Snow cover physical properties and impacts on surface atmospheric fluxes

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The unique physical properties of snow cover:

⇒ surface fluxes cooling the atmosphere

Main snow-related issues and challenges for NWP

Current performance of numerical snow models

Using surface temperature to detect weaknesses in the parametrization of heat fluxes
Snow physical properties exhibit an extreme diversity

A complex microstructure
- A porous medium made of ice, air, and liquid water
- Their relative proportion controls its physical properties
- Weather conditions control metamorphism and compaction

⇒ extreme and rapid changes of its physical properties

3D image of a Depth Hoar snow sample (Calonne et al., 2014)
Snow: altogether a white, grey and black medium

Unique radiative properties

- **white** in the visible spectrum affected by light-absorbing impurities
- **grey** in the near-infra-red spectrum affected by snow grain size
- **black** body in the thermal infra-red spectrum

⇒ very rapid changes of its albedo

(Warren and Wiscombe, 1980)

(Wiscombe and Warren, 1980)
Important snow albedo / atmosphere feedbacks: metamorphism and impurities concentration

Snow metamorphosis

- Warmer snow
  - grain growth
  - snow albedo decreases (near-infrared spectrum)
  - warmer snow

Surface melting
- Impurities are retained at the surface
- Snow albedo decreases
- Melt rate increases (visible spectrum)

Glacier Blanc (French Alps)

Higher darkening efficiency of impurities for larger snow grains
Important snow albedo / atmosphere feedbacks: metamorphism and impurities concentration

**Snow metamorphism**

- Warmer snow $\Rightarrow$ grain growth
- Warmer snow $\Rightarrow$ snow albedo decreases (near-infrared spectrum)
- Warmer snow $\Rightarrow$ warmer snow

**Surface impurities concentration by snow surface melting**

- Surface melting $\Rightarrow$ Impurities are retained at the surface
- Surface melting $\Rightarrow$ Snow albedo decreases (visible spectrum)
- Surface melting $\Rightarrow$ Melt rate increases

+ higher darkening efficiency of impurities for larger snow grains
Density controls inertia and conductivity

- light snow has an almost negligible thermal inertia
- light snow is a better insulator than industrial insulating materials

⇒ density is a critical snow variable

(Calonne et al., 2011)
Impact of snow insulation on soil/atmosphere decoupling

Soil temperature $\leftrightarrow$ snowpack depth and density

For a given mass, the snowpack thermal resistance $\sim \alpha \frac{1}{\text{density}^3}$
An important cooling factor in the climate system

- high albedo
- high thermal emission
- soil/atmosphere decoupling
- important melting latent heat sink
- upper temperature limited to 0°C

⇒ colder surface temperatures than other surfaces
⇒ amplified by the boundary layer stabilization
Snow Physics

Illustrative heat budget

Main energy fluxes at Col de Porte, French Alps

(Brun et al., 1989)

Date (DD/MM 1987)

Sensible
Latent
Short-Wave
Long-Wave

Main energy fluxes at Dome C, Antarctica

(Brun et al., 2011)

Date (DD/MM 2010)
Illustrative heat budget

Main energy fluxes at Col de Porte, French Alps

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Main energy fluxes at Dome C, Antarctica

(Brun et al., 2011)
1. Snow Physics

2. Main snow-related issues and challenges for NWP

3. Snowpack modelling: off-line simulations from reanalysis

4. Using surface temperature to improve the parametrization of heat fluxes

5. Conclusion

6. Add-ons
Main categories of issues

- Misrepresentation of snow/ice physical properties
- Weaknesses in the representation of heat fluxes under stable conditions (i.e. Holstag et al., 2013)
- Landscape heterogeneity
- Analysis of snow/ice properties from operational observation systems
Example of combined errors in snow physics and heat fluxes: Air temperature (T2m) at Sodankyla 2010-02-11

ARPEGE OPER: too large snow density and obs rejection

AROME dynamical adaptation: lower snow density

(Courtesy E. Bazile and http://fminwp.fmi.fi/mastverif/mastverif.html)
Example of errors in snow physics and heat fluxes:

