Upscaling in situ observations to surface mass balance estimates and models of the Greenland ice sheet

Mike MacFerrin
CIRES, University of Colorado
CESM LIWG Meeting, 9 Feb 2016
Greenland Surface Mass Balance, (2002-2014)

- Surface Mass Balance (SMB) accounts for 68% of mass loss and 79% of acceleration in Greenland, 2002-2014
- SMB is currently the dominant mechanism of mass loss

Velicogna, et al. (2014), GRL
Firn Densification

- A primary uncertainty in ice sheet altimetry
Firn Densification

- Firn Compaction Verification and Reconnaissance (FirnCover)
## Community Firn Model

- Vertical compaction models from published literature

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Journal/Conference/Book</th>
<th>Year</th>
<th>Journal/Conference/Book</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herron &amp; Langway, 1980</td>
<td>J. Glaciology, stress-based solution</td>
<td>1980</td>
<td>JGR Atmospheres</td>
</tr>
<tr>
<td>Herron &amp; Langway, 1980</td>
<td>J. Glaciology, analytic solution</td>
<td>1980</td>
<td>Tellus B</td>
</tr>
<tr>
<td>Essery et al., 2013</td>
<td>Advances in Water Resources</td>
<td>2013</td>
<td>The Cryosphere</td>
</tr>
<tr>
<td>Cummings et al., 2013</td>
<td>U. Montana Snow, Ice &amp; Climate</td>
<td>2013</td>
<td>J. Glaciology</td>
</tr>
<tr>
<td>Arthern et al., 2010</td>
<td>J. Geophysical Research</td>
<td>2010</td>
<td>Annals Glaciology</td>
</tr>
<tr>
<td>Goujon et al., 2003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barnola et al., 1991</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ligtenberg et al., 2011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simonsen et al., 2013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li &amp; Zwally, 2011</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Most make steady-state climate assumptions
CFM Results at Summit, Greenland

- Forced with 1958 – 2013 temperature and accumulation (RACMO)
- Total porosity differs up to 220%
Firn Model Initialization

- Compare firn models forced by identical current climate
- Extremely sensitive to initialization

**NASA-SE**

- Initialized 800 years, **mean** temp & accum 1958-2013 from RACMO
- Initialized 800 years, **looped** temp & accum 1958-1978 from RACMO

Max Stevens, University of Washington
Shallow Firn Saturation

- Runoff line jumped 25 km uphill in 2012
- Shallow firn was saturating in successive “big” melt years (2002, 2005, 2007, 2010), which “primed” the firn for runoff

Machguth et al. (2016), Nature Climate Change
Mapping ice lids with GPR

GPR Transect 5 km
Mapping Ice Lids with IceBridge

- Perched lids (>1 m thickness) span 60,000 km²
- Firn can saturate rapidly
- Runoff can migrate rapidly uphill
- In 2012, Ice lids in SW Greenland added 11±4% to regional runoff
Early saturation modeling

Solving for the ratio \((M/C)\), we obtain

\[
\frac{M}{C} \geq \left[ \frac{c}{L} T_f + \left( \frac{\rho_{pc} - \rho_c}{\rho_c} \right) \right] \left[ 1 + \left( \frac{\rho_{pc} - \rho_c}{\rho_c} \right) \right]^{-1} \tag{A2}
\]

Substituting typical numbers for density and temperature for Arctic surface snow at the start of the melt season (e.g., \(T_f = -15^\circ C\) and \(\rho_c = 0.3 \text{ g cm}^{-3}\)), \(M/C\) takes the value 0.697. This number turns out to be quite insensitive to reasonable variations in \(T_f\) and \(\rho_c\), and for a wide variety of firm conditions, the necessary condition for runoff can be stated simply as

\[
\frac{M}{C} \approx 0.7
\]

_Pfeffer, Meier & Illangasekare (1991), JGR_
Pfeffer, Meier & Illangasekare (1991), GRL

![Graph showing Melt and Accumulation Flux vs. Elevation](Image)

**TABLE 1. Parameters for Future Climate Scenarios**

<table>
<thead>
<tr>
<th>Climate Model</th>
<th>$\Delta T$, °C</th>
<th>$\Delta c/c$</th>
<th>Variation From Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>4</td>
<td>0.10</td>
<td>1°C cooler</td>
</tr>
<tr>
<td>I</td>
<td>3</td>
<td>0.10</td>
<td>1°C warmer</td>
</tr>
<tr>
<td>II</td>
<td>5</td>
<td>0.10</td>
<td>50% wetter</td>
</tr>
<tr>
<td>III</td>
<td>4</td>
<td>0.15</td>
<td>50% drier</td>
</tr>
<tr>
<td>IV</td>
<td>4</td>
<td>0.5</td>
<td>no change in accumulation</td>
</tr>
<tr>
<td>V</td>
<td>4</td>
<td>0.0</td>
<td>from present</td>
</tr>
</tbody>
</table>

Pfeffer, Meier & Illangasekare (1991), JGR
Early Saturation Modeling (cont’d)

Pfeffer, Meier & Illangasekare (1991), JGR
Early Saturation Modeling (cont’d)

Current observations in Southwest Greenland

Pfeffer, Meier & Illangasekare (1991), JGR
Early Saturation Modeling (cont’d)

Current observations in Southwest Greenland

Future?
Dye-2 Firn Cores, 2100 m.a.s.l.

- 1998 – less than 5% ice content
- 2013 – greater than 25% ice content in top 16 m
Dye-2 Firn Cores, 2100 m.a.s.l.

- 1998 – less than 5% ice content
- 2013 – greater than 25% ice content in top 16 m

KAN-U firn from 1980-1990s resembles Dye-2 now
Early Saturation Modeling (cont’d)

Current observations in Southwest Greenland

Future?

Pfeffer, Meier & Illangasekare (1991), JGR
Early Saturation Modeling (cont’d)

Pfeffer, Meier & Illangasekare (1991), JGR
Conclusions

- As temps rise, Surface Mass Balance (SMB) now dominant in Greenland
- Firn has “memory”
  - Initialization and ensemble strategies crucial for short-term simulations
- Community firn model (CFM) density intercomparisons are under way
- SMB exhibits high variability and non-linear “threshold” behaviors
- Spatial resolution is an issue (always is!), thoughtful parameterizations are necessary
Conclusions

- As temps rise, Surface Mass Balance (SMB) now dominant in Greenland

- Firn has “memory”
  - Initialization and ensemble strategies crucial for short-term simulations

- Community firn model (CFM) density intercomparisons are under way

- SMB exhibits high variability and non-linear “threshold” behaviors

- Spatial resolution is an issue (always is!), thoughtful parameterizations are necessary

- I’d like to contribute (a job?)
Questions?

University of Colorado
Boulder

CIRES

NASA

University of Washington