Land surface hydrology in ORCHIDEE

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ORCHIDEE
LAND SURFACE MODEL

Outline

1. **Introduction**
   - Scope of this specific training
2. **The multi-layer soil hydrology scheme**
   - Processes (soil moisture diffusion, boundary fluxes)
   - Parameters and options
3. **Surface forcing conditions**
   - Soil texture, vegetation / land cover

How to parameterize your simulations

More details on the Wiki

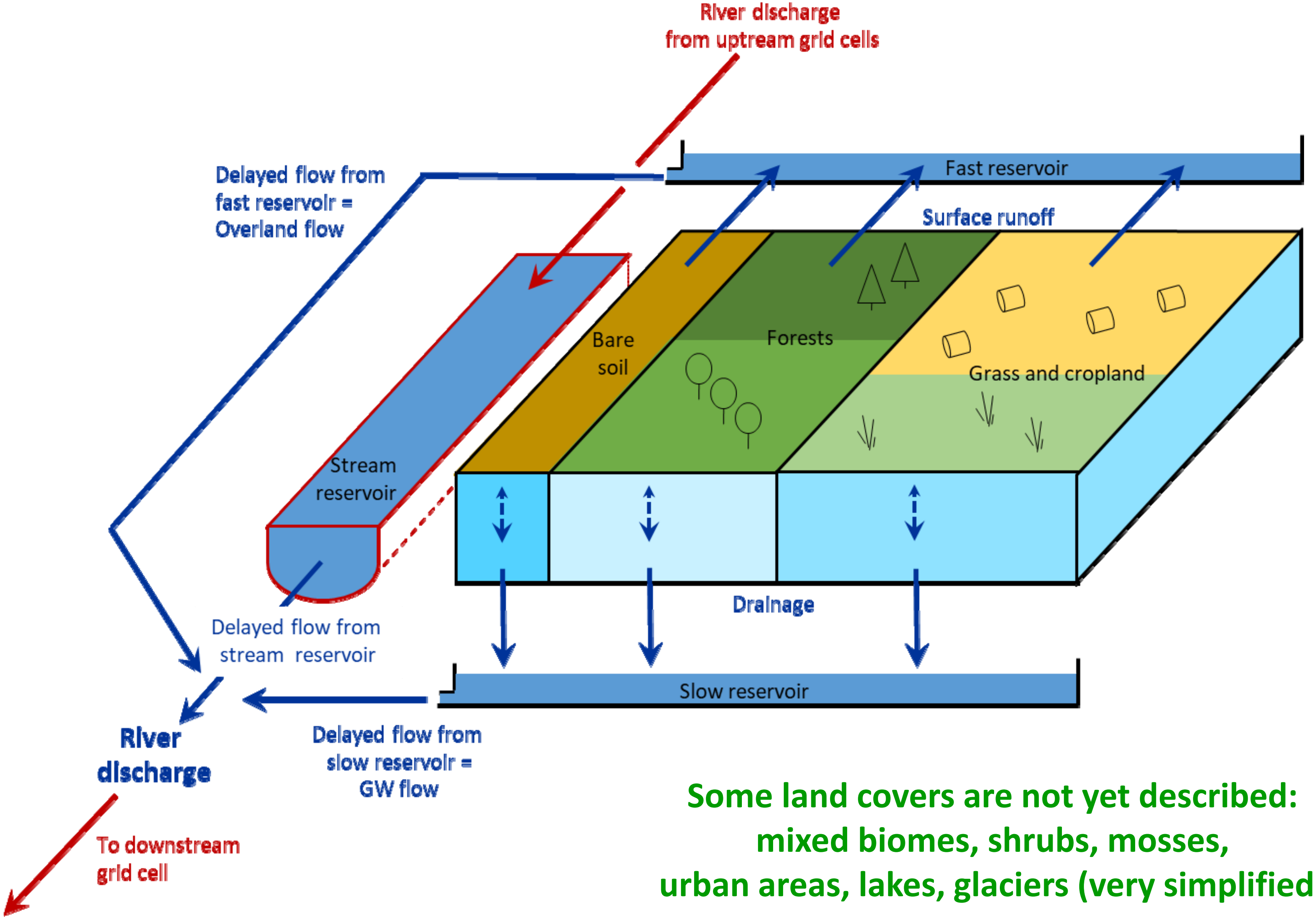
http://forge.ipsl.jussieu.fr/orchidee/attachment/wiki/Documentation/eqs_hydrol.pdf

Reference papers: de Rosnay et al., 2000; de Rosnay et al., 2002; d'Orgeval et al., 2008; Campoy et al., 2013 ; Tafasca et al., 2020

PhD theses : de Rosnay, 1999; d'Orgeval, 2006; Campoy, 2013; Tafasca, 2020

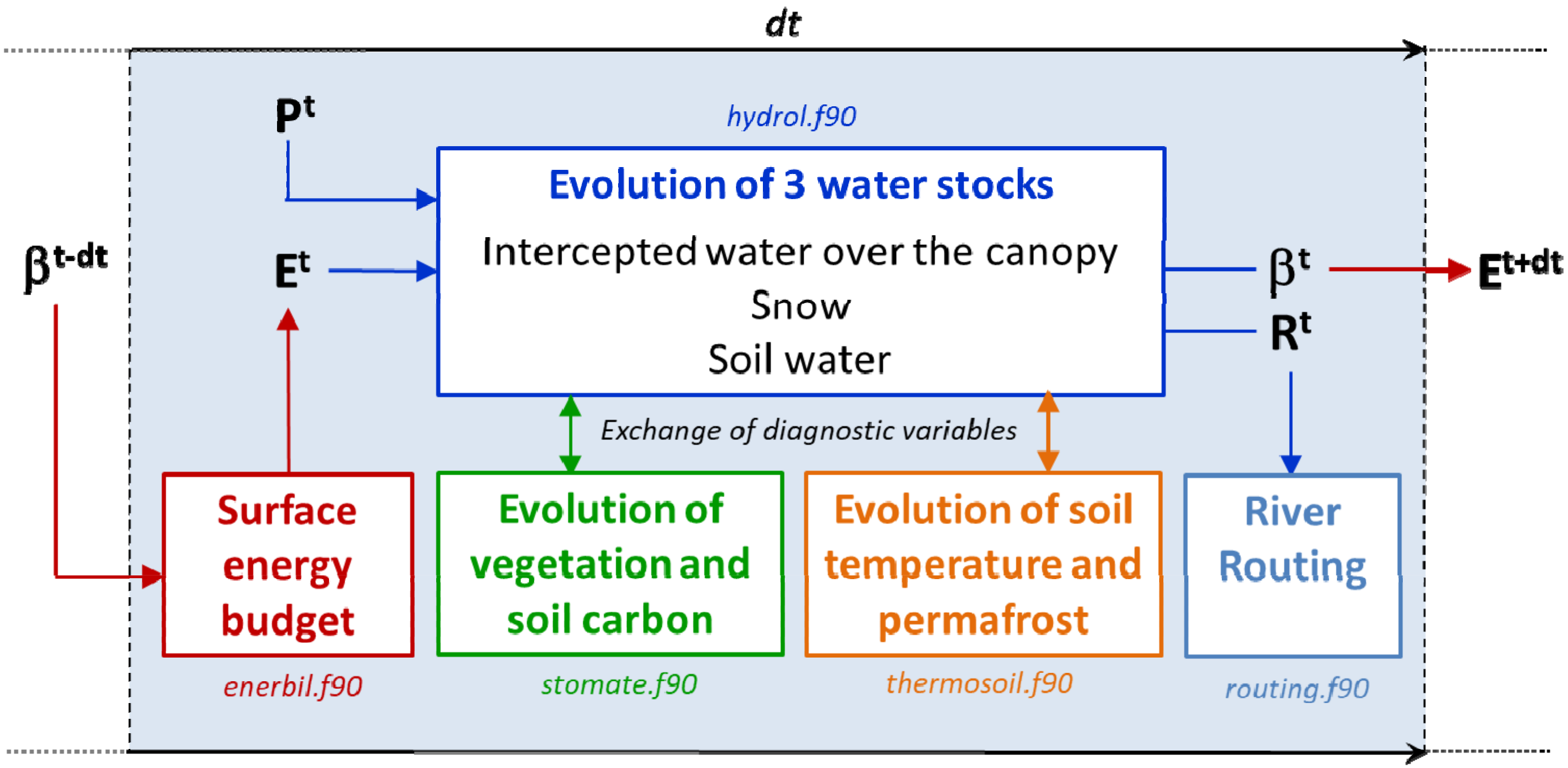
4. **A glance at the routing scheme**

Land surface hydrology



Some land covers are not yet described:
mixed biomes, shrubs, mosses,
urban areas, lakes, glaciers (very simplified)

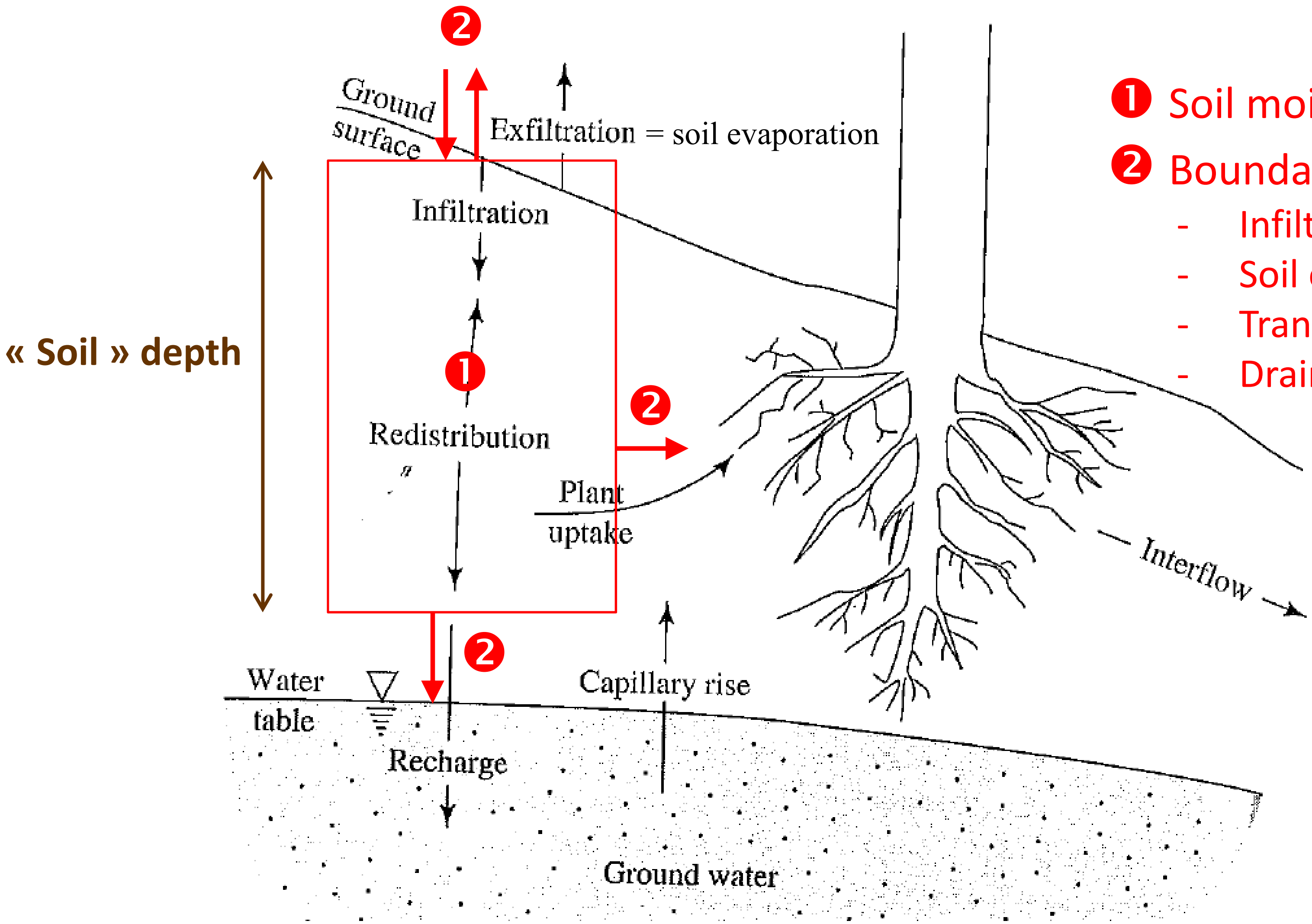
Soil hydrology and water budget



$$dS/dt = P - E - R$$

We will focus on soil water and the related water fluxes (soil hydrology)
No interception, no snow, no soil water freezing today

What is modeled ?



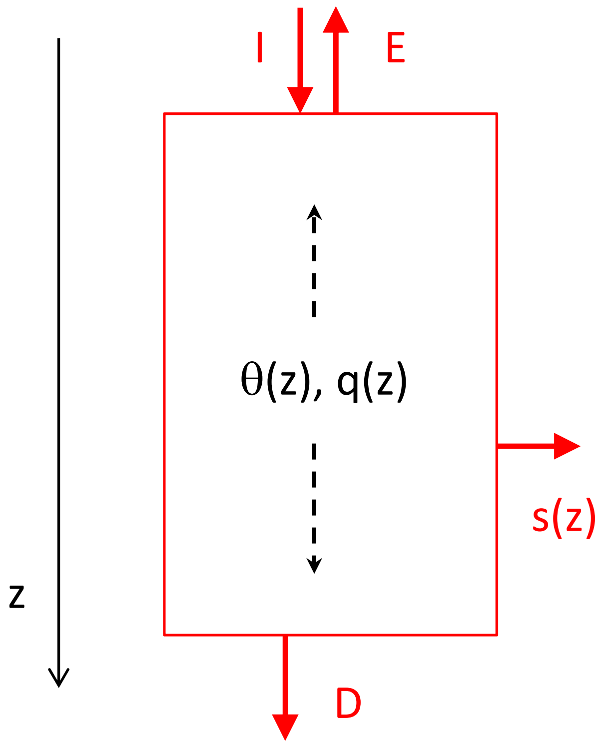
❶ Soil moisture diffusion

❷ Boundary fluxes

- Infiltration
- Soil evaporation
- Transpiration sink
- Drainage

How is SM diffusion modeled ?

