Snow processes in the ECMWF model

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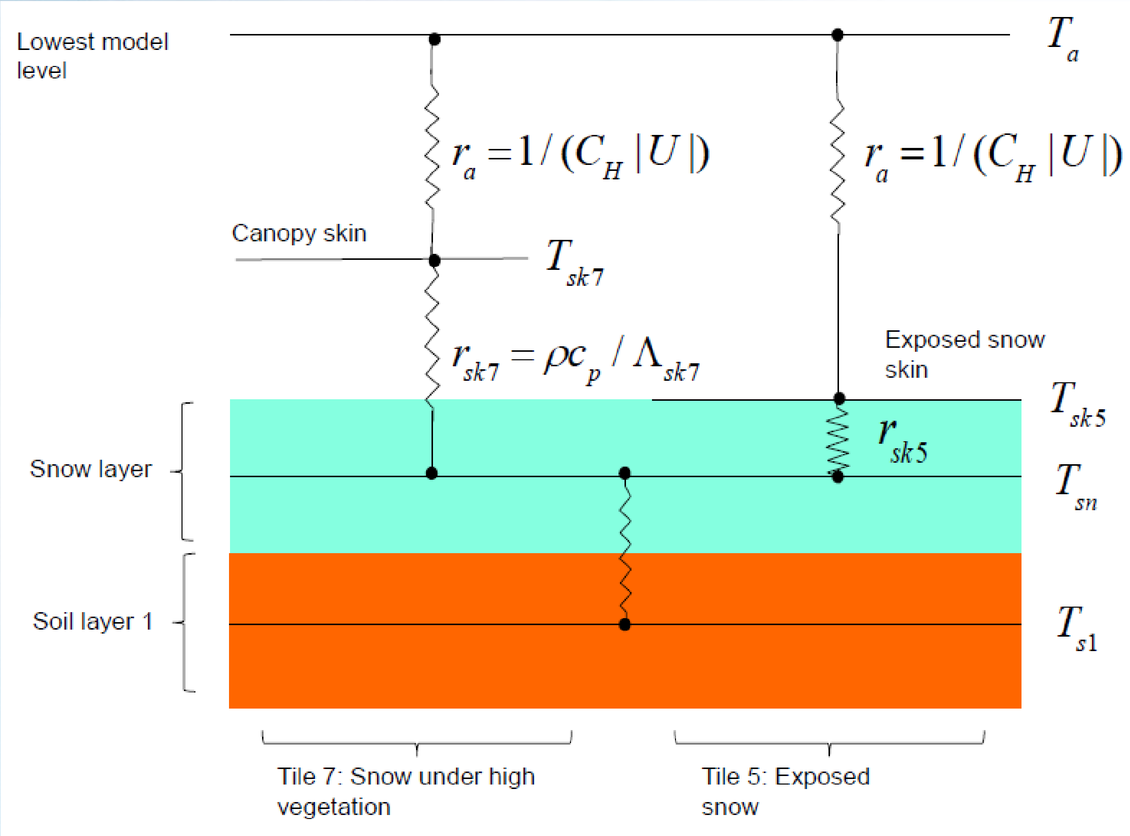
Outline

- Snow representation in the ECMWF model:
  - Energy/Water balance;
  - Density/ Albedo / Snow cover fraction;
  - Evaluation examples.

- Ongoing & future work:
  - Multi-layer snow scheme
  - Earth2Observe : multi-model perspective
  - Snow depth data assimilation

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

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

Heat capacity

Snow depth

Net radiation

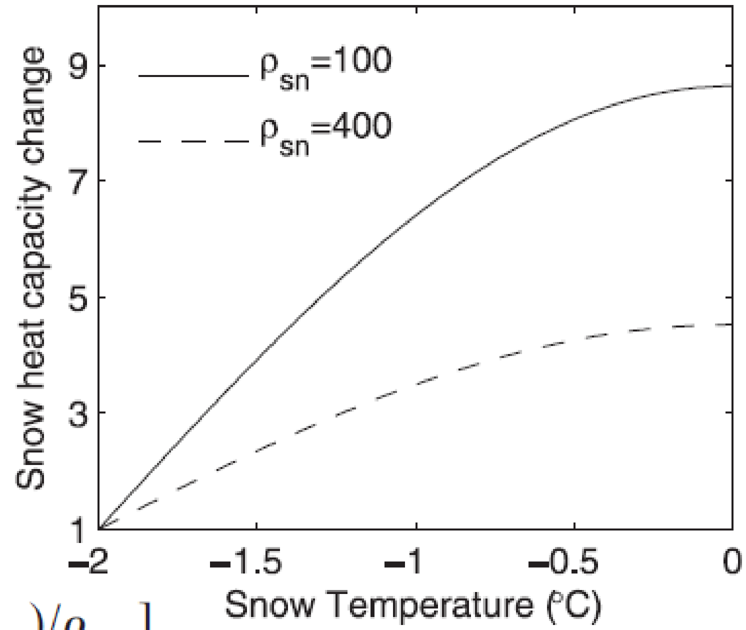
Latent

Sensible

Basal

Melting

Heat capacity barrier



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

Diagnostic liquid water

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

Internal freezing/melting

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

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**

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

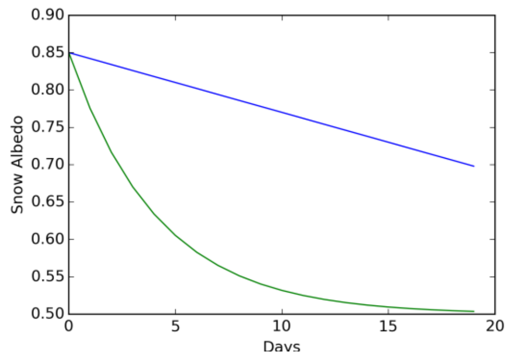
- **Snow density update after snowfall;**
- **Snowfall density as a function of Wind speed, and air temperature**

