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

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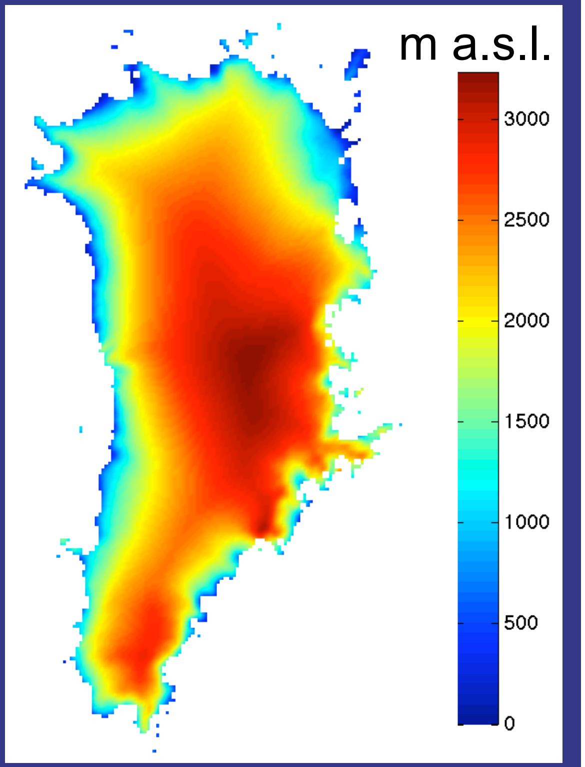

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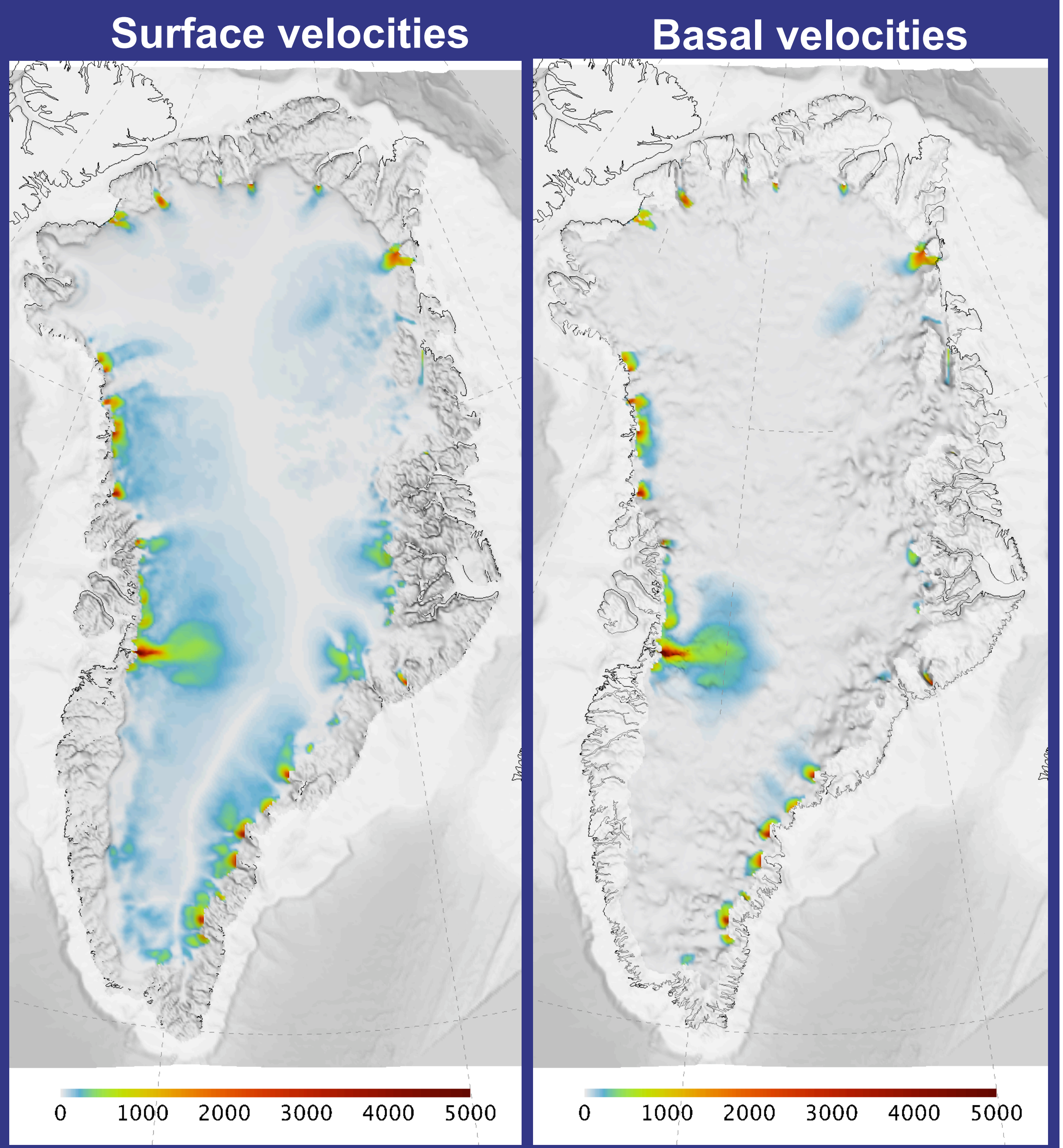
Background: PISM

- **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



5 km grid

PISM: Surface mass balance

Classical degree-day approach

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

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

T = air temperature
T_0 = threshold temperature below which there is no melt;
in PISM: T0 = 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**

- ***Greve**, R. (2005). Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. Ann. Glaciol., 42, 424-432.*

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 ?**

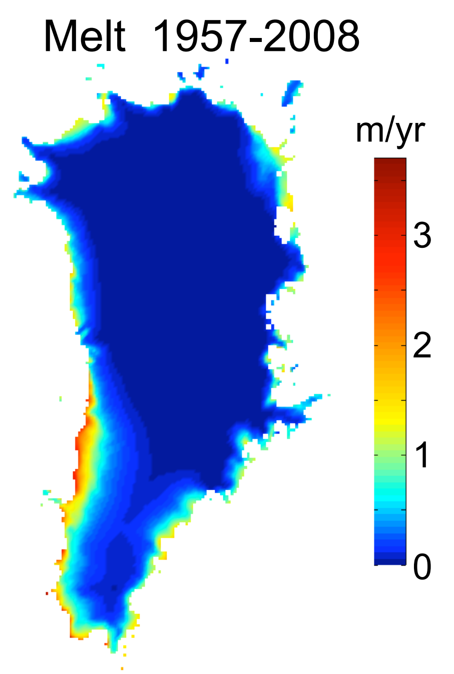
Data

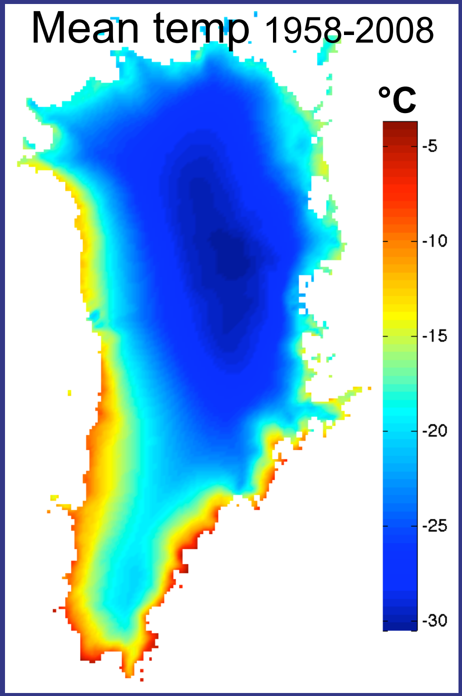
Model

- 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)





Ettema, J., M.R. van den Broeke, E. van Meijgaard, W.J. van de Berg, J.L. Bamber, J.E. Box, and R.C. Bales (2009), Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36 (L12501), doi:10.1029/2009GL038110.

Degree-day factors

Classical degree-day approach

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

Daily data

Melt rate

Degree-day factor

degree-day sum

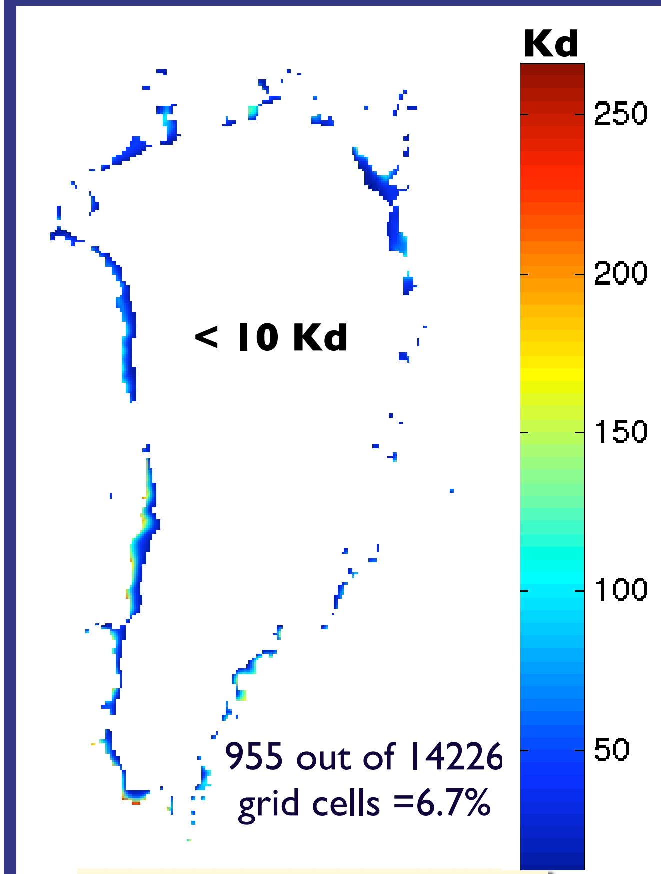
T = air temperature
T_0 = threshold temperature below which there is no melt;
in PISM: T0 = 0°C

$$\dot{M} = f_{snow/ice} T^{+}_{month}$$

Monthly data

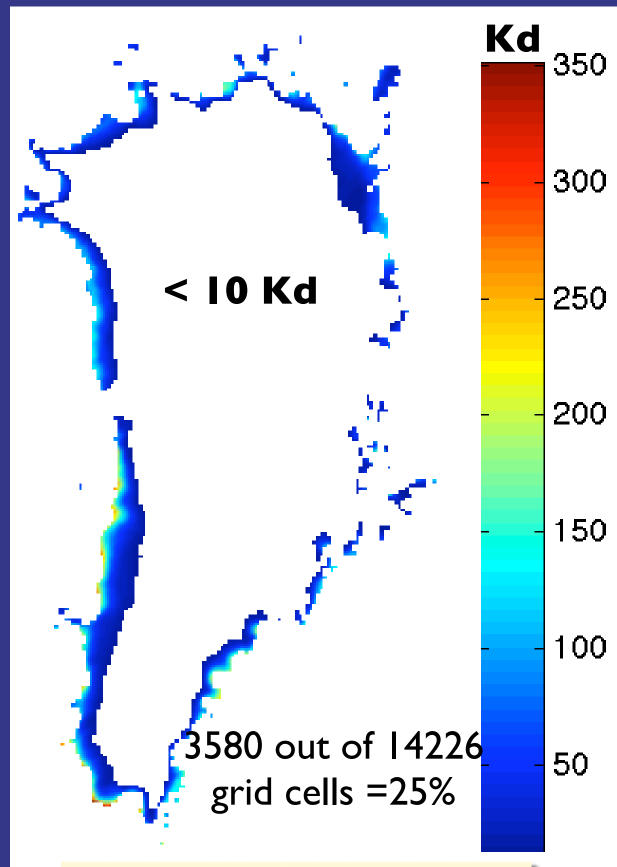
Positive degree-days and annual melt 1957-2008