1. We assume 1D vertical water flow below a flat surface



2. Continuity :

$$\frac{\partial \theta}{\partial t} + \frac{\partial q}{\partial z} = -s$$

3. Motion = diffusion equation because of low velocities in porous medium

$$q(z) = -K(z)\frac{\partial h}{\partial z}$$

Richards equation (2 + 3)

4. Hydraulic head h quantifies the gravity and pressure potentials

$$h = -z + \psi$$

ψ is the matric potential (in m, <0)

5. K and ψ depend on θ (unsaturated soils)

$$q(z) = -K(\theta)\left[\frac{\partial \psi}{\partial z} - 1\right]$$

$$q(z) = -D(\theta)\frac{\partial \theta}{\partial z} + K(\theta)$$

$$D(\theta) = K(\theta)\frac{\partial \psi}{\partial \theta}$$

D is the diffusivity (in $m^2.s^{-1}$)

θ : volumetric water content in $m^3.m^{-3}$
q : flux density in $m.s^{-1}$
s : transpiration sink in $m^3.m^{-3}.s^{-1}$
K : hydraulic conductivity in $m.s^{-1}$
h : hydraulic potential in m

Finite difference integration

- The differential equations of continuity and motion are solved using finite differences :

$$\frac{W_i(t+dt) - W_i(t)}{dt} = Q_{i-1}(t+dt) - Q_i(t+dt) - S_i$$

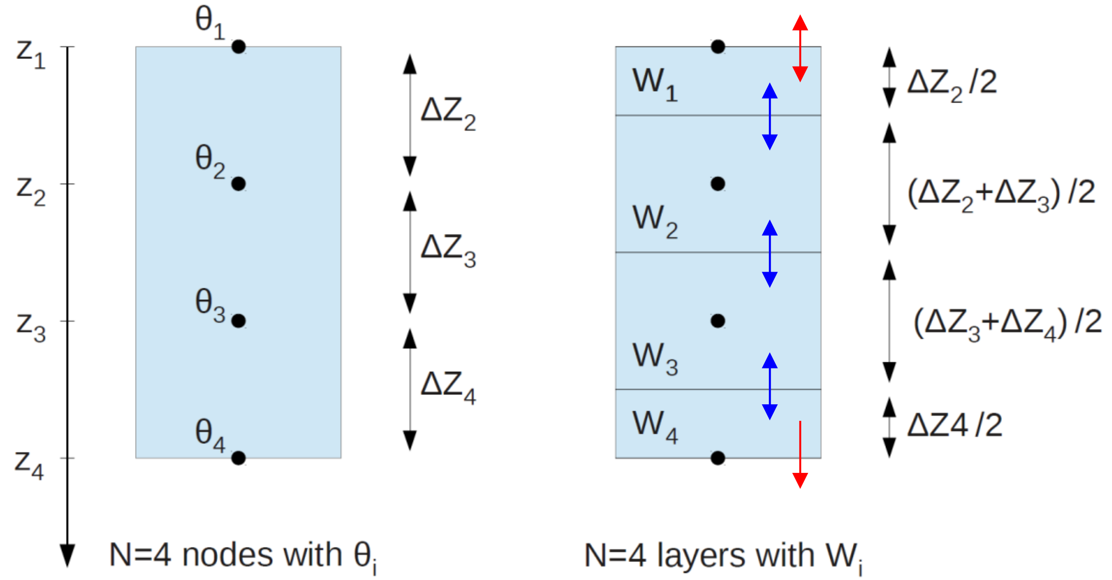
$$\frac{Q_i}{A} = -\frac{D(\theta_{i-1}) + D(\theta_i)}{2}\frac{\theta_i - \theta_{i-1}}{\Delta Z_i} + \frac{K(\theta_{i-1}) + K(\theta_i)}{2}$$

Si = transpiration sink

A: grid-cell area

- The soil column is discretized using N **nodes,** where we calculate **θi**
- Each node is contained in one **layer**, with a total water content **Wi**
- The fluxes **Qi** are calculated at the **interface** between two layers

tridiagonal matrix



N=4 nodes with θ_i
3 internode heights

N=4 layers with W_i
5 interfaces

Wi is obtained by vertical integration of θ(z) in layer i, assuming a linear variation of θ(z) between 2 nodes

$$W_i = [\Delta Z_i\,(3\,\theta_i + \theta_{i-1}) + \Delta Z_{i+1}\,(3\,\theta_i + \theta_{i+1})]/8$$

$$W_1 = [\Delta Z_2\,(3\,\theta_1 + \theta_2)]/8$$

$$W_N = [\Delta Z_N\,(3\,\theta_N + \theta_{N-1})]/8$$

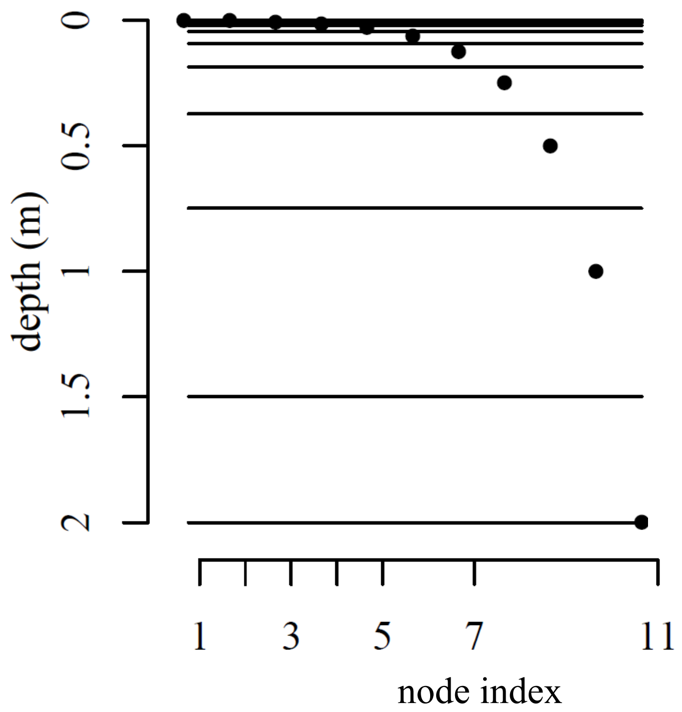
Vertical discretization

- The vertical discretization must permit an accurate calculation of θi and the related water fluxes Qi
- We need thin layers where θ is likely to exhibit sharp vertical gradients
  (to better approximate the local derivative)
- **Vertical discretization and boundary conditions must be decided together !**

By default, in hydrol, we use :

- 2-m soil
- 11 nodes (layers) with geometric increase of internode distance

(cf. de Rosnay et al., 2000)



i	≈ hi (mm)
1	1
2	3
3	6
4	12
5	23,5
6	47
7	94
8	188
9	375
10	751
11	500

Vertical discretization

- The vertical discretization must permit an accurate calculation of θi and the related water fluxes Qi
- We need thin layers where θ is likely to exhibit sharp vertical gradients (to better approximate the local derivative)
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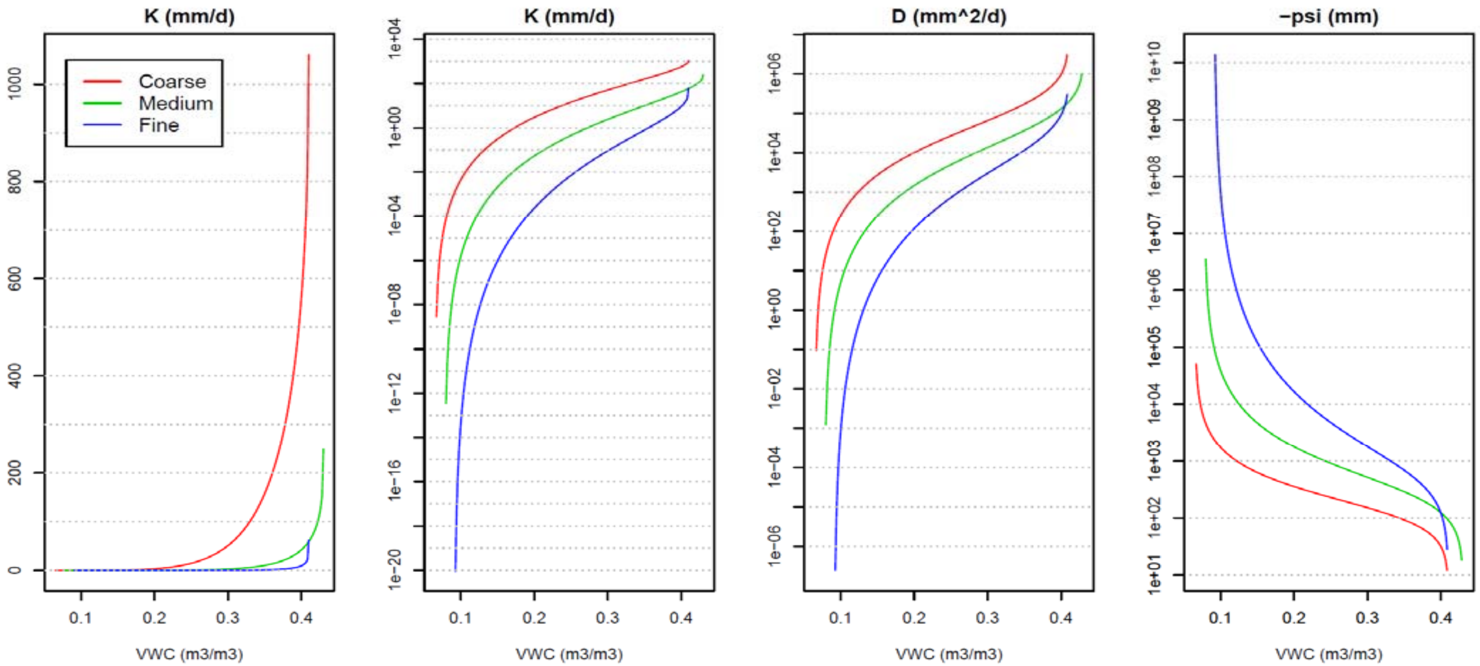
Alternative discretizations can be defined by externalized parameters (run.def)

DEPTH_MAX_H	2.0	m	Maximum depth of soil moisture	Maximum depth of soil for soil moisture (CWRR).
DEPTH_MAX_T	10.0	m	Maximum depth of the soil thermodynamics	Maximum depth of soil for temperature.
DEPTH_TOPTHICK	9.77517107e-04	m	Thickness of upper most Layer	Thickness of top hydrology layer for soil moisture (CWRR).
DEPTH_CSTTHICK	DEPTH_MAX_H	m	Depth at which constant layer thickness start	Depth at which constant layer thickness start (smaller than zmaxh/2)
DEPTH_GEOM	DEPTH_MAX_H	m	Depth at which we resume geometrical increases for temperature	Depth at which the thickness increases again for temperature.

The hydrodynamic parameters

- **K and D depend on saturated properties (measured on saturated soils) and on θ**
- Their dependance on θ is very non linear
- In ORCHIDEE, this is decribed by the so-called **Van Genuchten-Mualem relationships**:



$$K(\theta) = K_s \sqrt{\theta_f} \left(1 - \left(1 - \theta_f^{1/m}\right)^m\right)^2 \qquad \theta_f = (\theta - \theta_r)/(\theta_s - \theta_r)$$

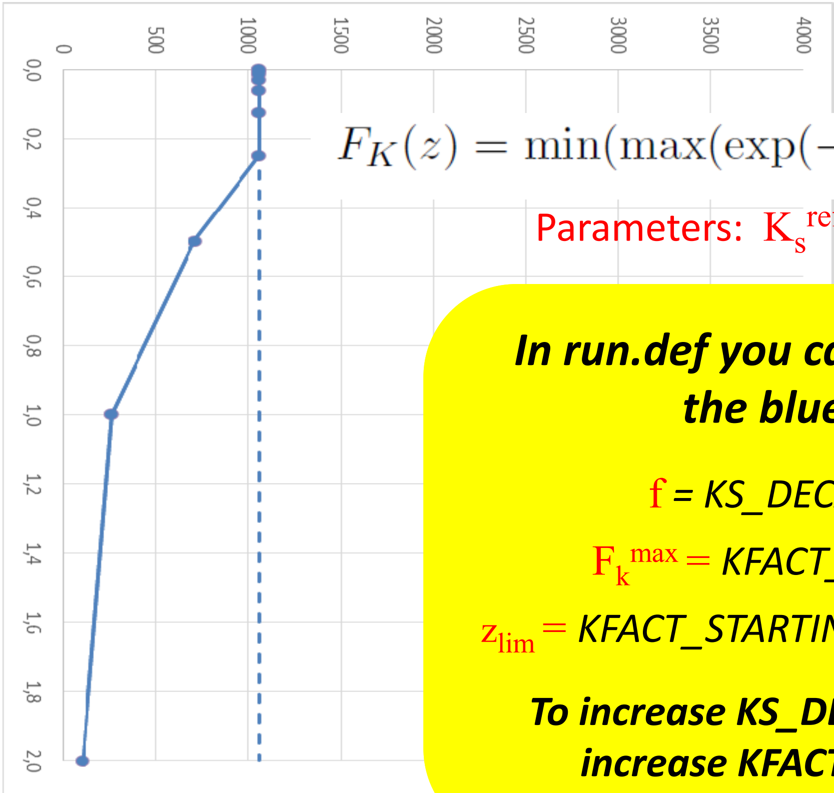
$$\psi(\theta) = -\frac{1}{\alpha} \left(\theta_f^{-1/m} - 1\right)^{1/n} \qquad m = 1 - 1/n$$

$$D(\theta) = \frac{(1-m)K(\theta)}{\alpha m} \frac{1}{\theta - \theta_r} \theta_f^{-1/m} . \left(\theta_f^{-1/m} - 1\right)^{-m}$$

The parameters
θ_s θ_r K_s n
$\alpha = -1/\psi_{ae}$
depend on soil texture

Modifications of Ks with depth

Ks(z) in mm/d



$$F_K(z) = \min(\max(\exp(-f(z - z_{\lim}), 1/F_K^{\max}), 1)$$

Parameters: K_s^{ref} f z_{lim} F_K^{max}

(2) Ks decreases exponentially with depth below 30 cm (Compaction)

In run.def you can easily change the blue profile

f = *KS_DECAY = 2. [m]*

F_k^{max} = *KFACT_MAX = 10. [-]*

z_{lim} = *KFACT_STARTING_DEPTH = 0.3 [m]*

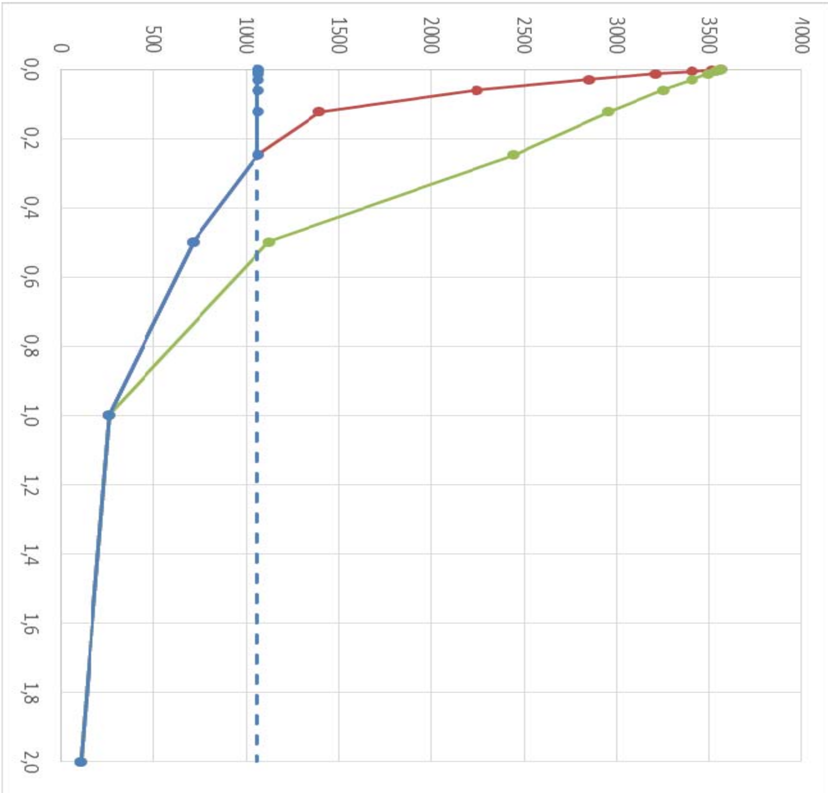
To increase KS_DECAY, you need to increase KFACT_MAX as well

(1) K_s^{ref} is defined based on soil texture

Here 1060 mm/d for Sandy Loam

Modifications of Ks with depth

Ks(z) in mm/d



(2) Ks decreases exponentially with depth below 30 cm (Compaction)

