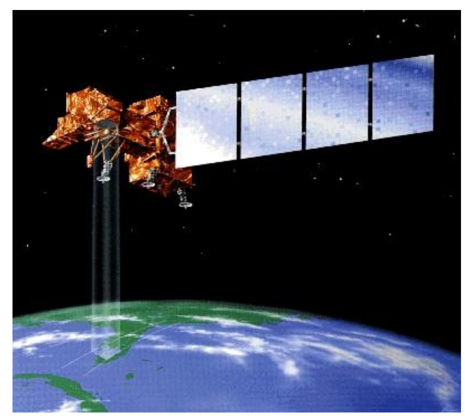
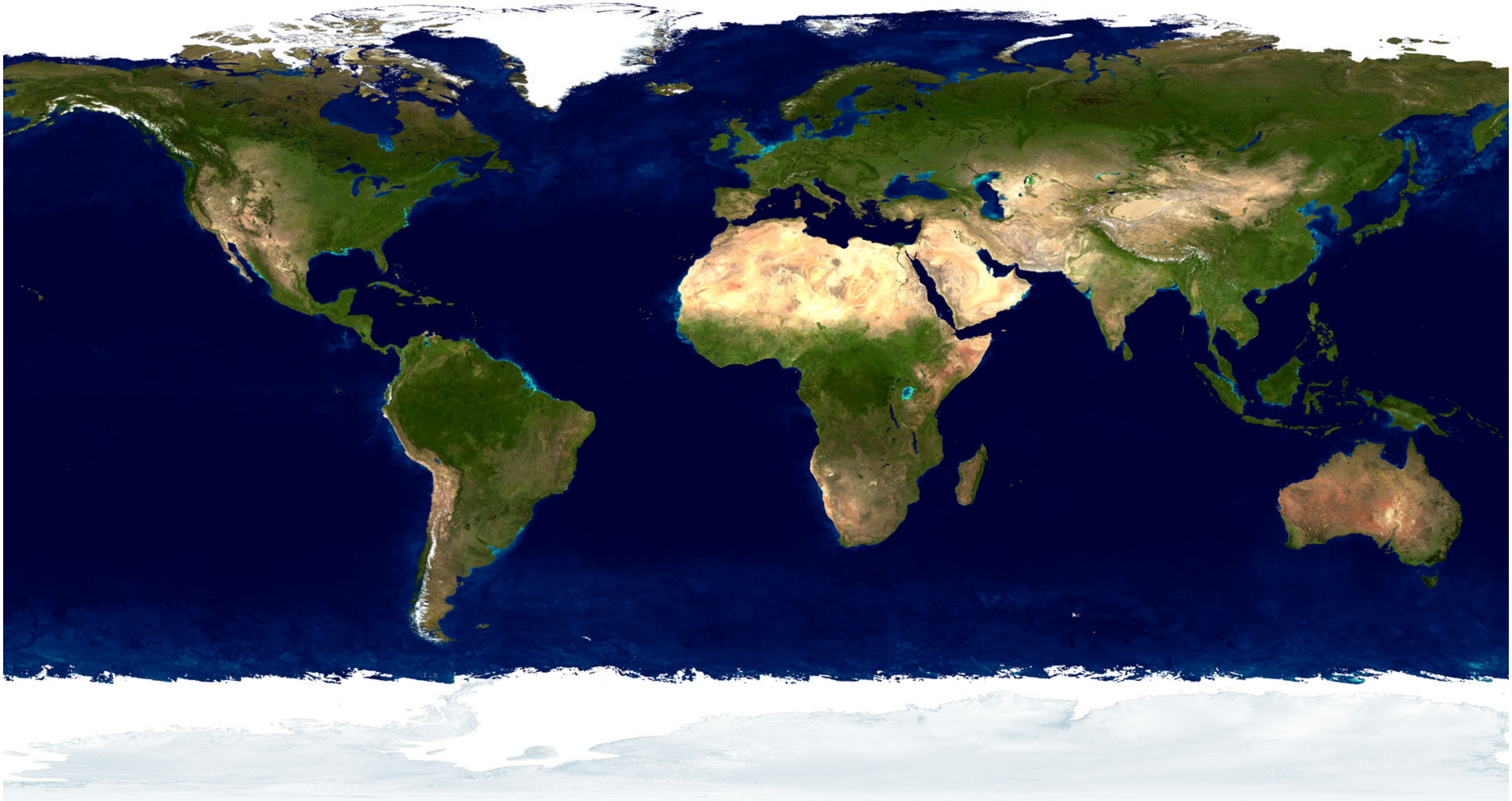
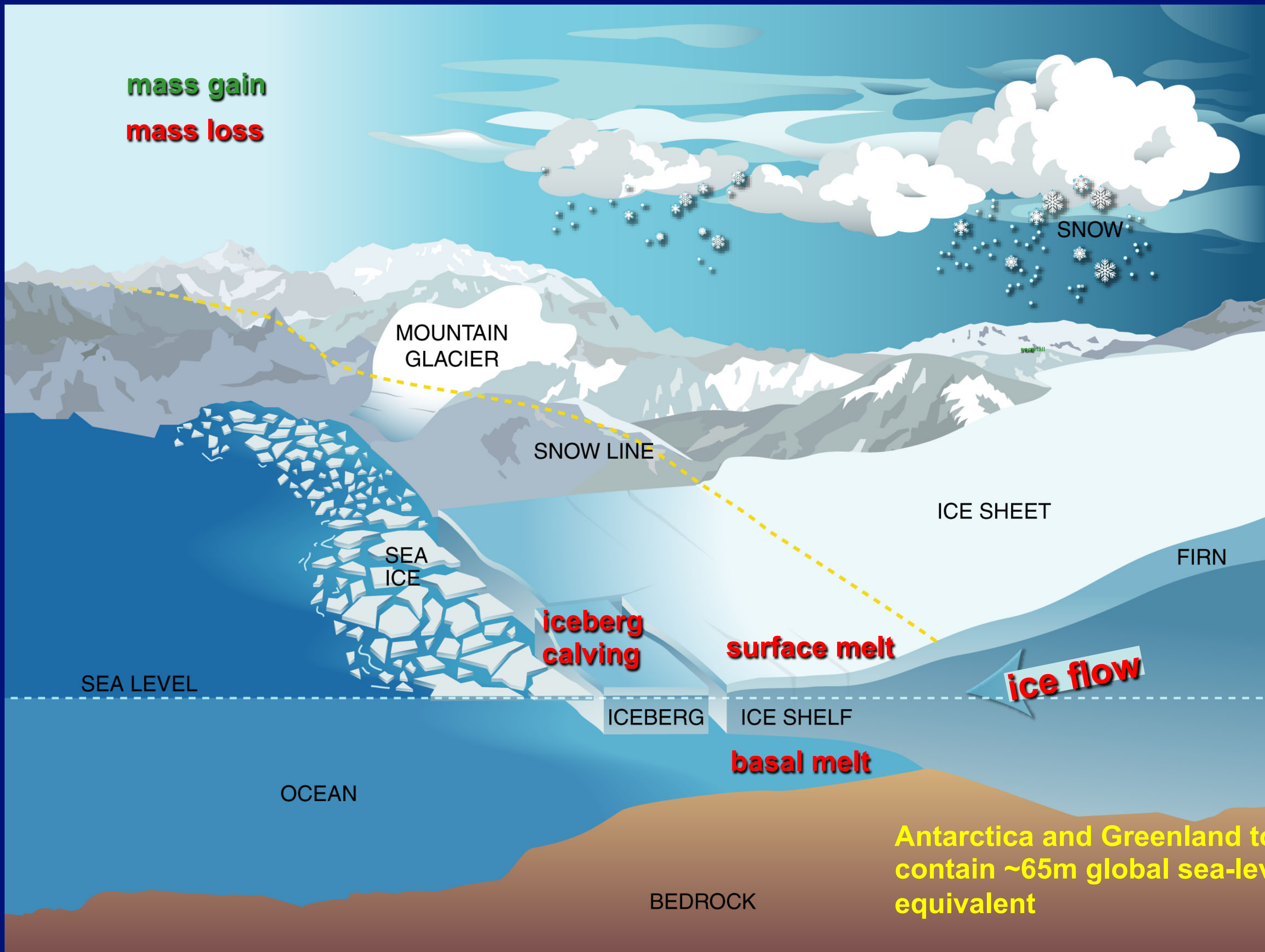
Satellite Remote Sensing
SIO 135/SIO 236

Applications of satellite altimetry and InSAR over the ice sheets



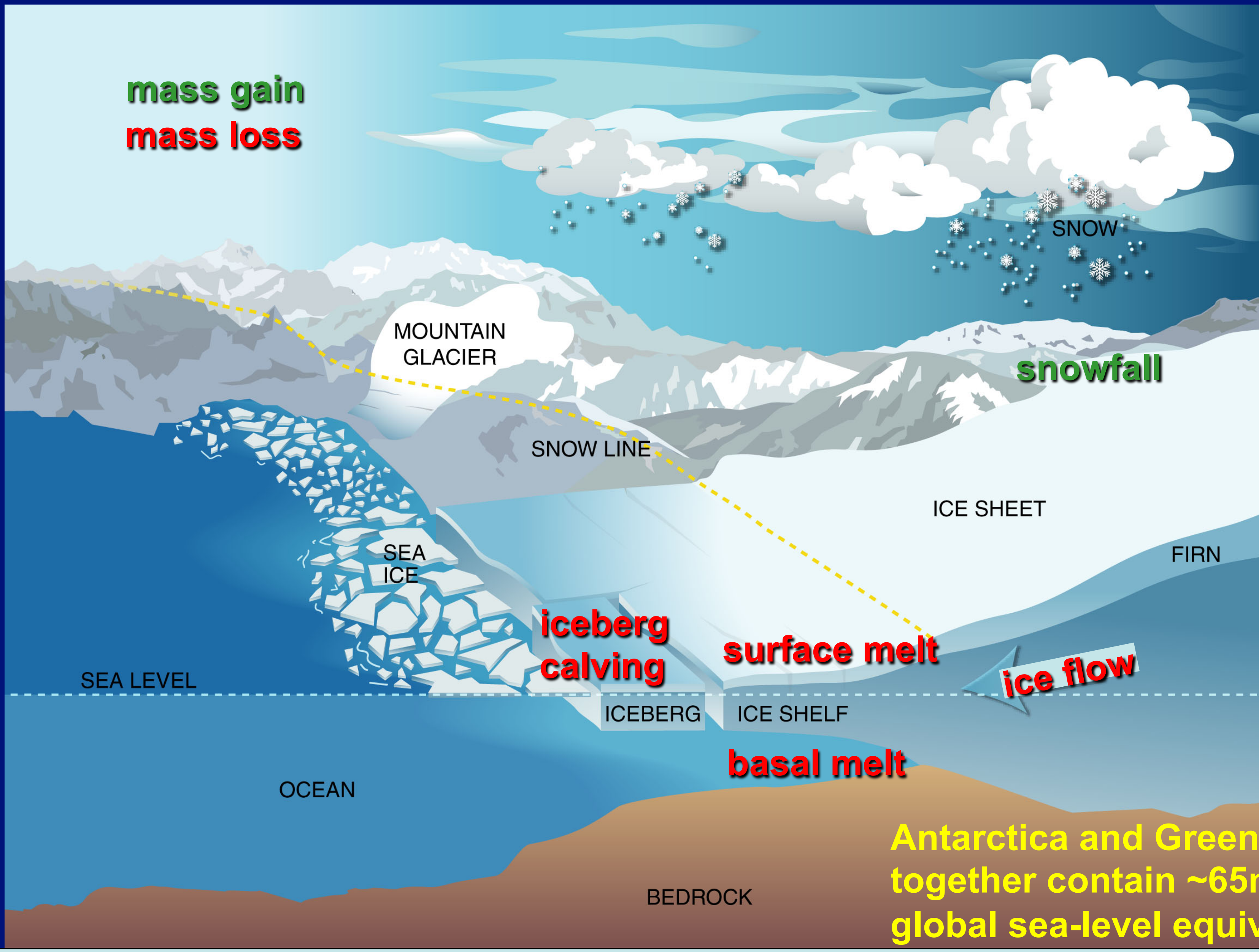


Ice sheet systems



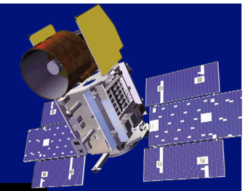
Antarctica and Greenland together contain ~65m global sea-level equivalent

Ice sheet systems

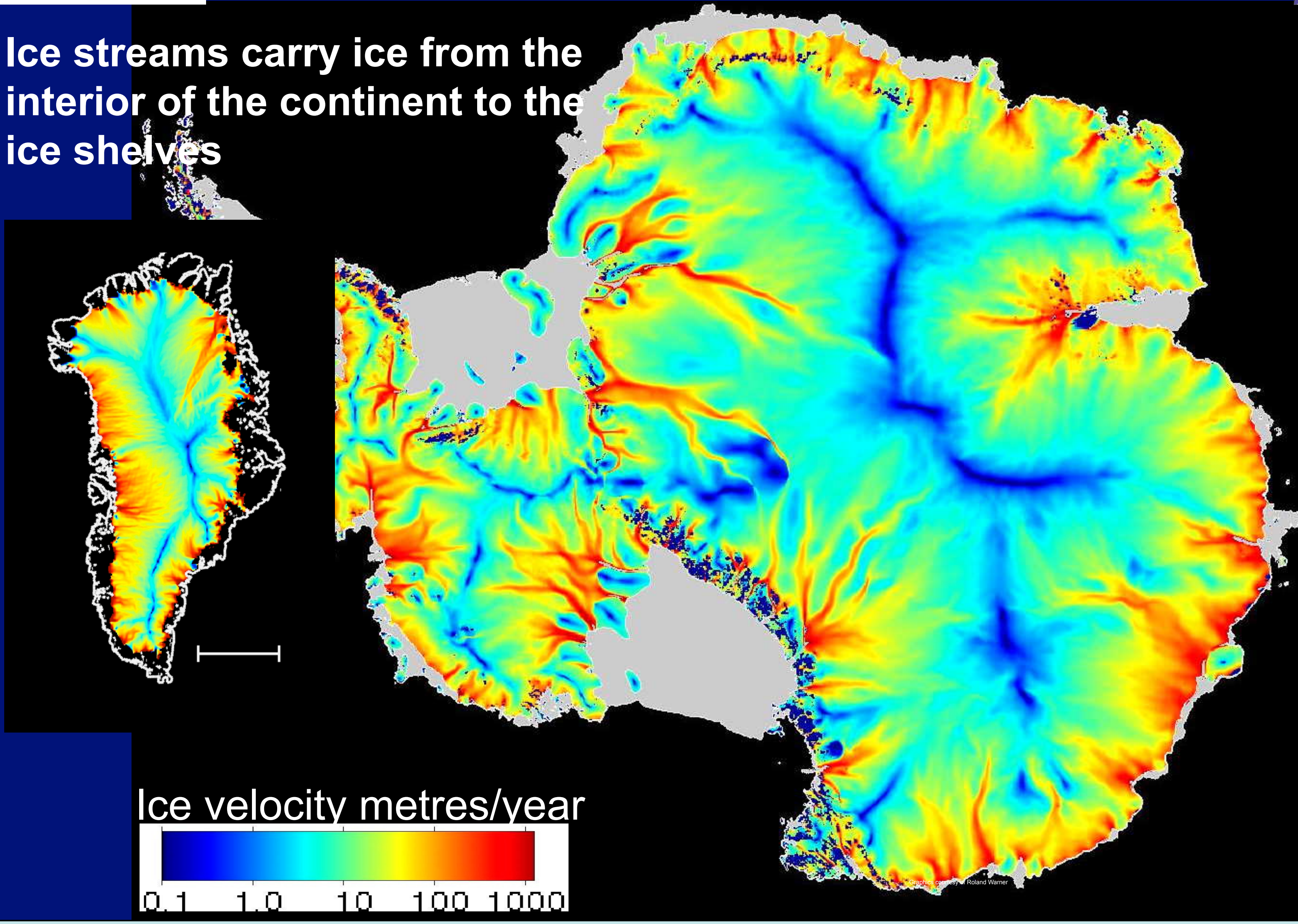


Antarctica and Greenland together contain ~65m global sea-level equivalent

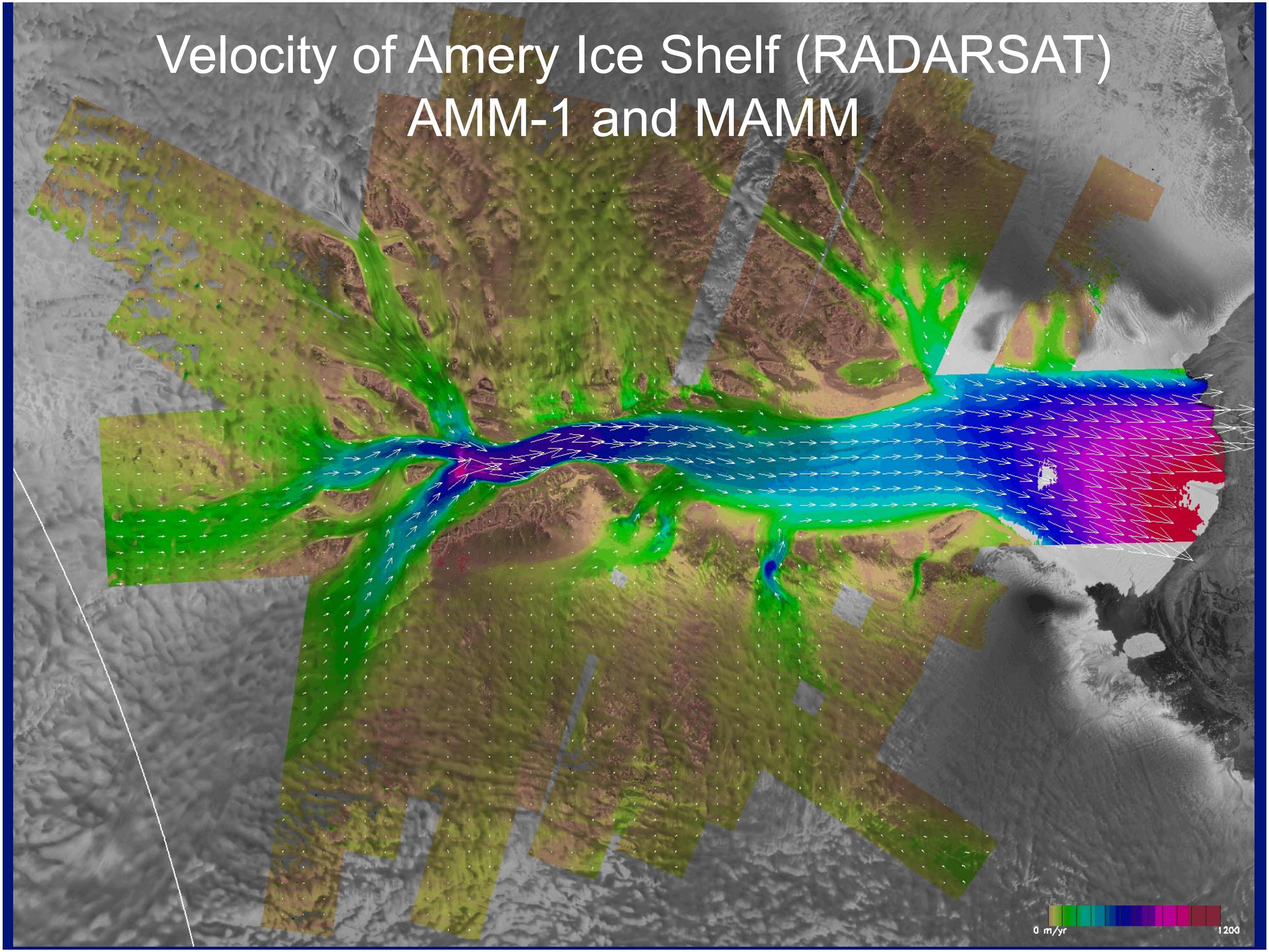
Antarctica's ice streams



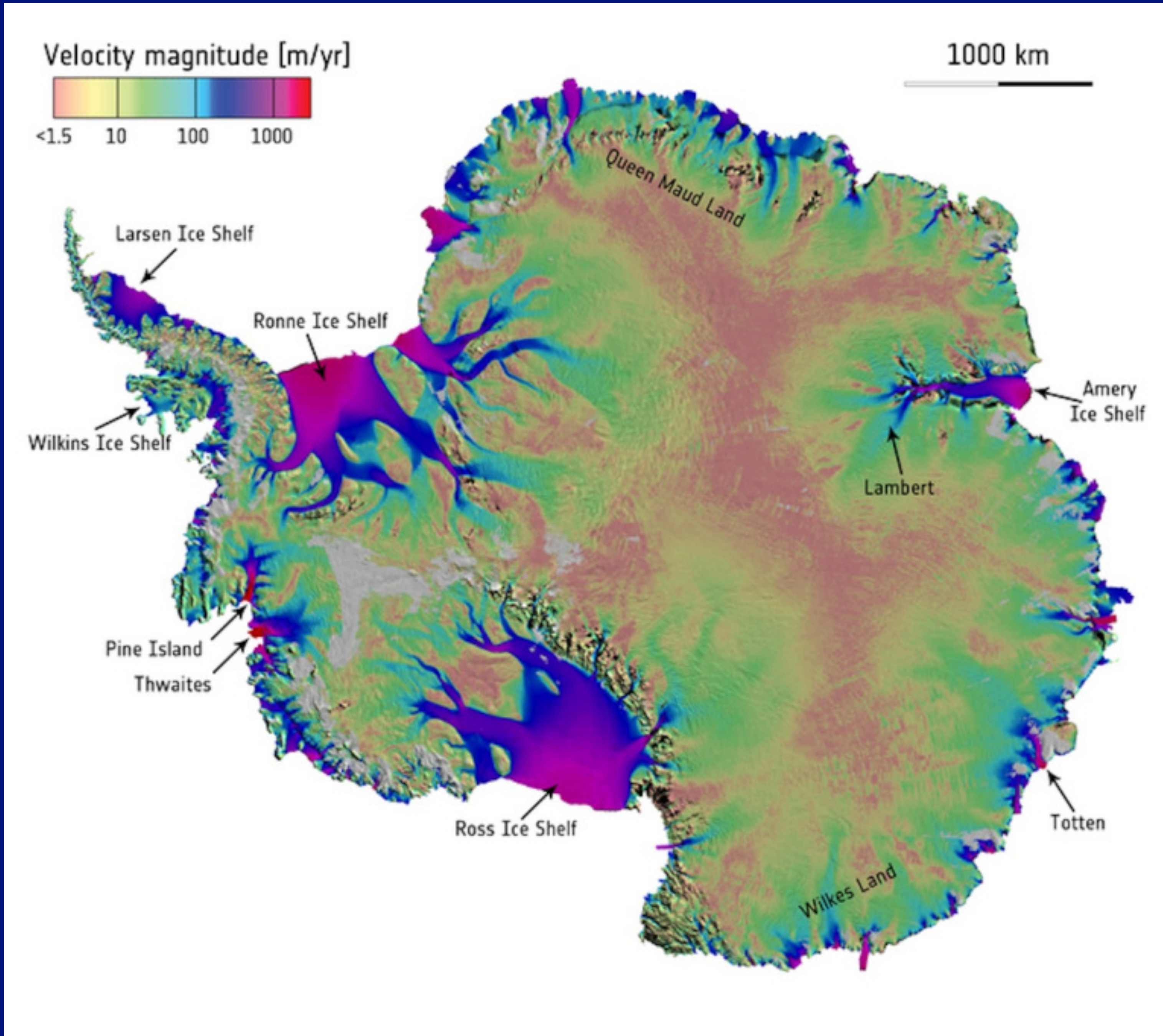
Ice streams carry ice from the interior of the continent to the ice shelves



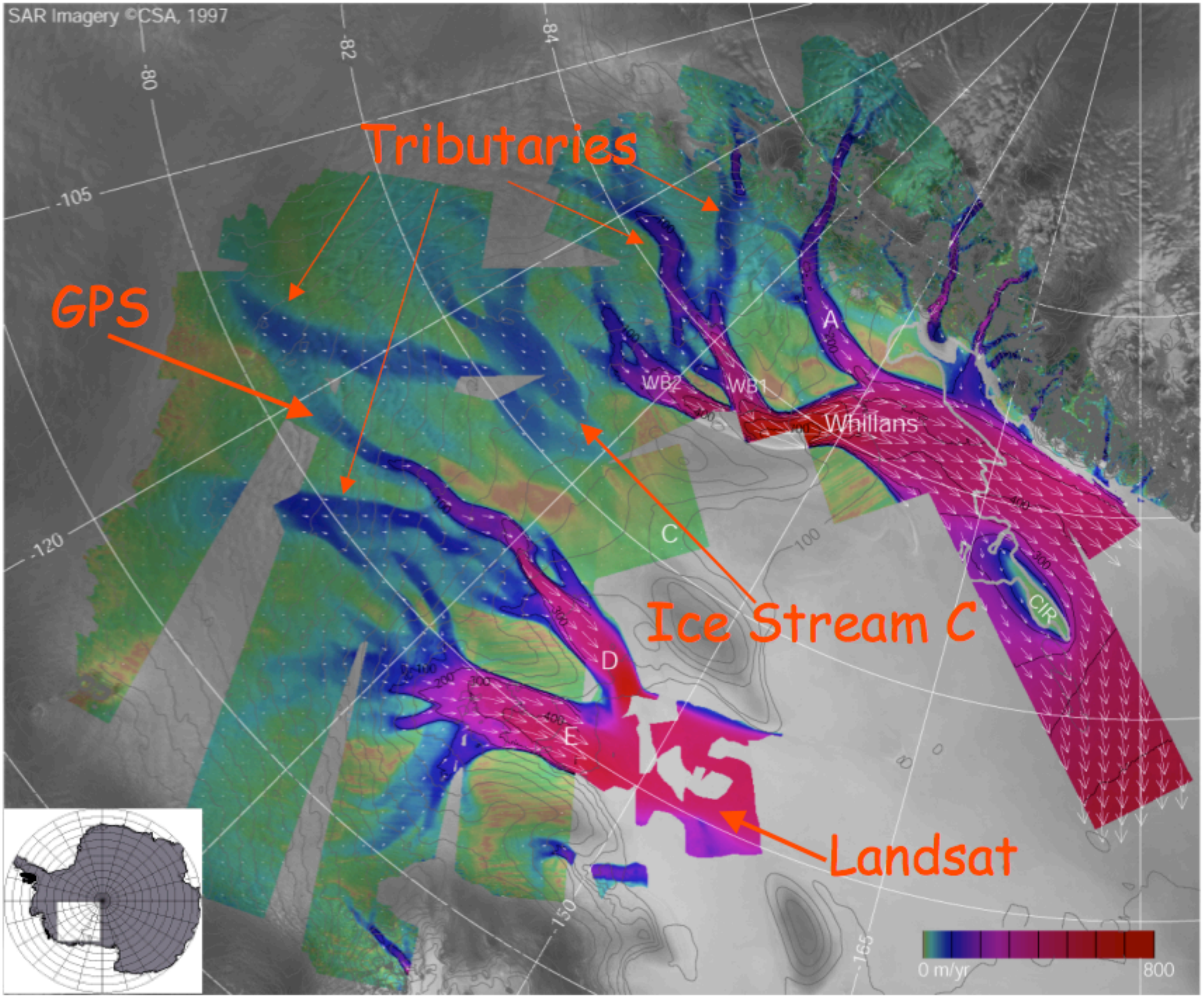
Velocity of Amery Ice Shelf (RADARSAT)
AMM-1 and MAMM



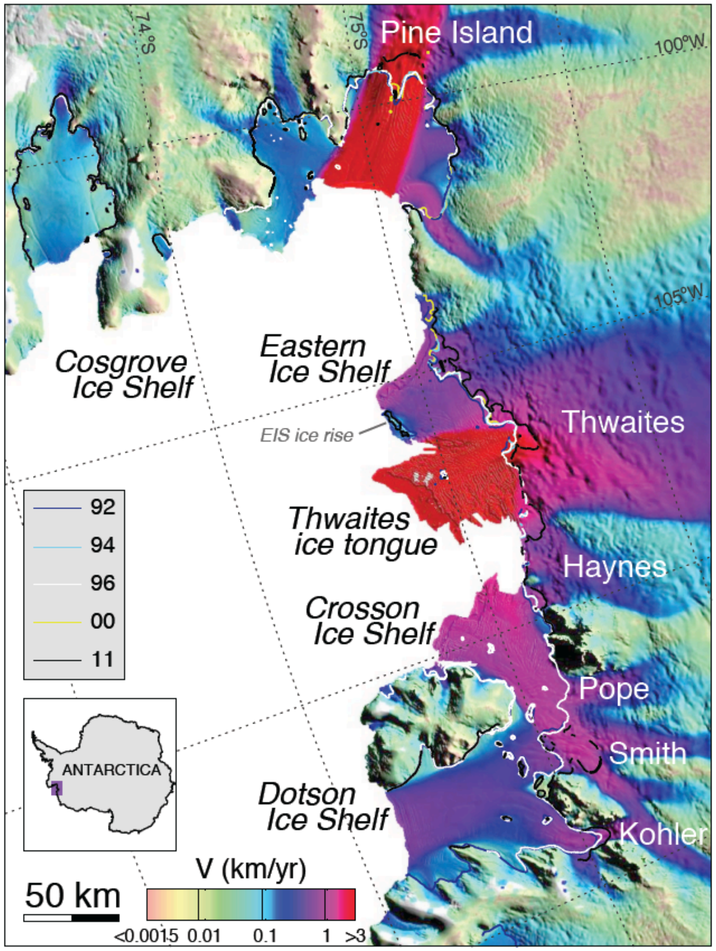
Monitoring ice sheets with SAR


Velocity magnitude [m/yr]
<1.5
10
100
1000
1000 km
Queen Maud Land
Larsen Ice Shelf
Ronne Ice Shelf
Wilkins Ice Shelf
Amery Ice Shelf
Lambert
Pine Island
Thwaites
Ross Ice Shelf
Totten
Wilkes Land

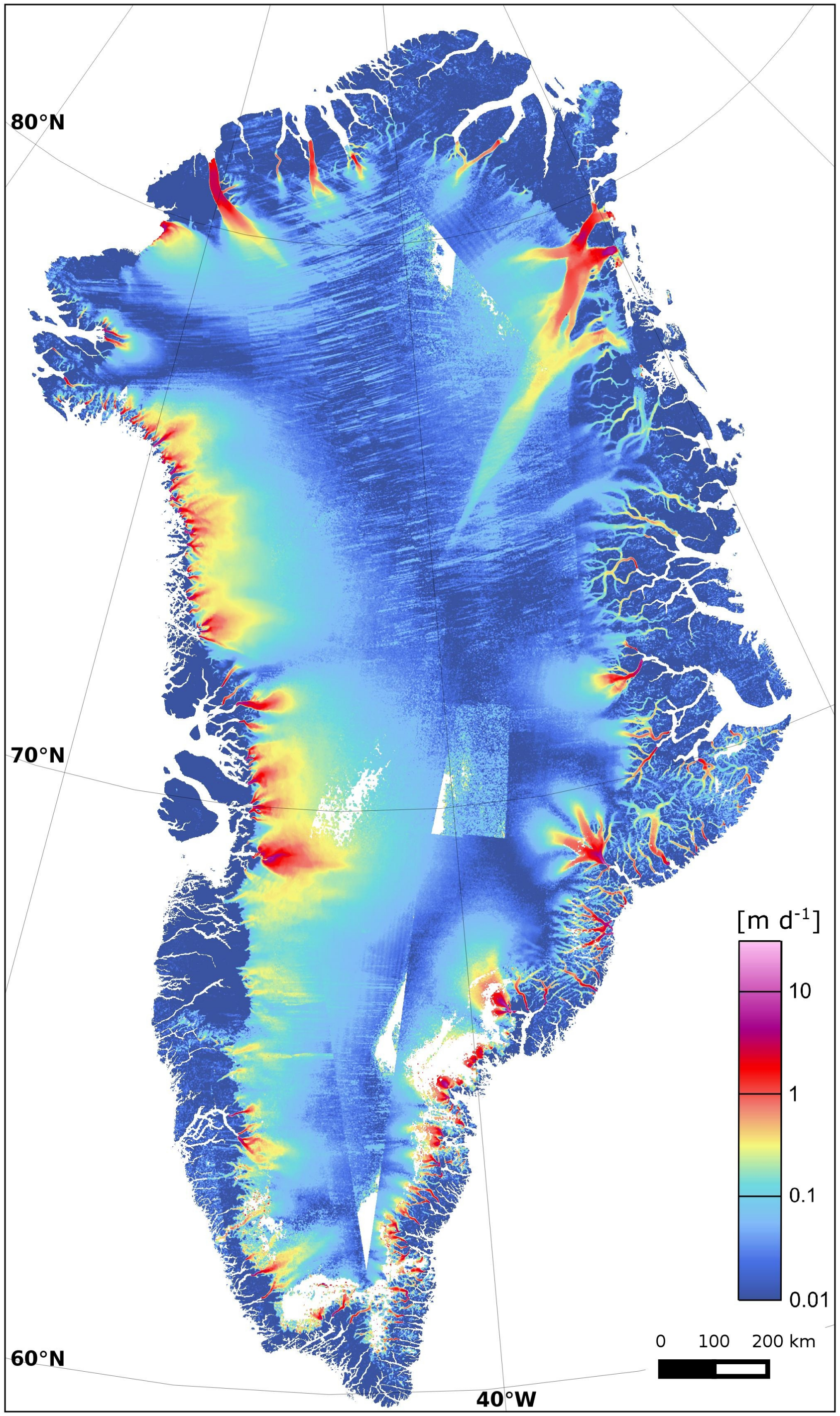
Velocity of Siple Coast ice streams



Rignot et al.



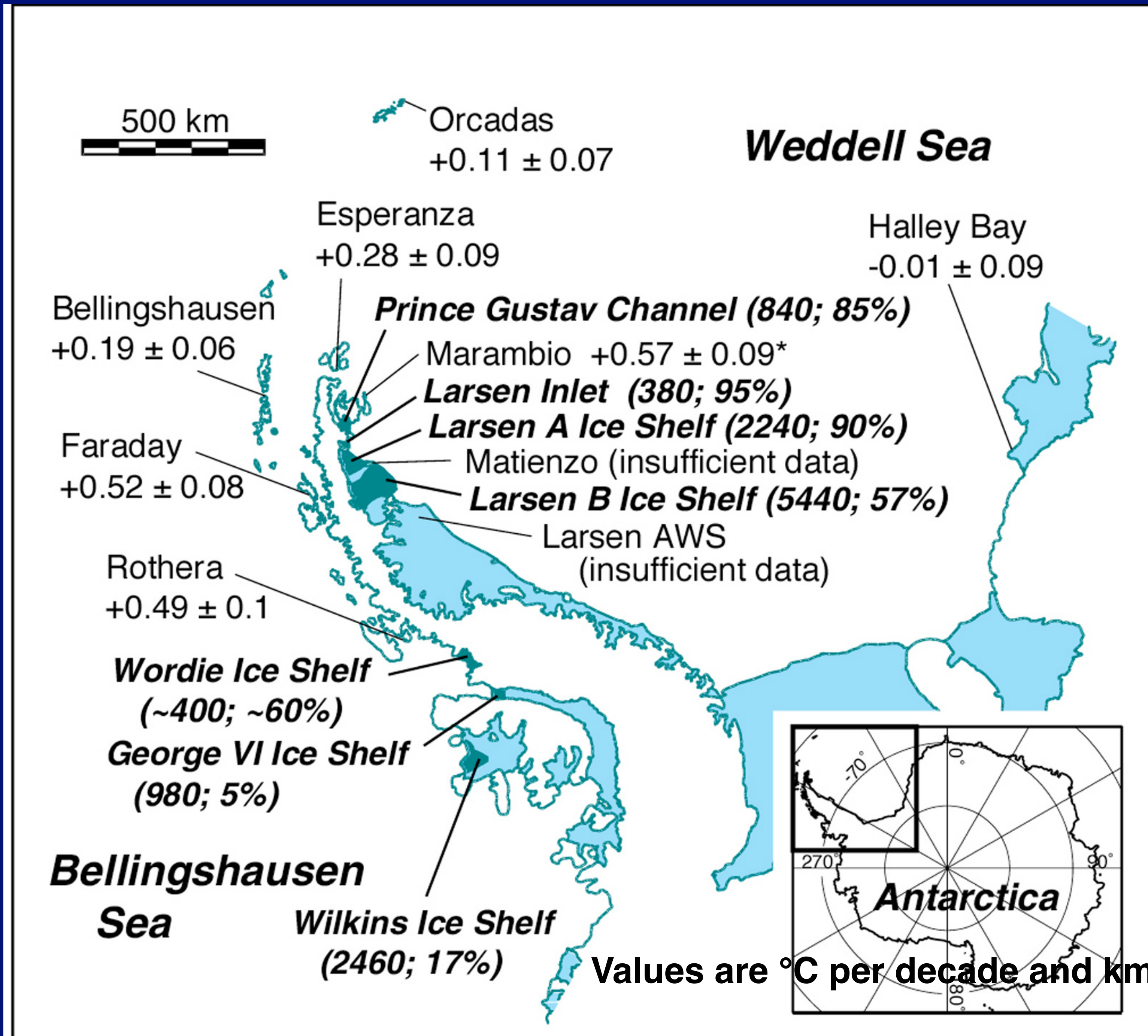
Pine Island
100°W
105°W
74°S
75°S
Cosgrove Ice Shelf
Eastern Ice Shelf
EIS ice rise
Thwaites
Thwaites ice tongue
Haynes
Crosson Ice Shelf
Pope
Smith
Dotson Ice Shelf
Kohler
92
94
96
00
11
ANTARCTICA
50 km
V (km/yr)
<0.0015 0.01 0.1 1 >3



Greenland (Sentinel-1)

Sentinel-1 Near Real Time Ice Velocity

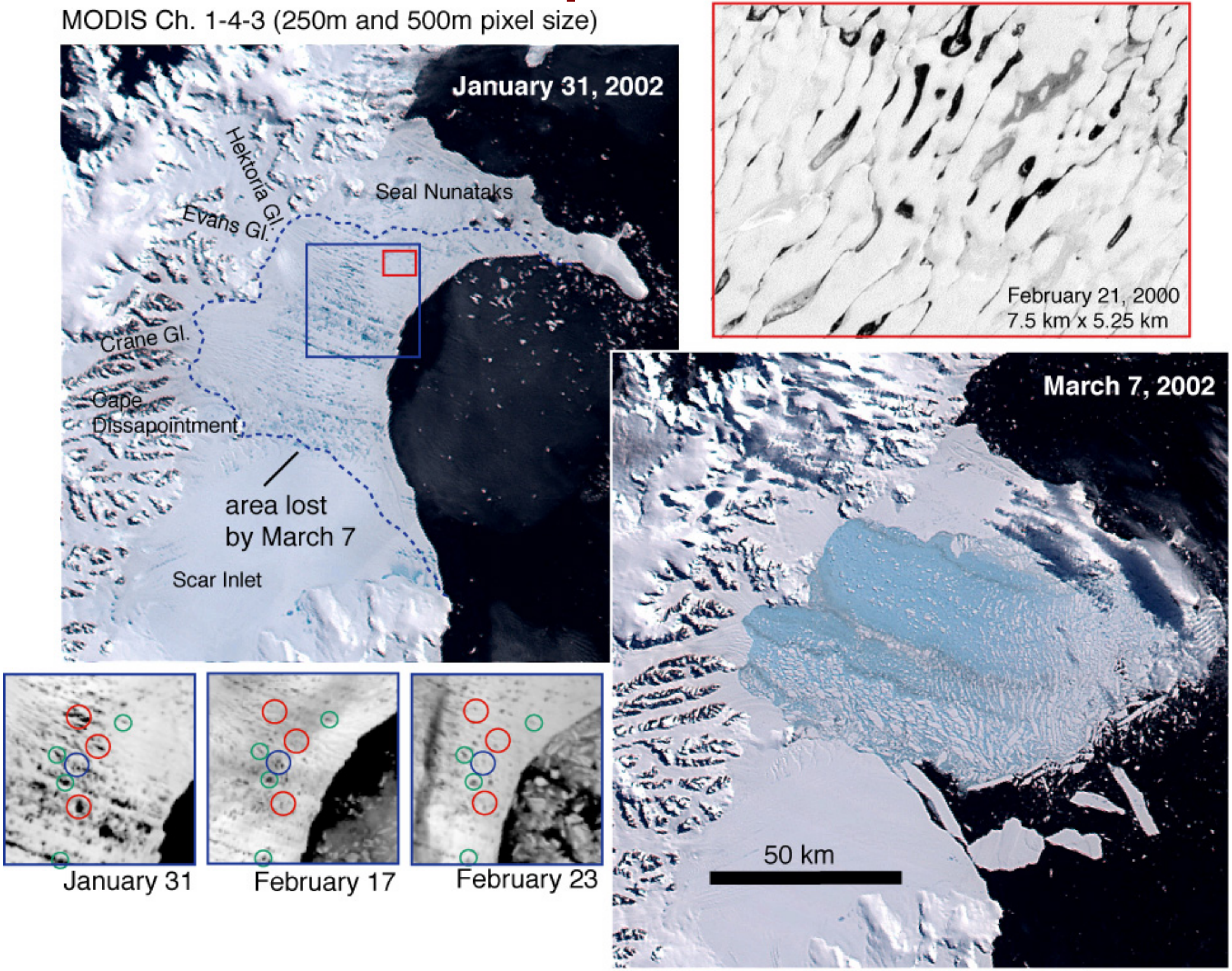
http://www.cpom.ucl.ac.uk/csopr/iv/



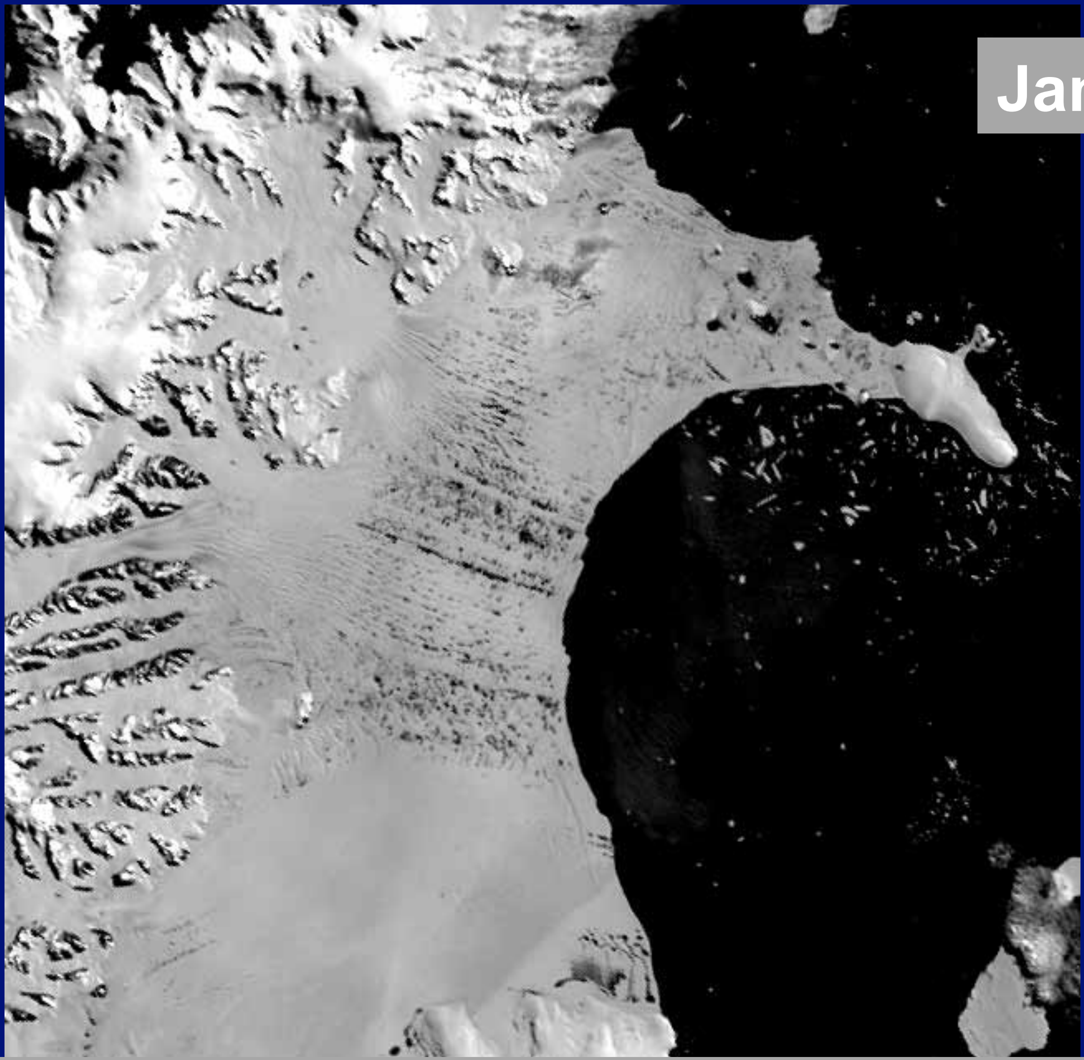
Values are °C per decade and km2

The Larsen B Breakup, 2002

Landsat 7 Band 8 (15m pixel size)



