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

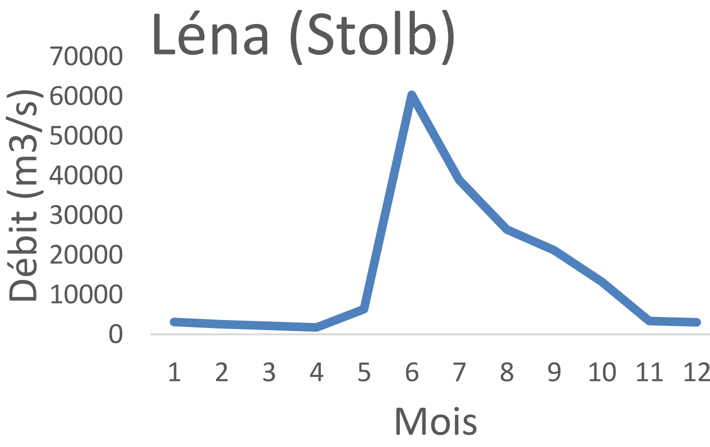
Presence of ice alters soil hydro-thermal properties

Thermal processes:

- Water phase changes produce/consume energy (latent heat of fusion), soil thawing/freezing slows down soil warming/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
- Reduce soil water availability for plants
- Impacts runoff and streamflows
- Impacts soil biological processes, respiration and methanogenesis, therefore carbone and methane emissions.



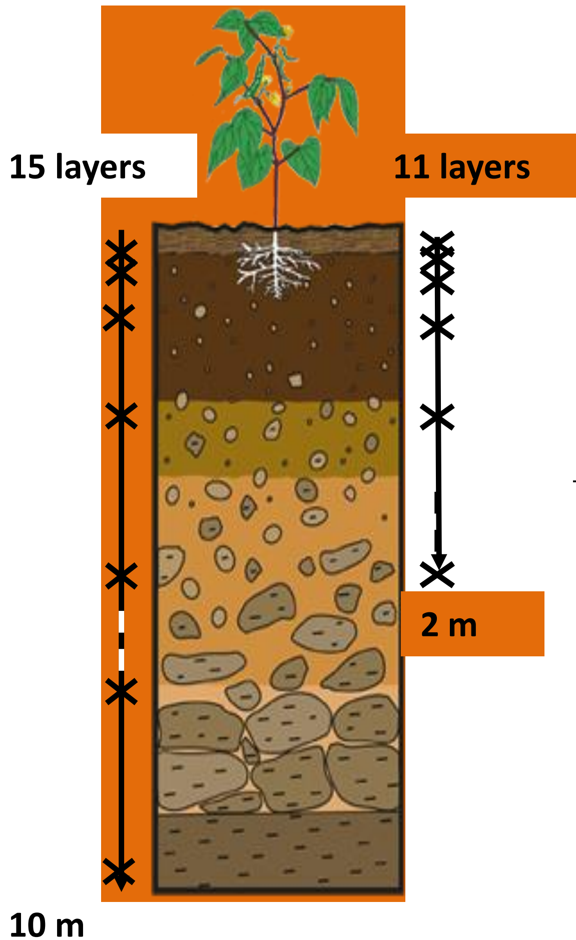
ORCHIDEE hydro and thermal processes without freezing

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 (Gouttevin et al., 2012)

thermics

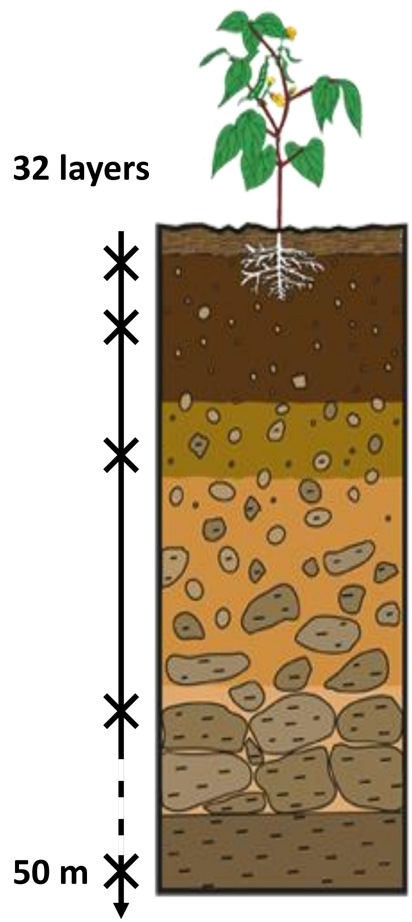
$$\sum F\downarrow_{rad\ net} + \sum F\downarrow_{turb\ net} = \kappa \frac{\partial T}{\partial z}$$

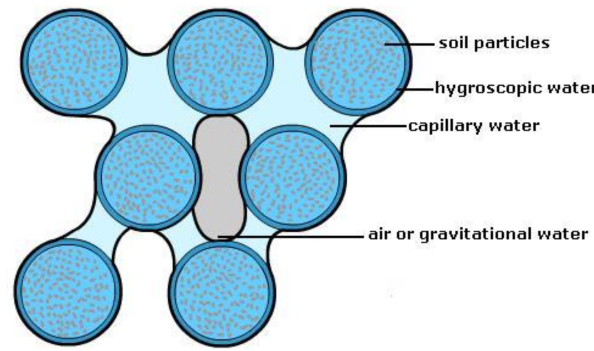
$$C\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \rho_i . L \frac{\partial \theta_i}{\partial t}$$

