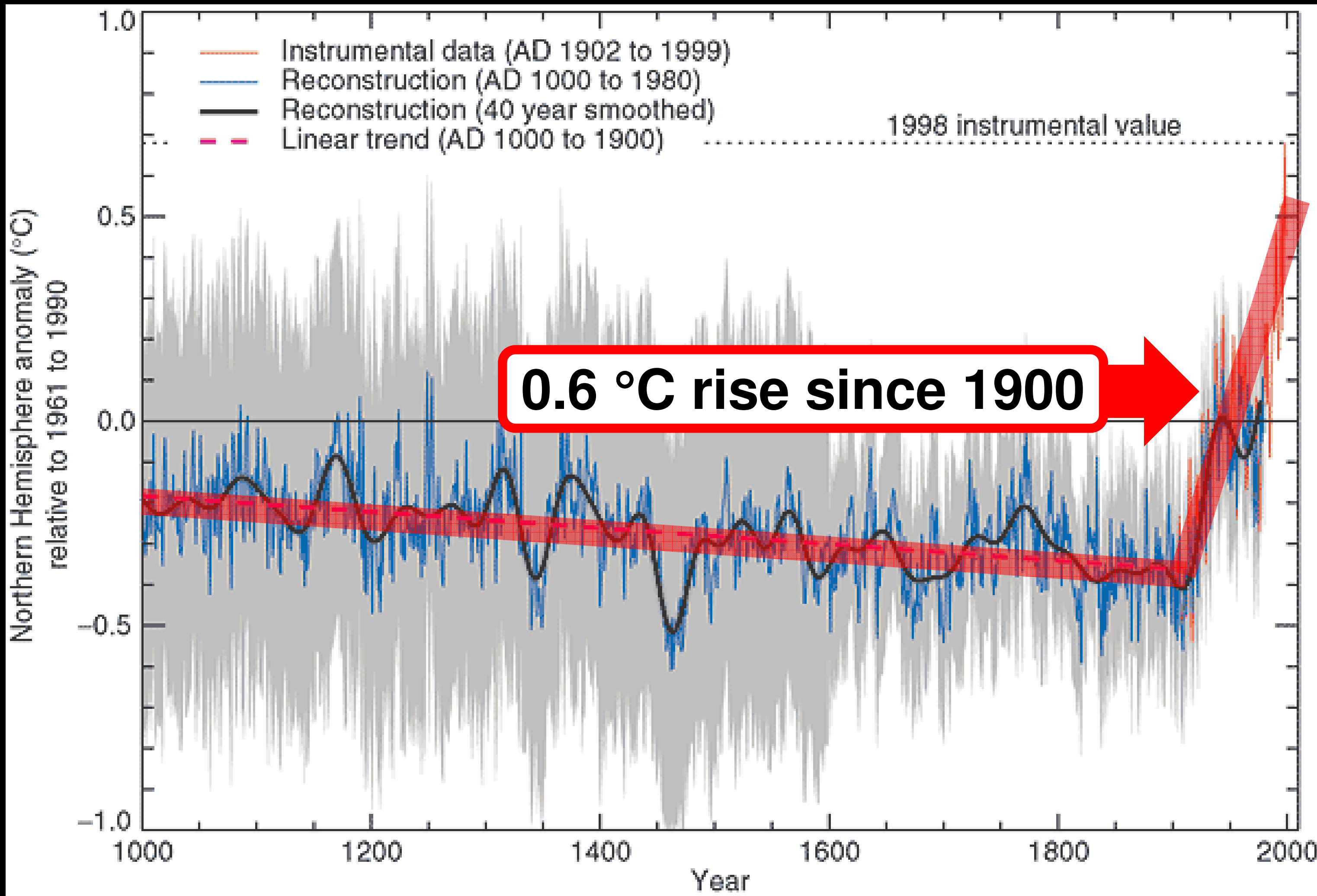
Temporal fluctuations in the motion of (selected) Arctic ice masses from satellite radar interferometry

or 'Two ways to find crevasses'...

Steve Palmer, Andrew Shepherd, Pete Nienow, Aud Sundal, Eero Rinne, Ian Joughin.

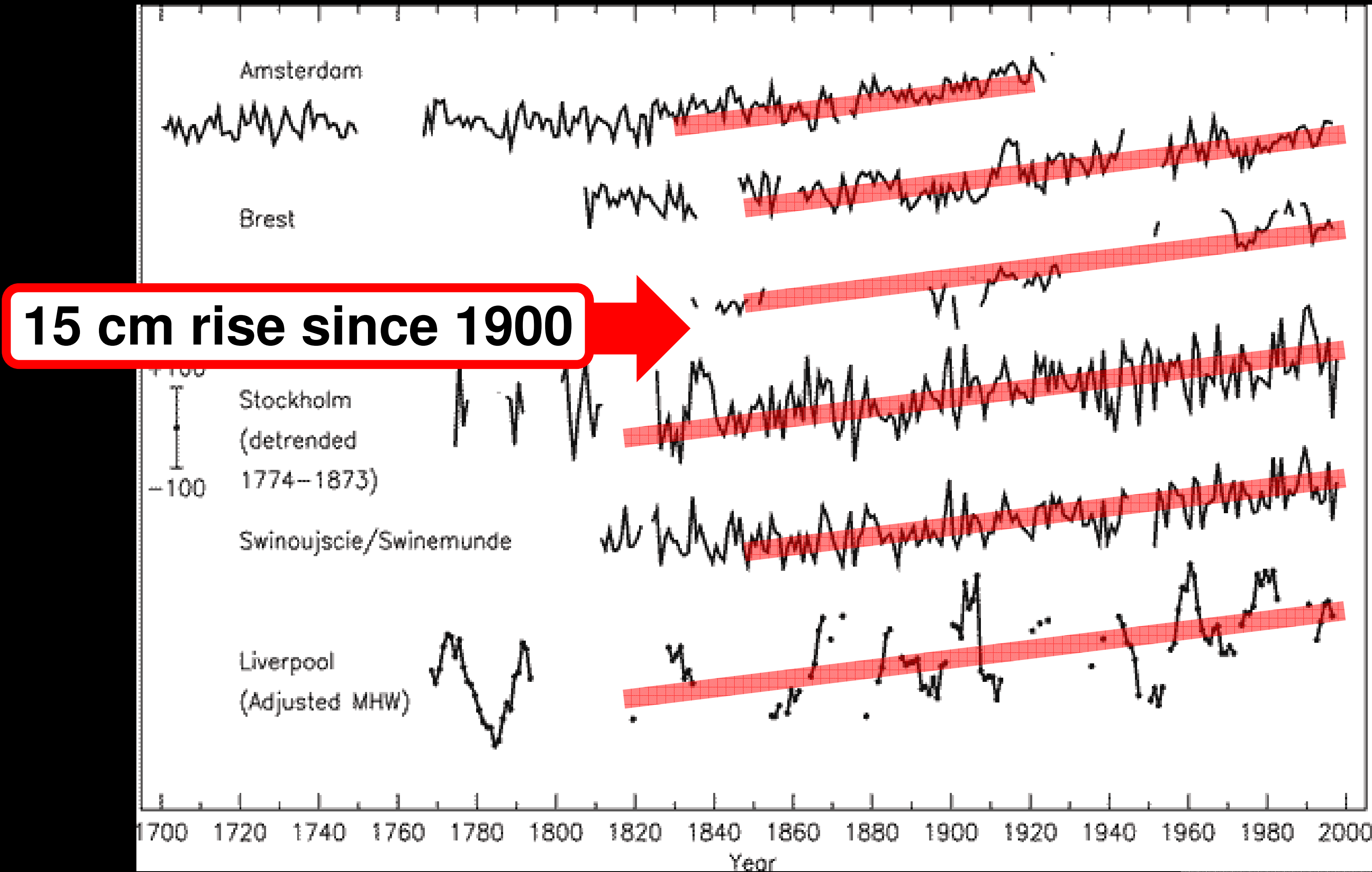
1. Introduction

- IPCC Assessment reports (1990, 1995, 2001, 2007)



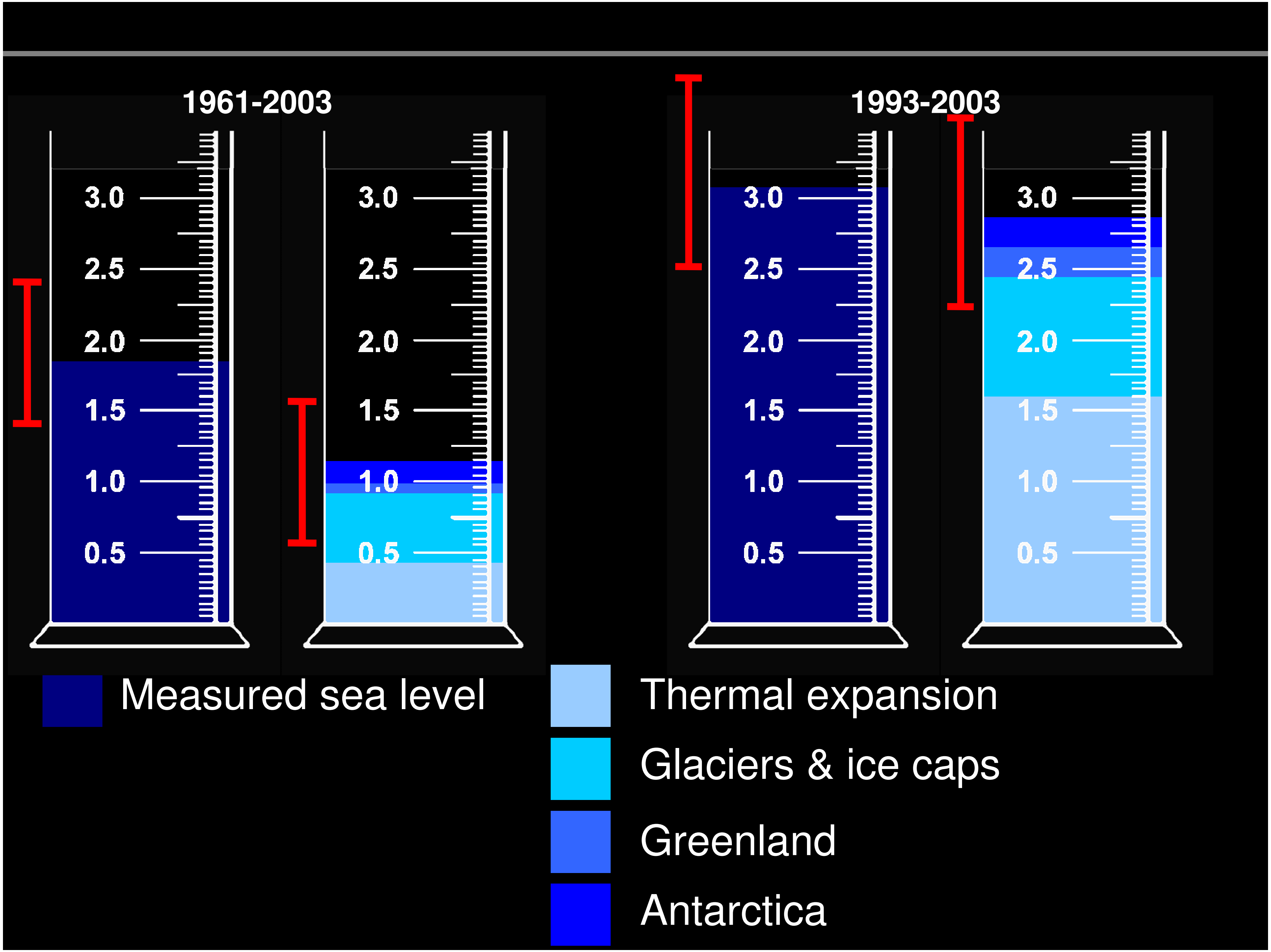
IPCC, 2001

• IPCC Assessment reports (1990, 1995, 2001, 2007)

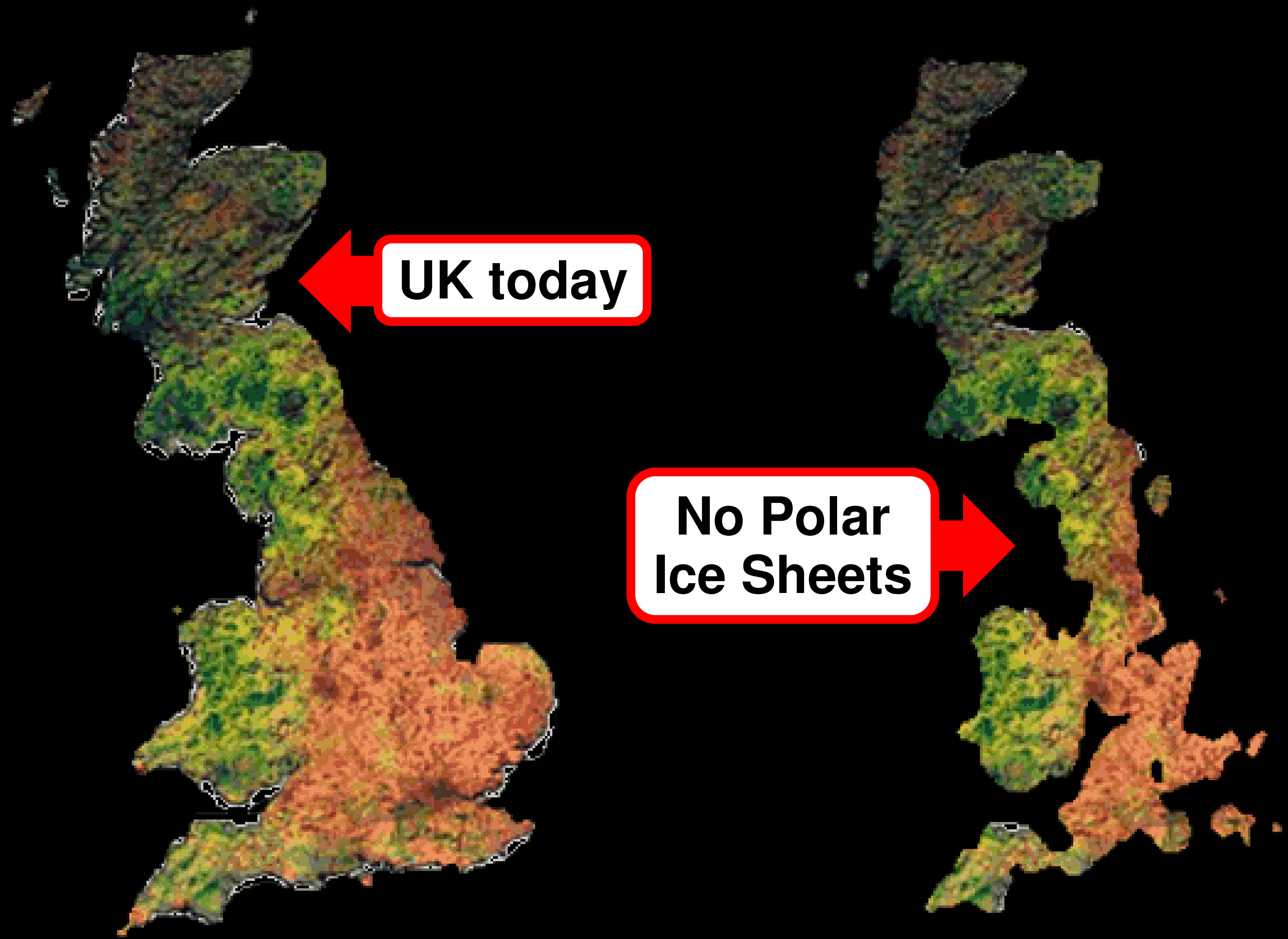


IPCC, 2001

Global sea level rise



1961-2003
1993-2003
3.0
2.5
2.0
1.5
1.0
0.5
Measured sea level
Thermal expansion
Glaciers & ice caps
Greenland
Antarctica


UK today
No Polar
Ice Sheets

- Range equals 1.0 to -0.15 mm yr^{-1} sea level contribution
- Factor 3 poorer certainty than last three IPCC reports !

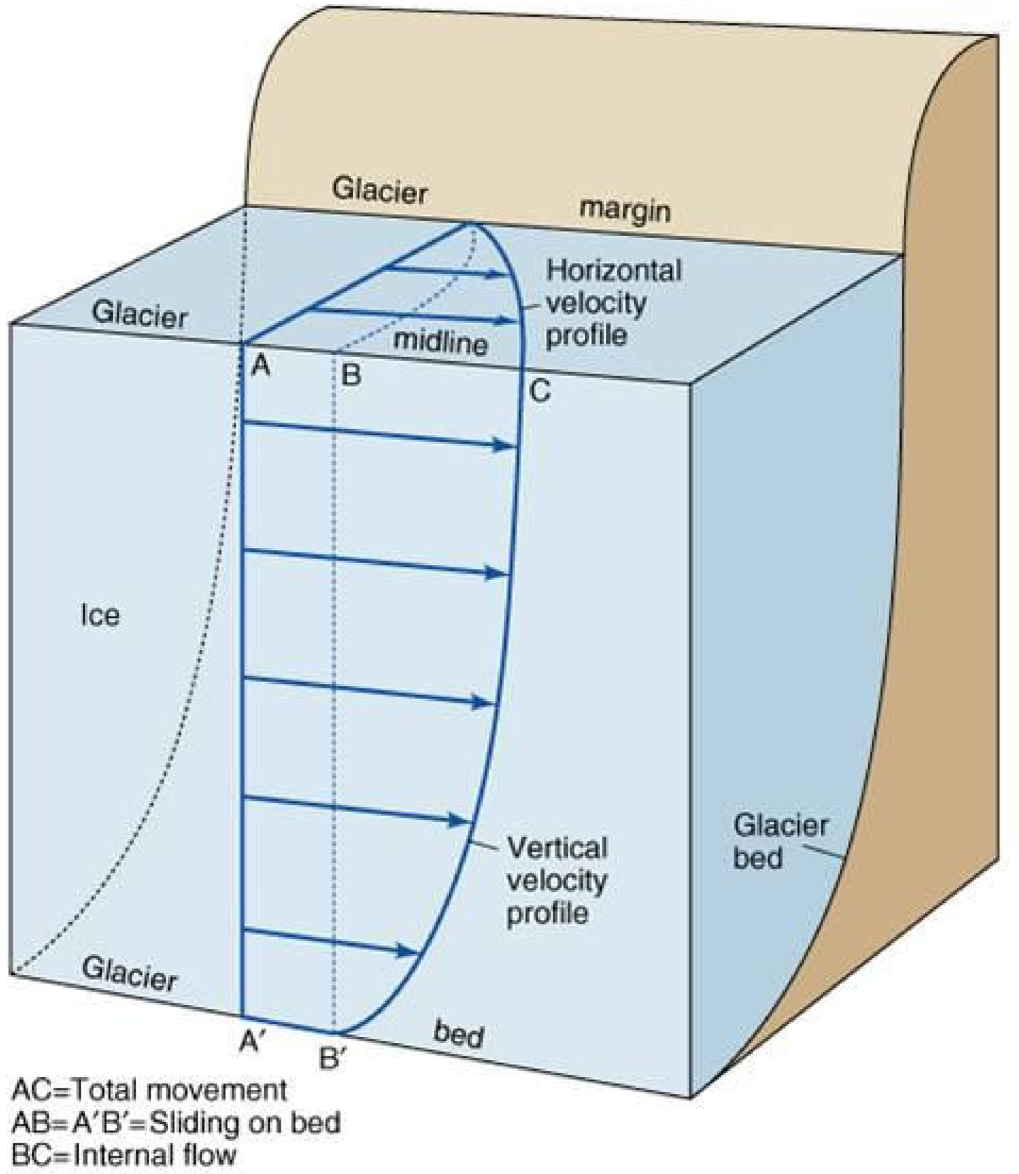
Table 1. Mass balance of the East Antarctic (EAIS) West Antarctic (WAIS) Antarctic (AIS) and Greenland (GIS) ice sheets as determined by a range of techniques and studies. Not all studies surveyed all of the ice sheets, and the surveys were conducted over different periods within the time frame 1992 to 2006. For comparison, 360 Gt of ice is equivalent to 1 mm of eustatic sea level rise.