Air temperature (T2m) at Sodankyla 2010-02-11

ARPEGE OPER: too large snow density and obs rejection

HIRLAM RCM: no obs rejection

(Courtesy E. Bazile and http://fminwp.fmi.fi/mastverif/mastverif.html)
Using reanalysis assimilating only the pressure to detect snow-related weaknesses: 20CR Humidity

Observations from station 59.62 N/65.78 E, elev.: 72.0m
Similar weaknesses in NCEP/CFSR analysis of humidity

Monthly mean of the 6 hour forecast relative humidity at 2m in NCEP-CFSR in March 1979
Red color is for 100 % relative humidity
Snow/soil/vegetation heterogeneity

(Picture from the Arctic Research Centre (FMI) Web site)
Difficulties in real-time snow/ice analysis

Main issues for snow analysis in NWP systems

- Snow cover retrievals from optical sensors are not possible under cloudy or shadowy conditions
- Snow Water Equivalent retrievals from micro-wave exhibit large errors, especially during melting and for shallow snowpacks
- Depth, albedo, density, liquid water content are not retrieved from space or are poorly reliable
- In-situ snow depth observations are unevenly distributed and suffer from diverse observation practises
A WMO Global Cryosphere Watch initiative for improving the access to in-situ snow depth observations

ECMWF Operational monitoring of SYNOP snow depth: number of observations on 2014 01 04 at 00UTC (21-09 UTC): observations gap in USA, China and southern hemisphere

http://www.ecmwf.int/products/forecasts/d/charts/monitoring/conventional/snow/

GCW Snow Watch initiative to improve in situ snow depth data access (NRT and rescue), Brun et al 2013

P. de Rosnay Snow data assimilation status, February 2014
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A large diversity in numerical snow models

- Detailed snowpack models for avalanches and snow research: Anderson, Crocus, SNOWTHERM, SNOWPACK, SMAP
- Simple uni-layer snow models for weather forecast and climate models: a lot!
- Intermediate complexity snow models embedded in weather prediction and climate models: ISBA-ES, JULES, SNICAR, HTESSEL...
- Detailed snow models in regional climate models simulating ice-sheets surface mass balance: RACMO, MAR
- Intermediate complexity snow models embedded in hydrological models: VIC, ...
Crocus / ISBA-DF: a coupled snowpack / soil model

(Brun et al., 1992; Vionnet et al., 2012)

Optional blowing snow processes: compaction and sublimation
Configuration of off-line Crocus simulations

ERA-interim reanalysis
ECMWF (Dee et al., 2011)

- ~ 80 km resolution
- precipitation from model forecasts: no use of any observed precipitation!
- radiation from model

Crocus snow model
ISBA-DF soil model

- Northern Hemisphere: 1°x 1° / 1979-2013
  27°N / 90°N
- Greenland: 15 km / 1979-2013
- Antarctica: 25 km / 2000-2011
Illustration of Era-interim / Crocus performance

Performance over 250 stations 1979-1993

- Very small bias and high correlations:
  - snow depth, date of maximum snow depth
  - onset and melt-out dates
- A few stations are poorly simulated
  (unresolved local meteorological conditions: wind, precipitation)

(Brun et al., 2013)
Evaluation of simulated snowpack density

Snow models derive vertical profiles of characteristics which are rarely measured:
- density, grain size, temperature, liquid water, soil temperature

(Brun et al., 2013)
Snow modelling to simulate the GrIS surface mass balance

**Reconstruction of melting events**

- **Observation:**
  - melting events from space-borne micro-wave radiometers
  - 2 different Snow Melt Index algorithms:
    * Mott and Anderson (1995)
    * Tedesco (2009)

- **Snow model:**
  - Surface temperature $\geq -0.1$ °C.
Performance in the reproduction of melting events

Better correlation between the model and TM algorithm between TM and MT algorithm (SMI extracted from Tedesco et al., 2013) (Dumont et al., 2014)
Current state of performance of snow models

Main points

- Atmospheric reanalyses provide very reliable forcing conditions for off-line runs of snow models.
- Detailed snowpack models simulate reasonably well depth, SWE, density, albedo, surface temperature, soil temperature, grain size and layering.
- Intermediate complexity models simulate reasonably well depth, SWE, density and albedo.
- Snowpack simulations exhibit performances quite similar to satellite products.
- Error compensations between different processes contribute to this performance (ex. Essery and Etchevers, 2004).

