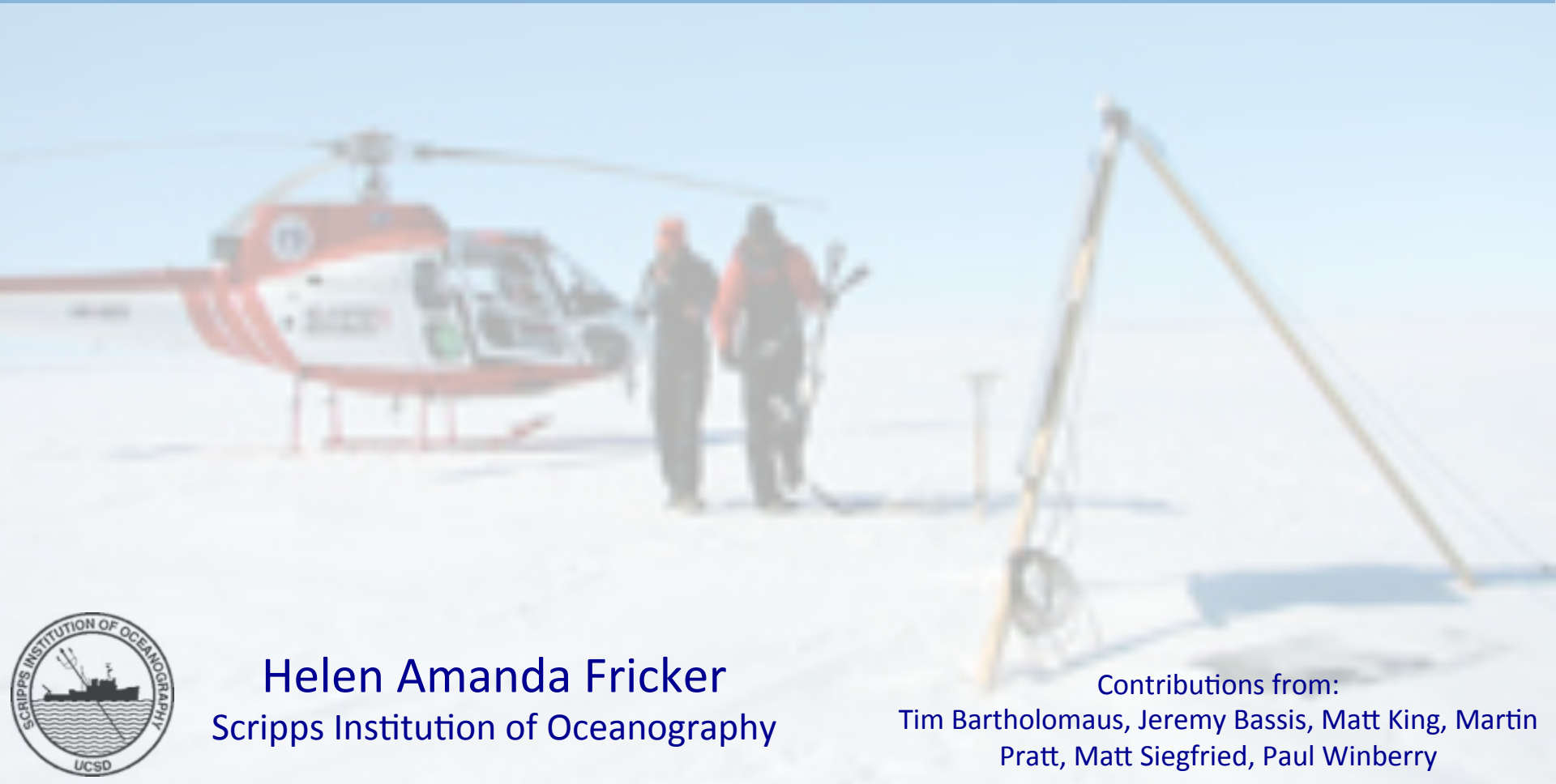
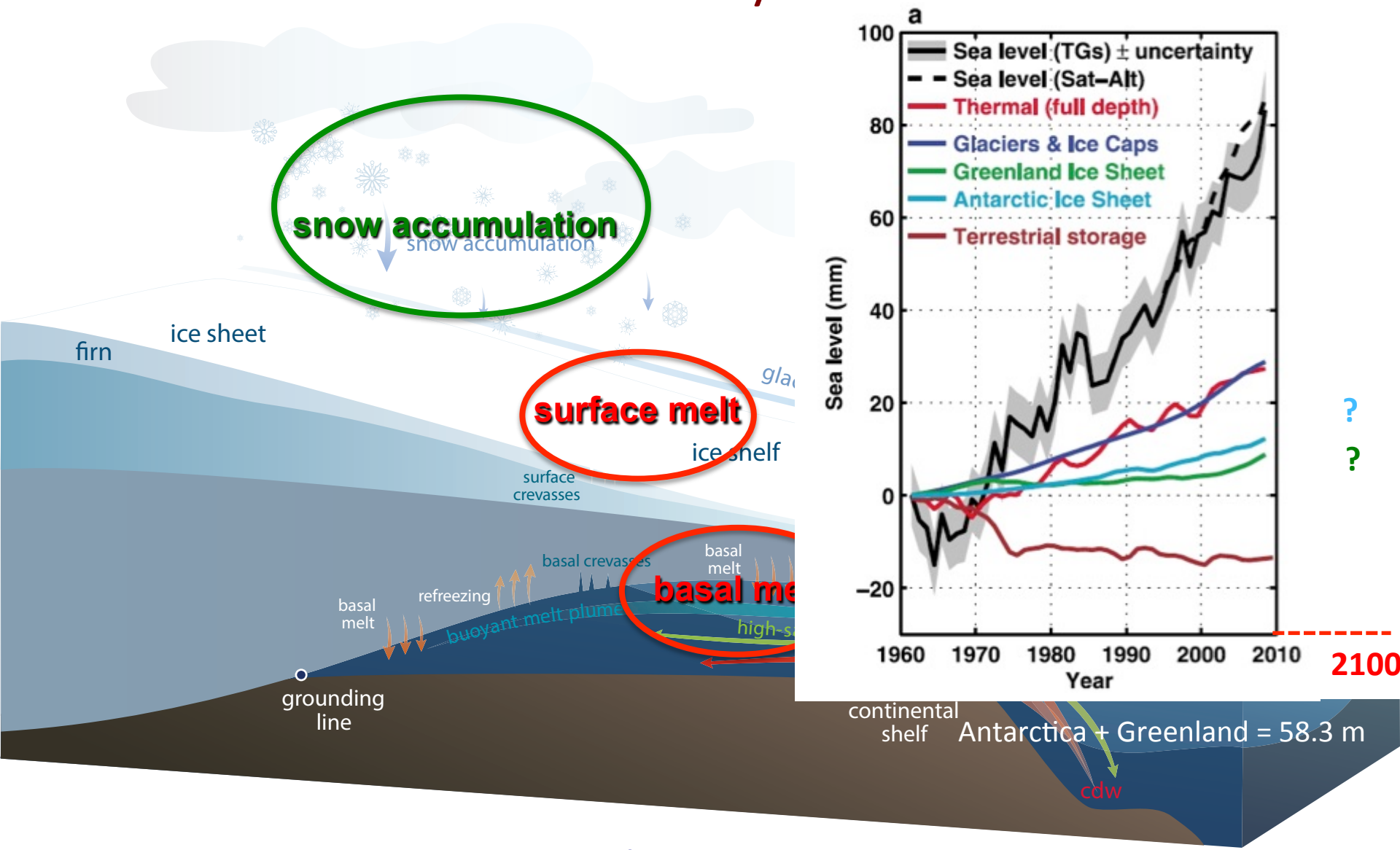
Contributions of geodesy and seismology to glaciology



Helen Amanda Fricker
Scripps Institution of Oceanography

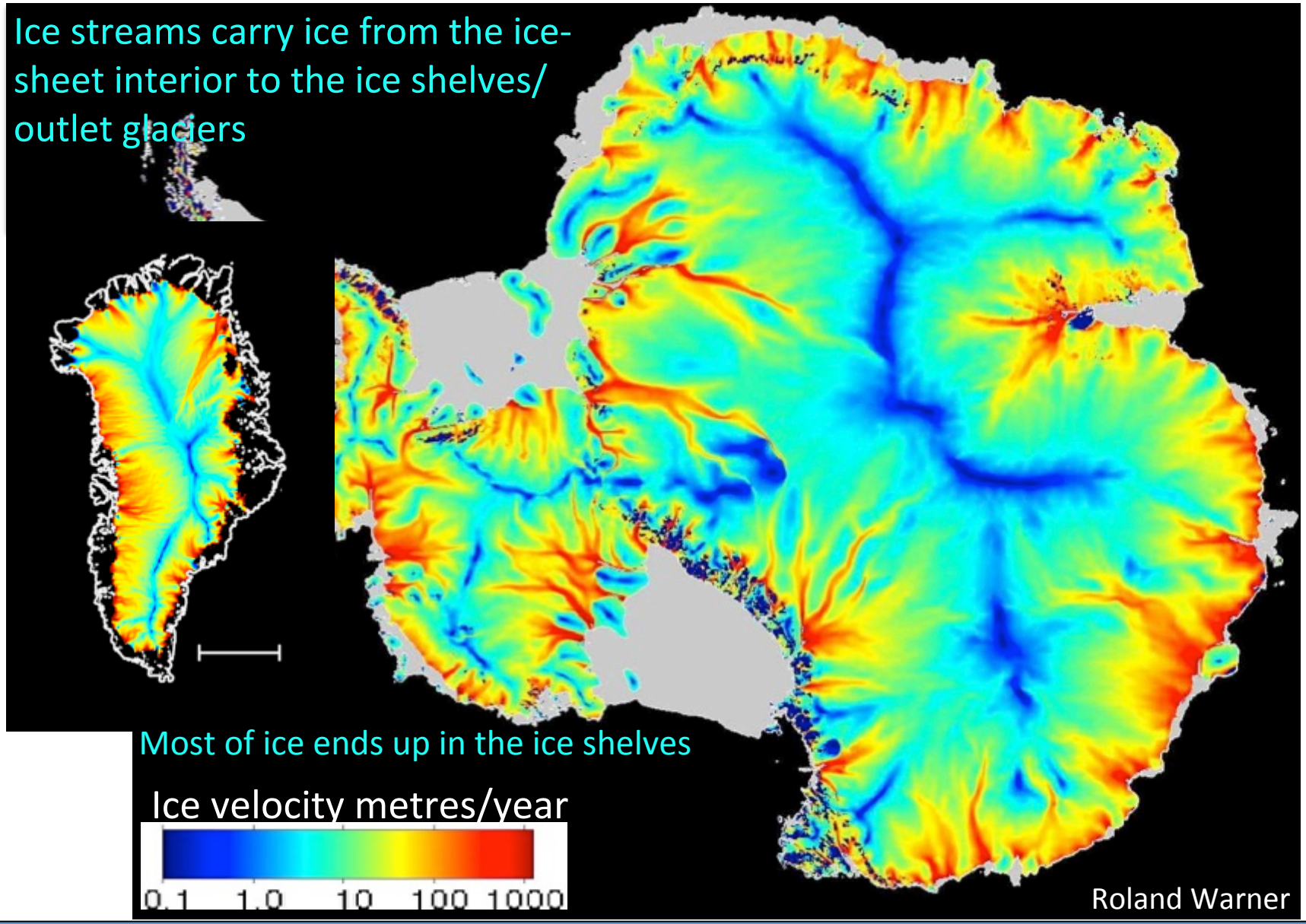
Contributions from:
Tim Bartholomaus, Jeremy Bassis, Matt King, Martin Pratt, Matt Siegfried, Paul Winberry

Ice sheet systems



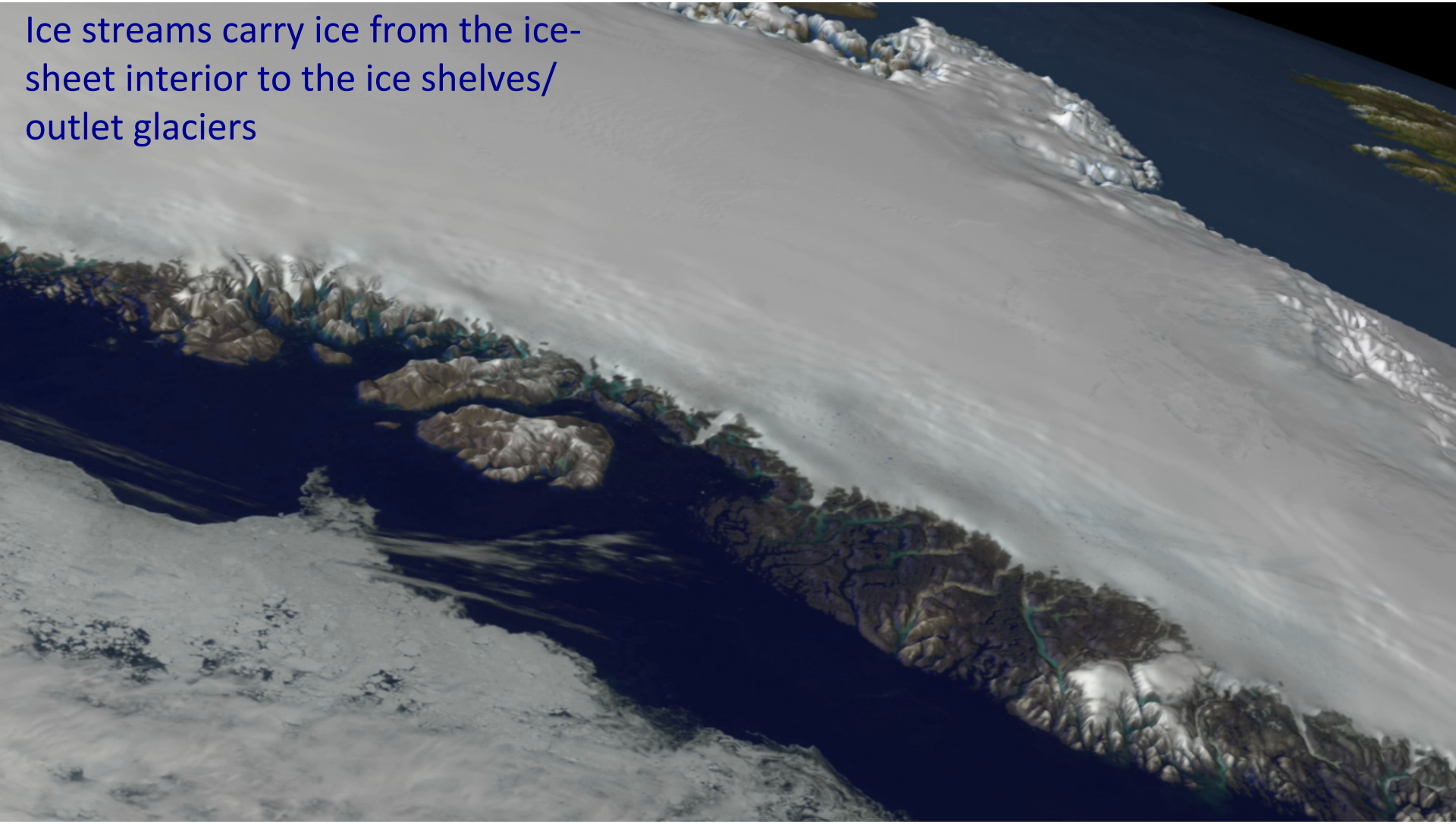
As global air temperatures continue to rise, all of these components – accumulation, melting and flow rates – are expected to increase.

