Rapid expansion of Greenland's low-permeability ice slabs through the 21st Century

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Photo by Dirk van As

Refrozen ice inhibiting runoff in Greenland

- **Firn not acting as the "buffer" it once was**

NATURE CLIMATE CHANGE | LETTER

Greenland meltwater storage in firn limited by near-surface ice formation

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Approximately half of Greenland's current annual mass loss is attributed to runoff from surface melt[1]. At higher elevations, however, melt does not necessarily equal runoff, because meltwater can refreeze in the porous near-surface snow and firn[2]. Two recent studies suggest that all[3] or most[3, 4] of Greenland's firn pore space is available for meltwater storage, making the firn an important buffer against contribution to sea level rise for decades to come[3]. Here, we employ *in situ* observations and historical legacy data

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Research article 30 May 2016

Extraordinary runoff from the Greenland ice sheet in 2012 amplified by hypsometry and depleted firn retention

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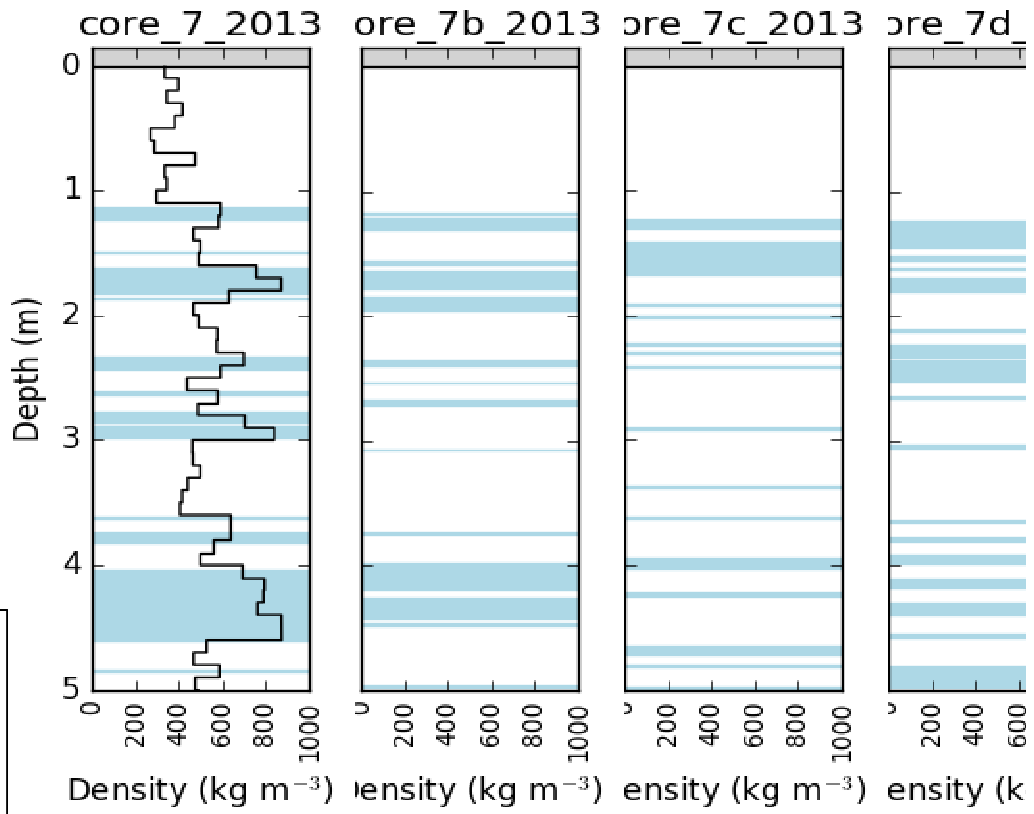
Ice "lenses" versus "slabs"

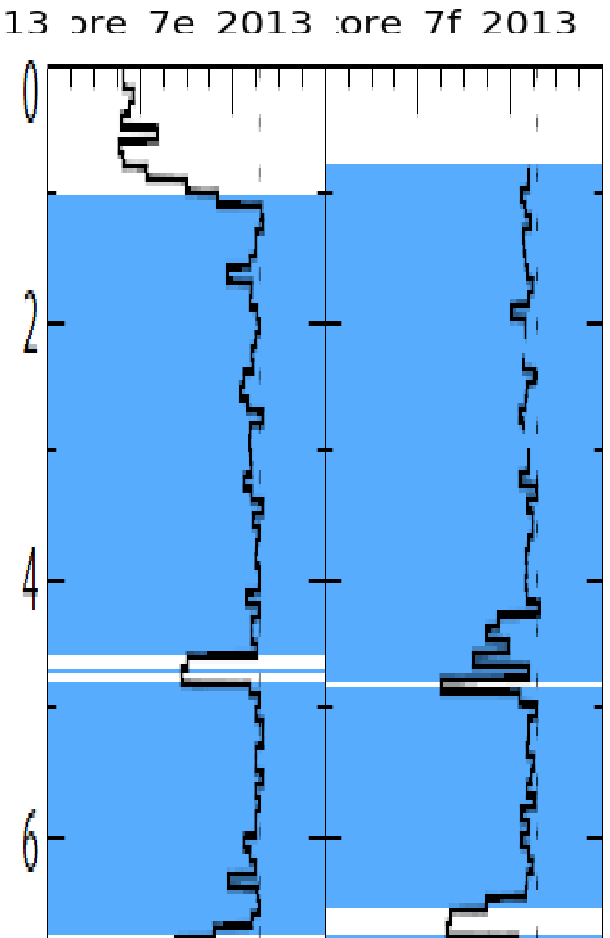
- Lenses <30-50 cm are spatially heterogeneous
- Runoff **only** yet seen over >1 m multi-annual "ice slabs"

ICE SLABS:
Layers of refrozen ice within firn ≥1 m thick and continuous for ≥1 kilometer.

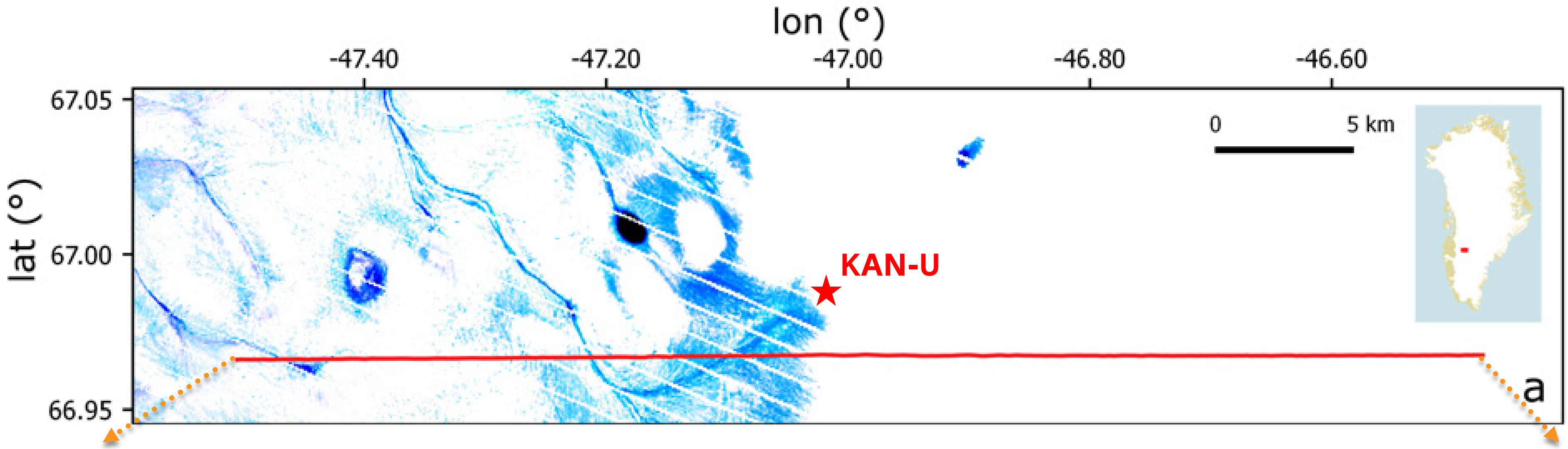
"Site 7", 2100 m a.s.l.