(1) K_s^{ref} is defined based on soil texture
Here 1060 mm/d for Sandy Loam

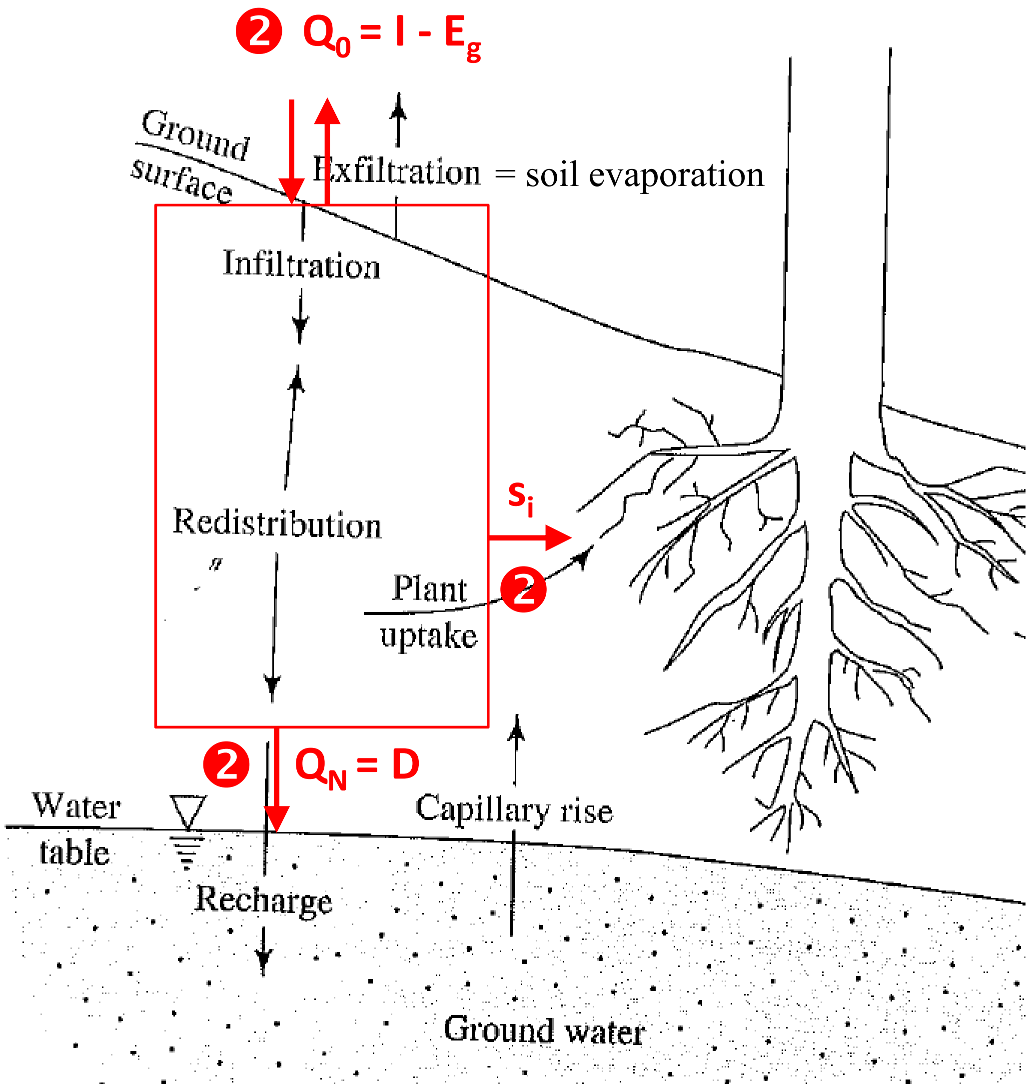
(3) Ks also increases towards the surface because of bioturbation
Red: grass PFTs,
c_j = humcste = 4
Yellow: forest PFTs,
c_j = humcste = 0.8

where c_j controls the exponential decay of root density

$R_j(z) = \exp(-c_j z)$

Several externalized parameters involved, cf eqs_hydrol.pdf

To sum up water diffusion



- **The soil is assumed to be unsaturated**
- **The prognostic variables are θi** (at the nodes)
- They are updated **simultaneously** (by solving a tridiagonal matrix)
- **Their evolution is driven by**
  - the soil properties K(z) and D(z)
  - the vertical discretization (soil depth and layer definition)
  - four boundary fluxes ❷
    - **transpiration sink s_i**
    - top and bottom boundary conditions:

      Q_0 = I - E_g and **Q_N = D**

      I: infiltration

      E_g : soil evaporation

      D: drainage

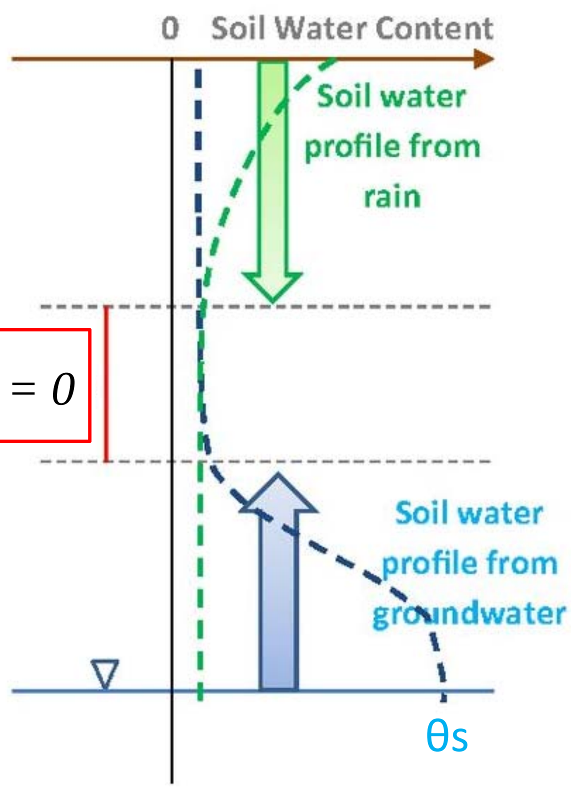
Which all depend on soil moisture

Drainage

By default : $Q_N = K(\theta_N)$

Based on the motion equation, this corresponds to a situation where θ does not show any vertical variations below the modeled soil

$$q(z) = -D(\theta)\frac{\partial\theta}{\partial z} + K(\theta)$$



$$\frac{\partial\theta}{\partial z} = 0$$

The code is also apt to use reduced drainage :

$Q_N = F.K(\theta_N)$ F in [0,1]

F is externalized by **FREE_DRAIN_COEF = 1.,1.,1.**

With F=0, you get an impermeable bottom:

- like in a bucket scheme
- leading to build a water table

But you need to adapt the vertical discretization!

Drainage

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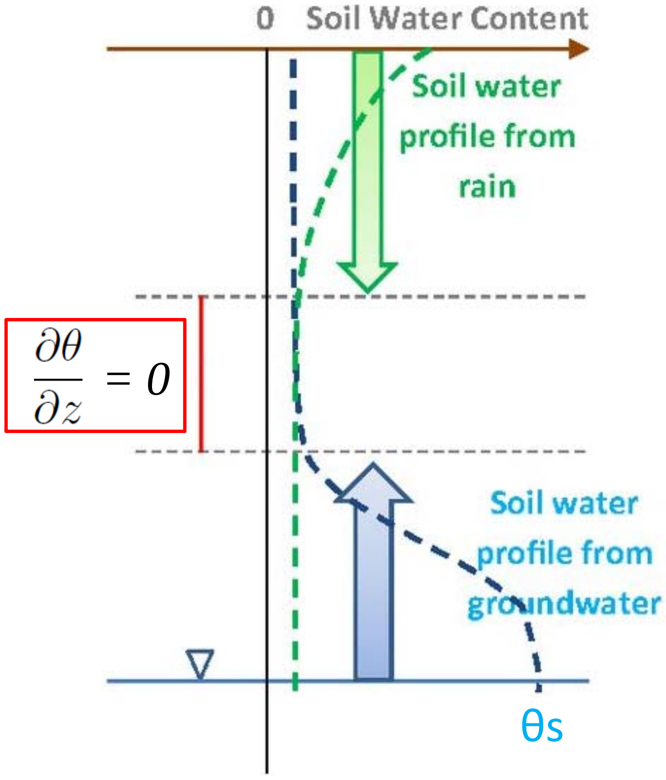
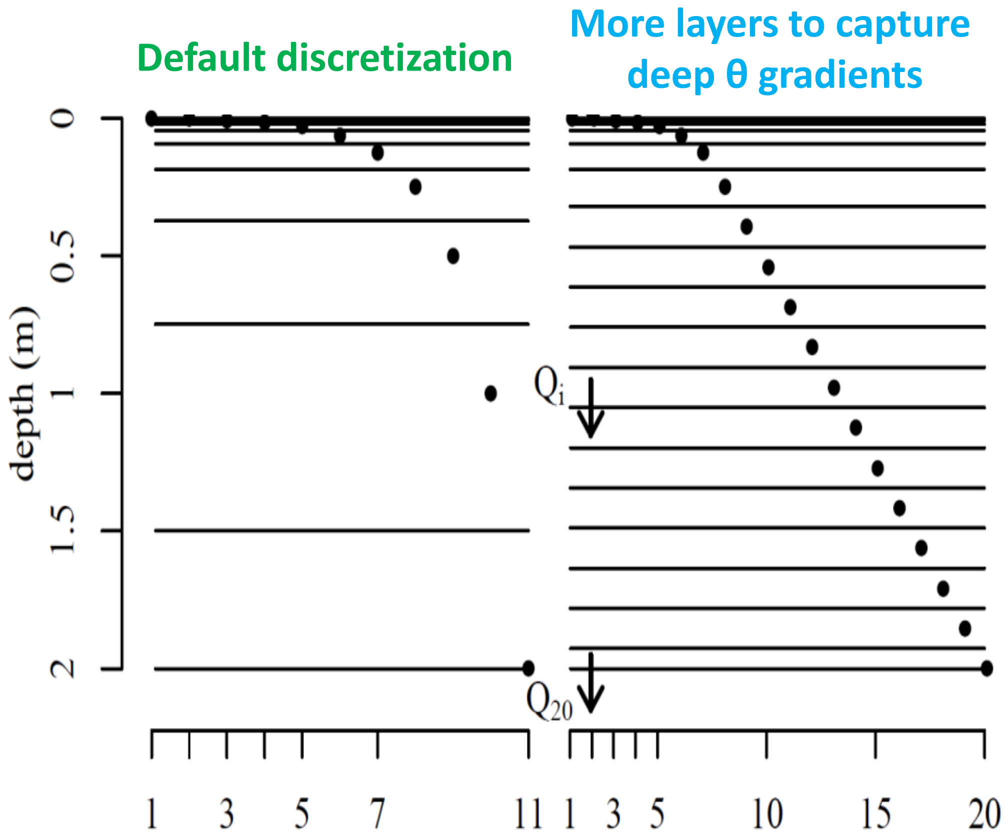
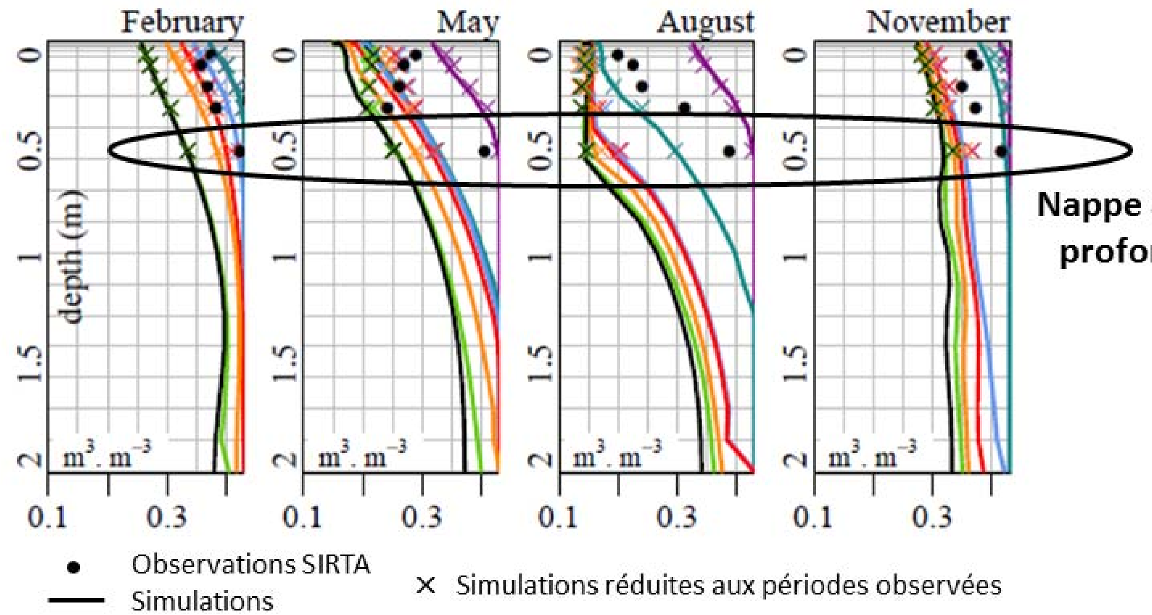




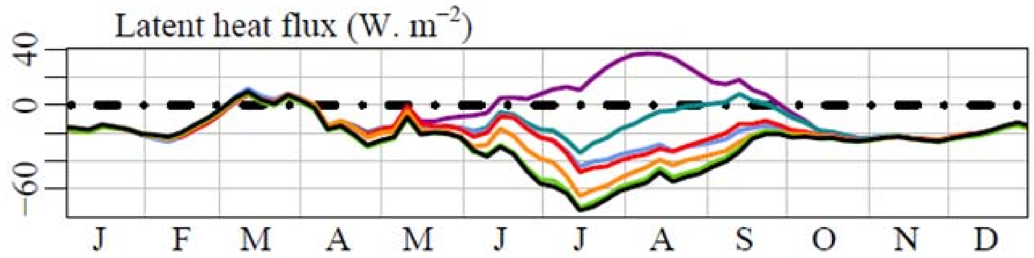
Drainage

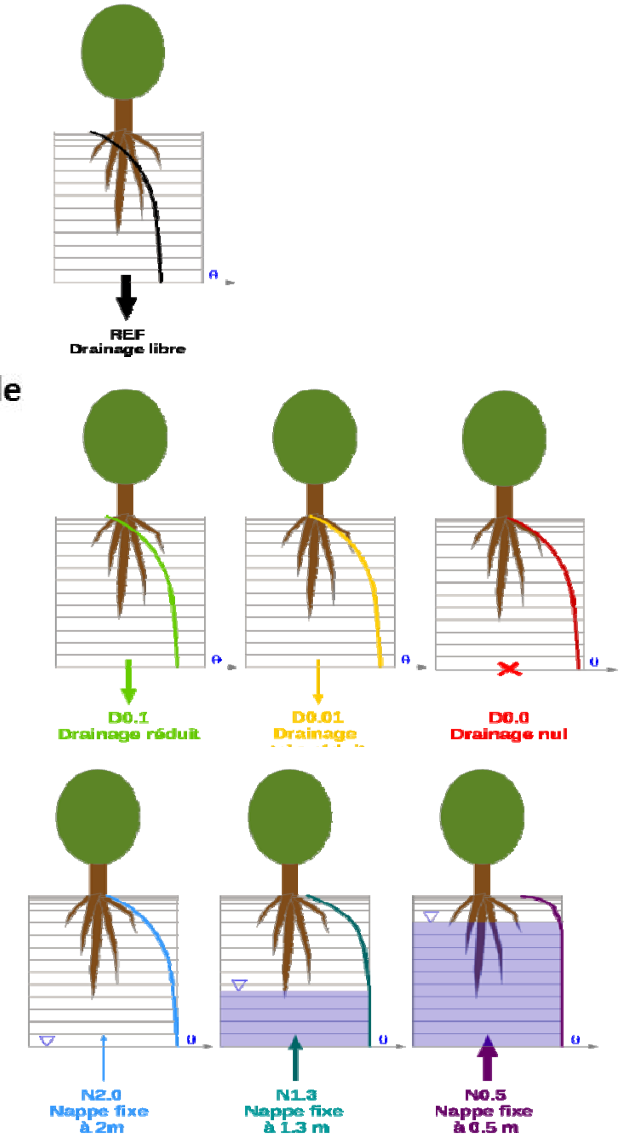
Simulations ORCHIDEE-LMDZ en zoomé-guidé au SIRTA

Comparaison à des mesures locales



Nappe à faible profondeur





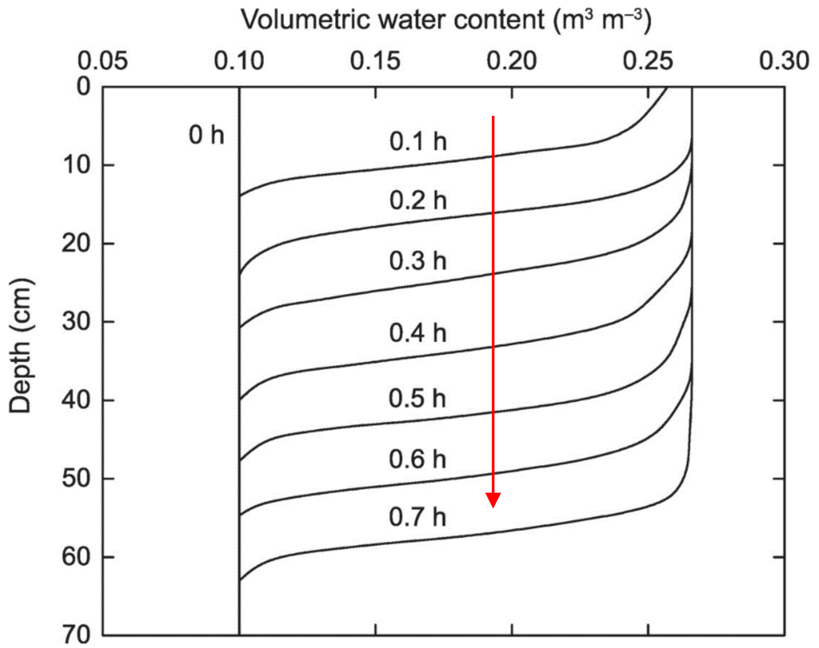
Campoy et al., 2013

Infiltration (and surface runoff)

- At the soil surface, throughfall can either infiltrate or run off (surface runoff)
- The routing scheme can also produce water to infiltrate (return flow, irrigation, etc.)

