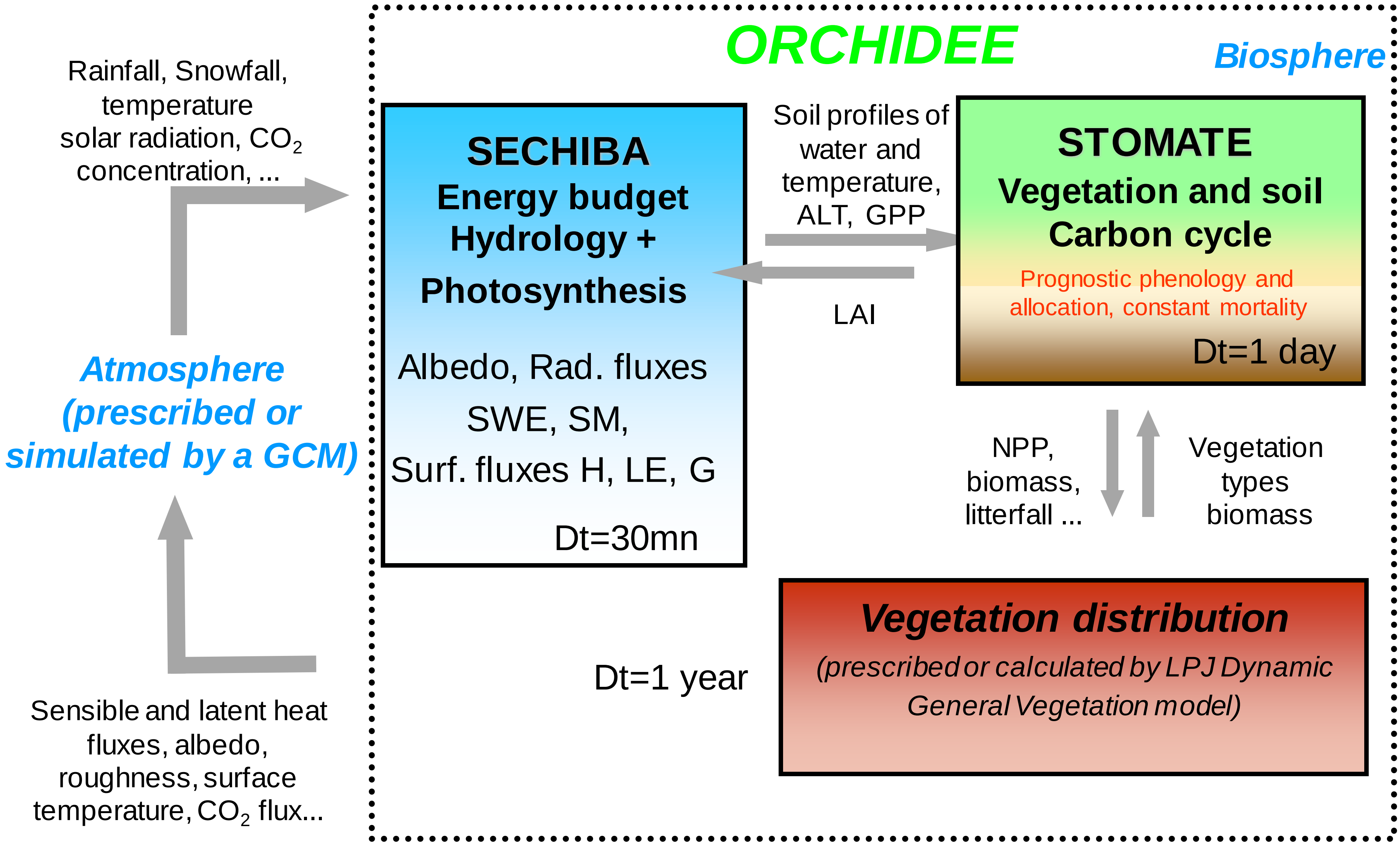
Snow and soil freezing processes in ORCHIDEE

Catherine Ottlé

catherine.ottle@lsce.ipsl.fr

ORCHIDEE


ORCHIDEE
Biosphere
Rainfall, Snowfall, temperature solar radiation, CO_2 concentration, ...
Atmosphere (prescribed or simulated by a GCM)
Sensible and latent heat fluxes, albedo, roughness, surface temperature, CO_2 flux...
SECHIBA
Energy budget
Hydrology +
Photosynthesis
Albedo, Rad. fluxes
SWE, SM,
Surf. fluxes H, LE, G
Dt=30mn
Soil profiles of water and temperature, ALT, GPP
LAI
STOMATE
Vegetation and soil Carbon cycle
Prognostic phenology and allocation, constant mortality
Dt=1 day
NPP, biomass, litterfall ...
Vegetation types biomass
Dt=1 year
Vegetation distribution
(prescribed or calculated by LPJ Dynamic General Vegetation model)

Snow modeling in ORCHIDEE

Snow in the Earth system

Modulation of energy and water exchanges between the surface and the atmosphere, major implications on the energy, water and carbon cycles

- High albedo of fresh snow → *feedbacks on energy balance*
- Low thermal conductivity → *Thermal insulation properties*

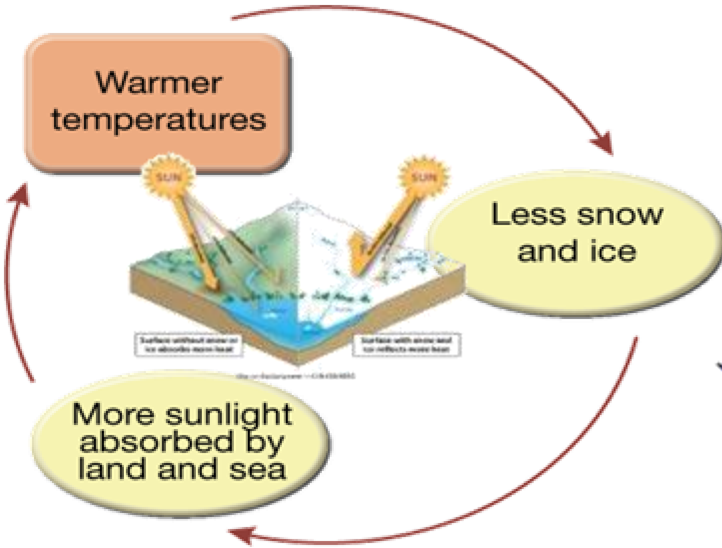
- *Over ice (lakes, rivers, ice sheets): Reduction of heat conduction flux → ice growth reduced*
- *Impacts ground freezing/thawing, i.e., soil temperatures, carbon decomposition, soil respiration and methane emissions*

- Phase change *(release of latent heat during refreezing processes, consumption of energy for melting, e.g: snow slows down soil warming in spring)*
- Reduction of soil roughness *(smoothing effect on vegetation)*
- Buffering water transfers to soil moisture and runoff
- Rapidly evolving with local meteorological conditions (temperature, wind, precipitation impact liquid water content, impurities, crystal structure, etc…)

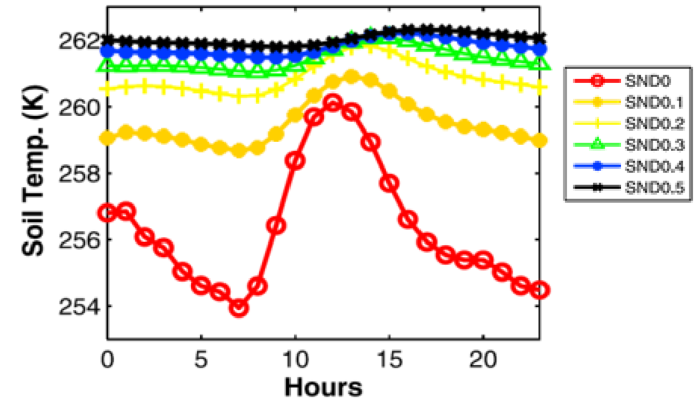
→ *Impacts on heat and water transfers (diurnal + seasonal) and climate variability*

Snow / Atmosphere / Vegetation feedbacks:

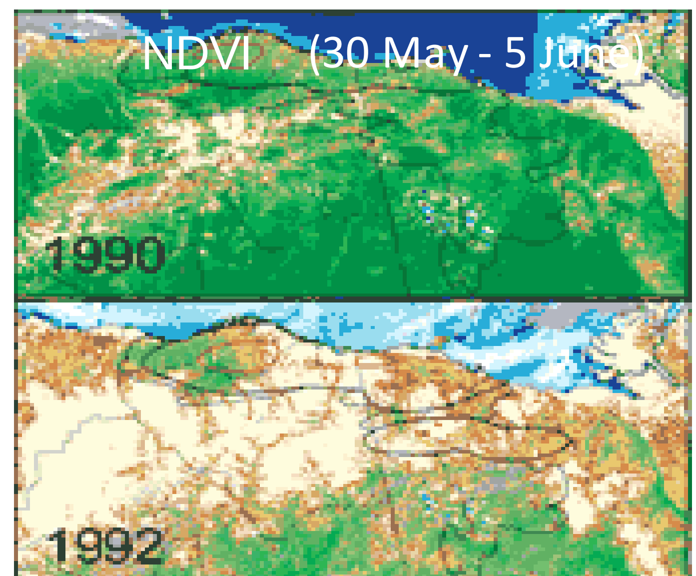
Less snow, warmer air temperatures



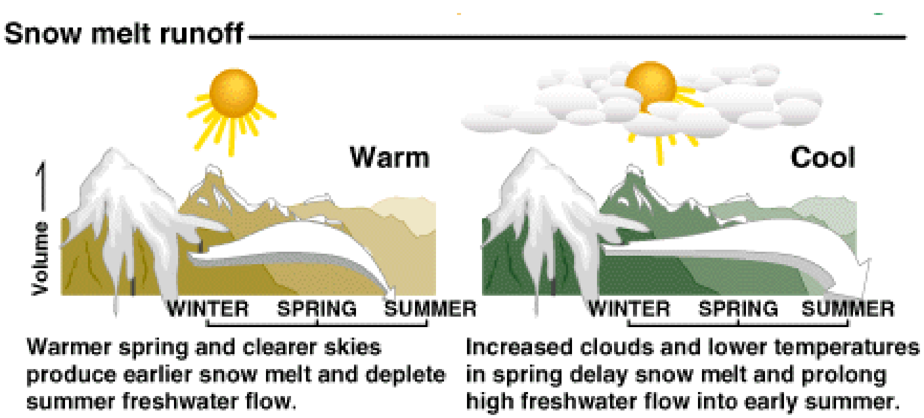
Less snow, colder soil temperatures in winter



Prolonged snow, later vegetation greening



Earlier snowmelt, earlier spring runoff

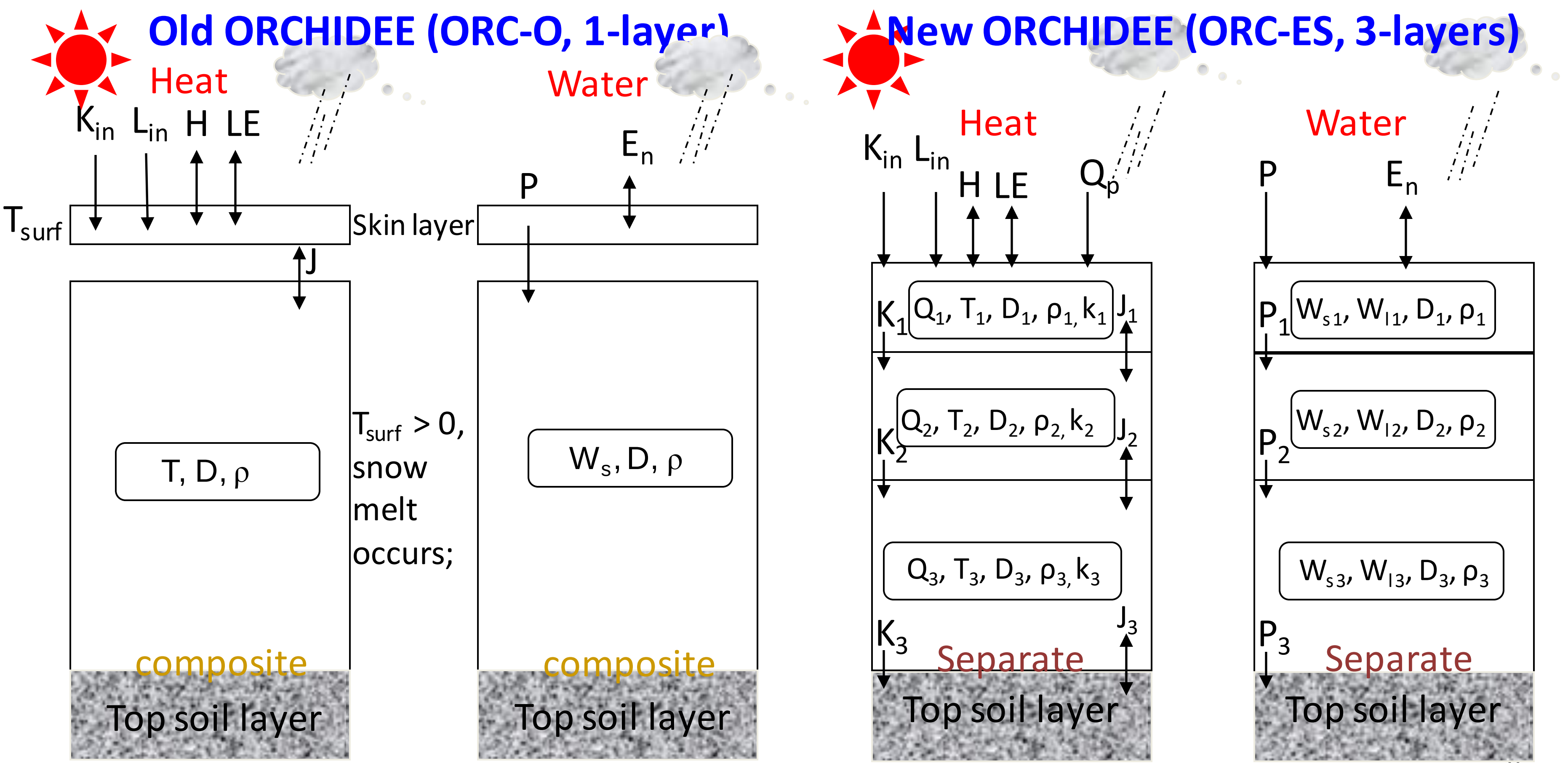


(Adapted from Cayan and Peterson, 1993)