Study	Survey period	Survey area 10^6 km^2 (%)	EAIS MB Gt yr^{-1}	WAIS MB Gt yr^{-1}	AIS MB Gt yr^{-1}	GIS MB Gt yr^{-1}
Wingham et al. [1998][1]	1992-1996	7.6 (54)	-1±53	-59±50	-60±76	
Krabill et al. [2000][1]	1993-1999	1.7 (12)				-47
Rignot and Thomas [2002][2]	1995-2000	7.2 (51)	22±23	-48±14	-26±37	
Davis and Li [2004]	1992-2002	8.5 (60)			+42±23	
Davis et al.[2005][1]	1992-2003	7.1 (50)	+45±7			
Velicogna and Wahr [2005][3]	2002-2004	1.7 (12)				-75±21
Zwally et al. [Dec 2005][1]	1992-2002	11.1 (77)	+16±11	-47±4	-31±12	+11±3
Rignot a… [2006][2]	1996…					-83±28 -127±28 -205±38
Velicogn…						
Ramillie…						-169±66
Wingham et al. [2006][1]	1992-2003	8.5 (60)			+27±29	
Velicogna and Wahr [2006][3]	2002-2006	1.7 (12)				-227±33
Chen et al. [2006][3]	2002-2005	1.7 (12)				-219±21
Luthcke et al. [2006][3]	2003-2005	1.7 (12)				-101±16
Range			-1 to +67	-136 to -47	-139 to +42	-227 to +11

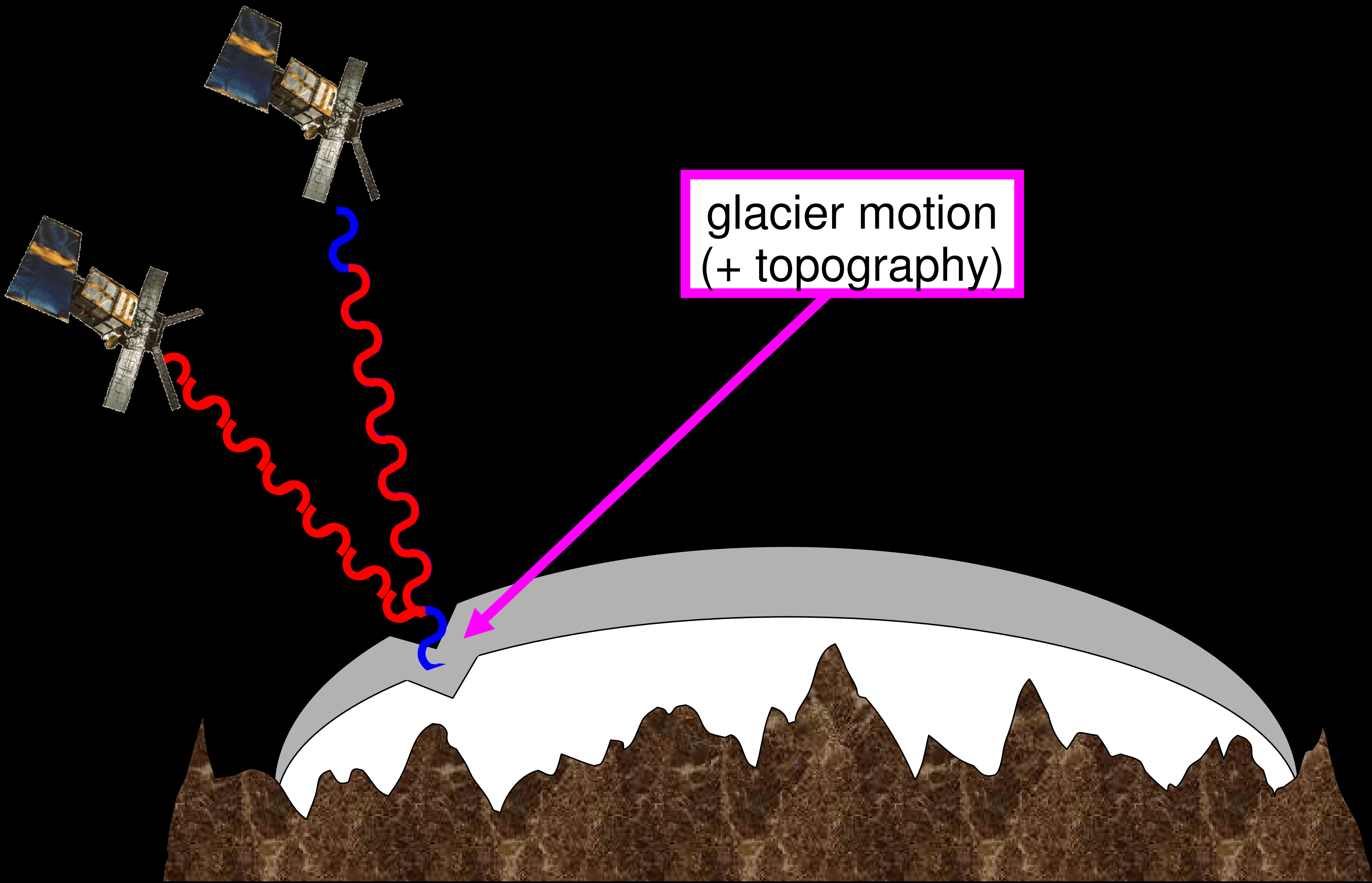
[1]Altimetry; [2]InSAR mass budget; [3]Gravimetry

-139 to +42 -227 to +11

2. Methods


Glacier
margin
Horizontal
velocity
profile
Glacier
midline
A
B
C
Ice
Vertical
velocity
profile
Glacier
bed
Glacier
bed
A′
B′
AC=Total movement
AB=A′B′=Sliding on bed
BC=Internal flow

InSAR



ERS 1&2 Tandem phase

1995/1996

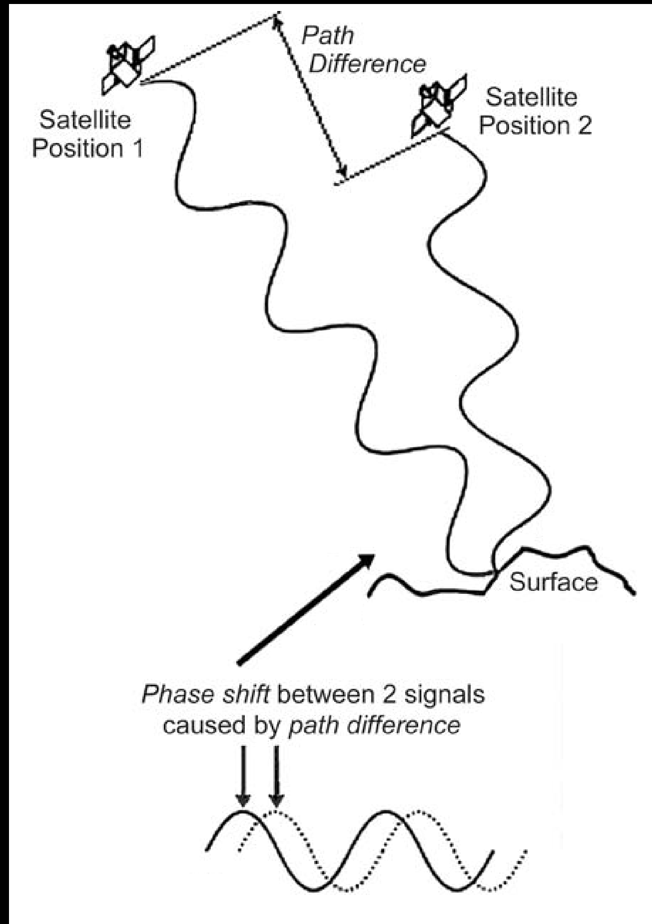
SAR image pairs used for InSAR

1-day separation

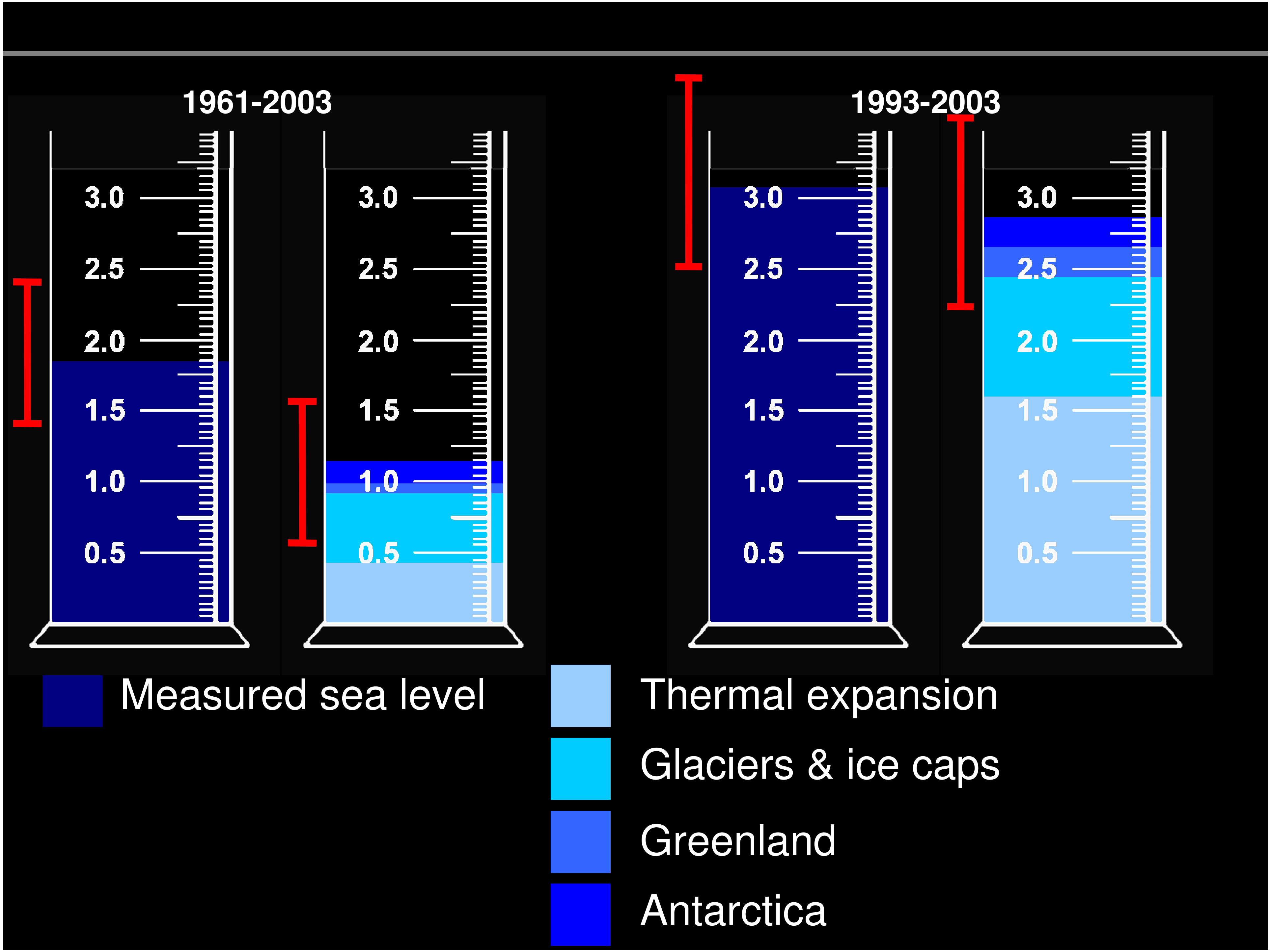
Phase differences contain topography and velocity information

Topography isolated by differencing winter pairs

Assumes identical flow



3. Ice caps



1961-2003
1993-2003
3.0
2.5
2.0
1.5
1.0
0.5
Measured sea level
Thermal expansion
Glaciers & ice caps
Greenland
Antarctica

Cryospheric component	Sea Level Equivalent (mm yr^{-1}) 1961–2003	1993–2003
Glaciers and Ice Caps	+0.32 to +0.68	+0.55 to +0.99
Greenland	–0.07 to +0.17	+0.14 to +0.28
Antarctica	–0.28 to +0.55	–0.14 to +0.55
Total (adding ranges)	–0.03 to +1.40	+0.55 to +1.82
Total (Gaussian errorsummation)	+0.22 to +1.15	+0.77 to +1.60

“The large uncertainties reflect the difficulties in estimating the global ice mass and its variability...**A regional extension of the monitored ice masses and an improvement of measurement and extrapolation techniques are urgently required**” - Lemke et al., 2007

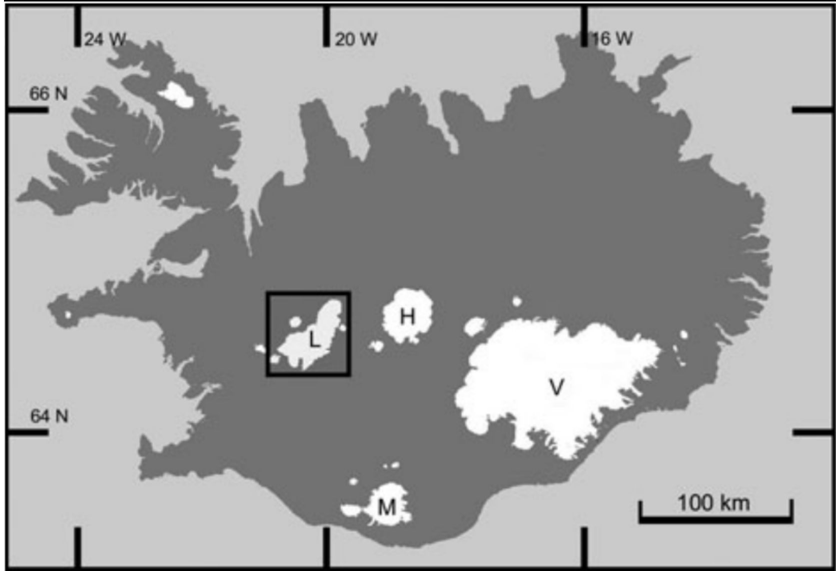
Ice caps - motivation

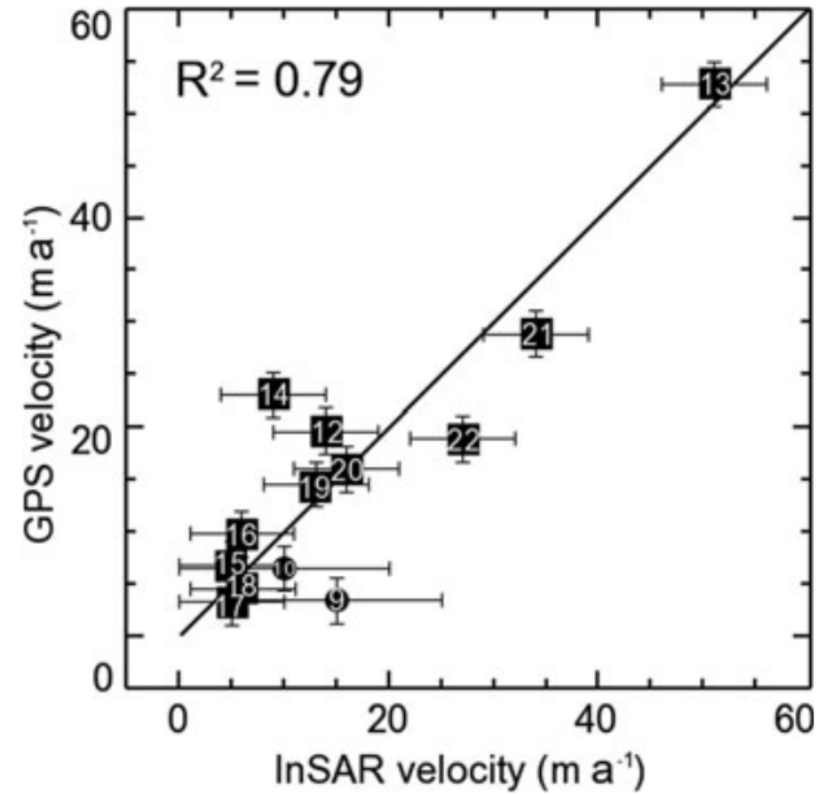
1. Natural laboratory for investigating the dynamics of both land- and marine-terminating glaciers
2. Maritime setting and size make them sensitive indicator of changes in climate
   - High rates of accumulation & ablation
3. Widely distributed – can reveal regional trends

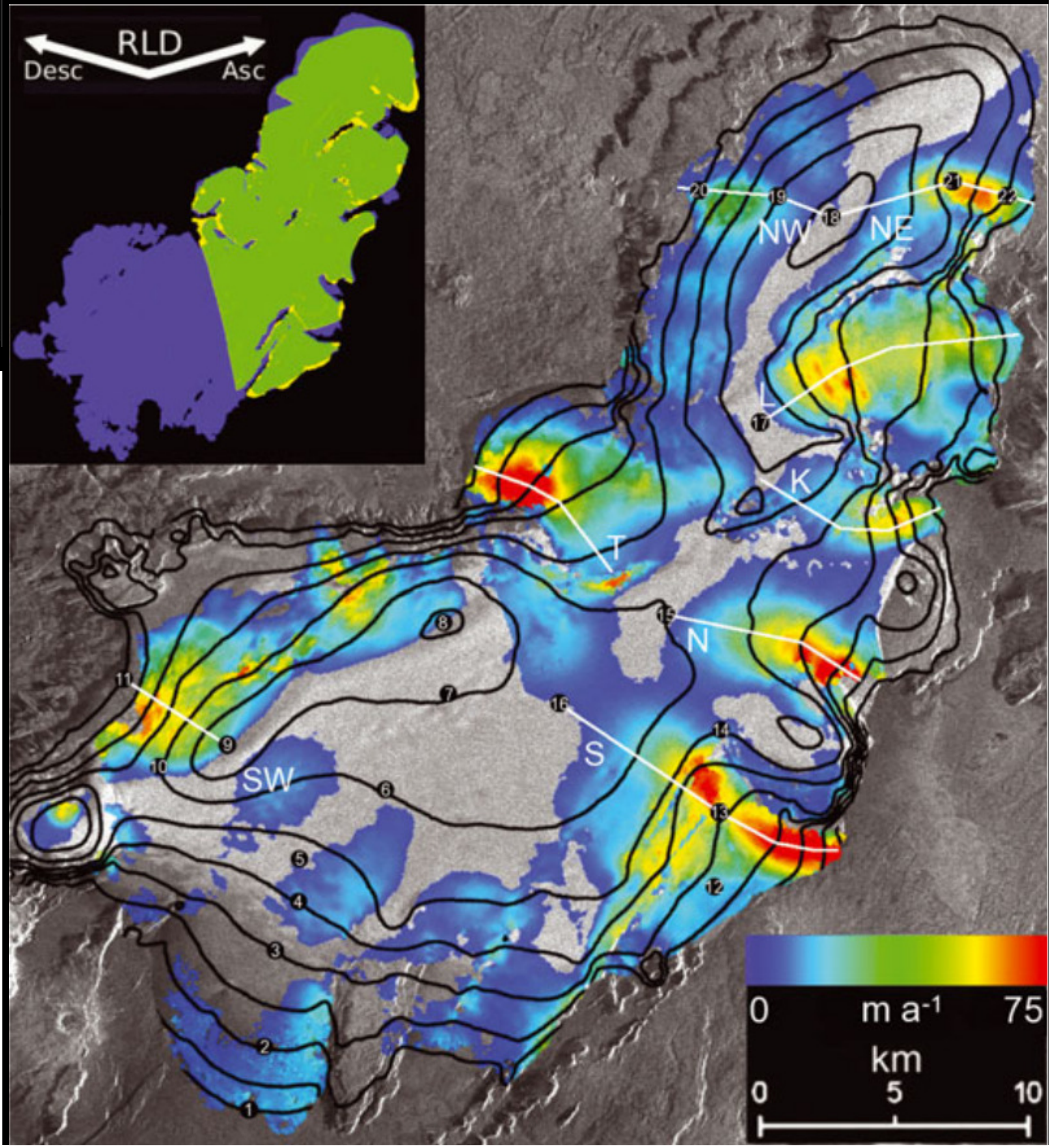
3.1. Langjokull Ice Cap

Palmer et al., Jglac, 2009

Langjokull Area = 925 km^2







Tourist Attractions

F2 | Gullfoss C4 | Jökulsá-canyon F2 | Mt. Dyrfjöll G2 | Reykhólar B2 | Þingvellir C4 |

F350


F350
ICELAND GLACIOLOGICAL SOCIETY

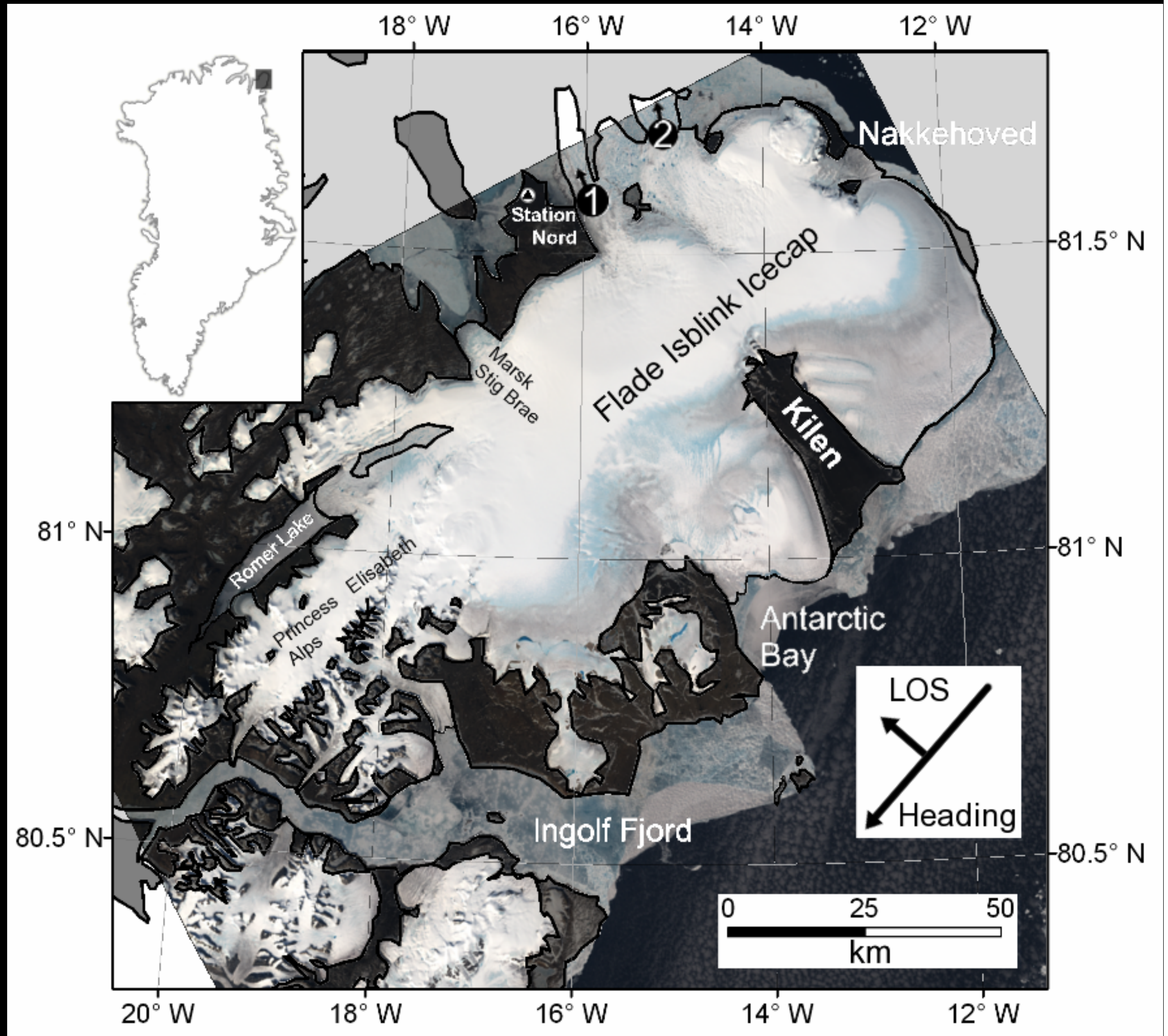

PATROL
PO-
444


3.2. Flade Isblink Ice Cap

Flade Isblink Ice Cap

8500 km^2
8 major outlet glaciers

- 6 marine
- 2 terminate in a lake



Palmer et al., in press (JGR-ES)