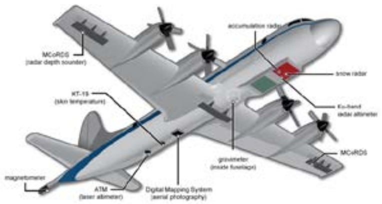


KAN-U, 1850 m a.s.l.

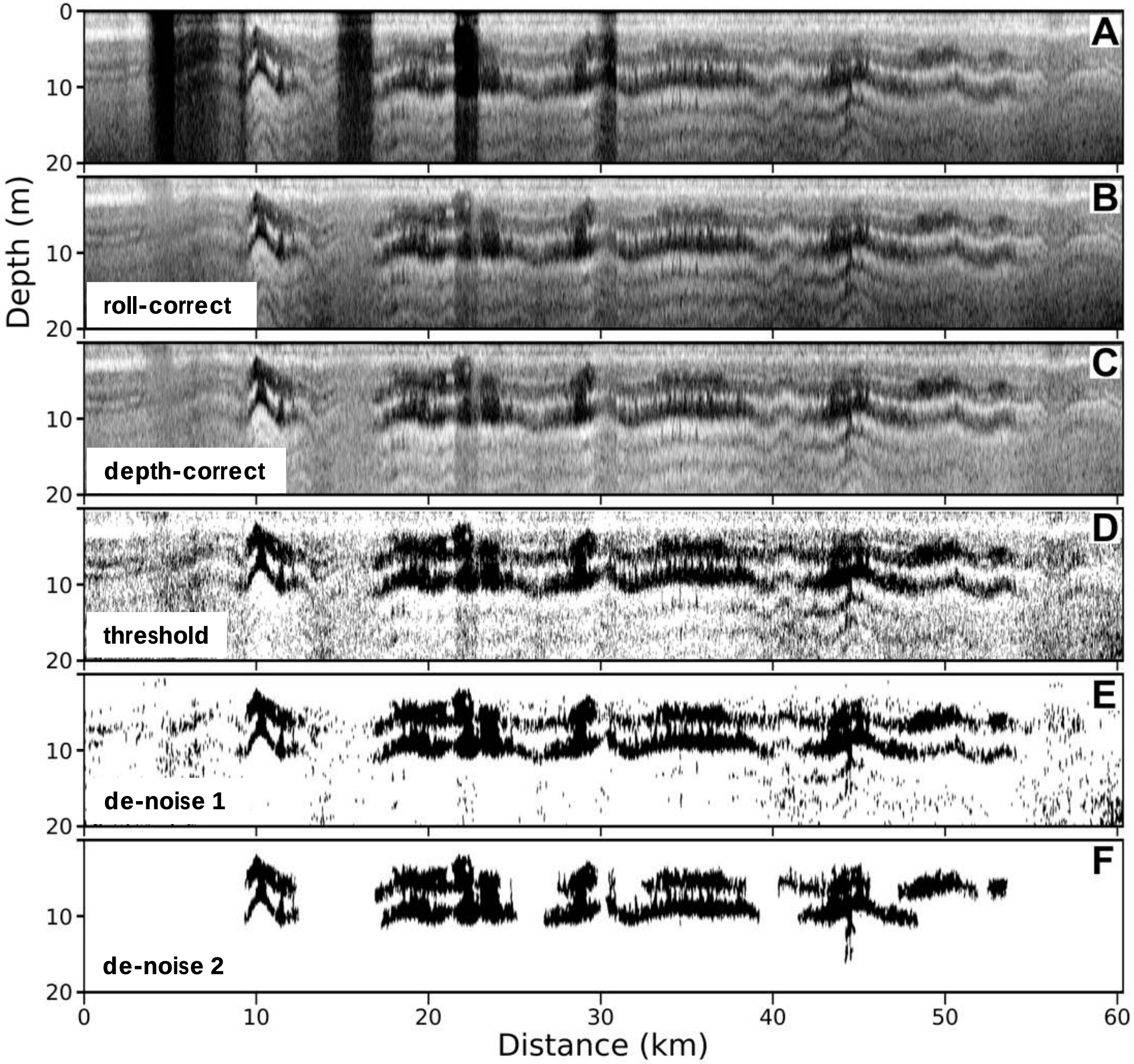


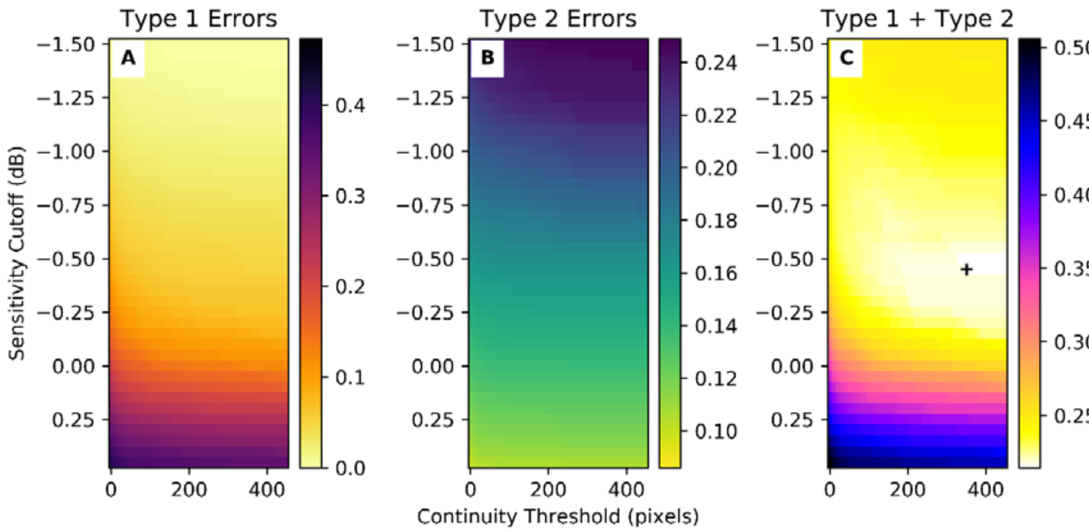
In Situ and IceBridge Radar

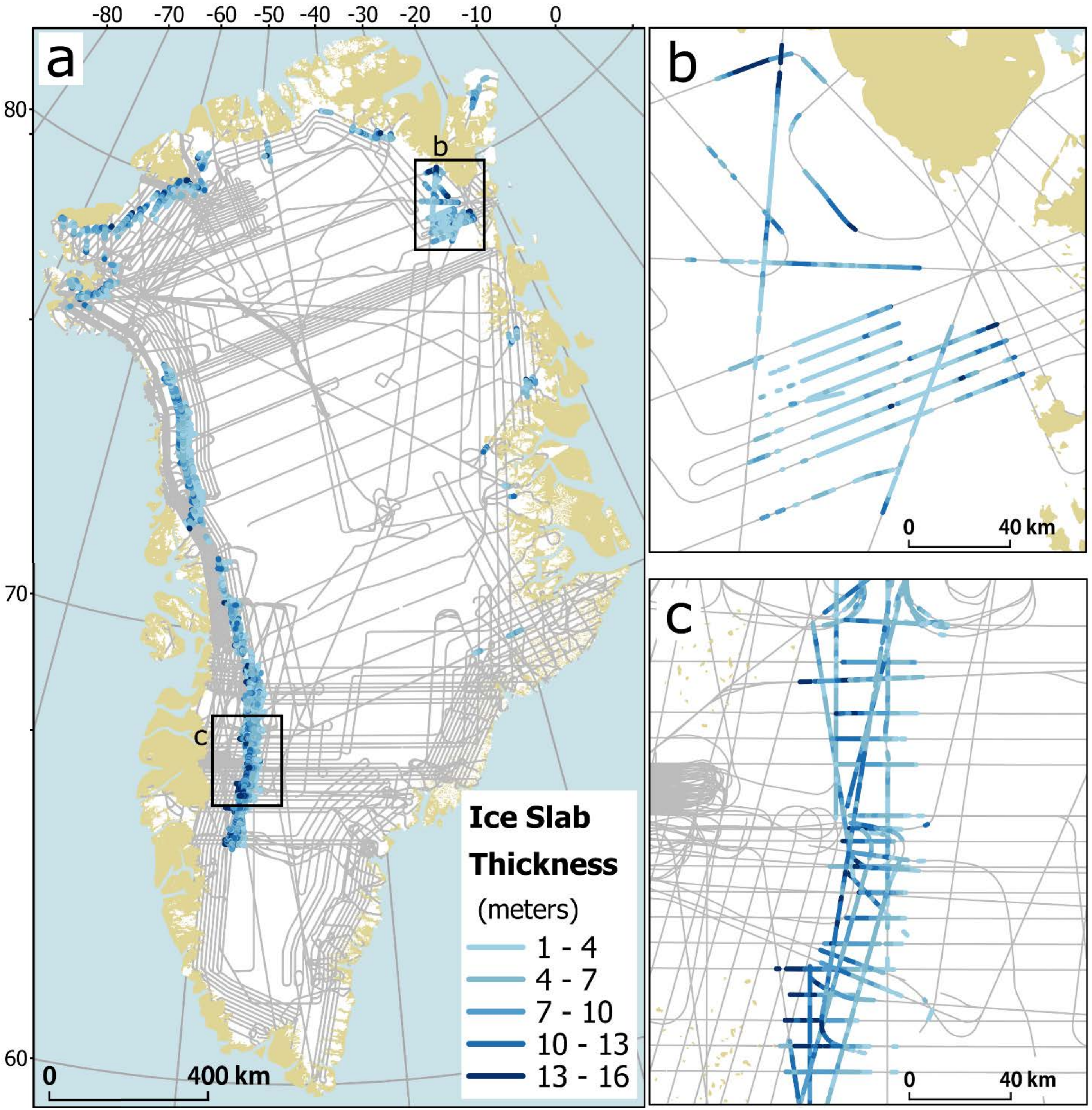




OIB Radar – Data Processing



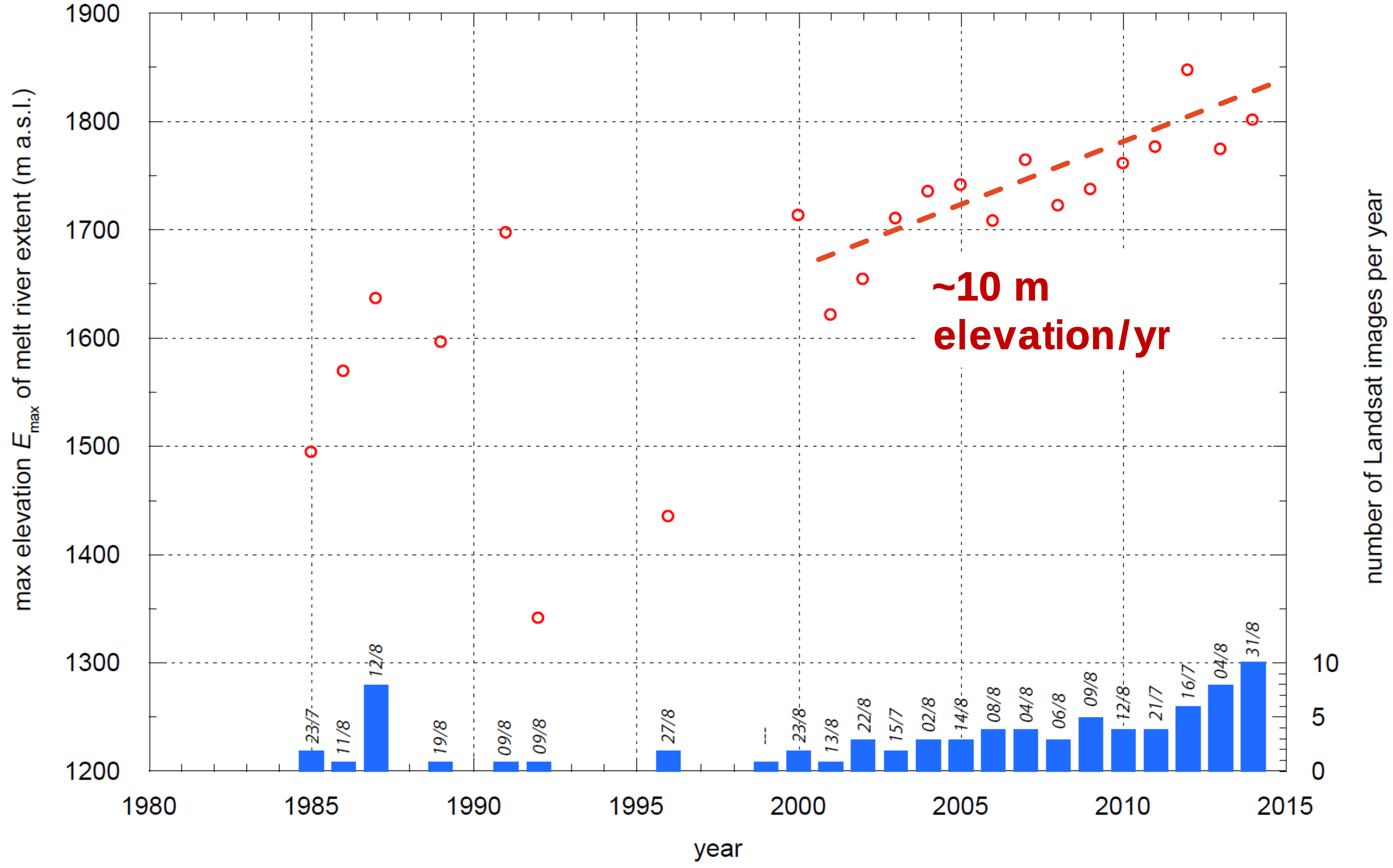




Ice Slabs in Greenland

- >69,000 km^2 of Greenland's firn (~5 % of Greenland)
- ~15-25% increase in runoff zone size
- Enhance runoff in WARM melt years

Uphill Migration of the K-Transect Runoff Line



Machguth, H., MacFerrin, M., van As, D., Box, J. E., Charalampidis, C., Colgan, W., … van de Wal, R. S. W. (2016). Greenland meltwater storage in firn limited by near-surface ice formation. *Nature Climate Change*, *6*(4), 390–393.

