Heat transfers, water infiltration and runoff in frozen soils: Representation in ORCHIDEE Land Surface Model

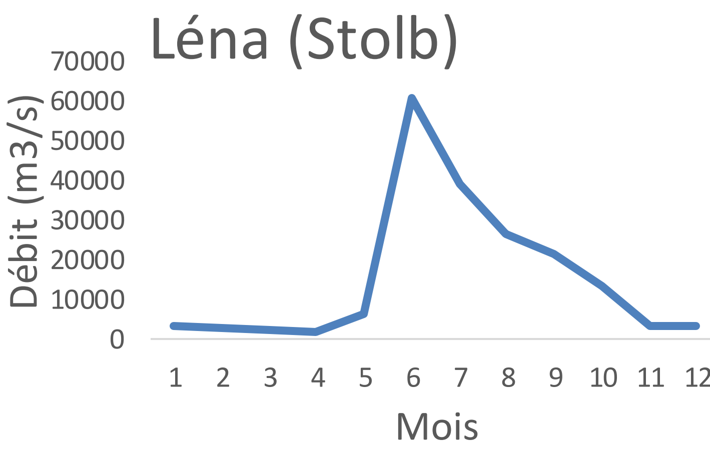
Presence of ice alters soil hydro-thermal properties

Thermal processes:

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

Hydrological processes:

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



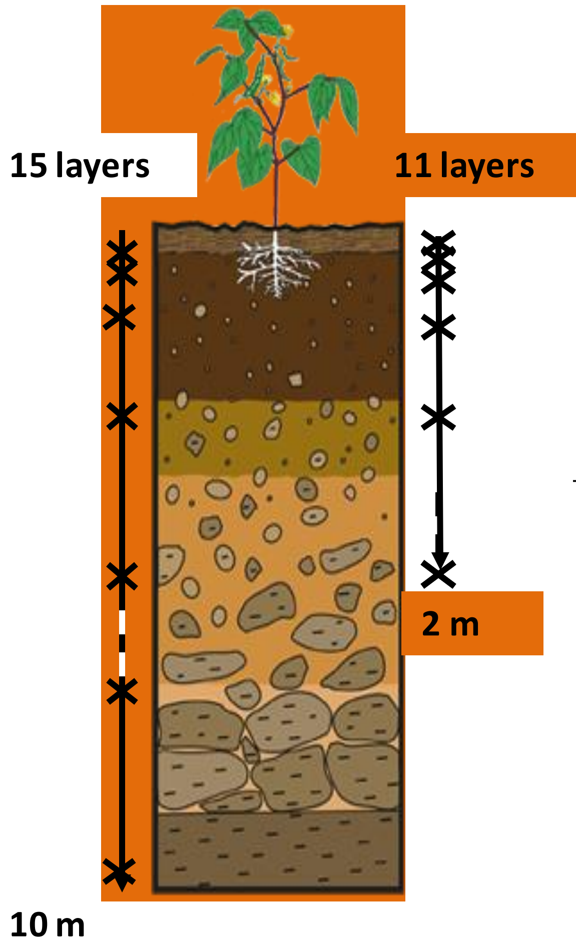
ORCHIDEE hydro and thermal processes without freezing (OK_Freeze= NO)

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= YES), Gouttevin et al., 2012

thermics

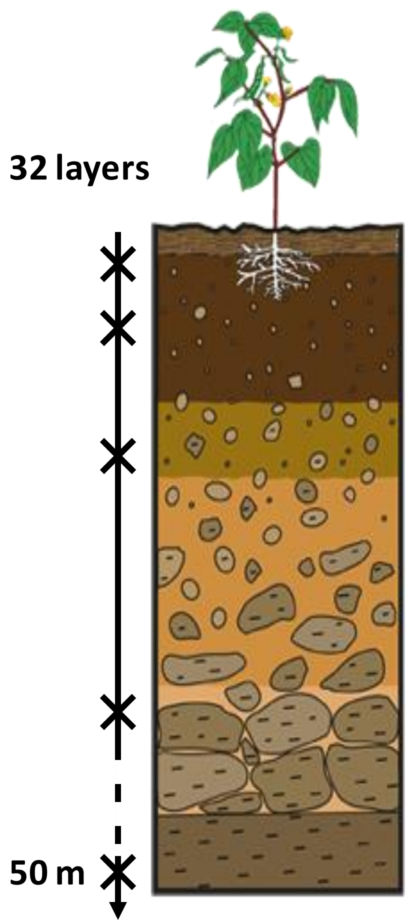
$$\sum F\downarrow_{rad\ \ net} + \sum F\downarrow_{turb\ \ net} = \kappa \frac{\partial T}{\partial z}$$

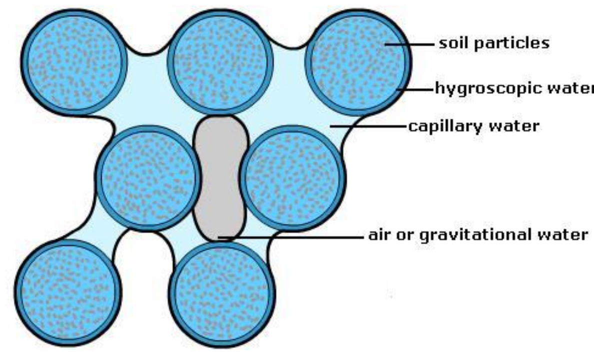
$$C\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \rho_i .L \frac{\partial \theta_i}{\partial t}$$

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

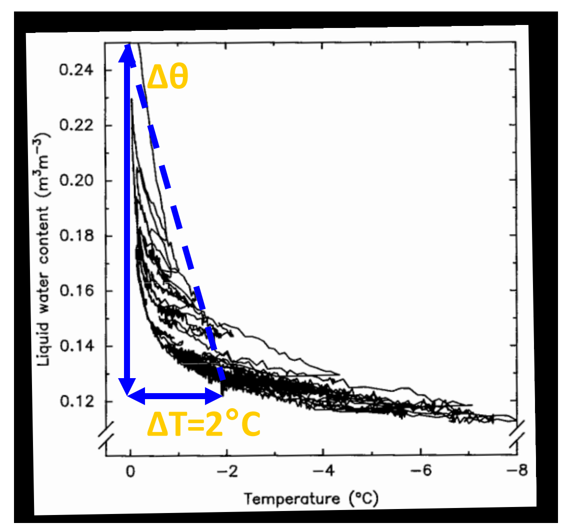
« freezing window »

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





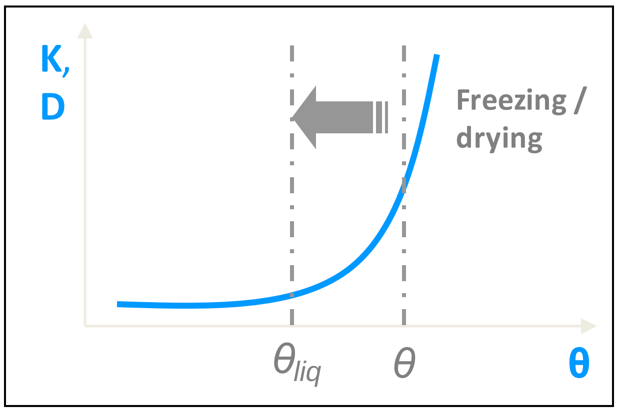
Soil water is stabilized by capillary interactions and freezes beyond the freezing point.



