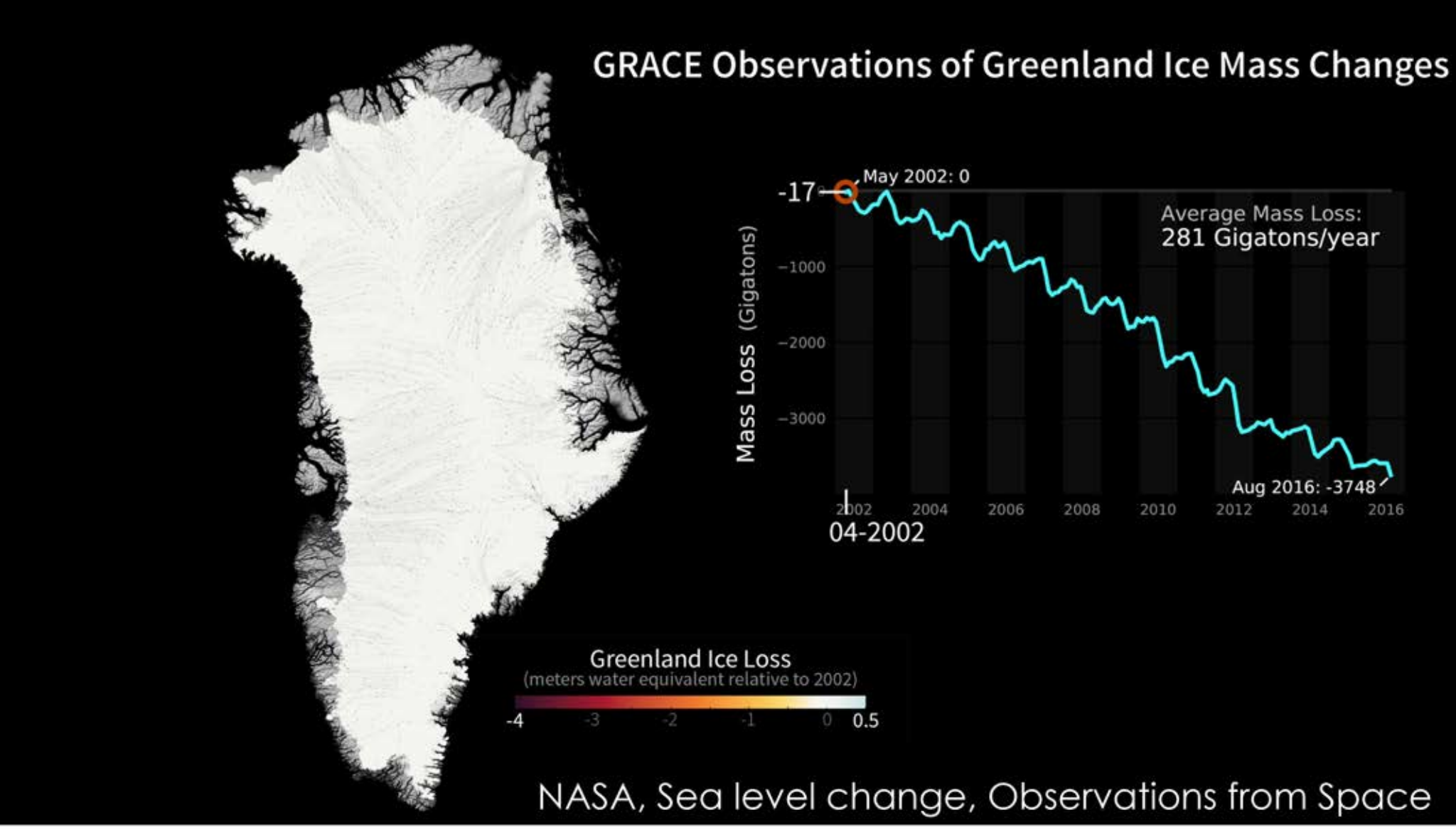
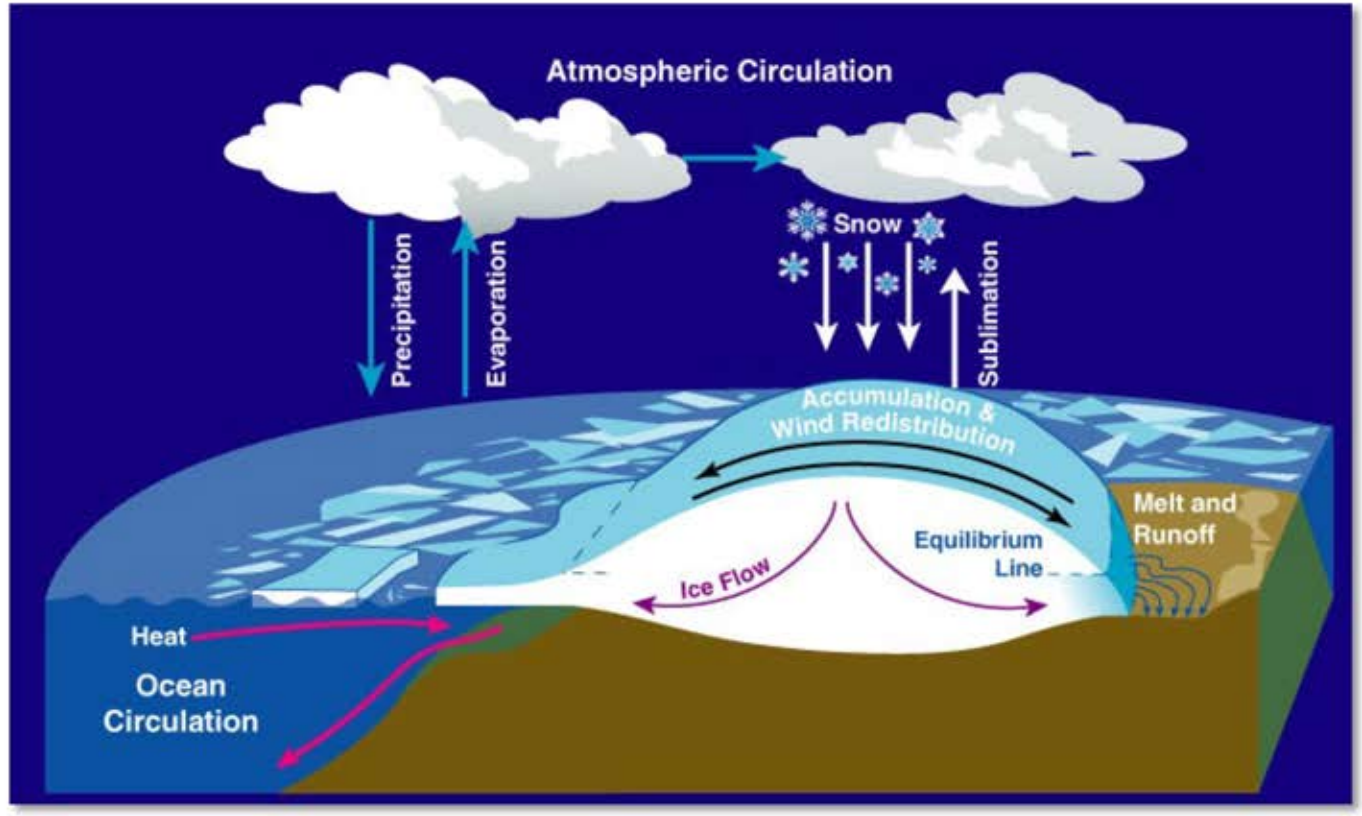


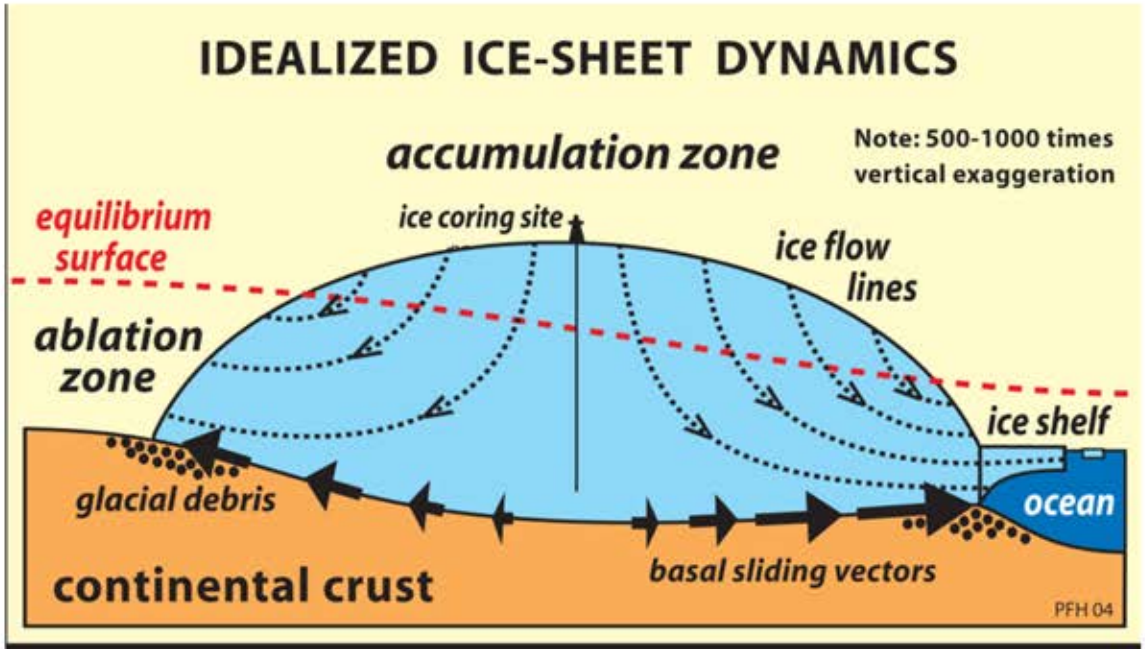
Observed Land Ice Changes

Csatho, Bea University at Buffalo, Buffalo, NY, USA

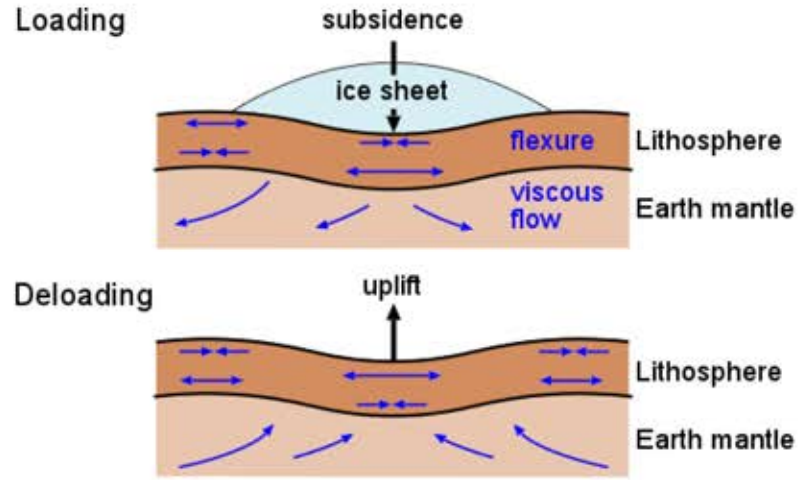
Processes:

- Ice-atmosphere
- Ice-ocean
- Ice-solid earth
- Ice internal

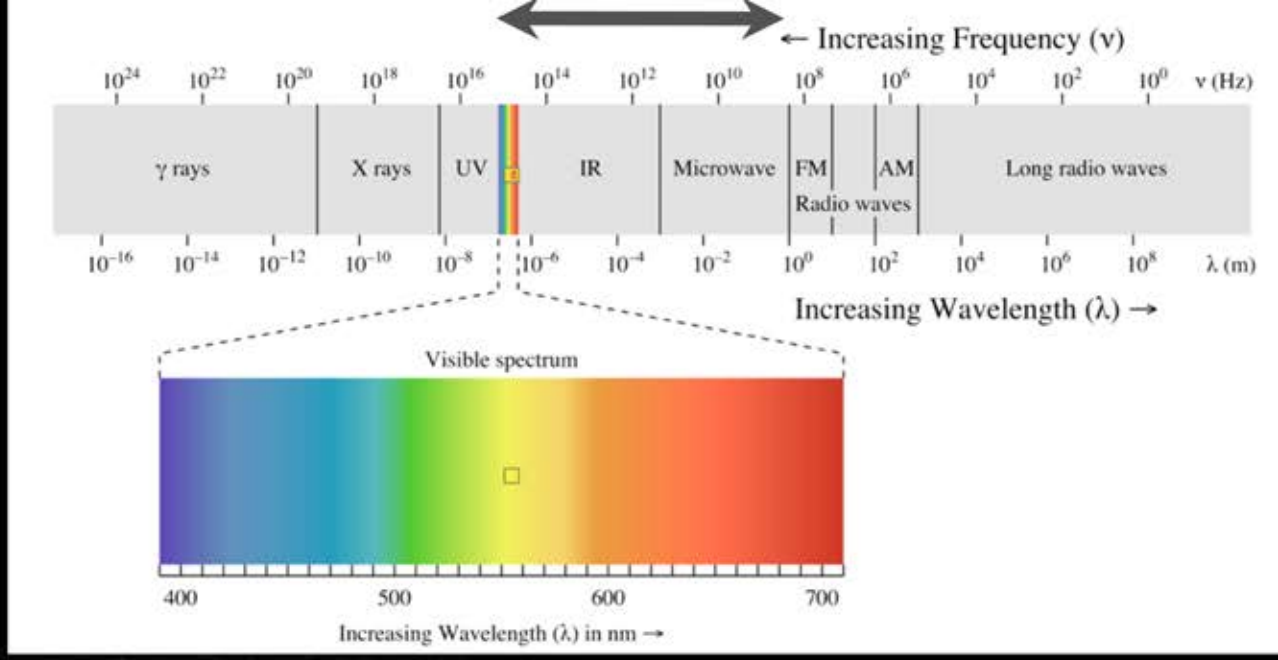




Ice Solid Earth Interaction



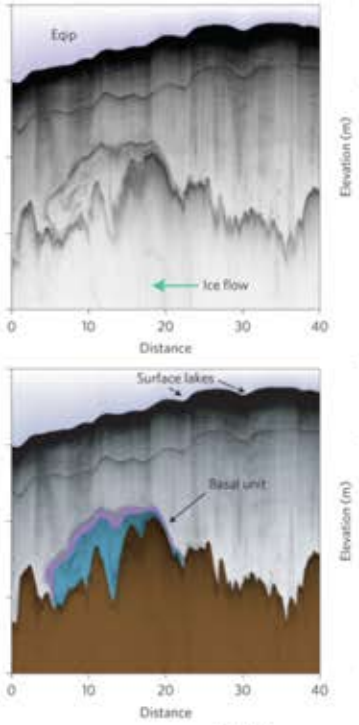
Observations NASA's fleet of satellites, 2015

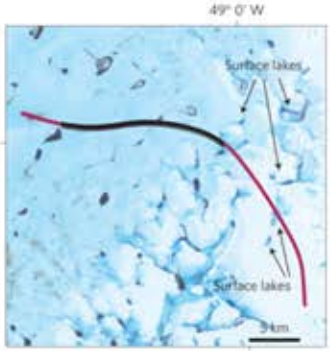


Visible: Landsat 7/8
Microwave (passive): Scanning Multi-channel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I)
Broadband: Clouds and the Earth's Radiant Energy System (CERES)
Laser (active): Ice, Cloud and land Elevation Satellite (ICESat)
Radar (InSAR): European Remote Satellite (ERS-1,2), RADARSAT-1,2
Gravity: Gravity Recovery and Climate Experiment (GRACE)

To characterize the state of land ice (ice sheets, ice caps and glaciers) and processes acting upon it, the geometry and properties of land ice surface, bed, ocean, atmosphere, etc. should be monitored

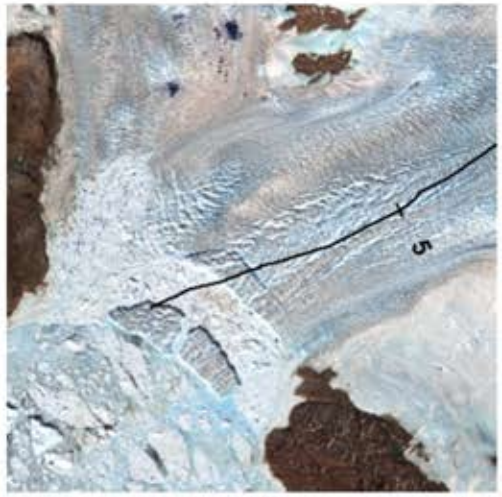
Ice Penetrating radar, internal structure, ice bed interface



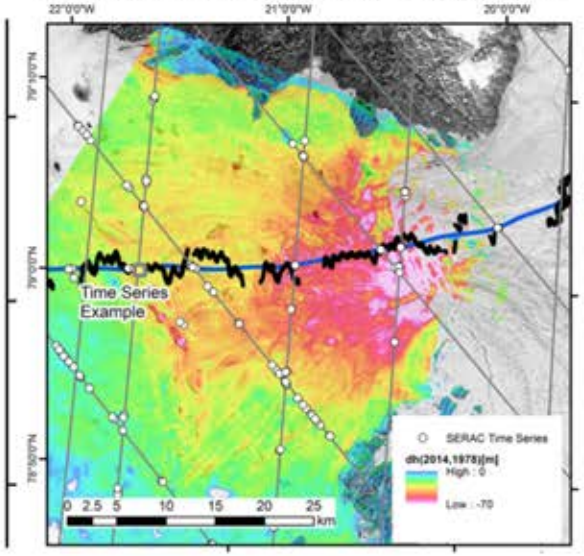


(Bell et al., 2014)

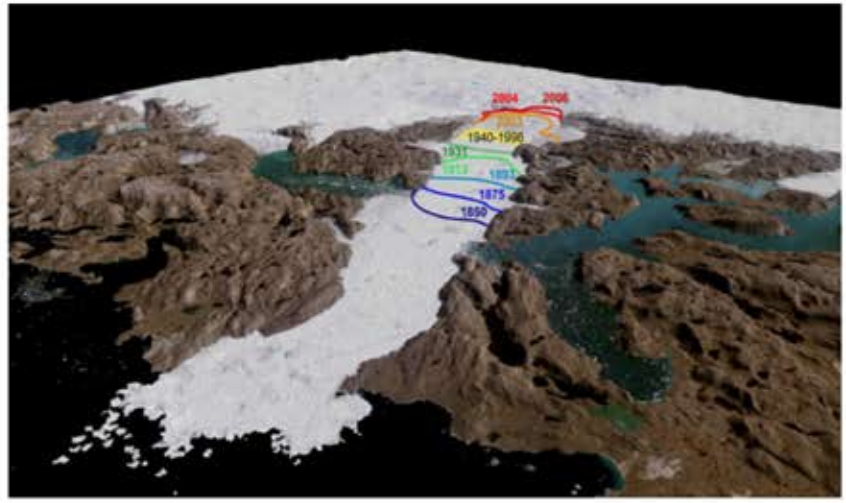
Upernavik Isstrøm, glacier 1; retreat of calving front in 2005, June 19, ASTER imagery