⇒ It is time to focus on issues related to snow/atmosphere coupling (see WCRP/CliC ESM-SnowMIP initiative).
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Summary of the study (Freville et al., 2014)

- Availability and evaluation of hourly MODIS surface temperature (Ts) in Antarctica
- Evaluation of ERA-interim Ts against MODIS Ts
- Evaluation of off-line simulations from ERA-interim forcings: Crocus and HTESSEL (ERA-interim land)
- Detection of a significant warm bias of ERA-interim over most of Antarctica
- Identification of an overestimation of surface heat fluxes under stable conditions in IFS
Availability of hourly MODIS Ts over Antarctica (2000-2011)

(Freville et al., 2014)
Evaluation of hourly MODIS Ts against in-situ data (2000-2011)

(Freville et al., 2014)
Bias of hourly ERA-interim Ts and Crocus Ts against MODIS hourly Ts (2000-2011)
RMSe of hourly ERA-interim Ts and Crocus Ts against MODIS hourly Ts (2000-2011)
Warm ERA-interim bias due to overestimated heat fluxes under very stable conditions (South Pole)

(Freville et al., 2014)
Conclusion

- Snow and ice are key cooling factors of the atmospheric boundary layer.
- Current snow models represent reasonably well many aspects of snow/atmosphere interactions.
- The derivation of surface heat fluxes under very stable conditions is still an issue.
- Remote-sensed surface temperature is a unique source of data for evaluating the performance of heat fluxes parameterization.
- A lot to be learnt from simulations and observations at local points.
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2 current major initiatives for improving snow/atmosphere simulations:

- GEWEX GABLS4 case from Dome C, Antarctica: heat surface fluxes and ABL evolution under extreme stability.
- WCRP/CliC ESM-SnowMIP: intercomparison of GCM-designed snow models in coupled and stand-alone simulations.
The GABLS4 Dome C (Antarctica) case in preparation : a unique opportunity to improve snow/ atmosphere coupled simulations (Bazile et al.)
Thanks for your attention!

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Comparison with GlobSnow SWE retrievals (1979-1993)

GlobSnow:
- ESA funded snow product developed by FMI
- Gridded daily SWE products based on in-situ snow depth observations and satellite Micro-Wave observations

(Luojus et al., 2011)

<table>
<thead>
<tr>
<th>All observations</th>
<th>GlobSnow V1</th>
<th>Crocus/ERA-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of obervations</td>
<td>137,379</td>
<td>109,189</td>
</tr>
<tr>
<td>bias (kg m$^{-2}$)</td>
<td>-4.8</td>
<td>0.9</td>
</tr>
<tr>
<td>RMSe(kg m$^{-2}$)</td>
<td>44.9</td>
<td>44.6</td>
</tr>
</tbody>
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The domain and the period sightly differ.
Snow simulations: ERA-Interim meteorological forcing / blowing snow sublimation

Crocus/ERA-Interim simulations and GlobSnow retrievals perform very similarly for SWE
Differences between GlobSnow SWE and Crocus/ERA-Interim SWE
Mean ERA-interim Heat fluxes August 2009
Evaluation of Crocus/ERA-interim versus satellite: NEEM hourly surface temperature (see Steen-Larsen et al., 2014)
Stand-alone Crocus Ts simulations from local forcings: Dome C Antarctica

(Brun et al., 2012)
Coupled Crocus/AROME surface and ABL simulations: Dome C Antarctica

(Brun et al., 2012)
IFS sensitivity to stability functions

Difference in 2-meter temperature (°C) averaged over January 1996 between simulations with two different stability functions in the ECMWF model (Viterbo et al. 1999; Beljaars 2012). The left panel shows the impact in the 1994 version of the ECMWF model and the right panel shows the impact of the same change in the 2011 model version. Color range in legend indicates temperature differences between -4 and 10 °C.

(Holtslag et al., 2013)