Land Surface: Snow

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Outline

- Snow in the climate system, an overview:
  - Observations;
  - Modeling;
  - Forecasts impact.
- Snow representation in the ECMWF model:
  - Energy/Water balance;
  - Density/ Albedo / Snow cover fraction;
  - Evaluation examples.
- Ongoing & future work.

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:**
    - **Effective de-coupling heat and moisture transfers.**
  - **Phase changes:**
    - **Delayed warming during the melt period.**

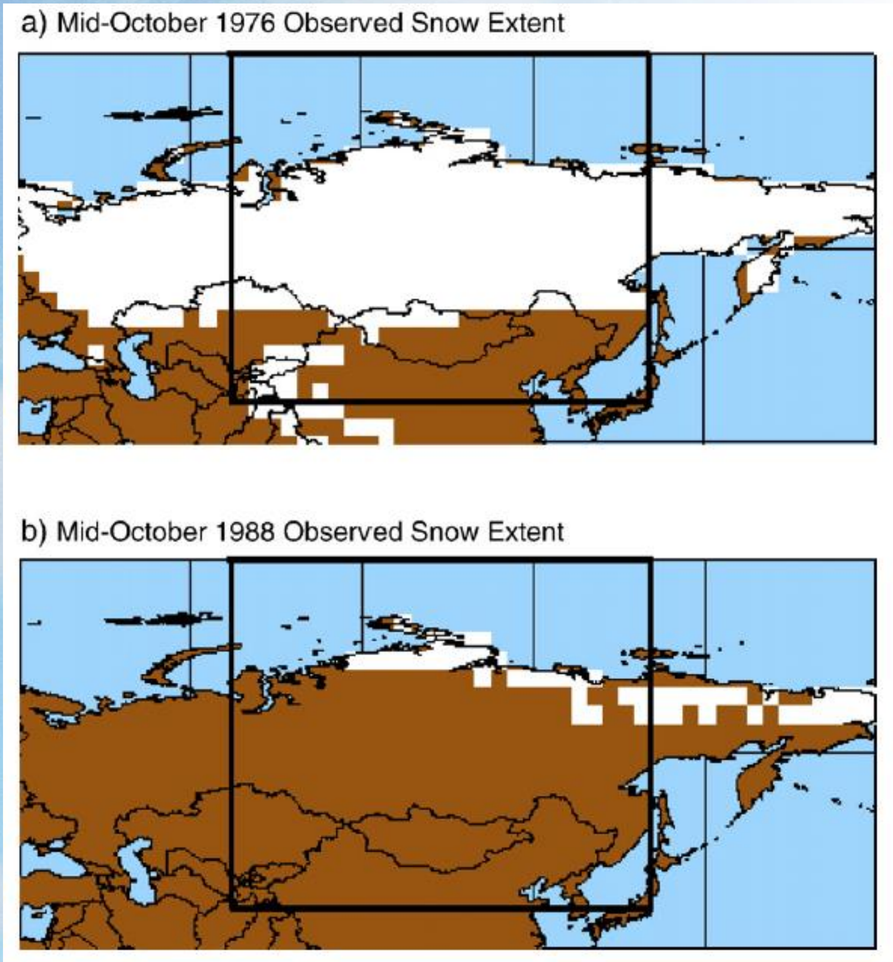
– **Implications for all forecasts ranges (medium to seasonal).**

– **Predictability impact.**

– **Climate change impacts.**

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

Snow cover and NH variability - observations



(Gong et al. 2007)

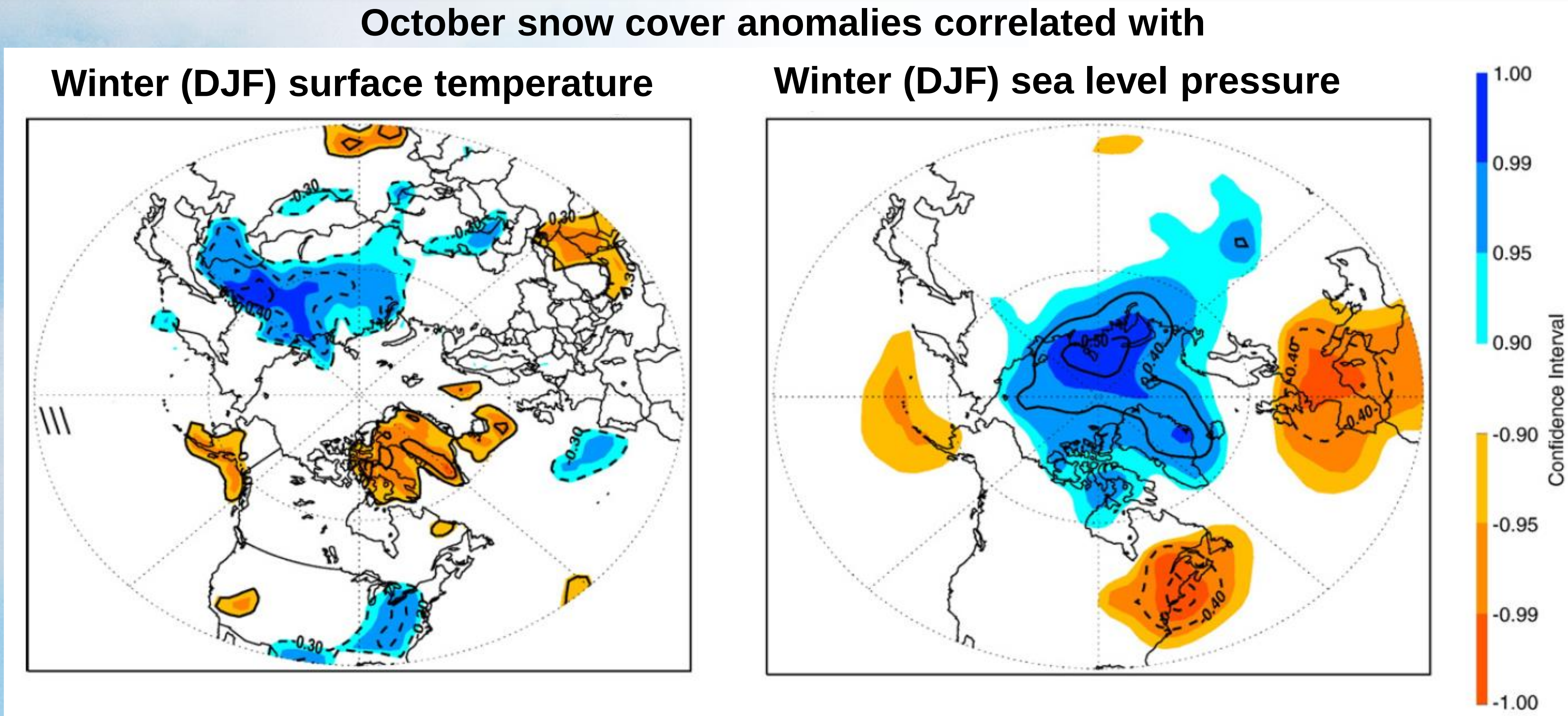
- In addition to cover a substantial part of the Northern hemisphere,
- Large inter-annual variability
- In particular during the accumulation period (e.g. Mid October)

- This has been widely studied as potential source of long-range predictability
- Can these anomalies in snow-cover in October influence Winter circulation ?