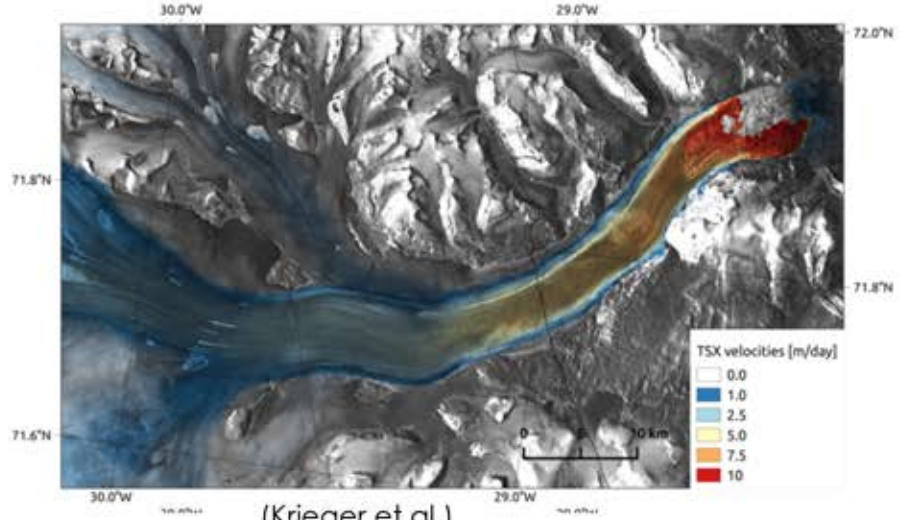
Zachariæ Isstrøm Ice thickness change from SPOT (2014) and aerial photo (1978) DEMs



Jakobshavn Isbræ retreat on draped Landsat mosaic

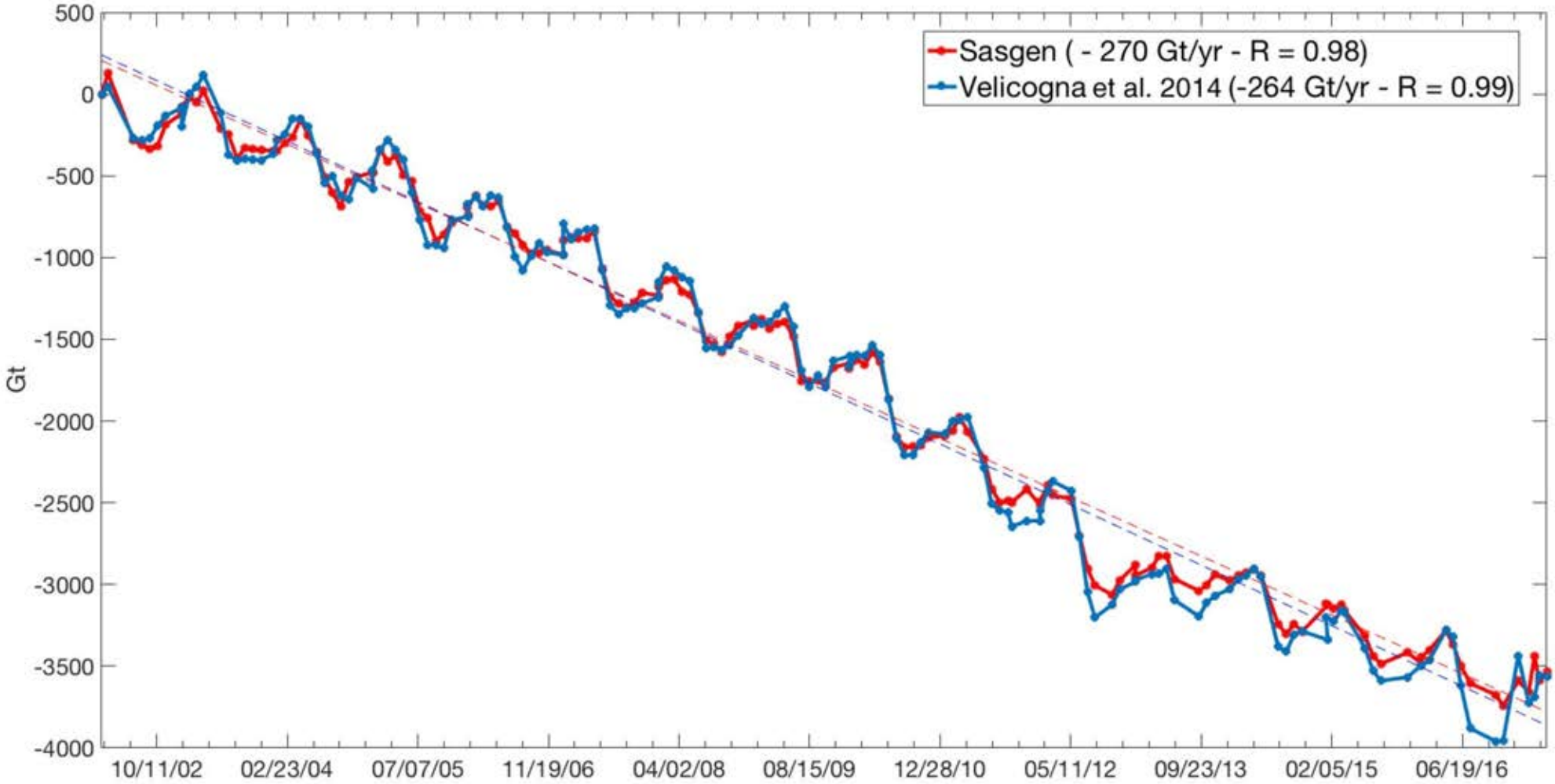


Velocity of Daugard-Jensen Glacier from TerraSAR-X

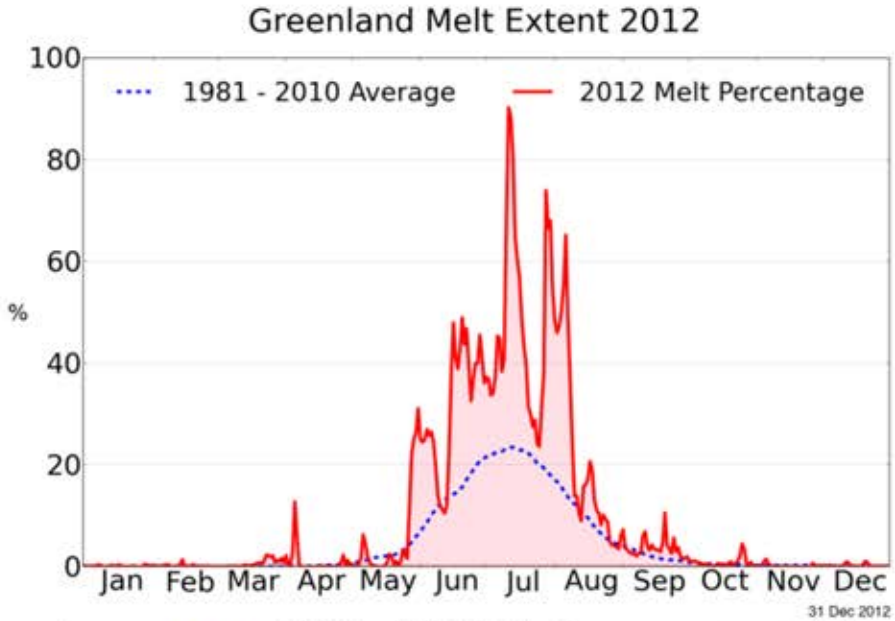


(Krieger et al.)

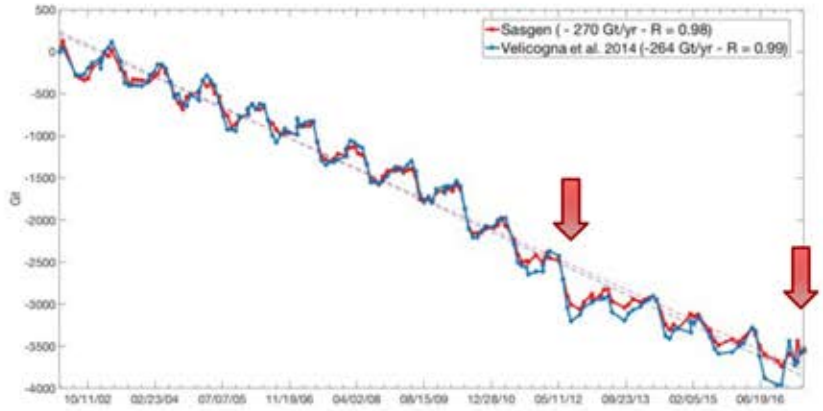
Change in the total mass (in Gt) of the Greenland ice sheet between April 2002 and June 2017, estimated from GRACE measurements



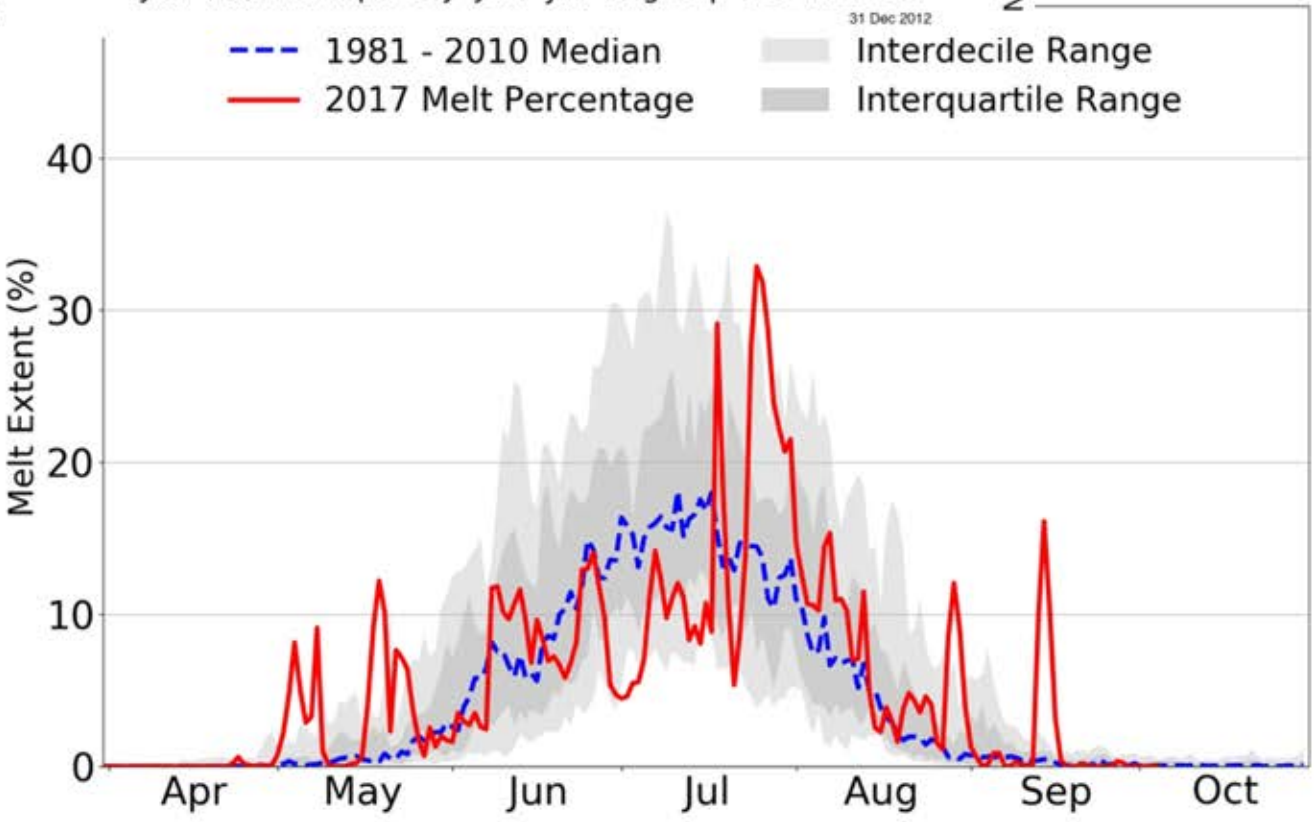
Arctic Report Card 2017



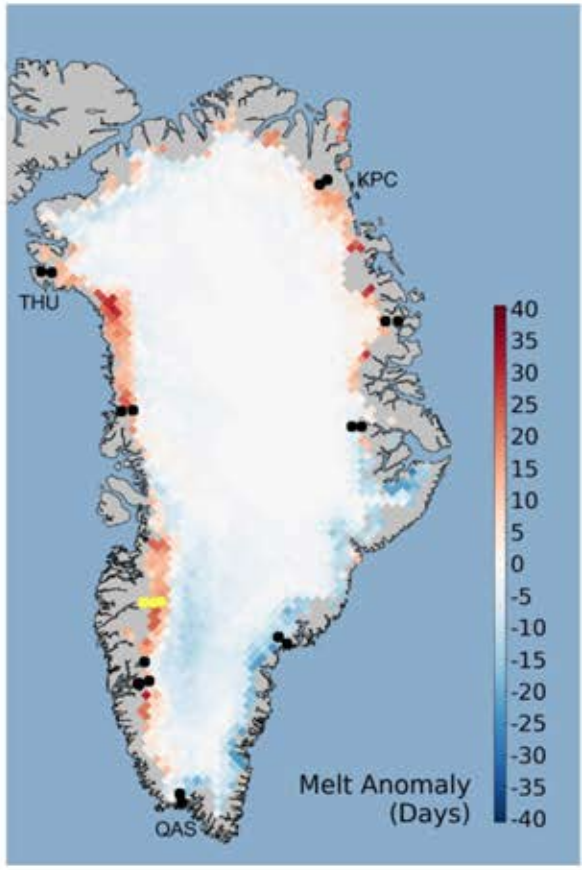
NSIDC / Thomas Mote, University of Georgia



a

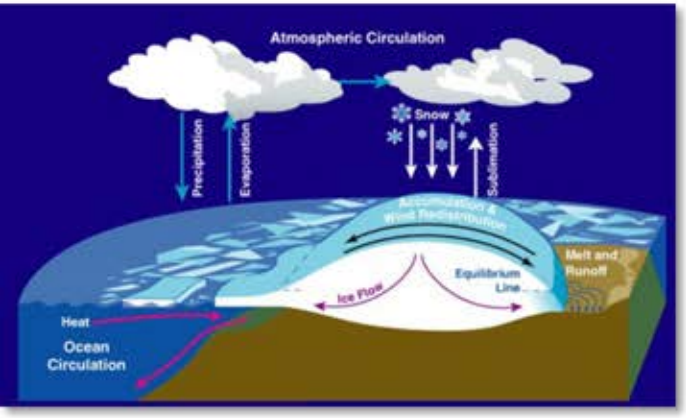


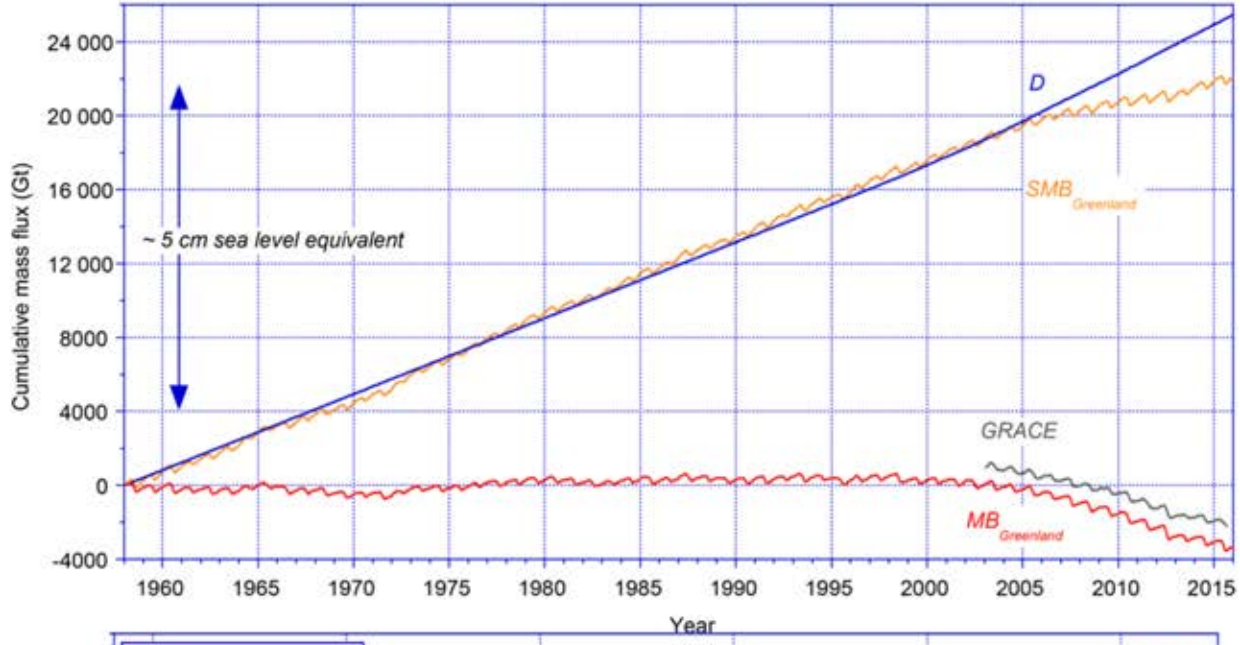
b



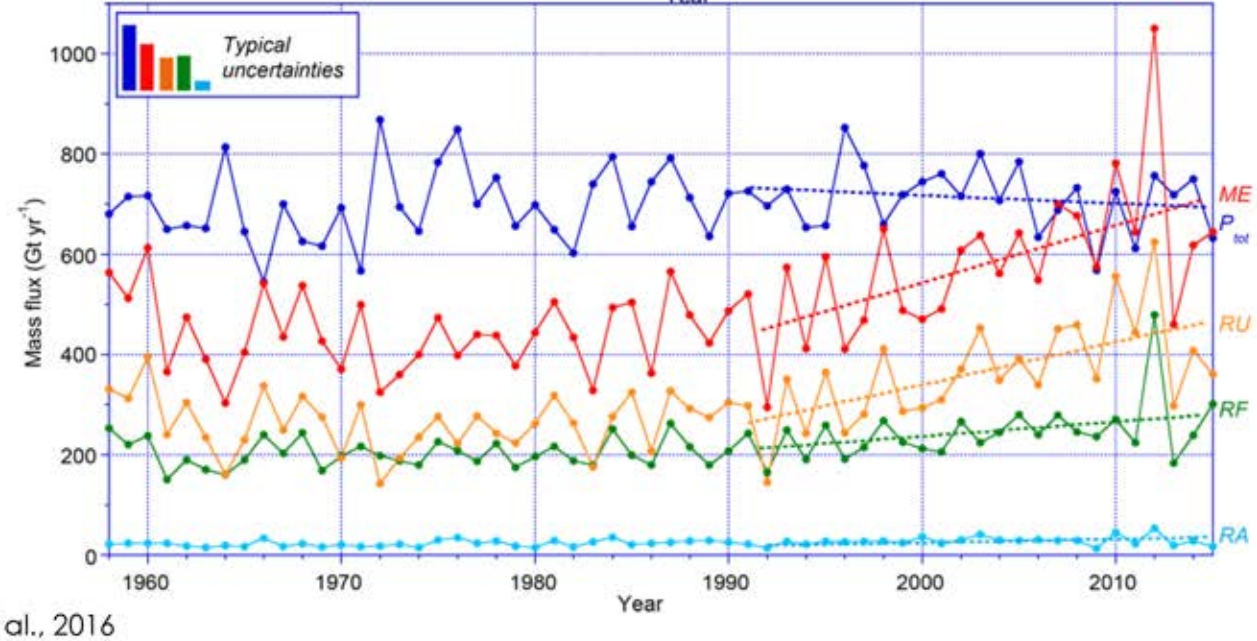
Arctic Report Card 2017

Timing and main contributors to GrIS mass loss





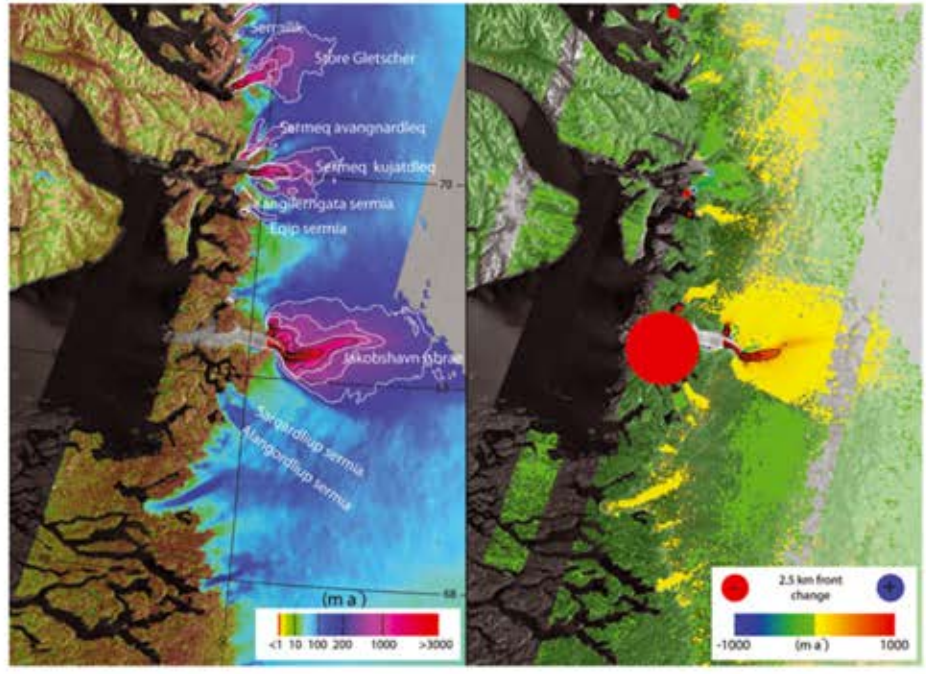
Total precipitation
Melt
Runoff
Refreezing
Rainfall