Positive degree-days, PDD (Kd)



based on **monthly** mean temperatures

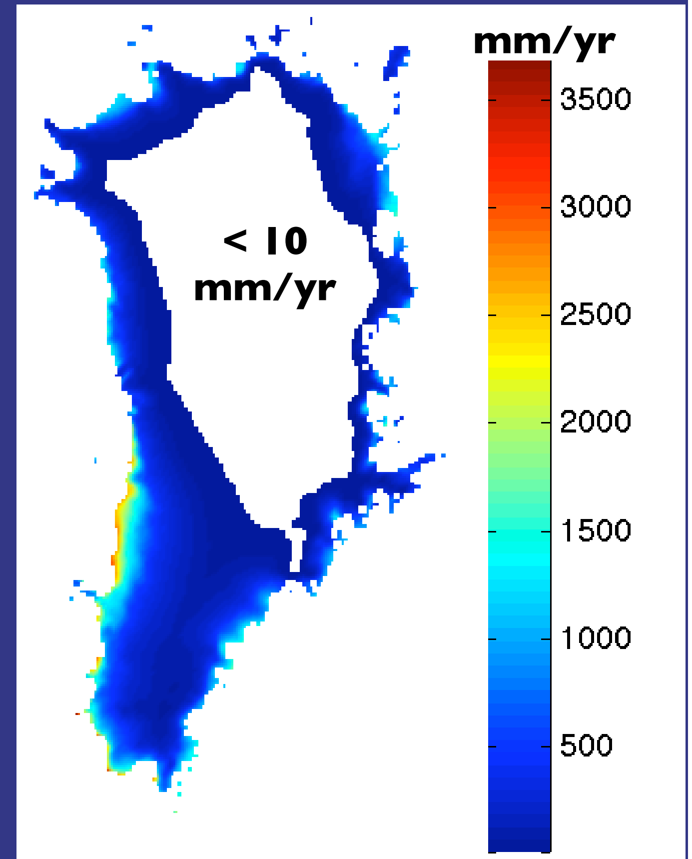
$$\dot{M} = f_{snow/ice} T^{+}_{month}$$



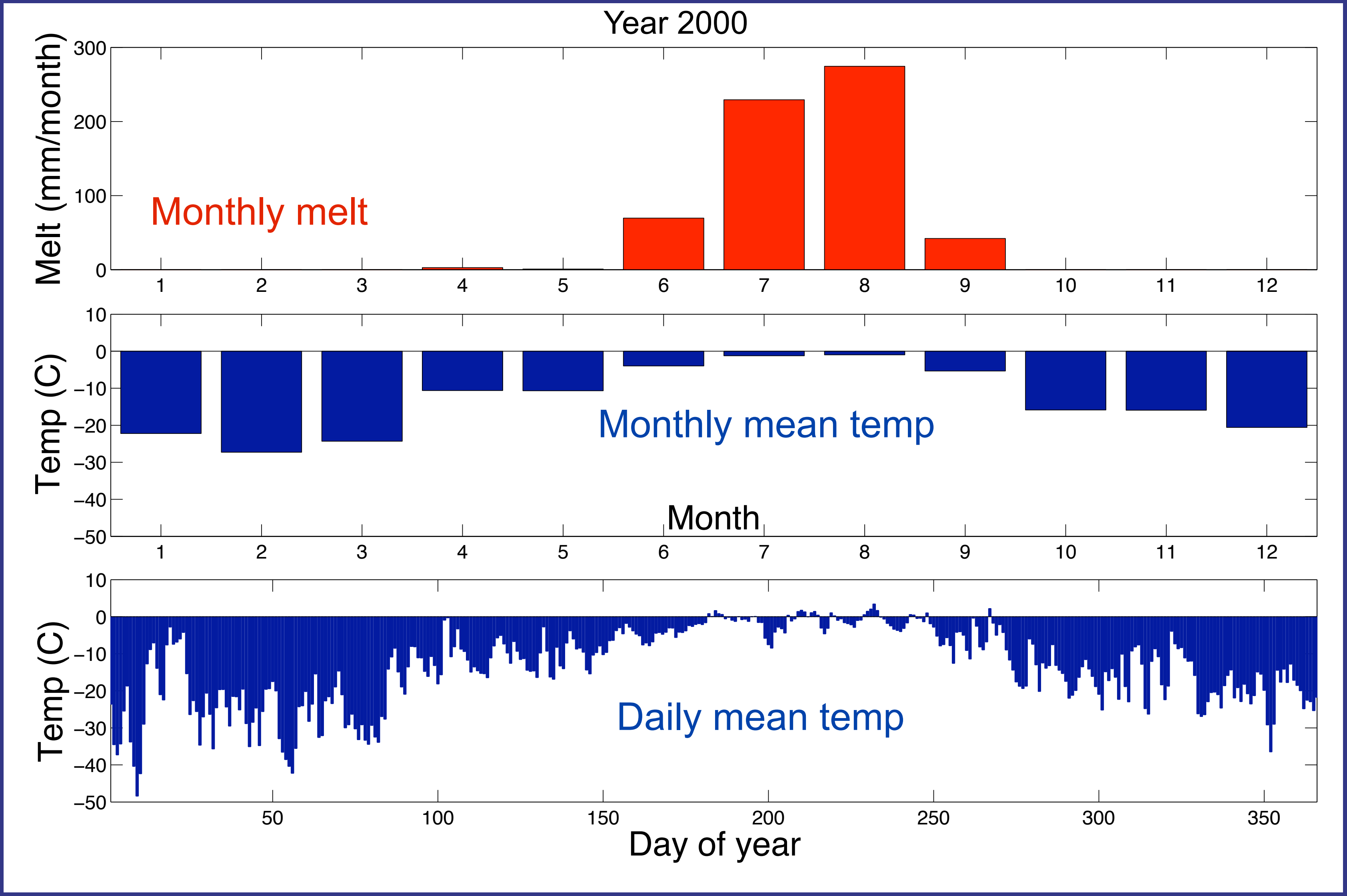
based on **daily** mean temperatures

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

Annual melt (mm/yr)



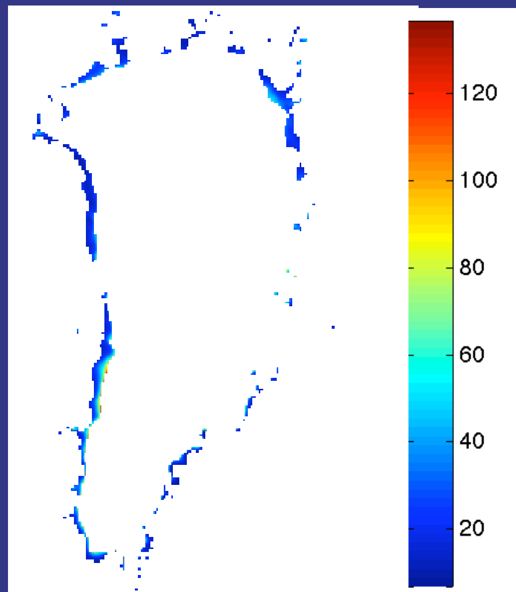
Daily and monthly mean temperature and monthly melt for one grid cell

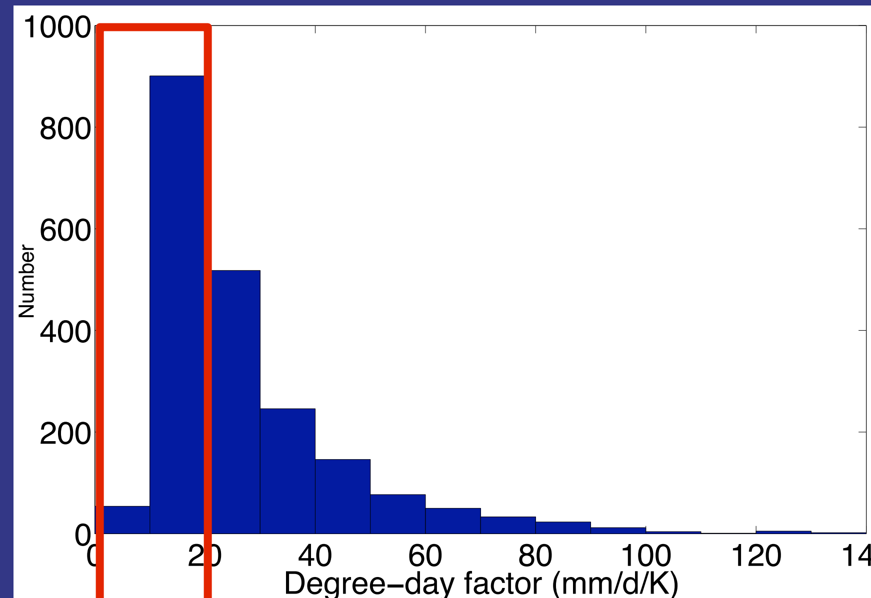


Degree-days factors averaged over 1957-2008

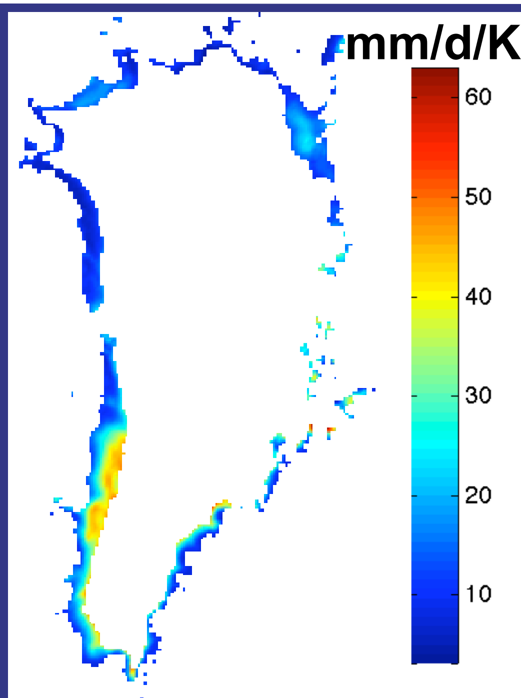
DDF = total melt/PDD over whole period, only for pixels with > 10 mm/yr melt and annual PDD > 10 dK