Other teleconnections:

- Snow cover in Eurasia and Indian summer monsoon: questionable (see Peings and Douville 2010)

Snow cover and NH variability - observations



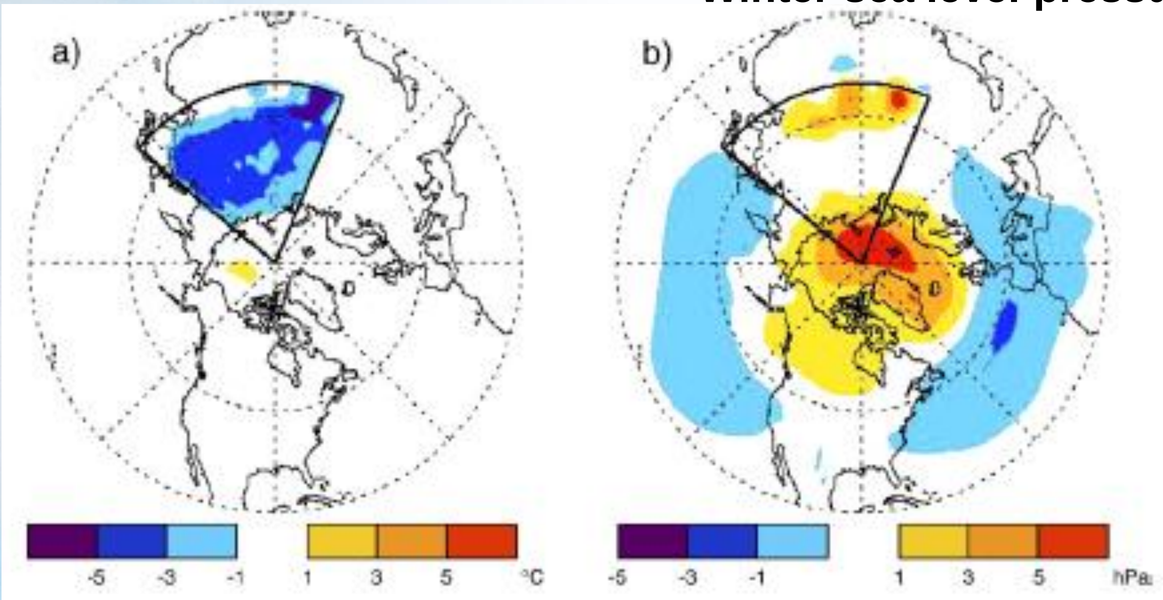
(Gong et al. 2007, Cohen and Saito 2003)

- **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 that beat current dynamical seasonal forecast systems (why… ?)**

Snow cover and NH variability – modeling studies

- **Experiment with high (low) snow cover in the Siberia region during Autumn (high-low):**

Autumn surface temperature response **Winter sea level pressure response**

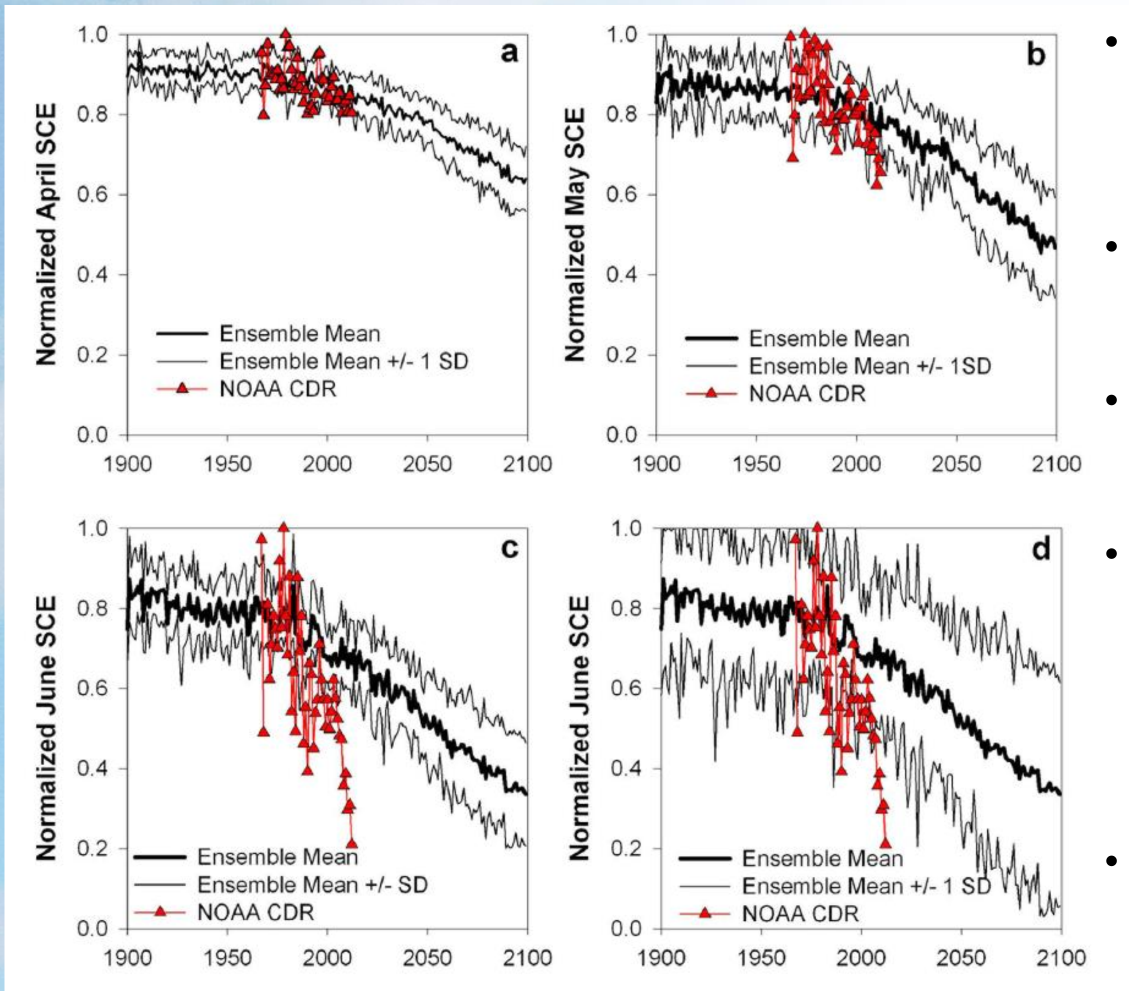


(Gong et al. 2007)

- **Cooling of surface temperature restricted to the region where snow was imposed during Autumn ;**

- **Hemispheric scale response latter in winter. See Gong et al. (2007) for a detailed chain of events from the surface cooling to a weakening of the stratospheric polar vortex and latter changes in the zonal wind anomalies in mid-latitudes in the troposphere.**