The role of ice streams



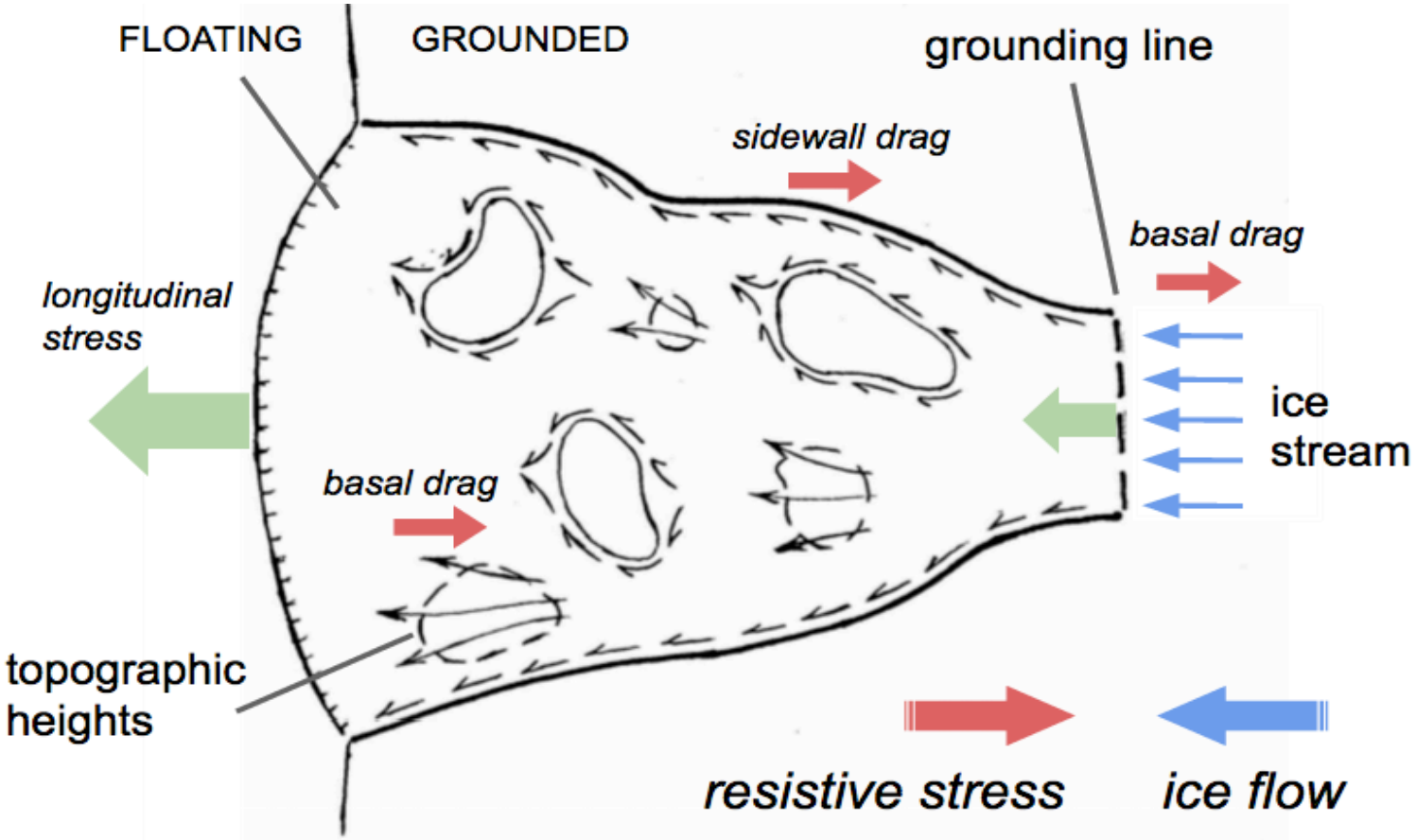
The role of ice streams

Ice streams carry ice from the ice-sheet interior to the ice shelves/ outlet glaciers



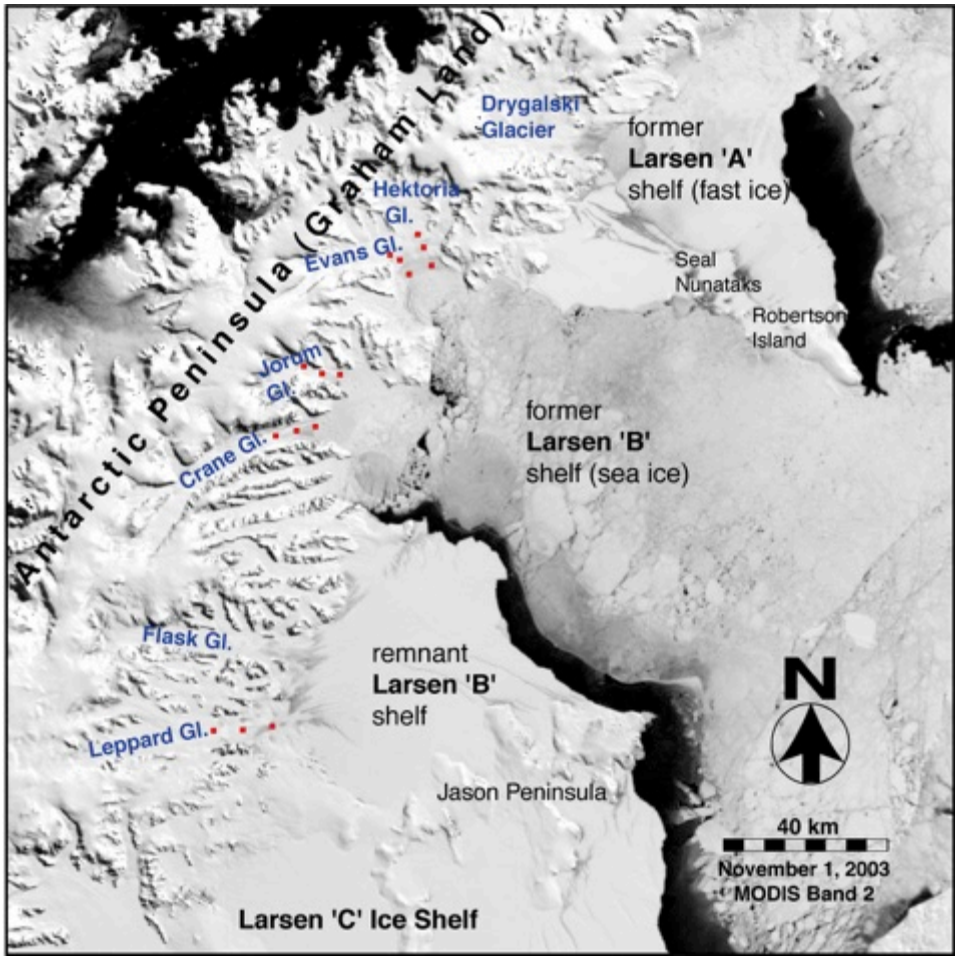
The role of ice shelves

Shrinking of ice shelves does not affect sea-level but ice shelves restrain the flow of the grounded ice through "buttressing"



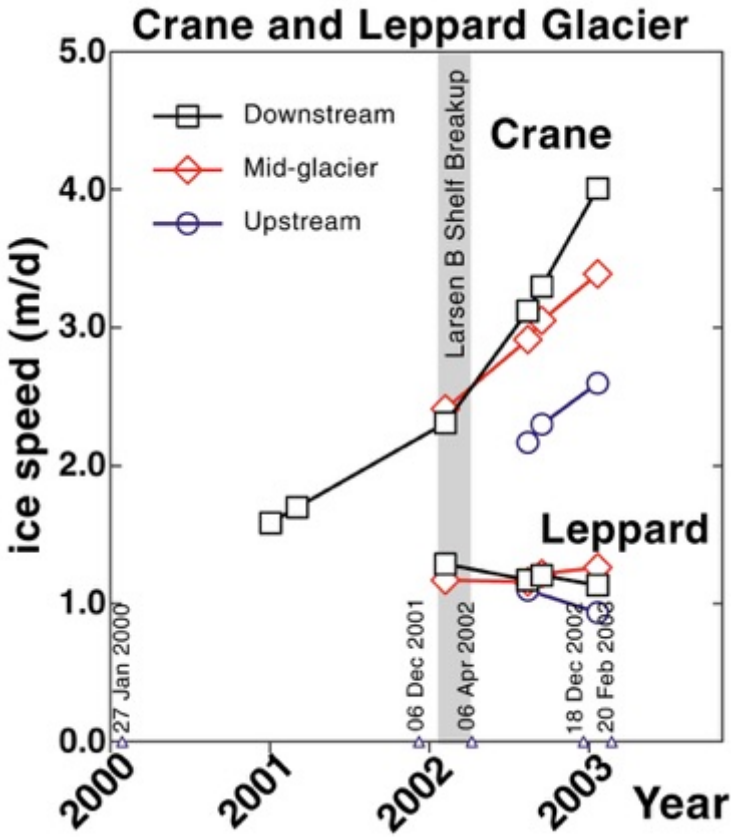
Plan view of an ice shelf

The role of ice shelves



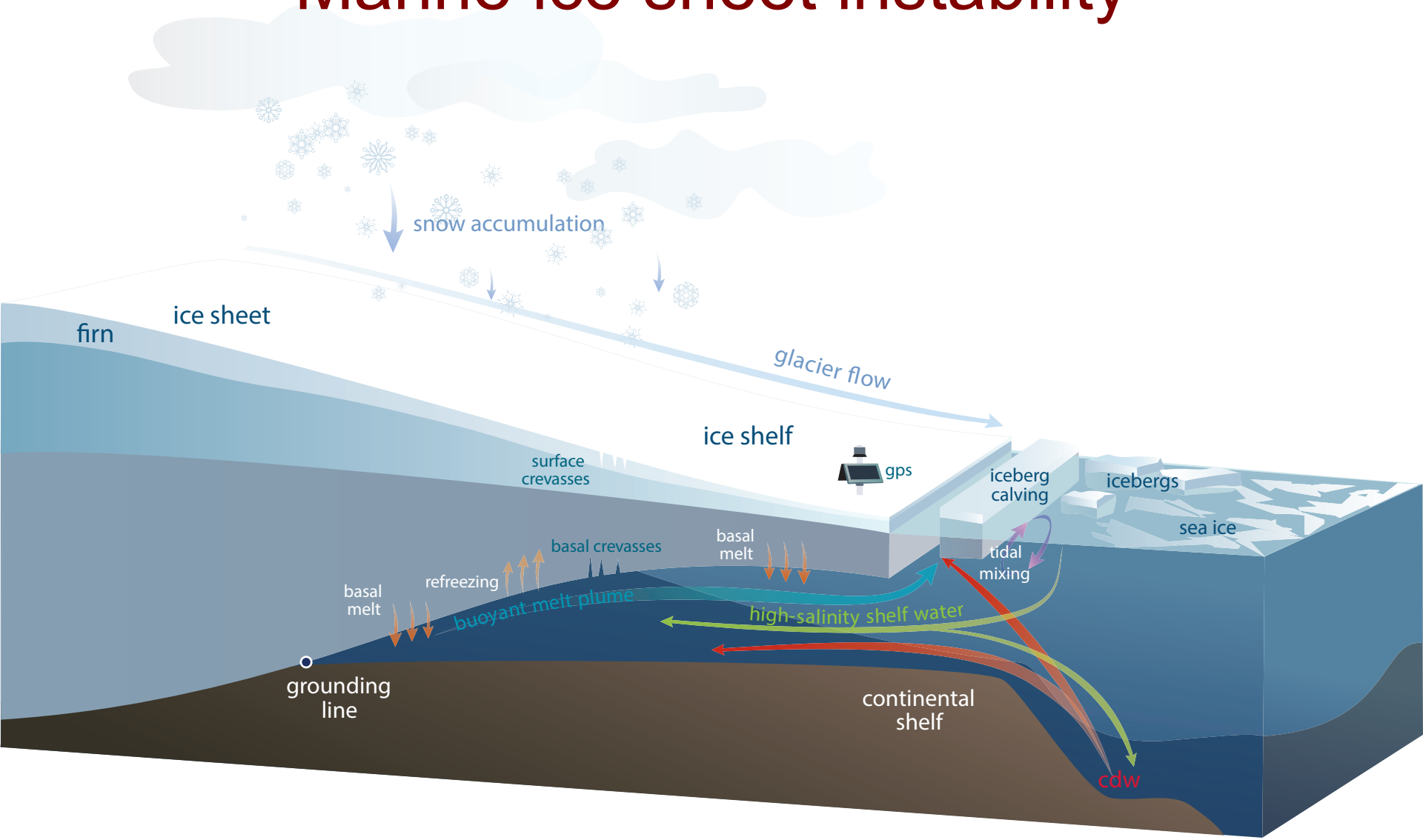
Removal of the northern 2/3 of the Larsen B had an instant effect on the speed of glaciers flowing into it

Acceleration increase occurred for all glaciers feeding the catastrophic breakup area (e.g. Crane)



No acceleration change was observed in glaciers south of the total break-up zone (e.g. Leppard).

Marine ice sheet instability



Instability due to grounding line being on reverse bedrock slope

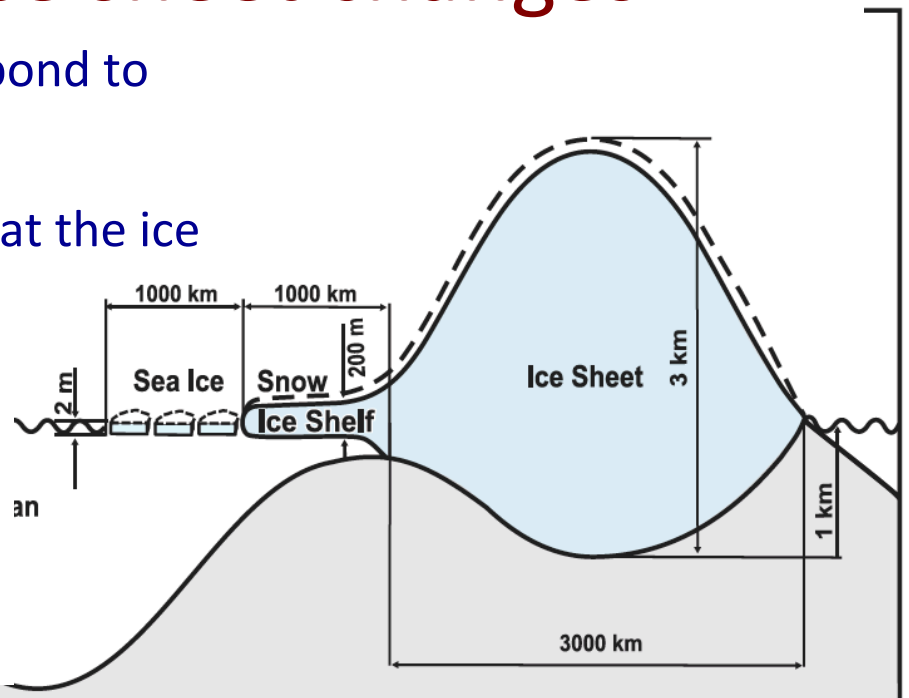
Time scales for ice sheet changes

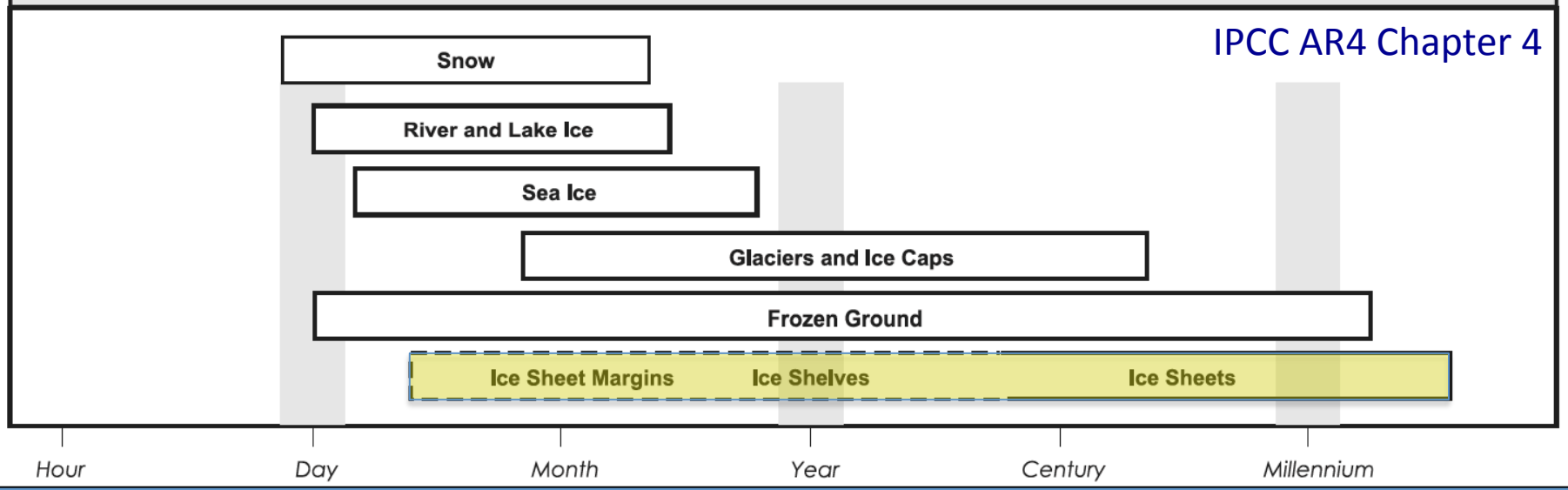
Ice sheets are vast and cold, and mainly respond to change on long time scales

Recently changes are occurring much faster at the ice margins & ice shelves

Both horizontal & vertical signals important

- *Horizontal:* ice sheet flow
- *Vertical:* ice sheet mass balance, tides, subglacial lakes



