Land Surface: Part III
Introduction to cold processes

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Outlines

- **Snow in the climate system, an overview**

- **Snow representation in the ECMWF model:**
  - Energy/Water balance
  - Density/ Albedo / Snow cover fraction
  - Challenges of the current formulation

Snow in the climate system

- Snow cover is the seconds largest component of the Cryosphere (after seasonally frozen ground) with a mean maximum areal extend of 47 million km^2 (98% in the Northern Hemisphere, and 1/3 of the total land);

- Several fundamental physical properties of snow modulate the energy/water exchanges between the surface and the atmosphere:
  - Surface reflectance:
    - Albedo, snow-albedo feedback.
  - Thermal properties (snow insulation):
    - Effective de-coupling of heat and moisture transfers.
  - Phase changes:
    - Delayed warming during the melt period.

➢ Implications for all forecasts ranges (medium to seasonal).

➢ Predictability impact.

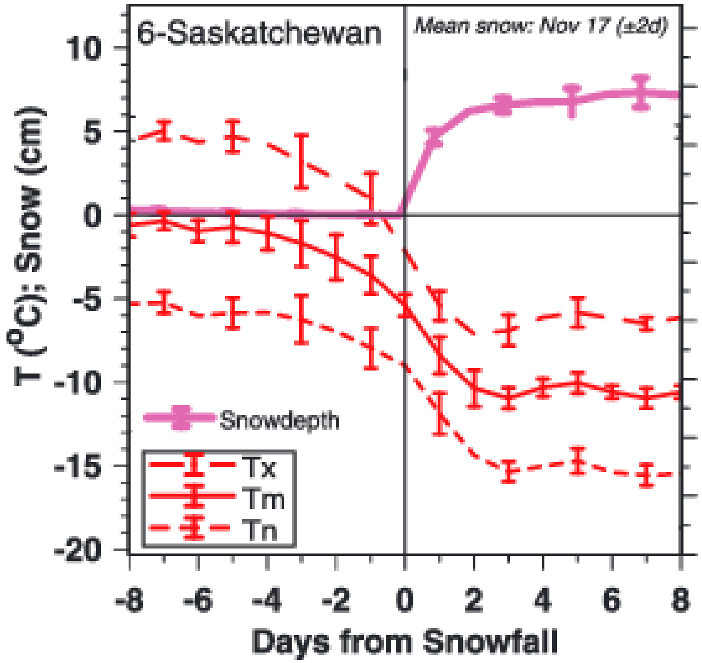
➢ Climate change impacts.

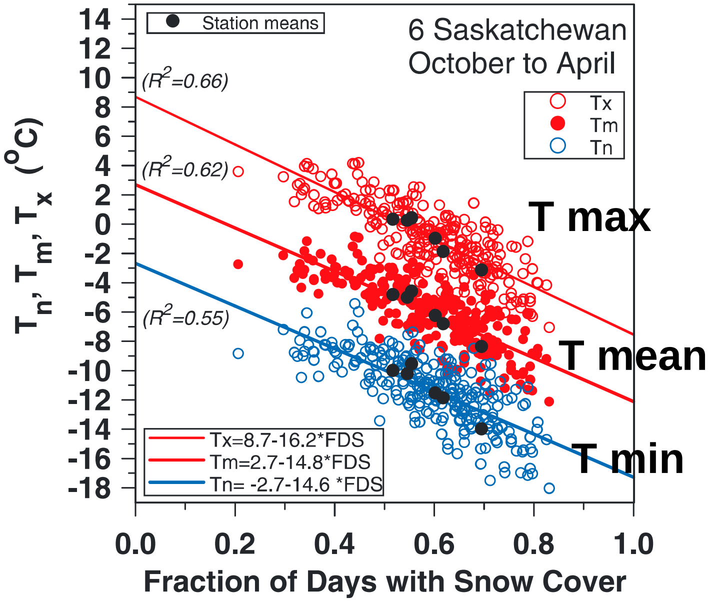
(see Armstrong and Brun (2008) for a good reference of snow and climate)

Impact of snow on near-surface temperature (observations)

Snow cover acts as a fast climate switch on near-surface air temperature.

- **Near-surface air temperature (min, max, mean) drops/rises of ~10 C during snow transitions (accumulation and ablation),** mainly due to changes in the net shortwave (albedo affect).

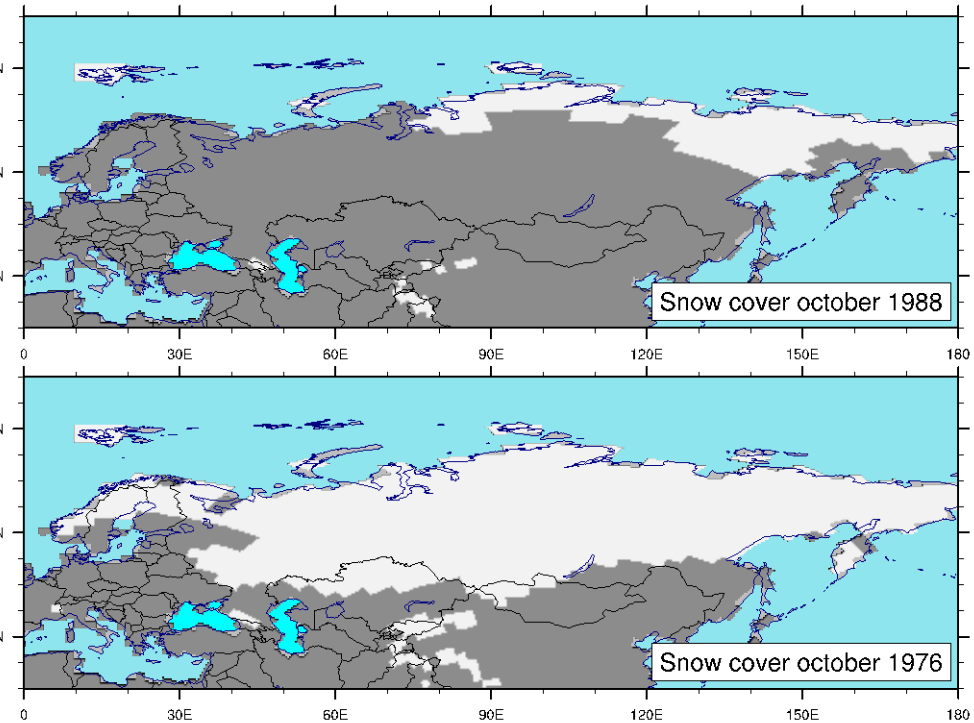




Climatology for six climate stations in the Canadian Prairies all having more than 30 years of data

Adapted from Betts et al 2014

Snow cover and NH variability



Snow cover extent from NOAA/NESDIS visible satellite observations

In addition to cover a substantial part of the Northern hemisphere snow cover shows

- large inter-annual variability, in particular during the accumulation period (e.g. Mid October)

This has been widely studied as potential source of long-range predictability

- Can these anomalies in snow cover in October influence winter circulation in NH?