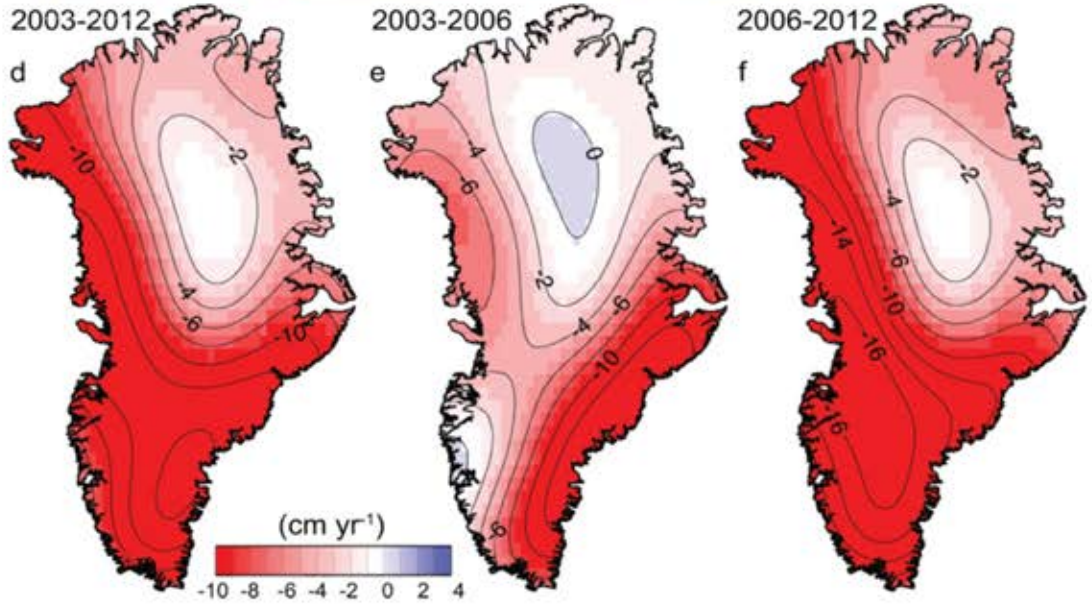
Broeke et al., 2016

Ice Sheet Velocity, Elevation and Mass Loss Patterns Change in Time

West Greenland flow speed for 2005/06 (left) and change in speed from 2000/01 to 2005/06 (right), from Joughin et al., 2010



Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year (IPCC, AR5; Velicogna, 2009)



Increasing the resolution of the GRACE record, mason solutions

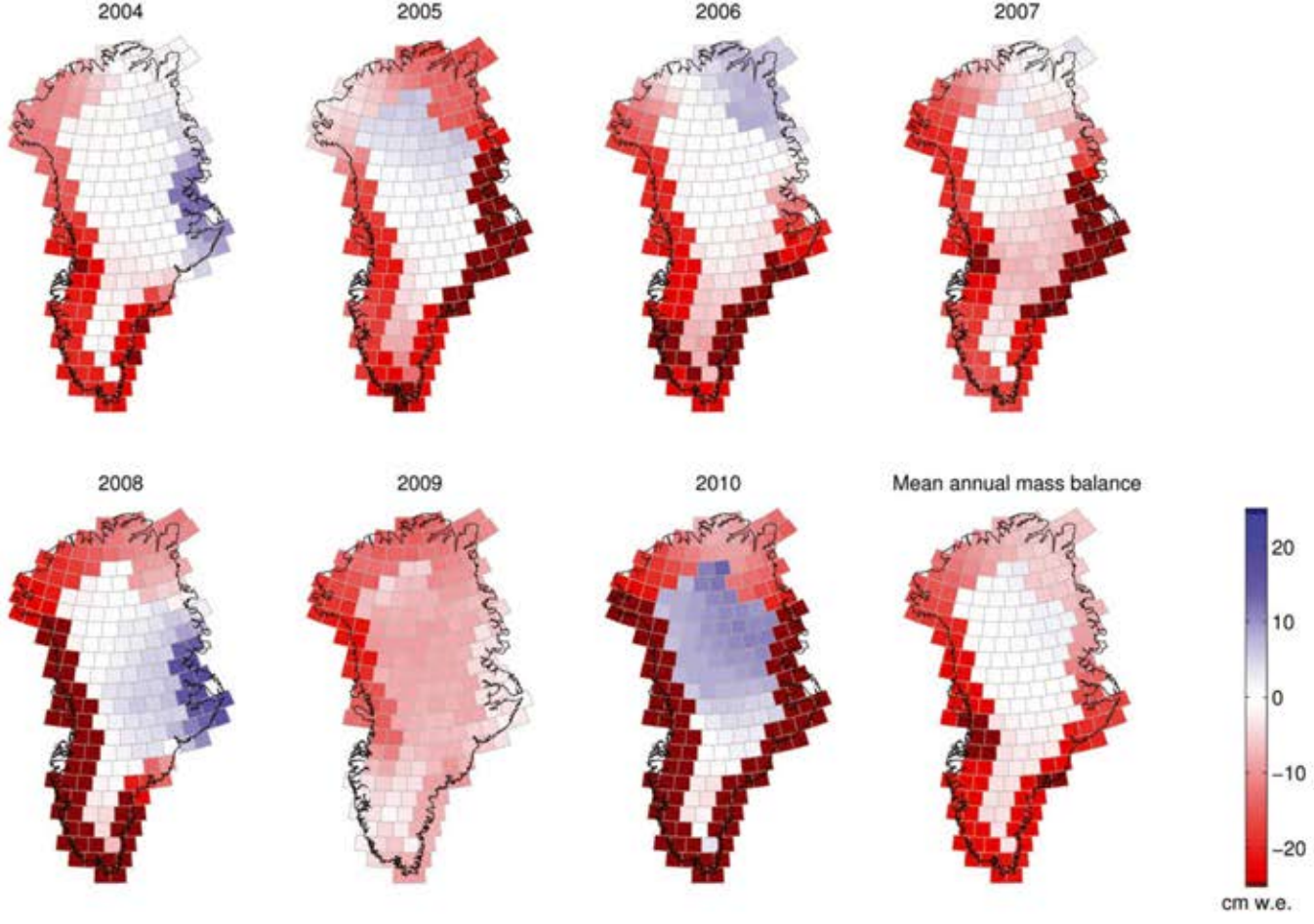
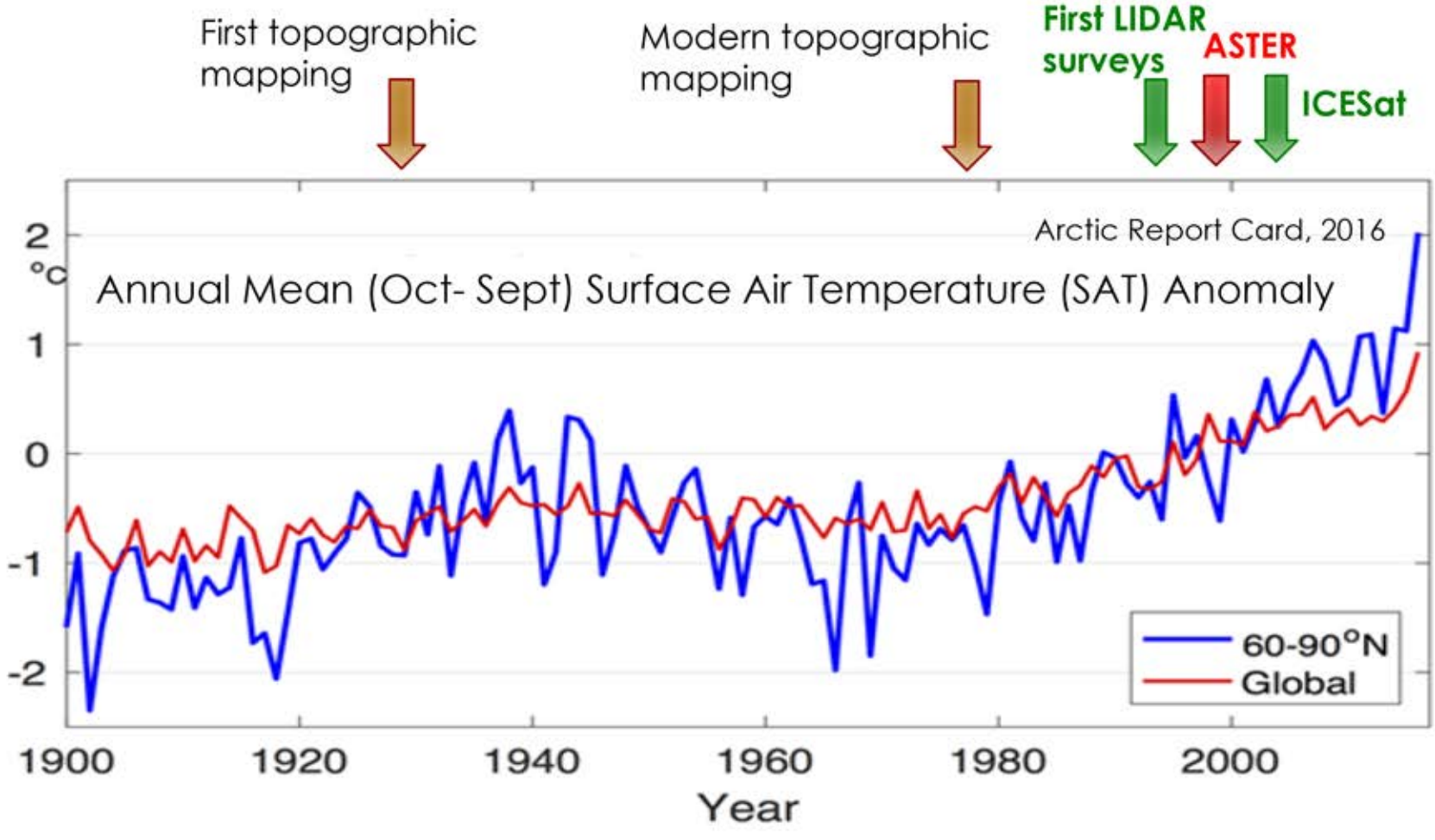


Fig. 10. The GIS annual mass balances and mean annual mass balance determined from the EEMD analysis of the v12 mascon solution. The timing of the seasons is determined by the mean EEMD extrema in Figure 8a, and the mass values are determined by the result of the EEMD method (summing the IMFs from the one preceding the 'annual' IMF to the final IMF) for each individual mascon time series at the time of the total GIS extrema.

Luthcke et al., 2014

Ice surface elevations provide a detailed record of past ice sheet extent, height and volume

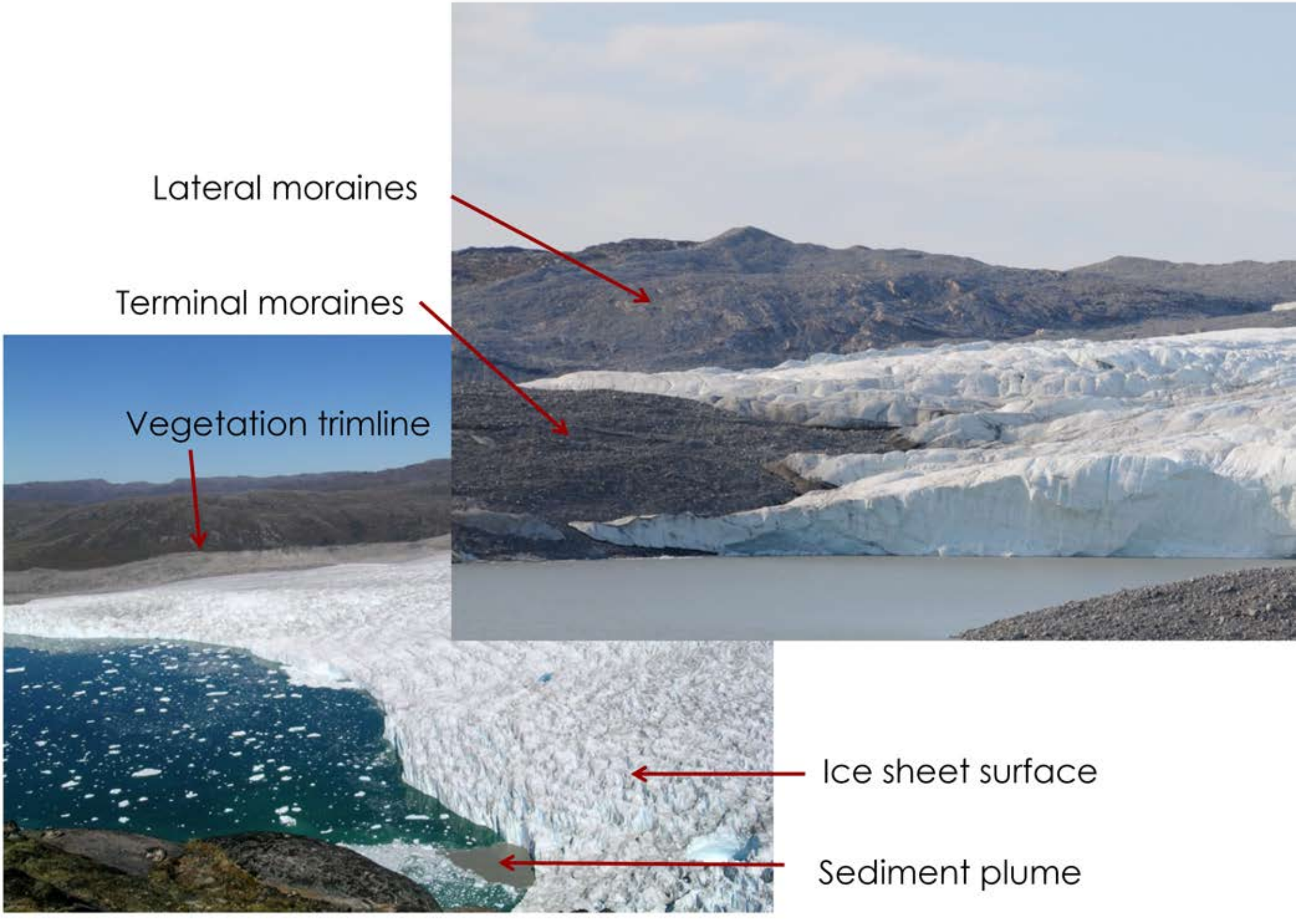


Aerial Photographs

Laser altimetry

Historical record and glacial geology

Free stereo satellite imagery, ASTER, WorldView

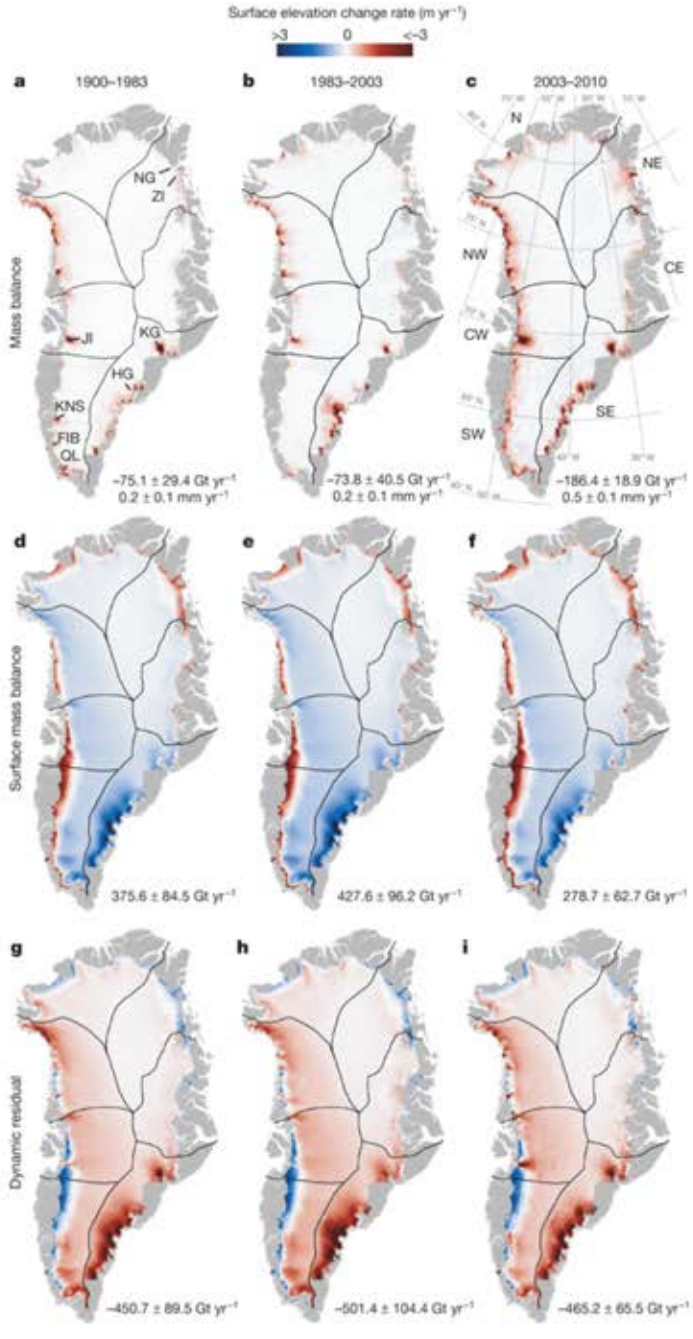

Lateral moraines
Terminal moraines
Vegetation trimline
Ice sheet surface
Sediment plume

