Resilience of the Greenland ice sheet firn layer in a future warming climate

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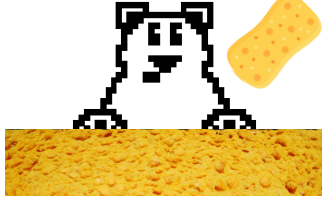
Land Ice and Paleoclimate Working Group meetings

Monday February 10 2020

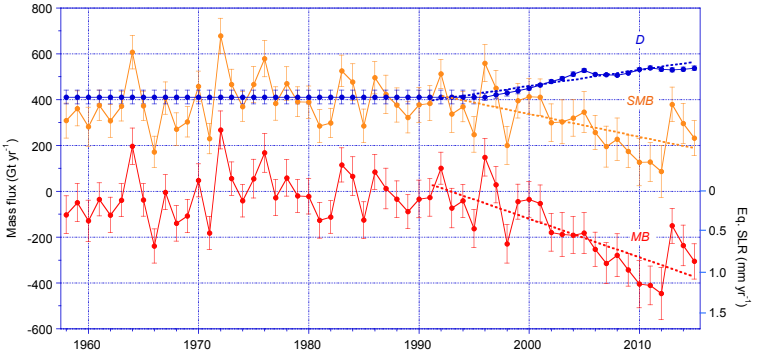


IMAU
Institute for Marine and Atmospheric research Utrecht

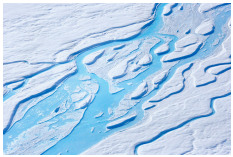
Universiteit Utrecht

Recent Greenland ice sheet mass loss

Mass Balance = Surface Mass Balance - Ice Discharge



Surface runoff



Icebergs calving

Pre-1991: approximate mass balance (MB ≈ 0)

Post-1991: mass loss (MB < 0) driven by increased surface runoff (60%)

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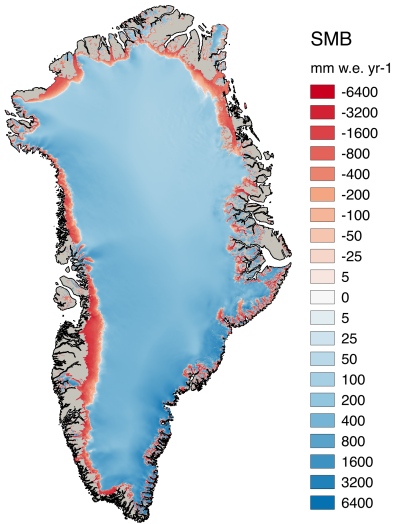
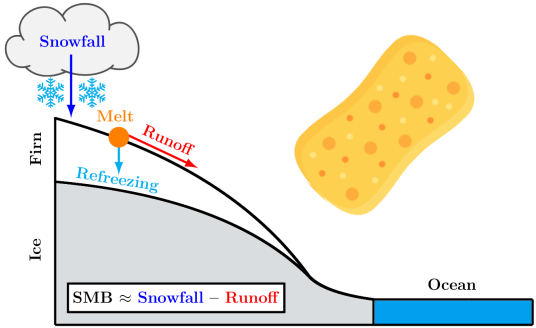
Firn sponge: Greenland ice sheet surface mass balance



SMB = Snowfall - Runoff

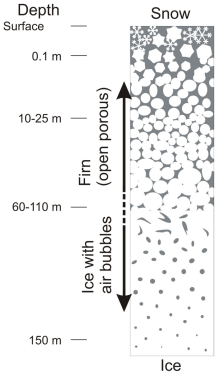


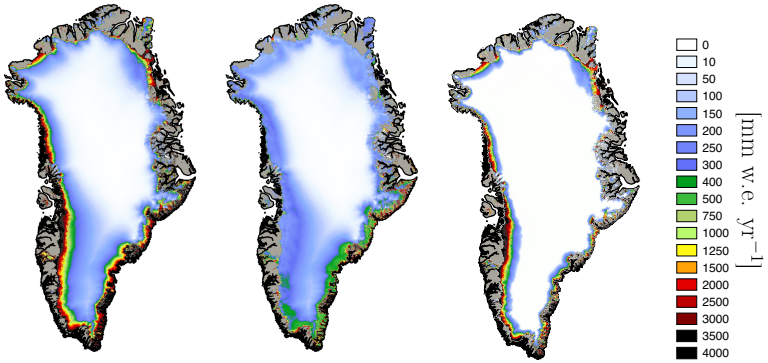
- Ablation zone: SMB < 0
- Accumulation zone: SMB > 0

