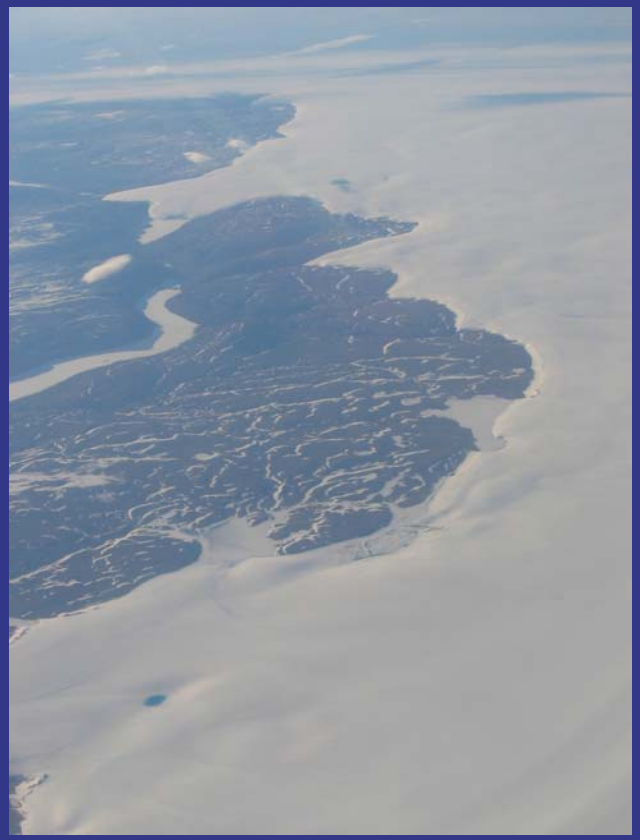
Improving degree-day melt modeling of the Greenland ice sheet in the Parallel Ice Sheet Model (PISM)



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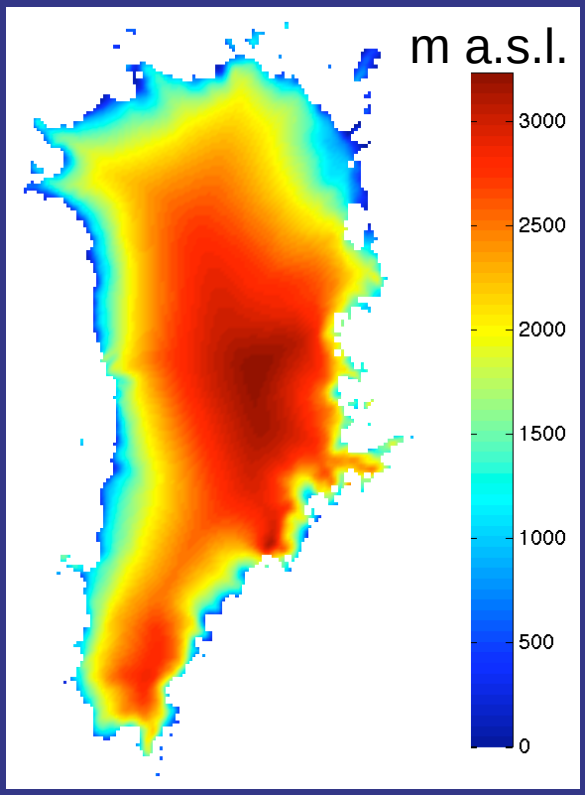
Janneke Ettema[3],
Ed Bueler[1],
Constantine Khroulev[1],
Dani Dellagiu[1]
Michiel van den Broeke[3]



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[3]Institute for Marine and Atmospheric Research, Utrecht University, The Netherlands

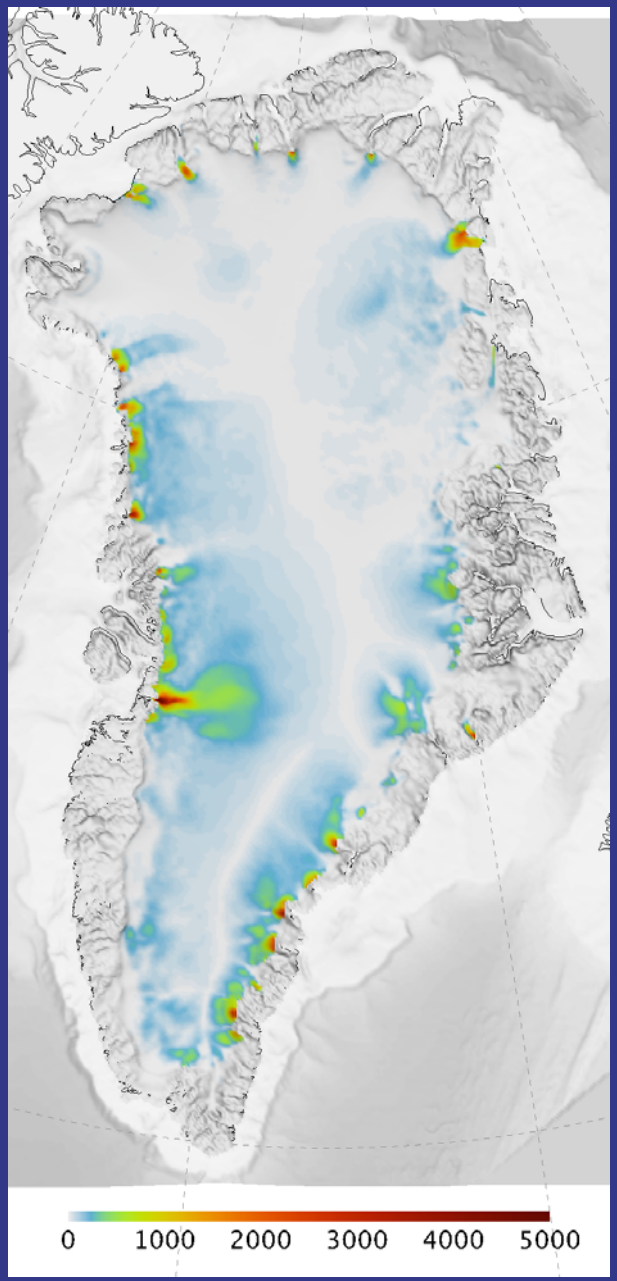
Background: PISM

- **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

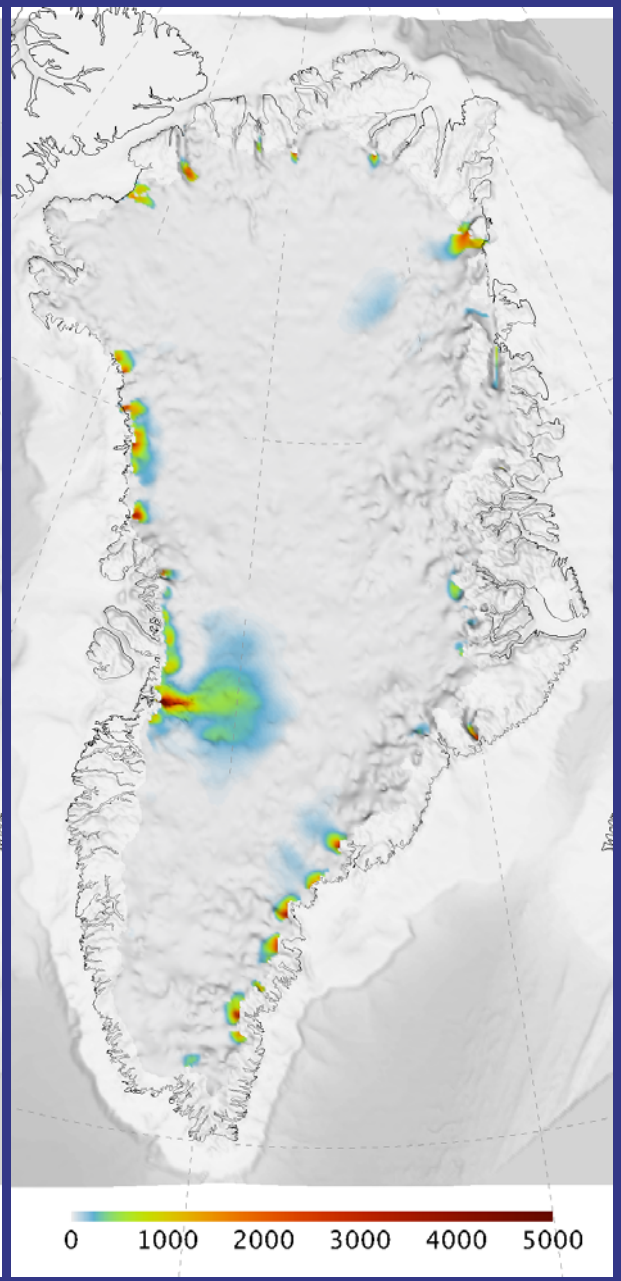
Features:

- 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

Surface velocities



Basal velocities



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.*

Objectives

to improve the melt model in PISM:

- **How good is the degree-day melt model that is currently implemented in PISM ?**
- **How do degree-day factors vary spatially and what do they depend on ?**
- **How can degree-day factors be parameterized in a better way that can be implemented into PISM ?**

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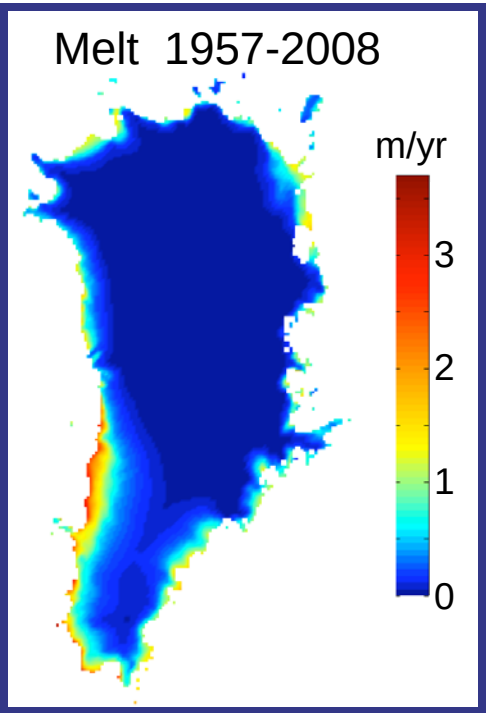
Data

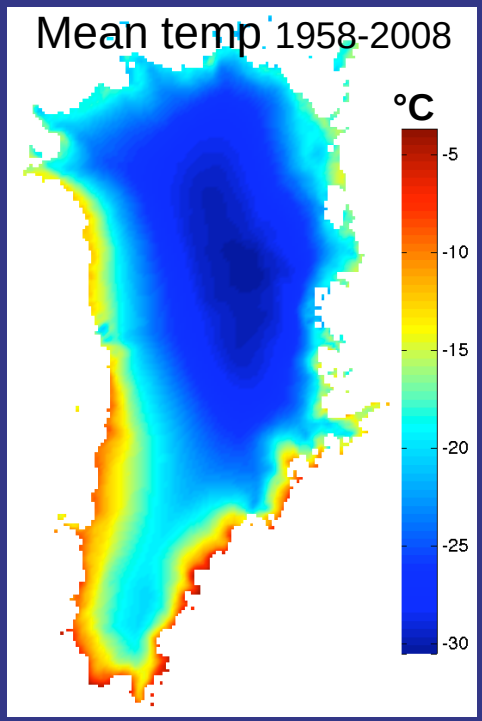
Model

- 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
- Daily mean 2 m air temperatures from which positive monthly degree-day sums are computed
- Monthly 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.

How good is the degree-day melt model in PISM ?