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

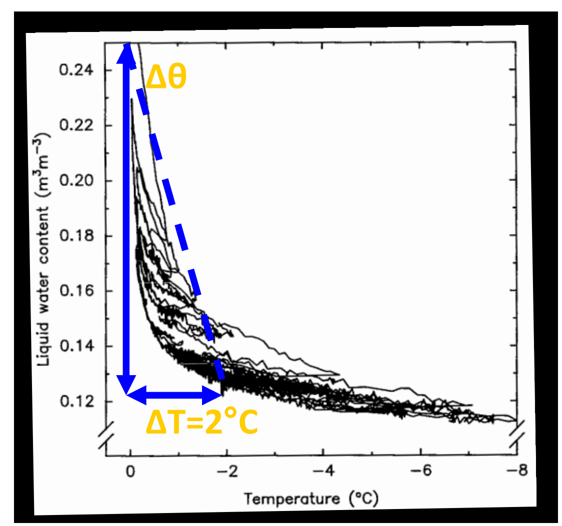
« freezing window »

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





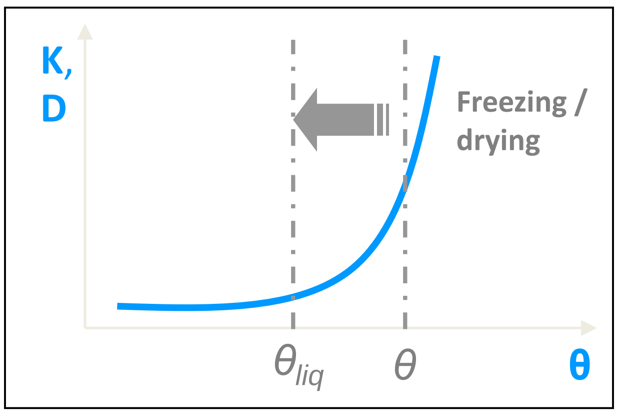
Soil water is stabilized by capillary interactions and freezes beyond the freezing point.