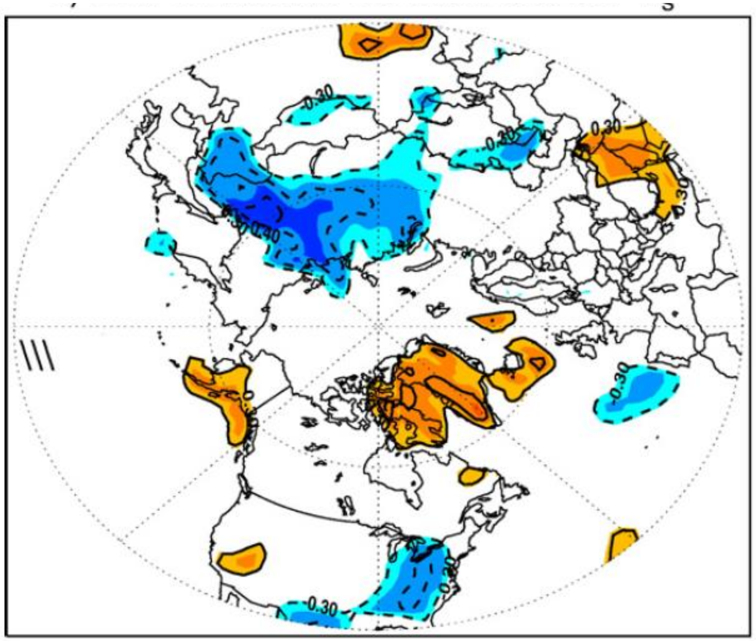
Other teleconnections:

- Potential link between snow cover in Eurasia and Indian summer monsoon (see Peings and Douville 2010)

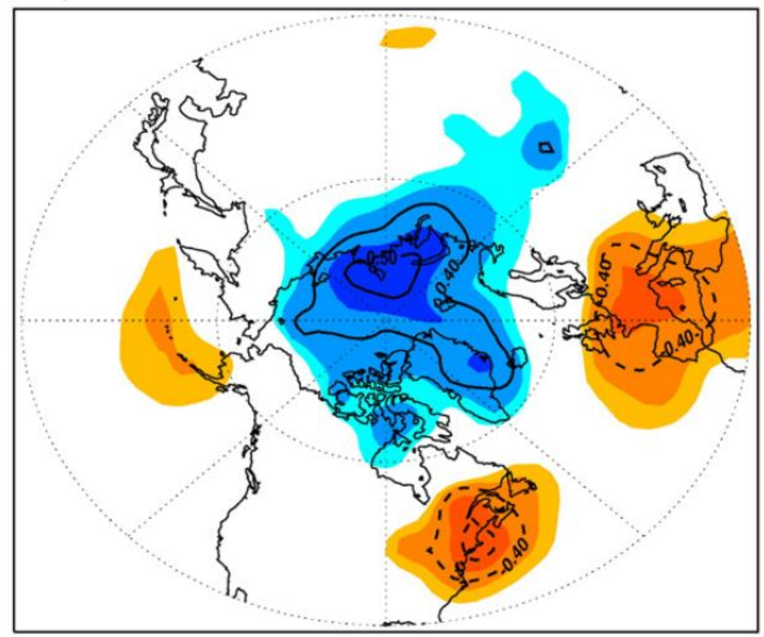
Snow cover and NH variability

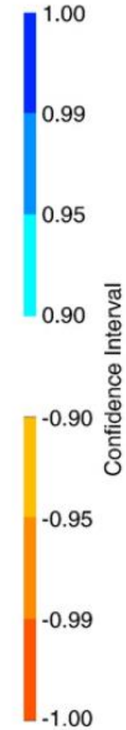
October snow cover anomalies (Eurasia) correlated with

Winter (DJF) surface temperature



Winter (DJF) sea level pressure

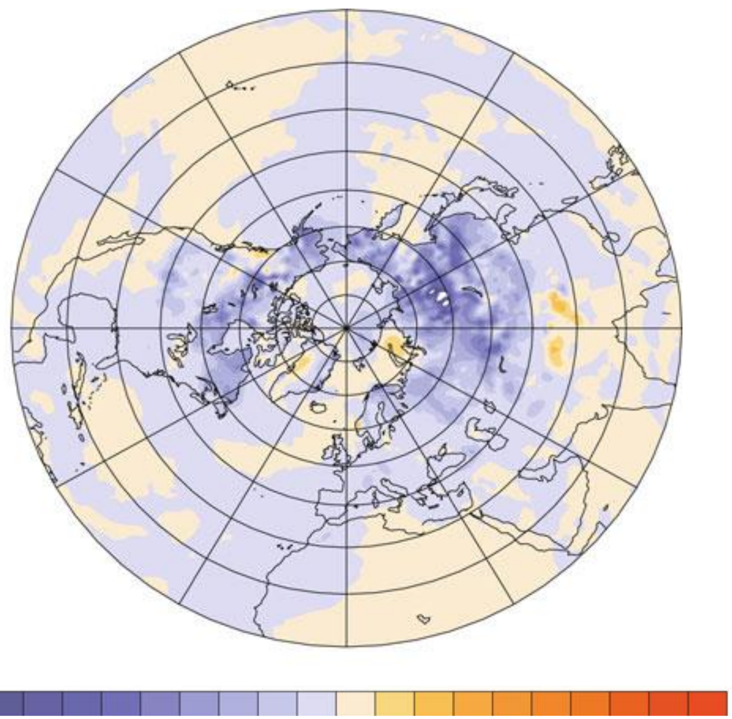




(Cohen and Saito 2003, Gong et al. 2007)

- The spatial anomaly patterns resemble the Artic Oscillation pattern of variability
- This allows the development of statistical prediction models for winter variability based on early Autumn snow cover