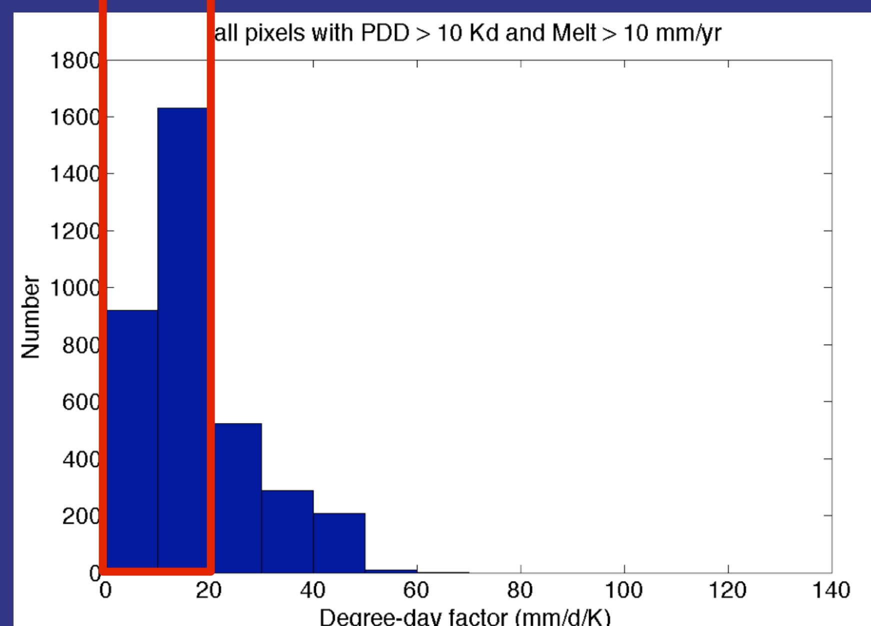
using **monthly** mean data





using **daily** mean data

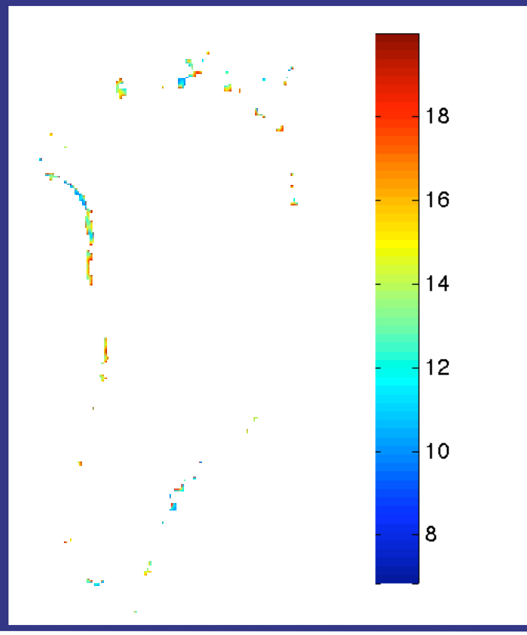


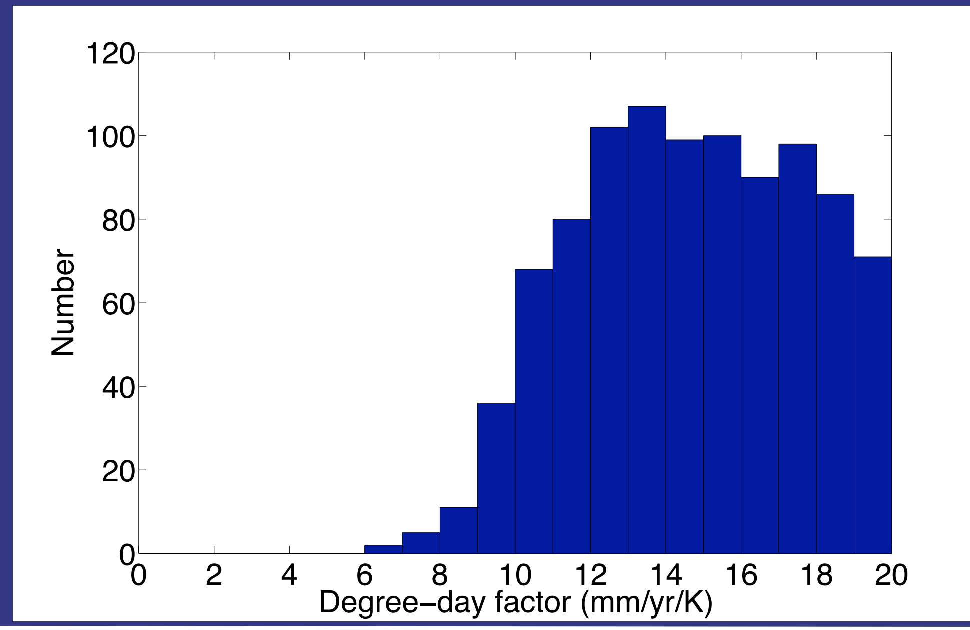


Degree-days factors averaged over 1957-2008

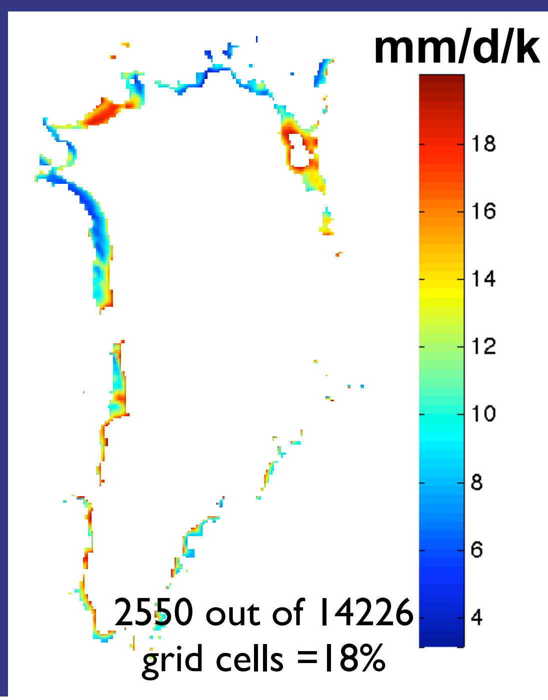
DDF < 20 mm/d/K

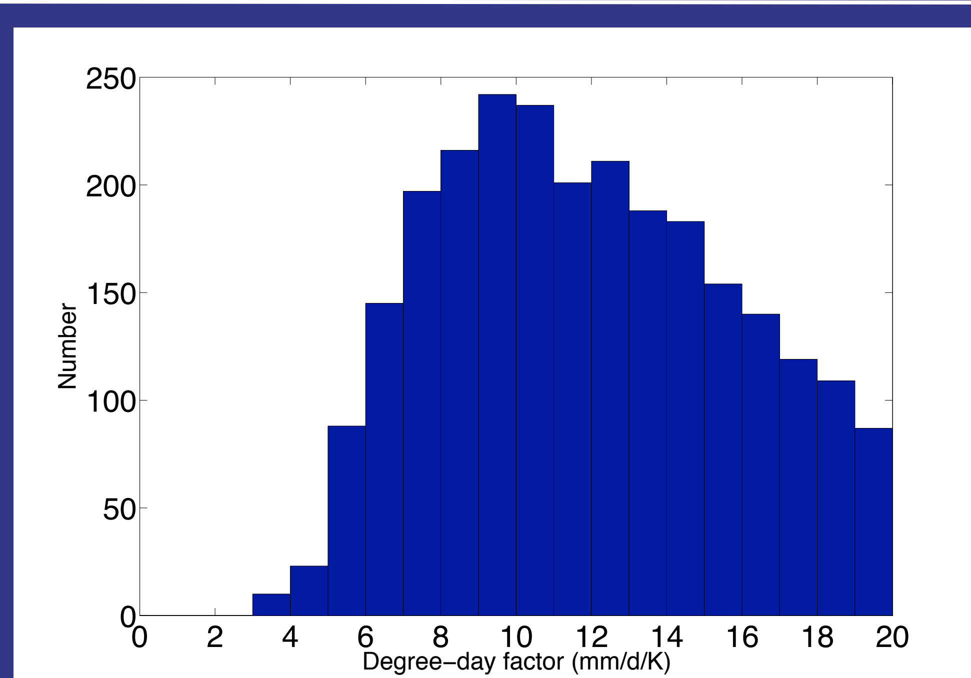
using **monthly** mean data





using **daily** mean data



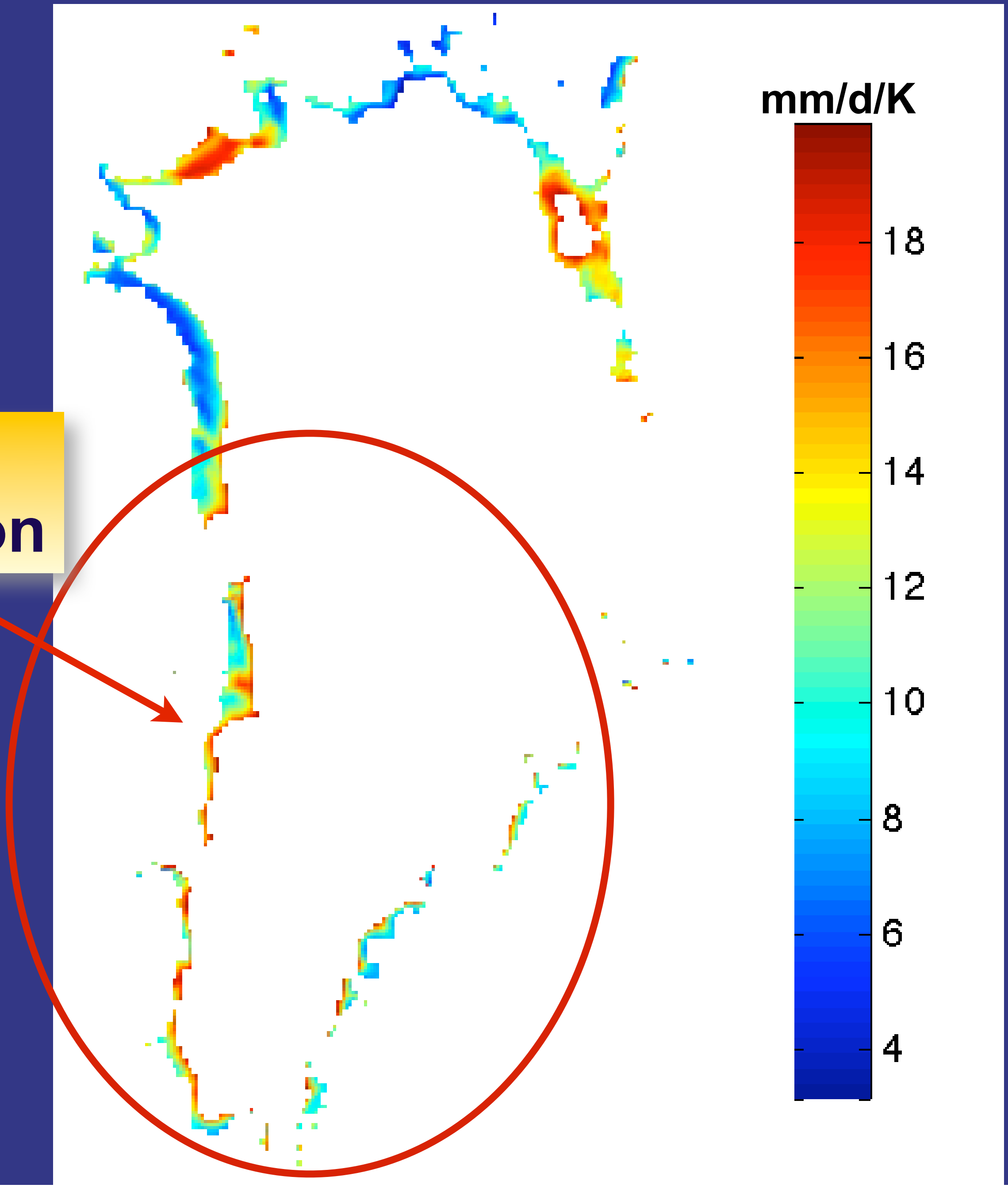


Degree-days factors averaged over 1957-2008

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



Lowering the threshold temperature T_0

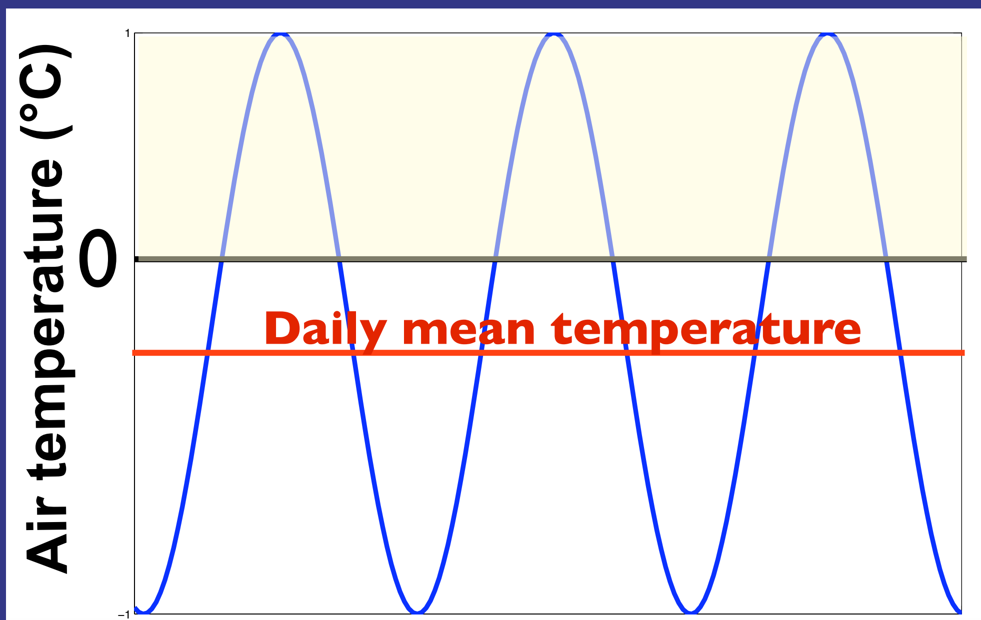
