Snow parameterizations in NWP and climate models

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Aspects of snow in NWP/climate models

IMPORTANT

The complexity should not violate assimilation and numerical stability

Give realistic lower boundary conditions for the atmosphere in the terms of surface fluxes (sensible/latent heat and momentum fluxes)

Represent a storage of water as hydrological memory for runoff

Insulation of the soil and its impact on soil thermal evolution

NWP

CLIMATE MODEL

Snow drift by wind

Internal snow structure in terms of size and character of snow crystals

LESS IMPORTANT

Important characteristics of snow

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Very high albedo and very variable with age, typical range 50-90%

Variable areal extent (snow cover fraction), 0-100%

Very low density and quite variable with age, typical range 50-450 kg/m^3

Low heat capacity, typically 2-7 $\cdot 10^5$ J/m^3 K (soil 14 $\cdot 10^5$ J/m^3 K)

Low heat conductivity, typically 0.1-0.5 W/m K (soil 0.3 W/m K)

Smooth surface, order of 10^{-3} m (open land 10^{-1} m)

Can hold liquid water, typically 3-6%

Modelling issues of snow in this talk

Number of layers in the snow

Albedo parameterisation

Snow fraction parameterisation

Snow density parameterisation

Snow heat conductivity parameterisation

Number of layers in the snow

Boone and Etchevers (2001) divided snow models into three main categories:

-Simple force-restore with composite snow-soil (SURFEX 1-layer ISBA) or single explicit snow layer (ECMWF, HIRLAM/RCA)

-Detailed internal-snow-process schemes with multiple layers of fine vertical resolution. Intended for e.g. snow avalanche modelling (SNOWPACK, Crocus, SNTHERM)

-Intermediate-complexity schemes with physics from the detailed schemes but with a limited amount of layers. Intended for NWP/Climate models. (SURFEX 3-layer)

Boone, A. and Etchevers, P., 2001: An intercomparison of three snow schemes of varying complexity coupled to the same land surface model: Local-scale evaluation at an alpine site. J. Hydrometeorol, 2, 374-394.

Snow albedo

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Pirazzini (2009) reports that

The positive snow albedo-temperature feedback is an important factor in the high-latitude amplification of the global warming. The model representation of snow and ice albedo is one of the most serious oversimplifications, causing large errors, in NWP and climate models.

Many albedo parameterisations can be divided into:

prognostic

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

ECMWF, old HTESSEL (Dutra et al., 2010)*

α_{min}=0.5, α_{max}=0.85

For snowfall>1mm/h: $\alpha_{sn}^{t+1}=\alpha_{max}$

temperature dependent

ECHAM5 (Roeckner et al., 2003)

$$\begin{cases} \alpha_{min}=0.3 & T=0 \\ \alpha = \text{linear change} & \\ \alpha_{max}=0.8 & T<-5 \end{cases}$$

Dutra, E., Balsamo, G., Viterbo, P., Miranda, P. M. A., Beljaars, A., Schär, C. and Elder, K. 2010: An improved snow scheme for the ECMWF land surface model: description and offline validation. In press.
Pirazzini, R. 2009. Challenges in Snow and Ice Albedo Parameterisations. Geophysica 45. 41-62.
Roeckner, E., et al. 2003. The atmospheric general circulation model ECHAM-5: model description. Max-Planck Institute for Meteorology Report No. 349, Hamburg, Germany, 140pp.

Snow albedo

Pedersen and Winther (2005) concluded:

Although, prognostic snow albedo formulations are considered to be superior to purely temperature dependent snow albedo formulations they are sensitive for the **threshold value of snowfall** used to reset the albedo to a high fresh-snow albedo at a snowfall event.

The **threshold is often set too high** which means that the **albedo tends to remain at too low values**. Also, **the decrease of albedo with time may be overestimated** in typical prognostic albedo parameterisations (for low temperatures).

Indeed, in a new version of RCA it has been shown that a modification of the prognostic snow albedo considering both the threshold and temperature factors significantly reduce the warm bias over Arctic regions in RCA.