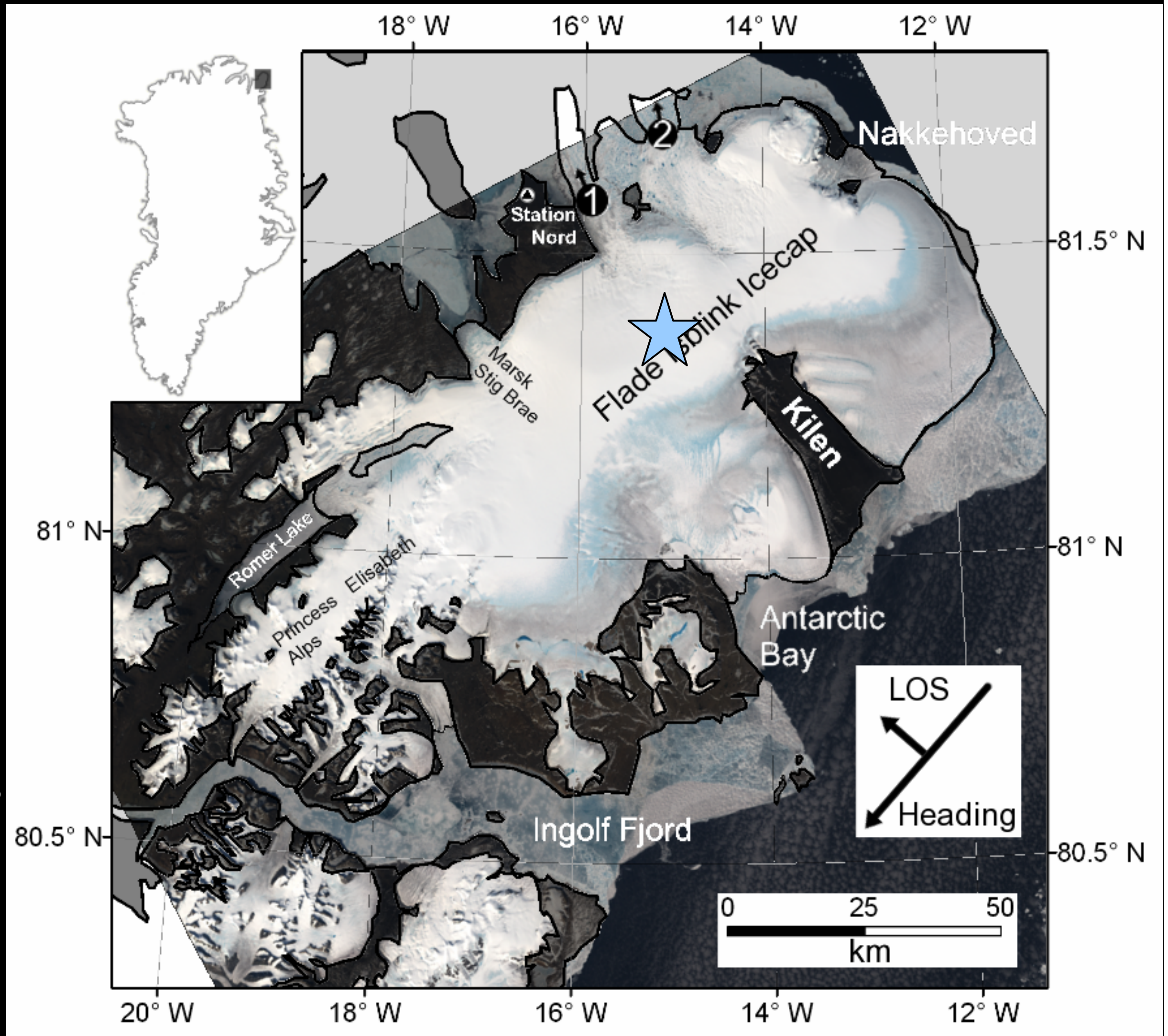
CreSIS/Niels Bohr Institute 2006

Radar survey at central summit, 430m ice core extracted

Ice thickness of 550m measured with radar

Higgins (1991)

Airborne photography used to measure 17-year mean flow rate (1961-1978) at single locations on 2 largest outlet glaciers.

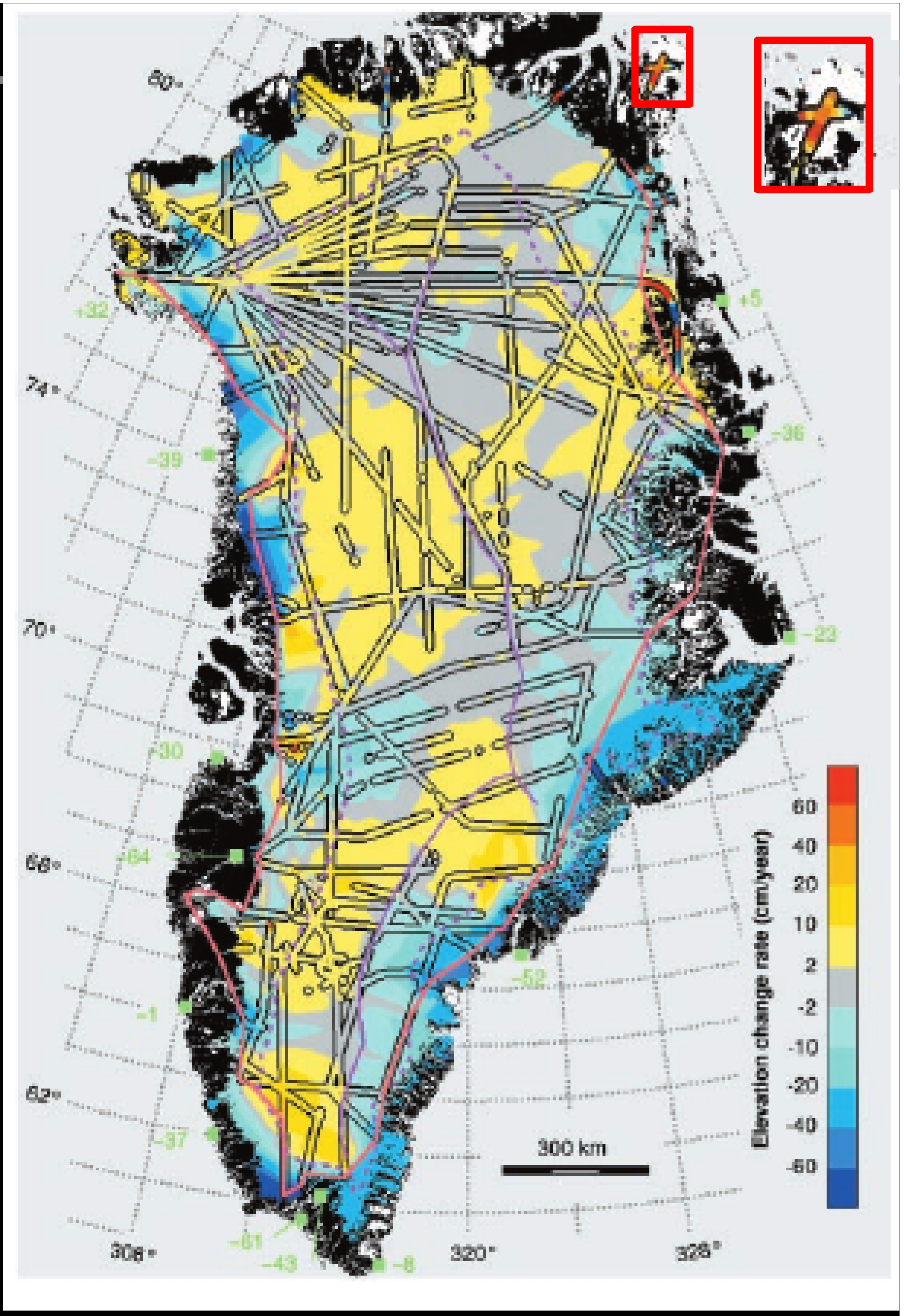


Positive elevation change

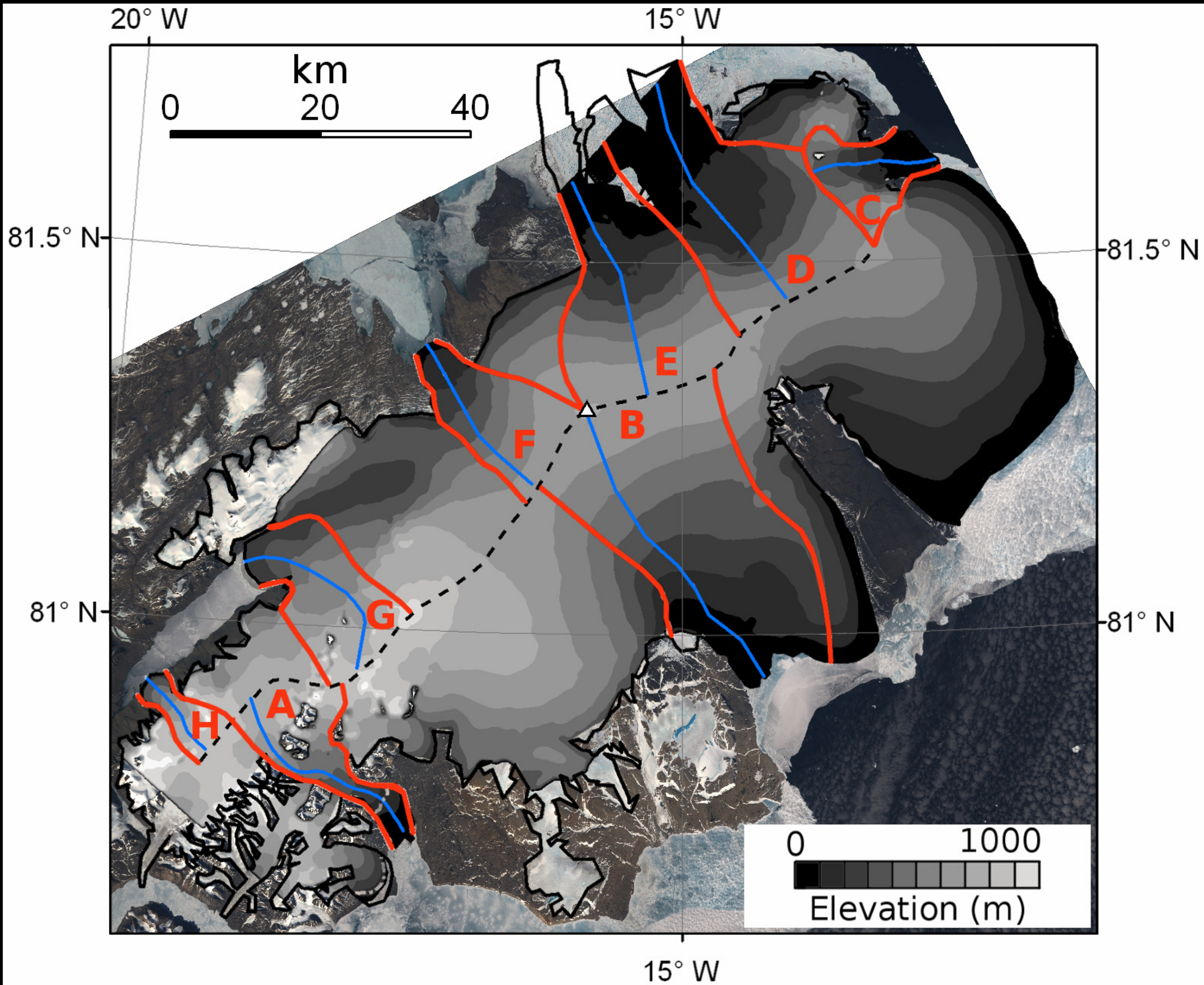
Krabill et al., (2000)

Aircraft laser altimeter 1994 & 1999

Mean thickening of ~0.5 m/year

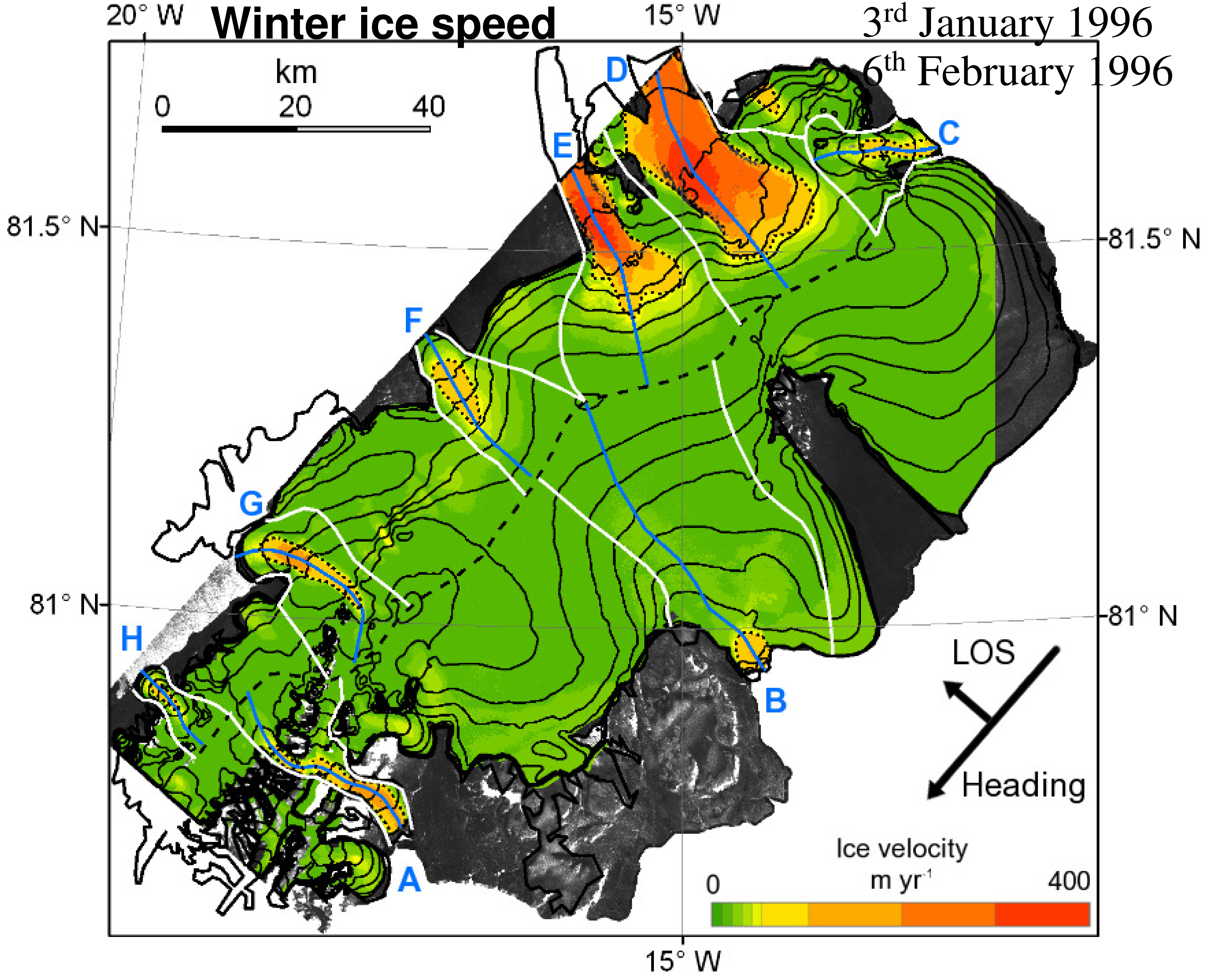


InSAR DEM

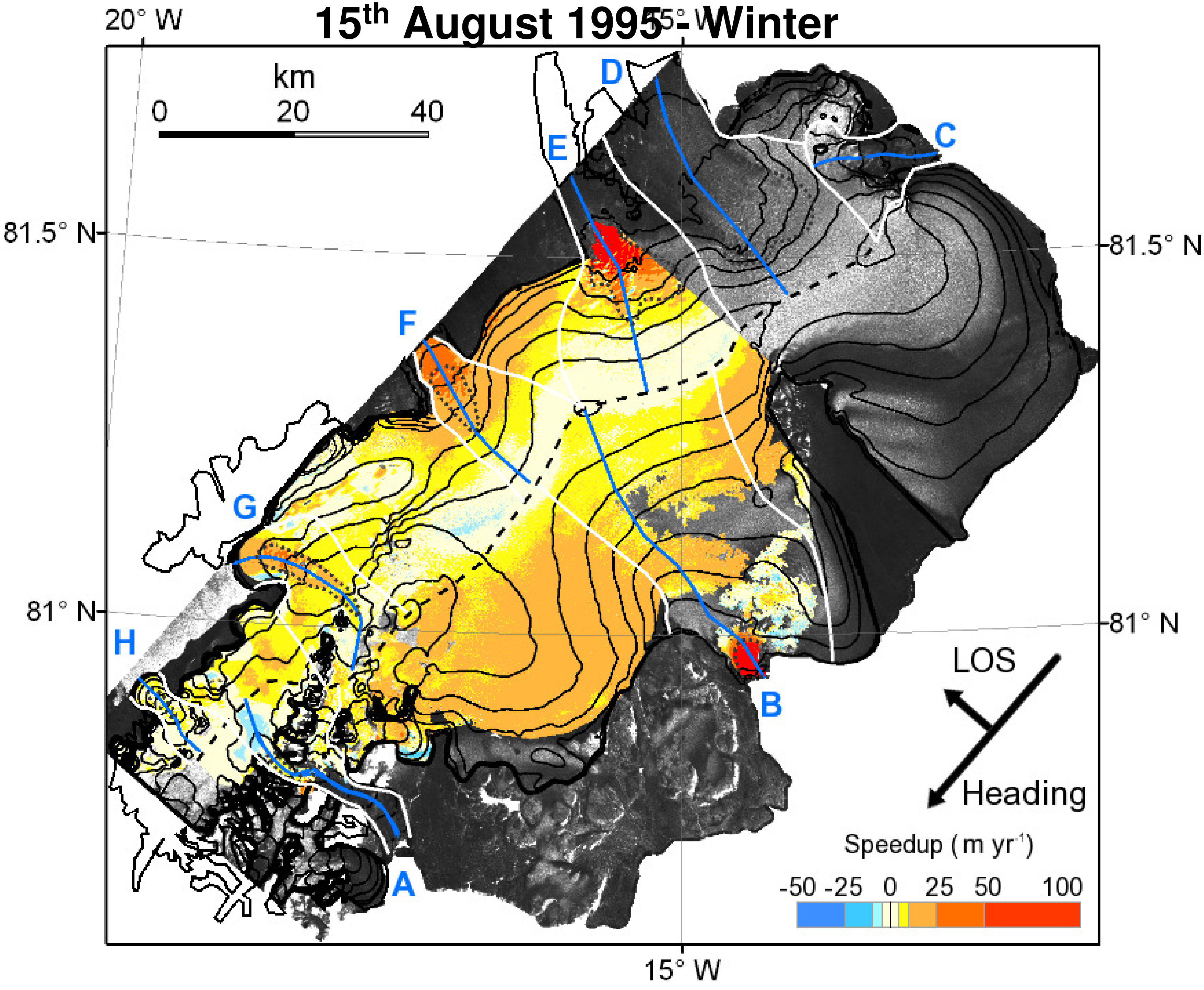

20° W
15° W
km
0
20
40
81.5° N
81.5° N
81° N
81° N
A
B
C
D
E
F
G
H
0
1000
Elevation (m)
15° W