GrIS changes since the LIA show stable patterns for SMB and dynamics related surface elevation and mass changes

Total

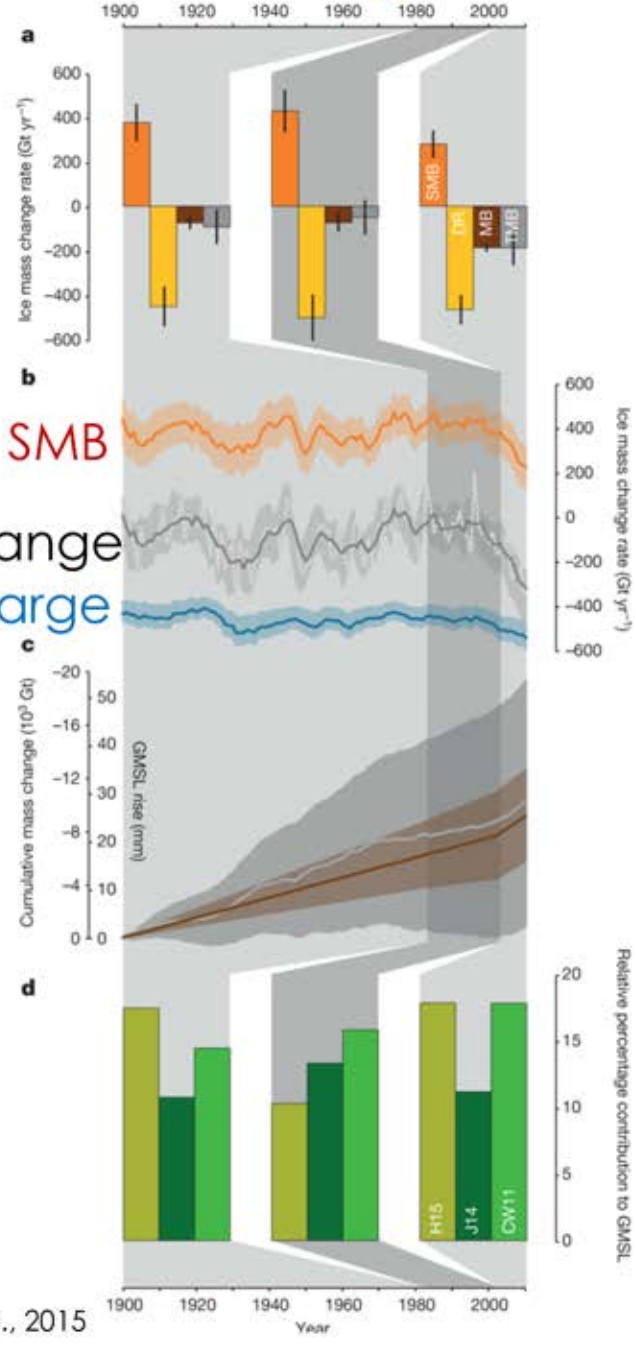
SMB

Dynamics



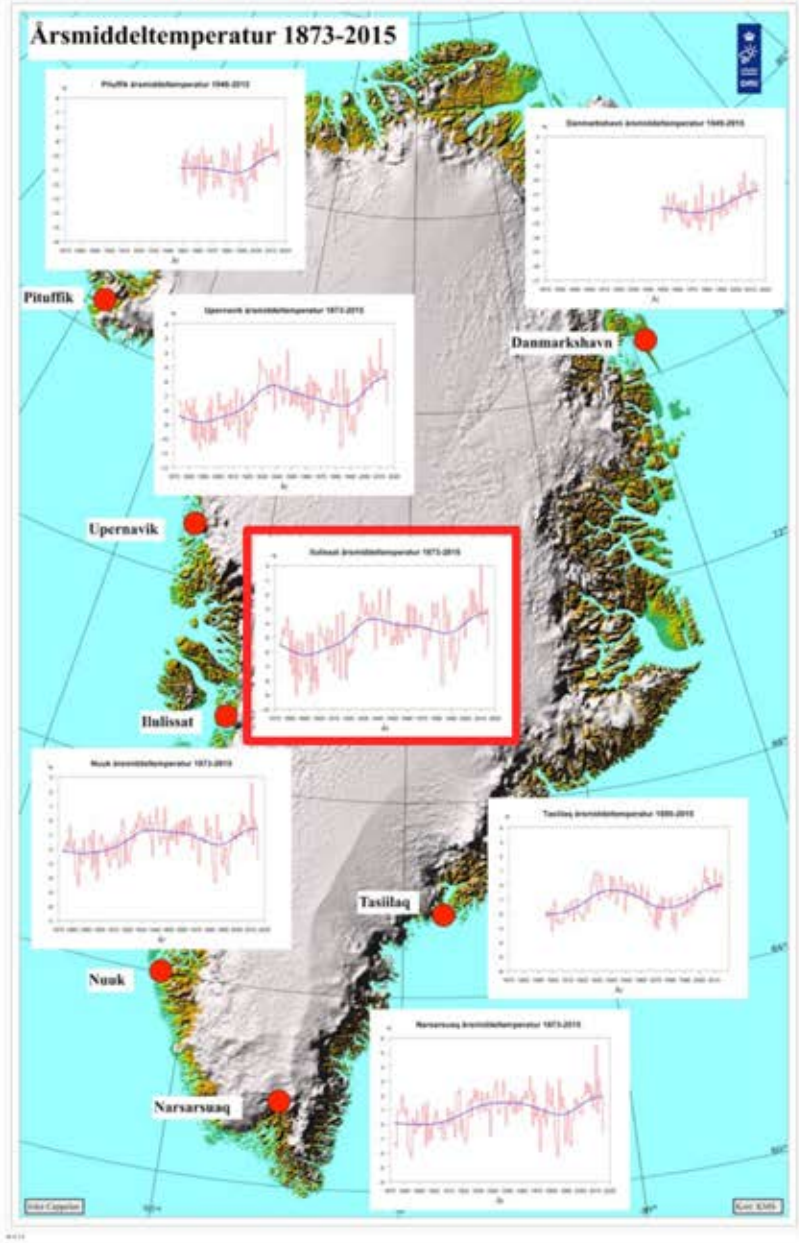
Mass change

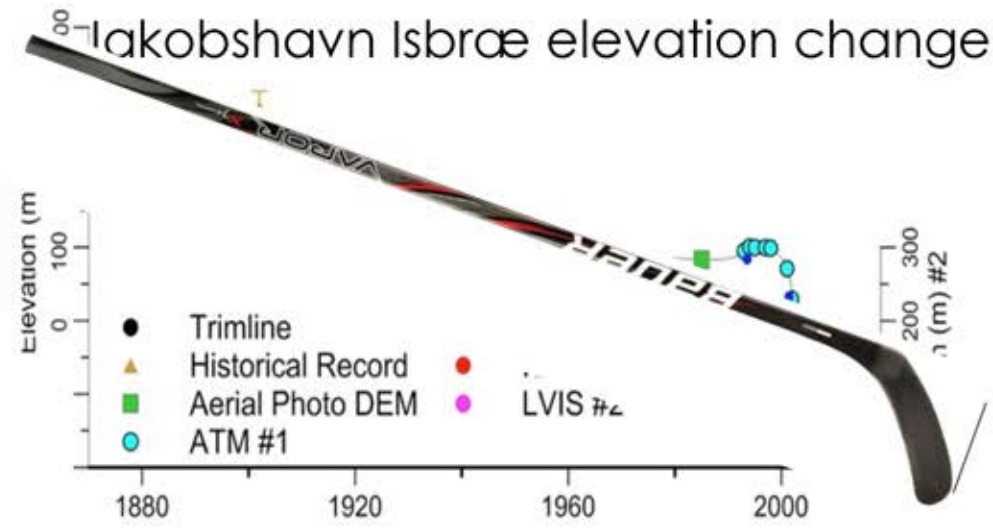
Discharge

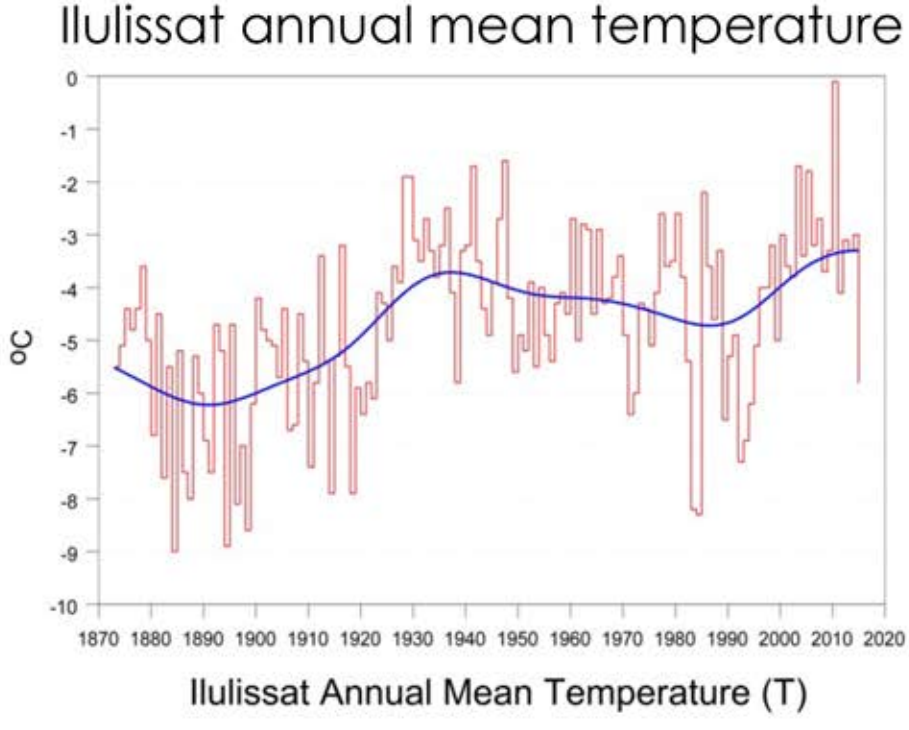


Kjeldsen et al., 2015

Long-term elevation change (proxy for mass balance) shows strong correlation with surface temperature, Jakobshavn Isbræ

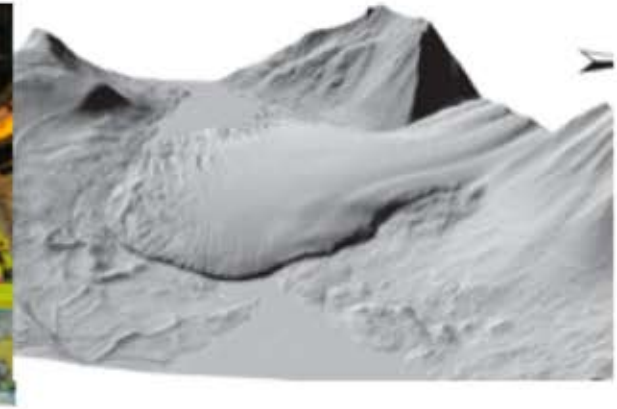


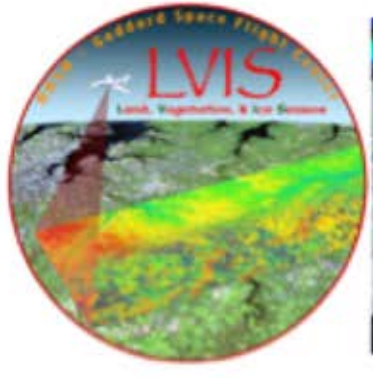


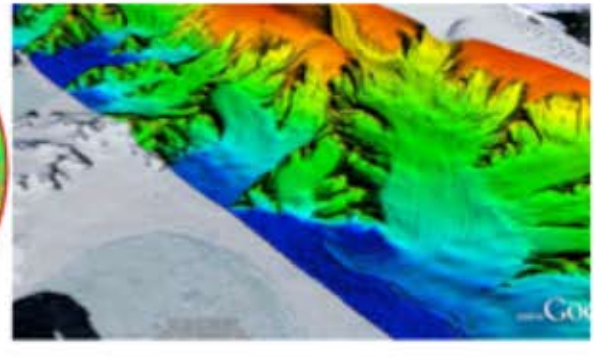


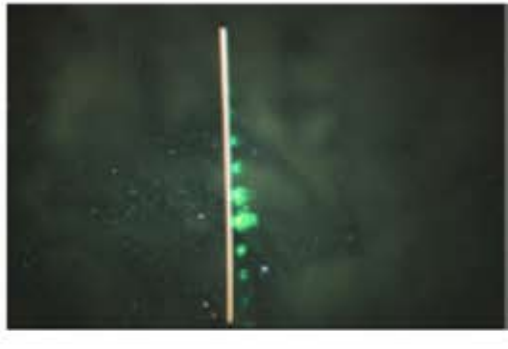
The Altimetry Record Instruments

- Airborne Topographic Mapper (ATM)
  - 1993-present, airborne conical scanner with high repetition rate (kHz), small footprint size (1-3 m), covering 200-400 m wide swaths. ICESS data, 50-70 m platelet size are used
- Land, Vegetation and Ice Sensor (LVIS)
  - 2009-2013 (in Greenland), airborne line scanner with medium repetition rate and footprint size (20-25 m), covering 2 km wide swaths. Data set is reduced by applying plane fitting to obtain 50 m platelet size.
- Ice, Cloud and land Elevation Satellite (ICESat)
  - 2003-2009, satellite laser profiler with low repetition rate (40 Hz), large footprints (70-100 m) separated spaced by 170 m. All valid observations are used (criteria for energy and waveform fitting from Smith et al., 2009).

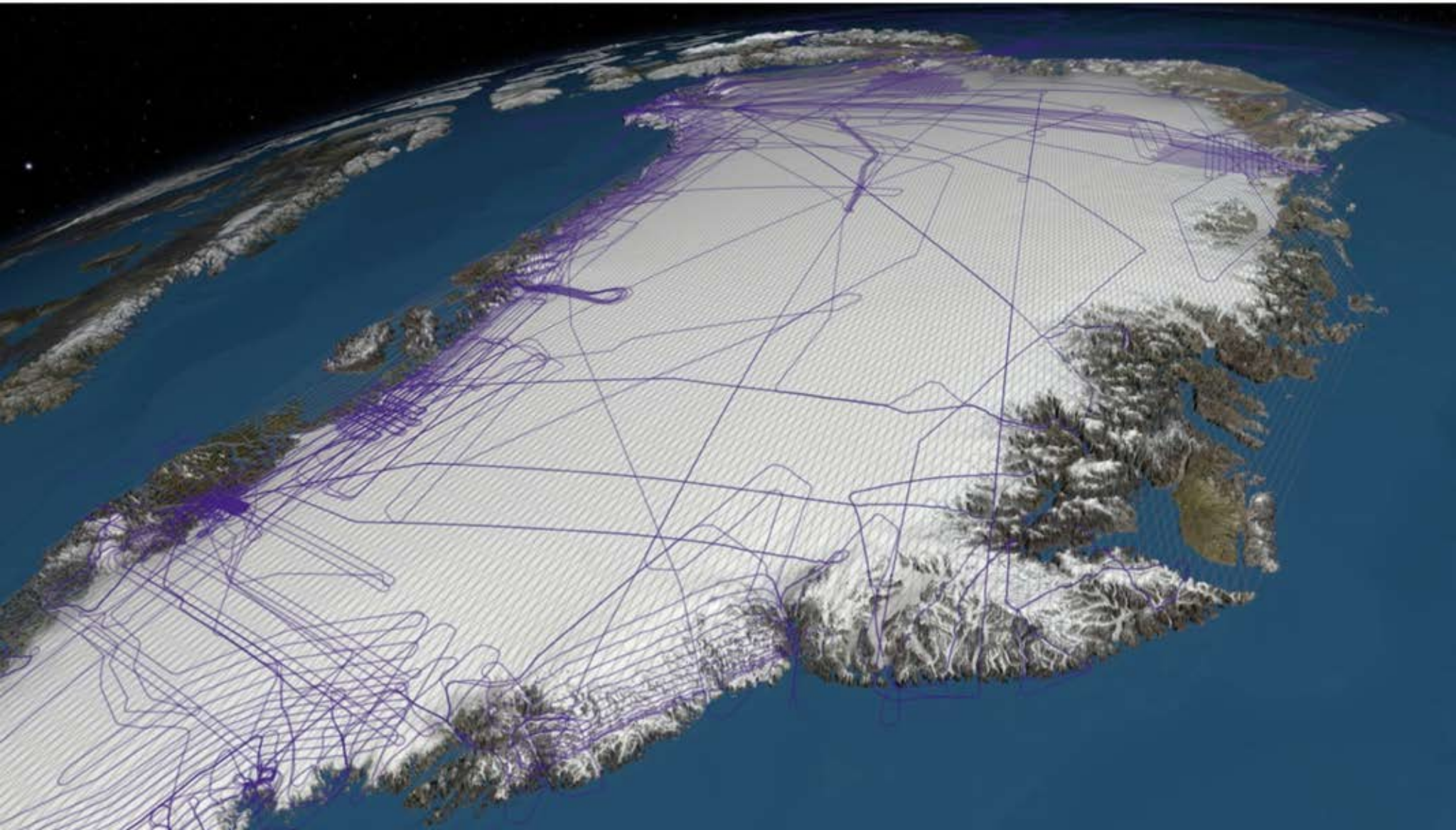




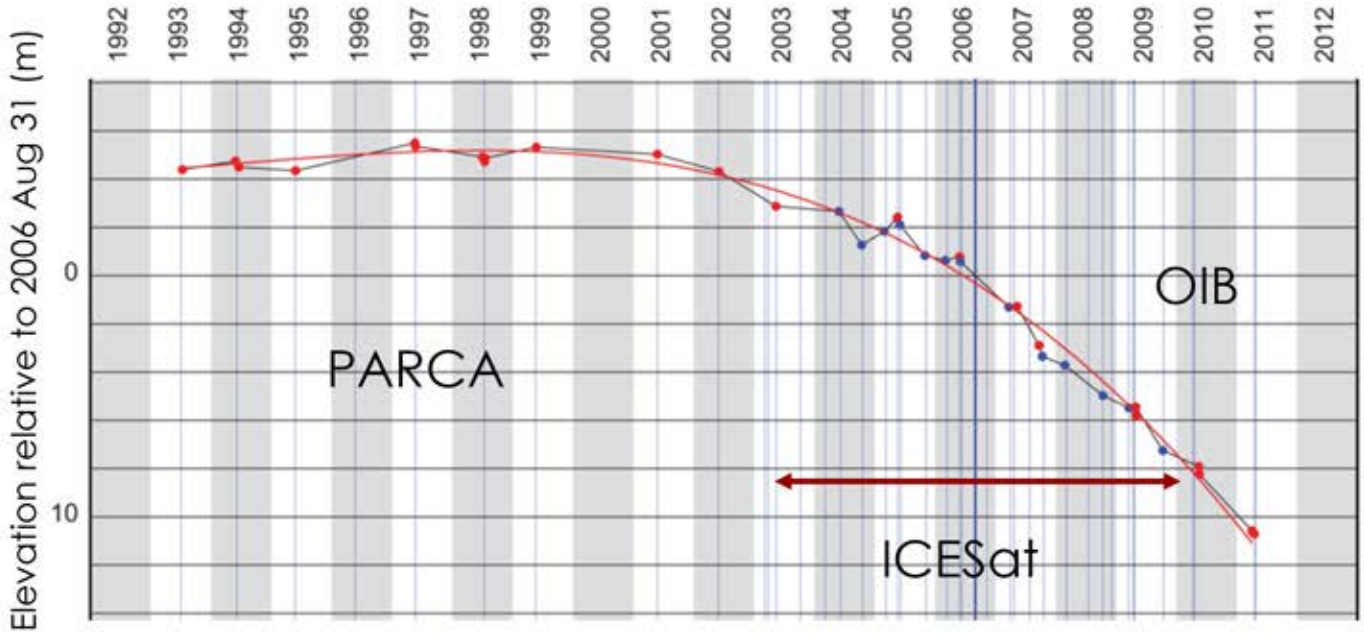


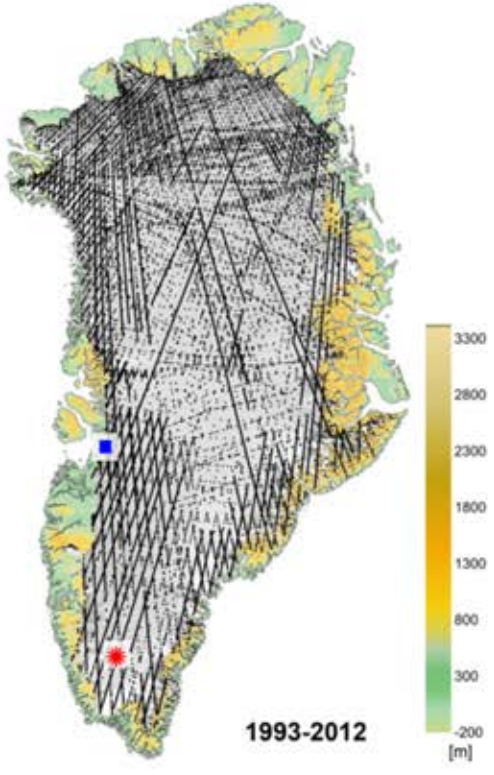


ICESat ground tracks (gray) and ATM/LVIS flight trajectories (purple)