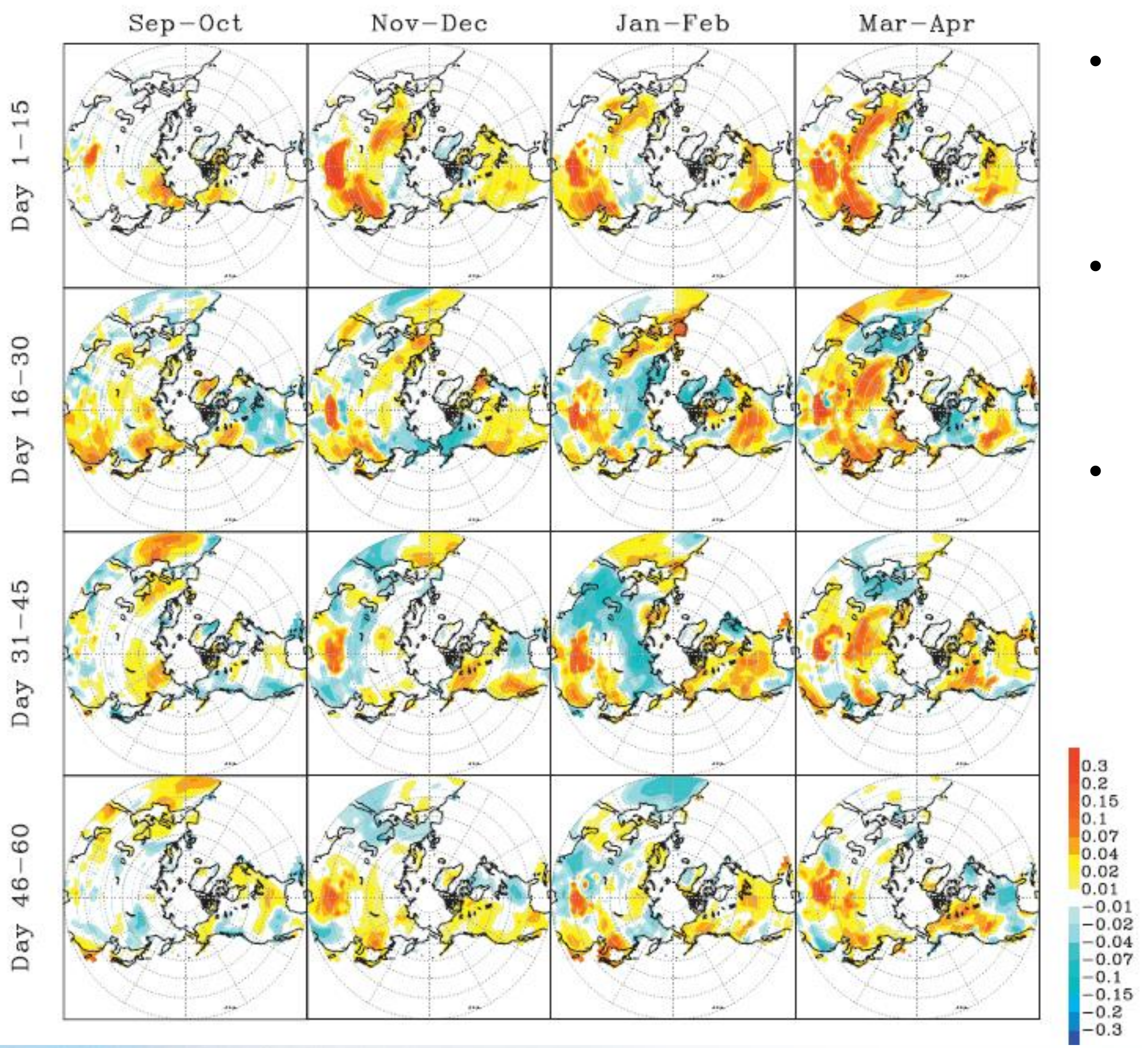
Trends and climate change implications



(Derksen and Brown 2012)

- **Snow cover extent in the N.H land:**
  - **Red satellite data**
  - **Black CMIP5 mean**
- **Normalized by maximum extend in each month**
- **April/May observed trends are within the CMIP5 range#**
- **June observed trend is very large in the last years and not captured by any model (models only get there around 2050 !)**
- **What are the models (we) missing?**

Snow initialization and sub-seasonal forecasts



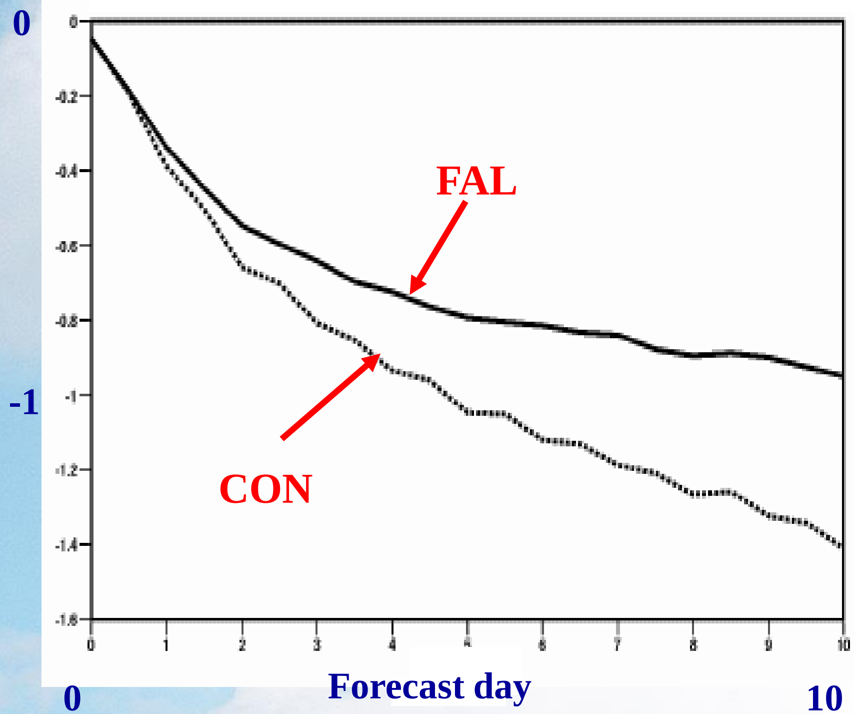
- **Changes in potential predictability r^2 between initializing snow depth or not**
- **General increase of about 10% in particular during the first month.**
- **In this study the signal in actual predictability is smaller, but there is still some signal..**

Jeong et al. 2012

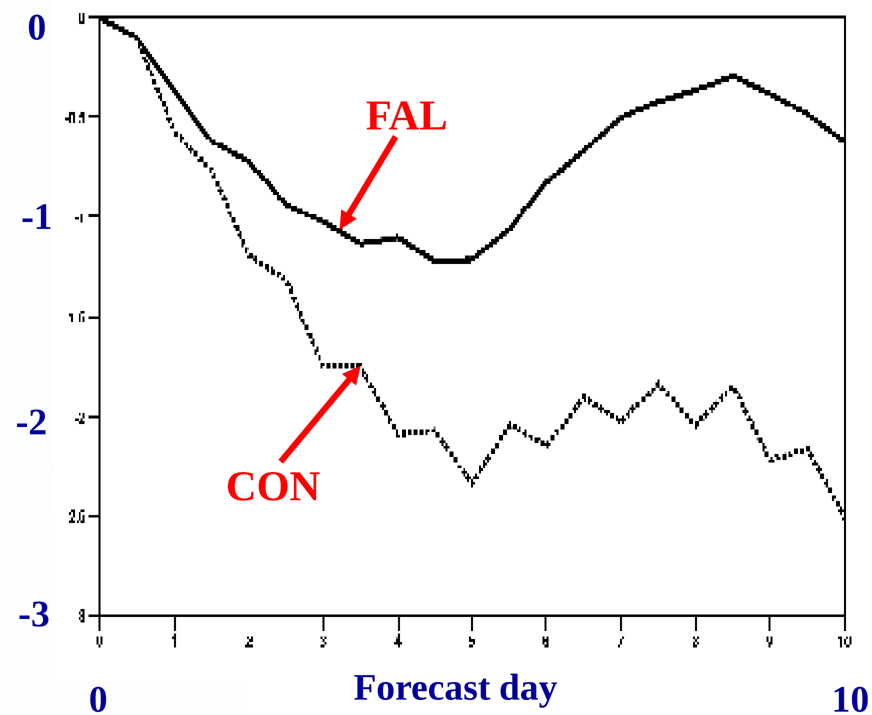
Case study: Boreal forest albedo (2)