Excess Melt

Modified from Pfeffer , Meier & Illangasekare (1991)

Cold Content

$$Excess\ Melt = \left(\frac{M+R}{C} - \left[\left(\frac{\mathbb{C}}{L} T_f + \frac{\rho_r - \rho_c}{\rho_c} \right) \left(1 + \frac{\rho_r - \rho_c}{\rho_c} \right)^{-1} \right] \right) \cdot C$$

Melt & Rain

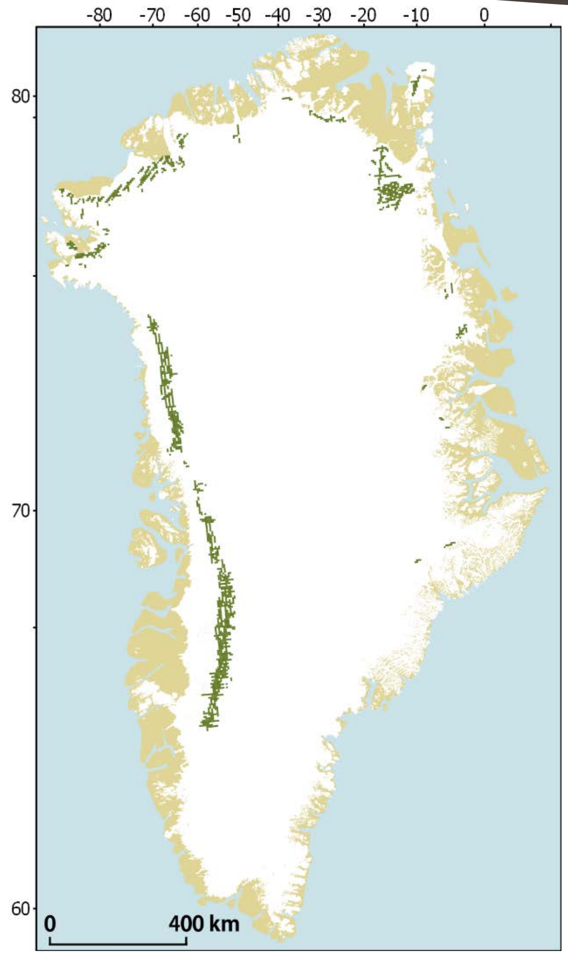
Available Pore Space

M = melt (kg m^{-2})
C = snowfall (kg m^{-2})
R = rain (kg m^{-2})
L = latent heat of fusion of ice (J kg^{-1})
$\mathbb{C}$ = heat capacity of water (J kg^{-1} °C^{-1})
T_f = firn temperature (°C below freezing)
ρ_r = density of refrozen ice (kg m^{-3})
ρ_c = density of fresh snow (kg m^{-3})