Meltwater refreezing: firn buffer capacity

Firn: porous snow

Melt - Refreezing = Runoff

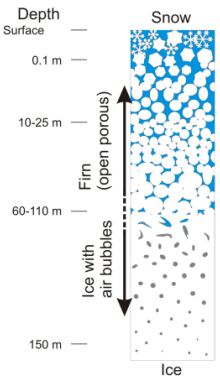




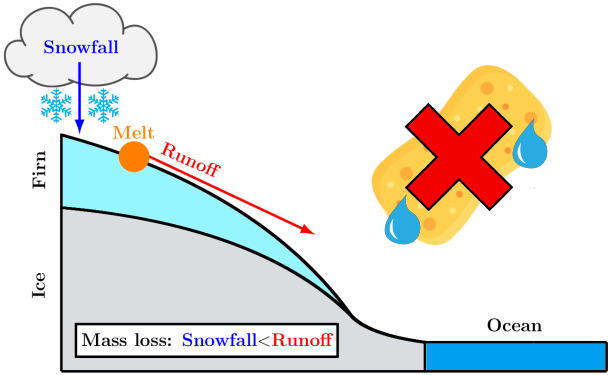
Firn covers 90% of the ice sheet and retains ∼45% of melt, mitigating runoff

What if firn saturates in a warmer climate?

Saturated firn:



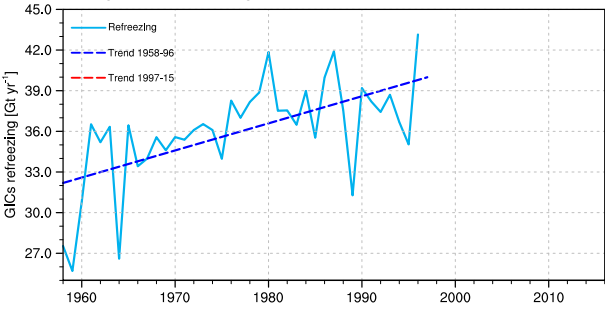
Melt = Runoff



Firn is saturated and retains ∼0% of melt, accelerating runoff mass loss

Tipping point in refreezing accelerates the mass loss

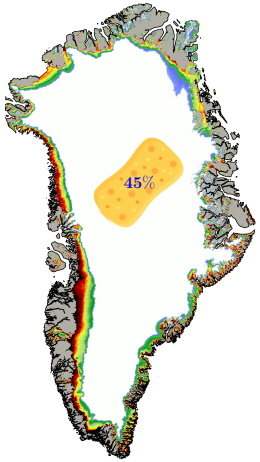
Peripheral ice caps



The ice sheet has not crossed a tipping point yet

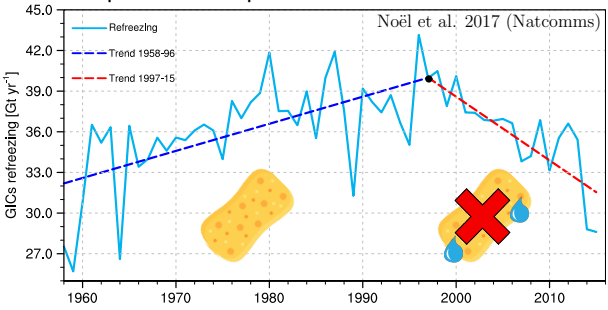
1. When can we expect a tipping point in refreezing?
2. How would it affect the future rate of sea level rise?

Present-day runoff (1958-2018)



