Snow and soil freezing updates for CMIP6 ORCHIDEE version

C. Ottlé, F. Maignan

with contributions of S. Charbit, Ch. Dumas, F. Wang, T. Wang, J. Polcher, J. Ghattas, Ph. Peylin, V. Bastrikov, F. Cherouy, G. Krinner, I. Gouttevin, A. Ducharne et al.,

Snow in the Earth system

Modulation of energy exchanges between the surface and the atmosphere

+ Major implications on the hydrological cycle

High albedo of fresh snow (also function of weather conditions) → *feedbacks on energy balance*

Low thermal conductivity

- *Over ice (lakes, rivers, ice sheets): Reduction of heat flux → ice growth is reduced*
- *Impacts ground freezing/thawing, i.e., soil temperatures, carbon decomposition, soil respiration and methane emissions*

↓

Thermal insulating properties

Phase change *(release of latent heat during refreezing processes, consumption of energy for melting, e.g: snow slows down soil warming in spring)*

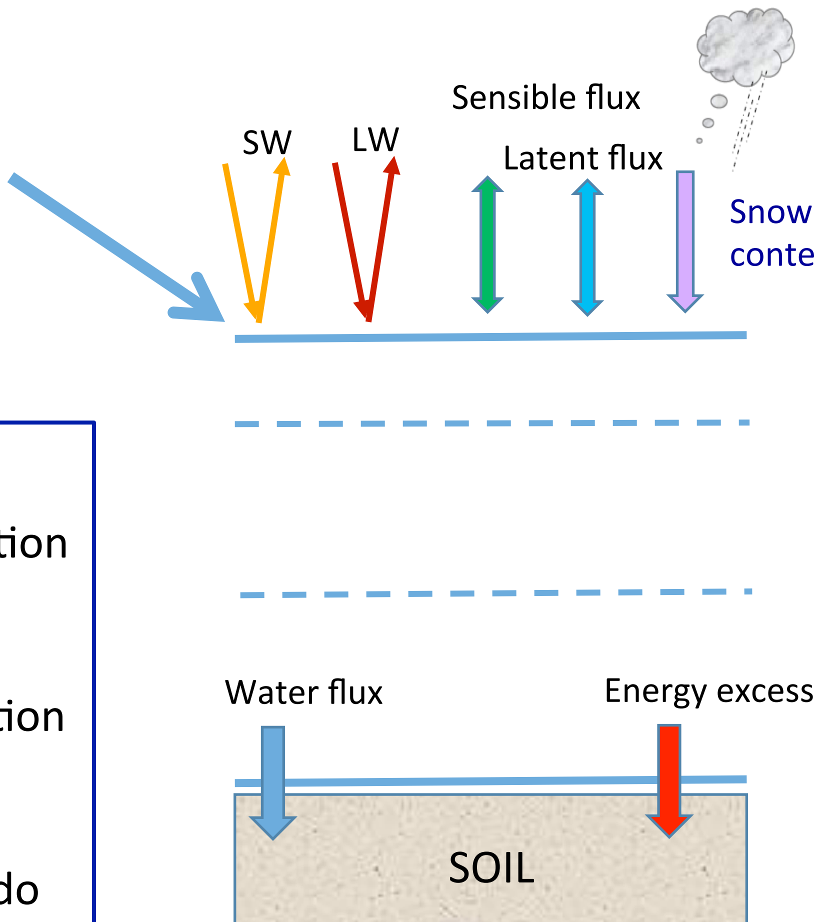
Rapidly evolving with local meteorological conditions (temperature, wind, liquid water content, crystal structure…)

↳ *Impacts on heat and water transfers (diurnal + seasonal) and climate variability,*

Three-layers snow model : Explicitsnow

- Initially developed by Aaron Boone in CNRM for SURFEX-ISBA
- Adapted in 2012 by Tao Wang at LSCE and implemented in ORCHIDEE (Wang et al. 2013)
- Only for vegetated surfaces and bare soils (i.e. bio surfaces)
- For nobio surfaces (ice sheets and glaciers) : 1-layer snow model 1D (CMIP5 scheme)

Surface types: fractional snow and vegetation covers



Processes :

Diffusive heat equation
Freezing/thawing
Snow compaction
Melt water percolation
Runoff
Sublimation
Snow aging → albedo

Outputs:

For each layer :