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

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

Degree-day factors after Greve (2005)
based on Tarasov and Peltier, 1999

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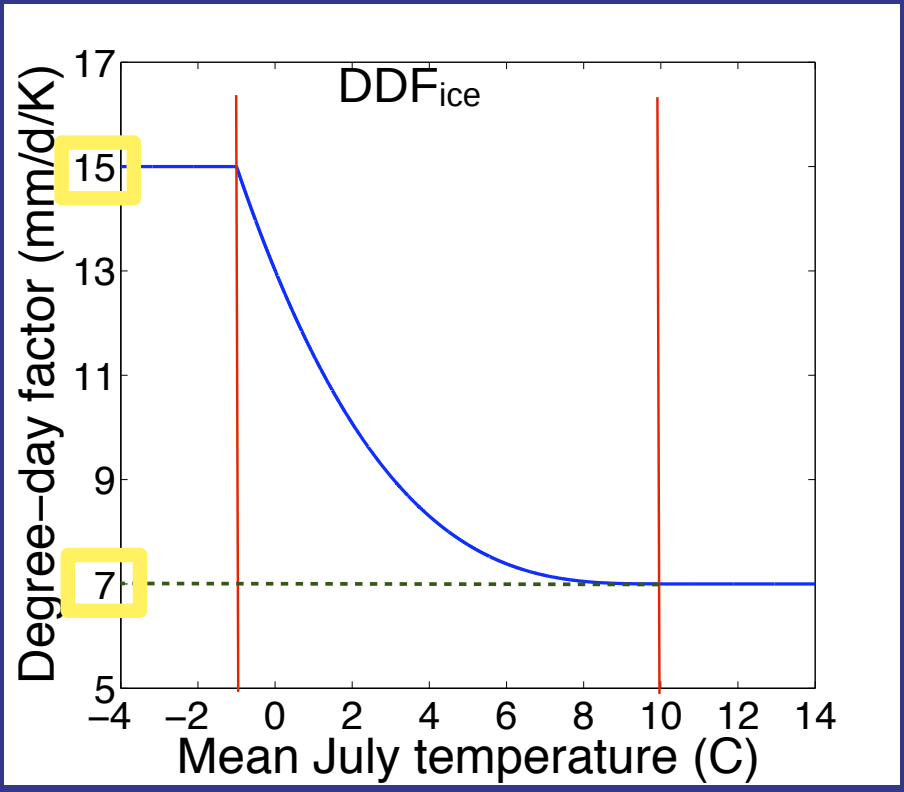

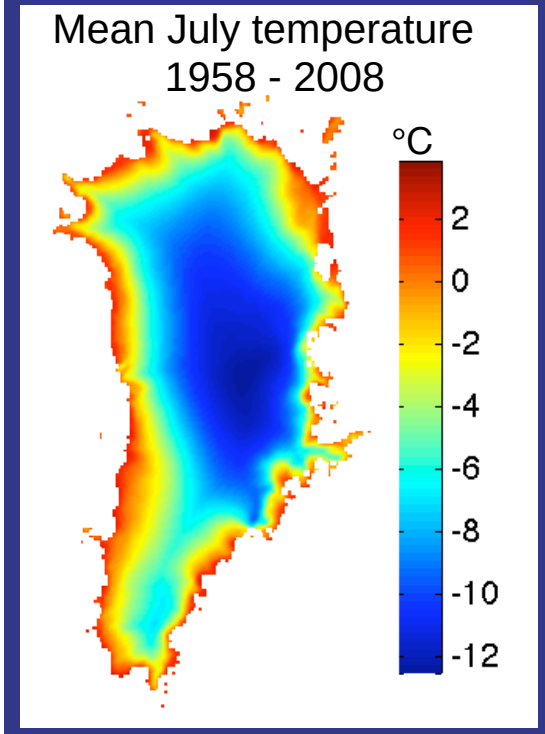

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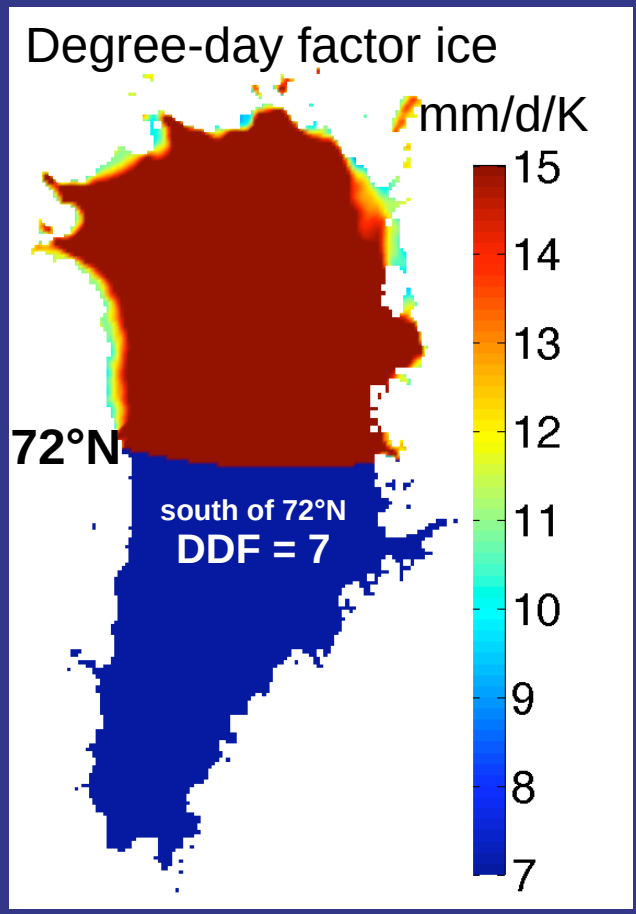
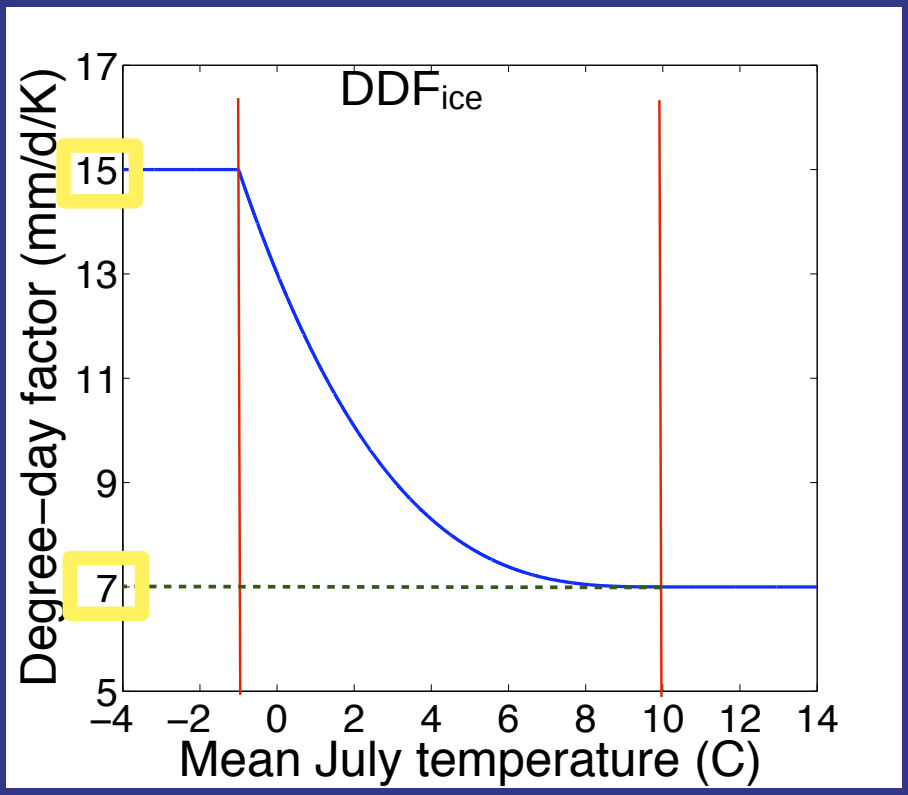
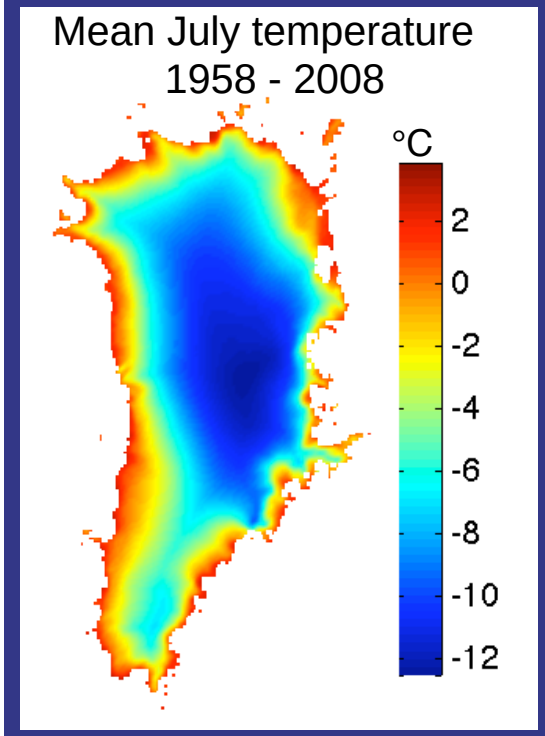






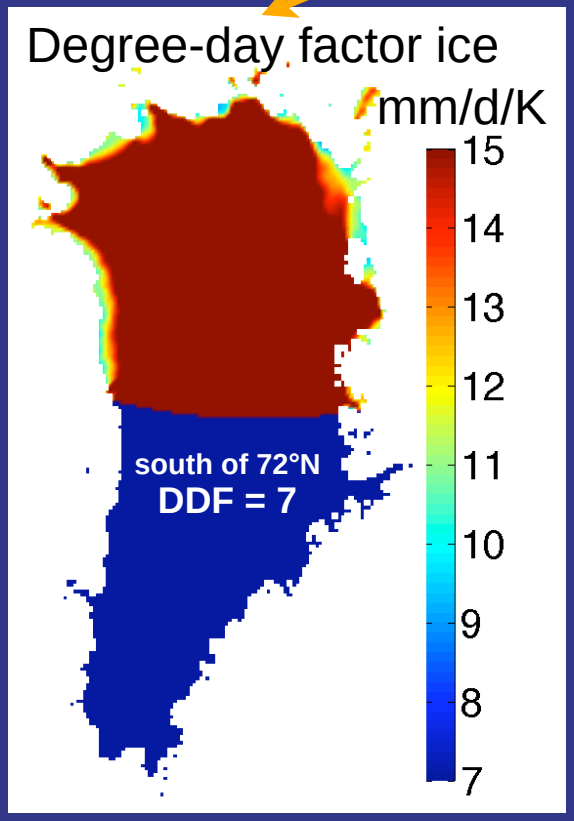
PISM: Melt after Greve (2005)

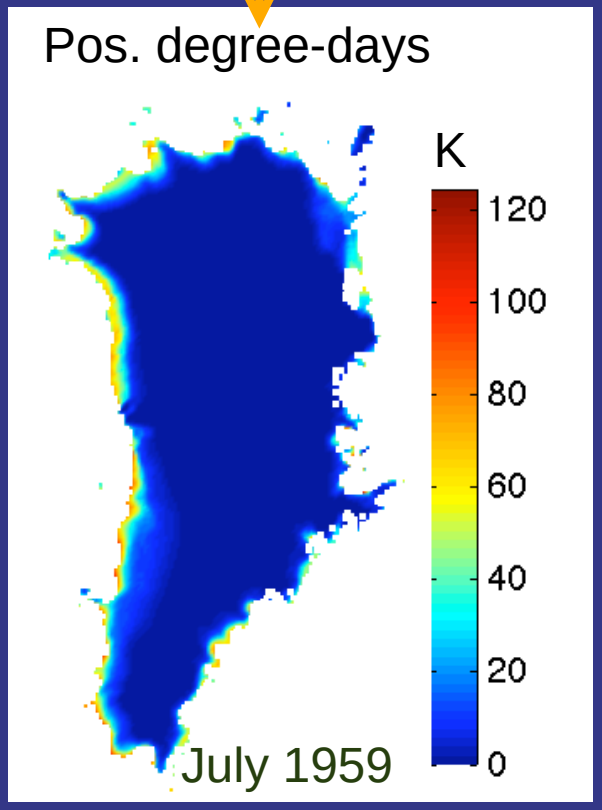
$$\dot{M} = f_{snow/ice} \sum_{1}^{n} (T - T_0)$$