Tipping point in refreezing accelerates the mass loss

Peripheral ice caps



The ice sheet has not crossed a tipping point yet

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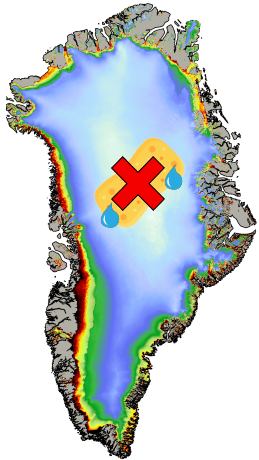
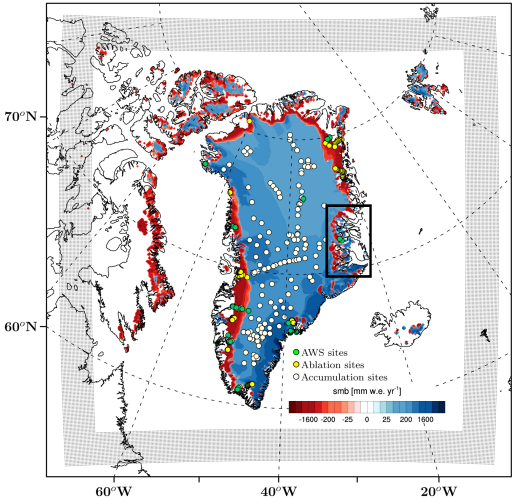
Future tipping point

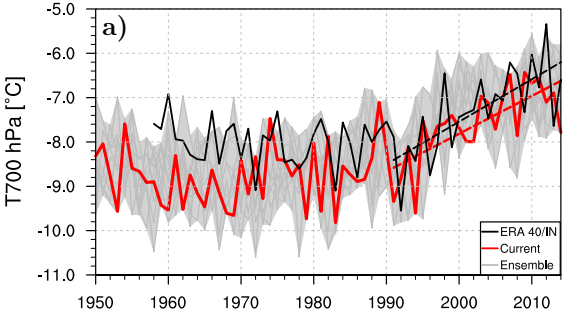


CESM2 as a climate forcing for RACMO2 (1950-2014)

SMB at 11 km (1950-2014)



Temperature at 700 hPa in CESM2 (1950-2014)



- One out of eleven historical member
- Good agreement with reanalyses (bias ≈ -0.4°C)

Refining the model resolution: global to local scale

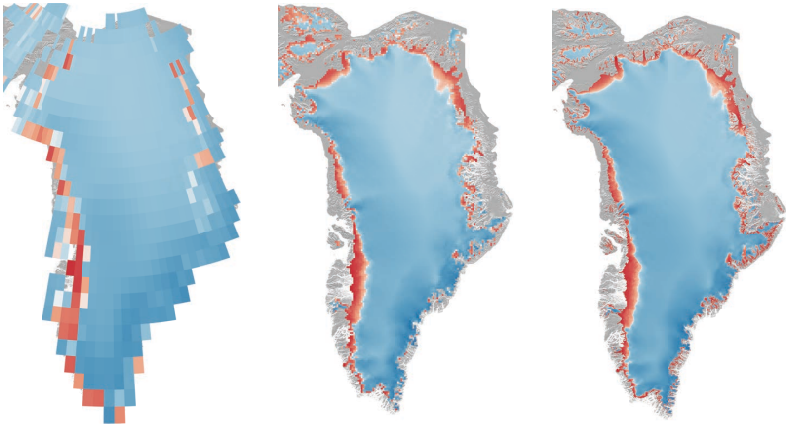
CESM2: ∼111 km

RACMO2: ∼11 km

Local: 1 km

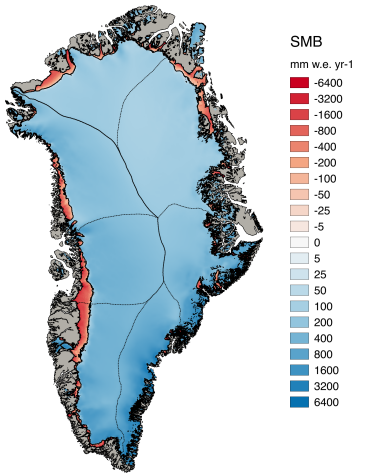
Downscaling

Noël et al. (2016)

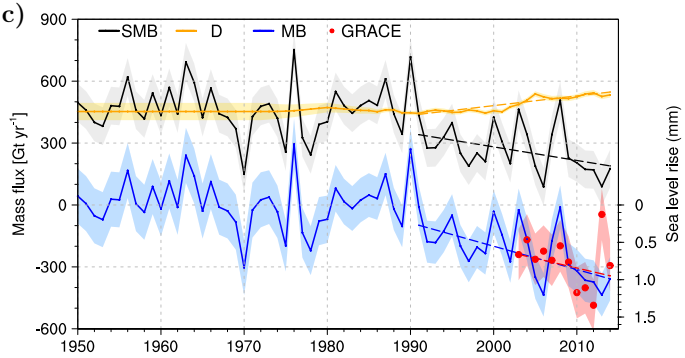


Performance of CESM2-RACMO2: historical 1950-2014

SMB = 430 Gt yr^{-1} (1950-1990)