Impact of snow on near-surface temperature (modelling)



-4 0 +4

Temperature difference (K)

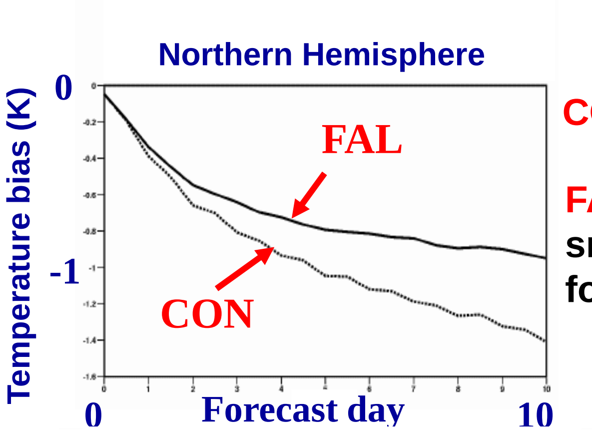
(Adapted from Orsolini et al. 2013)

- A **thicker** snowpack leads to **colder near-surface temperatures** (up to 4K in this example), because of the **stronger insulation** of the lower atmosphere from the warmer soil below

Ensemble-mean 2m-temperature difference at day 15, between ensemble of simulations initialized with **larger values** of snow depth and ensemble initialized with **lower values** of snow depth

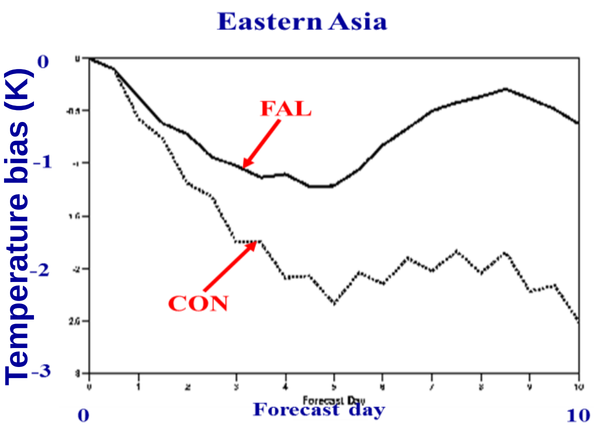
Medium-range Case study: Boreal forest albedo

850 hPa temperature bias
20 forecasts every 3 days, March-April 1996
No data assimilation



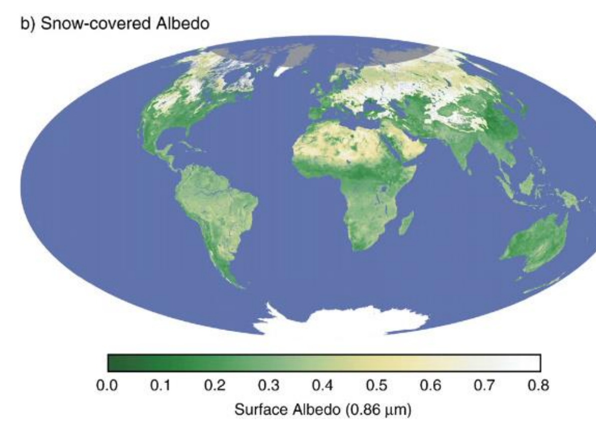
CON: control exp

FAL: lower value of snow albedo over forest



Viterbo and Betts 1999

- Snow covered boreal forests have a much lower albedo than snow-covered grassland to their south and tundra to their north; the presence of boreal forests has a direct control on the climate of high-latitudes.



Considering a lower value of snow Forest ALbedo was beneficial.

Moody et al 2007

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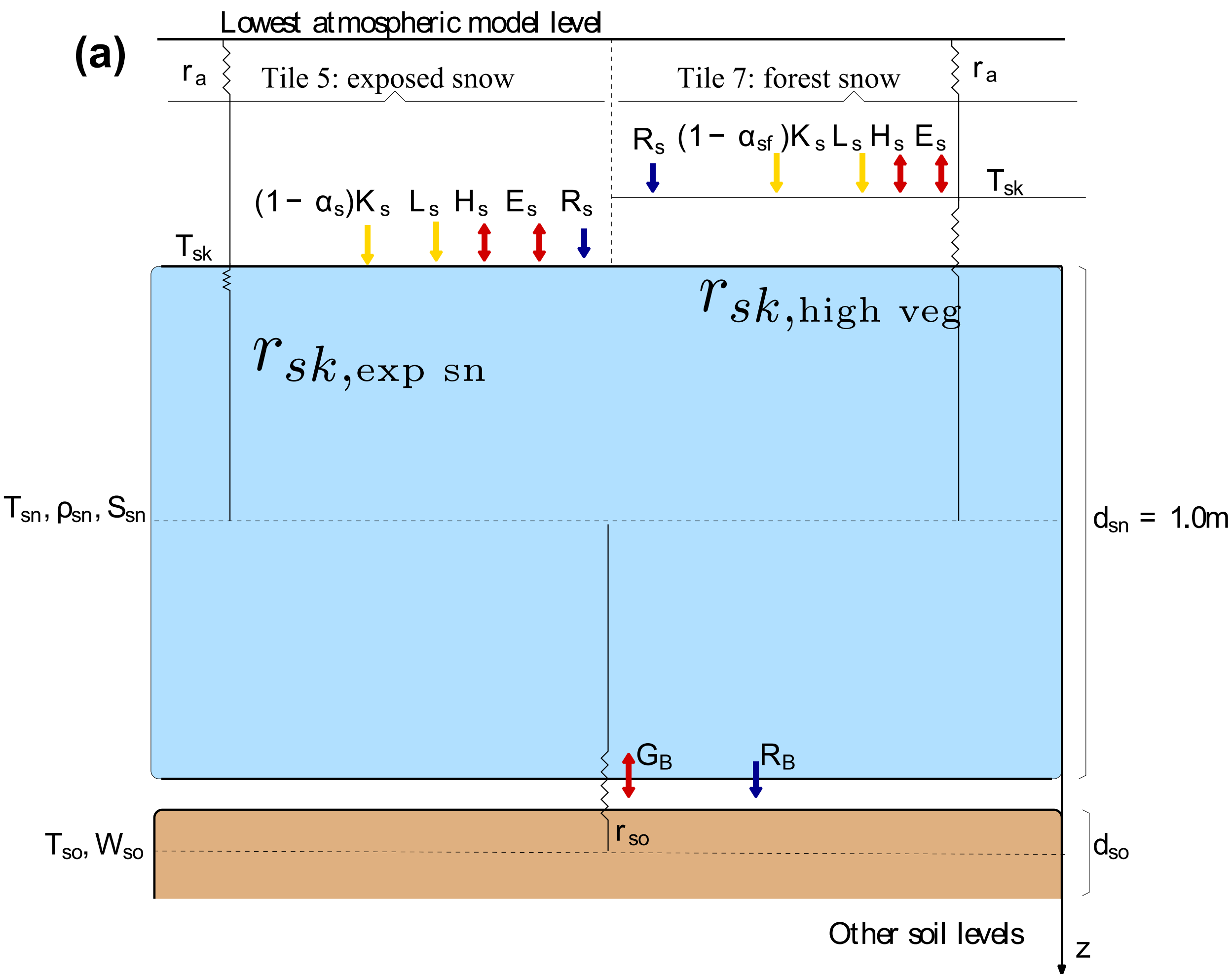
Snow at ECMWF – the HTESSEL land-surface scheme