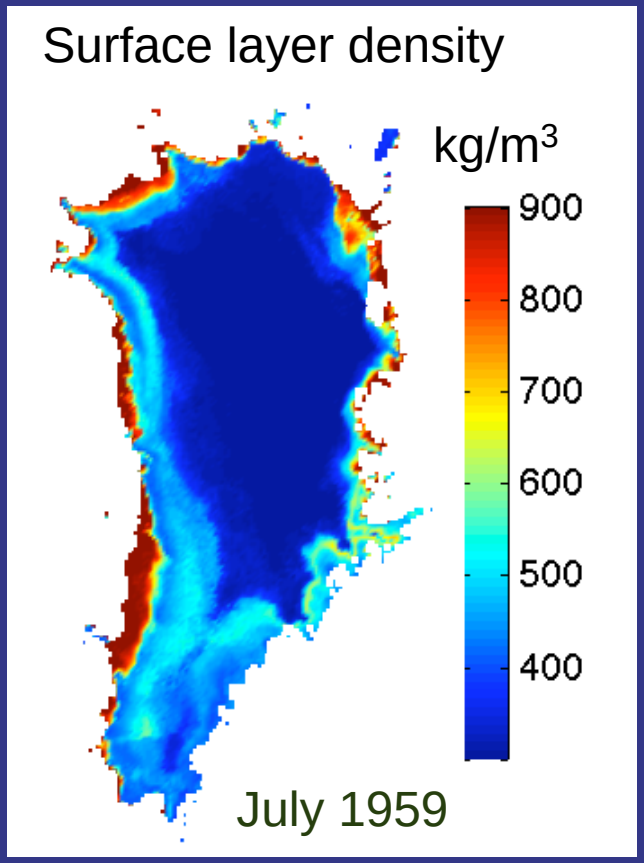
Degree-day factor

Degree-day sum

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







Density fields used to decide whether surface is ice or snow

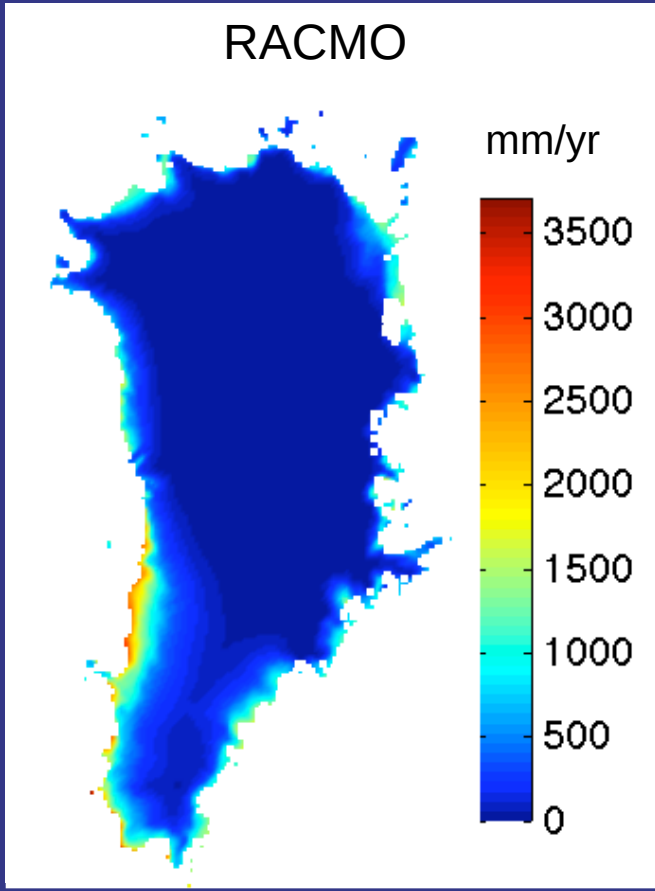
<350 kg/m3 = snow: f_{snow},

>850 kg/m3 = ice: f_{ice}

linear interpolation of DDFs in between

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

Mean over 1957-2008



Mean annual melt
243 mm/yr
427 Gt/yr

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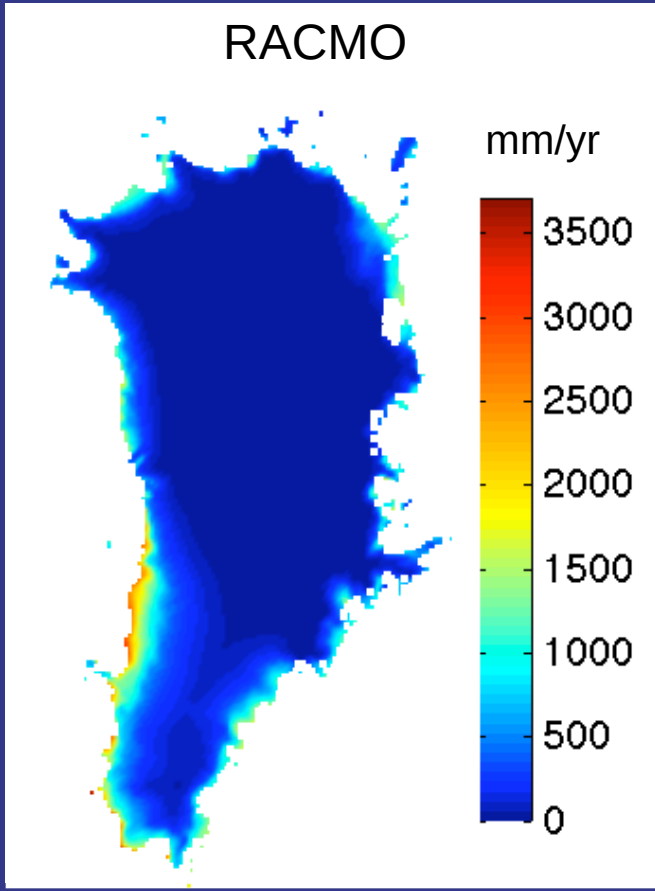
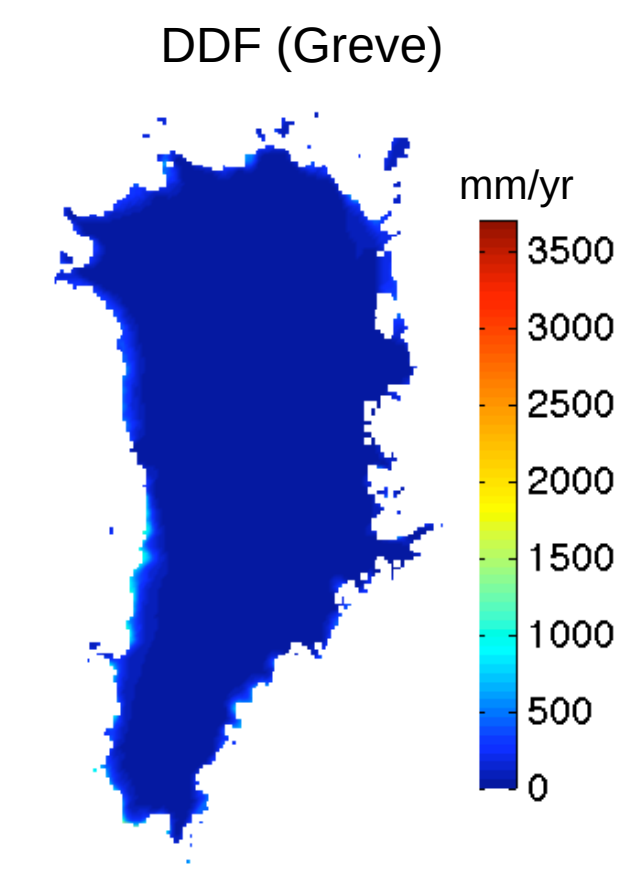




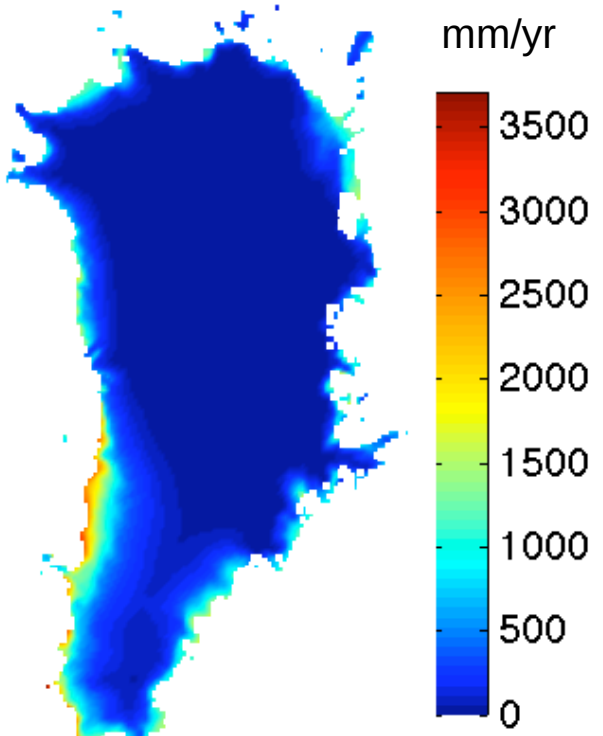
Mean annual melt
243 mm/yr
427 Gt/yr

Mean annual melt
55 mm/yr
93 Gt/yr

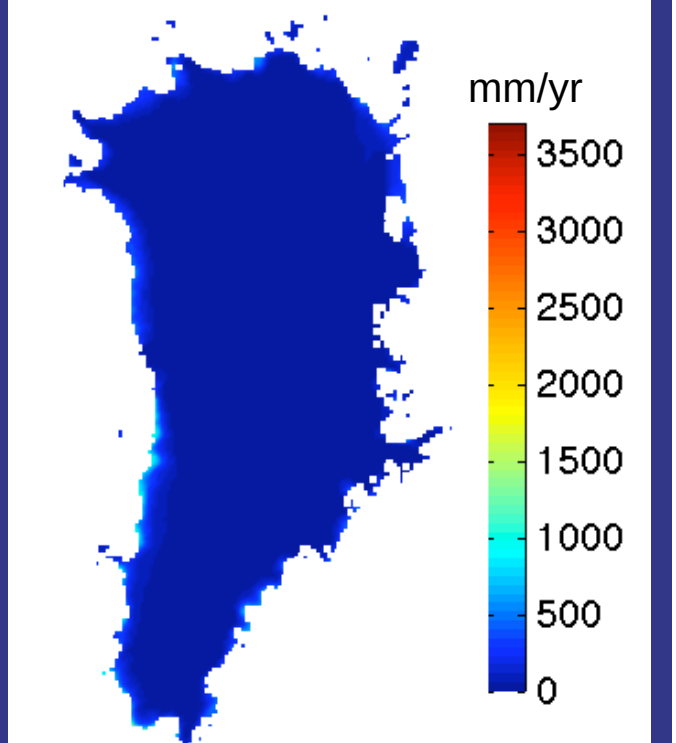
How does the PDD model (Greve, 2005) compare to RACMO ?

Mean over 1957-2008

RACMO

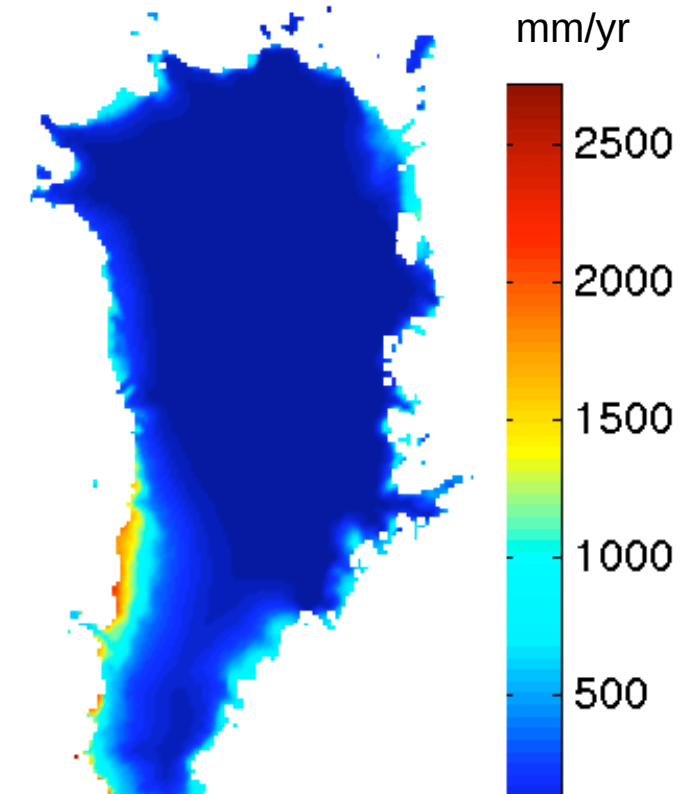


DDF (Greve)



Difference

RACMO minus Degree-day



Mean annual melt
243 mm/yr
427 Gt/yr

Mean annual melt
55 mm/yr
93 Gt/yr

Difference
190 mm/yr
333 Gt/yr !!!

Objectives

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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

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

Degree-day factor

Degree-day sum

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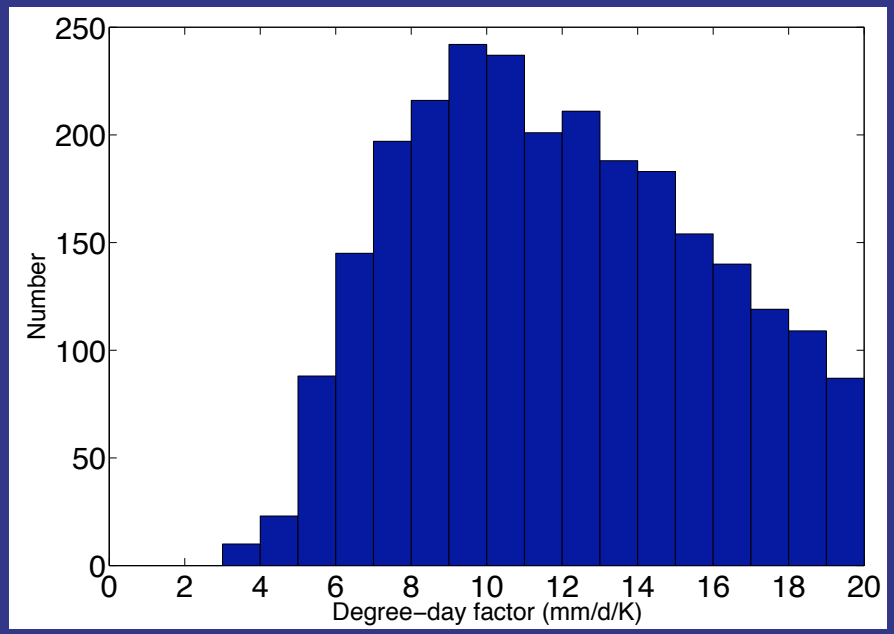