Pedersen, C. A. and Winther, J.-G. 2005. Intercomparison and validation of snow albedo parameterization schemes in climate models. Climate Dynamics. 25, 351–362. doi: 10.1007/s00382-005-0037-0

Different parameterisations of snow albedo

Temperature

Accumulated snowfall

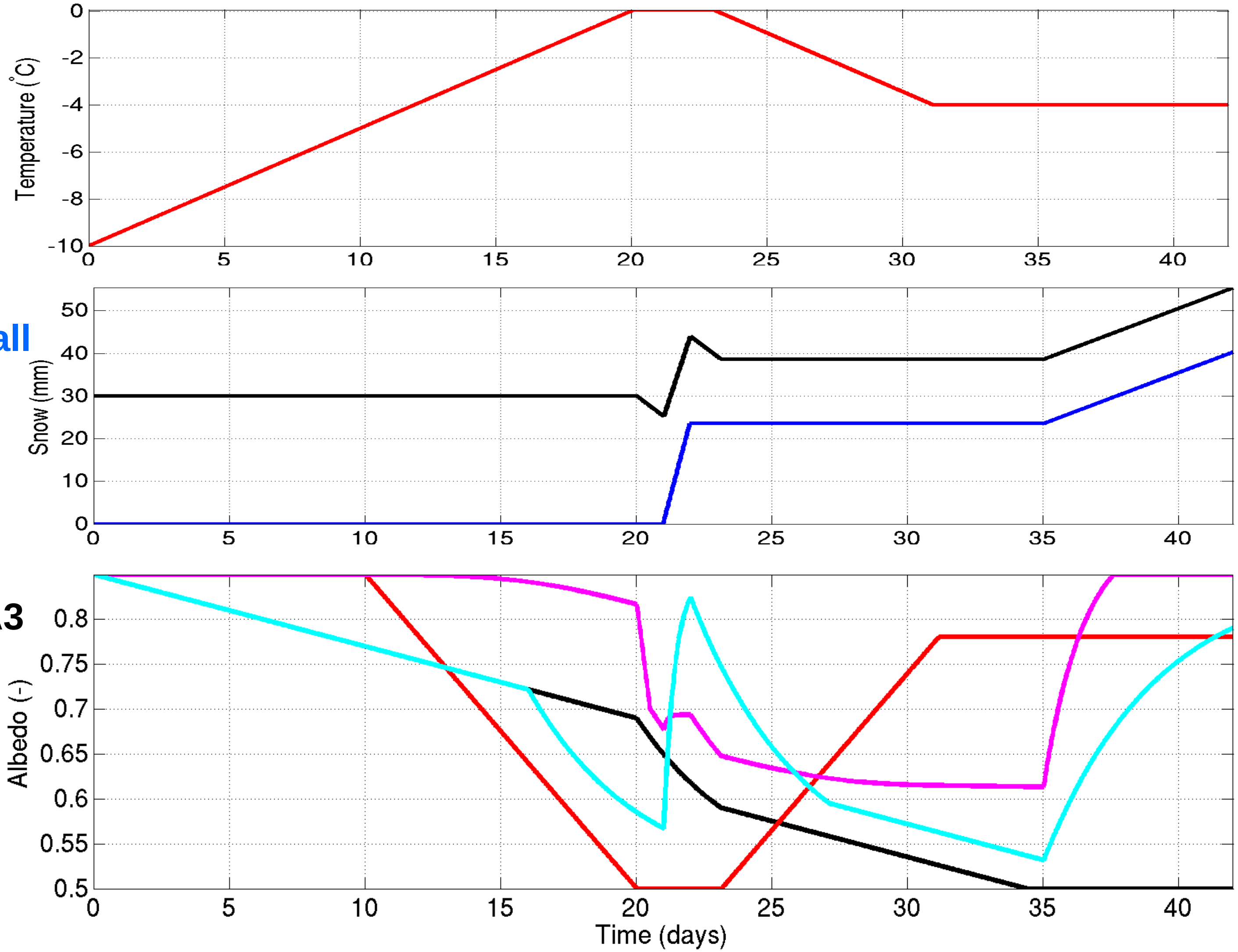
Snow water eq.

old HTESSEL & RCA3

new HTESSEL

RCA4

ECHAM5



Snow cover fraction

Simpler parameterizations of snow cover fraction (SCF) usually relate SCF to the snow water equivalent (SWE) or the snow depth (Hsn) along with some critical value. Examples are

$$f_s = \frac{S_n}{S_n + 0.01}$$

ECHAM4

S_{crit}=10 mm

$$c_{sn} = \min\left(1, \frac{S}{15}\right).$$

ECMWF / Old HTESSEL

S_{crit}=15 mm

$$P_{ncv} = \frac{h_n}{h_n + 5 \times z_0}$$

The fraction P_{nc} is calculated as:

$$P_{nc} = \min(1, W_n/W_1) \qquad (W_1 = 70\ mm)$$

ARPEGE-Climate Version 5.1

SCF=$S_n/S_{crit}(t)$

HIRLAM newsnow

Where $S_{crit}(t)$ seasonal dependent (15-40 mm)