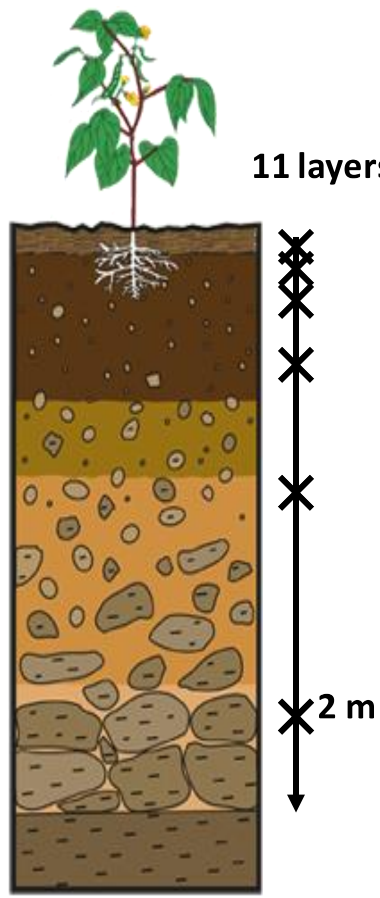
Spaans and Backer, 1996

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} ?**



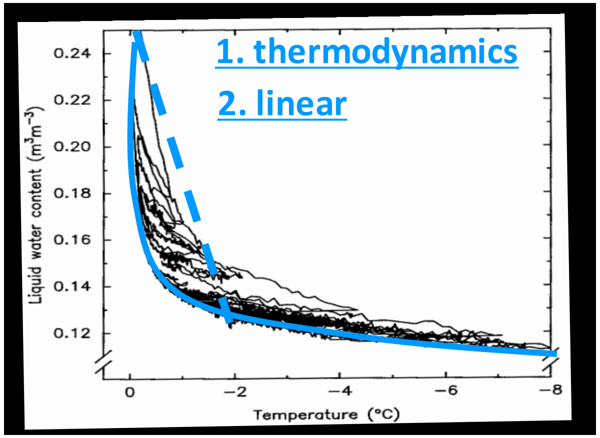
hydrology

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

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

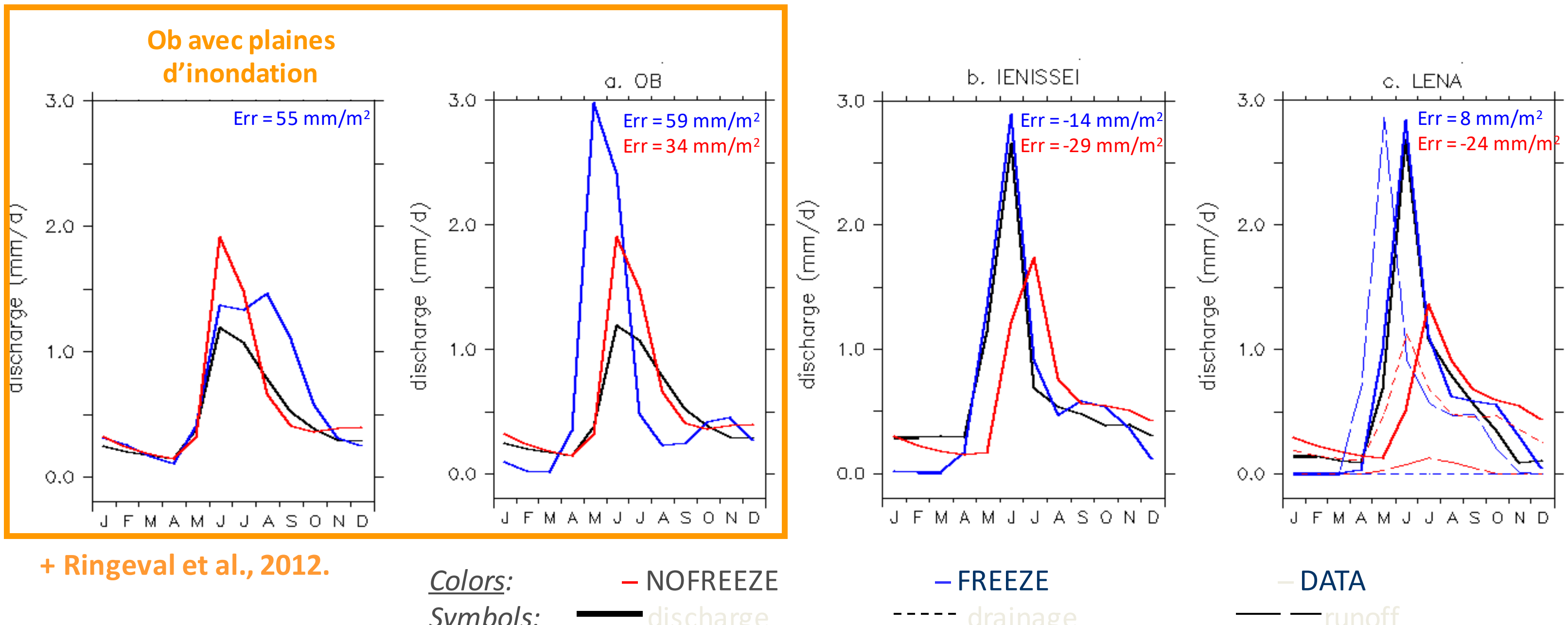
$$\frac{\partial \theta(z,t)}{\partial z} = 0 \Leftrightarrow q = K(\theta)$$

Diagnostic of soil liquid water



Spaans and Backer, 1996

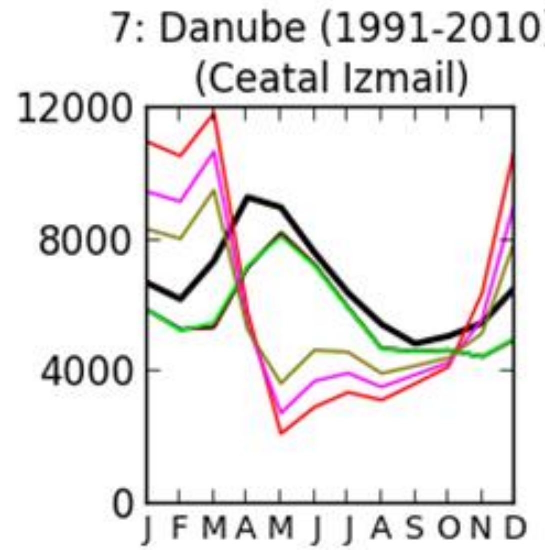
- Linear parameterization with soil temperature (default version)
- Thermodynamics (balance between energy state of absorbed and capillary water and energy drop induced by water phase change), Keyword=OK_thermodynamical_freezing



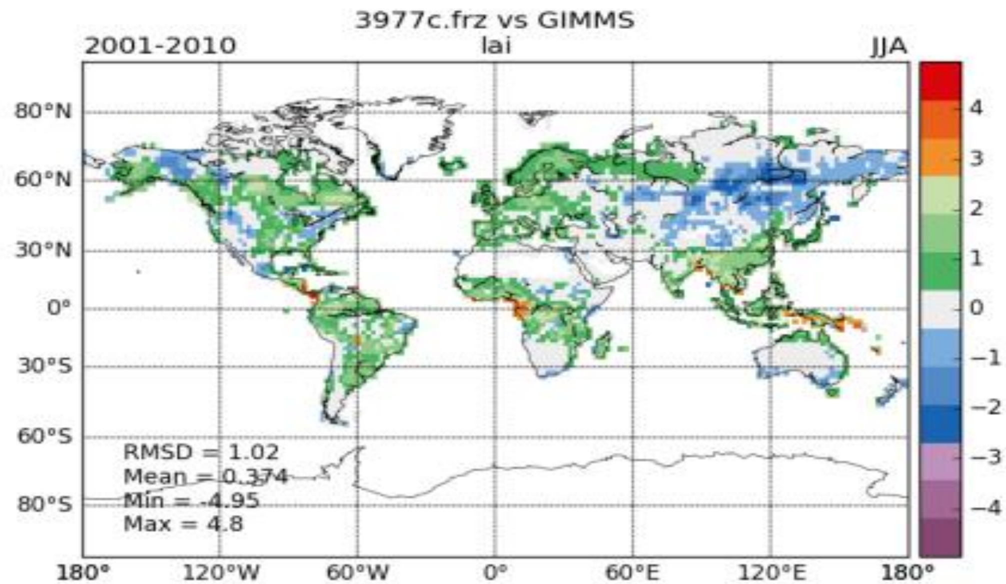
Gouttevin et al., 2012a.

Improvements and drawbacks

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



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

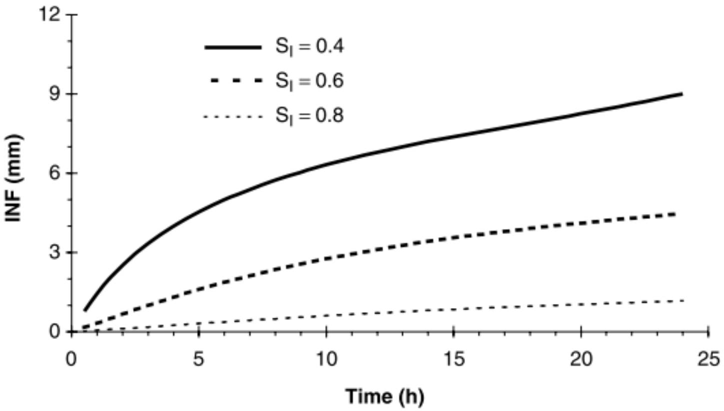


Drastic reduction of infiltration for soils partly frozen (top layers).
Scale issue: frozen soils are permeable because of soil structural aggregates, cracks, dead roots, land cover variability…

Accounting for soil hydric state and frozen intensity

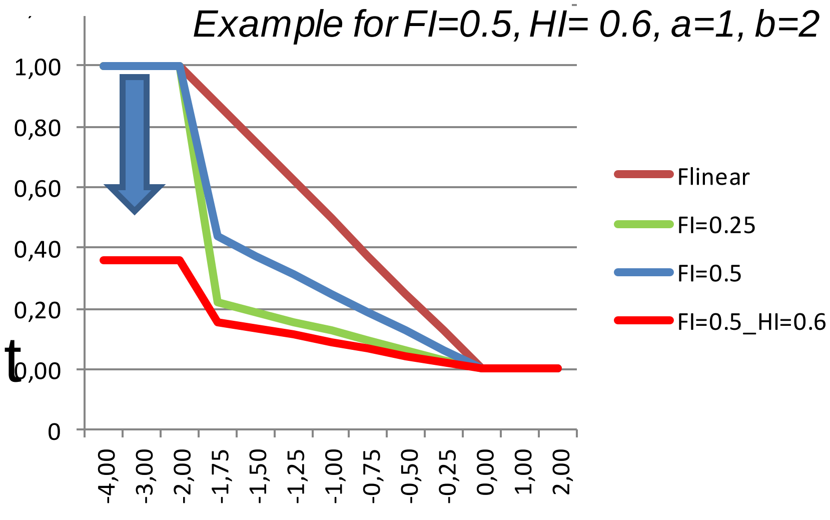
- Soil water content (and soil texture) has more impact on infiltration than soil temperature.

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



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

Frozen fraction



Soil temperature

The wetter the soil, the lower the permeability

≅ model infiltration with soil ice content

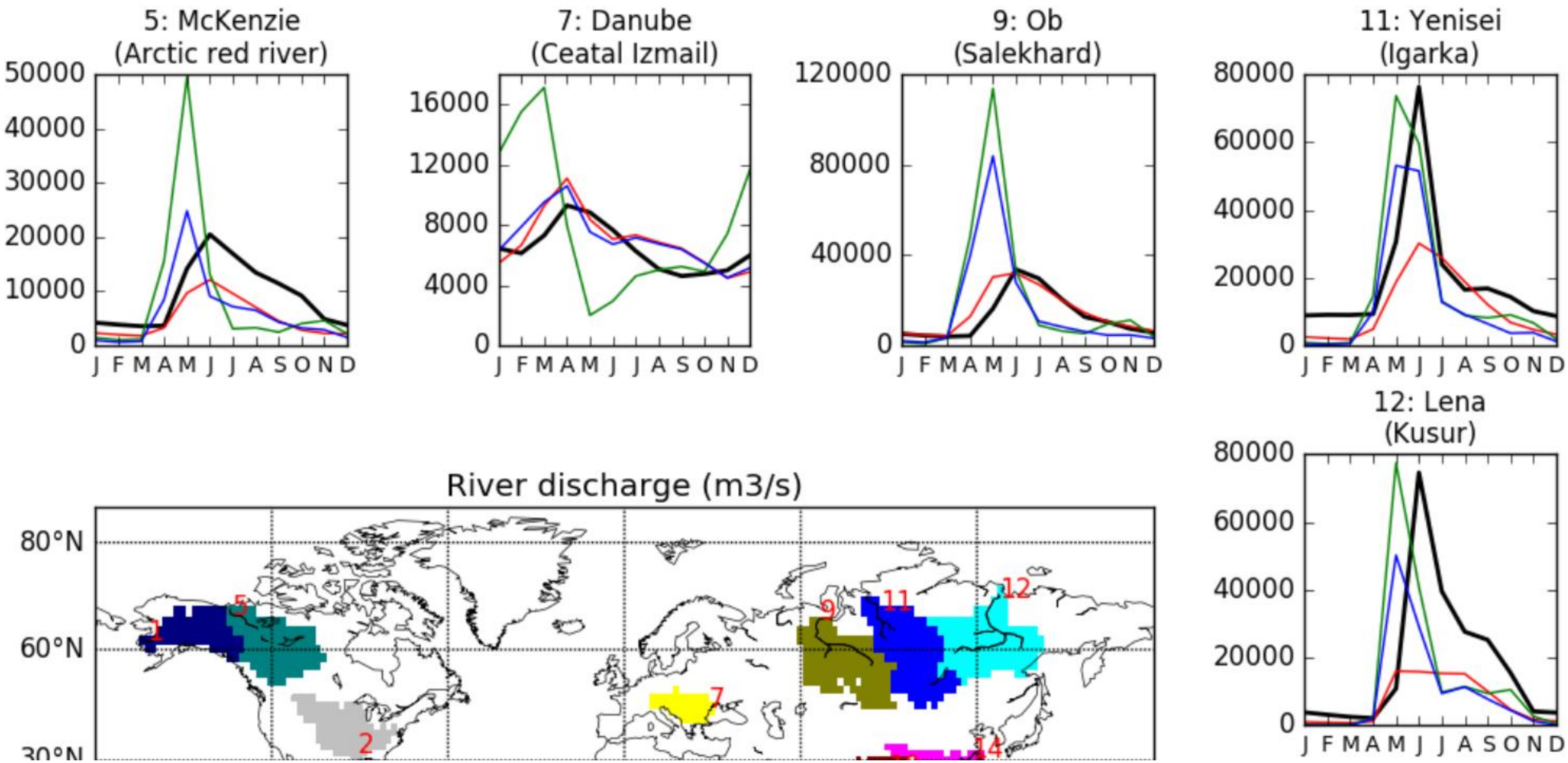
$$Froz_{frac} = HI^b * FI^a * Froz_{frac}$$