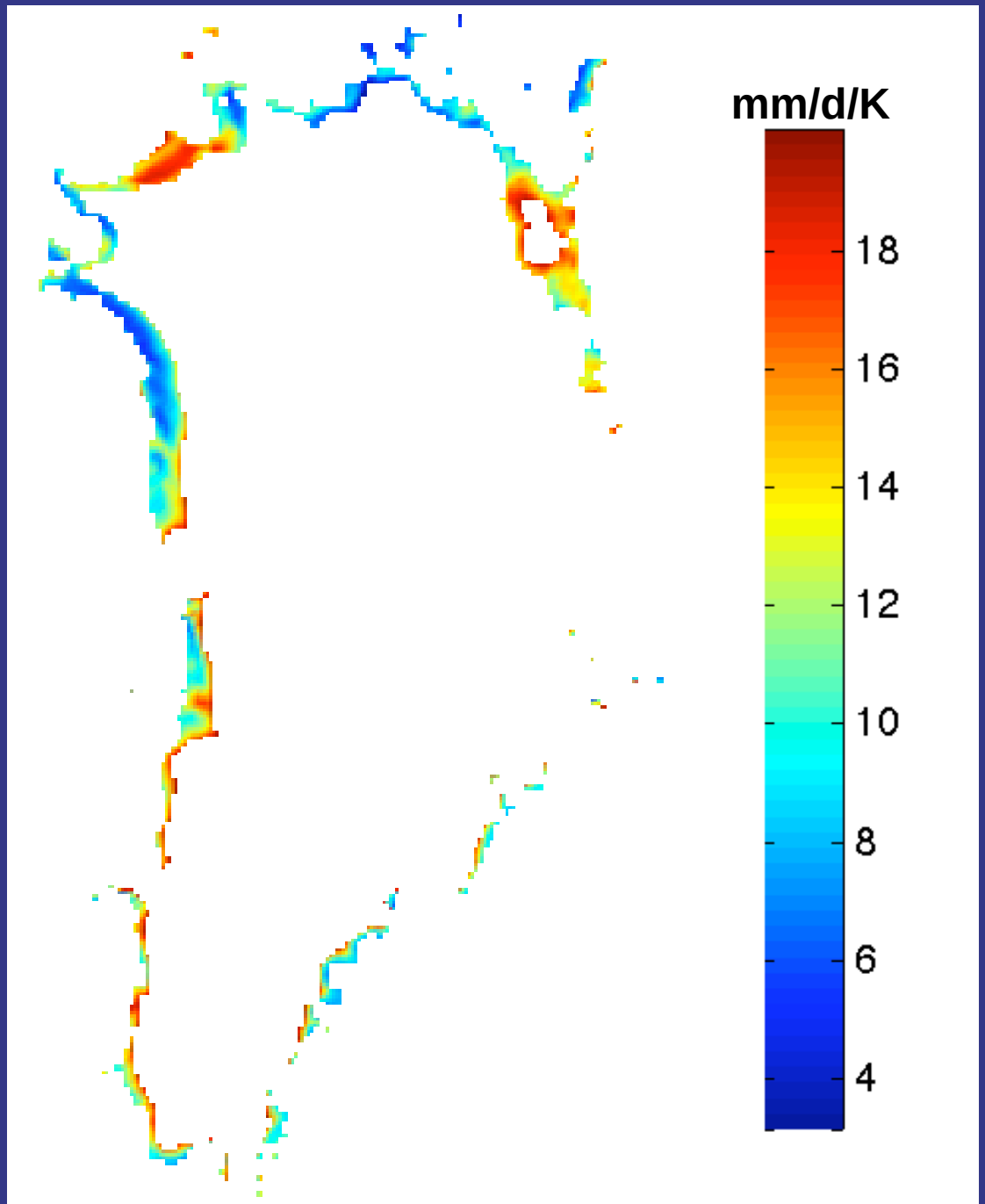

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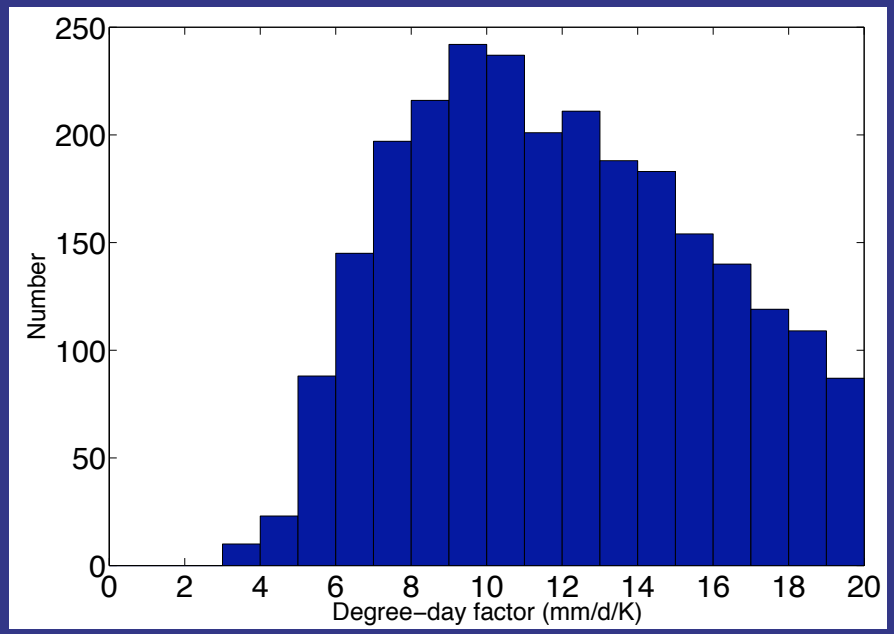
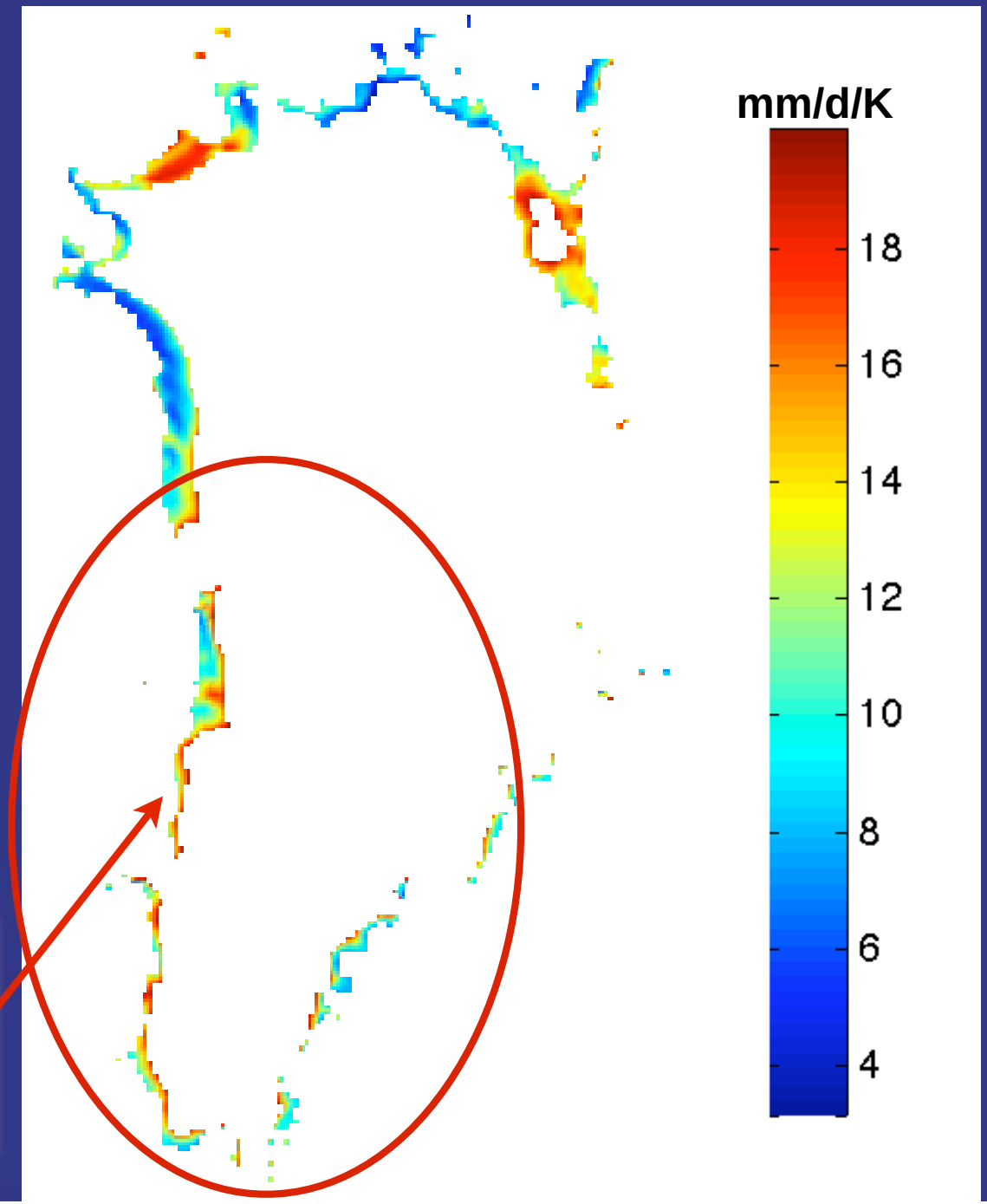
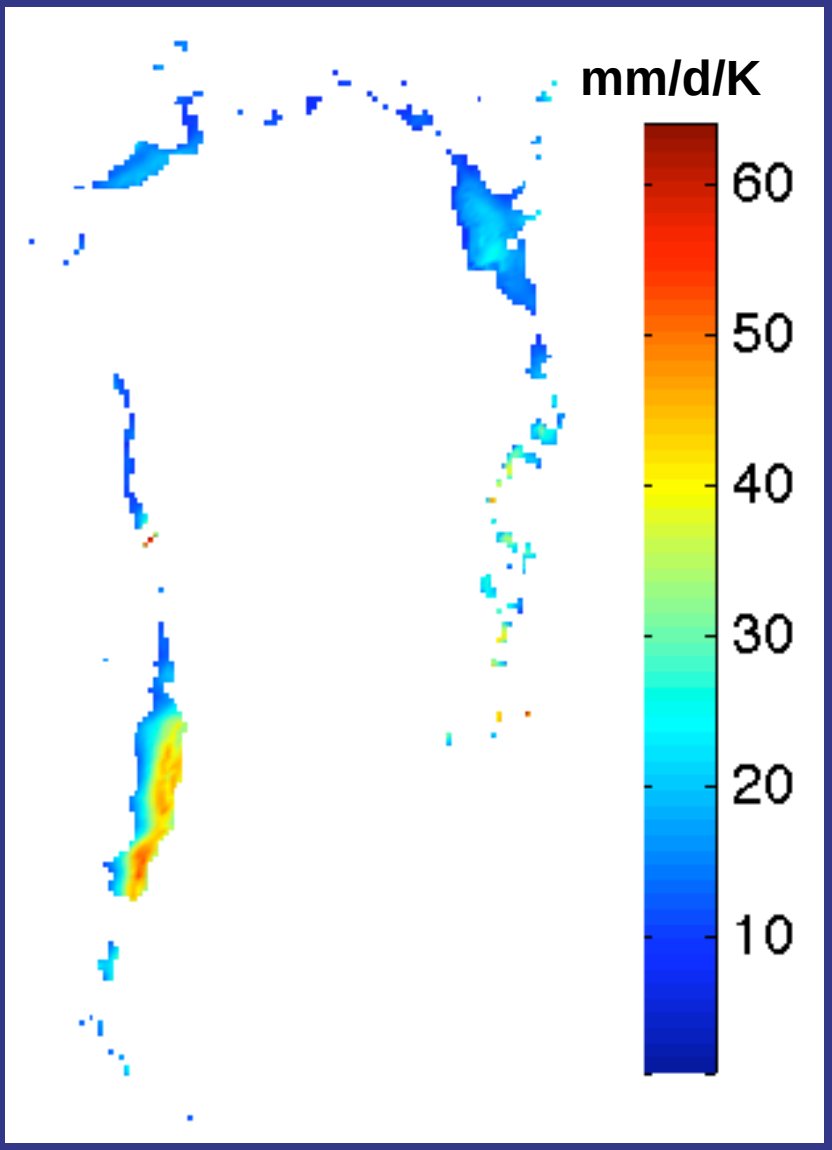
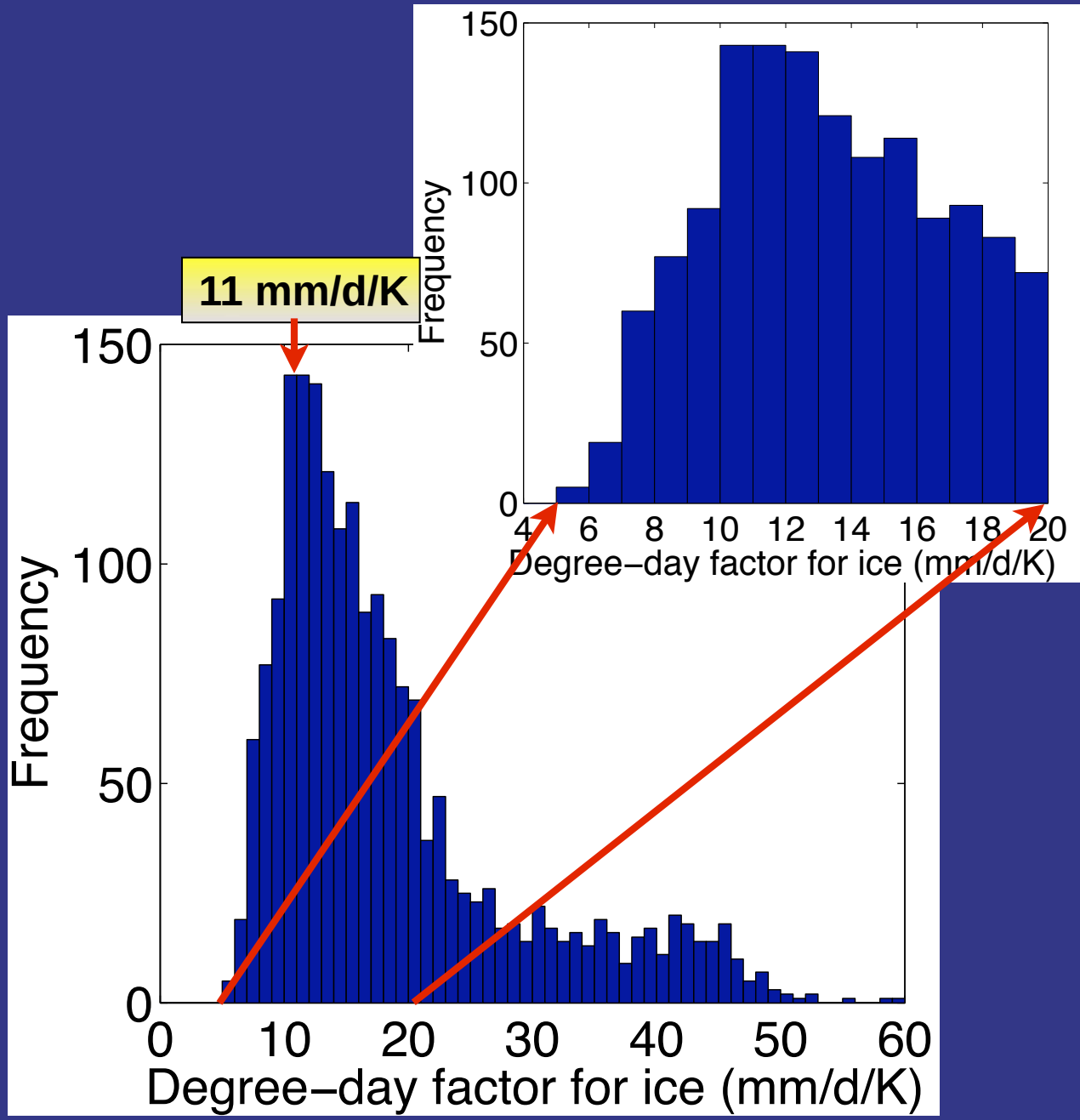