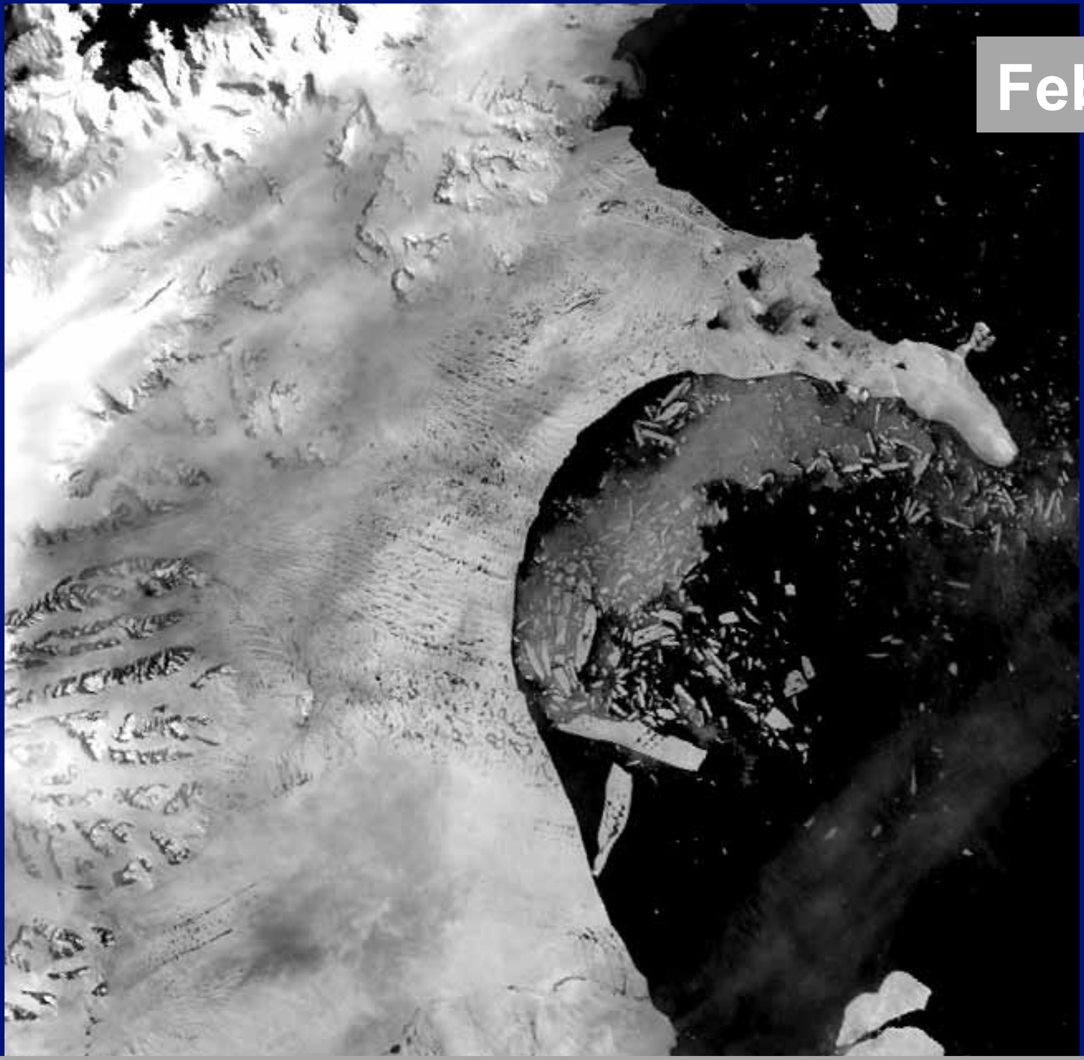
Collapse of Larsen B Ice Shelf



Jan 31 2002

MODIS images courtesy of Ted Scambos, NSIDC

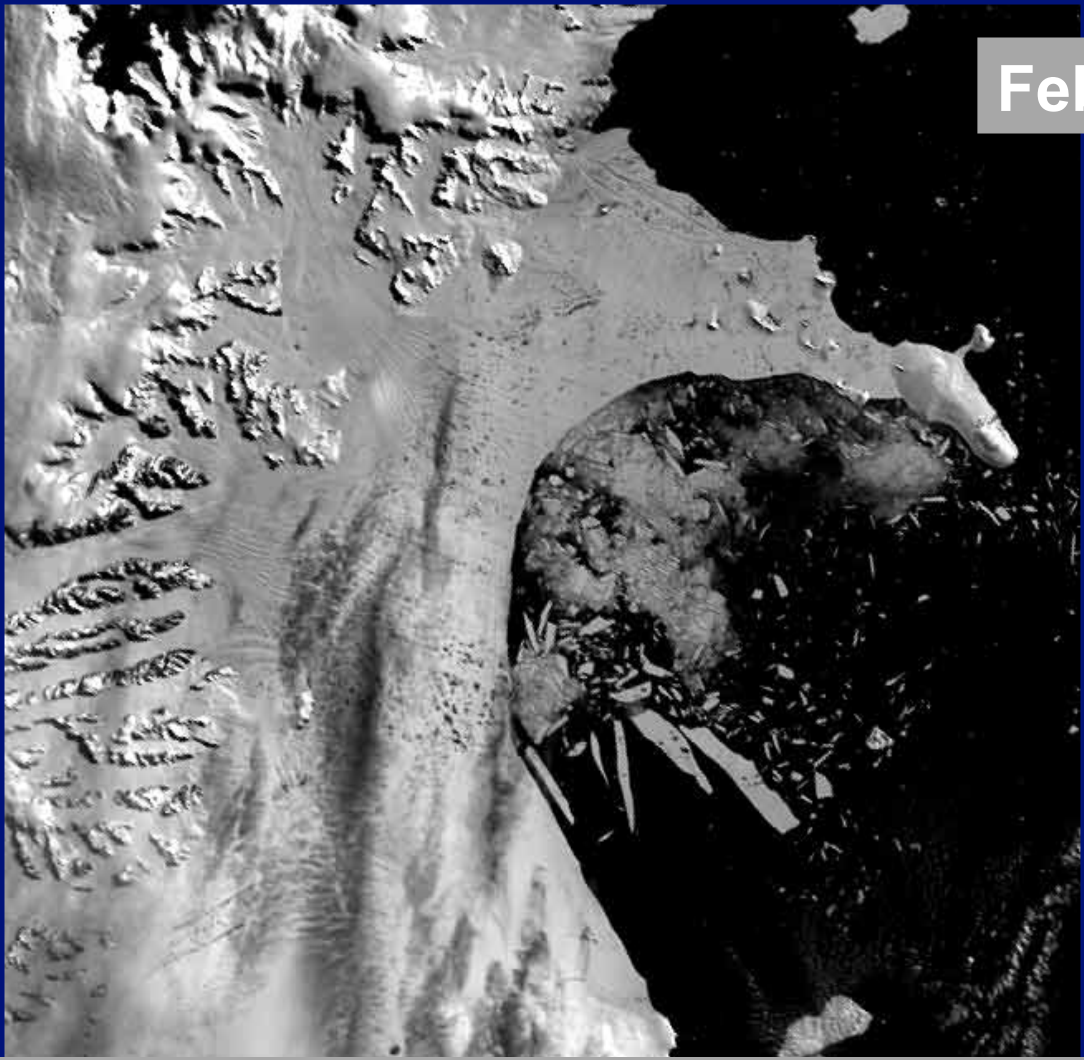
Collapse of Larsen B Ice Shelf



Feb 17 2002

MODIS images courtesy of Ted Scambos, NSIDC

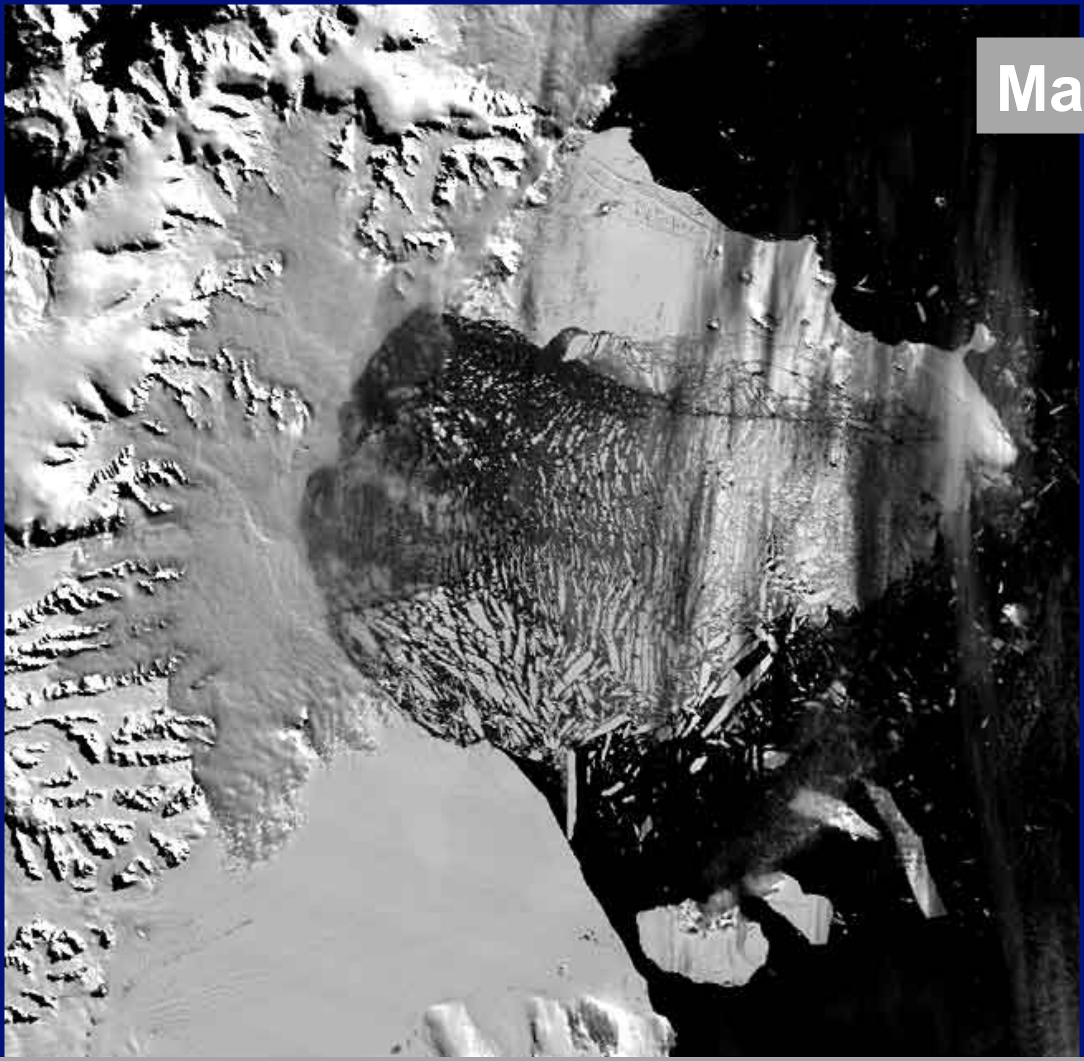
Collapse of Larsen B Ice Shelf



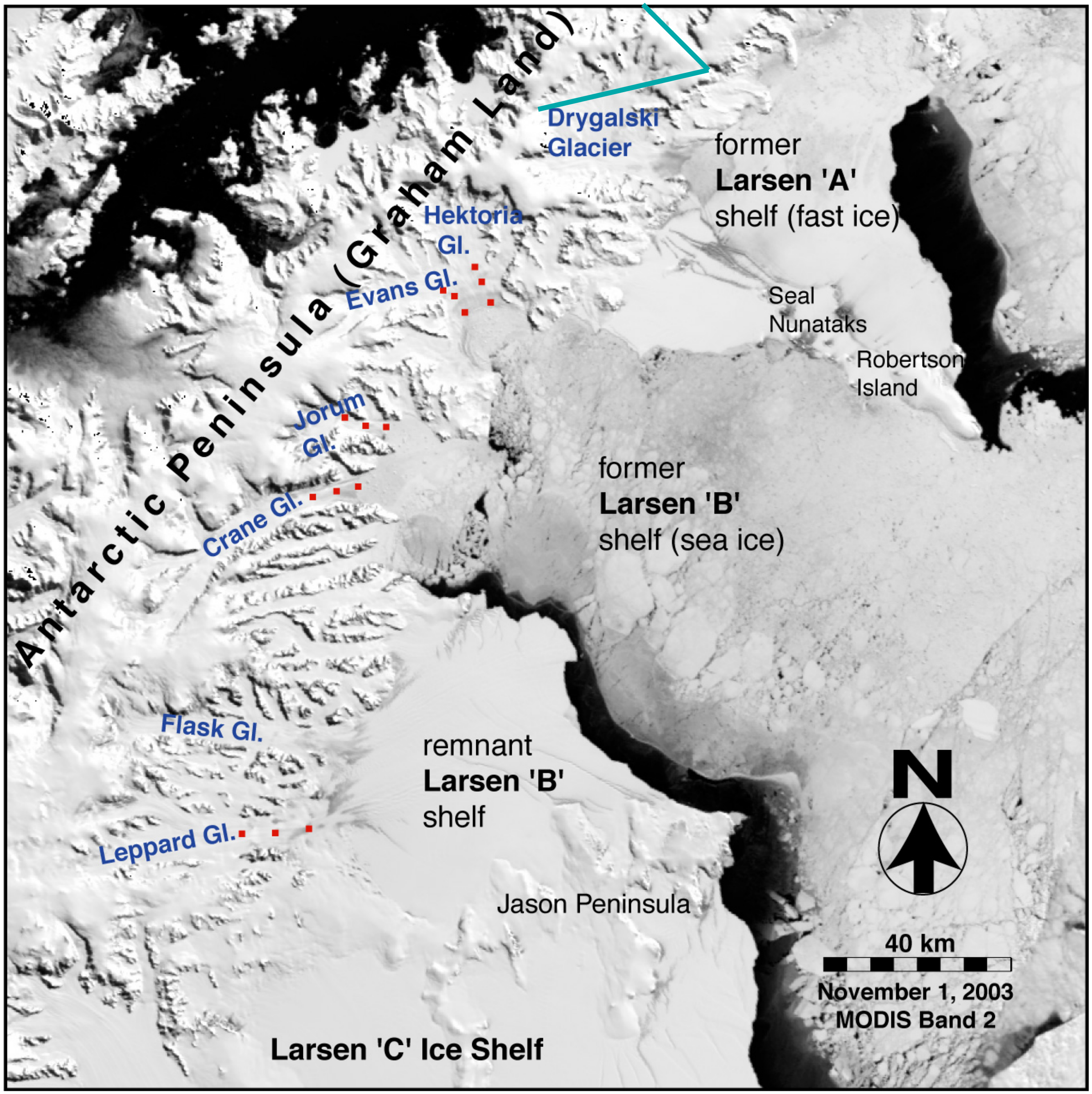
Feb 23 2002

MODIS images courtesy of Ted Scambos, NSIDC

Collapse of Larsen B Ice Shelf



MODIS images courtesy of Ted Scambos, NSIDC

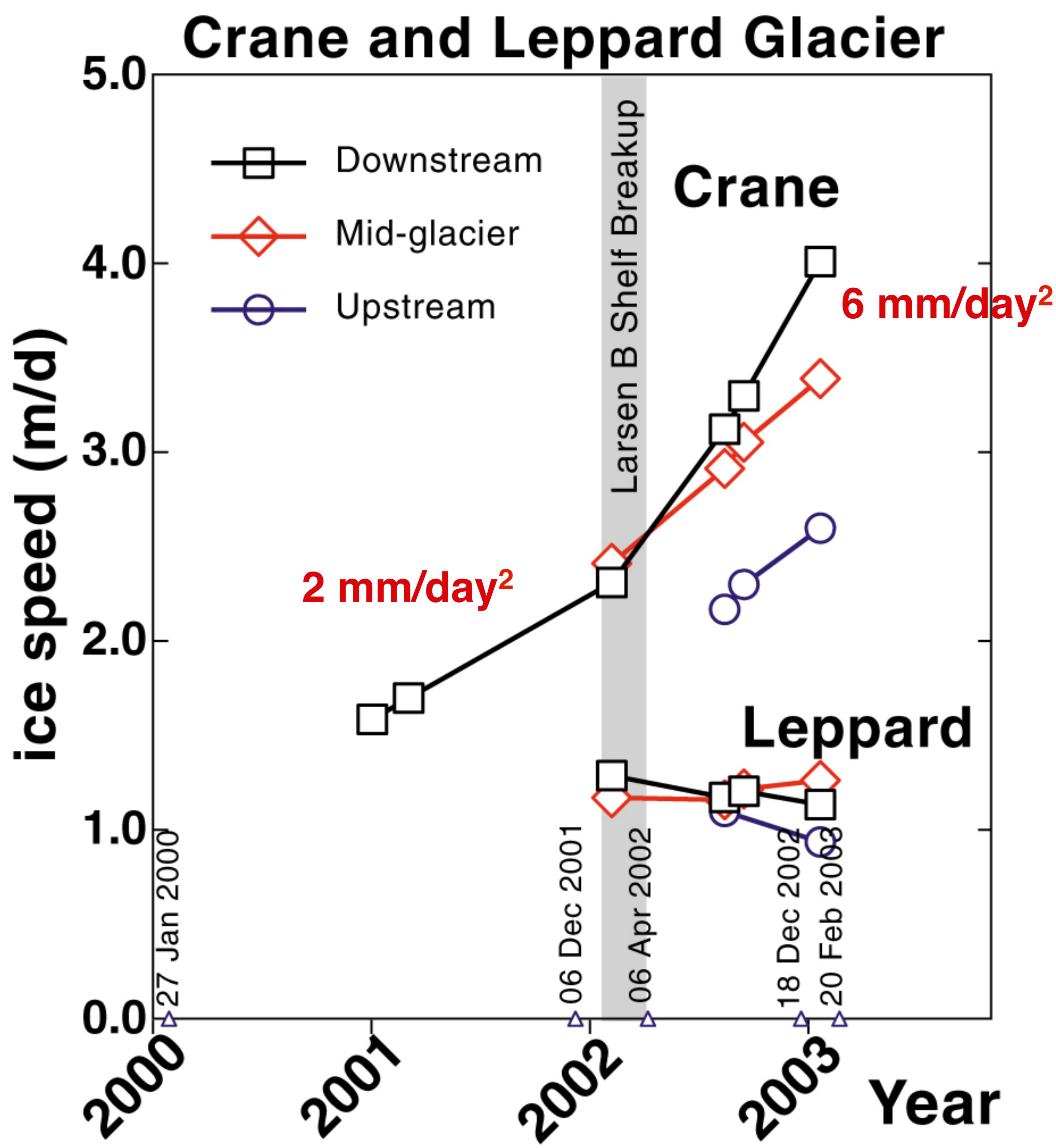


Larsen B glaciers:

Removal of the northern 2/3rds of the Larsen B ice shelf in Feb Mar., 2002 had a profound, rapid effect on the glacier spee and mass flux.

Although the glaciers were al-ready increasing in speed (pro ably due to pre-2002 retreats and local climate warming), an acceleration increase occurred for all glaciers feedin the catastrophic breakup area.

Conversely, NO acceleration change was observed in glacie south of the total break-up zon

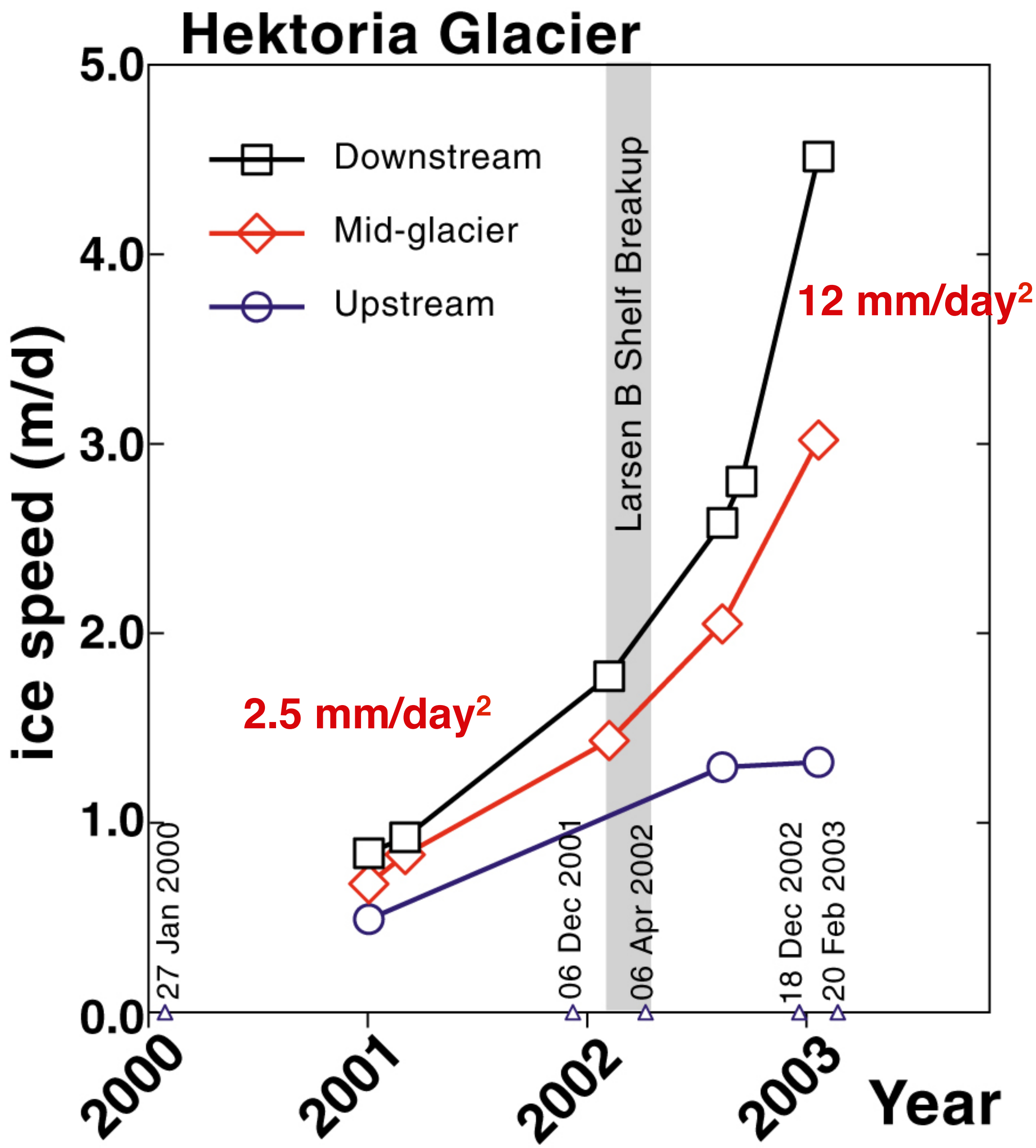


Larsen B breakup Glaciers:

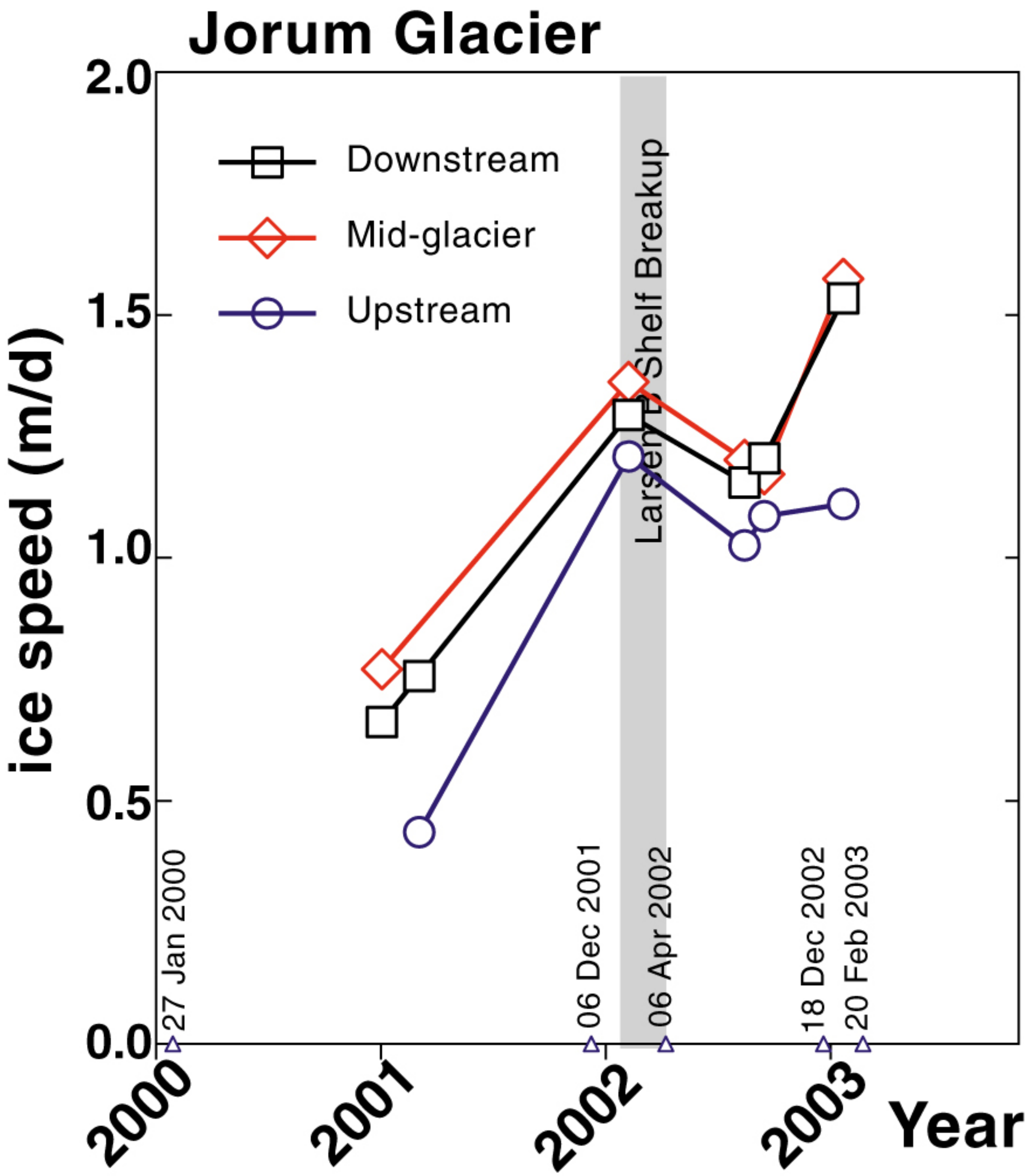
- **Hektoria**
- **Evans**
- **Crane**

Glaciers still fronted by extensive shelf:

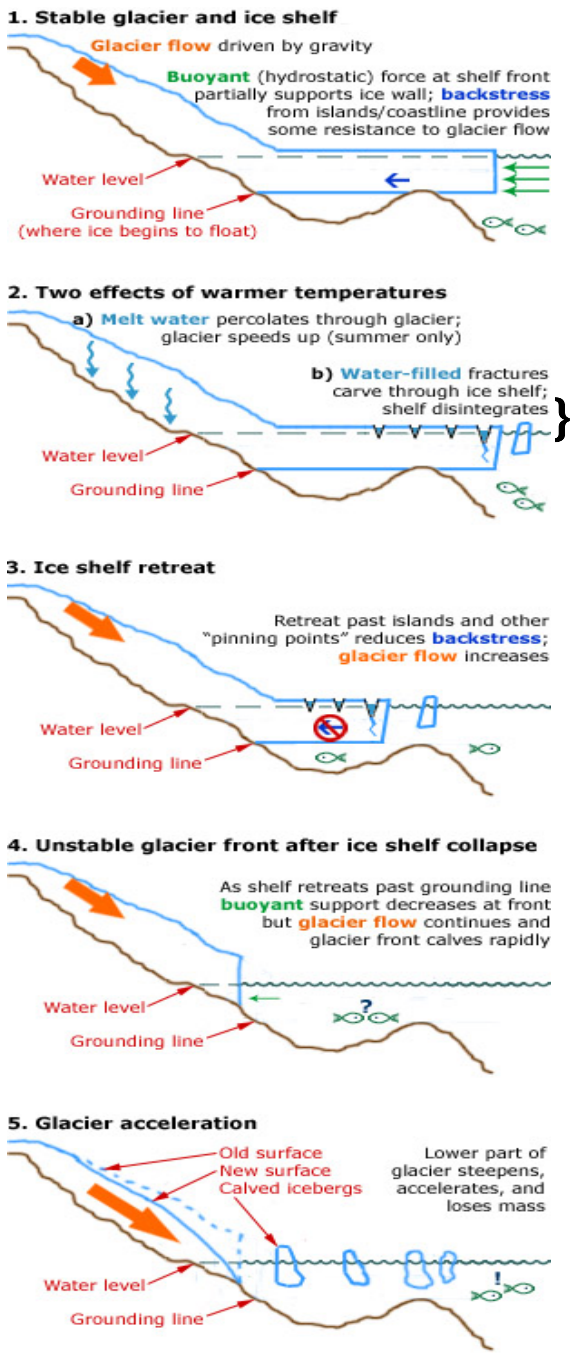
- **Flask**
- **Leppard**



Evans glacier shows a similar pattern



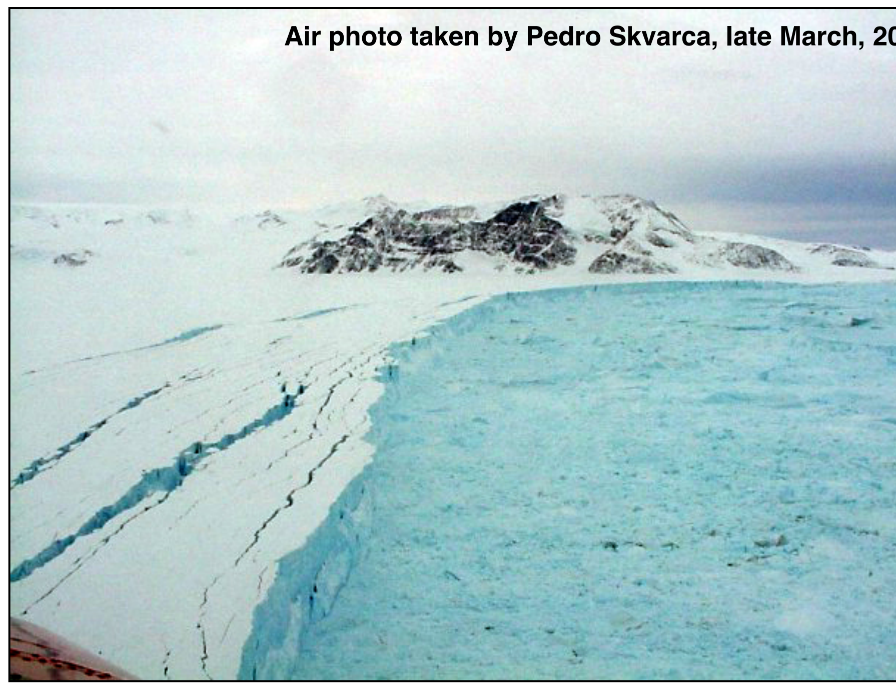
Jorum shows speed-up, but there may be a modification due to summer melt percolation



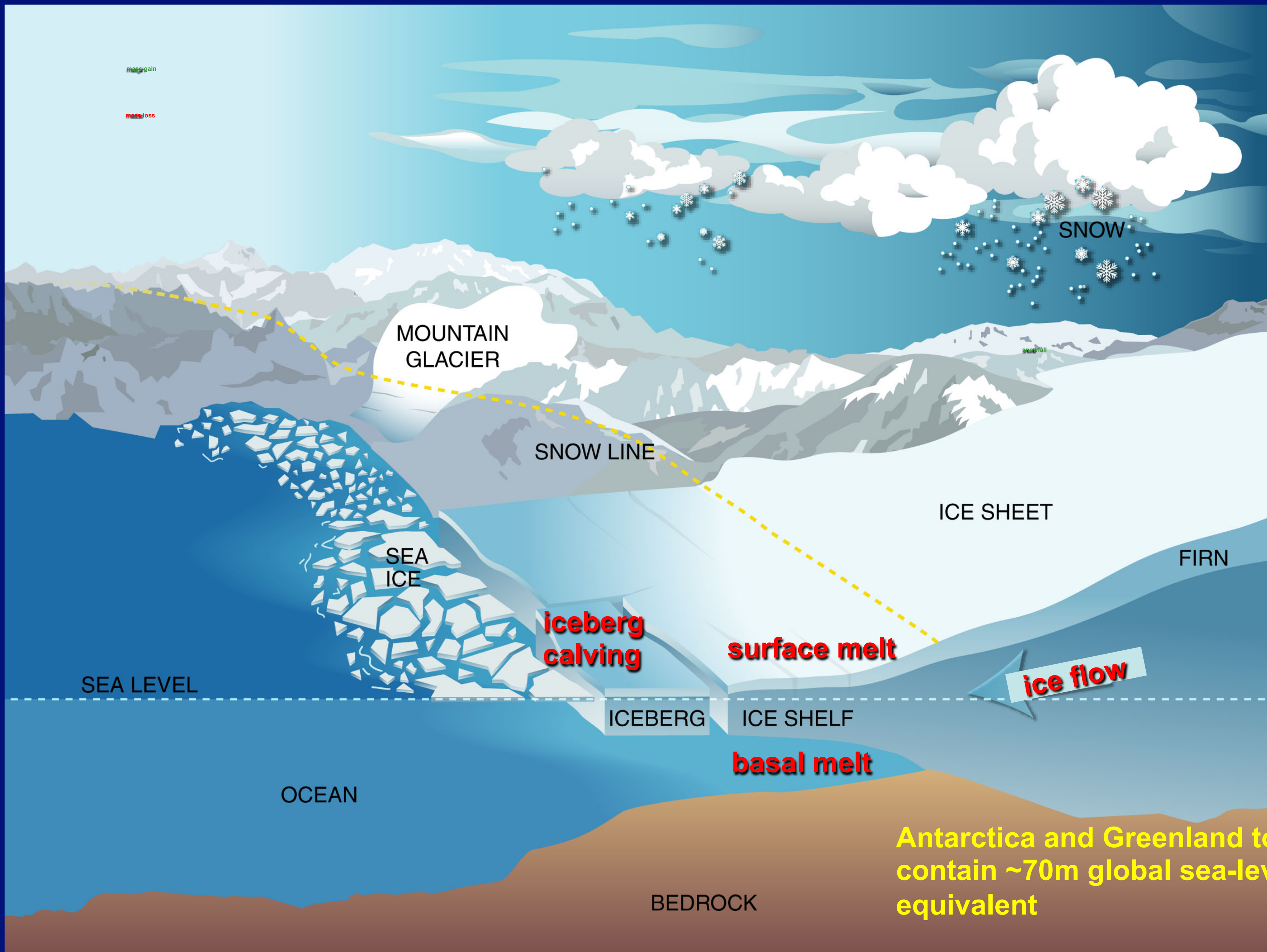
OR -
Effects of warmer water on underside and ice front

After shelf or ice tongue loss, the news is the same… faster glaciers.

- Loss of shelf backstress an initial effect, but..
  - the more dramatic effect may be due to increasing 'freeboard' as glacier retreats above the grounding line. Collapse of this taller, lightly grounded ice front leads to higher slope in the lower glacier and increased driving stress.
- Converting to tidewater glaciers

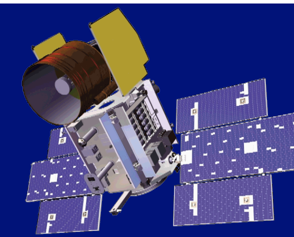


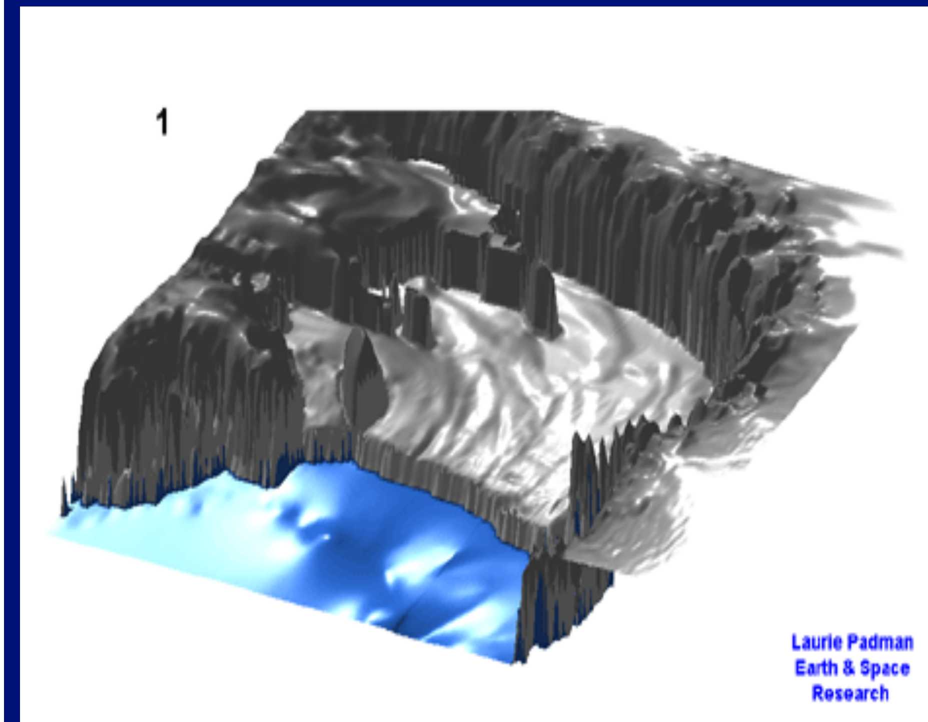
Ice sheet systems



Antarctica and Greenland together contain ~70m global sea-level equivalent

Ice shelf grounding zone (GZ)





Tide model of Ross Ice Shelf run over 25 hours

- Transition zone between fully floating & fully grounded ice
- Often poorly defined by pre-ICESat datasets
- Regions of significant basal melt
- Complex physics: coupling of bedrock, till, ice & ocean
- Can rapidly evolve in response to changes in ice thickness & sea level
- Monitoring GZs is important part of ice sheet change detection, the primary goal of the ICESat Mission

Features near the grounding zone

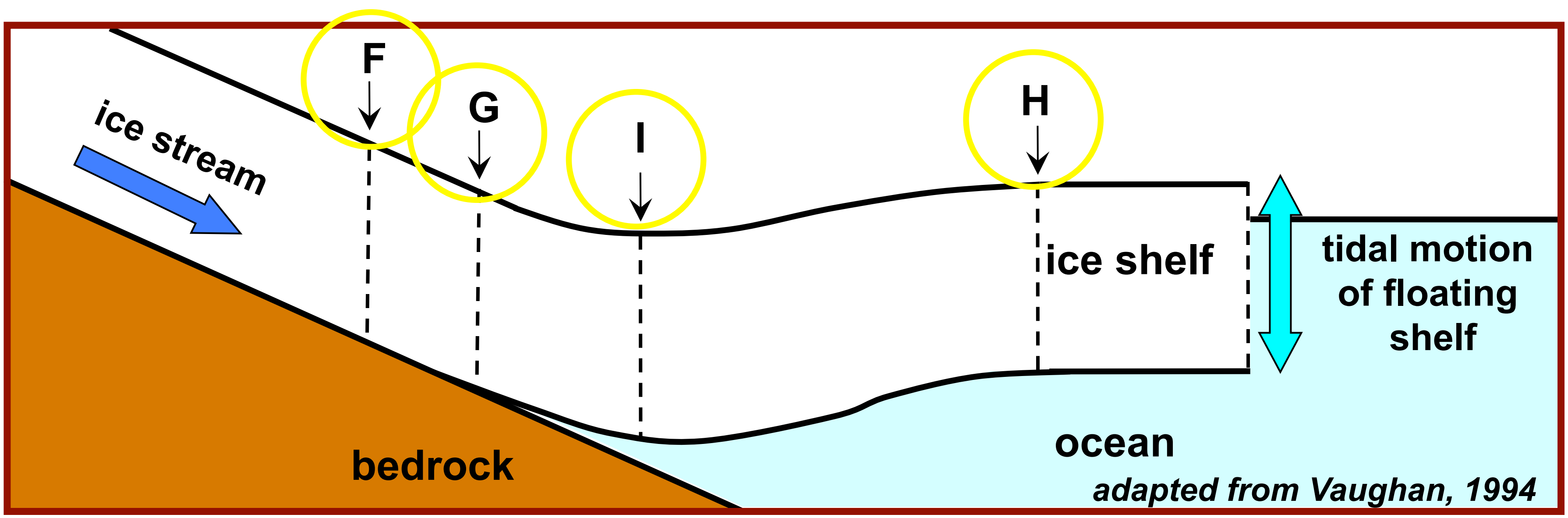
H: inshore limit of the hydrostatic zone of free floating ice shelf ice

I: inflexion point - in some cases this may just be a change in slope

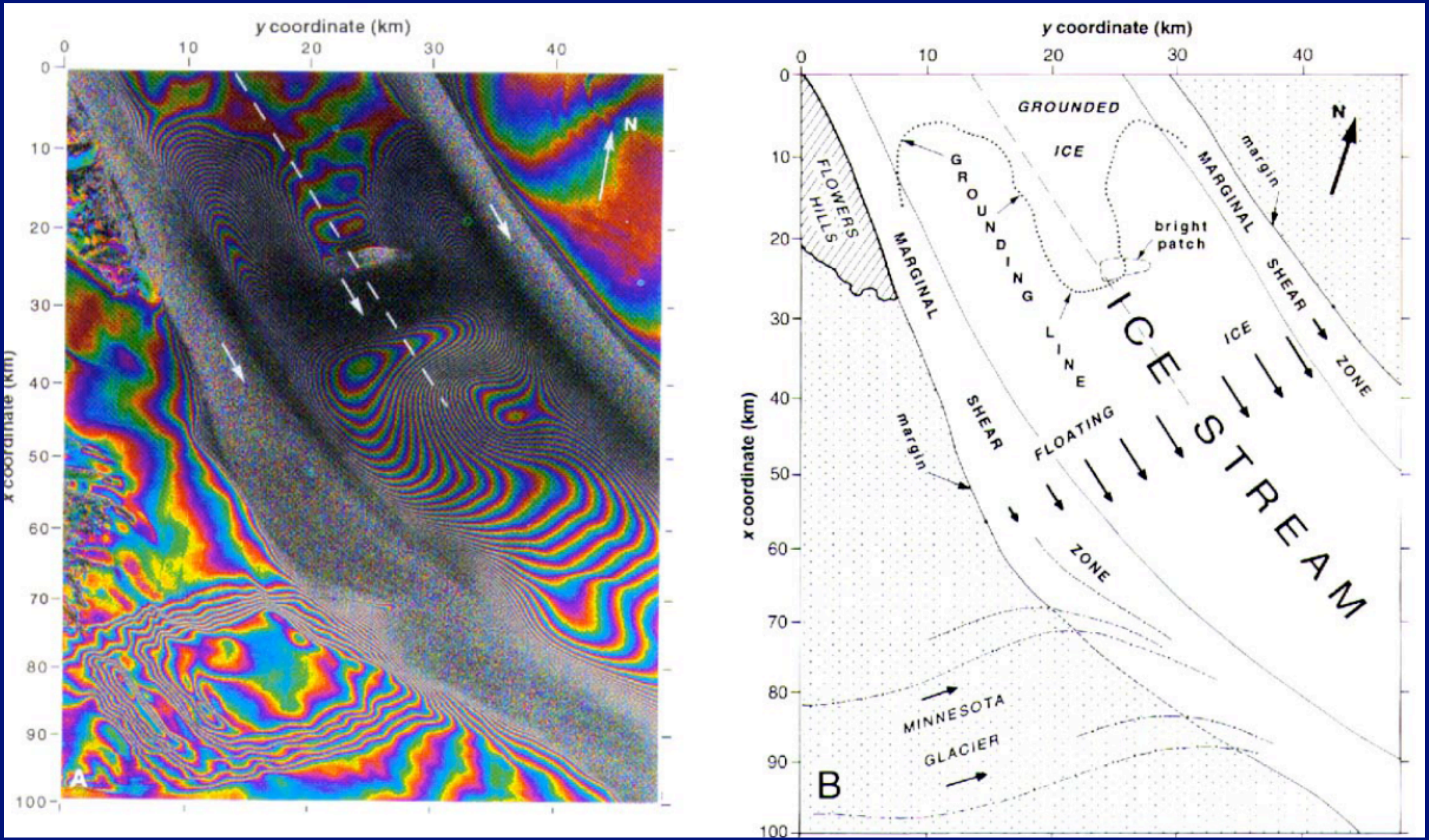
G: limit of ice flotation

F: limit of ice flexure from tidal movement

Relative locations of these features will change depending on ice thickness, bedrock topography & properties etc.