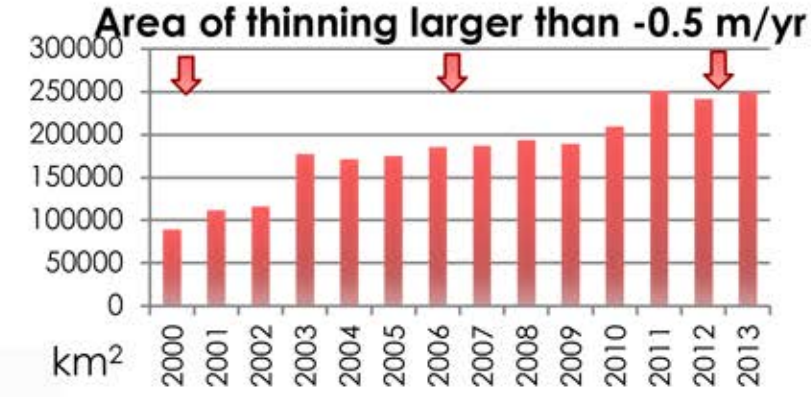
The Altimetry Record: Methodology

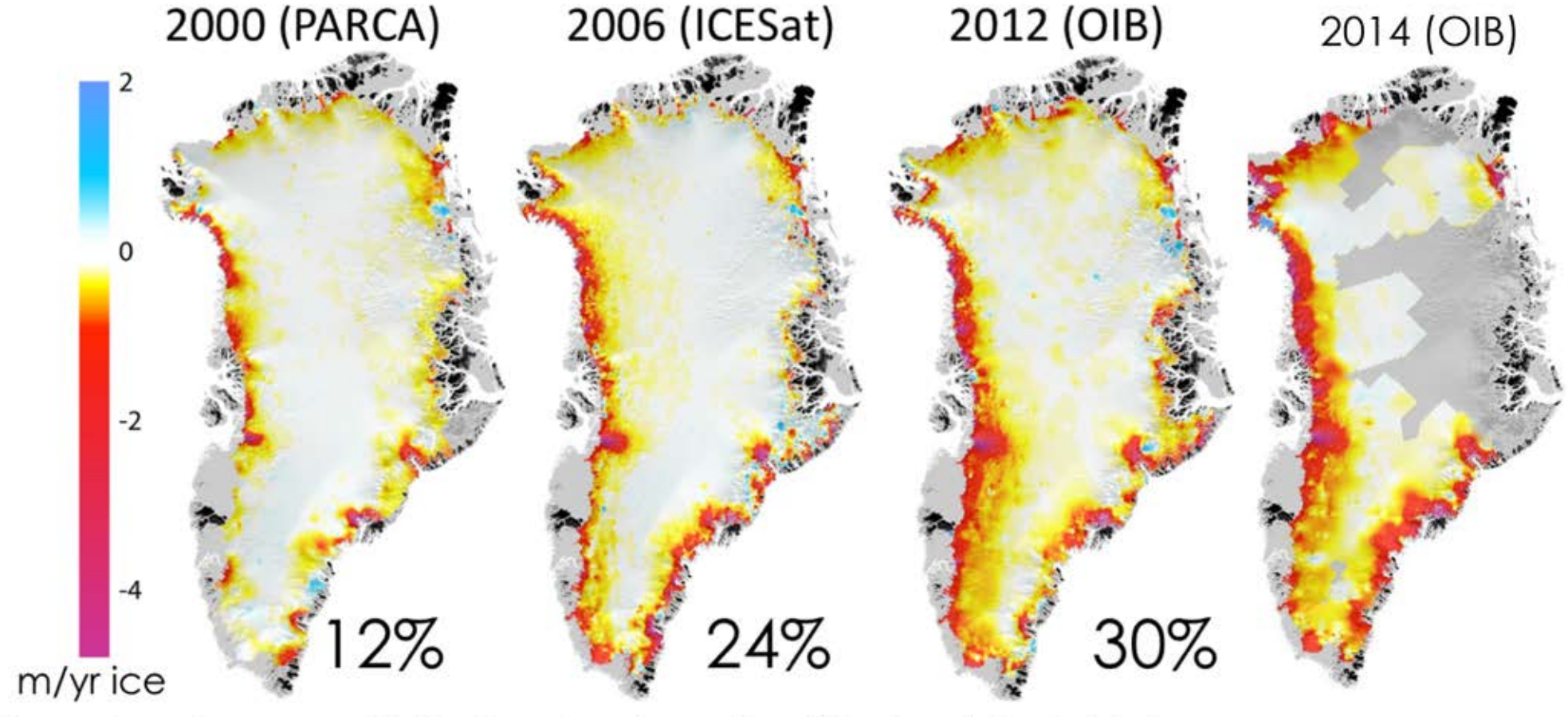




- Surface Elevation Reconstruction And Change detection (SERAC, Schenk and Csatho, 2012)
- Accurate and detailed ice surface change histories are reconstructed in more than 100,000 locations by combining all laser altimetry measurements on the Greenland Ice Sheet (Csatho et al., 2014, PNAS)

OIB Measures the Increasing Extent of Thinning in Vulnerable Ice Sheet Marginal Region

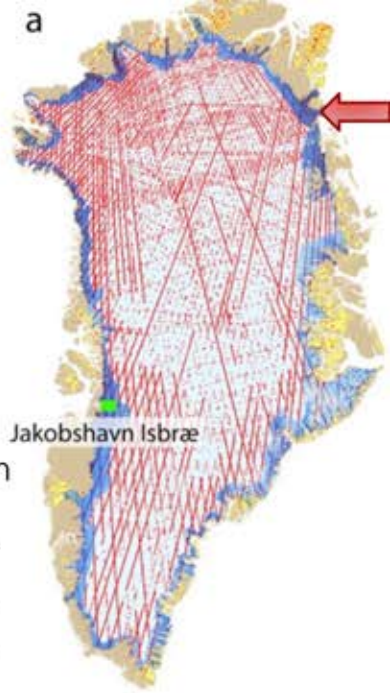


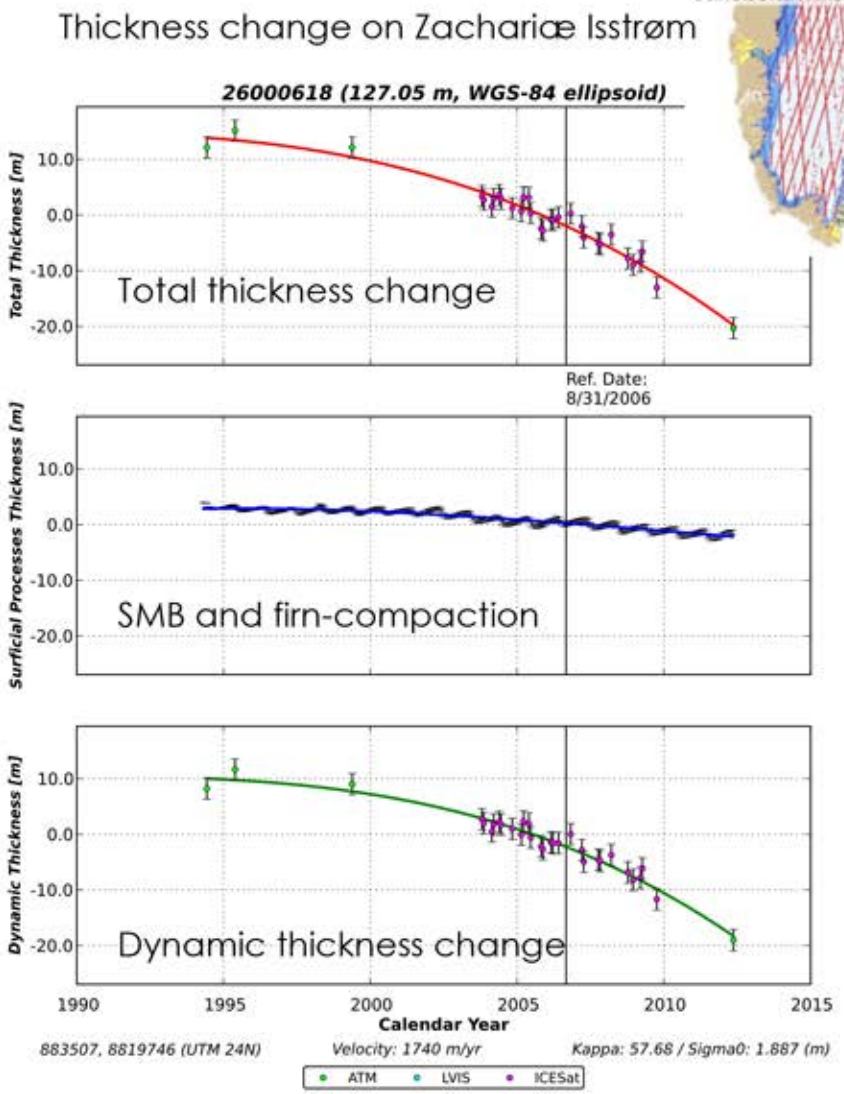


Percentage shows area with thinning rates of more than 0.5 m/yr, relative to total area below 2200 m elevation (790,000 km²)

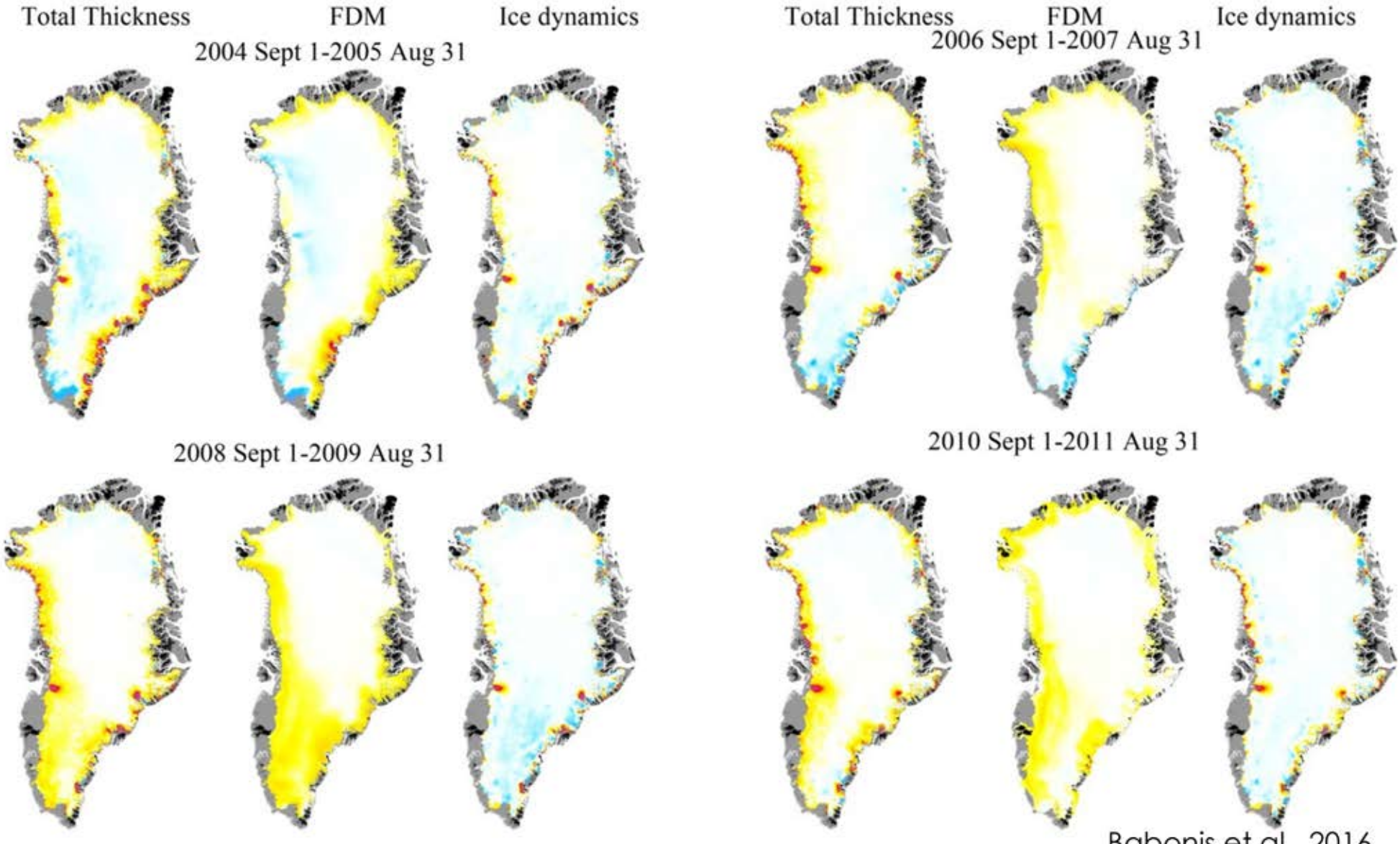
Partitioning Ice Thickness Changes into Surficial Processes and Ice Dynamics

- **Time series of ice thickness change (A)** from altimetry observations, corrected to remove Glacial Isostatic Adjustment
- **Firn densification (B)** from RACMO GR2.3 (FDM, Munneke et al., 2015)
- **Dynamic thickness change (C) =** thickness change reconstructed from altimetry observations (A) **minus** climate induced thickness changes on the surface (B)
- **Mass change =** dynamic thickness change (C)*ice density + SMB anomaly
- **Annual change rates** are calculated from analytical curves fitted to times series



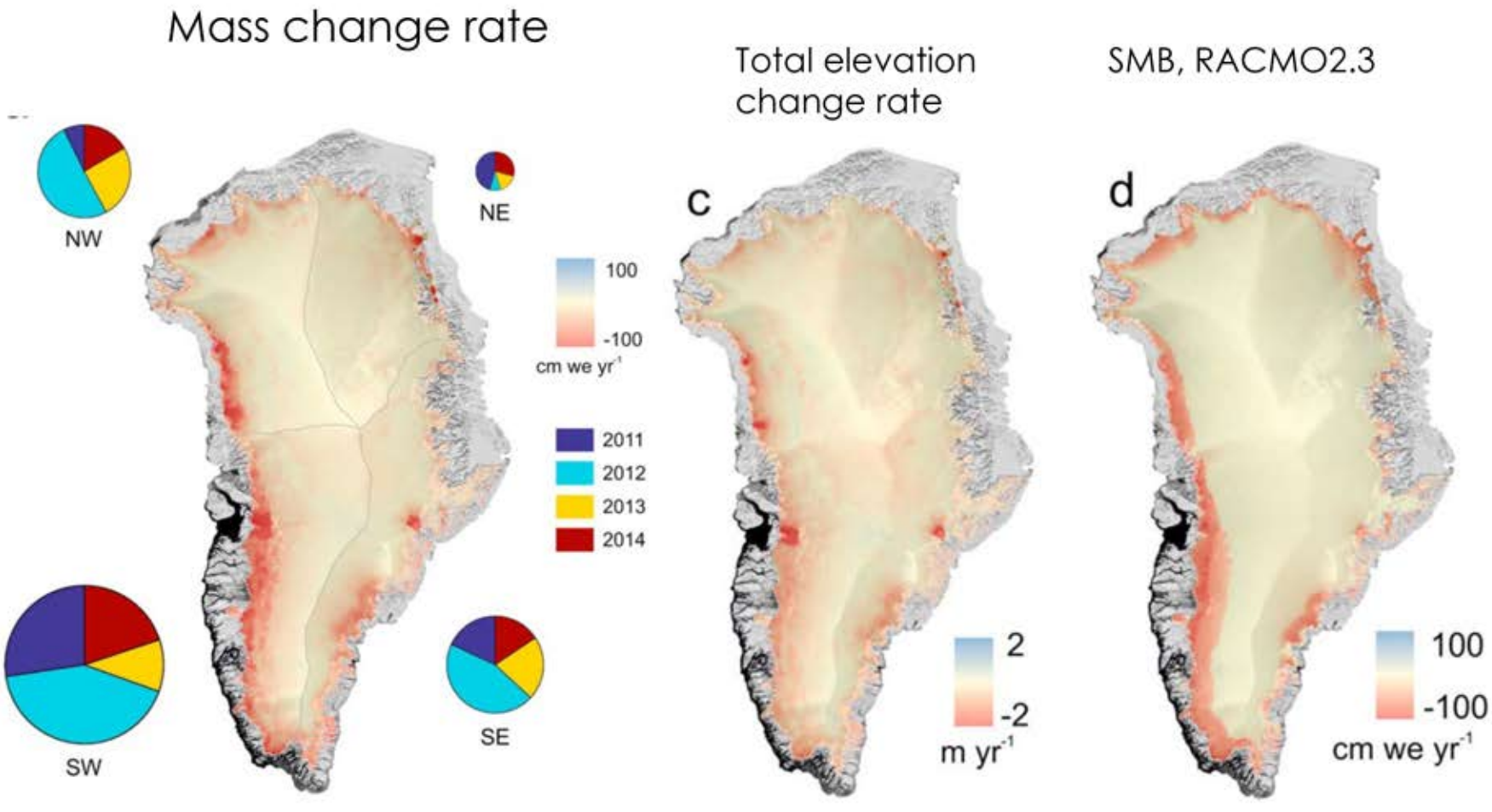


A complicated puzzle: Interannual variation of ice thickness changes from laser altimetry, 2004-2010, partitioned into SMB (RACMO) and ice dynamics