ORCHIDEE Snow developments (Wang et al., 2013)

ISBA-ES (Boone et al.,)

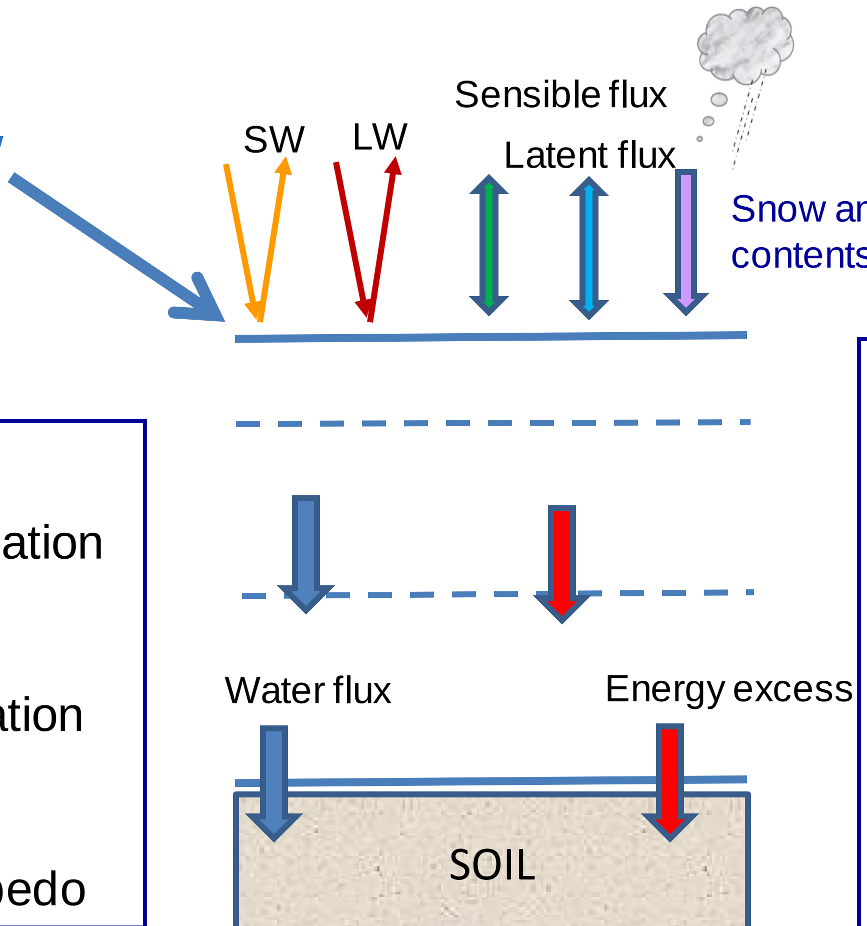
- ✓ Single layer **vs**. Three layers
- ✓ Composite **vs.** Separate snow structure
- ✓ Snow density(ρ) and snow thermal conductivity (k) (constant **vs.** variable)
- ✓ Snow compaction representation
- ✓ Thawing and refreezing processes (no **vs.** yes)
- ✓ Water flow and radiative transfer between layers (no **vs.** yes)
- ✓ New snow fraction and albedo parametrization
- ✓ Snow impacts on roughness length



Three-layers snow model : Explicitsnow

- 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:

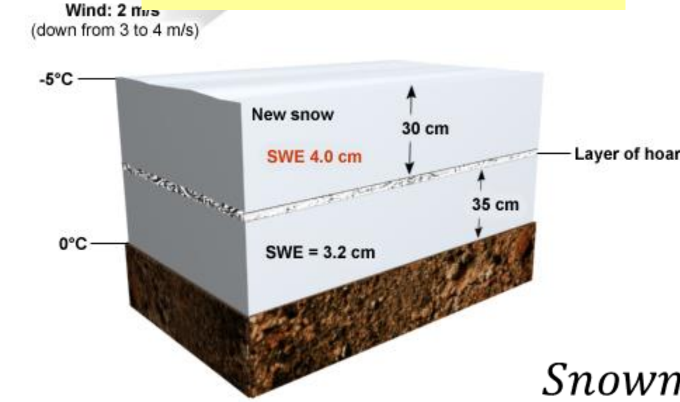
Snow mass and runoff

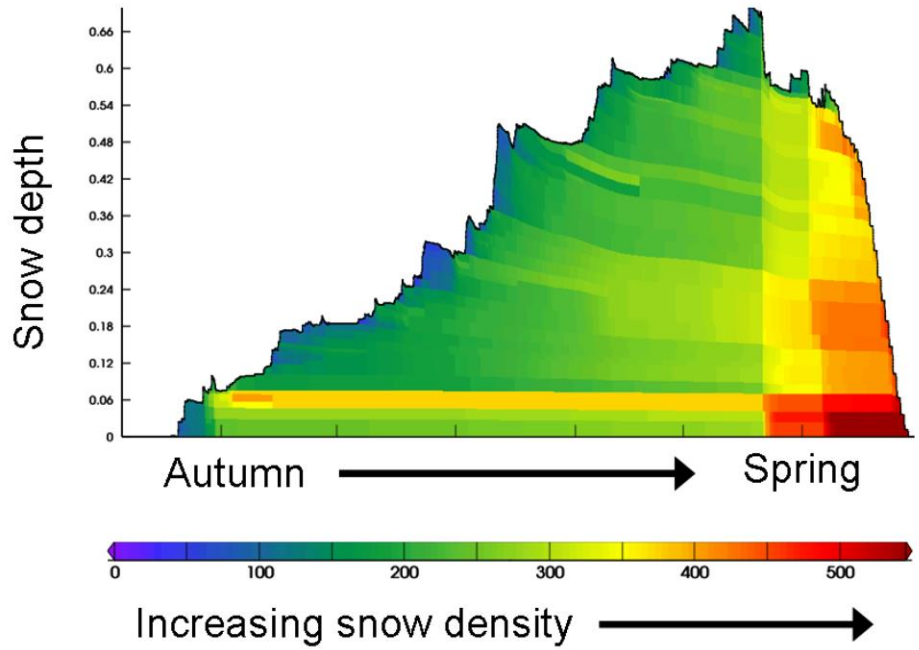
Main features of ORCHIDEE snow module

- **Freezing-thaw processes and snow compaction (leading to spatio-temporal variation in snow density)**

Freeze-thaw

Snow compaction





$$Snowmass = SWE(\frac{kg}{m^2}) = depth_{snow}\ (m) * dens_{snow}(\frac{kg}{m^3})$$

Main features of ORCHIDEE snow module

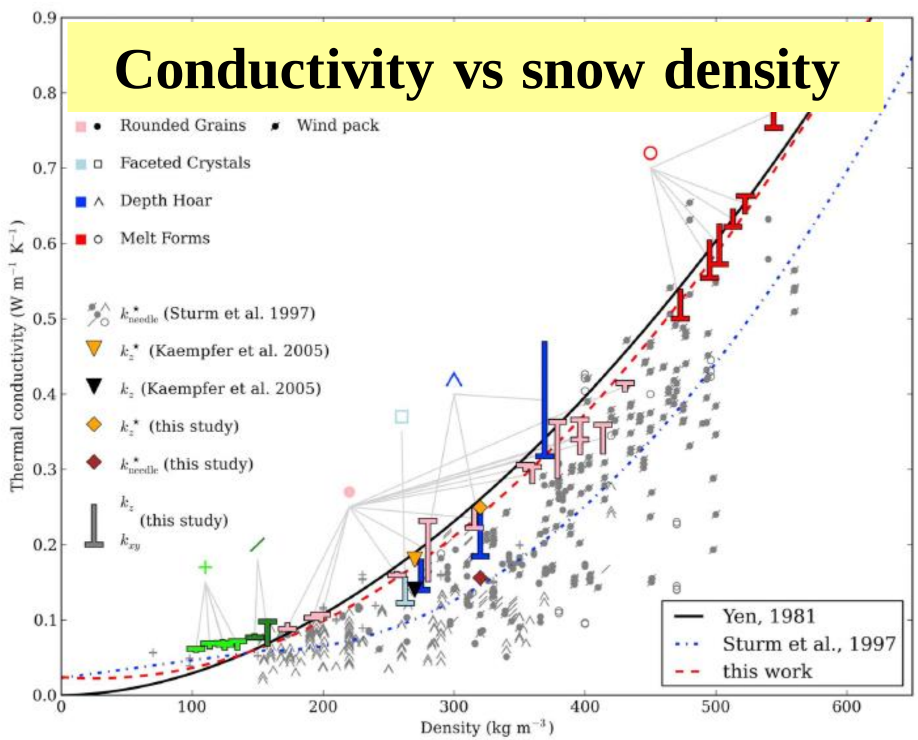
- **Snow thermal conductivity and capacity as a function of snow density and snow temperature (only for κ)**

Snow thermal conductivity

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

Snow thermal capacity

Determine soil temperature and snow metamorphism



Main features of ORCHIDEE snow module

- Snow fraction on vegetated surface (Swenson & Lawrence, 2012)

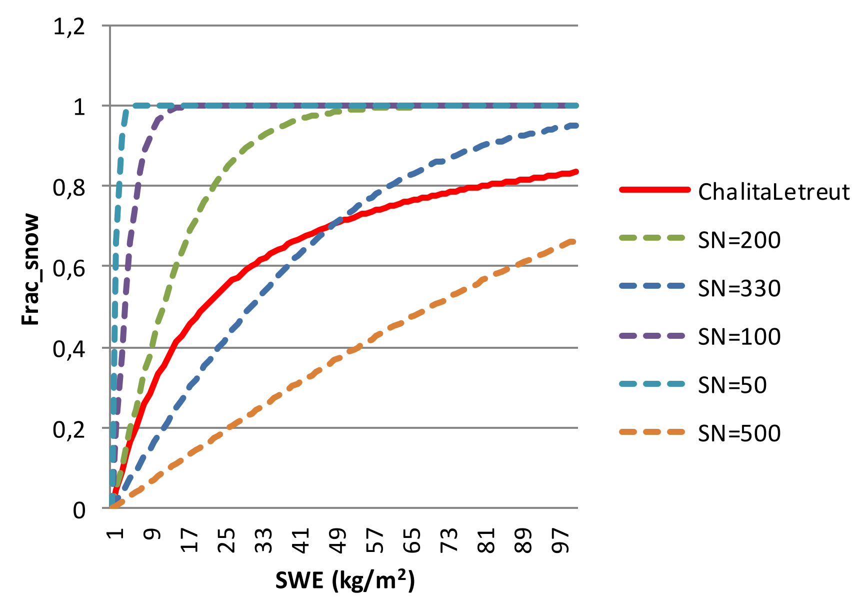
$$frac_{\text{snow, veg}} = \tanh\left(\frac{50 \cdot d_{\text{snow}}}{0.025 \cdot \rho_{\text{snow}}}\right)$$

- Snow fraction on glaciers (Chalita & Letreut, 1994)

$$frac_{\text{snow, nobio}} = \frac{\text{SWE}}{\text{SWE+20}}$$

with ρ_{snow}= 330kg/m^3

Work in progress, more calibration is required against satellite data



Main features of ORCHIDEE snow module

- Snow albedo: depend on snow age (snowfall, aging factors), vegetation type, calculated in “condveg_albedo.f90”

$$\boxed{age_{\text{snow,i+1}} = (age_{\text{snow,i}} + (1 - age_{\text{snow,i}}/age_{\text{snow,max}}) \cdot dt) \cdot \exp(-precip_{\text{snow}}/trans_{\text{snow}})}$$

$$alb_{\text{snow,veg}} = \frac{\sum_{\text{pft}=1}^{13} frac_{\text{max,pft}} \cdot [alb_{\text{snow,aged,pft}} + alb_{\text{snow,dec,pft}} \cdot \exp(-age_{\text{snow}}/tcst_{\text{snow}})]}{\sum_{\text{pft}=1}^{13} frac_{\text{max,pft}}}$$

$$alb_{\text{snow,nobio}} = alb_{\text{snow,aged,1}} + alb_{\text{snow,dec,1}} \cdot \exp(-age_{\text{snow}}/tcst_{\text{snow}})$$

