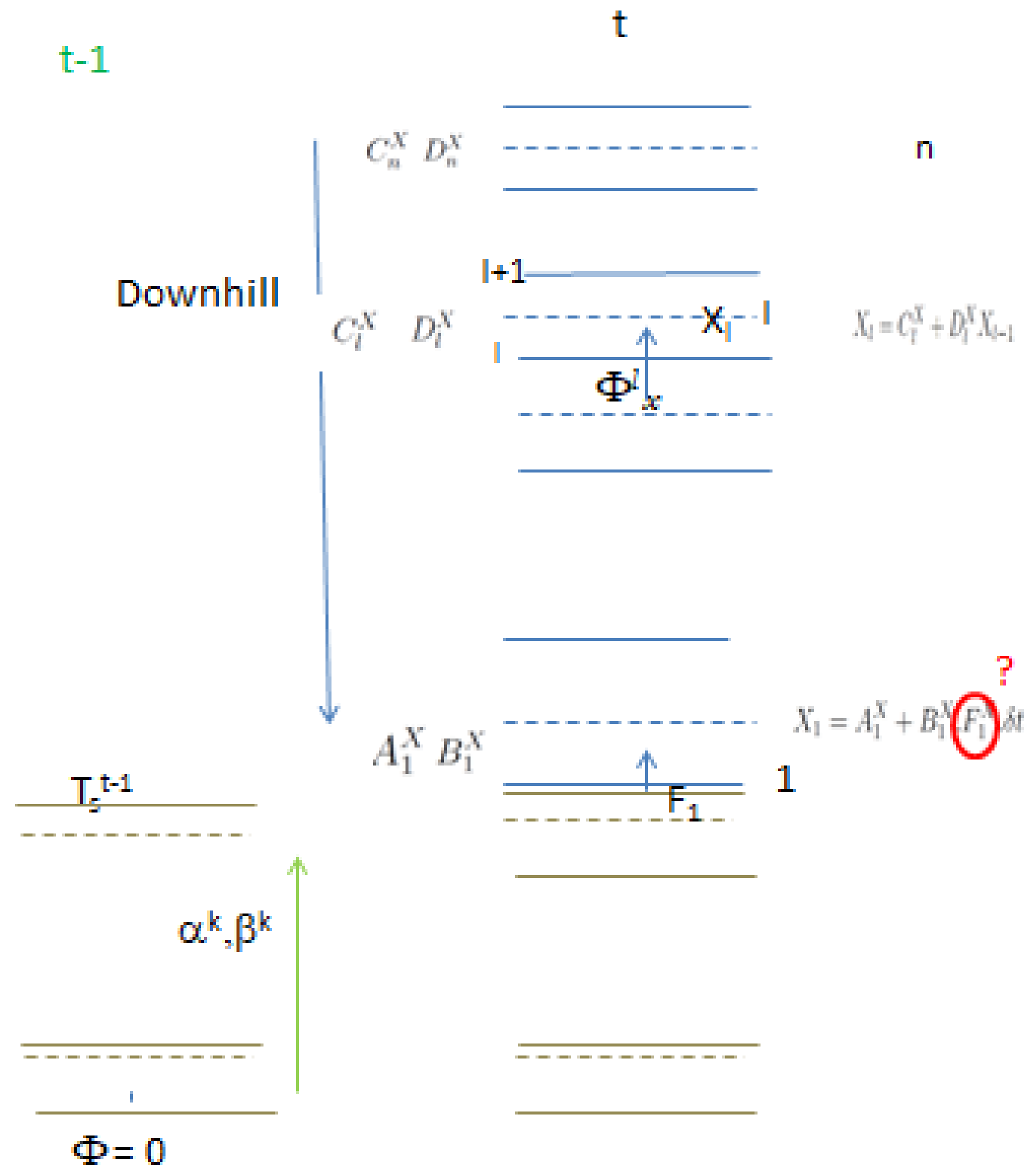
2) Solve L.z=y for vector z (forward substitution step)

3) Solve U.x=z for vector x (backward substitution step)

Courtesy of E. Millour

Implicit approach scheme

In LMDZ
climb_hq_down
and
climb_wind_down



At t α_k and β_κ depend on T_k at the previous time step and on the underlying layers:
They can be pre-computed