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

Northern Hemisphere



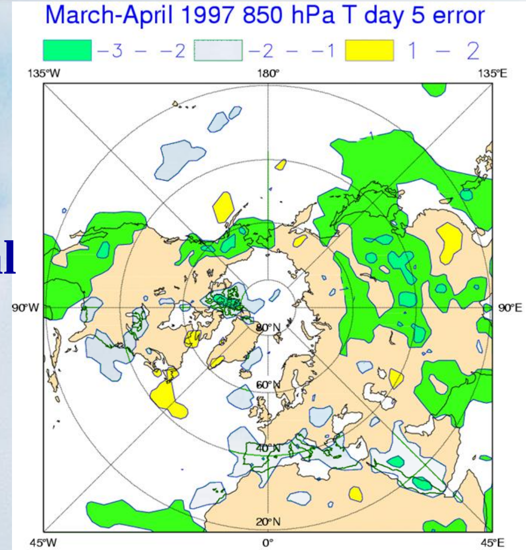
Eastern Asia



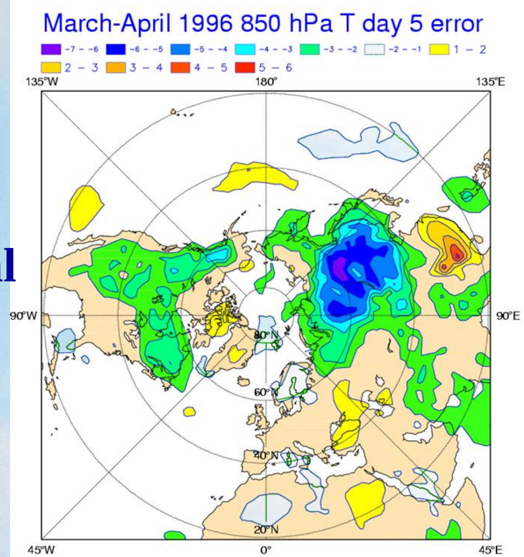
Considering a lower value of snow Forest ALbedo was beneficial.

Case study: Boreal forest albedo (3)

1997 Operational Bias (FAL)



1996 Operational Bias (CON)



- The surface albedo is the direct regulator of the energy available to the surface. The albedo of natural surfaces has a limited range (0.1-0.3), but in non-forested snow covered areas can reach values up to 0.8.
- Snow covered boreal forests have a much lower albedo than grassland to their south and tundra to their north; the presence of boreal forests has a direct control on the climate of high-latitudes.

Viterbo and Betts 1999

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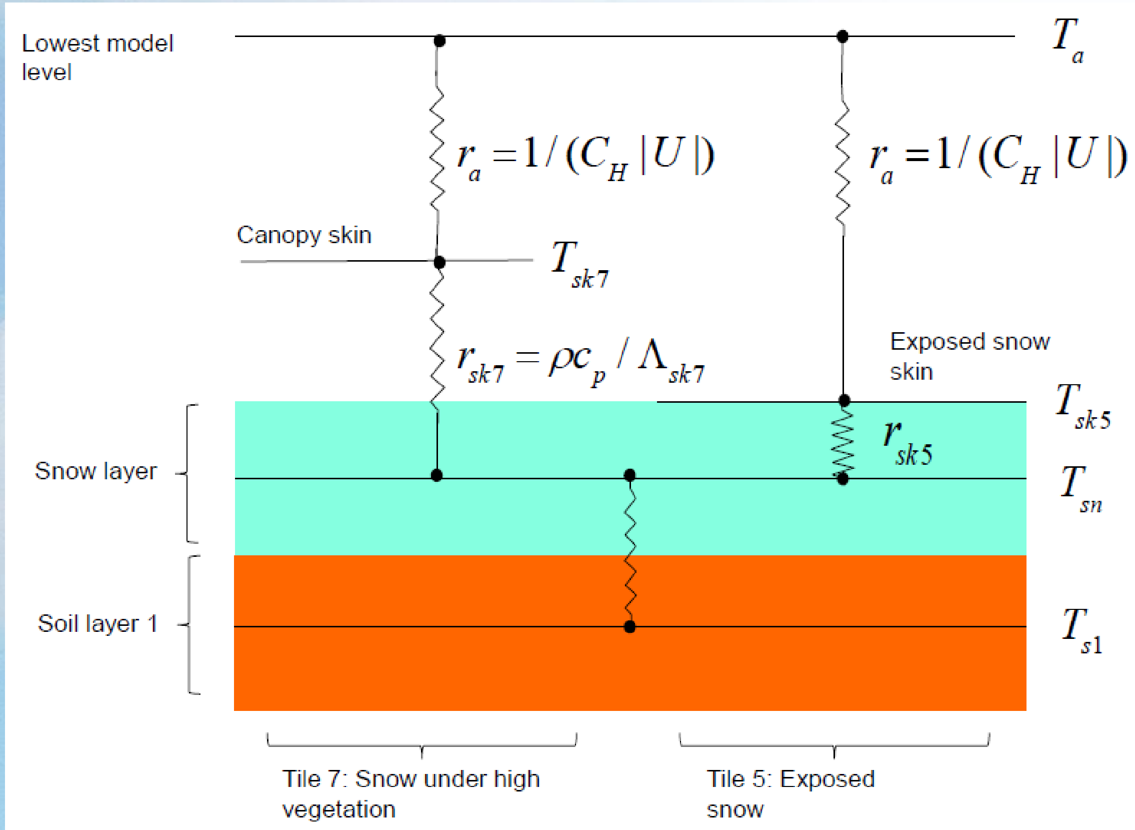
Snow in HTESSEL



Two tiles:

1) **Exposed snow;**
2) **Snow under high vegetation**

Single snow-pack evolution

Prognostic evolution:

1) **Snow mass**
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

Snow in HTESSEL – energy balance

Heat capacity — Snow depth — Net radiation — Latent — Sensible — Basal — Melting

$$\left[(\rho C)_{sn} D_{sn} + L_f S_l^c \frac{\partial f(T_{sn})}{\partial T_{sn}}\right] \frac{\partial T_{sn}}{\partial t} = R_{sn}^N - L_s E_{sn} - H_{sn} - G_{sn}^B - L_f M_{sn}$$