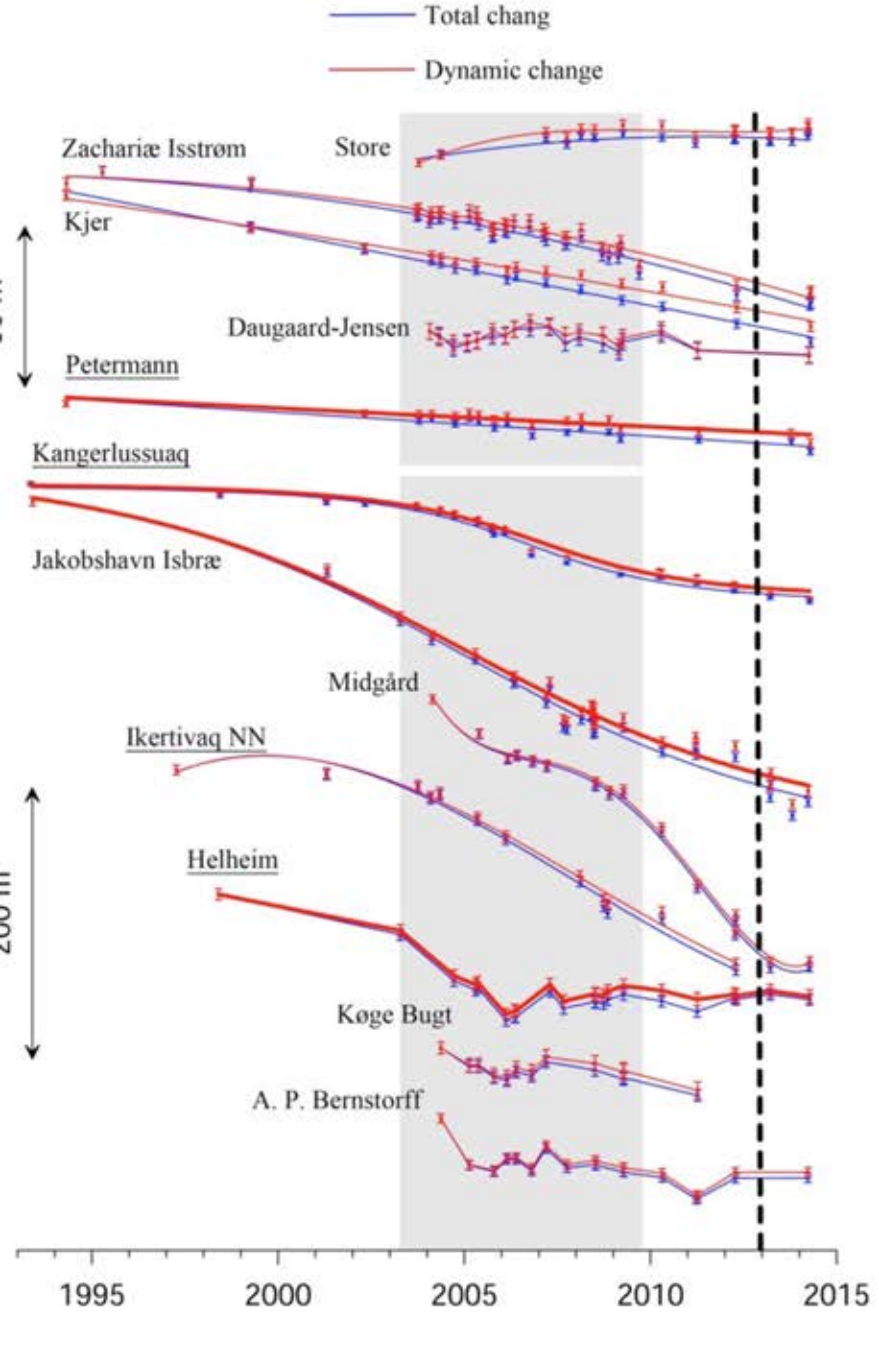


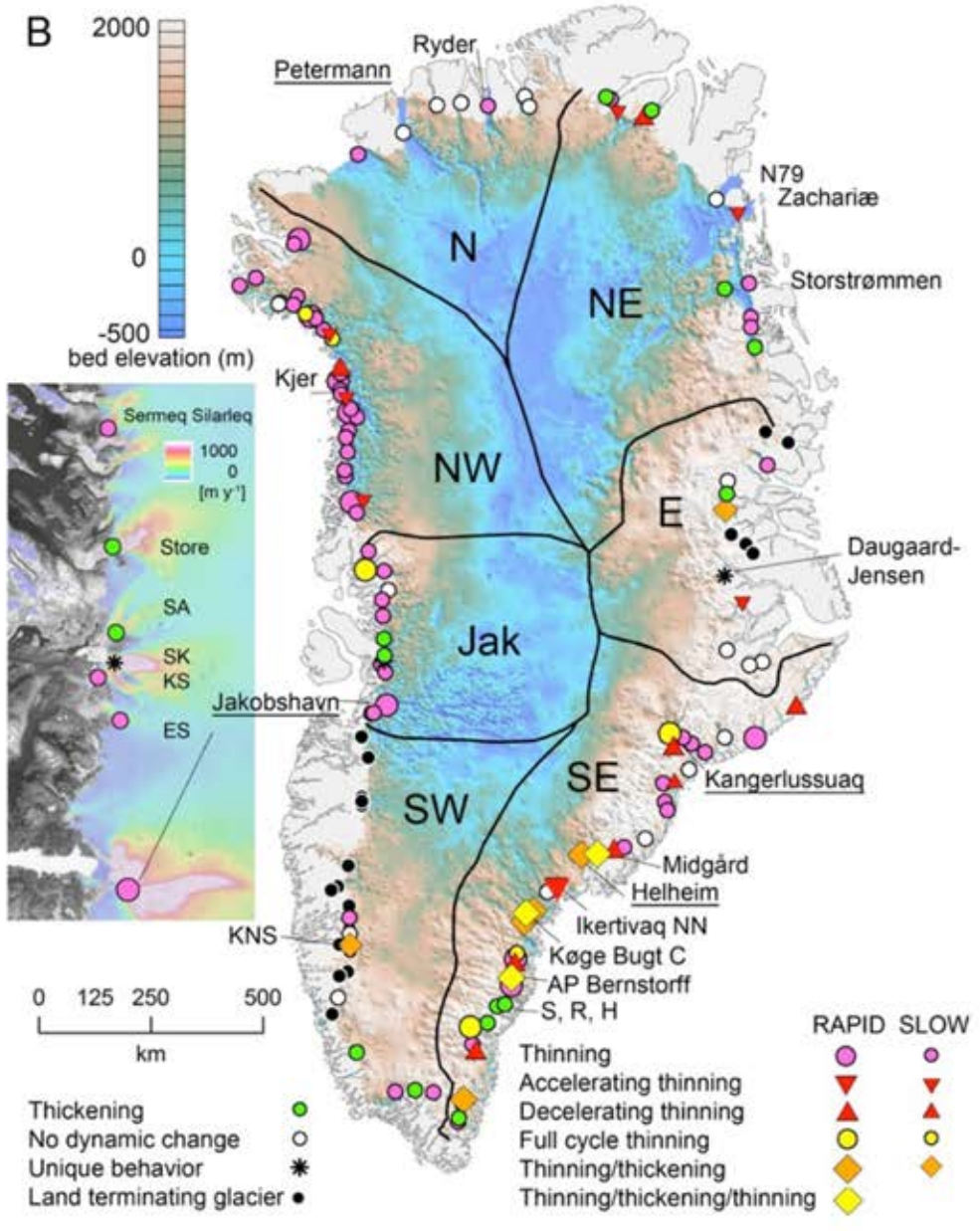
Babonis et al., 2016

Interannual variations in 2011-2014 from CryoSat-2 altimetry, McMillan et al., 2016



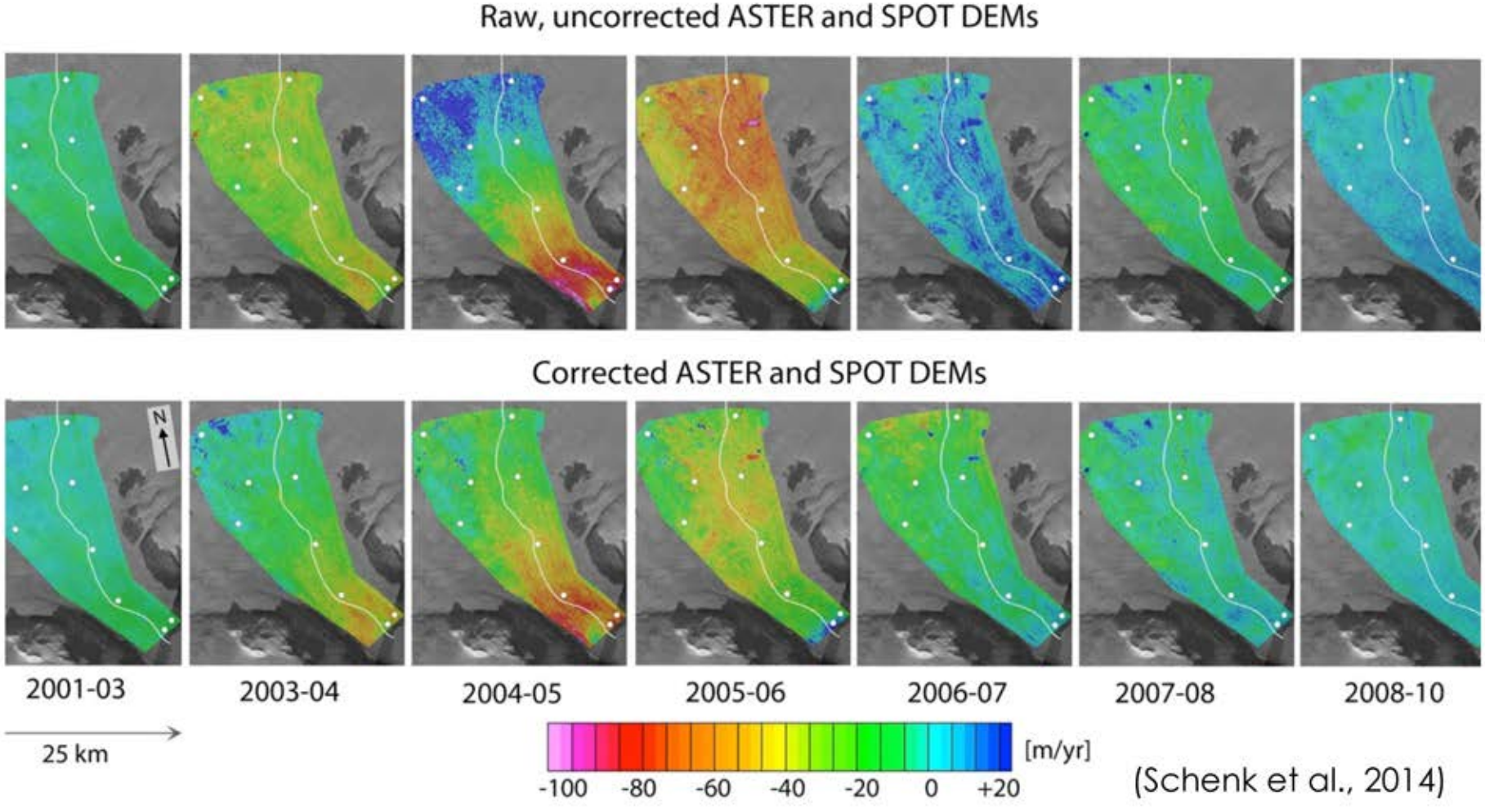
Toward Process Understanding: Outlet Glacier Classification based on Dynamic Thickness Change Pattern (1993-2014)





Fusion of Altimetry with DEMs

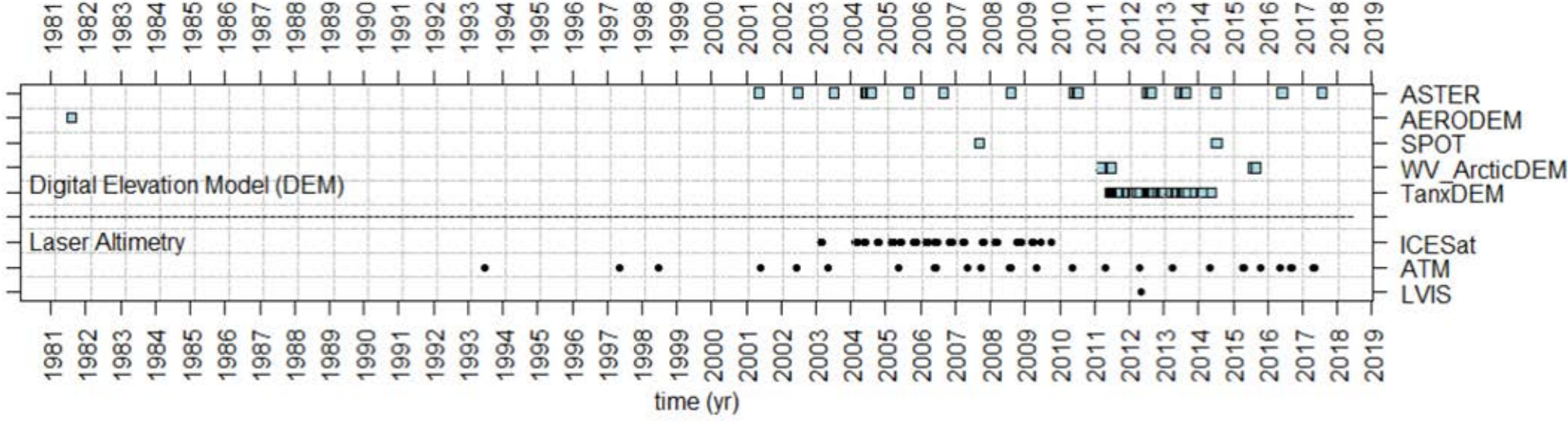
- Correction of DEMs to remove systematic errors
- Spatiotemporal densification of surface elevation change histories
- Investigation of processes in 3D, extending study from repeat centerlines



(Schenk et al., 2014)

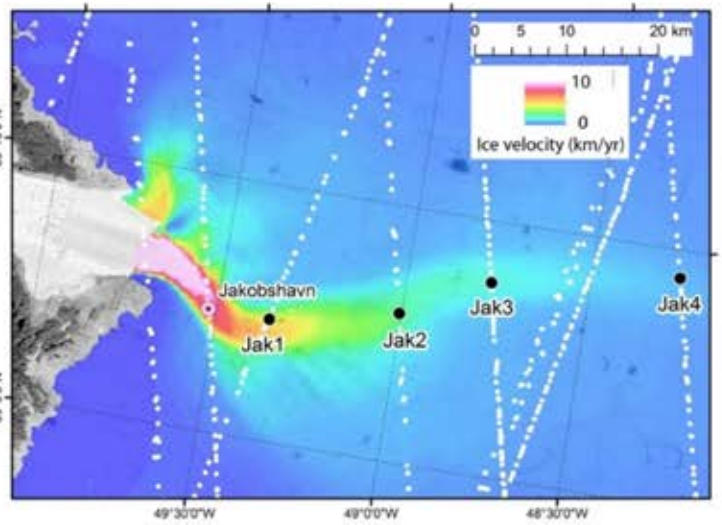
Hydrological/sedimentary control on ice dynamics inferred at Helheim Glacier from robust elevation record

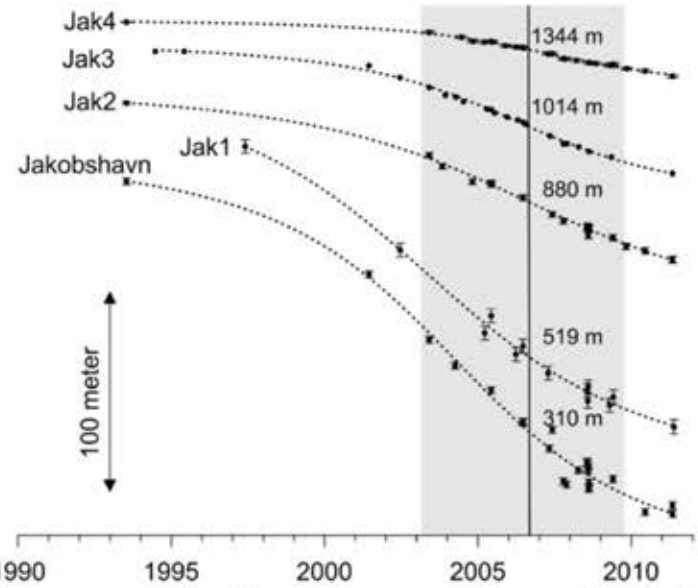
Robert et al., in prep.