Hourdin 1993

Implicit approach at the interface

Radiation = LW_{up} + LW_{dn} + SW_{up} + SW_{dn}

(depends only on T_s)

Turbulent flux : $H_{(sensible)}$ + $L_{(Latent)}$

Soil heat conduction : G

depends on Ts and air values

depends on Ts

Radiation = $H_{(sensible)}$ + $L_{(Latent)}$ + G

Implicit approach scheme : Solving for the surface temperature

- Surface boundary condition:

Continuity of the fluxes and the temperature between sub-surface and atmosphere

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

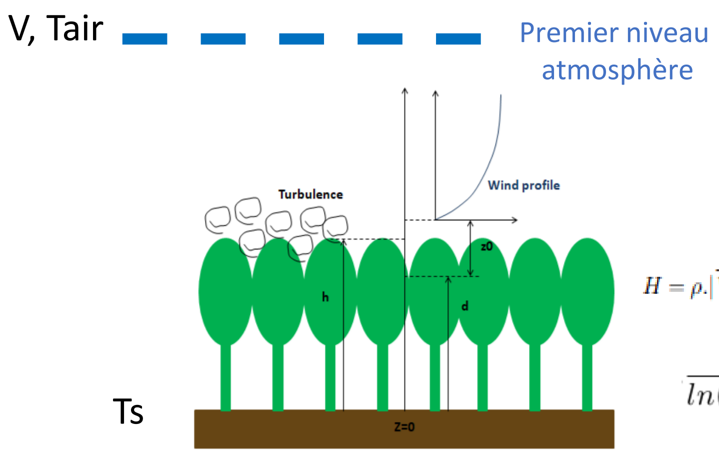
Solved using the sensitivity of the flux to the surface temperature to calculate the flux at the new time-step

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

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

$$T_S^t = f(SW_{net} + LW_d, T_S^0, F_S^0)$$

Remarks on the land – surface

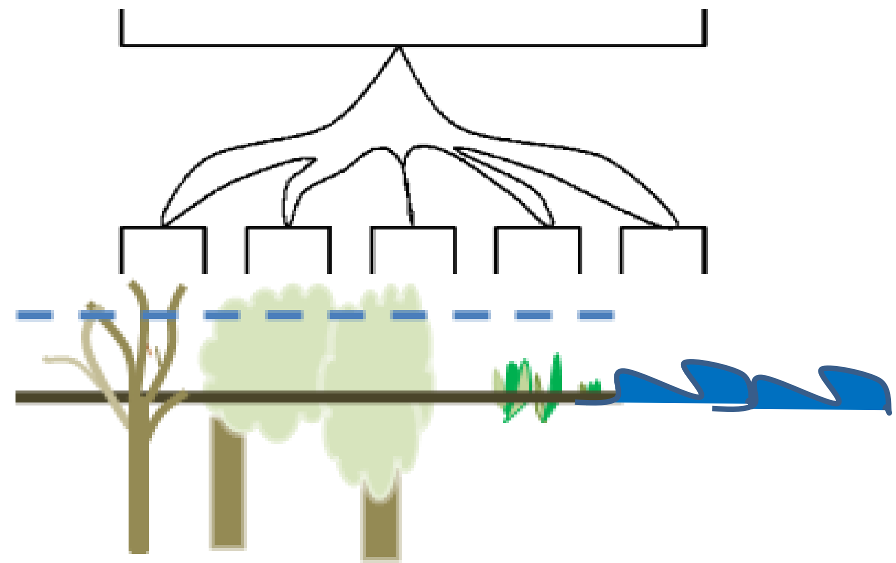


$$H = \rho.|\vec{V}|.C_d.C_p(T_{surf} - T_{air})$$

$$\downarrow$$

$$\frac{\kappa^2}{ln(\frac{z}{z_0})ln(\frac{z}{z_{0t}})} f_H(R_i)$$

d= displacement height (LMDZ: d=0)
h= hauteur de la végétation
Z_{0m}= roughness height



. agrégation de paramètres: $z_{0effectif}$
Ou/et
Agrégation de flux

A partir de mesures faites sur des terrains homogènes
Pas de cadre théorique pour passer à des valeurs utilisables à l'échelle de la maille
Surface herbeuse Duynkerke z0m dépend fortement LAI et u*
$z_{0h} << z_{0m}$, Fonction empirique z0m/z0h= exp(-k/B) ou prescrit

