Modelling of snow 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 heat, moisture and momentum fluxes)
- Represent a storage of water as hydrological memory for runoff
- Insulation of the soil and its impact on soil thermal evolution
- Internal snow structure in terms of size and character of snow crystals

**LESS IMPORTANT**
- Snow drift by wind
Important characteristics of snow

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, roughness in 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

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

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

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

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

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.

Most albedo parameterisations can be divided into:

**prognostic**

\[
\alpha_{sn}^{t+1} = \begin{cases} 
\alpha_{sn}^t - \tau_a \Delta t / \tau_1 \\
(\alpha_{sn}^t - \alpha_{min}) \exp(-\tau_f \Delta t / \tau_1) + \alpha_{min}
\end{cases}
\]

**temperature dependent**

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

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

\(\alpha_{min} = 0.5, \alpha_{max} = 0.85\)

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

ECHAM5 (Roeckner et al., 2003)

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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 the Rossby Centre regional climate model (RCA) it has been shown that a modification of the prognostic snow albedo considering both the threshold and temperature factors significantly reduces a warm bias over Arctic regions.
Different parameterisations of snow albedo

Temperature

Accumulated snowfall
Snow water eq.

old HTESSEL
new HTESSEL
RCA
ECHAM5
Simpler parameterizations of snow cover fraction (SCF) usually relates SCF to the snow water equivalent (SWE) or the snow depth (Hsn) along with some critical value. Two examples are

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

ECMWF / Old HTESSEL

\[S_{\text{crit}}=15 \text{ mm}\]

\[
P_{nev} = \frac{h_n}{h_n + 5 \times z_0}
\]

The fraction \(P_{nc}\) is calculated as:

\[
P_{nc} = \min(1, W_n/W_1) \quad (W_1 = 70 \text{ mm})
\]

ARPEGE-Climate Version 5.1
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.

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

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

\[\text{SCF} = \frac{S_n}{(S_n + \rho_{sn} \cdot 5 \cdot z_{0veg})}\]

Different parameterisations of snow fraction

S = 12 mm

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

\[
\rho_{sn}^* = \frac{S\rho_{sn}^i + \Delta t F \rho_{min}}{S + \Delta t F}
\]

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


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

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:

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

- overburden
- thermal metamorphism
- compaction related to melt water retained in the snowpack

(Anderson 1976; Boone and Etchevers 2001)

\(\sigma_{sn}\) is pressure of the overlaying snow (Pa)
\(\eta_{sn}\) is snow viscosity (Pa s)

Different parameterisations of snow density

Temperature

Accumulated snowfall

Snow water eq.

old HTESSEL
New HTESSEL
Snow heat conductivity

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

Over Siberia 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):

\[ \hat{\lambda}_{sno} = \hat{\lambda}_{air} + (7.75 \times 10^{-5} \rho_{sno} + 1.105 \times 10^{-6} \rho_{sno}^2)(\hat{\lambda}_{ice} - \hat{\lambda}_{air}) \]

Gives a range for \( \hat{\lambda}_{sno} \) is 0.149–0.459 for the Northern Hemisphere.

Implications of snow heat conductivity

Imagine a grid box partly covered by snow but where the soil is not tiled.

- **Autumn heat release**
  - The whole soil column cools via snow-free soil.
  - Underestimated heat transport to snow.

- **Spring warming**
  - The whole soil column warms via snow-free soil.
  - Overestimated heat transport to snow.
Imagine a grid box partly covered by snow and where the soil is tiled.

**Implications of snow heat conductivity**

- **Autumn heat release**: Cooling of soil beneath snow via snow-free soil is reduced.
- **Spring warming**: Warming of soil beneath snow via snow-free soil is reduced.
Interaction of snow and vegetation

Introduction of multi-energy balance including snow in SURFEX

Vegetation can be everything between grass and forest!

Low sun elevation at high latitudes
Interaction of snow and vegetation

Introduction of multi-energy balance including snow in SURFEX

Snow well below the base of vegetation canopy

Snow partly covering vegetation canopy

Snow well above the top of vegetation canopy

Enable studies (and forecasts) including complex interactions of snow/vegetation w.r.t. turbulent fluxes, radiation, blowing snow,…

We need forest/snow observations for evaluation!!
Conclusions
Also from a recent snow Workshop in Kuopio, Finland

Snow albedo = f( ageing , temperature ) is more realistic than f( one of the factors )

Modelling of snow fraction should include the hysteresis effect of snow growth/melt. Orography should be accounted for since snow melt is more patchy in mountainous terrain.

New formulation of snow density leads to more realistic snow thermal insulation and consequently more realistic soil temperatures.

Use separate soil columns beneath snow and for bare soil/vegetation part of a grid box. Otherwise, e.g. during spring time we can have melting of snow from below when the bare soil part is heated.

Multi-energy balance including snow gives e.g. more realistic energy partitioning in forest areas.

Other aspects not considered: horizontal redistribution of snow due to wind, interception of snow, black carbon on snow reducing albedo...
THANKS!
Snow liquid water

\[ S^c_l = S \left[ r_{l,\text{min}} + (r_{l,\text{max}} - r_{l,\text{min}}) \max \left( 0, \frac{\rho_{sn,l} - \rho_{sn}}{\rho_{sn,l}} \right) \right] \]

ECMWF / New HTESSEL
Dutra et al. (2010) following
Anderson (1976)
\( r_{l,\text{min}} = 0.03, r_{l,\text{max}} = 0.1, \rho_{sn,l} = 200 \text{ kg/m}^3 \)