Results

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

➔ River discharge (m^3/ s)

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



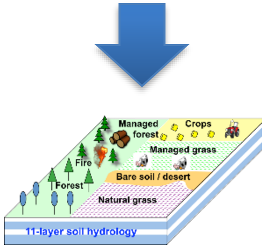
→ But severe issues in coupled mode…

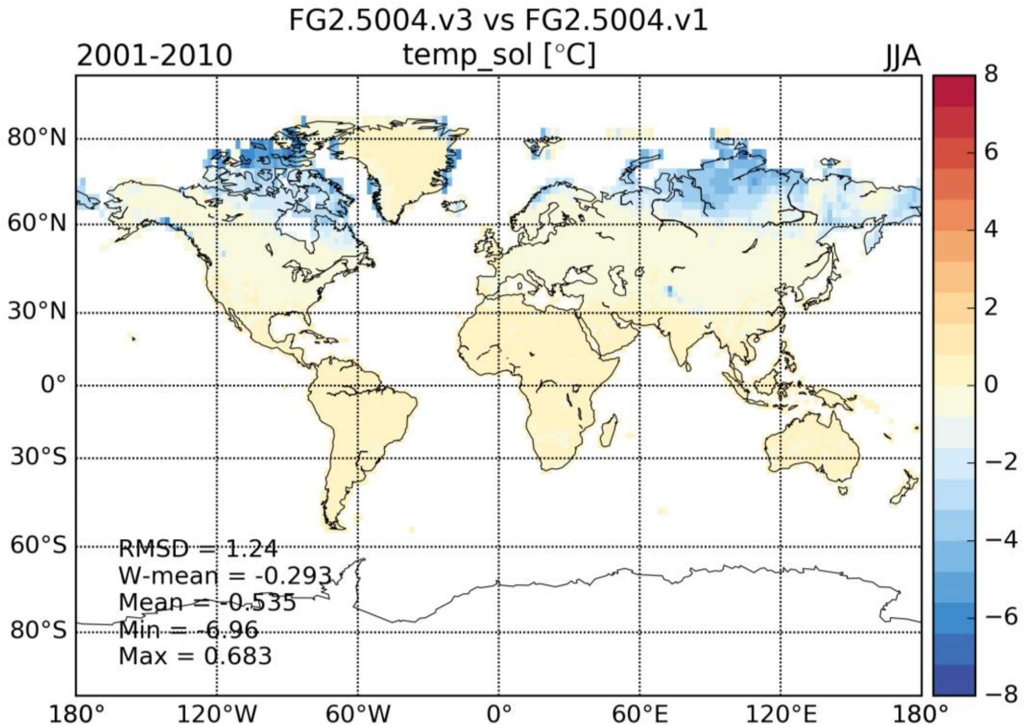
Soil freezing: forced simulations

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

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

CRU-NCEP





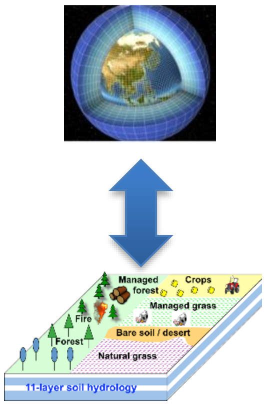
Delta Surface Temperature (summer, °C):

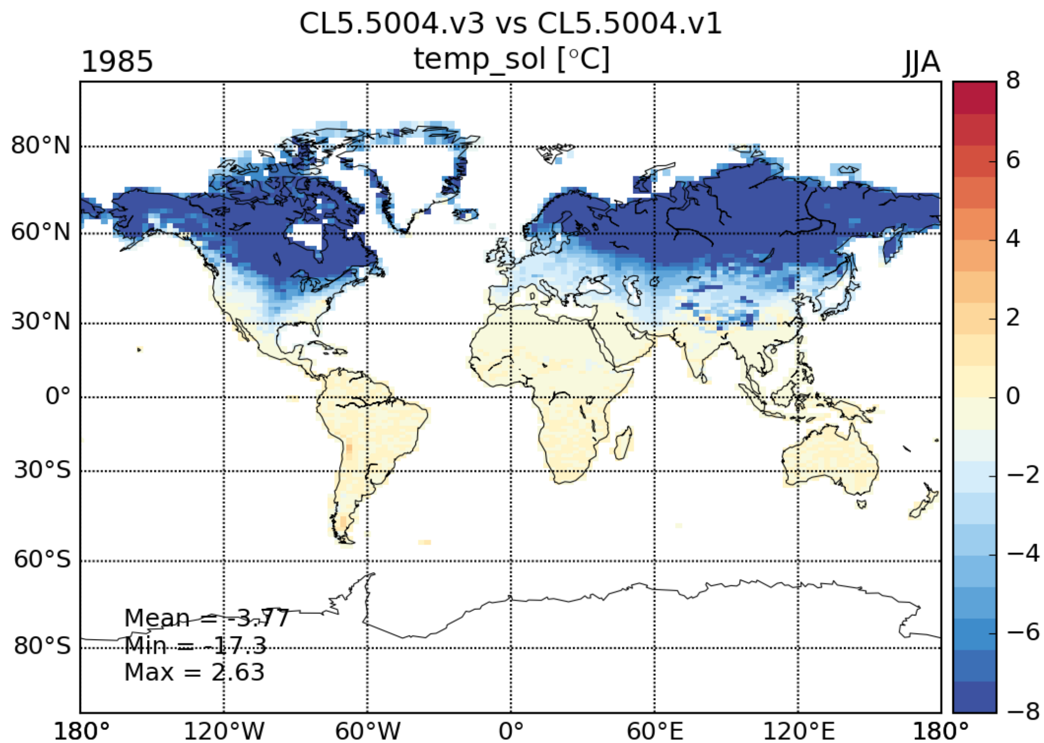
‘freezing’ minus ‘no freezing’

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):

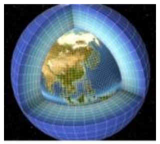
'freezing' minus 'no freezing'

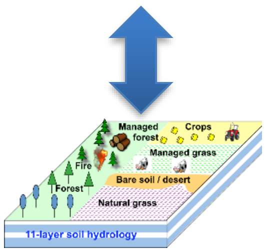
Soil freezing : coupled simulations

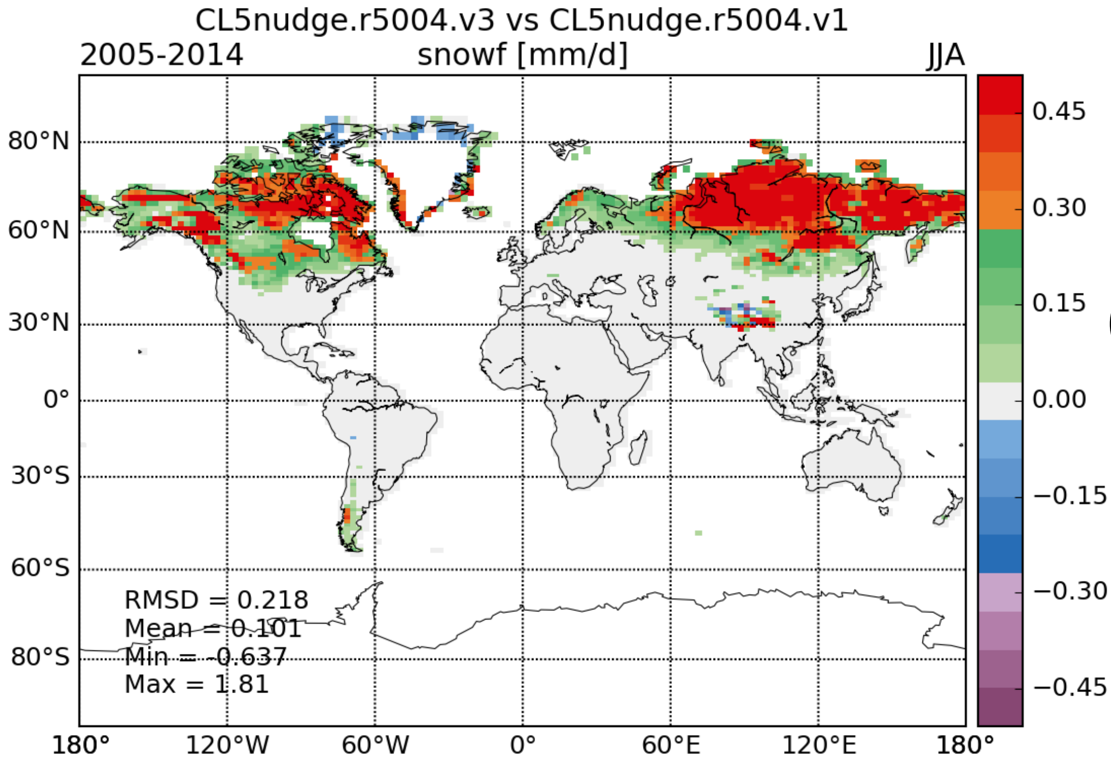
Freezing ➔ Increase winter soil/air temp. (≈ 1°C)