Winter ice speed

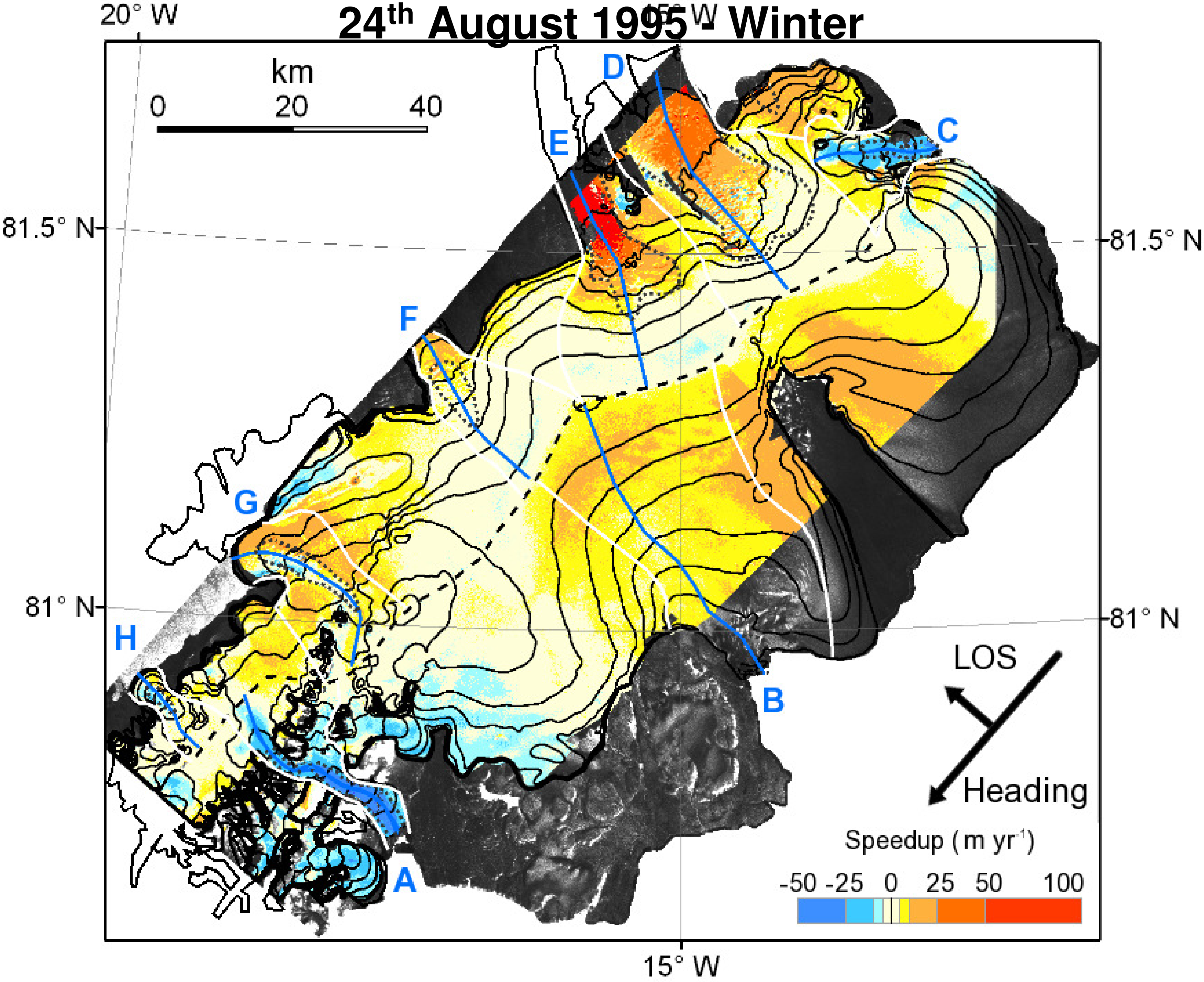
3rd January 1996
6th February 1996



15th August 1995 - Winter



24th August 1995 - Winter



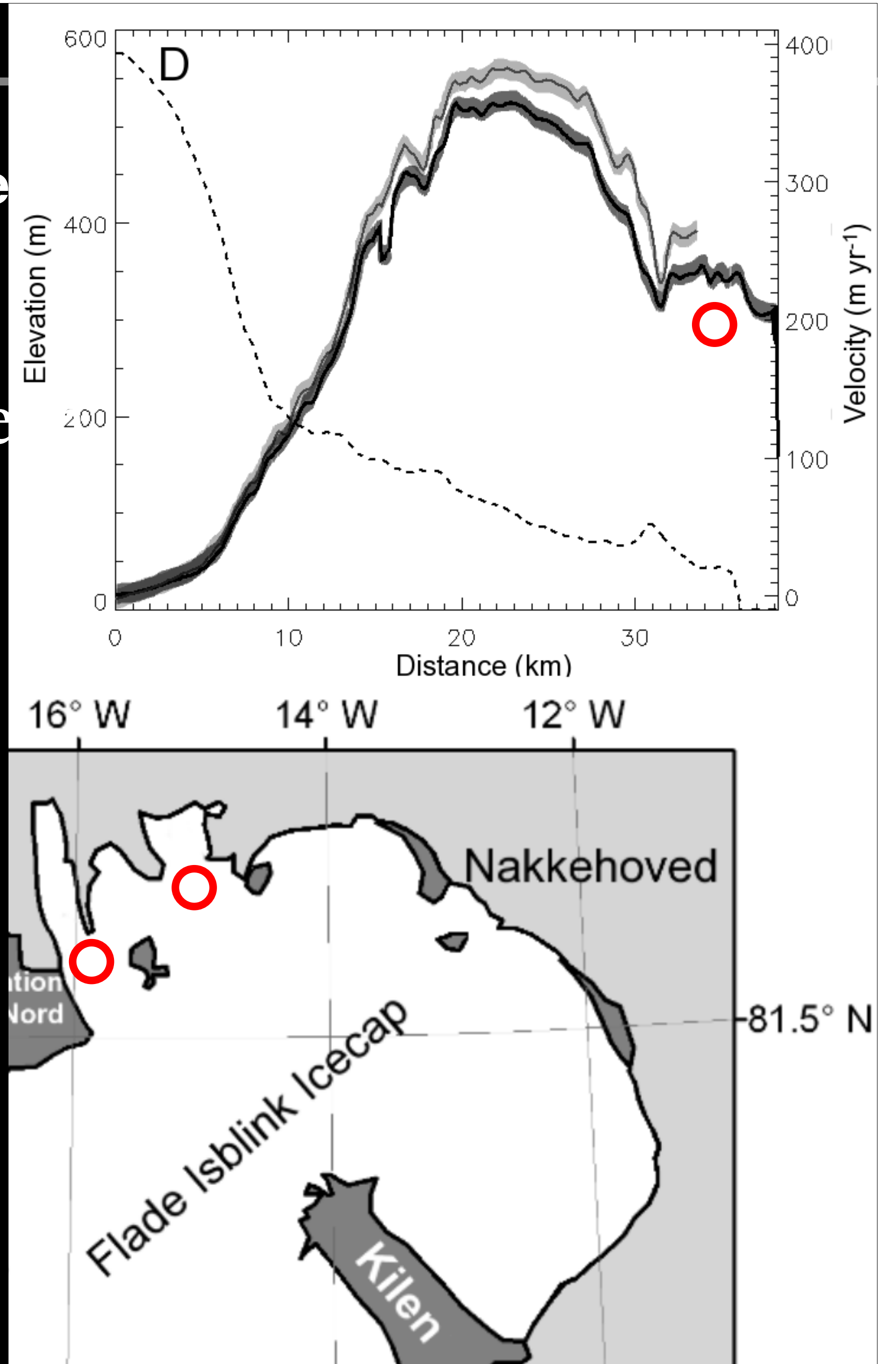
Comparison with previous measureme
(Higgins, 1991)

Faster flow at D in winter Jan/Feb 1996 than 17-year me rate (1961-1978)

Changes in surface mass balance?

Aliasing of periodic changes?

Surge?



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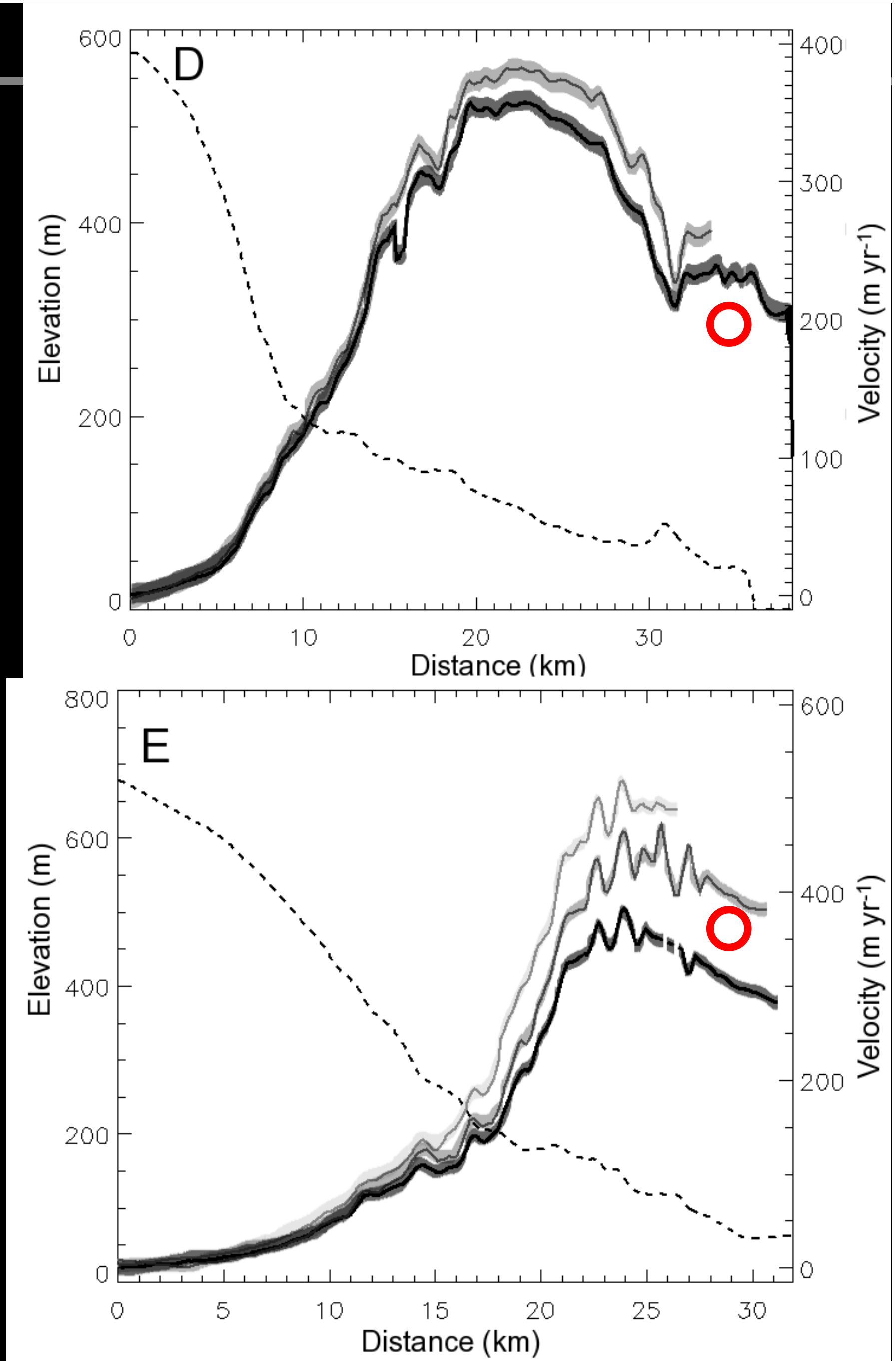


Summary

Fine-resolution digital elevation model of the FIIC

100 m horizontal resolution and covers 91 % of the FIIC

First maps of ice flow

We mapped the ice flow speed of 90 % of the FIIC in winter 1996

82 % on 15th August 1995 (faster over 39 % of FIIC)

60 % on 24th 1995 (faster over 30 % of FIIC)

Summary

7 of the 8 FIIC outlet glaciers exhibited seasonal variations in ice speeds

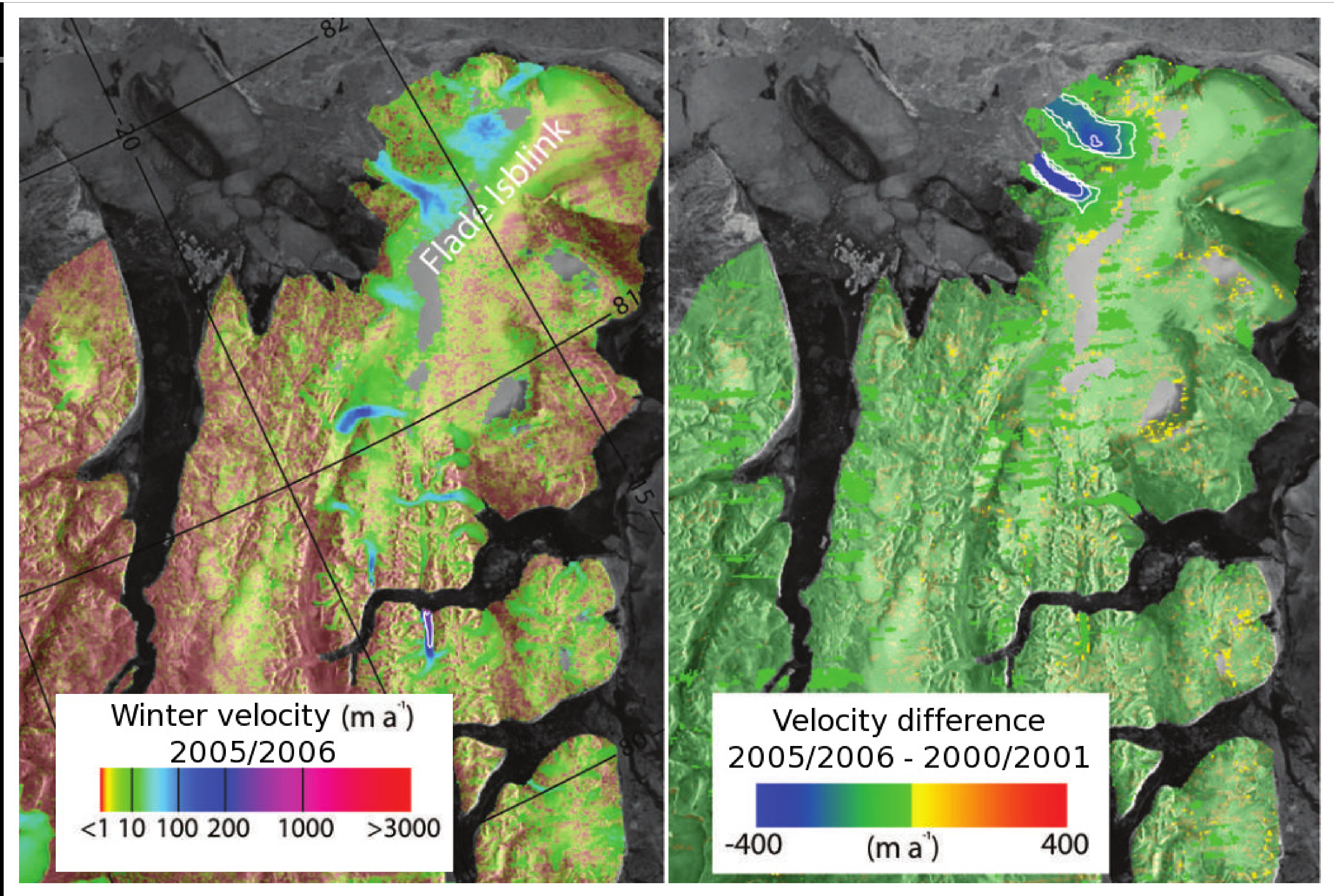
no variation observed at the smallest glacier.

Large range of seasonality in the glaciers draining a single ice cap

no simple relationship between glacier type and seasonality of motion.

Evidence of inter-annual changes in flow speed at the largest outlet glaciers.

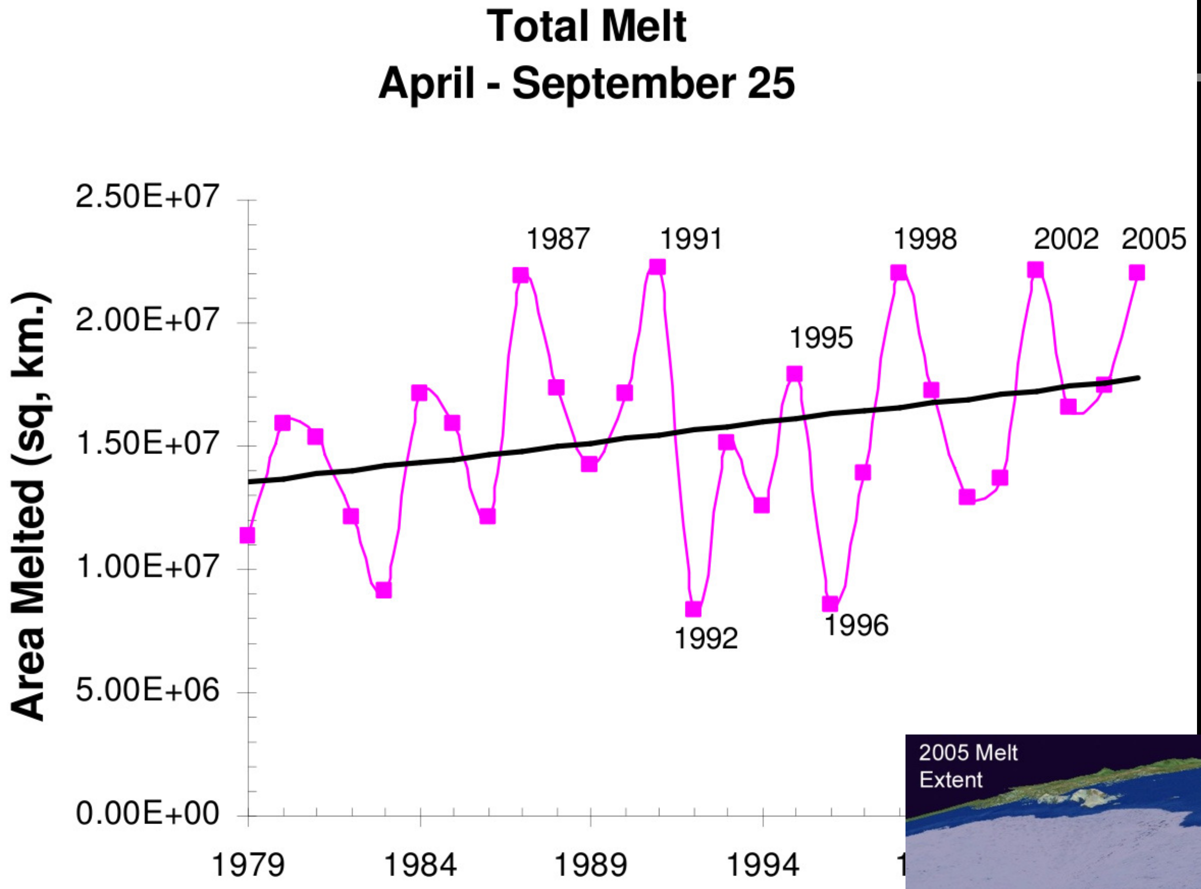
Is this related to observed positive elevation trend?



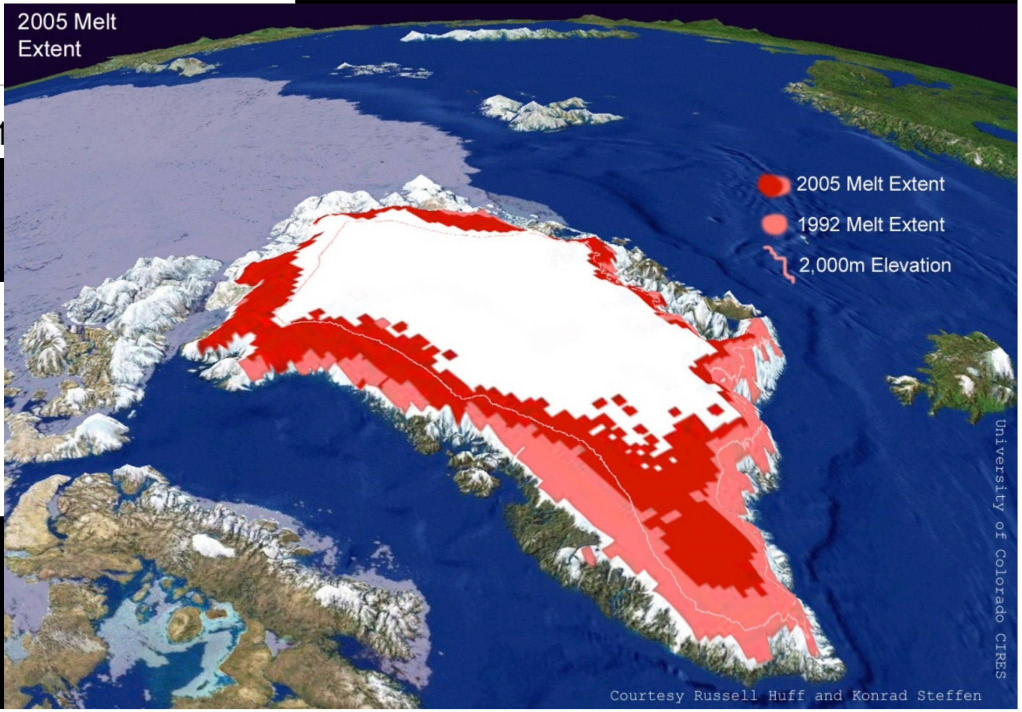
Joughin et al., 2010 Journal of Glaciology, *56*(197).

4. West Greenland

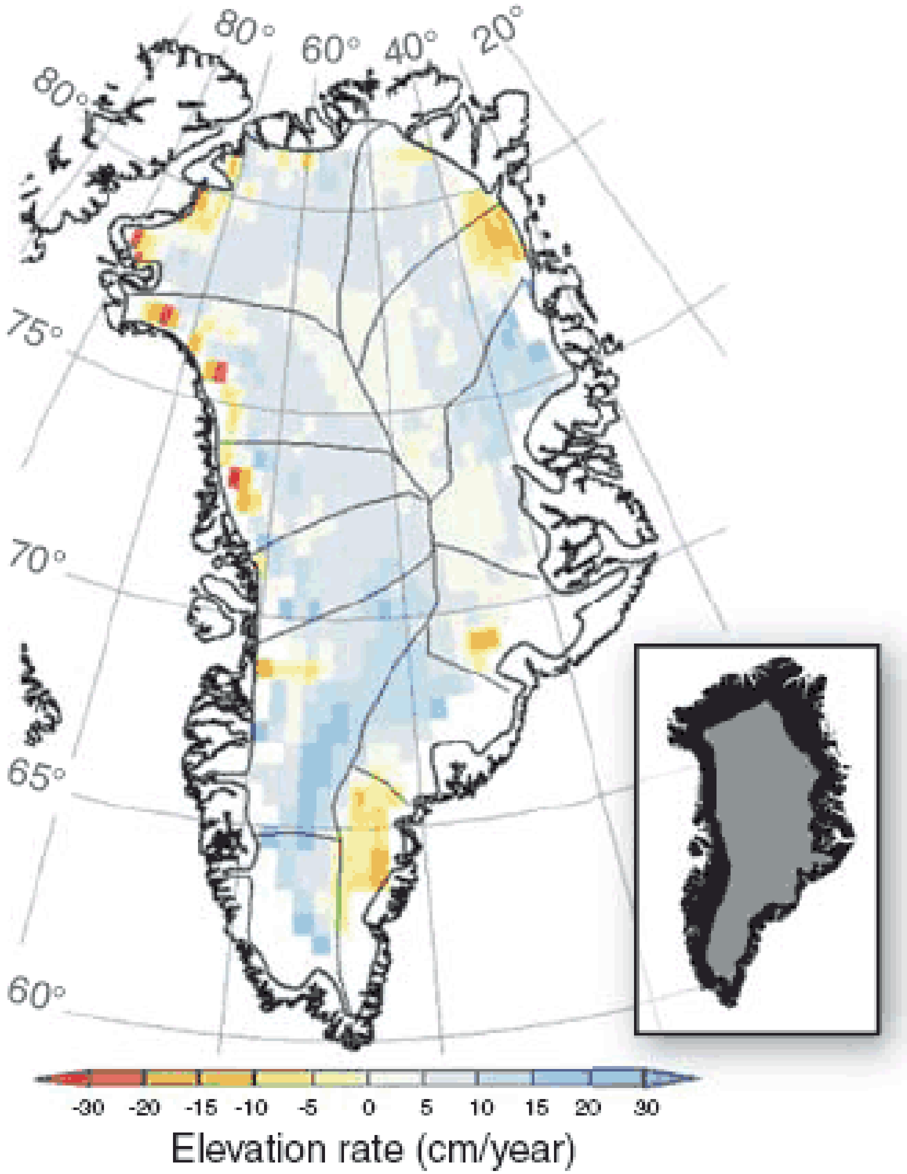
3. Greenland



Steffen et al.



