Parameterizing Greenland’s surface mass balance in the Parallel Ice Sheet Model (PISM)

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**Background: PISM**

- **Parallel Ice Sheet Model**
  is an open source, fully-parallel, high-resolution ice sheet model

- one of the models used in SeaRISE assessment (*Sea-level Response to Ice Sheet Evolution*) to project the ice sheet contributions to sea level in the next 100-200 years

**Features:**

- a hierarchy of available stress balances, including shallow ice and shelf approximations, a hybrid of these, and a (planned) higher-order scheme

- a polythermal, enthalpy-based conservation of energy scheme

- complete documentation for users and developers

- [www.pism-docs.org](http://www.pism-docs.org)

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**Surface velocities**

**Basal velocities**

*5 km grid*
PISM: Surface mass balance

Classical degree-day approach

\[
\dot{M} = f_{\text{snow/ice}} \sum_{1}^{n} (T - T_0)
\]

- **Melt rate**
- **Degree-day factor**
- **Degree-day sum**

\[T = \text{air temperature}\]
\[T_0 = \text{threshold temperature below which there is no melt; in PISM: } T_0 = 0°C\]

Typical values for snow = 3-5 mm/d/K, ice = 6-10 mm/d/K

- **degree-day sum** is computed from positive temperatures multiplied by the duration (in days) when it is > 0°C
- **degree-day factors** according to Greve (2005), *Ann. Glac.*, → function of latitude and mean July temperature

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Purpose

to improve the degree-day model in PISM:

- How do degree-day factors vary spatially?
- How do they vary in time: seasons, trends?
- What do they depend on?
- How good is the degree-day model that is currently implemented in PISM?
- How can degree-day factors be parameterized in a way that can be implemented into PISM?
Data

Model
- RACMO2/GR Regional Climate Model
- lateral atmospheric forcings: ERA40 and ECMWF operational analysis
- resolution 11 km
- September 1957 - December 2008 (51.3 years)

Data
- Monthly melt
- Monthly and daily mean 2 m air temperatures
- Daily near-surface glacier density (to distinguish between snow and ice)

Degree-day factors

Classical degree-day approach

\[ \dot{M} = f_{\text{snow} / \text{ice}} \sum_{1}^{n} (T - T_0) \]

- Melt rate
- Degree-day factor
- Degree-day sum

\[ T = \text{air temperature} \]
\[ T_0 = \text{threshold temperature below which there is no melt;} \]
\[ \text{in PISM: } T_0 = 0^\circ C \]

Daily data

Monthly data
Positive degree-days and annual melt 1957-2008

Positive degree-days, PDD (Kd)

Annual melt (mm/yr)

Positive degree-days, PDD (Kd)

Based on daily mean temperatures

Based on monthly mean temperatures

\[
\dot{M} = f_{\text{snow/ice}} T_{\text{month}}^+
\]

\[
\dot{M} = f_{\text{snow/ice}} \sum_{1}^{n} (T - T_0)
\]
Daily and monthly mean temperature and monthly melt for one grid cell.
Degree-days factors averaged over 1957-2008

DDF = total melt/PDD over whole period, only for pixels with > 10 mm/yr melt and annual PDD > 10 dK

using monthly mean data

using daily mean data
Degree-days factors averaged over 1957-2008

DDF < 20 mm/d/K

Using monthly mean data

Using daily mean data

2550 out of 14,226 grid cells = 18%
Degree-days factors averaged over 1957-2008

DDF for grid cells with > 10 mm/yr melt and annual PDD > 10 dK, and DDF < 20 mm/d/K

using **daily** mean data

Degree-day factors increase with elevation
Van den Broeke et al. (2010, GRL in press) suggest lowering the temperature threshold from 273.15 K to 268 K.

\[ M = f_{\text{snow/ice}} \sum_{i=1}^{n} (T - T_0) \]

---> more realistic pattern of DDF, i.e. high DDF at low elevations and vice versa.

degree-day sums based on daily temperatures underestimate melt because of hourly temperatures above freezing while daily mean temp is below freezing.