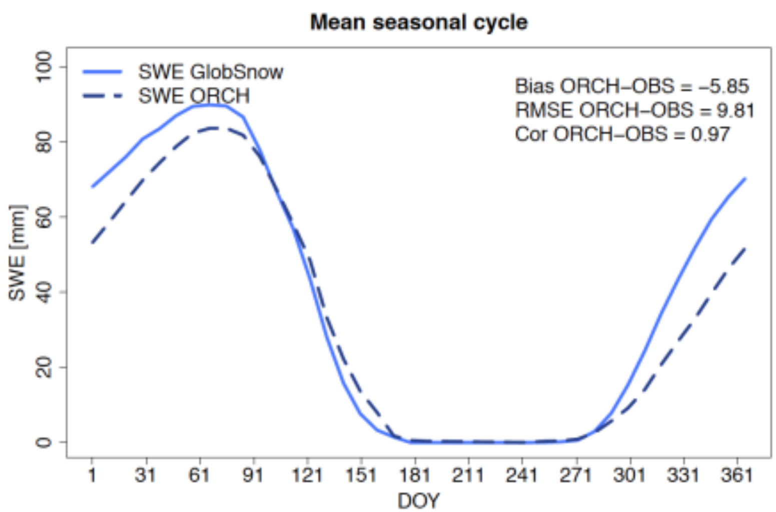
Snow temperature
Water content
Heat content
Depth and thickness
Snow density