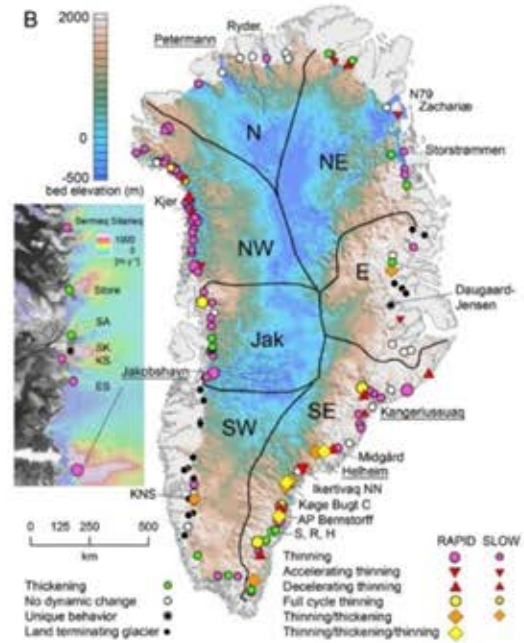


Motivation: Normal glacier behavior vs. complex

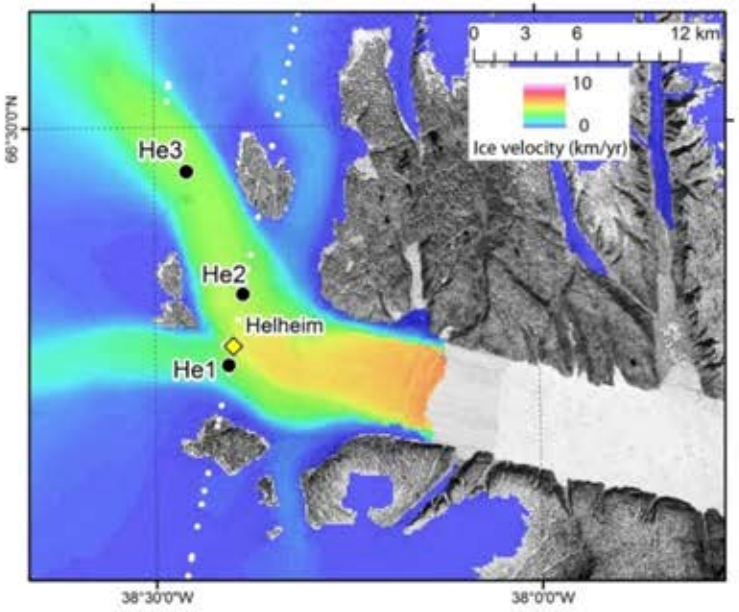
- Jakobshavn Isbrae: **Thinning is delayed** and **decreases in magnitude inland**

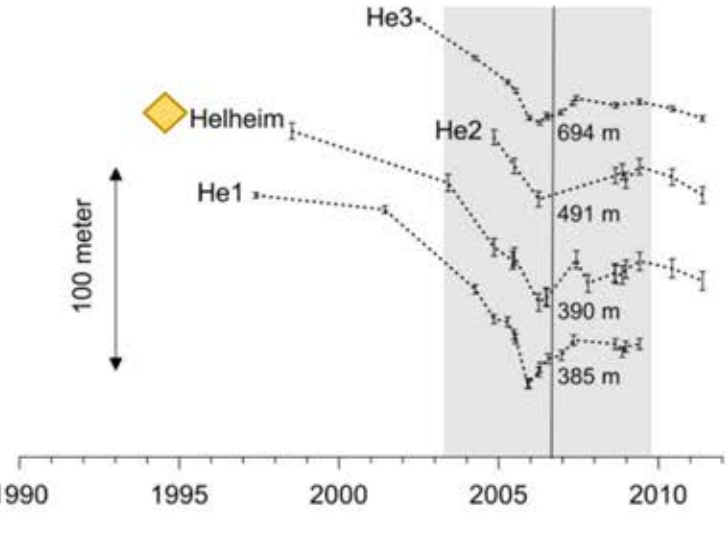






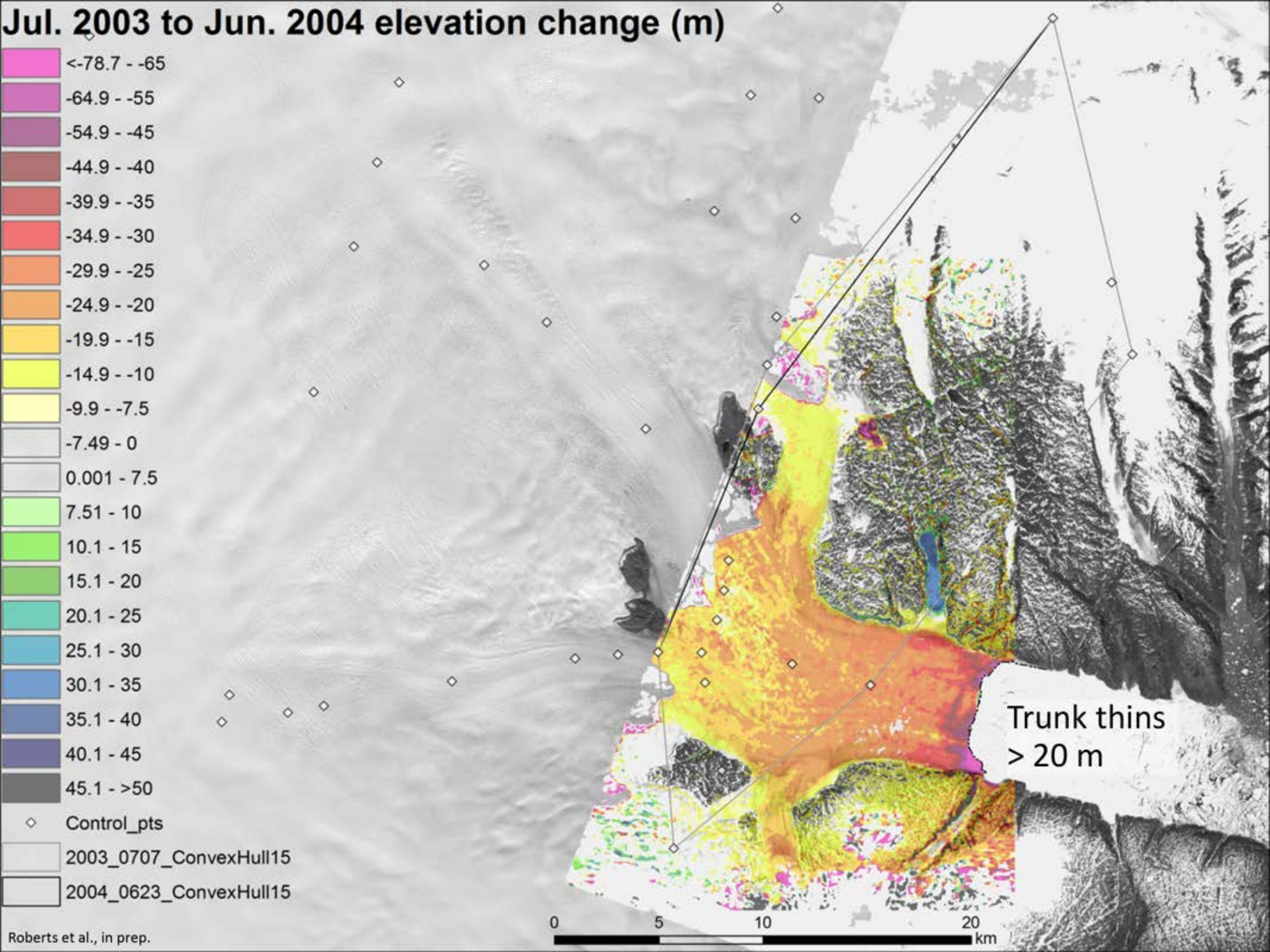
- Helheim Glacier: Irregular thickness variations = a separate, high-frequency process

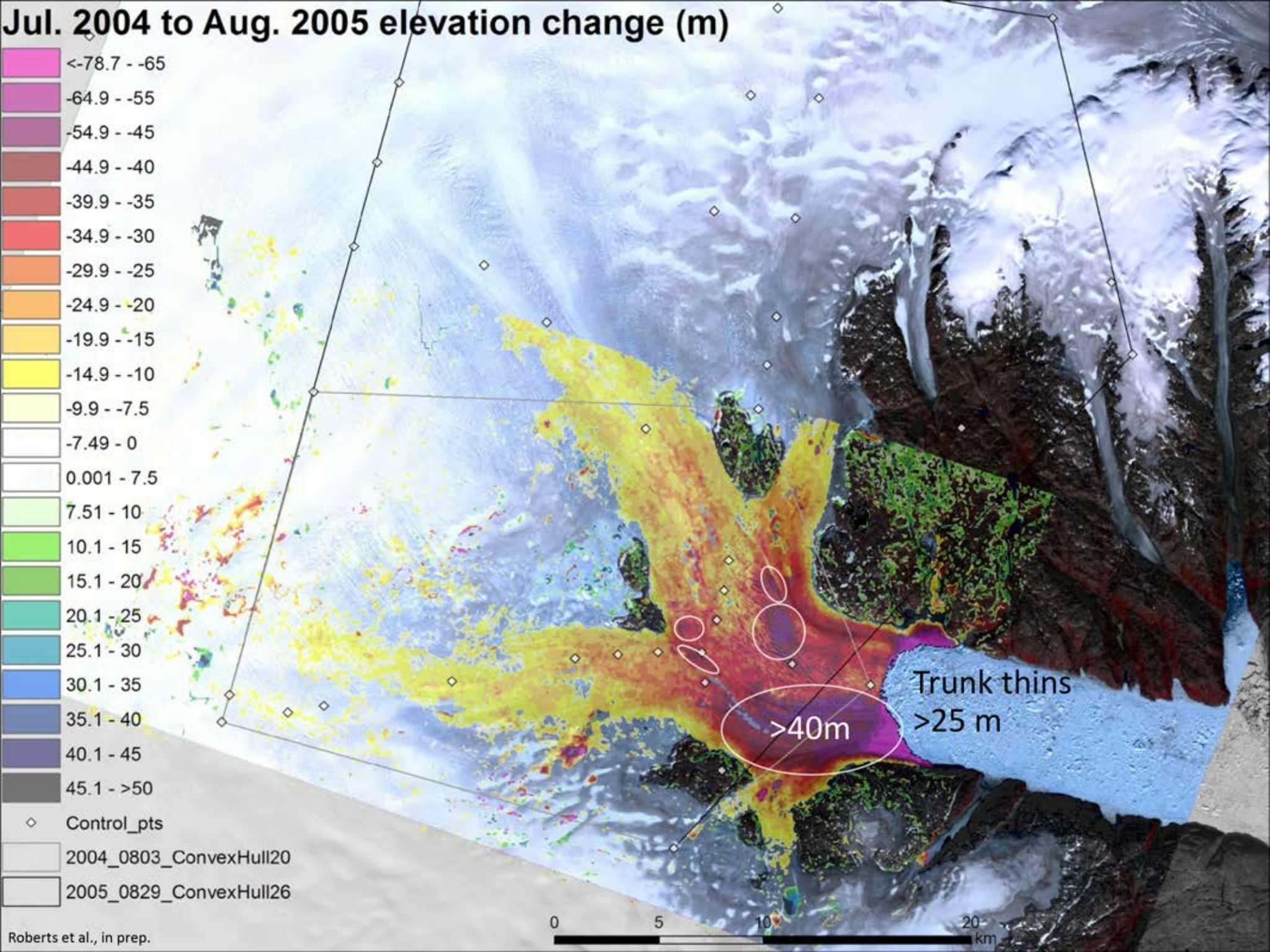


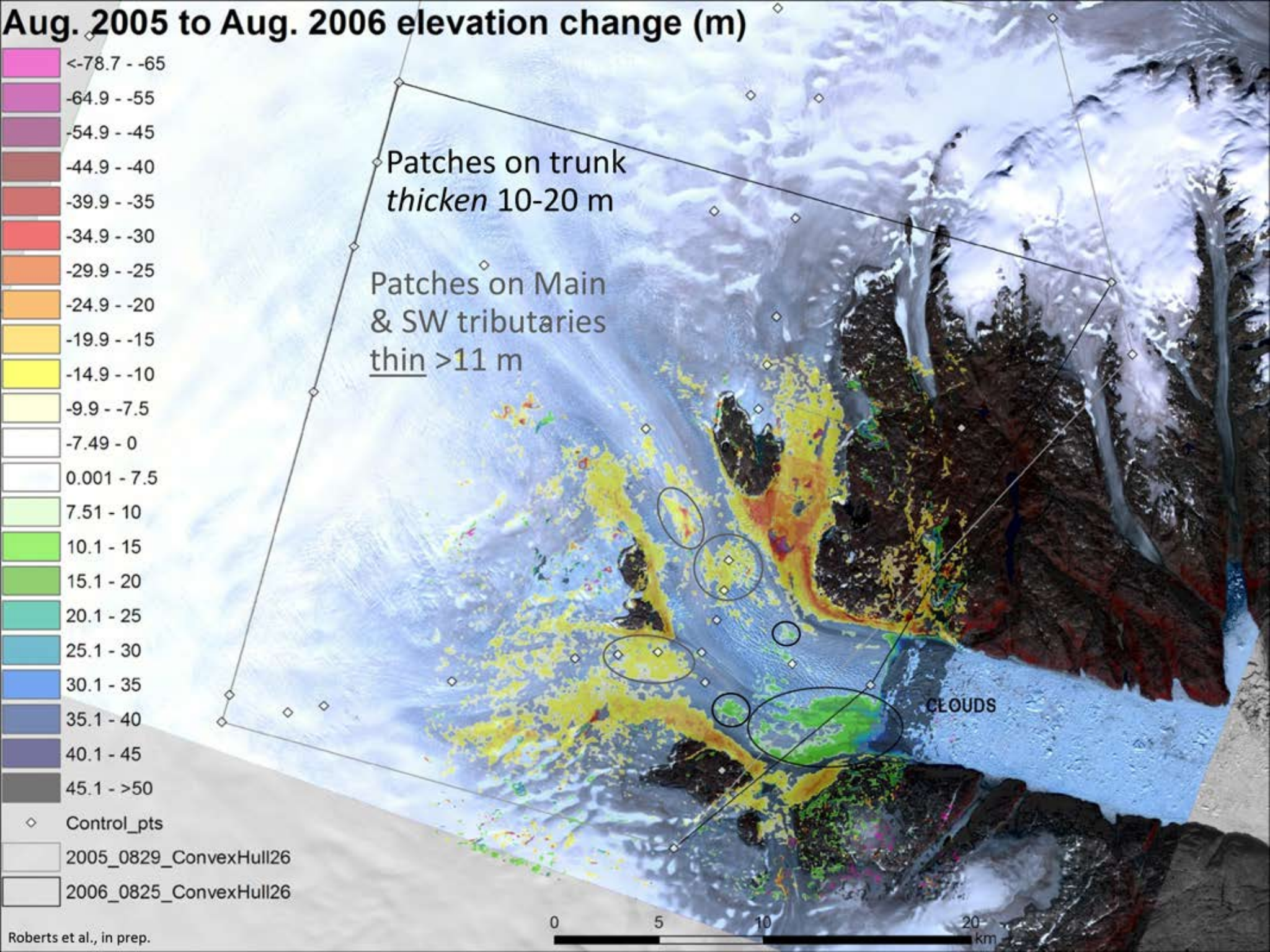


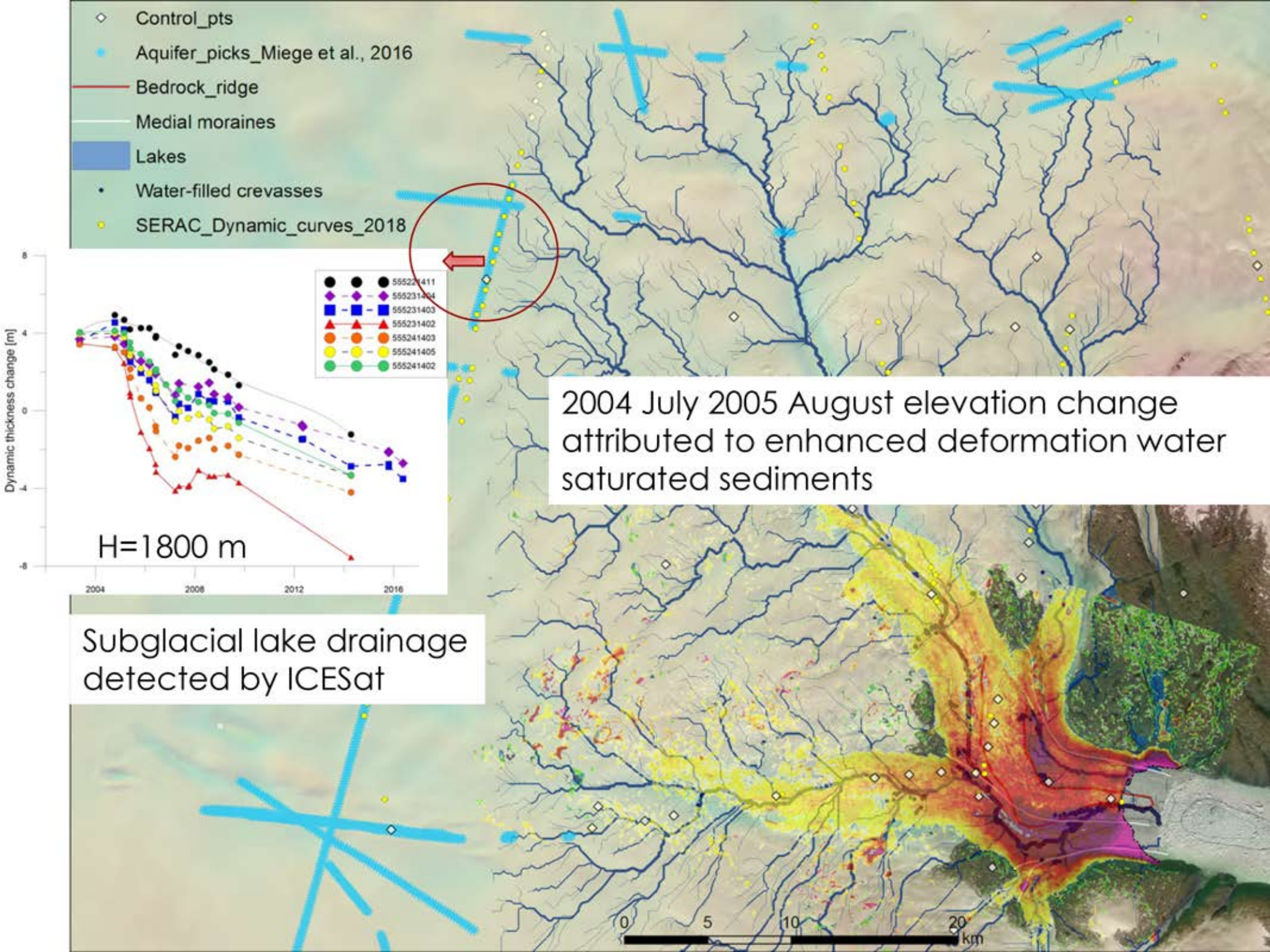
- **Helheim Glacier behaves similarly even 20+ km from terminus**

Csatho et al., 2014


Jul. 2003 to Jun. 2004 elevation change (m)
<-78.7 - -65
-64.9 - -55
-54.9 - -45
-44.9 - -40
-39.9 - -35
-34.9 - -30
-29.9 - -25
-24.9 - -20
-19.9 - -15
-14.9 - -10
-9.9 - -7.5
-7.49 - 0
0.001 - 7.5
7.51 - 10
10.1 - 15
15.1 - 20
20.1 - 25
25.1 - 30
30.1 - 35
35.1 - 40
40.1 - 45
45.1 - >50
Control_pts
2003_0707_ConvexHull15
2004_0623_ConvexHull15
Trunk thins
> 20 m
0
5
10
20
km
Roberts et al., in prep.


Jul. 2004 to Aug. 2005 elevation change (m)
<-78.7 - -65
-64.9 - -55
-54.9 - -45
-44.9 - -40
-39.9 - -35
-34.9 - -30
-29.9 - -25
-24.9 - -20
-19.9 - -15
-14.9 - -10
-9.9 - -7.5
-7.49 - 0
0.001 - 7.5
7.51 - 10
10.1 - 15
15.1 - 20
20.1 - 25
25.1 - 30
30.1 - 35
35.1 - 40
40.1 - 45
45.1 - >50
Control_pts
2004_0803_ConvexHull20
2005_0829_ConvexHull26
Trunk thins
>25 m
>40m
0
5
10
20
km
Roberts et al., in prep.

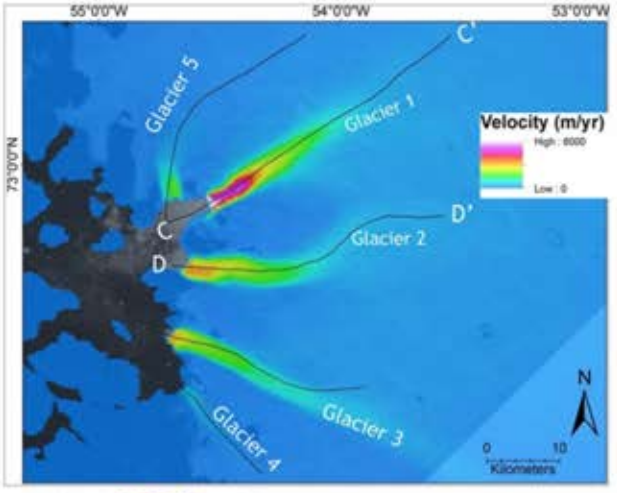

Aug. 2005 to Aug. 2006 elevation change (m)
<-78.7 - -65
-64.9 - -55
-54.9 - -45
-44.9 - -40
-39.9 - -35
-34.9 - -30
-29.9 - -25
-24.9 - -20
-19.9 - -15
-14.9 - -10
-9.9 - -7.5
-7.49 - 0
0.001 - 7.5
7.51 - 10
10.1 - 15
15.1 - 20
20.1 - 25
25.1 - 30
30.1 - 35
35.1 - 40
40.1 - 45
45.1 - >50
Control_pts
2005_0829_ConvexHull26
2006_0825_ConvexHull26
Patches on trunk
thicken 10-20 m
Patches on Main
& SW tributaries
thin >11 m
CLOUDS
0
5
10
20
km
Roberts et al., in prep.