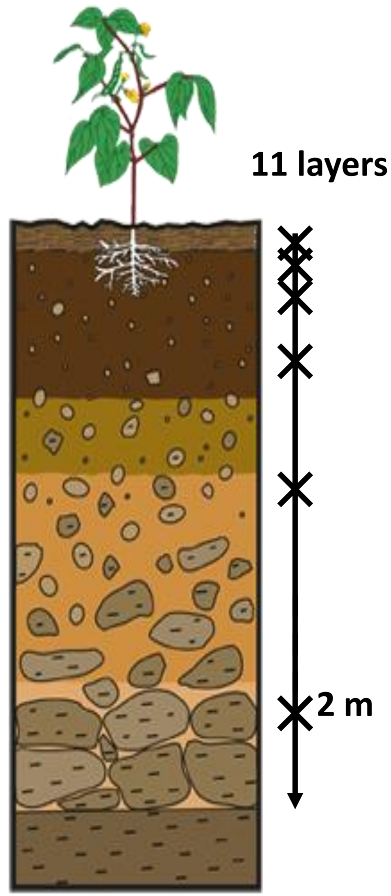
Spaans and Backer, 1996

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} ?**



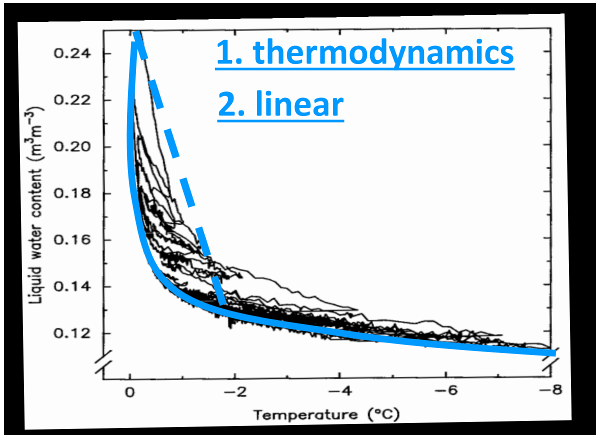
hydrology

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

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

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

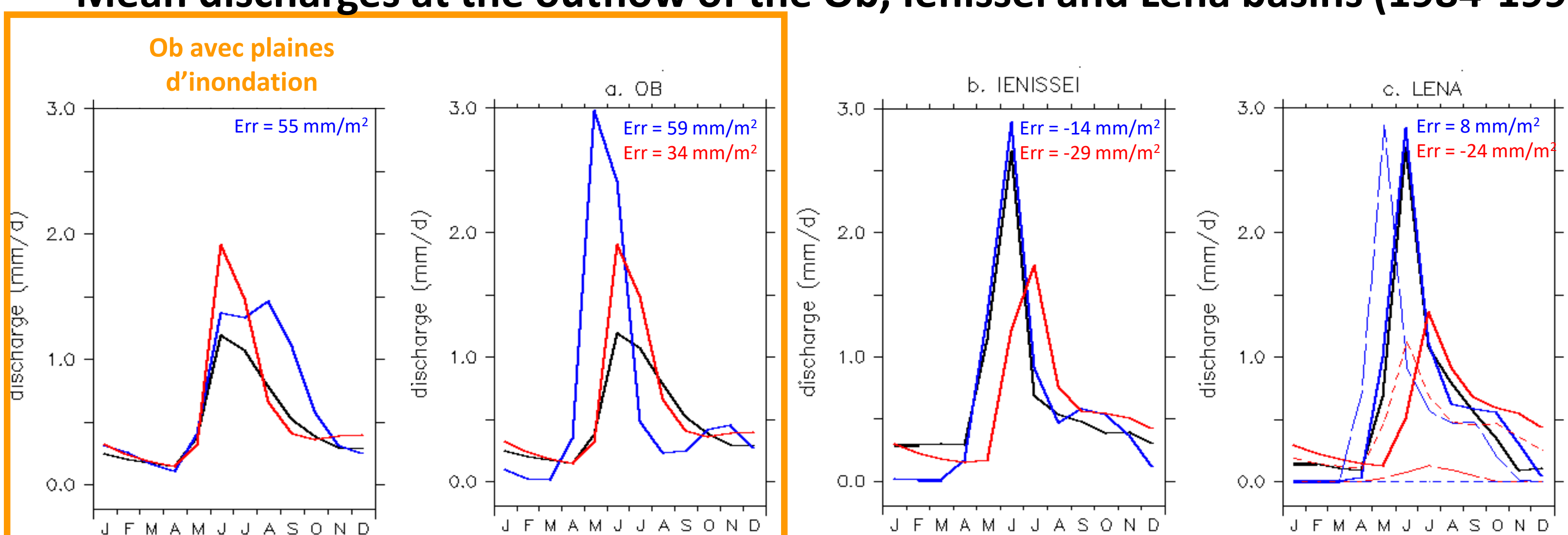
Diagnostic of soil liquid water



Spaans and Backer, 1996

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

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



+ Ringeval et al., 2012.

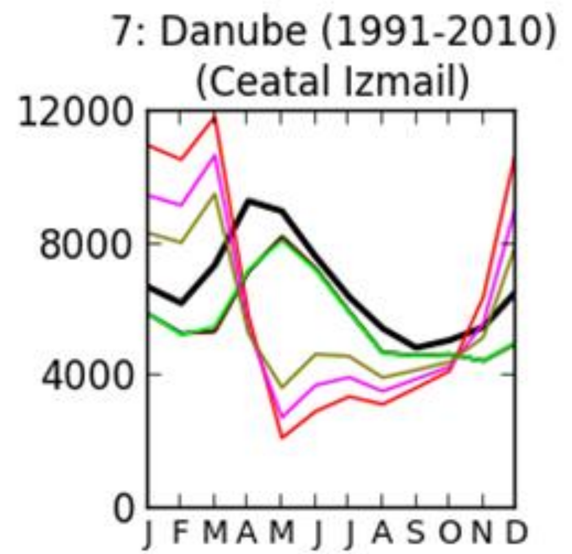
Colors: – NOFREEZE – FREEZE – DATA

Symbols: discharge drainage runoff

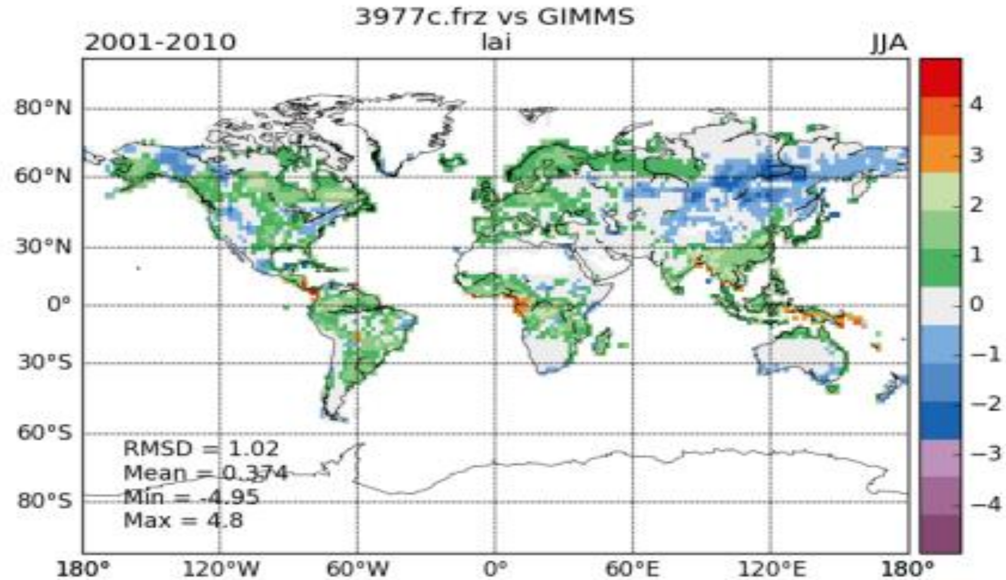
Gouttevin et al., 2012a.

Improvements and drawbacks

Freeze model improves streamflows in arctic regions but degradatation in catchments less influenced by soil freezing (ex. Danube or Missisipi). 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).