And also:
Snow mass and runoff

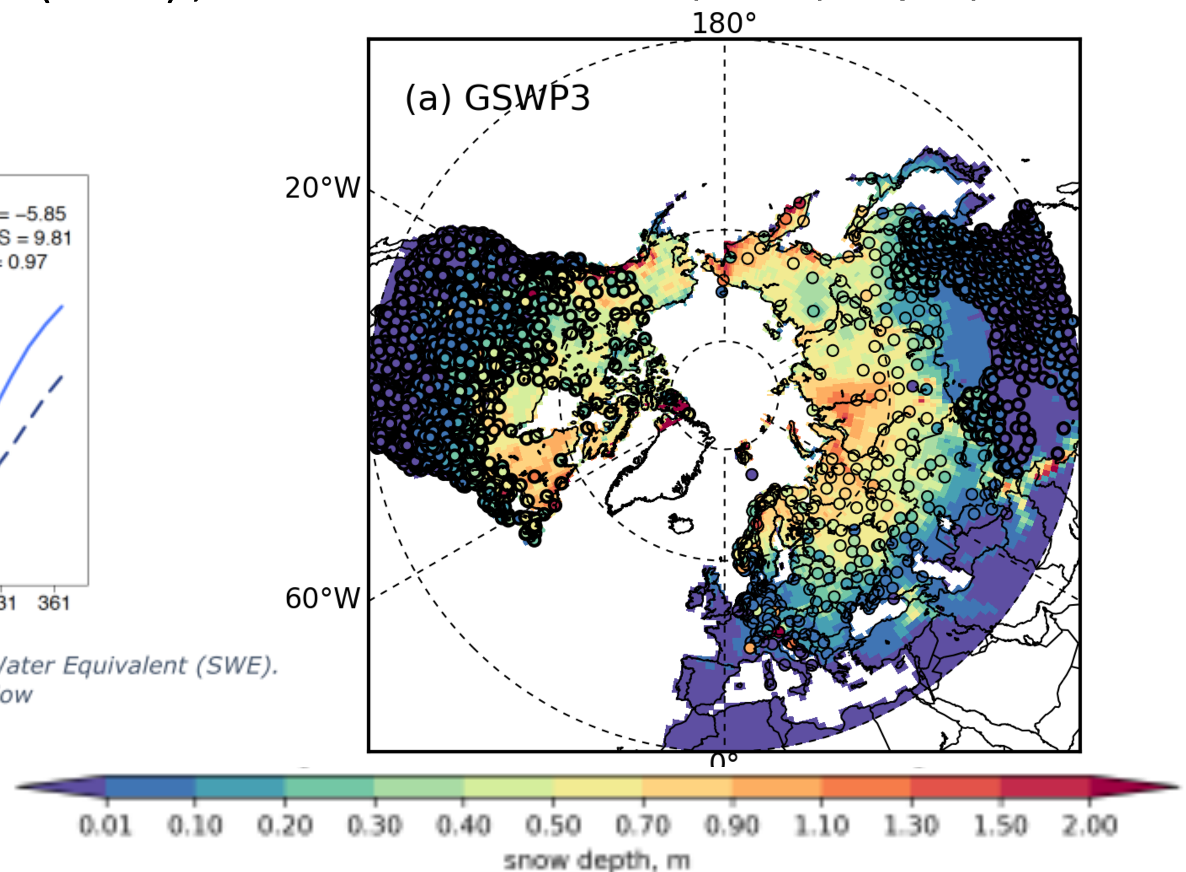
Evaluation/improvements

- Code modifications/debugging to make the calculation of the soil/snow layers temperatures fully implicit, check /calibrate the parametrisations of the snow fraction, snow roughness, snow albedo, density, conductivity, etc…

- Evaluation at site scale, regional and global scales and various temporal scales (Wang et al., 2013, 2015, … PhD S. Dantec (2017) on Siberia, Guimberteau et al., 2017, on northern latitudes (GMD) , on different variables , SWE, depth, runoff, …



Cycle moyen sibérien pour la période 1979-2009 du Snow Water Equivalent (SWE). Comparaison d'ORCHIDEE avec le produit GLobSNow



Water infiltration and runoff in frozen soils: representation in ORCHIDEE Land Surface Model)

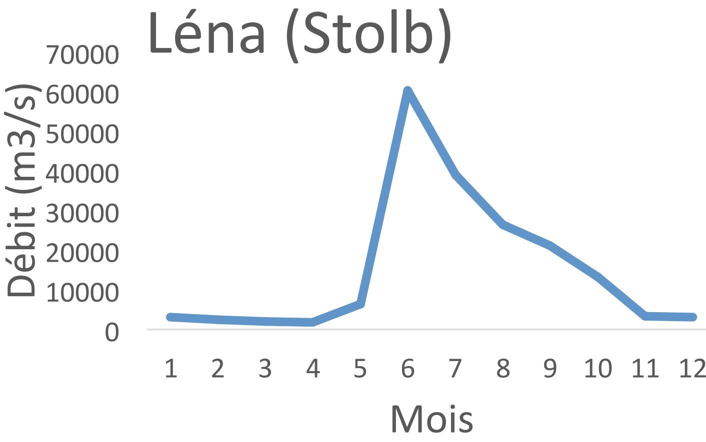
Presence of ice alters soil hydro-thermal properties

Thermal processes:

- Water phase changes produce/consume energy (latent heat of fusion), soil thawing/freezing slows down soil warming/colding in spring/fall …
- Larger thermal conductivity and lower heat capacity

Hydrological processes:

- Lower hydric conductivity and diffusivity : Soil ice prevents infiltration of snowmelt and rainfall
- Reduce soil water availability for plants
- Impacts runoff and streamflows
- Impacts soil biological processes, respiration and methanogenesis, therefore carbone and methane emissions…



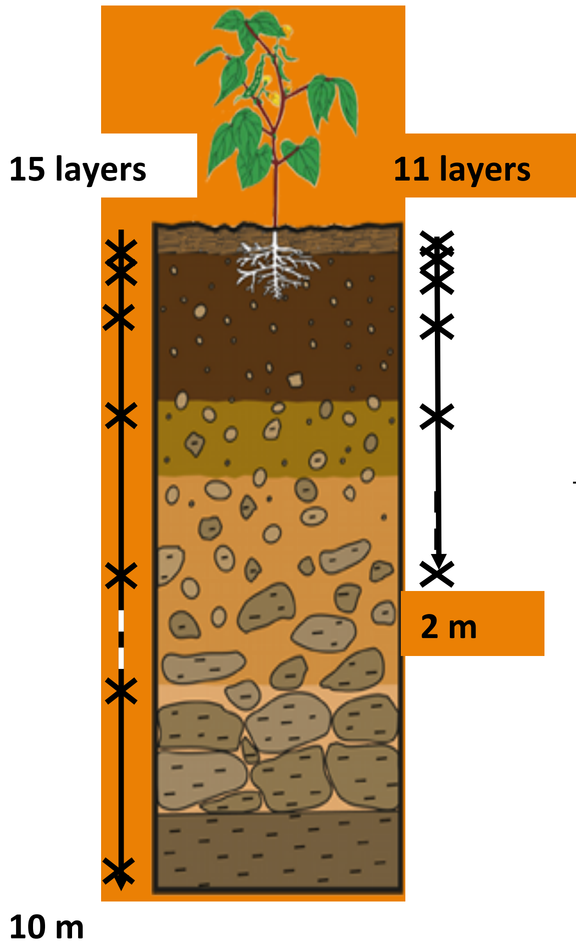
ORCHIDEE hydro and thermal processes without freezing (CMIP5)

