Observing and modelling meltwater retention in snow and firn

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OBSERVING AND MODELLING MELTWATER RETENTION IN SNOW AND FIRN

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Dry snow zone at top of Greenland ice sheet
No melt and no runoff
Close to the ELA

Melt water from surface snow moves within the shallow snowcover and collects in a depression with underlying impermeable ice
Below ELA
Melt water collects into large slush fields
GGU’s REFREEZING STUDIES 1981-92

- In 1981. Fixing the mass balance of Nordbogletscher (1)
- In 1991-1992 studying refreezing in more detail at Pâkitsoq (2)
- The trick is to work in lower firn area with medium-high firn density
NORDBOGLETSCHER 1981

- Measured mass balance on Nordbogletscher 1979-83
- Measured mass change in surface layer
- Discussion about possible refreezing of meltwater below surface layer
- Snow scooter traverse to upper accumulation area to drill a SIPRE core
- Solidly frozen firn so meltwater from surface melt must be refrozen

General increase of firn density with depth with frequent ice layers
Main densification by formation of ice layers due to refreezing of meltwater from the snow surface (Left). Firn probably goes through 2-3 cycles of refreezing before becoming permanently frozen. Ice layers are formed within this “transient refreezing zone”.

Moderate densification due to density increase in ice-free samples (Right)
Several years of mass balance study by “flying squad” techniques showed that detailed study of firm profiles needs a less stressed schedule.

In May 1992 we establish a tent camp in the lower accumulation area at Pâkitsoq and moved around the area measuring five firn profiles without the distraction of a waiting helicopter.

Note the lack of horizon in the upper picture: we could not have safely landed with a helicopter in such conditions but we could move around with skis with perfect safety.
Field area in lower accumulation area between Swiss Station and end of EGIG traverse.

In our conceptual model, runoff limit is where wetting front meets impermeable ice, assuming very low temperatures.
RUNOFF LIMITED BY SNOW DENSITY

Simple density mixing model

As there is no run-off, and neglecting density variations below the wetted layer, the net result of an annual cycle of accumulation, melting and refreezing is to add a new firn layer, of density $\rho_2$ and thickness $(C - M)/\rho_0$, to the ice-sheet surface. From conservation of mass, the material in this layer must be equal to the snow accumulation:

$$C = \rho_2(C - M)/\rho_0.$$  \hfill (2)

With some re-arrangement, the density of firn just below the wetted layer is:

$$\rho_2 = \rho_0/(1 - (M/C)).$$  \hfill (3)

Alternatively, the melting $M/C$ required to achieve the density $\rho_2$ is:

$$M/C = (\rho_2 - \rho_0)/\rho_2$$  \hfill (4)

which is given by Shumskii (1964, p. 416). The density $\rho_2$ increases with the melt $M$ in agreement with Benson (1959, p. 35).

In steady-state model, the density at depth will be result of several equal cycles of refreeze.
MODELLING FIRN DENSITY

- Density modelled as M/C where M is calculated from degree-day model
- Density declines rapidly with altitude
- With temperature change +1 deg, large density changes at lower altitudes and smaller changes at greater altitudes
- Density profile is probably already different from that shown in the lower graph
RUNOFF LIMIT

Runoff limit where:

\[
M/C = (\rho_2 - \rho_0)/\rho_2
\]

At Pâkitsoq, \(\rho_2 = 890\) & \(\rho_0 = 375\;\text{kg m}^{-3}\) so \(M/C \sim 0.58\)

Runoff limit is where \(M > 0.58\;\text{C}\). (Other values in literature)

Realistic for very cold snow where wetting front never meets snow at 0 deg before it meets impermeable ice. For full geographic range of glaciers need to include snow temperature. There are probably some glaciers with little or no refreezing!
Repeated measurement of temperature is right approach but it all went wrong because of exceptionally low melting in summer 1992.