Degree-day factors increase with elevation



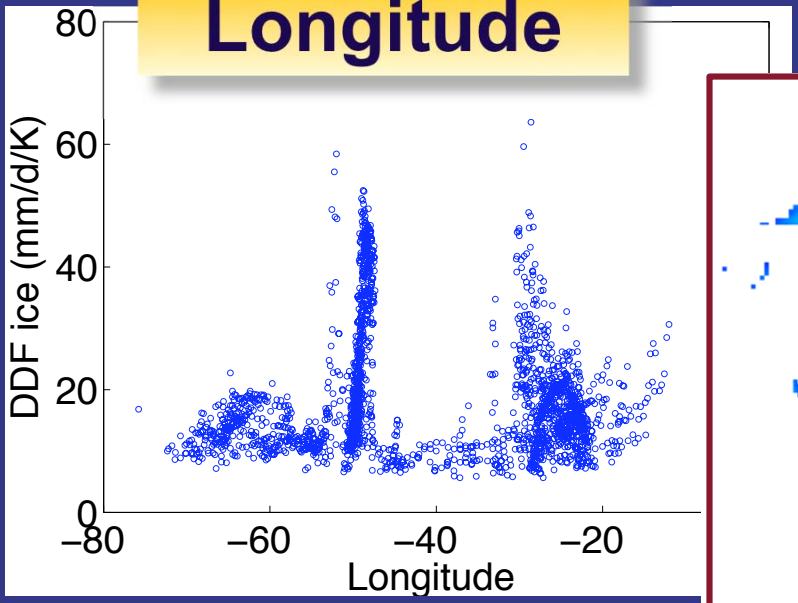
- Degree-days factors for **ice** averaged over 1958-2008





What do the degree-day factors for ice depend on?

Longitude



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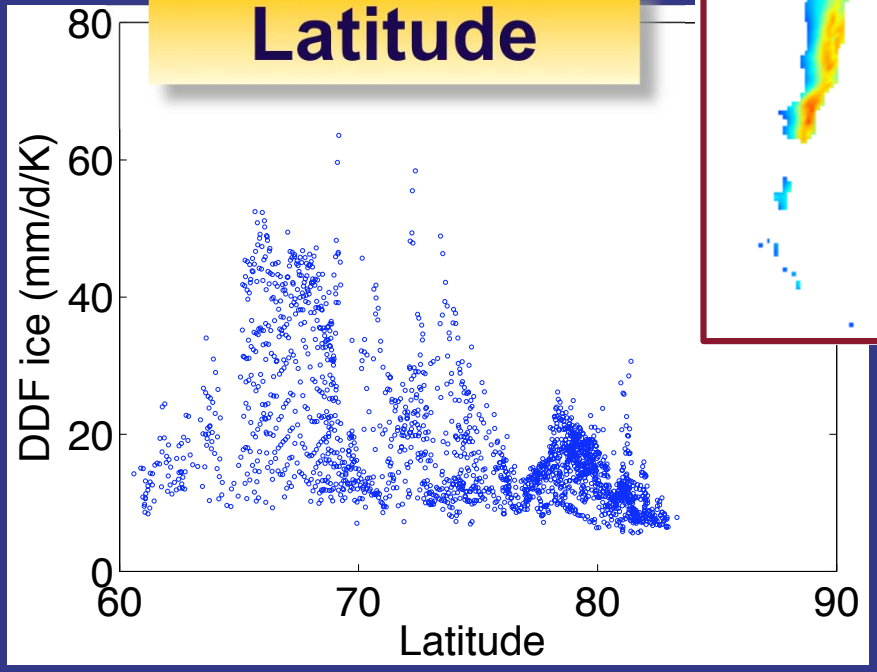

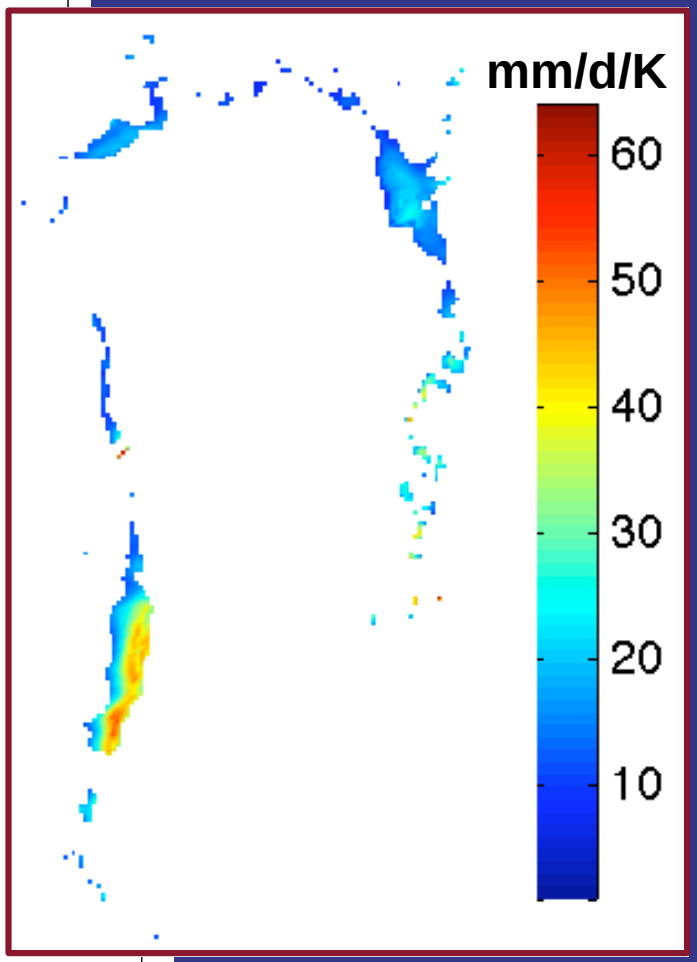

Means over ice-covered months 1958 - 2008 for each pixel

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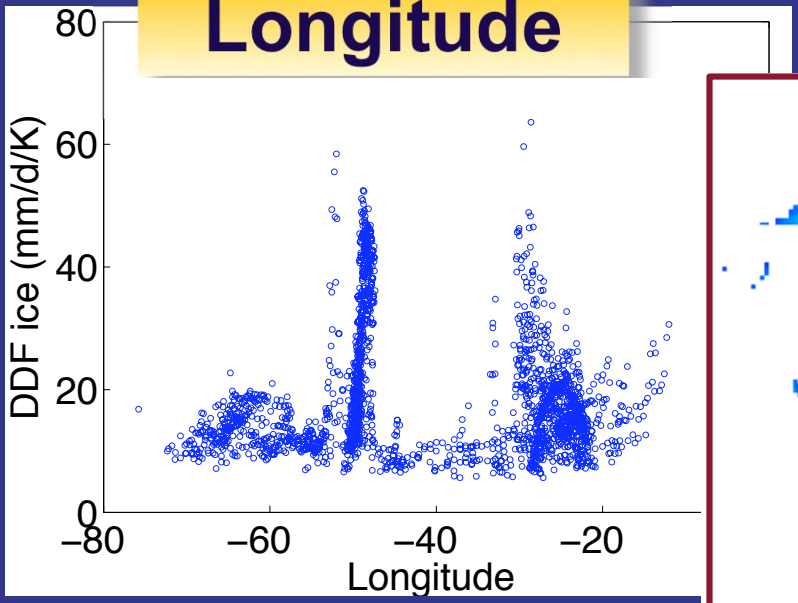
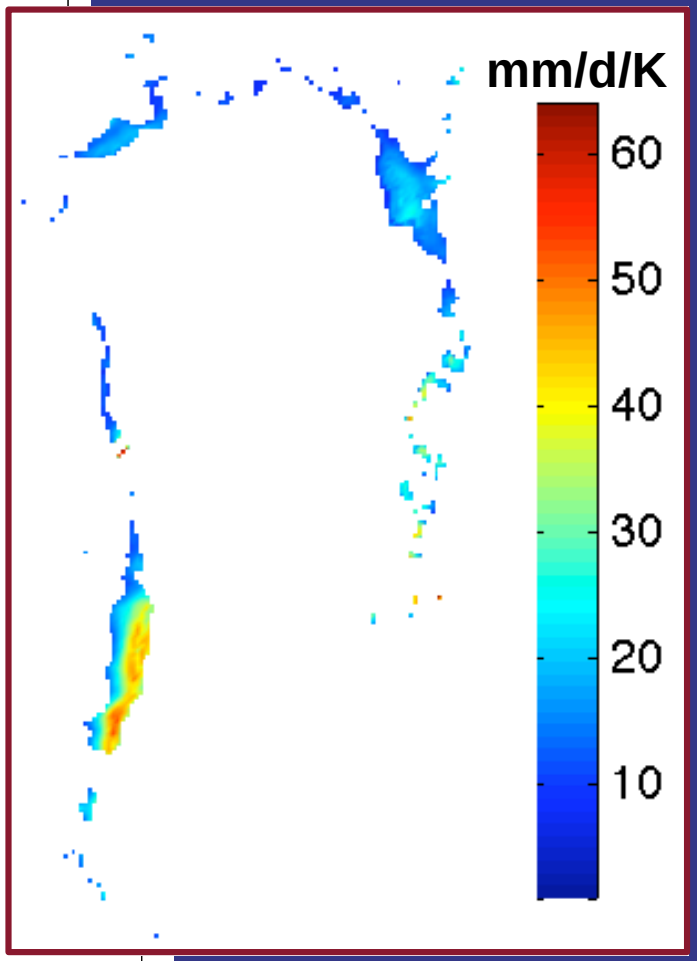
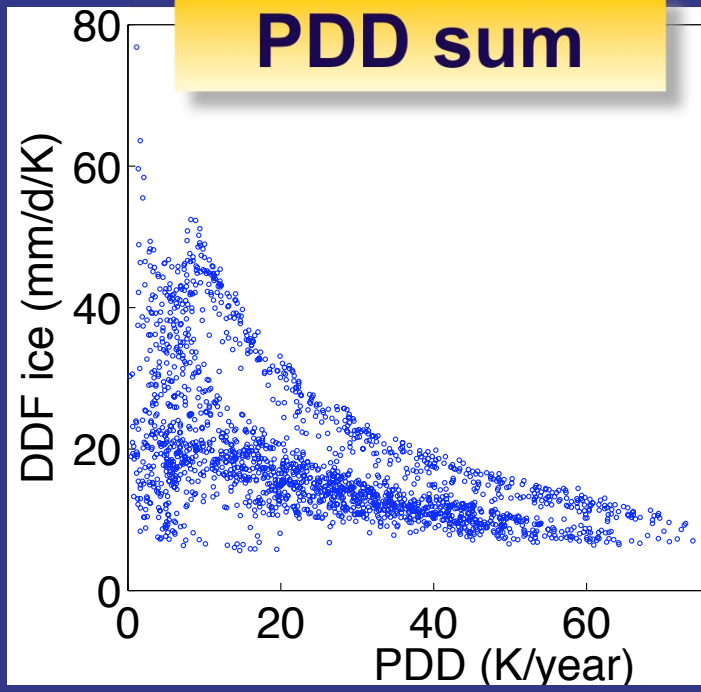
Longitude