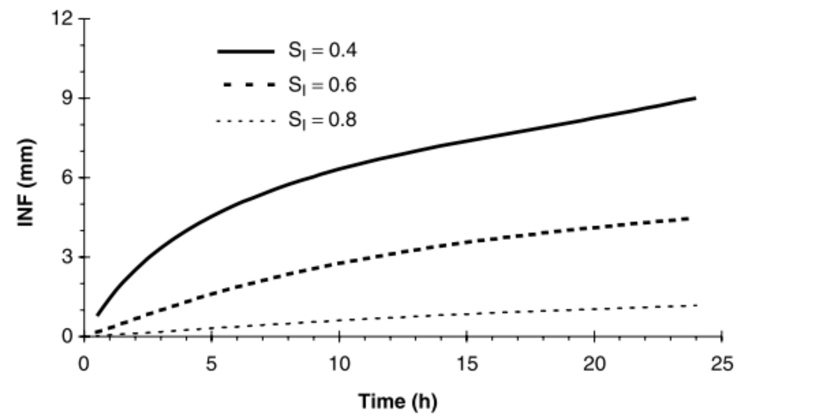


Drastic reduction of infiltration for soils partly frozen (top layers).
Scale issue: frozen soils are permeable because of soil structural aggregates, cracks, dead roots, land cover variability…

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 ($\theta = \theta_{sat}$)

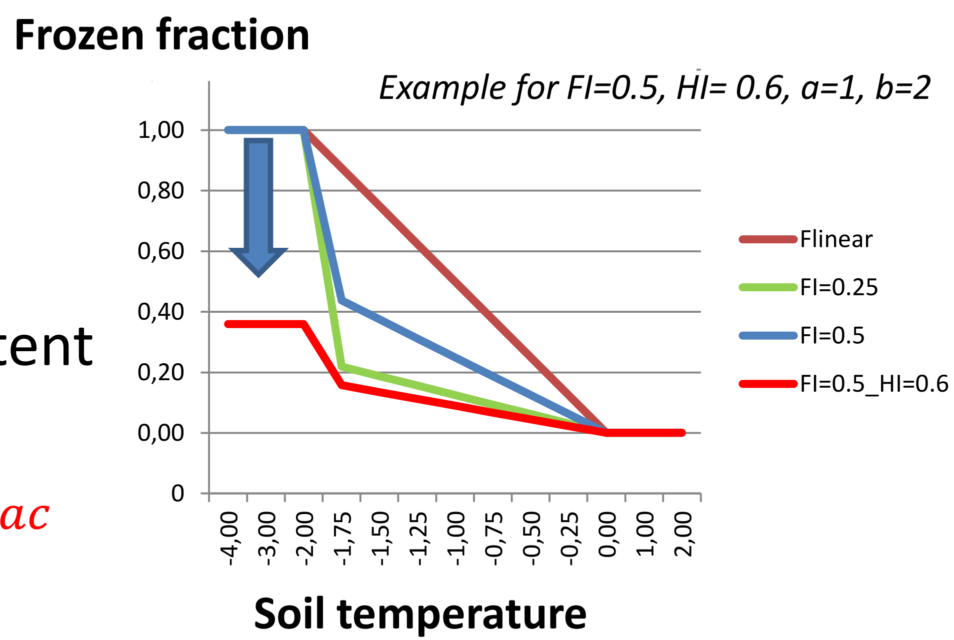


in cumulative infiltration, INF, with time into a frozen, silty clay soil with $S_I = 0{\cdot}4, 0{\cdot}6, 0{\cdot}8$ and $T_I = -6\,°C$, S
Infiltration at hour 12 is 6·8 mm, 3·1 mm and 0·7 mm for $S_I = 0{\cdot}4, 0{\cdot}6, 0{\cdot}8$ respectively