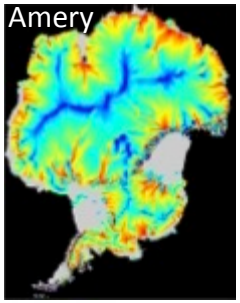


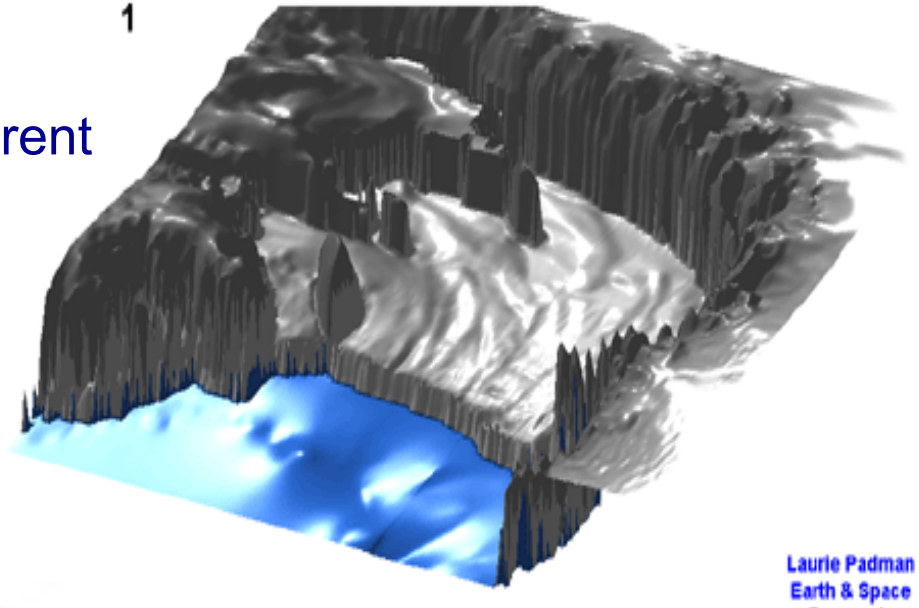
IPCC AR4 Chapter 4

Ice shelf tidal motion

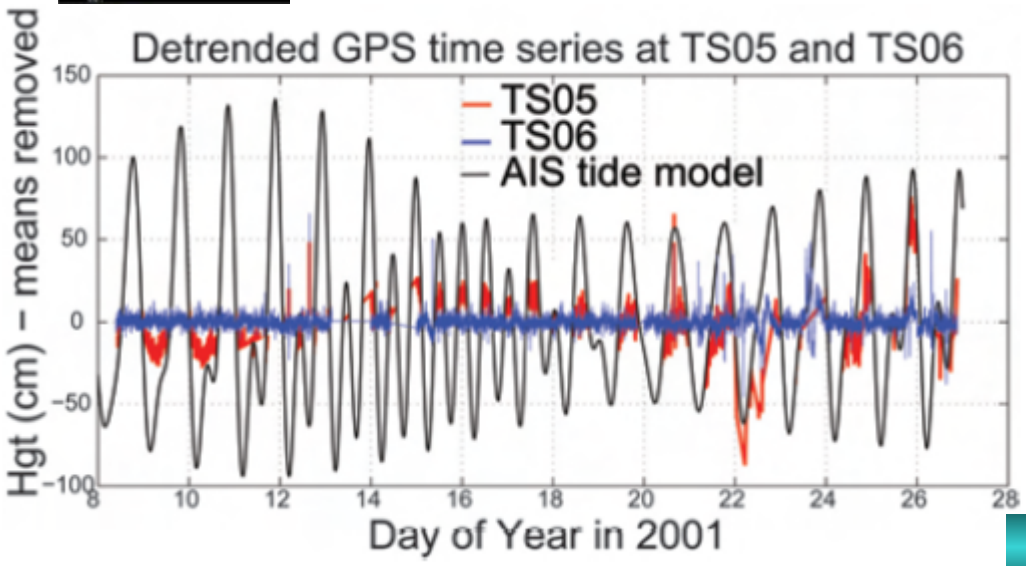
Ice shelves float on the ocean in hydrostatic equilibrium & move with tides

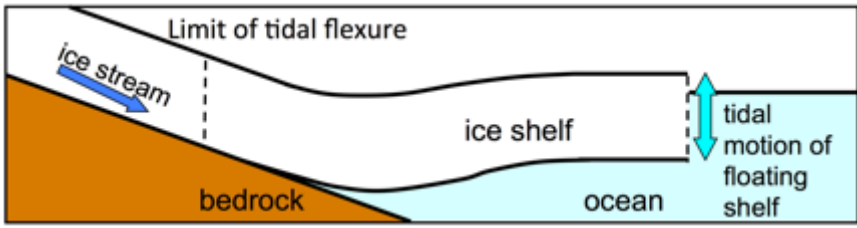
GPS height measurements made at different tidal states show this vertical motion





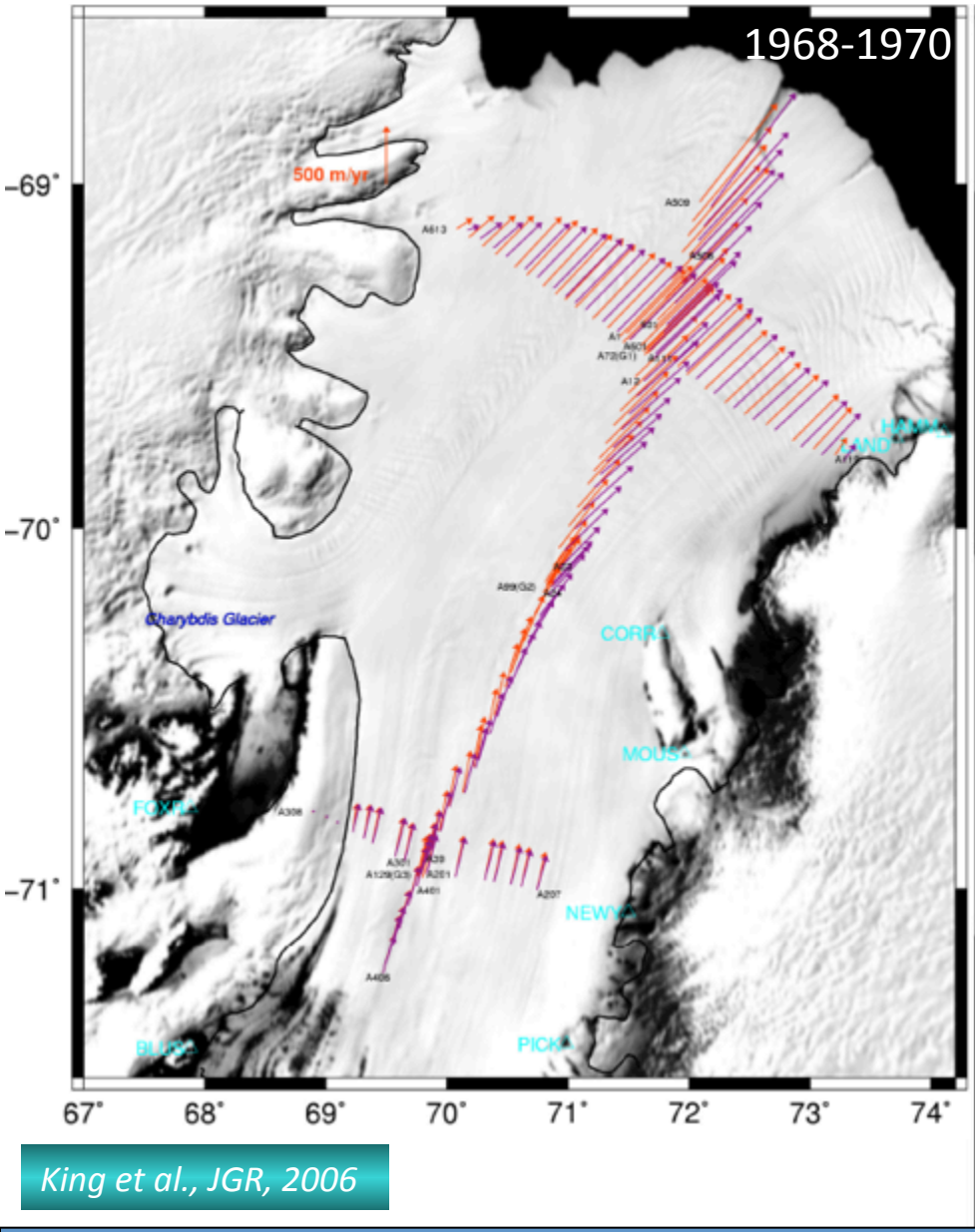
Laurie Padman
Earth & Space Research

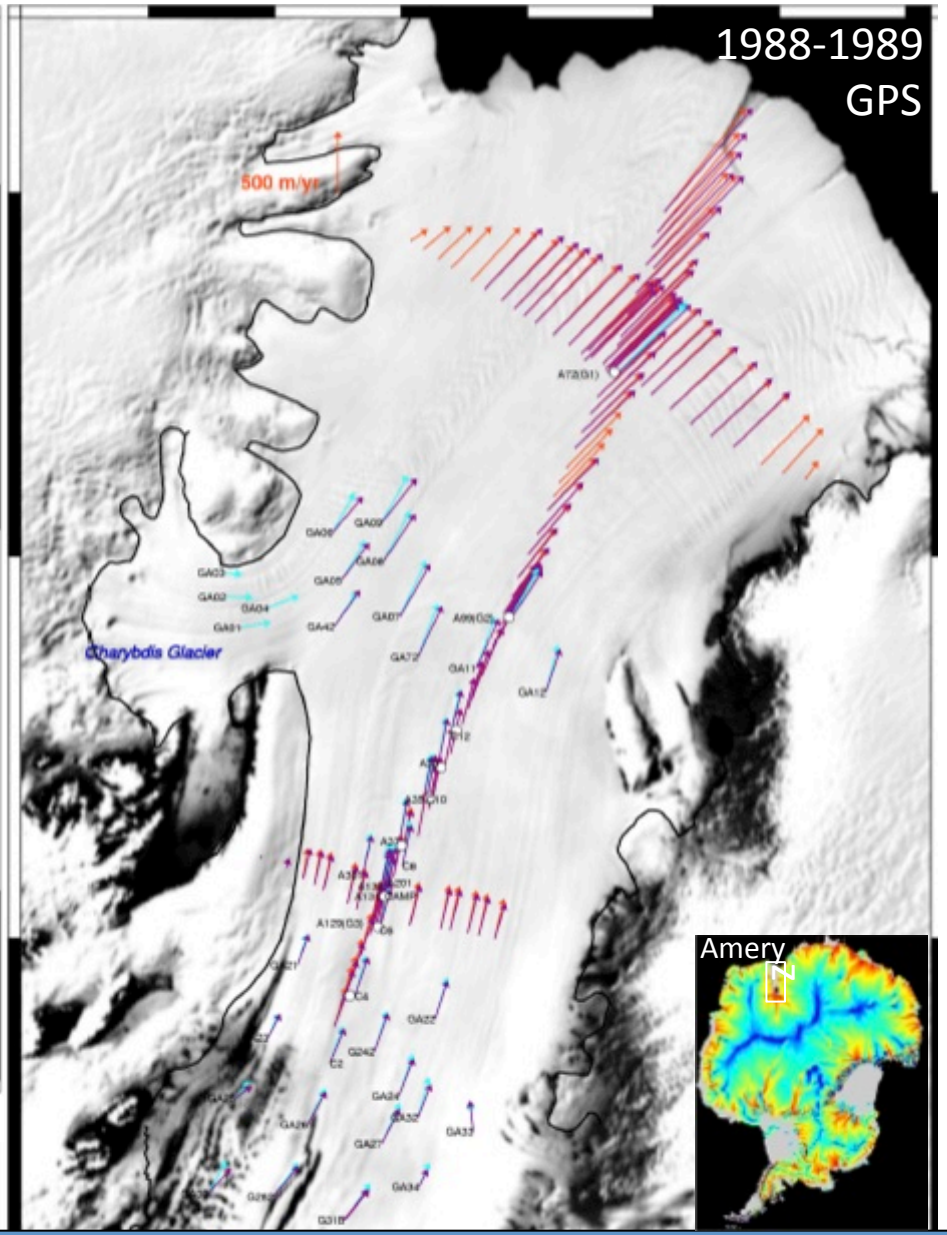




Fricker et al., 2009

Steady-state ice sheet motion (20 years)

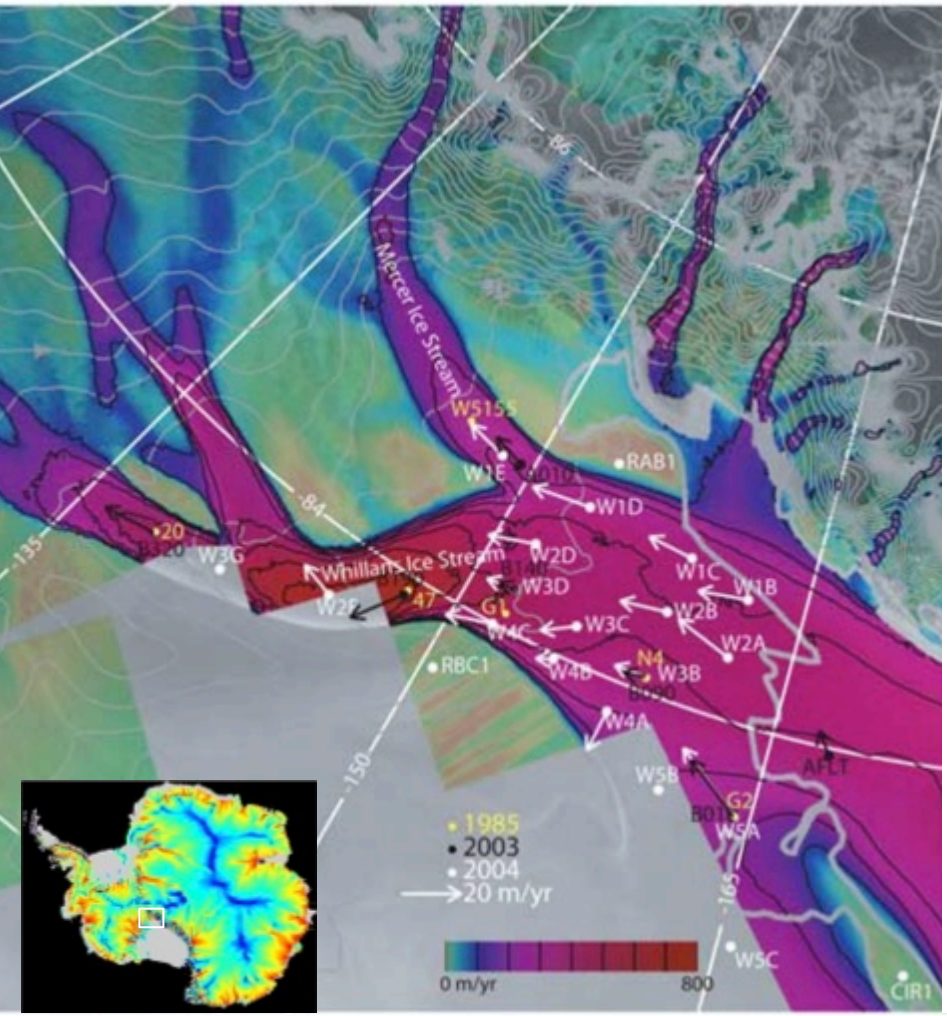


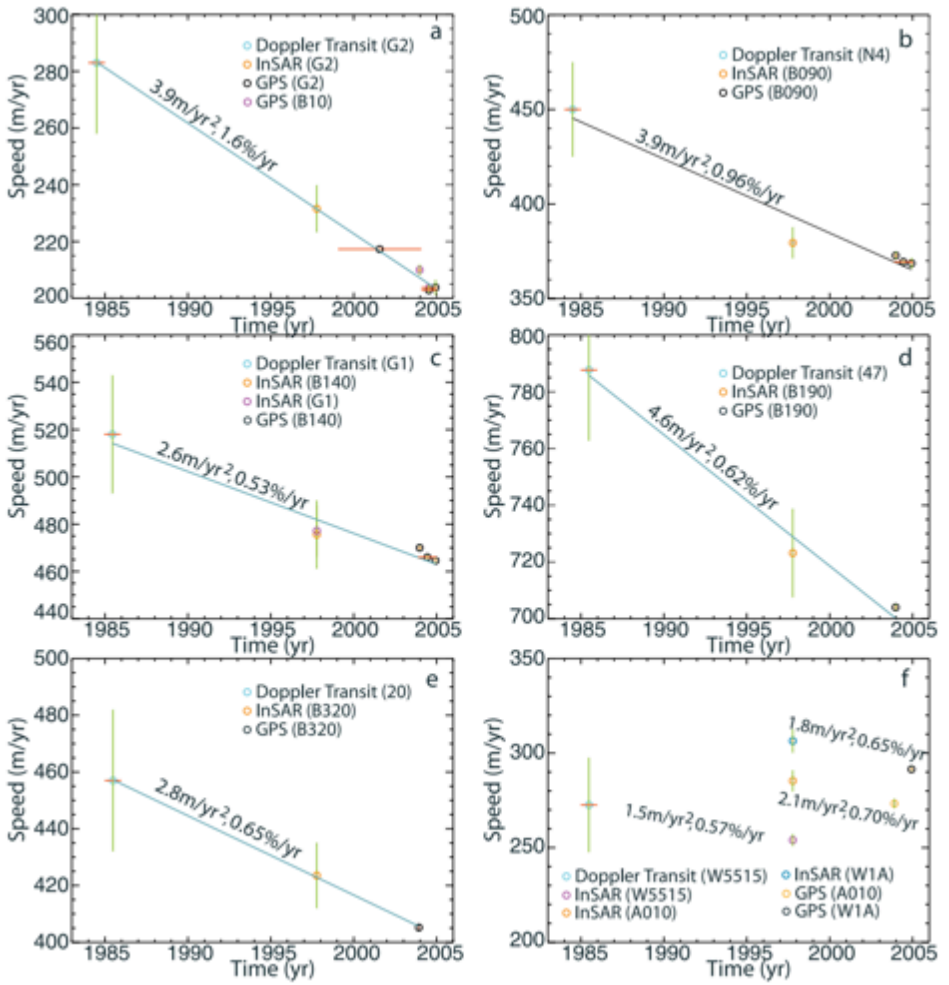


King et al., JGR, 2006

Time-varying ice sheet motion

Whillans Ice Stream slowing down (1985-2005)