- Passive microwave suggests high variability and potential secular trend in melting



- Greenland ice sheet is *losing* mass at coast due to melting and glacier acceleration

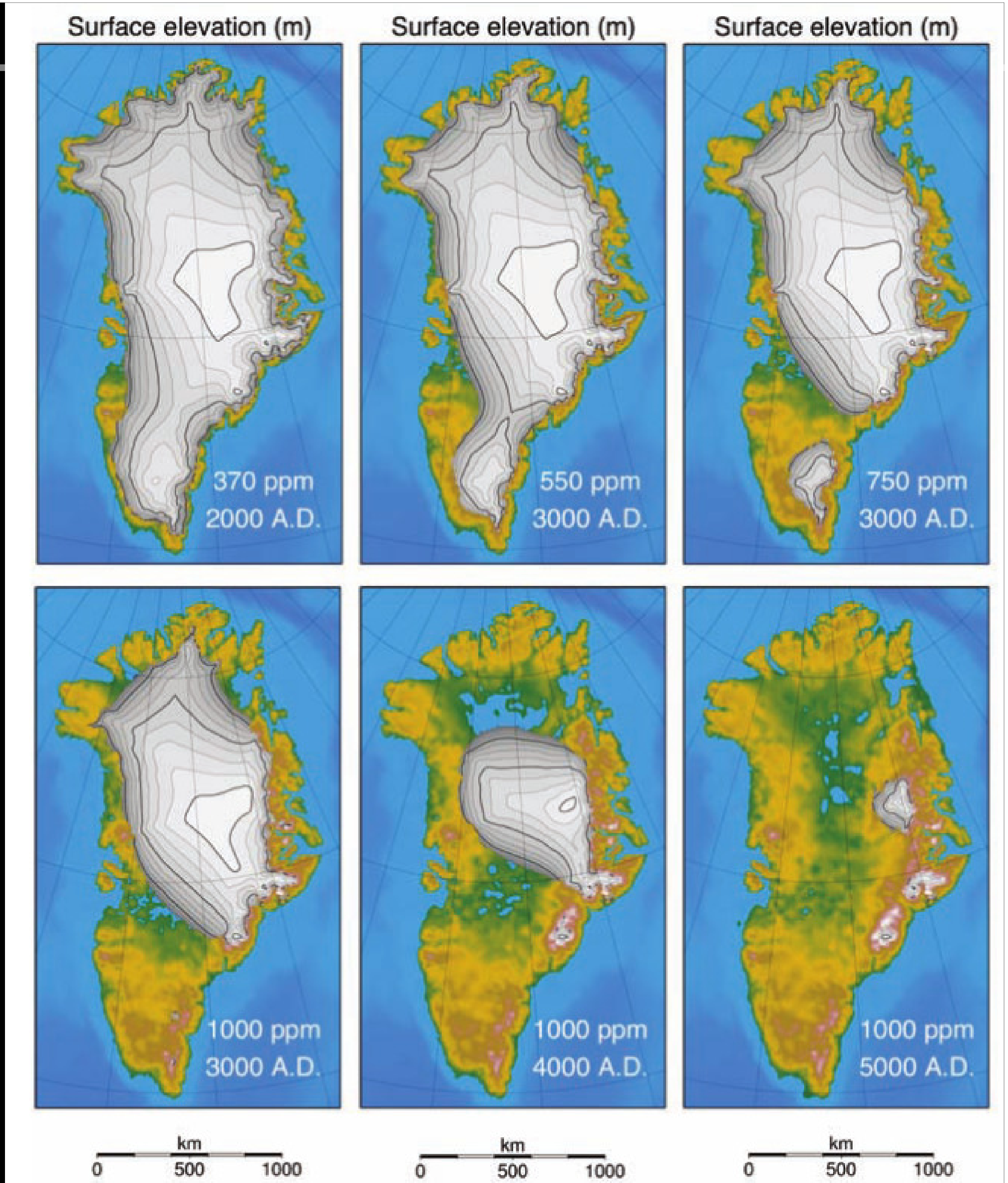
- …but, Greenland is *gaining* mass in interior due to increased snowfall

- All 3 processes will evolve as climate warms

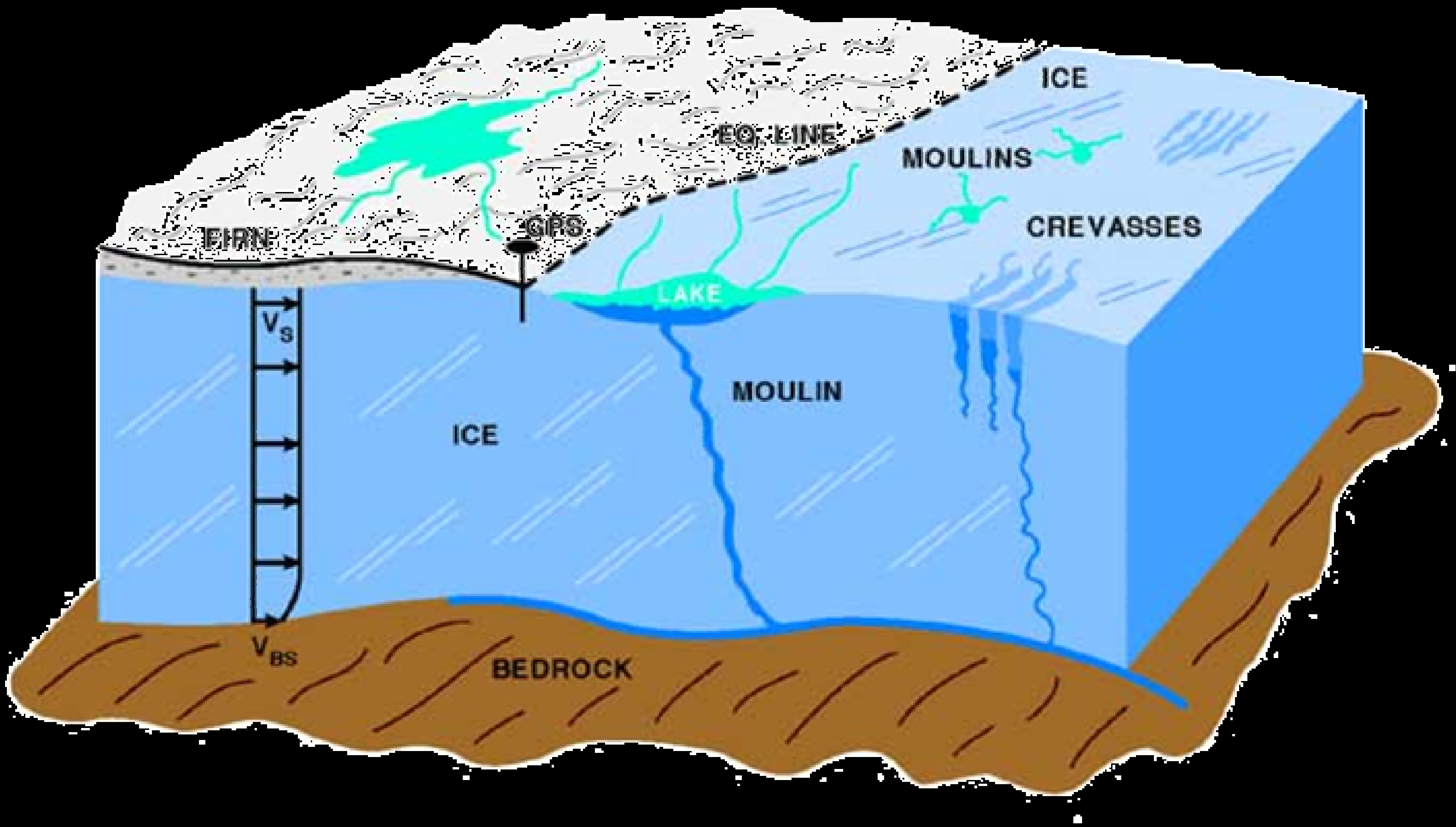
Johannesson et al., 2006, Science

❄ Projections of sea level rise due to Greenland ice sheet melting range from 2-8 m in 3000 years

❄ ….but, current generation of ice sheet models include no dynamic feedback



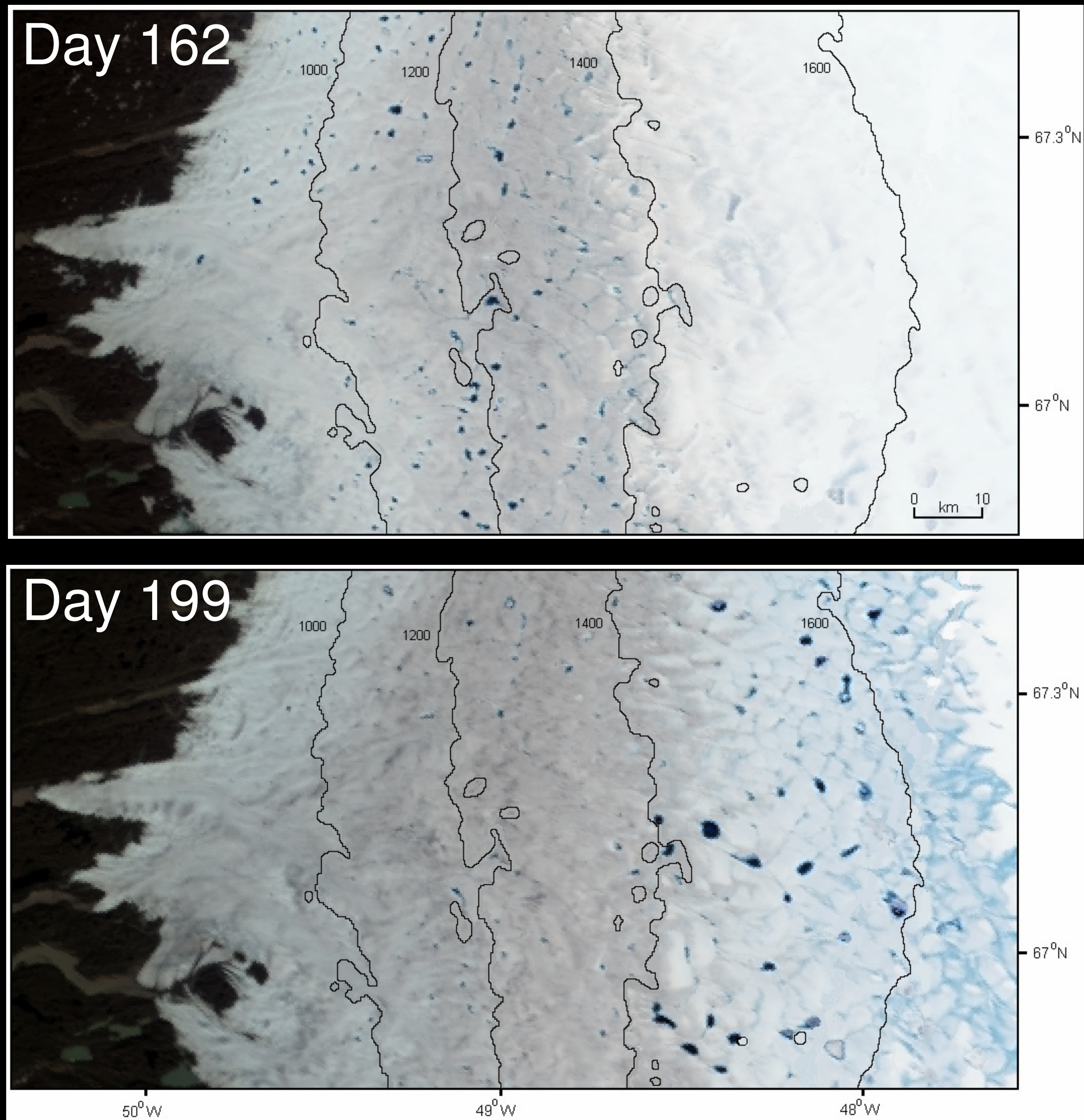
Alley et al., 2005, Science



Zwally et al., 2002, Science

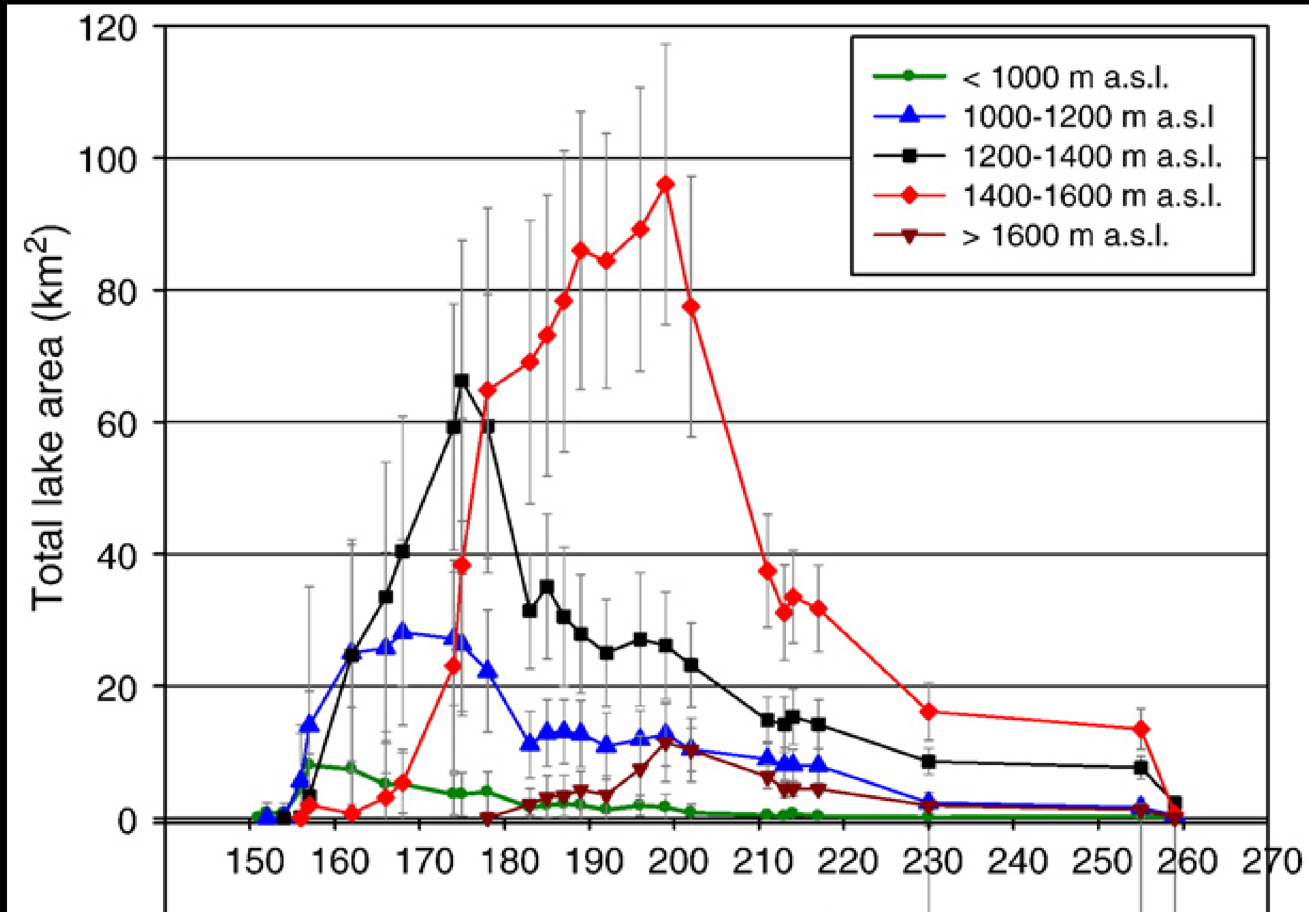
❄ Hypothesis that melting triggers fracture and basal lubrication

- Supra-glacial lakes visible in daily MODIS satellite imagery
- Distribution evolves over each season with warming and draining



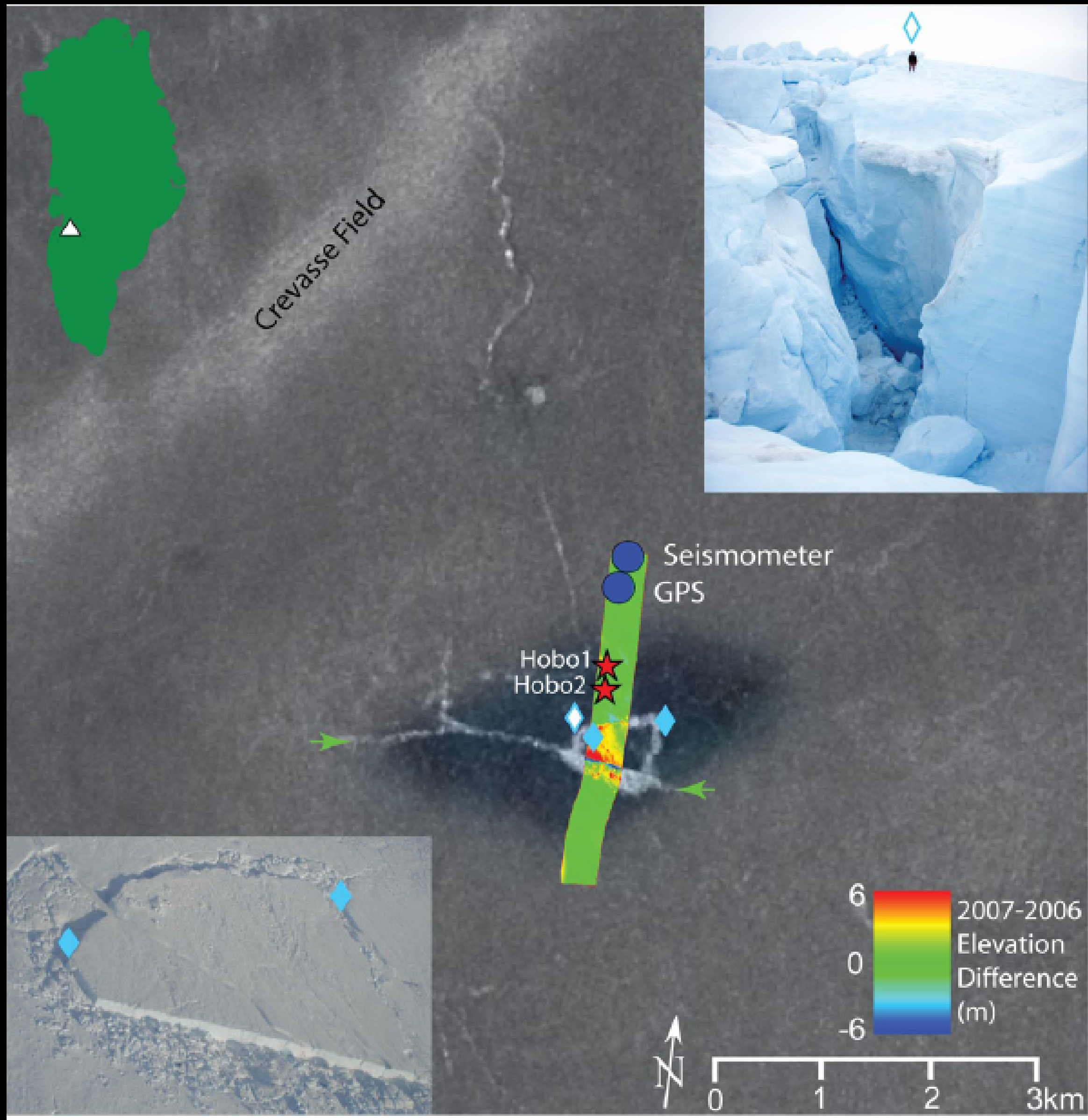
- Date of maximum area varies with altitude

- Area correlated with modelled runoff



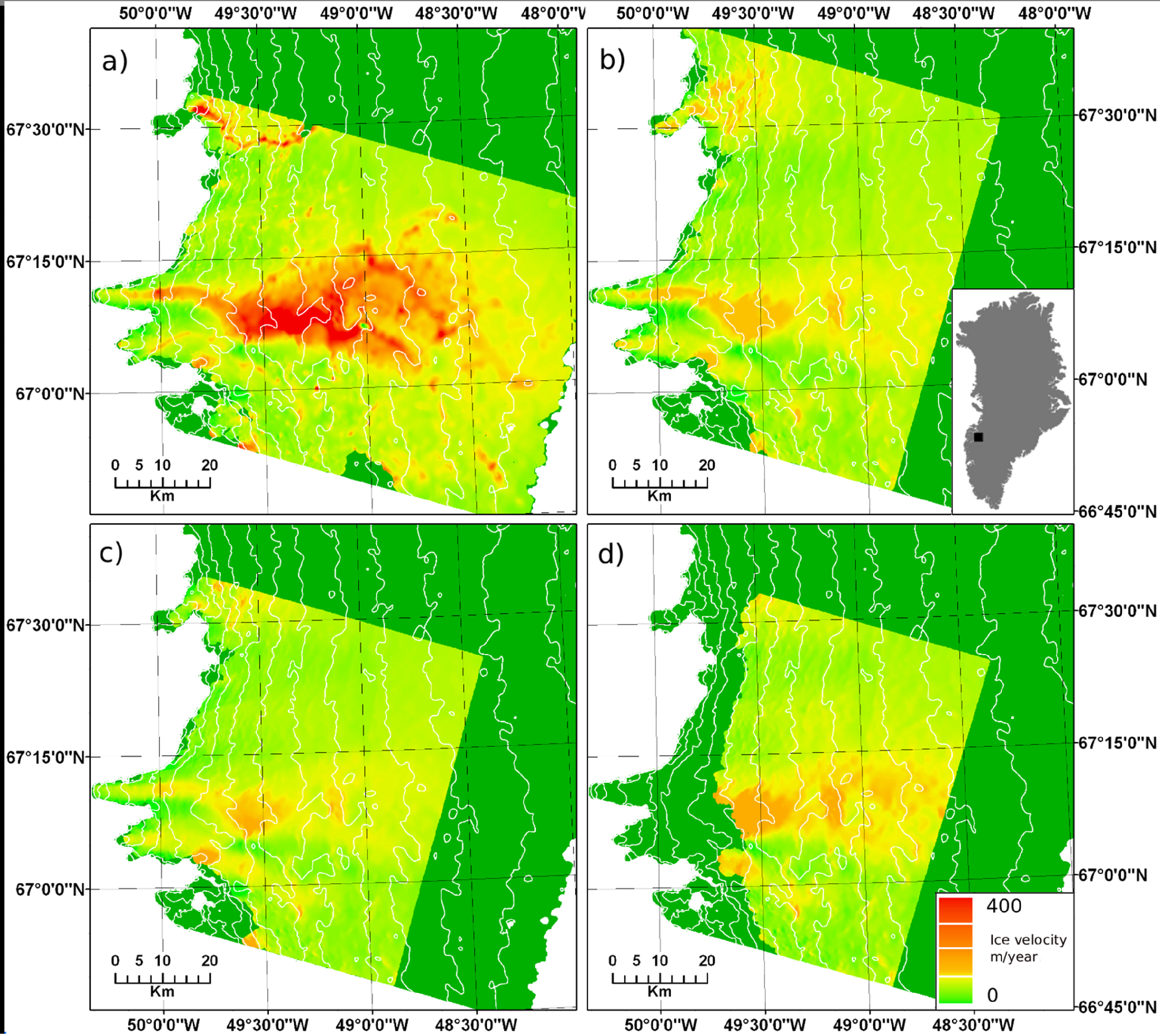
Sundal et al., 2009, RSE.