InSAR detection of grounding lines

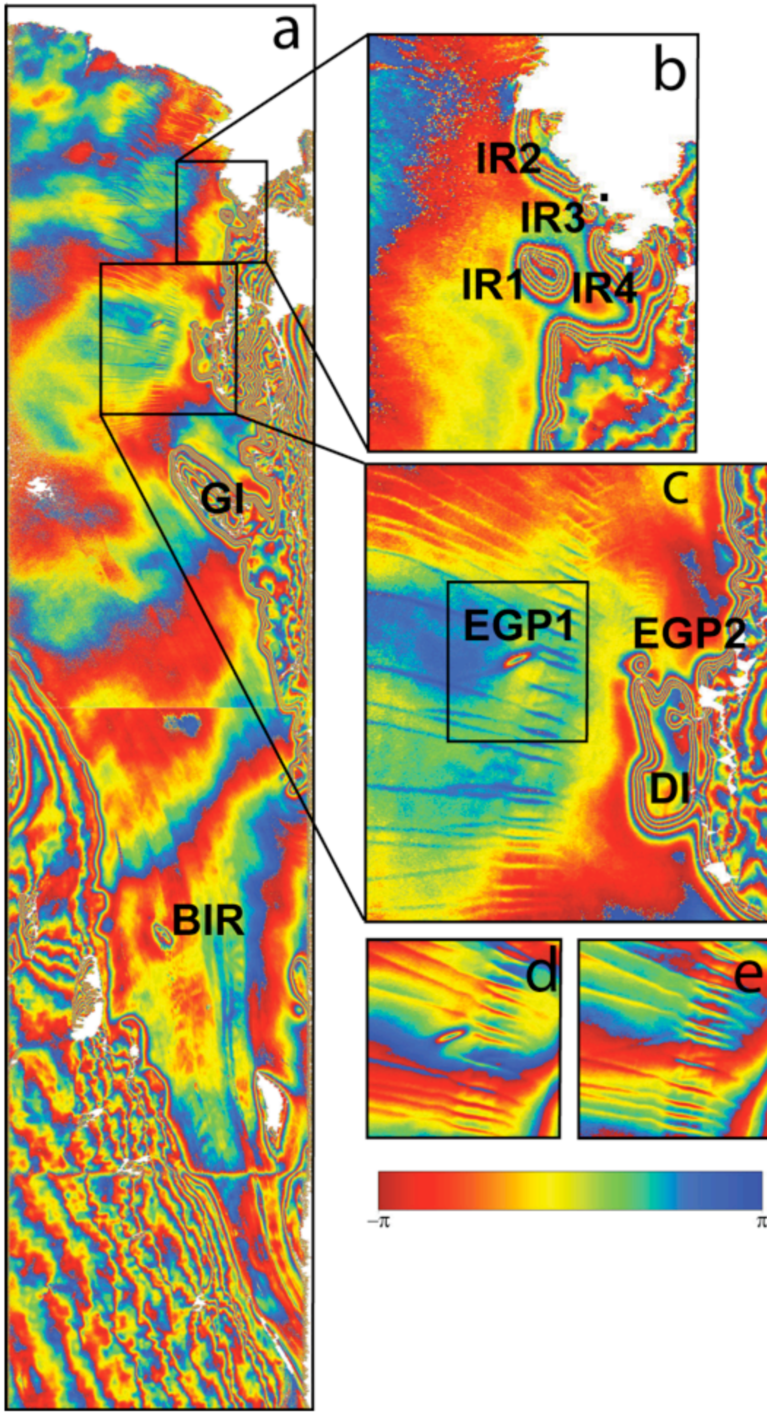


Interferogram of the Rutford Ice Stream, West Antarctica. Both the rapid flow of the ice stream and the location of the grounding line are visible. The fringes show displacements over a 6 day period with each color cycle representing 28mm of LOS displacement. Courtesy D. Goldstein, JPL.

InSAR detection of grounding lines

Differential SAR Interferometry (DSI)

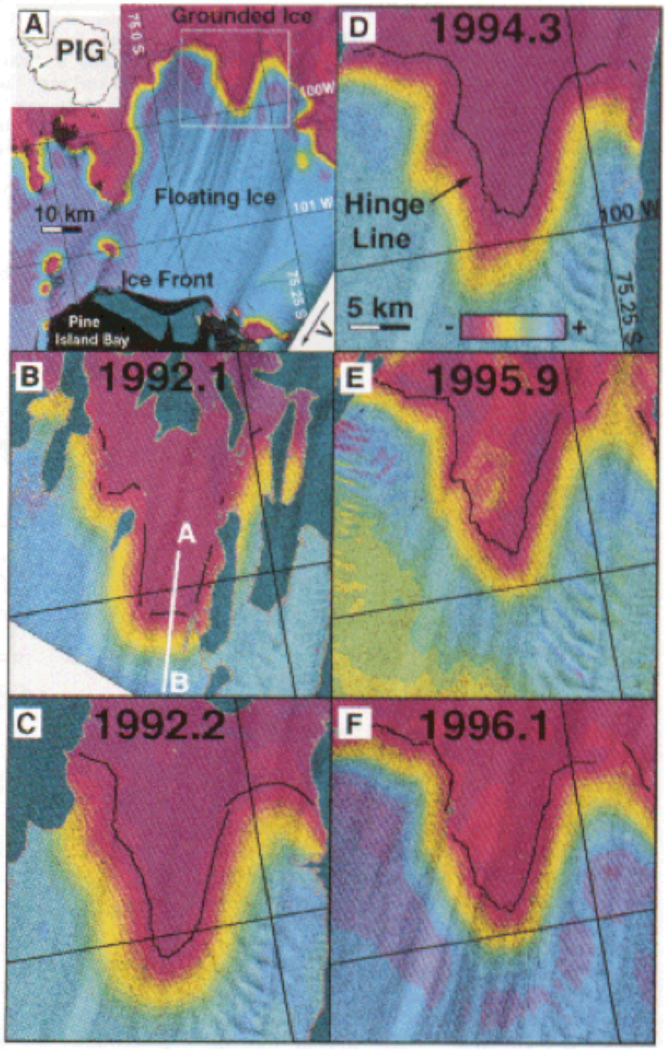
Difference between two interferograms over same time interval (to remove ice flow)

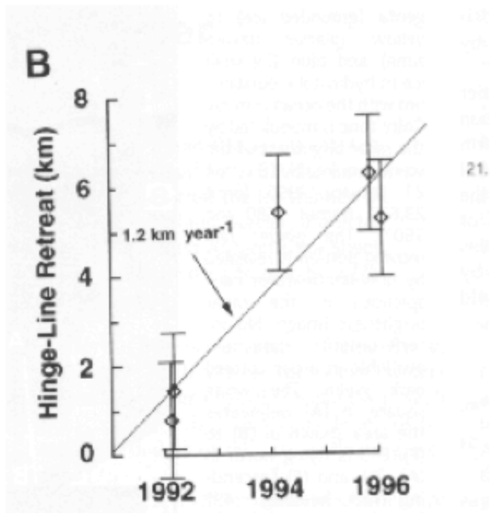


Fi

InSAR detection of grounding lines

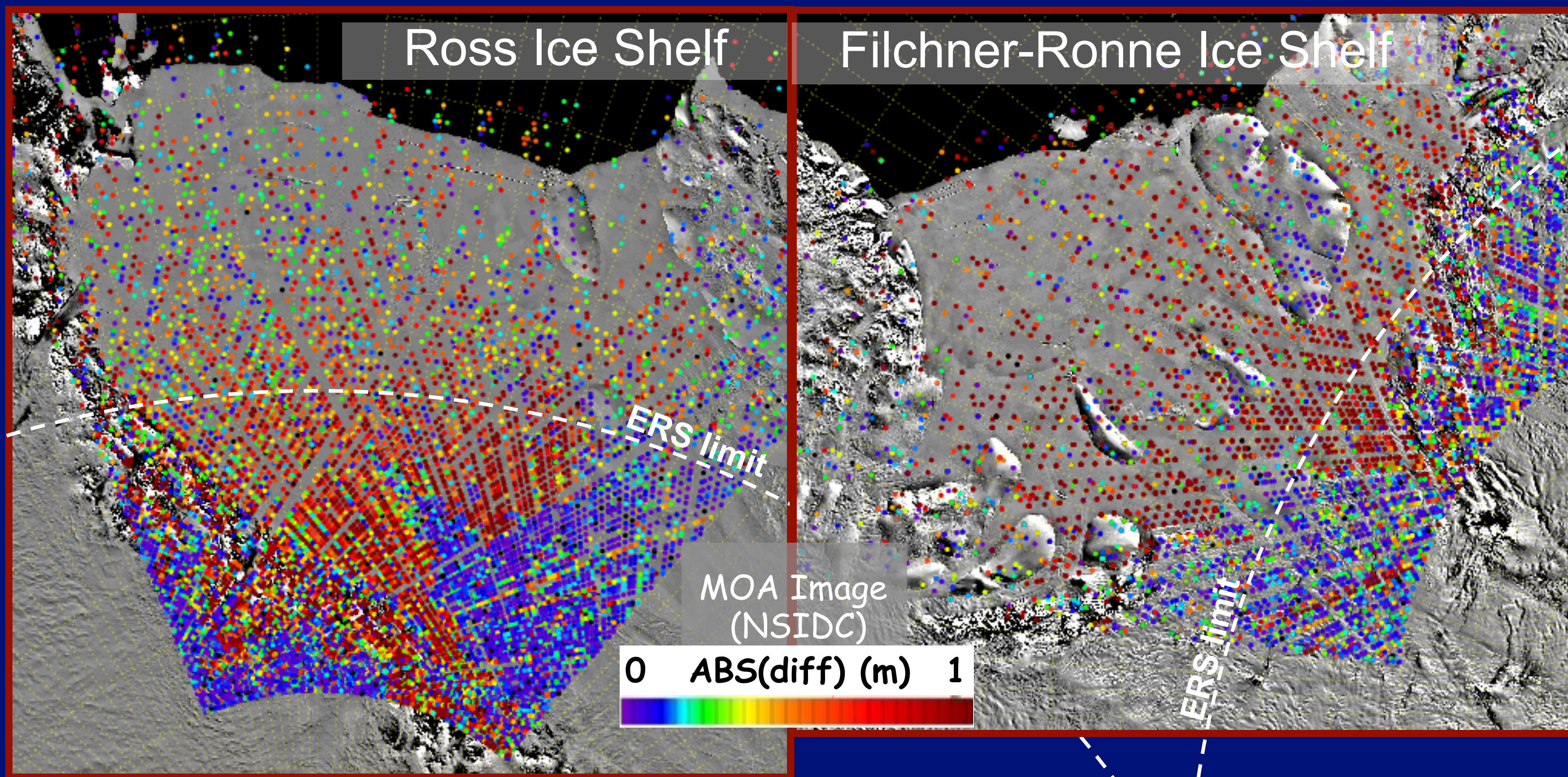
Example: Glacier Recession, Pine Island Glacier, Antarctica





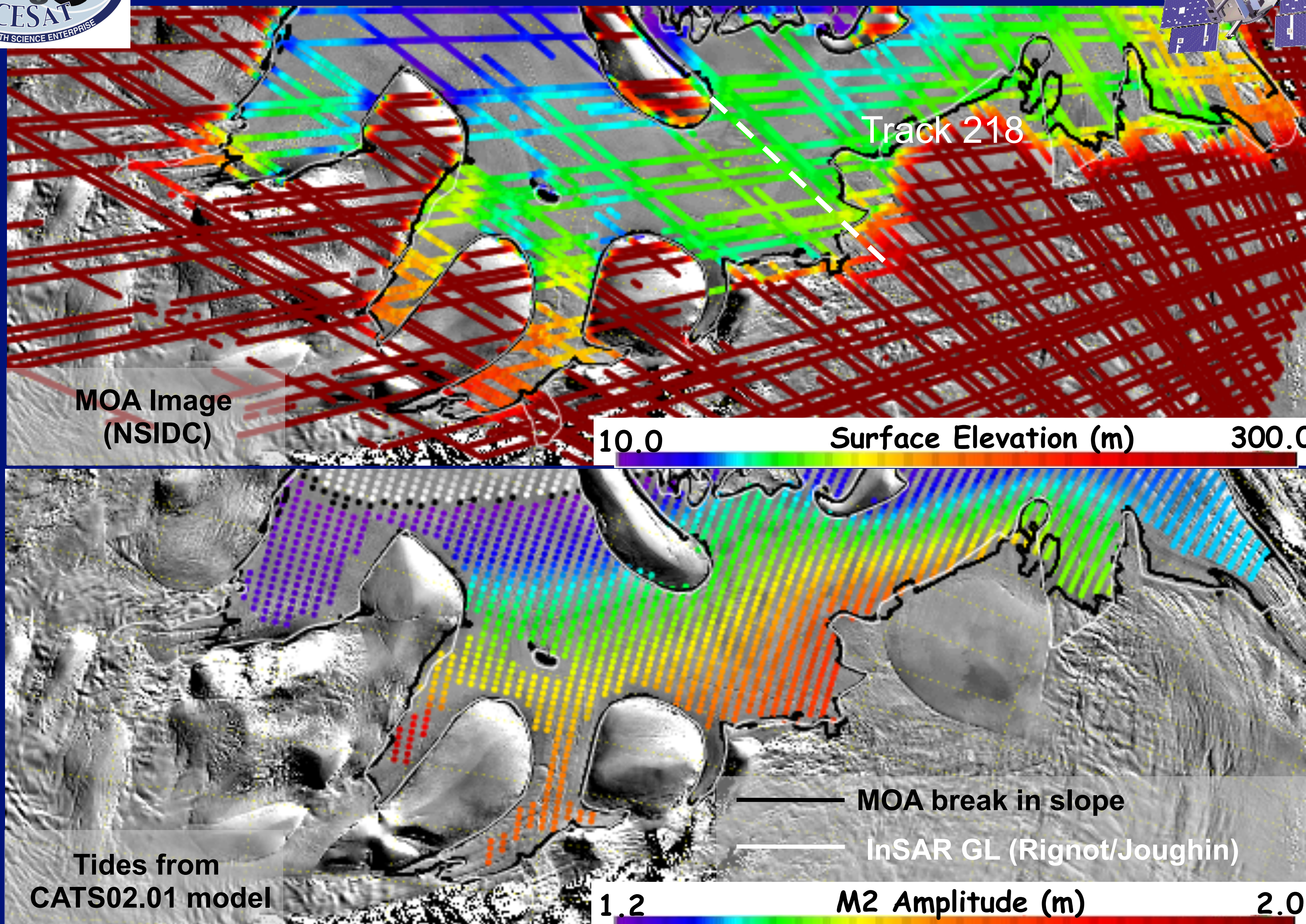
Reference: Rignot, Science, 1998

ICESat crossover differences

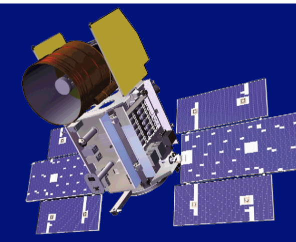


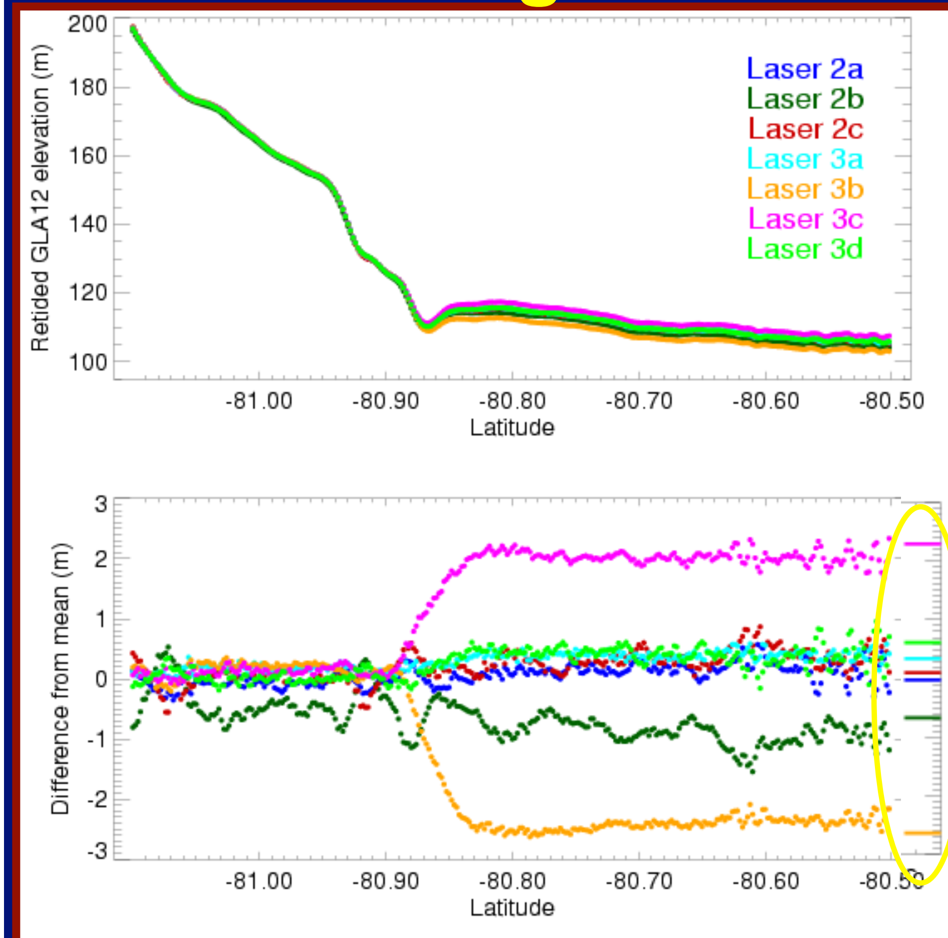
- ICESat coverage extends much further south than ERS
- Xover differences are large over the ice shelves due to tides
- High along-track resolution of ICESat (65m footprint, 172m spacing) allows accurate identification of GZs

Southern Filchner-Ronne Ice Shelf

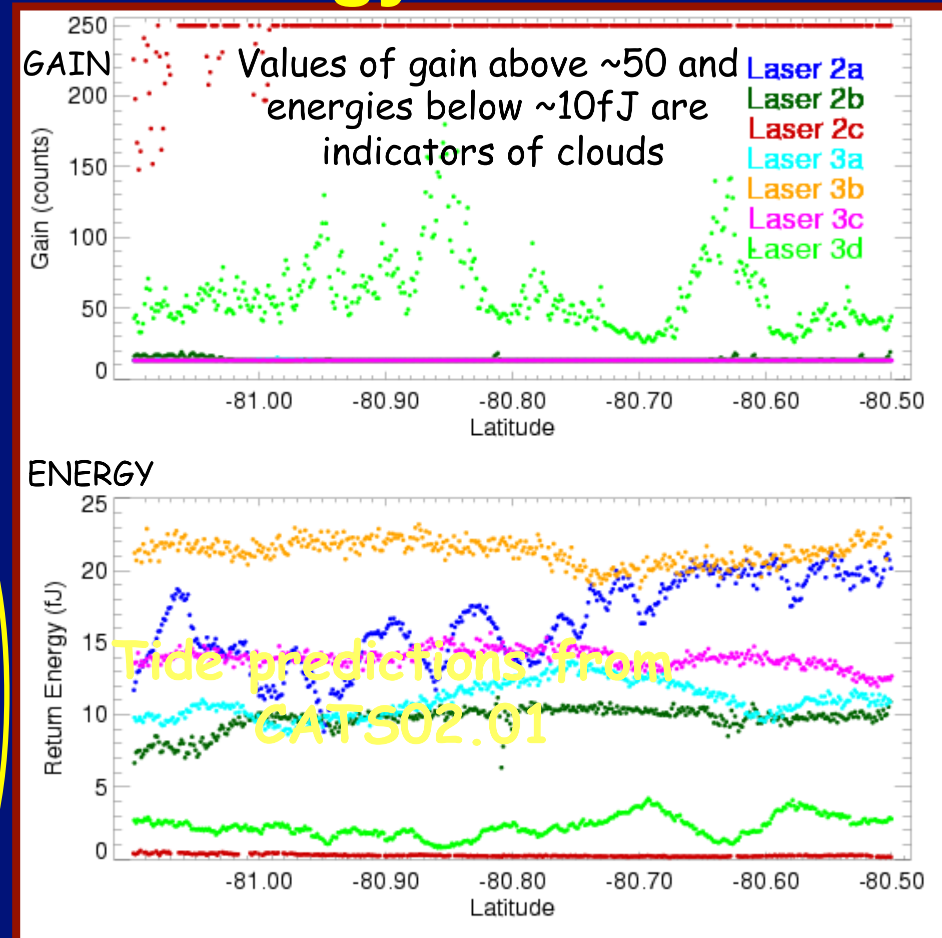


Repeat track data filtering using gain and return energy



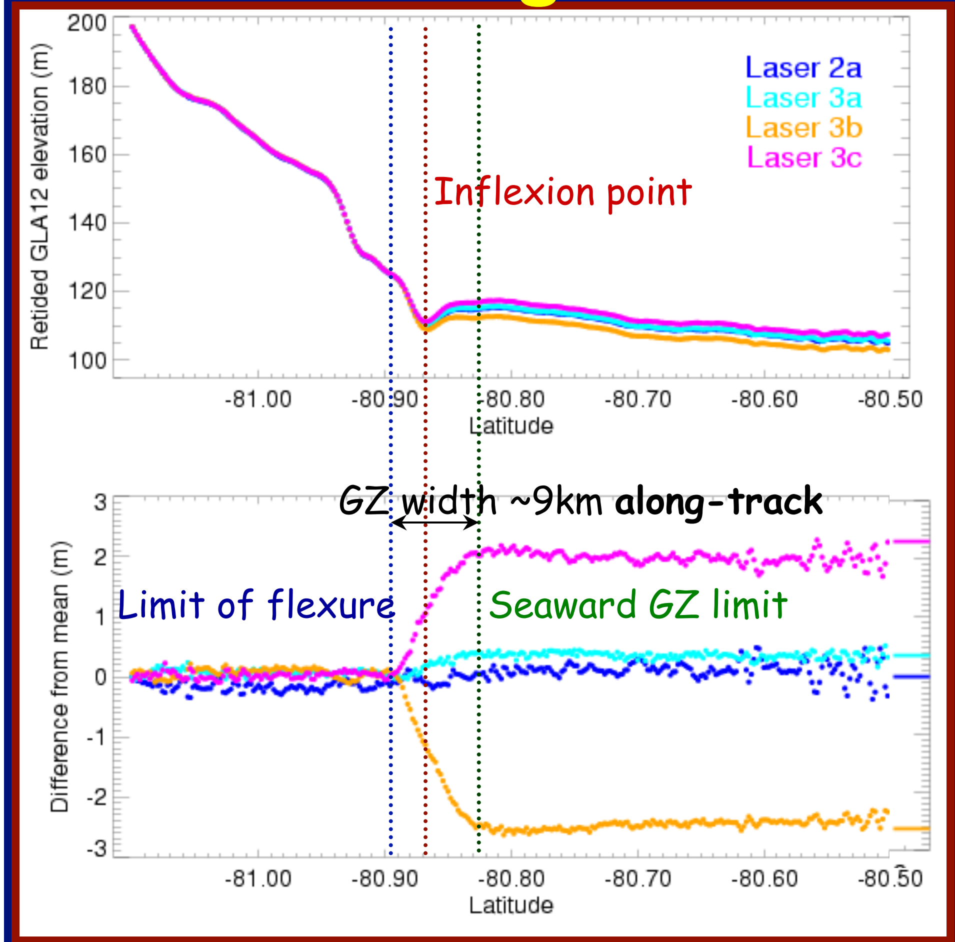


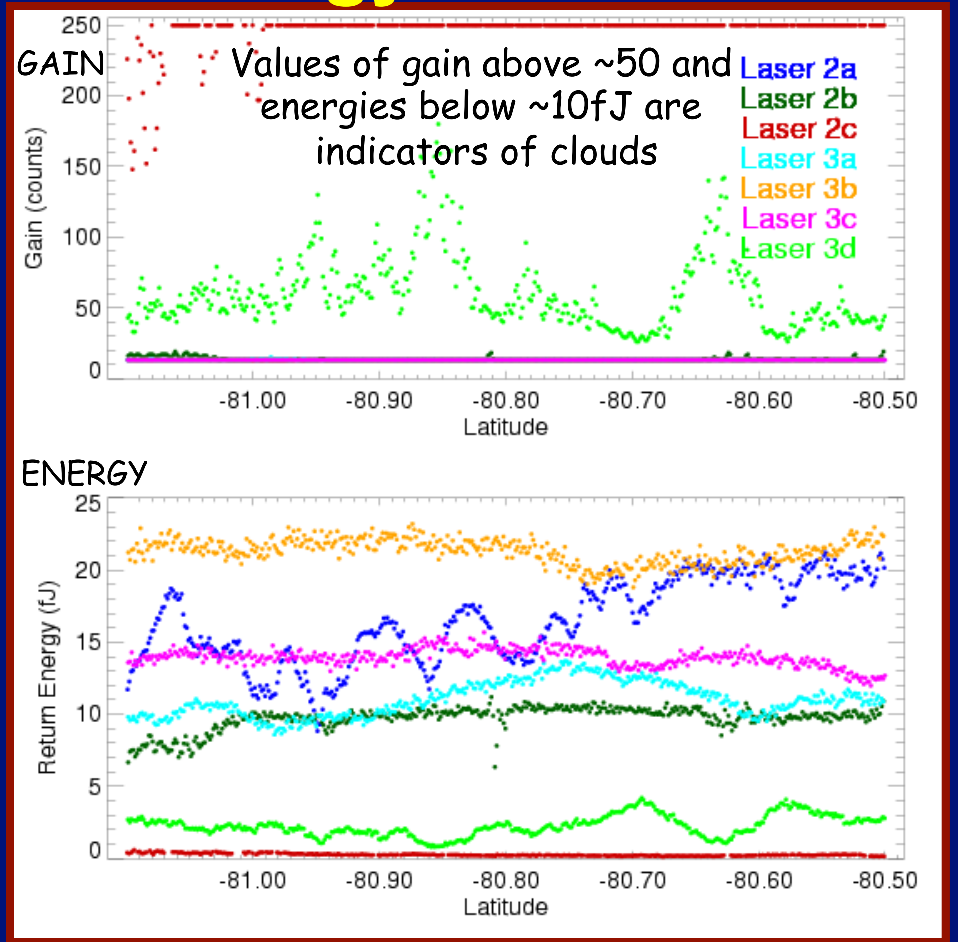
ICESat elevations (top) & anomalies (bottom) for all 7 operations periods



Gain & energy for all repeats: note high gain and low energy for Laser 2c & Laser 3d

Repeat track data filtering using gain and return energy

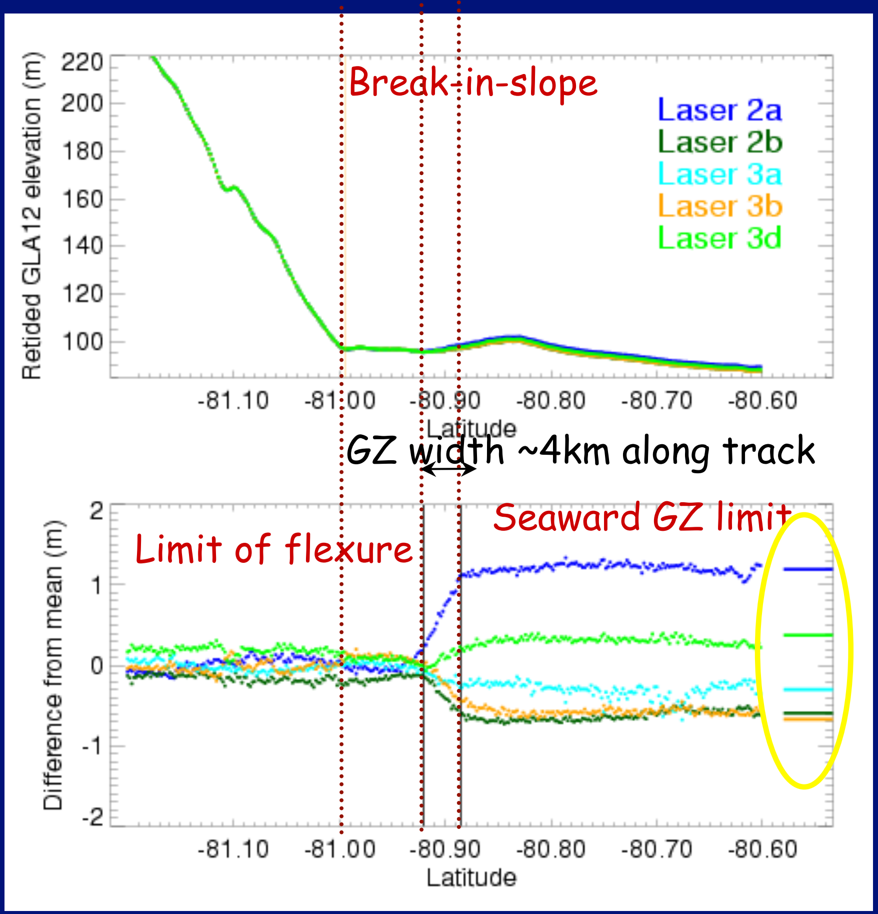


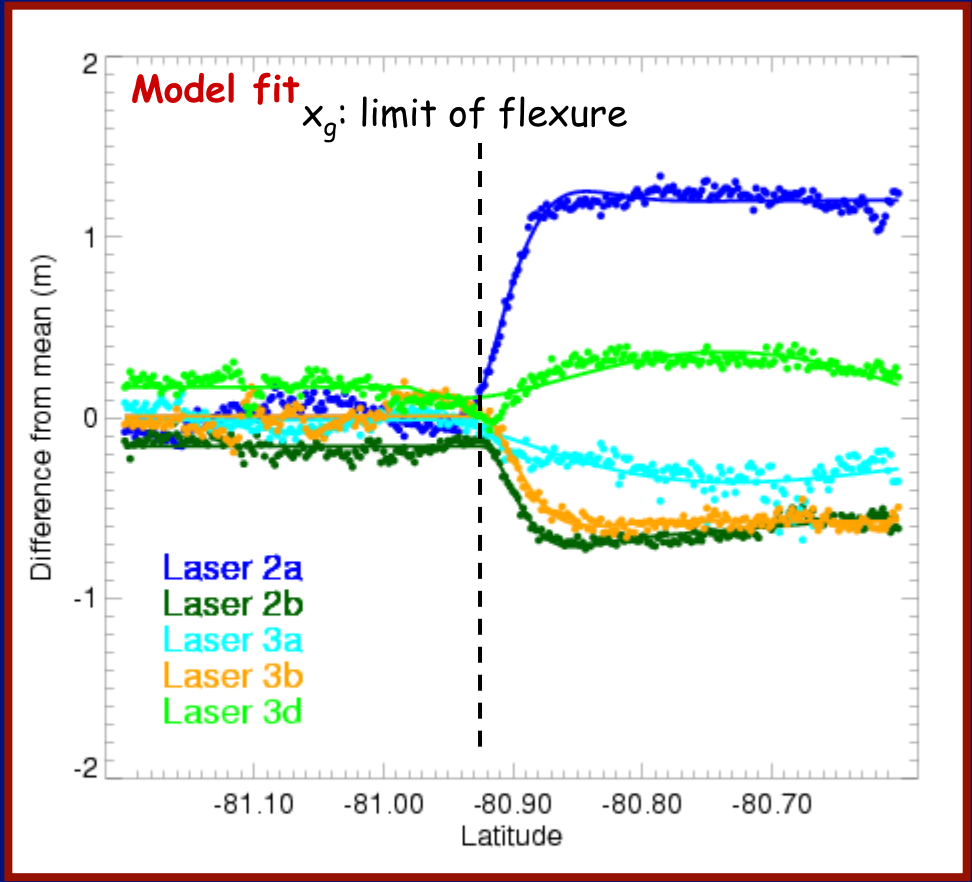


Laser 2b, Laser 2c & Laser 3d removed NB: if use just Laser 2a & 3a then low SNR

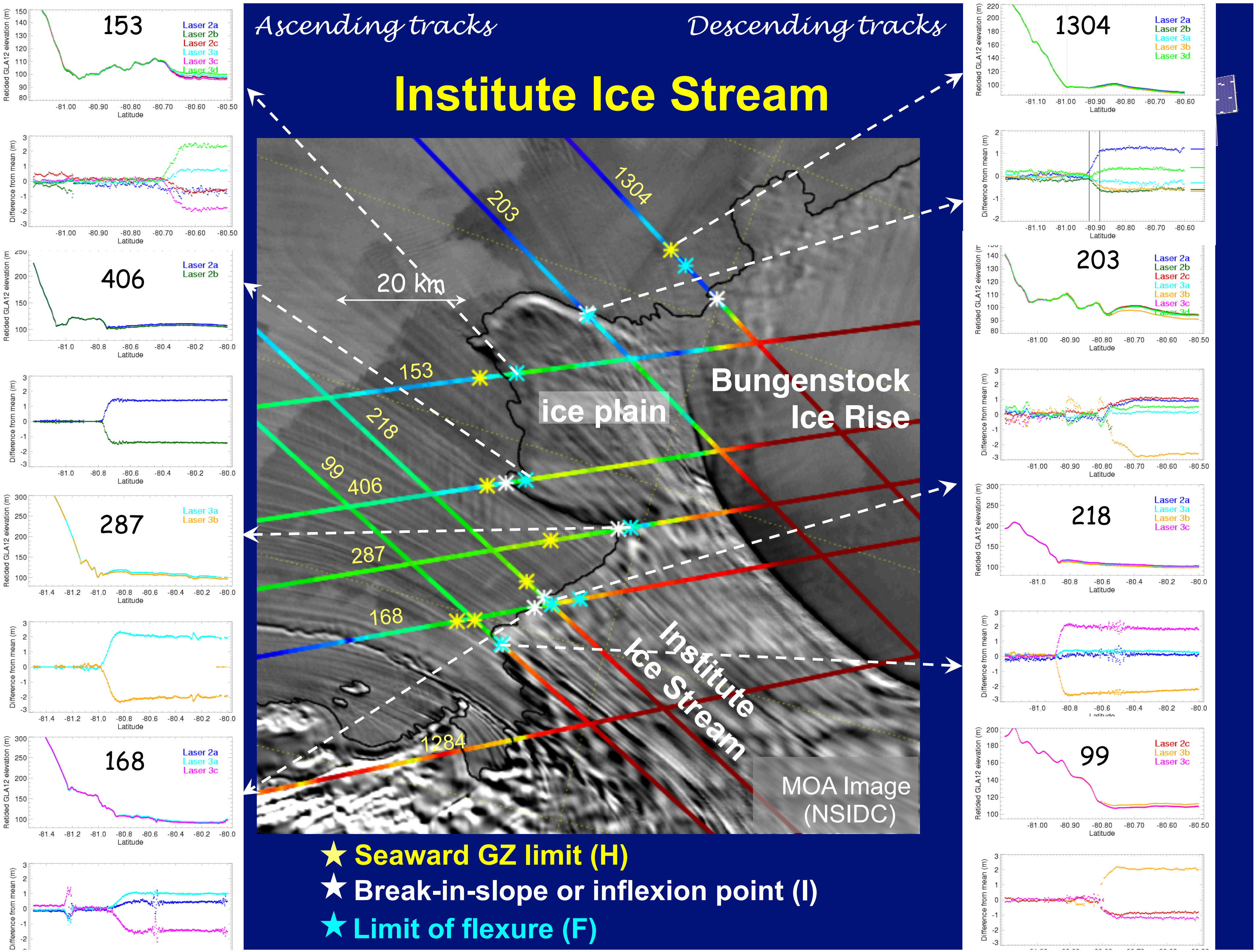
Gain & energy for all repeats: note high gain and low energy for Laser 2c & Laser 3d

Track 1304: ICESat data and flexure model fit



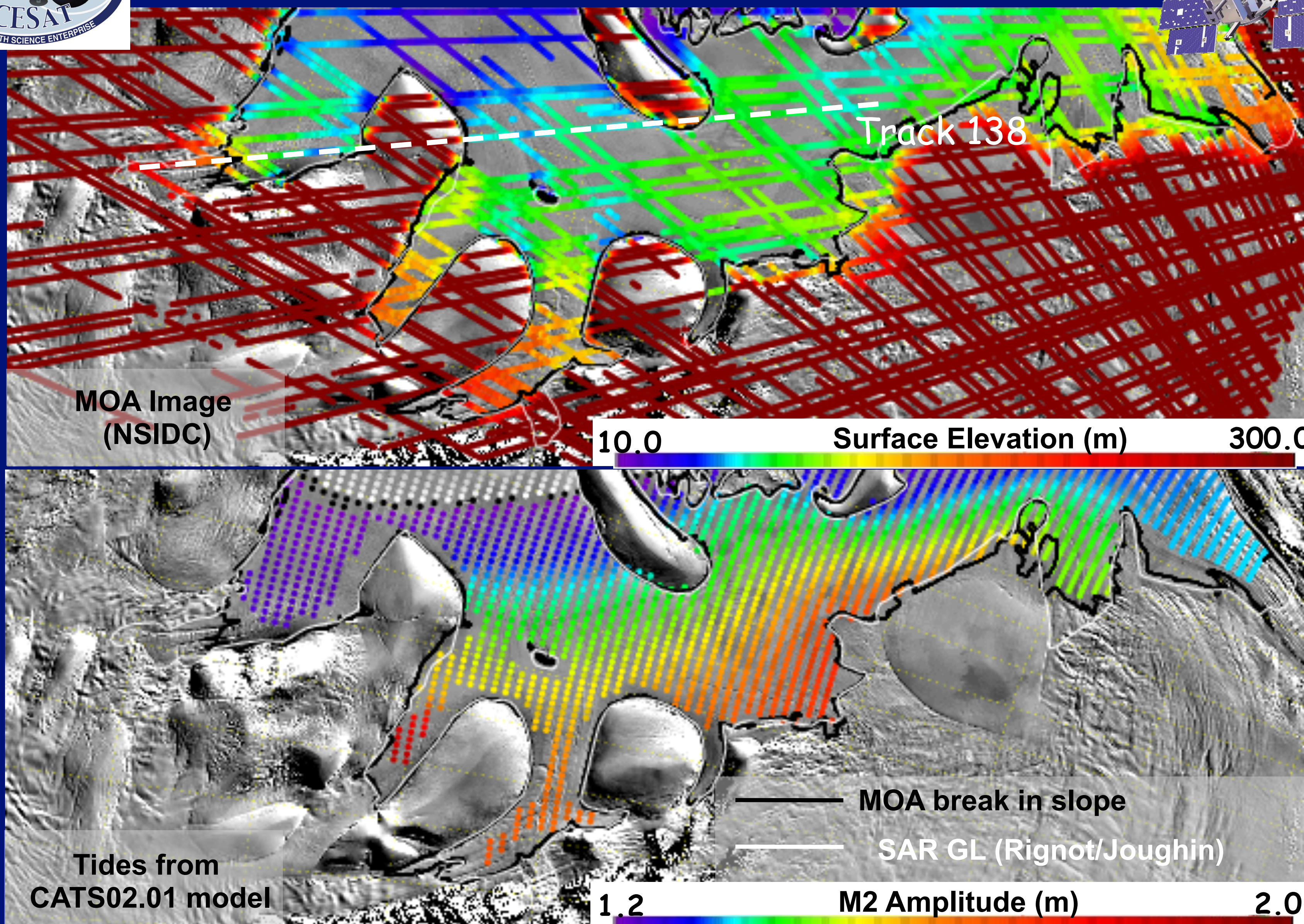


Tide predictions from CATS02.01

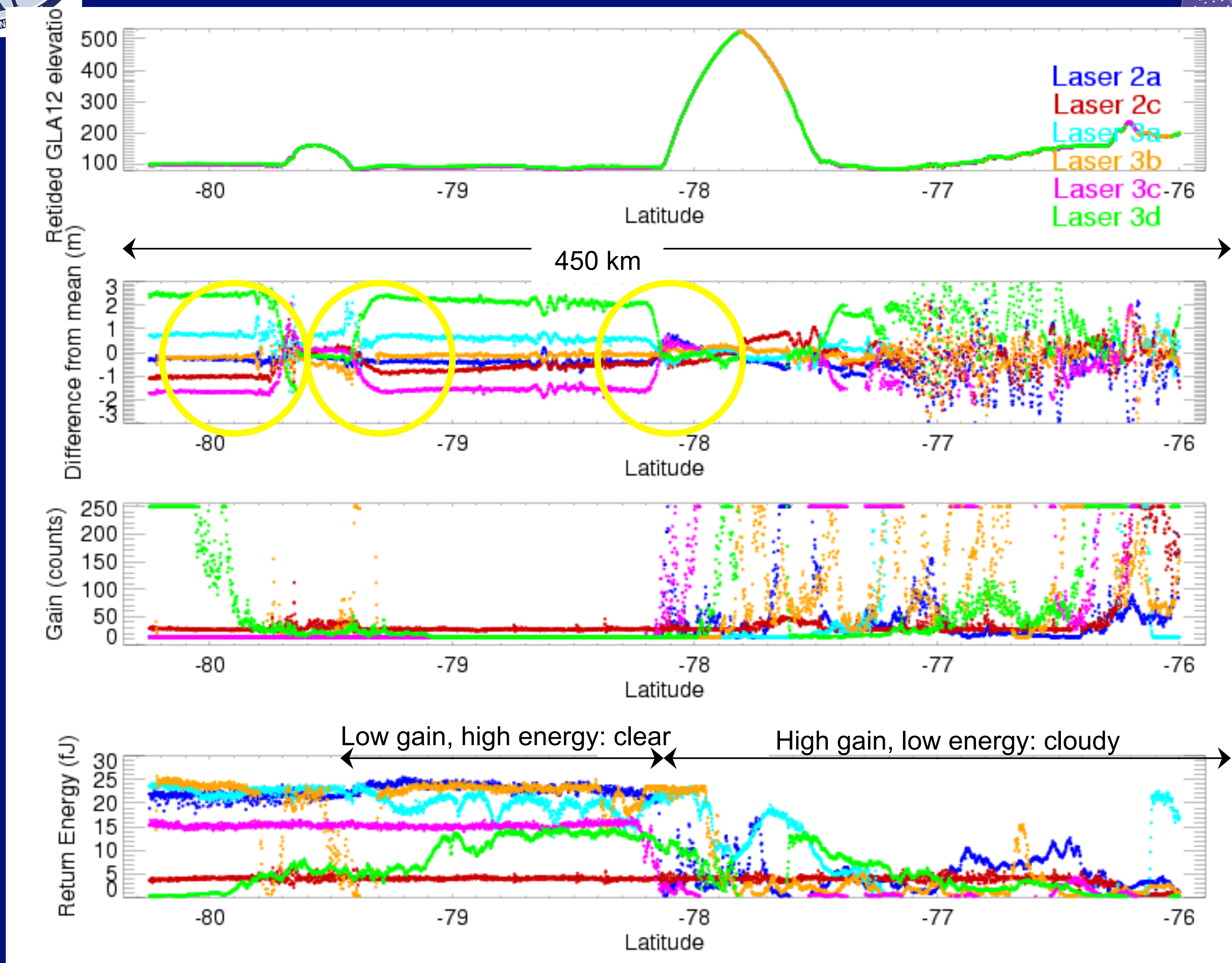


Ascending tracks
Descending tracks
Institute Ice Stream
20 km
1304
203
153
218
99
406
287
168
1284
ice plain
Bungenstock Ice Rise
Institute Ice Stream
MOA Image (NSIDC)
★ Seaward GZ limit (H)
★ Break-in-slope or inflexion point (I)
★ Limit of flexure (F)
Retided GLA12 elevation (m)
Difference from mean (m)
Latitude
Laser 2a
Laser 2b
Laser 2c
Laser 3a
Laser 3b
Laser 3c
Laser 3d