PDD sum



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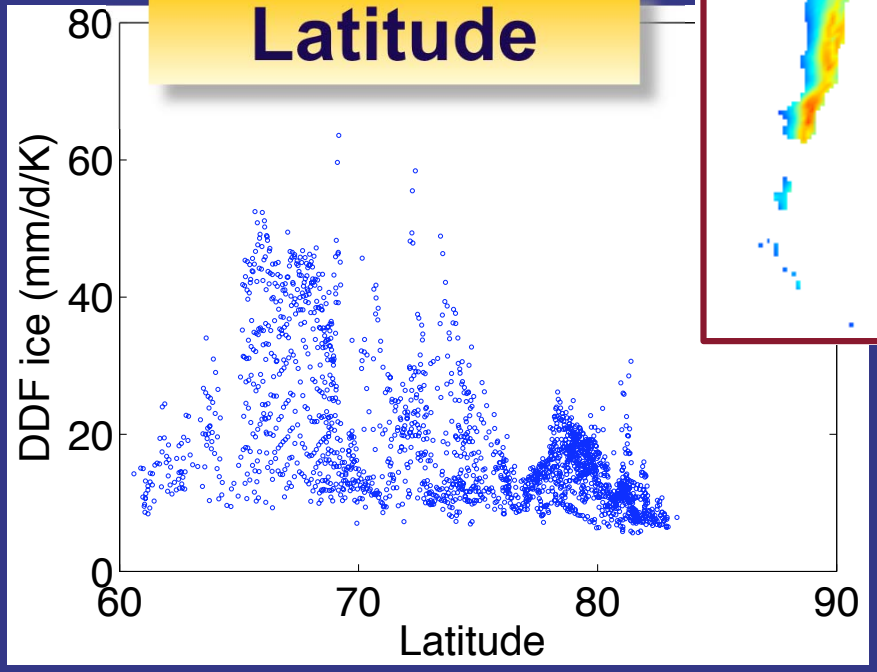

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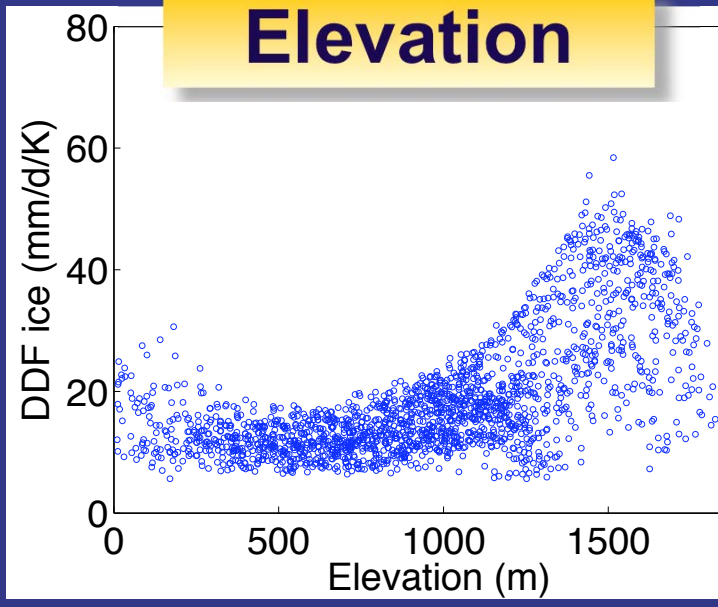
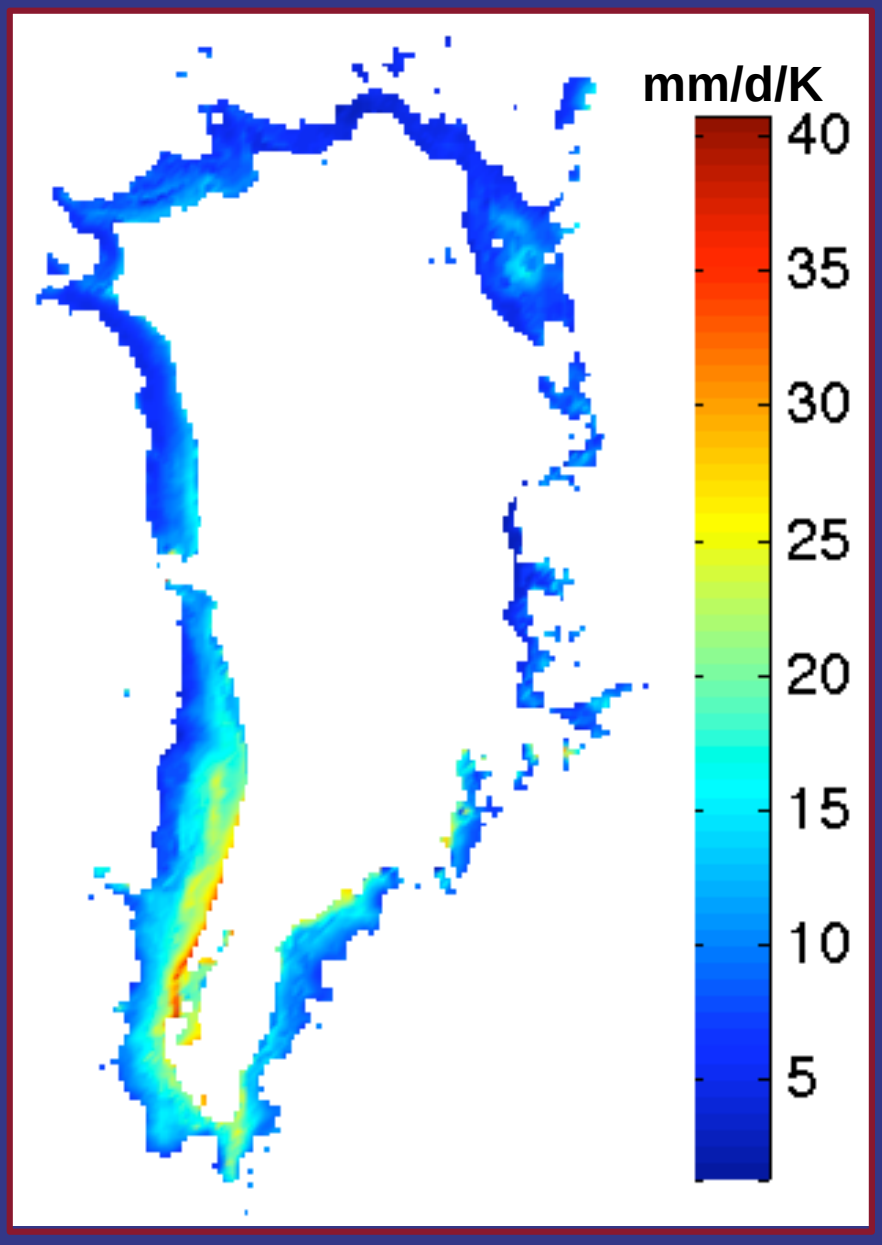
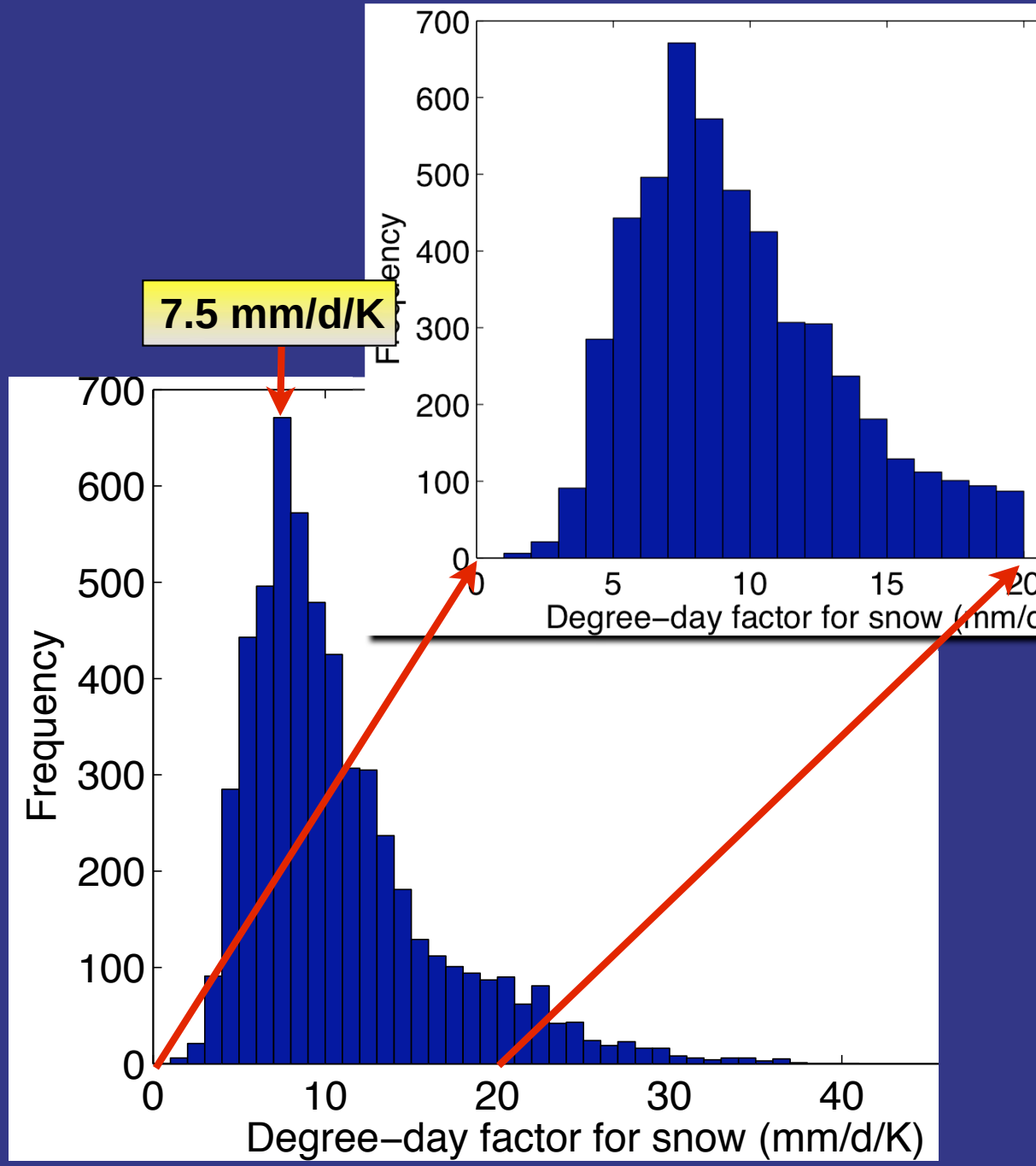
Elevation



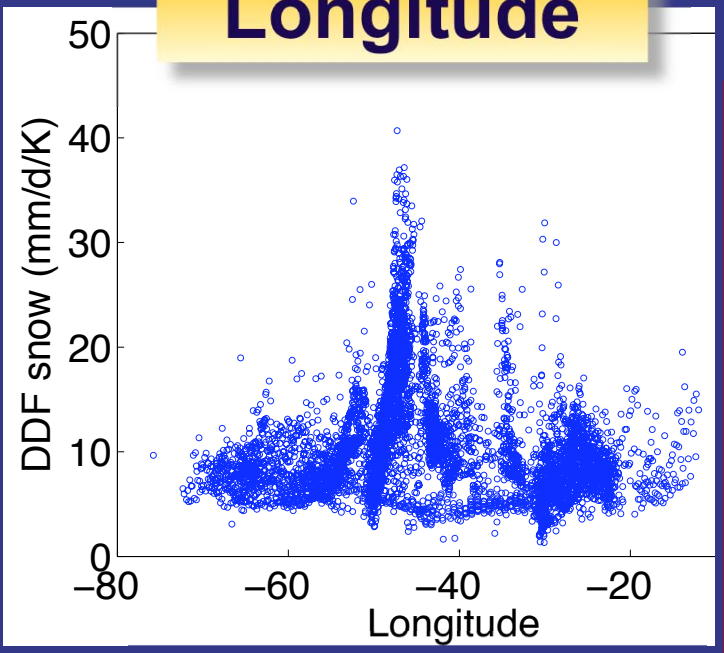
- Degree-days factors for **snow** averaged over 1958-2008