➔ decrease summer soil/air temp. (6°-8°C)

➔ increase snowfall (high sensitivity to surface/air temperature)







Delta snow cover (summer, mm/d)

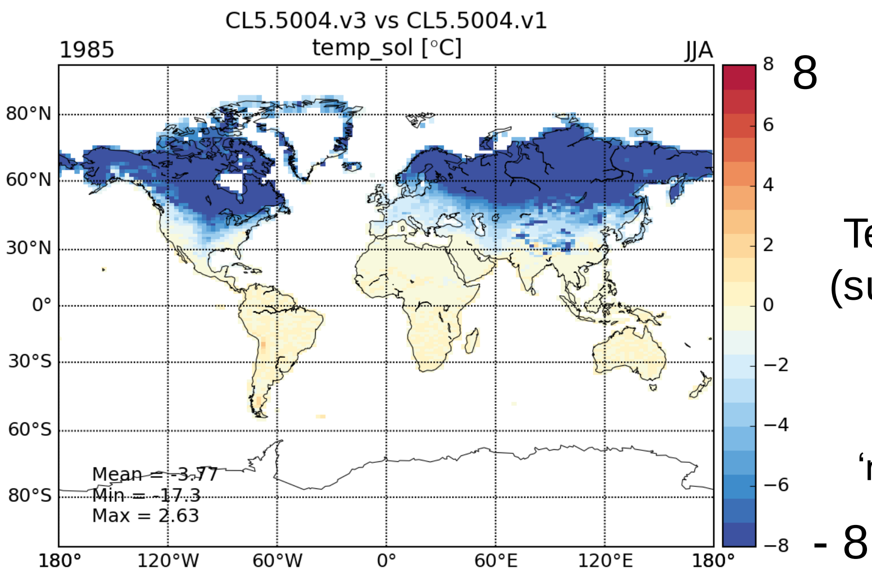
'freezing' minus 'no freezing'

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

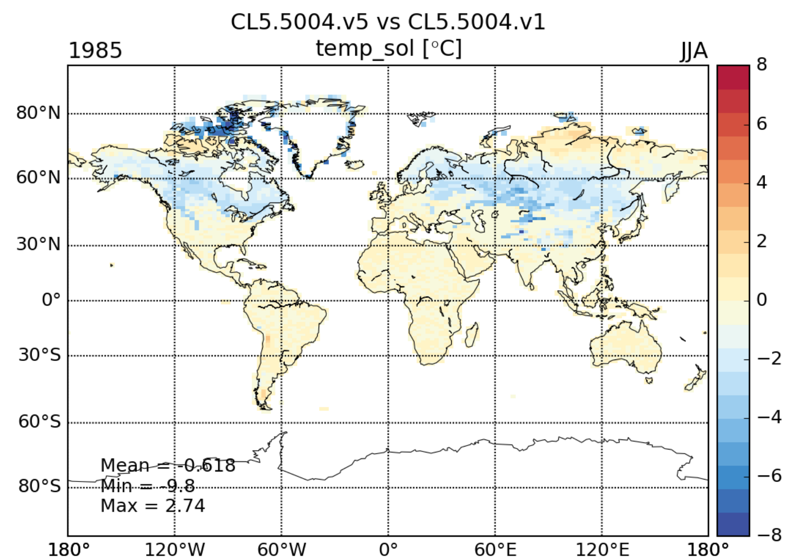
Standard soil conductivity

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



Delta
Surface
Temperature
(summer, °C):

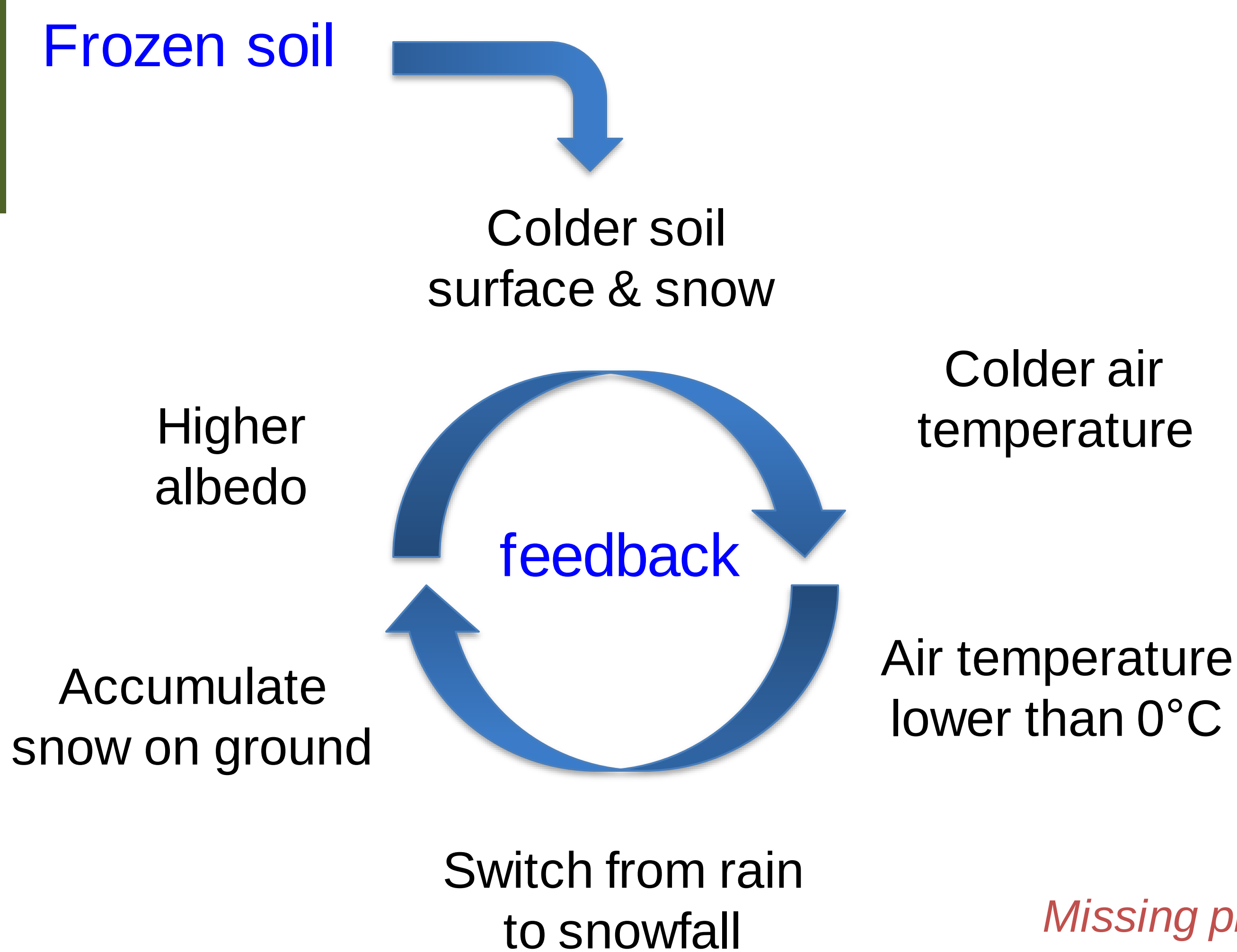
'freezing'
minus
'no freezing'



Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time

Spring
&
Summer

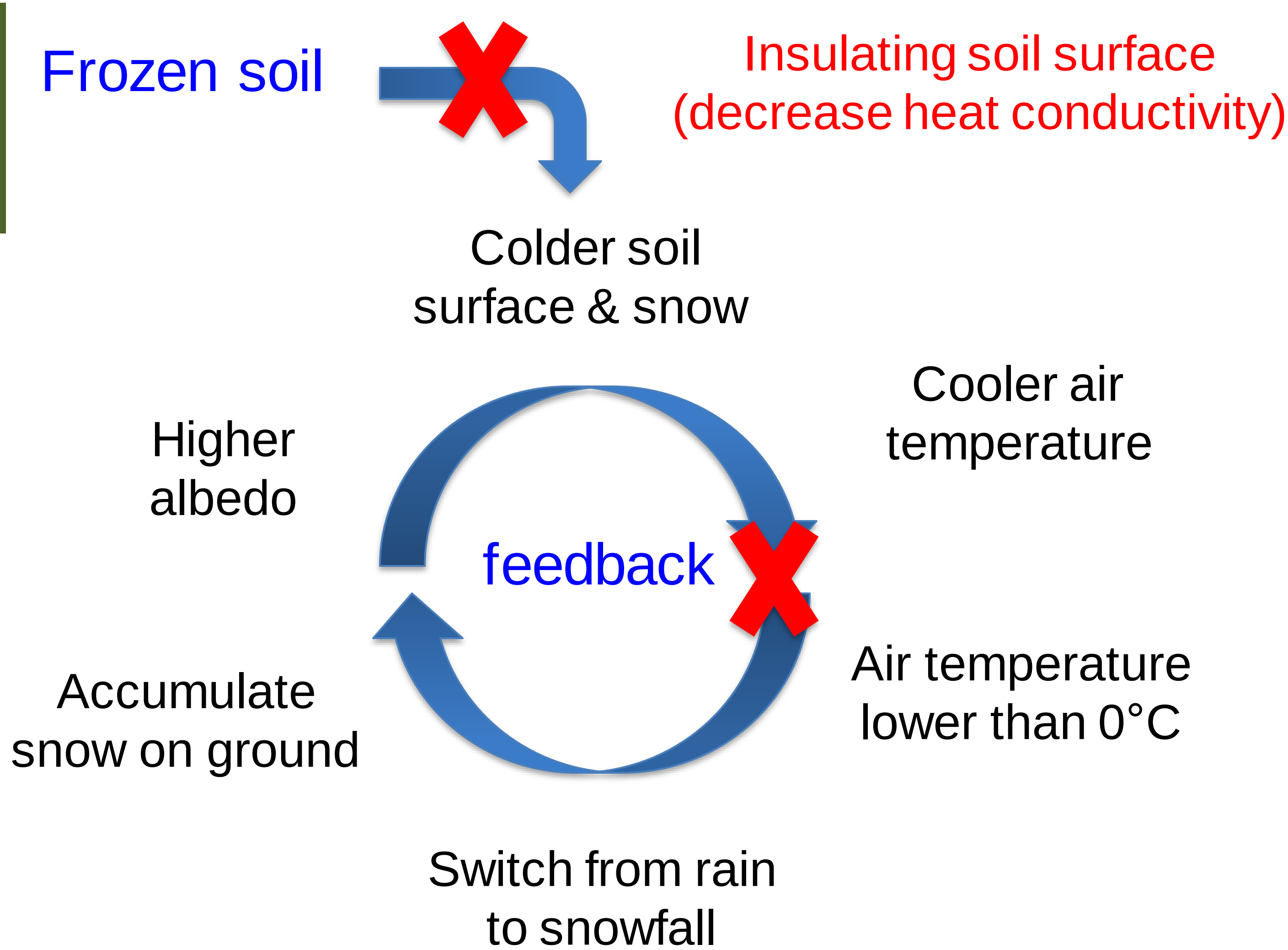


Missing processes: carbon and mosses

Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time

Spring & Summer



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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 and water cycles