- **Van den Broeke et al. (2010, GRL in press) suggest lowering the temperature threshold from 273.15 K to 268 K**

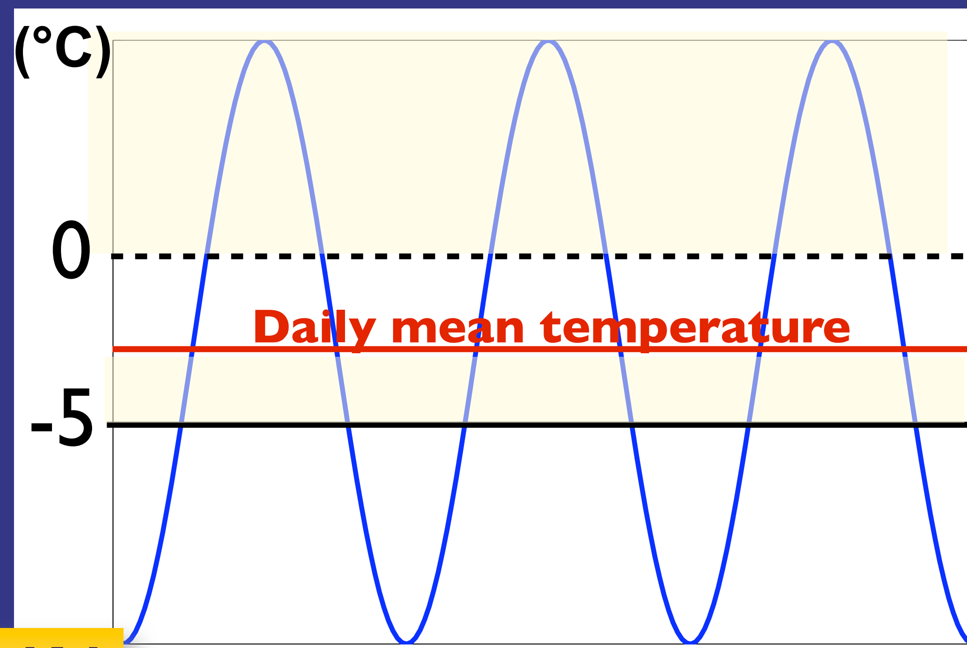
$$\dot{M} = f_{snow/ice} \sum_{1}^{n} (T - T_0)$$

Degree-day factor

Degree-day sum

- **--> 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

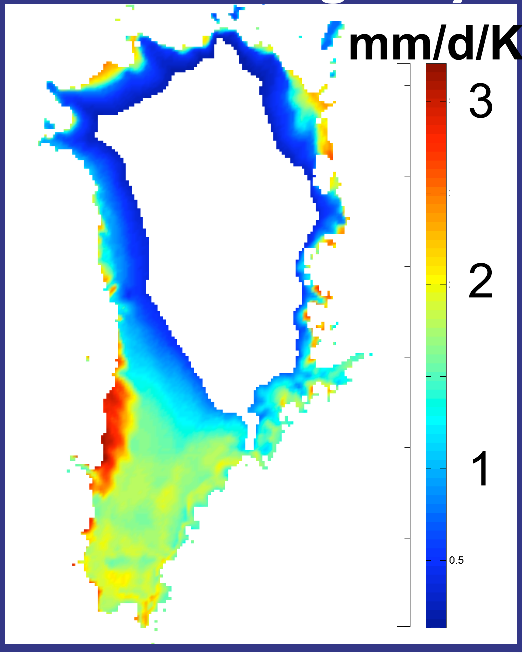
Degree-day sum > 0 Kd

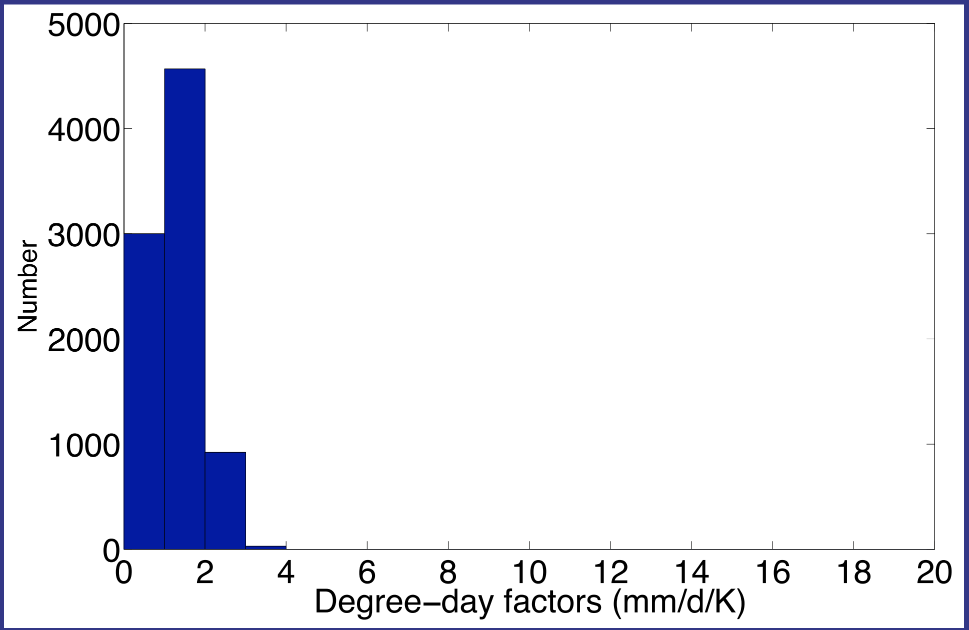
Degree-days factors averaged over 1957-2008

using daily mean temperatures

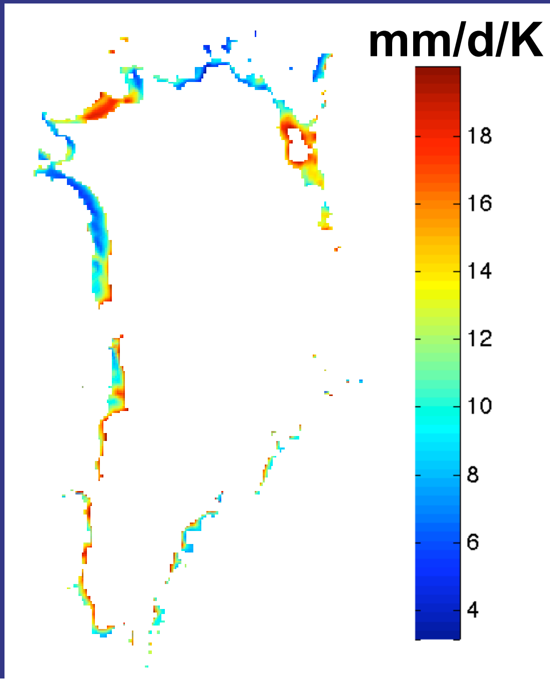
T_0 = 268 K

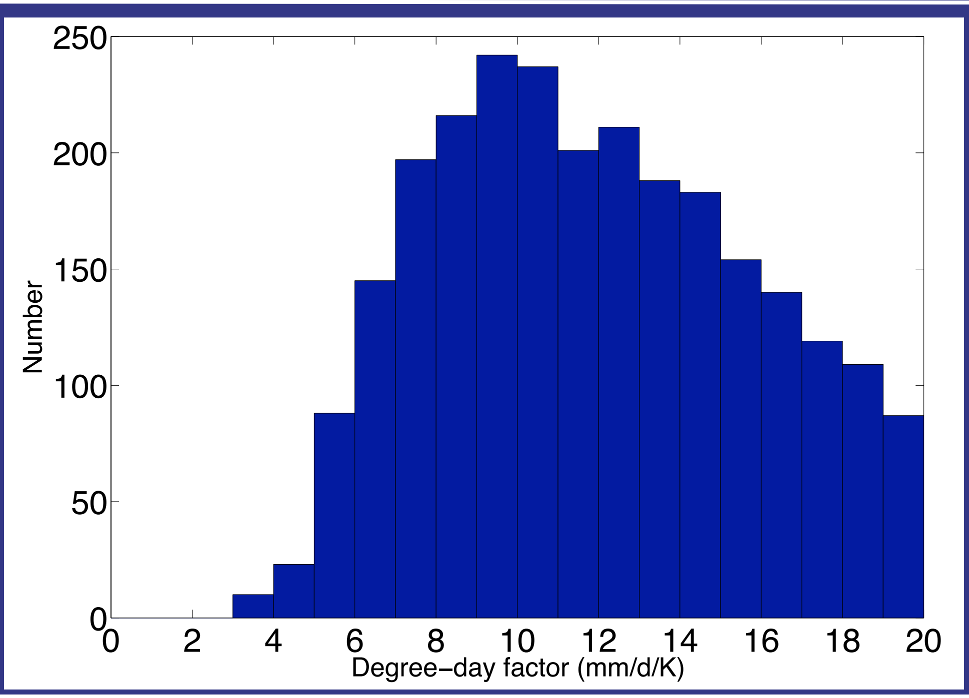
Van den Broeke et al., 2010. Temperature thresholds for degree-day modelling of Greenland ice sheet melt rates. GRL in press