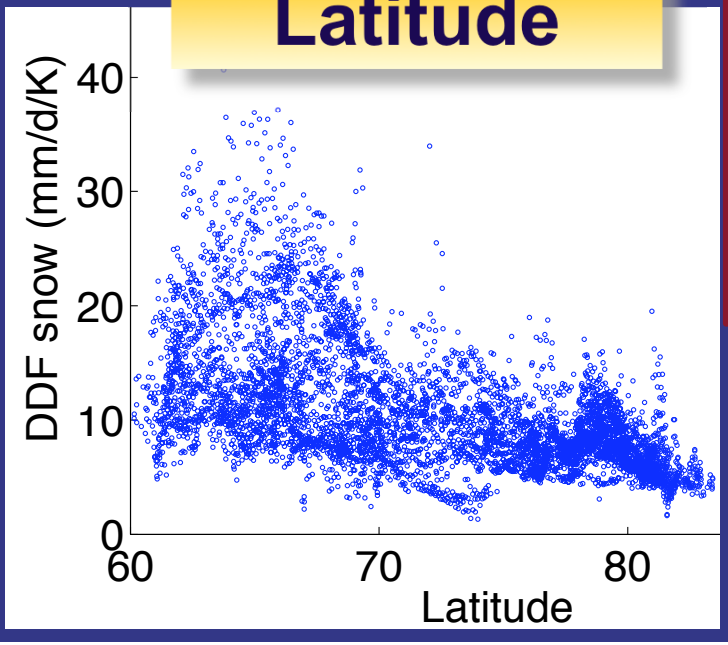


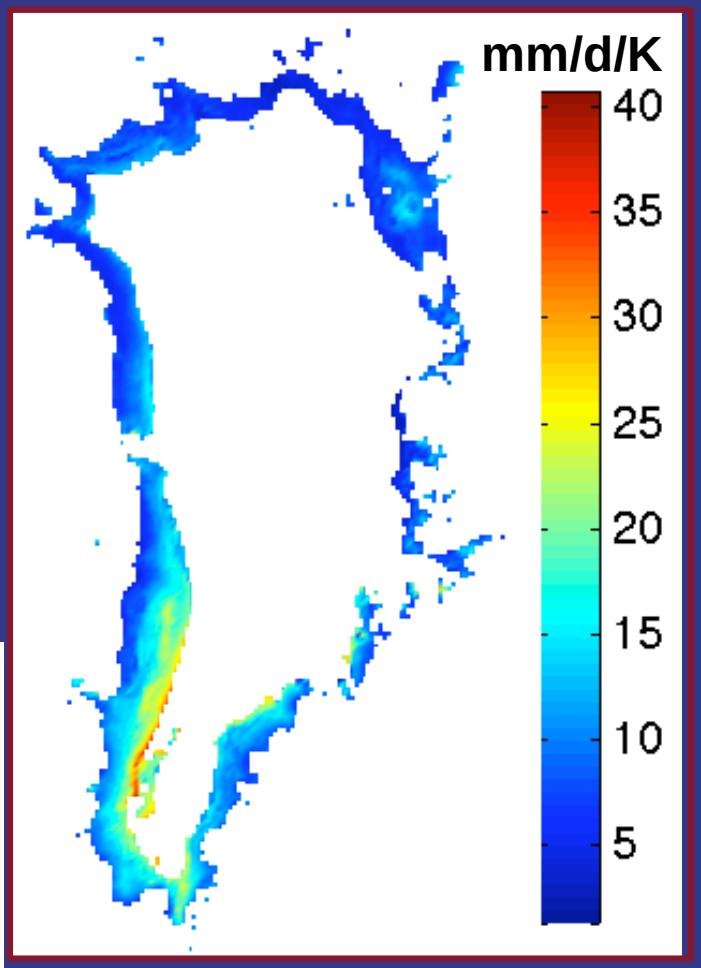
What do the degree-day factors for snow depend on?

Longitude



Latitude





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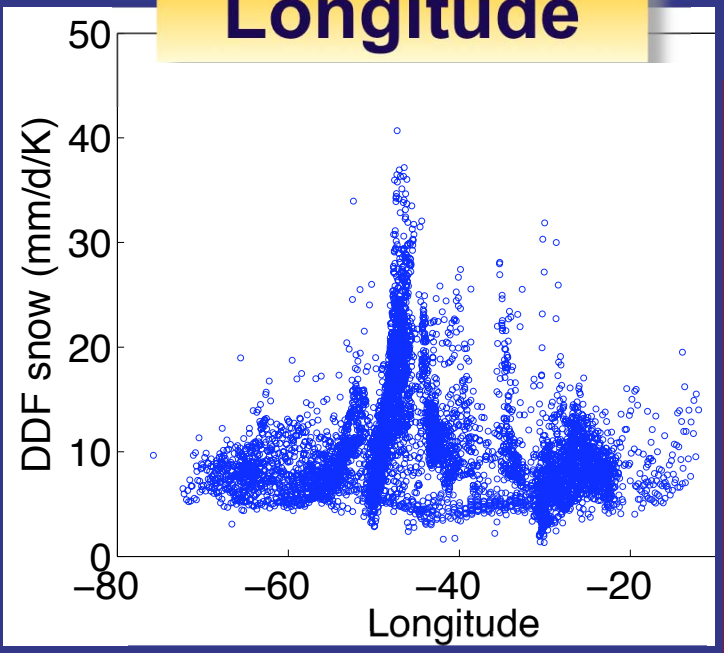

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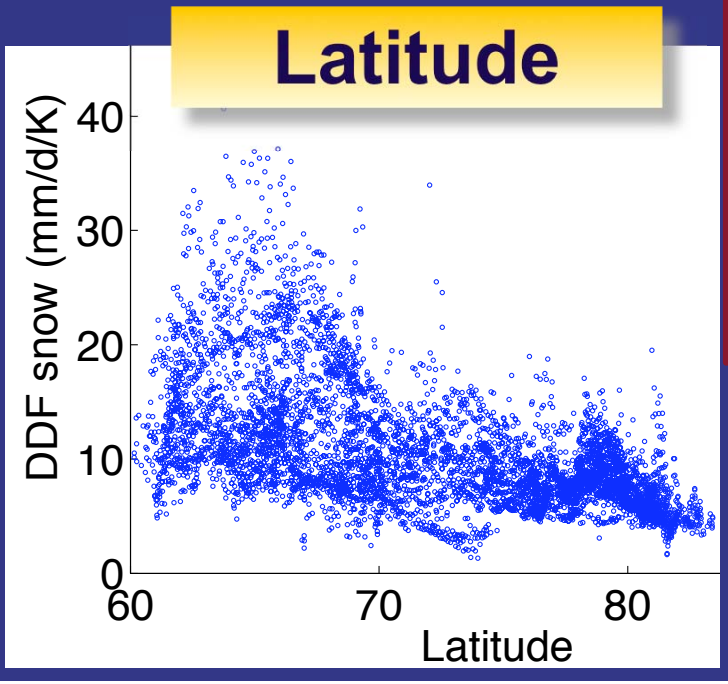
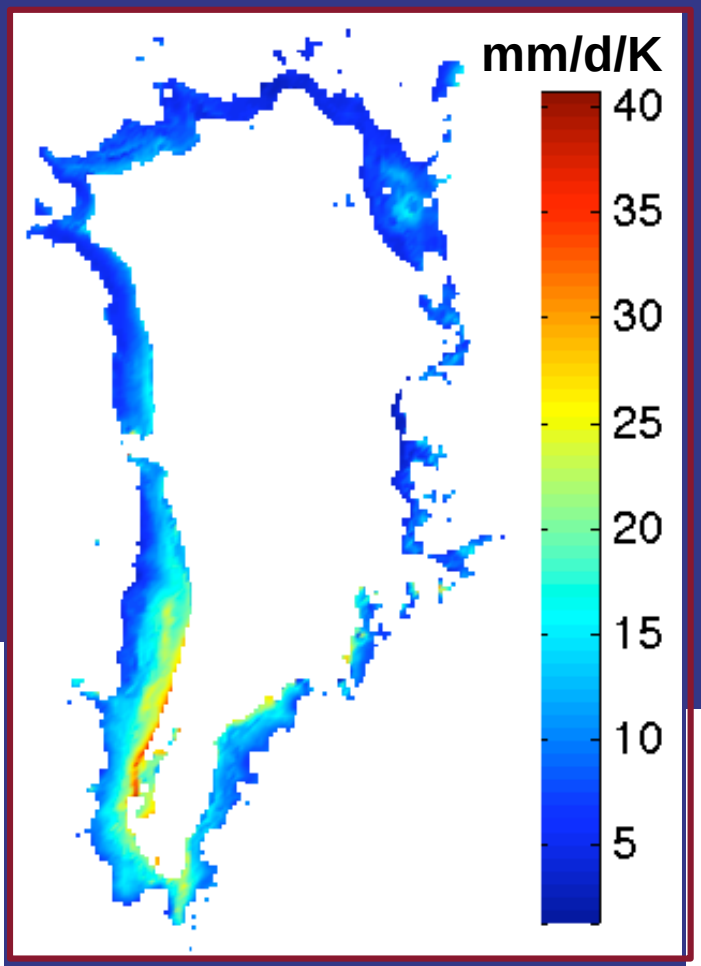
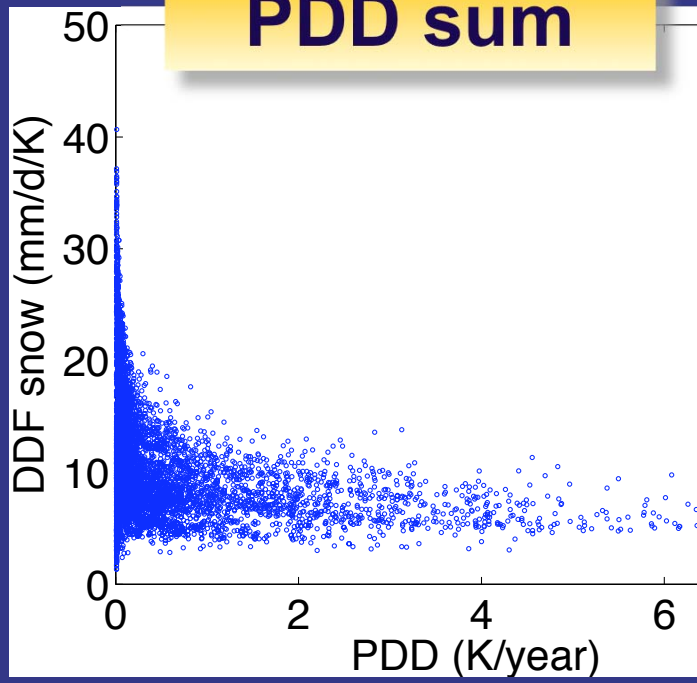