The wetter the soil, the lower the permeability

≅ model infiltration with soil ice content

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

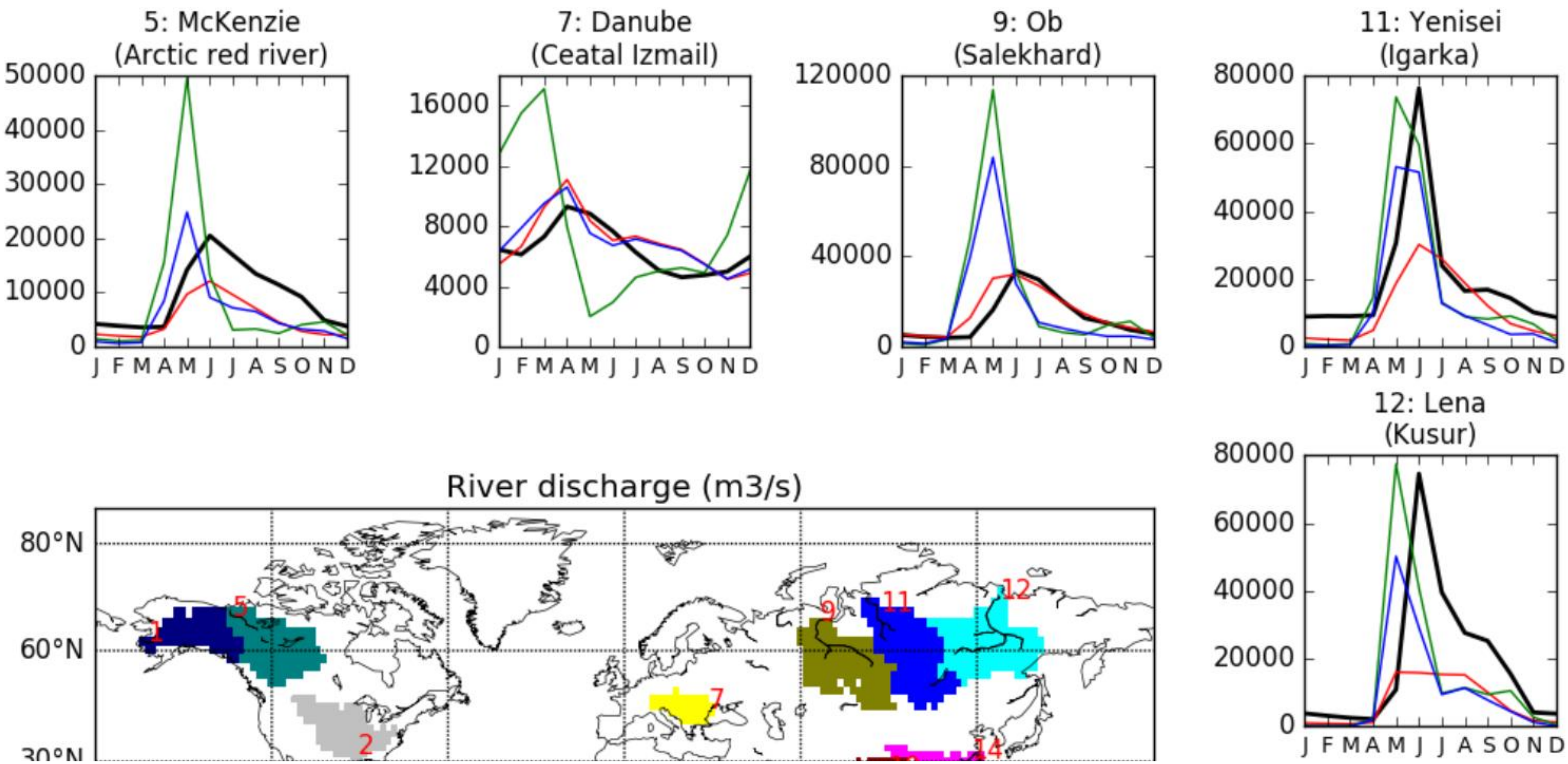


Results

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

➔ River discharge (m^3/ s)

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



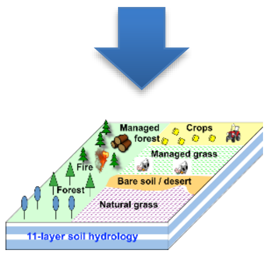
→ But severe issues in coupled mode…

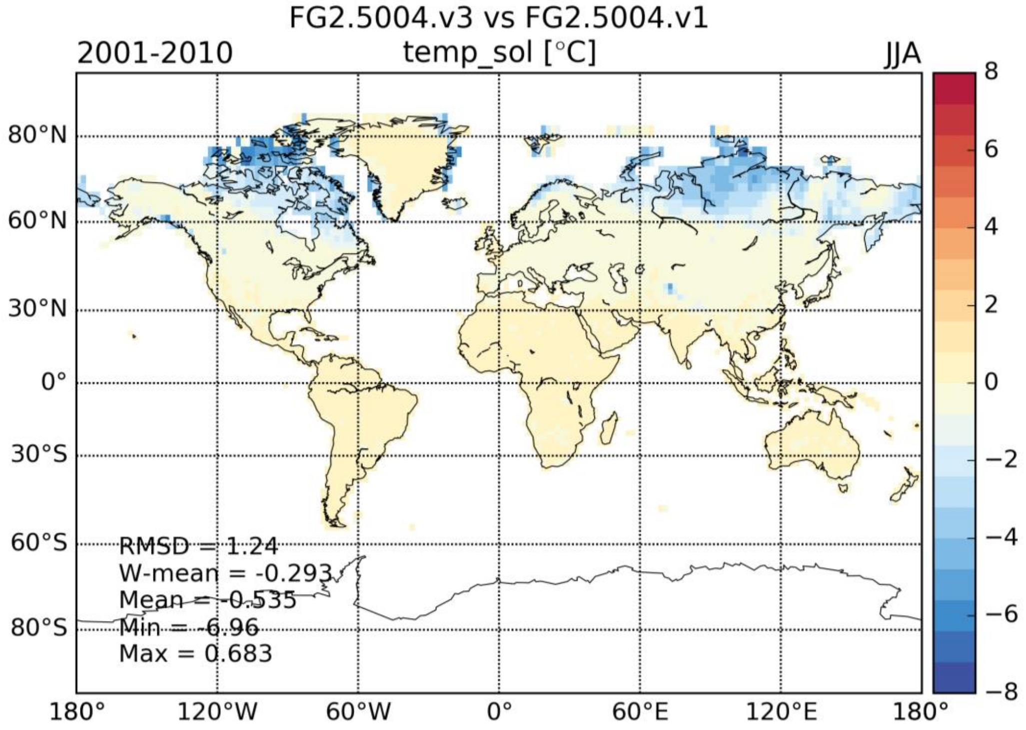
Soil freezing: forced simulations

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

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

CRU-NCEP





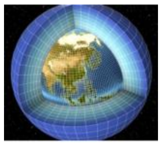
Delta Surface Temperature (summer, °C):

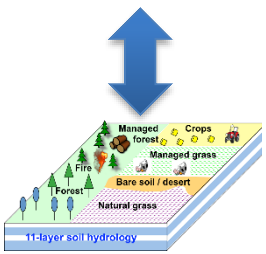
'freezing' minus 'no freezing'