thermics

$$\sum F\downarrow_{rad\ \ net} + \sum F\downarrow_{turb\ \ net} = \kappa \frac{\partial T}{\partial z}$$

$$C\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

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



hydrology

$$q = P^{\text{infiltrable}} - E^{pot}$$

$$\frac{\partial \theta(z,t)}{\partial t} = \frac{\partial}{\partial z}.[D(\theta).\frac{\partial \theta(z,t)}{\partial z} + K(\theta)]$$

$$\frac{\partial \theta(z,t)}{\partial z} = 0 \Leftrightarrow q = F \times K(\theta)$$

with F=1

$$0 \le F \le 1$$

ORCHIDEE freezing processes (Gouttevin et al., 2012)

thermics

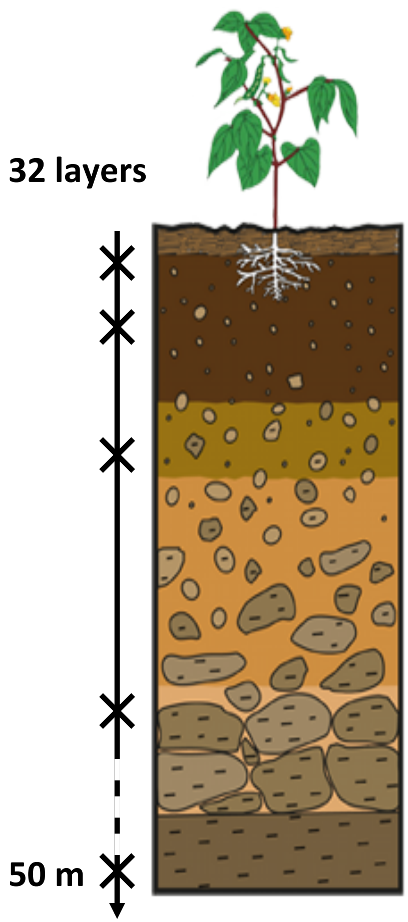
$$\sum F\downarrow_{rad\ net} + \sum F\downarrow_{turb\ net} = \kappa\frac{\partial T}{\partial z}$$

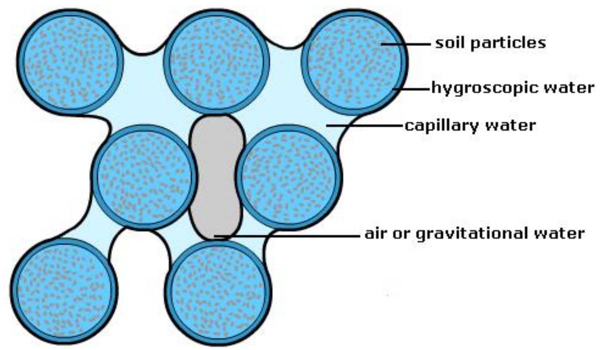
$$C\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial z^2} + \rho_i . L\frac{\partial \theta_i}{\partial t}$$

$$\left(C - \rho_i . L\frac{\partial \theta_i}{\partial T}\right)\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial z^2}$$

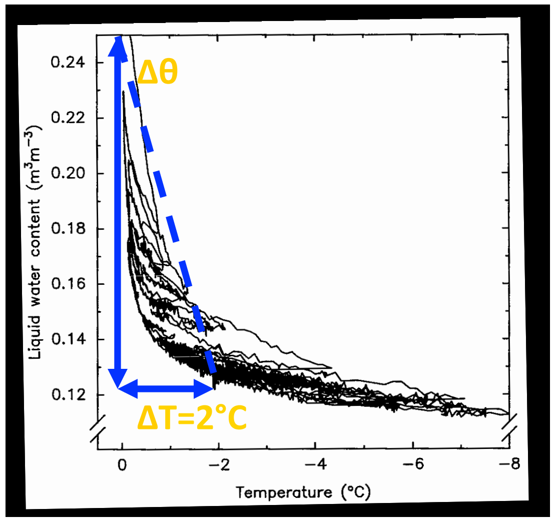
« freezing window »