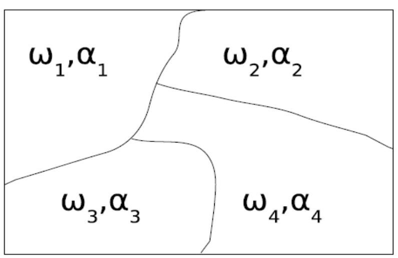
IPSL : Agrégation de paramètres sur continents
Agrégation de flux mailles mixtes (océan, continents, sea-ice,…)

Coupling between atmospheric column(s) and sub-surfaces

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

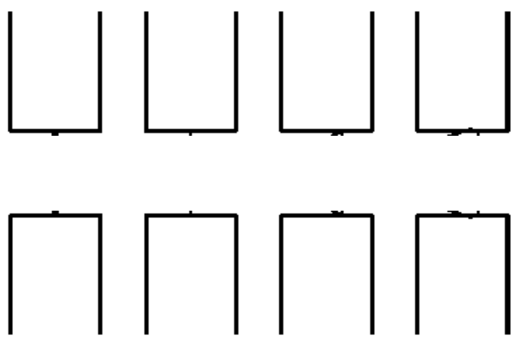
Sub-surfaces

$$\sum_i \omega_i = 1$$



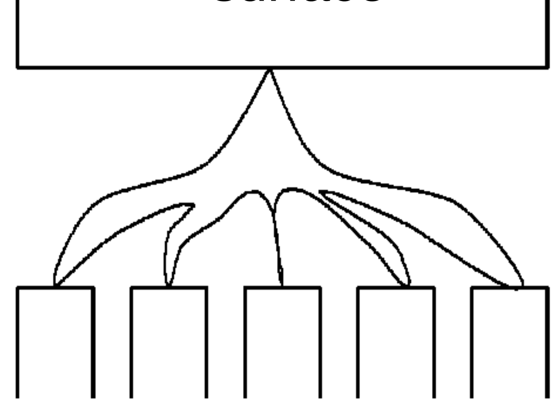
Turbulent flux

One PBL over **each** sub-surface



Radiative flux

One column **covers all** the sub-surface



Each sub surface has to compute F_1 using variables X_1, A_1 and B_1

The boundary layer tendencies in the atmosphere are mixed between sub-columns (equivalent of averaging the surface flux)

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

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

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

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

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

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

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

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 emissivity.

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

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

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

$$\bar{T} = \frac{\sum_i \omega_i \epsilon_i T_i}{\bar{\epsilon}} \qquad (5)$$

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

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

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

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

Due to radiative code limitation, in LMDZ, we always must have $\varepsilon_i = 1$
Energy conservation: the radiation is computed by the atmospheric model,

Atmosphere/surface coupling in LMDZOR

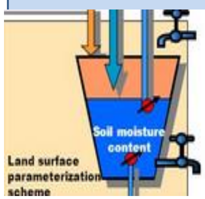
LMDZ (phylmd)