Degree-day sum (based on daily mean T) = 0 Kd
Melt is underestimated

Degree-day sum > 0 Kd
Degree-days factors averaged over 1957-2008 using daily mean temperatures

\[ T_0 = 268 \text{ K} \]

Van den Broeke et al., 2010. Temperature thresholds for degree-day modelling of Greenland ice sheet melt rates. GRL in press

\[ T_0 = 273.15 \text{ K} \]
Degree-days factors for various threshold temperatures

\[ \dot{M} = f_{snow/ice} \sum_{1}^{n} (T - T_0) \]

- \( T_0 = 268 \text{ K} \)
- \( T_0 = 269 \text{ K} \)
- \( T_0 = 270 \text{ K} \)
- \( T_0 = 271 \text{ K} \)
- \( T_0 = 272 \text{ K} \)
- \( T_0 = 273.15 \text{ K} \)

\[ M = f_{snow/ice} \sum_{1}^{n} (T - T_0) \]
How does the temp threshold affect degree-day factors?

Degree-day sum (based on daily mean T) = 0 Kd
Melt is underestimated

Degree-day sum > 0 Kd
Melt is underestimated

Degree-day sum = positive but there is no melt
--> Melt is overestimated
Purpose

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Degree-day factors after Greve (2005)

- **DDF_{snow} = 3 mm/d/K for entire Greenland**
- **DDF_{ice}**:
  - South of 72$^\circ$N: 7 mm/d/K
  - North of 72$^\circ$N: function of mean July temperature

\[
\beta_{\text{ice}} = \begin{cases} 
\beta_{\text{ice}}^W \\
\beta_{\text{ice}}^W + \frac{\beta_{\text{ice}}^C - \beta_{\text{ice}}^W}{(T_W - T_C)^3} (T_W - T_{mj})^3 \\
\beta_{\text{ice}}^C 
\end{cases}
\]

- \( T_{mj} \geq T_W \), \( T_C \leq T_{mj} \leq T_W \), \( T_{mj} \leq T_C \),

Based on Tarasov and Peltier, 1999
PISM: Melt after Greve (2005)

\[ \dot{M} = f_{\text{snow/ice}} \sum_{1}^{n} (T - T_0) \]

Degree-day factor
Degree-day sum

Degree-day factor ice

\[ f_{\text{snow}} = 3 \text{ mm/d/K} \]
over entire Greenland

Surface layer density

July 1959

Density fields used to decide whether surface is ice or snow:

\(<350 \text{ kg/m}^3 = \text{ snow: } f_{\text{snow}}\)

\(>850 \text{ kg/m}^3 = \text{ ice: } f_{\text{ice}}\)

Linear interpolation in between
How does the PDD model (Greve, 2005) compare to RACMO?

Mean over 1957-2008

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean Annual Melt</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RACMO</td>
<td>243 mm/yr</td>
<td><strong>190 mm/yr</strong></td>
</tr>
<tr>
<td>DDF (Greve)</td>
<td>55 mm/yr</td>
<td><strong>333 Gt !!!</strong></td>
</tr>
</tbody>
</table>

**Mean annual melt**
- RACMO: 243 mm/yr
- DDF (Greve): 55 mm/yr

**Total melt**
- RACMO: 427 Gt
- DDF (Greve): 93 Gt

**Difference**
- **333 Gt !!!**
Conclusions

- Degree-day factors vary strongly in space; no clear geographical pattern
- Factors depend on the way the PDD sum is computed (averaging interval, threshold temperatures)
- Parameterization by Greve (2005) applied to RACMO temperature fields leads to considerable underestimation of melt compared to RACMO (>300 Gt/yr)

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Mean July temperature 1996 - 2006
Comparison RACMO - Fausto-parameterization

RACMO
(Ettema et al., 2009)

Parameterization
(Fausto et al., 2009)

Difference
RACMO - Parameterization

Parameterization (Fausto et al., 2009)

\[ T_{\text{July}} = d + a \ z + b \ \text{lat} + c \ \text{lon} \]
DDF according to Greve (2005) using RACMO positive degree-day sums based on daily data
Degree-days factors for various threshold temperatures

 Arrow up means DDF increase with increasing elevation
 Arrows down is opposite
Degree-days factors for various threshold temperatures

- $T_0 = 269 \text{ K}$
- $T_0 = 270 \text{ K}$
- $T_0 = 271 \text{ K}$
- $T_0 = 272 \text{ K}$
- $T_0 = 273.15 \text{ K}$
Degree-days factors derived from T0=268 to 270 versus T0 = 273.15 K