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





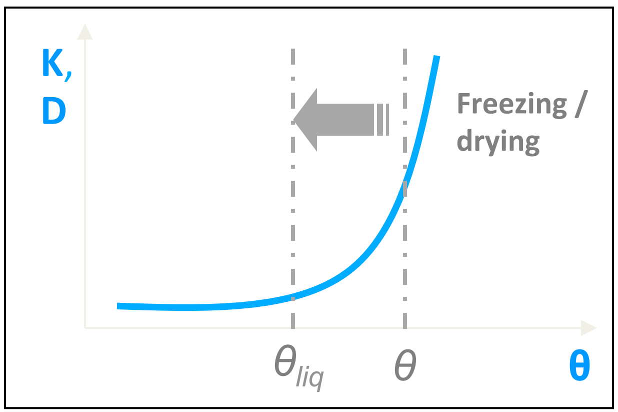
Soil water is stabilized by capillary interactions and freezes beyond the freezing point.



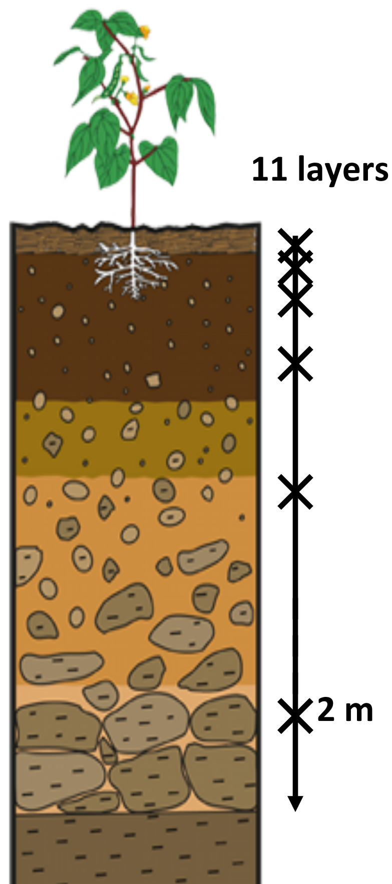
Spaans and Backer, 1996

ORCHIDEE freezing processes
Gouttevin et al., 2012

Schematic evolution of K and D as a function of θ



- **Freezing-drying analogy**
- **How to diagnose θ_{liq} ?**



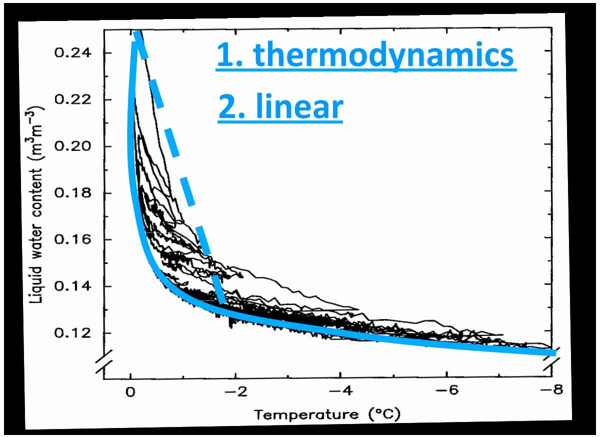
hydrology

$$q = P^{infiltrable} - E^{pot}$$

$$\frac{\partial \theta(z,t)}{\partial t} = \frac{\partial}{\partial z}.[D(\theta).\frac{\partial \theta(z,t)}{\partial z} + K(\theta)]$$