- Lakes drain in 1-2 hours !
- Water travels through 1km of ice
- Once at base, subglacial hydrology becomes complex

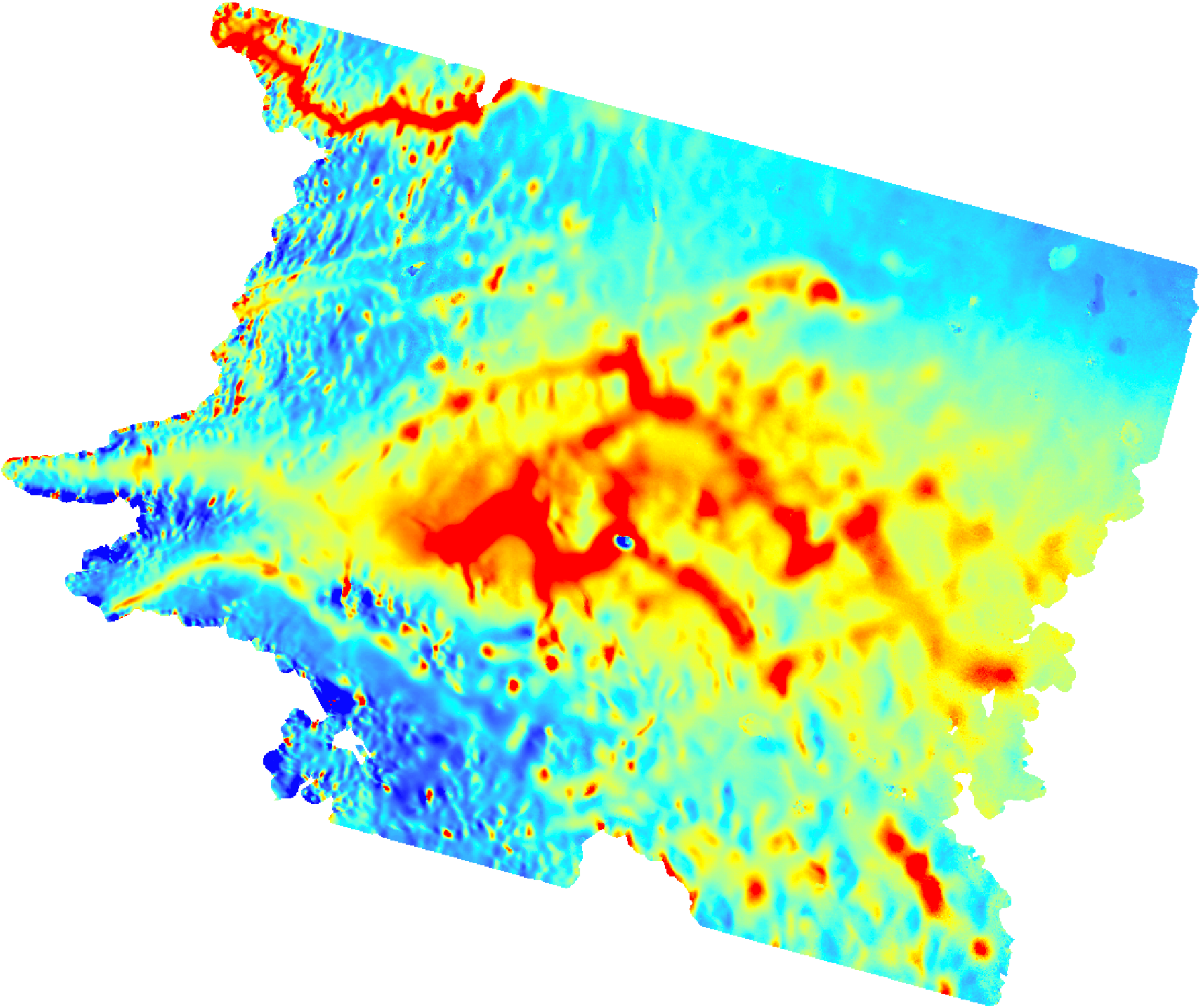


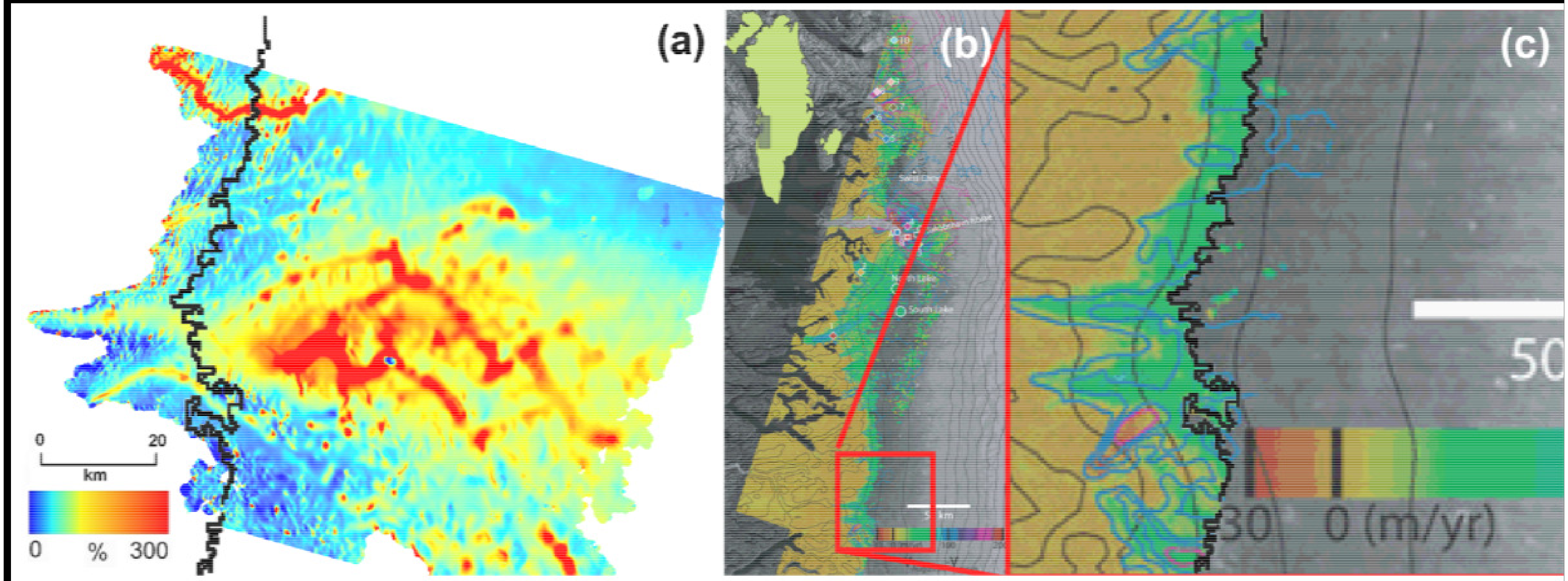
Das et al., 2008, Science


766
627
Majoriaq
672
623
764
724
800
Maniitsoq
816
585
695
Isunnguata Sermia
453
500
584
ajornitsut
Kangerlussuaq
600
520
Ørkendalen
Ammalortup Nunaa
706
Isorlersuaq
Umiiviit
708
830
Iperaarissap Nunaa
700
700

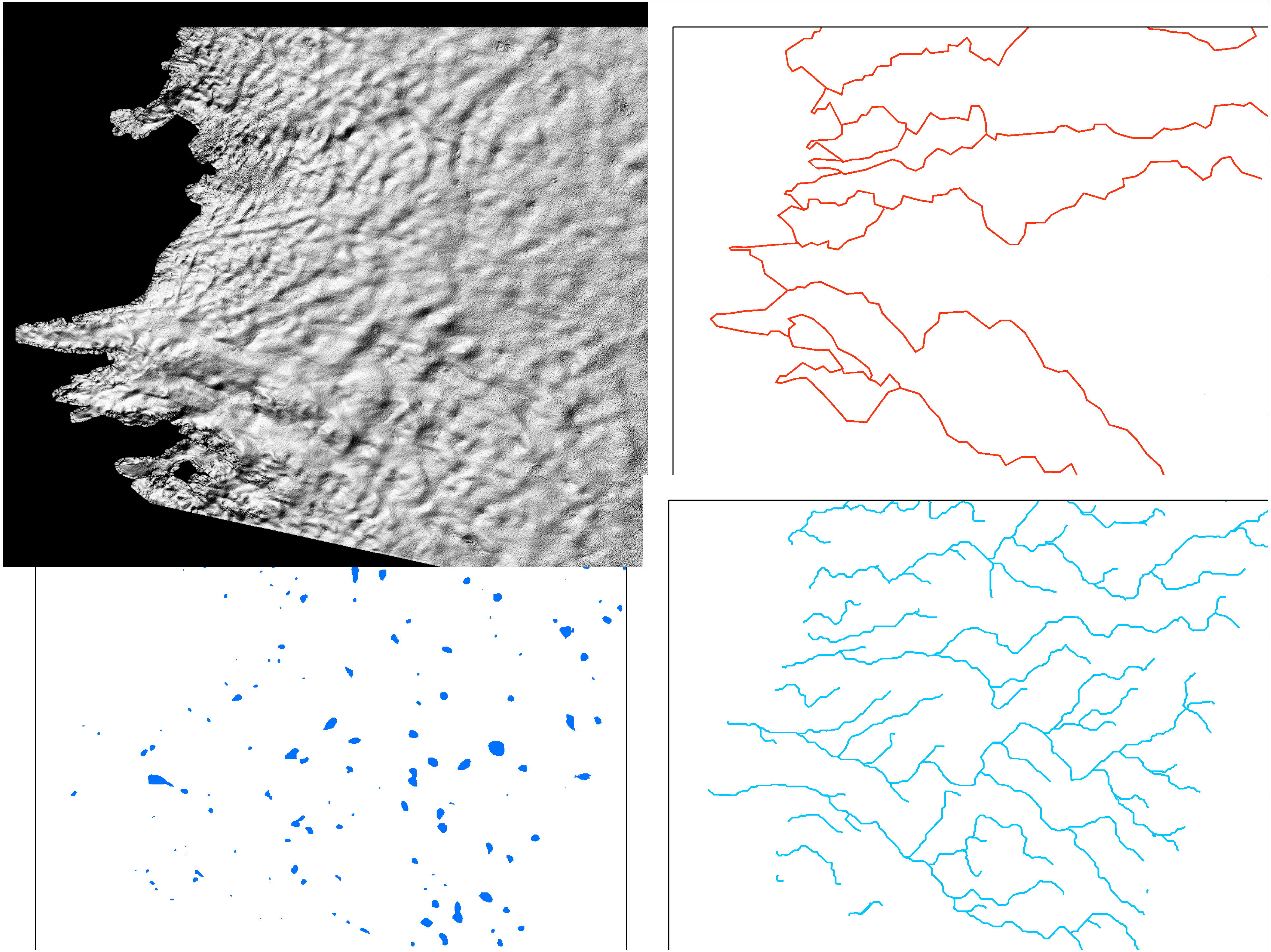


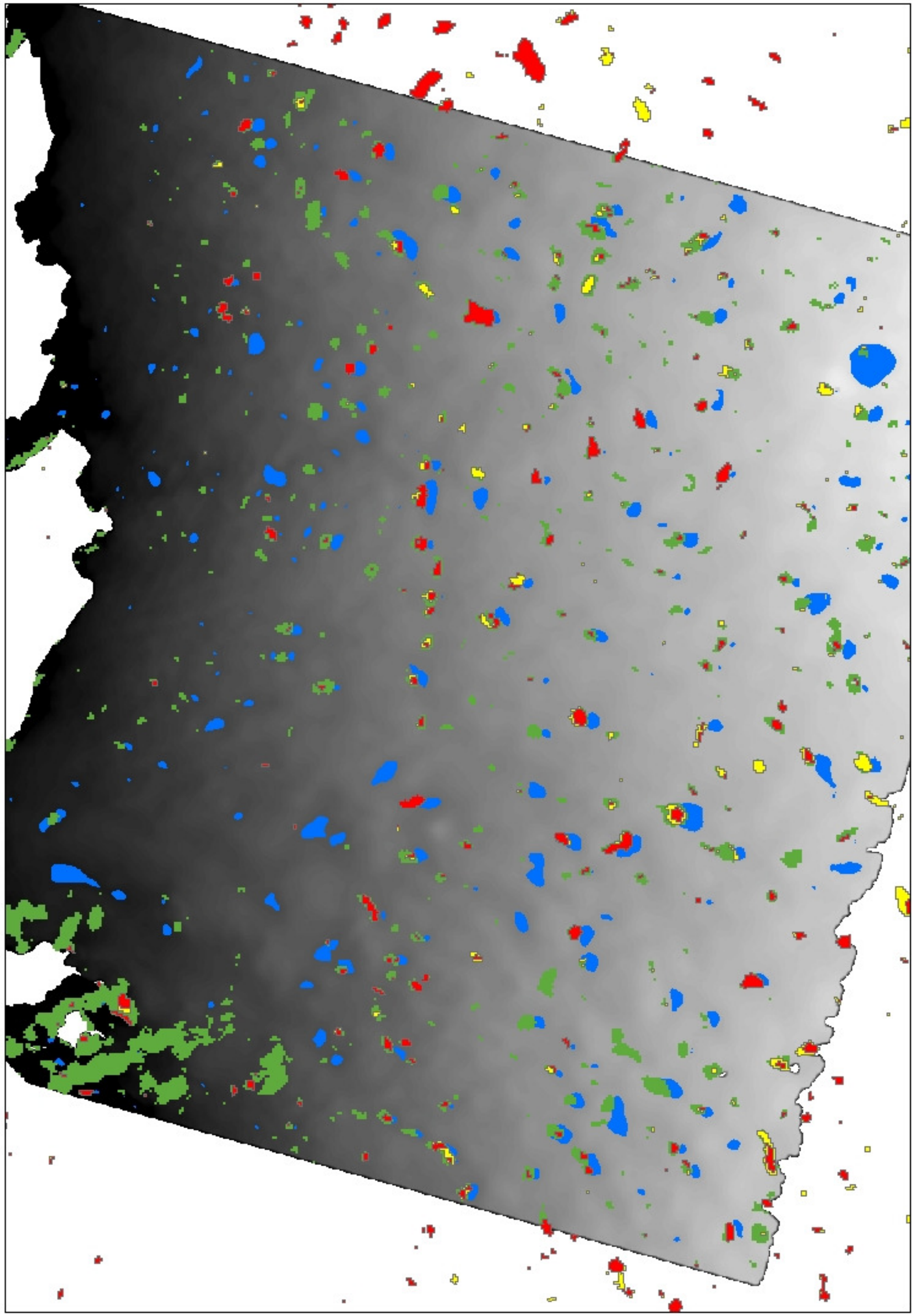
a)
b)
c)
d)
50°0'0"W
49°30'0"W
49°0'0"W
48°30'0"W
48°0'0"W
67°30'0"N
67°15'0"N
67°0'0"N
66°45'0"N
0 5 10 20
Km
400
Ice velocity
m/year
0