Snow cover fraction

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However, the relationship between SCF and Hsn shows a clear seasonality dependence (a hysteresis effect); the increase of SCF with Hsn in autumn is more rapid than the decrease of SCF with Hsn during the spring melting period.

$$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno}/\rho_{new})^m}\right)$$

NCAR CLM
Niu and Yang (2007)
z_{0g}=0.01 m, ρ_{new}=100 kg m^{-3}, m~1.6

$$A_{sn} = A_{snlim} \tanh(100 sn),$$ growing

$$A_{sn} = \frac{sn}{sn_{max} \Delta_{snfrd}}, A_{sn} \leq A_{snlim},$$ established and melting

RCA
Lindström and Gardelin (1999)
A_{snlim}=0.985, sn_{max}=max seasonal sn,
Δ_{snfrd}=0.6 + 0.001 $z0_{oro}$

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

ECMWF / New HTESSEL
Dutra et al. (2010)
A_{snlim}=0.985, sn_{max}=max seasonal sn

$SCF=S_n/(S_n+ \rho_{sn}*5*z_{0veg})$

SURFEX/ISBA
Douville et al. (1995)

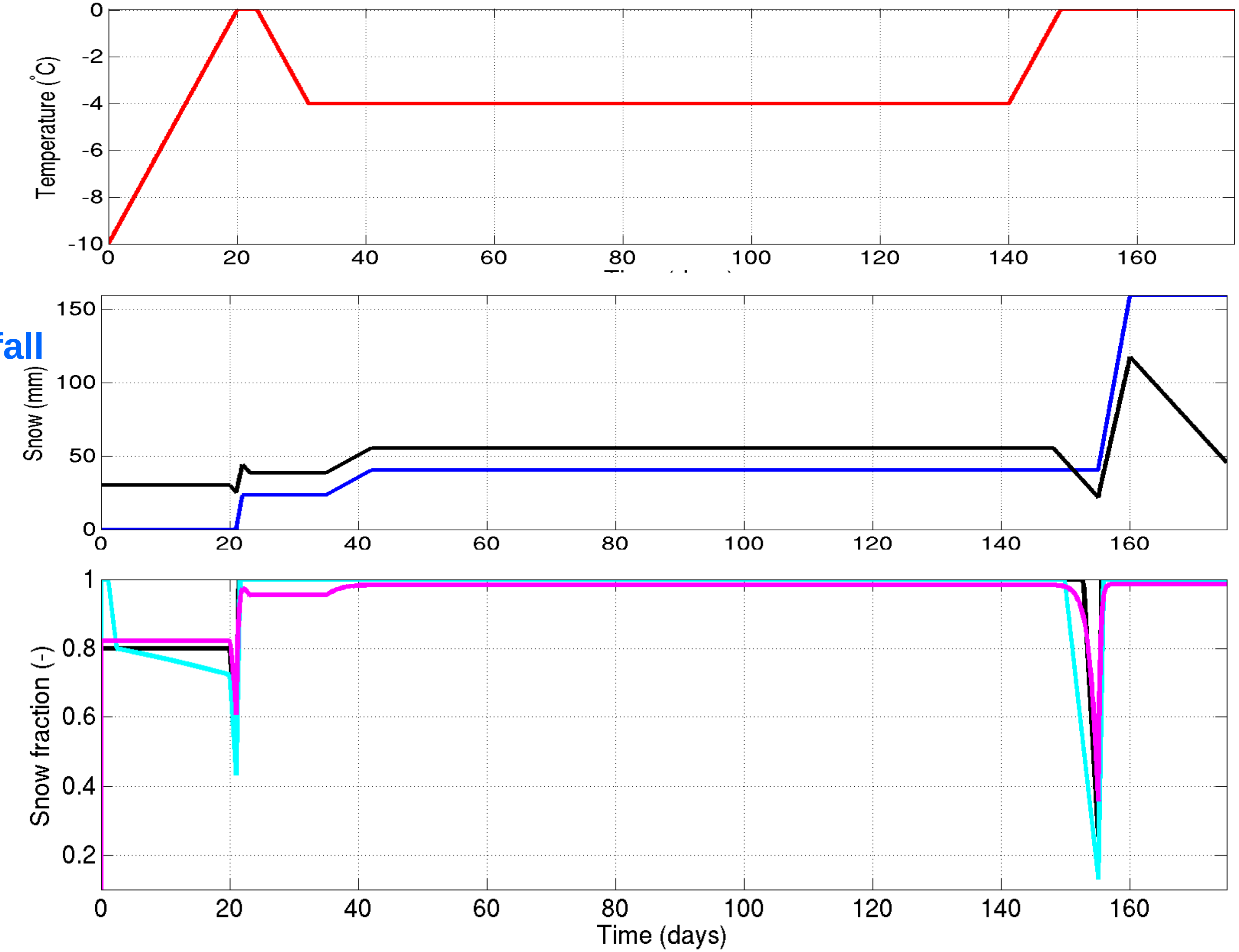
Douville, H., J.-F. Royer, J.-F. Mahfouf, 1995. A new snow parameterization for the Météo-France climate model, Clim. Dyn., 12, 21–35.
Lindström, G. and Gardelin, M. 1999. A simple snow parameterization scheme intended for the RCA model based on the HBV runoff model. SWECLIM Newsletter 6, SMHI, Sweden, 16–20.
Niu G.-Y and Z.-L. Yang, 2007. An observation-based formulation of snow cover fraction and its evaluation over large North American river basins, J. Geophys. Res., 112, D21101, doi:10.1029/2007JD008674.