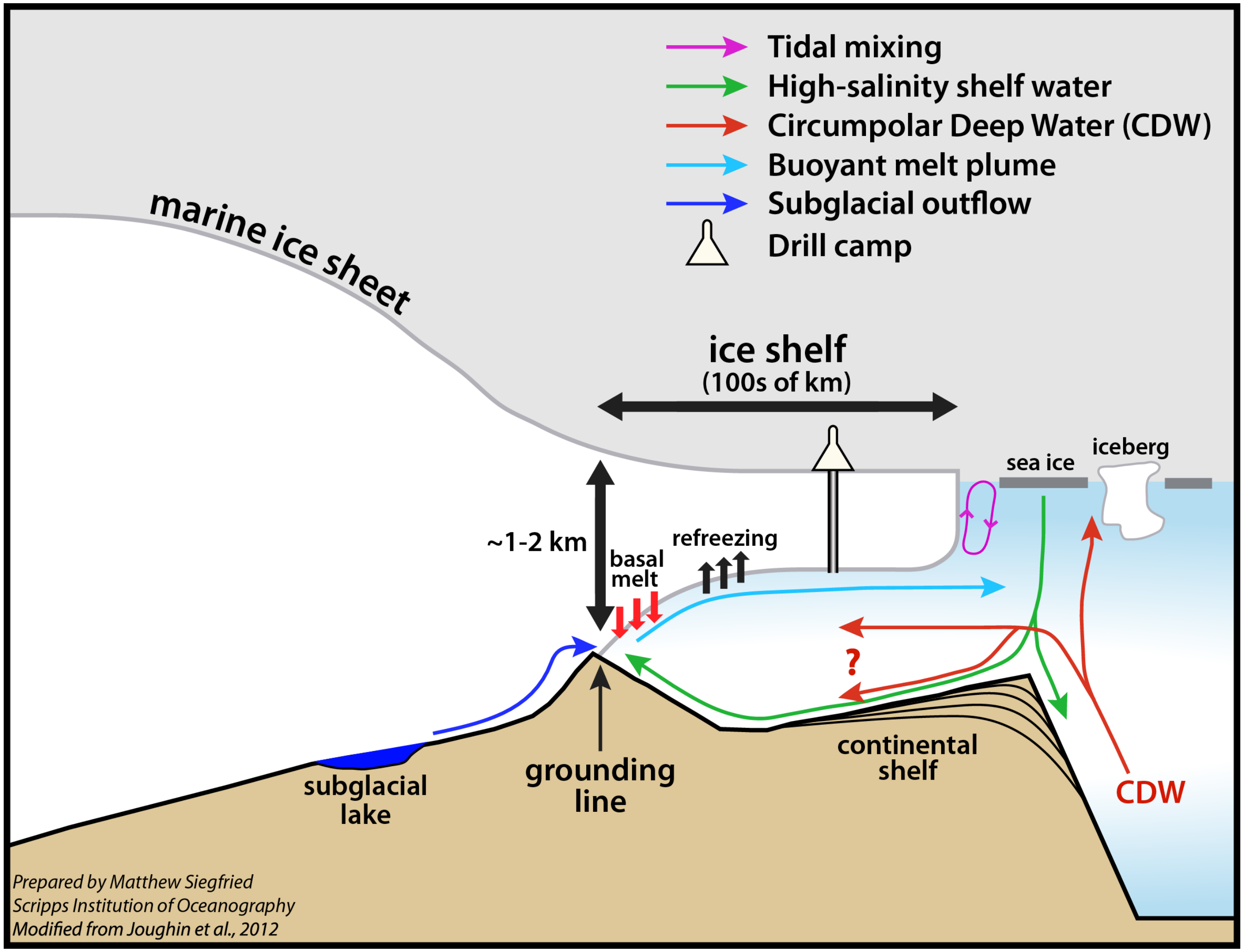
Southern Filchner-Ronne Ice Shelf



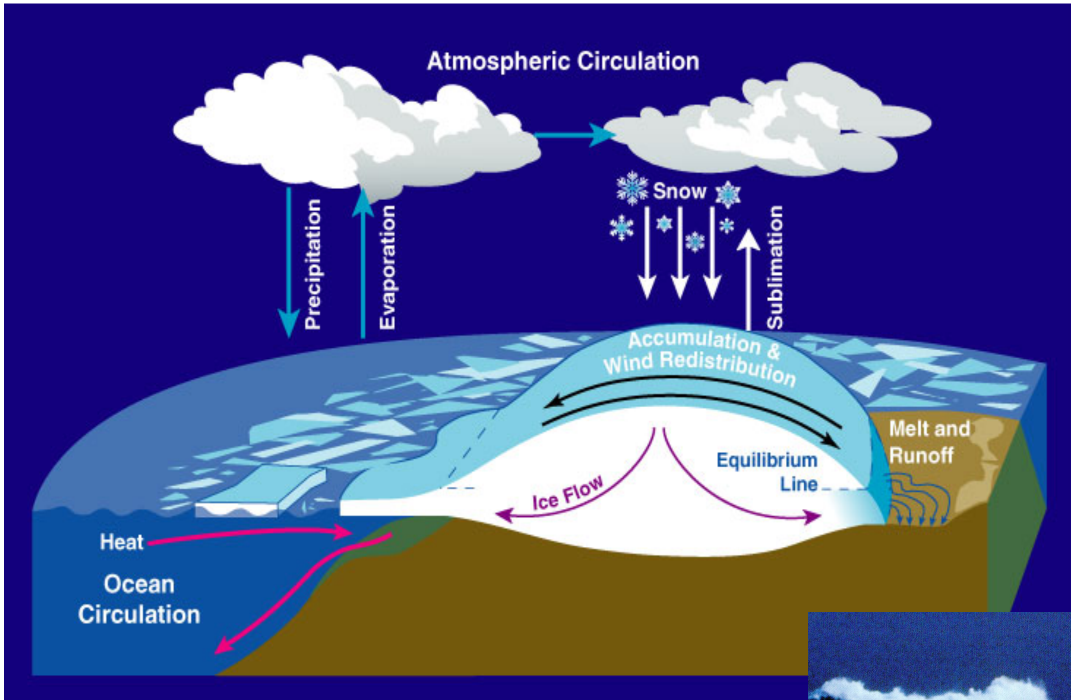
Track 138 across southern FRIS

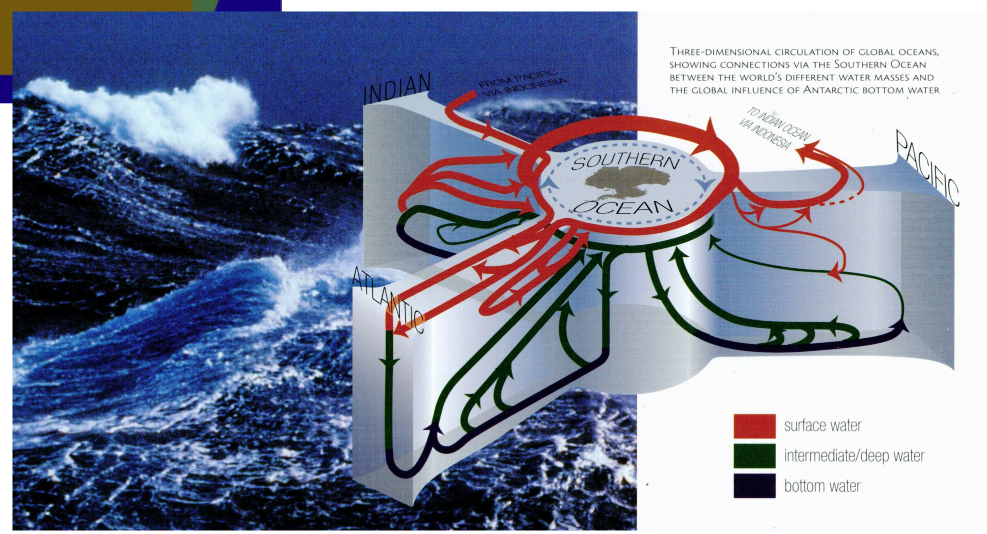


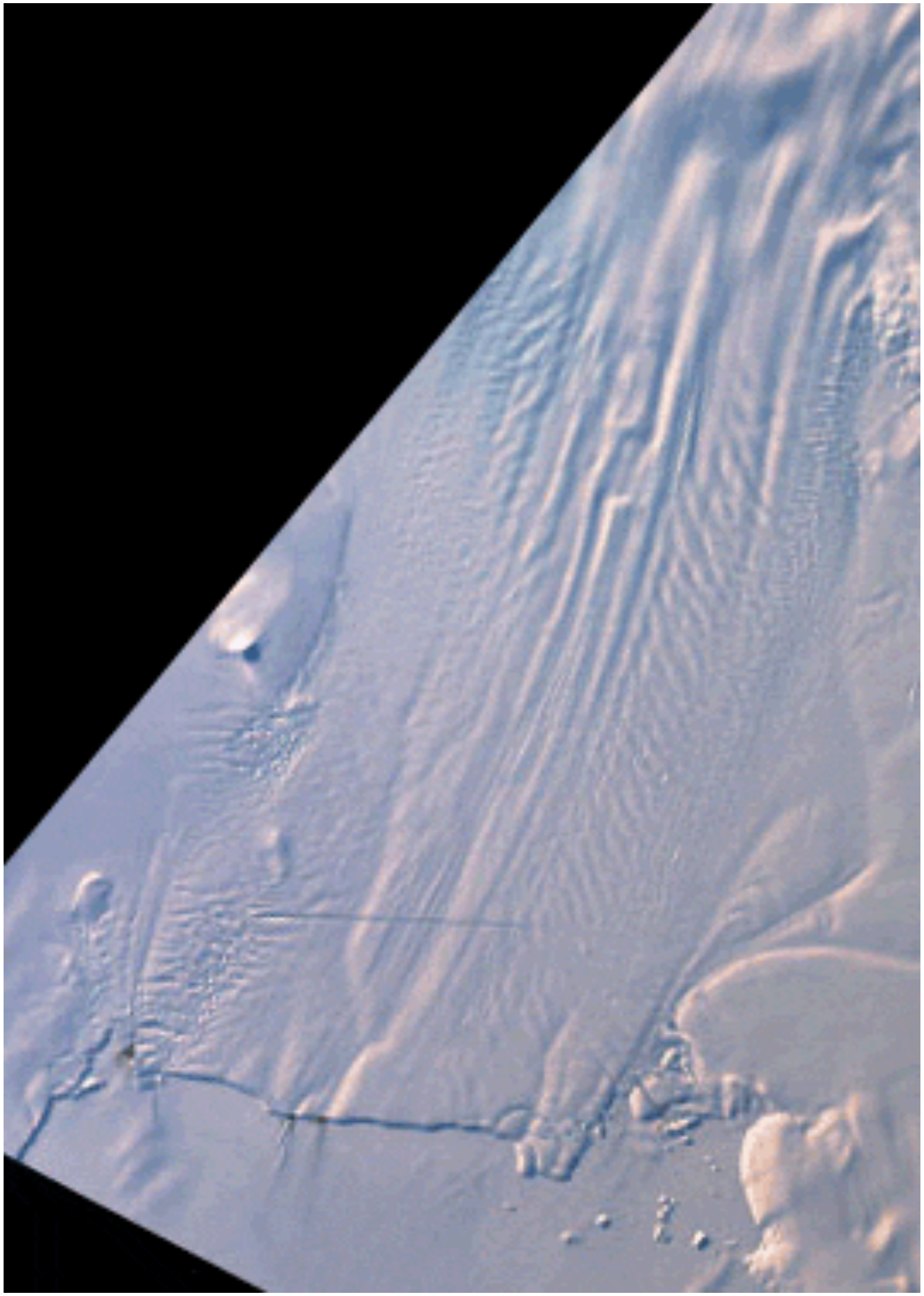
Marine ice sheet instability



Antarctica is an interdisciplinary system







Iceberg calving

Tabular iceberg calving from Pine Island Glacier

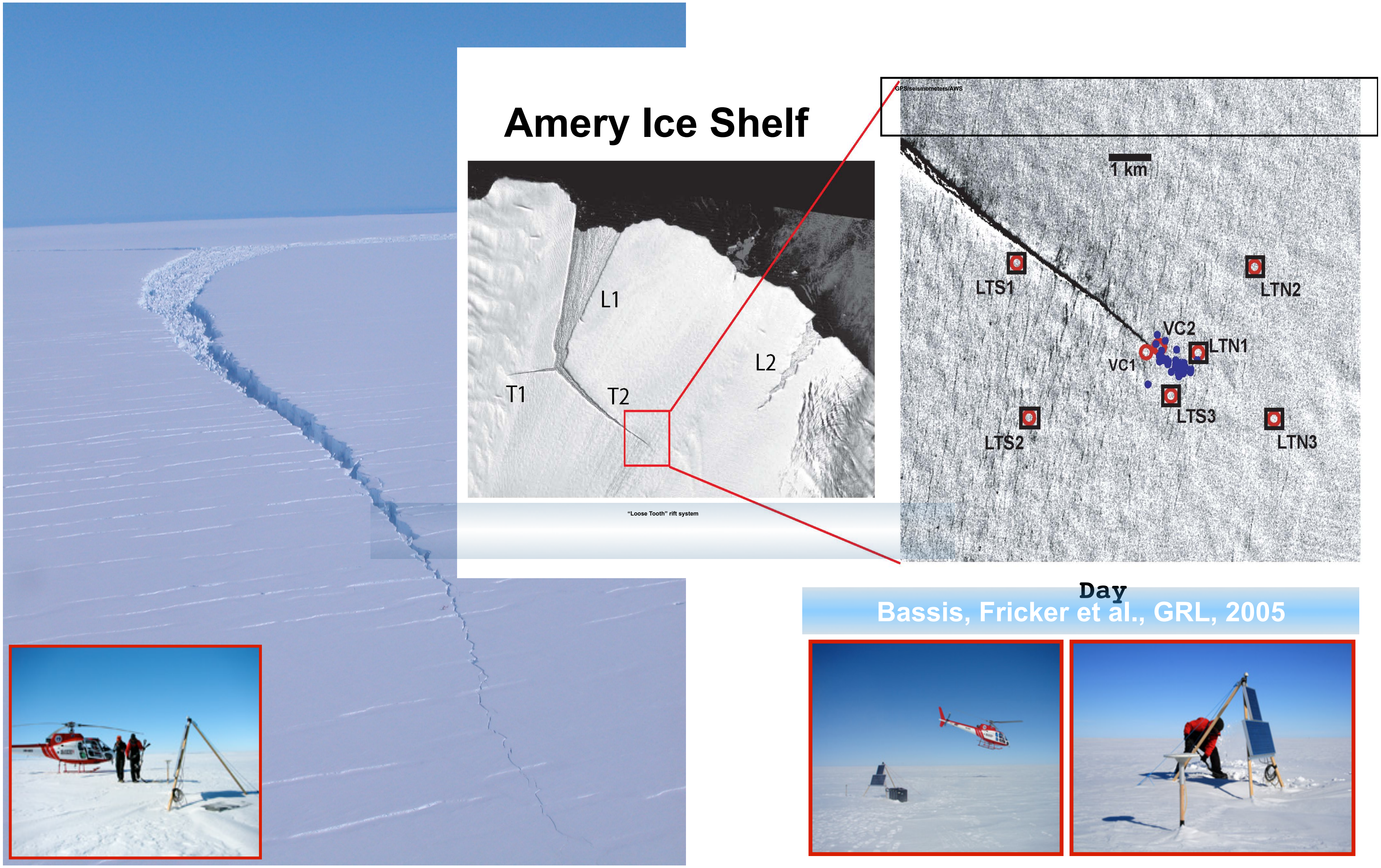
NASA/GSFC/LaRC/JPL MISR Team
David Diner (JPL)

Monitoring iceberg calving

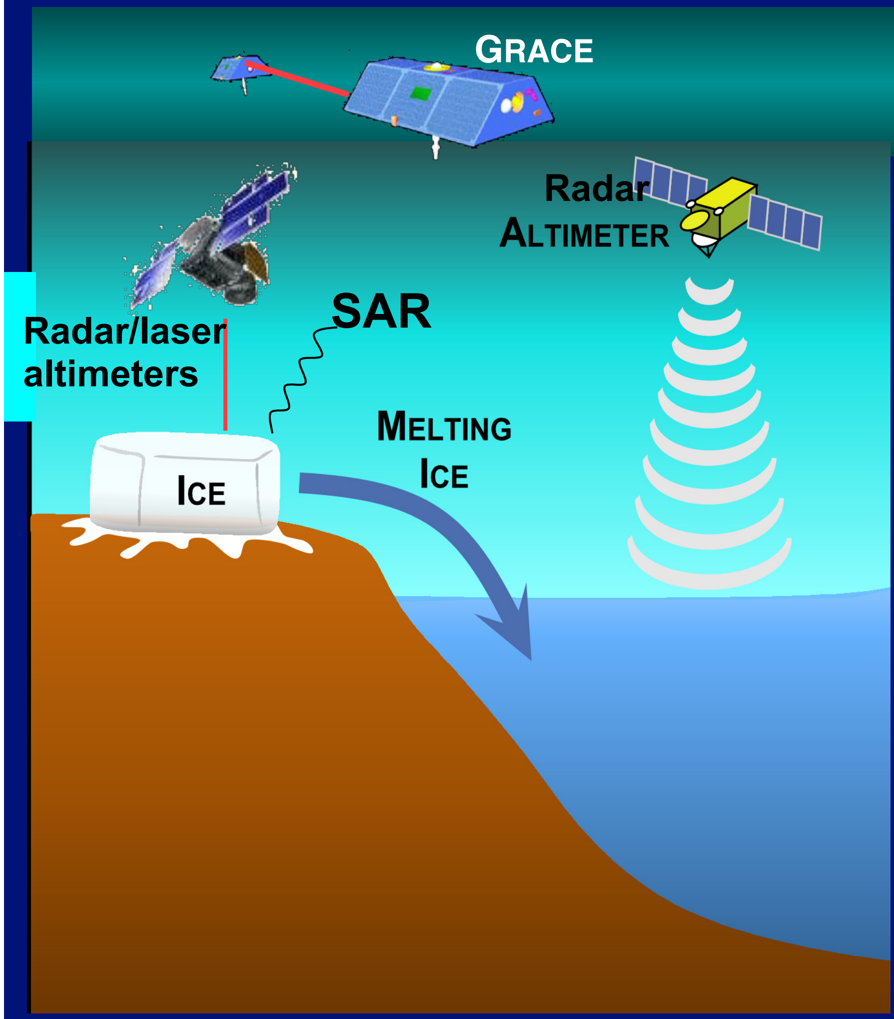
- Four year field program (funded by NASA 2002-03 and NSF 2004-07), in collaboration with Australian Antarctic Division
- Rift motion and "icequakes" monitored with GPS and seismometer stations

Bassis, Fricker et al., GRL, 2005

Monitoring iceberg calving



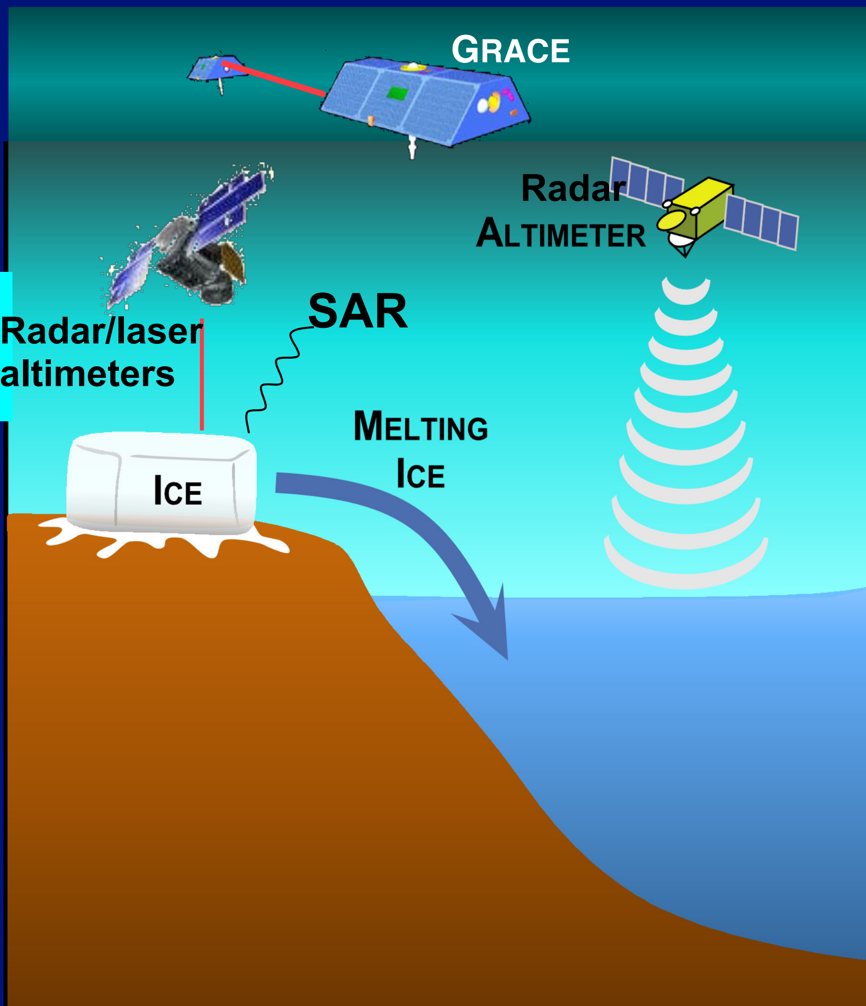
Measuring ice sheet mass balance (and sea-level rise)

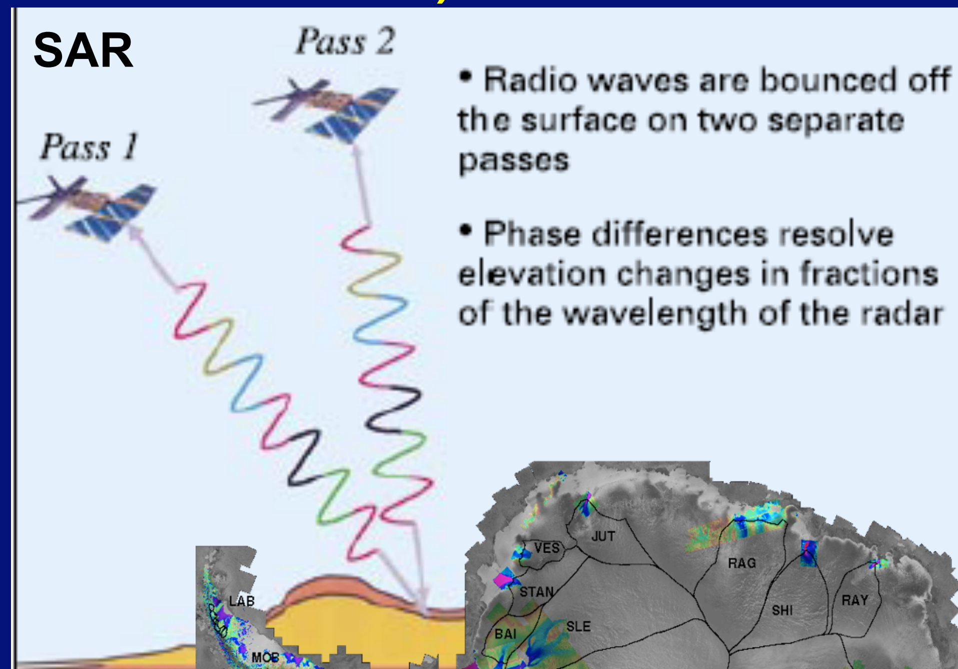


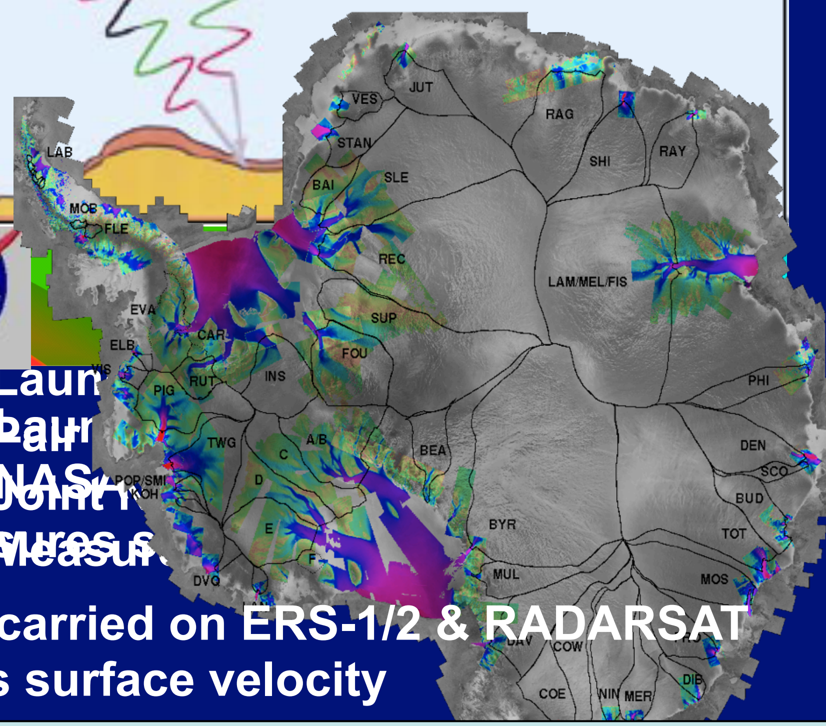
Three methods used to assess "health" of an ice sheet by satellite:

- ★ Direct measurement of change in elevation with time (using altimeters)
- ★ Measurement of mass change with time (using GRACE)
- ★ Estimation of mass fluxes (Input-output method)

Measuring ice sheet mass balance (and sea-level rise)

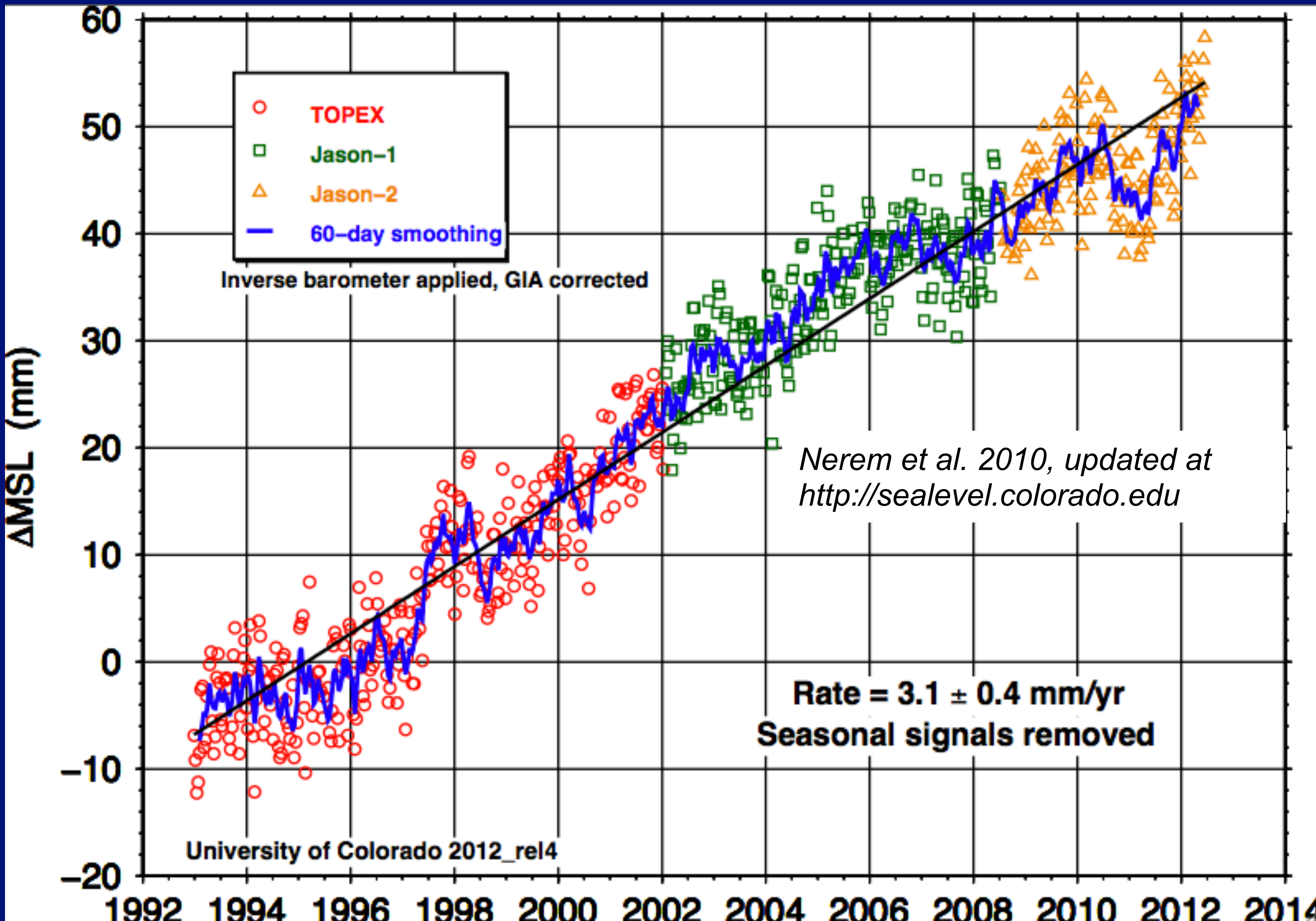






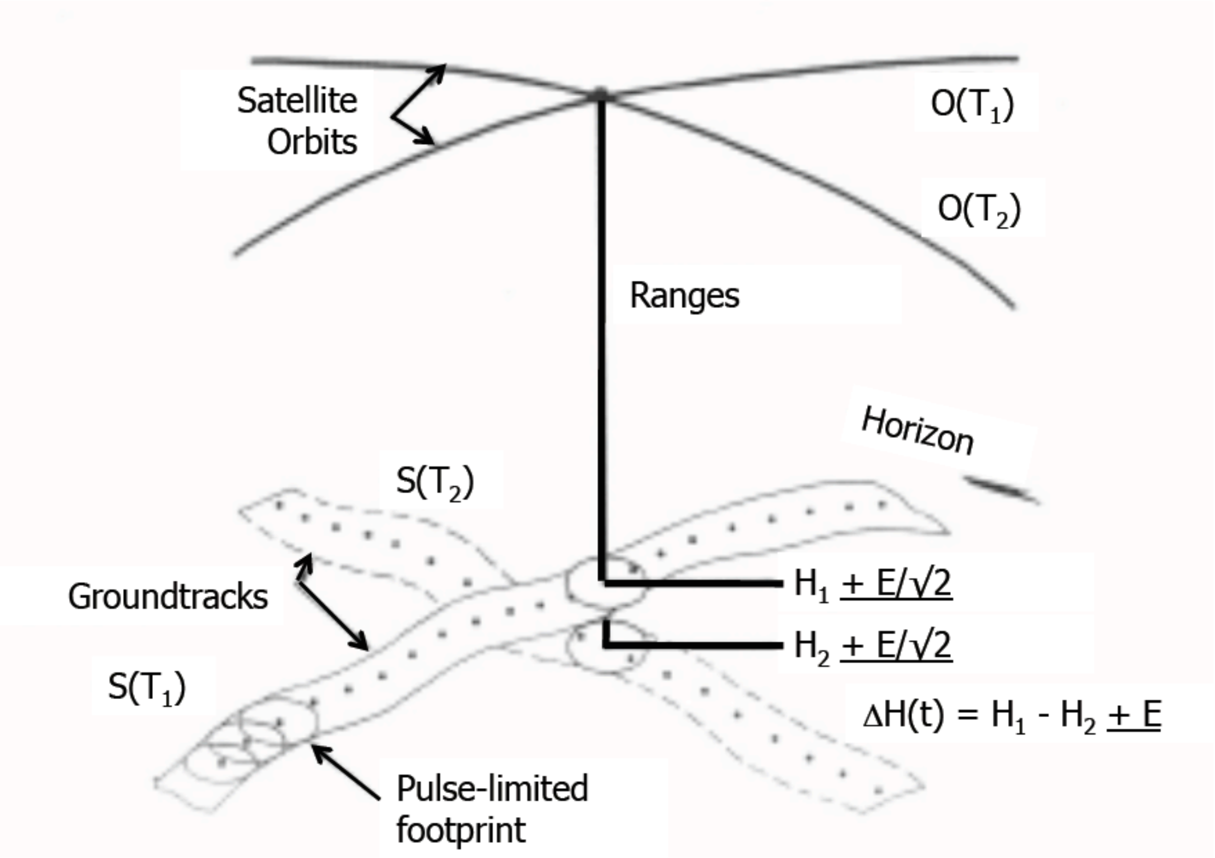
- Laun
- Laun Pair
- NASA Joint
- Measures s Measur
- SAR carried on ERS-1/2 & RADARSAT
- Gives surface velocity

Average global mean sea level rise 1993-2012

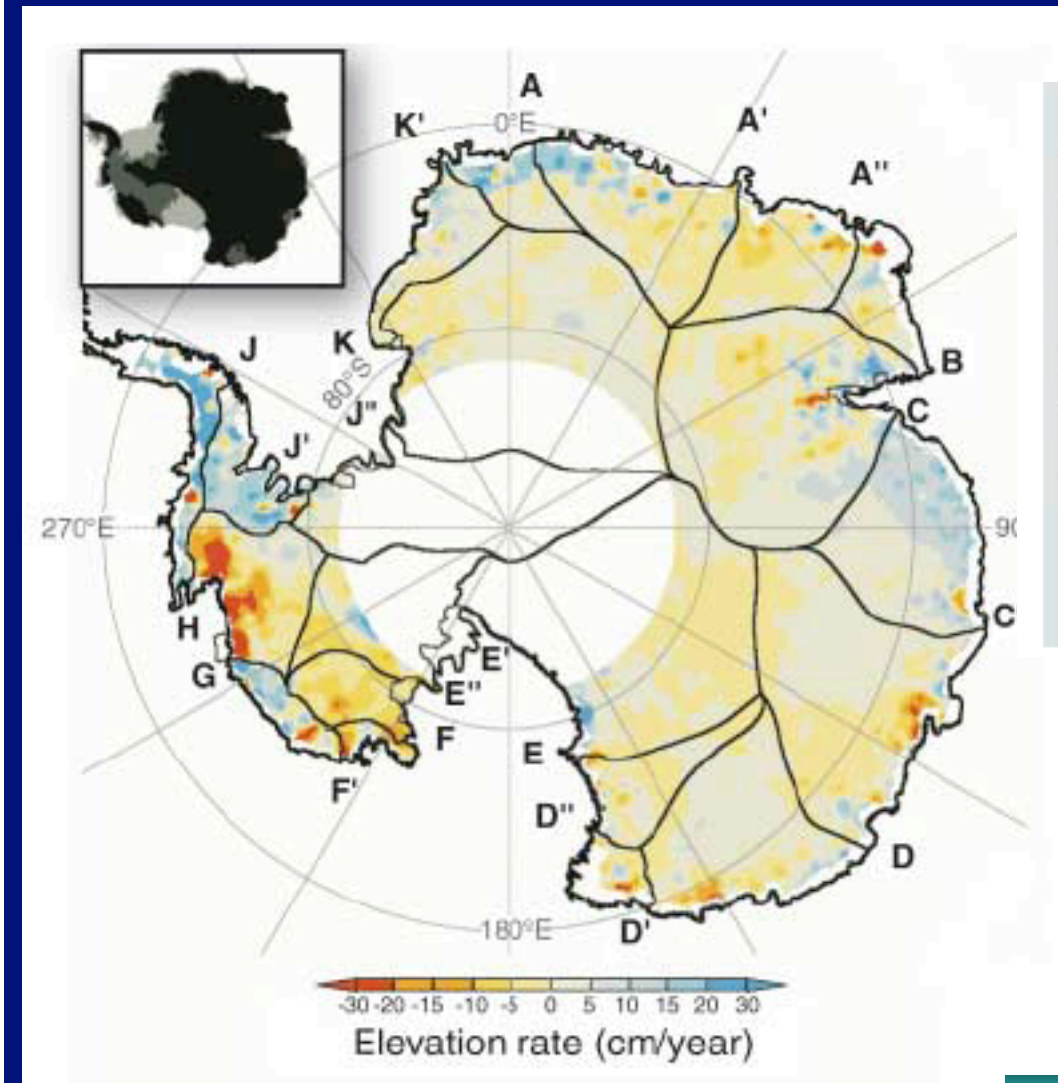


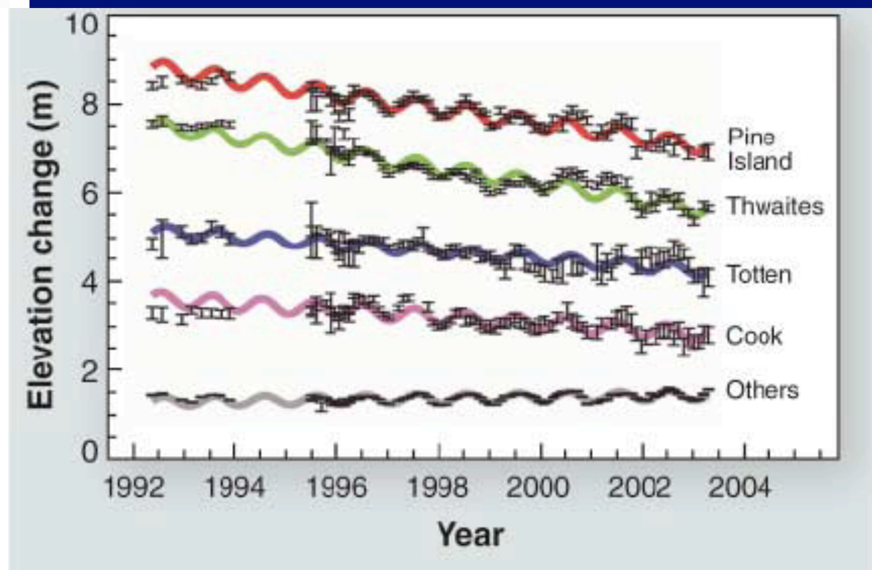
About 1/3 of this rate is attributed to thermal expansion and about 2/3 comes from the melting, retreat, etc. of glaciers and ice caps.

Altimetry Crossovers



Antarctica dH/dt 1992-2003
ERS satellite radar altimetry





- WAIS losing 50 Gta^{-1}, EAIS gaining 25 Gta^{-1} → net loss 25 Gta^{-1}
- Particular ice streams or glaciers are dominating the mass balance for the whole ice sheet

Shepherd and Wingham, Science 2007

Antarctica/Greenland dH/dt 2003-2008
ICESat laser altimetry

Pritchard and others, Nature, 2007

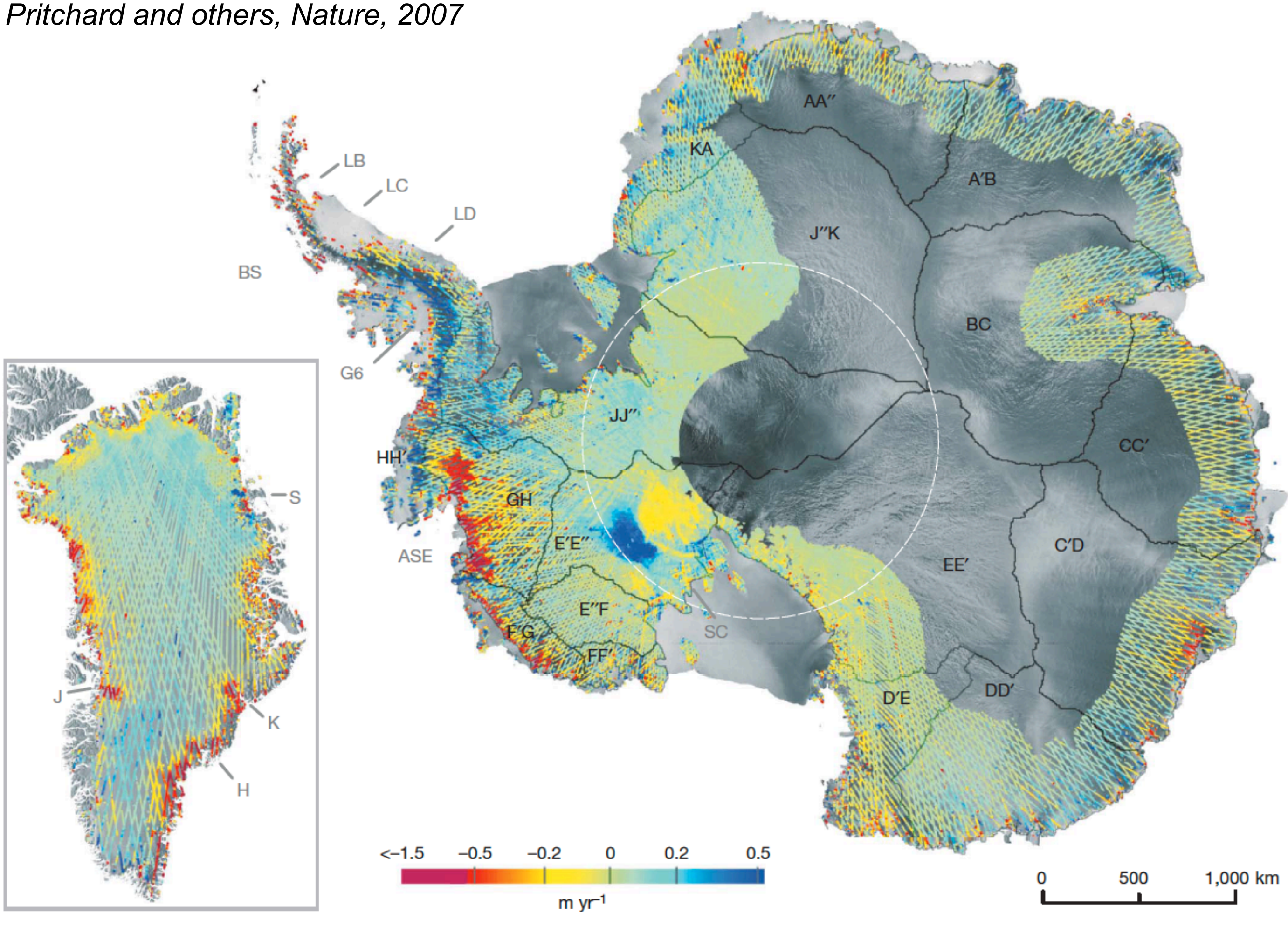
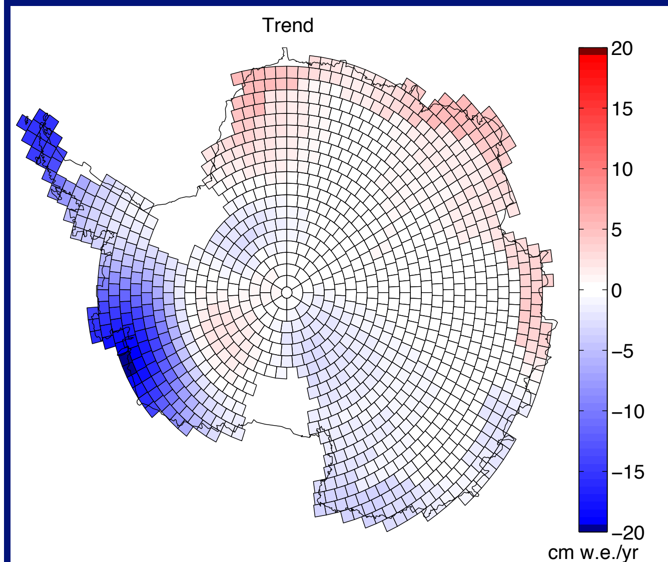
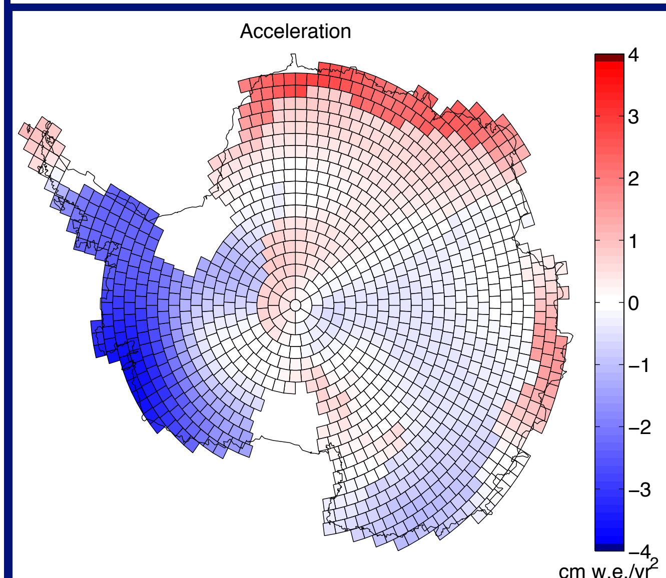
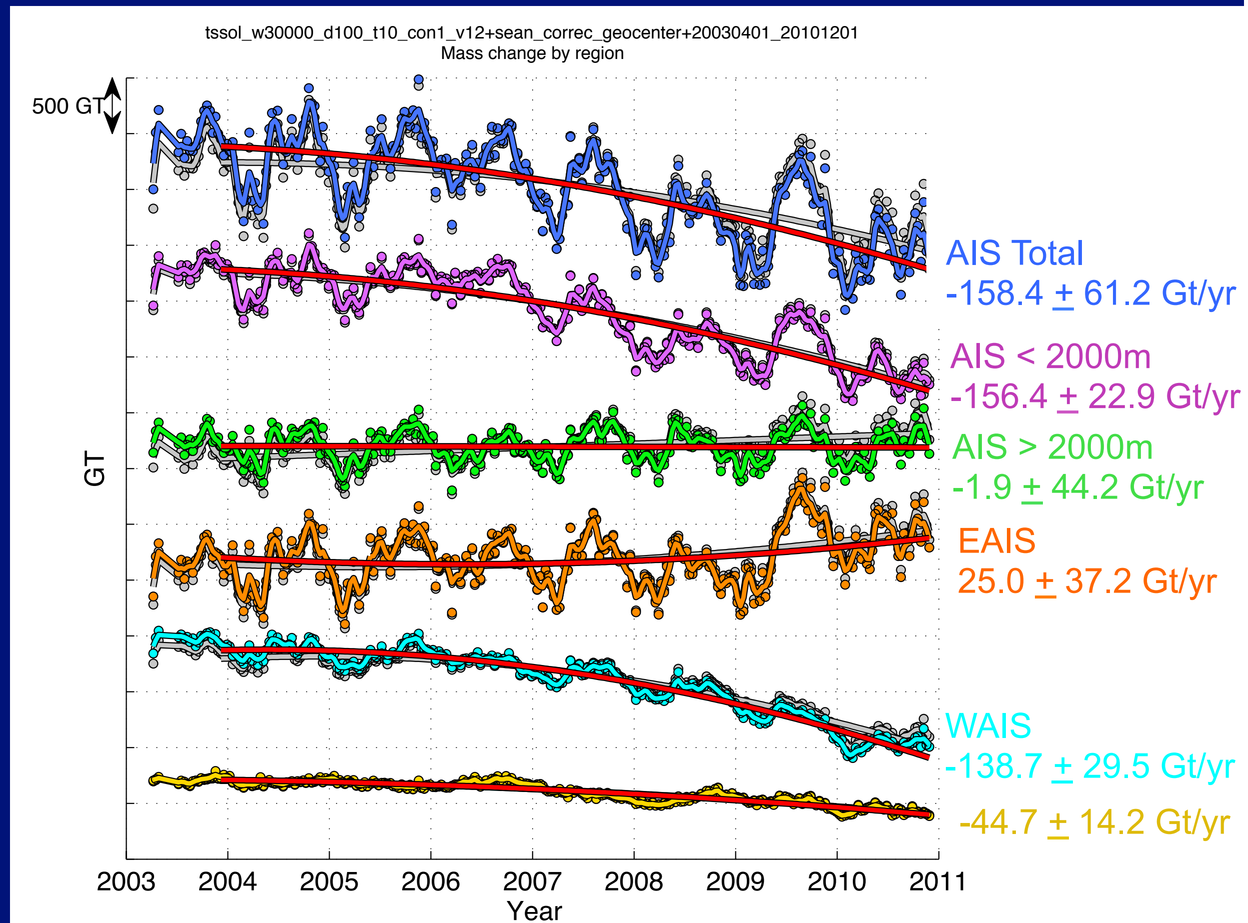


Figure 2 | Rate of change of surface elevation for Antarctica and Greenland. Change measurements are median filtered (10-km radius), spatially averaged (5-km radius) and gridded to 3 km, from intervals (Δt) of at least 365 d, over the period 2003–2007 (mean Δt is 728 d for Antarctica and 746 d for Greenland). East Antarctic data cropped to 2,500-m altitude. White dashed line (at 81.5° S) shows southern limit of radar altimetry measurements. Labels are for sites and drainage sectors (see text).