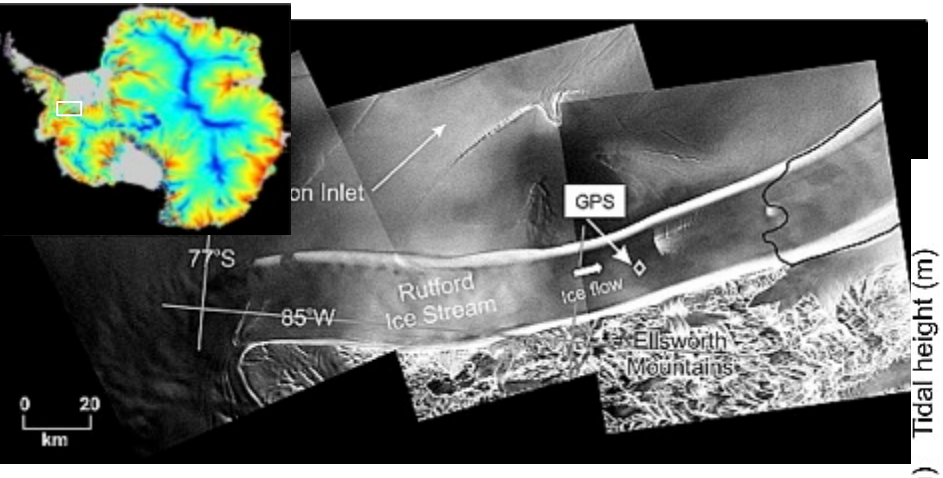


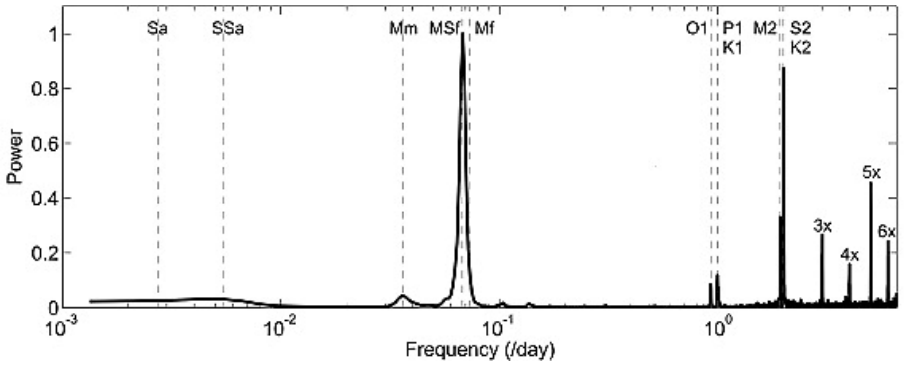


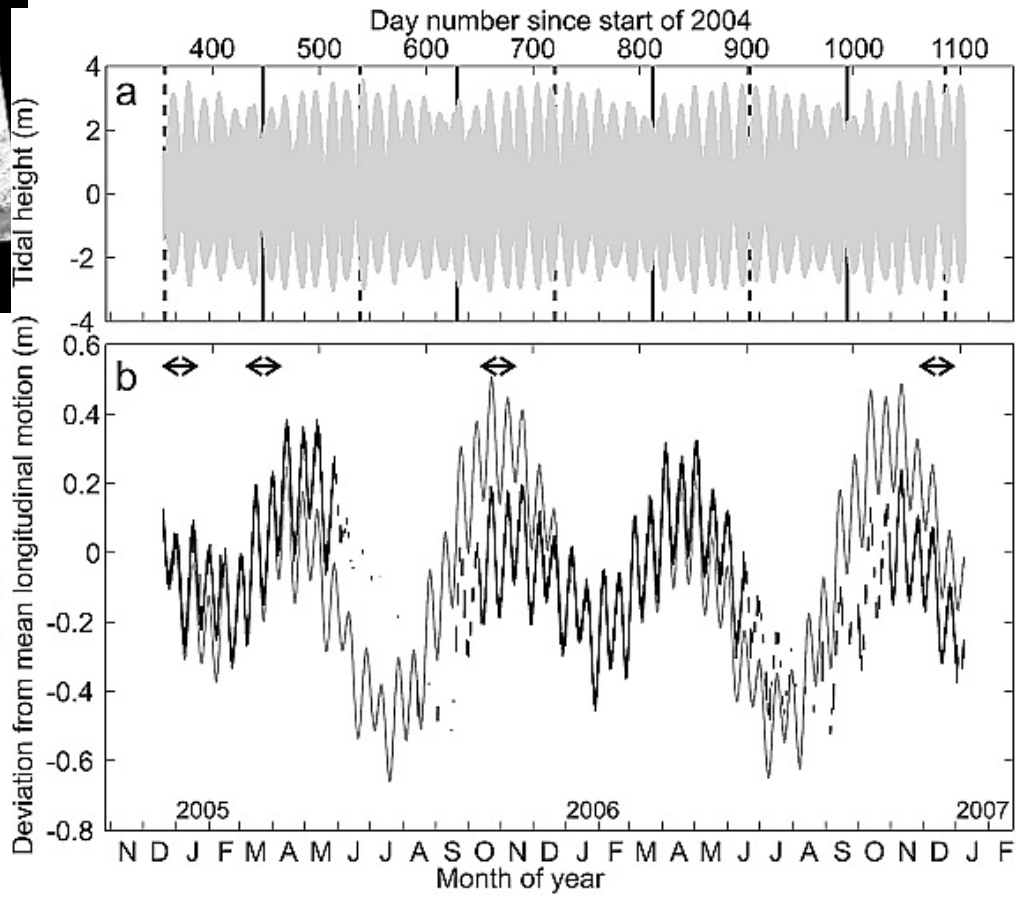
Joughin et al., GRL, 2005

Time-varying ice sheet motion

Ice flow modulated by tides at up to annual periods on Rutford Ice Stream, West Antarctica

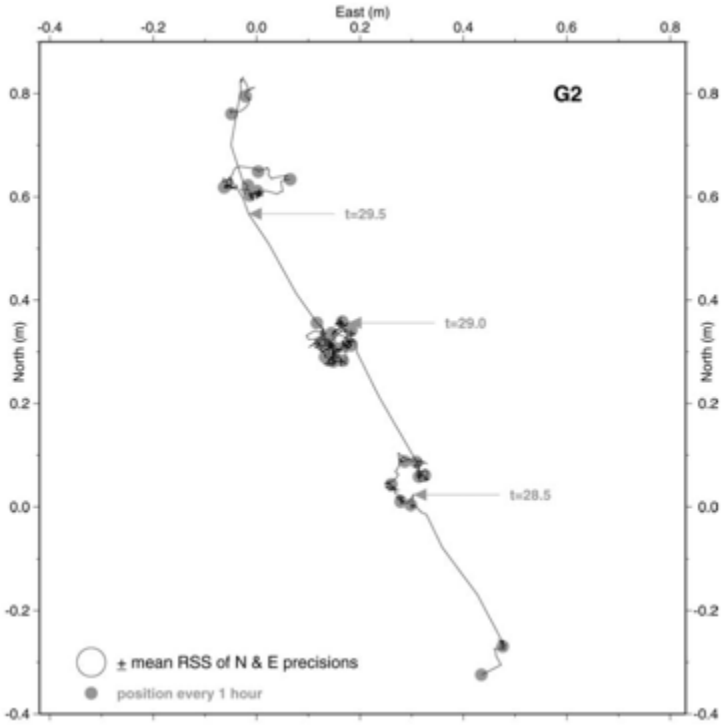






Murray et al., GRL, 2007

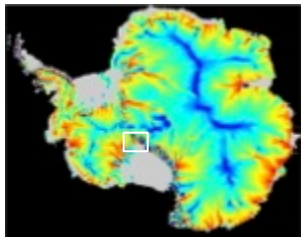
Time-varying ice sheet motion

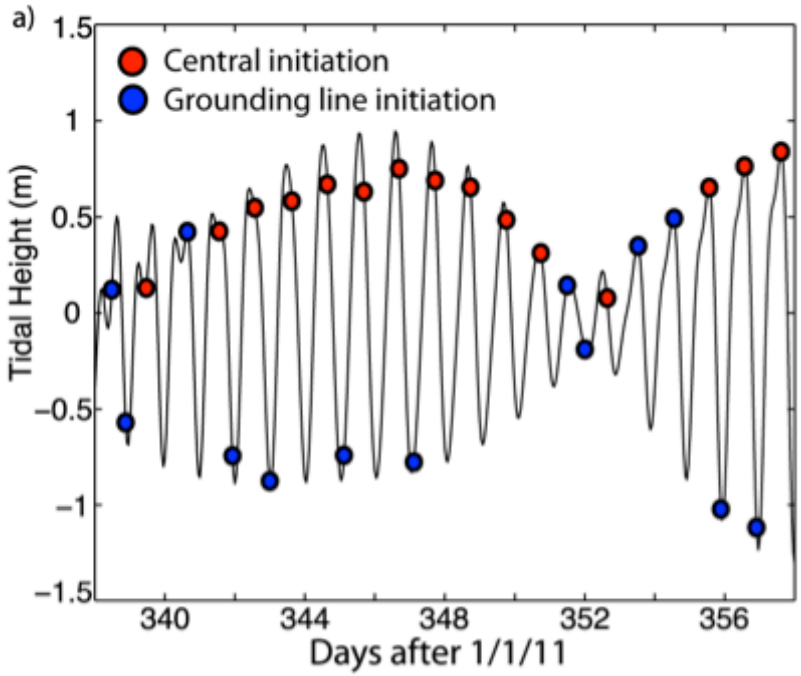


Stick–slip on the Whillans Ice Stream first observed in Jan. 1999 with GPS

Tidal modulation controls when slip events occur during spring tides

Bindschadler et al., 2002





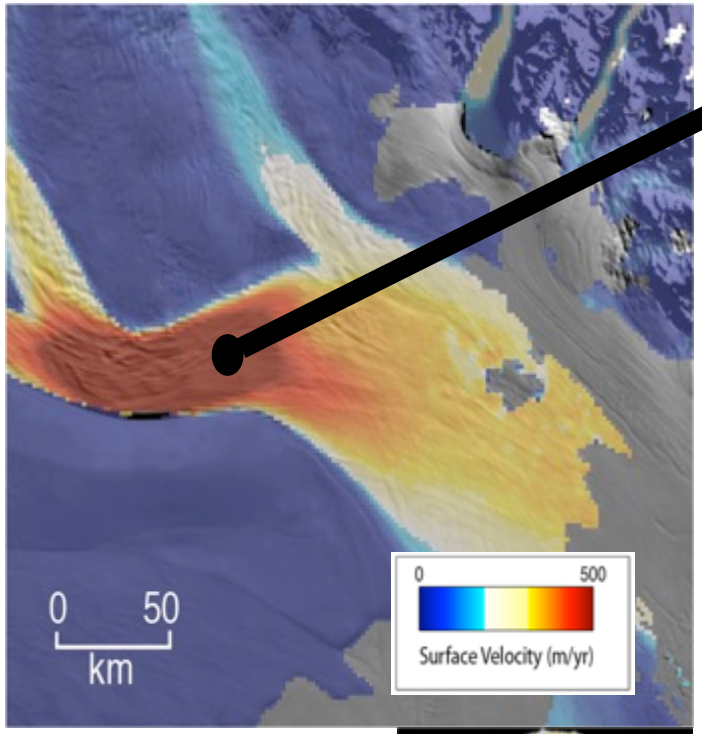
Slip events follow shortly after peak high tide, then again at low tide.

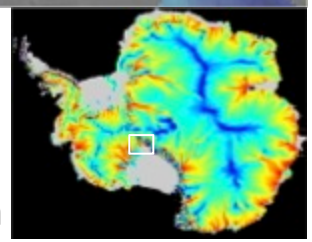
Low tide events are increasingly being 'skipped'.

Pratt et al., 2014

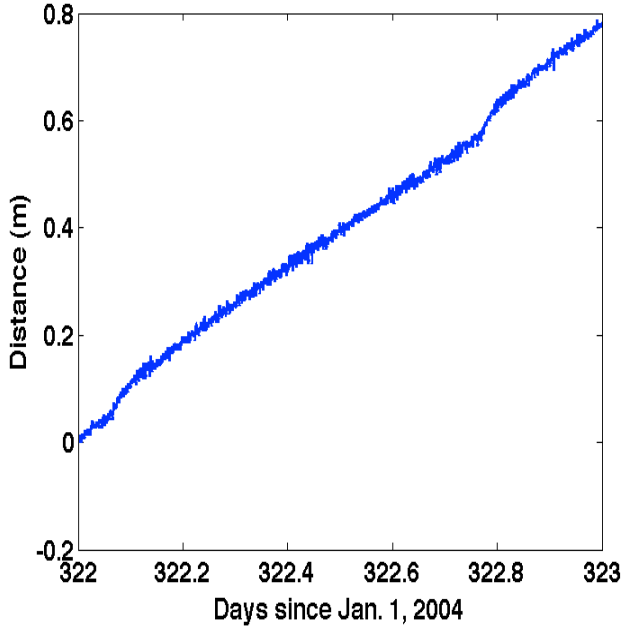
Time-varying ice sheet motion

Like faults, ice streams display a range of dynamic behavior





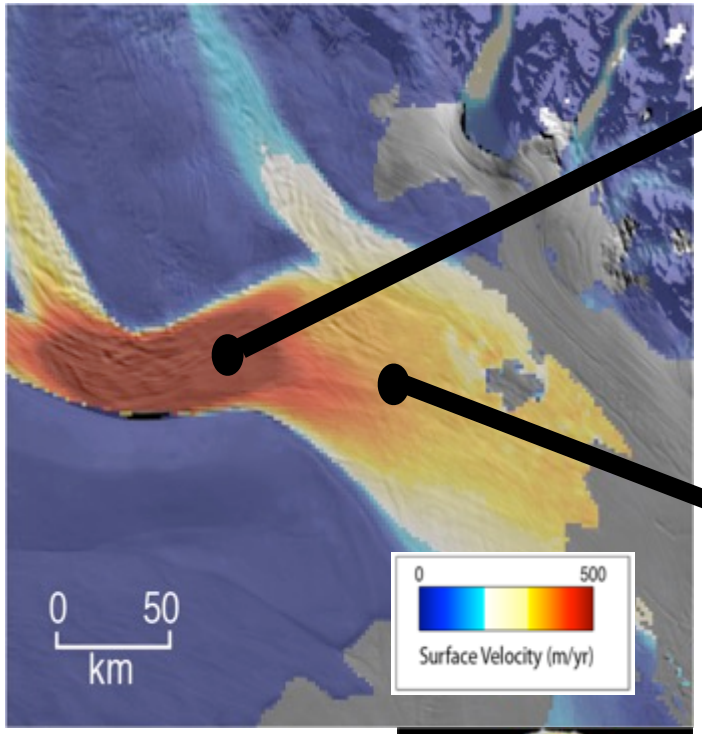
Whillans Ice Stream

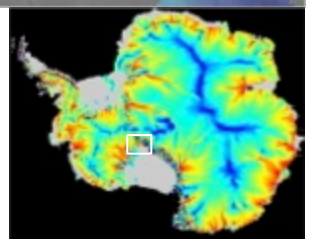


Slide from Paul Winberry

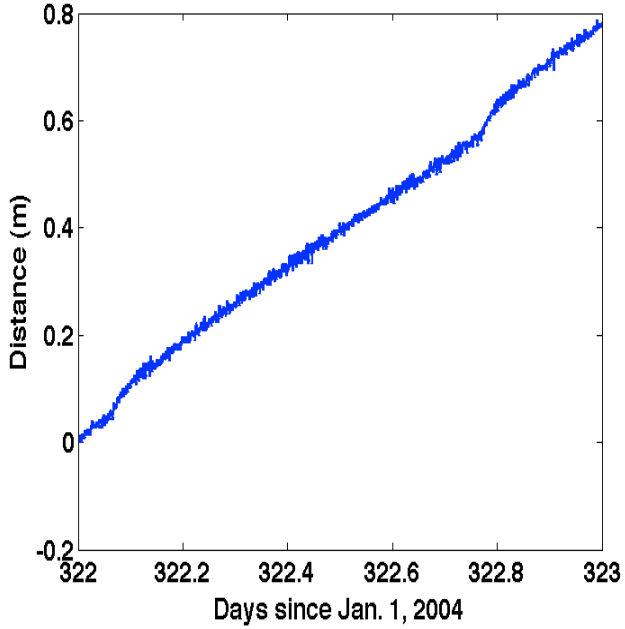
Time-varying ice sheet motion

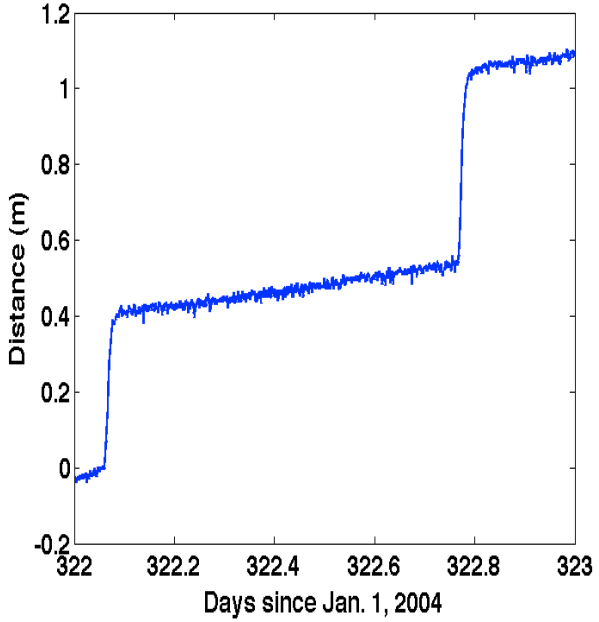
Like faults, ice streams display a range of dynamic behavior