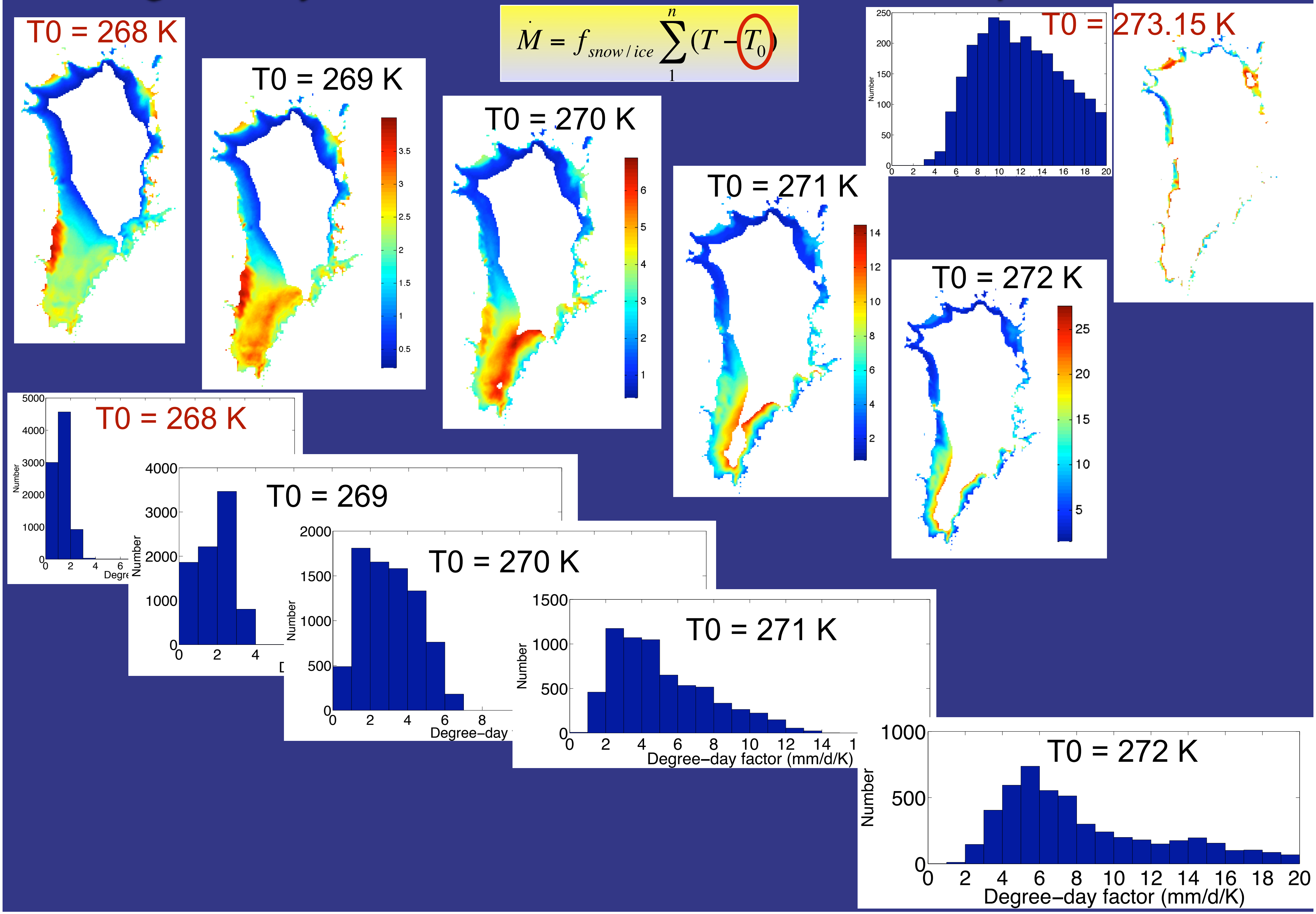
T_0 = 273.15 K



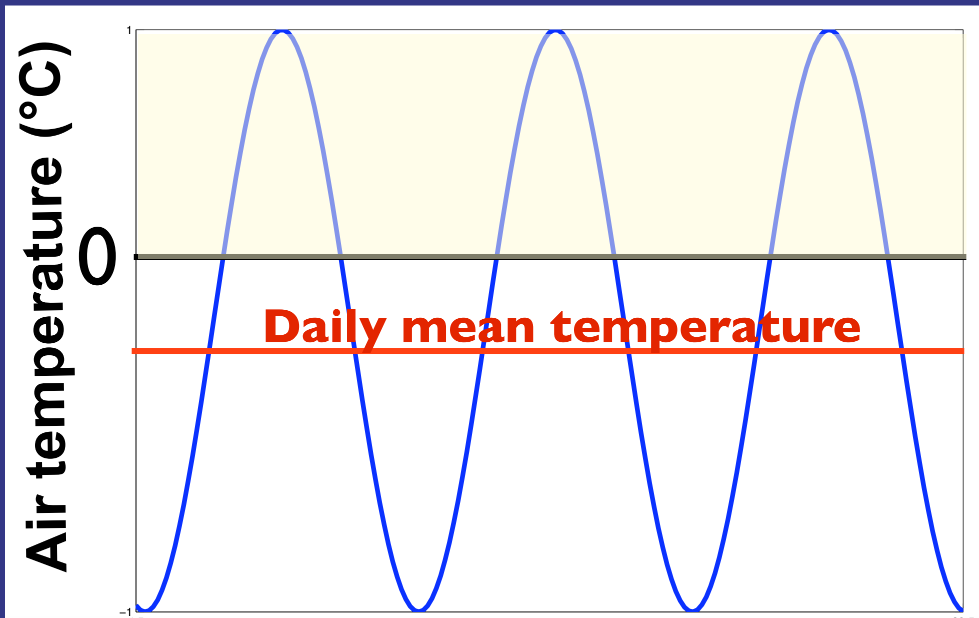


Degree-days factors for various threshold temperatures

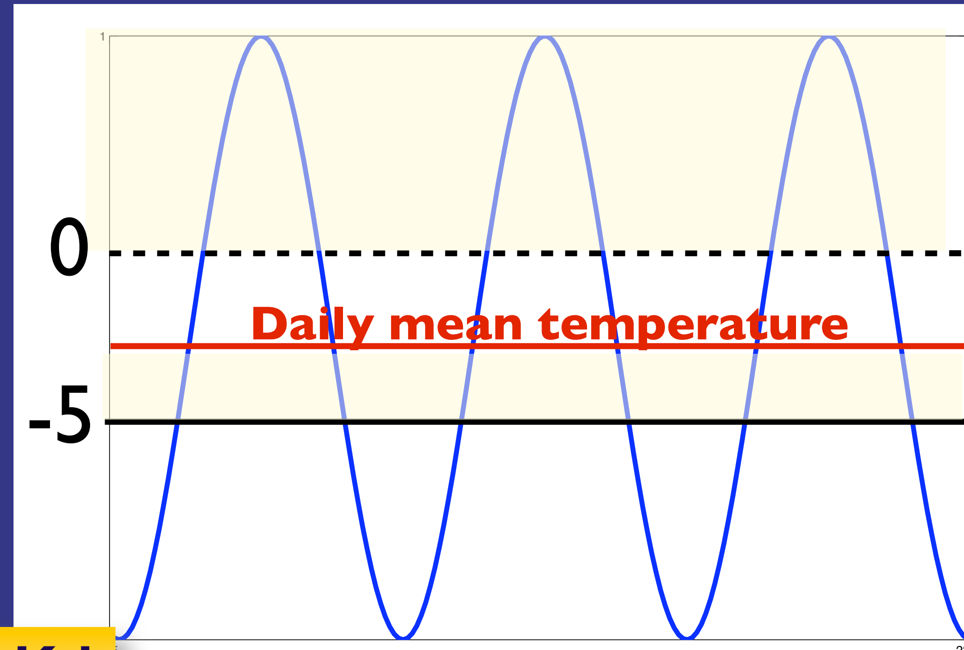
$$\dot{M} = f_{snow/ice} \sum_{1}^{n} (T - T_0)$$



How does the temp threshold affect degree-day factors?