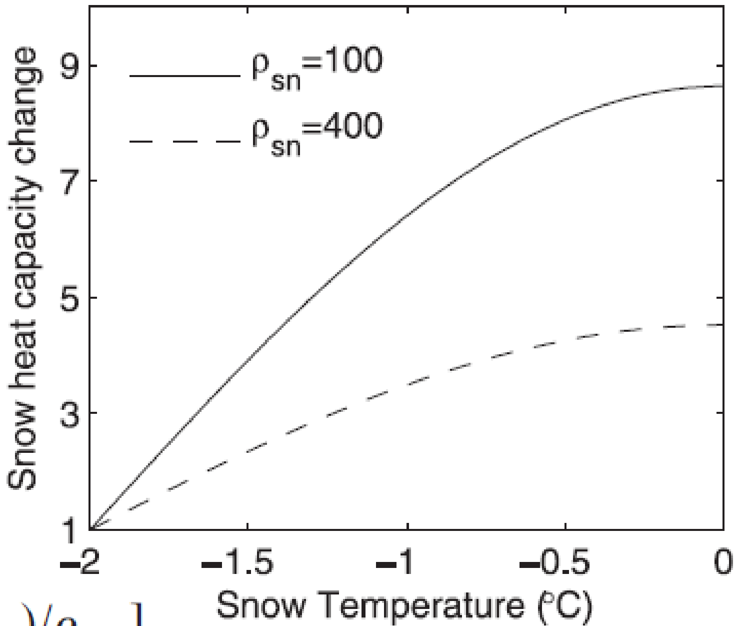
Heat capacity barrier

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

Diagnostic liquid water

$$Q_{sn}^{INT} = L_f M_{sn}^{INT} = L_f \frac{\partial S_l}{\partial t}$$

Internal freezing/melting



$$S_l^c = S[r_{l,\min} + (r_{l,\max} - r_{l,\min}) \max(0, \rho_{sn,l} - \rho_{sn})/\rho_{sn,l}]$$

Snow liquid water capacity

Snow in HTESSEL – water balance

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

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

- **Rainfall and Sublimation only over the snow cover fraction**
- **Rainfall is considered to reach 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**

Before 2009 liquid water was not considered

Snow in HTESSEL – density

$$\frac{1}{\rho_{\mathrm{sn}}}\frac{\partial \rho_{\mathrm{sn}}}{\partial t} = \frac{\sigma_{\mathrm{sn}}}{\eta_{\mathrm{sn}}(T_{\mathrm{sn}}, \rho_{\mathrm{sn}})} + \xi_{\mathrm{sn}}(T_{\mathrm{sn}}, \rho_{\mathrm{sn}}) + \frac{\max(0, Q_{\mathrm{sn}}^{\mathrm{INT}})}{L_f(S - S_l)}$$

- 1st term: overburden – increase density due to the snow weight
- 2nd term: thermal metamorphism: snow crystal destruction with time as function of temperature and density
- 3rd term: Increased density due to re-freezing

$$\rho_{sn}^{*} = \frac{S + \Delta t F}{\frac{\Delta t F}{\rho_{new}} + \frac{S}{\rho_{sn}^{t}}}$$

- Snow density update after snowfall;
- Snowfall density as a function of Wind speed, and air temperature

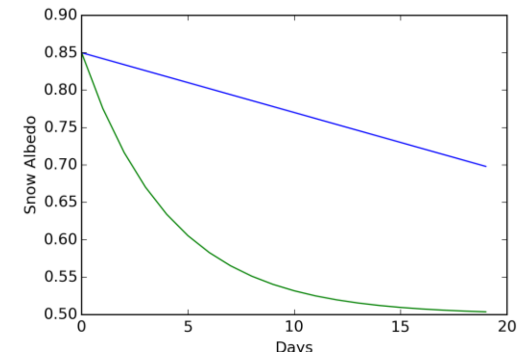
$$\rho_{\mathrm{sn}}^{t+1} = (\rho_{\mathrm{sn}}^{*} - \rho_{\mathrm{sn}_{\max}}) \exp(-\tau_f \Delta t/\tau_1) + \rho_{\mathrm{sn}_{\max}}$$

Snow density formulation before 2009

ECMWF

Snow in HTESSEL – snow albedo

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



- **Linear decay in normal conditions;**
- **Exponential decay in melting conditions;**
- **Min/Max albedos of 0.5 and 0.85.**

$$\alpha_{sn}^{t+1} = \alpha_{sn}^{t} + \min\left(1, \frac{F\Delta t}{10}\right)(\alpha_{max} - \alpha_{sn}^{t})$$

- **Reset snow albedo after snowfall : requires 10 kg m^2 to reset to maximum**

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 we keep the albedo constant (derived from Satellite data)**
- **Neglect seasonal variations**

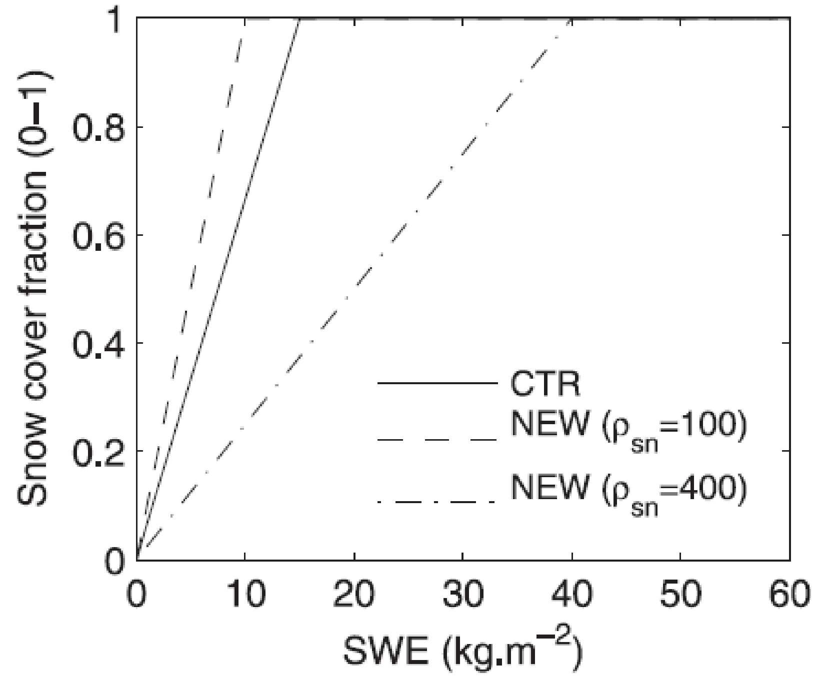
Snow in HTESSEL – snow cover fraction

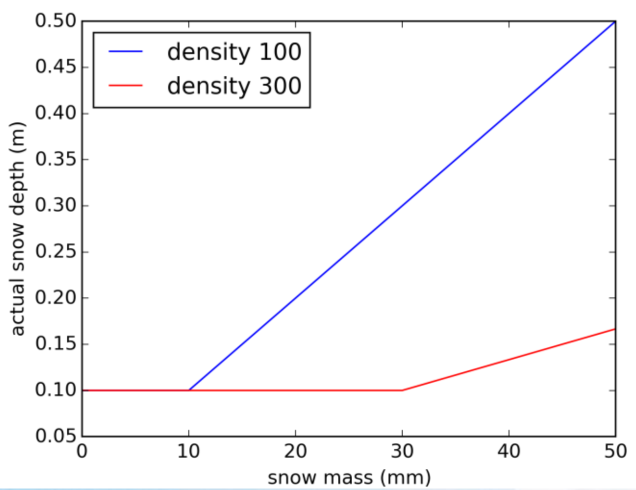
$$c_{sn} = \min\left(1, \frac{S/\rho_{sn}}{0.1}\right)$$