Two tiles:
1) **Exposed snow;**
2) **Snow under high vegetation**

Single layer snow-pack

Prognostic evolution:
1) **Snow mass (snow water eq.)**
2) **Snow density**
3) **Snow temperature**
4) **Snow Albedo**

Diagnostics:
1) **Snow depth**
2) **Snow cover fraction**
3) **Liquid water content**

See Dutra et al. 2010 for more details

Energy balance of the snowpack in HTESSEL

Net radiation | Latent | Sensible | Basal | Melting

$$(\text{Heat capacity}) \frac{\partial T_{sn}}{\partial t} = \boxed{R_{sn}^{N} - L_s E_{sn} - H_{sn}} - \boxed{G_{sn}^{B}} - L_f M_{sn}$$

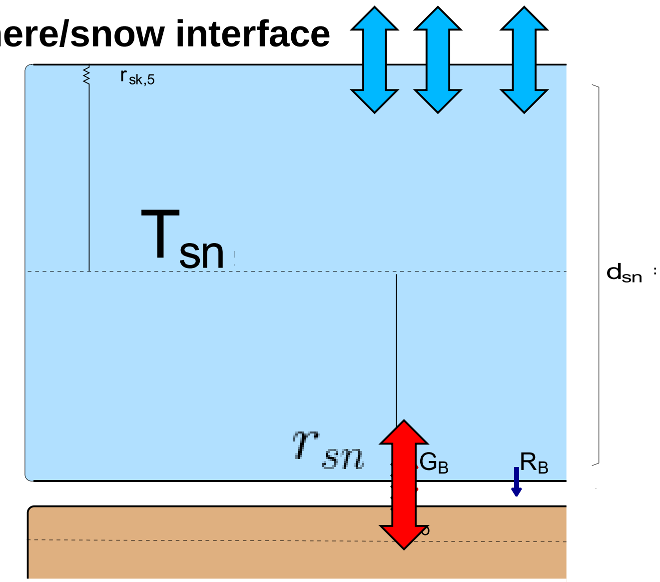
↑ Layer-averaged snow temperature

$$G_{sn}^{B} = \frac{(T_{sn} - T_{so})}{r_{sn}}$$

$$r_{sn} = \frac{0.5 d_{sn}}{\lambda_{sn}} + \frac{1}{\Lambda_{so}}$$

Snow conductivity Soil **skin** conductivity

Atmosphere/snow interface



R_{sn}^{N} : heat flux due to net radiation

$L_s E_{sn}$: Latent heat flux due to snow sublimation

H_{sn} : Sensible heat flux due to turbulent processes

G_{sn}^{B} : basal heat flux in/from the soil due to conduction

$L_f M_{sn}$: Latent heat flux due to snow melting

Heat capacity and snow temperature tendency

$$\left\{ \textbf{Heat capacity} \right\} \frac{\partial T_{sn}}{\partial t}$$

The change with time of the energy of the snowpack is the product of the snow heat capacity and the variation with time of the layer-averaged snow temperature.

↓

Total snow heat capacity is composed by two terms

(1) ↙ ↘ **(2)**

Snow depth

$$\left[(\rho C)_{sn} D_{sn} \right.$$

Volumetric Snow heat capacity

Heat capacity and snow temperature tendency

Heat capacity $\frac{\partial T_{sn}}{\partial t}$

The change with time of the energy absorbed by the snowpack is the product of the snow heat capacity and the variation with time of the layer-averaged snow temperature.

Total snow heat capacity is composed by two terms

(1) **Snow depth**

$$\left[(\rho C)_{sn} D_{sn} \right]$$

Volumetric Snow heat capacity

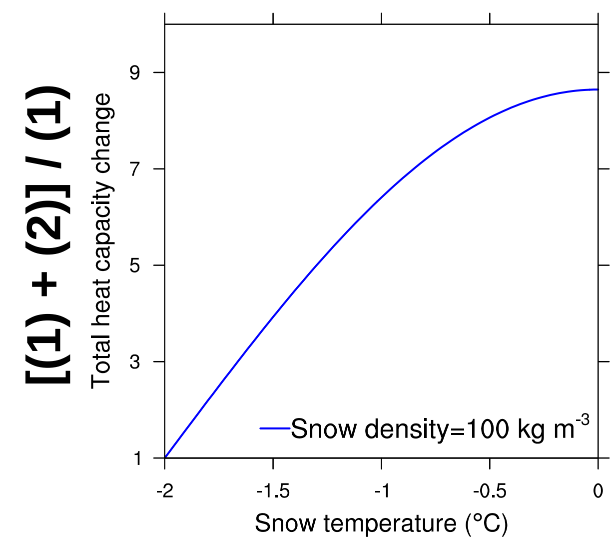
(2)

$$L_f S_l^c \frac{\partial f(T_{sn})}{\partial T_{sn}}$$

Heat capacity barrier

Diagnostic liquid water — Liquid water capacity

$$S_l = S_l(T_{sn}, S, \rho_{sn}) \approx f(T_{sn}) S_l^c(S, \rho_{sn})$$



ECMWF

Water balance

Snow mass

$$\frac{\partial S}{\partial t} = F + c_{sn} F_l - c_{sn} E_{sn} - R_{sn}$$

Snowfall **Rainfall** **Sublimation** **Snow runoff**

- **Rainfall and Sublimation only over the snow cover fraction**
- **Rainfall reaches the snow at freezing point**
- **Runoff is the rate at which liquid water leaves the snowpack**
- **Runoff is generated when the liquid water content exceeds the snow liquid water capacity**