Antarctica ice mass change 2003-2011
GRACE





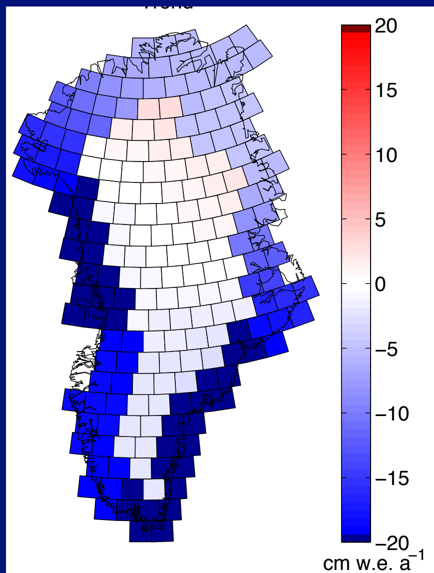


360 Gt = 1 mm of sea level rise

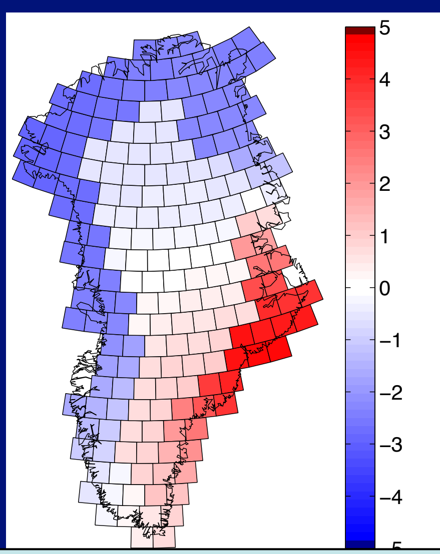
Luthcke et al., submitted July 2012

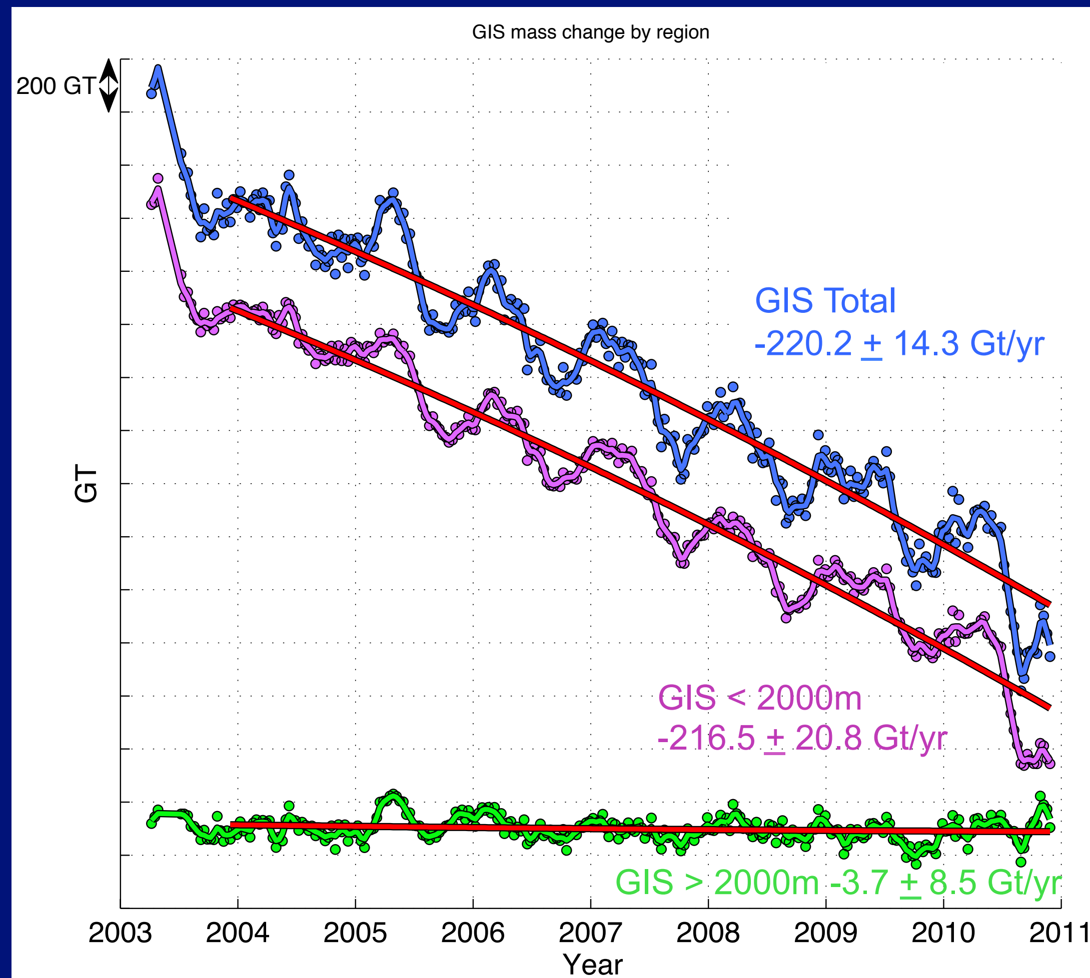
Greenland ice mass change 2003-2011 GRACE

Trend



Acceleration

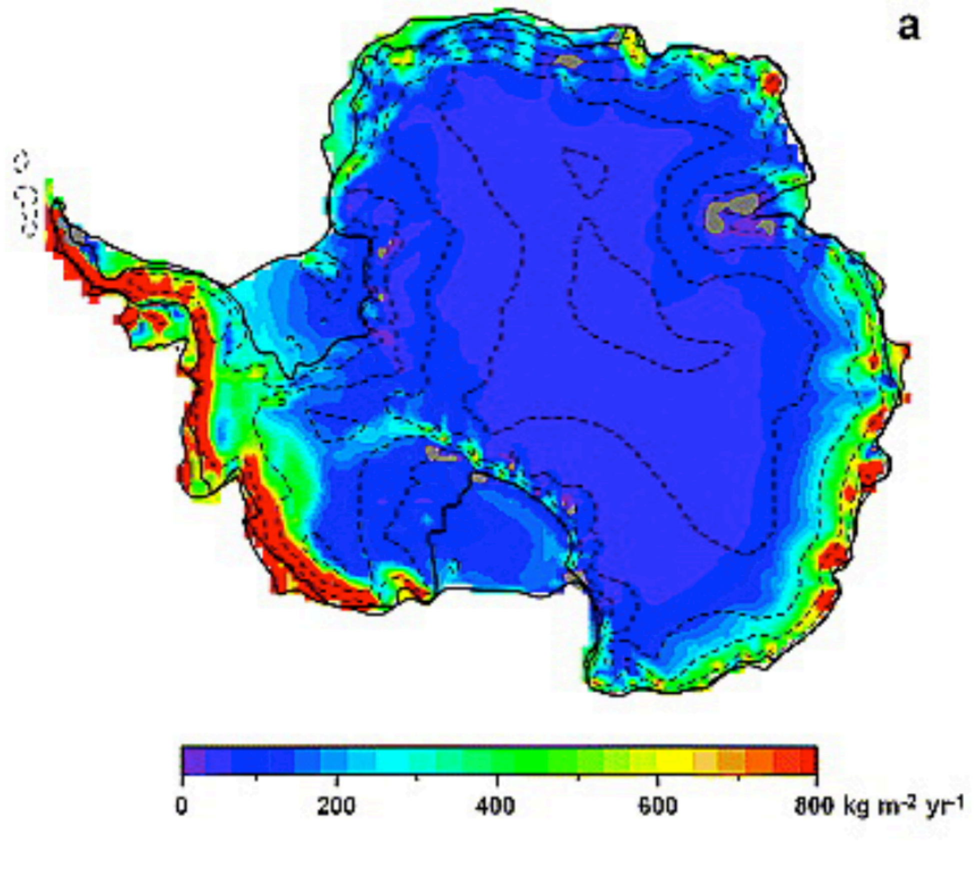




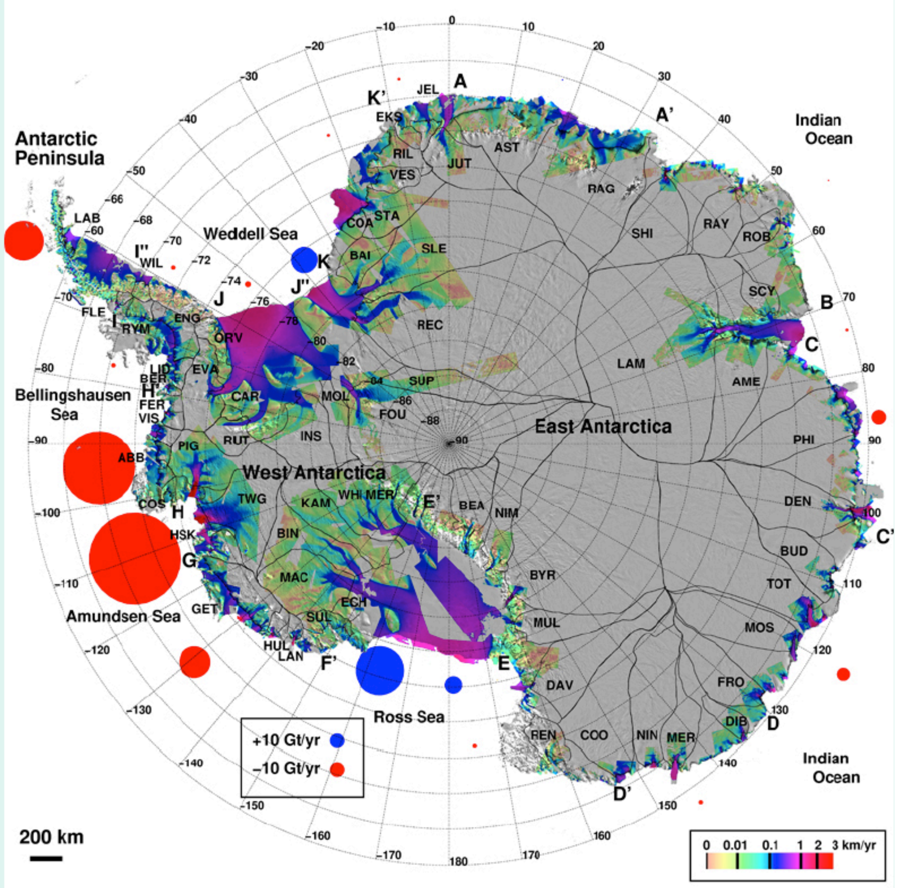
Luthcke et al., submitted July 2012

Antarctica mass loss 2006
Mass flux estimates

InSAR survey of ice motion + surface mass balance from Regional Climate Models



Van den Broeke et al. 2006

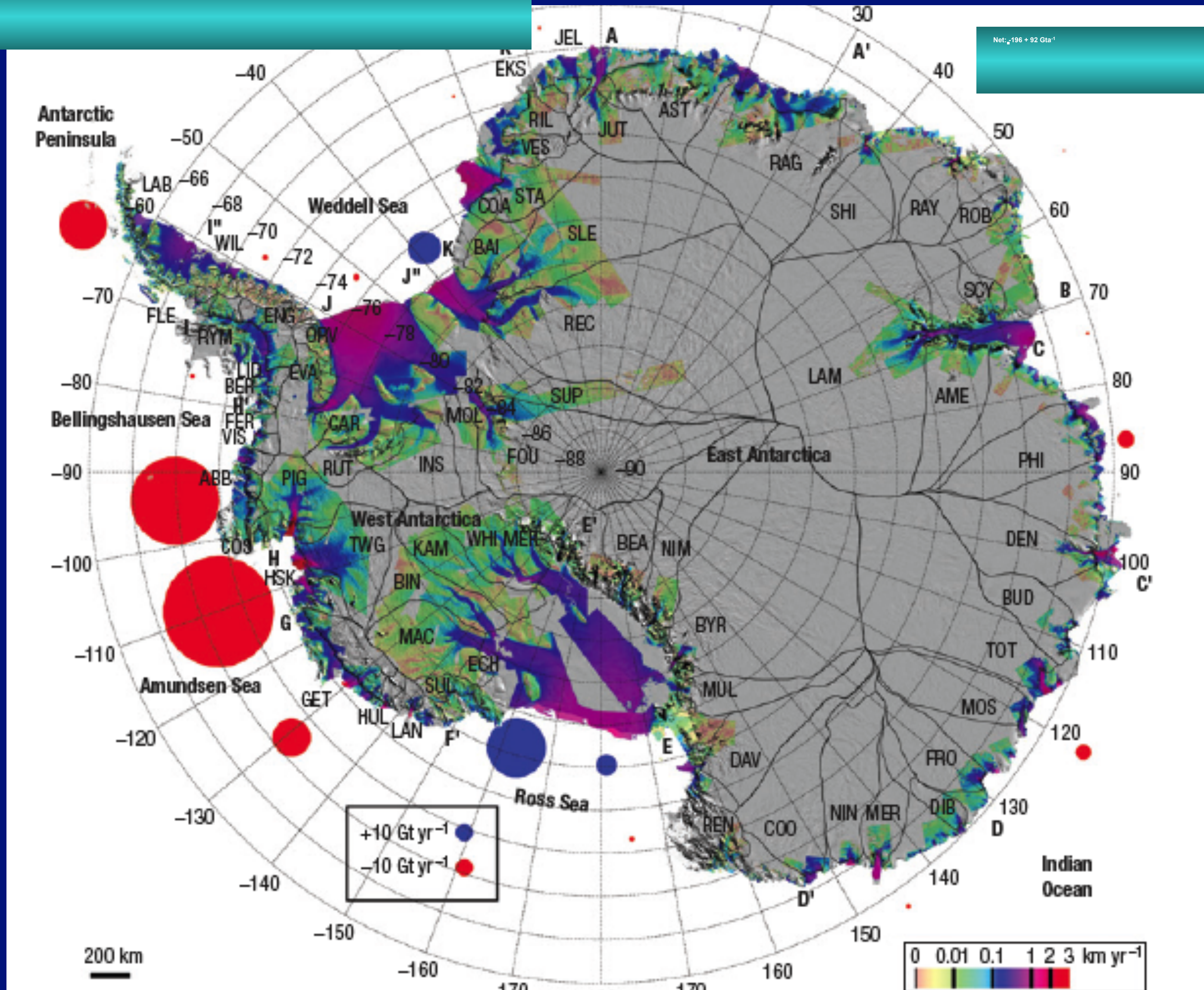


Rignot et al. 2008

Antarctica mass loss 2006
Mass flux estimates

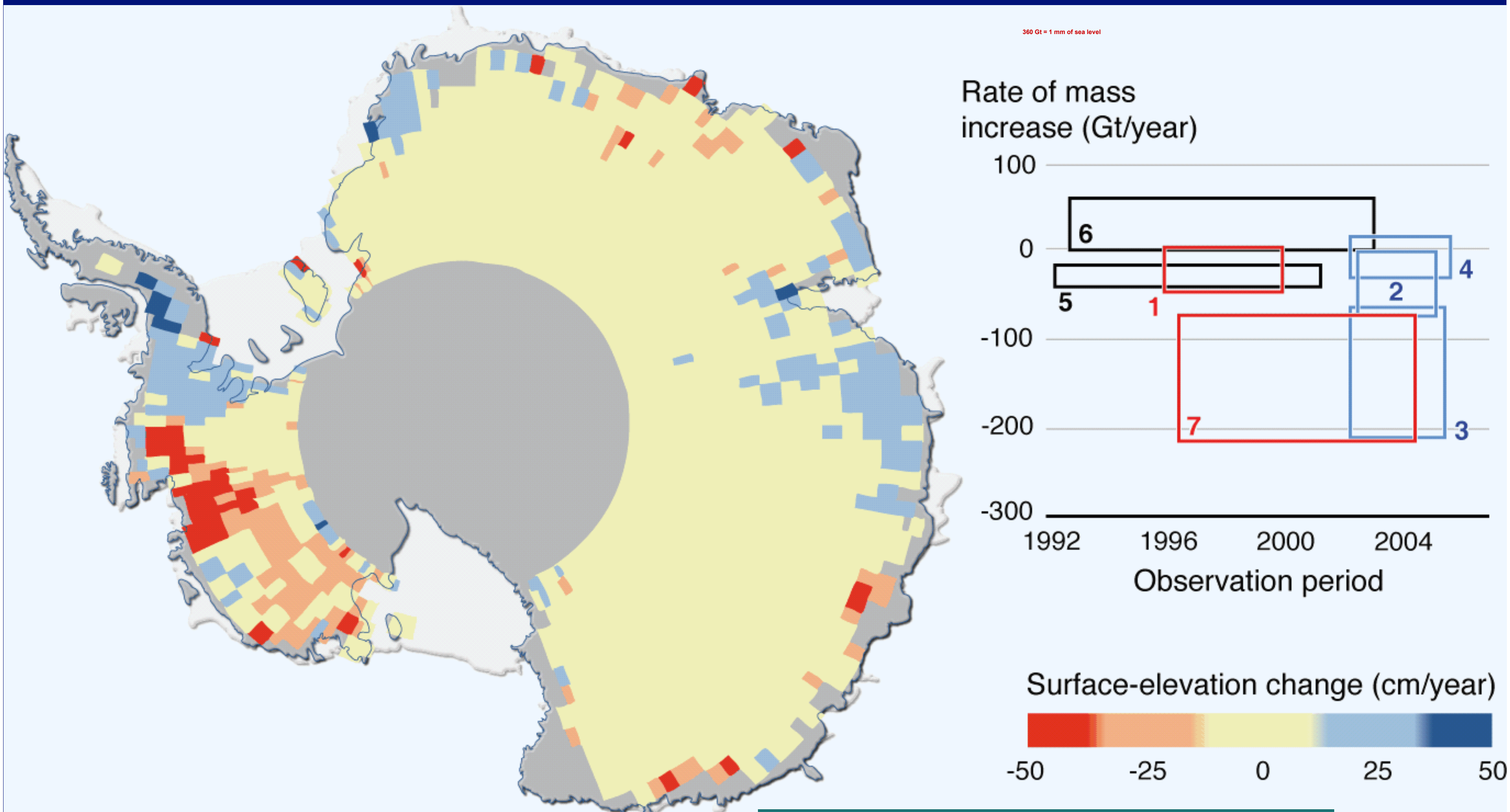
Rignot et al., Nature Geoscience, 2008

Net: $-196 + 92$ $Gt a^{-1}$



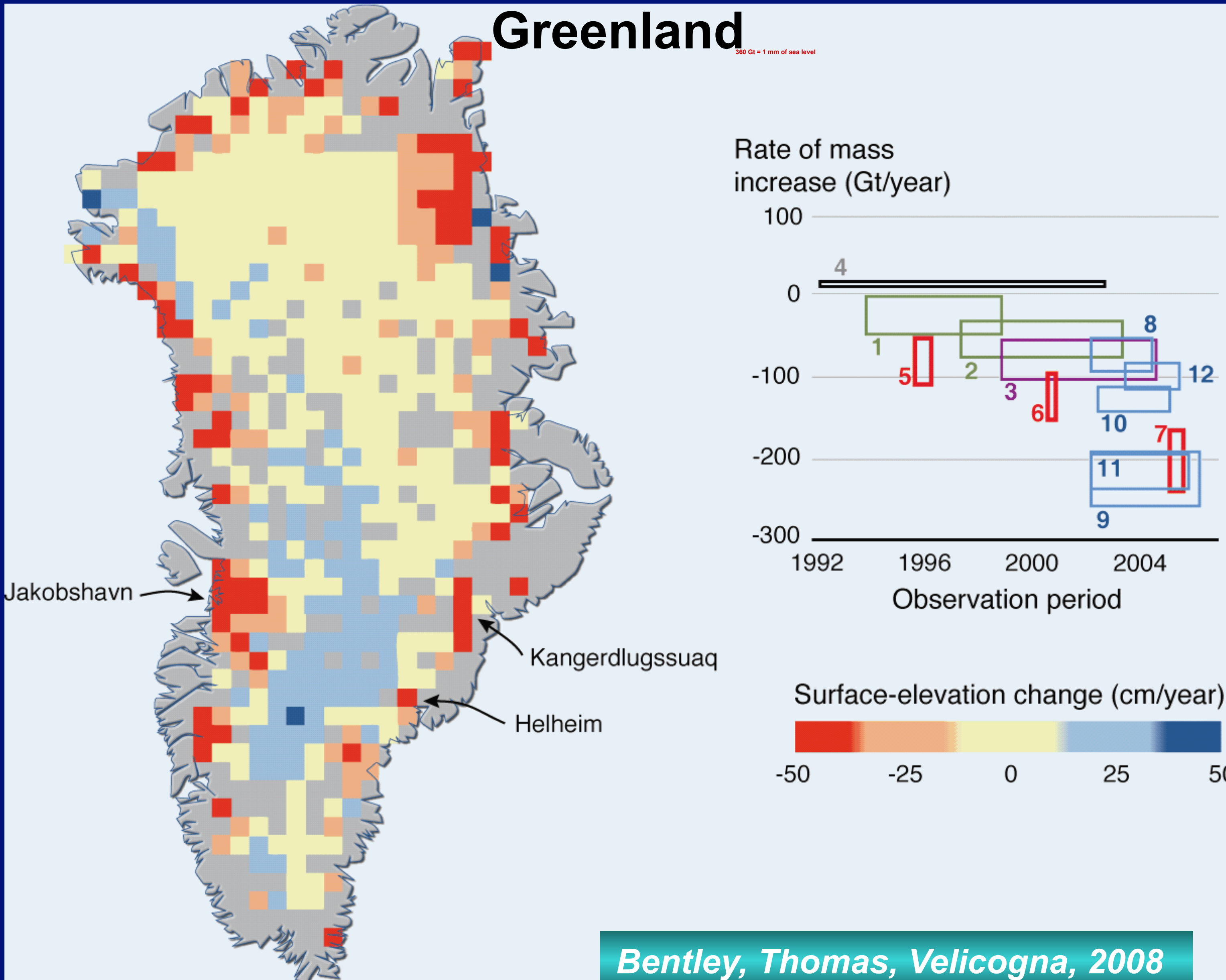
Summary: ice sheet mass change

Antarctica

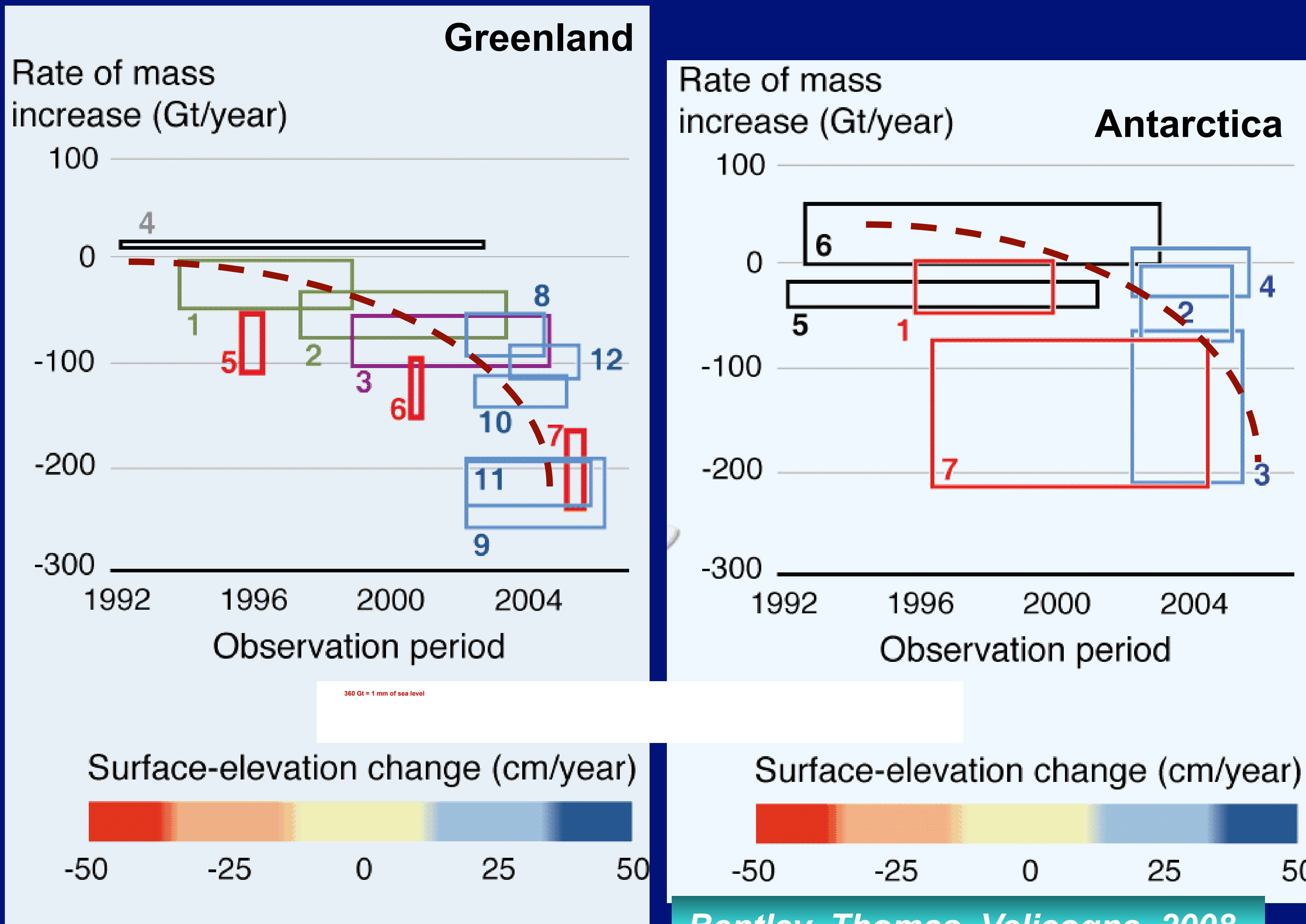


Bentley, Thomas, Velicogna, 2008

Summary: ice sheet mass change

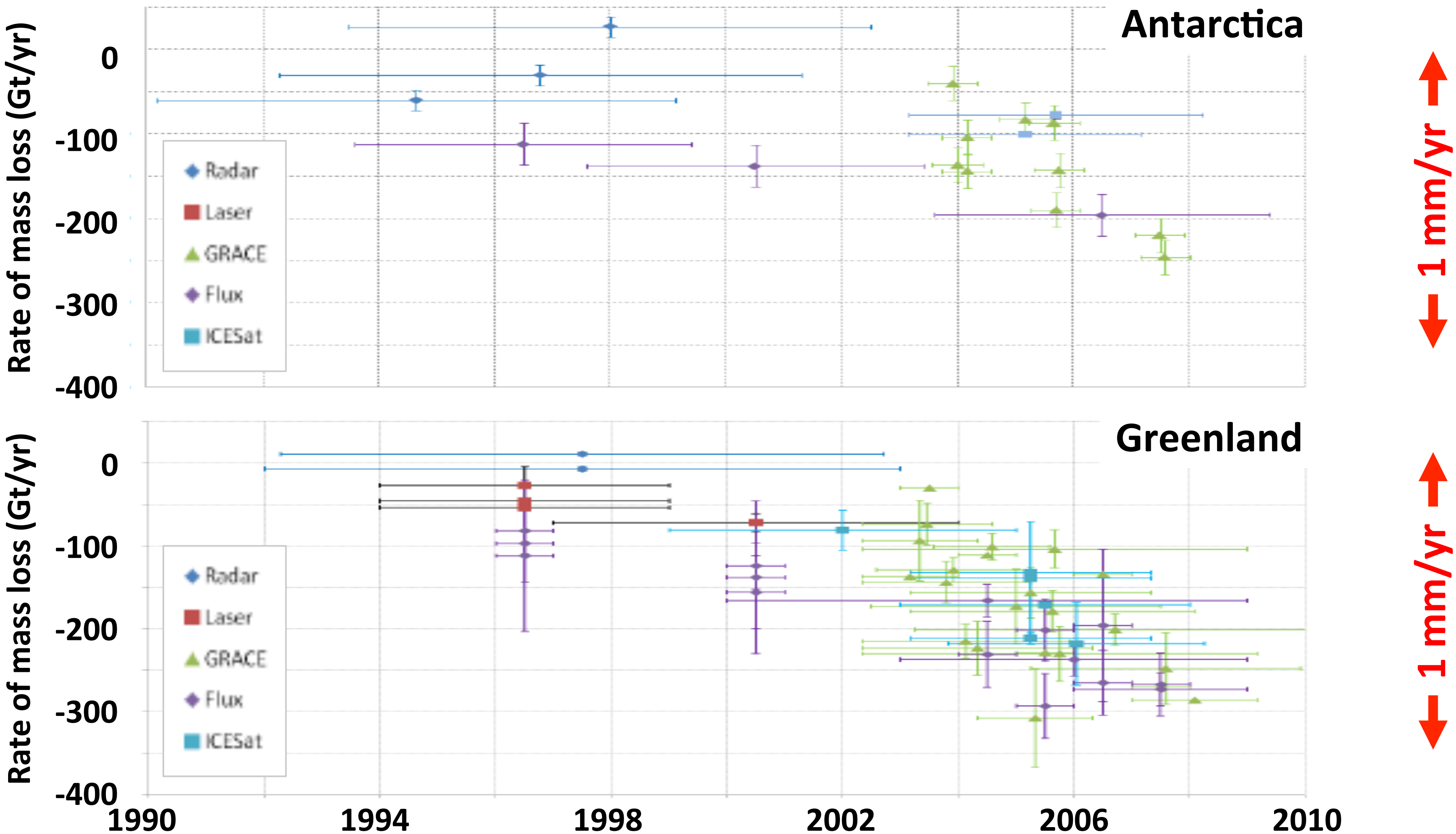


Summary: ice sheet mass change



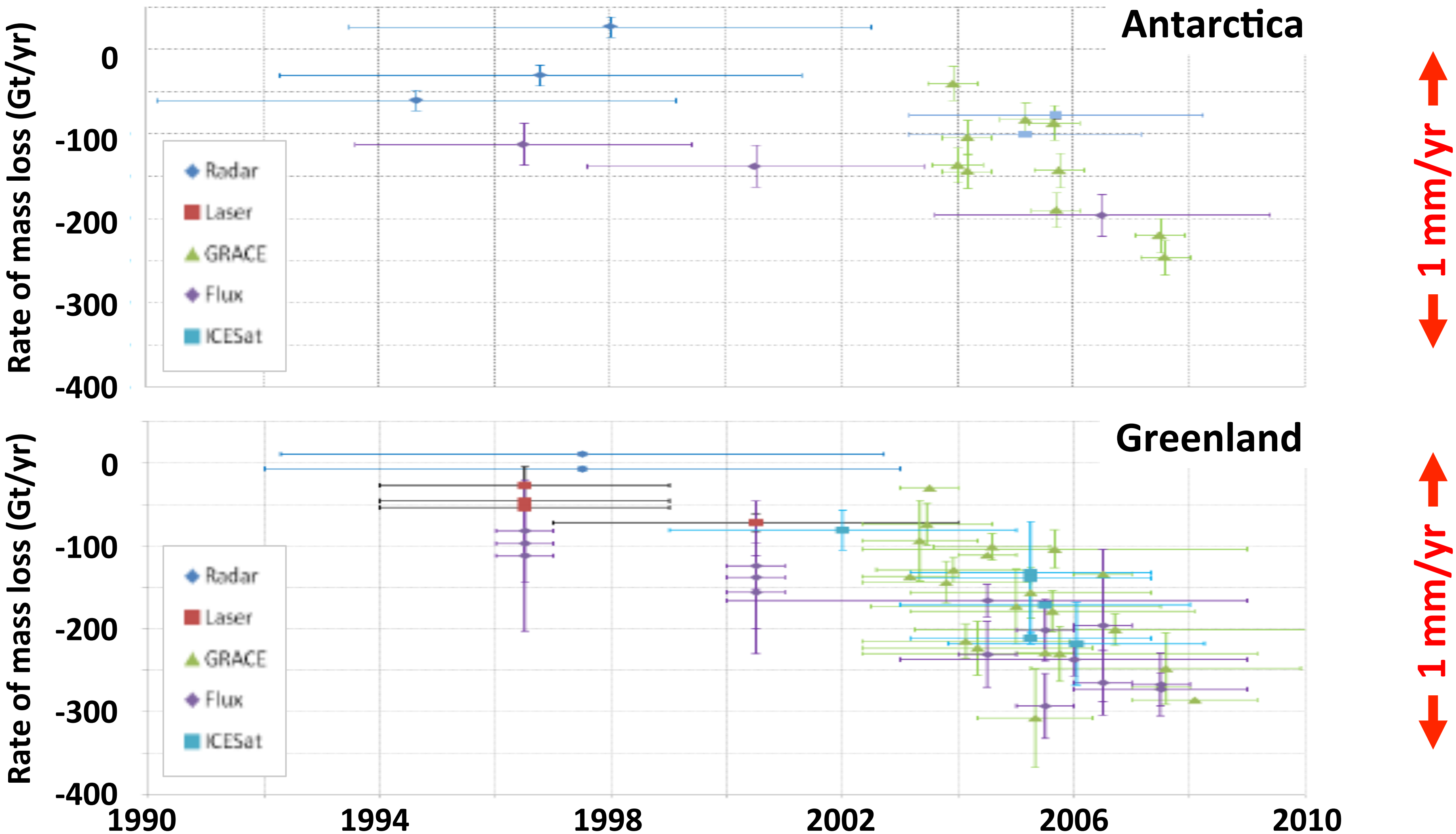
Bentley, Thomas, Velicogna, 2008

Summary: ice sheet mass change



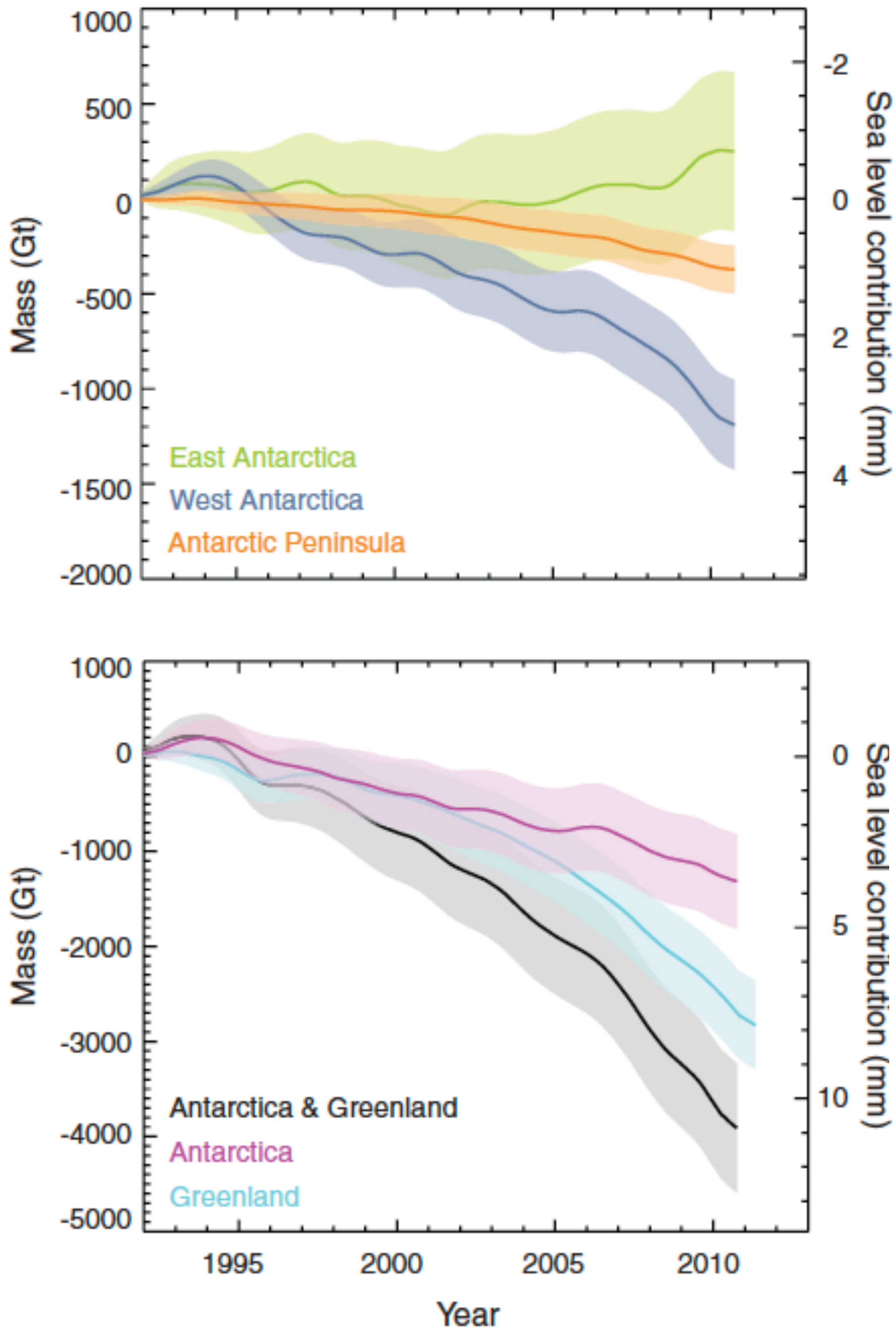
Satellite estimates of ice sheet mass balance range from +69 to -676 Gt/yr

Summary: ice sheet mass change



Differences are due to:

i. spatial and temporal sampling
ii. limitations of the geodetic techniques
iii. differences in processing methods



Ice Sheet Mass Balance Intercomparison Exercise (IMBIE)

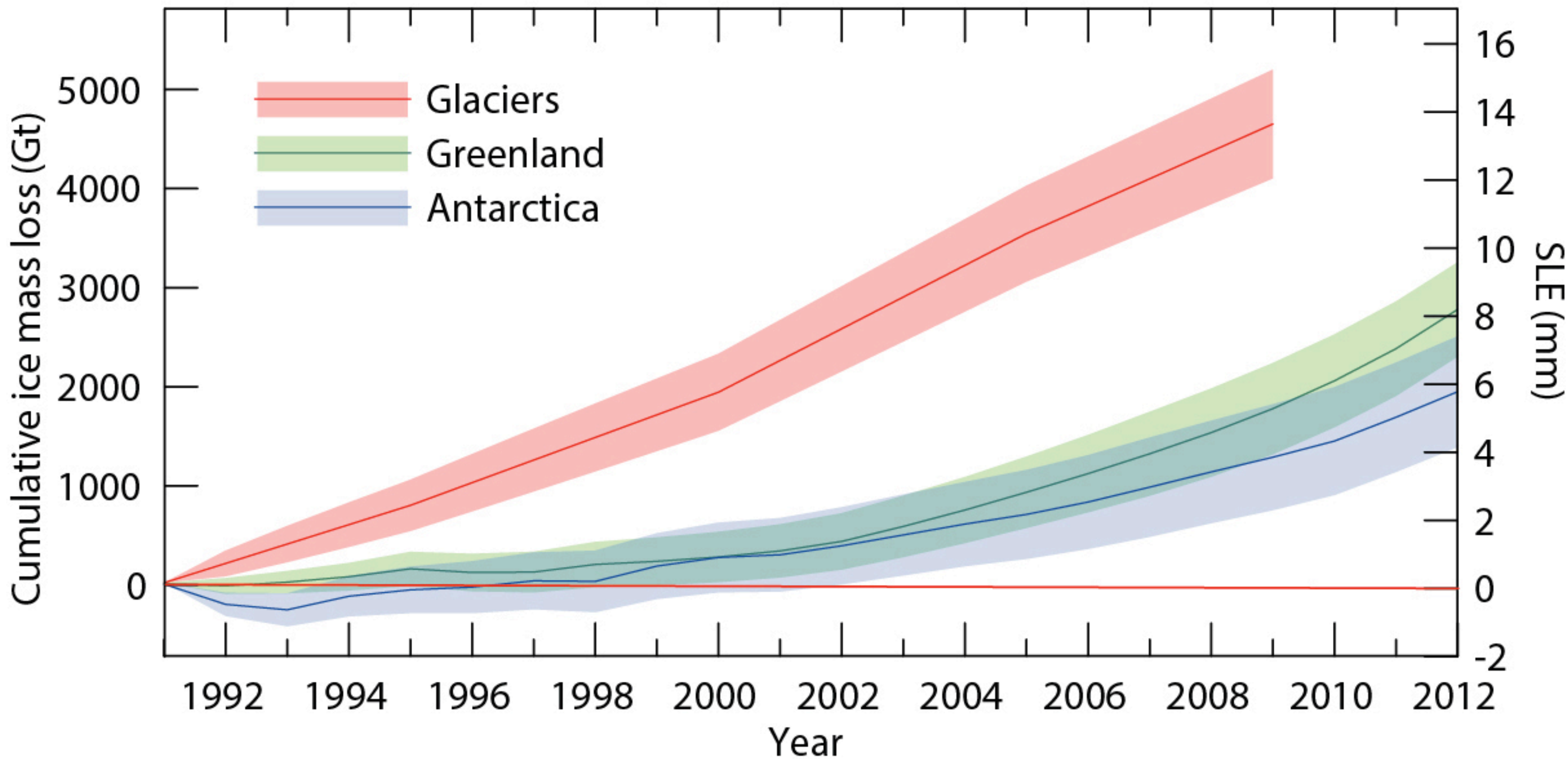
A Reconciled Estimate of Ice-Sheet Mass Balance

Andrew Shepherd,[1]* Erik R. Ivins,[2]* Geruo A,[3] Valentina R. Barletta,[4] Mike J. Bentley,[5] Srinivas Bettadpur,[6] Kate H. Briggs,[1] David H. Bromwich,[7] René Forsberg,[4] Natalia Galin,[8] Martin Horwath,[9] Stan Jacobs,[10] Ian Joughin,[11] Matt A. King,[12,27] Jan T. M. Lenaerts,[13] Jilu Li,[14] Stefan R. M. Ligtenberg,[13] Adrian Luckman,[15] Scott B. Luthcke,[16] Malcolm McMillan,[1] Rakia Meister,[8] Glenn Milne,[17] Jeremie Mouginot,[18] Alan Muir,[8] Julien P. Nicolas,[7] John Paden,[14] Antony J. Payne,[19] Hamish Pritchard,[20] Eric Rignot,[18,2] Helmut Rott,[21] Louise Sandberg Sørensen,[4] Ted A. Scambos,[22] Bernd Scheuchl,[18] Ernst J. O. Schrama,[23] Ben Smith,[11] Aud V. Sundal,[1] Jan H. van Angelen,[13] Willem J. van de Berg,[13] Michiel R. van den Broeke,[13] David G. Vaughan,[20] Isabella Velicogna,[18,2] John Wahr,[3] Pippa L. Whitehouse,[5] Duncan J. Wingham,[8] Donghui Yi,[24] Duncan Young,[25] H. Jay Zwally[26]

We combined an ensemble of satellite altimetry, interferometry, and gravimetry data sets using common geographical regions, time intervals, and models of surface mass balance and glacial isostatic adjustment to estimate the mass balance of Earth's polar ice sheets. We find that there is good agreement between different satellite methods—especially in Greenland and

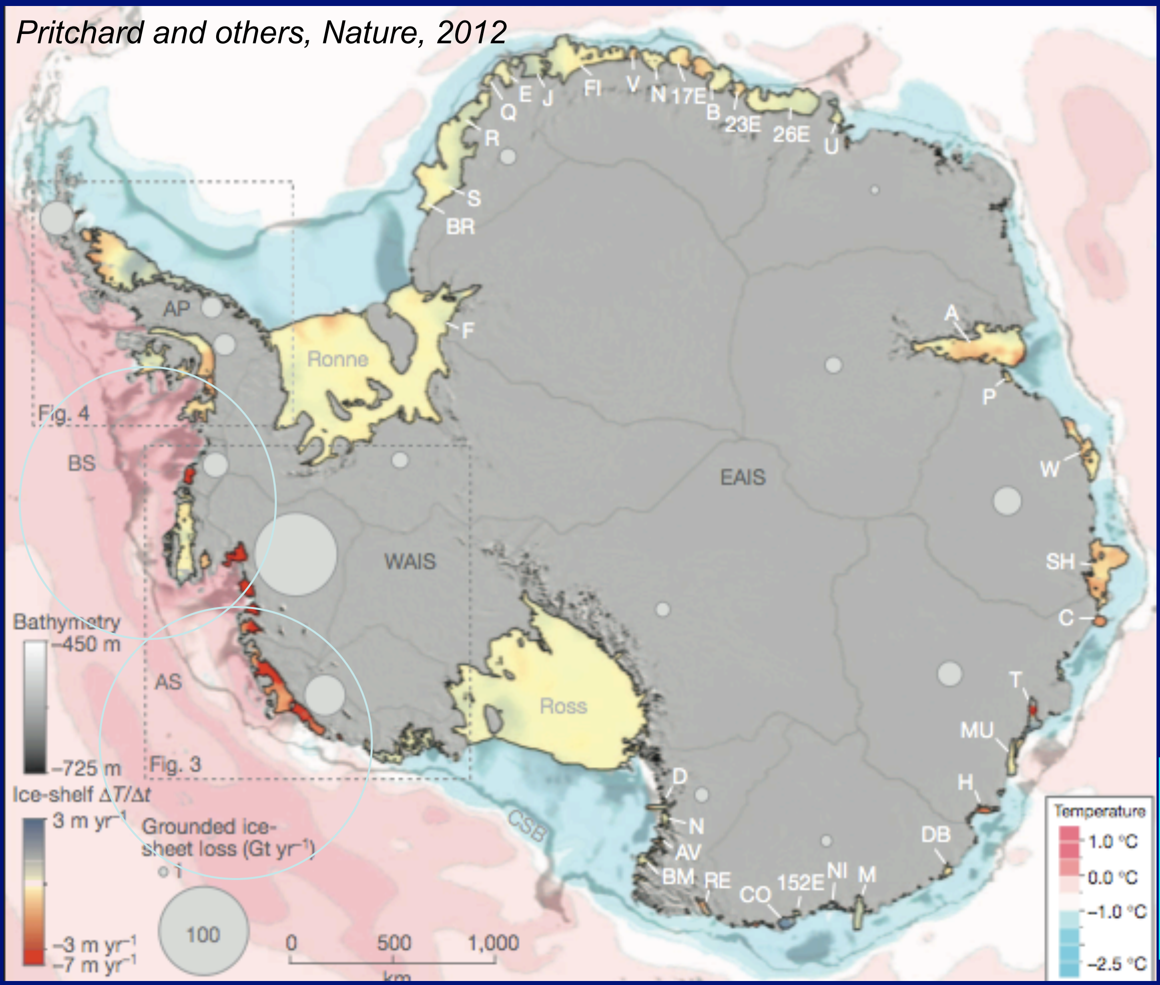
Shepherd et al., Science, 2012

Cumulative ice loss 1992-2012



IPCC AR5 Chapter 4

Antarctic ice shelves dH/dt 2003-2008
ICESat laser altimetry



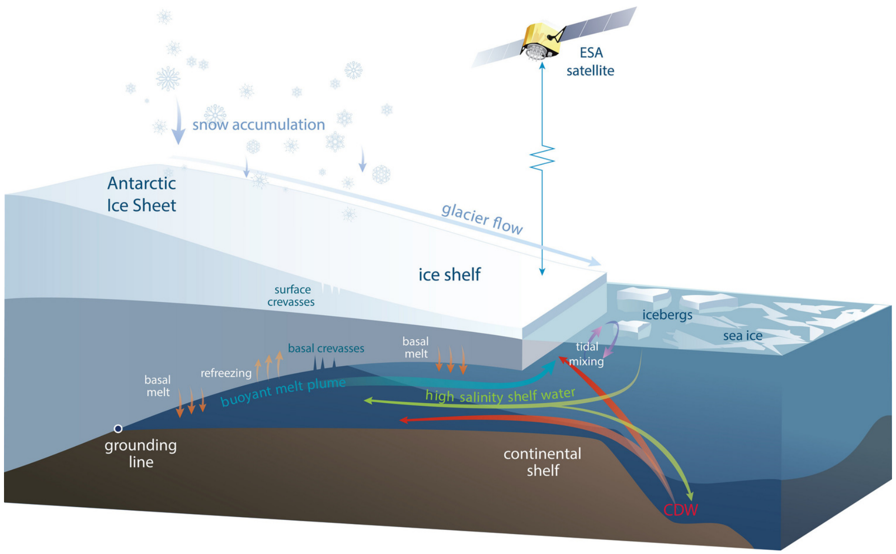
The distribution of Antarctic ice-shelf thinning is regional, and is most rapid along the Amundsen and Bellingshausen Sea coasts.