- ✓ High albedo of fresh snow ➡ *feedbacks on energy balance*
- ✓ Low thermal conductivity ➡ *Thermal insulating properties*

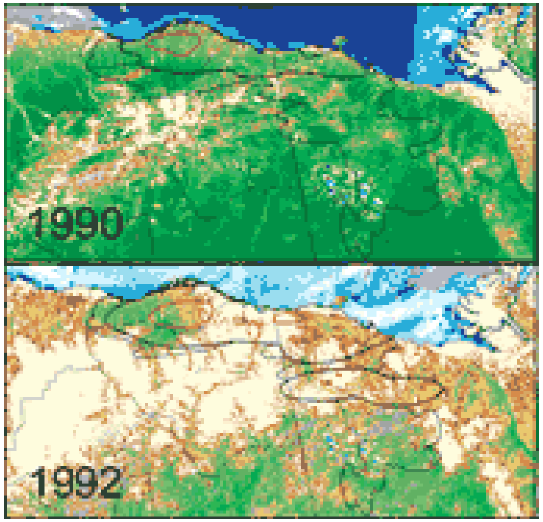
➡
- *Over ice (lakes, rivers, ice sheets): Reduction of heat conduction flux → ice growth reduced*
- *Impacts ground freezing/thawing, i.e., soil temperatures, carbon decomposition, soil respiration and methane emissions*

- ✓ Water phase changes *(release of latent heat during refreezing, consumption of energy for melting, e.g: snow slows down soil warming in spring)*
- ✓ Reduction of soil roughness *(smoothing effect on snowed vegetation)*
- ✓ Buffering water transfers to runoff
- ✓ Rapidly evolving with local meteorological conditions (temperature, wind, liquid water content, crystal structure…)

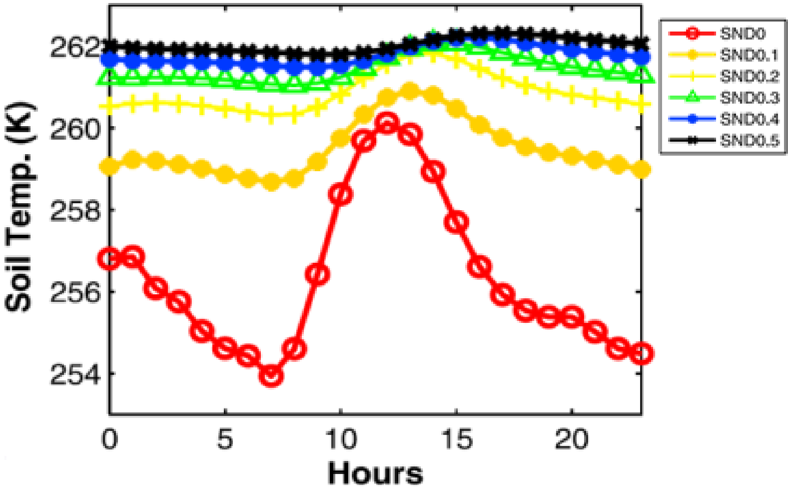
➡ *Impacts heat and water transfers (diurnal + seasonal) and climate variability*

Snow / Atmosphere / Vegetation feedbacks:

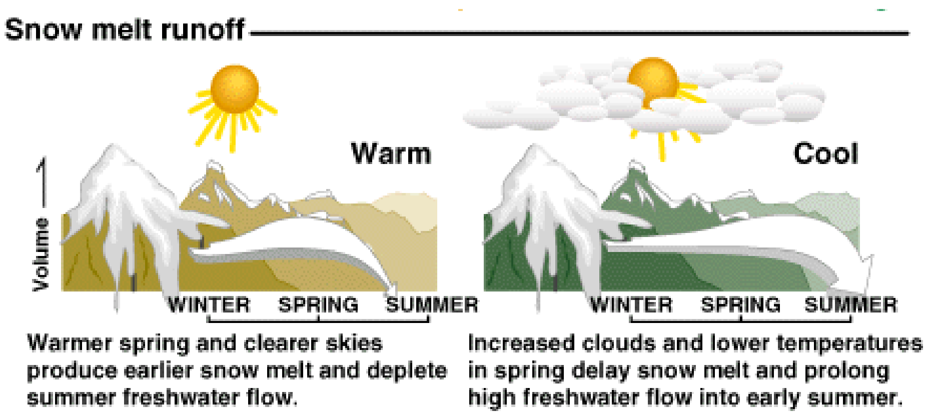
Prolonged snow, later vegetation greening



Less snow, colder soil temperatures in winter

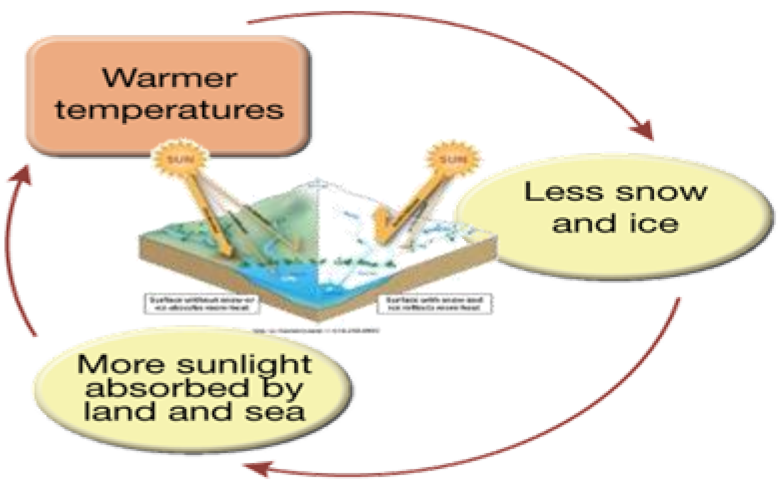


Earlier snowmelt, earlier spring runoff



(Adapted from Cayan and Peterson, 1993)

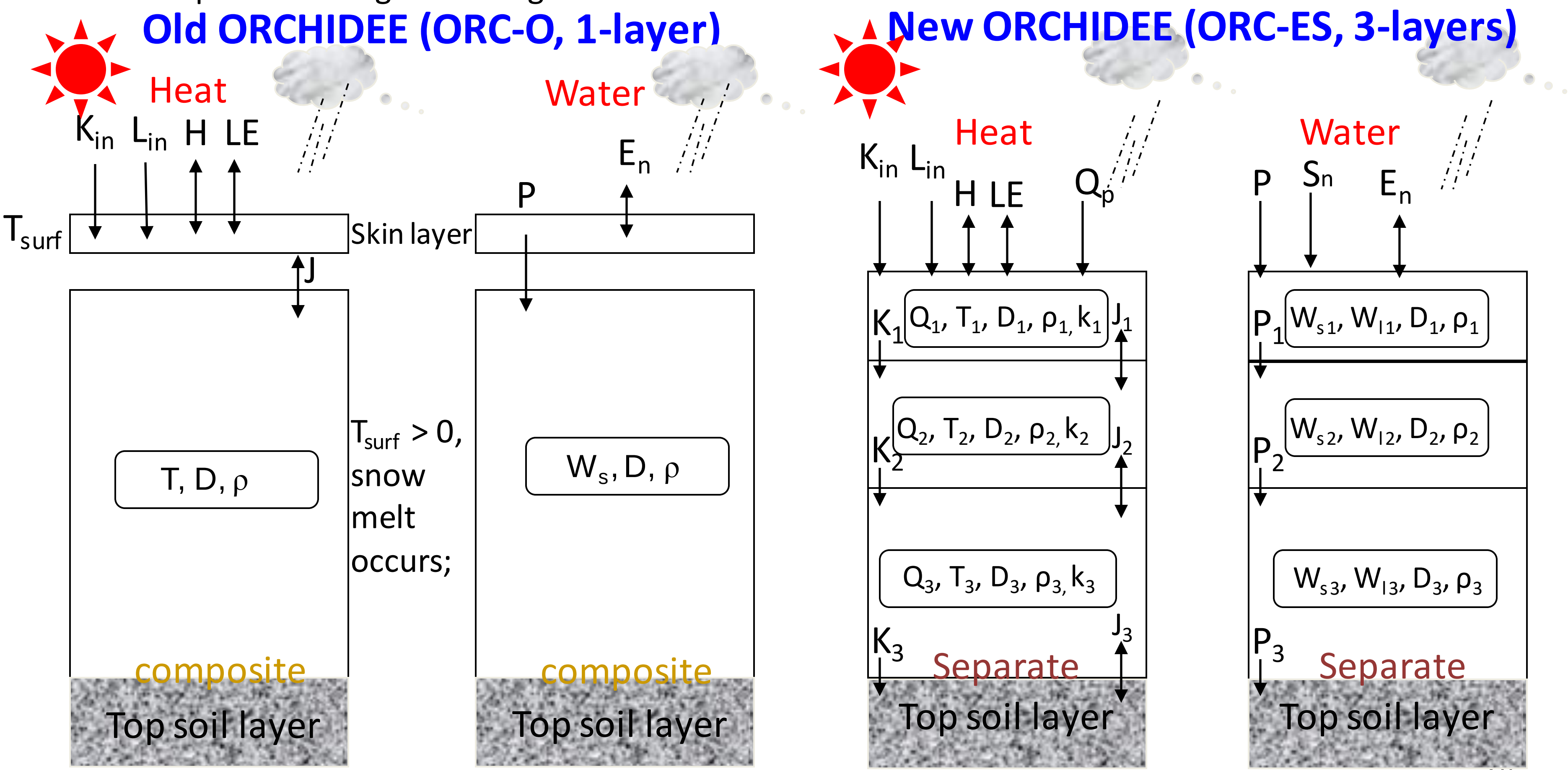
Less snow, warmer air temperatures with positive feedbacks