Albedo of the grid cell:

$$albedo = frac_{\text{veg}} \left[(1 - frac_{\text{snow,veg}}) \cdot alb_{\text{veg}} + frac_{\text{snow,veg}} \cdot alb_{\text{snow,veg}}\right] +$$

$$+ frac_{\text{nobio}} \left[(1 - frac_{\text{snow,nobio}}) \cdot alb_{\text{nobio}} + frac_{\text{snow,nobio}} \cdot alb_{\text{snow,nobio}})\right]$$

with: $$alb_{\text{veg}} = frac_{\text{bs}} \cdot alb_{\text{bs}} + \sum_{\text{pft}=2}^{13} frac_{\text{pft}} \cdot alb_{\text{leaf,pft}}$$

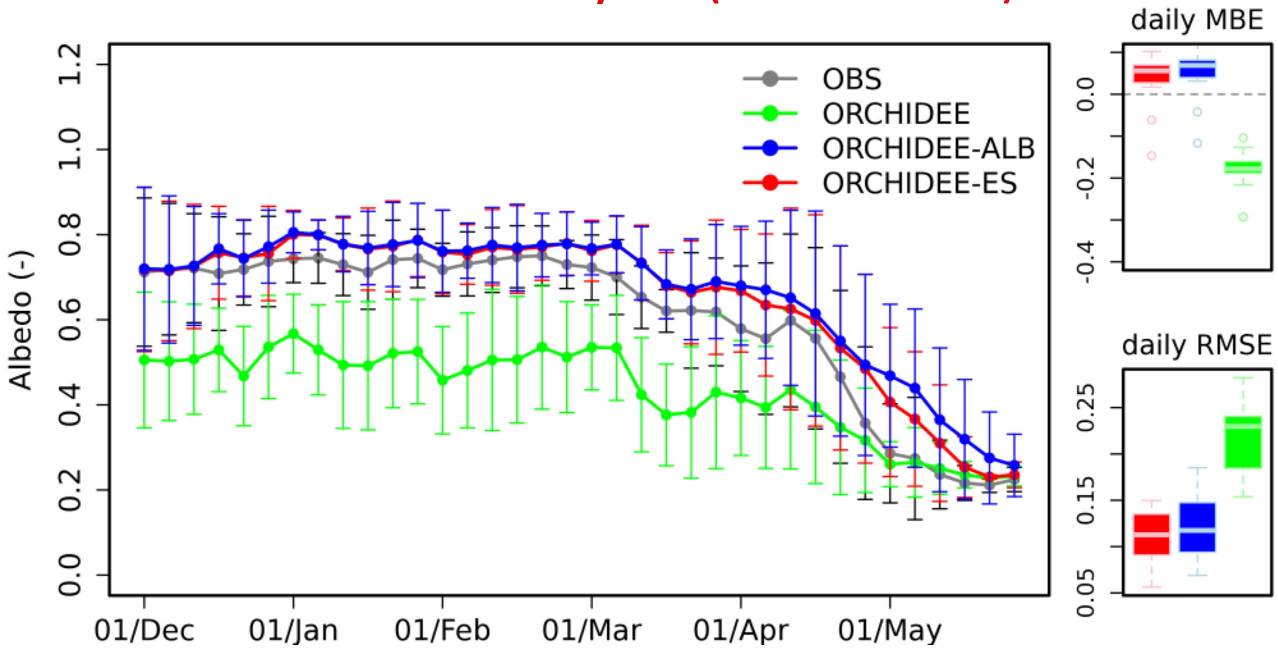
Main features of ORCHIDEE snow module

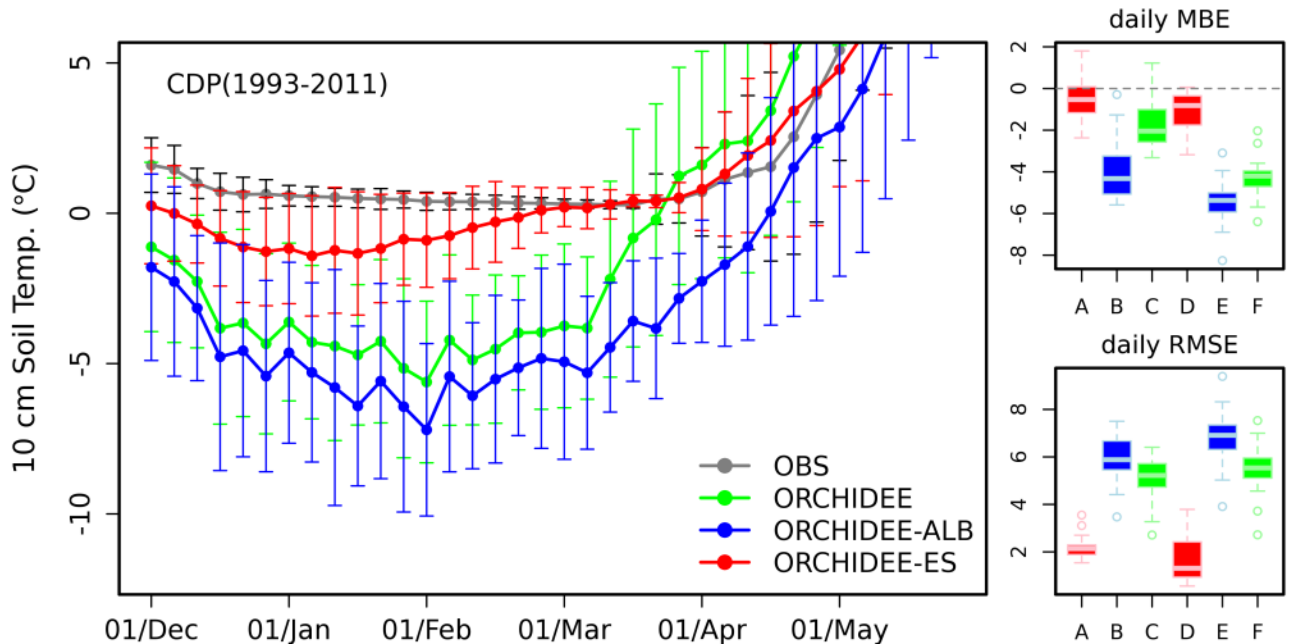
- Snow roughness (condveg.f90)

$$\frac{1}{\left[\ln(z_r/z_{0t})\right]^2} = \frac{f_{sg}}{\left[\ln(z_r/z_{0n})\right]^2} + \frac{1-f_{sg}}{\left[\ln(z_r/z_0)\right]^2}$$

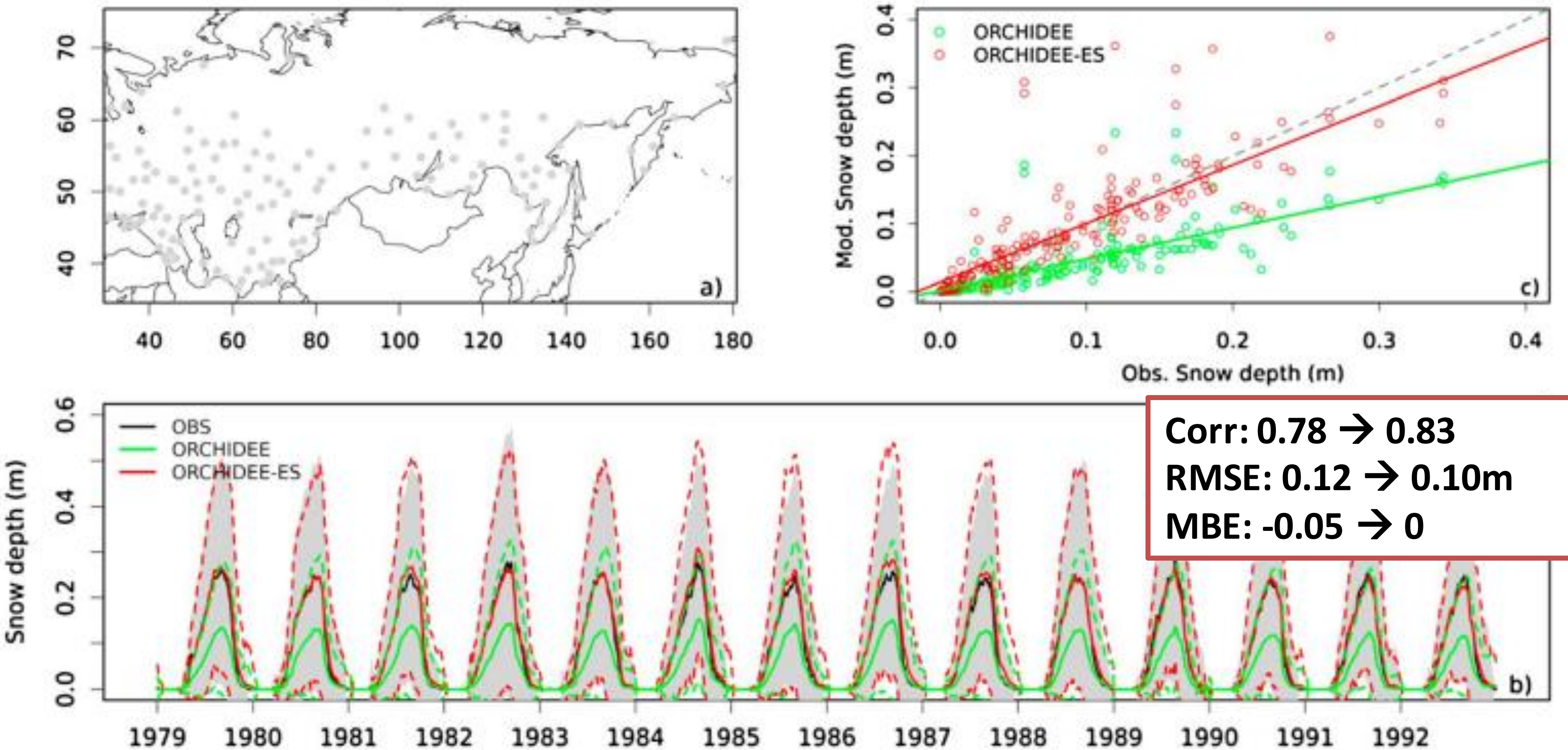
where f_{sg} is snow cover fraction, z_{0t} is surface roughness length after considering snow cover, z_0 is the vegetation or surface roughness length (m), z_{0n} is the snow surface roughness length baseline value (0.001 m), and z_r is the blending height (10 m in ORCHIDEE).

Evaluation results (Albedo and soil temperature), Col de Porte, mean seasonal cycle (1993-2011)





Evaluation results (Daily snow depth, density, SWE), Northern Eurasia, 165 stations HSDSD (1979-1992)



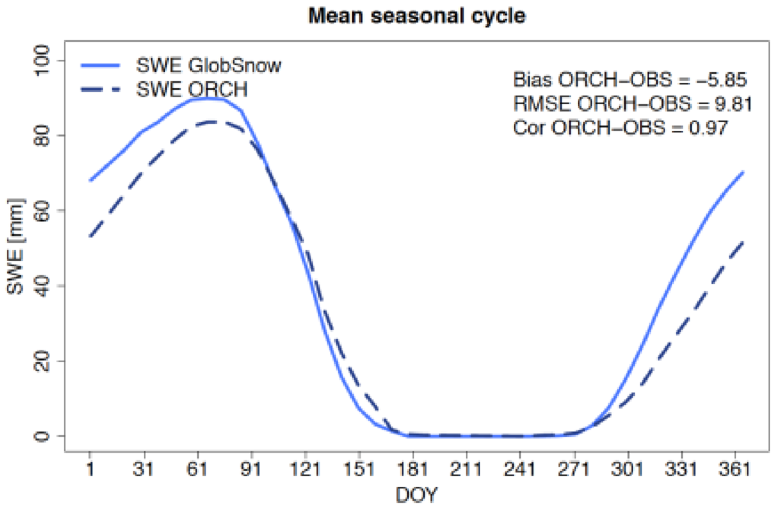
Corr: 0.78 → 0.83
RMSE: 0.12 → 0.10m
MBE: -0.05 → 0

Figure 10. (a) Spatial distribution of stations ($n = 165$) having at least 10 years with near complete (>360 days) year-round continuous snow cover; (b) mean daily snow depth comparison between observation and simulations across stations over the period 1979–1992. The gray region represents ± 1 standard deviation of mean daily observation. The dashed blue (or red) line represents ± 1 standard deviation of mean daily ORCHIDEE (or ORCHIDEE-ES) values; (c) the scatter plot of multiyear averaged (1979–1992) annual snow depth between observation and simulations across stations.