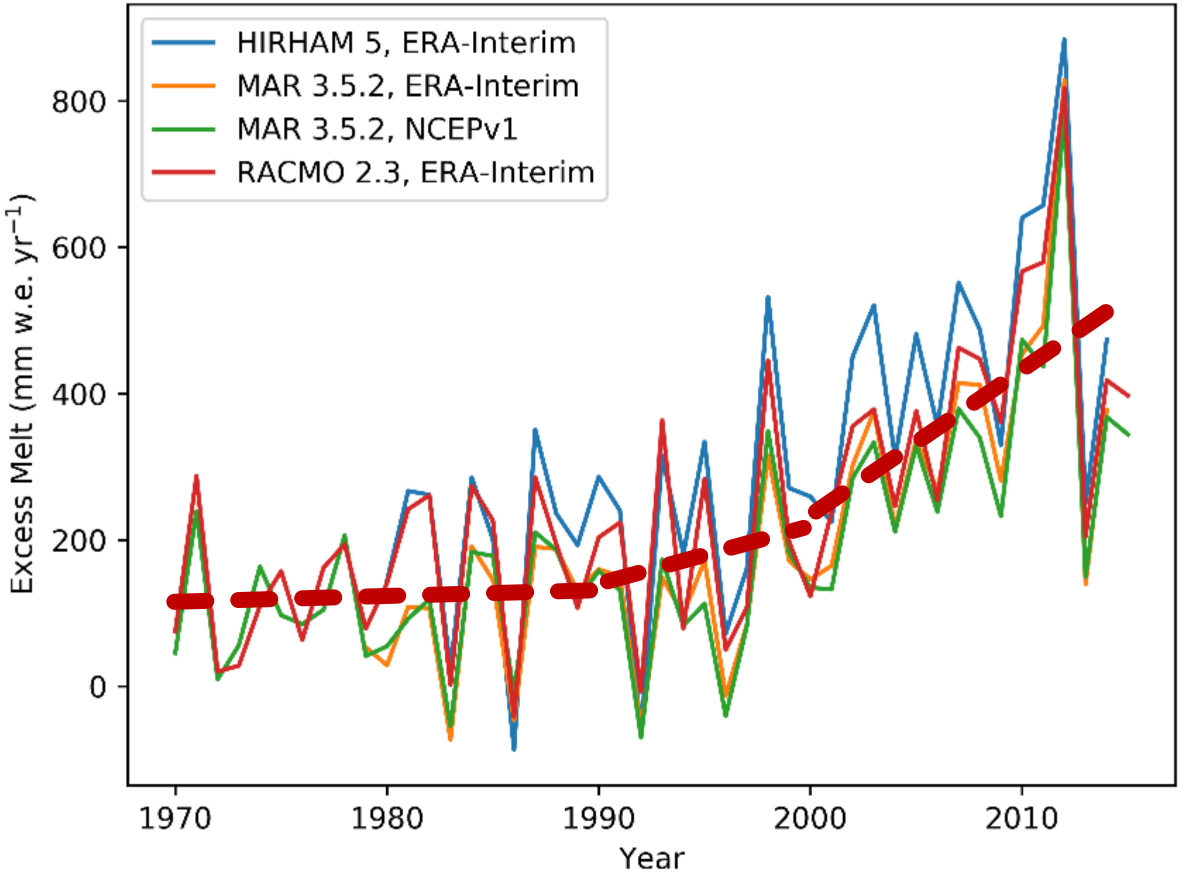
$Excess\ Melt < 0$ **BUFFERING** ❄

$Excess\ Melt > 0$ **SATURATING** 💧

Excess Melt Trends



- Slight increases after 1990
- Larger increases after 2000



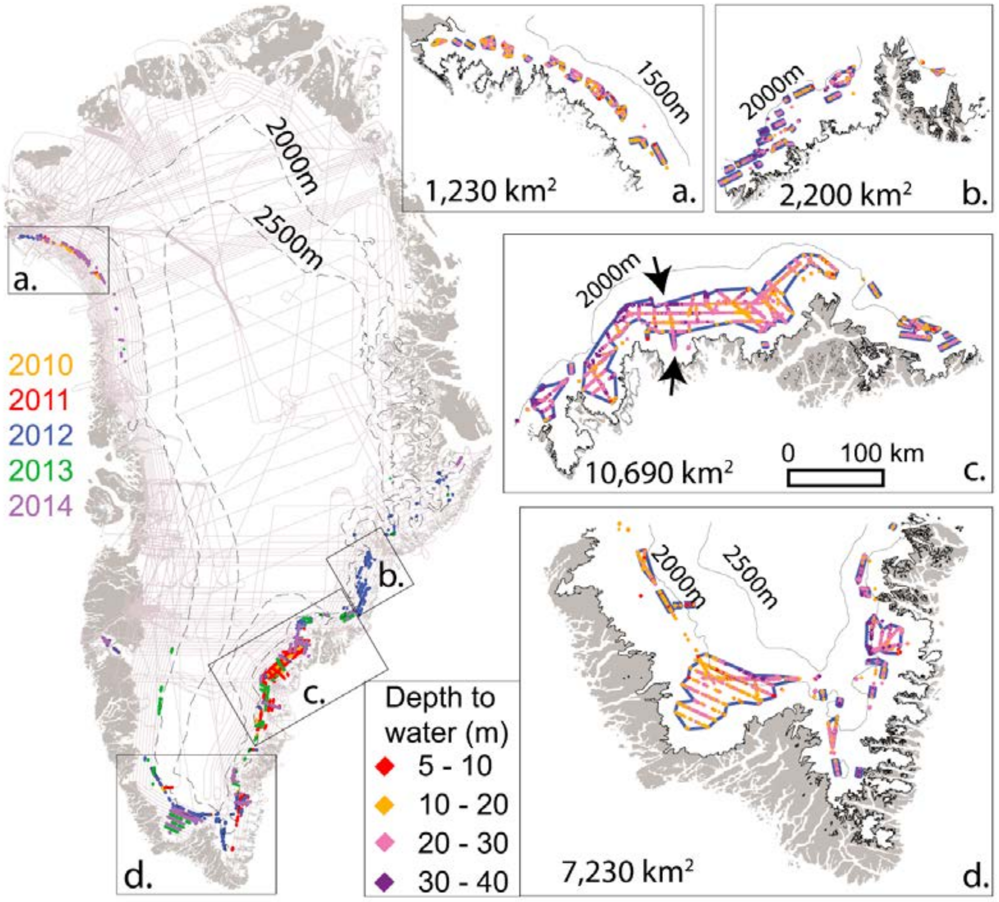
Accumulation Cutoff

- Perennial Firn Aquifers (PFAs) form in **high**-accumulation areas

  Forster, et al. (2014), Koenig, et al. (2013), Miege, et al (2016)

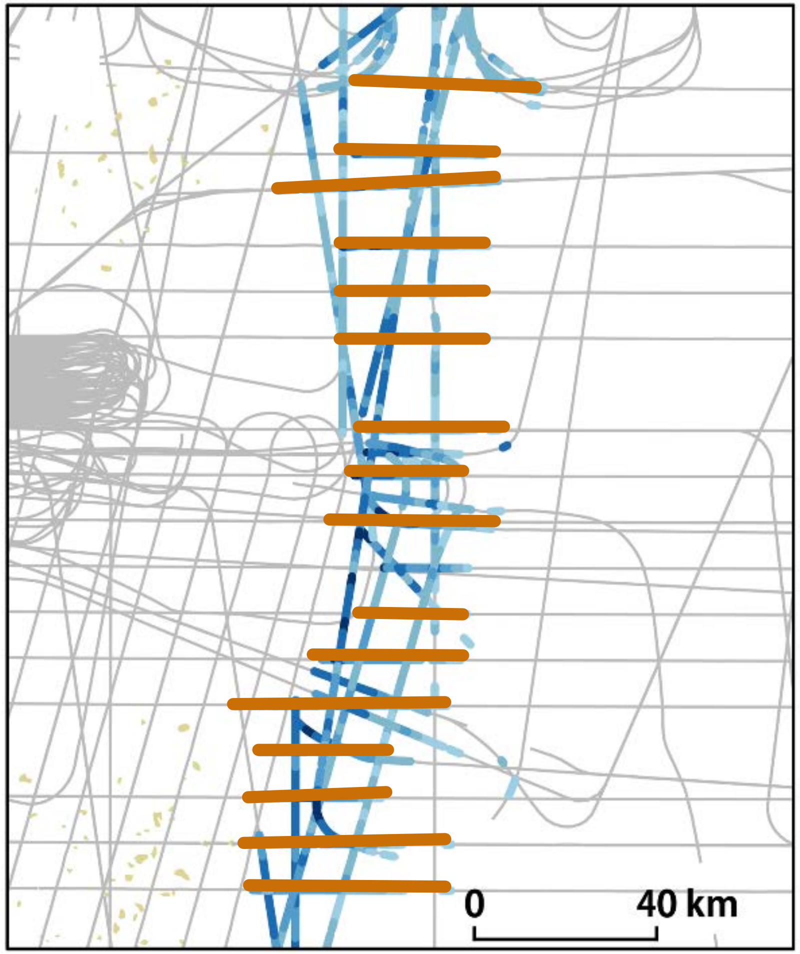
- Ice Slabs only form in **low**-accumulation areas

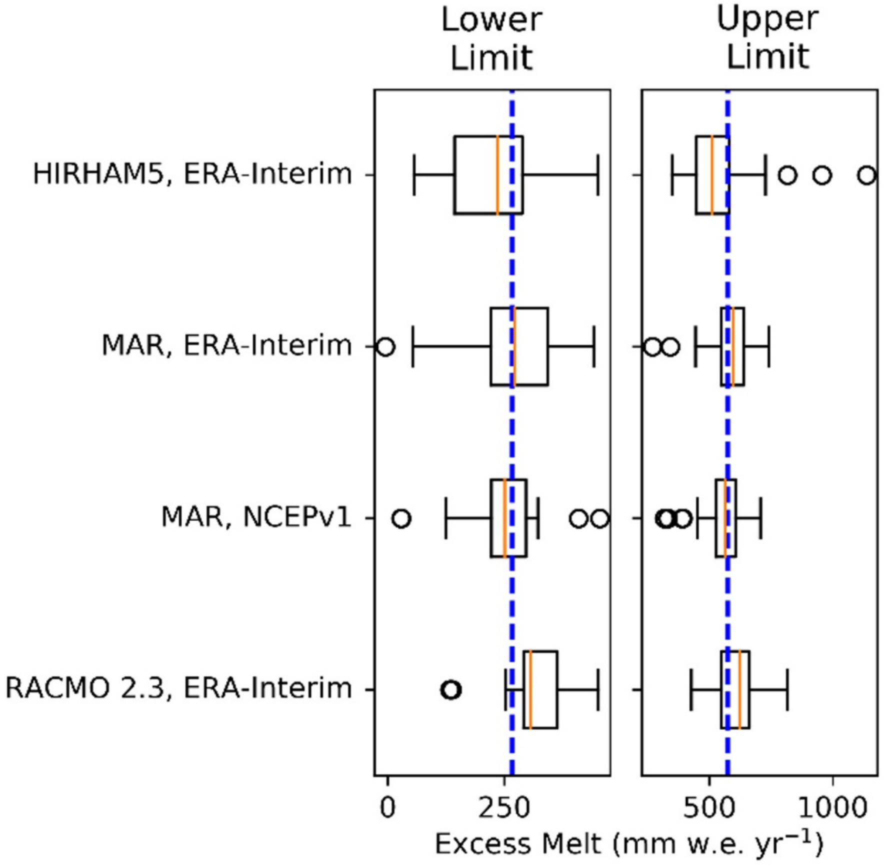
≤ **572 mm** w.e. / year (~1.8 m snow)



Miege, et al (2016)

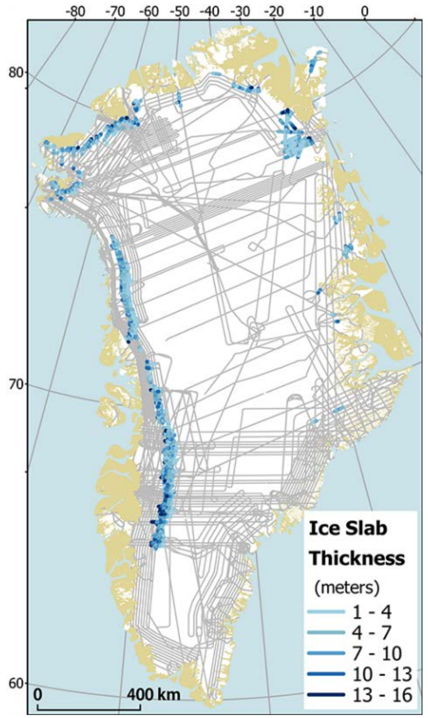
How much Excess Melt causes ice slabs?