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

Snow density formulation before 2009

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**

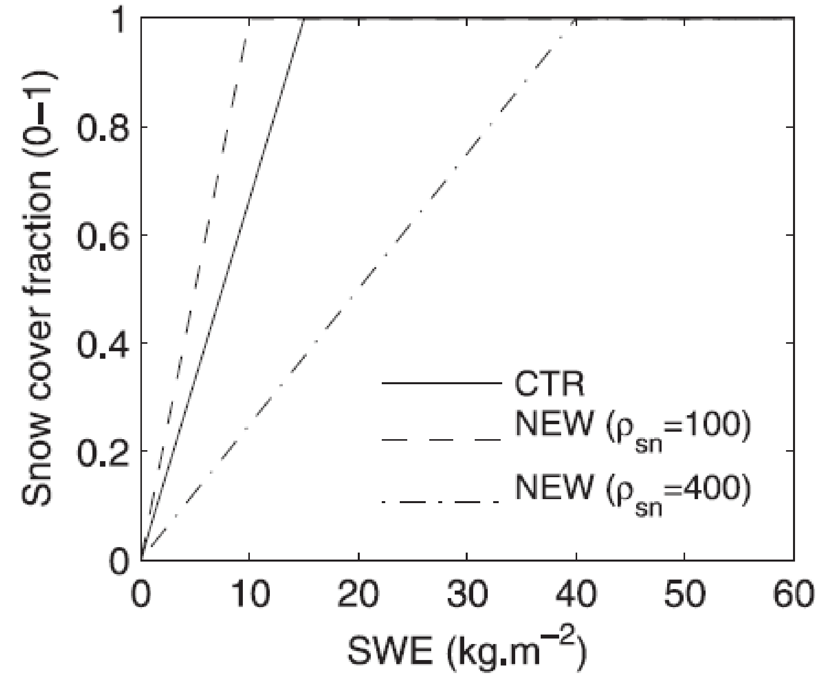
Snow in HTESSEL – snow cover fraction

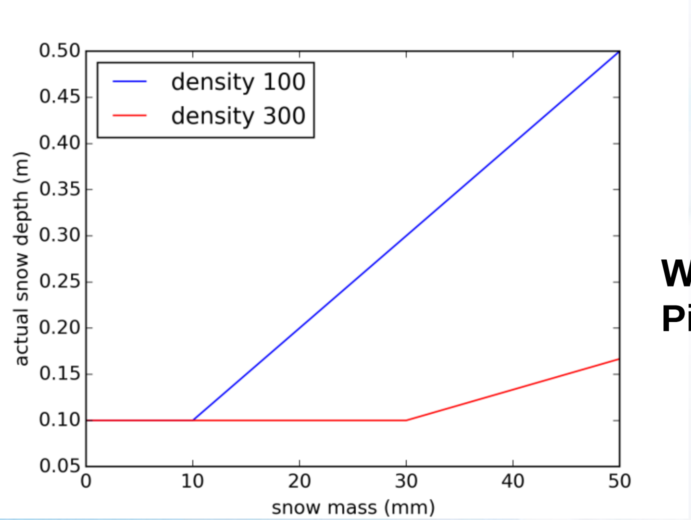
$$c_{sn} = \min\left(1, \frac{S/\rho_{sn}}{0.1}\right)$$

Snow cover fraction as a function of snow depth

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

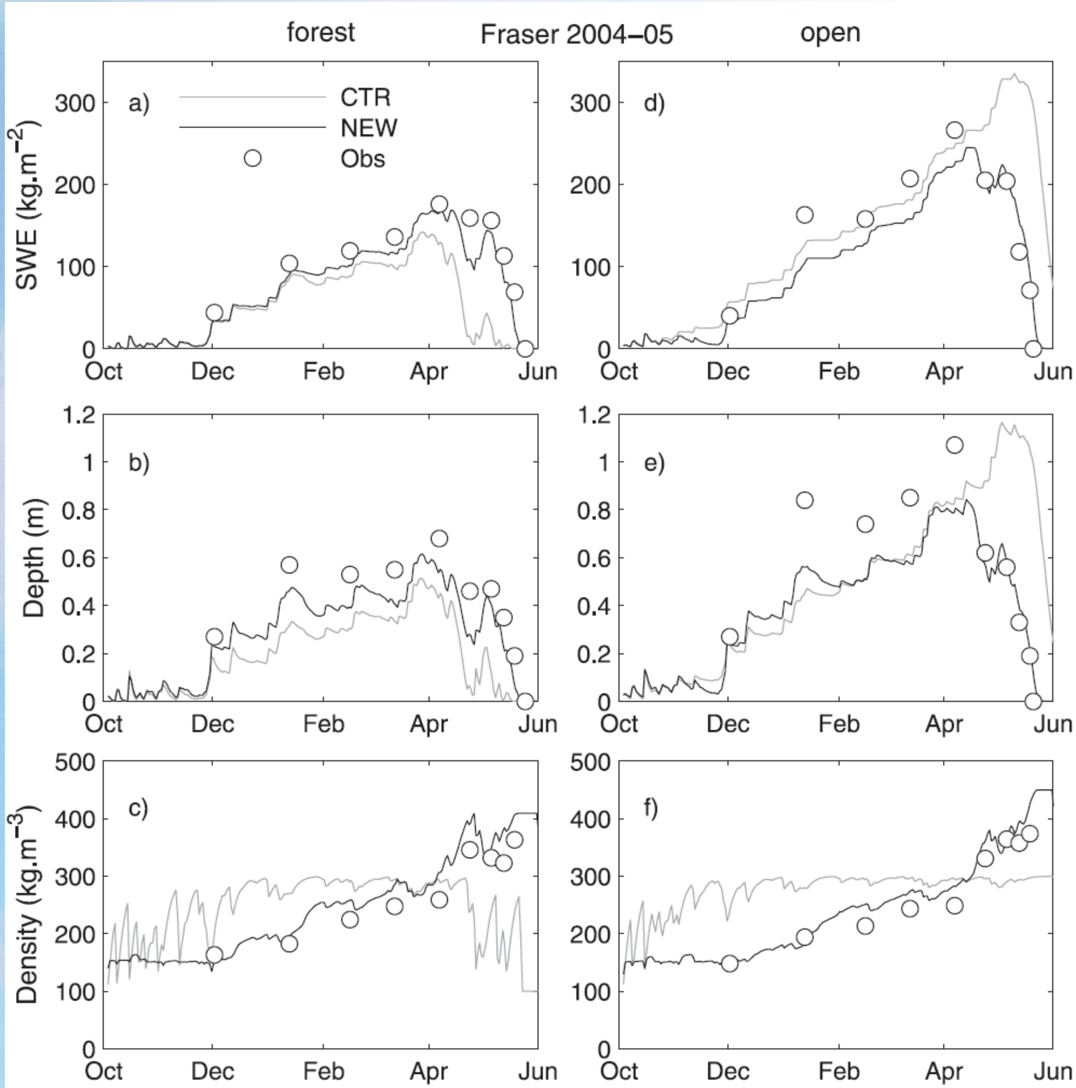
- **Actual snow depth:** $$D_{sn} = \frac{1}{\rho_{sn}} \frac{S}{c_{sn}}$$