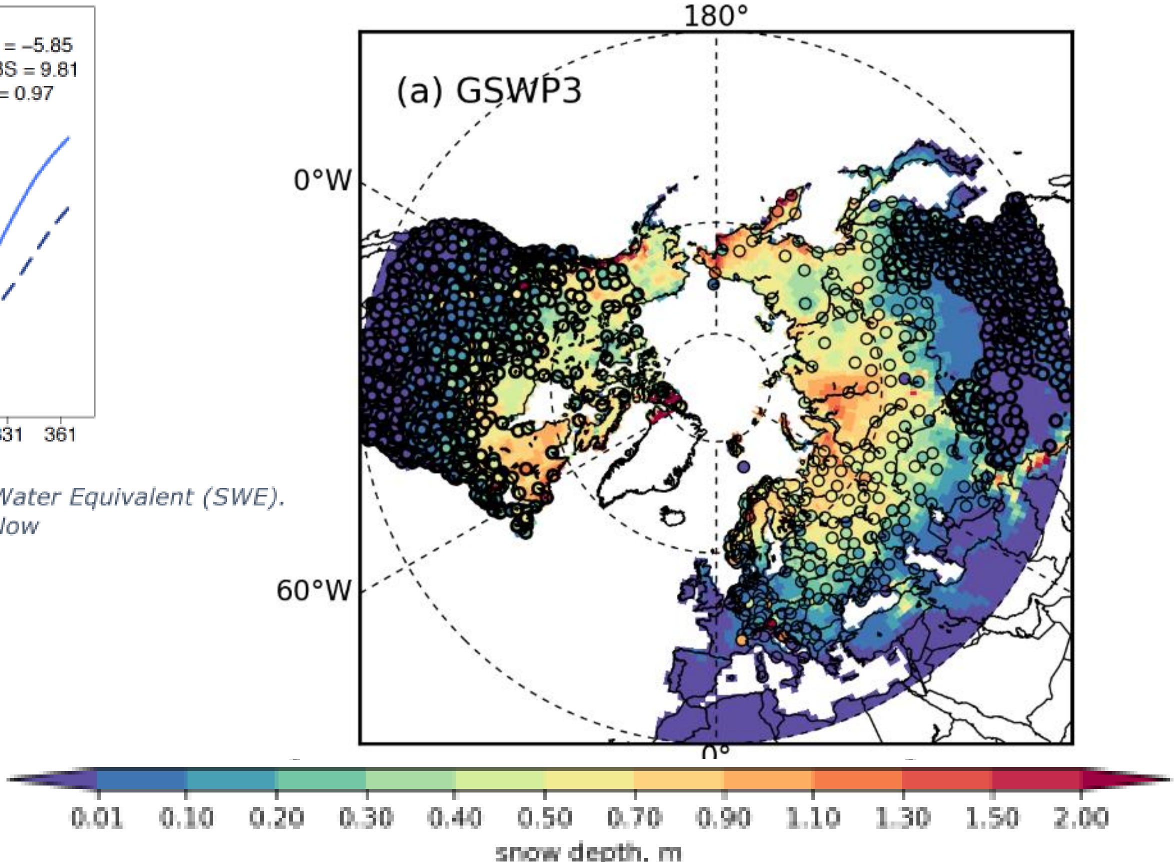
Wang et al., JGR, 2013

Model evaluation

- 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, …



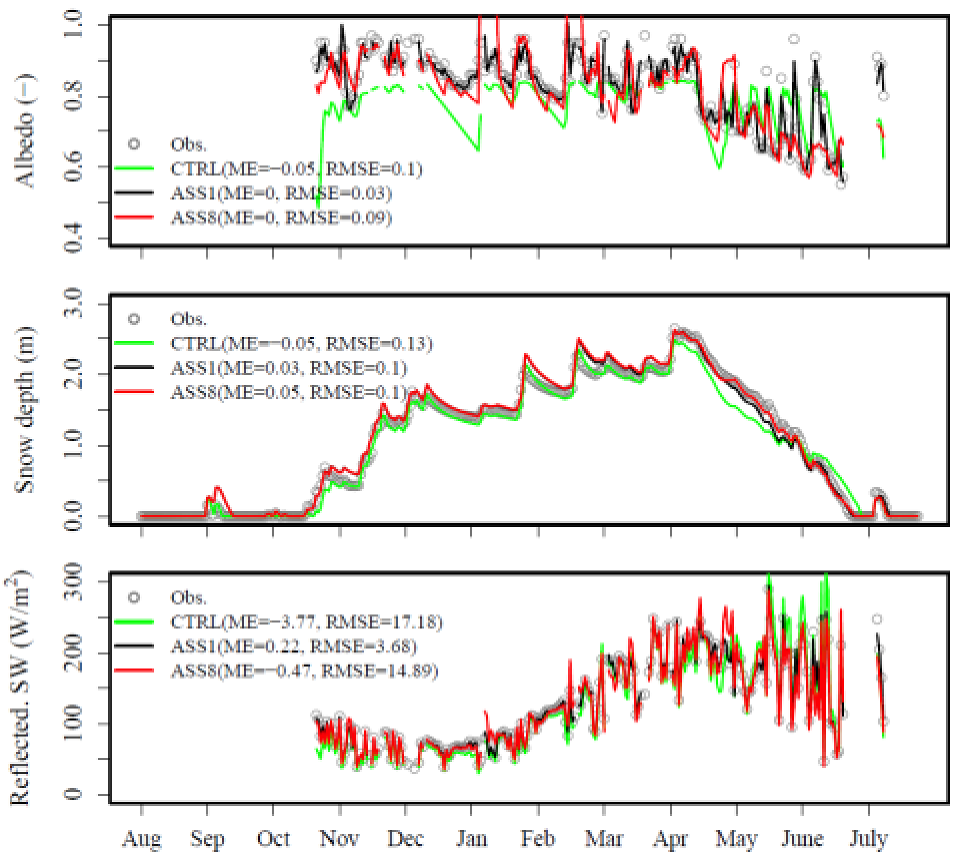
Cycle moyen sibérien pour la période 1979-2009 du Snow Water Equivalent (SWE). Comparaison d'ORCHIDEE avec le produit GLobSNow



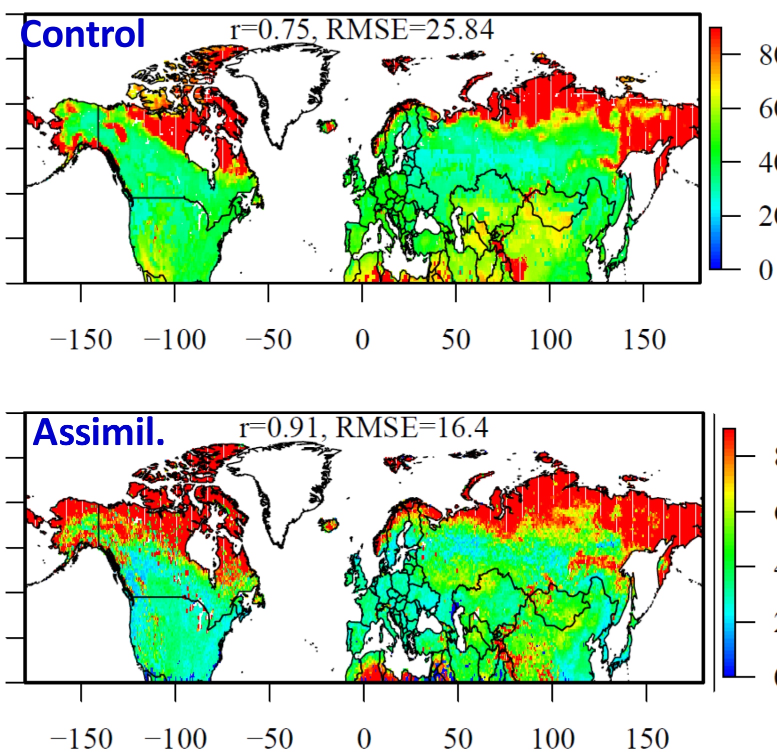
How to constrain snow albedo feedback in model ?

Option 1: Developing physical-based snow albedo scheme taking into account snow grain size, impurity content *etc*

Option 2: Data assimilation from ***in-situ*** or albedo product (GlobAlbedo)



In-situ snow albedo assimilation, Alpine site, WFJ)



Wang et al. (2015)

LMDZ coupled simulations (Wang et al., 2015)