$$\frac{\partial \theta(z,t)}{\partial z} = 0 \Leftrightarrow q = K(\theta)$$

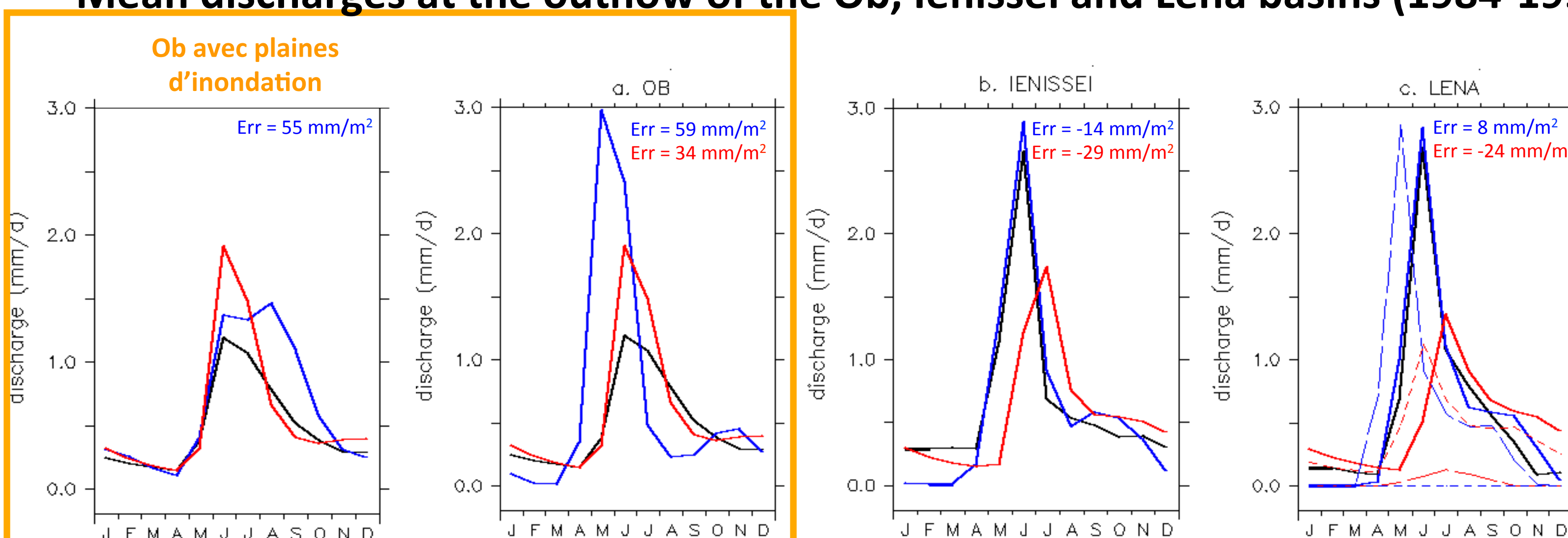
Diagnostic of soil liquid water



Spaans and Backer, 1996

- Linear parameterization with soil temperature
- Thermodynamics (balance between energy state of absorbed and capillary water and energy drop induced by phase change)

Mean discharges at the outflow of the Ob, Ienissei and Lena basins (1984-1994)



+ Ringeval et al., 2012.