### Table 2. Temperatures profiles in the lower accumulation area, Pâkitsoq. Units are °C

<table>
<thead>
<tr>
<th>Stake</th>
<th>Date</th>
<th>Depth below surface - metres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m a.s.l</td>
<td>1 m 2 4 6 8 10</td>
</tr>
<tr>
<td>122</td>
<td>30/7/92</td>
<td>1180 -9.4 -10.9 -10.5 -10.0</td>
</tr>
<tr>
<td>151</td>
<td>1/8/92</td>
<td>1440 -8.5 -9.7 -9.3 -9.0</td>
</tr>
<tr>
<td>157</td>
<td>19/8/91</td>
<td>1510 -0.1 -0.5 -3.2 -7.5 -9.6 -9.9</td>
</tr>
<tr>
<td>14/5/92</td>
<td>-14.7 -13.8 -11.8 -9.8 -9.1 -9.0</td>
<td></td>
</tr>
<tr>
<td>1/8/92</td>
<td>-8.1 -10.2 -11.3 -10.7 -10.1 -9.6</td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>15/5/92</td>
<td>1530 -15.6 -14.7 -13.8 -11.7 m -9.2</td>
</tr>
<tr>
<td>2/8/92</td>
<td>-7.0 -9.4 -11.4 -11.2 m -10.2</td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>19/8/91</td>
<td>1620 0.0 -0.1 -4.0 -9.7 -12.4 -12.8</td>
</tr>
<tr>
<td>2/8/92</td>
<td>-10.7 -12.3 -13.0 -12.8 -12.2 -12.1</td>
<td></td>
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<tr>
<td>165</td>
<td>13/5/92</td>
<td>1620 -16.3 -15.5 -13.7 -12.4 -11.8 -12.0</td>
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<tr>
<td>2/8/92</td>
<td>-10.9 -12.5 -13.5 -13.2 -12.7 -12.5</td>
<td></td>
</tr>
</tbody>
</table>
# FIRN DENSITY AND MELT

Higher firn density at lower elevation
Higher firn density at shallow depth
Violation of Sorge’s Law!

## Table 6. Thickness of annual firn layer and melt rate estimated as a function of firn density

<table>
<thead>
<tr>
<th>Stake 157</th>
<th>High density</th>
<th>Low density</th>
<th>Mean density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>3–4</td>
<td>4–10</td>
<td></td>
</tr>
<tr>
<td>Firn density (kg m(^{-3}))</td>
<td>850</td>
<td>600</td>
<td>730</td>
</tr>
<tr>
<td>Annual firn thickness (m)</td>
<td>0.71</td>
<td>1.00</td>
<td>0.82</td>
</tr>
<tr>
<td>Melt/accumulation ratio</td>
<td>0.56</td>
<td>0.38</td>
<td>0.49</td>
</tr>
<tr>
<td>Annual accumulation (kg m(^{-2}))</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Annual melt (kg m(^{-2}))</td>
<td>340</td>
<td>230</td>
<td>290</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stake 163</th>
<th>High density</th>
<th>Low density</th>
<th>Mean density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>3–4</td>
<td>4–10</td>
<td></td>
</tr>
<tr>
<td>Firn density (kg m(^{-3}))</td>
<td>730</td>
<td>600</td>
<td>660</td>
</tr>
<tr>
<td>Annual firn thickness (m)</td>
<td>0.82</td>
<td>1.00</td>
<td>0.91</td>
</tr>
<tr>
<td>Melt/accumulation ratio</td>
<td>0.49</td>
<td>0.38</td>
<td>0.44</td>
</tr>
<tr>
<td>Annual accumulation (kg m(^{-2}))</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Annual melt (kg m(^{-2}))</td>
<td>290</td>
<td>230</td>
<td>260</td>
</tr>
</tbody>
</table>
A NEW FIELD EXPERIMENT?

Monitor variations of firn density and temperature over 2-3 melt/refreeze cycles

• At several sites (5?) in lower accumulation area
• Field camp for several days in May and flying visit in August
• Temperatures profiles down to 10 m measured twice a year (May and August)
• Continuous logging of snow temperatures May to August supplemented with logging of snow surface elevation
• Firn profiles down to 10 m measured by hand coring in May of each year
NEW MODELLING EXPERIMENTS

• Develop numerical model with hydraulics of meltwater movement and thermodynamics of heat conduction and phase change

• Use model to study refreezing under different climate regimes (sub-polar and temperate) and to simulate effects of climate change.

• Use archived model runs to develop multiple regression model of refreezing characteristics as function of simple climate variables like summer mean temperature, annual temperature range and annual precipitation.
THE END