Spinup
IPSL AR5
1901-1920

→

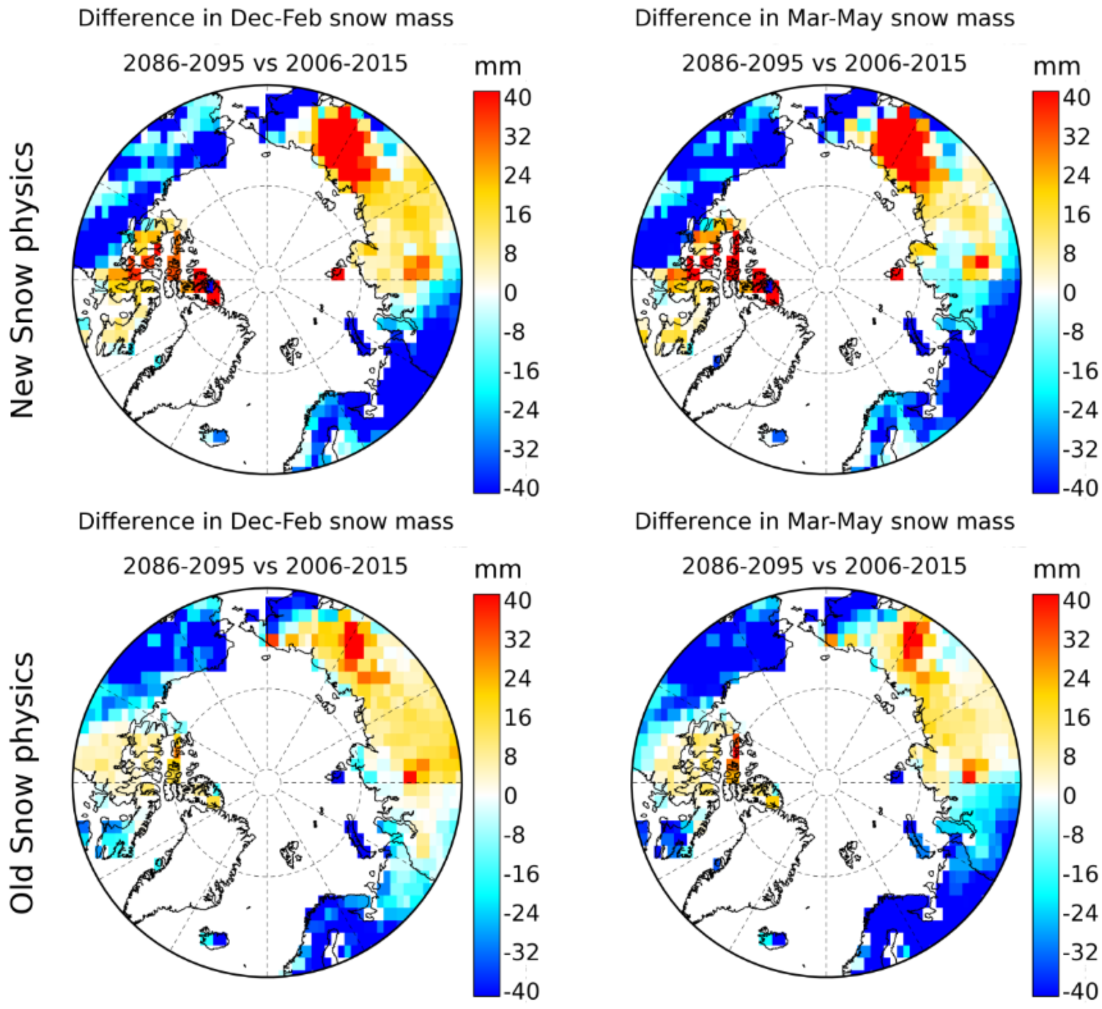
IPSL
1921-2005

→

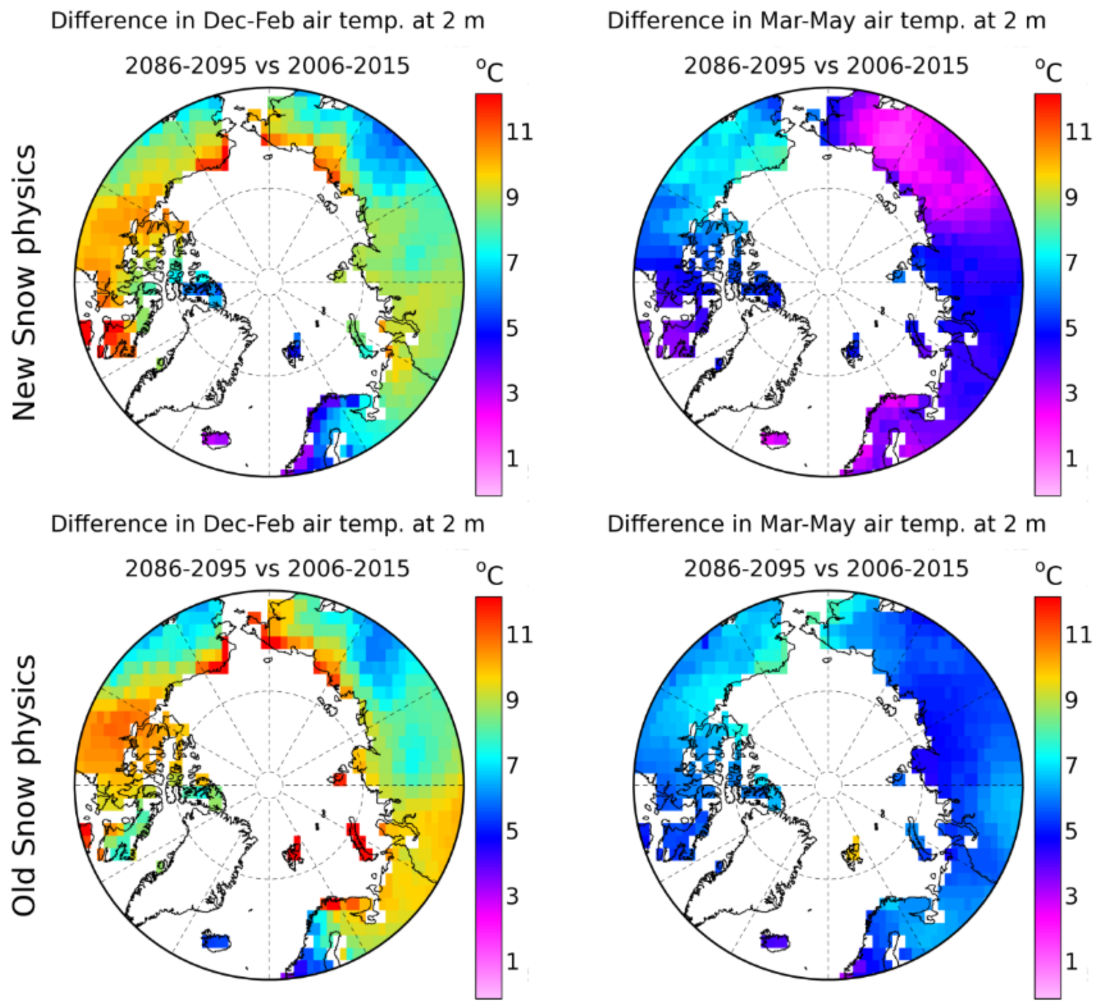
Coupled RCP 8.5
MICT V3 + LMDZ

IPSL AR5 RCP 8.5

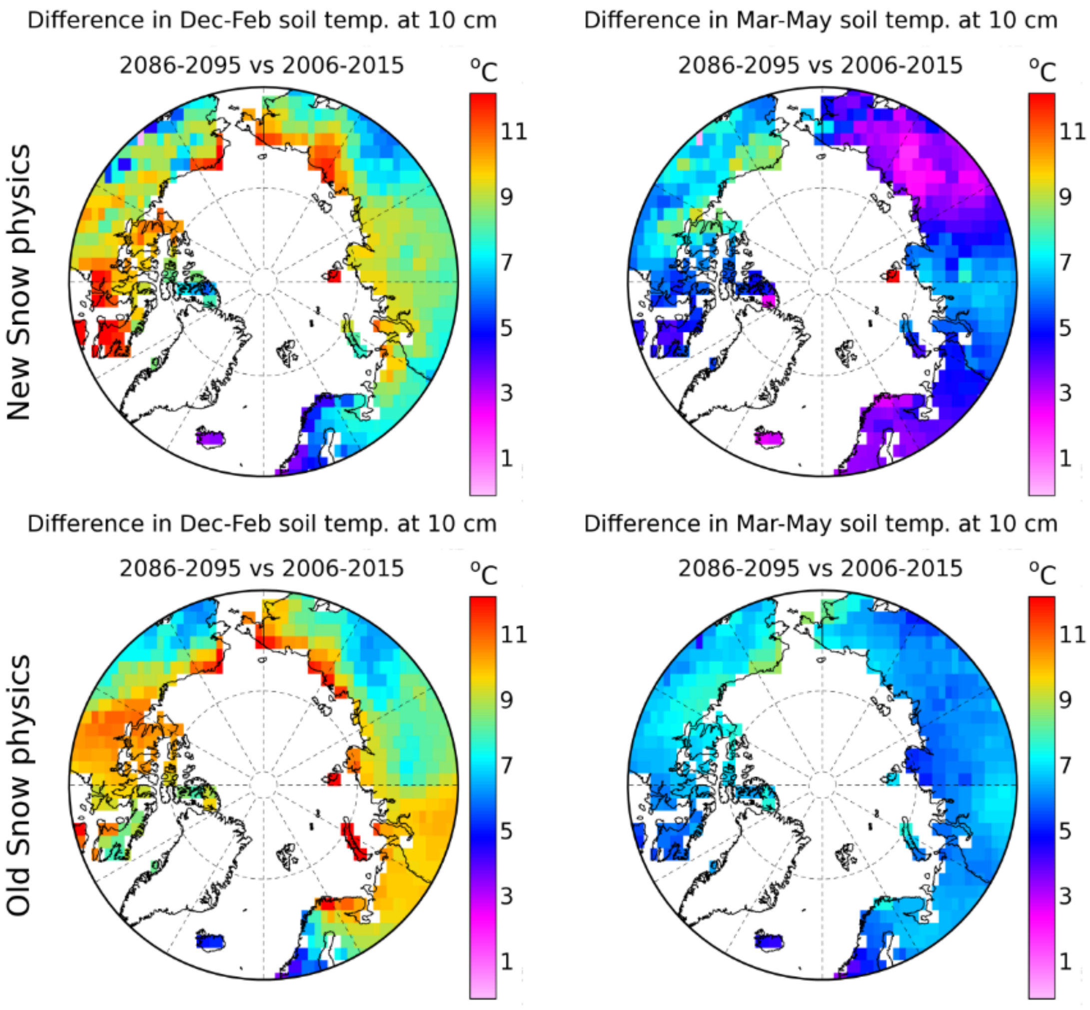
Changes in snow mass from LMDz-ORCHIDEE



Changes in air temperature at 2 meters from LMDz-ORCHIDEE



Changes in soil temperature at 10 cm from LMDz-ORCHIDEE



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Snow model implementation

- Organized in a separate block of modules « explicitsnow.f90 », call in hydrol.f90,
- Implicit resolution (snow and soil temperature profiles calculated in one single step in thermosoil.f90) but explicit representation of the energy budget at the snow-soil interface (soil-snow heat flux calculated using the soil temperature at previous time step)
- Snow fraction used for all radiative and thermal processes (not only for surface albedo as done previously)
- Snow temperature profile is calculated first neglecting phase changes and updated after calculation of thawing/refreezing processes
- Water and Energy conservative

Procedure

- Snowfall mass and heat content are added to the uppermost snow layer. Snow density, depth, temperature and liquid water content are updated in the surface layer. Snowfall is assumed to have the same temperature as the uppermost snow layer upon reaching the surface, therefore the advective heat flux from snowfall can be neglected (in the surface energy budget).
- The snow thicknesses are reset and the vertical profiles of mass and heat are redistributed while conserving the total snow pack mass and heat
- Snow layer heat content, density and depth are used to diagnose Ts_i and Wl_i
- Compaction is calculated and ρ_i and Ds_i are updated. Snow mass and heat content are unaltered. Surface snow albedo and snow thermal conductivity are calculated
- The linearized system of equations is solved simultaneously with the soil temperature profile to estimate the preliminary profile of Ts_i and the surface flux at the soil interface (Gs_0)
- Phase changes, water flows and changes in liquid water storage are evaluated. Profiles of Ts_i, Wl_i, ρ_i and Ds_i are updated.
- The heat content Hs_i is updated from the profiles of Ts_i, Wl_i, ρ_i and Ds_i, and saved for the next time step along with the updated profiles of ρ_i and Ds_i. Snow surface fluxes, runoff and the heat flux at the snow/soil/vegetation interface are output.

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

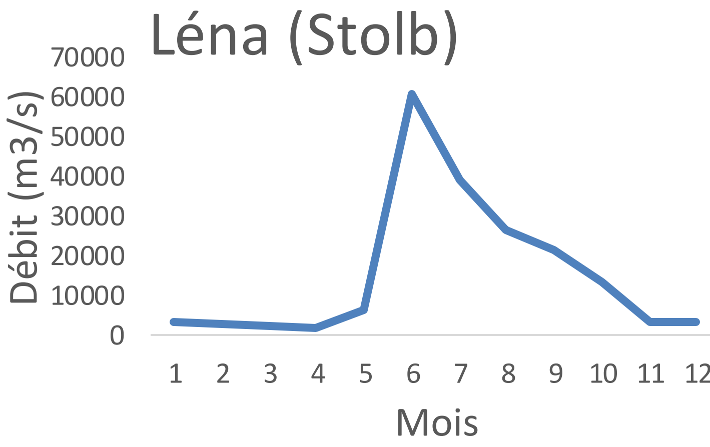
Presence of ice alters soil hydro-thermal properties

Thermal processes:

– Phase changes produce/consume energy (latent heat of fusion), soil thawing/freezing slows down soil warming/cooling 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…



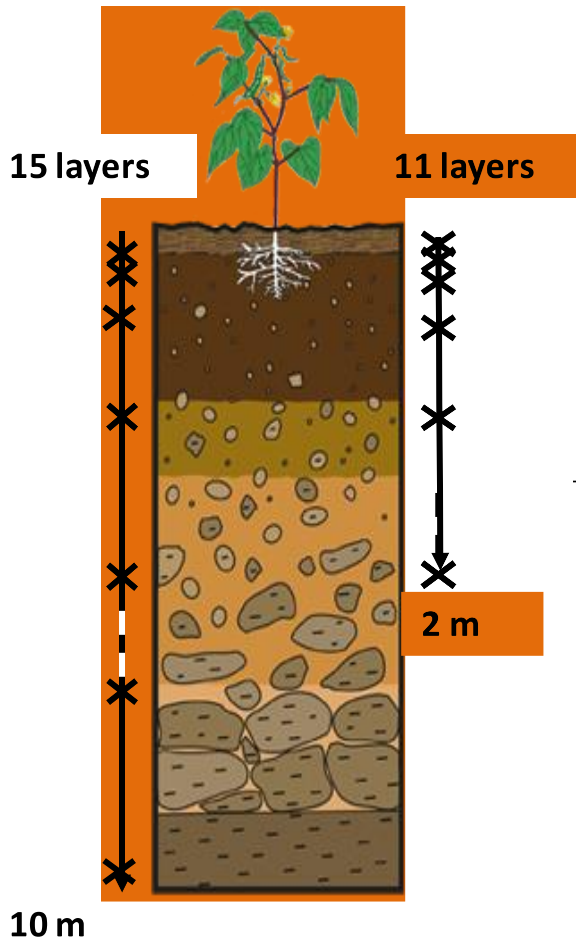
ORCHIDEE hydro and thermal processes without freezing

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 (OK_Freeze) (Gouttevin et al., 2012)

thermics

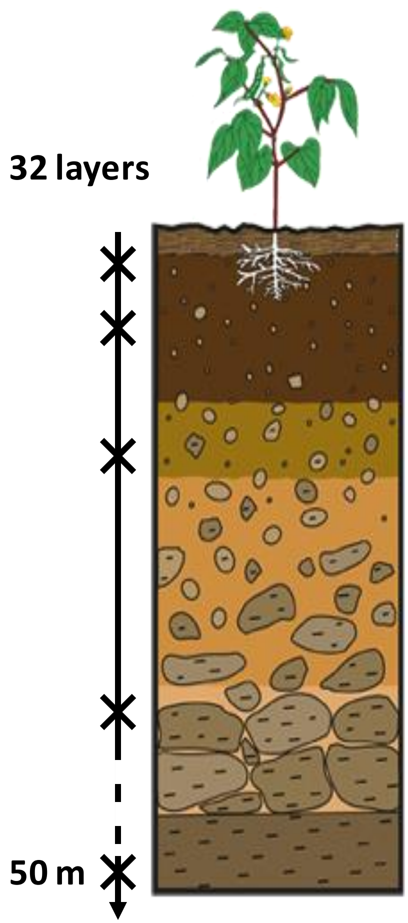
$$\sum F\downarrow_{rad\ net} + \sum F\downarrow_{turb\ net} = \kappa \frac{\partial T}{\partial z}$$