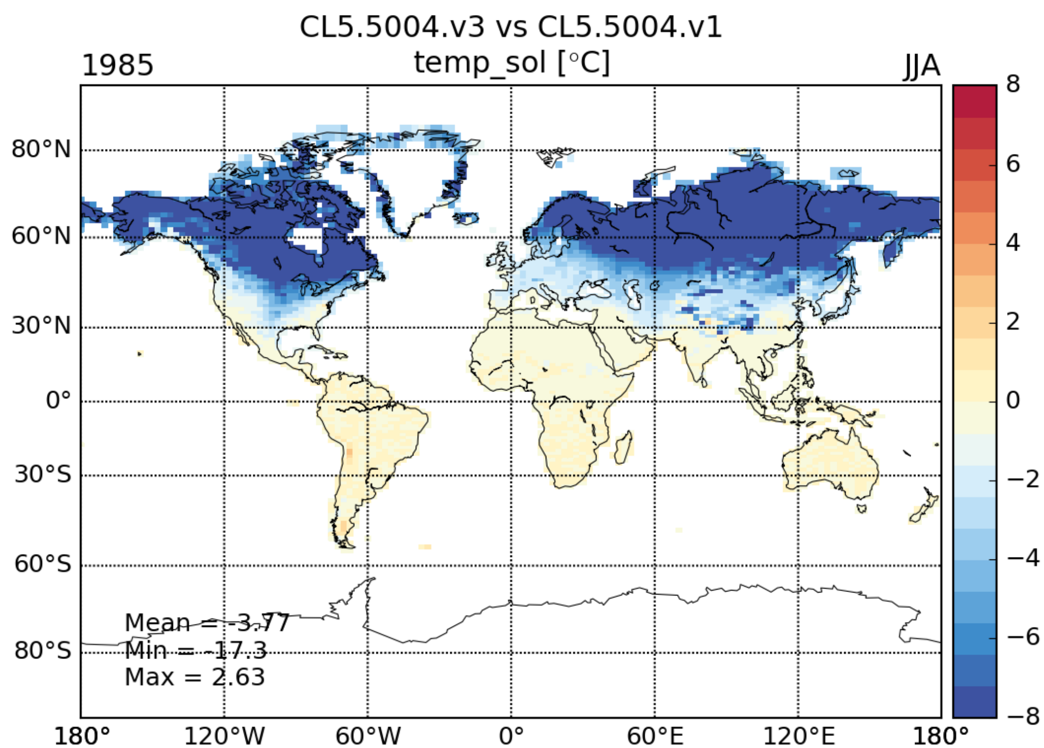
Soil freezing : coupled simulations

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

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





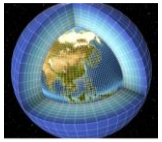


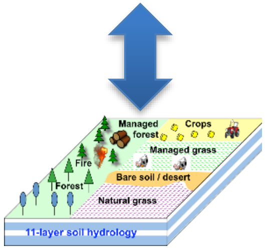
Delta Surface Temperature (summer, °C):

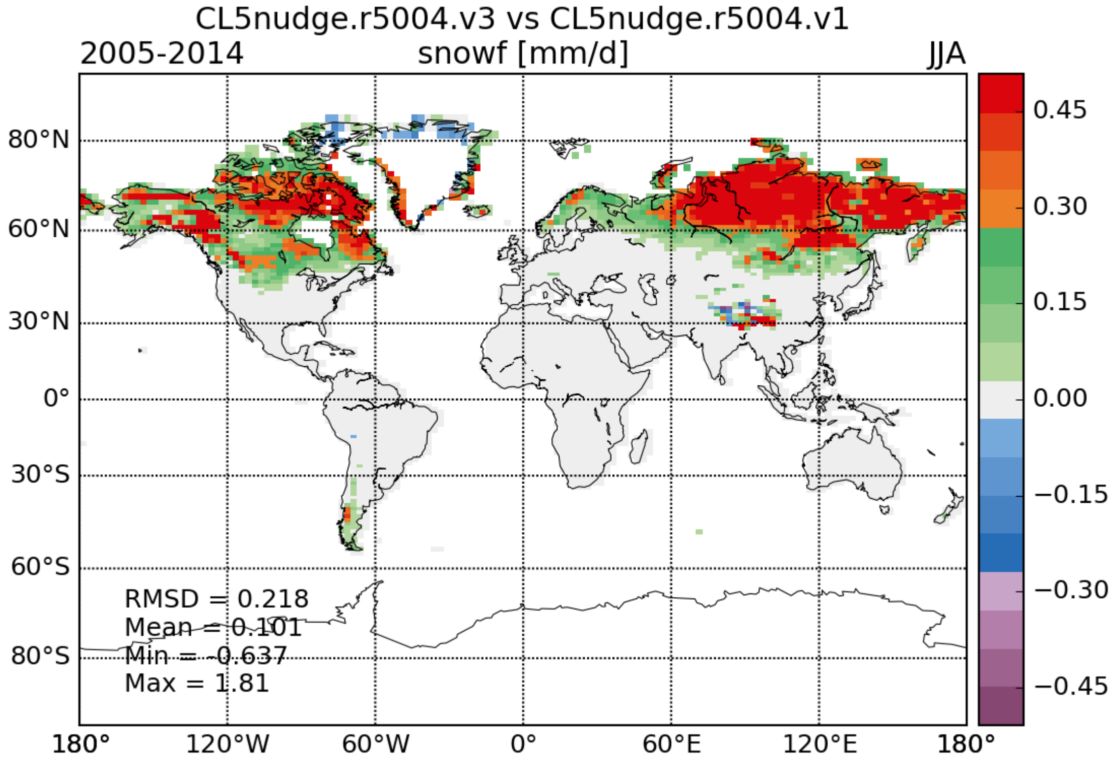
‘freezing’ minus ‘no freezing’

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)