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

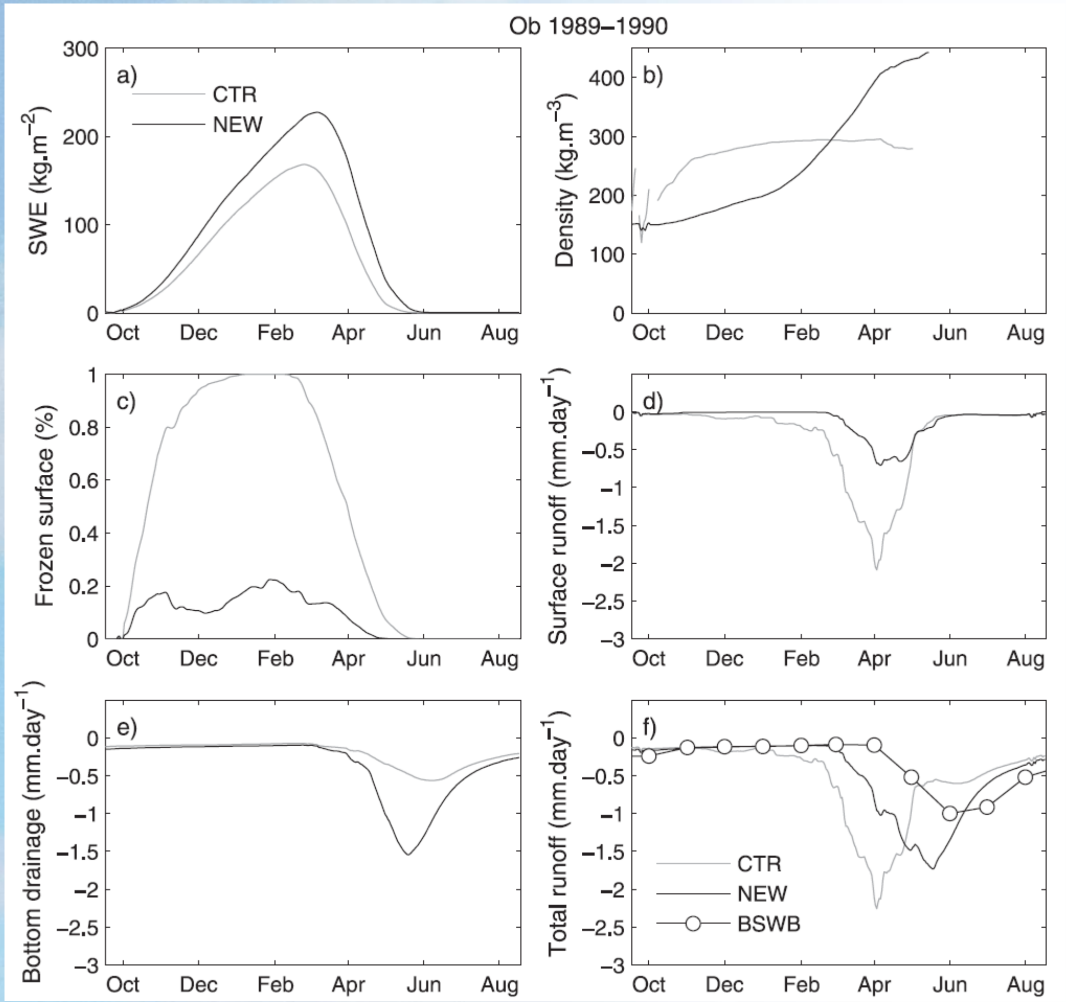
Point evaluation



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)