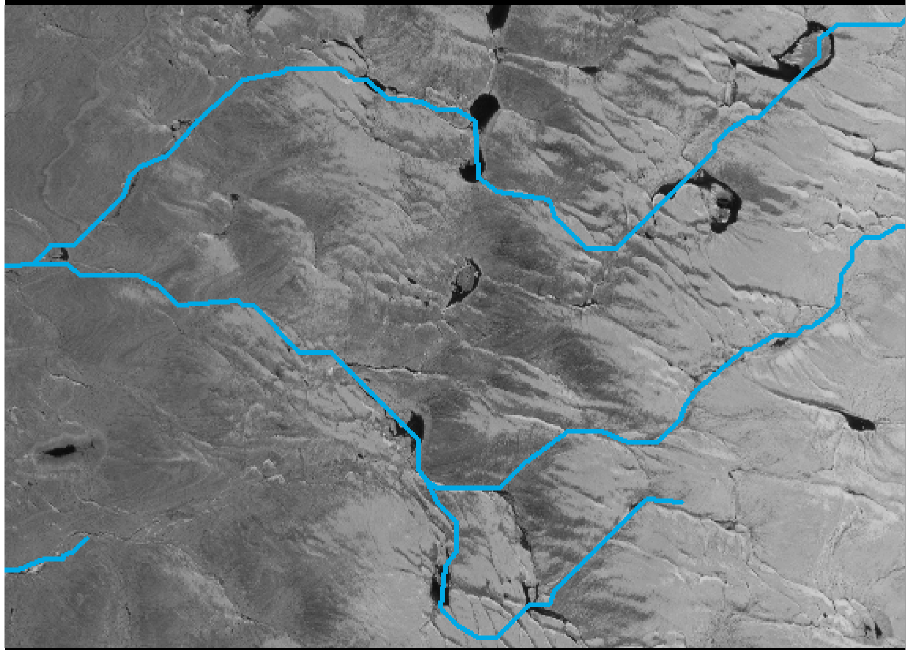


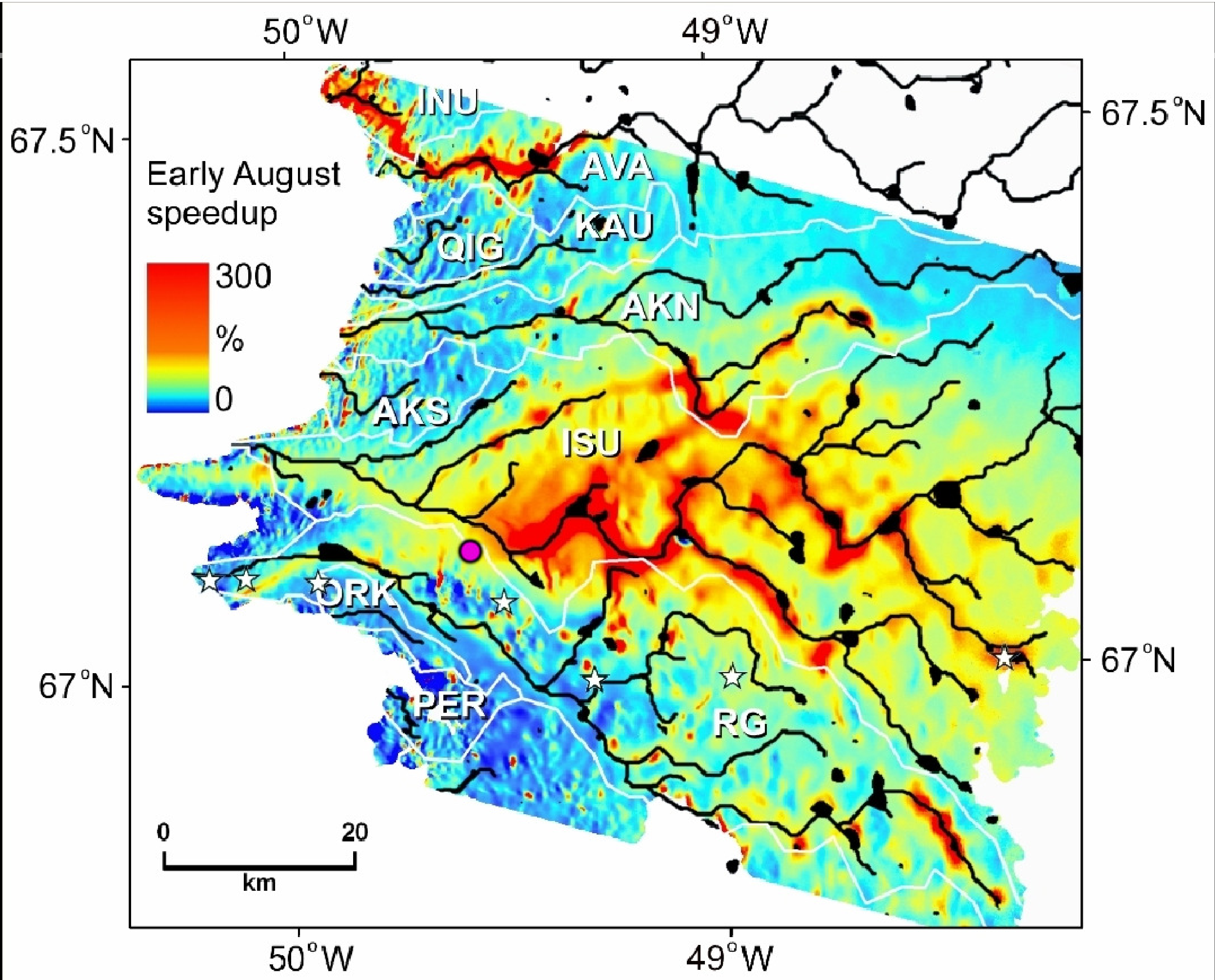


Joughin et al., 2008, Science



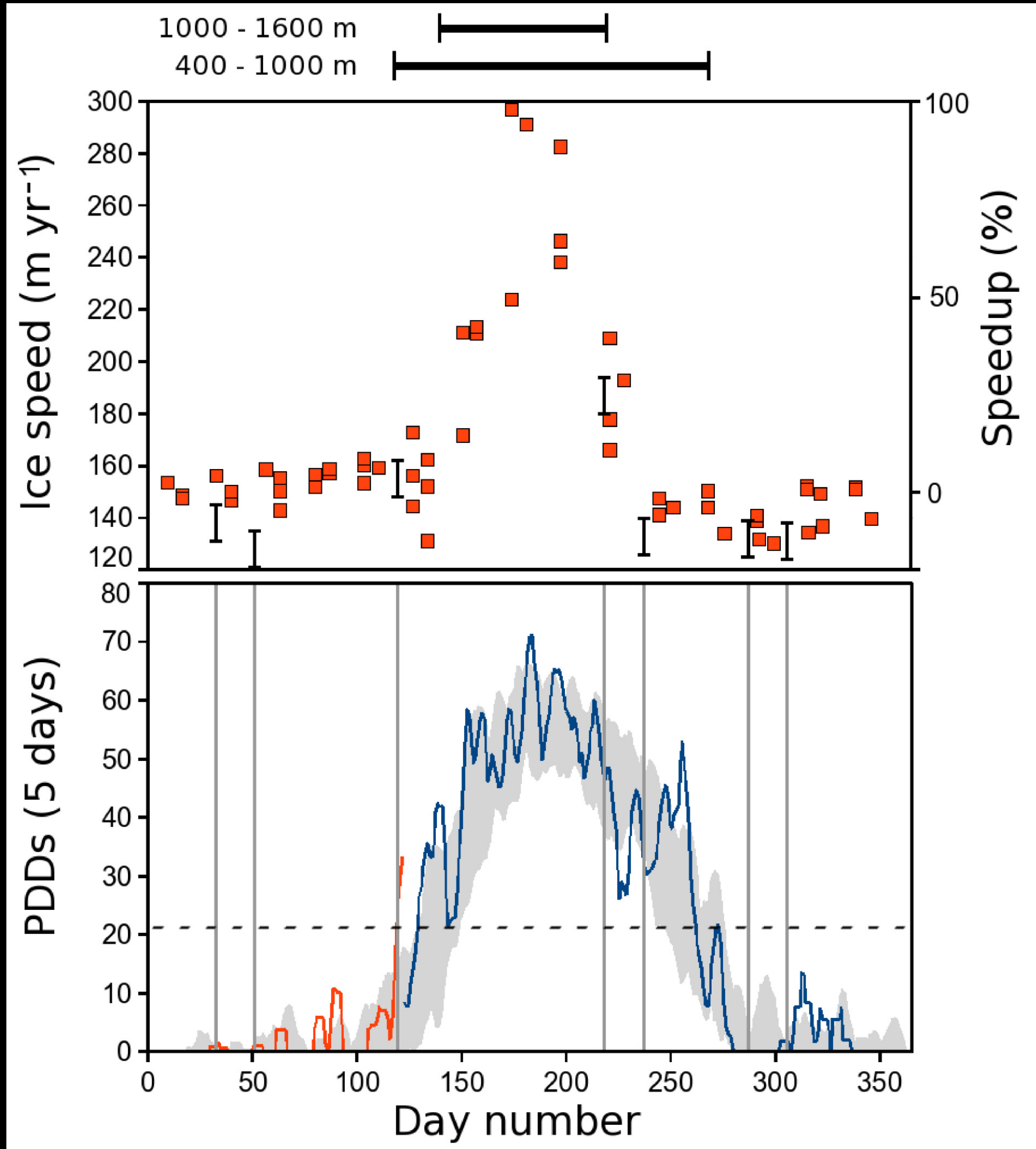





50°W
49°W
67.5°N
67°N
Early August speedup
300
%
0
INU
AVA
KAU
QIG
AKN
AKS
ISU
ORK
PER
RG
0
20
km

❄ In places, evolution of ice speed closely follows melting

❄ High variability in late-summer temperature

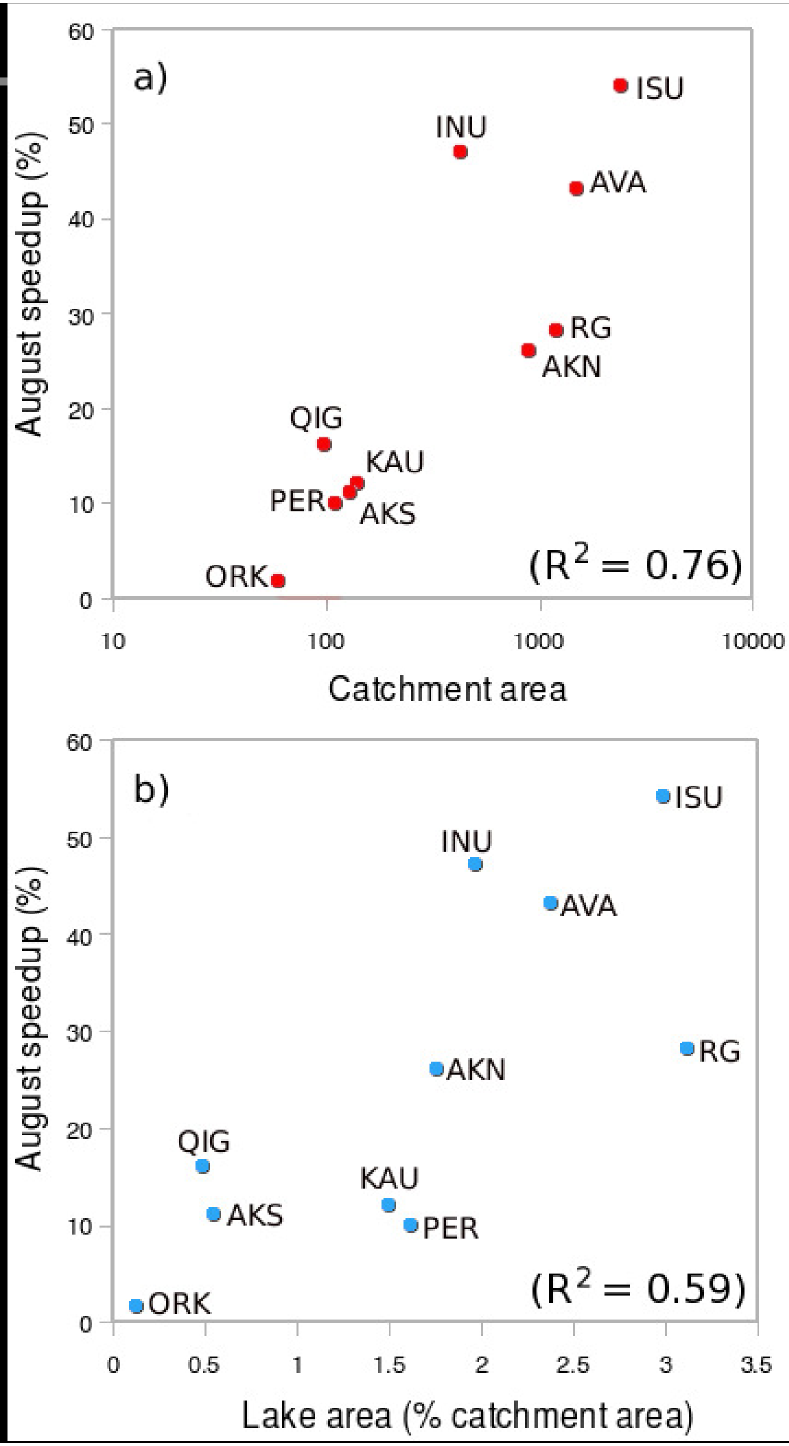


Palmer et al., in press, EPSL

Correlations (r-squared):

Catchment area V runoff = 0.94
Catchment area V #sinks = 0.92

Catchment area V speedup = 0.76
Fractional lake area V speedup = 0.59



1. Late-summer (seasonal?) velocity fluctuations are driven by surface melt-water penetrating to the ice sheet base
2. Supra-glacial lakes appear to be a key factor in priming water conduits linking the ice surface and base
3. BUT...doesn't necessarily follow that more melting will lead to faster ice sheet flow...
   Van de Wal et al., 2008; Sundal et al. (in review); Schoof et al, (in review).
4. We need more field and remote sensing observations (and better models) improve our predictions of the future evolution of the Greenland Ice Sheet.

Limitations

Temporal sampling is poor

Summertime data may not be representative

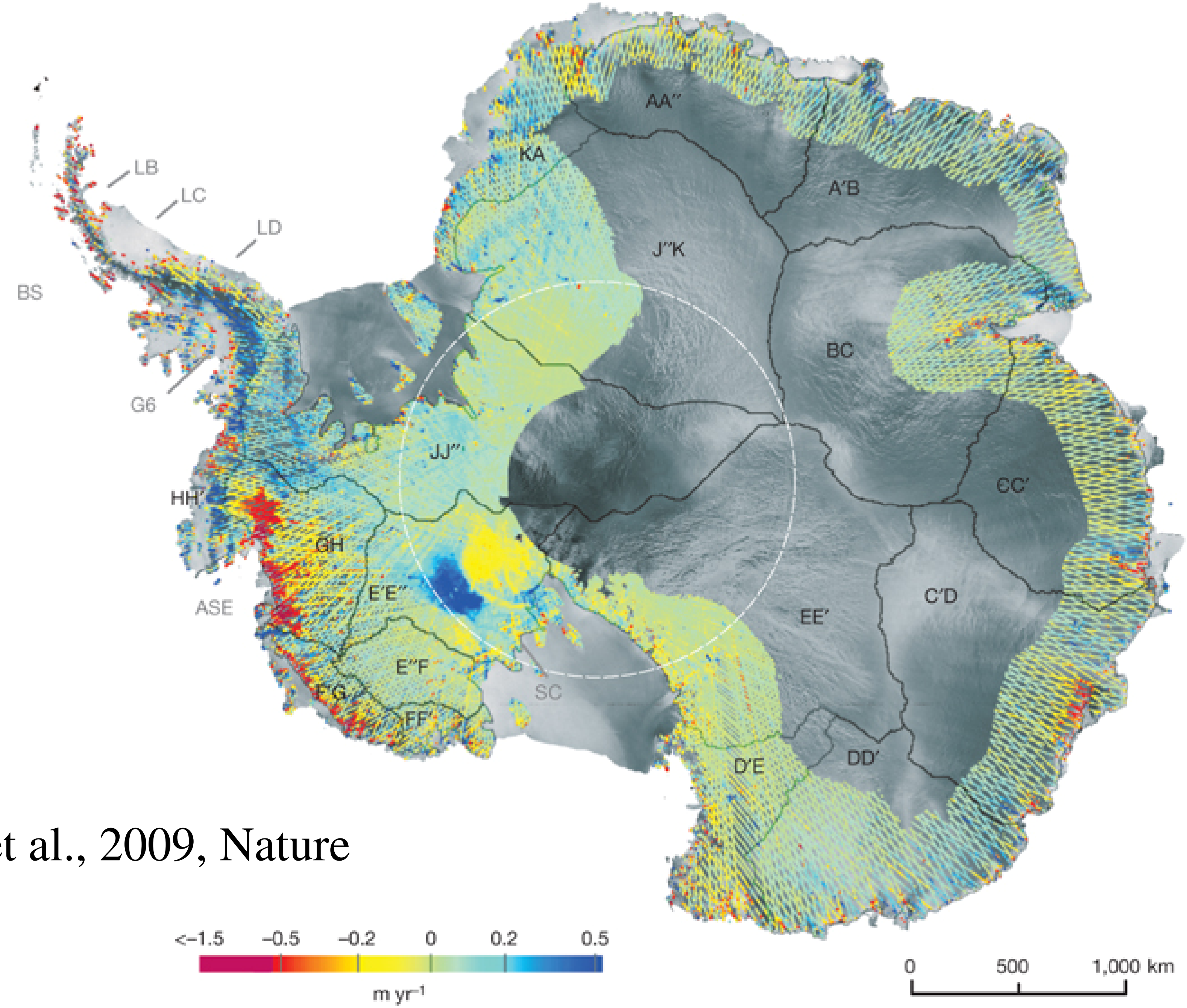
Descending pass data only

Errors are large for motion in the azimuth direction

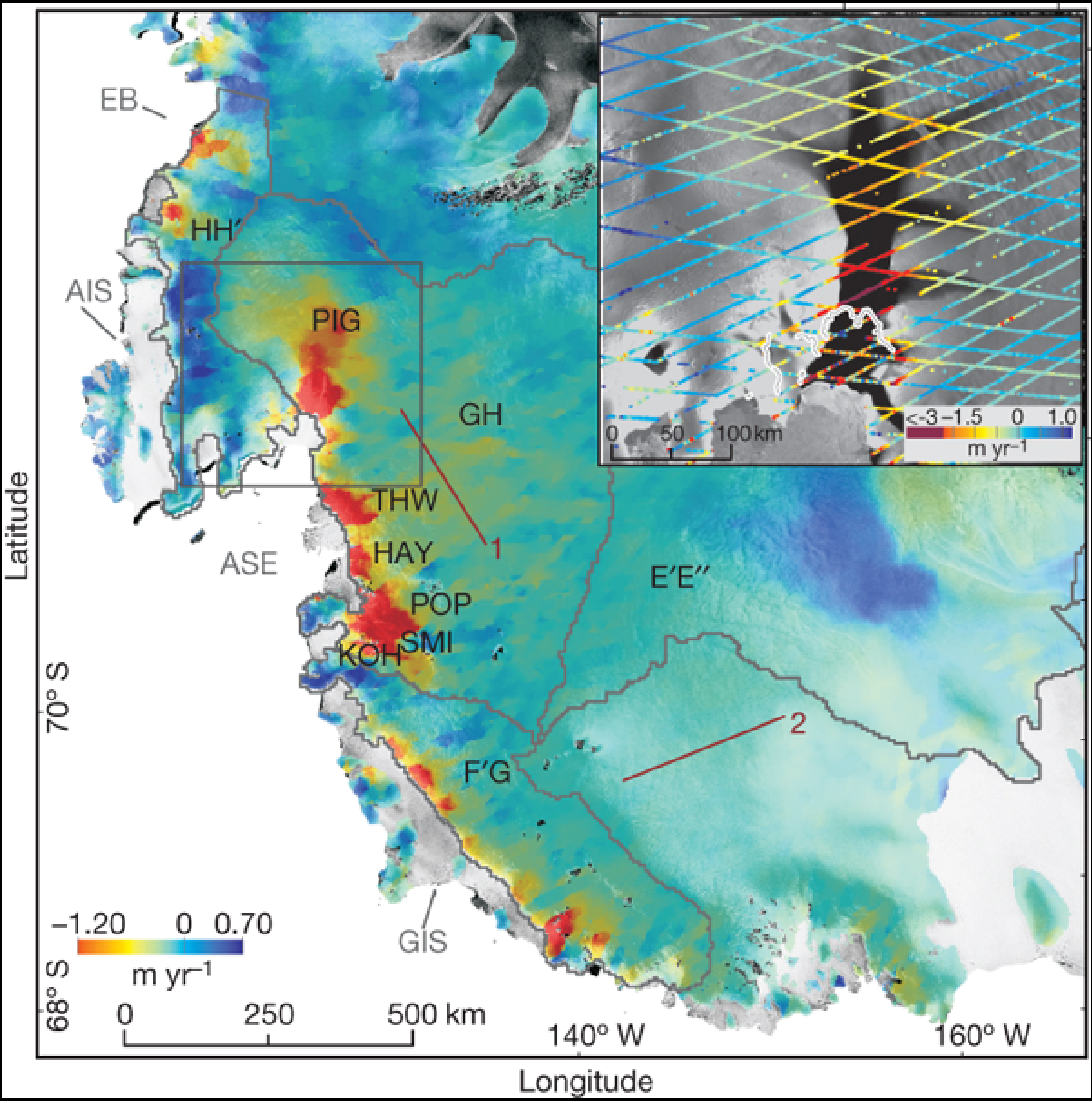
Assumption of surface parallel flow

Errors arise for areas affected by tidal motion or uplift due to drainage of surface water to the bed

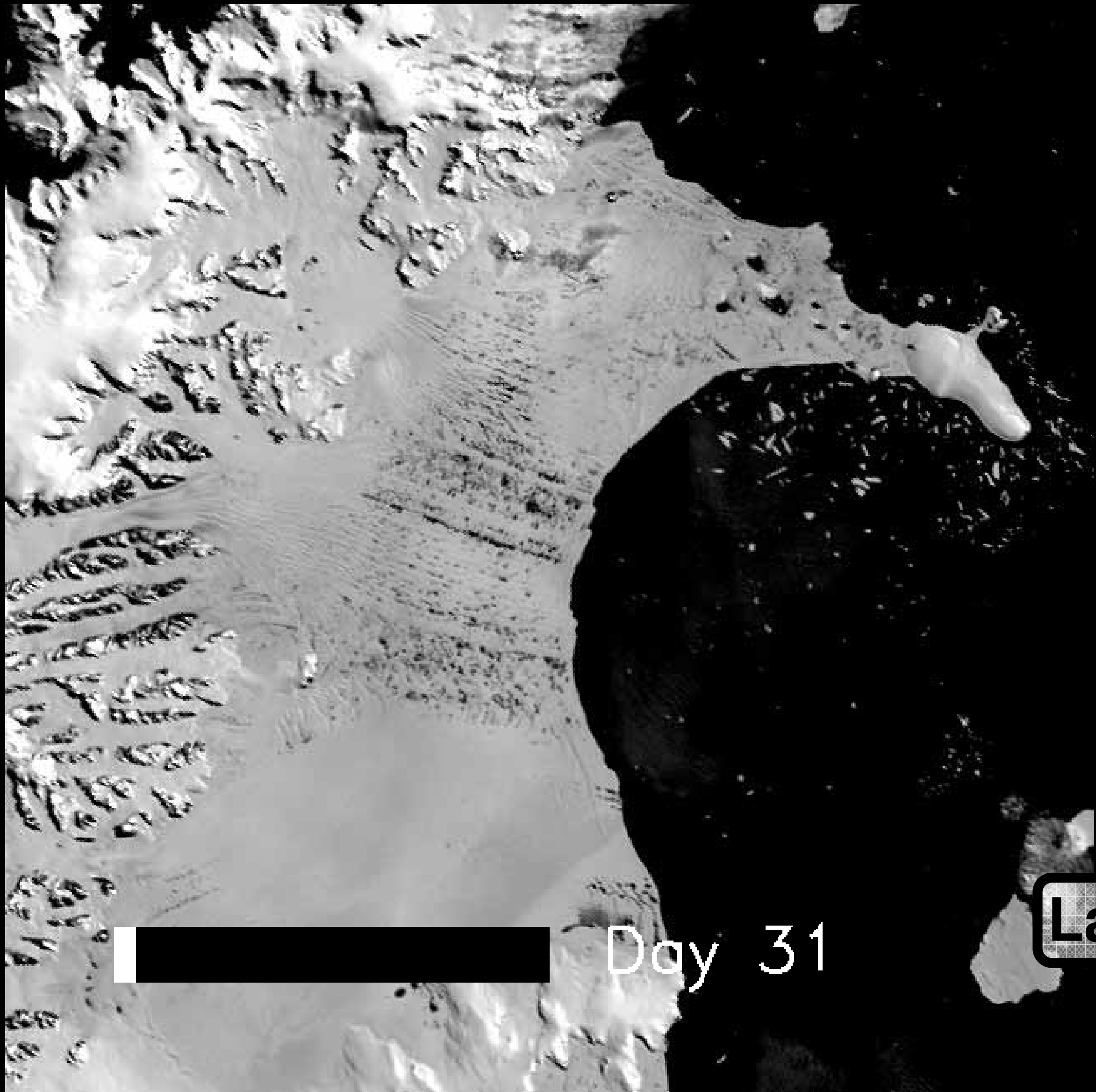
5. Antarctica (Bonus content)



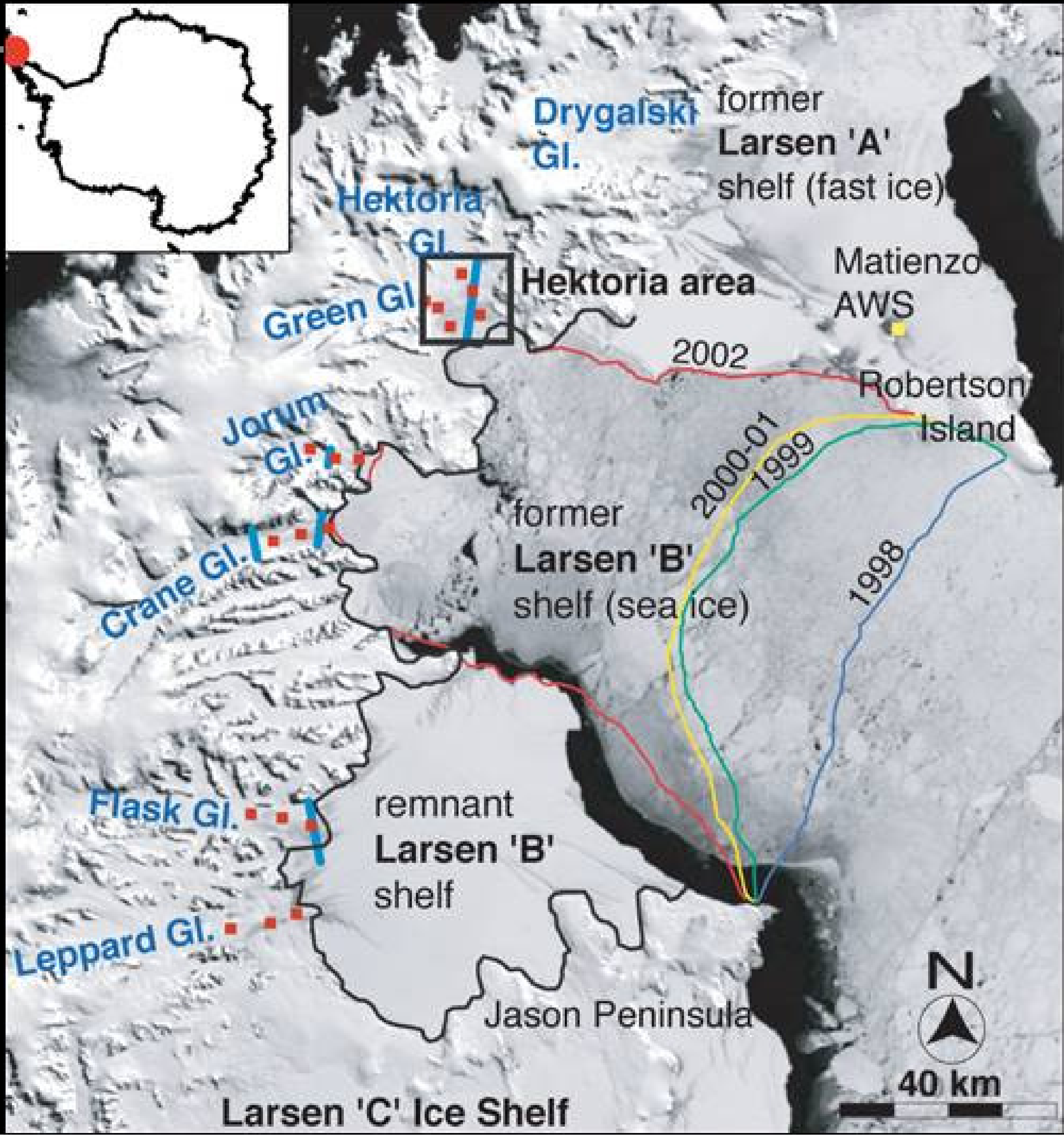
Pritchard et al., 2009, Nature


EB
HH′
AIS
PIG
GH
THW
1
HAY
ASE
E′E″
POP
SMI
KOH
70° S
2
F′G
GIS
−1.20
0
0.70
m yr−1
68° S
0
250
500 km
140° W
160° W
Latitude
Longitude
<−3
−1.5
0
1.0
m yr−1
0
50
100 km