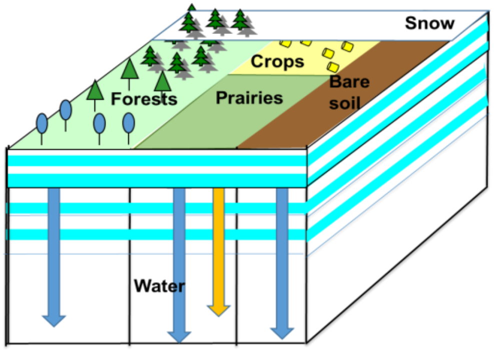
ORCHIDEE Snow developments (Wang et al., 2013)

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
- ✓ Water flow and radiative transfer between layers
- ✓ New snow cover fraction and albedo parametrization
- ✓ Snow impacts on roughness length

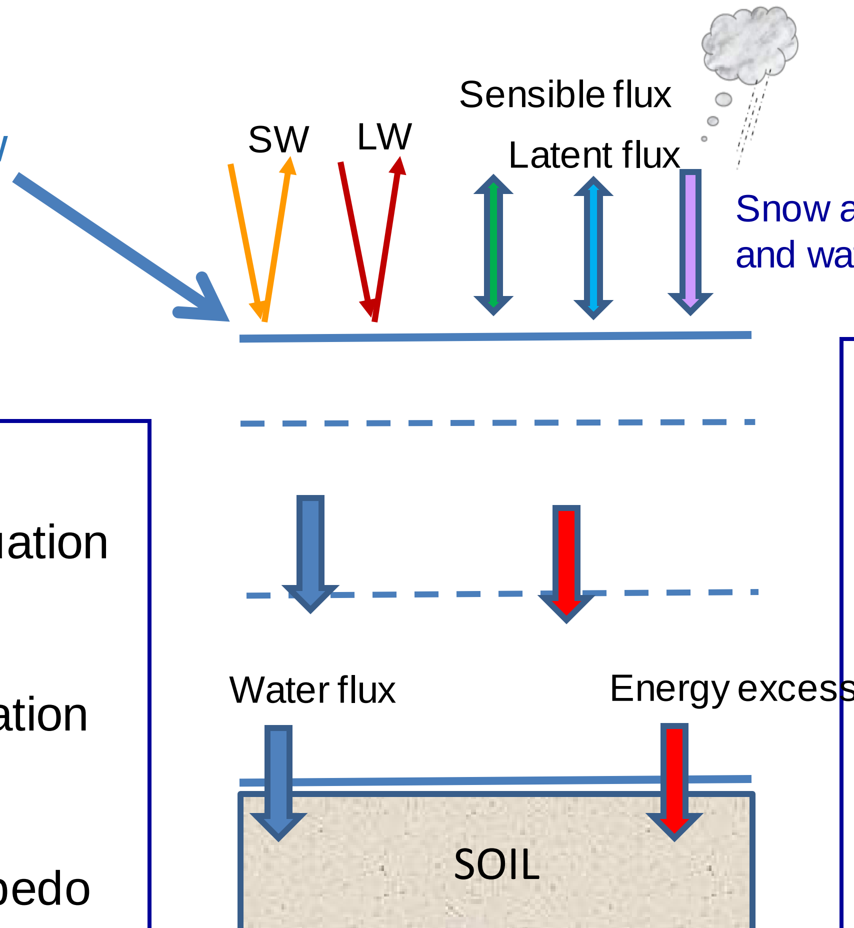


Three-layers snow model : Explicitsnow



- Only for vegetated surfaces and bare soils (i.e. bio surfaces)
- For nobio surfaces (ice sheets and glaciers) : 1-layer ORC-O

Surface types: fractional snow and vegetation covers



Processes :

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

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

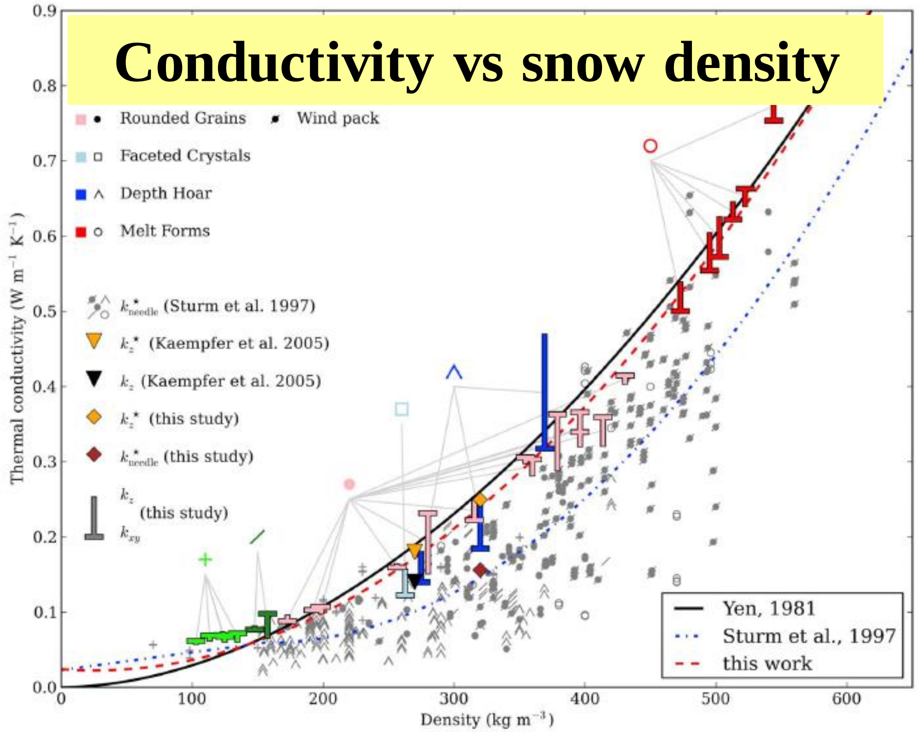
- **Snow thermal conductivity and capacity as a function of snow density and snow temperature (only for κ)**

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



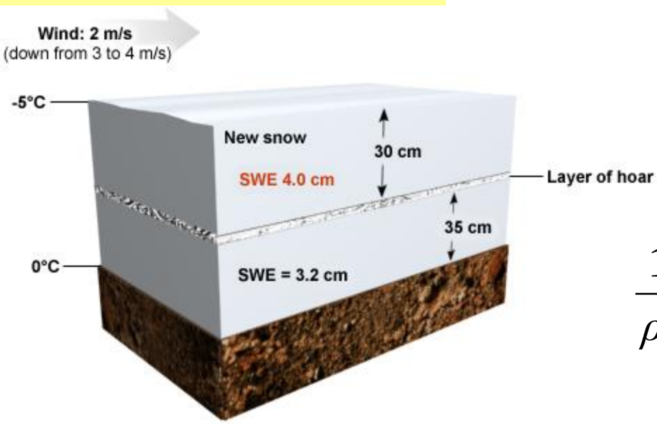
Main features of ORCHIDEE snow module

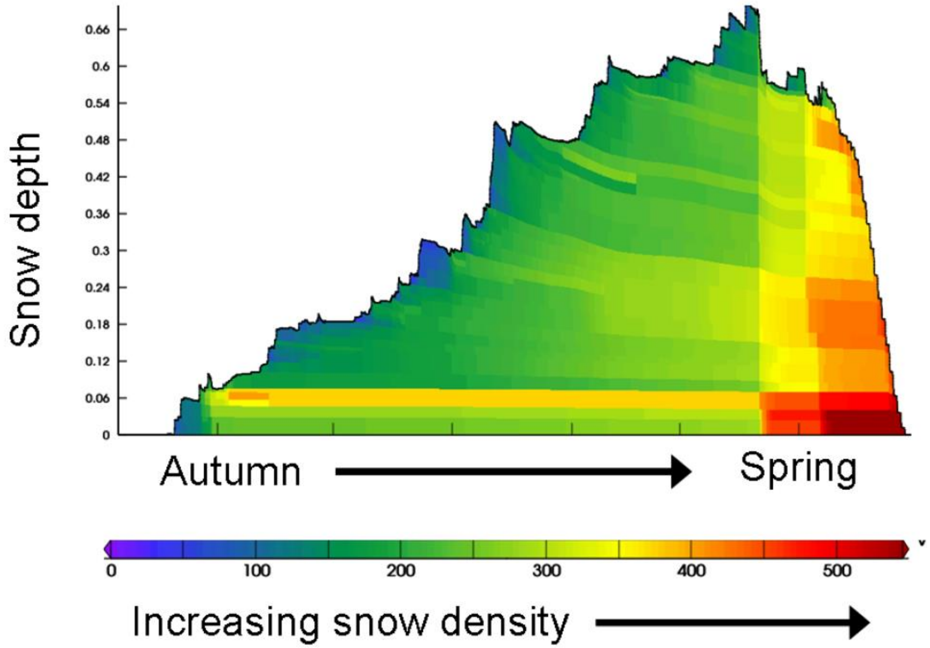
- **Freezing-thawing processes and snow compaction (leading to spatio-temporal variation in snow density)**

Freeze-thaw

Calculation of liquid water content

Snow compaction





$$\frac{1}{\rho_j}\frac{\partial \rho_j}{\partial t} = \frac{\sigma_j}{\eta_j(T_j,\rho_j)} + a_c \exp\left[-b_c(T_f - T_j) - c_c \max(0, \rho_j - \rho_c)\right]$$

= weight of the overlying snow+ metamorphism

Snow cover fraction

- On vegetated surfaces

  (Svenson & Lawrence, 2012)

$$Frac_{snow,veg} = \tanh \frac{d_{snow}}{2.5\, Z_{0g} \left(\rho_{snow} / \rho_{new} \right)^{m}}$$