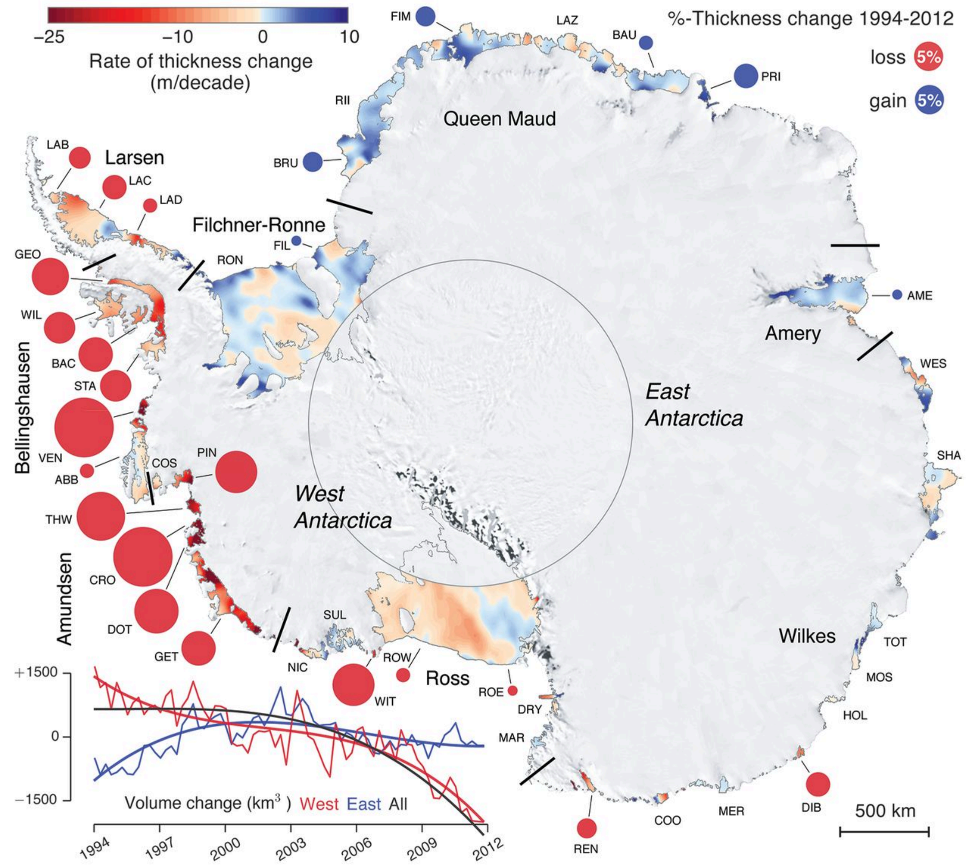
All thinning ice shelves have accelerating glaciers behind them

Most thinning ice shelves related to warming ocean currents

The warmer the seawater gets, the less resistance to flow there is in the outlet glaciers, and the more rapidly they dump their ice into the sea.

Antarctica is losing its marginal ice shelves at an accelerated rate

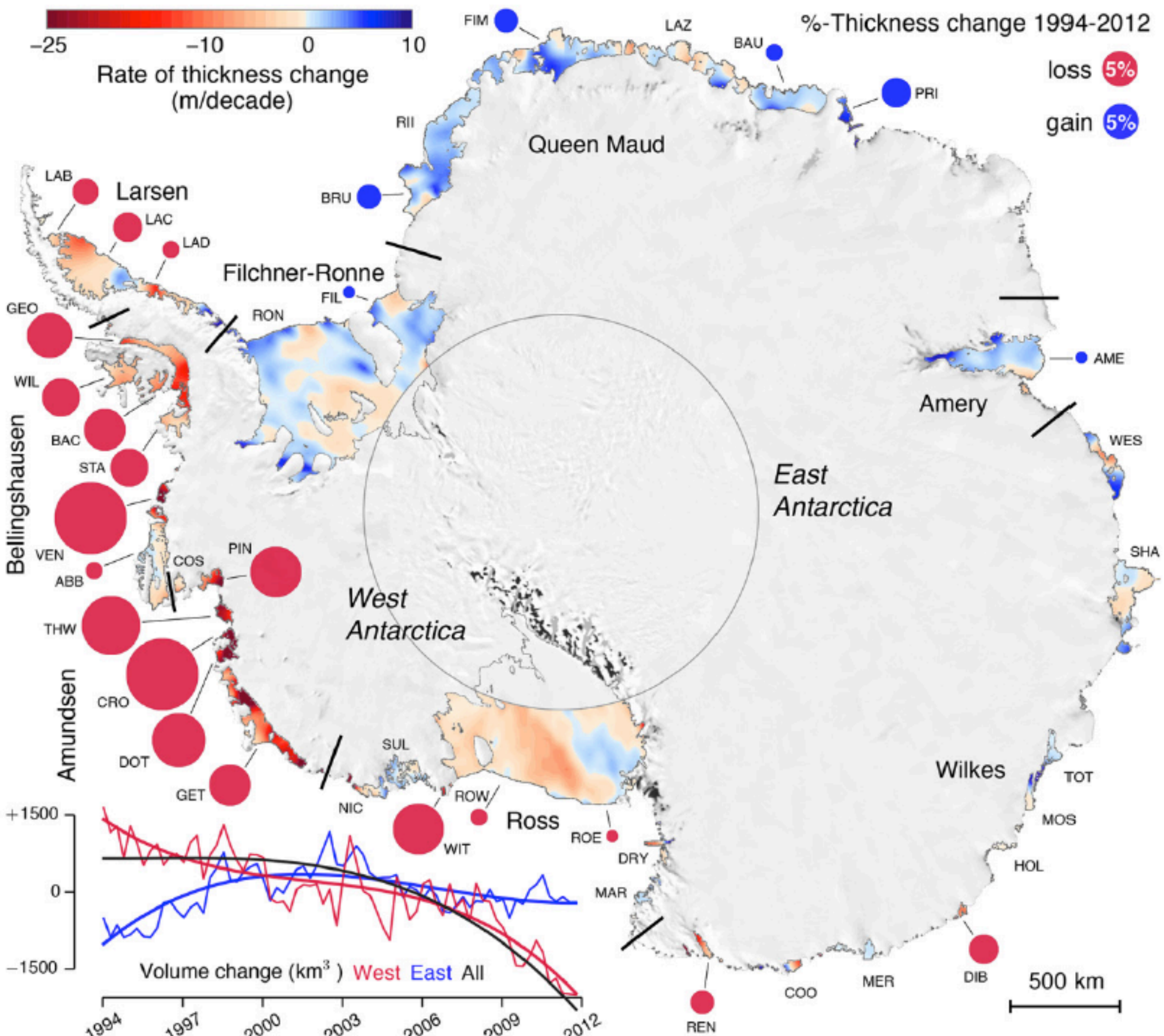




Paolo F.S., H.A. Fricker, L. Padman, Volume loss from Antarctic ice shelves is accelerating, *Science* (2015). doi:10.1126/science.aaa0940

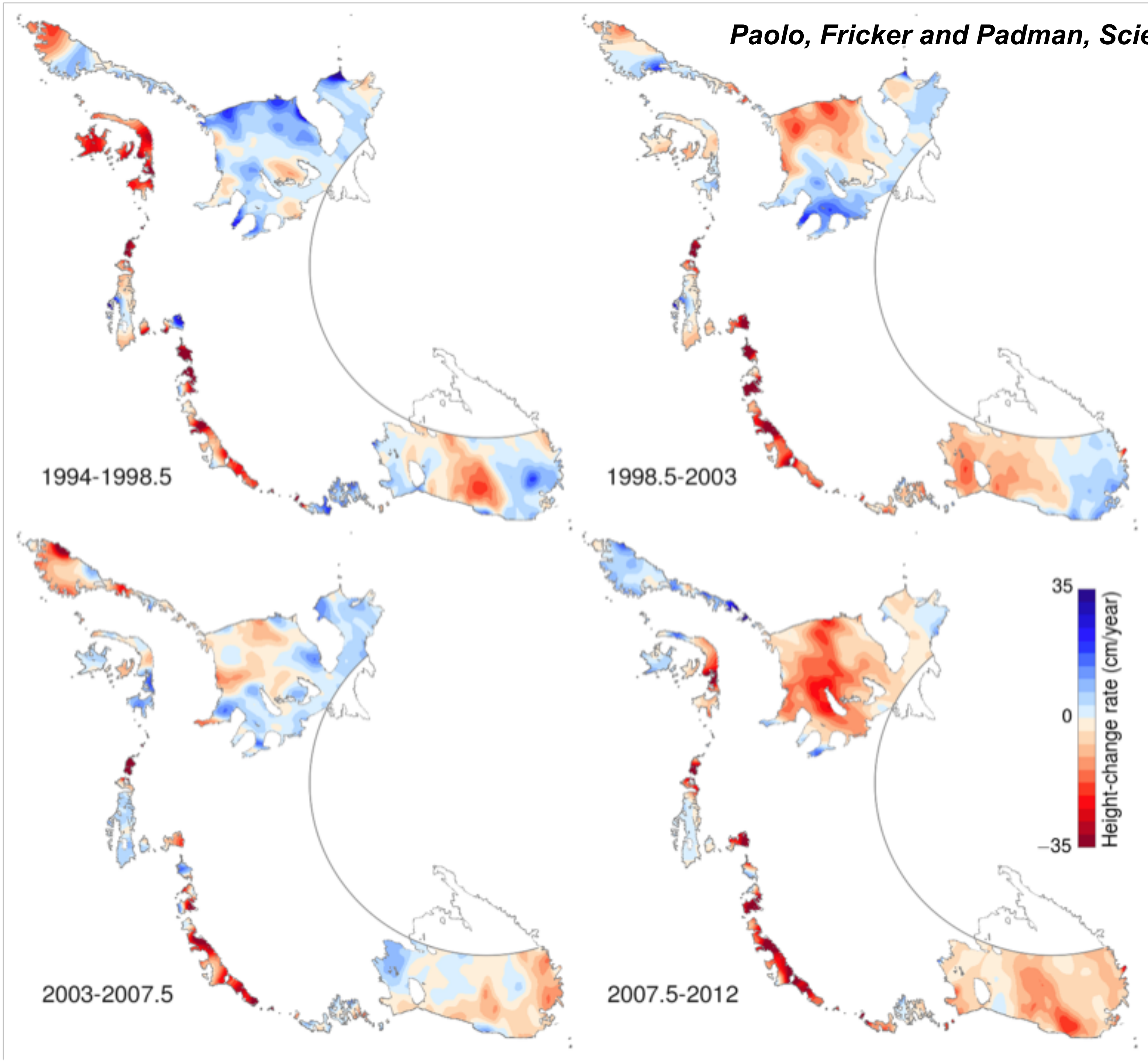
- We integrated measurements from three overlapping satellite altimetry missions (from 1994 to 2012)
- We developed methods to process and analyze 18 years of satellite radar-altimeter data over icy surfaces
- We constructed the most comprehensive record of changes in Antarctic ice-shelf height to date
- We showed that Antarctic ice-shelf volume loss is accelerating
- We showed that some key ice shelves could disappear completely within this century
- We showed that ice shelves can respond quickly to changes in atmospheric and oceanic conditions
- We showed that single satellite missions are insufficient to draw conclusion about the long-term response of ice she

Volume loss from ice shelves is accelerating

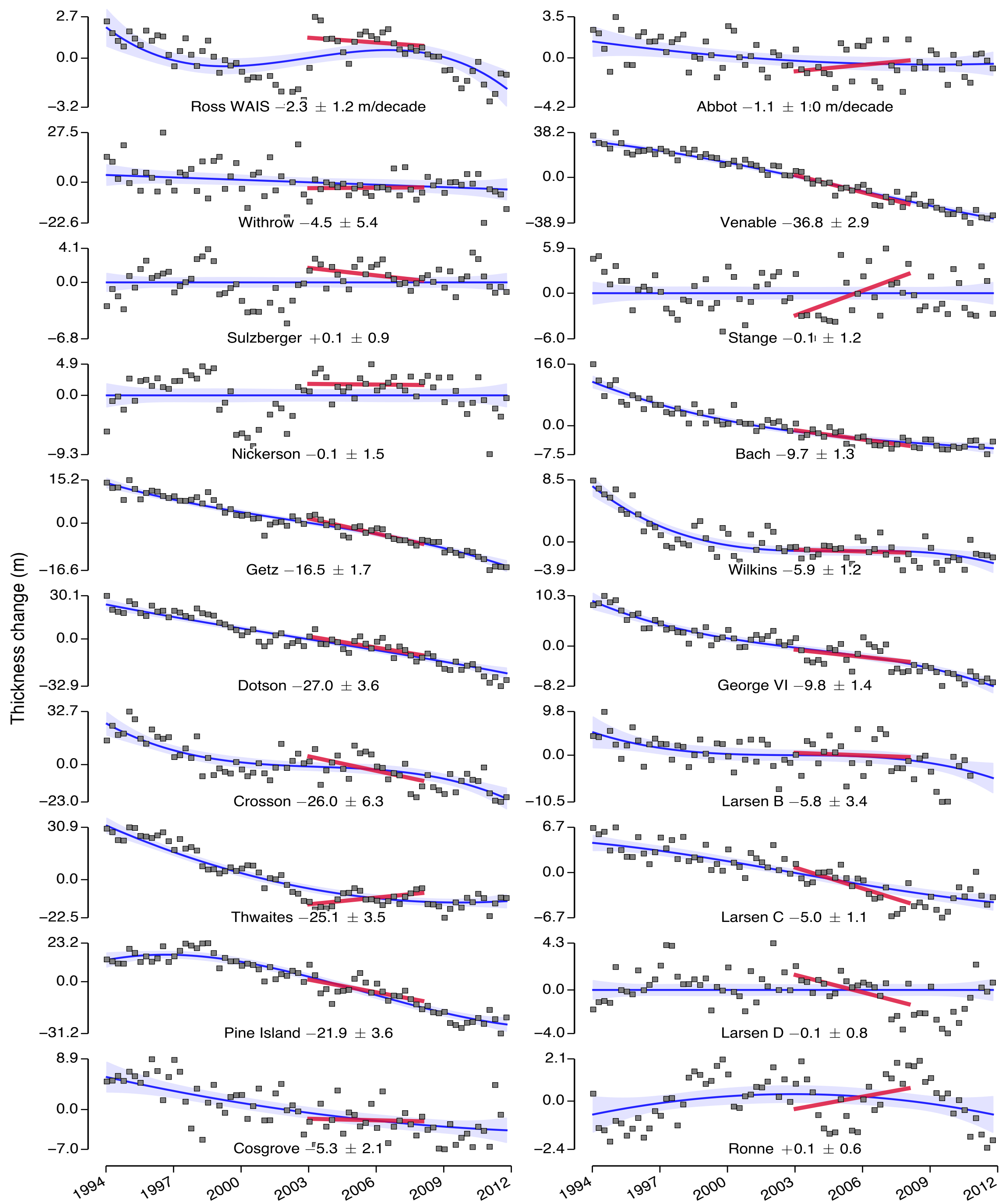


Paolo, Fricker and Padman, Science 2

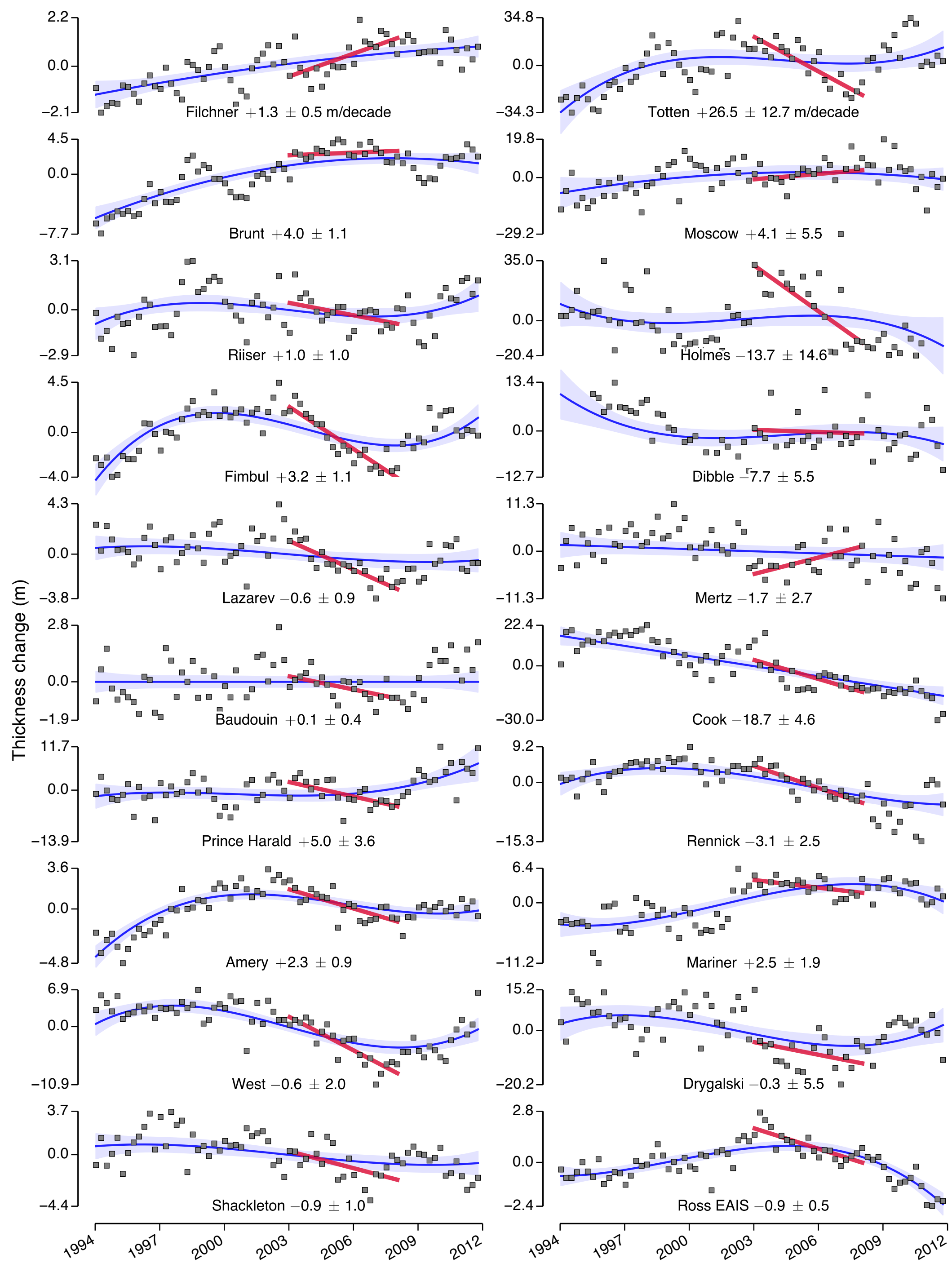
Paolo, Fricker and Padman, Science 2015




Ice-shelf thinning
West Antarctica
1994-2012
meters
0
-20
-40
-60
Year 1994.0

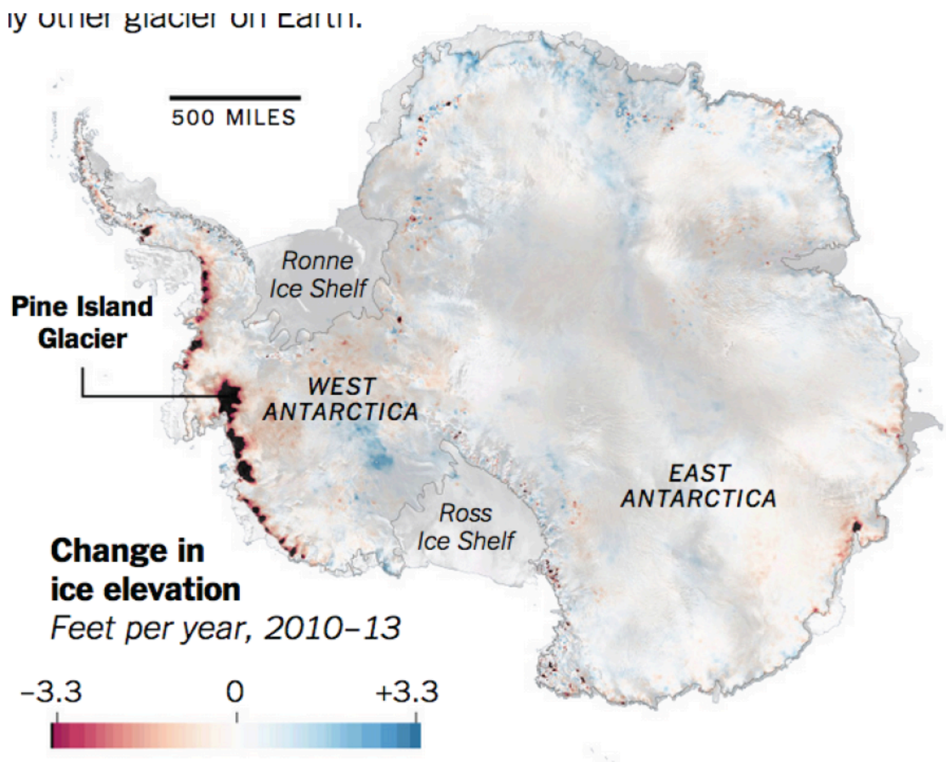


Thickness change (m)
Ross WAIS −2.3 ± 1.2 m/decade
Abbot −1.1 ± 1.0 m/decade
Withrow −4.5 ± 5.4
Venable −36.8 ± 2.9
Sulzberger +0.1 ± 0.9
Stange −0.1 ± 1.2
Nickerson −0.1 ± 1.5
Bach −9.7 ± 1.3
Getz −16.5 ± 1.7
Wilkins −5.9 ± 1.2
Dotson −27.0 ± 3.6
George VI −9.8 ± 1.4
Crosson −26.0 ± 6.3
Larsen B −5.8 ± 3.4
Thwaites −25.1 ± 3.5
Larsen C −5.0 ± 1.1
Pine Island −21.9 ± 3.6
Larsen D −0.1 ± 0.8
Cosgrove −5.3 ± 2.1
Ronne +0.1 ± 0.6
1994
1997
2000
2003
2006
2009
2012



Thickness change (m)
Filchner +1.3 ± 0.5 m/decade
Totten +26.5 ± 12.7 m/decade
Brunt +4.0 ± 1.1
Moscow +4.1 ± 5.5
Riiser +1.0 ± 1.0
Holmes −13.7 ± 14.6
Fimbul +3.2 ± 1.1
Dibble −7.7 ± 5.5
Lazarev −0.6 ± 0.9
Mertz −1.7 ± 2.7
Baudouin +0.1 ± 0.4
Cook −18.7 ± 4.6
Prince Harald +5.0 ± 3.6
Rennick −3.1 ± 2.5
Amery +2.3 ± 0.9
Mariner +2.5 ± 1.9
West −0.6 ± 2.0
Drygalski −0.3 ± 5.5
Shackleton −0.9 ± 1.0
Ross EAIS −0.9 ± 0.5
1994
1997
2000
2003
2006
2009
2012

Current(er) status of Antarctica

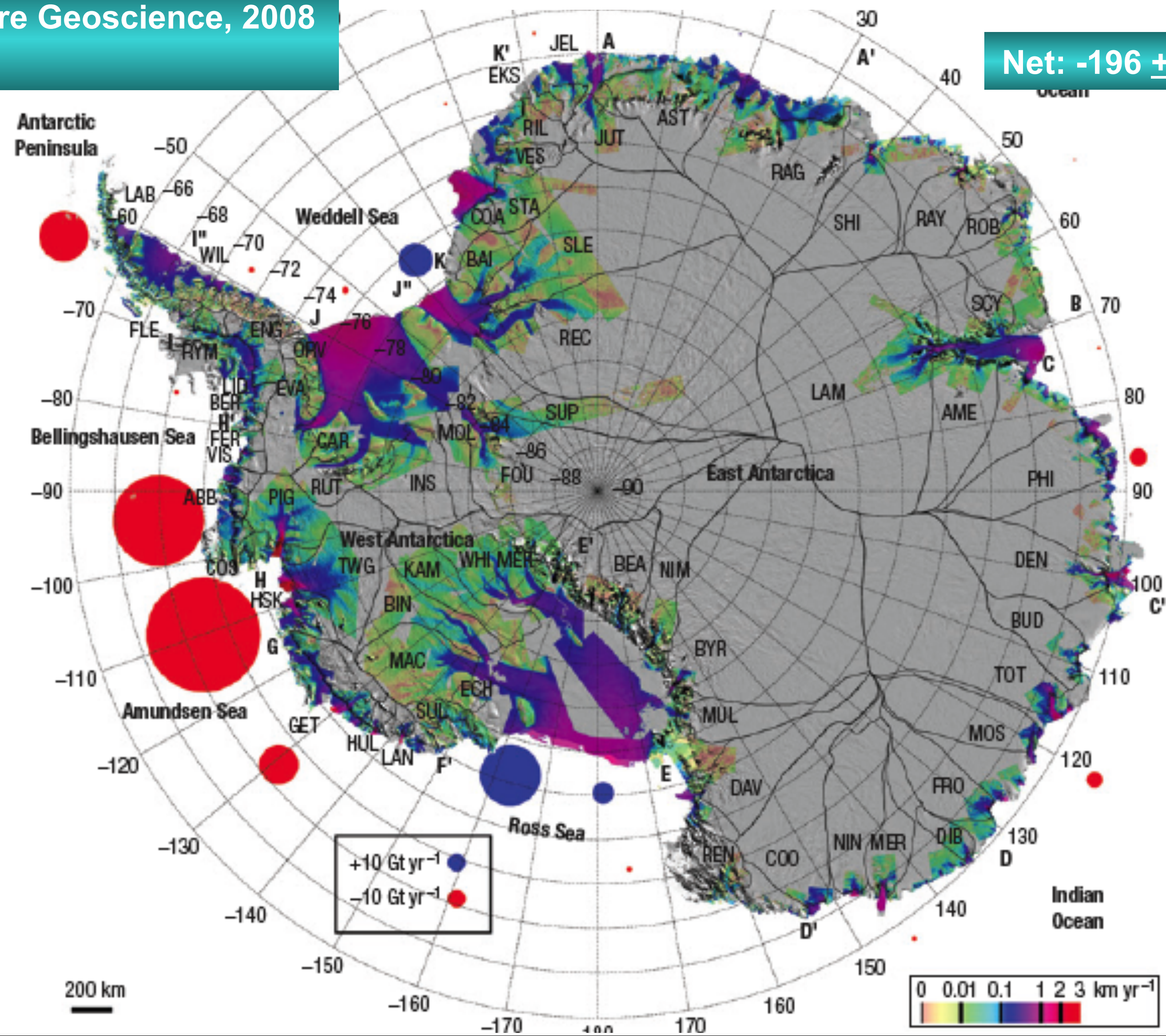


McMillan et al., 2014 (*GRL*), illustrated by NYT

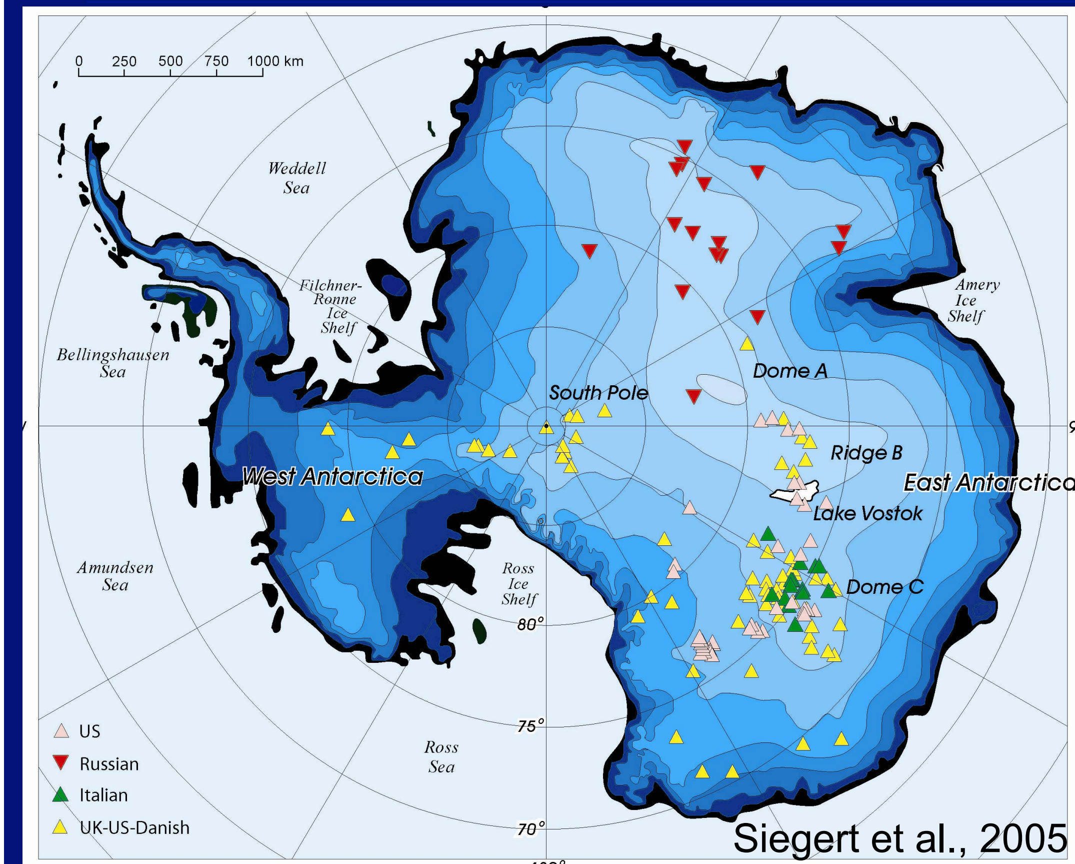
Antarctica mass loss 2006
Mass flux estimates

Rignot et al., Nature Geoscience, 2008

Net: -196 ± 92 Gta^{-1}

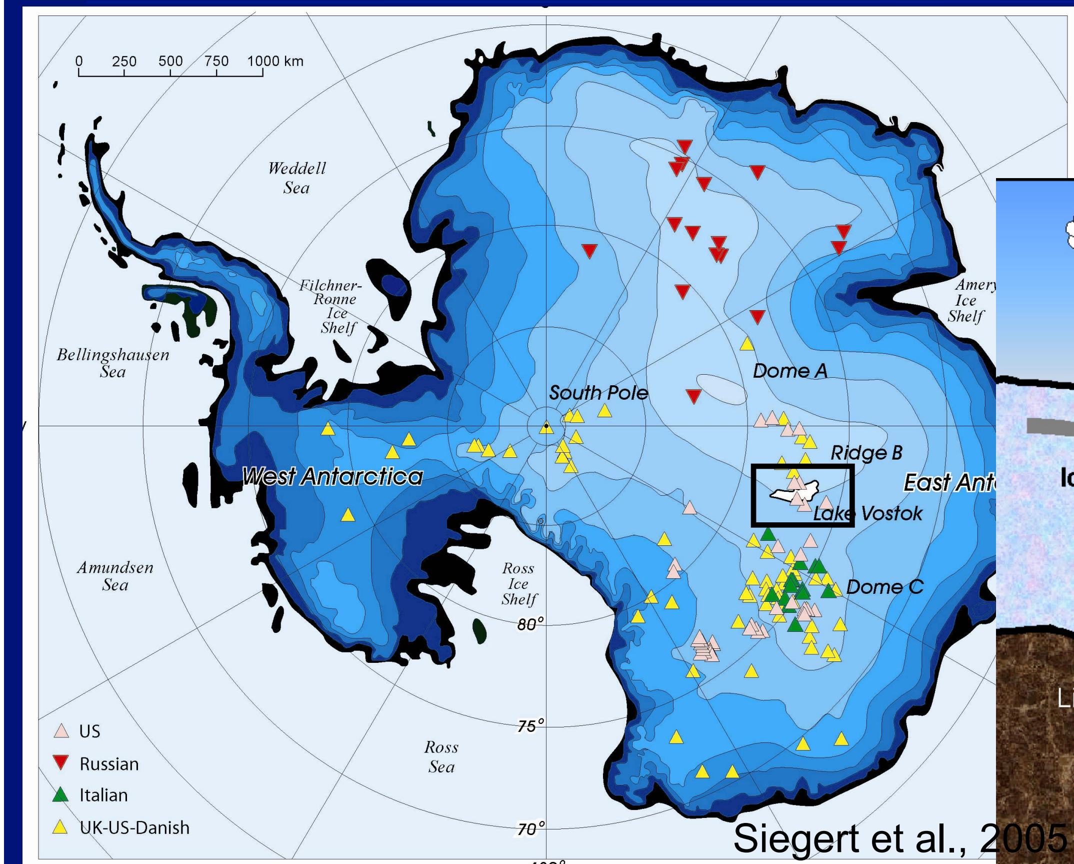


Antarctic subglacial water

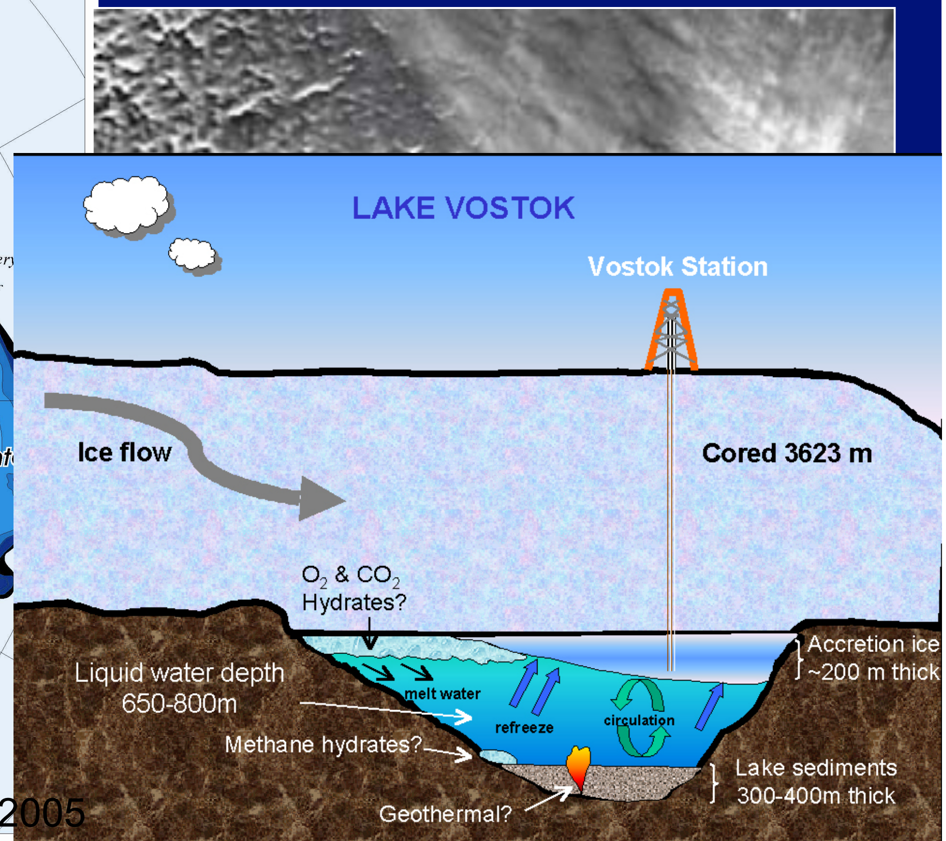


- There are 145 documented subglacial lakes under the Antarctic ice sheet – the first lake discovery was made in the 1960s

Antarctic subglacial water

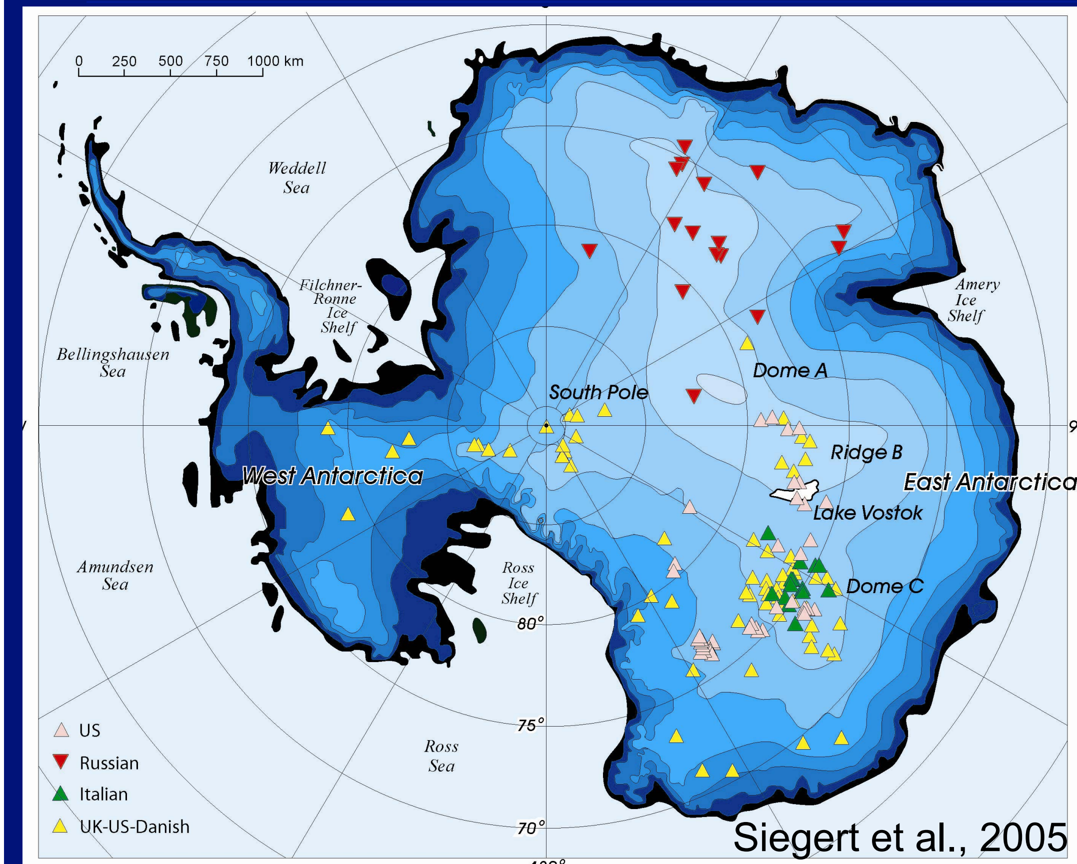


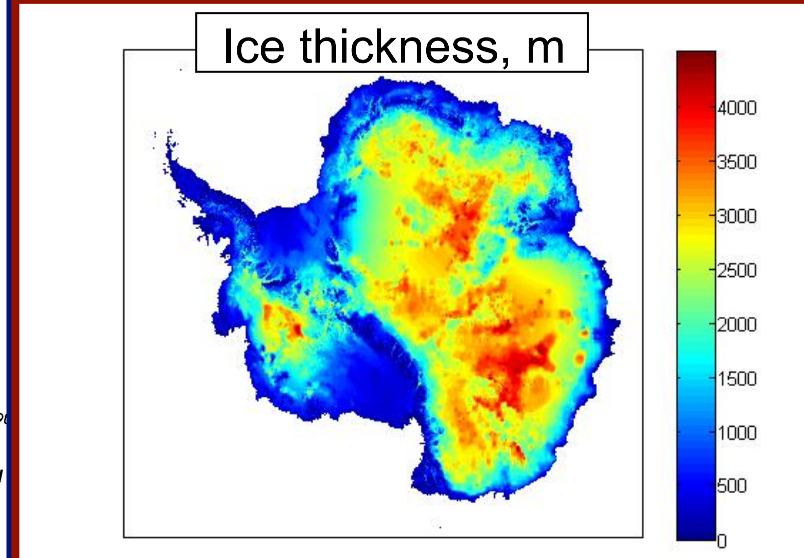
Siegert et al., 2005

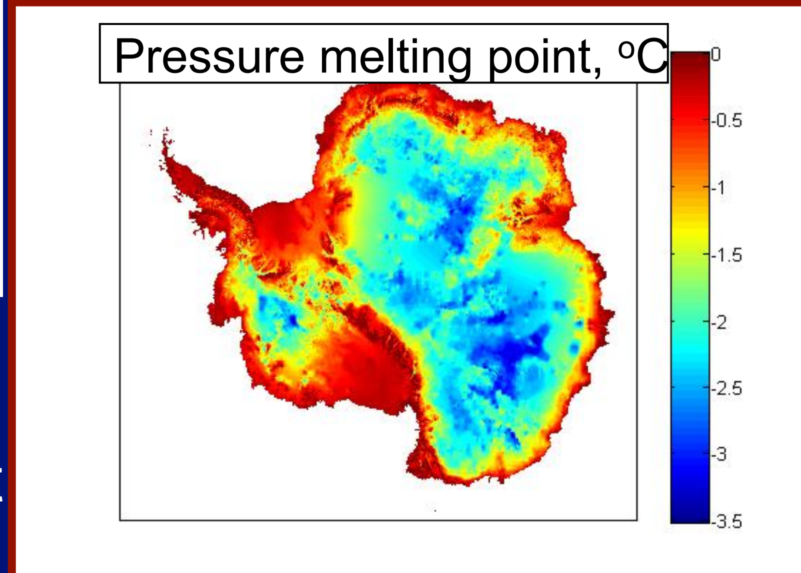


- Lake Vostok (discovered 1993) is the largest known subglacial lake; its area is 14,000 km^2 - about the same area as Lake Ontario but it is twice as deep (volume 5,400 km^3)