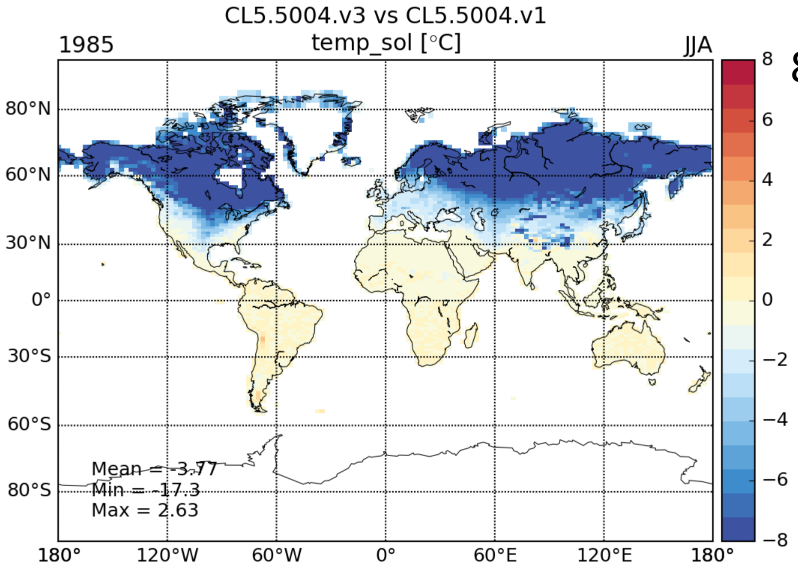
Delta snow cover (summer, mm/d):

'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

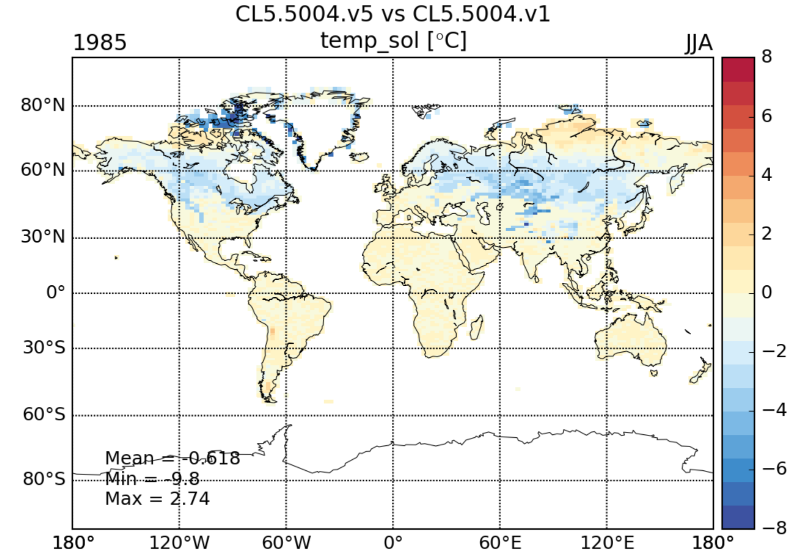
Standard soil conductivity



Delta Surface Temperature (summer, °C):

'freezing' minus 'no freezing'

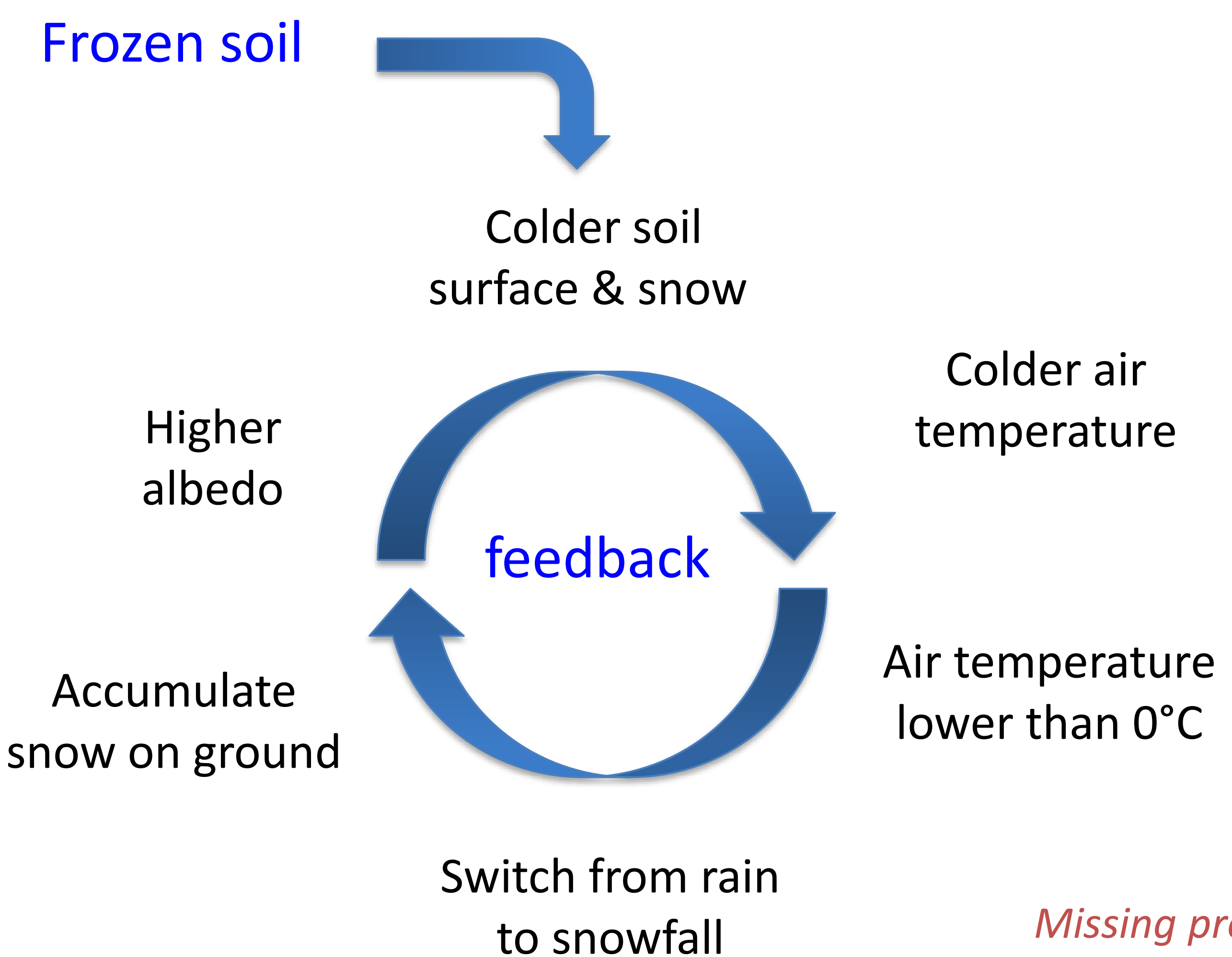
decrease conductivity for upper 10 cm (to that of mosses)



Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time

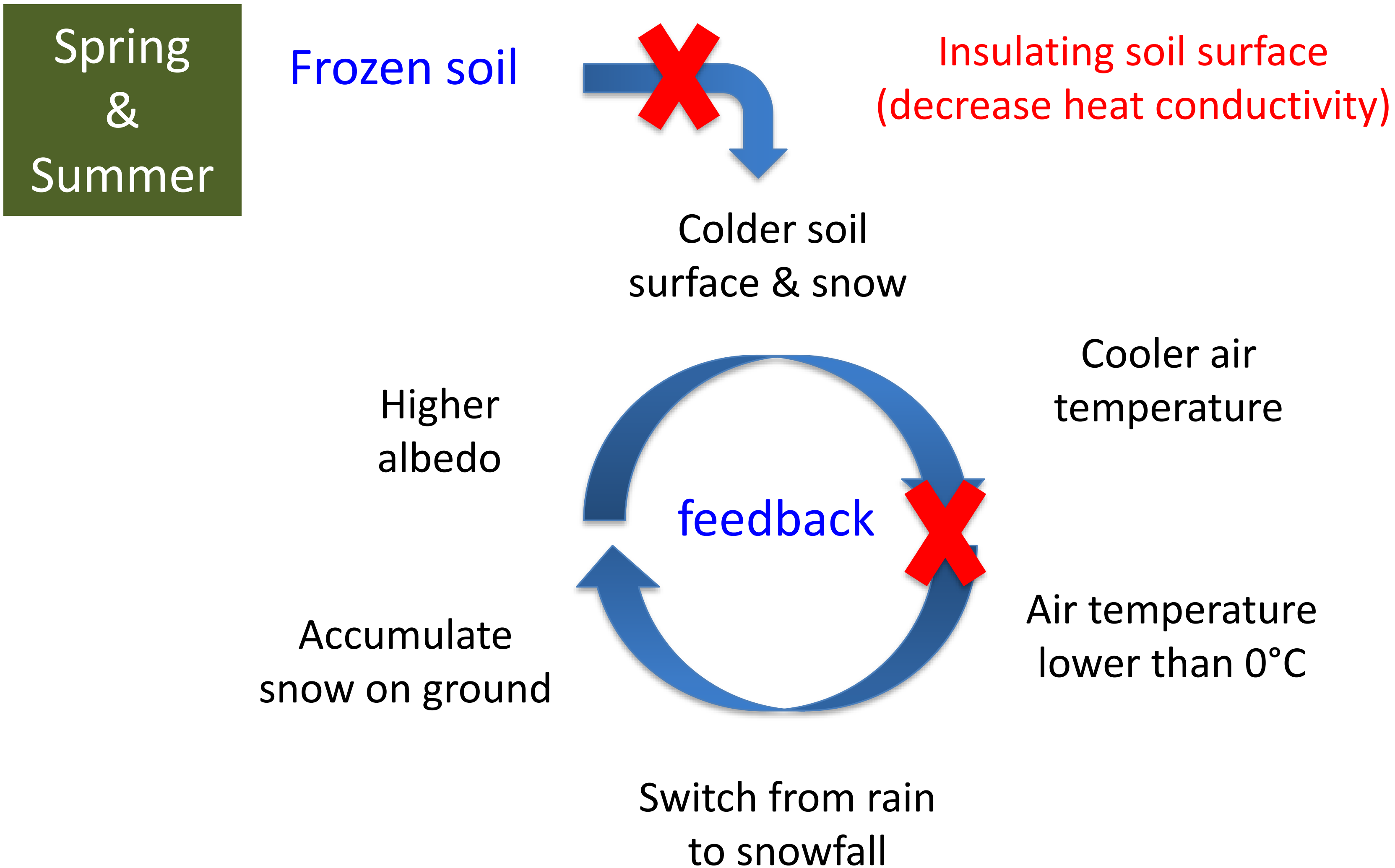
Spring
&
Summer



Missing processes: carbon and mosses insulation !

Soil freezing : coupled simulations

➔ Large feedback loop during spring/summer time



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