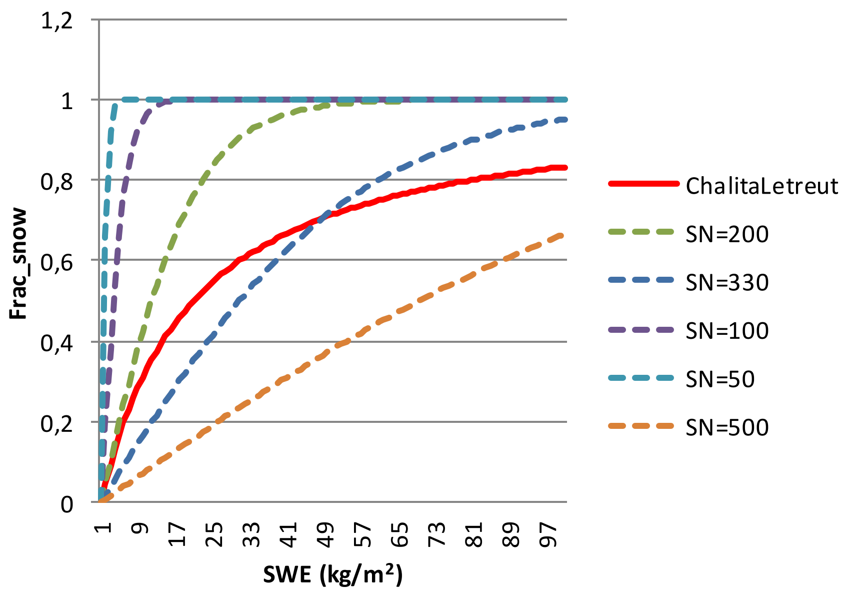
With m=1, Z_{0g} = 0.01m and ρ_{new}= 50 kg/m^3

- On glaciers/ice sheets

  (Chalita & Letreut, 1994)

$$Frac_{snow,nobio} = \frac{\mathrm{SWE}}{\mathrm{SWE+20}}$$

With ρ_{snow}= 330 kg/m^3 and $SWE = \rho_{snow} . d_{snow}$



New parametrization allows to represent the differences between the accumulation/ablation phases of the snow cover /snow amount relationship

Albedo of snowed surfaces

- Snow albedo: depend on snow age (precip, aging factors), surface type, calculated in "condveg_albedo.f90"

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

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

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

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

- Snow roughness (condveg.f90)

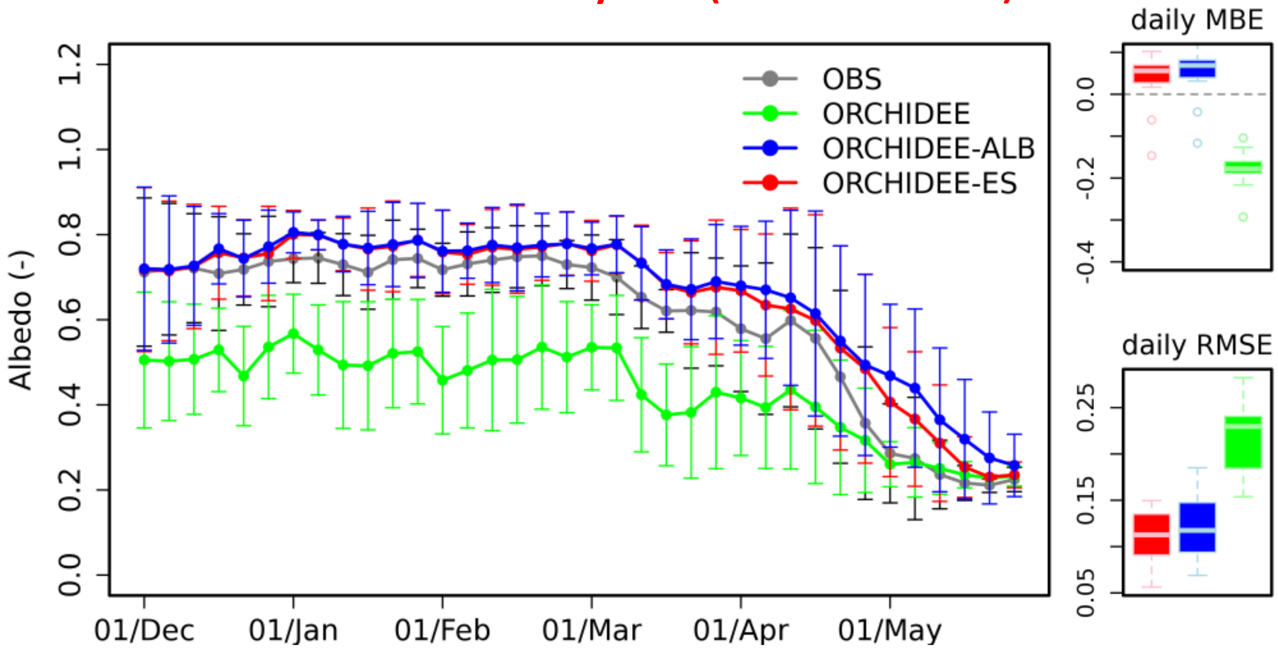
$$\frac{1}{\ln\left[z_r / z_{0t}\right]^2} = \frac{Frac_{snowveg}}{\ln\left[z_r / z_{0n}\right]^2} + \frac{1 - Frac_{snowveg}}{\ln\left[z_r / z_0\right]^2}$$

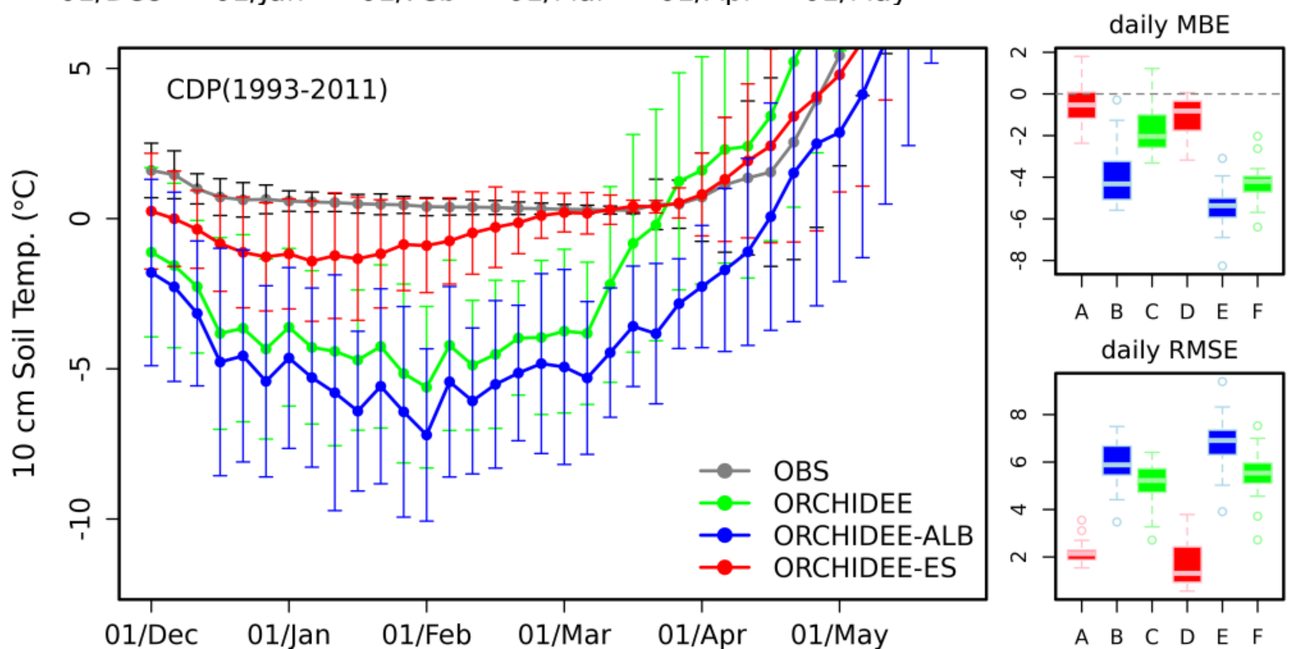
where $Frac_{snowveg}$ is snow cover fraction, z_{0t} is surface roughness length after considering snow cover, z_0 is the vegetation or surface roughness length (m), z_{0n} is the snow surface roughness length baseline value (0.001 m), and z_r is the blending height (10 m in ORCHIDEE).