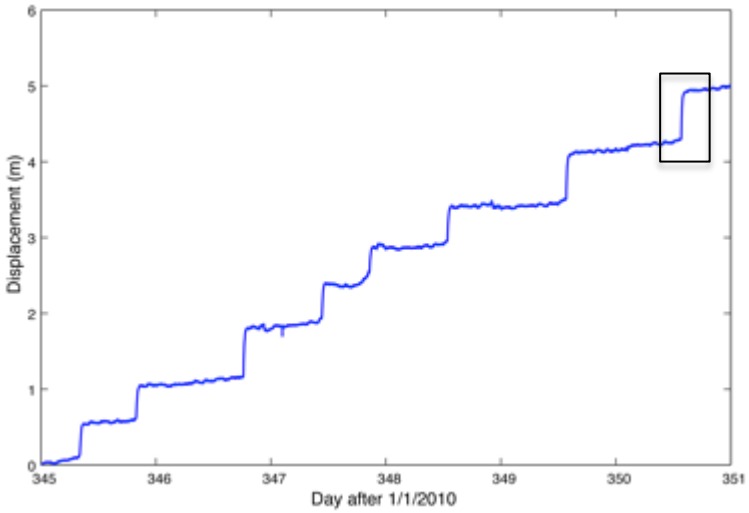
Whillans Ice Stream



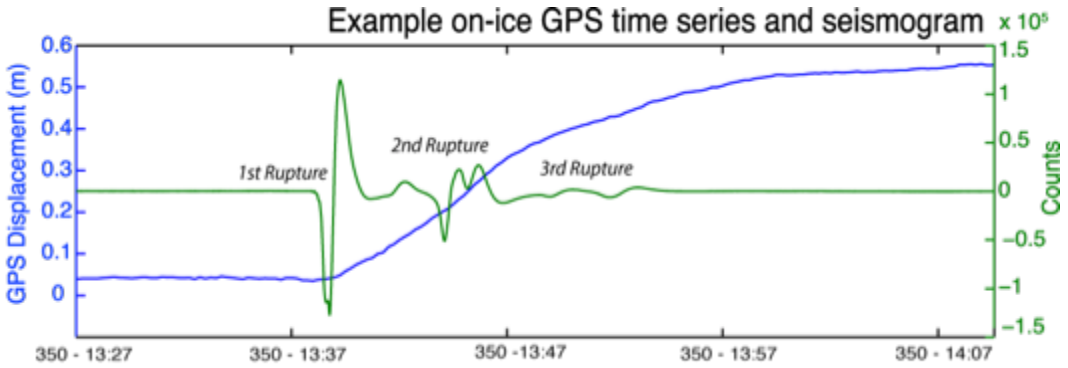


Slide from Paul Winberry

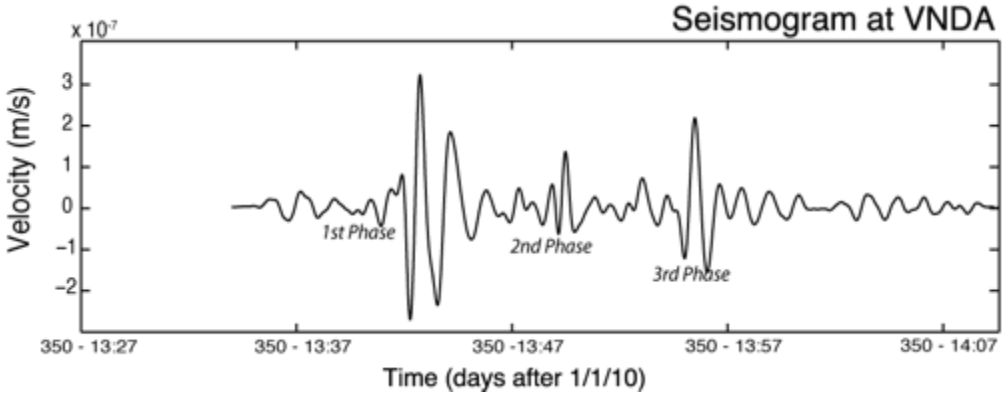
Time-varying ice sheet motion



Pratt et al., 2014



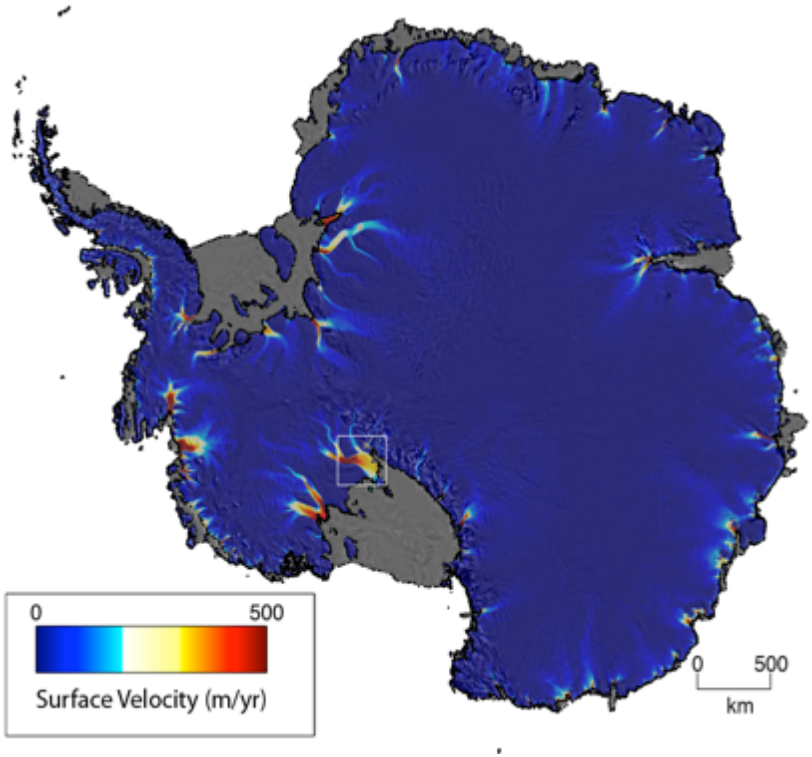
Neither GPS nor seismic are able to resolve motion at all frequencies



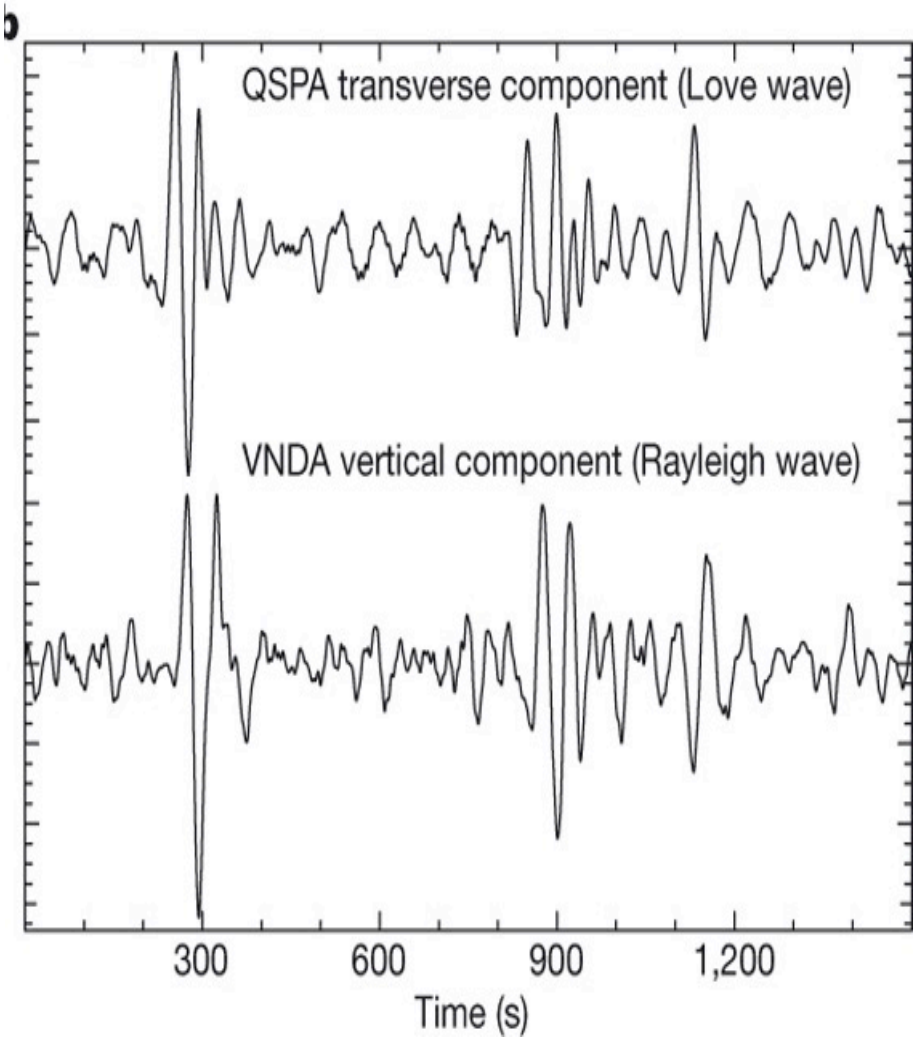
Ice sheet seismic activity

Whillans also produces large glacial earthquakes

"icequakes"



Whillans Events are ~M 7



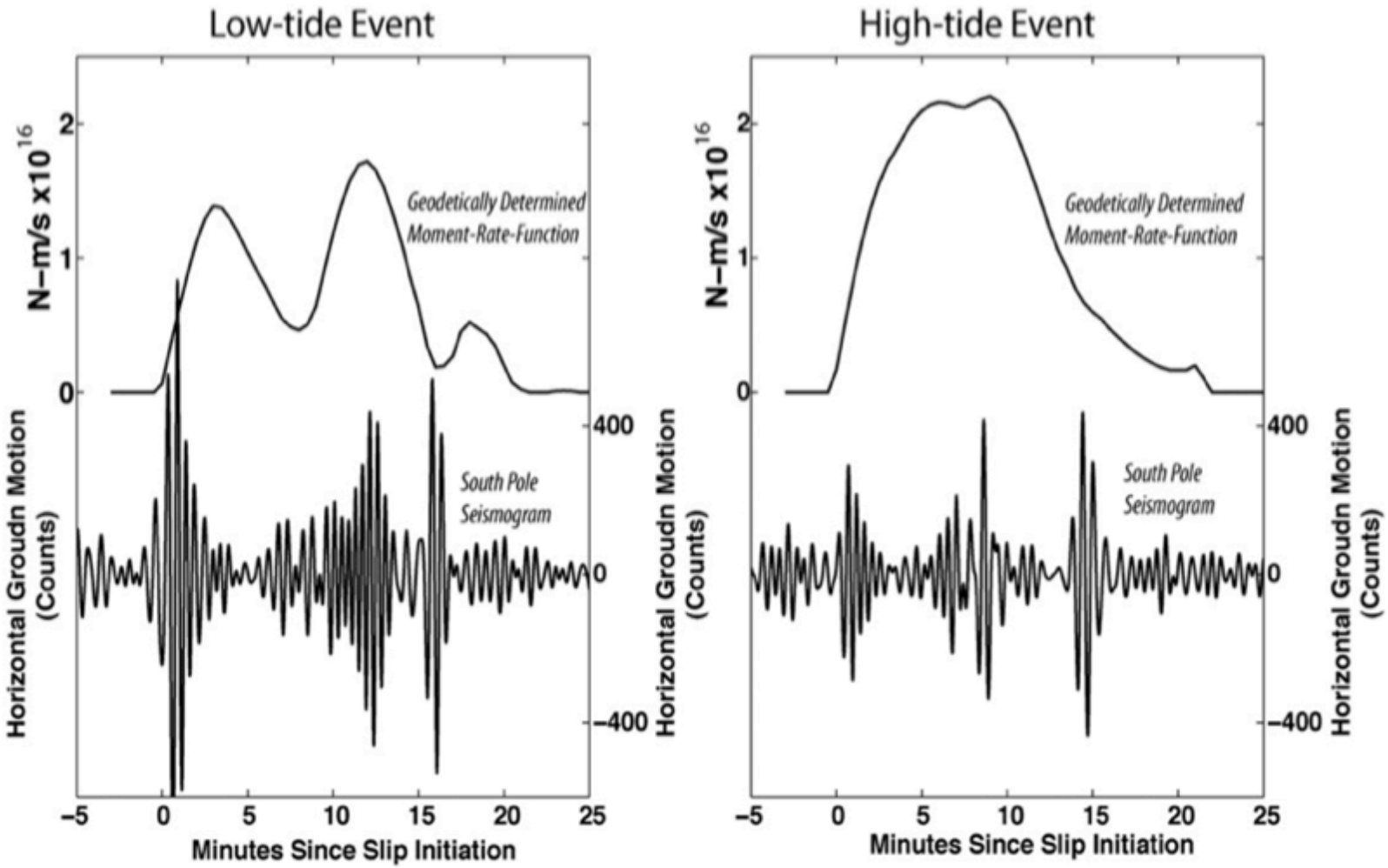
Wiens et al., Nature, 2008

"Glacio-seismology"

Slide from Paul Winberry

Ice sheet seismic activity

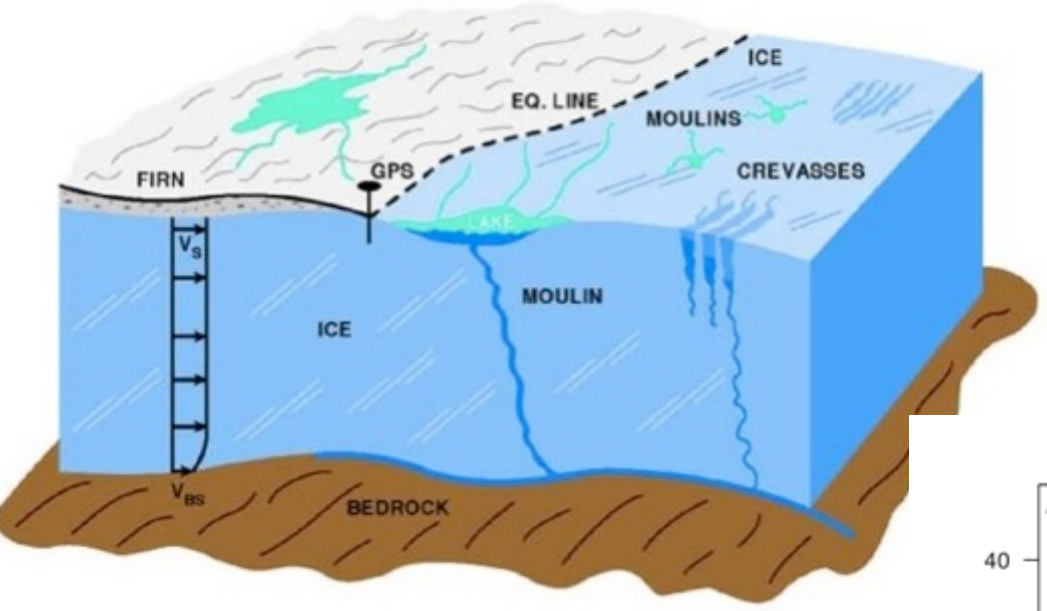
Each event is different due to a tidal pacing in stressing rate