Different parameterisations of snow fraction SMHI

Temperature

Accumulated snowfall
Snow water eq.

old HTESSEL
new HTESSEL
RCA



Snow density

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Many prognostic parameterisations of density has a simple exponenetial increase of density with time along with some restoring function due to new fresh low-density snow, like:

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

$$\rho_{sn}^{t+1} = \left(\rho_{sn}^{*} - \rho_{sn_{\max}}\right)\exp\left(-\tau_f \, \Delta t / \tau_1\right) + \rho_{sn_{\max}}$$

ECMWF / Old HTESSEL

Dutra et al. (2010)

ρ_{snmax}=300 kg/m3, ρ_{snmin}=100 kg/m3

τ_f=0.24, τ_1=86400 s

Based on
Douville et al. (1995) and
Verseghy (1991).

However, Dutra et al. (2010) concluded that this type of parameterization underestimates the snow thermal insulation and overestimate soil freezing.

Douville, H., Royer, J.F. and Mahfouf, J.F., 1995: A New Snow Parameterization for the Meteo-France Climate Model .1. Validation in Stand-Alone Experiments. Climate Dyn., 12, 21-35.

Verseghy, D.L., 1991: Class-a Canadian Land Surface Scheme for Gcms .1. Soil Model. Int. J. Climatol., 11, 111-133.

Snow density

A more physically parameterisation taking into account overburden of snow, thermal metamorphism and compaction related to liquid water in the snow is used in SURFEX 3-layer snow scheme and is recently introduced in ECMWF New HTESSEL:

$$\frac{1}{\rho_{sn}}\frac{\partial \rho_{sn}}{\partial t} = \underbrace{\frac{\sigma_{sn}}{\eta_{sn}\left(T_{sn,}\rho_{sn}\right)}}_{\text{overburden}} + \underbrace{\xi_{sn}\left(T_{sn},\rho_{sn}\right)}_{\text{thermal metamorphism}} + \underbrace{\frac{\max\left(0, Q_{sn}^{INT}\right)}{L_f\left(S - S_l\right)}}_{\text{compaction related to melt water retained in the snowpack}}$$

overburden (Anderson 1976; Boone and Etchevers 2001)

thermal metamorphism

compaction related to melt water retained in the snowpack Lynch- Stieglitz (1994)

σ_{sn} *is* pressure of the overlaying snow (Pa)
η_{sn} is snow viscosity (Pa s)

Anderson, E.A., 1976: A point energy and mass balance model of a snow cover. NOAA Tech. Rep. , NWQ 19, 150 pp.
Lynch-Stieglitz, M., 1994: The Development and Validation of a Simple Snow Model for the Giss Gcm. J. Climate, 7, 1842-1855.