Snow cover fraction as a function of snow depth

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

- **Actual snow depth:** $$D_{\mathrm{sn}} = \frac{1}{\rho_{\mathrm{sn}}} \frac{S}{c_{\mathrm{sn}}}$$





We have a depth "barrier" at 10 cm
Pile the snow as snow mass / snow-cover fraction reduces

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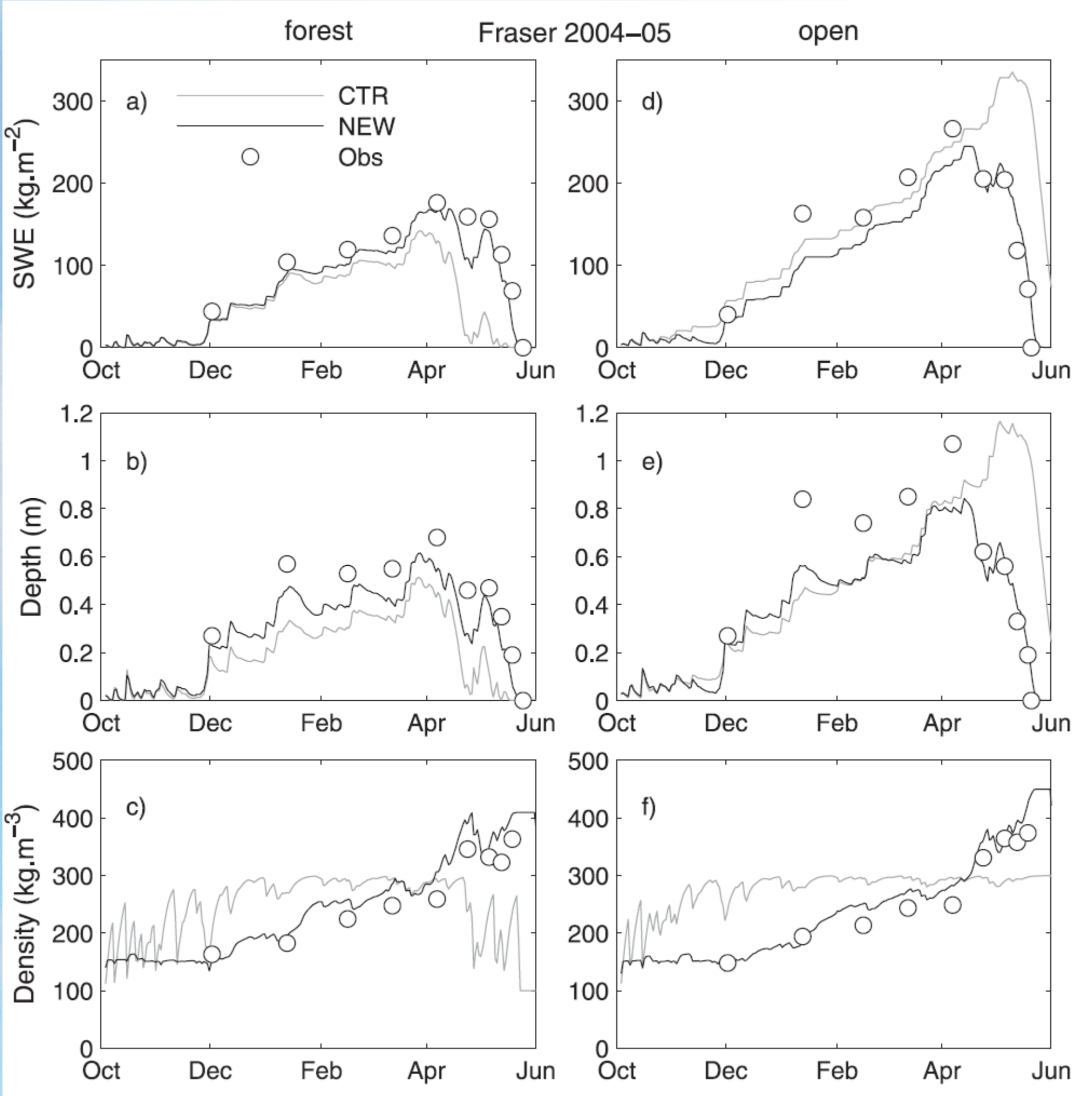
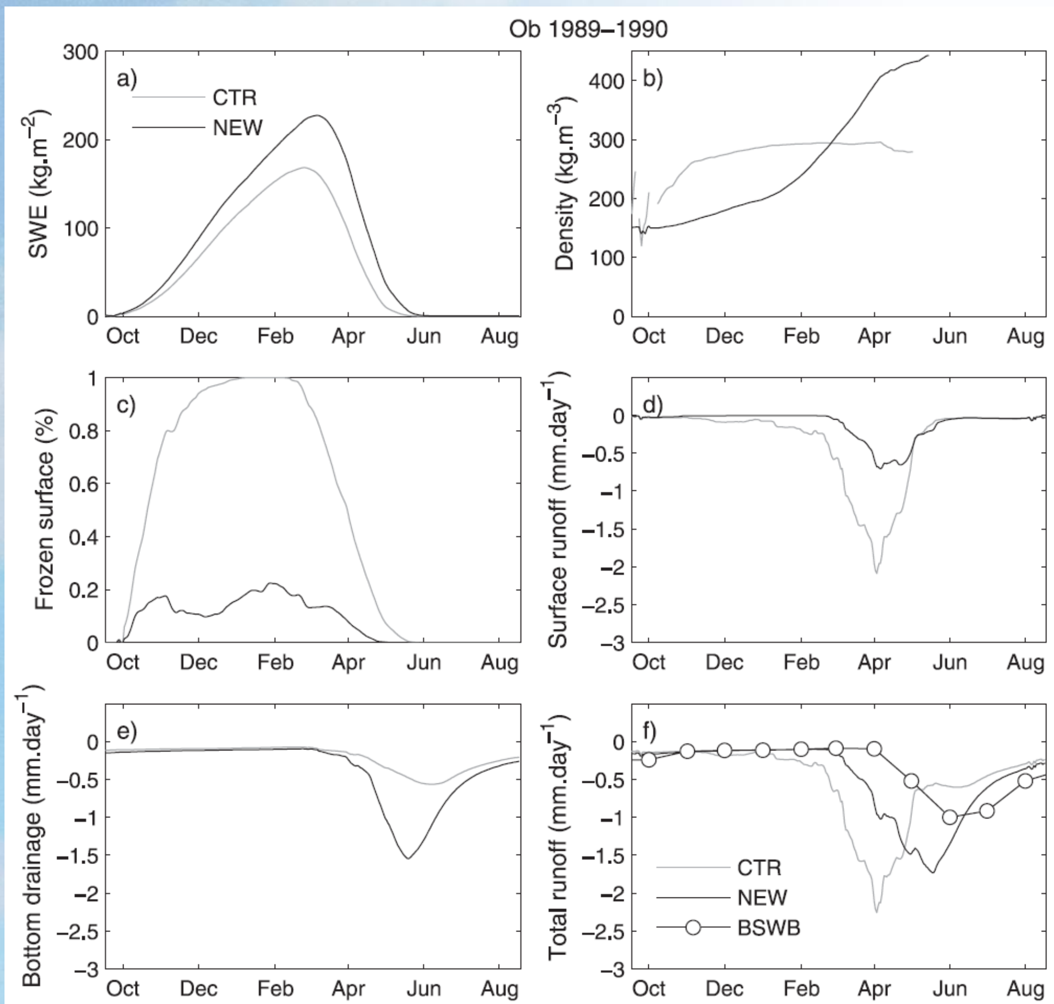
Point evaluation