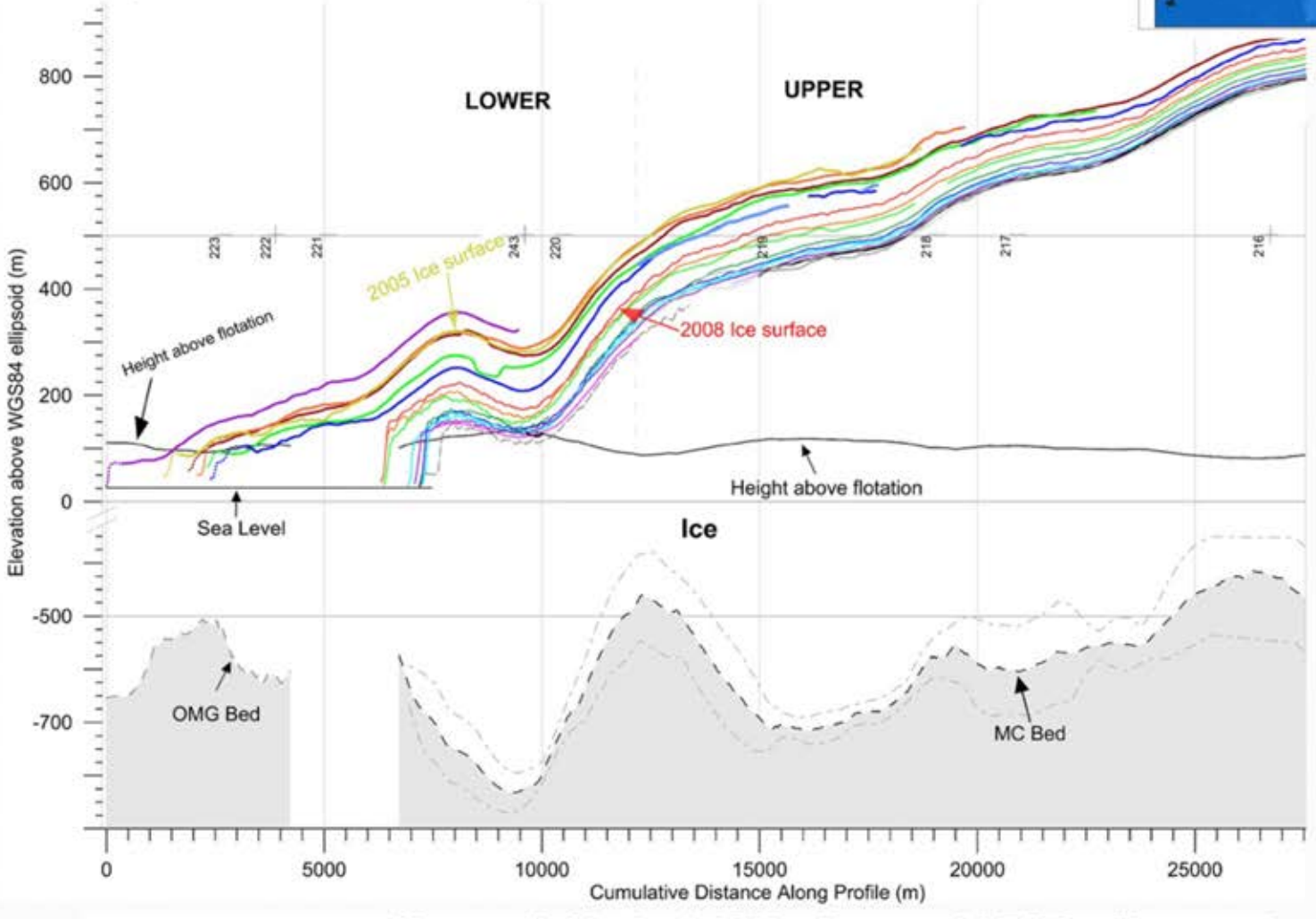

Control_pts
Aquifer_picks_Miege et al., 2016
Bedrock_ridge
Medial moraines
Lakes
Water-filled crevasses
SERAC_Dynamic_curves_2018
Dynamic thickness change [m]
555231403
555231402
555241403
555241405
555241402
H=1800 m
2004
2008
2012
2016
2004 July 2005 August elevation change attributed to enhanced deformation water saturated sediments
Subglacial lake drainage detected by ICESat
0
5
10
20
km

Rapid thinning of grounded "tongue" of Upernavik Glacier 1

dh(1985-2005)=~50 m dh(2005-2006)=~50 m

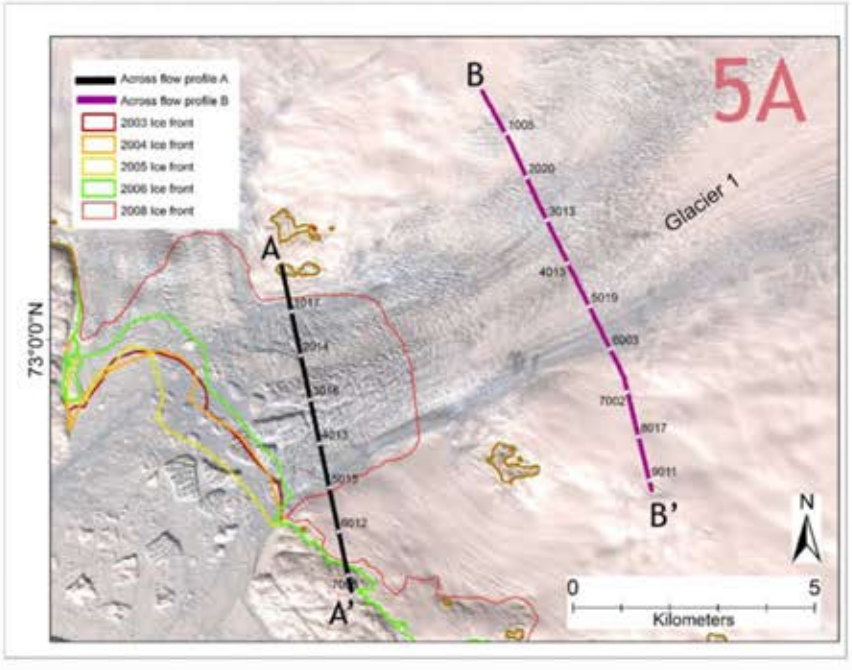
(Wendler et al., in prep)

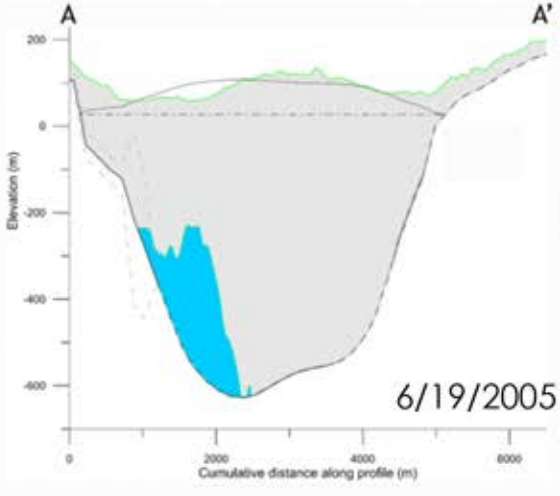


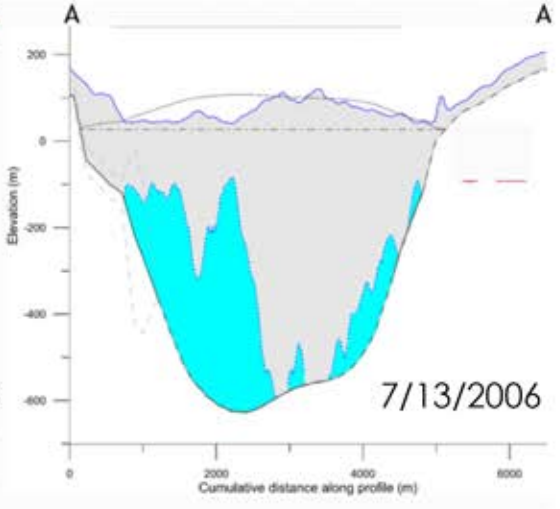


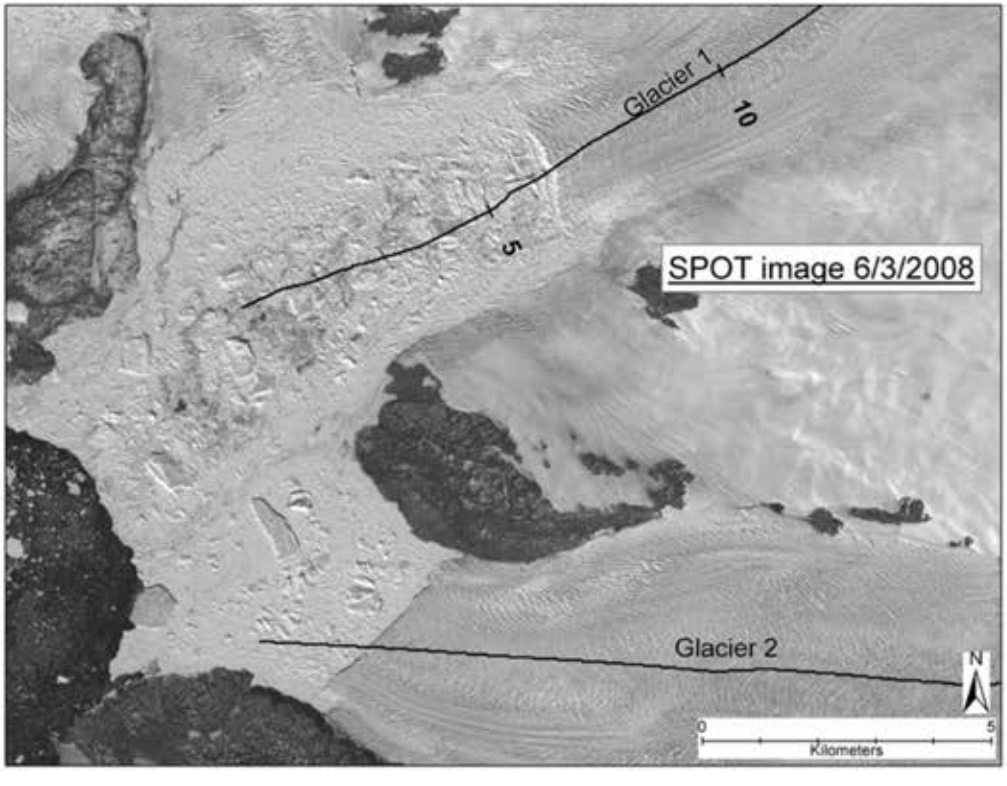
- 1985 Aerial DEM_F
- 61203 IC_AST_F
- 41804 IC_AST_F
- 61905 IC_AST_F
- 71306 IC_AST_F
- 50607 SC_AST_F
- 50407 ATM
- 60308 SC_SPOT
- 41709 ATM
- 51910 ATM
- 51611 ATM
- 51512 ATM
- 50413 SC_SETSM
- 41813 ATM
- 70214 SC_AST_F
- 42614 ATM
- 51115 ATM
- 60215 SC_AST_F
- 61515 SC_AST_F
- 73116 SC_AST (Front)
- 73116 SC_AST_F
- 91416 SC_AST_F

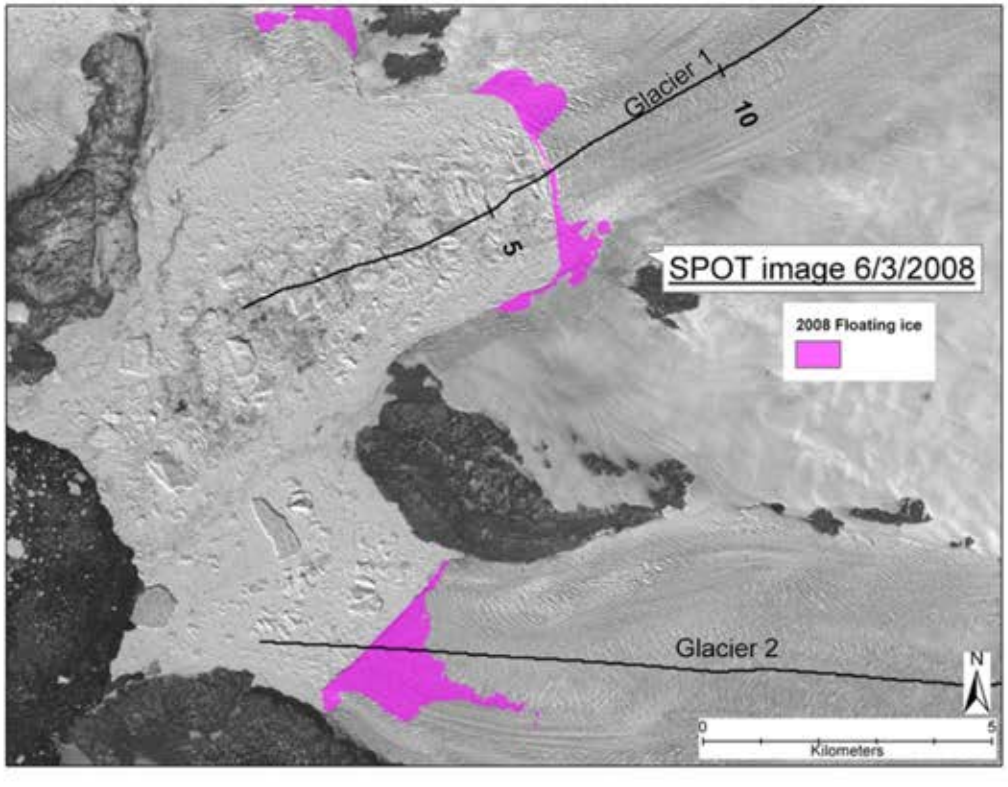
Stable glacier centerline and evolution of floating along margins





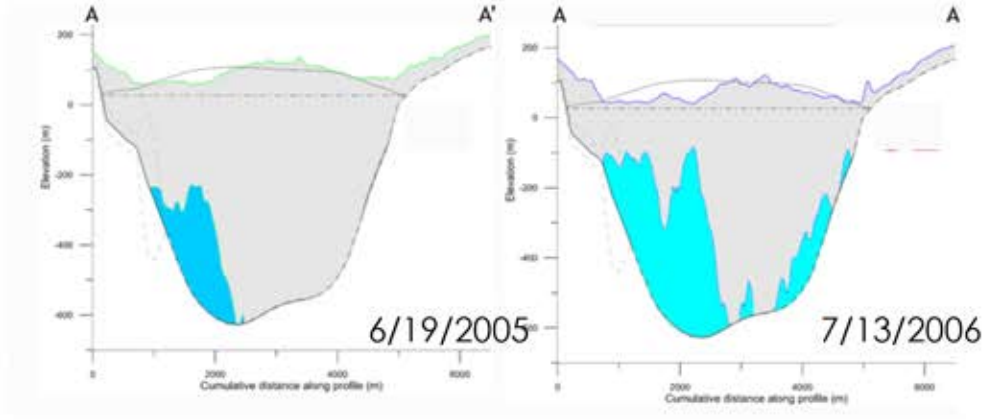




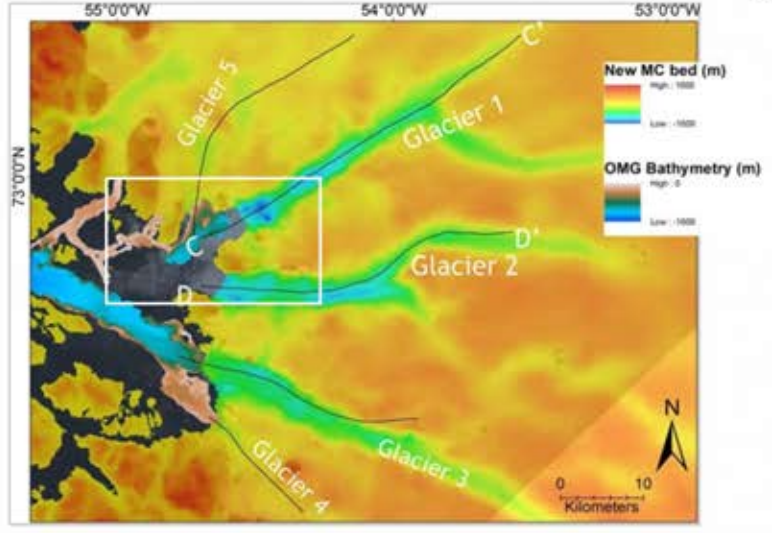


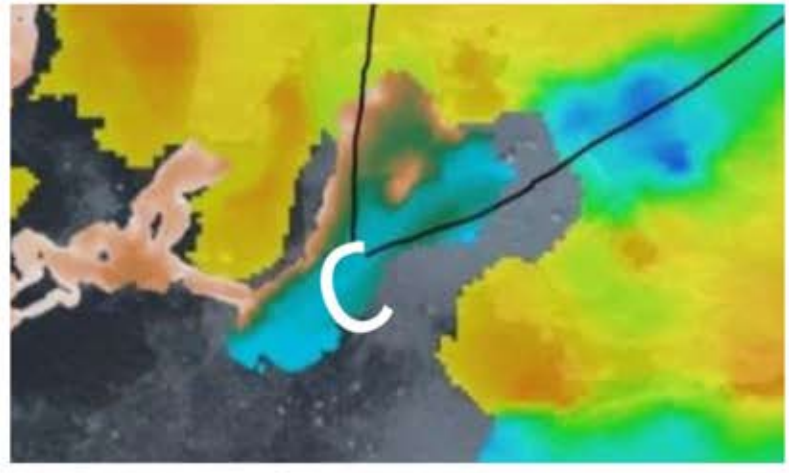
Interpretation

- Trough along the fjord walls troughs could preferential pathways for warm, salty Atlantic waters to reach the glacier front resulting in large basal melt rates.
- Persistent positive SMB anomalies allowed a small seasonal floating tongue to persist longer into the summer season, i.e. calving off later in the season compared to normal.
- The cavity under the tongue exposed the floating ice to high basal melt rates caused by subglacial freshwater discharge-driven circulation transporting warmer ocean water into the cavity.
- Freshwater discharge is expected to be the largest at the glacier margin as meltwater reaching the bed through crevasses opened by hydrofracturing in depressions along glacier margins was flowing in the lateral troughs toward to calving front.
- The region above the terminus disintegrated once the ice was floating on both sides of the central, grounded region.



BedMachine V3 and OMG bathymetry





Conclusions

- Land ice observations reveal long-term trends, interannual variation and spatial variability
- Ice sheet mass loss and outlet glacier thinning and retreat are broadly consistent with increasing air and ocean temperatures
- Detailed local histories indicate a complex interplay of bed geometry, ocean temperatures and subglacial geology, modulating to long-term trend of mass loss, speed-up and retreat
- More glacier histories are needed to tease out the processes!
- Close collaboration between observationists and modelers could lead to an improved understanding of land ice processes → resulting in more reliable prognosis of future ice sheet behavior

Acknowledgements

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