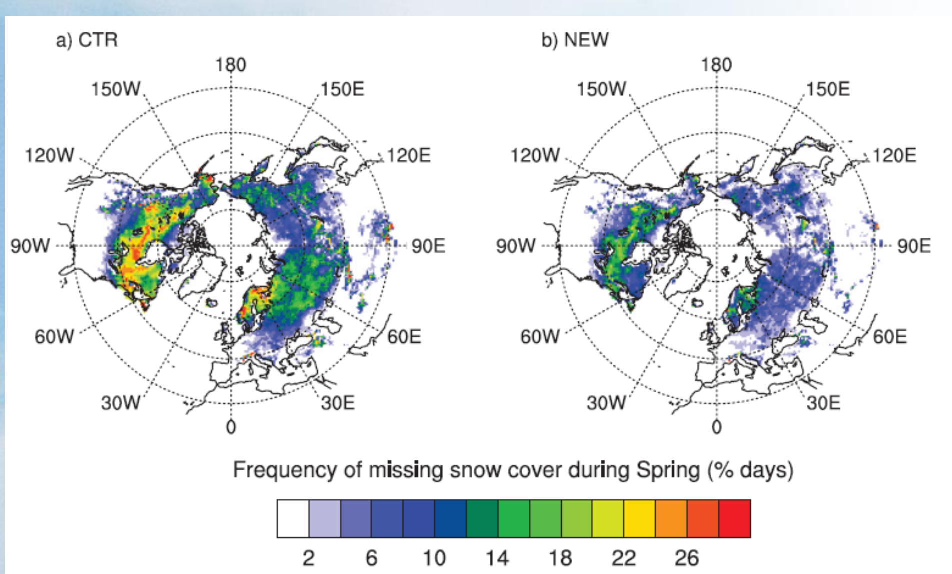
- **Increase in snow mass**
  - **Interception of rainfall**

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

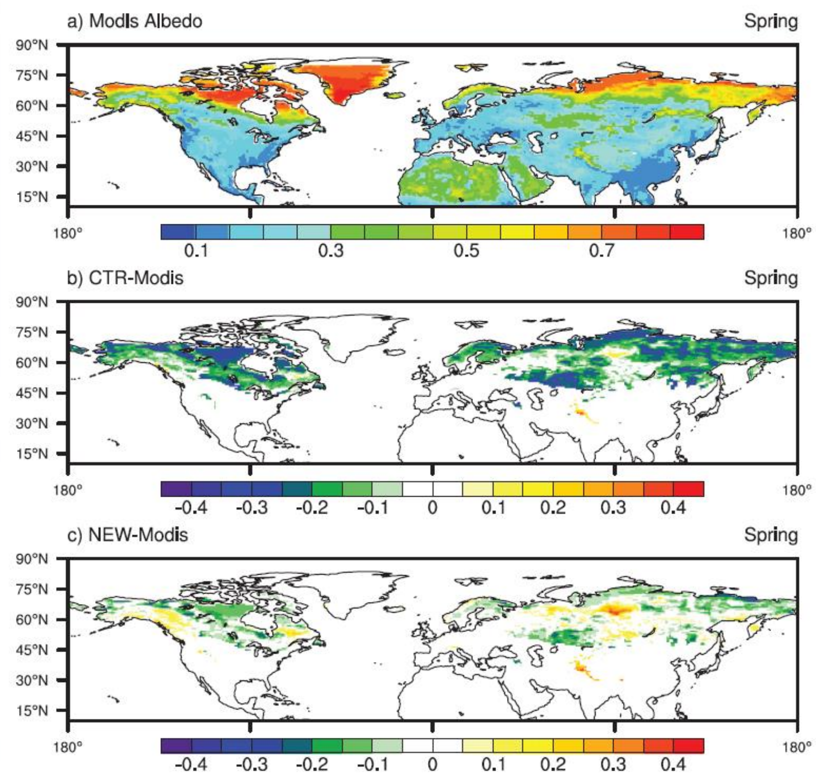
- **Reduction of soil freezing**
- **Increase of surface runoff**
- **Decrease of bottom drainage**
- **Improvement of total runoff**

- **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)

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- Ongoing & future work:
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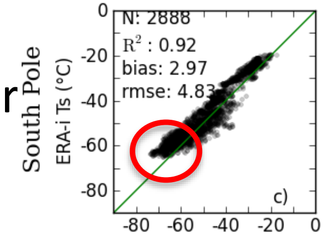
  - Snow depth data assimilation

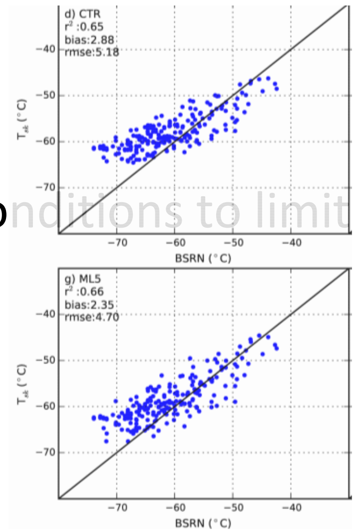
Snow/Soil multi-layer

- Why ?
  - Represent a shorter time-scale to the snow/soil temperature
    - representation of very cold surface events (snow);
    - Enhance diurnal cycle & match with satellite soil moisture;



Fréville et al. 2014
Skin temperature vs MODIS

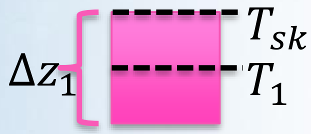
- Snow multi-layer :
  - Flexible number of layers (main tests with 5);
  - New prognostic snow liquid water content;
  - Simple iteration of the surface energy balance in melting conditions to limit skin temperature at freezing point;



- Soil multi-layer:
  - Flexible number of layer (main tests with 9);
  - Identical with 4 layers (current configuration);
- New thermal coupling formulation for the skin conductivity (both for snow & soil)