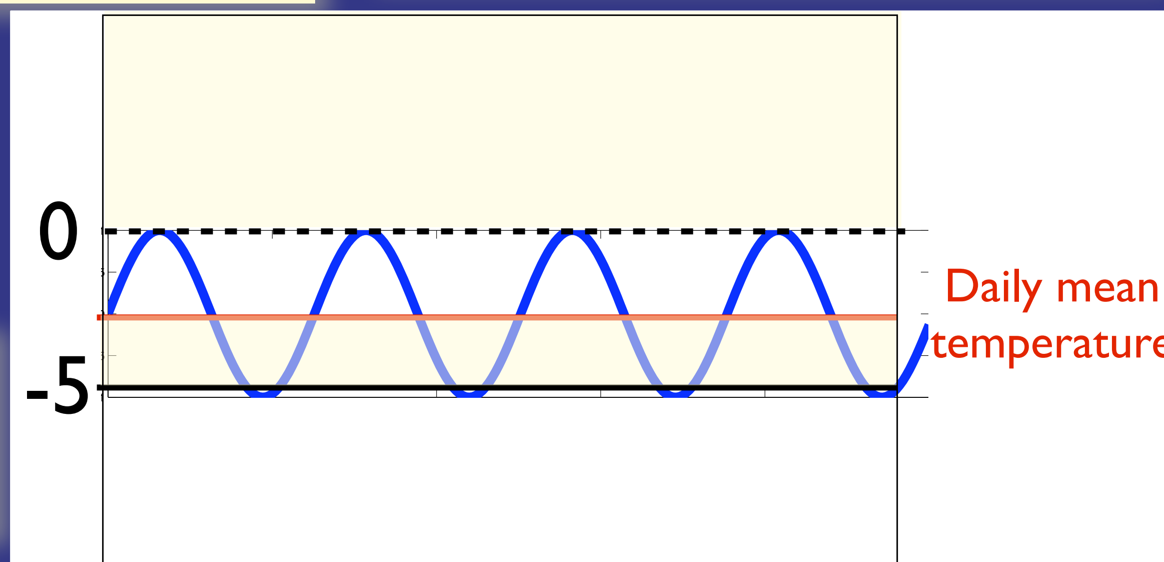


Degree-day sum (based on daily mean T) **= 0 Kd**
Melt is underestimated



Degree-day sum > 0 Kd

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



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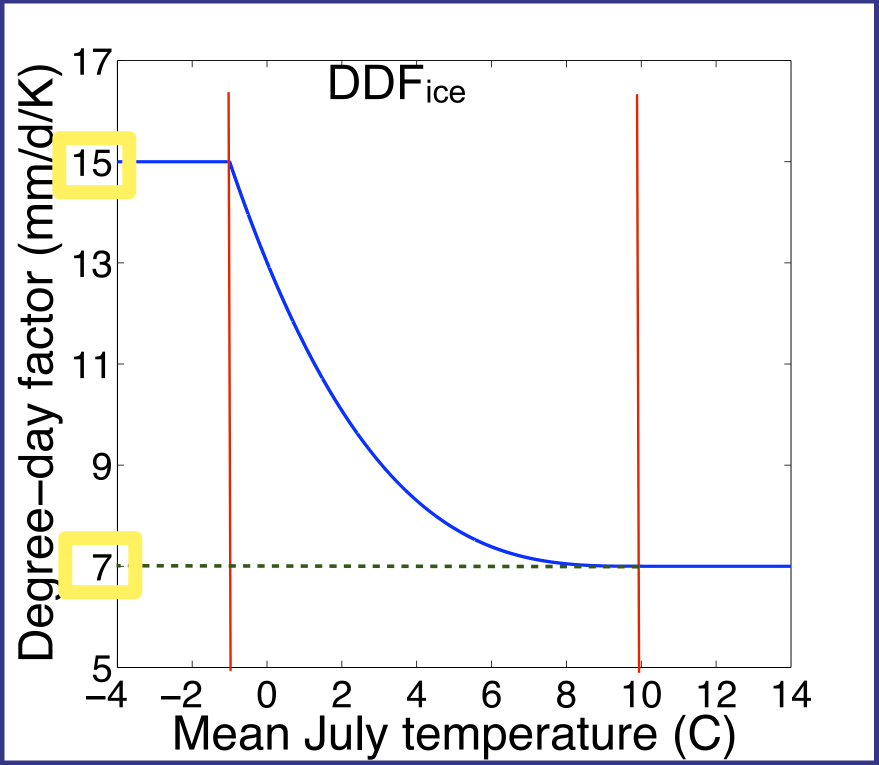
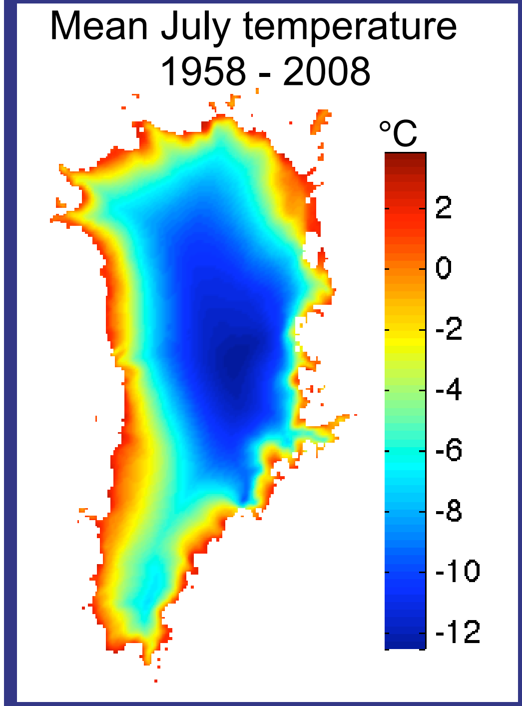
Degree-day factors after Greve (2005)

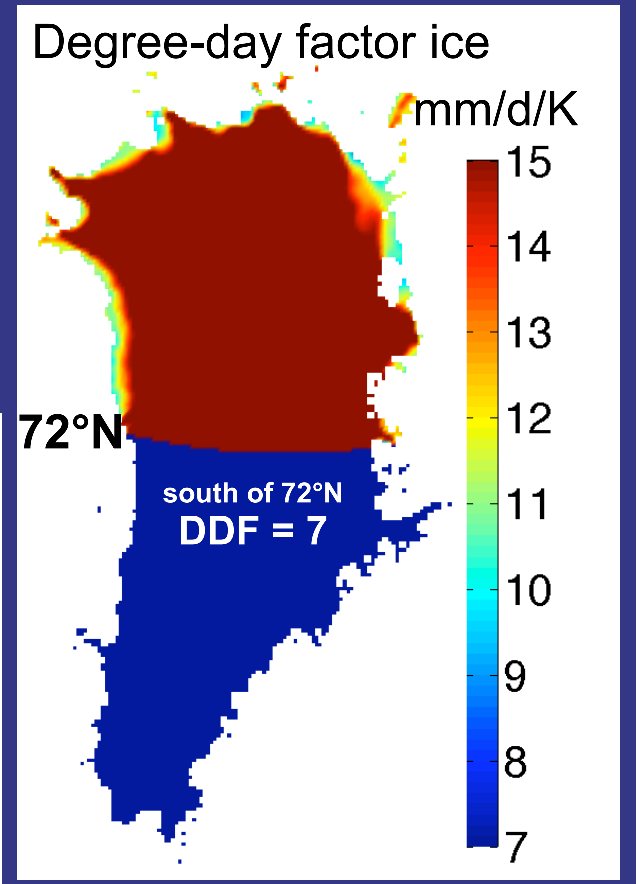
based on Tarasov and Peltier, 1999

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

$$\beta_{ice} = \begin{cases} \beta^{w}_{ice} & T_{mj} \geq T_{w}, \\ \beta^{w}_{ice} + \frac{\beta^{c}_{ice} - \beta^{w}_{ice}}{(T_{w} - T_{c})^{3}} \left(T_{w} - T_{mj}\right)^{3} & T_{c} \leq T_{mj} \leq T_{w}, \\ \beta^{c}_{ice} & T_{mj} \leq T_{c}, \end{cases}$$





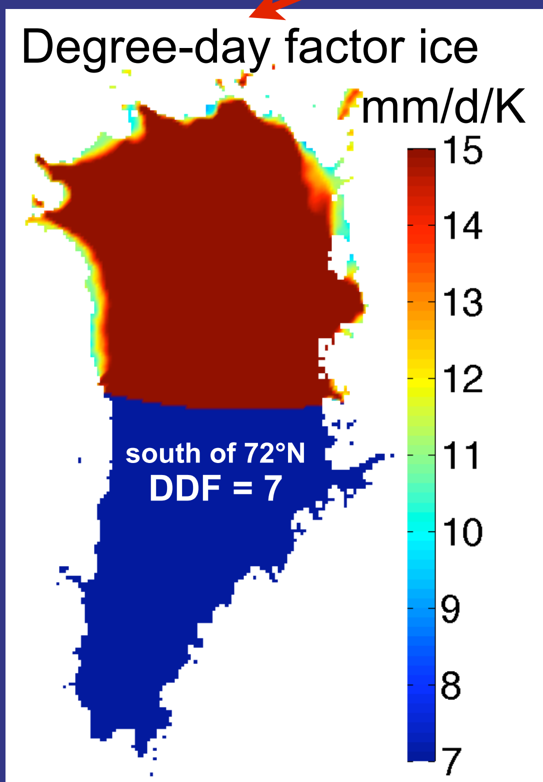


PISM: Melt after Greve (2005)

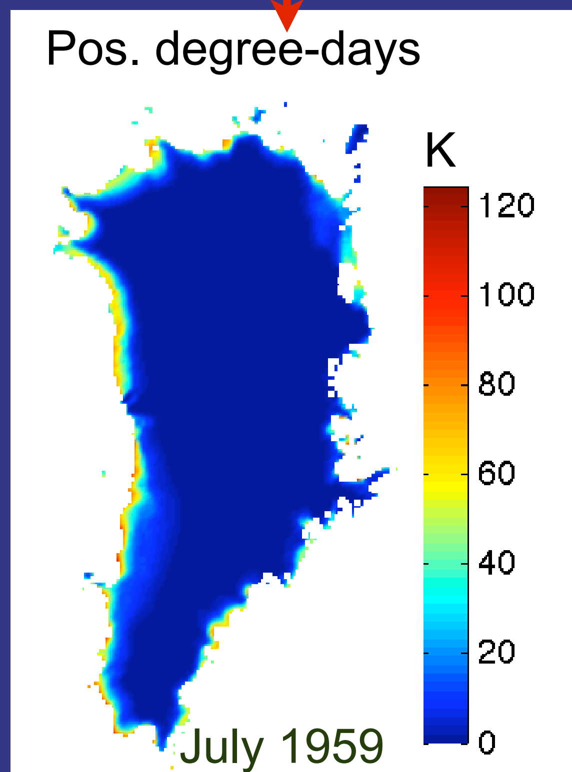
$$\dot{M} = f_{snow/ice} \sum_{1}^{n} (T - T_0)$$