Point simulations (offline) in a forest and open areas nearby
CTR (gray) : model before 2009
NEW (black) : current model

- **Better simulations of snow mass**
  - **Albedo changes**
  - **Liquid water representation**
- **Improved snow density**
  - **Before – exponential increase**
  - **Snow follows closely observations. Still some problems during melting**

Basin scale evaluation



Regional offline simulations over the Ob (Siberia basin)

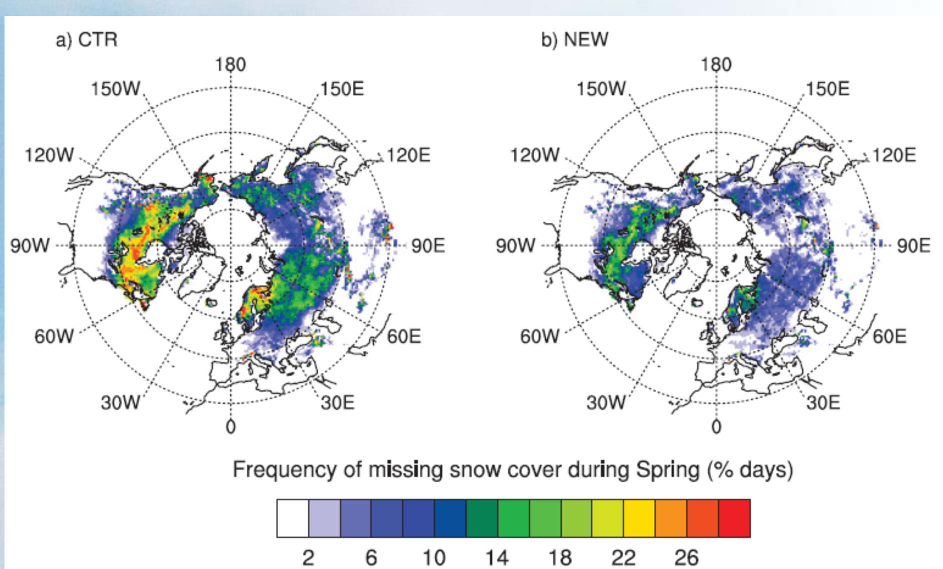
- **Increase in snow mass**
  - **Interception of rainfall**

- **Lower densities during accumulation/winter seasons**

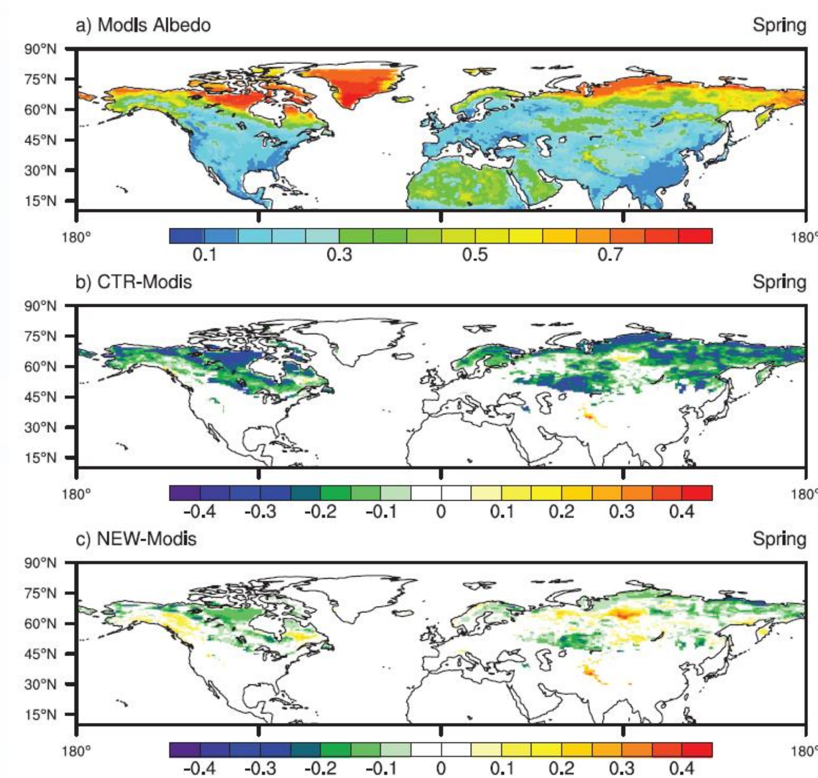
- **Reduction of soil freezing**
- **Increase of surface runoff**
- **Decrease of bottom drainage**
- **Improvement of total runoff**

- **Lower densities -> less coupling -> less soil freezing -> less surface runoff**