Snow multi-layer

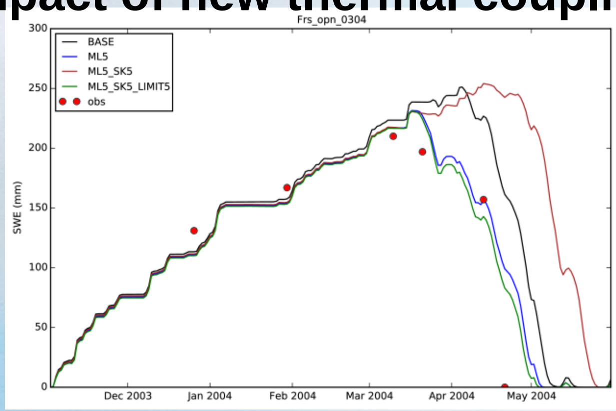
Ground flux $= \Lambda_{sk,i}(T_{sk,i} - T_1)$



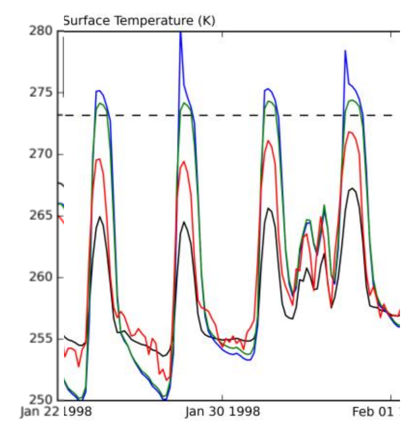
$$\Lambda_{sk,i} = 2\frac{\lambda_1}{\Delta z_1},$$

Applied both for the snow & bare soil instead of a constant value

Impact of new thermal coupling & EB iteration

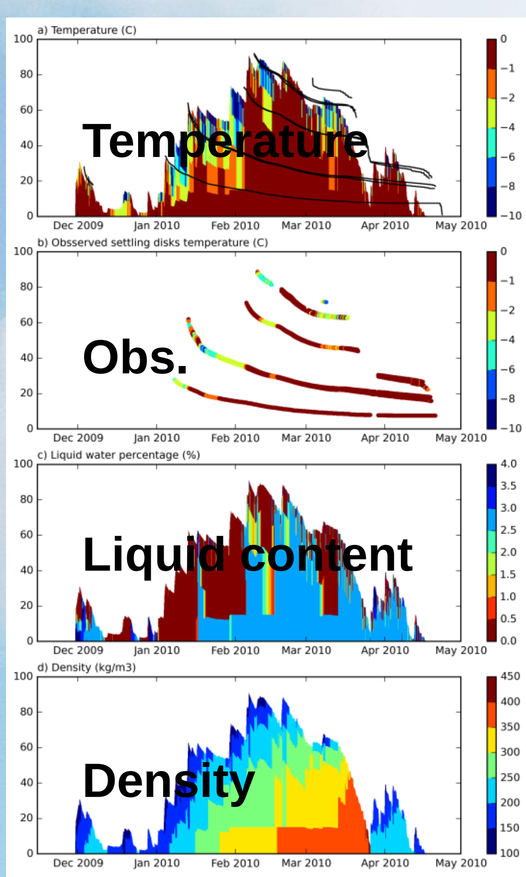


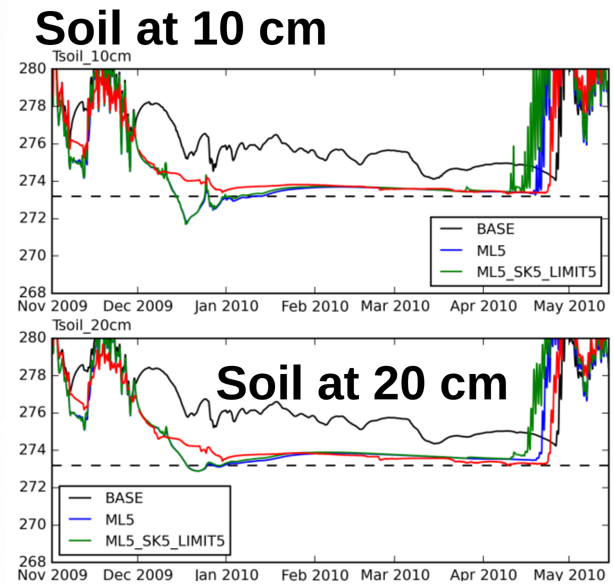
CTR
ML5 current coupling
ML5 new coupling
ML5 new coupling & EB iteration



- **New thermal coupling is a diagnostic instead of a "tunable" parameter;**
- **EB iteration partially avoids numerical instabilities and keeps Tsk <= freezing point ;**
- **Could consider reformulating the EB tiling approach…**