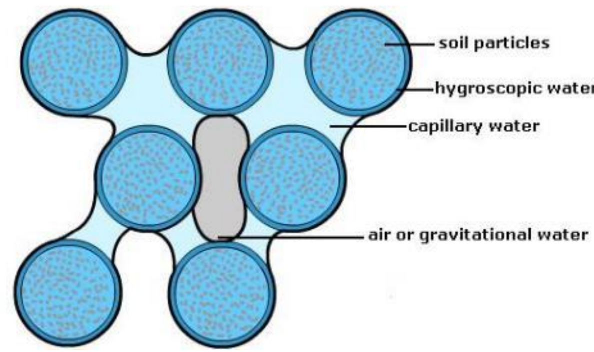
$$C\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \rho_i .L \frac{\partial \theta_i}{\partial t}$$

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

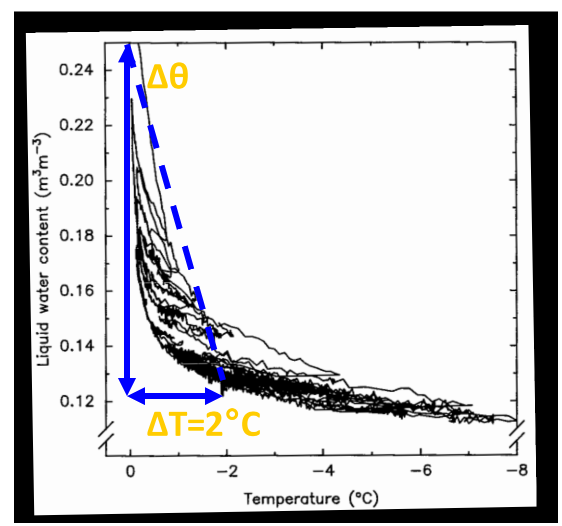
« freezing window »

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





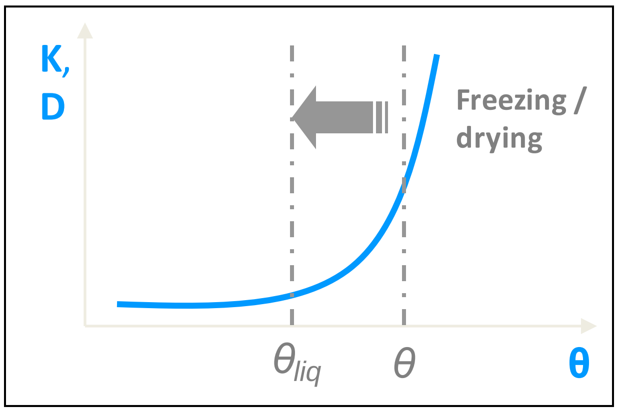
Soil water is stabilized by capillary interactions and freezes beyond the freezing point.



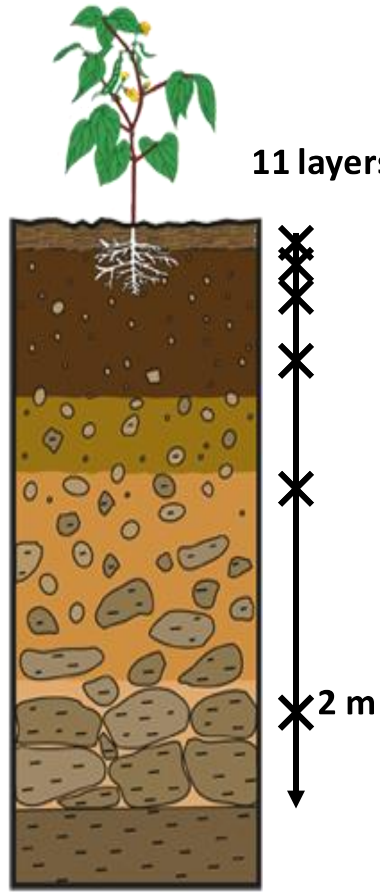
Spaans and Backer, 1996

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} ?



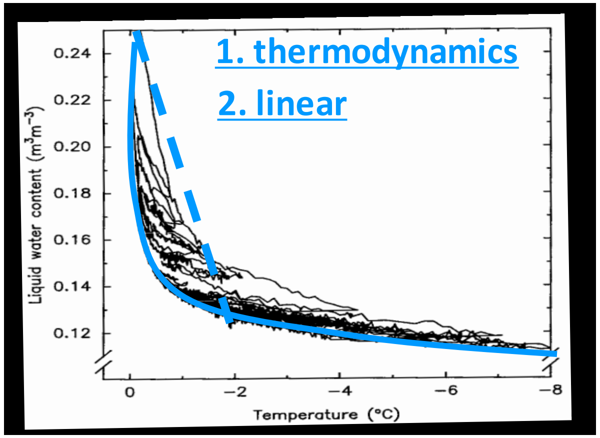
hydrology

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

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

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

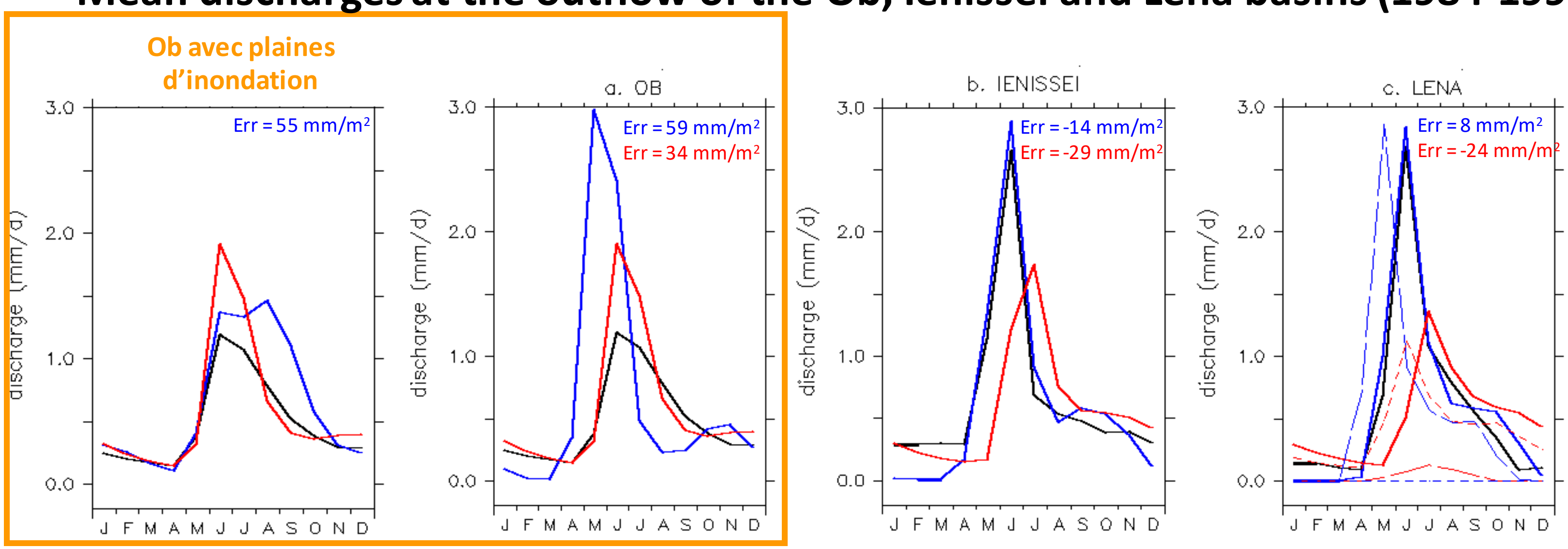
Diagnostic of soil liquid water



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.

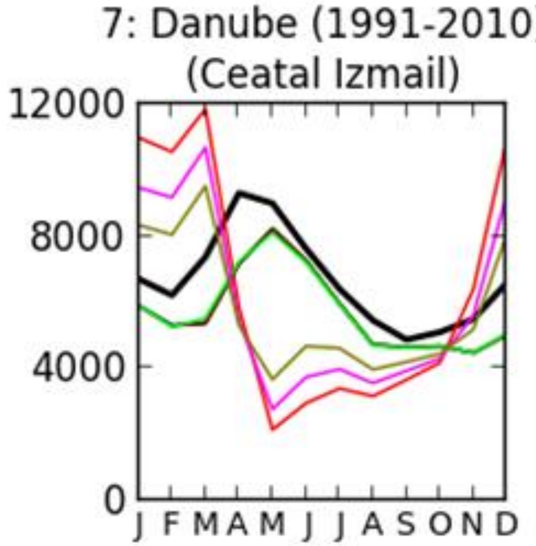
Colors: NOFREEZE FREEZE DATA

Symbols: discharge drainage runoff

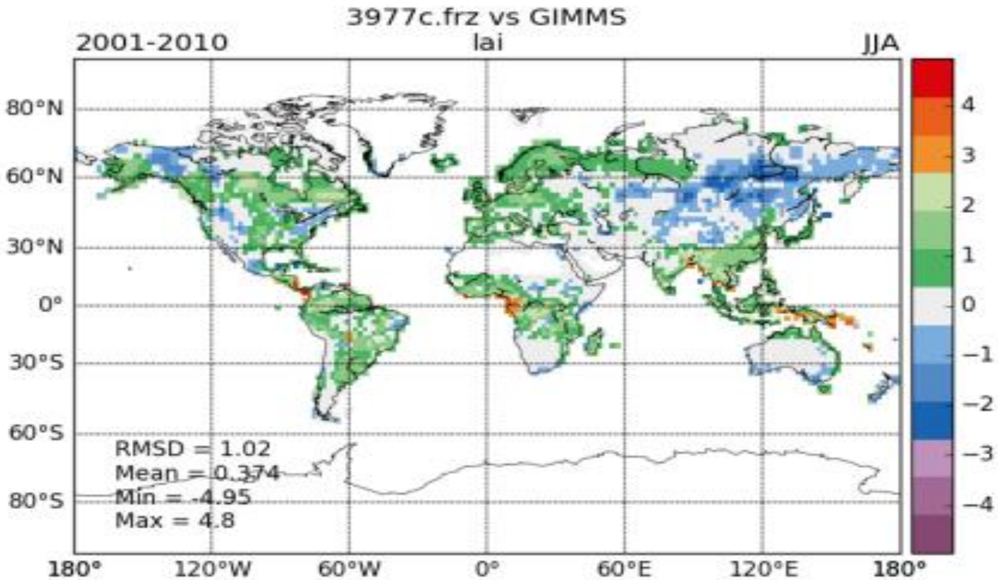
Gouttevin et al., 2012a.

Improvements and drawbacks

Freeze model improves streamflows in arctic regions but degradation in catchments less influenced by soil freezing (ex. Danube or Missisipi). Higher and earlier than observations, springtime runoff.



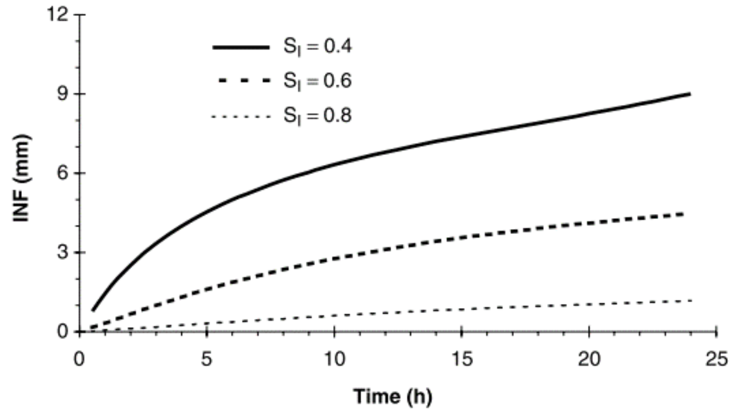
Identification of hydric stressed regions (too low soil moisture, evapotranspiration, GPP, … underestimation of biomass (LAI), warm temperature biases in coupled LMDZ simulations).