} P_0

- The modeling of infiltration relies on gravitational fluxes: $q(z) = K(\theta)$ — Soil absorption is neglected
- With **wetting front propagation based on time splitting procedure** and **sub-grid-variability of K** (because the grid-cells are large)



Idealized result from some field experiment

Iterative saturation of the layers from top to bottom

The infiltration rate in layer i depends $K(\theta_i)$ but it is reduced to account for subgrid variability

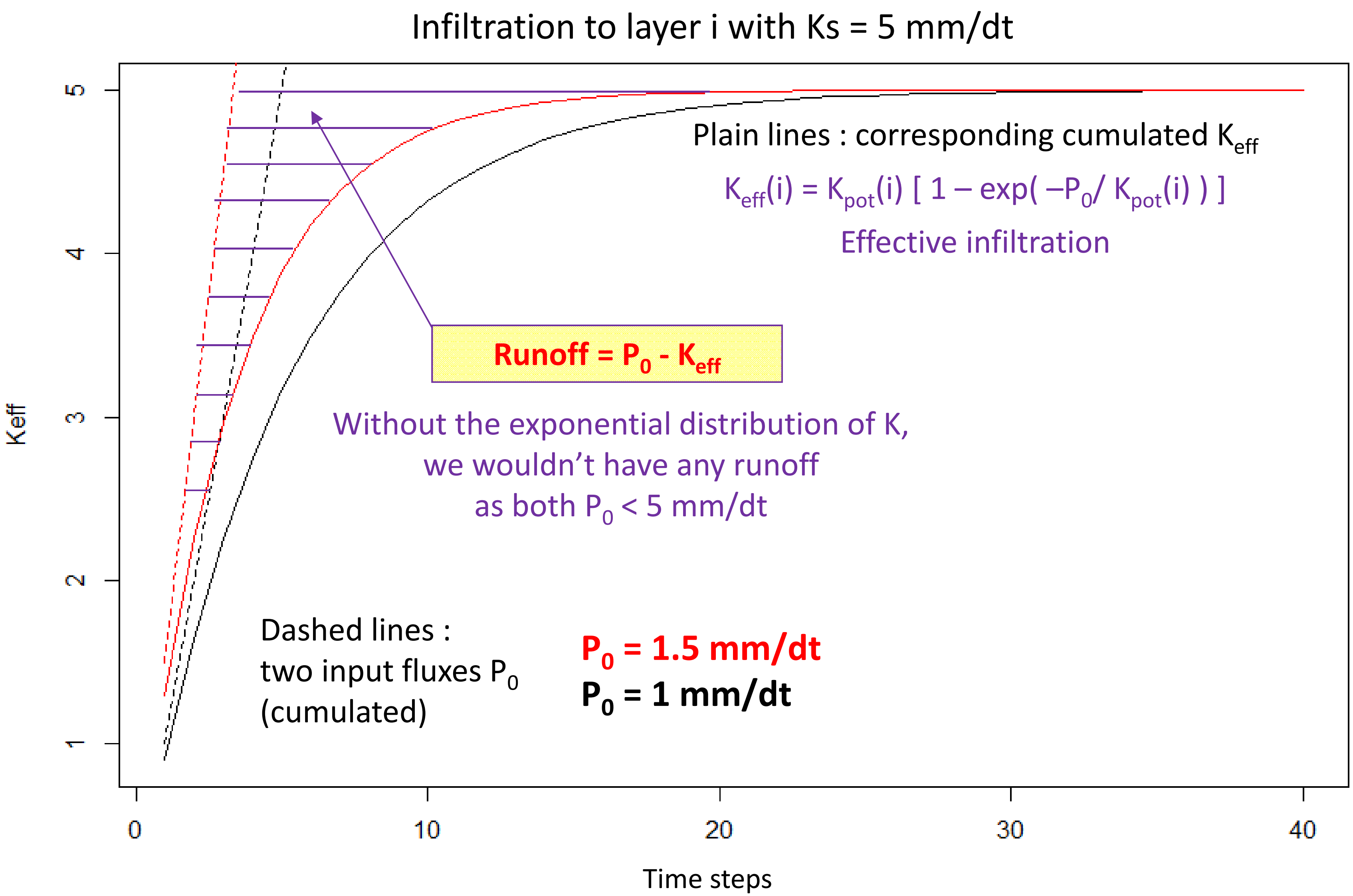
We consider an exponential distribution of K with a mean of $K(\theta_i)$

- K_{eff} is the mean of K values < P_0
- Runoff production where $P_0 > K$

The time to saturate a layer depends on K_{eff} and soil moisture deficit ($W_{sat} - W$)

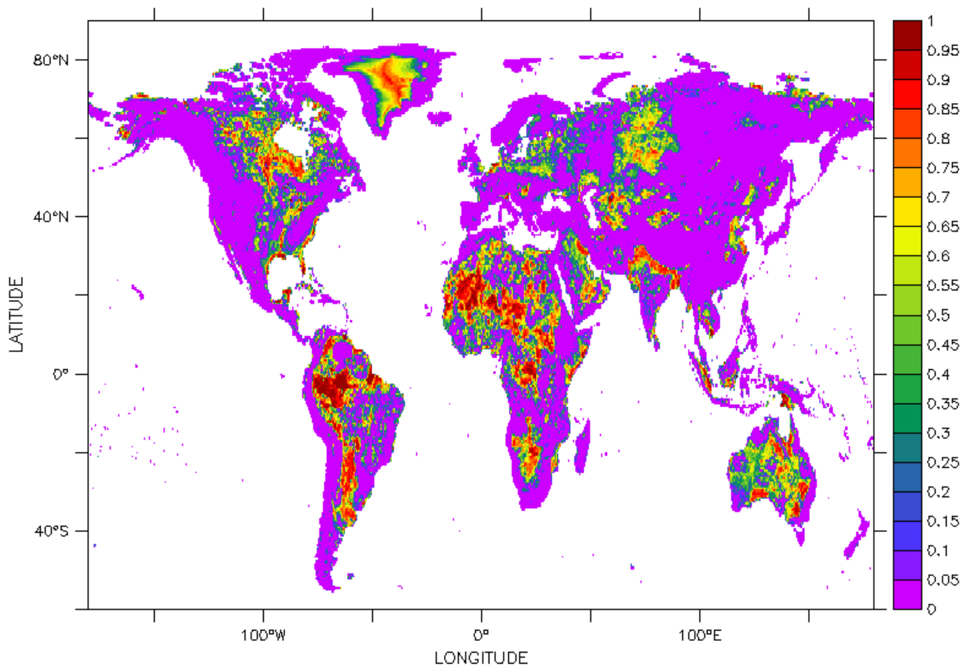
Stop when P_0 fully infiltrated or time step is over

Infiltration (and surface runoff)



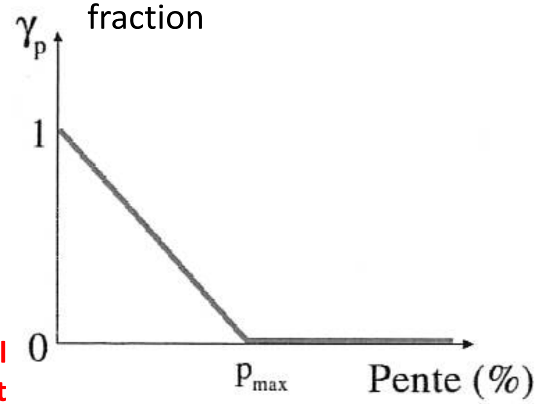
Infiltration (and surface runoff)

- Surface runoff can **reinfiltrate** in flat areas, after ponding



Reinfiltration fraction

A lot of reinfil in flat areas



Very simple in practice

$P_0 - \Sigma K_{eff}(i) = R_s^{pot}$

Ponding for future reinfiltration

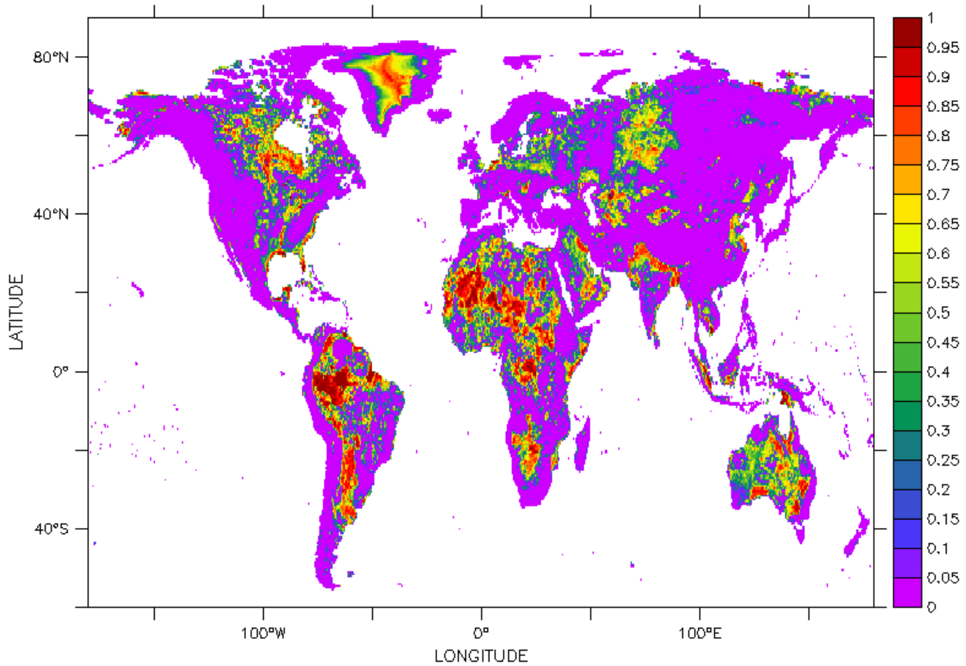
$\gamma_p R_s^{pot}$

Effective surface runoff

$R_s = (1-\gamma_p) R_s^{pot}$

Infiltration (and surface runoff)

- Surface runoff can **reinfiltrate** in flat areas, after ponding



Reinfiltration fraction

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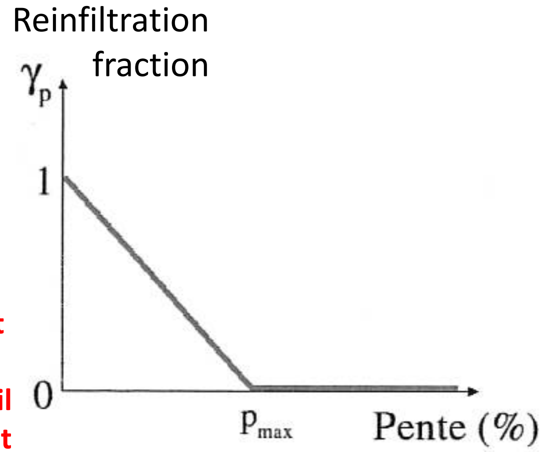

p_{max} is externalized as
SLOPE_NOREINF = 0.5 [%]

You can also force a uniform γ_p
REINF_SLOPE = 0.1 [-]

Soil evaporation (E_g)

1. The soil evaporation involved in the surface boundary flux ($Q_0 = I - E_g$) is given by the energy budget, given water stress $\beta_g^{t\text{-}dt}$ from previous time step
2. **Another issue is to calculate the stress function β_g^t** to calculate soil evaporation at the next time step
3. **This is done in hydrol by a supply/demand approach** based on the soil moisture at the end of the time step

E_g can proceed at potential rate unless the soil cannot supply it

$$E_g = \min(E^*_{\text{pot}}, Q_{\text{up}})$$

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$$E_g = \min(E^*_{\text{pot}}, Q_{\text{up}})$$

$$E^*_{\text{pot}} = \frac{\rho}{r_a}(q_{\text{sat}}(T_w) - q_{\text{a}}) < E_{\text{pot}} = \frac{\rho}{r_a}(q_{\text{sat}}(T_s) - q_{\text{a}})$$

$$\beta_g = E_g / E_{\text{pot}}$$

Q_{up} is calculated by 1 or 2 integrations of the water diffusion:

(a) We apply E^*_{pot} as a boundary flux at the top, and test if θ_i remains above θ_r
If it does, then $Q_{up} = E^*_{pot} = E_g$

(b) Else, we force $\theta_1 = \theta_r$ and this drives an upward flux: the surface value Q_0 gives Q_{up}

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3. **This is done in hydrol by a supply/demand approach** based on the soil moisture at the end of the time step

E_g can proceed at potential rate unless cannot supply it

4. **We can reduce the demand using a soil resistance (Sellers et al., 1992)**

$$r_{\text{soil}} = \exp(8.206 - 4.255 L/L_s)$$

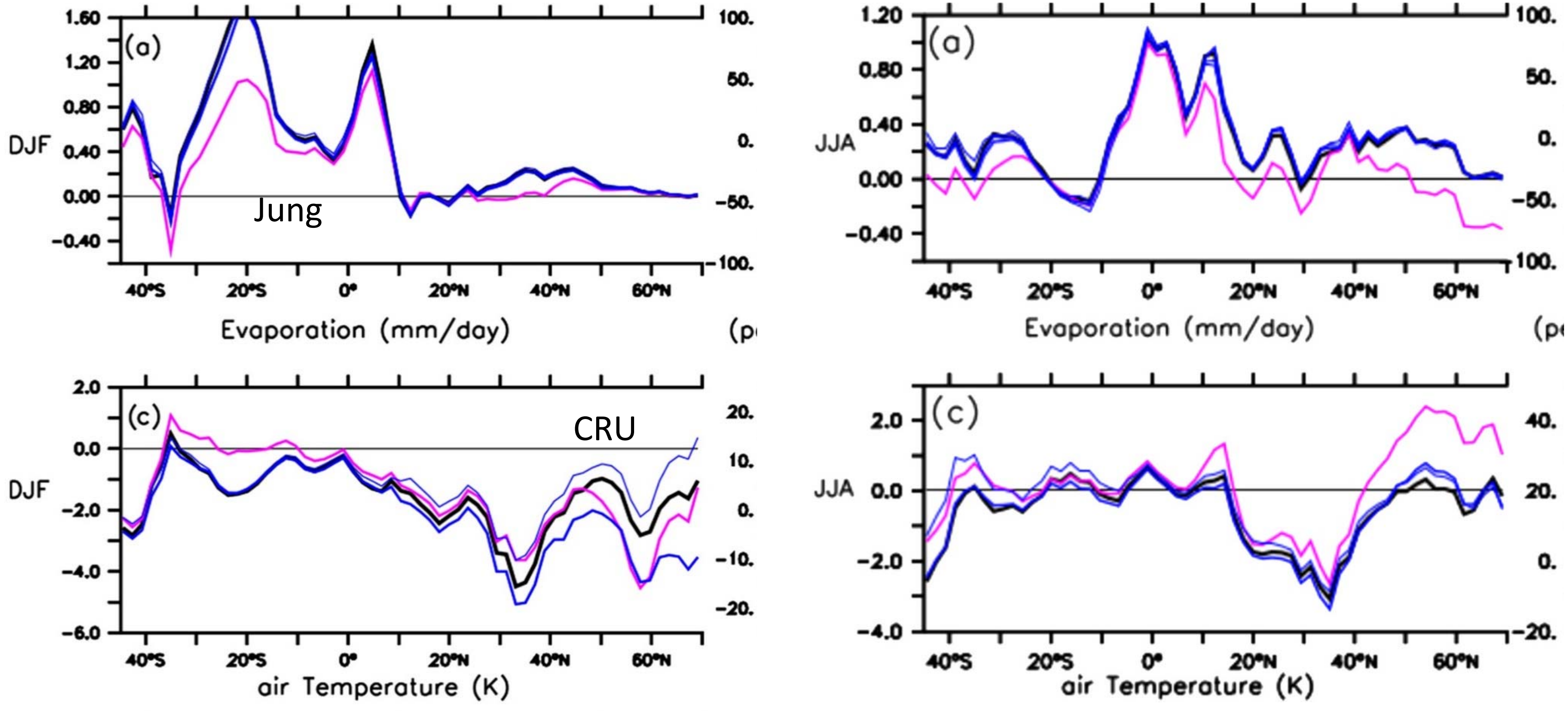
L is the soil moisture in the 4 top layers
Ls is the equivalent at saturation