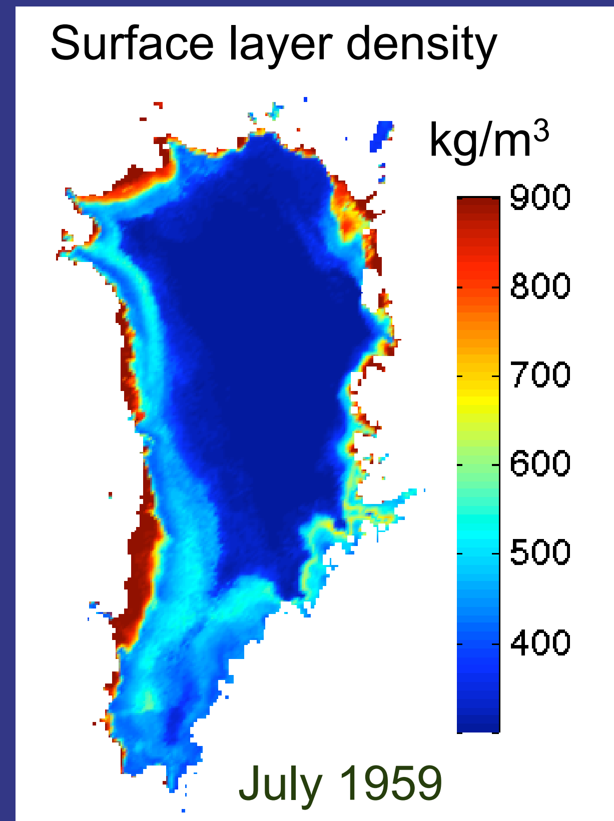
Degree-day factor

Degree-day sum



f_{snow} = 3 mm/d/K over entire Greenland

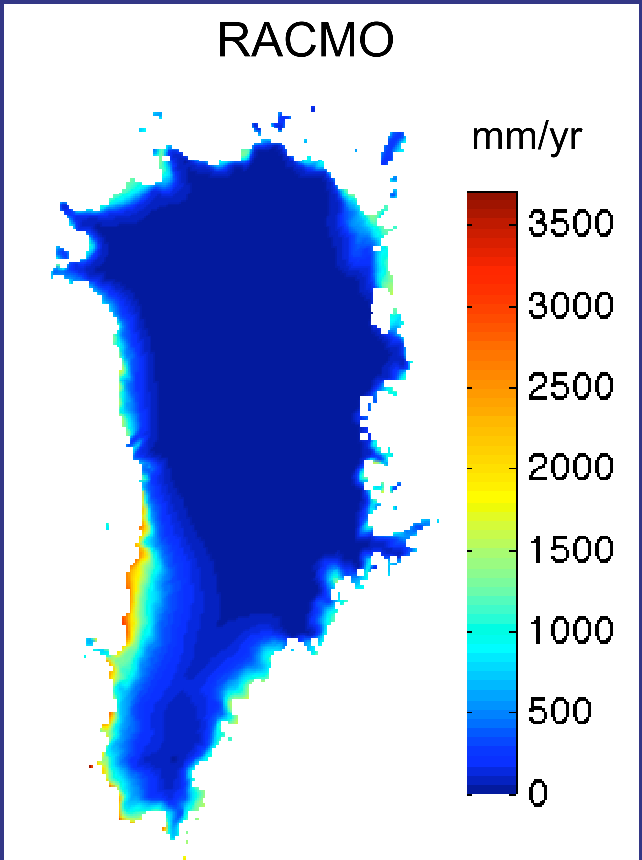


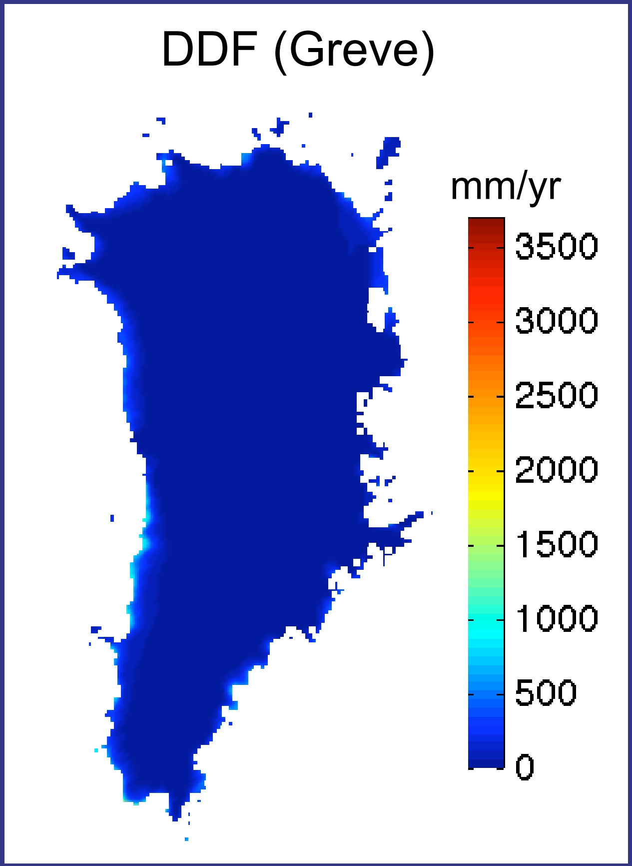


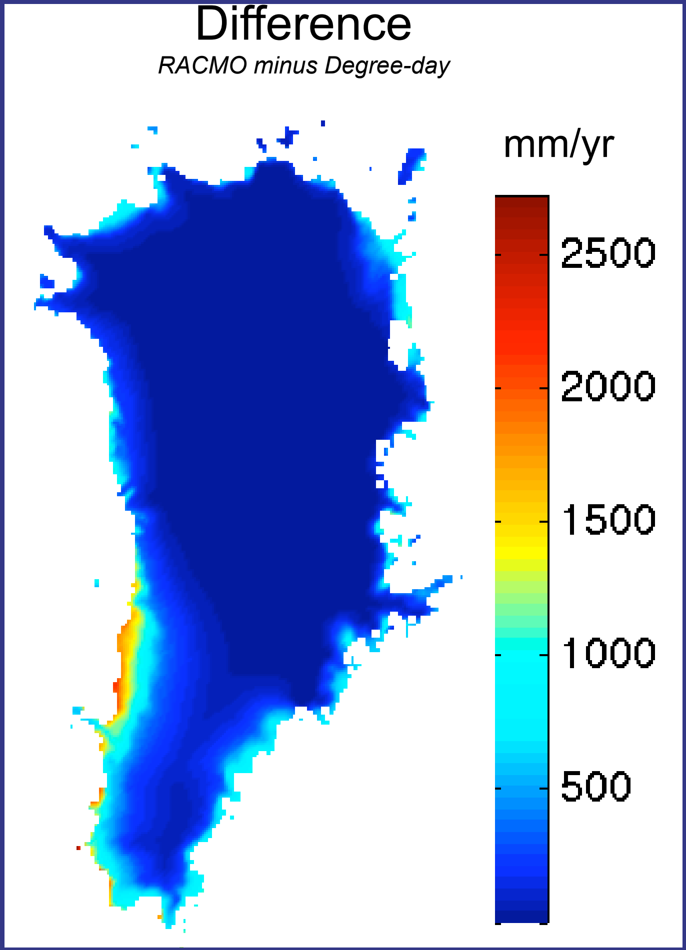
density fields used to decide whether surface is ice or snow
<350 kg/m3 = snow: f_{snow},
>850 kg/m3 = ice: f_{ice}
linear interpolation in between

How does the PDD model (Greve, 2005) compare to RACMO ?

Mean over 1957-2008







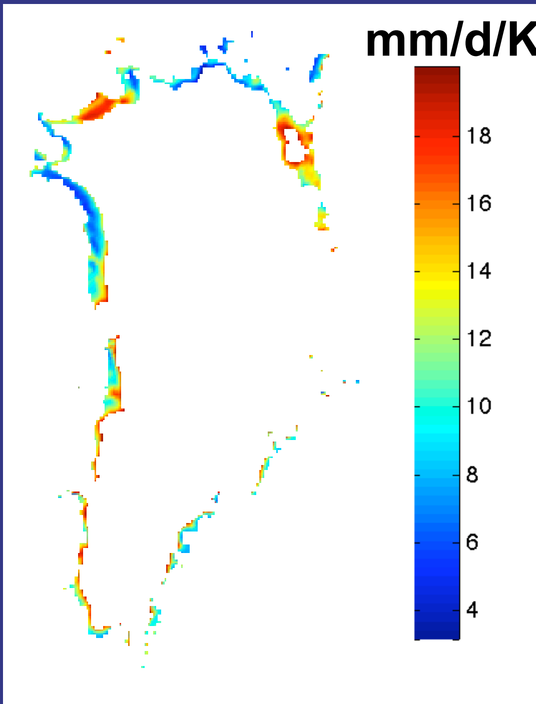
Mean annual melt
243 mm/yr
427 Gt

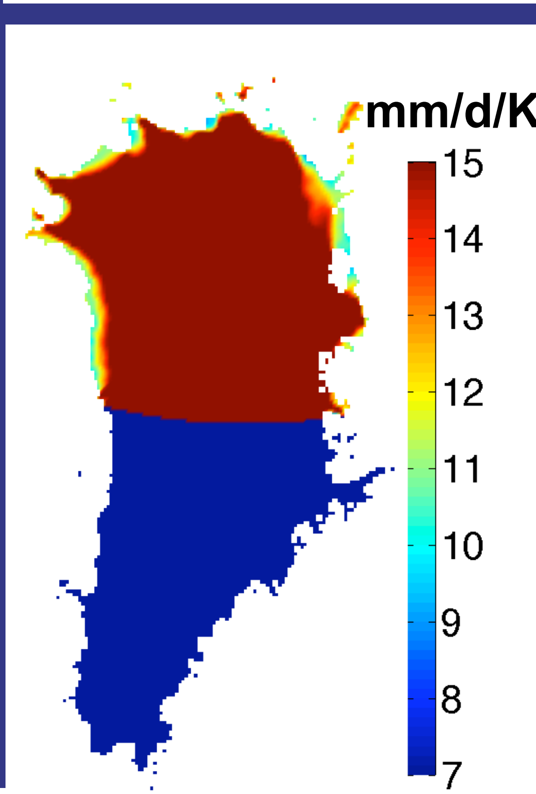
Mean annual melt
55 mm/yr
93 Gt

Difference
190 mm/yr
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)**

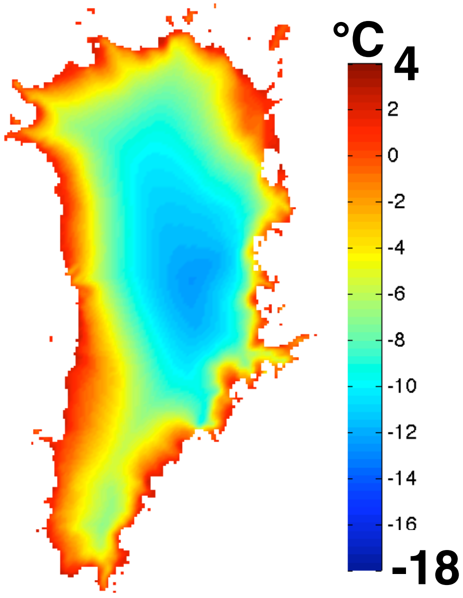




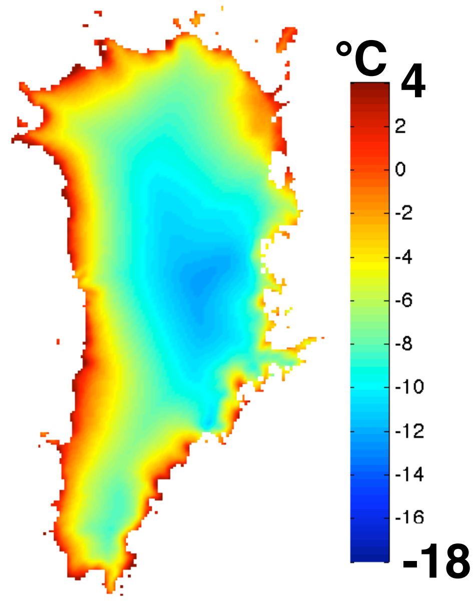
The project is funded by the NASA Modeling, Analysis, and Prediction program (grant # NNX09AJ38G)

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

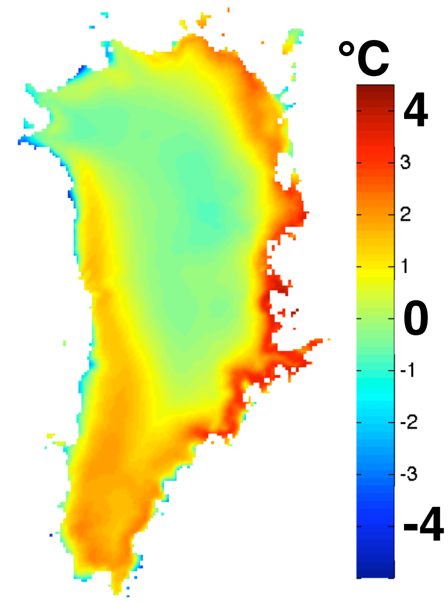
RACMO
(Ettema et al., 2009)



Parameterization
(Fausto et al., 2009)