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
,

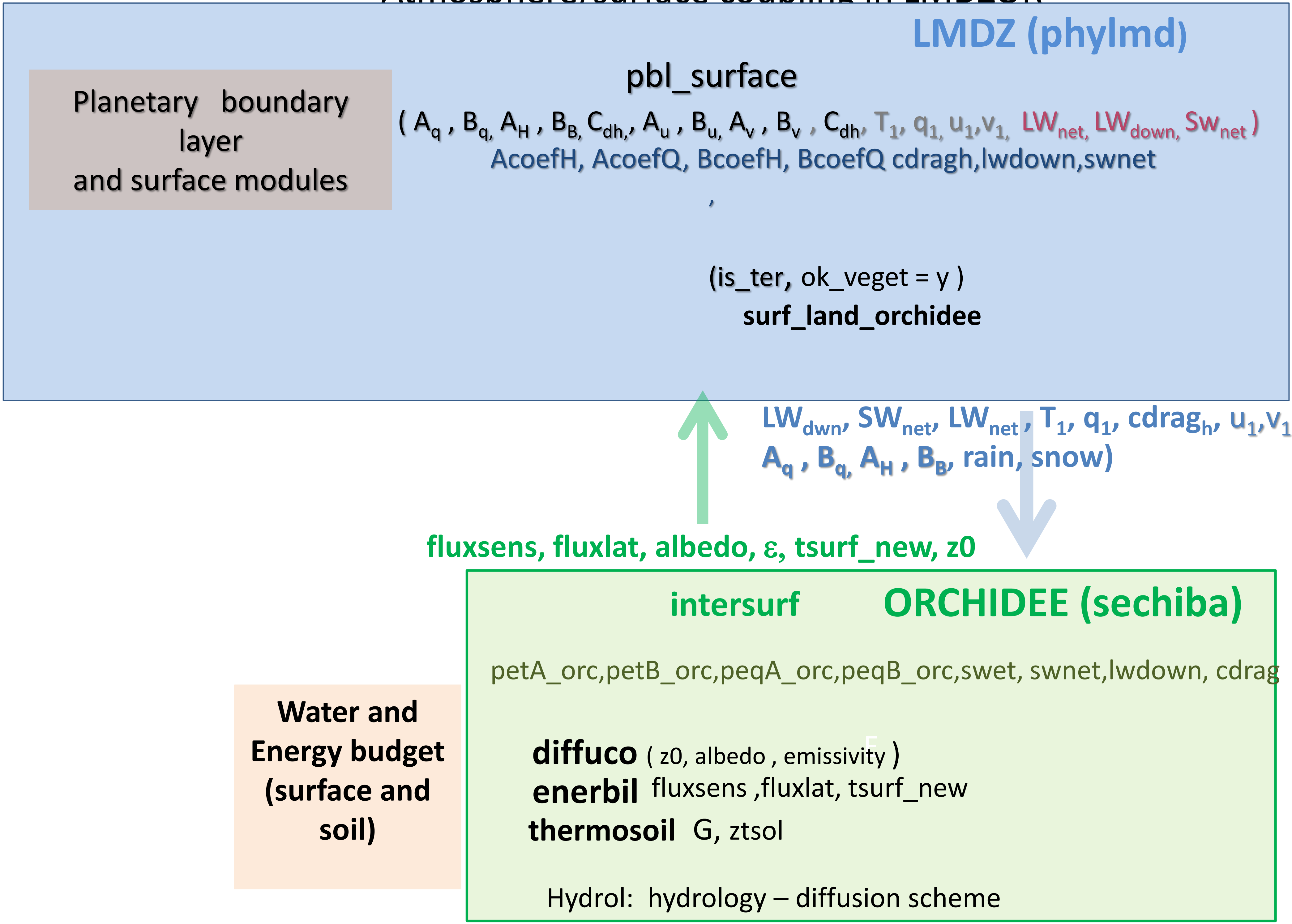
(is_ter, ok_veget = n)
surf_land_bucket



(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



Atmosphere/surface coupling in LMDZOR

LMDZ (phylmd)

Planetary boundary layer
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pbl_surface

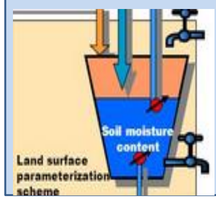
(A_q , $B_{q,}$ A_H , $B_{B,}$ $C_{dh,}$, A_u , $B_{u,}$ A_v , B_v , C_{dh}, T_1, $q_{1,}$ u_1,$v_{1,}$ $LW_{net,}$ $LW_{down,}$ Sw_{net})

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

,

(is_ter, ok_veget = n)

surf_land_bucket



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

THANK YOU FOR YOUR ATTENTION

- Technical note **:** Description of the interface with the surface and the computation of the turbulent diffusion in LMDZ (J.L.Dufresne)
- Thèse F. Hourdin 1993 (section 3.3.3 and annexes)
- 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/

Case of the continental surface

- Surface energy budget

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

$$SW_{net} + LW_d \underbrace{- \varepsilon\sigma T_s^4 + F + L}_{\text{depends on Ts}} + \Phi_0 = 0$$

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

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

- Heat conduction in the soil: diffusion equation :