In run.def :
DO_ROIL = y
(default = n)

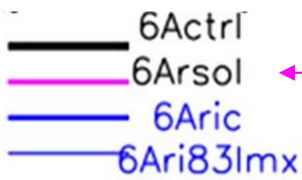
$$E_g = \min\left(\rho\frac{q_{sat}(T_w) - q_a}{r_a + r_{soil}}, Q_{up}\right)$$

The minimum is still found via 1 or 2 integrations of the water diffusion

Soil evaporation (E_g)



Moyennes zonales des biais

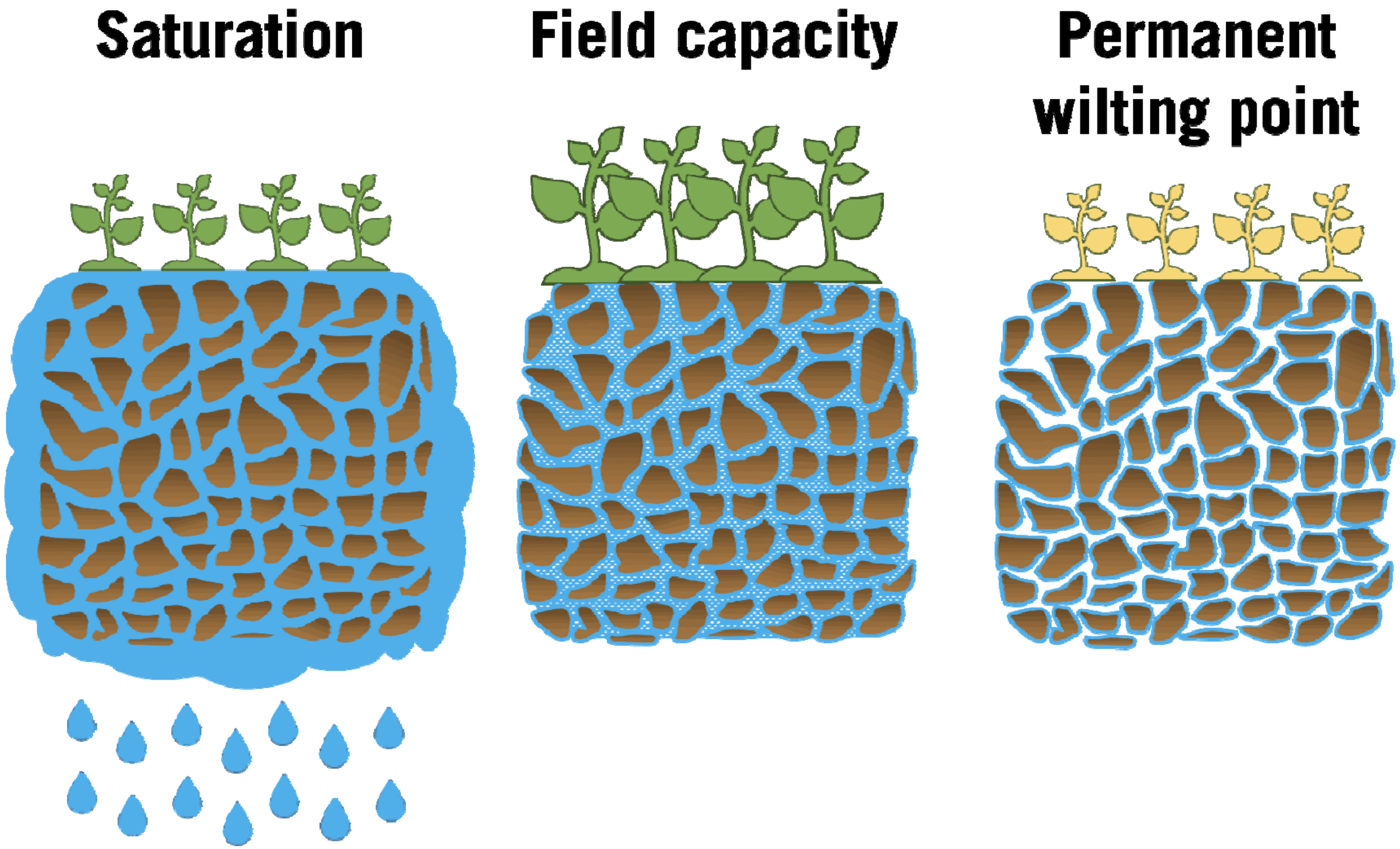


DO_RSOIL = y

Cheruy et al., 2020 → simulations with LMDZOR to prepare CMIP6

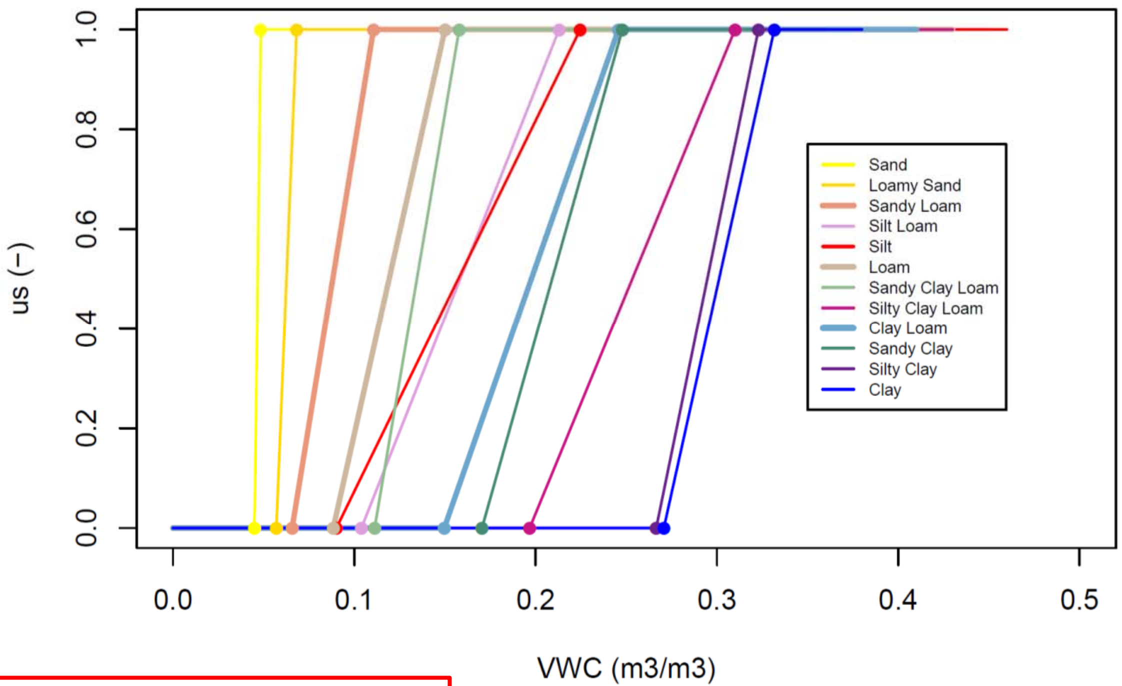
The transpiration sink

Transpiration depends on soil moisture



The transpiration sink

The dependance of transpiration on soil moisture is conveyed by the water stress u_s



$$u_s(i) = (W_i - W_w)/(W_{\%} - W_w) * n_{root}$$

n_{root} : mean root density in layer i

$W_{\%}$: moisture at which u_s becomes 1 (no stress)

$$W_{\%} = W_w + p_{\%} \text{ AWC}$$

The smaller $p_{\%}$ the smaller the water stress

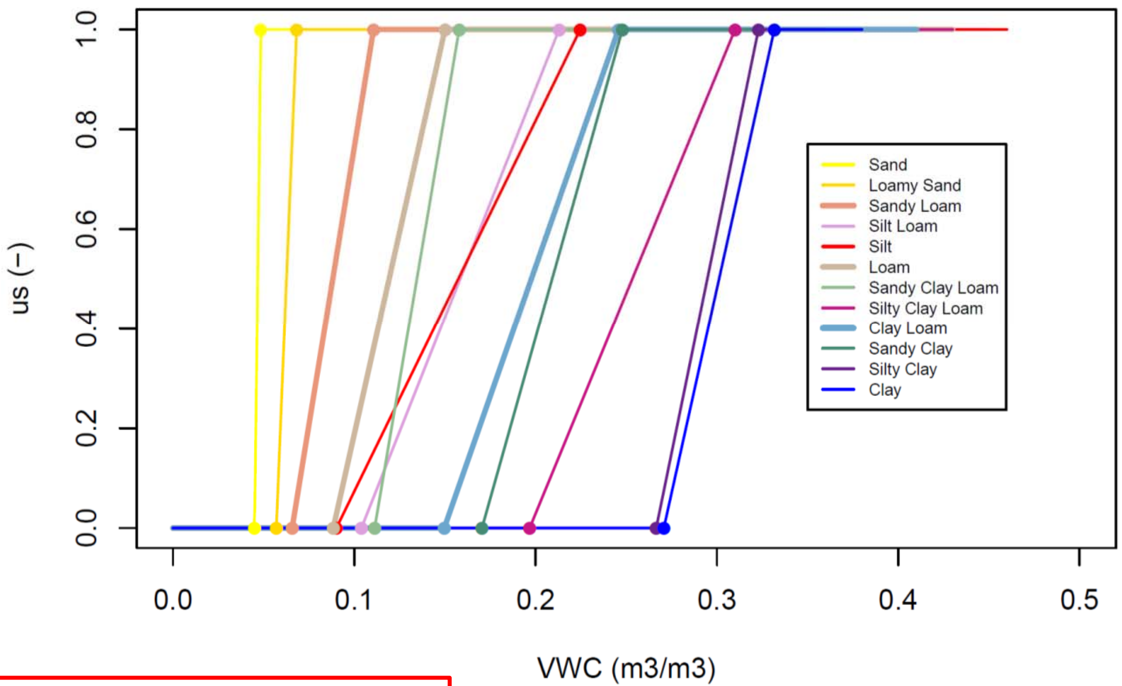
W_w = wilting point

W_f = field capacity

AWC = $W_f - W_w$

The transpiration sink

The dependance of transpiration on soil moisture is conveyed by the water stress u_s



$$u_s(i) = (W_i - W_w)/(W_{\%} - W_w) * n_{root}$$

$W_{\%}$: moisture at which u_s becomes 1 (no stress)

$W_{\%} = W_w + p_{\%}$ AWC

The smaller $p_{\%}$ the smaller the water stress

$p_{\%}$ is externalized as WETNESS_TRANSPIR_MAX

= 0.8, 0.8, …, 0.8

(13 times as for soil texture classes)

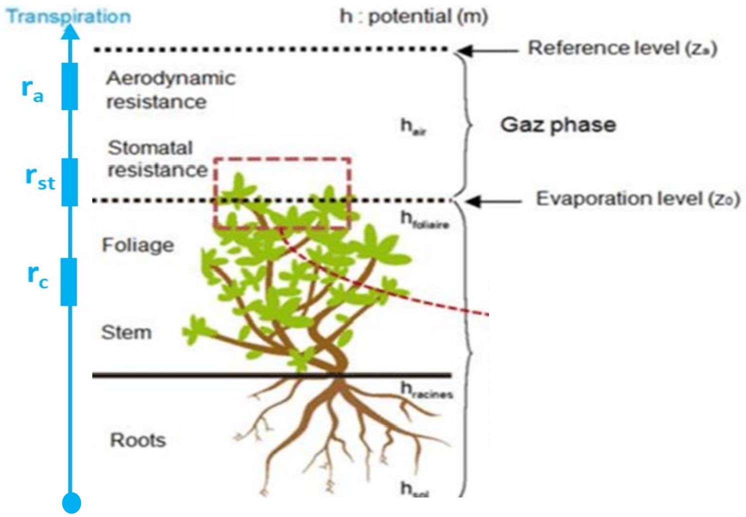
The transpiration sink

The dependance of transpiration on soil moisture is conveyed by $u_s(i)$

❶ $U_s = \Sigma_i u_s$ is used to calculate the stomatal resistance r_{st}

$$T_r = \rho \left(1 - \frac{I}{I_{max}}\right) \frac{q_{sat}(T_s) - q_{air}}{r_a + r_c + r_{st}}$$

r_{st} also depends on light, CO_2, LAI, air temperature and vpd, and on nitrogen limitation in the trunk (CN)



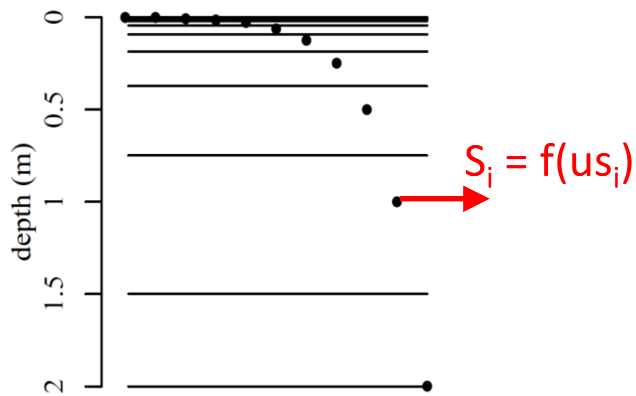
In the code :
U_s = humrel

❷ u_s is used to distribute Tr between the soil layers

$$T_r = \Sigma S_i$$

$$U_s = \Sigma us_i$$

$$S_i = T_r\, us_i / U_s$$



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2. **The multi-layer soil hydrology scheme**
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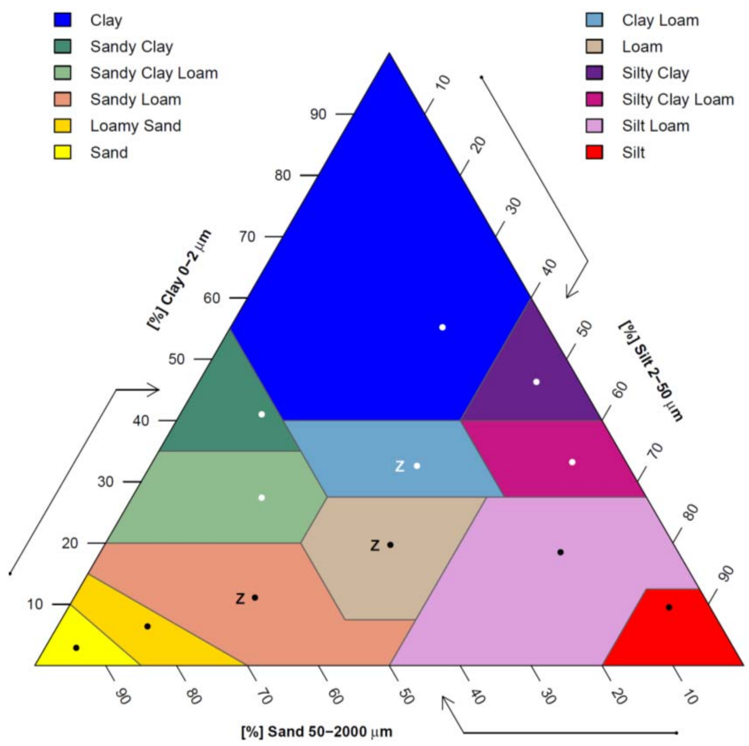
3. **Surface forcing conditions**
   – Soil texture
   – Vegetation / land cover
4. **A glance at the routing scheme**