Drastic reduction of infiltration for soils partly frozen (top layers). Scale issue: frozen soils are permeable because of soil structural aggregates, cracks, dead roots, land cover variability…

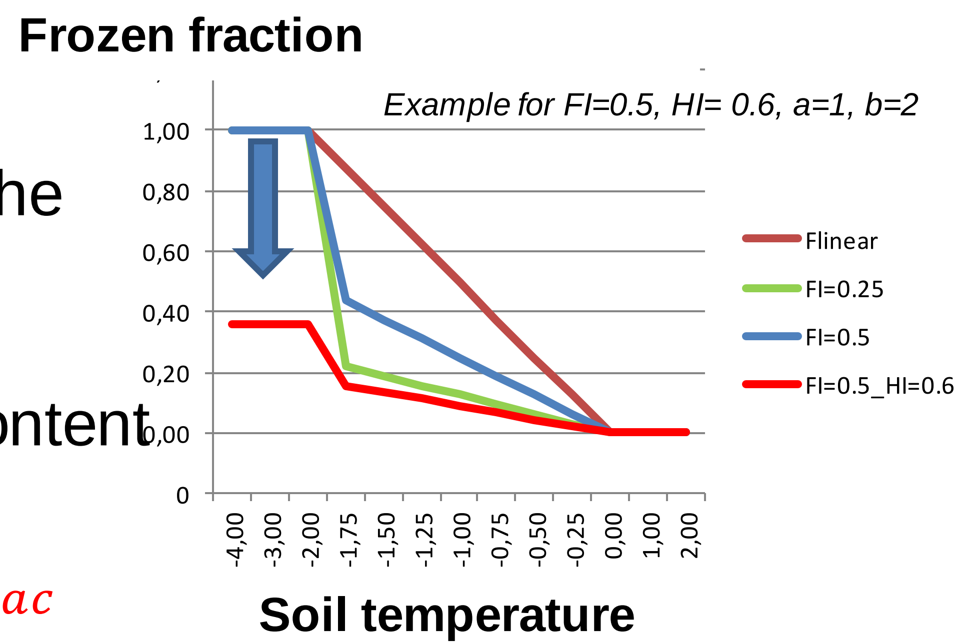
Accounting for soil hydric state and frozen intensity

- Soil water content (and soil texture) has more impact on infiltration than soil temperature.



in cumulative infiltration, INF, with time into a frozen, silty clay soil with $S_I = 0{\cdot}4, 0{\cdot}6, 0{\cdot}8$ and $T_I = -6\,°C$, S_0
Infiltration at hour 12 is 6·8 mm, 3·1 mm and 0·7 mm for $S_I = 0{\cdot}4, 0{\cdot}6, 0{\cdot}8$ respectively

- Definition of a soil hydric index (HI), ranging between ~0.3 and 1 $(\theta = \theta_{sat})$



The wetter the soil, the lower the permeability

≅ model infiltration with soil ice content

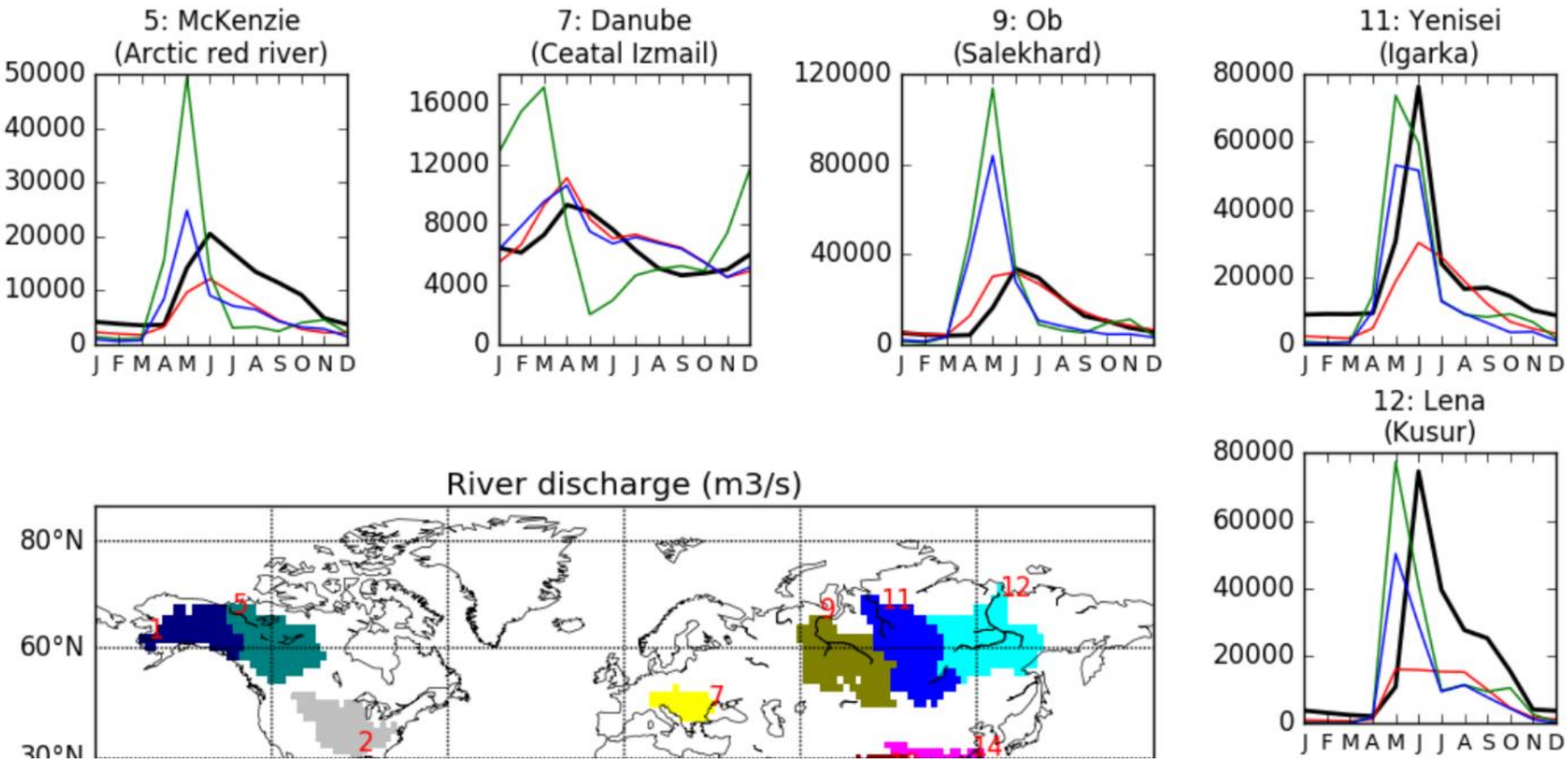
$$Froz_{frac} = HI^b * FIa * Froz_{frac}$$

Results

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

➔ River discharge (m³/ s)

OBS (GRDC)
ORC STD
ORC Freeze std
ORC Freeze optim



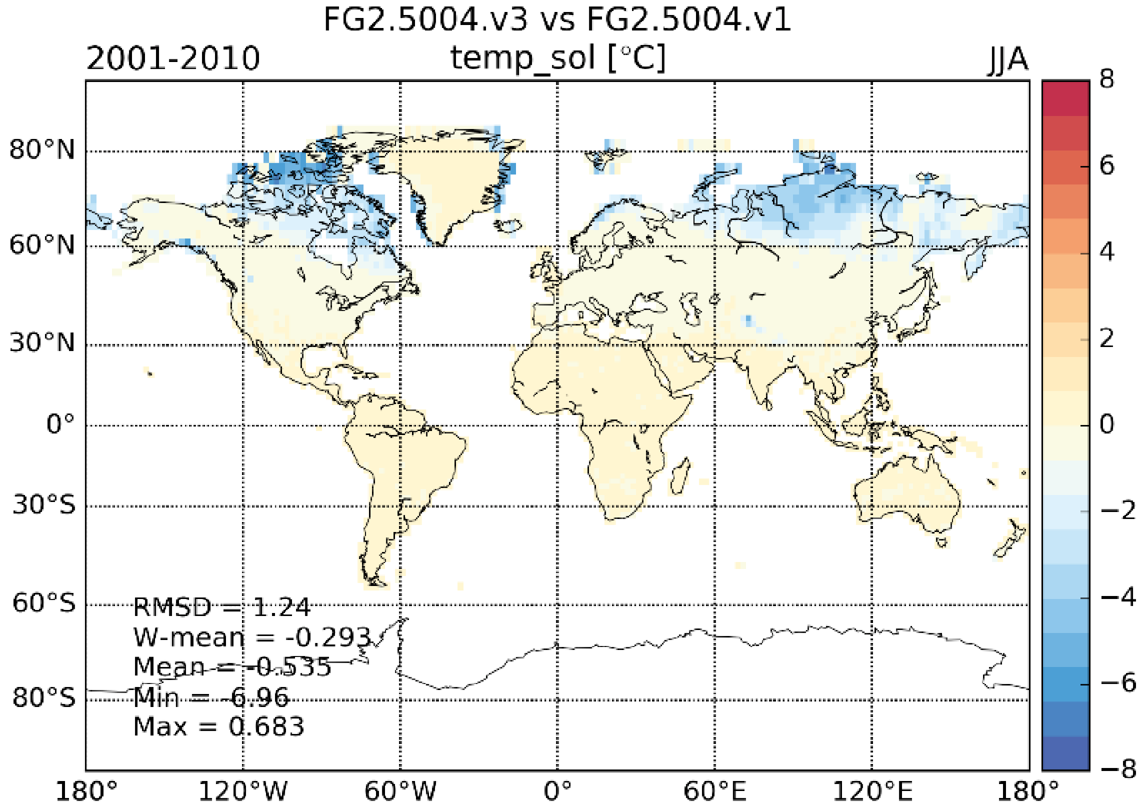
→ But severe issues in coupled mode…

Soil freezing: forced simulations

Freezing ➔ Increase winter soil/air temp. (≈ 1°C)

➔ decrease summer soil/air temp. (≈1°-2°C)

CRU-NCEP

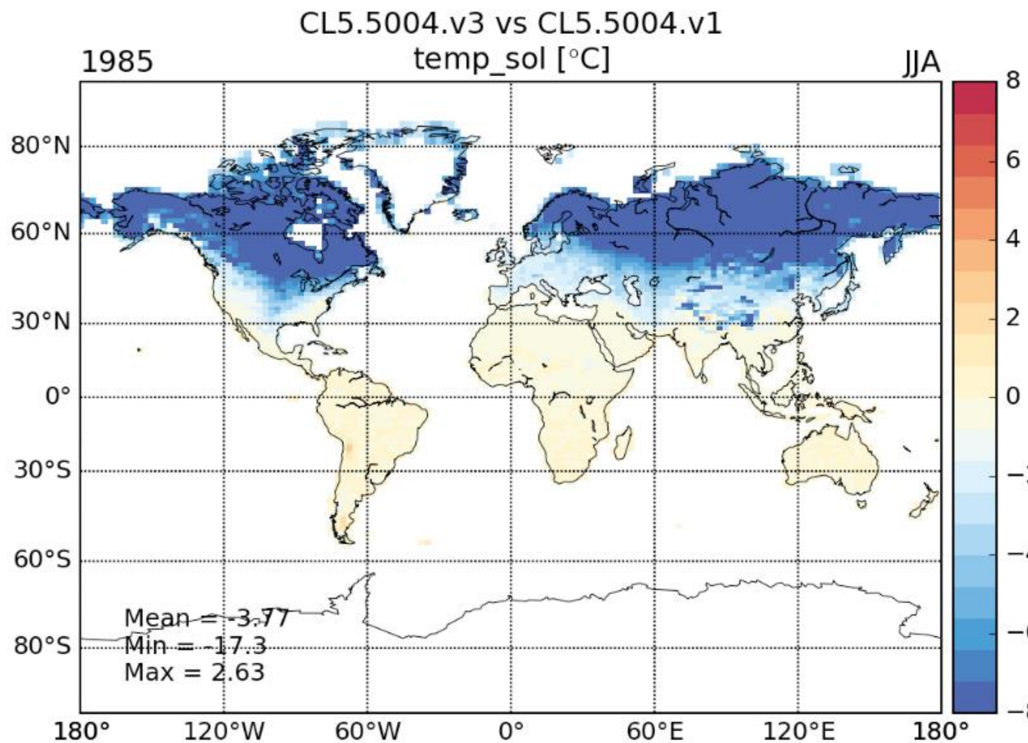


Delta Surface Temperature (summer, °C):

'freezing' minus 'no freezing'

Soil freezing : coupled simulations

Freezing ➔ Increase winter soil/air temp. (≈ 1°C)
➔ decrease summer soil/air temp. (6°- 8°C)

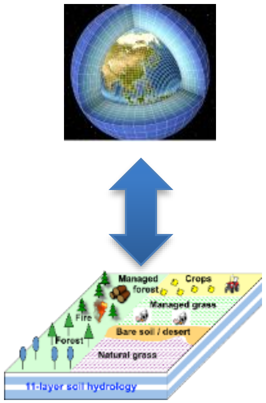


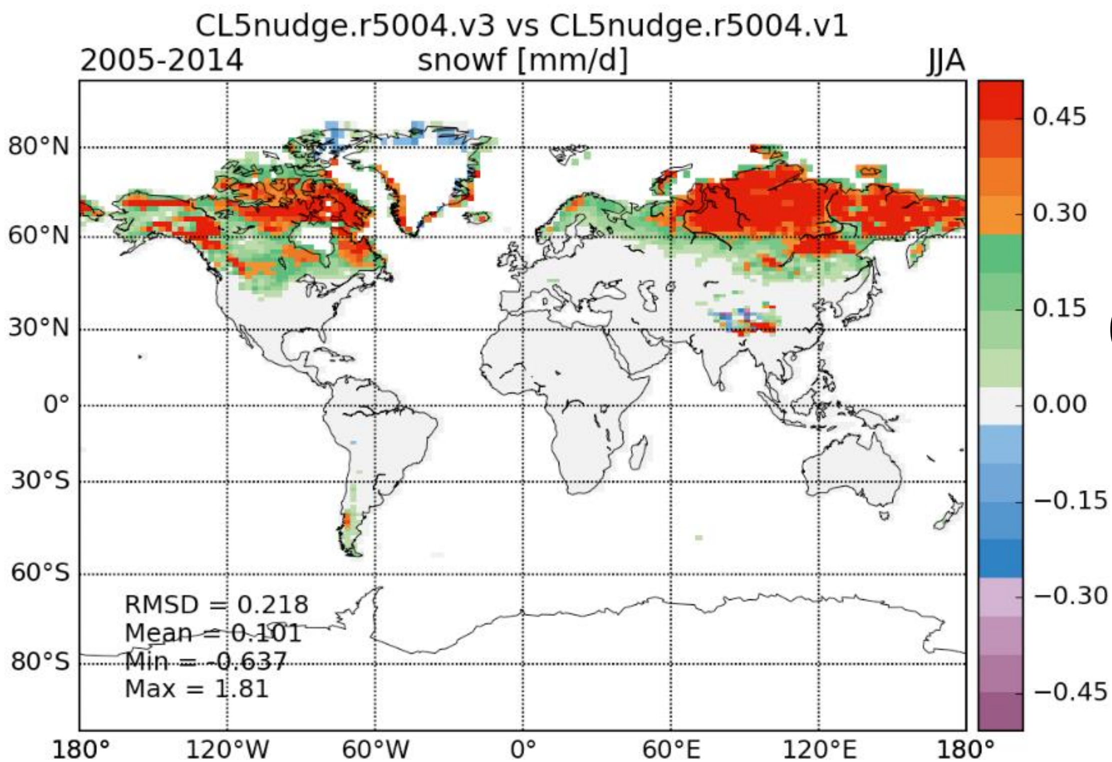
Delta Surface Temperature (summer, °C):