~266 – 573 mm w.e. / yr for 10 years or more has caused ice slabs to form in Greenland

Mapping with RCMs & Reanalysis

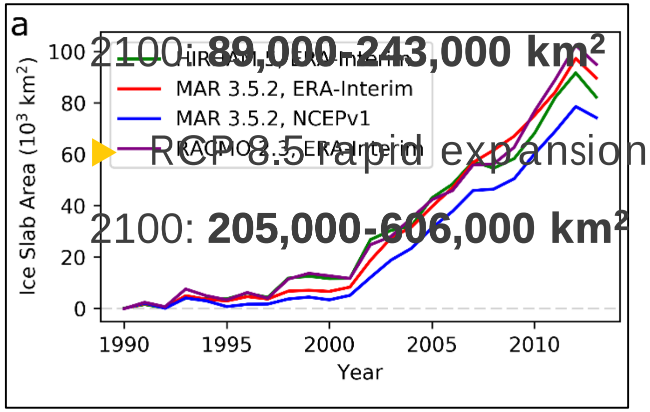


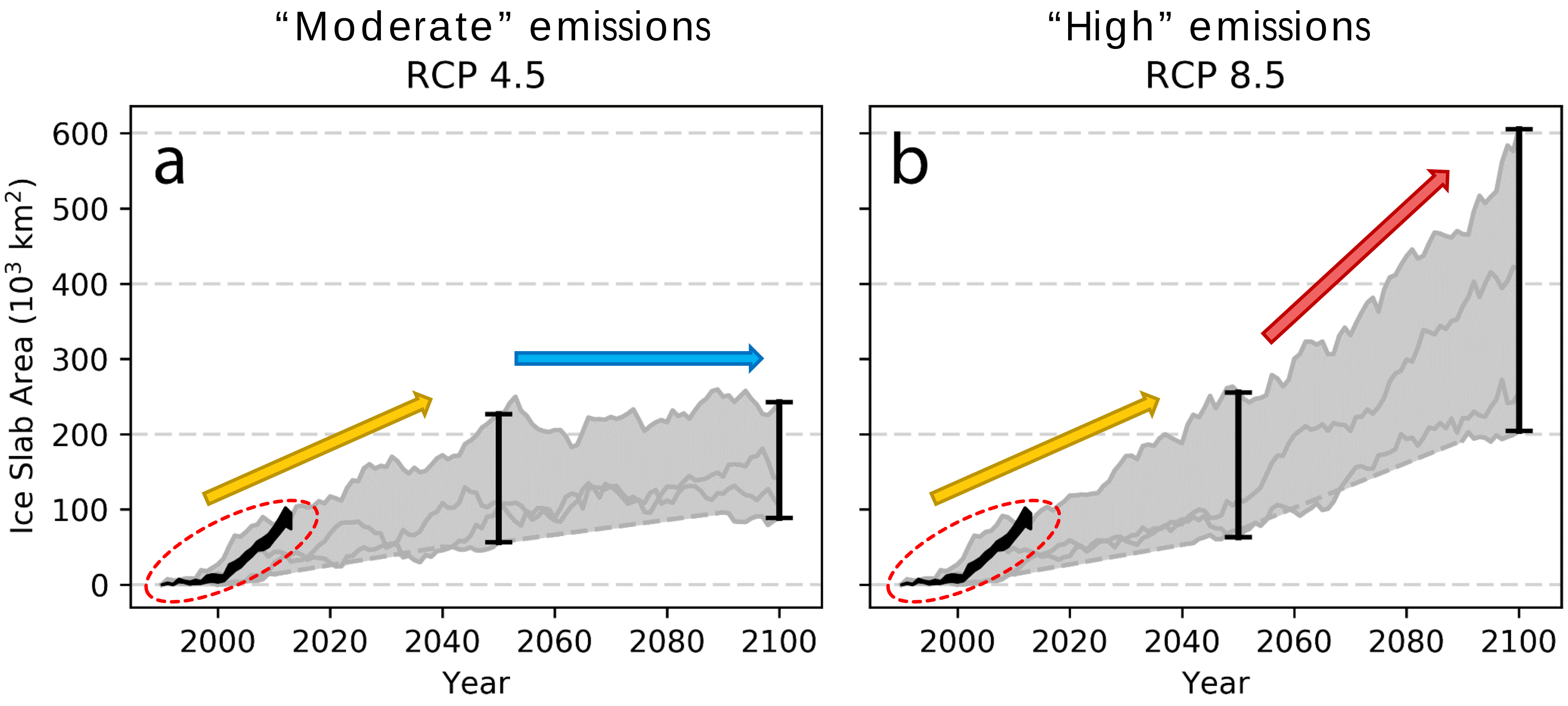
- 2014 extent 74,000-95,000 km^2

Modeling ice slabs with GCMs

- HIRHAM 5, ECEarth
- MAR 3.5.2, CanESM2
- MAR 3.5.2, MIROC5
- MAR 3.5.2, NorESM1
- RACMO 2.1, HadGEM2

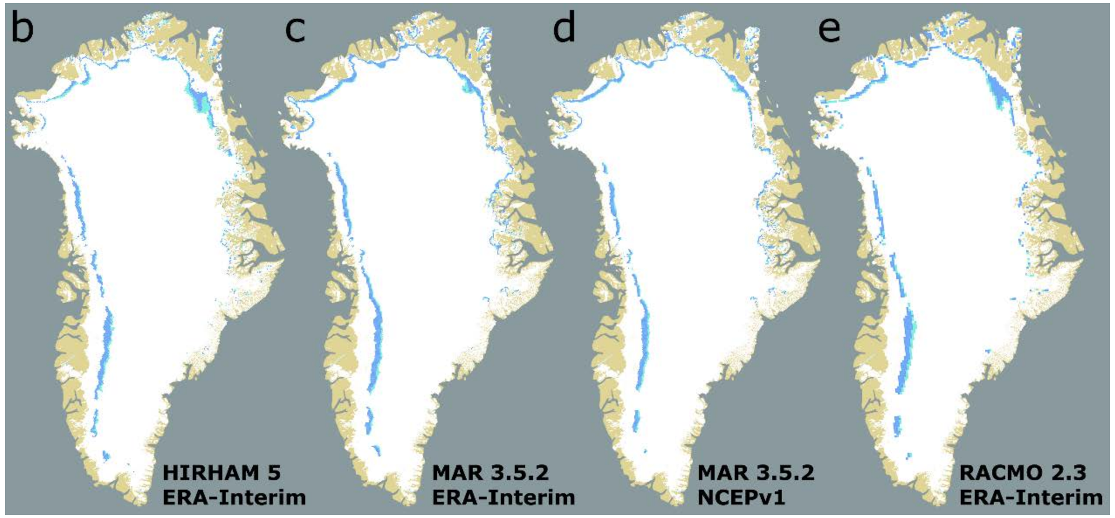
- **1990-2050:**
  - Ice slab extent doubles from 2013
- **2050-2100:**
  - RCP 4.5 steady
  - 2100: **89,000-243,000 km²**
  - RCP 8.5 rapid expansion
  - 2100: **205,000-606,000 km²**