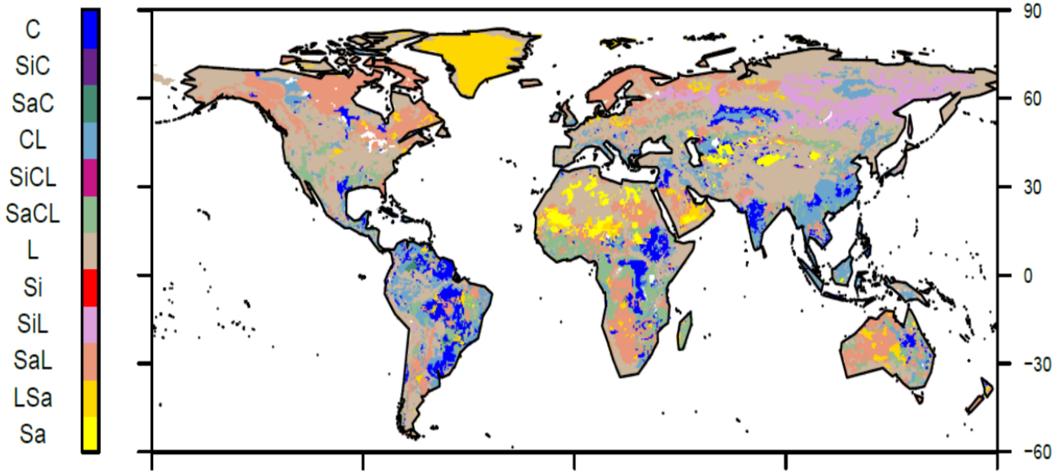
The role of soil texture

- **In hydrol, the main soil properties are:**
  - Van Genuchten parameters: θ_s θ_r K_s^{ref} n α $(= -1/\psi_{ae})$
  - derived field capacity and wilting point: θ_w θ_f
  - clay_fraction for stomate, and thermal properties for thermosoil
- **They are defined based on soil texture**
  (in the real world, they can depend on other factors, as soil structure, OMC, etc.)
- Soil texture is defined by the % of sand, silt, clay particles in a soil sample (granulometry)
- **It can be summarized by soil textural classes**
- By default, ORCHIDEE reads texture from the 1°x1° map of Zobler (1986) **with 3 USDA classes:** Sandy Loam , Loam , Clay Loam
- Alternative soil maps **with 12 USDA classes**:
  - 1/12° map of Reynolds et al. (2000)
  - 0.5°map from SoilGrids (Hengl et al. 2014)
- **In each grid-cell, we use the dominant texture**

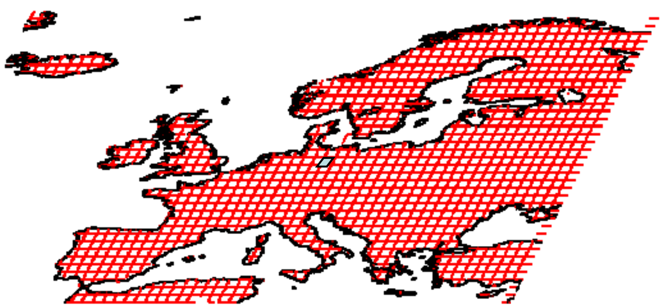


The role of soil texture

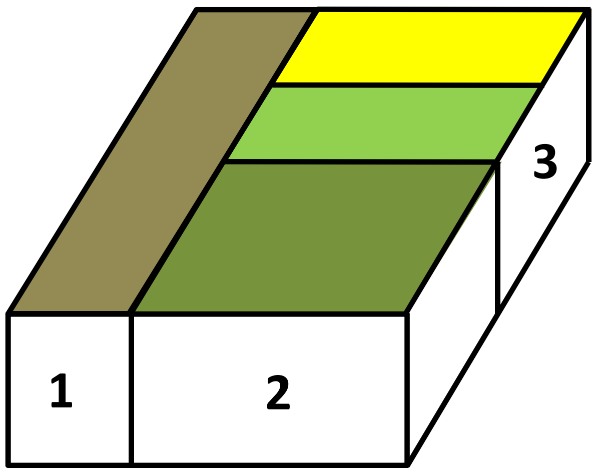
5’ soil texture map of Reynolds et al. (2000)



Dominant texture in each ORCHIDEE grid-cell:
defining the hydraulic properties

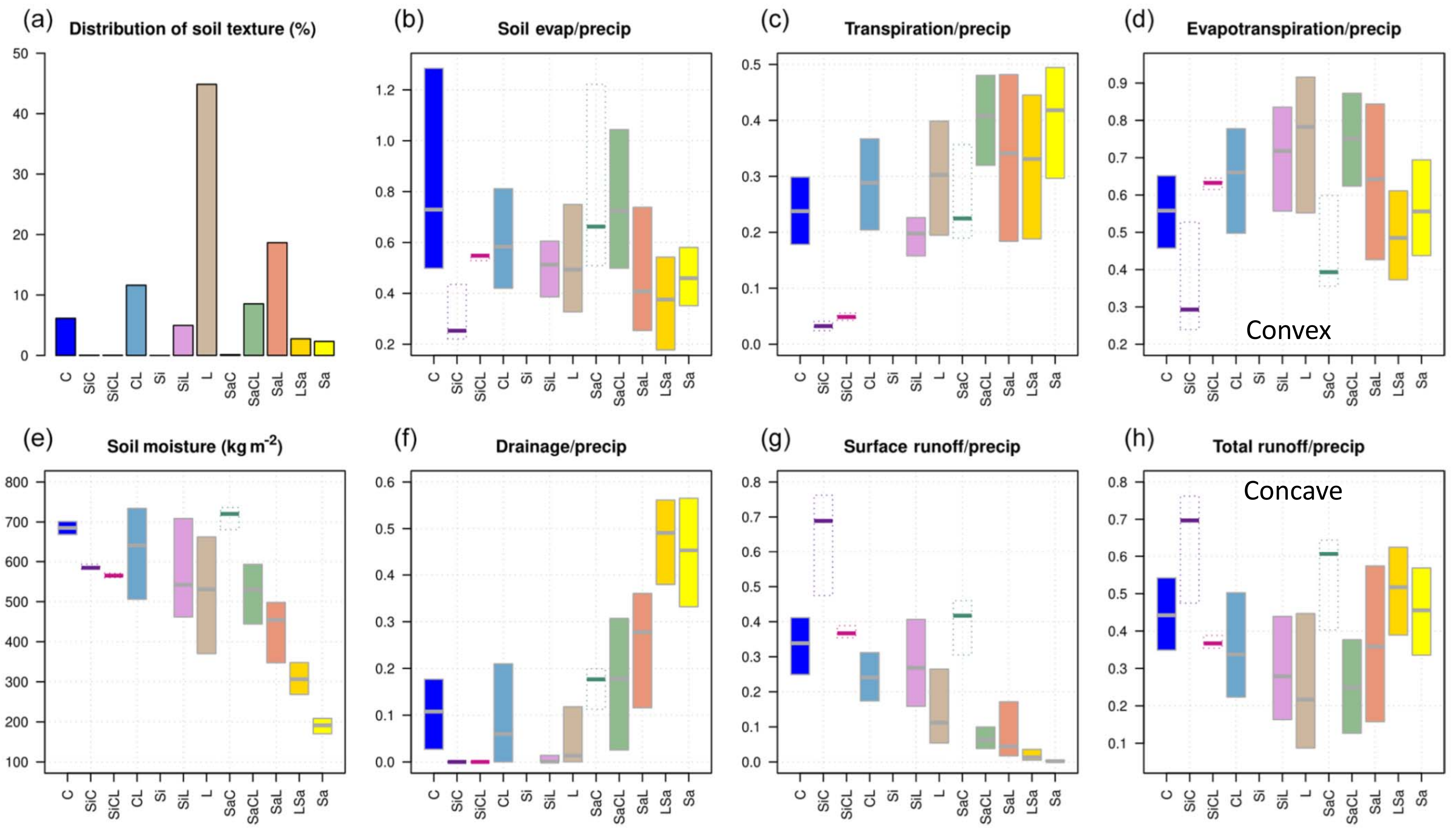


Sub-grid scale heterogenity:
3 soil columns based on PFTs
with independent water budget
but same texture



1: Bare soil PFT
2: All Forest PFTs
3: All grassland and cropland PFTs

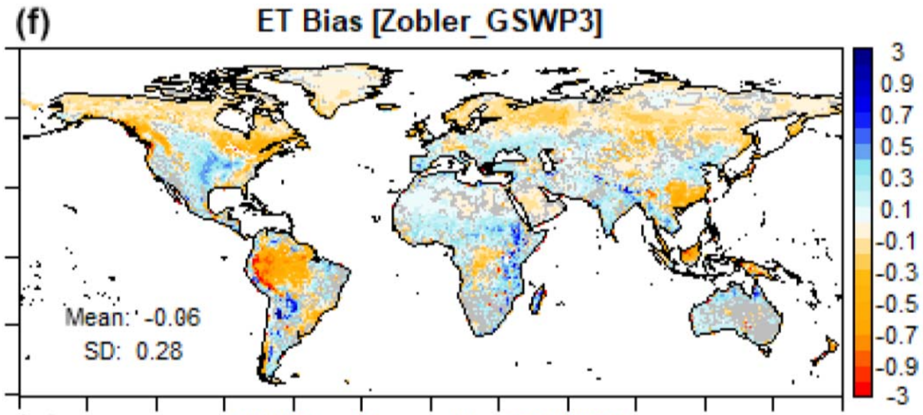
The role of soil texture



Variability of simulated variables over land surface (excluding Antarctica and Greenland) within each soil texture class. Reynolds soil map, with GSWP3 meteorological forcing over 1980–2010.

Tafasca et al., 2020

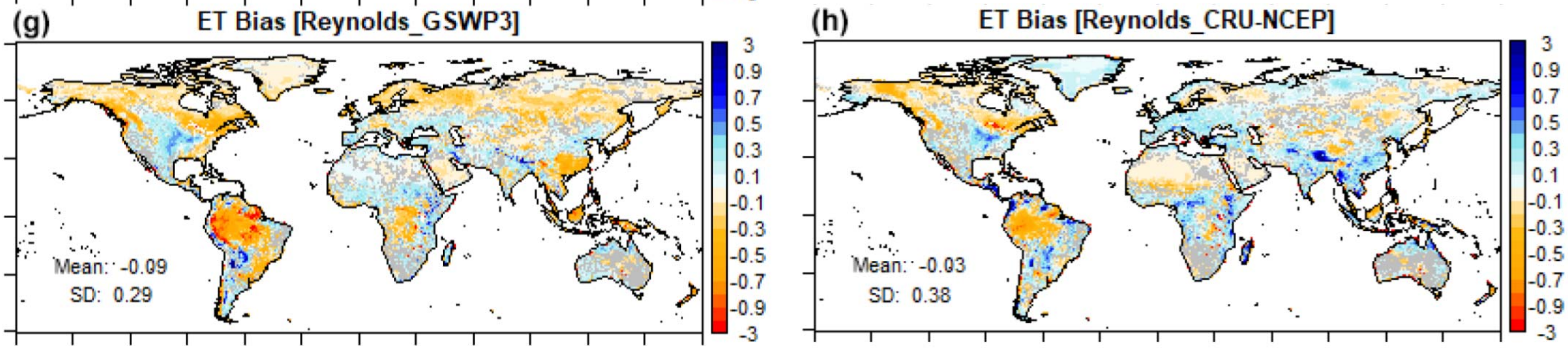
The role of soil texture



ET bias against GLEAM3 product over 1980–2010

- with different soil maps (vertically)
- with different meteorological datasets (horizontally)

For branch 2.2, version CMIP6.

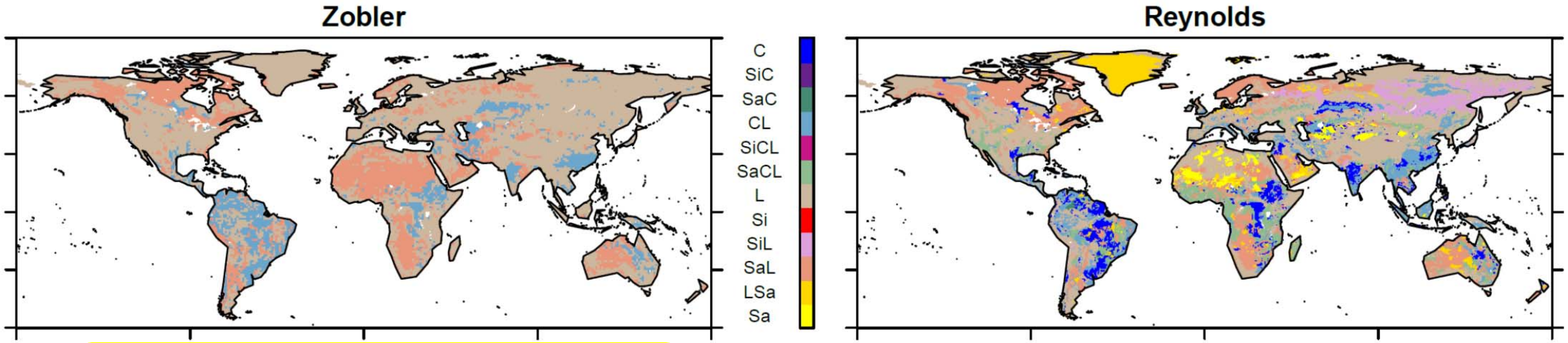


The influence of the soil texture map is much smaller than the one of the atmospheric forcing

Tafasca et al., 2020

The role of soil texture

Soil hydraulic and thermal properties are defined from soil texture,
with now 13 classes (12 USDA + Clay Oxisols)



Default map
SOILTYPE_CLASSIF = zobler;
SOILCLASS_FILE = soils_param.nc

For Reynolds map, add in run.def
SOILTYPE_CLASSIF = usda;
SOILCLASS_FILE = soils_param_usda.nc

You can also force the value of soil properties :

- Either to uniform values
- Or by reading maps of soil parameters

Details on https://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation/Ancillary

Other controls of soil parameters

What was said before about texture is for MINERAL soils (no organic matter)