'freezing' minus 'no freezing'

Soil freezing : coupled simulations

Freezing ➔ Increase winter soil/air temp. (≈ 1°C)
➔ decrease summer soil/air temp. (6°-8°C)
➔ increase snowfall (high sensitivity to surface/air temperature)





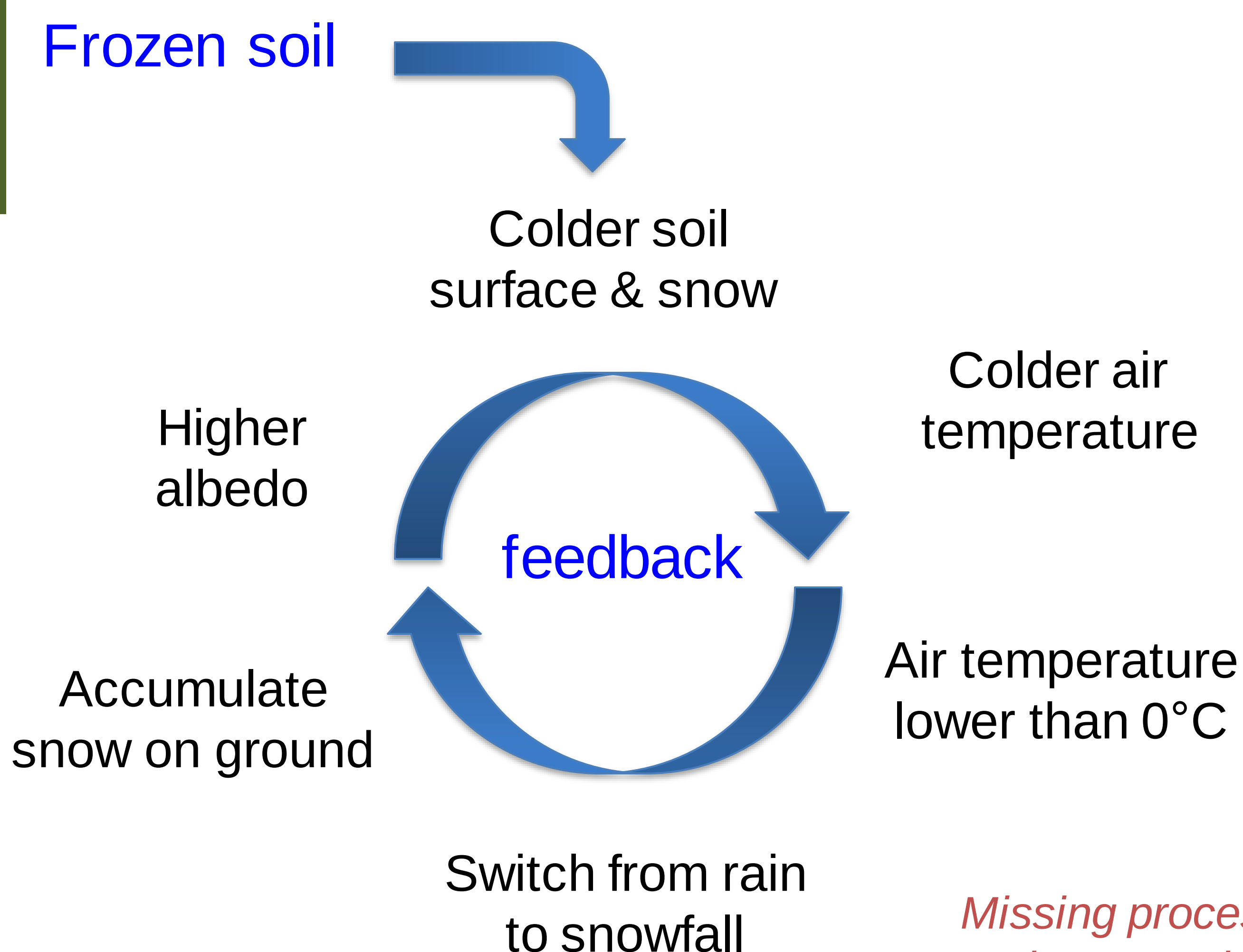
Delta snowfall (summer, mm/d)

'freezing' minus 'no freezing'

Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time

Spring & Summer

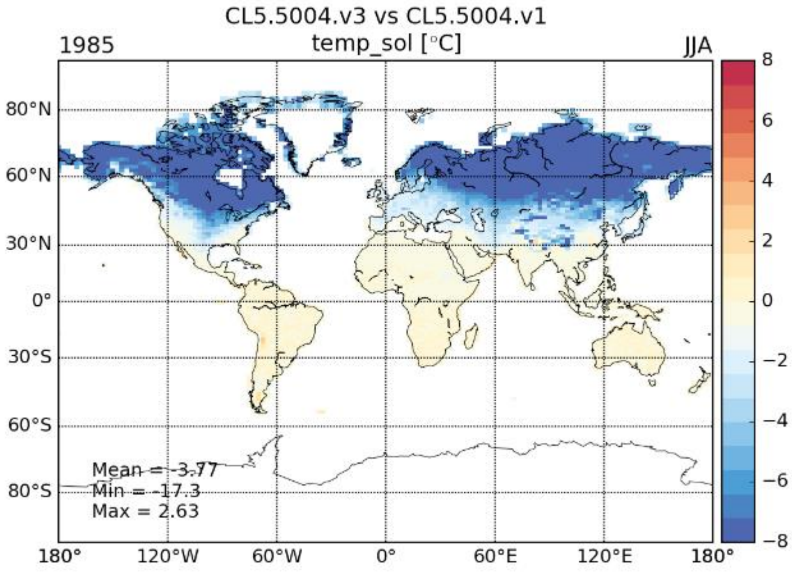


Missing processes: carbon and mosses insulation !

Soil freezing : coupled simulations

Freezing ➔ Increase winter soil/air temp. (≈ 1°C)
➔ decrease summer soil/air temp.
➔ increase snowfall
➔ Highly sensitive to surface heat conductivity

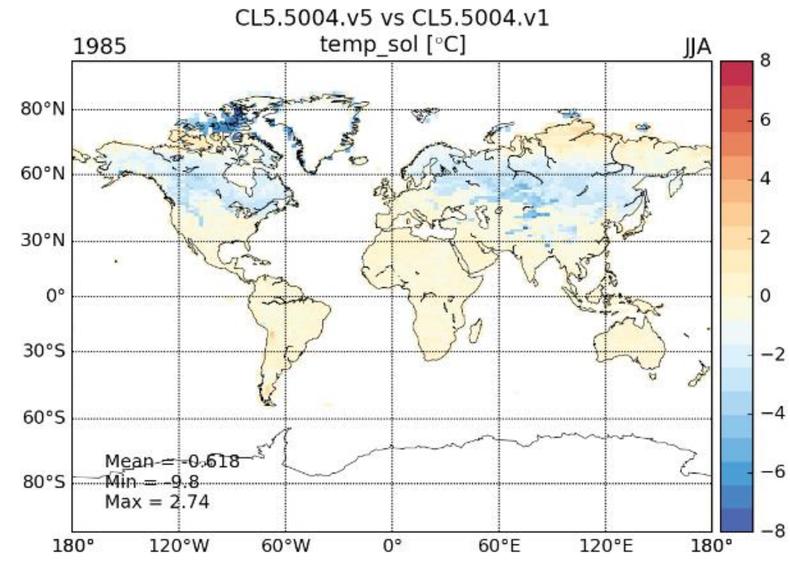
Standard soil conductivity



Delta Surface Temperature (summer, °C):

'freezing' minus 'no freezing'

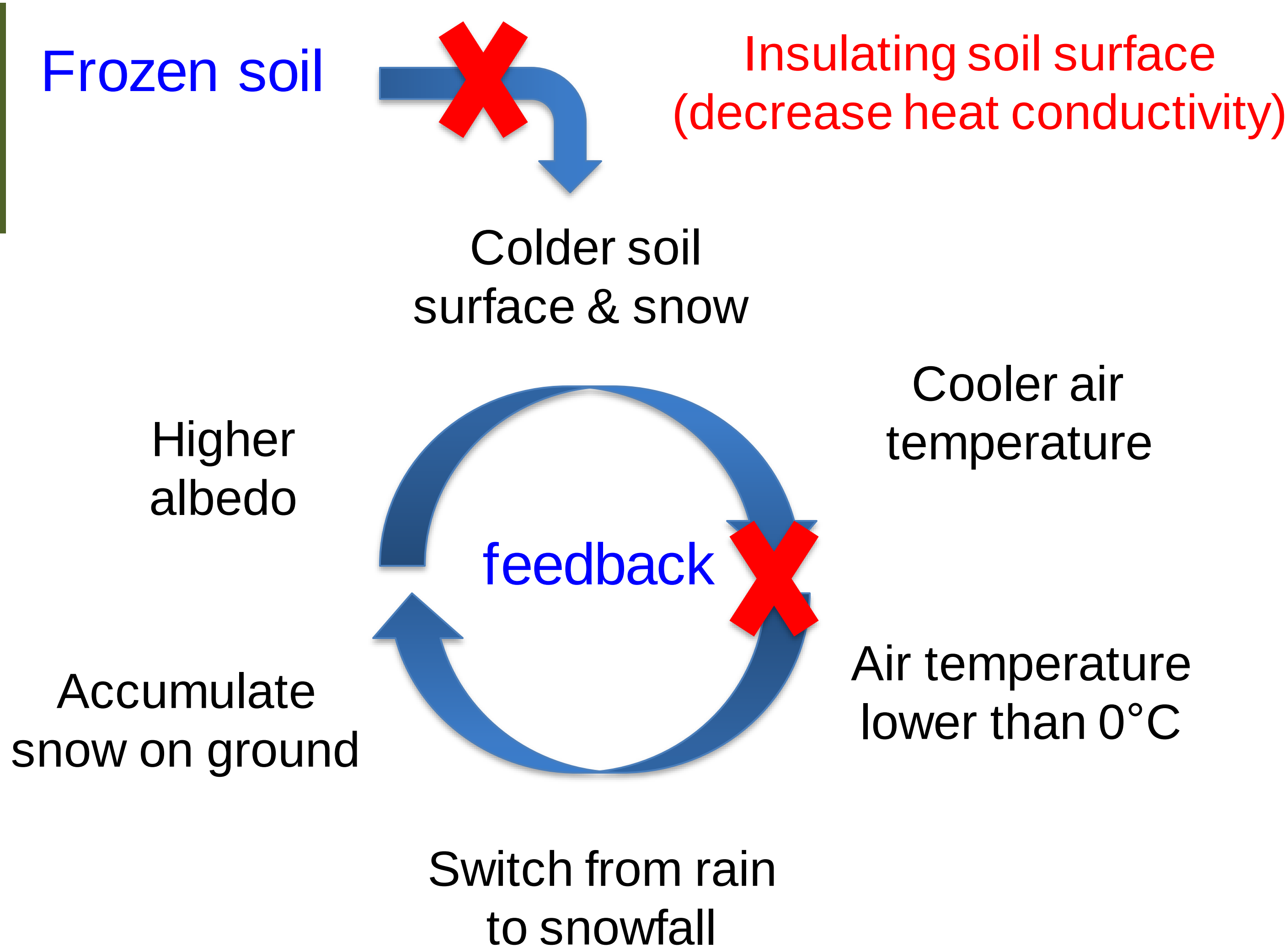
decrease conductivity
for upper 10 cm (to that of mosses)



Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time

Spring & Summer



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Thanks for your attention !