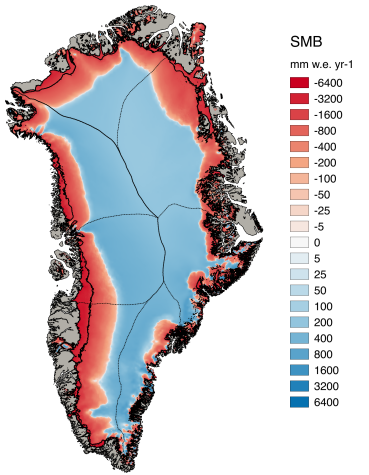
Mass Balance = SMB - Ice Discharge



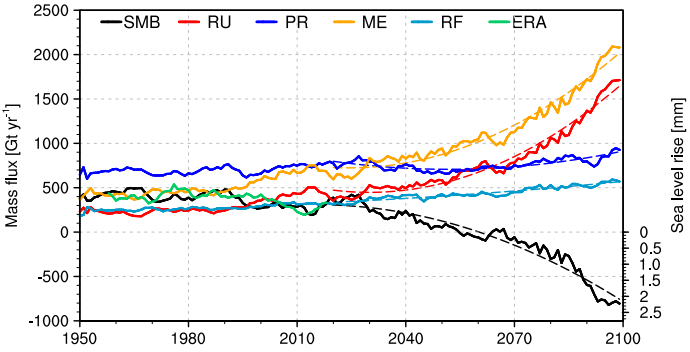
- Pre-1991: ice sheet in approximate mass balance
- Post-1991: mass loss acceleration in line with GRACE

Greenland ice sheet under a SSP8.5 scenario by 2100

SMB = -590 Gt yr^{-1} (2080-2099)

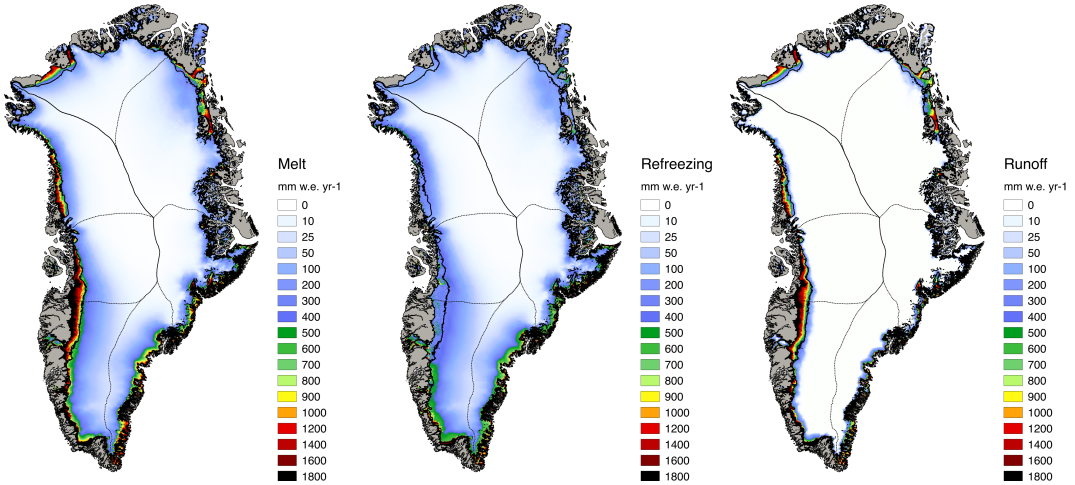


SMB = Precip - Runoff ($\approx$ Melt - Refreezing)