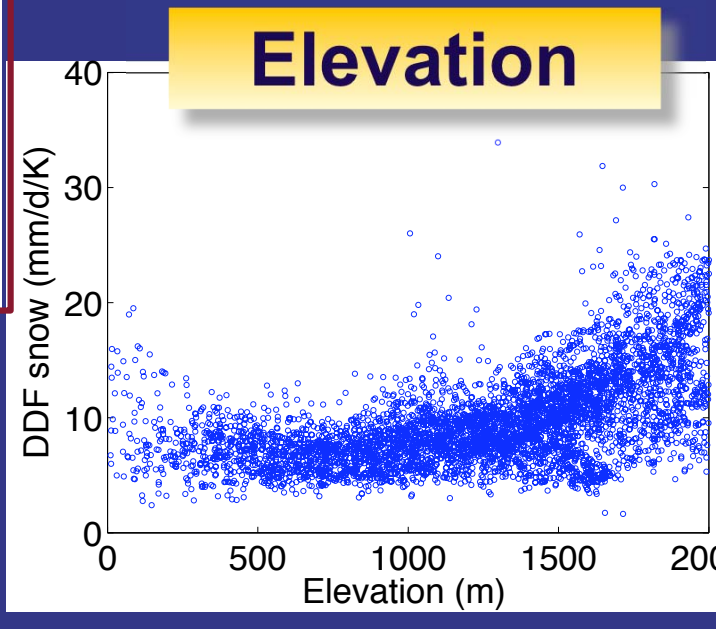


Means over ice-covered months 1958 - 2008 for each pixel

PDD sum



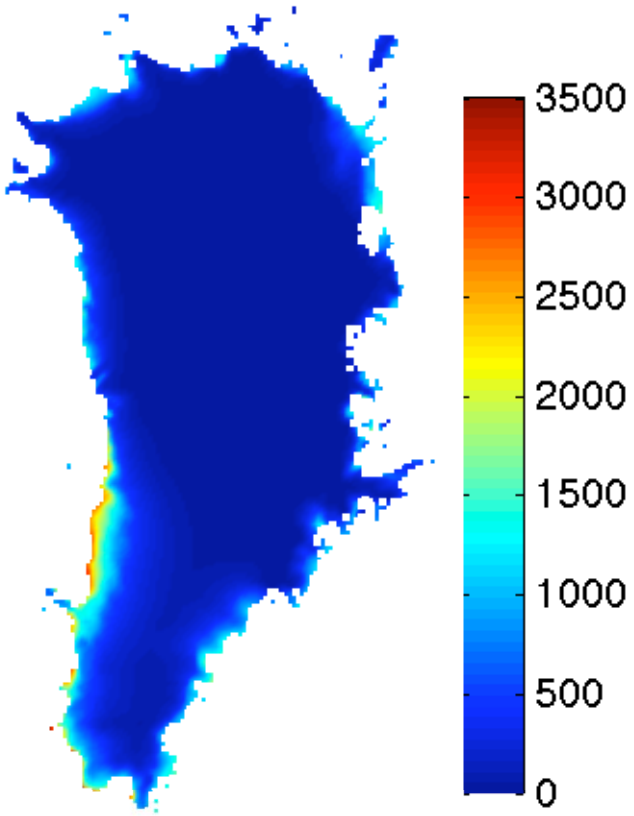
Elevation



- Using spatially constant mean degree-day factors

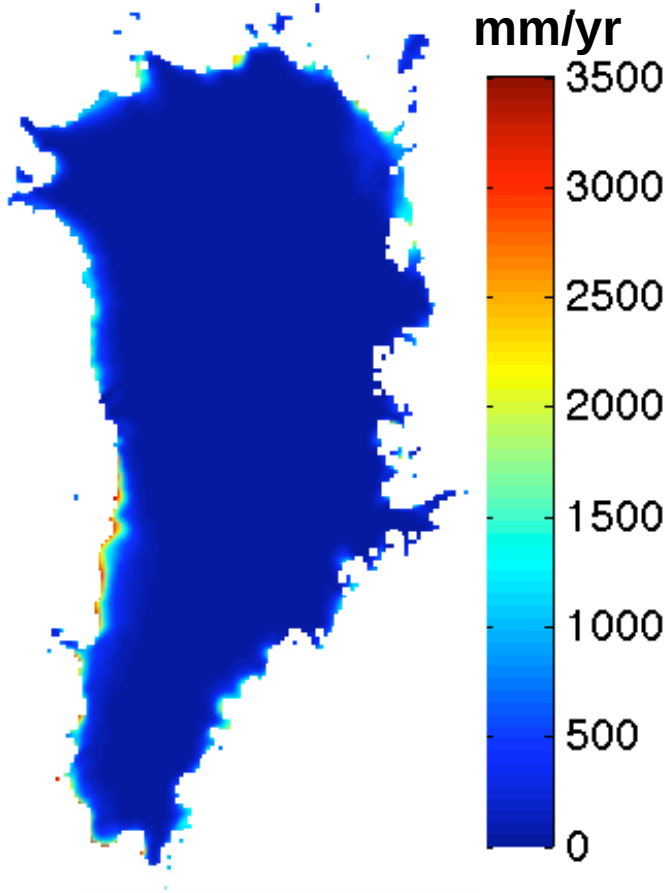
DDF_snow = 10.8 mm/d/K; DDF_ice = 18.7 mm/d/K

RACMO melt



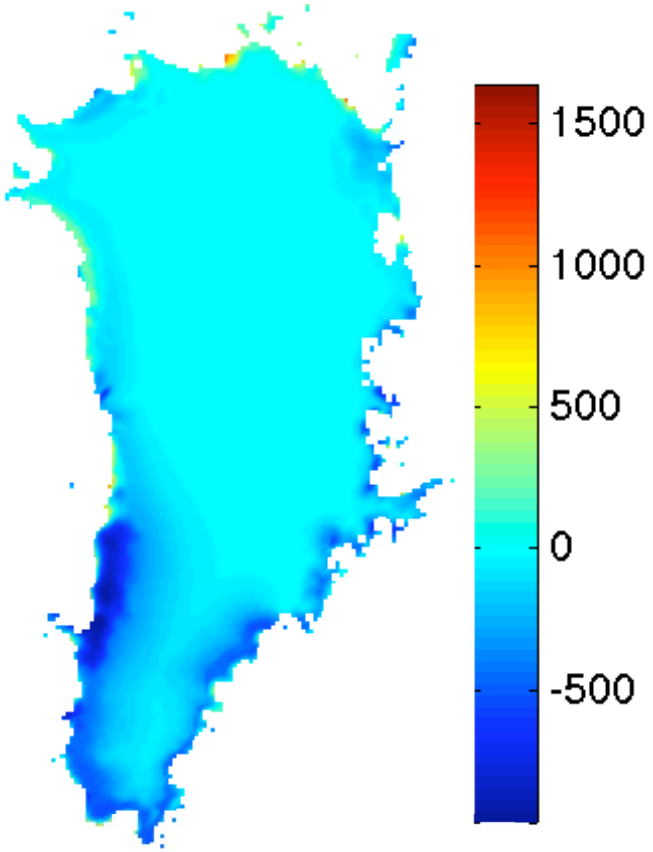
243 mm/yr
427 Gt/yr

Modeled melt



170 mm/yr
299 Gt/yr

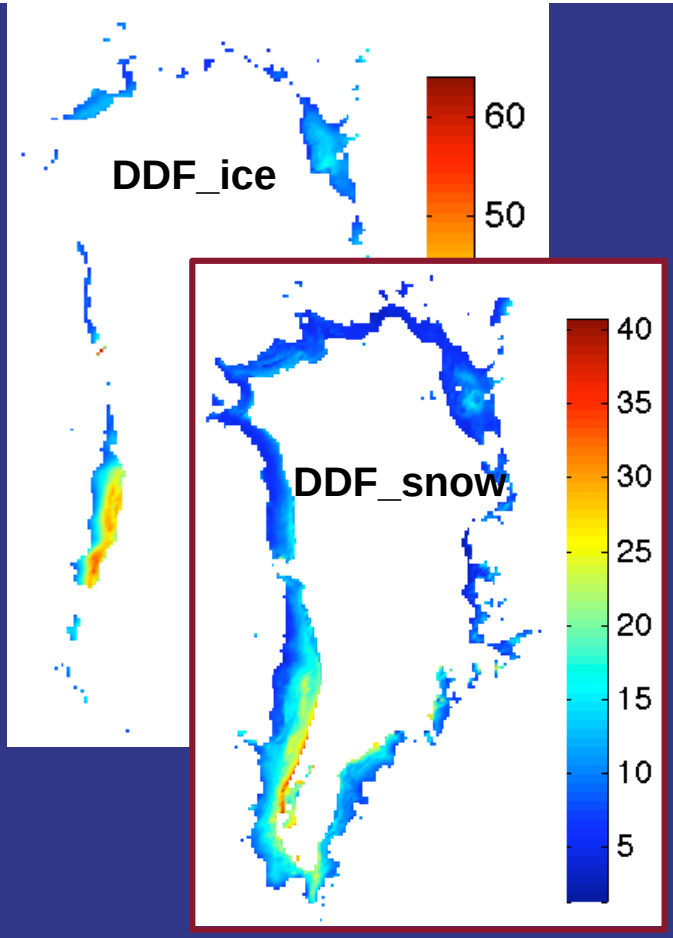
Difference
(Modeled minus RACMO)



73 mm/yr
128 Gt/yr

Conclusions

- **Degree-day factors vary strongly in space; no clear geographical pattern; increase with elevation**
- **Uncertainties in degree-day estimates due to the uncertainties in RACMOs temperature, melt rates and surface densities**



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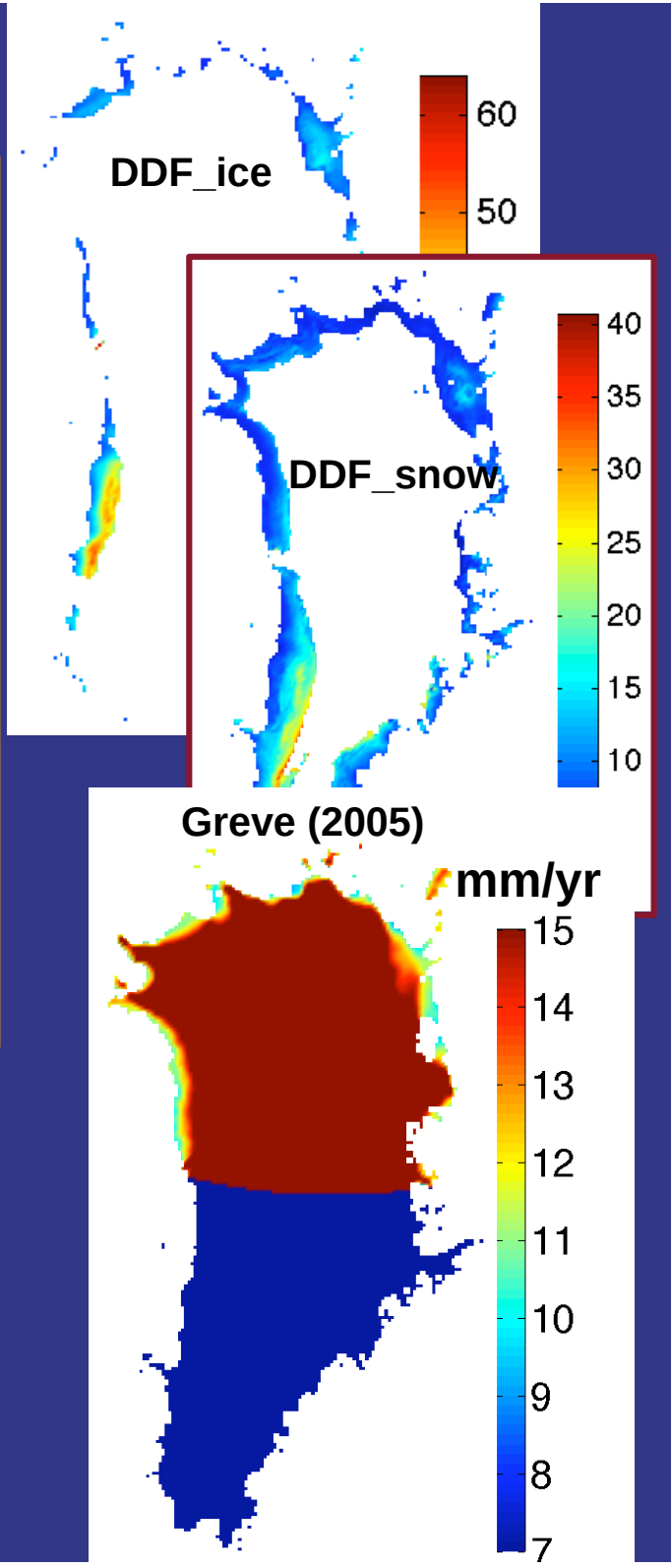
- Parameterization by Greve (2005) applied to RACMO temperature fields leads to considerable underestimation of melt compared to RACMO (>300 Gt/yr)



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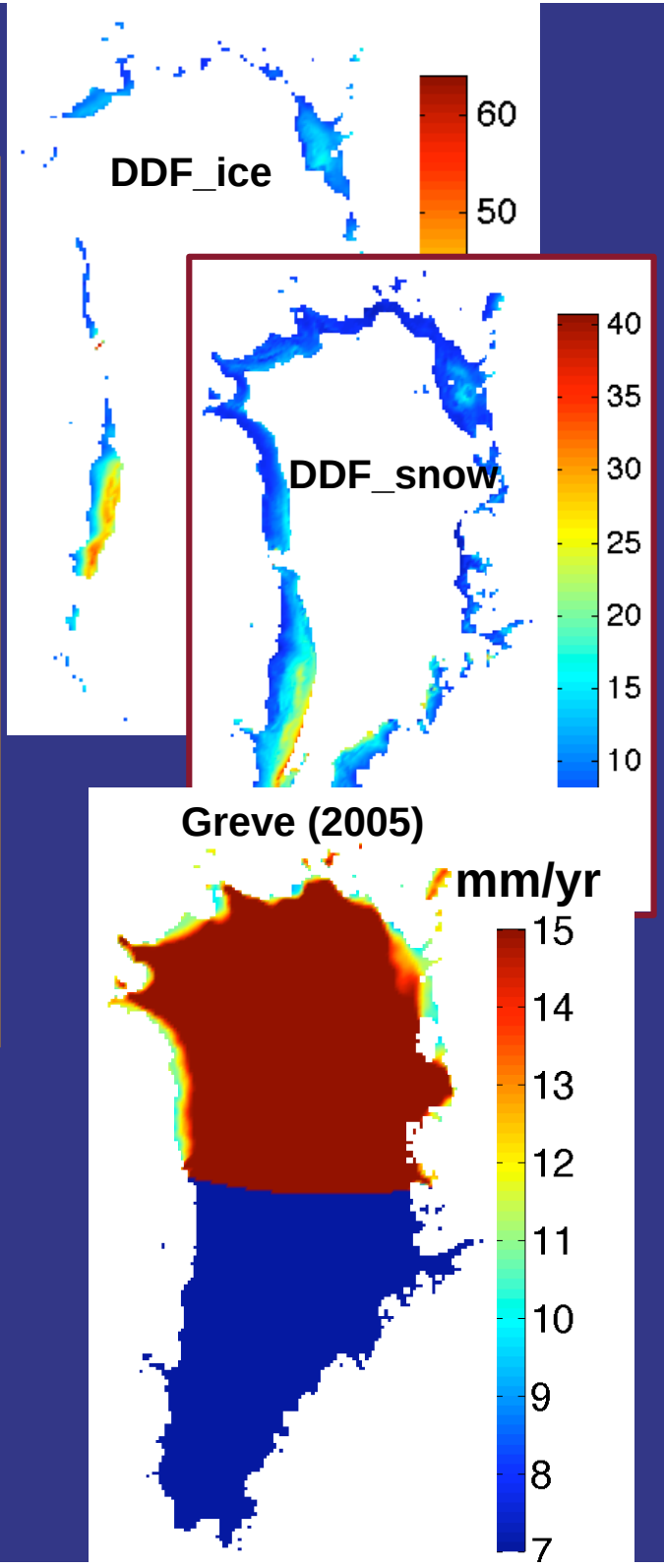

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