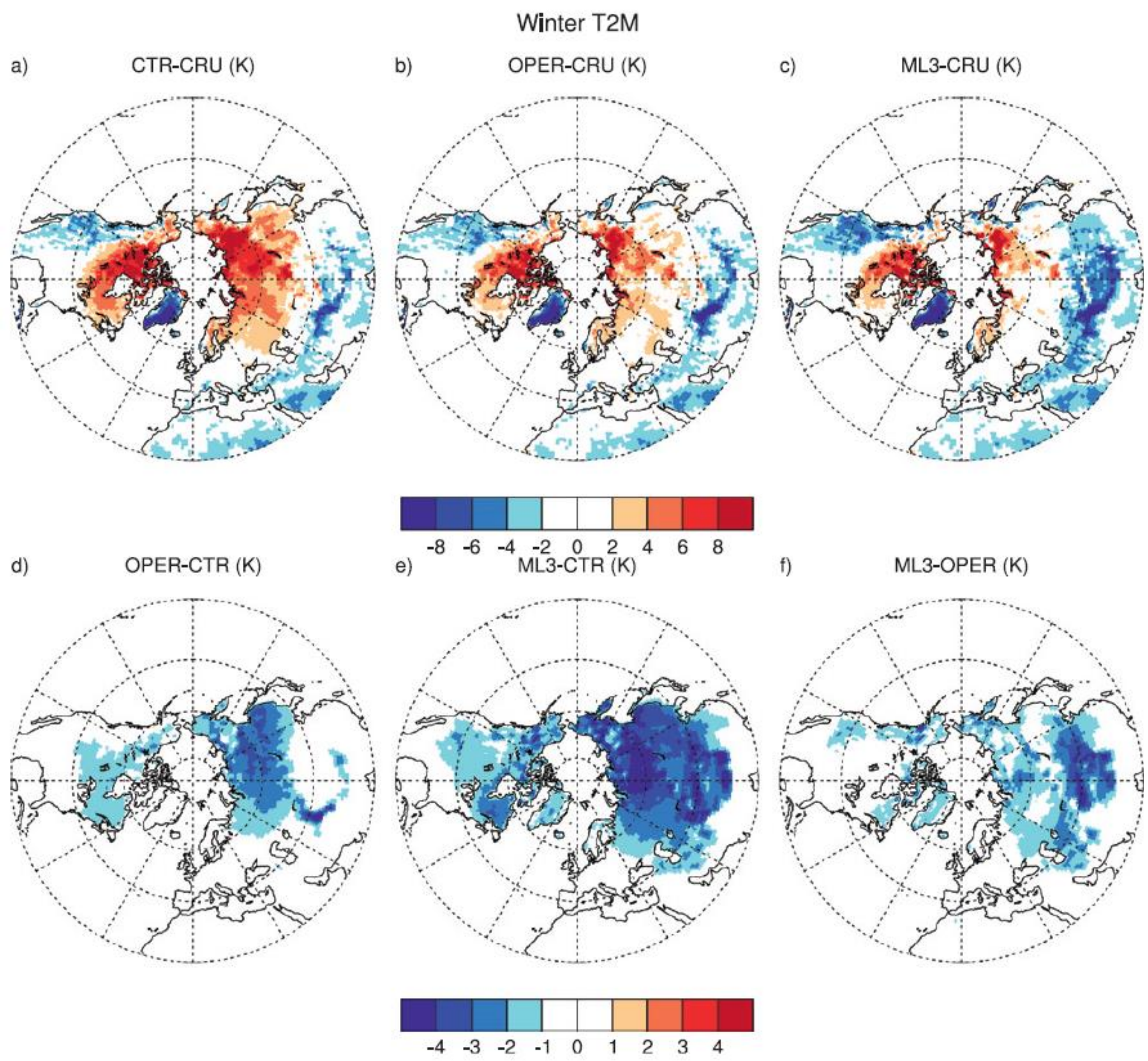
Snow multi-layer





- **Still some work to do with the Albedo parameterization;**
  - **Undesirable coupling between snow temperature and Albedo**
  - **Maybe consider a formulation based on snow grain size ?**
  - **Snow cover fraction ?**
  - **Vegetation?**

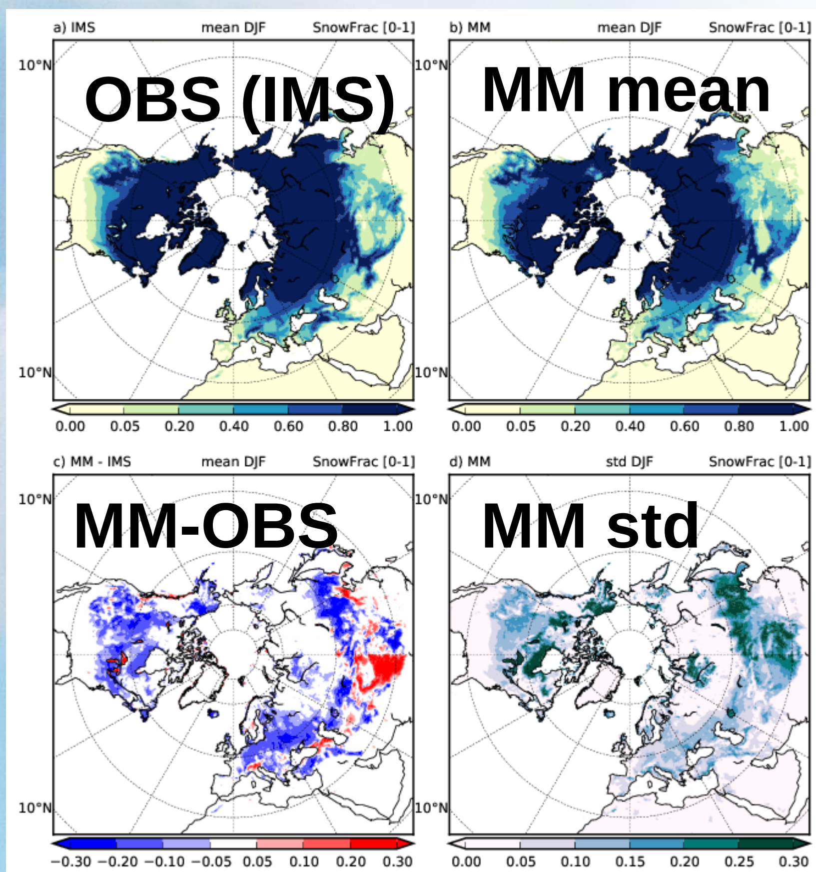
Ongoing – multi-layer (2)