Snow density evolution

$$\frac{1}{\rho_{\mathrm{sn}}}\frac{\partial\rho_{\mathrm{sn}}}{\partial t} = \frac{\sigma_{\mathrm{sn}}}{\eta_{\mathrm{sn}}(T_{\mathrm{sn}},\rho_{\mathrm{sn}})} + \xi_{\mathrm{sn}}(T_{\mathrm{sn}},\rho_{\mathrm{sn}}) + Q_{\mathrm{sn}}^{\mathrm{INT}}$$

On the right hand side of the equation:

- 1st term: overburden : increase of density due to the snow weight
- 2nd term: thermal metamorphism: change of shape of snow crystal with time
- 3rd term: Increase of density due to internal melting → diagnostic liquid water

Thermal metamorphism is parametrized as a function of snow temperature and density. **No explicit simulation of snow metamorphism**

Snow density evolution

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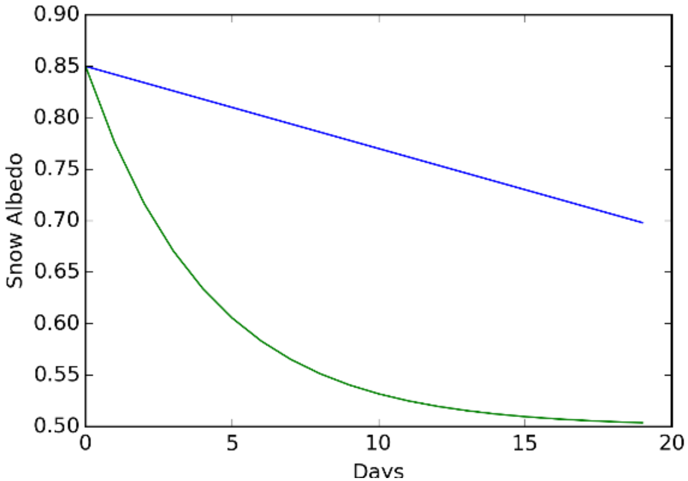
What about new snow after a snowfall?

- New snow density updated after snowfall;
- Snowfall density (ρ_{new}) as a function of Wind speed and air temperature.

Snow albedo evolution over open/exposed area

For snow in exposed area snow albedo is a prognostic field, computed using an empirical parametrization for snow aging

$$\alpha_{sn}^{t+1} = \begin{cases} \alpha_{sn}^{t} - \tau_a \Delta t/\tau_1, & M_{sn} = 0 \\ (\alpha_{sn}^{t} - \alpha_{min}) \exp(-\tau_f \Delta t/\tau_1) + \alpha_{min}, & M_{sn} > 0 \end{cases}$$



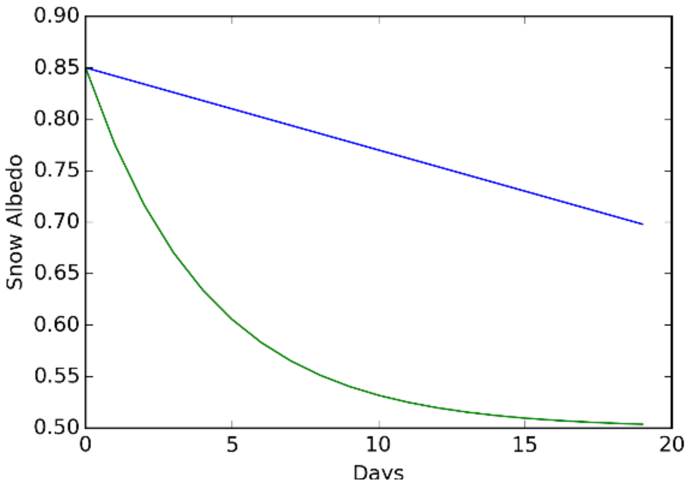
The rate of change of albedo depends on the snow conditions:

- **Non melting:** linear decay (**blue line**);
- **Melting conditions:** exponential (**green line**);

- In melting conditions snow gets darker at a faster rate.
- A parametrization based on snow microphysical properties (optical diameter) would be more appropriate to avoid the coupling between albedo and snow temperature

Snow albedo evolution over open/exposed area

For snow in exposed area the temporal evolution of snow albedo is computed at each time-step using an empirical parametrization for snow aging



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What about new snow after a snowfall?

- Albedo is updated after every snowfall
- The increment depends on the amount of snow that falls: for 10kg/m^2 of snow the albedo is increased to the maximum value (0.85)

Snow albedo evolution in forest area

In high vegetation area (forests) the snow albedo is fixed to a constant value depending on the vegetation type (look-up tables)

- **Derived from Satellite data**
- **Neglect seasonal variations**
- **Neglect snow interception by the canopy**

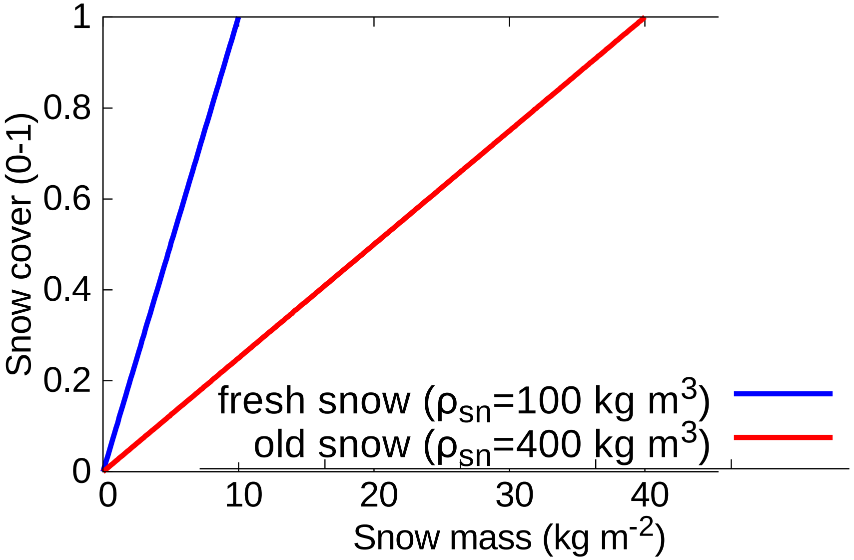
Vegetation type	Albedo
Evergreen needleleaf trees	0.27
Deciduous needleleaf trees	0.33
Deciduous broadleaf trees	0.31
Evergreen broadleaf trees	0.38
Mixed forest–woodland	0.29
Interrupted forest	0.29