Difference
RACMO - Parameterization

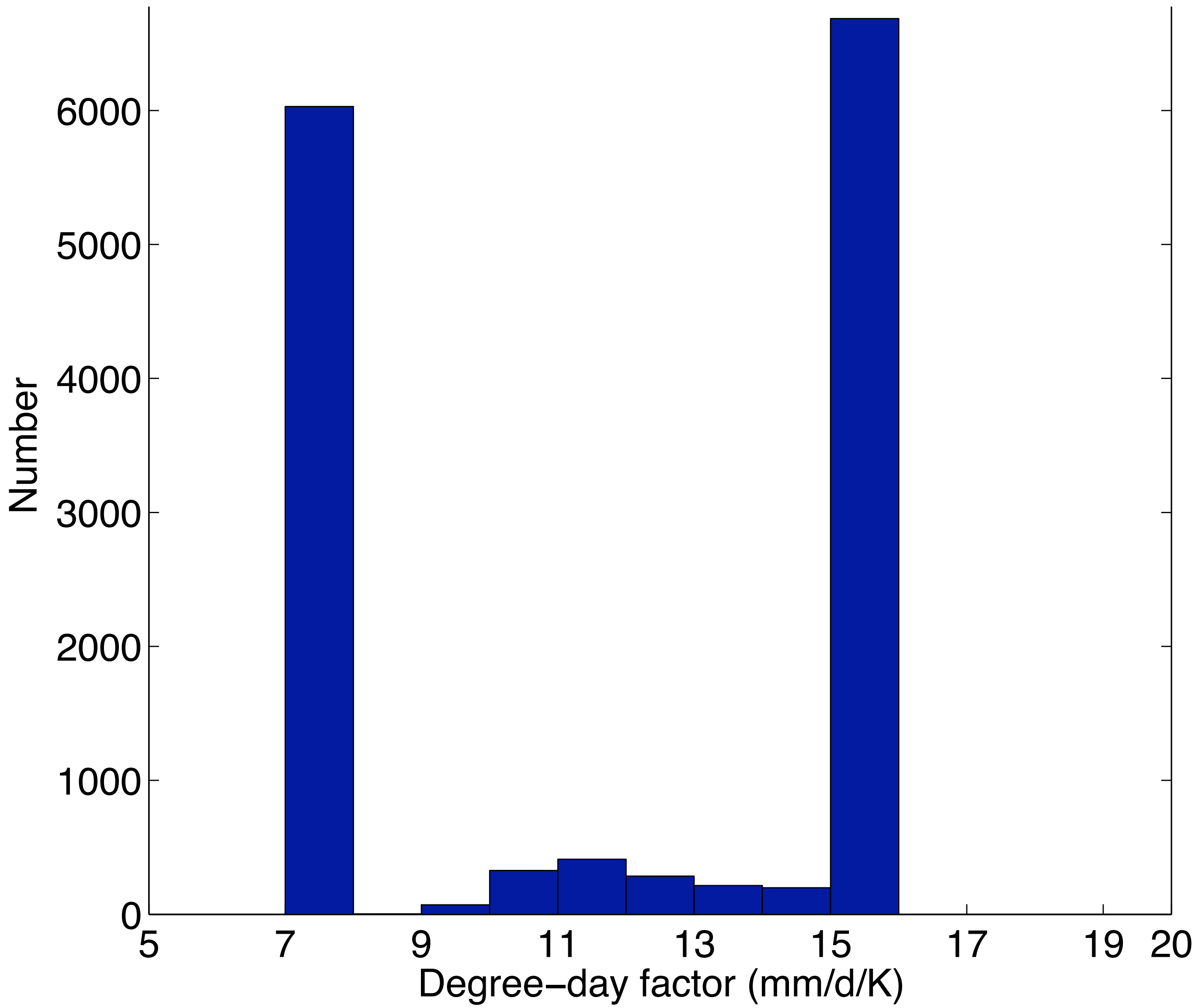


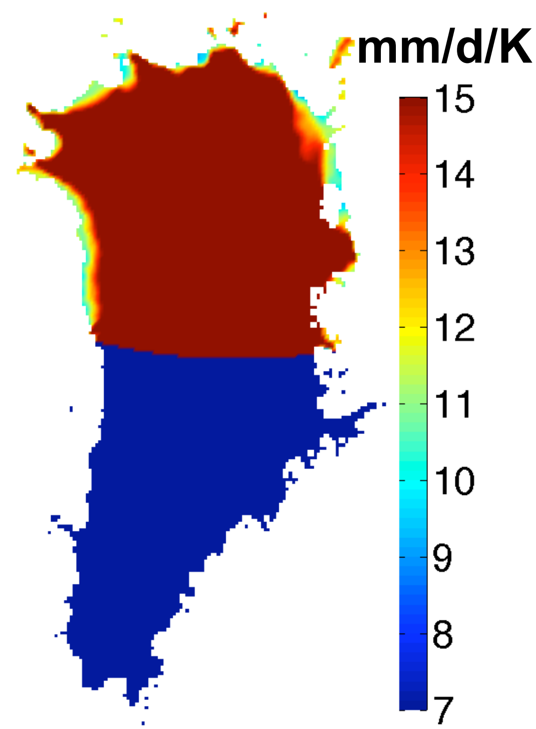
mean = 0.63
max = 4.48
min = -5.00
std.dev = 1.11

Parameterization *(Fausto et al., 2009)*

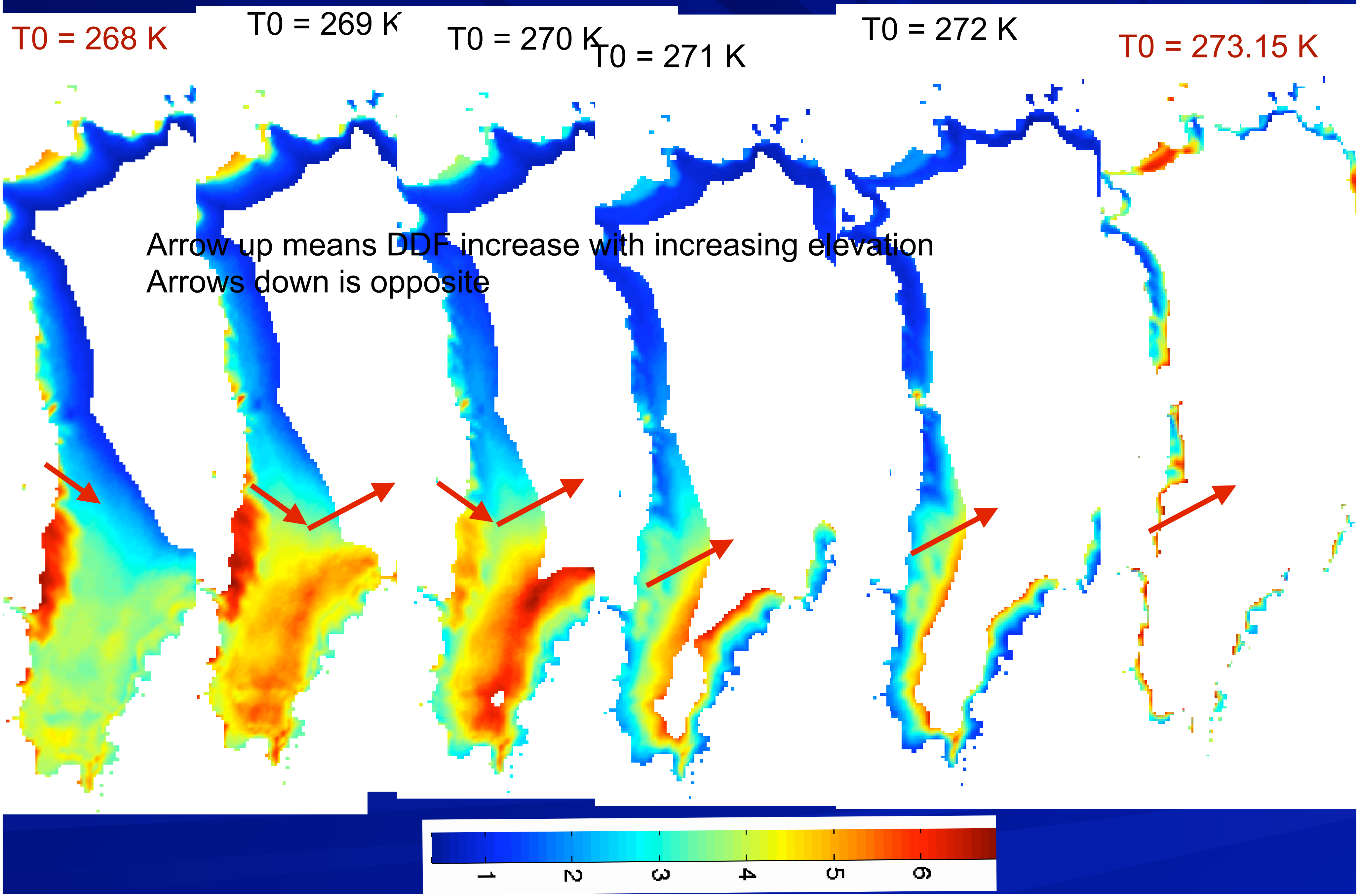
$$T_{July} = d + a\,z + b\,lat + c\,lon$$

DDF according to Greve (2005) using RACMO positive degree-day sums based on daily data

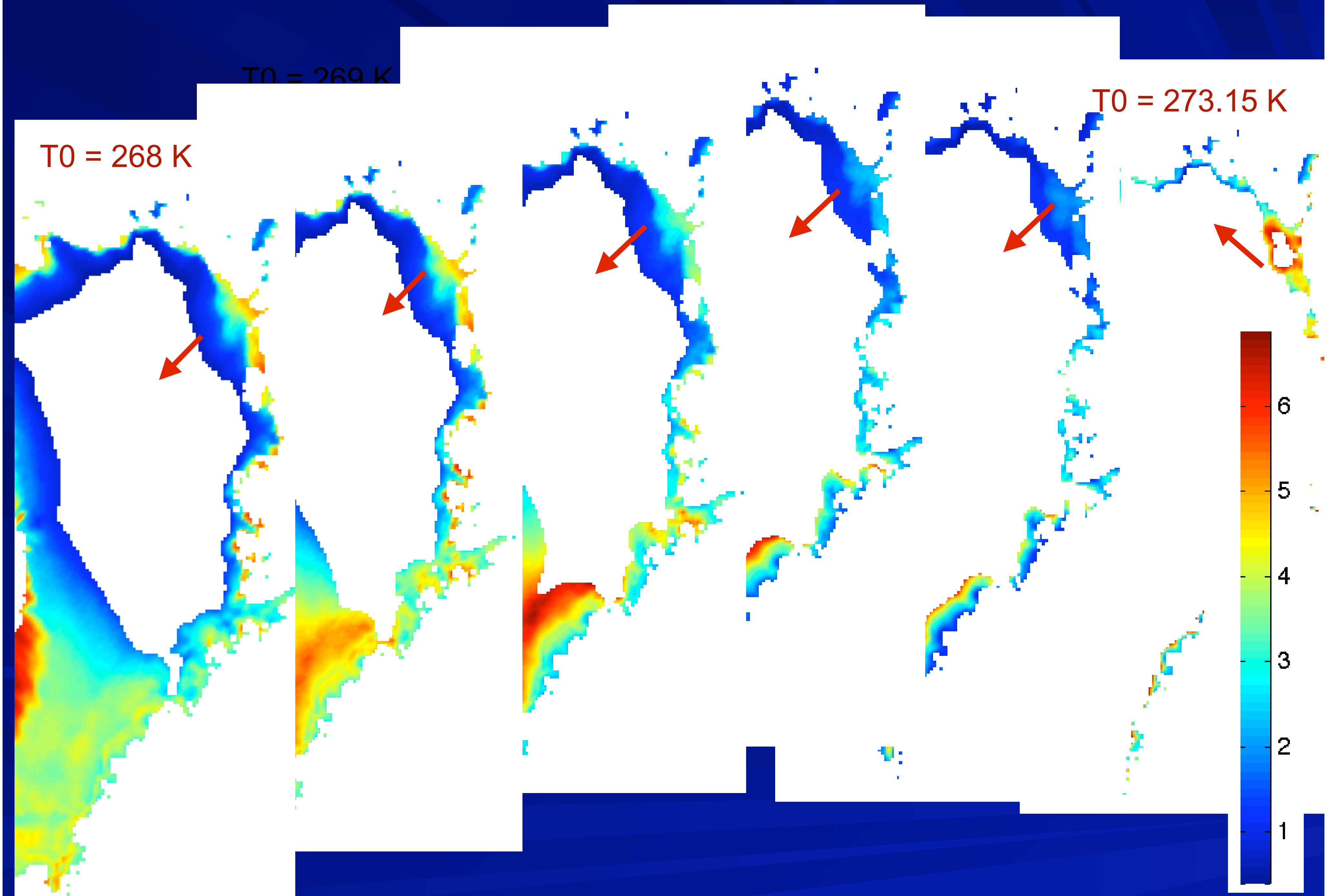




Degree-days factors for various threshold temperatures



Degree-days factors for various threshold temperatures



Degree-days factors derived from T0=268 to 270 versus T0 = 273.15 K