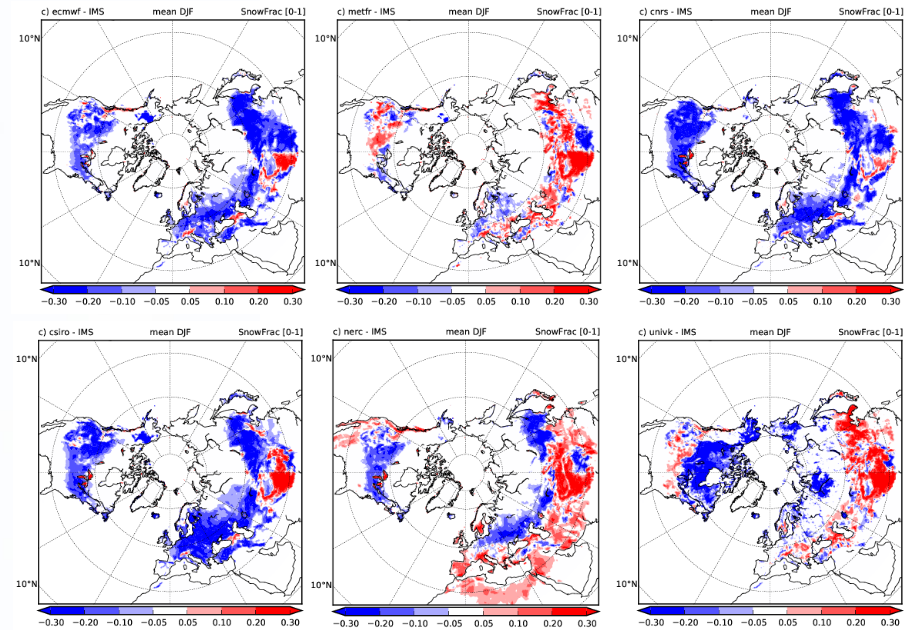
Climate simulations, impact on 2-meters temperature:

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

Earth2Observe: MM DJF snow cover

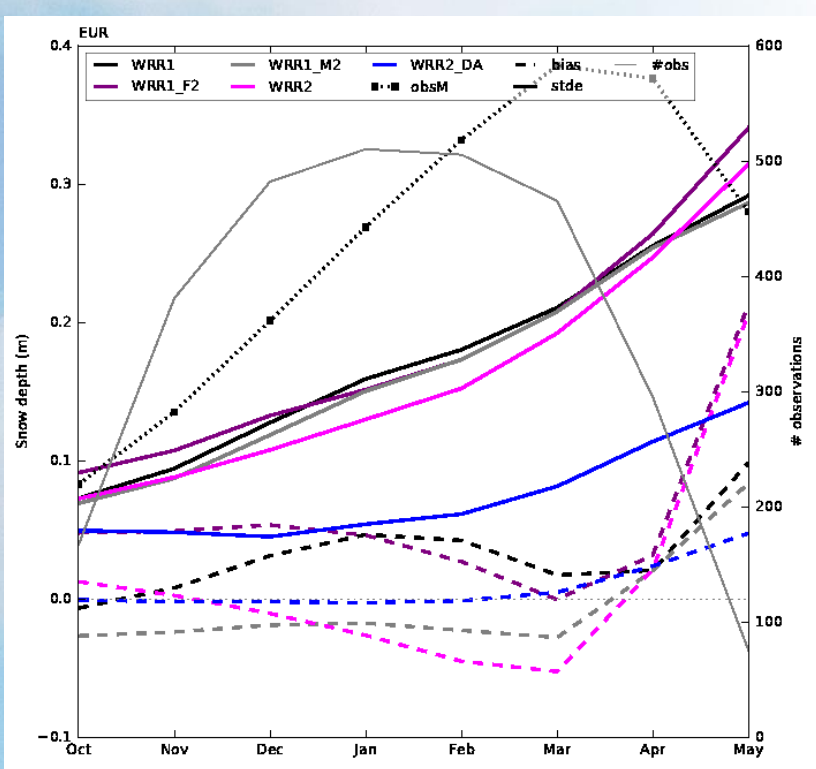


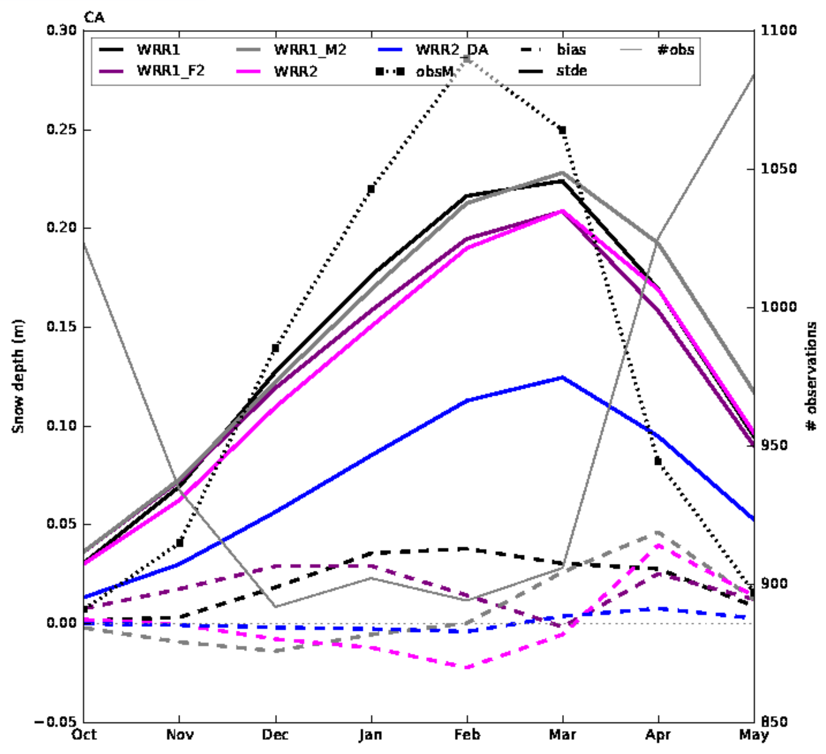
Individual model-OBS



- **Areas of larger errors in the MM tend to be areas with larger MM std;**
- **MM is not a model realization, should be evaluated considering the spread:**
  - **e.g.: West/East Tibetan Plateau: systematic bias vs MM uncertainty.**