- **For snow under high vegetation the albedo is much lower than over exposed area.**

Snow cover fraction

Snow cover fraction is the part of a grid cell of the model covered by snow.
It is parametrized as a function of snow mass and density:

$$c_{sn} = \min\left(1, \frac{S/\rho_{sn}}{0.1}\right)$$



We assume that when there are 10cm of snow on the ground, then the grid cell is completely covered by snow:

- **Affects the tile fraction: direct albedo effect**
- **Energy balance indirectly**

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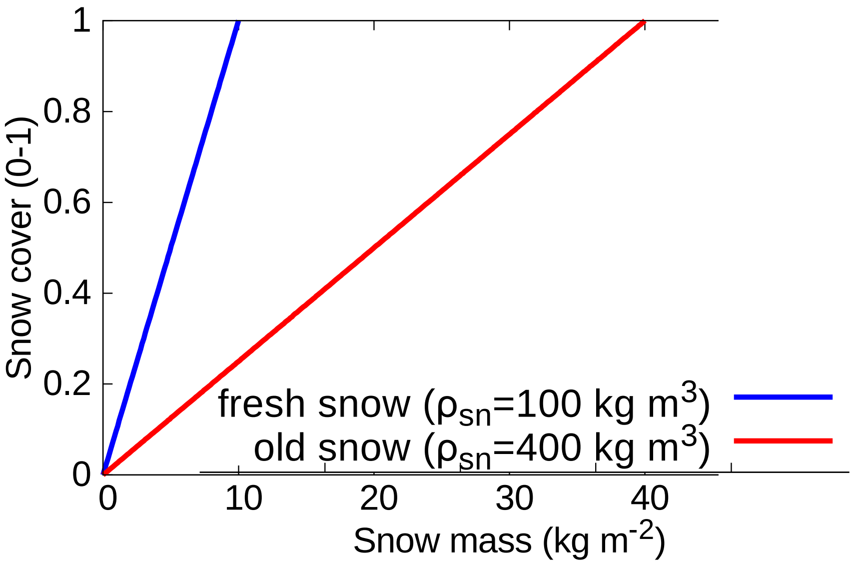

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- **Affects the tile fraction: direct albedo effect**
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➔ The actual snow depth, is normalized by snow cover fraction (as used by the energy balance), **leading to a depth barrier at the 10cm**

actual snow depth:

$$D_{sn} = \frac{1}{\rho_{sn}} \frac{S}{c_{sn}}$$

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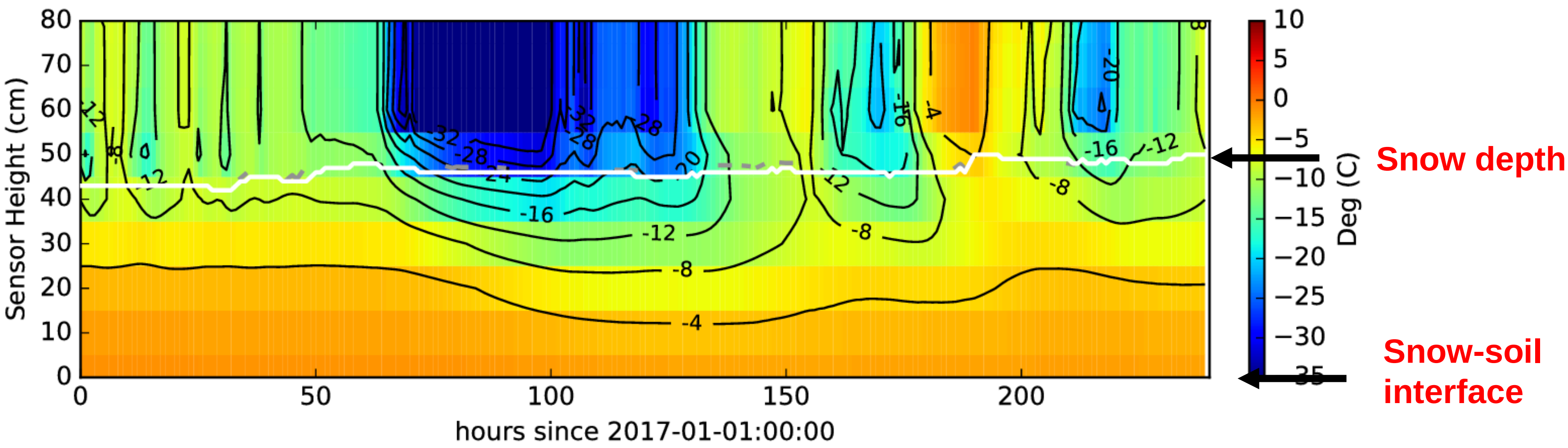
Challenges of the single-layer snow scheme

Snow is a porous medium characterized by large internal vertical gradients of temperature and density

- These cannot be represented using a single snow layer!

Measured temperature profiles within the snowpack (below white line) and air temperature (above white line)



Observations in Sodankyla, Finland, 67N
From 1st Jan 2017 to 10th Jan 2017.