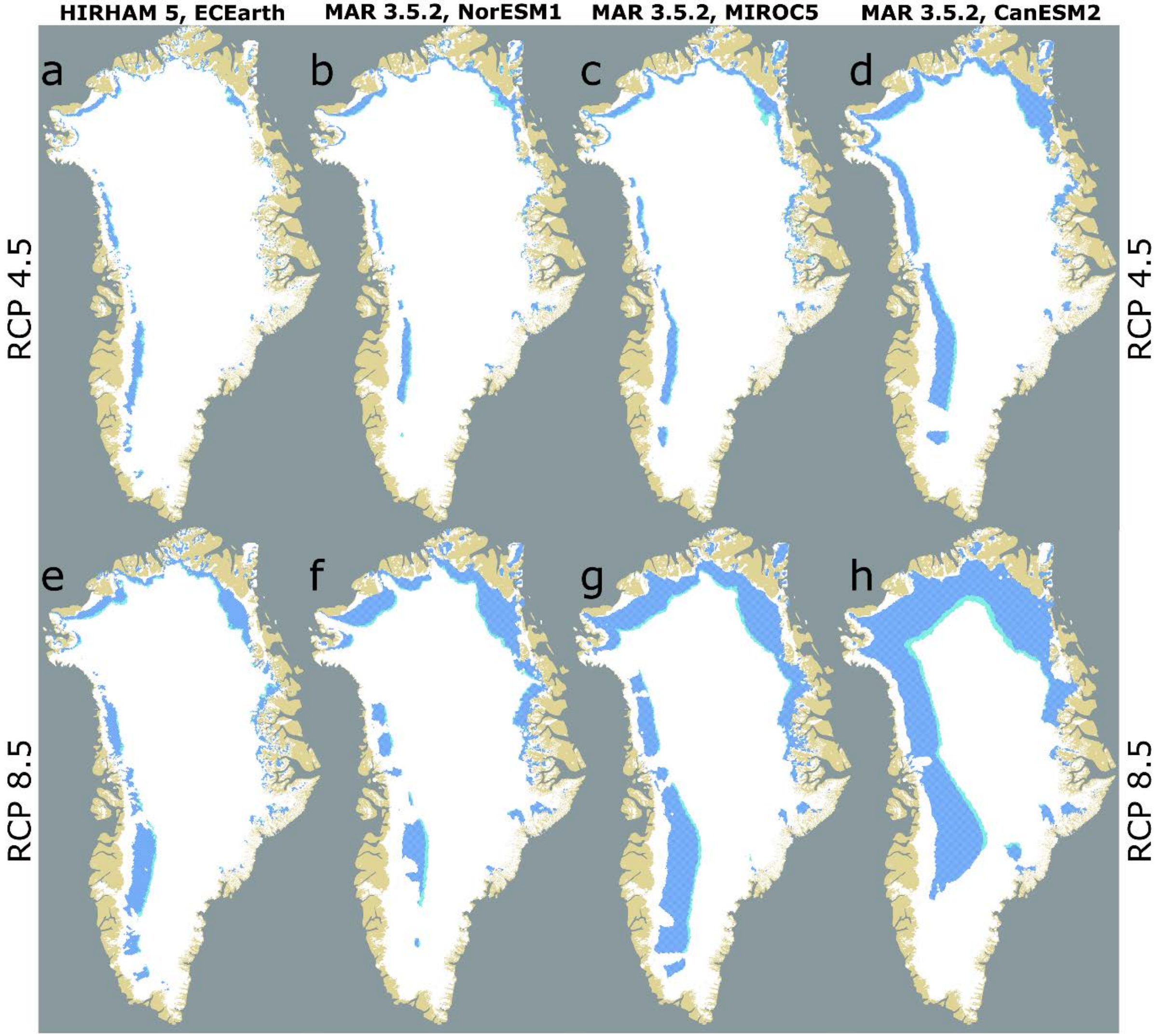


Boundary forcing is critical

Bounded by **Reanalysis** (2013)



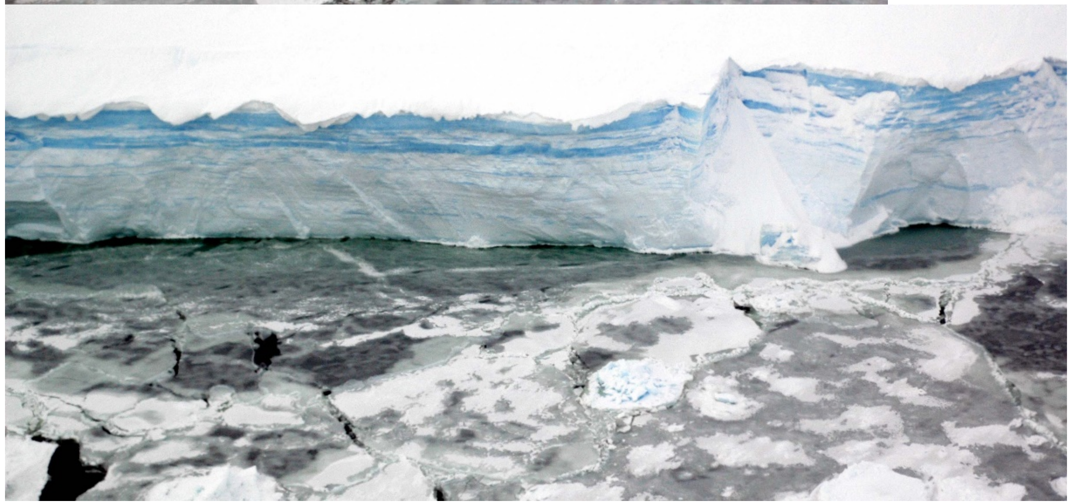
Bounded by **GCMs** (2100)



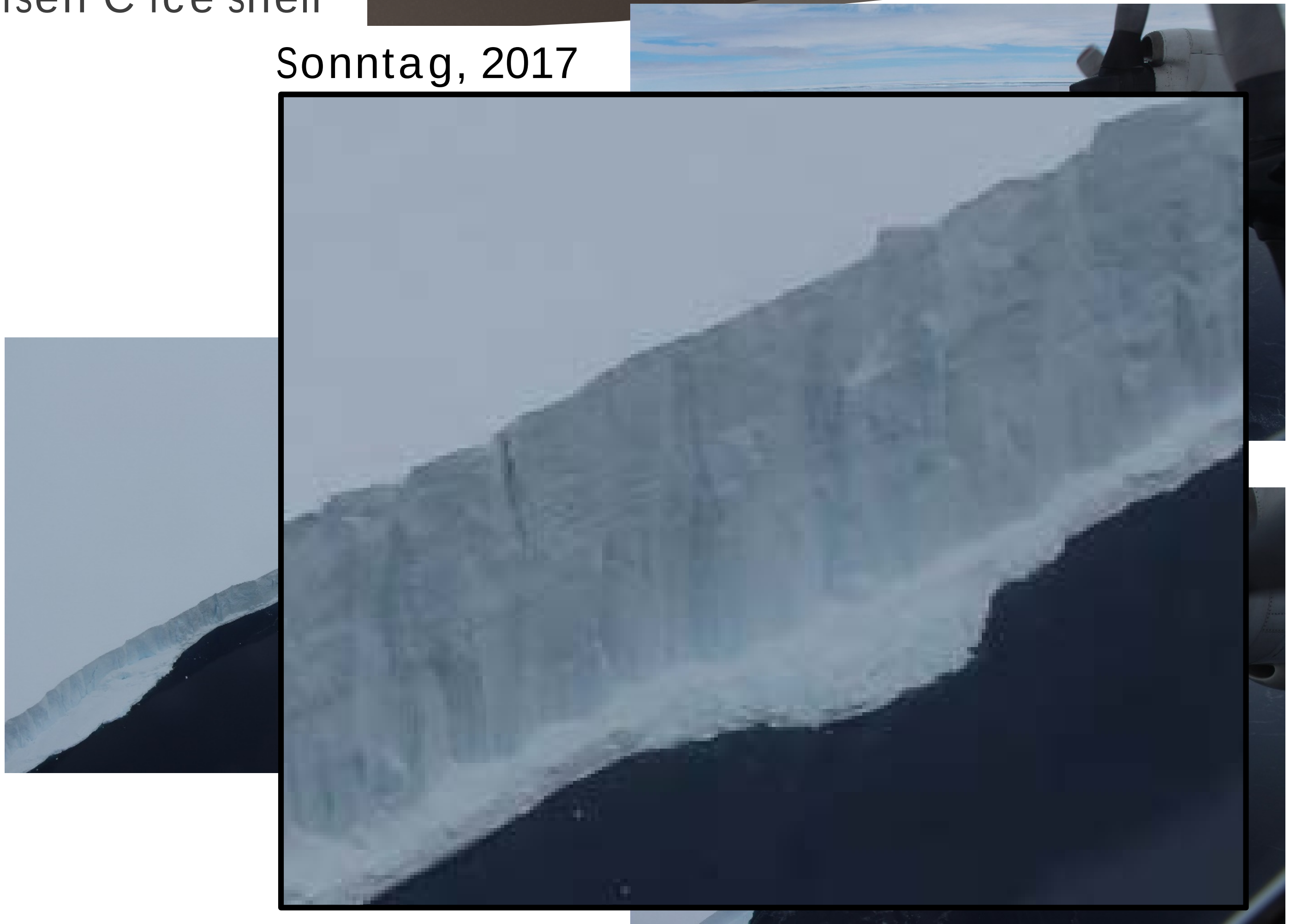
Ice Slabs in Antarctica?