Winberry et al., EPSL, 2011

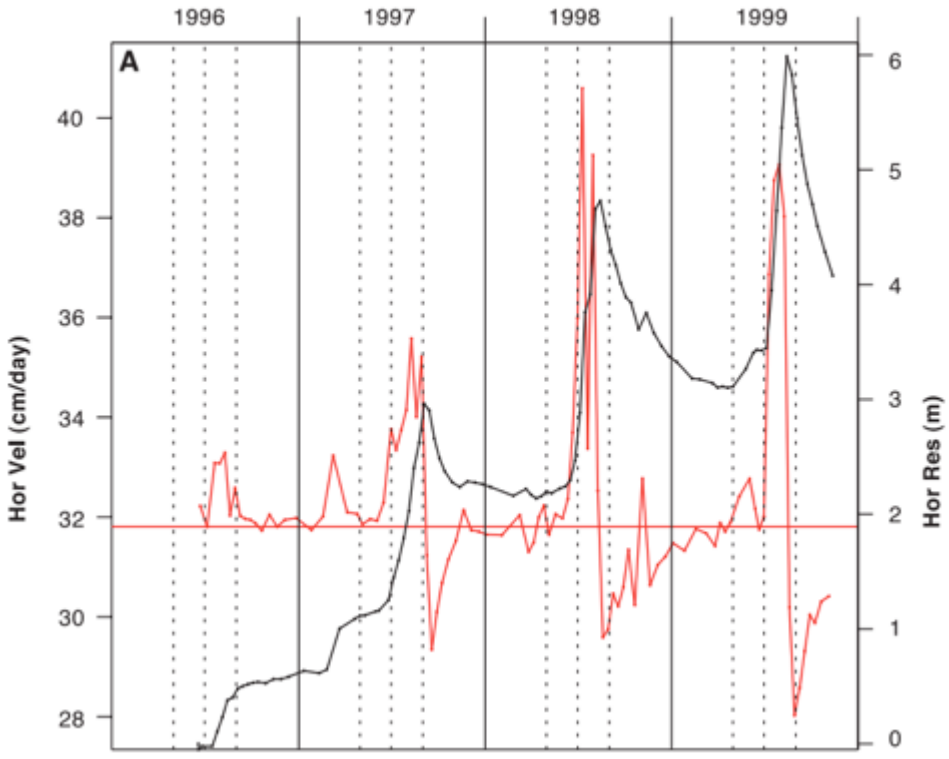
Slide from Paul Winberry

Time-varying ice sheet motion



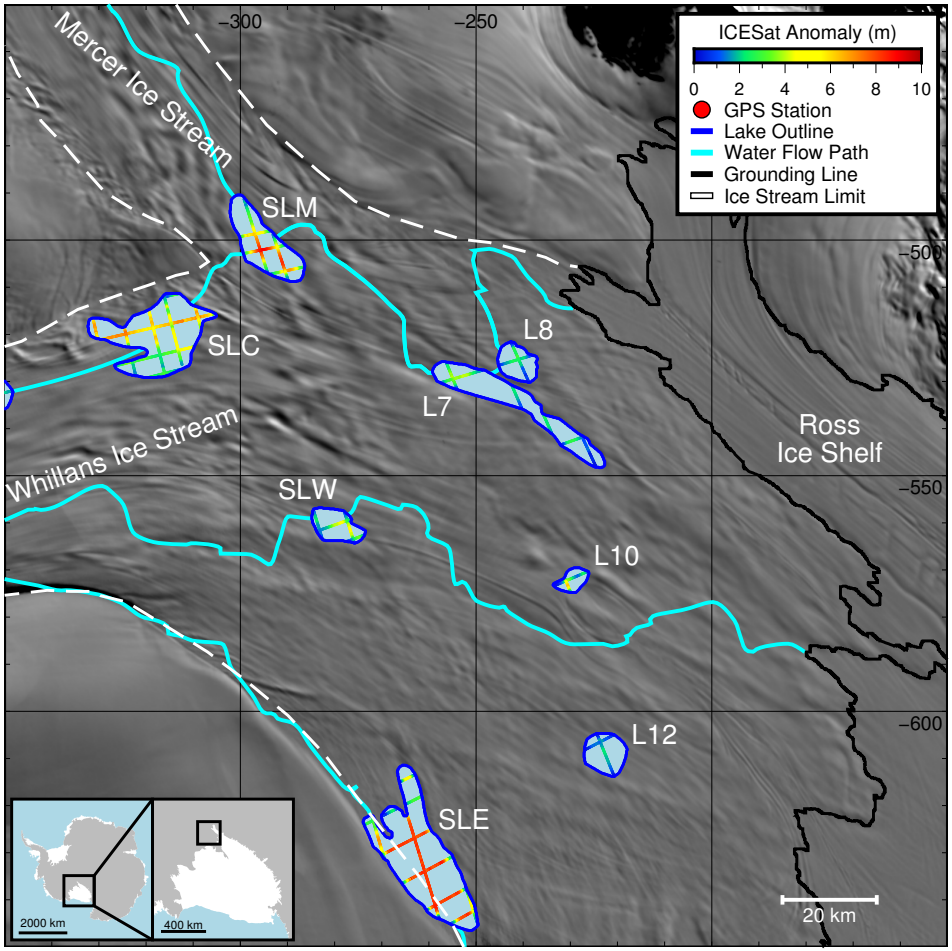
Zwally et al., 2002

Flow rates increase during summer because surface meltwater reaches ice sheet base