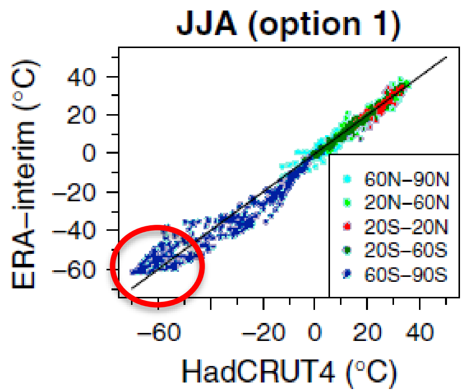
Thanks to Jonathan Day for the figures

ECMWF

Challenges in the coupled model (ERA-I)

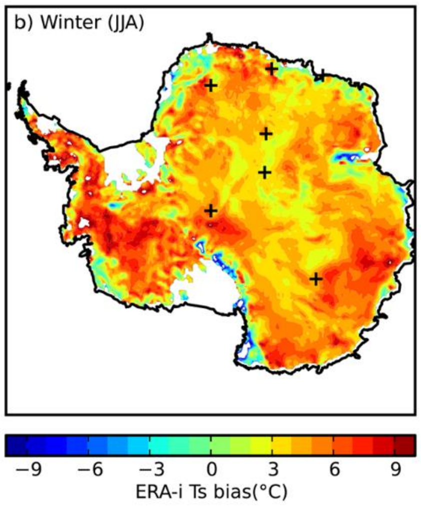
Several studies reported a warm bias of surface & T2m in Antarctica during the polar night

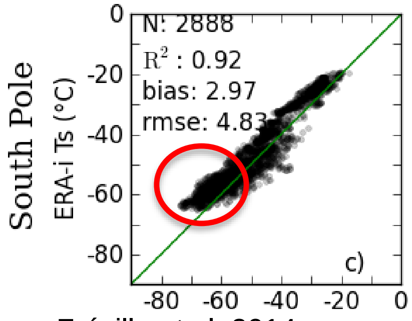
- Can it be associated with the surface turbulent fluxes under very stable conditions?
- Land-atmosphere coupling (too large snow thermal inertia)?



Mitchell & Jone 2005
T2m ERAI vs HadCRUT4

Fréville et al. 2014
Skin temperature vs MODIS

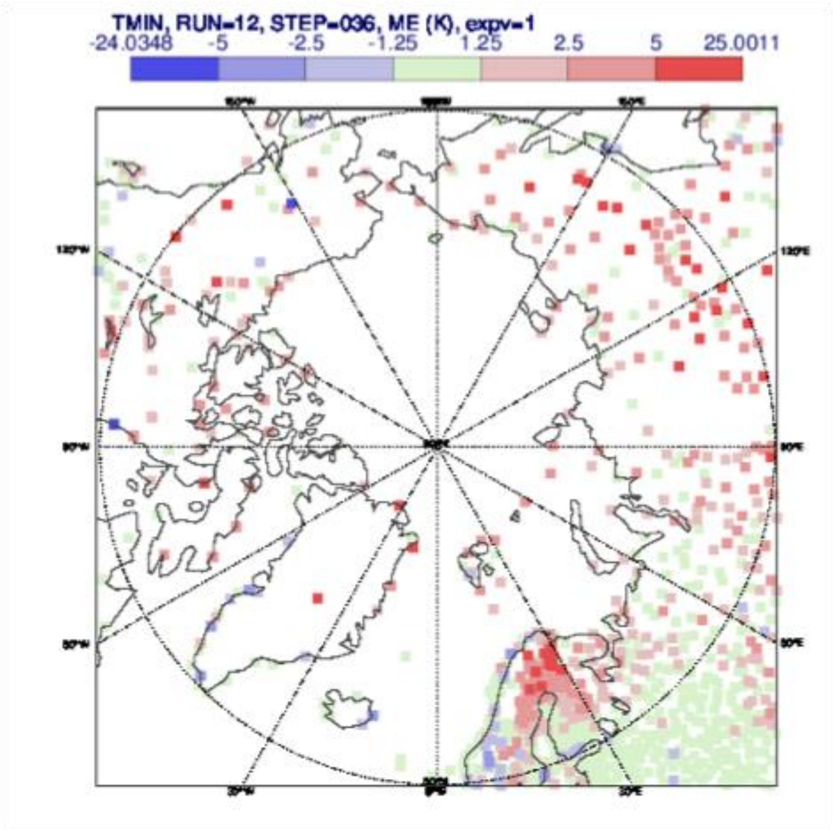




Fréville et al. 2014
Skin temperature vs MODIS

Challenges in the coupled model (Operational)

Mean error in daily minimum temperature January-March

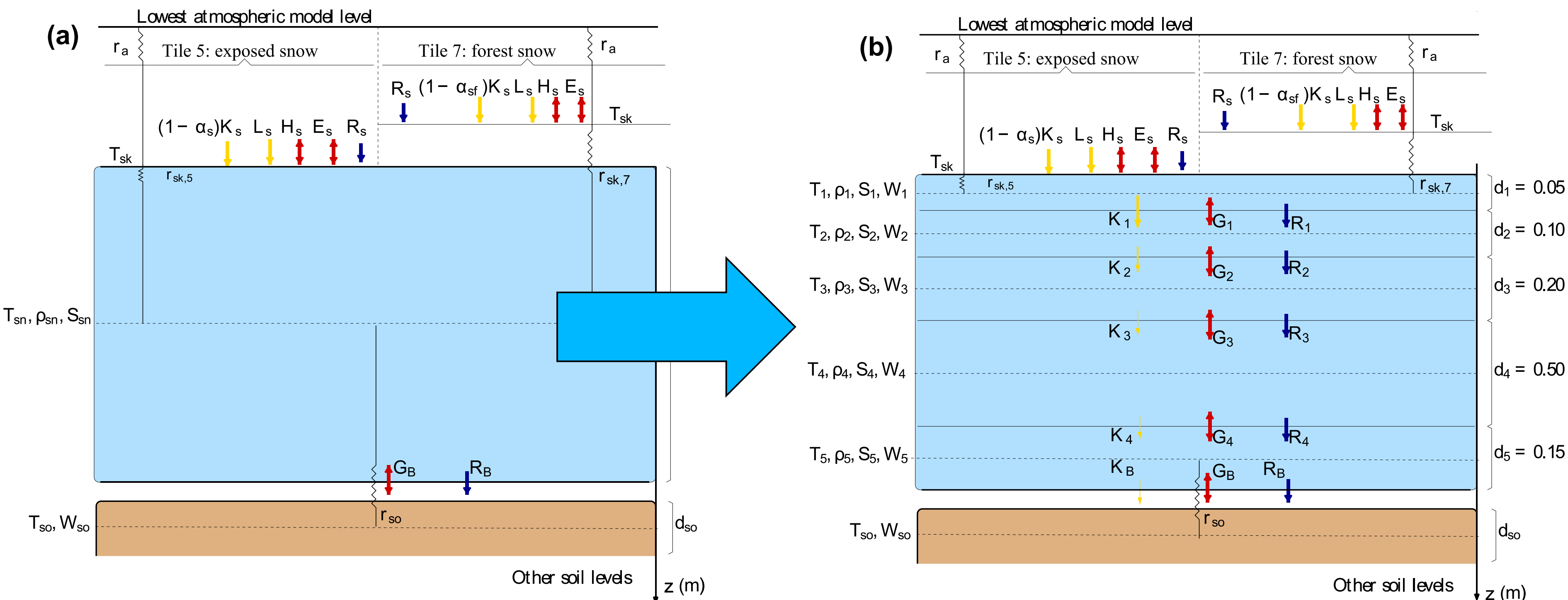


- Wintertime minimum temperature is generally overestimated (warm bias) over the Arctic region