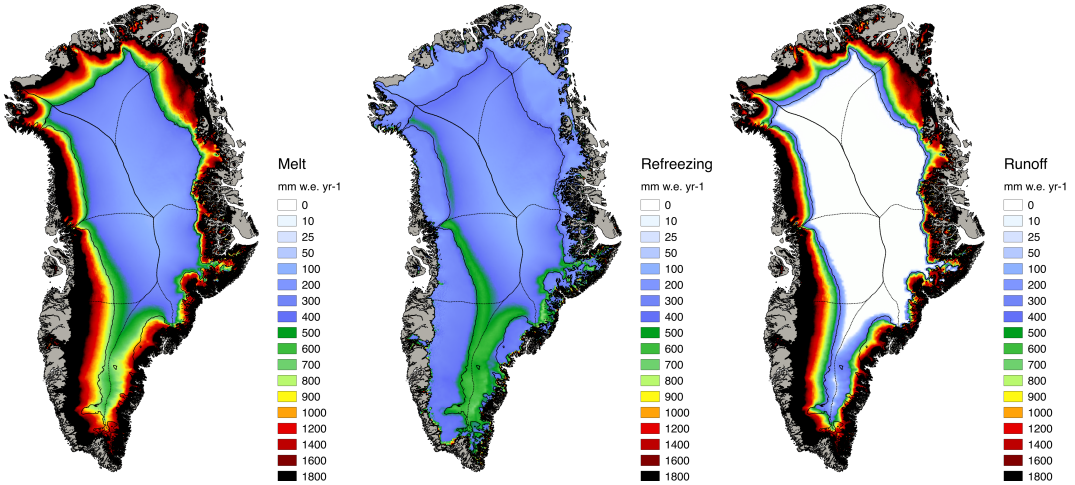
- Post-2020: nonlinear runoff increase drives SMB decline
- Tipping point: refreezing still partly buffers enhanced melt

Ice sheet in approximate mass balance (1950-1990)



440 Gt yr^{-1} 255 Gt yr^{-1} 235 Gt yr^{-1}

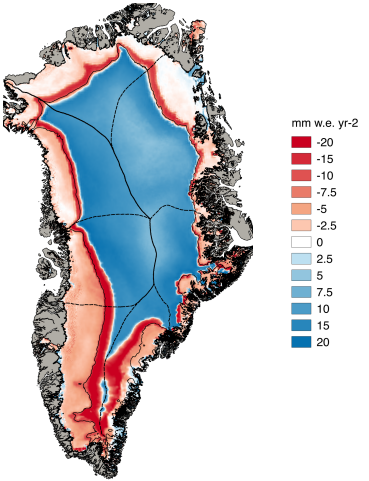
Ice sheet under a SSP8.5 scenario (2080-2099)

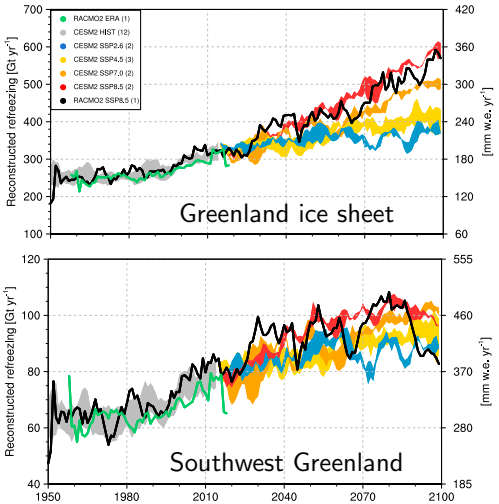


1790 Gt yr^{-1} (4x) 540 Gt yr^{-1} (2x) 1420 Gt yr^{-1} (6x)

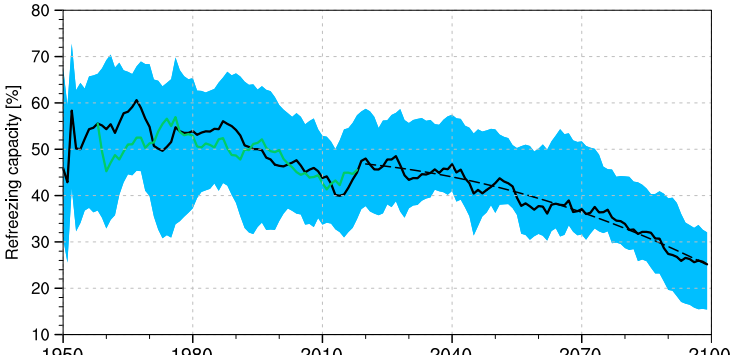
Regional tipping point in refreezing (2080-2099)

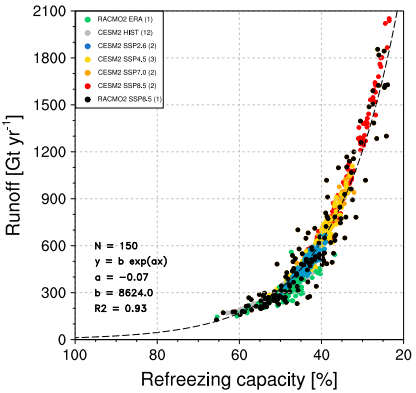
Refreezing trend (2080-2099)