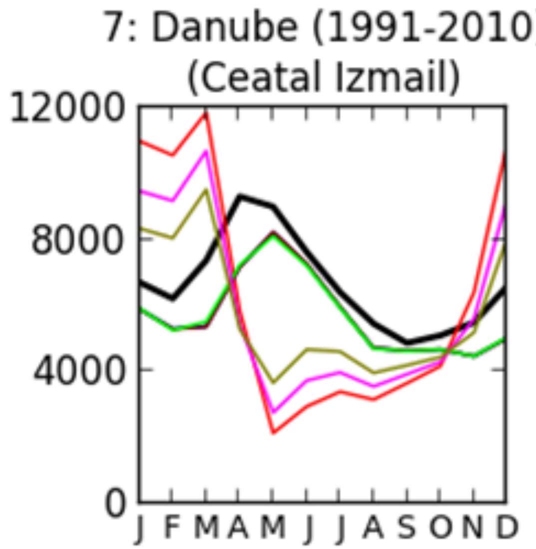
Colors: – NOFREEZE – FREEZE – DATA

Symbols: discharge ----- drainage — — runoff

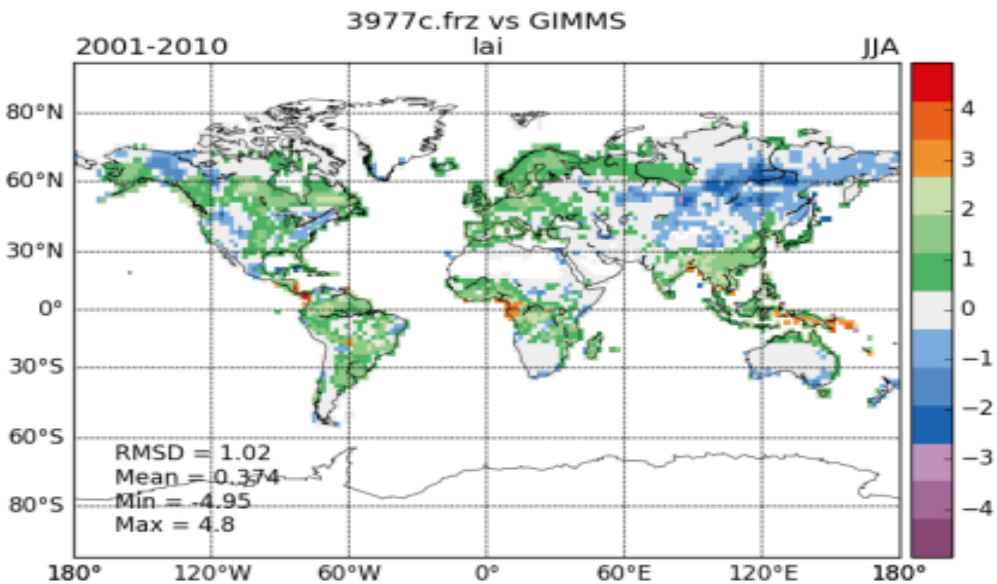
Gouttevin et al., 2012a.

Improvements and drawbacks

Freeze model improves streamflows in arctic regions but degradatation in catchments less influenced by soil freezing (ex. Danube or Missisipi). Springtime runoff higher and earlier than observations.



Identification of hydric stressed regions (too low soil moisture, evapotranspiration, GPP, … underestimation of biomass (LAI), warm temperature biases in coupled LMDZ simulations).



Drastic reduction of infiltration for soils partly/superficially frozen.

Scale issue: frozen soils are permeable because of soil structural aggregates, cracks, dead roots, land cover spatial variability…

Revision of the parametrization of the water frozen fraction infiltration modeled with soil ice content

Modulation with indices quantifying the frozen state (FI) and the soil hydric state (HI) since soil water content (and soil texture) impact also infiltration in frozen conditions. The wetter the soil, the lower the permeability.

→ FI approached with the integral of the frozen fraction over the first 2m soil depth, FI ranging between 0 and 1

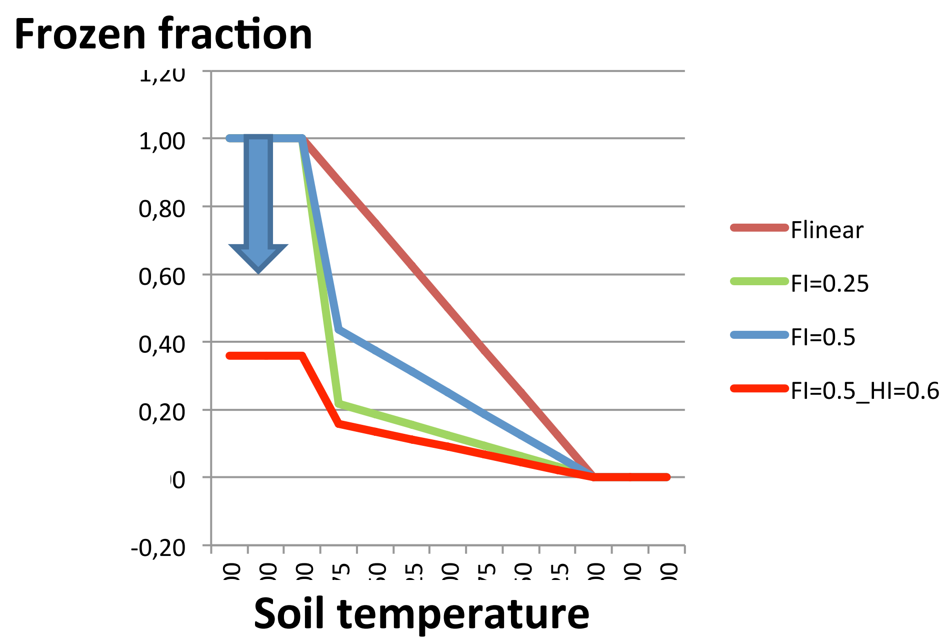
→ HI = relative soil moisture on the first meter of soil, ranging between (θ_r/θ_{sat}) and 1

Calibration of the reduction functions:

$$Froz_{frac} = HI^b * FI^a * Froz_{frac}$$

Example for FI=0.5, HI= 0.6, a=1, b=2

Final values chosen



Results

Improved runoff, soil moisture, LAI, evapotranspiration, surface temperature… in offline and coupled mode