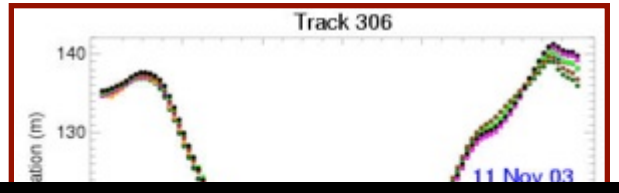


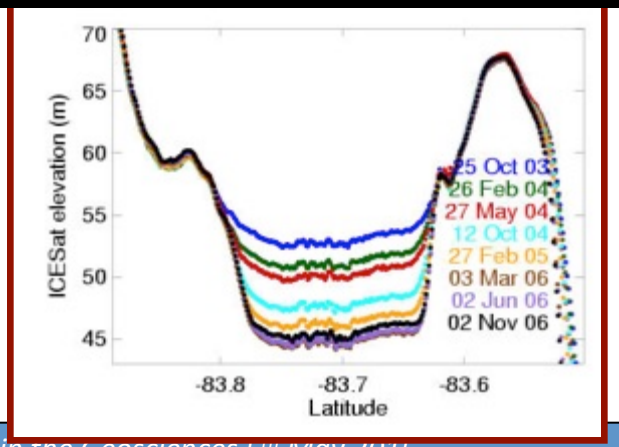
Detection of subglacial water activity

ICESat 2003-2009



Whillans Ice Stream

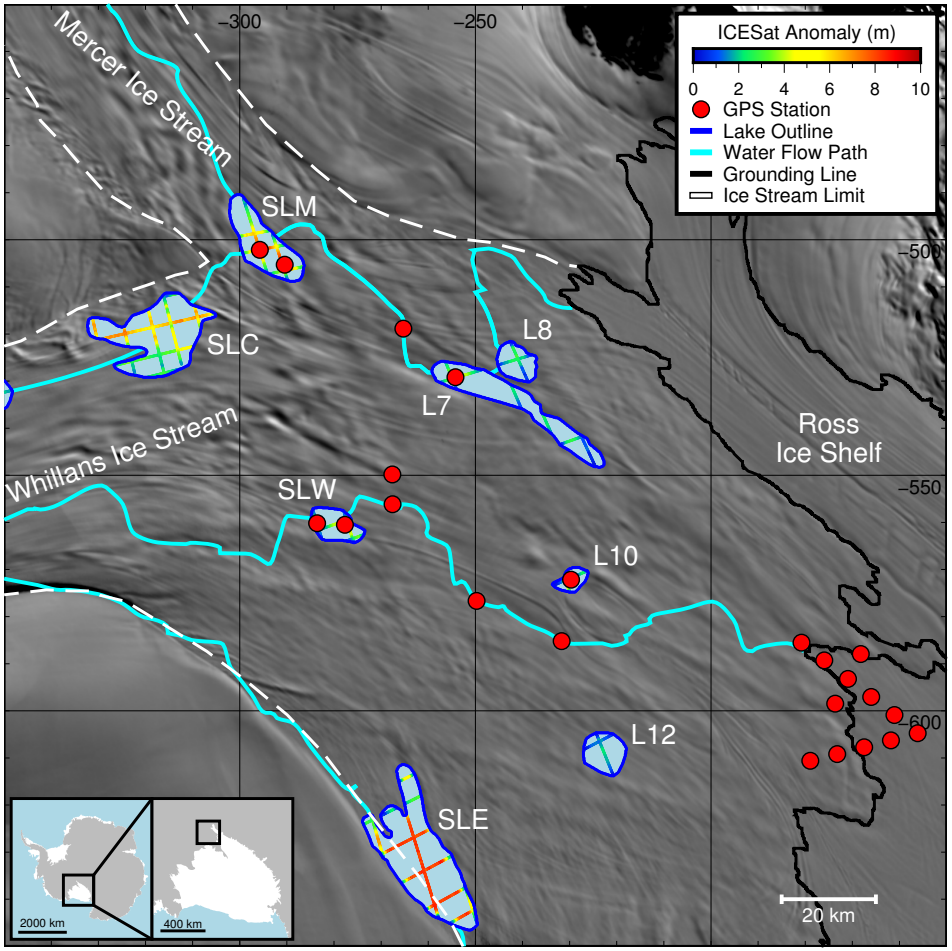




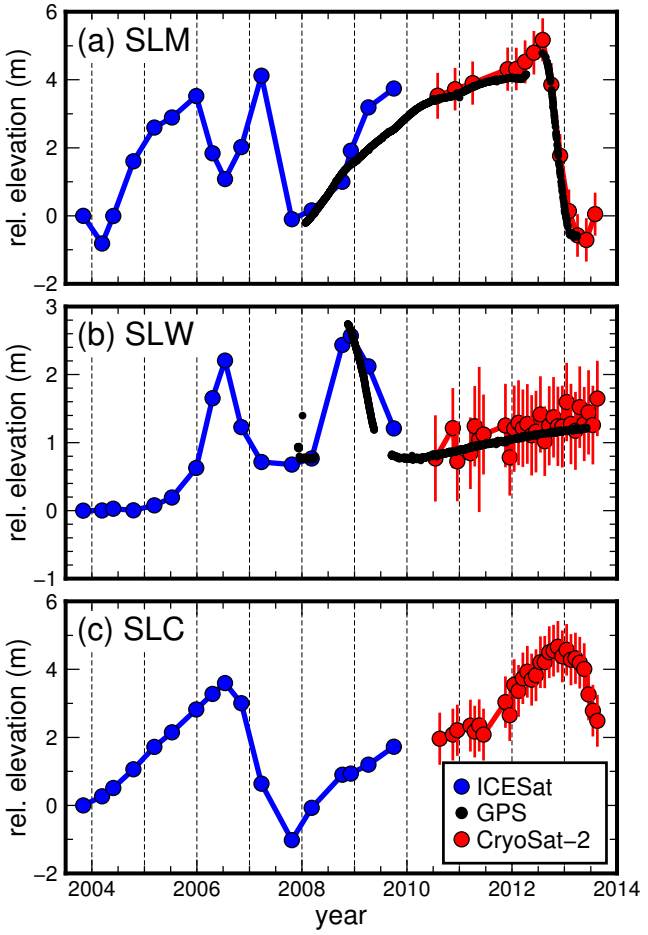
Fricker et al., Science, 2007

Detection of subglacial water activity

ICESat 2003-2009 + GPS 2008-2014

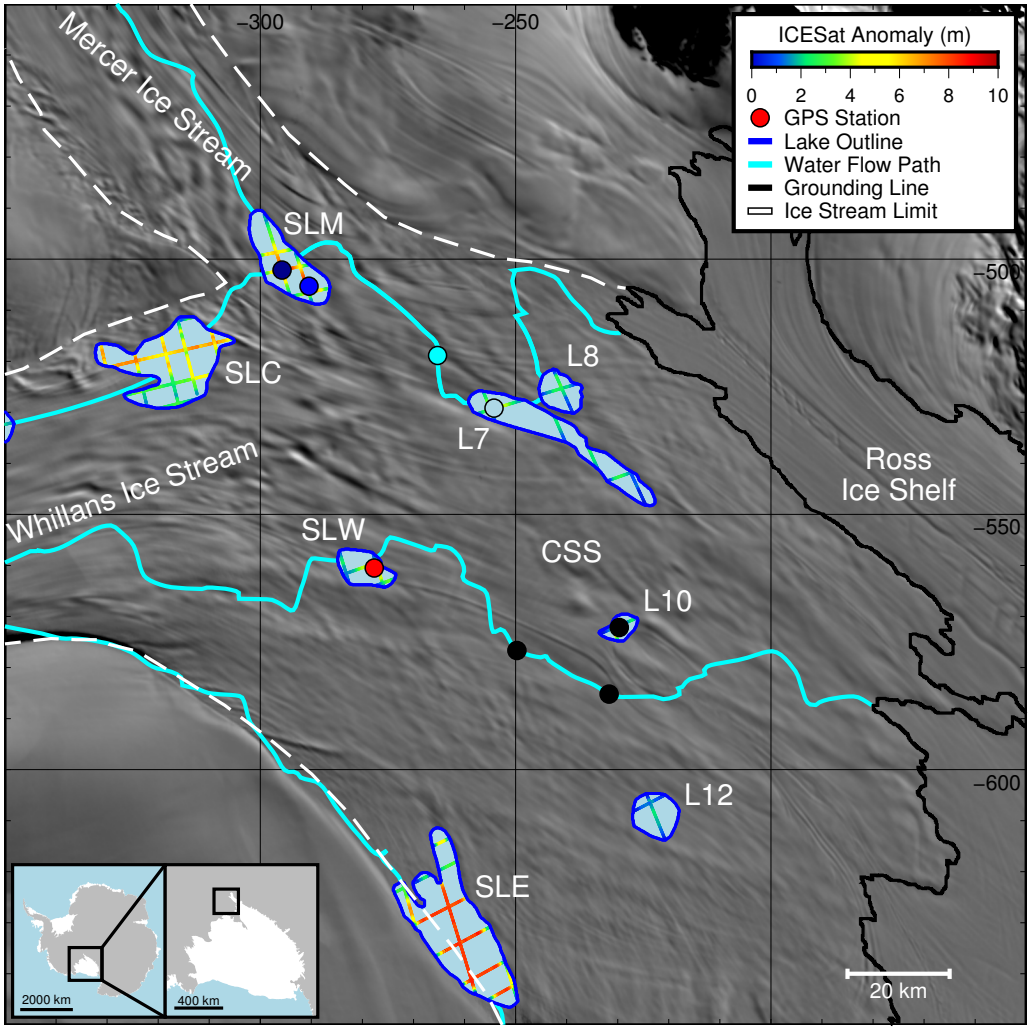


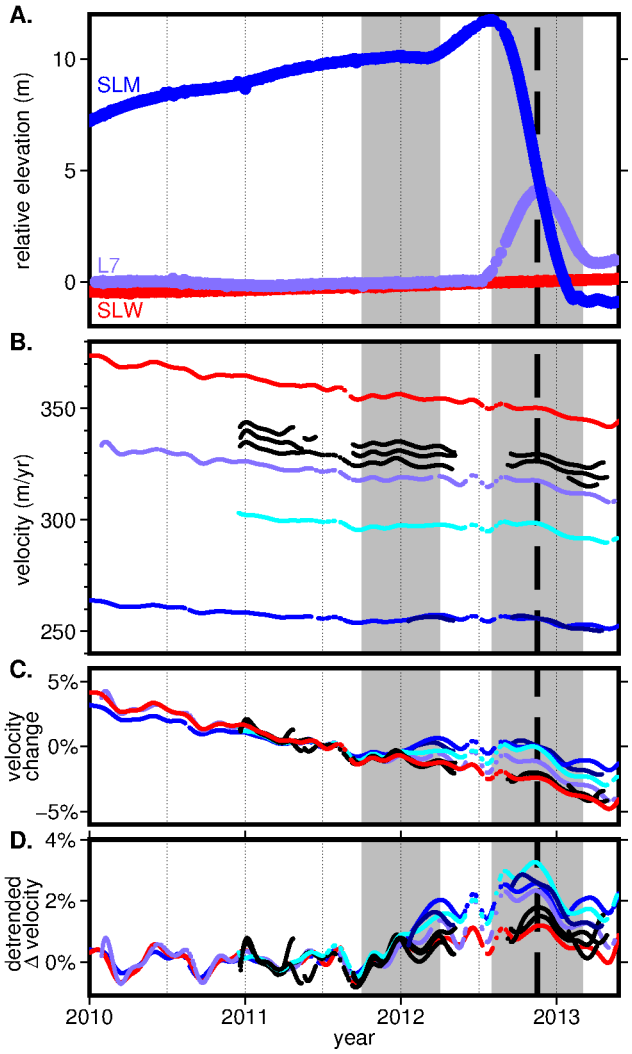
Whillans Ice Stream, West Antarctica



Siegfried et al., GRL, 2014

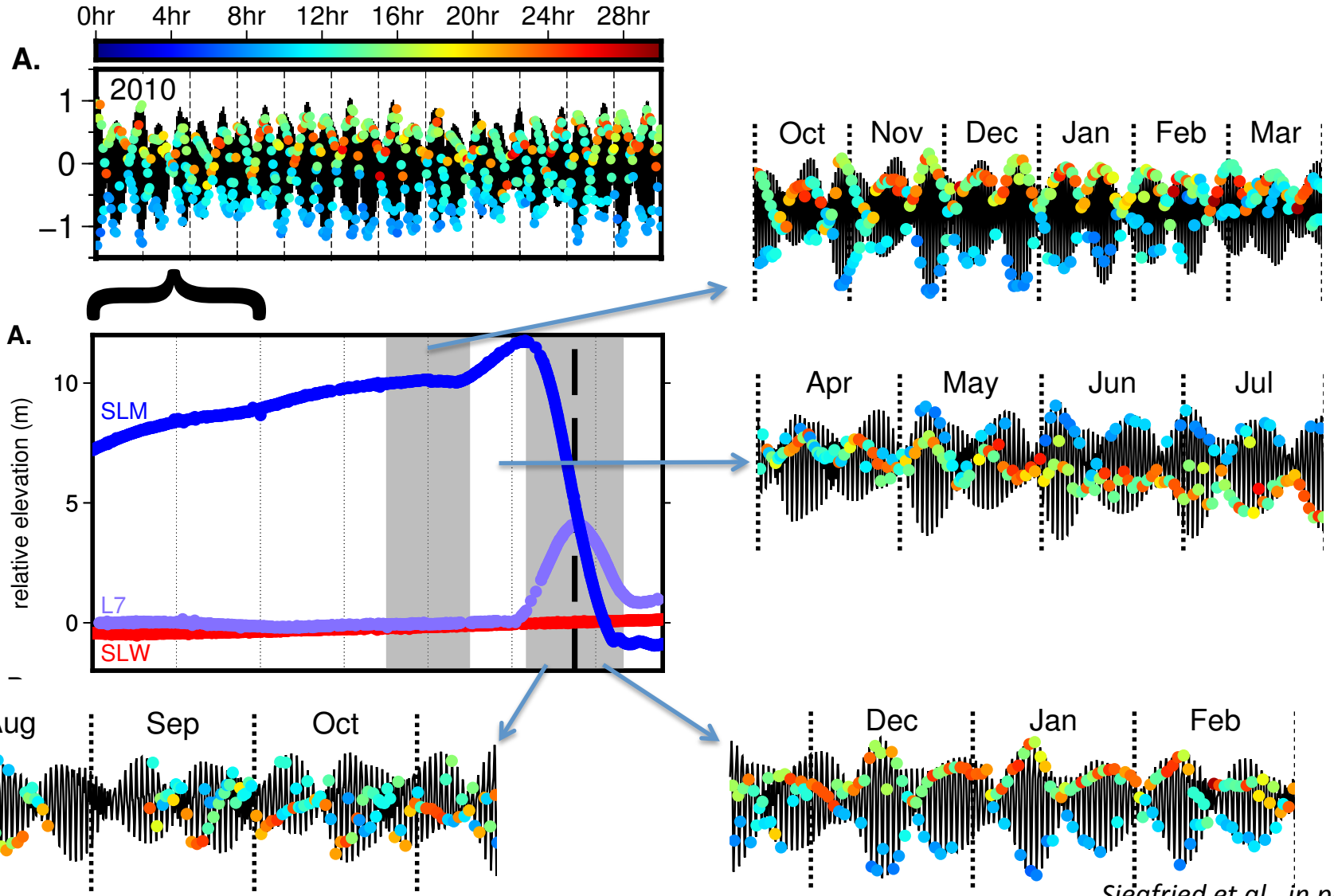
Whillans Ice Plain Dynamics





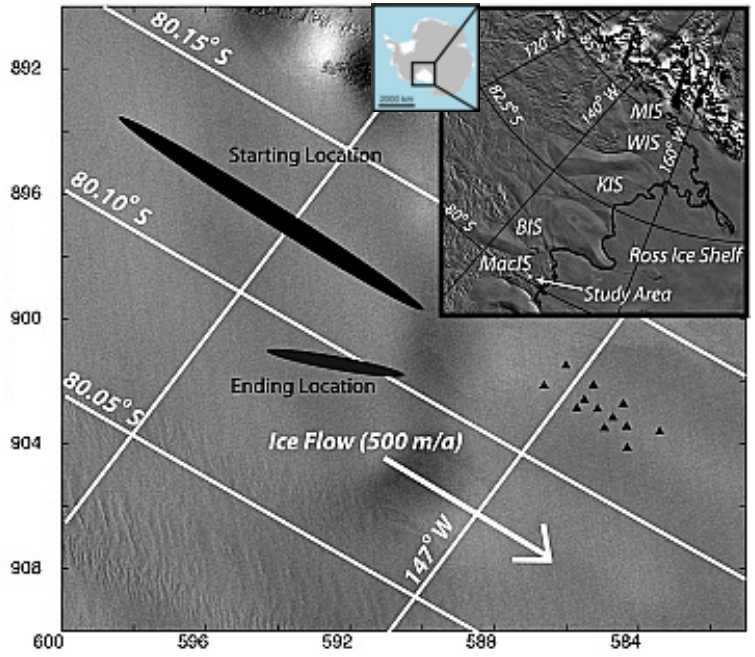
Siegfried et al., in prep

Whillans Ice Plain Dynamics

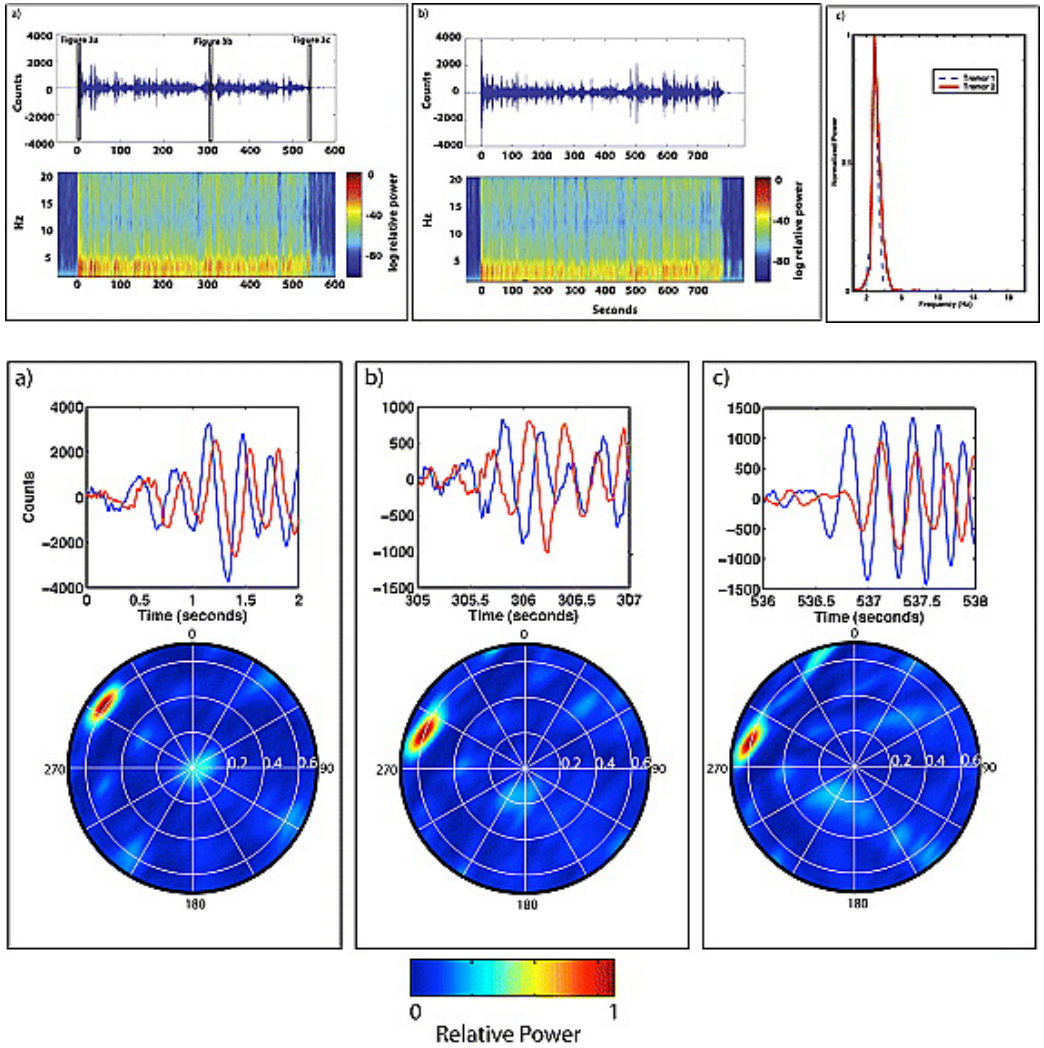


Siegfried et al., in prep

Seismic detection of subglacial water activity



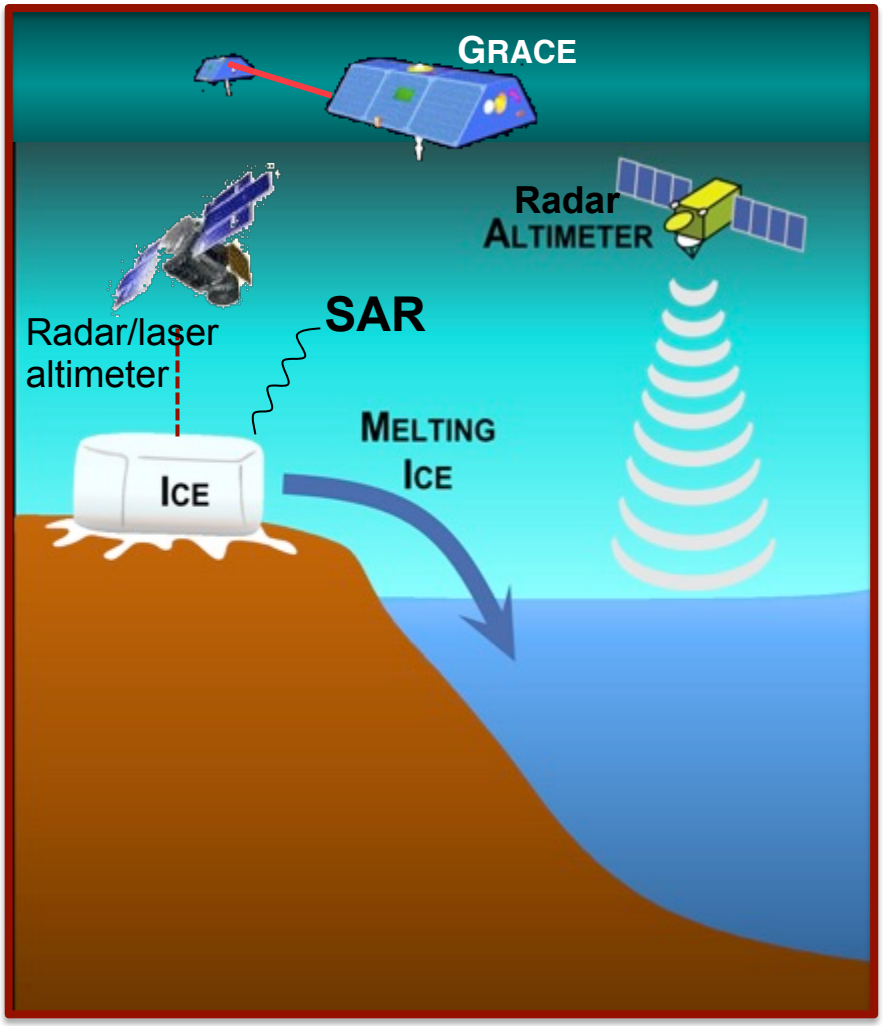
MacAyeal Ice Stream, West Antarctica



Harmonic tremor interpreted as water travelling in a conduit under the ice stream

Winberry et al., GRL, 2009

Estimating ice sheet mass balance



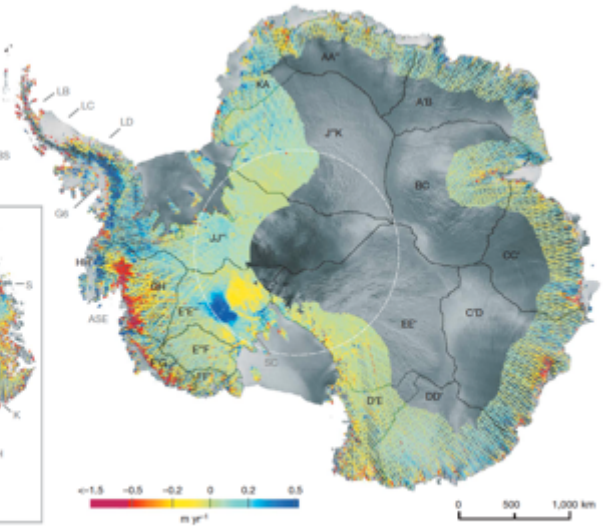
Three methods used to assess ice sheet mass balance from satellites:

- ★ Direct measurement of change in height with time (using altimetry) — Needs GPS ground-truth
- ★ Measurement of mass change with time (using GRACE) — Needs GIA
- ★ Estimation of mass fluxes (input-output method) — Needs GPS velocities