From one single-layer to multiple vertical layers…

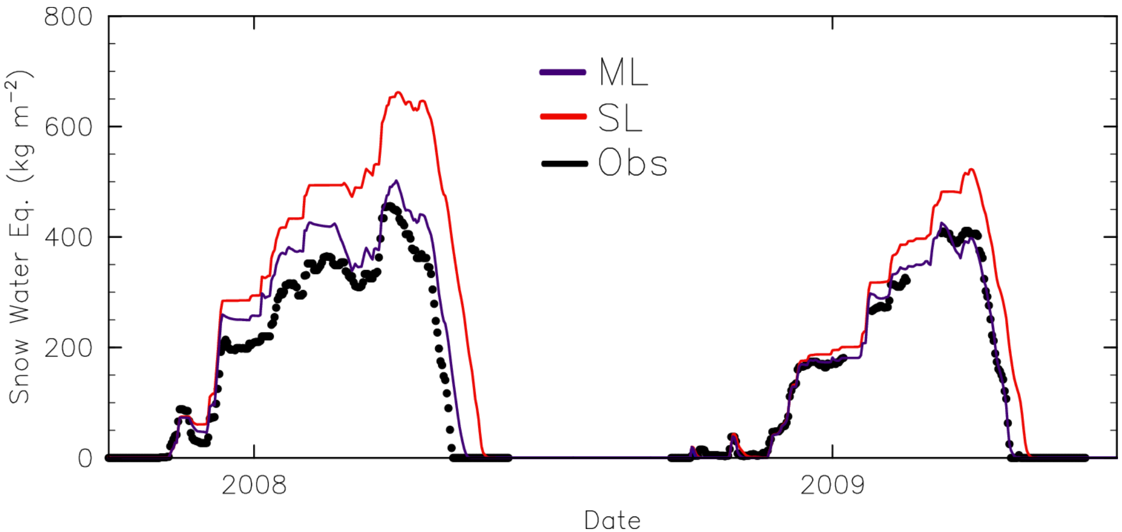
Using one vertical layer to represent the snow implies that thick snowpack have a large thermal inertia. Using more than one vertical layer (multi-layer) to discretize the snowpack enables:

- a better description of the internal thermal properties of the snow (temperature and density gradients)
- to represent fast time-scales at the snow-atmosphere interface (reduced thermal inertia) → enhanced representation of radiative cooling events



Simulations with single and multi-layer snow schemes (offline)

Point simulations (offline) at Col de Port an open area in the French Alps



SL : current single-layer snow scheme

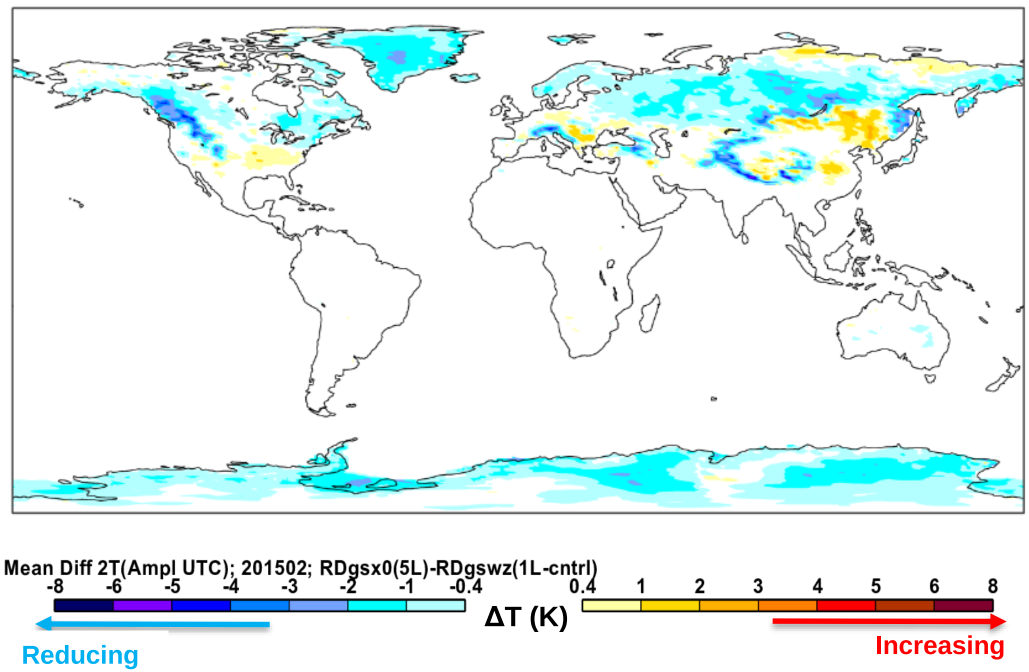
ML: new multi-layer snow scheme

Better simulations of snow mass using multiple vertical layers (up to 5):

- Melting events during the season better represented because of lower thermal inertia of top snow layer
- Improved timing of ablation

Simulations with single and multi-layer snow schemes (coupled)

Difference of the minimum 2-metre temperature for Feb 2015 between **coupled** simulations performed using the **multi-layer snow** scheme and a **single-layer scheme**



- Simulation at horizontal resolution ~36km and 137 vertical levels;

  Continuous simulations over a full year (2015) nudged towards the reanalysis in the upper troposphere

Summary

- **Snow is a major component of the climate system. Because of its unique properties, snow impacts all forecast ranges, from the medium range to seasonal.**
- **Physically-based snowpack schemes solving the energy and mass balances, are used in numerical weather predictions to simulate the space-time variability of snow and the coupling with the atmosphere.**
- **More physical complexity in the snow scheme is required to resolve snow-related processes on a range of time-scales from (sub)-diurnal to seasonal.**