Antarctic subglacial water

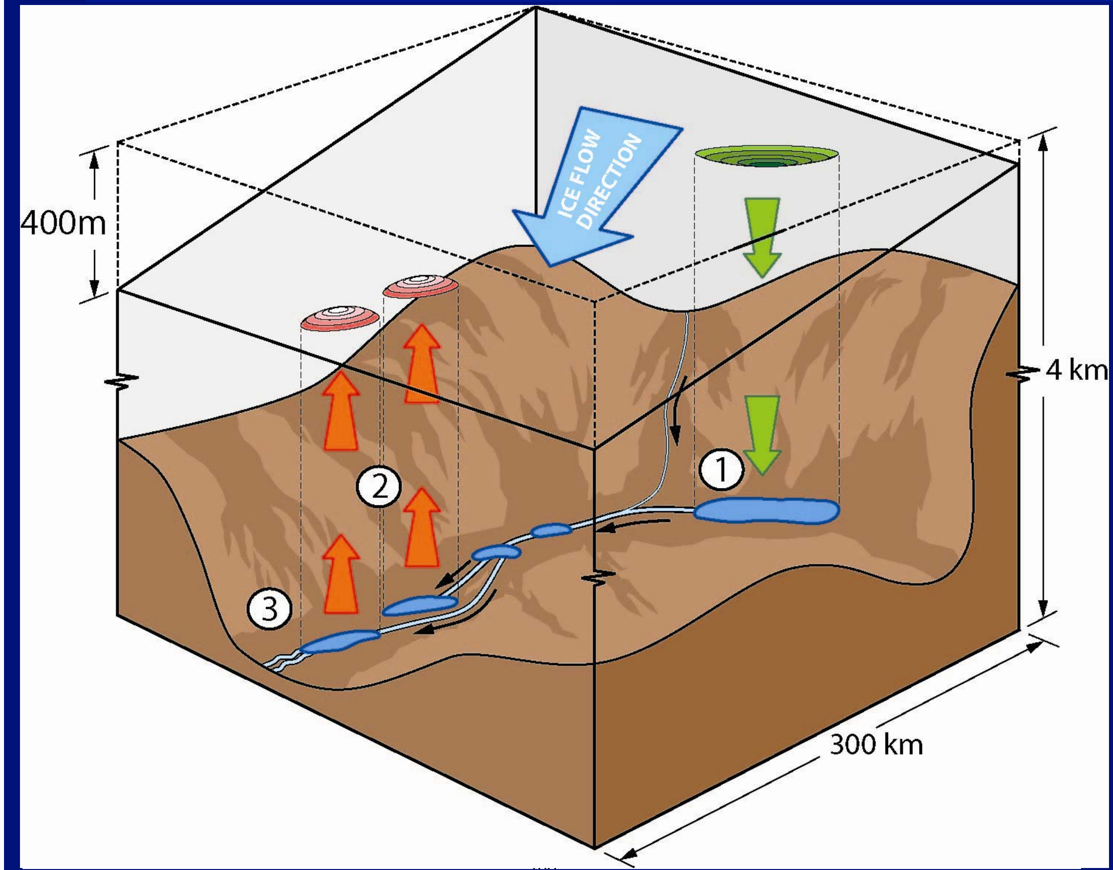


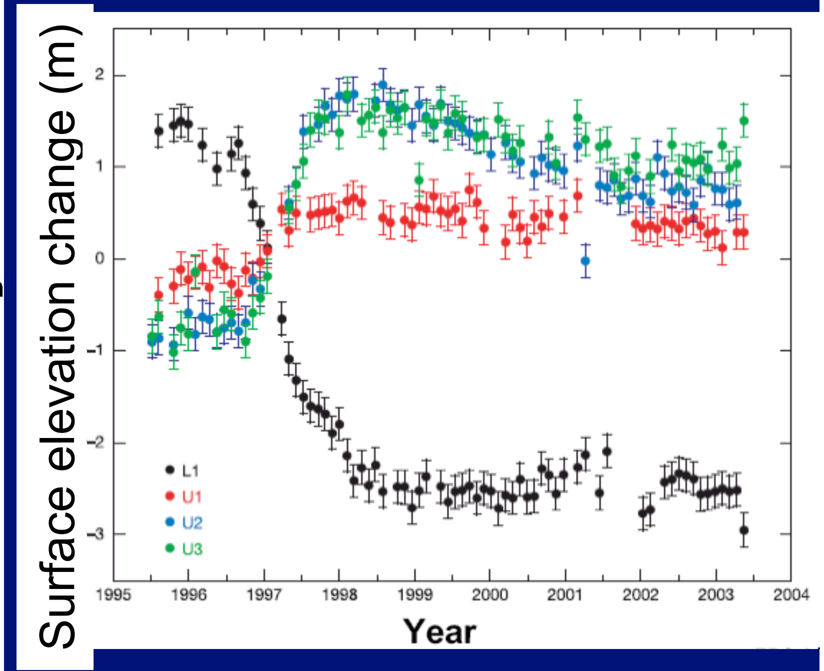




- The water below the ice remains liquid by the pressure of the ice sheet above and by geothermal heating

Antarctic subglacial water

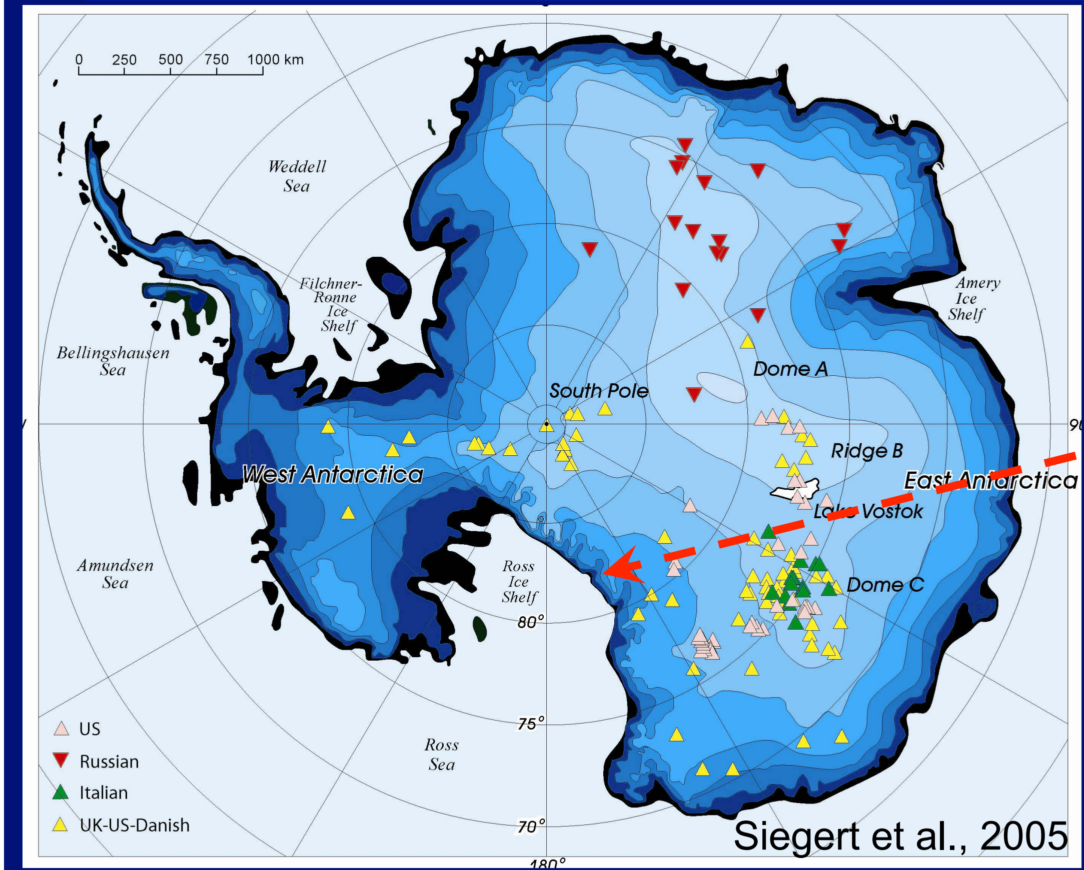


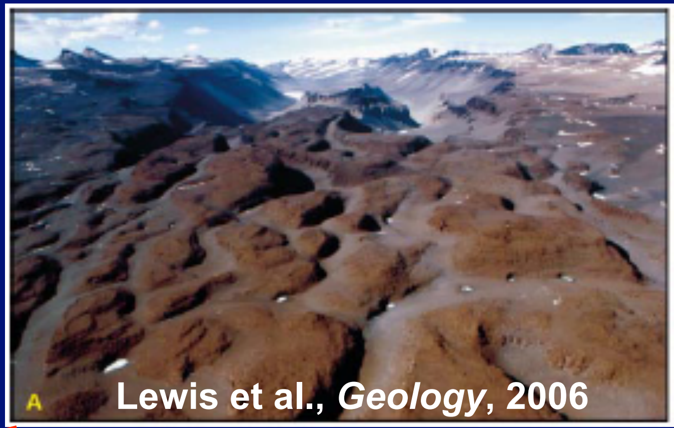


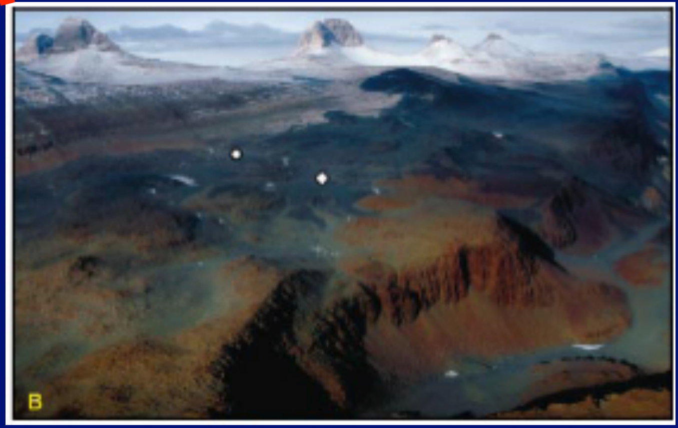
Wingham et al. Nature, 2006

- Until recently water flow was thought to be a steady trickle, however results by Gray et al. (GRL, 2005) and Wingham et al. (Nature, 2006) has shown that subglacial water can move rapidly in large quantities ➔ “subglacial floods”

Antarctic subglacial water

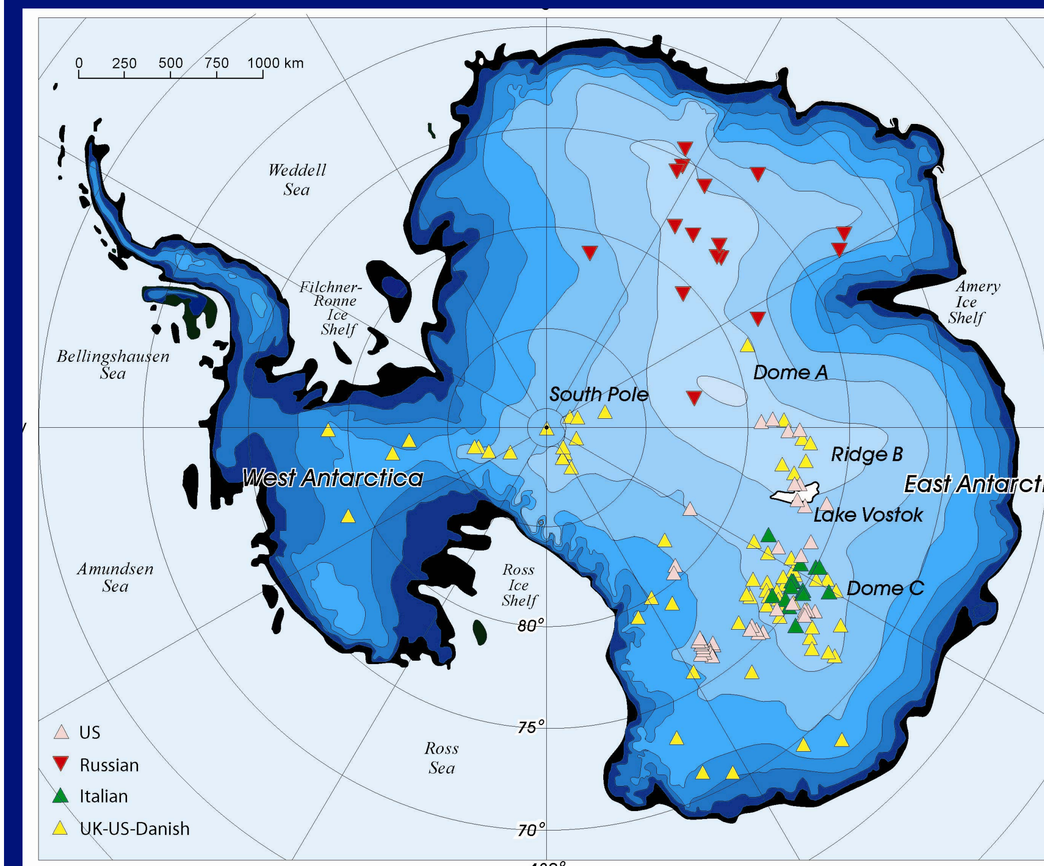


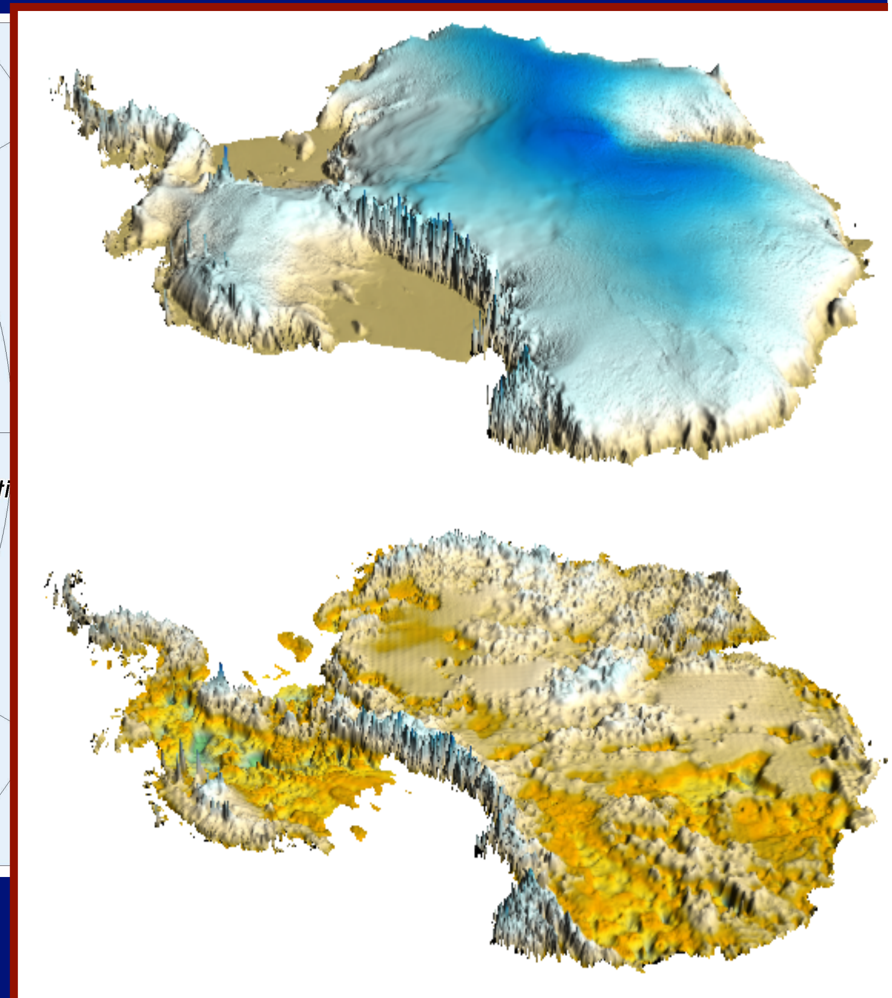




- There is evidence for large scale subglacial water movement in the Transantarctic Mountains – a feature known as the Labyrinth – believed to have last flooded between ~12 & 14 million years ago

Antarctic elevation and bedrock

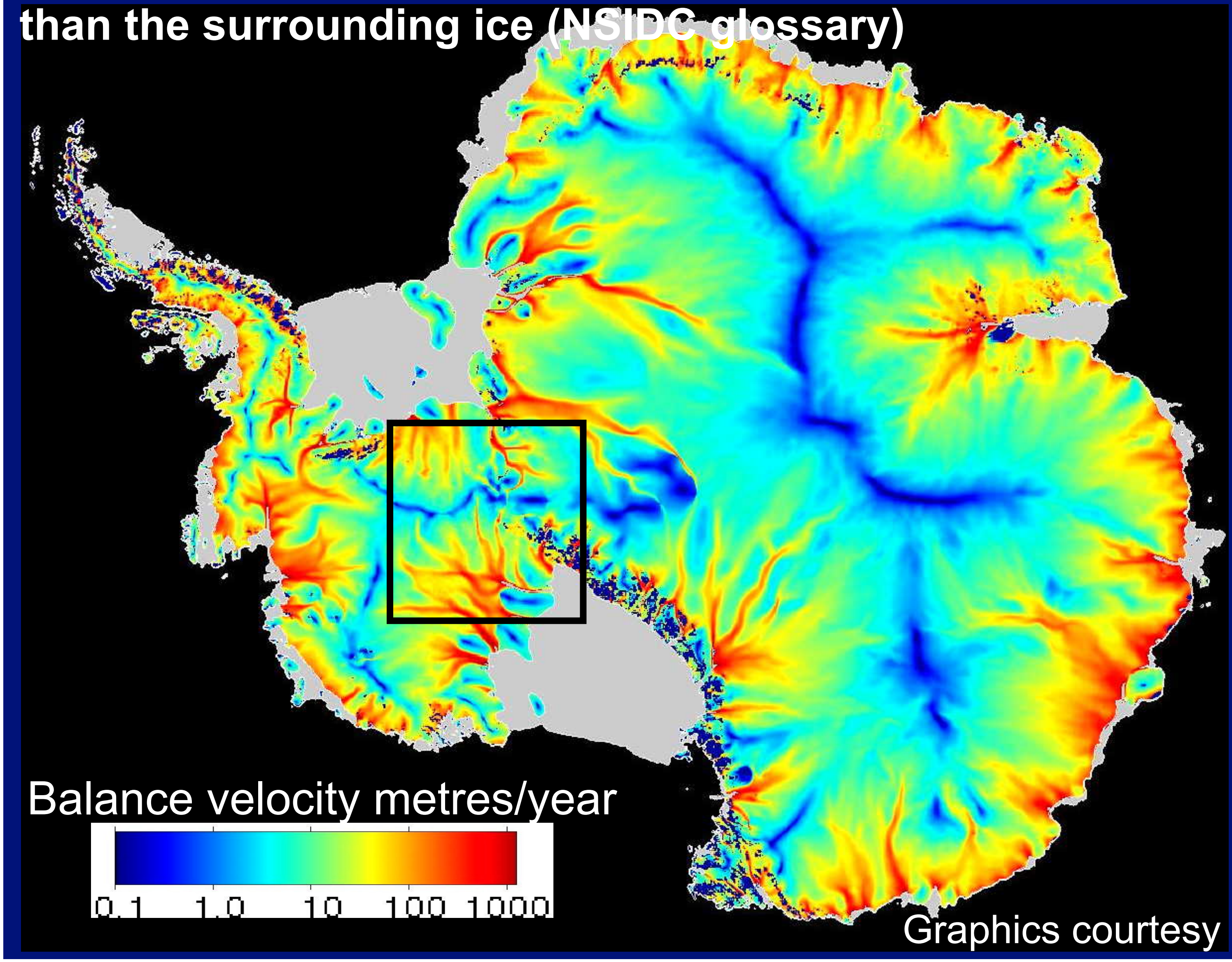




- Flow of water between lakes governed mainly by the surface topography ➔ water can travel “uphill”

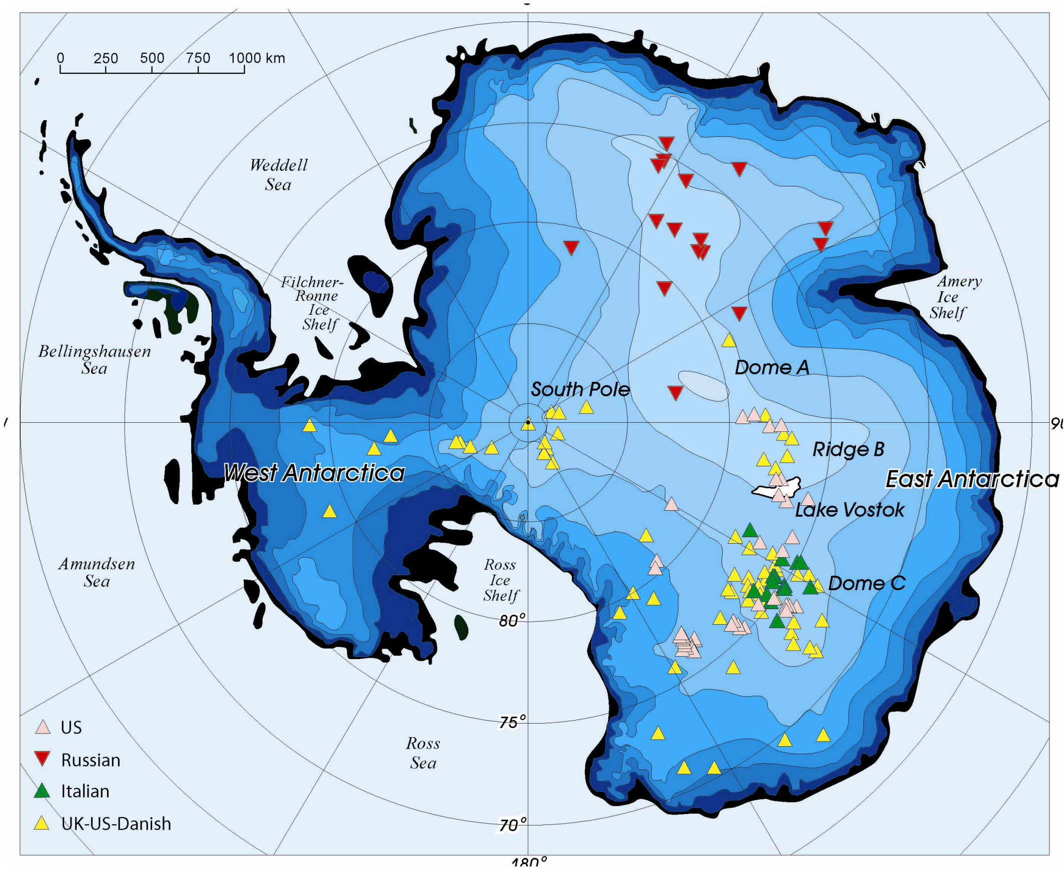
Antarctica's ice streams

ice stream: a current of ice in an ice sheet or ice cap that flows faster than the surrounding ice (NSIDC glossary)



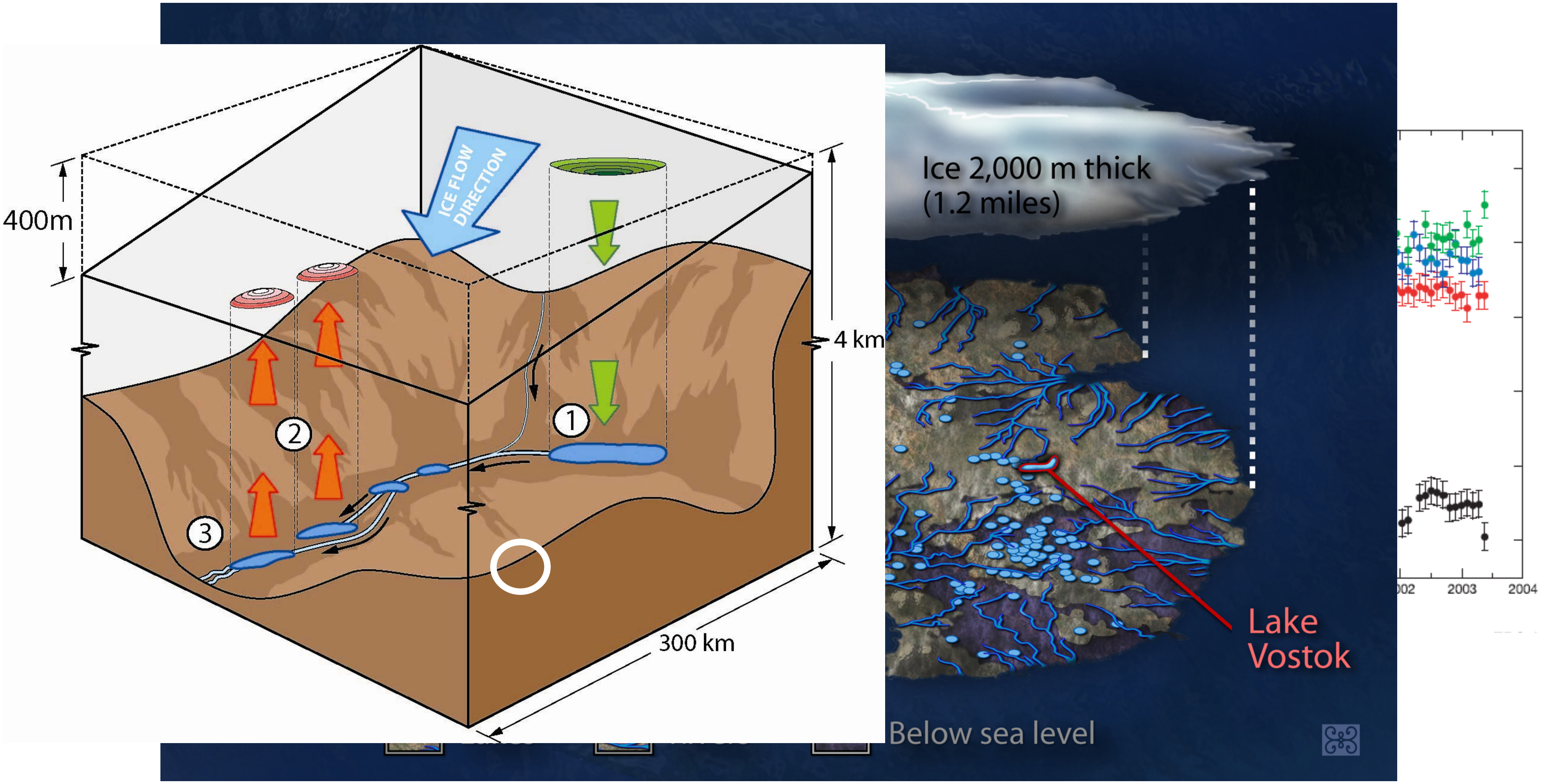
Graphics courtesy of Roland Warner

Antarctic subglacial lakes



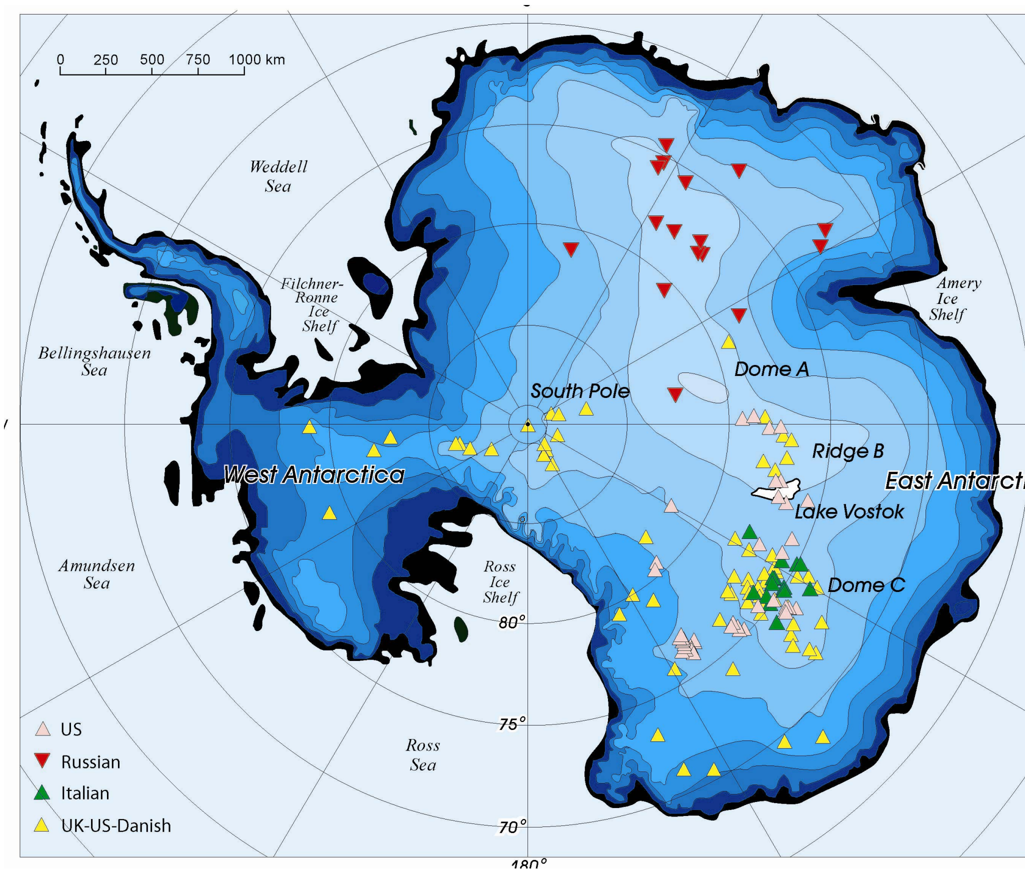
- ★ Subglacial lake inventory from Martin Siegert and others, 2005.
- ★ Most of these lakes were derived by airborne radar sounding.
- ★ These are "inactive" lakes mainly located near the ice margins and slow moving parts of the ice sheet

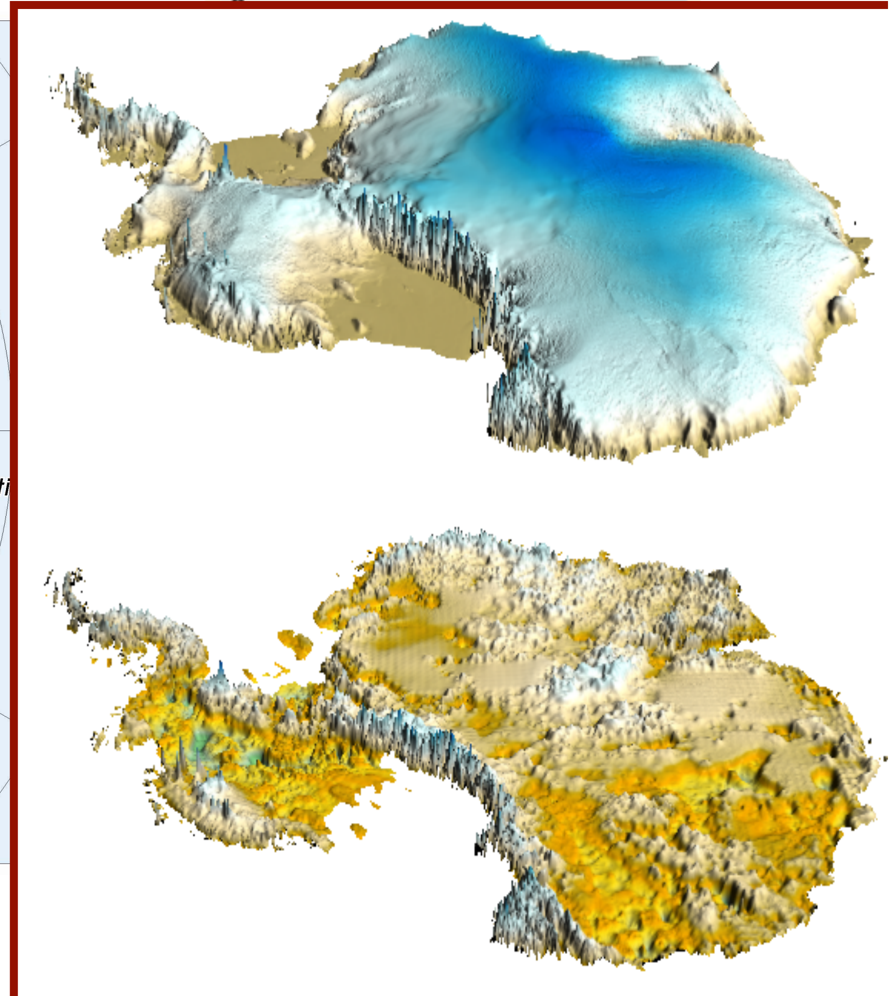
Antarctic subglacial water



- Results by Gray et al. (GRL, 2005), Wingham et al. (Nature, 2006) & Fricker et al. (Science, 2007) showed that subglacial water can move rapidly in large quantities ➔ "subglacial floods"

Antarctic elevation and bedrock

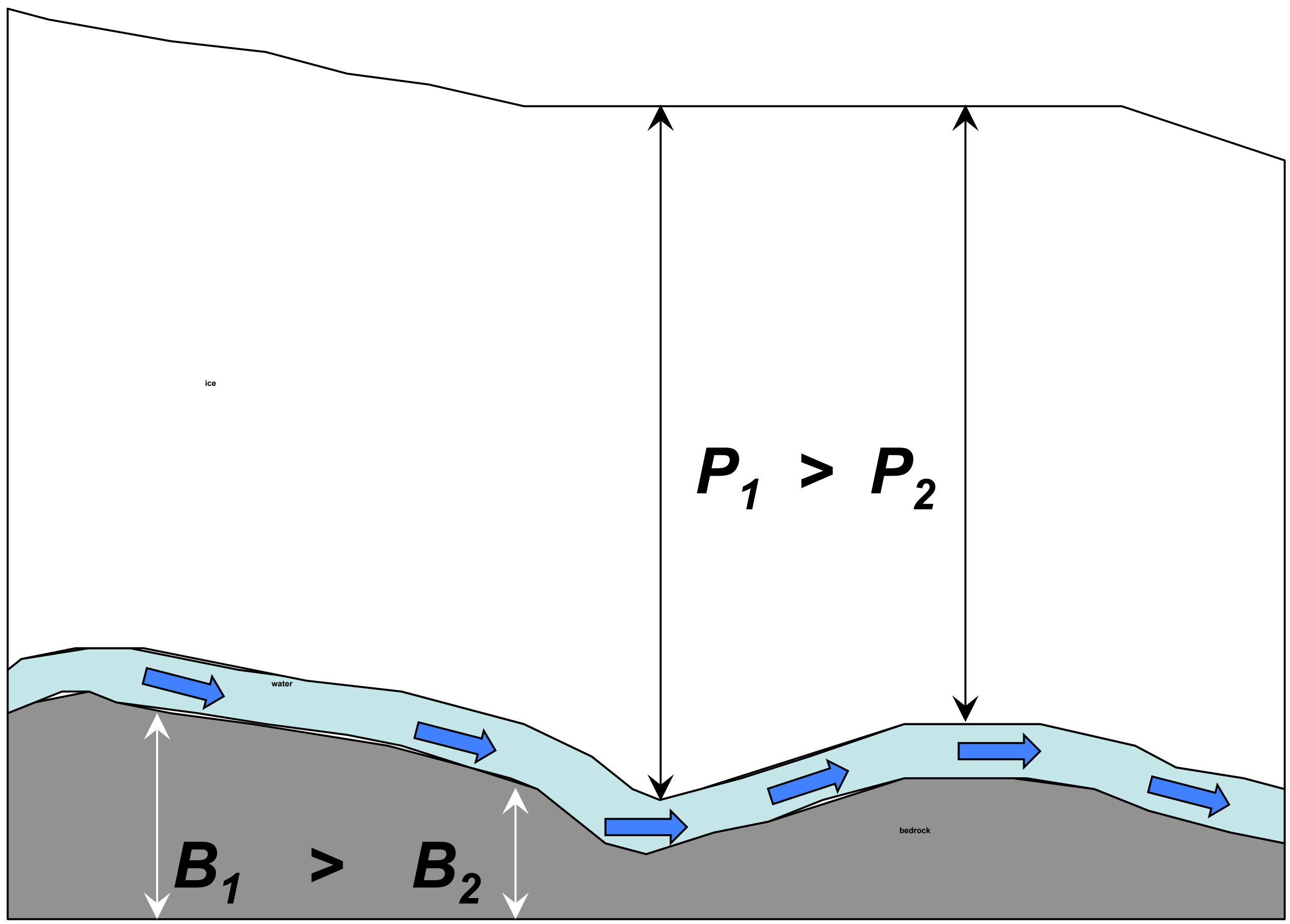




Flow of water between lakes governed by the hydropotential which is dominated by the surface topography ➔ water can travel "uphill"

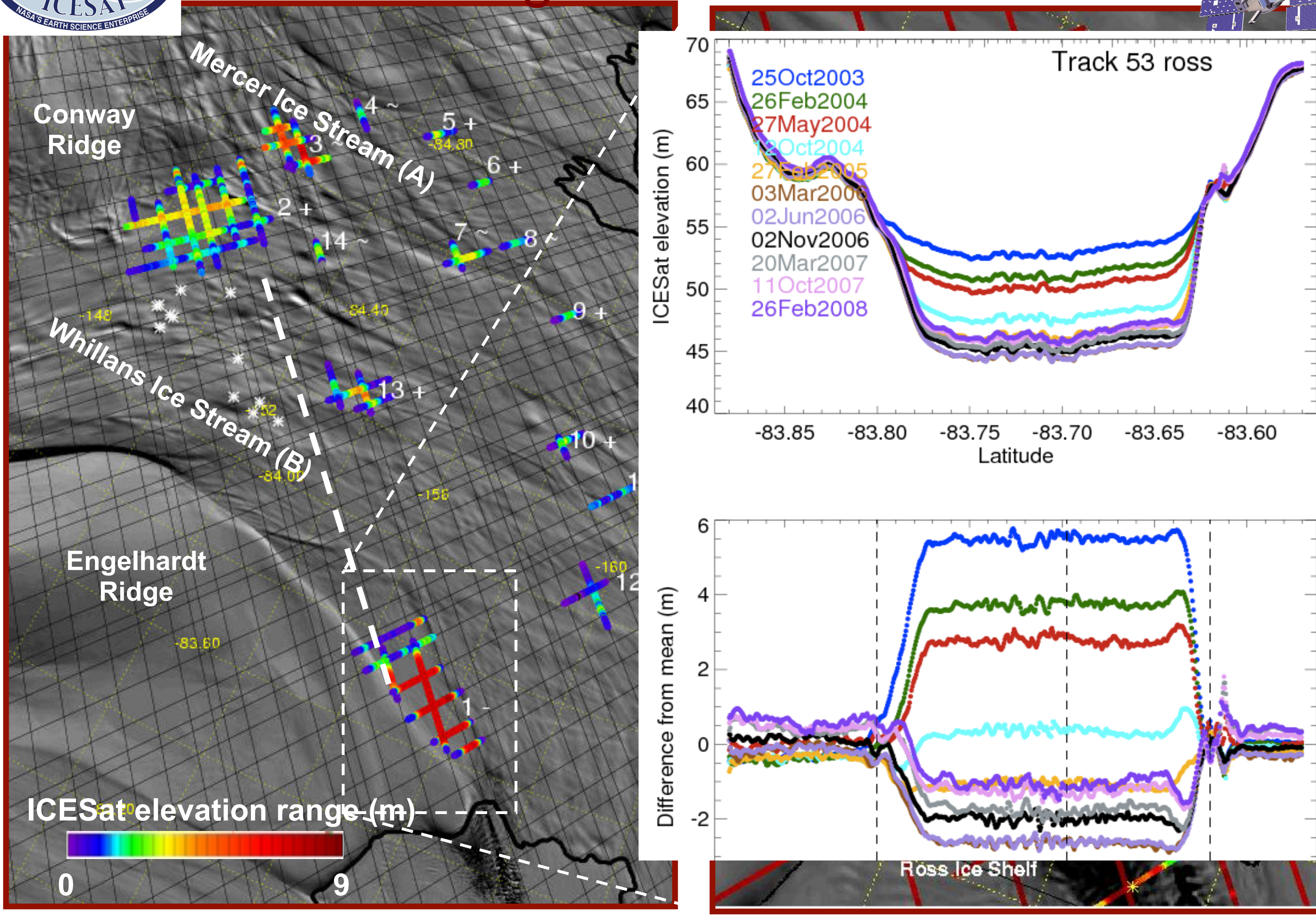
How does water flow under ice?