Reduced refreezing capacity drives nonlinear runoff mass loss

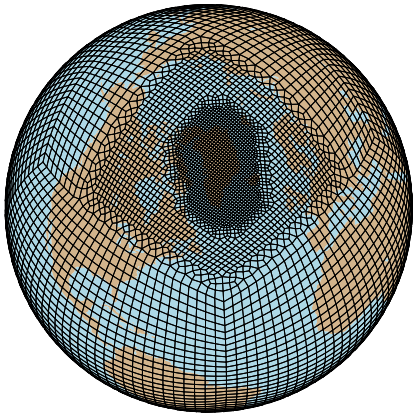




Greenland's firn refreezing capacity declines from $\sim 45\%$ to $\sim 30\%$ by 2100, accelerating runoff

Projecting the evolution of the firn buffer: VR-CESM2 (2015-2300)

Community Earth System Model
Variable-Resolution version 2



- Fully-coupled global model (CMIP6):
  - ⇒ Atm-ocean-ice interactions
  - ⇒ Firn processes (refreezing/runoff)
  - ⇒ Ice dynamics (retreat/thinning)
- VR-CESM2: 111 km ⇒ 12 km ⇒ 1 km
- Long-term runs: 1950-2300
  - ⇒ Historical: model evaluation
  - ⇒ Projections: SSP2.6-8.5 scenarios

Firn response to climate warming

Take home message

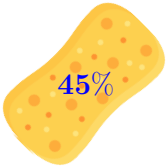
What? **Resilience of the Greenland firn in a warmer climate**

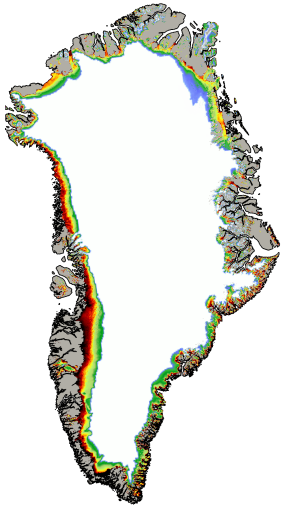
Why? **Tipping point in refreezing accelerates mass loss**

1. When can we expect a tipping point in refreezing?
2. How would it affect the future rate of sea level rise?

How? **Variable Resolution CESM2**

1. Fully-coupled global model (atm-ocean-ice)
2. Unprecedented spatial resolution (12 km $\Rightarrow$ 1 km)
3. Long-term scenario projections (SSP2.6/8.5; 2015-2300)





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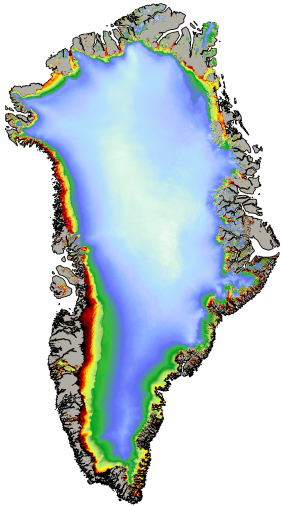

Thank you for your attention!
Any questions?

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Statistical downscaling procedure

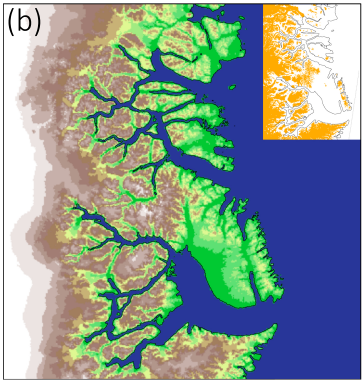
Downscaling: SMB to 1km (1958-2018)

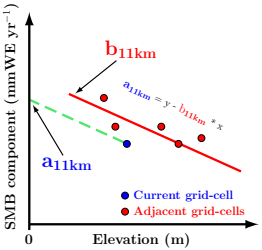
- Select: 5-8 adjacent 11 km ice cells
- Regression: a_{11km} and b_{11km}
- Bi-linear int.: a_{1km} and b_{1km}
- $X_{corr} = a_{1km} + b_{1km} \times height_{1km}$

Additional corrections:

- RU_{corr} = ice albedo overestimation

SMB $_{1km} \approx$ PR - RU$_{corr}$





Cross-model correlation and scenario reconstructions