- Larsen C ice shelf

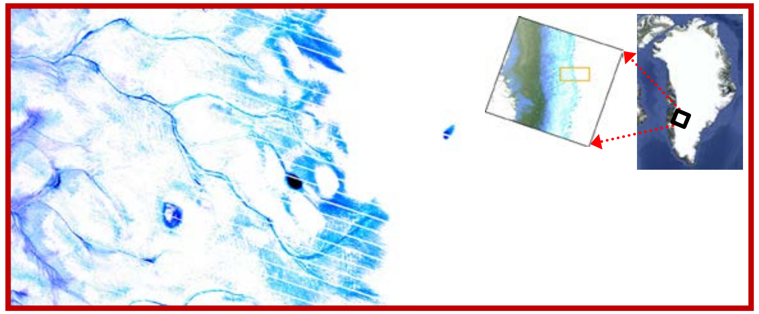
Scambos, 2006

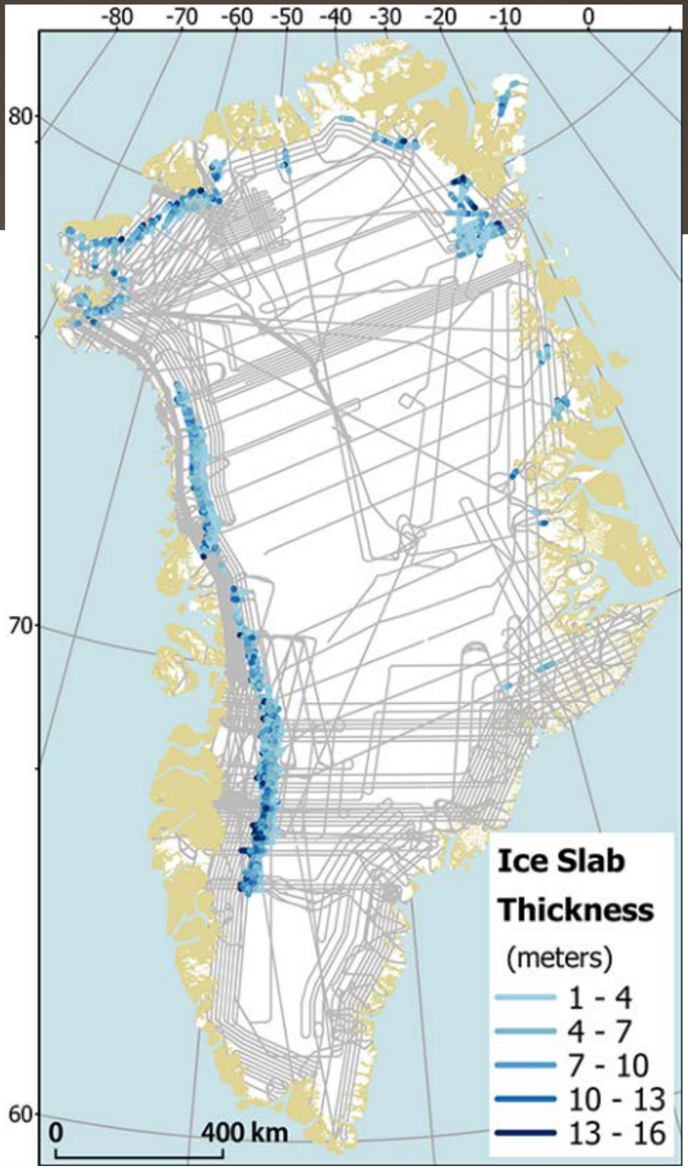


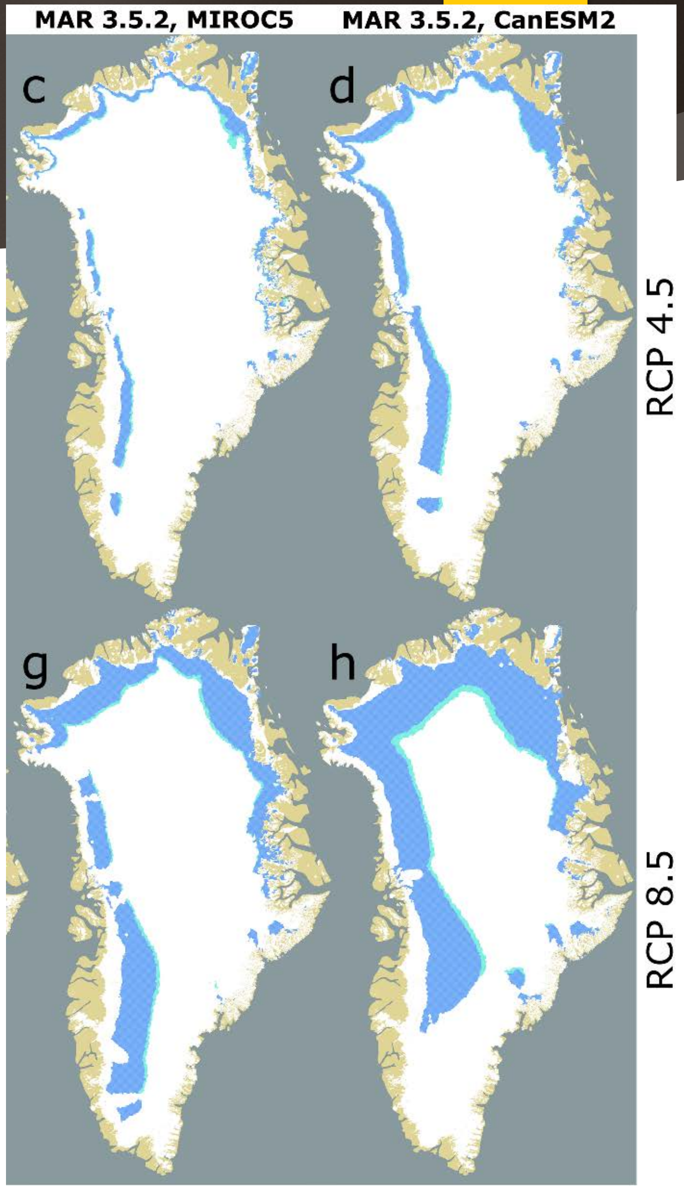
Sonntag, 2017



Questions?




-80 -70 -60 -50 -40 -30 -20 -10 0
80
70
60
Ice Slab Thickness
(meters)
1 - 4
4 - 7
7 - 10
10 - 13
13 - 16
0
400 km


MAR 3.5.2, MIROC5
MAR 3.5.2, CanESM2
c
d
g
h
RCP 4.5
RCP 8.5

Slabs growing thicker: KAN-U, 2009-2017