Water moves from places with high pressure ➔ places with low pressure
Ice overburden pressure P_i plays the role of a pump

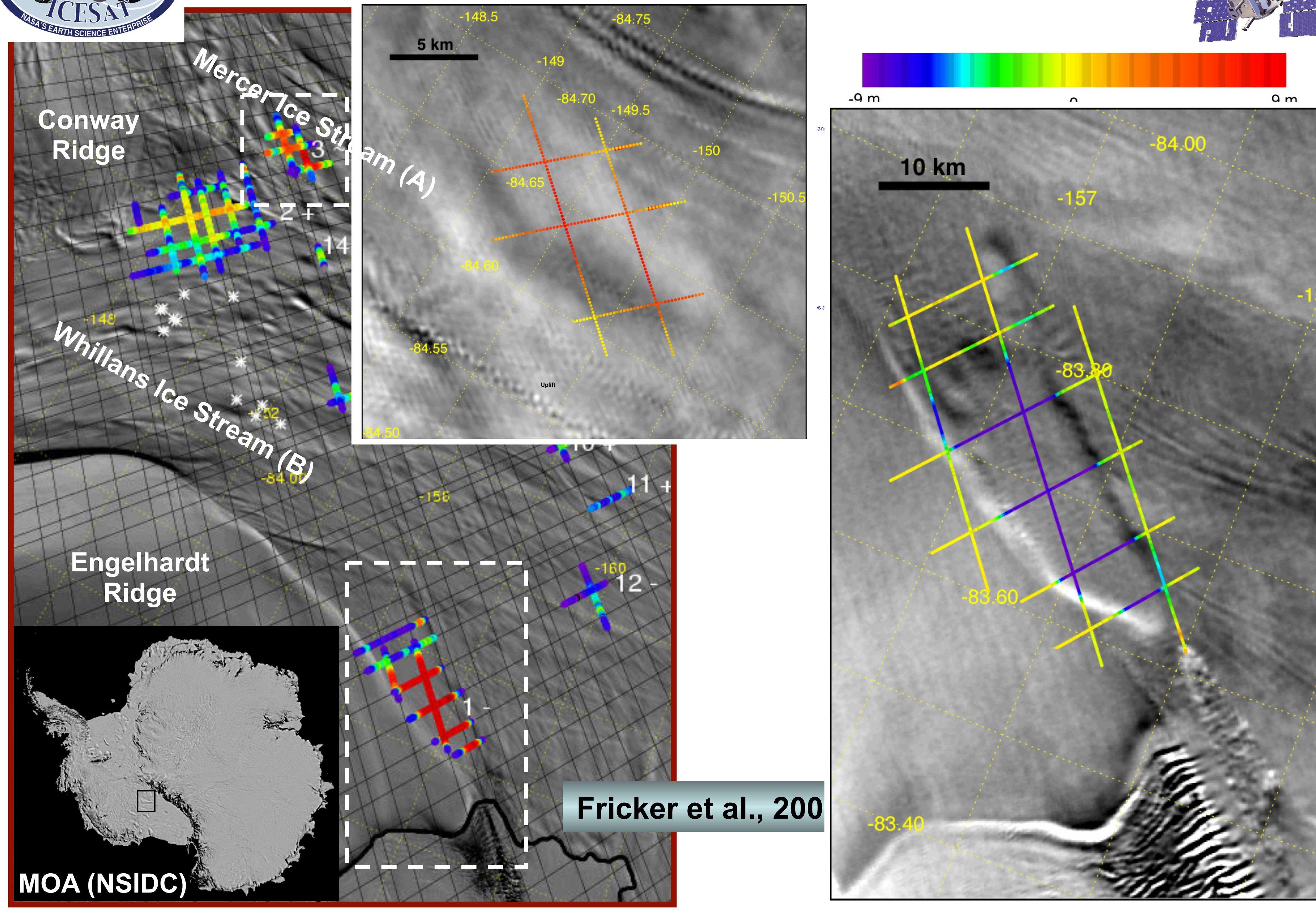


$$\Phi = \rho_w g B + P_i$$

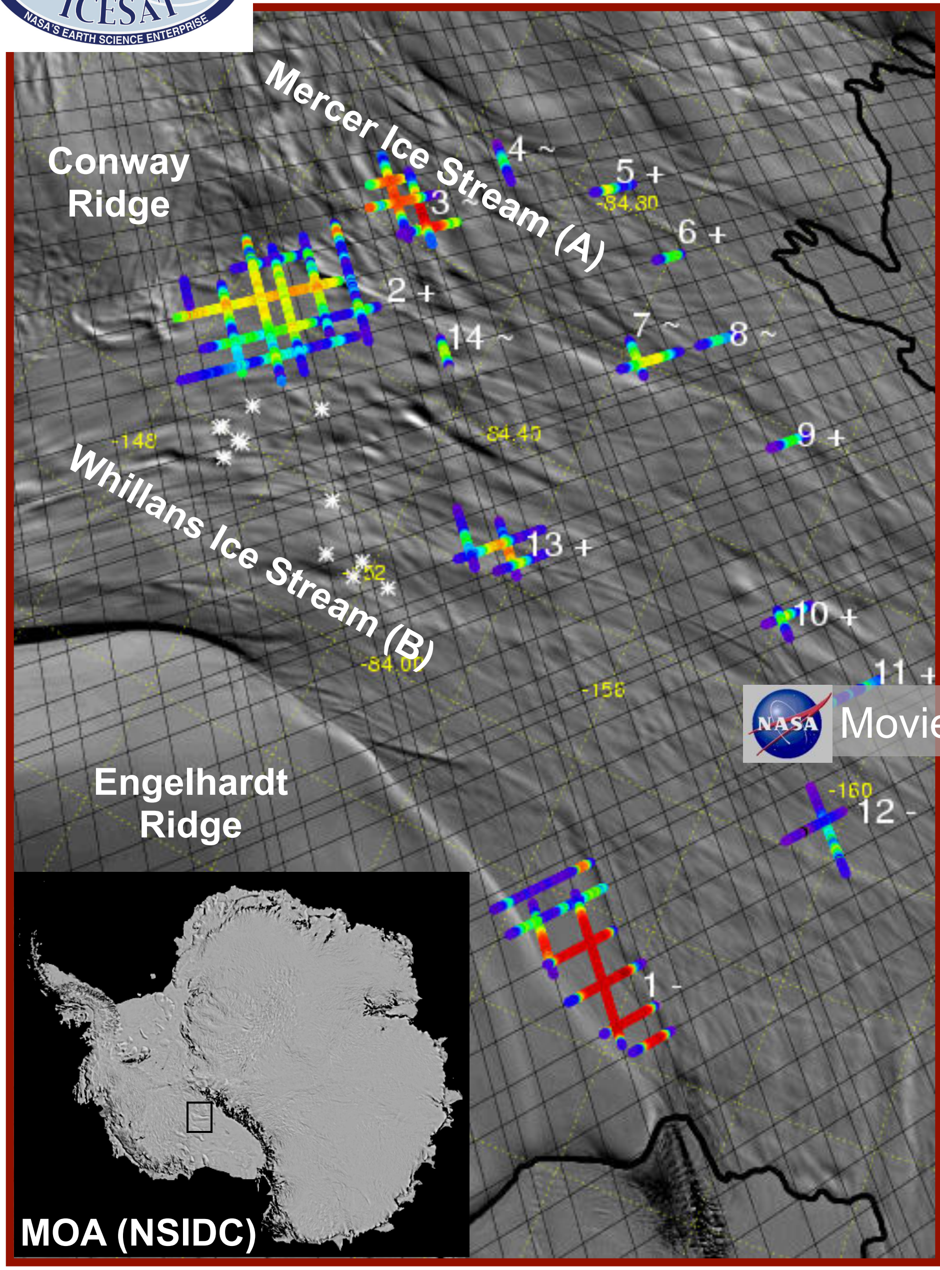
Detecting lakes with ICESat



Satellite image differencing



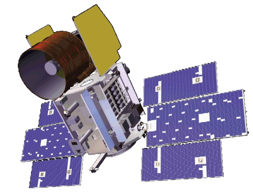
Subglacial water transport



Movie courtesy of NASA GSFC Conceptual Image Lab

The signals are the surface expressions of subglacial water moving beneath the ice streams

Active subglacial lake inventory



An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008)

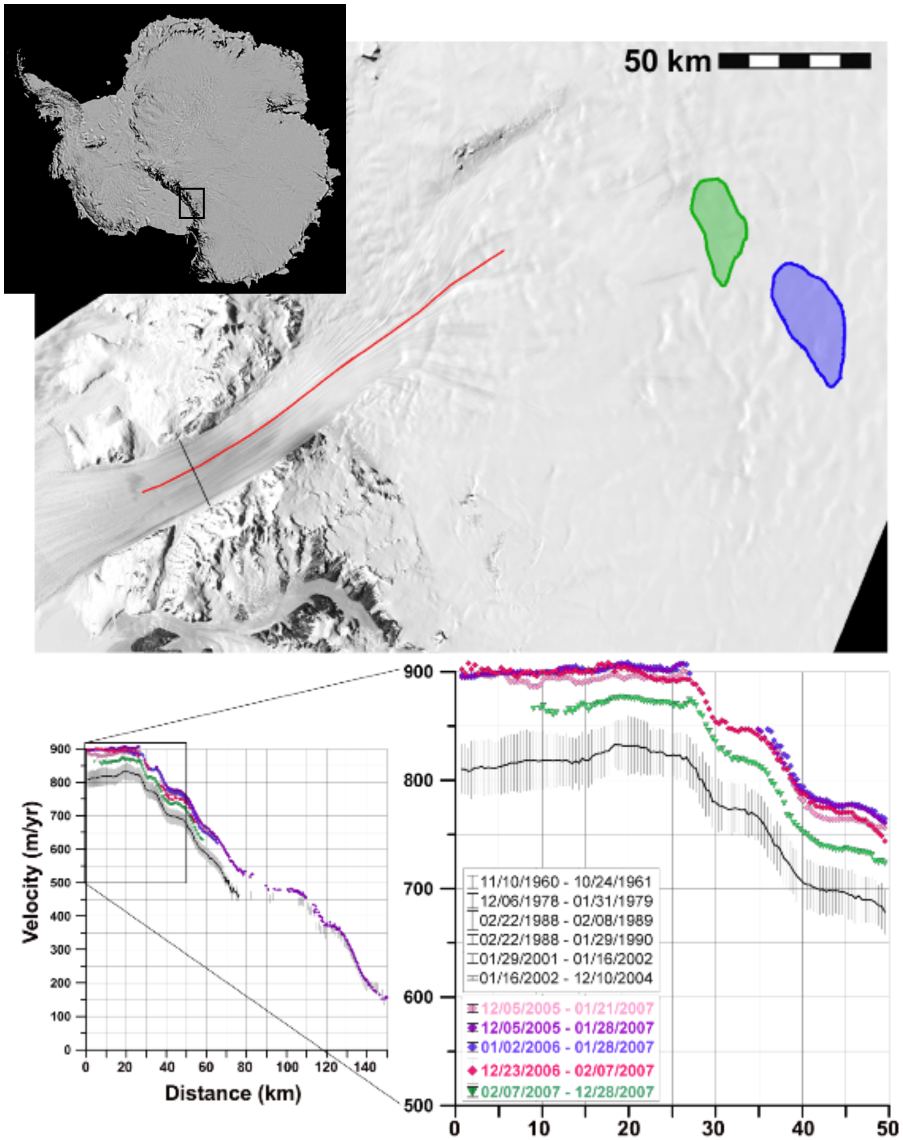
Benjamin E. SMITH,[1] Helen A. FRICKER,[2] Ian R. JOUGHIN,[1] Slawek TULACZYK[3]

[1]*Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Box 355640, Seattle, Washington 98105-6698, USA*
E-mail: bsmith@apl.washington.edu
[2]*Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093-0225, USA*
[3]*Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, California 95064, USA*

ABSTRACT. Through the detection of surface deformation in response to water movement, recent satellite studies have demonstrated the existence of subglacial lakes in Antarctica that fill and drain on timescales of months to years. These studies, however, were confined to specific regions of the ice sheet. Here we present the first comprehensive study of these 'active' lakes for the Antarctic ice sheet north of 86° S, based on 4.5 years (2003–08) of NASA's Ice, Cloud and land Elevation Satellite (ICESat) laser altimeter data. Our analysis has detected 124 lakes that were active during this period, and we estimate volume changes for each lake. The ICESat-detected lakes are prevalent in coastal Antarctica, and are present under most of the largest ice-stream catchments. Lakes sometimes appear to transfer water from one to another, but also often exchange water with distributed sources undetectable by ICESat, suggesting that the lakes may provide water to or withdraw water from the hydrologic systems that lubricate glacier flow. Thus, these reservoirs may contribute pulses of water to produce rapid temporal changes in glacier speeds, but also may withdraw water at other times to slow flow.

Smith et al., 2009

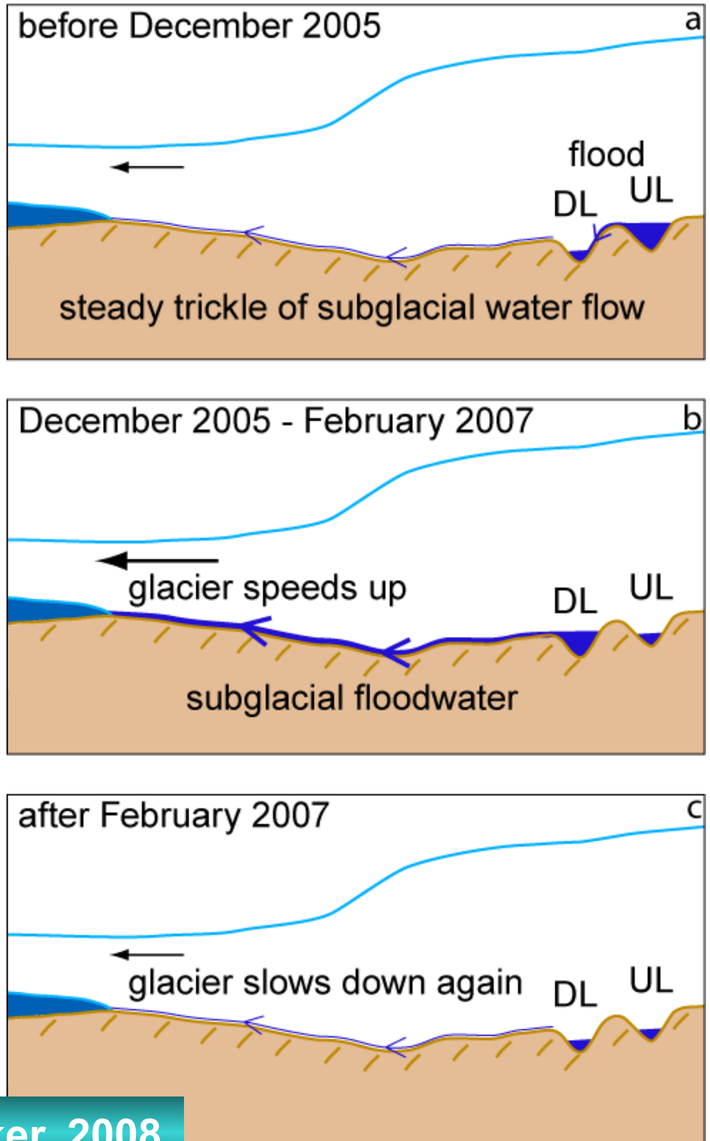
Link between lakes & ice dynamics



- ❖ Byrd Glacier velocity increased by 10% for a period o 14 months from December 2005
- ❖ Speed-up started within one month of initiation of drainage c subglacial lake upstream (1.7 km^3 water)
- ❖ First evidence of direct link between subglacial floods and ice dynamics

Stearns, Smith and Hamilton, 2008

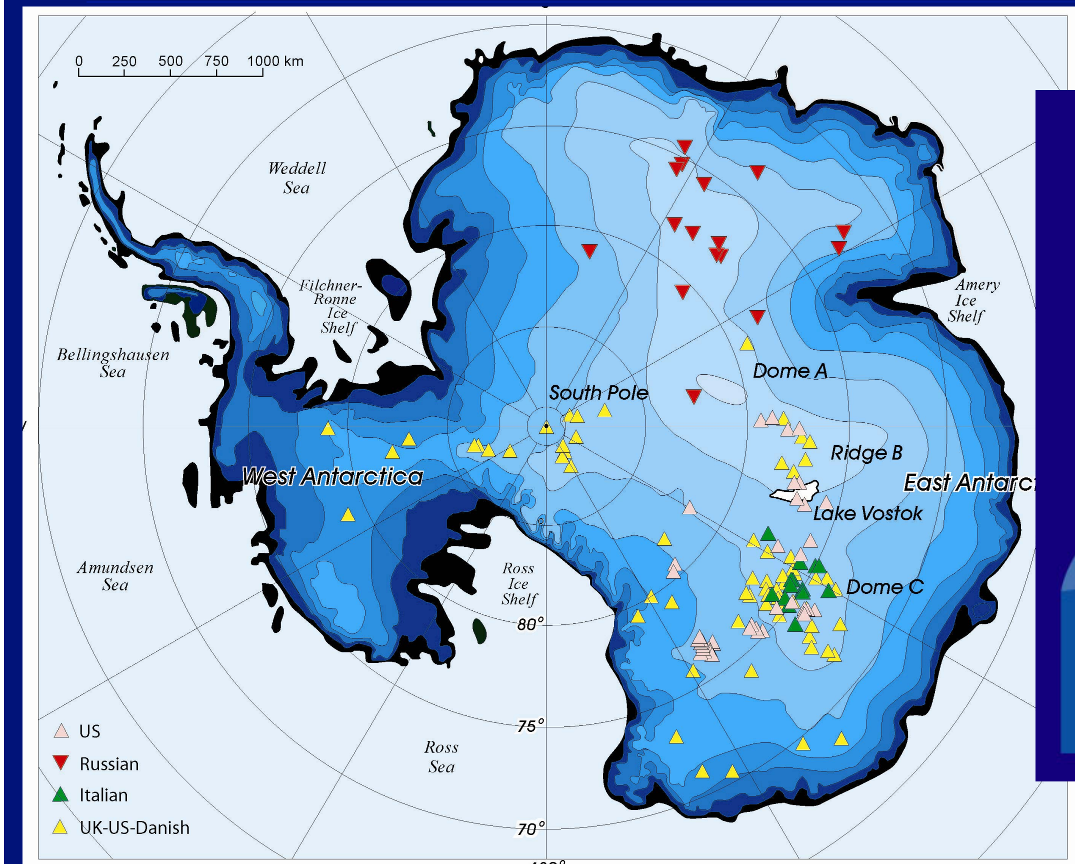
Link between lines & ice dynamics

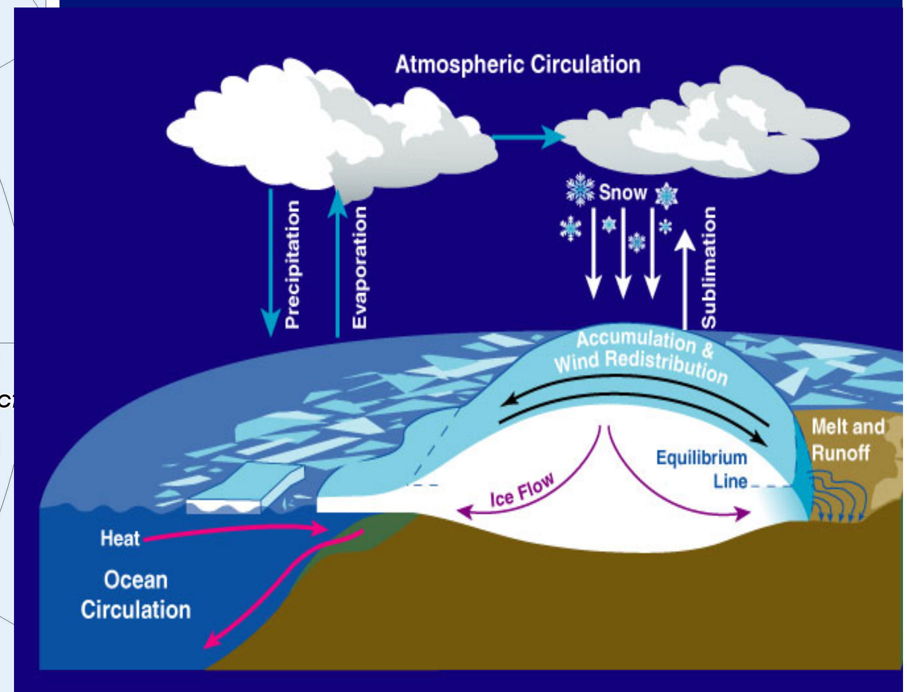


Fricker, 2008

- Byrd Glacier velocity increased by 10% for a period of 14 months from December 2005
- Speed-up started within one month of initiation of drainage of subglacial lake upstream (1.7 km^3 water)
- First evidence of direct link between subglacial floods and ice dynamics
- Few repeat velocity measurements available for ICESat period (2003–08); no other links yet found

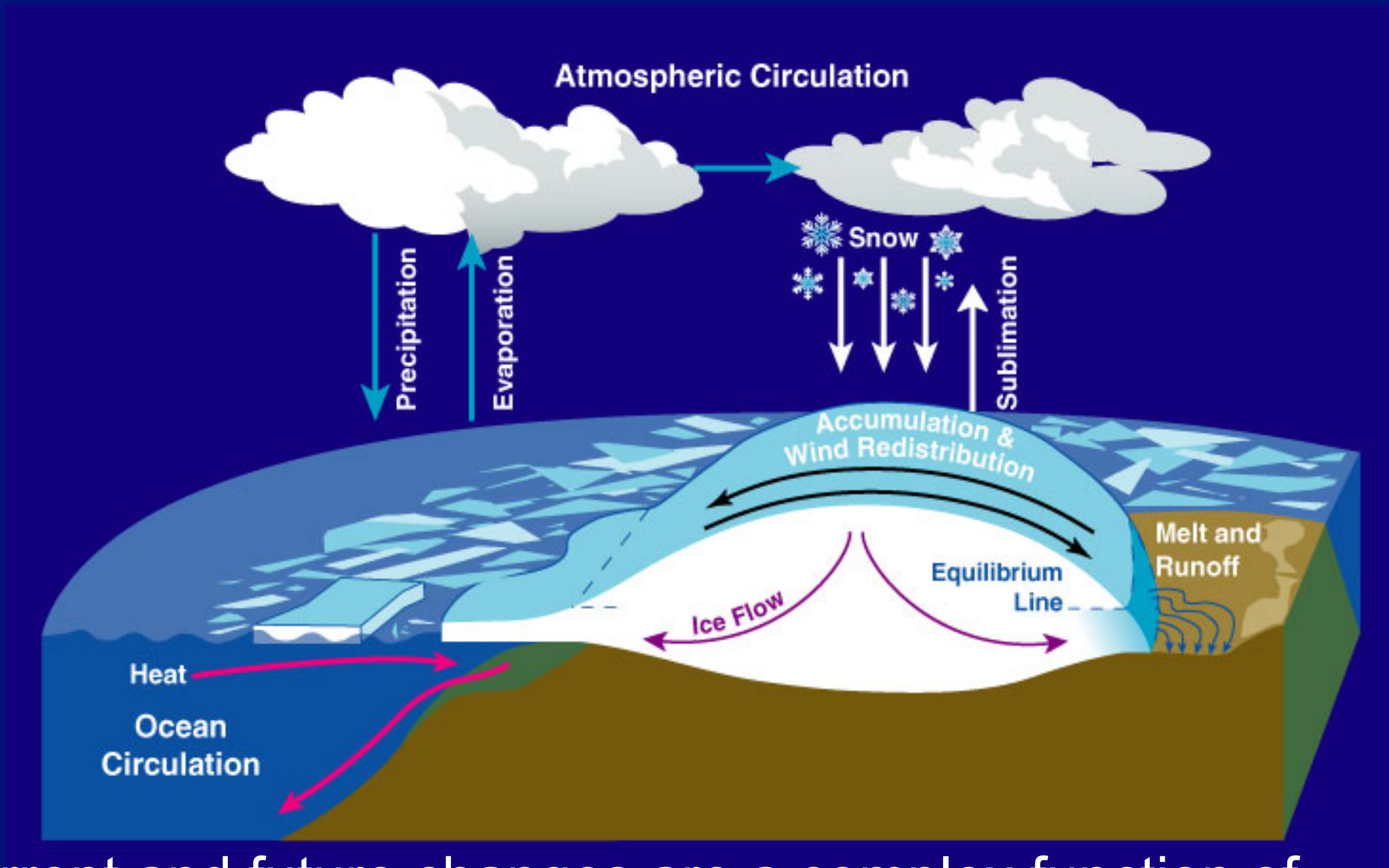
Antarctic subglacial water





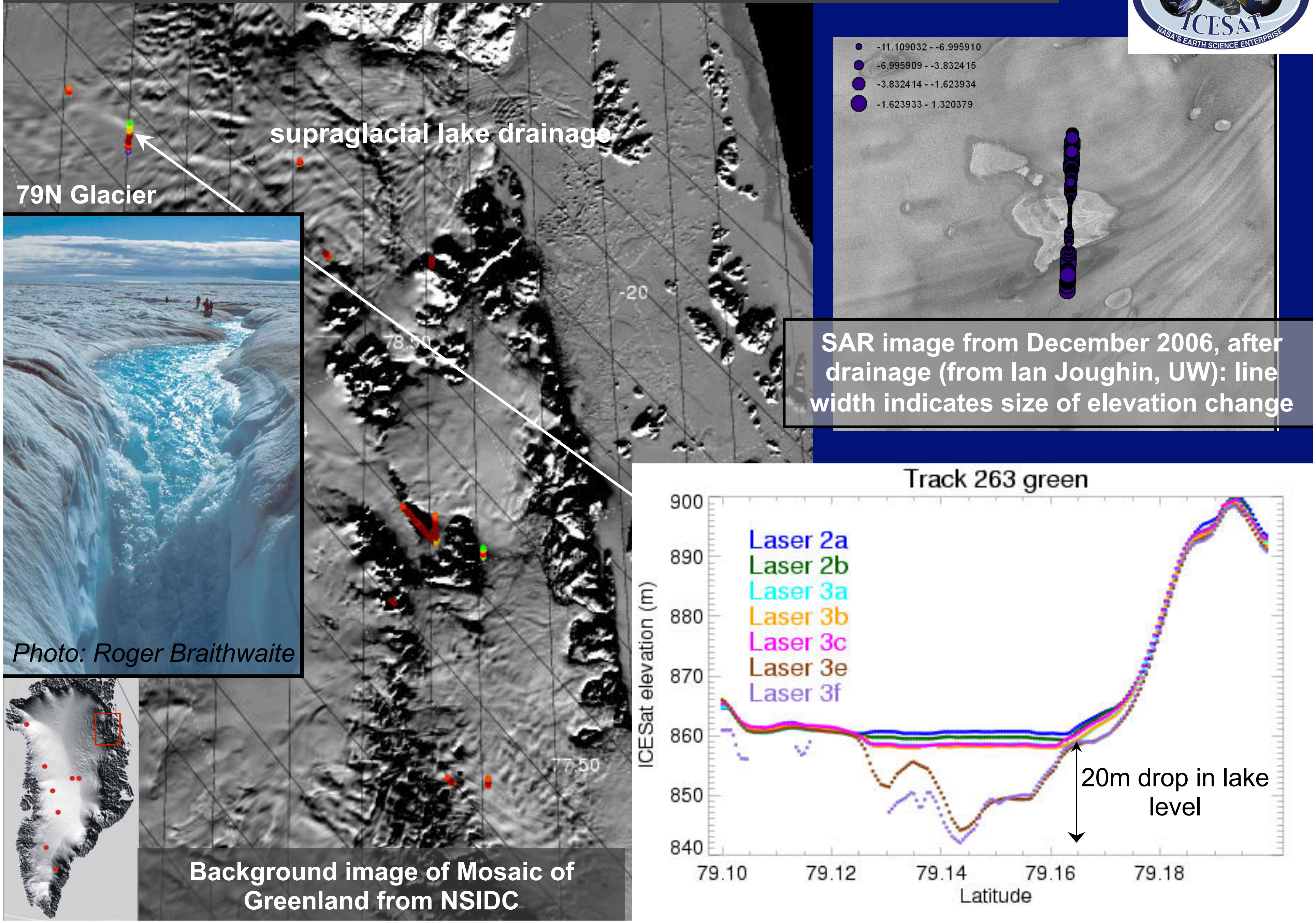
- Knowledge of subglacial water movement is fundamental to our understanding of ice stream dynamics and critical to predicting future behaviour and sea-level contribution

Antarctic Ice Sheet Mass Balance

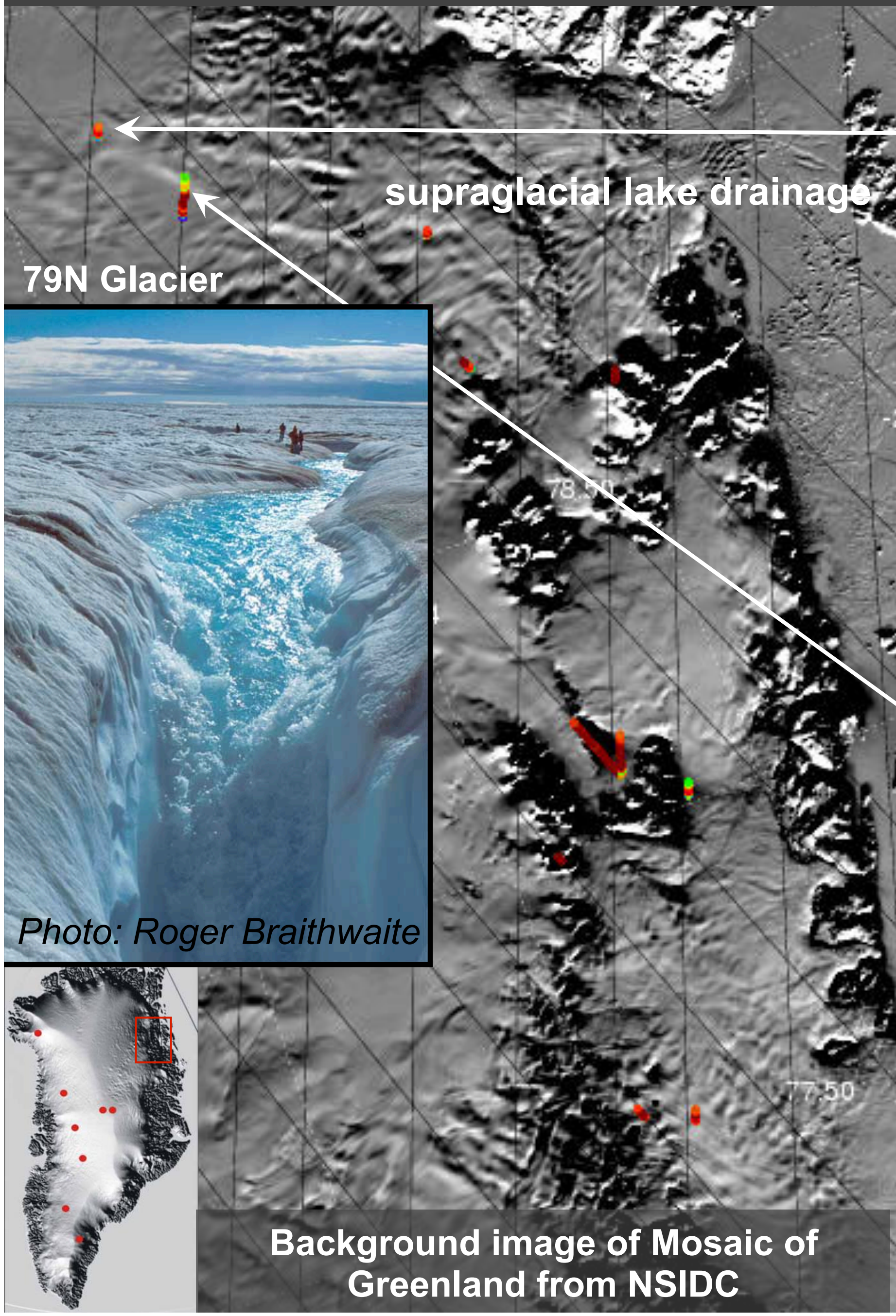


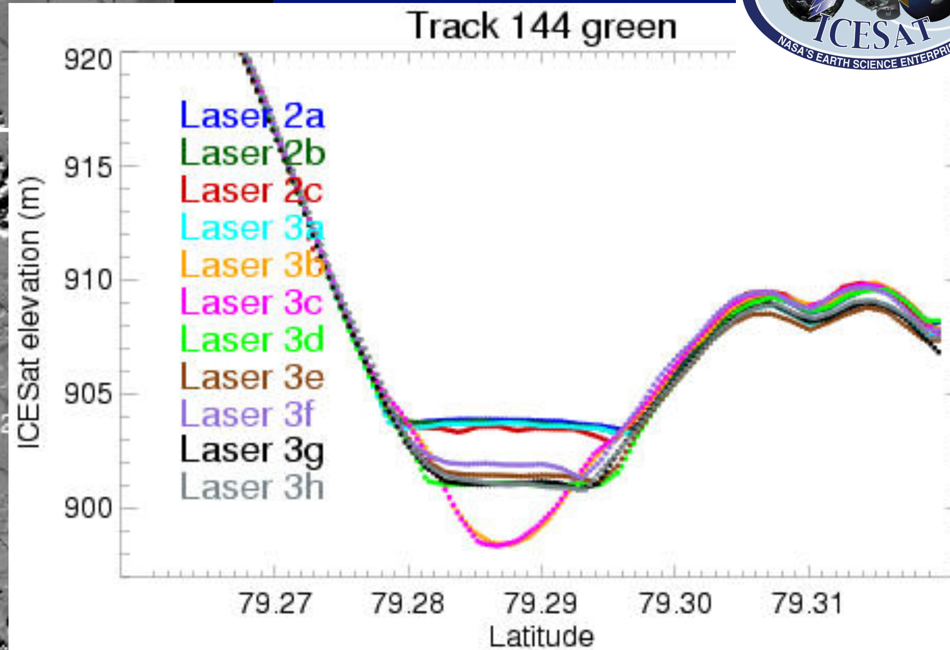
- Current and future changes are a complex function of accumulation and melting as well as dynamic ice sheet behaviour
- Predicting the future requires careful incorporation of subglacial water processes into ice sheet models

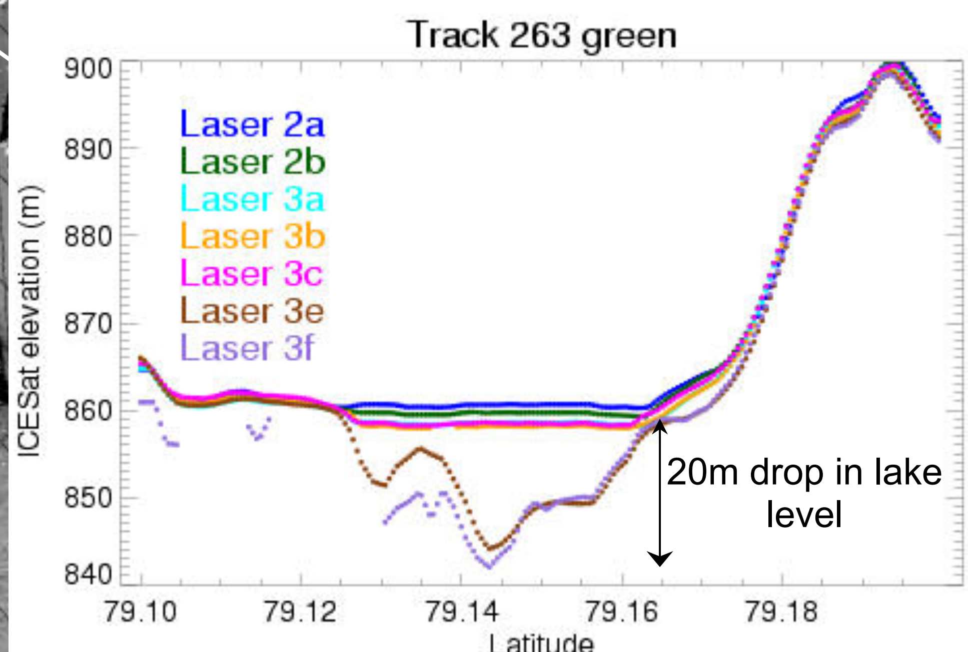
Preliminary Results: Northeastern Greenland



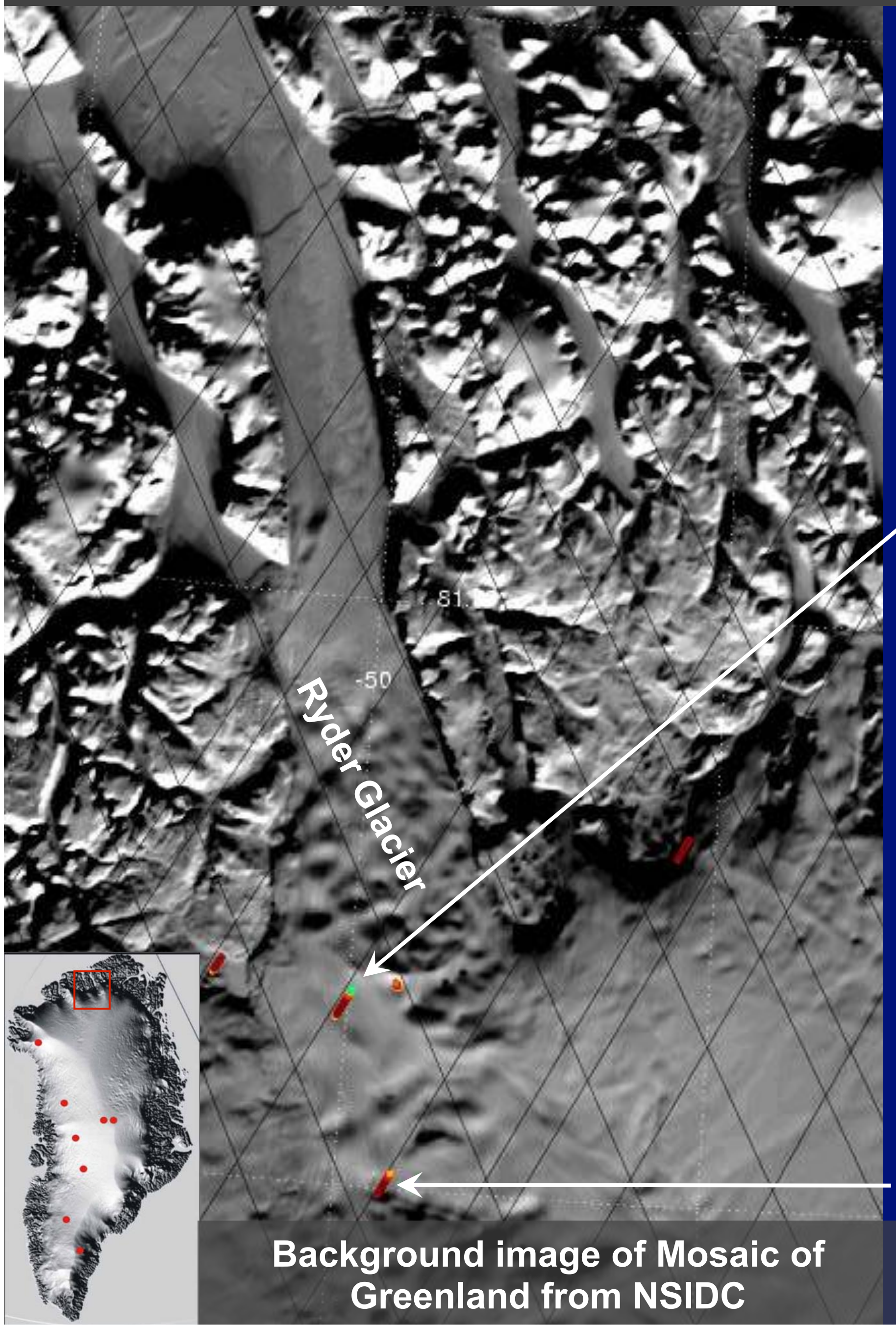
Preliminary Results: Northeastern Greenland



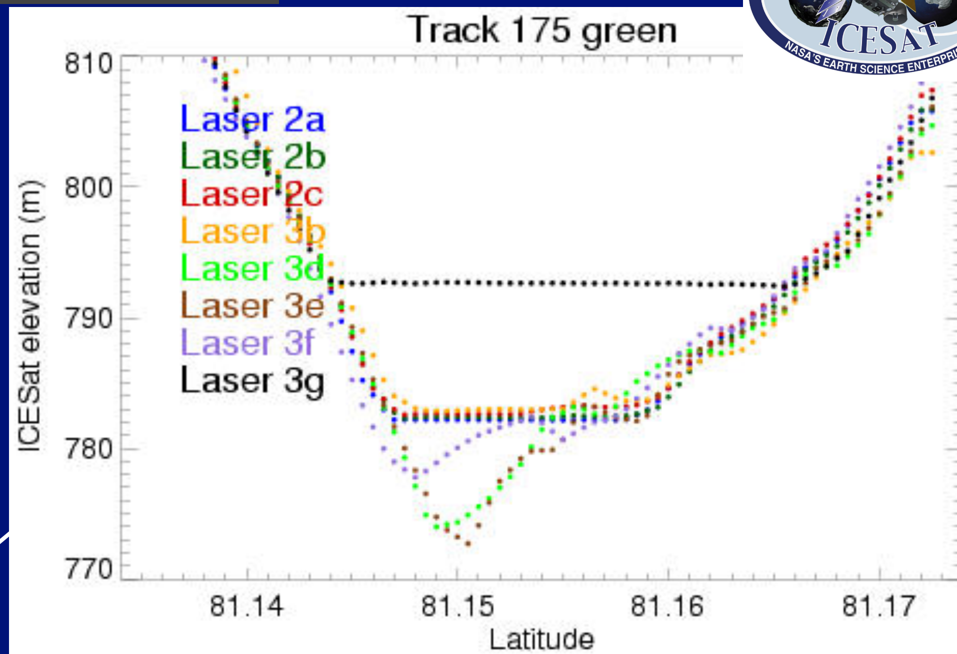


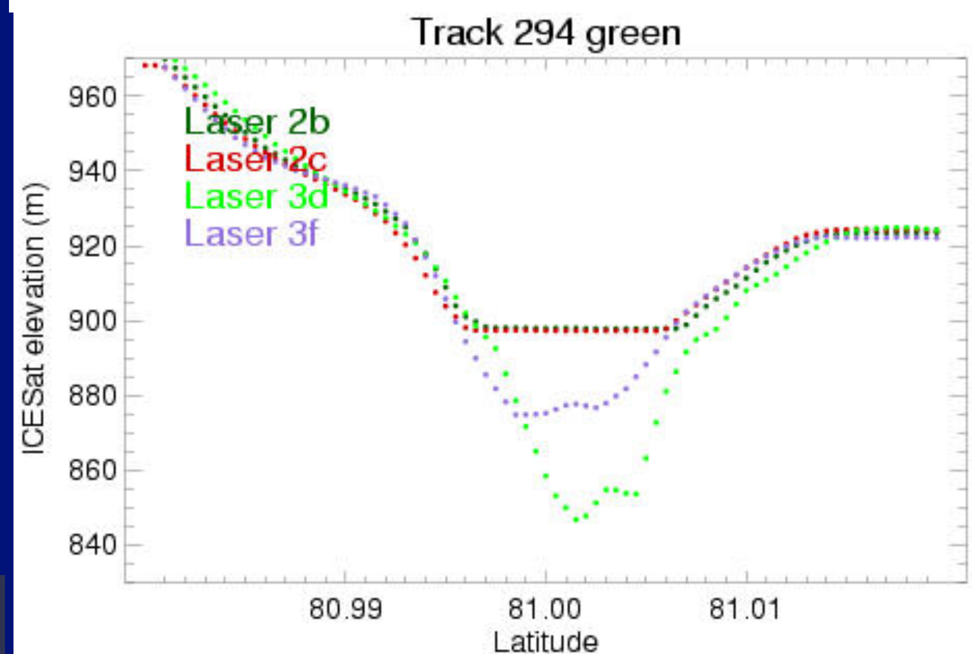


Northern Greenland: Ryder Glacier

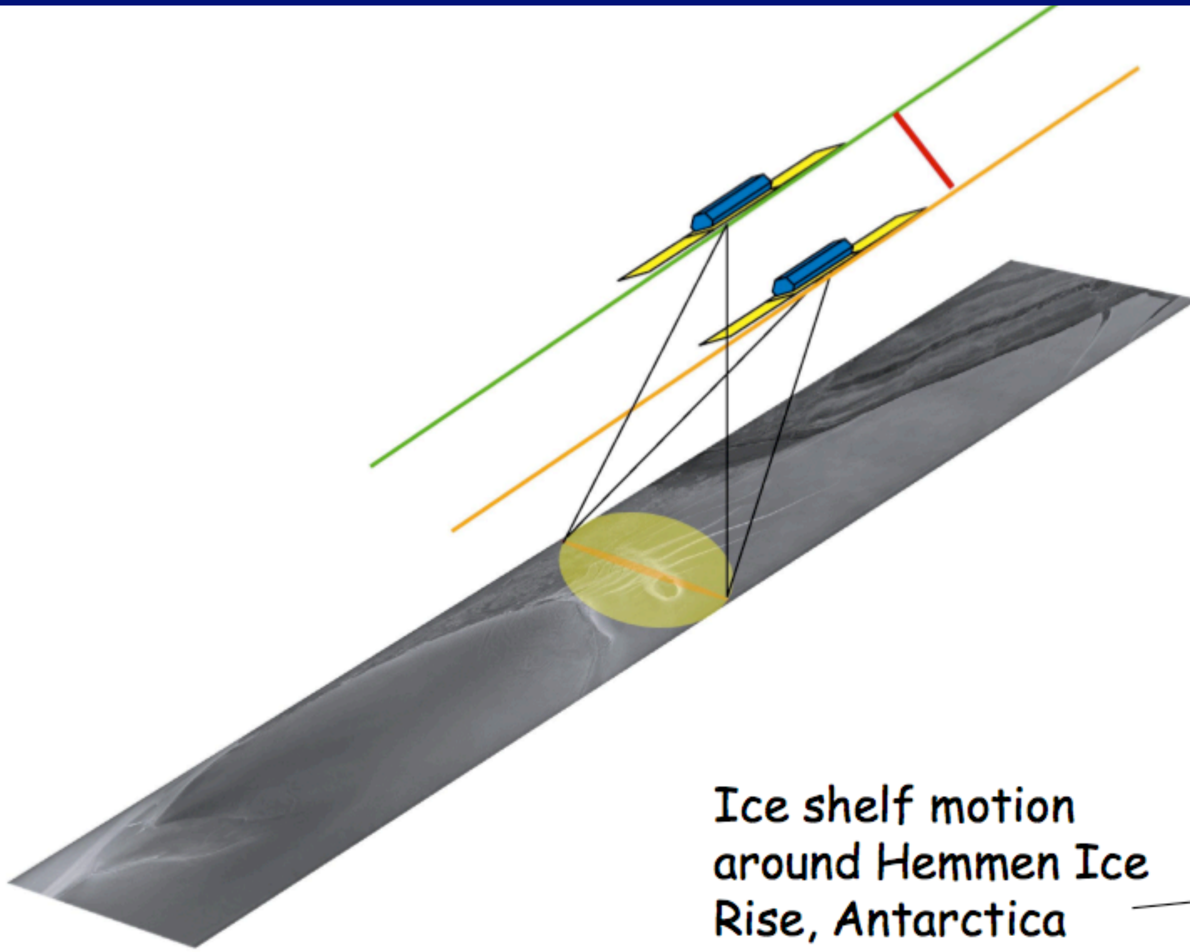


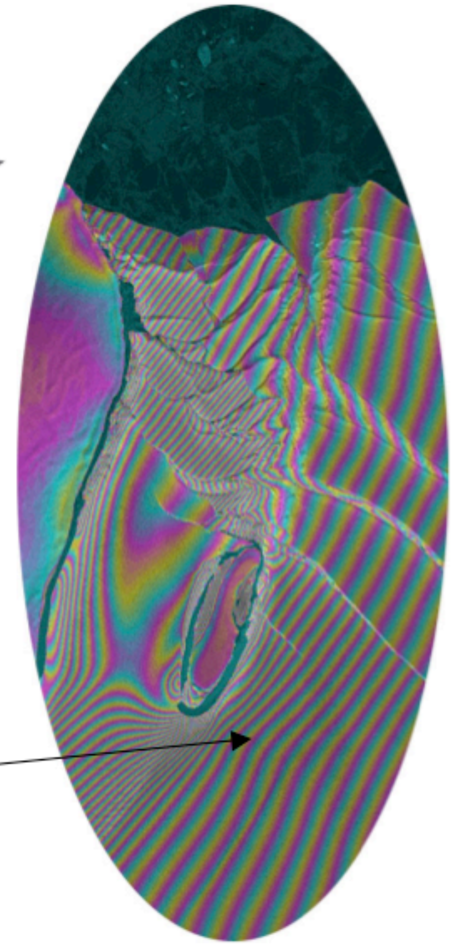
Background image of Mosaic of Greenland from NSIDC





InSAR over ice shef rifts





Ice shelf motion around Hemmen Ice Rise, Antarctica

Images can be combined to form an interferogram that is sensitive to both topography and motion