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

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

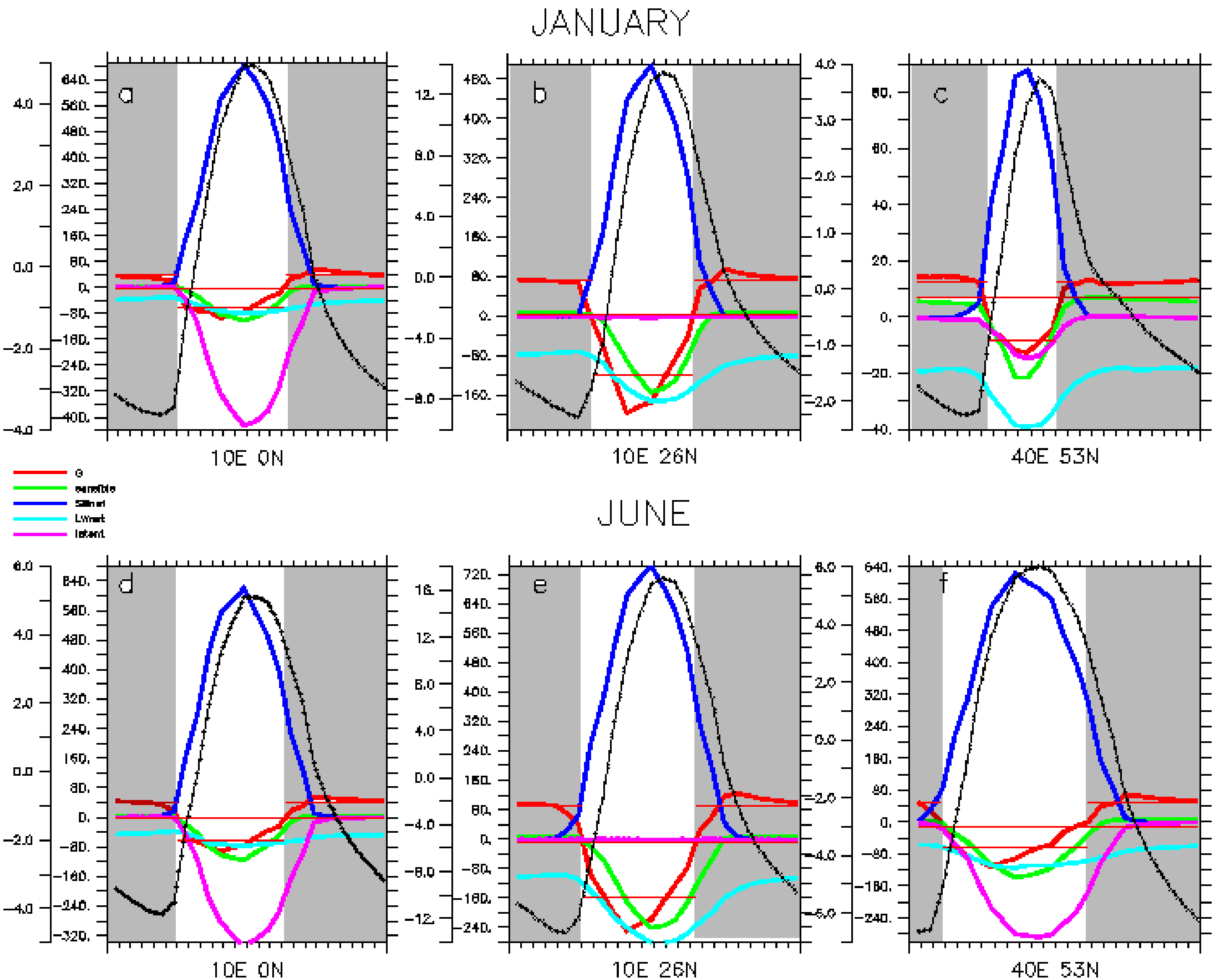
Boundary conditions:

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

Surface energy budget:

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

Case of the continental surface



Fast Variations requires an implicit approach to solve the energy budget equations

Cheruy et al. 2019

Case of the continental surface

$$\begin{cases} F^t_{s,H} = A^1{}_H + B^1{}_H F^t_{s,H} \partial t & \textit{Turbulent diffusion Atmosphere} \\ F^t_{s,H} = \frac{1}{zikt}(H^t_1 - H^t_s) \quad \frac{1}{zikt} = \rho |\vec{v}| C_d & \textit{Bulk formulation} \end{cases}$$

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

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

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

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

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