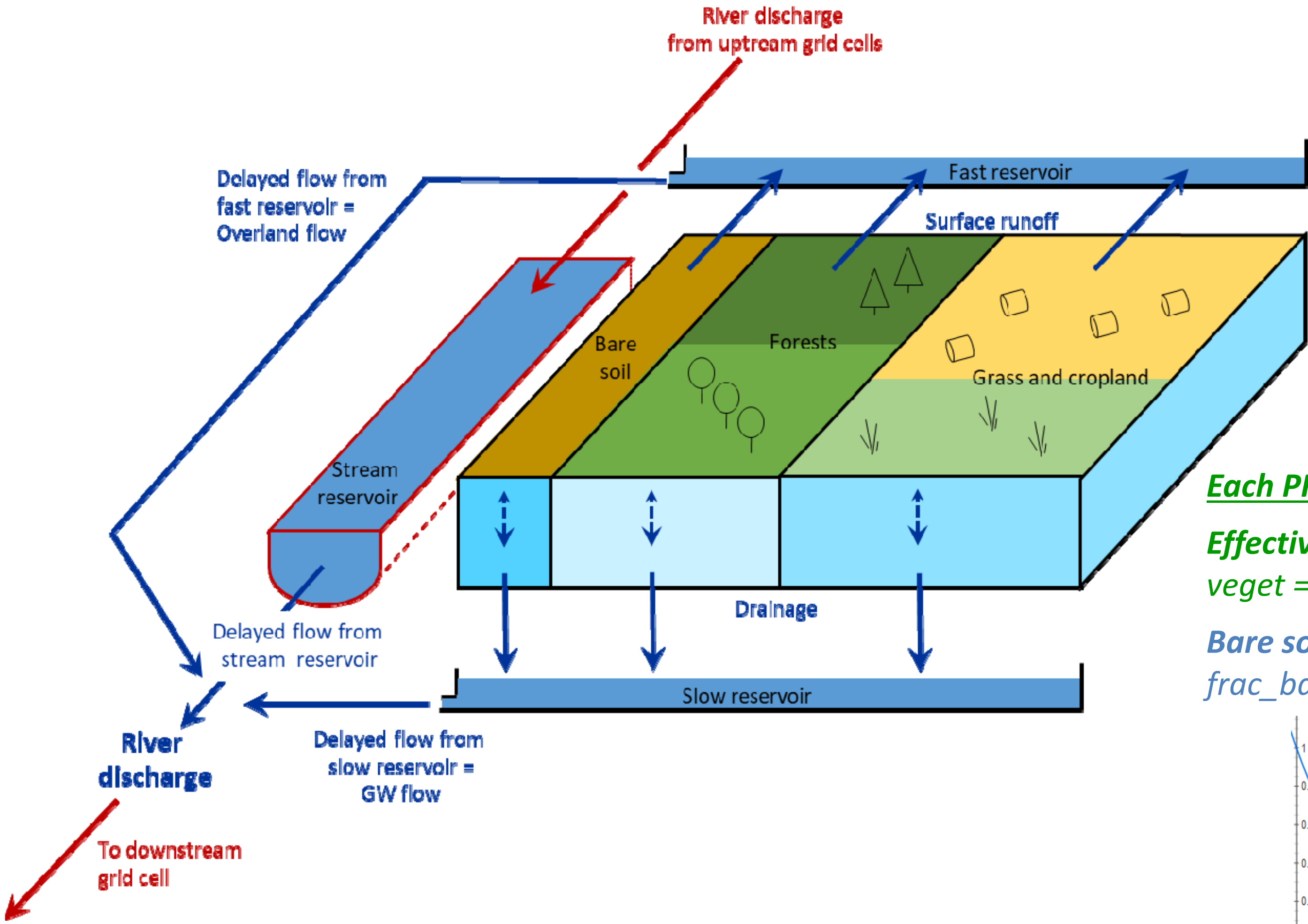
- This is the default in the trunk
- If you set OK_SOIL_CARBON_DISCRETIZATION = y then
  - θ_s and K_s^{ref} will depend on soil organic carbon but only for thermosoil (not for hydrol) ➝ This is a bug and it is being corrected
  - The other soil parameters (θ_r , n, $\alpha = -1/\psi_{ae}$) do not depend on soil organic carbon as in MICT (Guimberteau, Zhu, et al., 2018)

Soil freezing also impacts soil hydraulic and thermic parameters

- Reduced θ_s and K_s^{ref}
- Impacts on infiltration, water redistrinution, and all water fluxes

Interactions with the vegetation/LC

1. Horizontally, PFTs define soil tiles with independent water budget (below ground tiling)



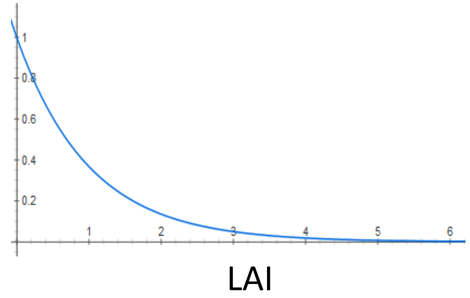
Each PFT with

Effective vegetation fraction (Tr & IL)

veget = veget_max (1 - exp(- LAI))

Bare soil fraction (Eg)

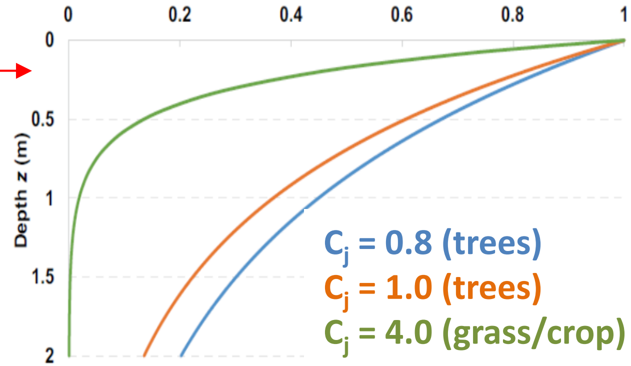
*frac_bare = veget_max * exp(- LAI)*



Interactions with the vegetation/LC

2. Vertically, ORCHIDEE defines a root density profile

In each PFT j $R_j(z) = \exp(-c_j\, z)$



In each soil layer i $n_{root}(i)$ is the mean root density with $\Sigma_i n_{root}(i) = 1$

They control:

(1) the water stress us on transpiration in each soil layer i

$$u_s(i) = (W_i - W_w)/(W_\% - W_w) * n_{root}$$

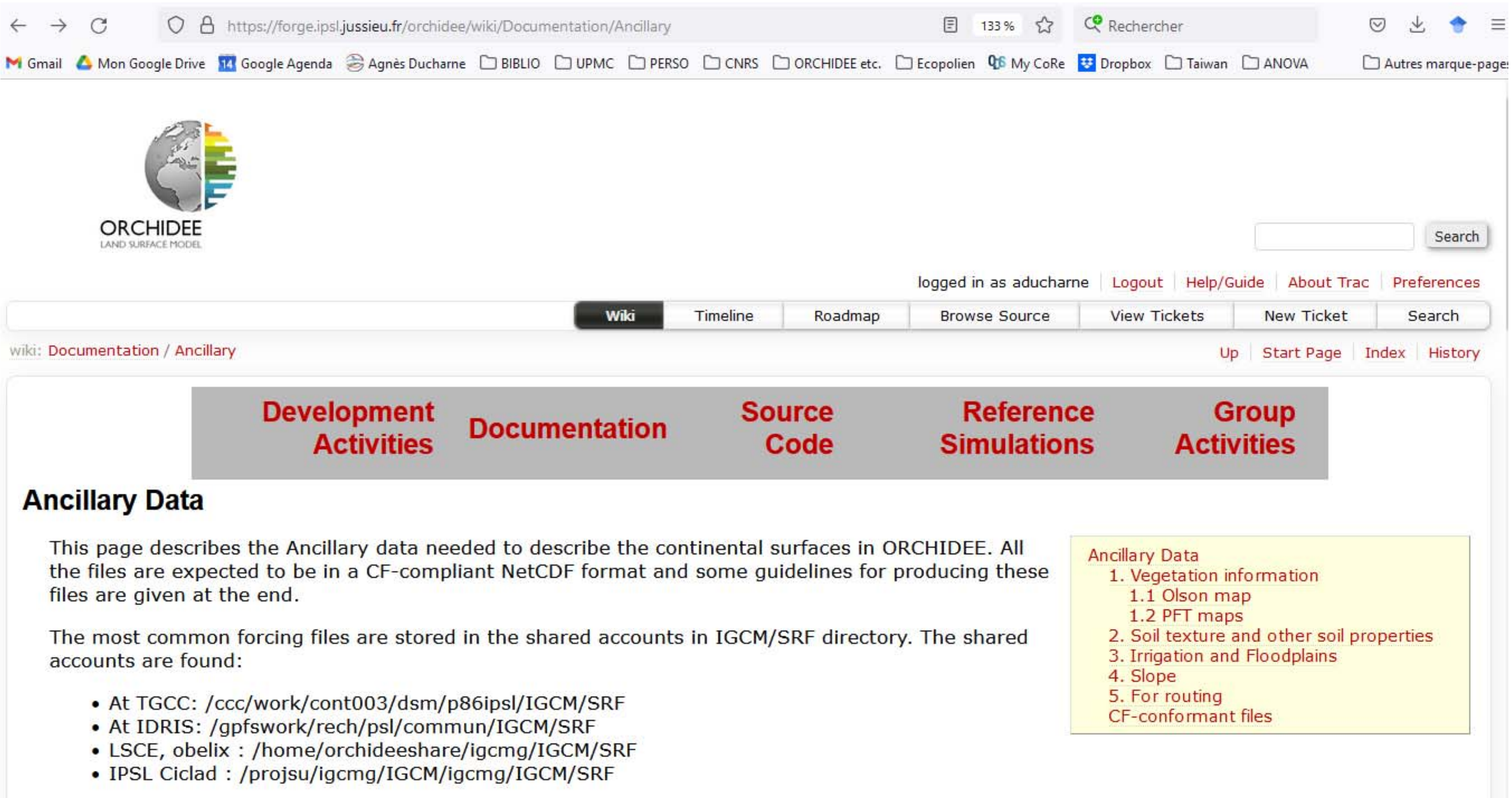
(2) the increase of Ks towards the surface

In the code, c_j is called humcste and defined in constantes_mtc.f90

It is externalized as HYDROL_HUMCSTE

= 5.0, 0.8, 0.8, 1.0, 0.8, 0.8, 1.0, 1.0, 0.8, 4.0, 4.0, 4.0, 4.0
(for 13 MTCs)

Which maps are used for hydrology?



https://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation/Ancillary

Gmail | Mon Google Drive | Google Agenda | Agnès Ducharne | BIBLIO | UPMC | PERSO | CNRS | ORCHIDEE etc. | Ecopolien | My CoRe | Dropbox | Taiwan | ANOVA | Autres marque-pages

ORCHIDEE LAND SURFACE MODEL

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Development Activities | Documentation | Source Code | Reference Simulations | Group Activities

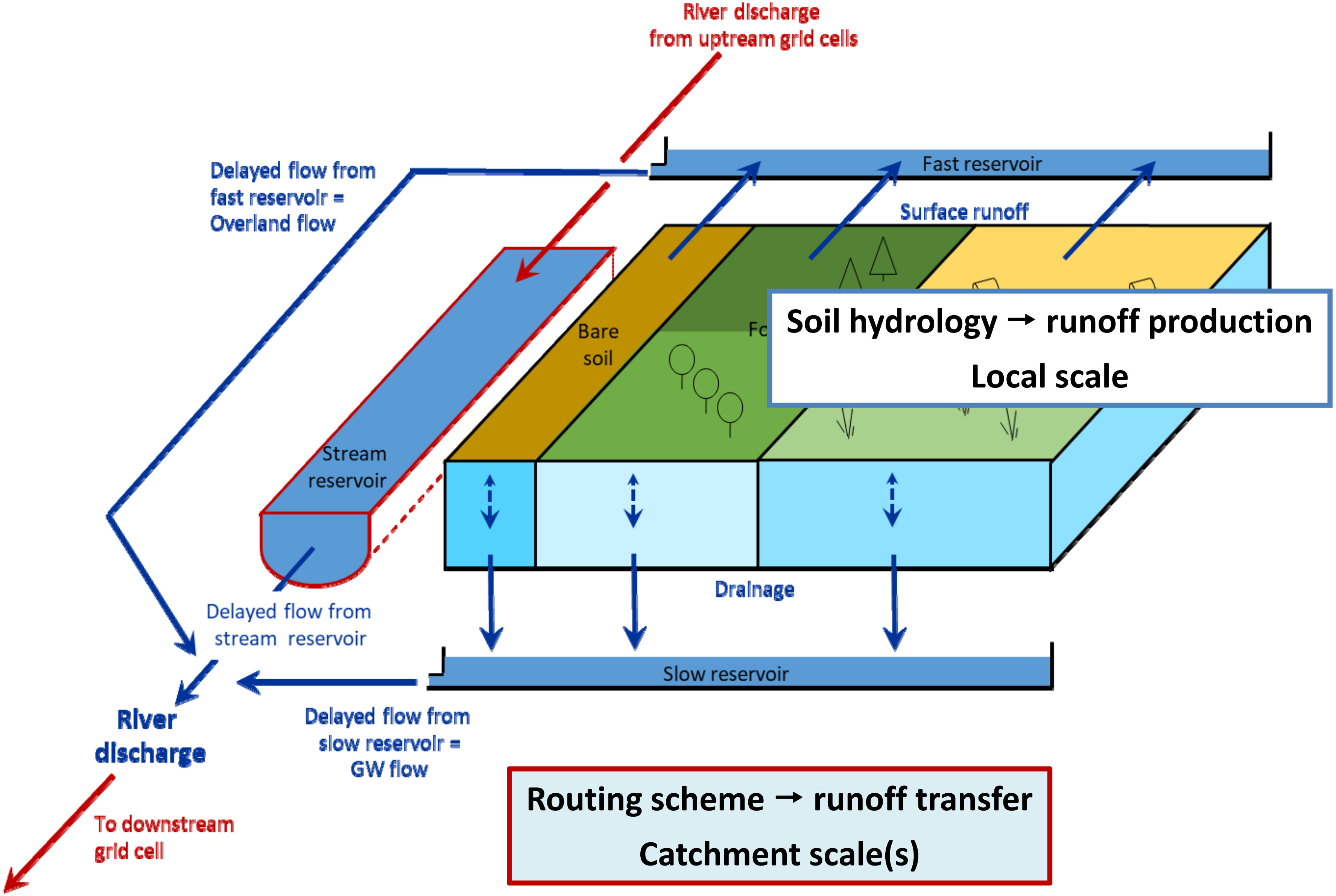
Ancillary Data

This page describes the Ancillary data needed to describe the continental surfaces in ORCHIDEE. All the files are expected to be in a CF-compliant NetCDF format and some guidelines for producing these files are given at the end.