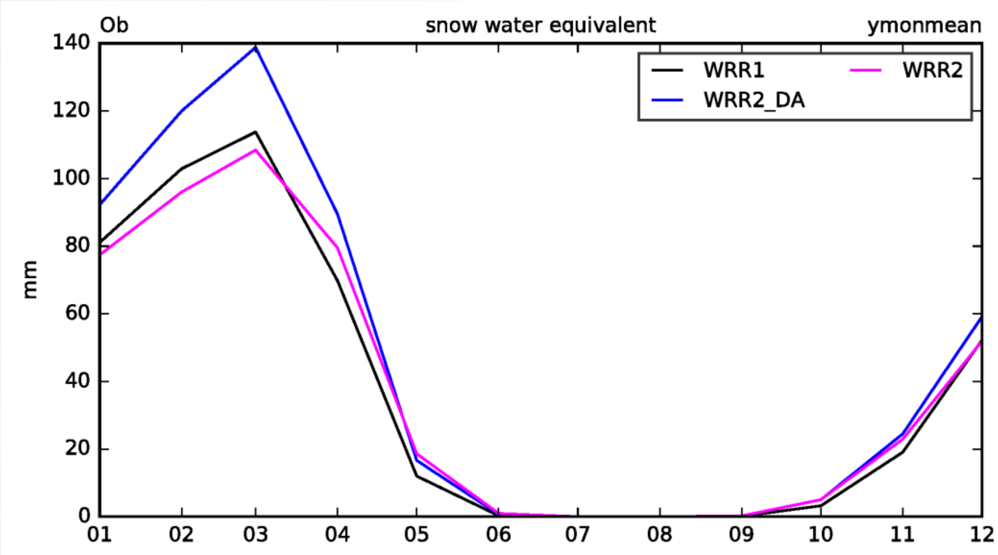
Testing of stand-alone snow data assimilation





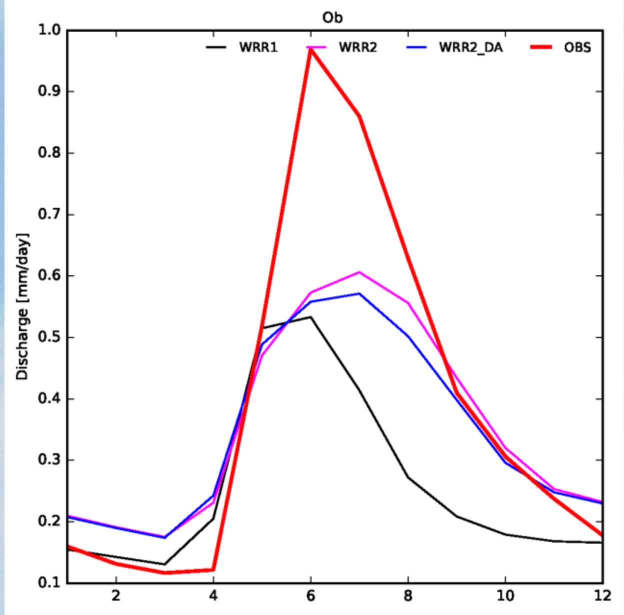
- **Snow 2D OI using the GHCN daily snow depth**
- **Reduction of the bias and standard deviation of the errors (2000-2010) (blue lines)**
- **Some positive impact of the multi-layer scheme over Eurasia (magenta line)**
- **What about the remaining water cycle components ?**

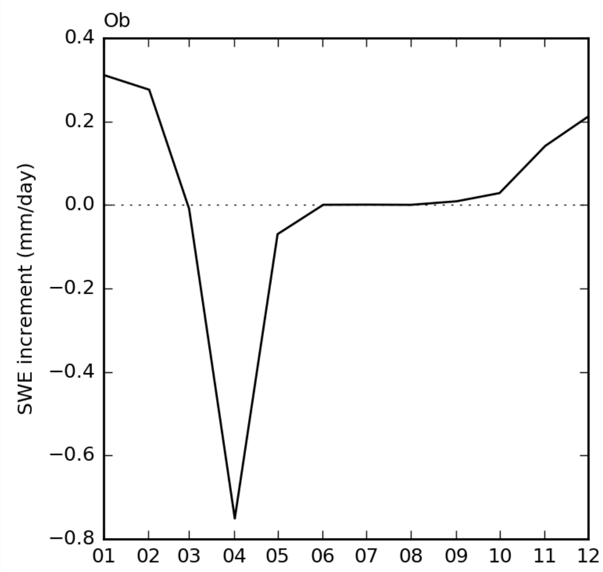
Testing of stand-alone snow data assimilation



- **Snow data assimilation is increasing the snow mass over the Ob basin (general over N. Eurasia):**
  - **Is it realistic ? (need to validate against SWE)**
  - **Compensating for Snow density problems ?**
  - **What is the impact on runoff ?**

Testing of stand-alone snow data assimilation





- **The increase snow mass has a small impact on runoff, with a slight reduction:**
  - **All the snow increments added during winter are also removed during April**
  - **The current scheme does not trigger snow melt effectively (sign of late melting in the model ?)**
  - **The current "direct insertion" of snow depth increments in to snow mass is effective for the snow depth but not for the water balance.**

Final notes

- 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 (in the multi-layer);
- 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);
- Soil Freezing
  - Once the soil is frozen there is no infiltration (sub-grid scale variability ? Preferential flow?)
- Snow albedo and snow cover fraction
  - sub-grid scale variability and orography
- How to map snow depth increments from the Snow 2D OI in the model prognostics;
- **Lack of detailed evaluation over the Himalaya-Tibetan Plateau :**
  - **Region with large multi-model variability;**
  - **This would be a very interesting region to further test the multi-layer and snow albedo / cover fraction schemes.**

THANKS