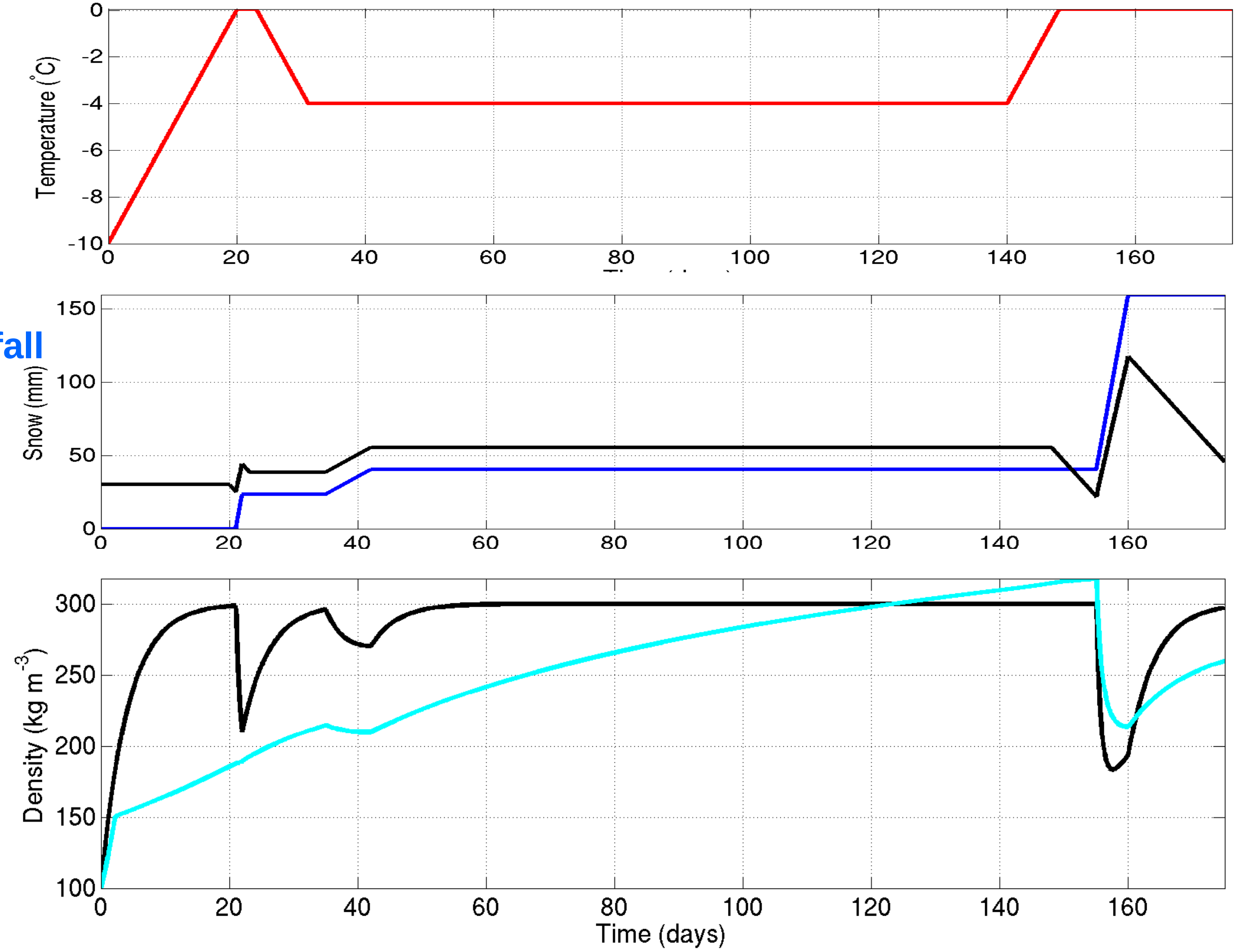
Different parameterisations of snow density

Temperature

Accumulated snowfall

Snow water eq.

old HTESSEL &
RCA3 &
HIRLAM newsnow
New HTESSEL



Snow heat conductivity

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Cook et al. (2008) used a GCM to test the sensitivity of land surface and climate processes to snow thermal conductivity.

Over Sibera and Northern Canada they report changes in soil temperature up to 20 K, and in the air temperature up to 6 K, during winter, just by prescribing snow thermal conductivity to its observed upper and lower limits (0.1 – 0.5 W/mK). High values drove increased heat flux into the ground during the summer, with resulting air temperature anomalies of -1 to -2 K.

Thermal conductivity of the snow in CLM3 is based on Jordan (1991):

$$\lambda_{sno} = \lambda_{air} + \left(7.75 \times 10^{-5}\rho_{sno} + 1.105 \times 10^{-6}\rho_{sno}^2\right)(\lambda_{ice} - \lambda_{air})$$

Gives a range for λ_{sno} is 0.149–0.459 for the Northern Hemisphere

Cook, B.I., Bonan, G.B., Levis, S. and Epstein, H.E., 2008: The thermoinsulation effect of snow cover within a climate model. Climate Dyn., 31, 107-124.


THANKS!
Drakensberg, South Africa, August 2006

Snow liquid water

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

ECMWF / New HTESSEL

Dutra et al. (2010) following Anderson (1976)

$r_{l,min}$=0.03, $r_{l,max}$=0.1, $\rho_{sn,l}$=200 kg/m3

Anderson, E.A., 1976: A point energy and mass balance model of a snow cover. NOAA Tech. Rep. , NWQ 19, 150 pp.