The most common forcing files are stored in the shared accounts in IGCM/SRF directory. The shared accounts are found:

- At TGCC: /ccc/work/cont003/dsm/p86ipsl/IGCM/SRF
- At IDRIS: /gpfswork/rech/psl/commun/IGCM/SRF
- LSCE, obelix : /home/orchideeshare/igcmg/IGCM/SRF
- IPSL Ciclad : /projsu/igcmg/IGCM/igcmg/IGCM/SRF

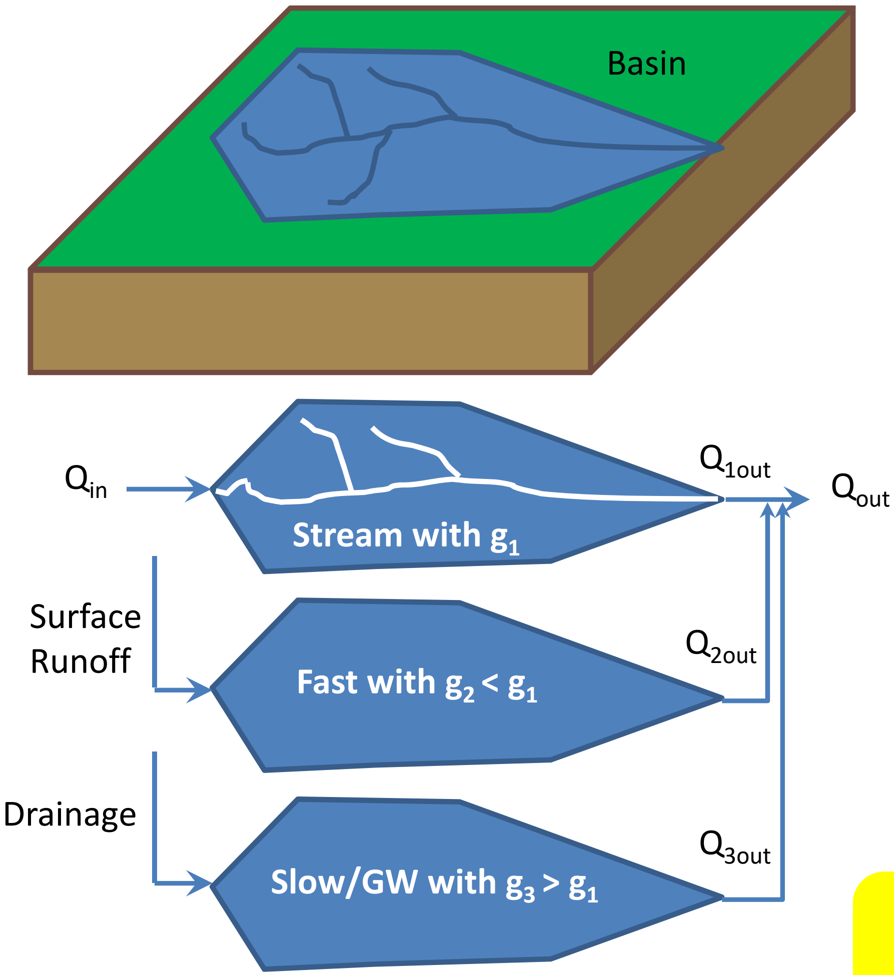
Soil vs « catchment » hydrology



Overview of the standard version

Separate basins/HTUs in each grid-cell

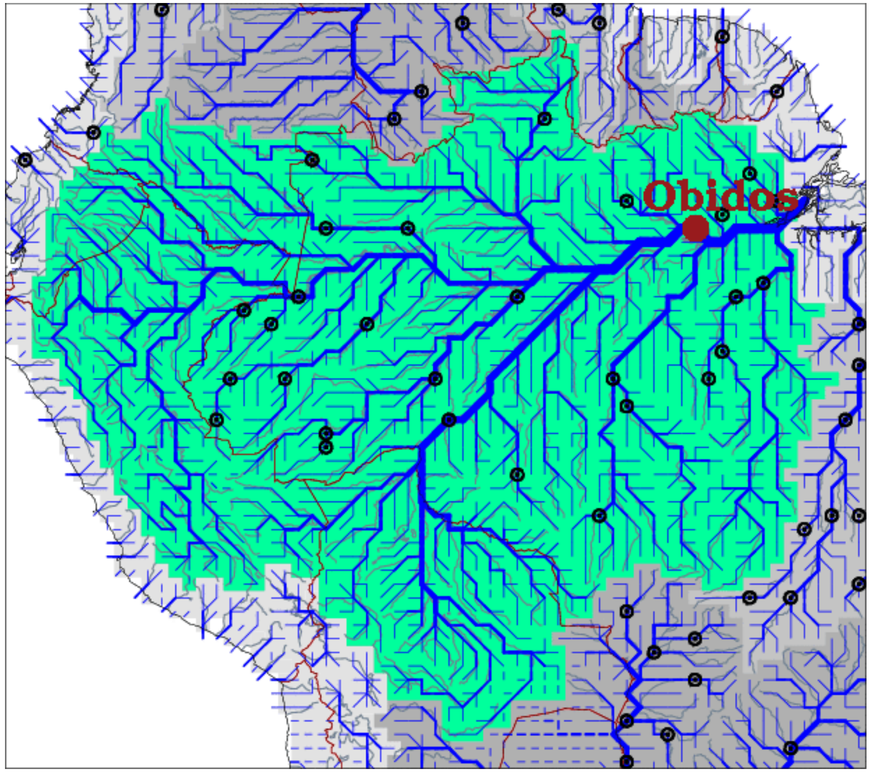
with 3 reservoirs for streams, hillslopes and GW



Residence times $\tau_i = g_i \, \Delta x / \sqrt{slope}$

Cascade of stream reservoirs

along the river network



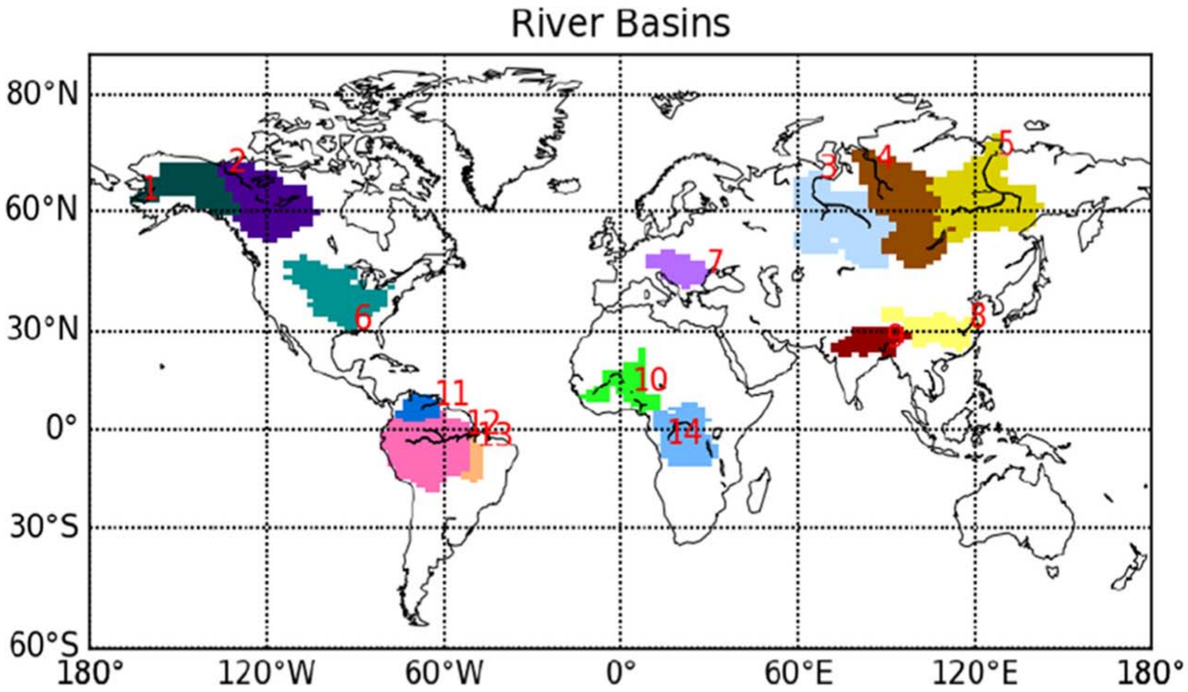
River network based on 0.5° topography

See slides of M. Guimberteau, Training 2016

Polcher 2003 ; Ngo-Duc et al. 2007 ; Guimberteau et al., 2012

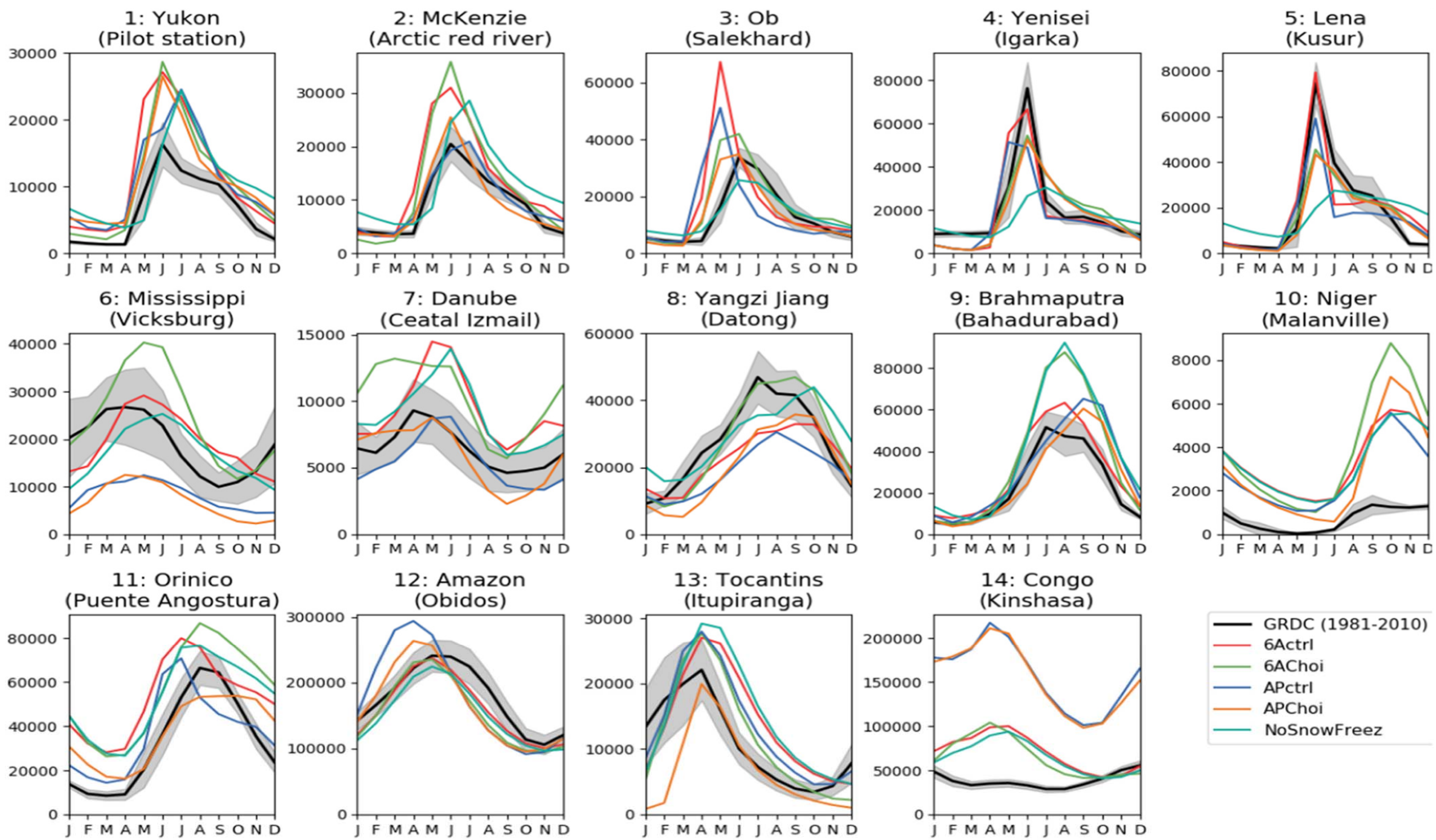
Results for CMIP6

- Land-atmosphere simulations over 1981-2010 with prescribed SST from AMIP
- Resolution 144 x 143 (2.5x1.25°) x 79
- Comparison of IPSL-CM6A (6Actrl) to IPSL-CM5 (APchoi) and other configurations
- River discharge at the outlet of 14 major river basins against observed record (GRDC)



Cheruy et al., 2020

4. A glance at the routing scheme



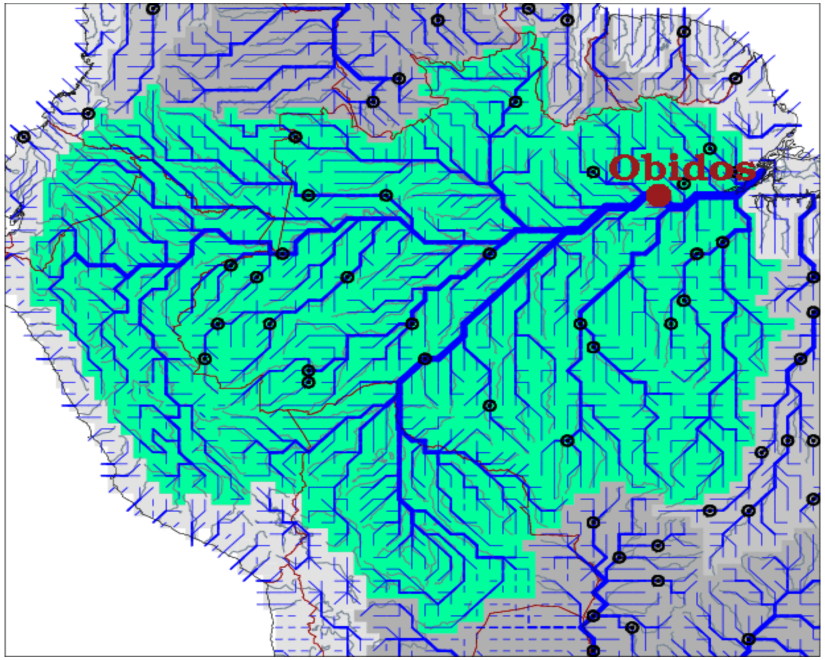
Improvement of **simulated discharge** from IPSL-CM6A (6Actrl) to IPSL-CM5 (APchoi) in most river basins

Mostly related to improvements of simulated precipitation

+ Freezing in Yenisei and Lena

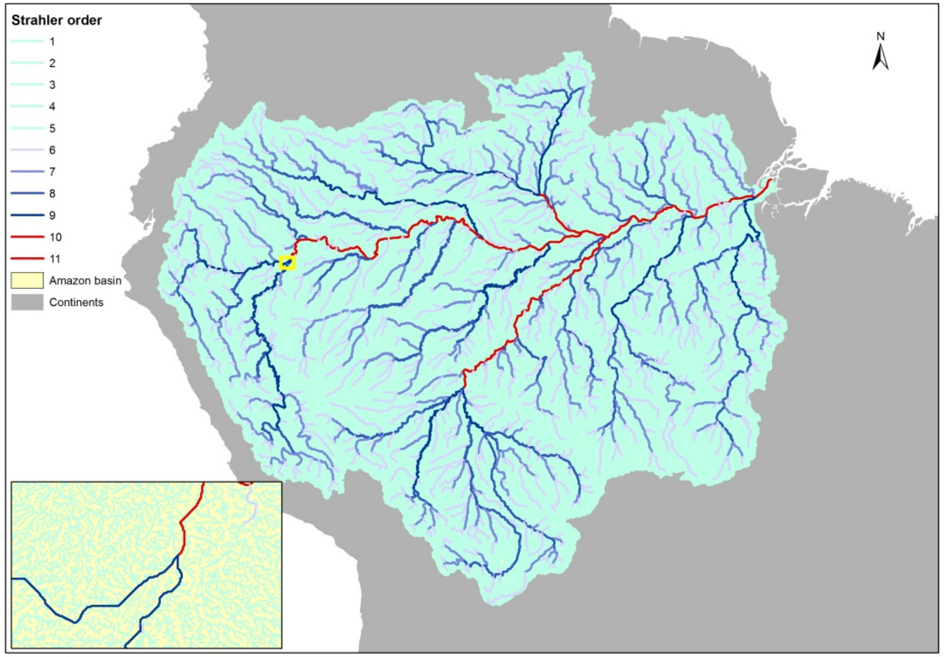
Work in progress for a higher resolution routing

River network based on
0.5° topography



Only valid if ORCHIDEE resolution ≥ 0.5°

Higher resolution river network based on
HydroSHEDS (1 km) or MERIT-Hydro (2km)



2 versions of the routing scheme able to deal with high resolution topography

ROUTING_METHOD = standard (default)

Residence times independent from ORCHIDEE resolution - But can be defined in run.def

Options for irrigation and flooding

ROUTING_METHOD = highres (Polcher et al., 2023)
With options for irrigation and flooding

ROUTING_METHOD = native
Evaluation work in progress

Soil hydrology in a nutshell

- **During a time step, the soil hydrology scheme :**
  - Updates the soil moisture as a function of precipitation and evapotranspiration
  - Calculates the related fluxes (infiltration, surface runoff, drainage)
  - Calculates the water stresses for transpiration and soil evaporation of the next time step
  - Calculates some soil moisture metrics for thermosoil and stomate
- **The equations can be complex, but the parametrization is intended to work without intervention**
  - Default input maps are defined in COMP/sechiba.card
  - Defaults parameters are defined in PARAM/run.def and code
  - Lots of debugging over the past years
- **You can adapt the behavior of the soil hydrology scheme**
  - Easy : change externalised parameters in PARAM/run.def
  - A bit less easy: use different input maps (you need to comply to the format)
  - More difficult: change the code (welcome to orchidee-dev!)
- **Routing scheme is quickly evolving**

Thank you for your attention
Questions ?

ORCHIDEE
LAND SURFACE MODEL