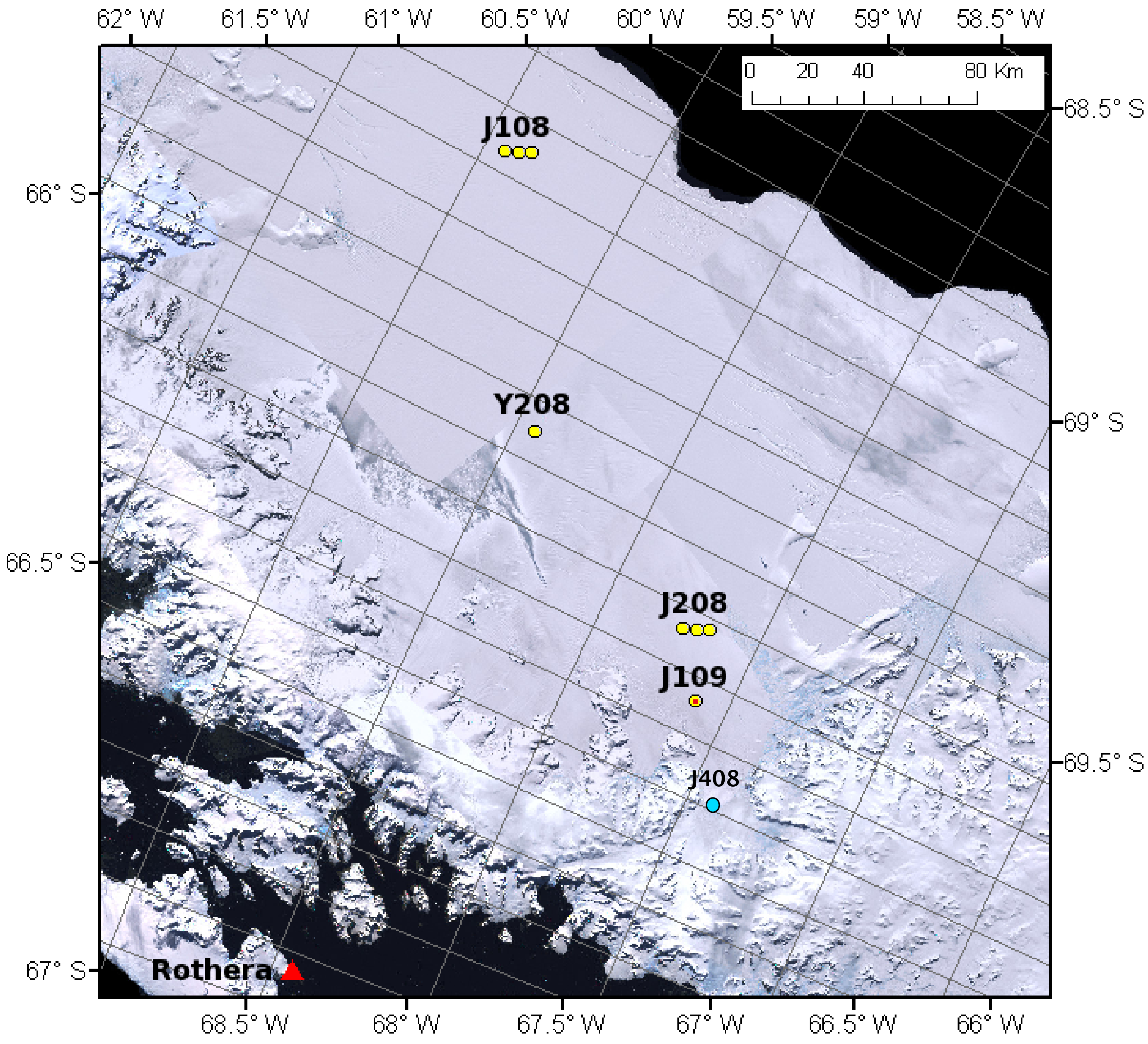
- Abrupt climate change



Larsen Ice Shelf, 2002



Drygalski Gl.
former
Larsen 'A'
shelf (fast ice)
Hektoria Gl.
Hektoria area
Green Gl.
Matienzo AWS
2002
Robertson Island
Jorum Gl.
2000-01
1999
former
Larsen 'B'
shelf (sea ice)
1998
Crane Gl.
Flask Gl.
remnant
Larsen 'B'
shelf
Leppard Gl.
Jason Peninsula
N
40 km
Larsen 'C' Ice Shelf


62° W
61.5° W
61° W
60.5° W
60° W
59.5° W
59° W
58.5° W
0 20 40 80 Km
68.5° S
66° S
69° S
66.5° S
69.5° S
67° S
J108
Y208
J208
J109
J408
Rothera
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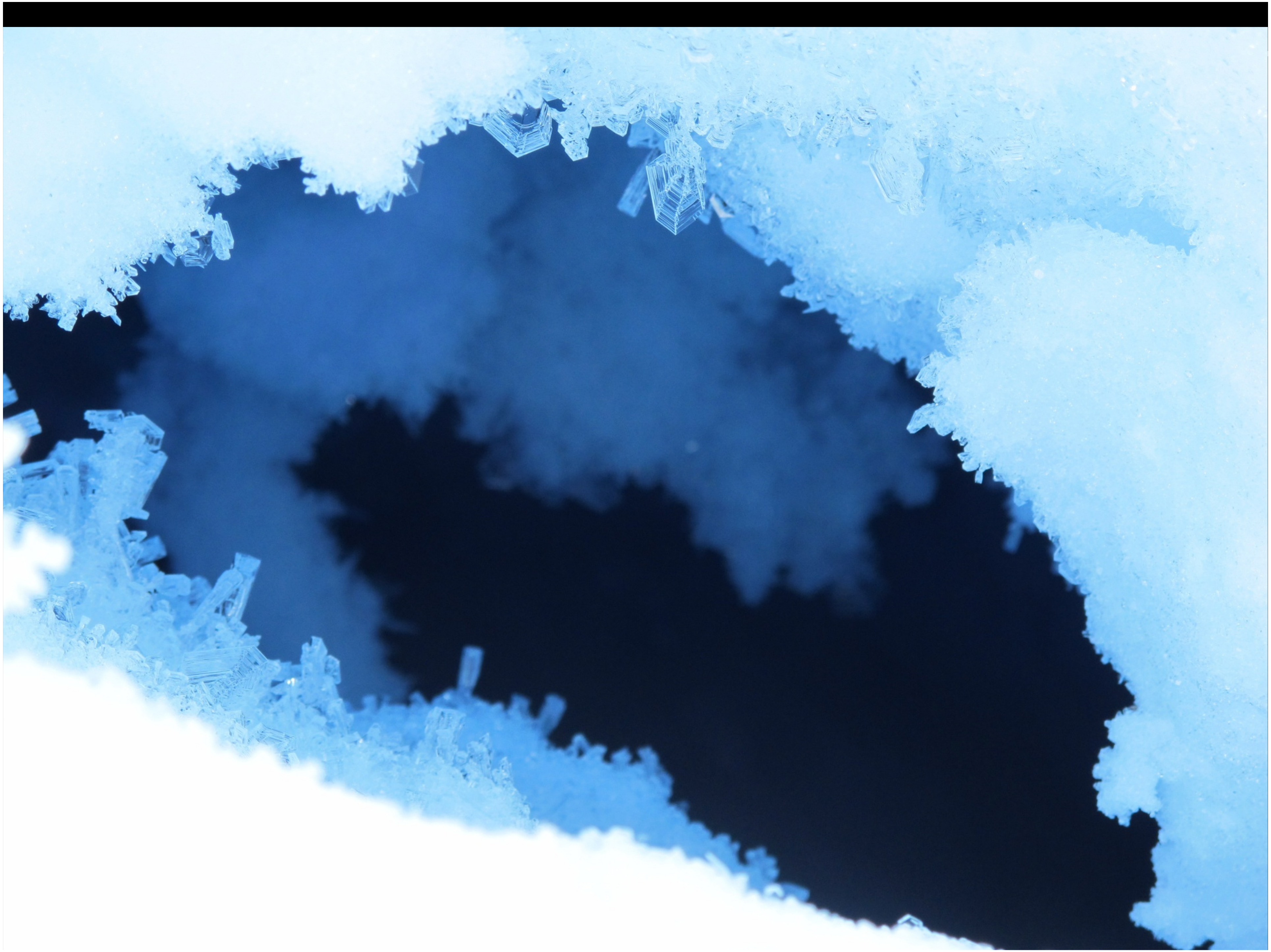
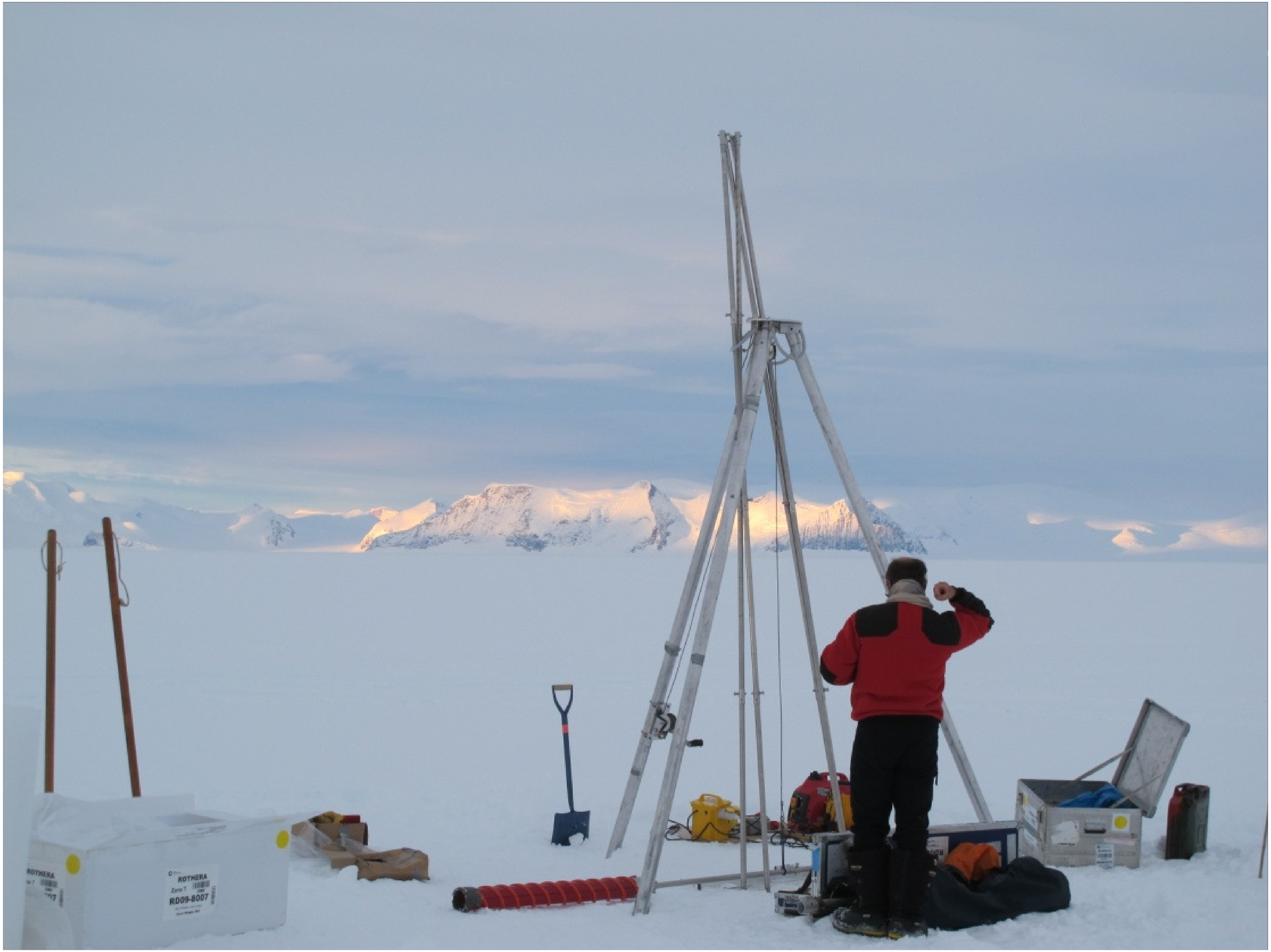
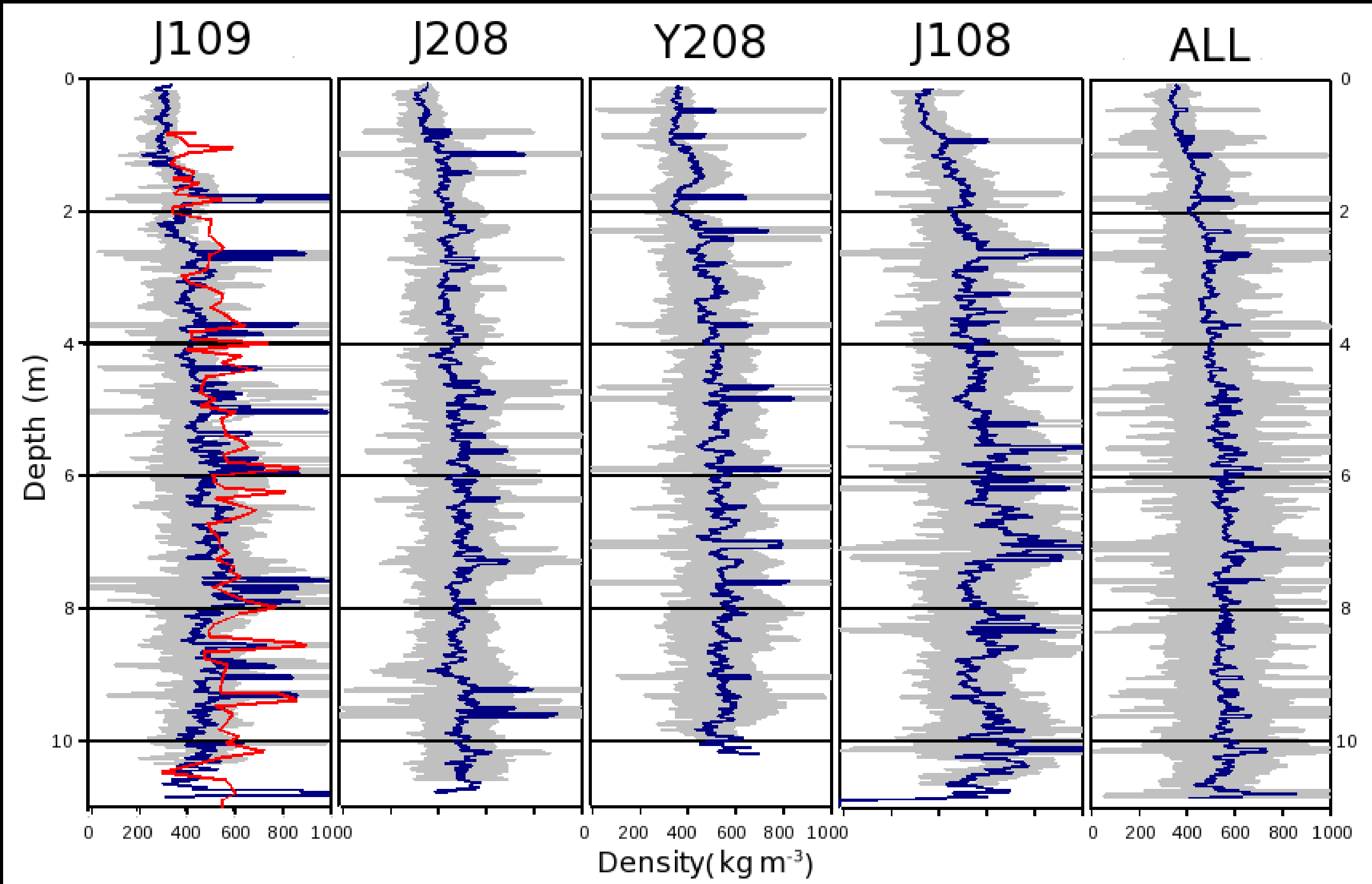
67.5° W
67° W
66.5° W
66° W




ROTHERA
Zone 7
RD09-8007
ROTHERA


ROTHERA
RD09-8006


J109
J208
Y208
J108
ALL
Depth (m)
Density(kg m-3)
0
2
4
6
8
10
0 200 400 600 800 1000


VP-


2009
ski-doo

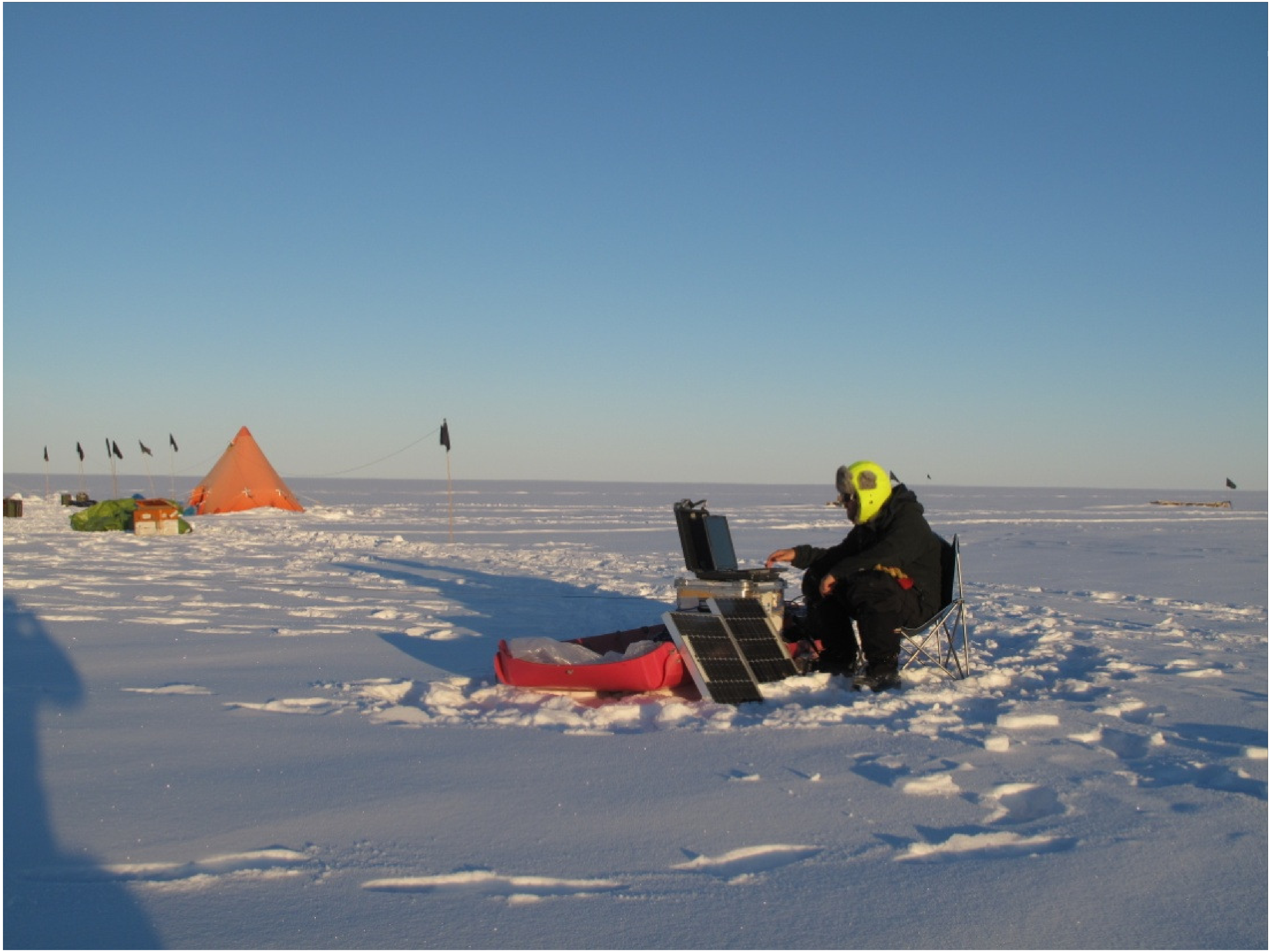




VP-FB


VP-FBC


08F-R




KATHERINE
3,26