Snow model implementation

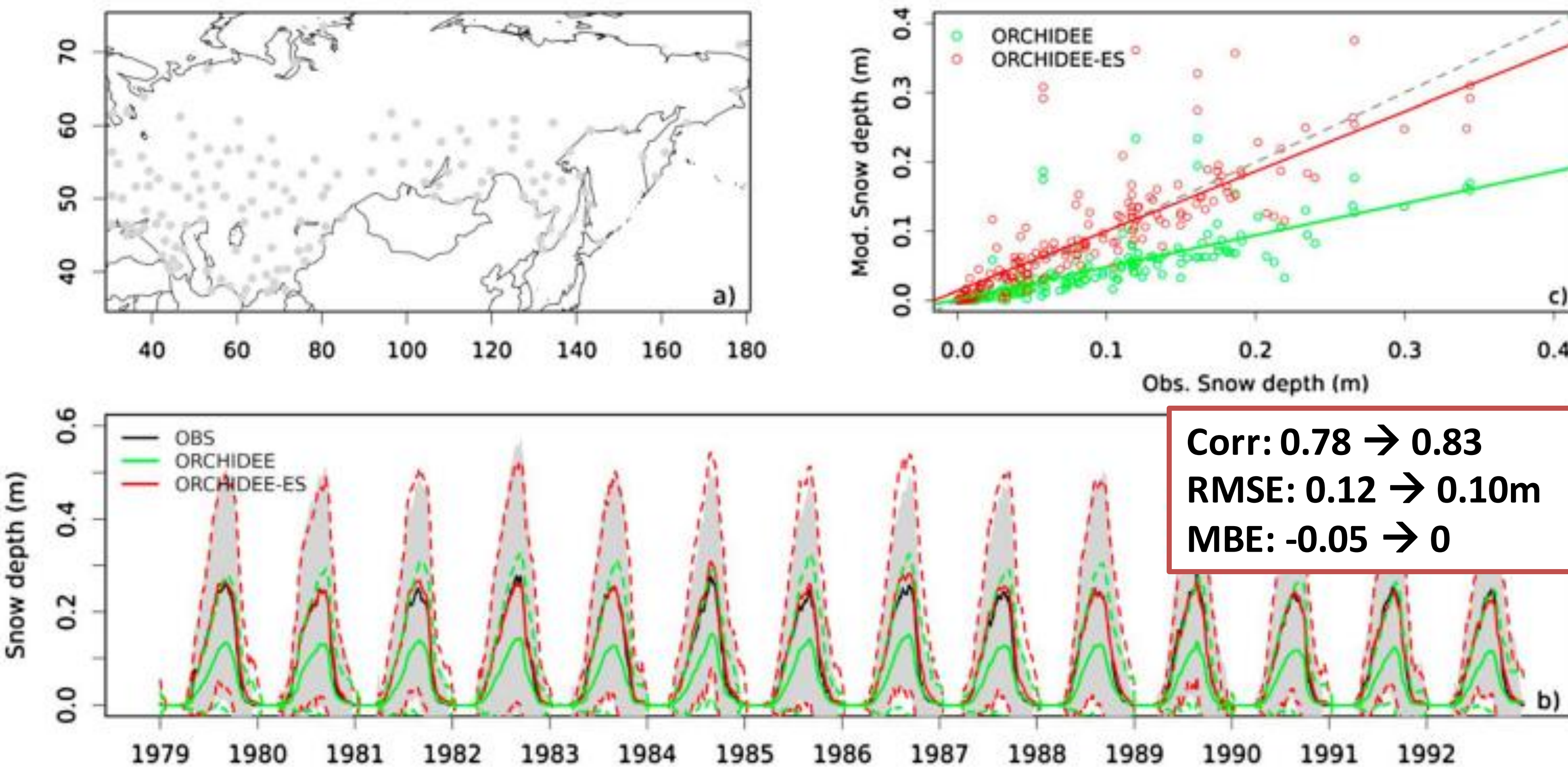
- Organized in a separate block of modules « explicitsnow.f90 », call in hydrol.f90,
- Implicit resolution (snow and soil temperature profiles calculated in one single step) but explicit representation of the energy budget at the snow-soil interface (soil-snow heat flux calculated using the soil temperature 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
- Fracsnow and albedo are calculated in condveg.f90 after mass budget calculation
- Water and Energy conservative

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)



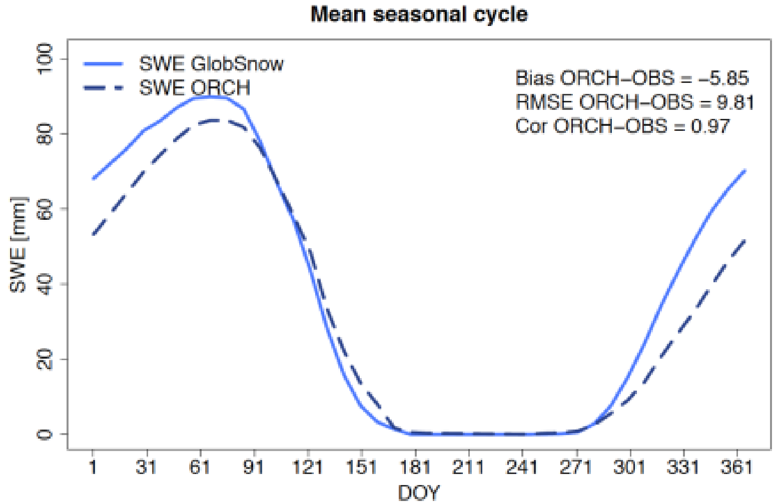
Corr: 0.78 → 0.83
RMSE: 0.12 → 0.10m
MBE: -0.05 → 0

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.

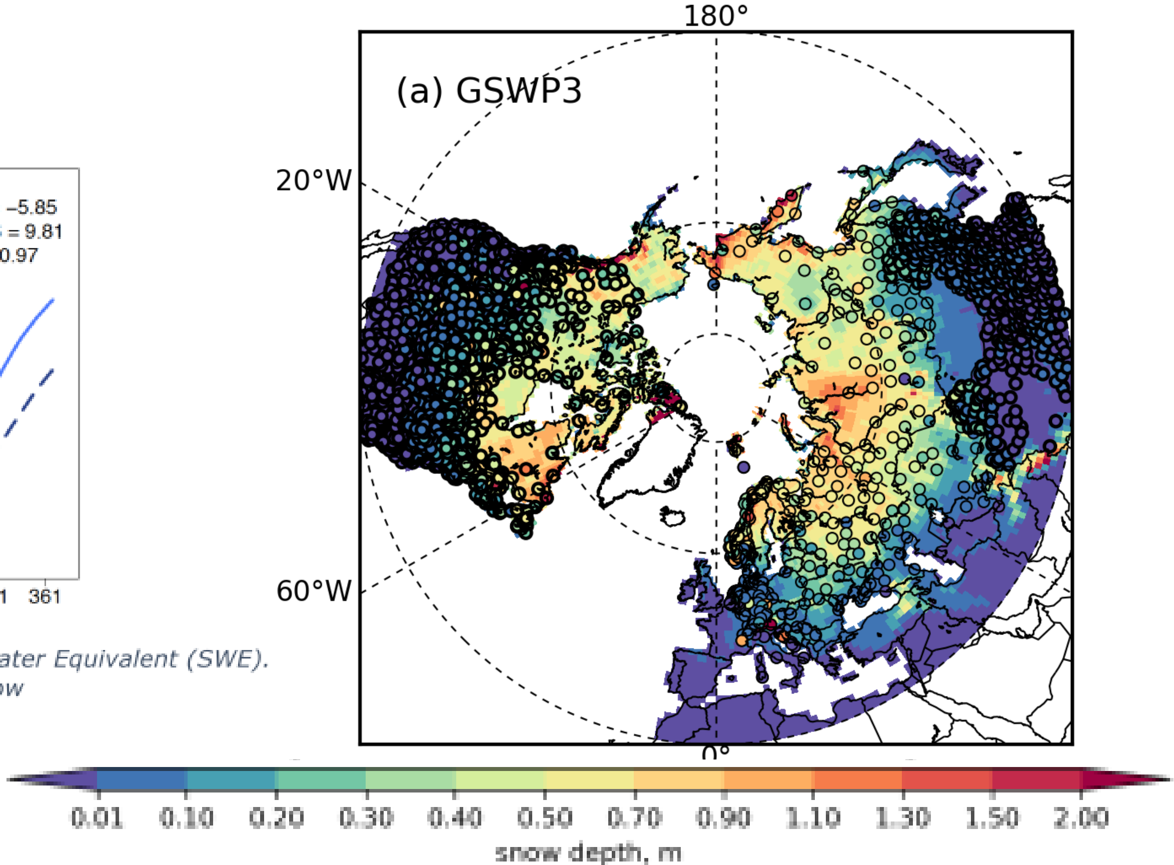
Wang et al., JGR, 2013

Snow model evaluation

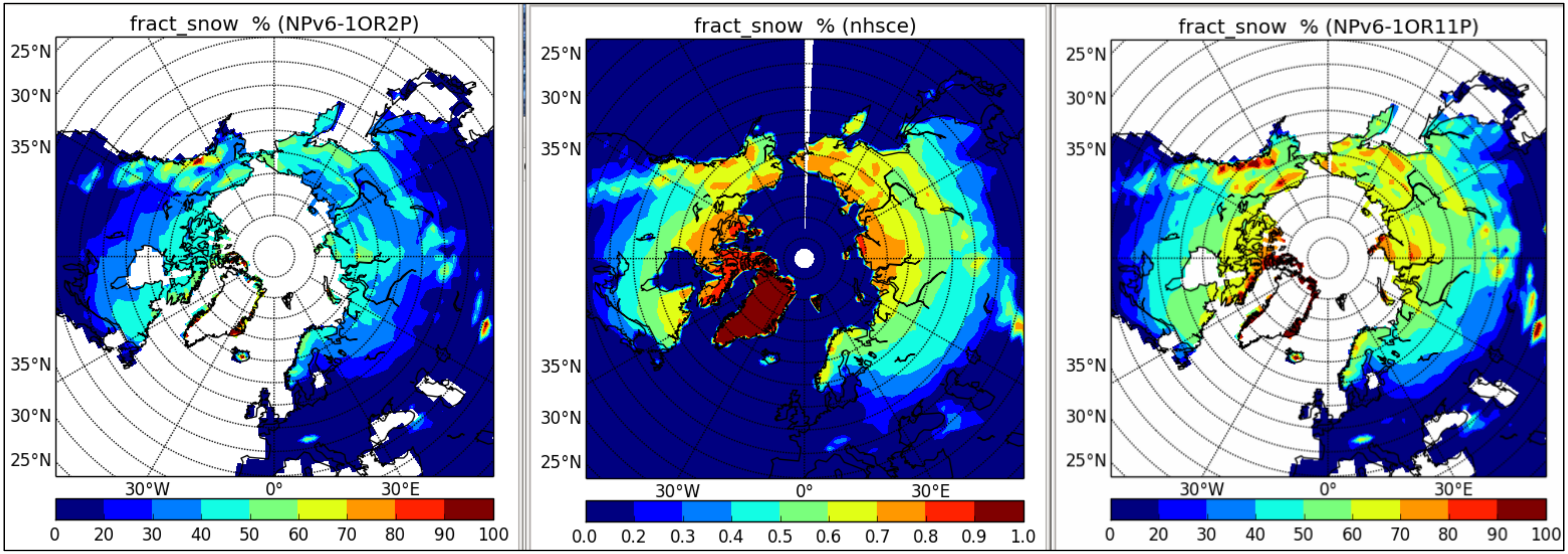
- Evaluation at site scale, regional and global scales and various temporal scales (Wang et al., 2013, 2015, … PhD S. Dantec (2017) on Siberia, Guimberteau et al., 2017, on northern latitudes (GMD) , on different variables , SWE, depth, runoff, …



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



Snow Cover Fraction (CMIP6 compared to CMIP5)



ORCHIDEE – CMIP5 Observations ORCHIDEE – CMIP6

Cheruy et al., 2020, JAMES, submitted

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