Snow in HTESSEL – Snow cover / albedo

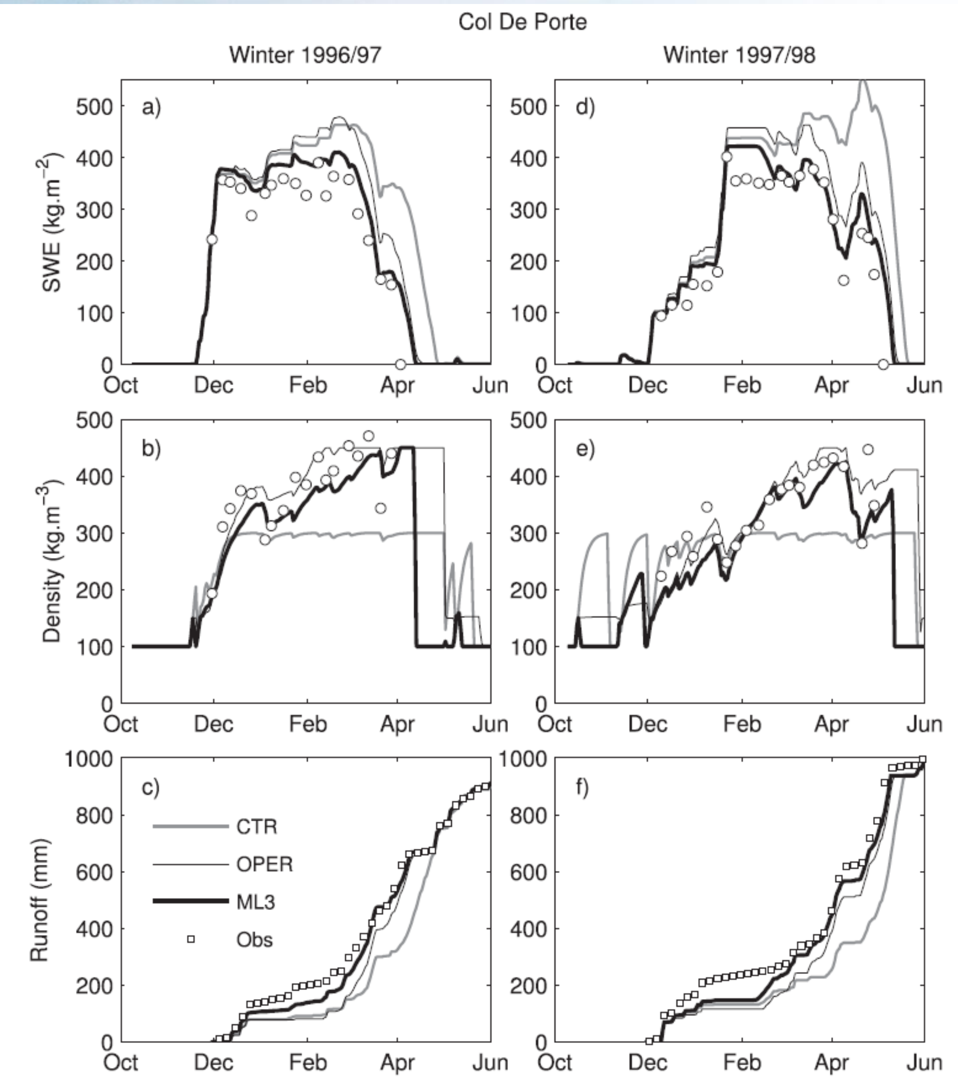


Frequency of missing snow cover (early melting)
Largely reduced in the current model



The early spring snow melt was in part associated with a negative bias in albedo (less albedo + energy absorbed => faster melting)

Near-future work – multi-layer (1)



$$(\rho C)_{\text{sn},i} D_{\text{sn},i} \frac{\partial T_{\text{sn},i}}{\partial t} = G_{\text{sn},i-1} - G_{\text{sn},i} - Q_{\text{sn},i}$$

Energy balance for each snow layer

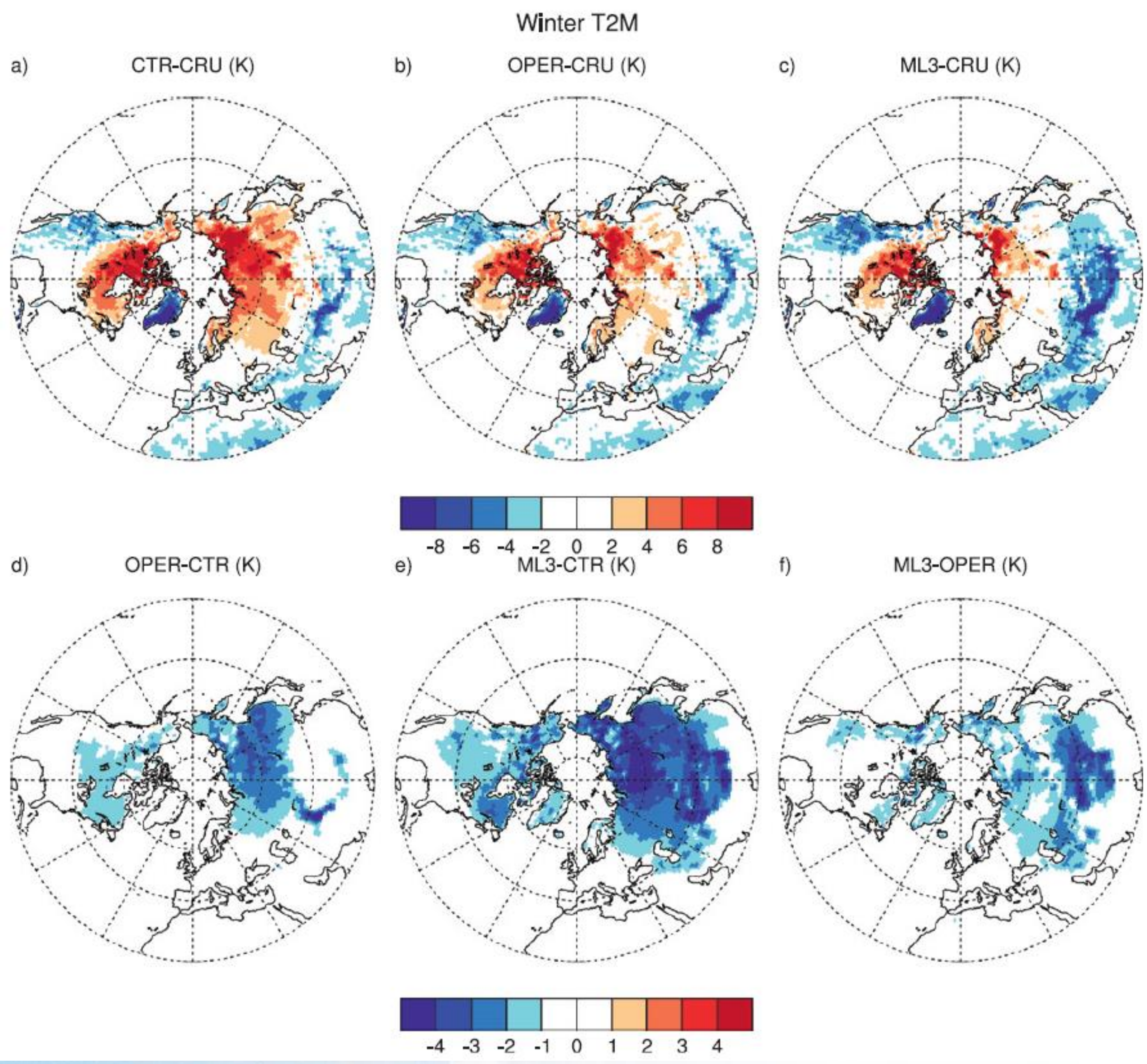
Point simulations in the Alps:

Improved simulations of deep snow pack (e.g. melting episodes during winter)

Similar evolution of snow density

Improved snow runoff simulations

Near-future work – multi-layer (2)



Climate simulations, impact on 2-meters temperature:

Multi-layer snow leads to a stronger cooling of surface temperature
Increased decoupling as each snow layer is thermally insulated

Snow in HTESSEL – neglected processes

- Rain on snow
  - Rainfall is assumed to fall at freezing point : No heat flux advection
  - Rainfall interception partially treated but would require a prognostic liquid water reservoir for a proper evolution;
- Blowing snow
  - No snow mass displacement (reasonable at the resolutions we ran the model);
  - Neglect the effects of blowing snow sublimation (estimates of about +/- 5 kg m ^{2} during a winter season over Siberia (Brun et. al 2012);
- Snowfall interception by vegetation:
  - Changes albedo, different sublimation rates;
- Vertical structure of snowpack
  - Single layer cannot represent the vertical structure (memory); Thermal implications;
- Snow on top of Glaciers / Sea-ice
  - Glaciers set to 10 meters of snow ! And no snow on top of sea-ice
- Any others?

Further Reading

Armstrong, R. L., and Brun, E., 2008: *Snow and Climate. Physical processes, surface energy exchange and modeling.* Cambridge University press, 222 pp.

Brun, E., V. Vionnet, et al. (2012). "Simulation of Northern Eurasian Local Snow Depth, Mass, and Density Using a Detailed Snowpack Model and Meteorological Reanalyses." Journal of Hydrometeorology 14(1): 203-219.

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