Antarctic ice sheet mass change

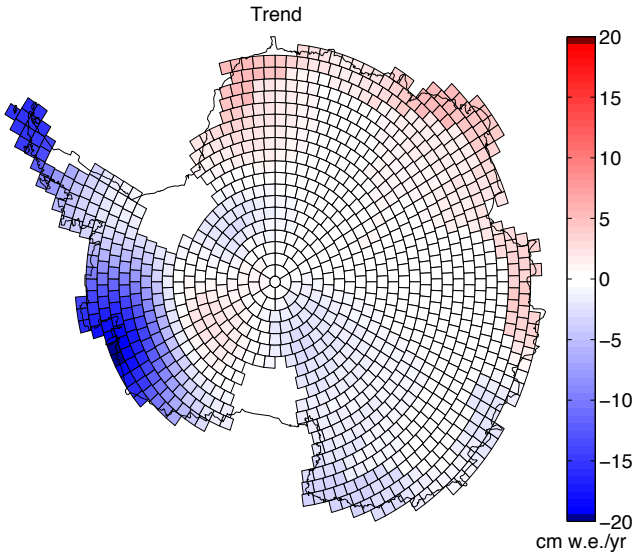
ICESat laser altimetry

Pritchard et al., Nature, 2007



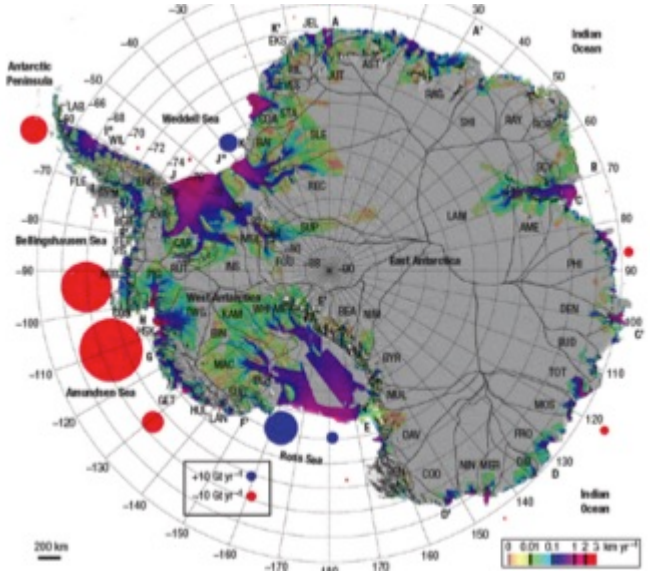
GRACE

Luthcke et al., 2013



Input/output

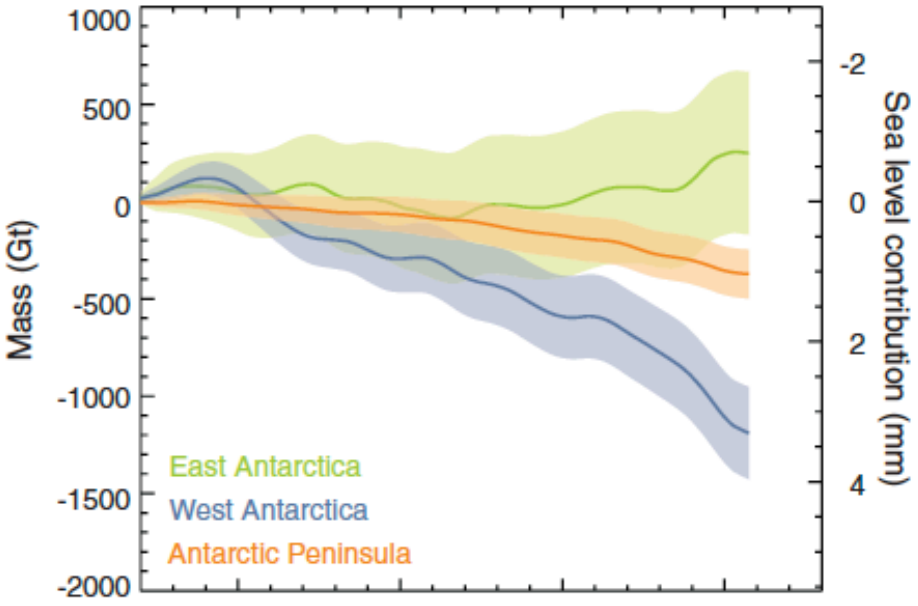
Rignot et al., NatGeo, 2008

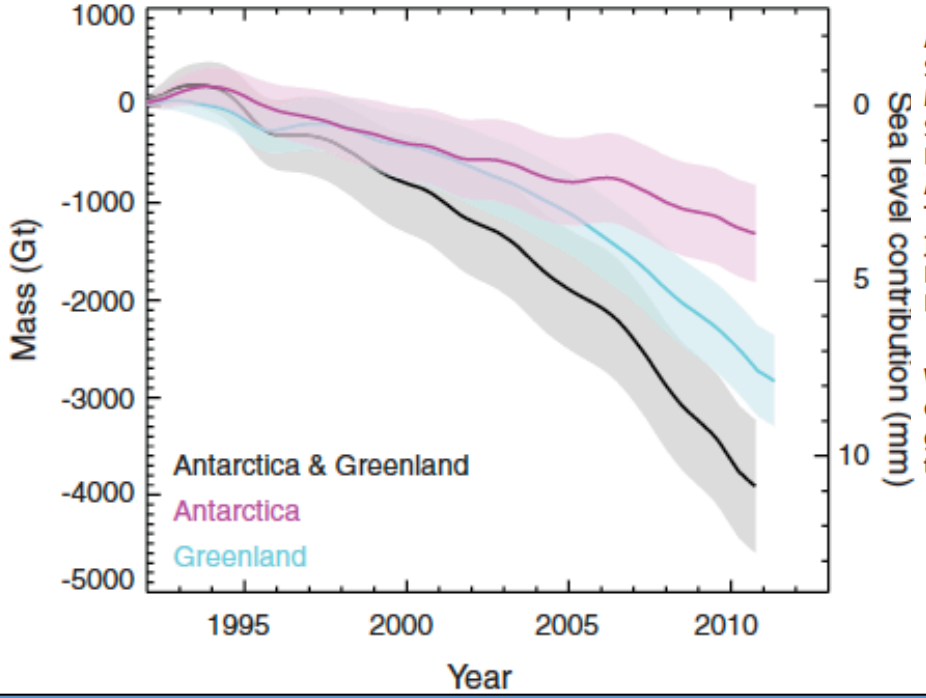


Some discrepancy between results from the three methods

All agree there is net mass loss

Ice Sheet Mass Balance Intercomparison Exercise (IMBIE)





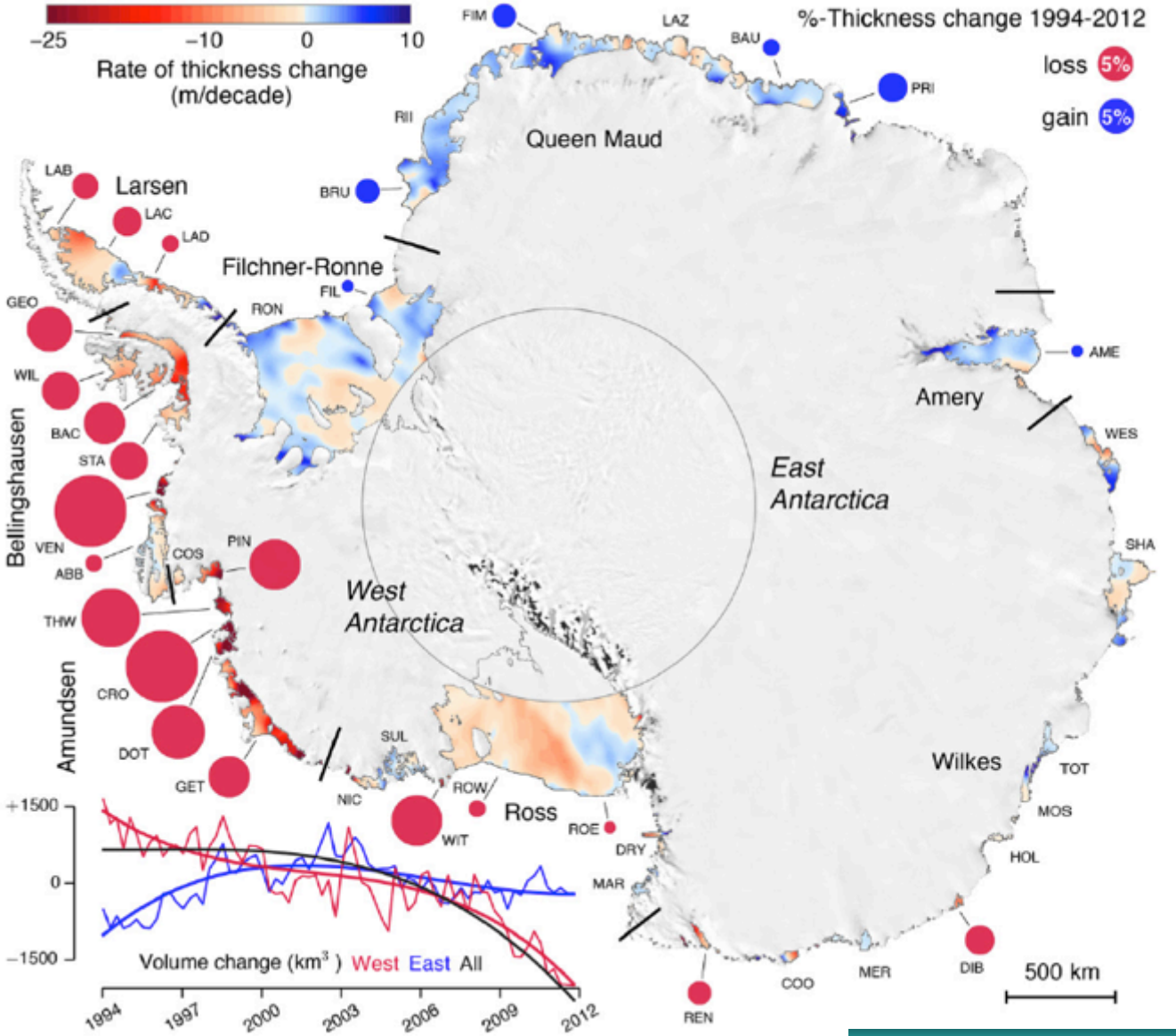
A Reconciled Estimate of Ice-Sheet Mass Balance

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]

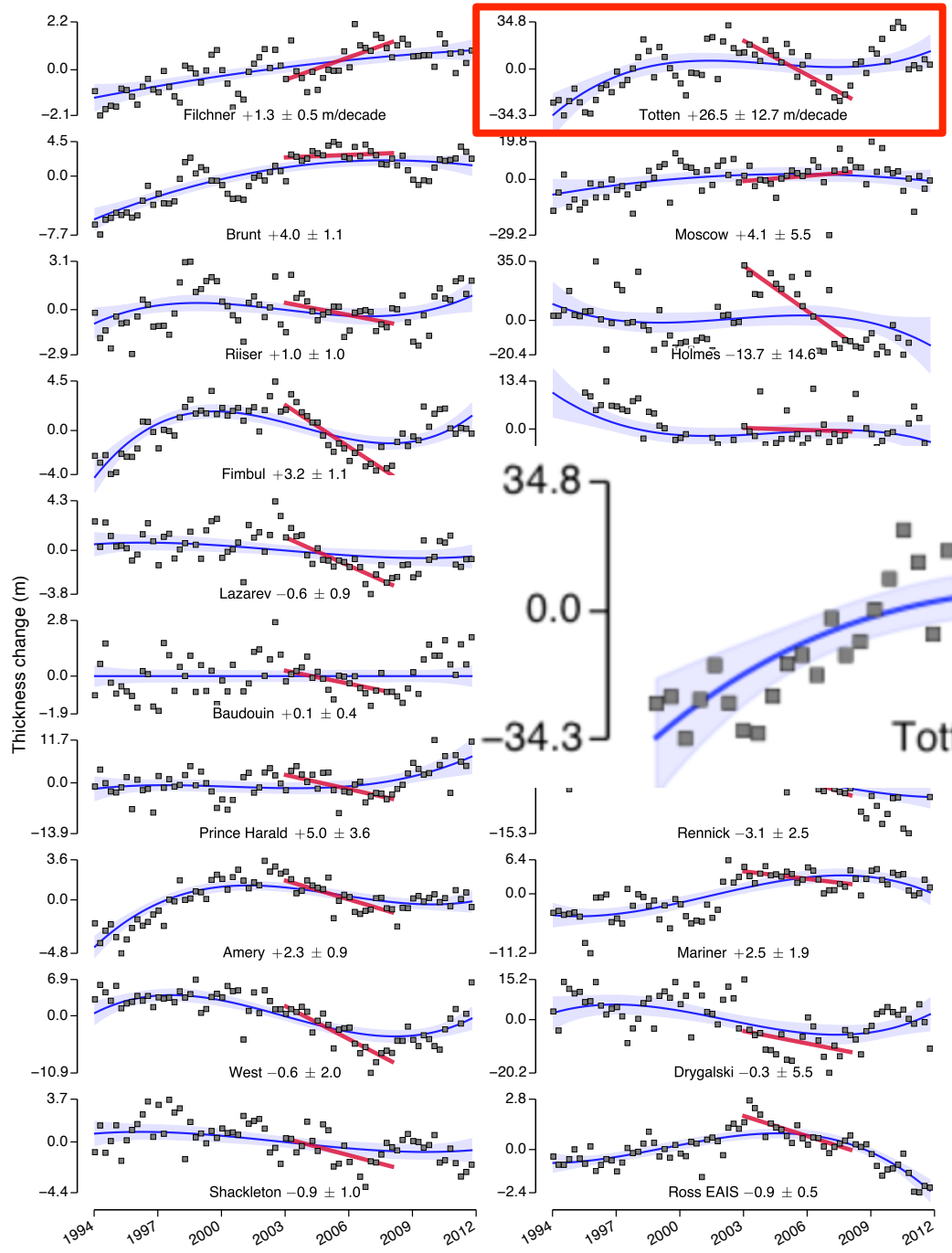
We combined an ensemble of satellite altimetry, interferometry, and gravimetry data sets using common geographical regions, time intervals, and models of surface mass balance and glacial isostatic adjustment to estimate the mass balance of Earth's polar ice sheets. We find that there is good agreement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

Shepherd et al., Science, 2012

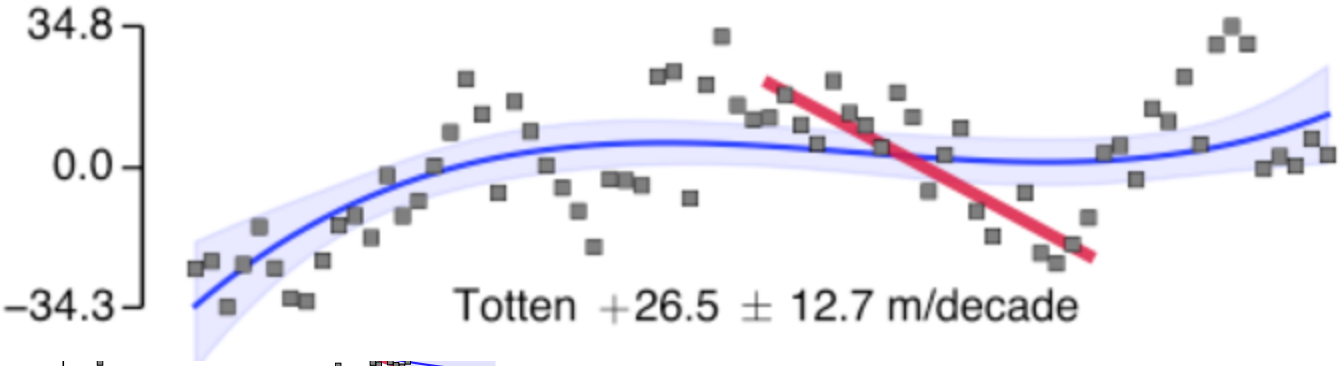
Volume loss from ice shelves is accelerating



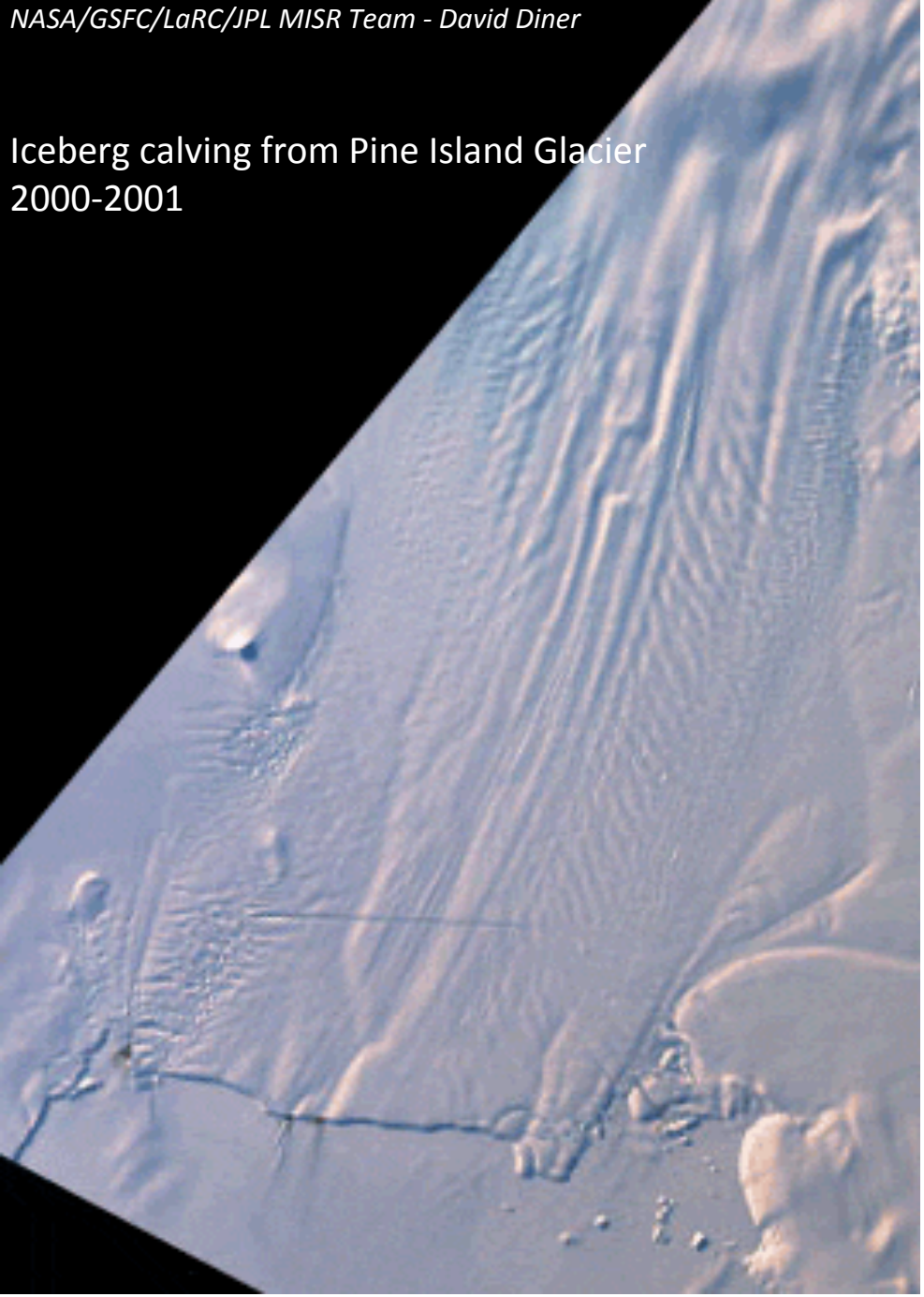
Paolo, Fricker and Padman, Science 2015



Note the interannual variability



Paolo, Fricker and Padman, Science 2015



Iceberg calving from Pine Island Glacier
2000-2001

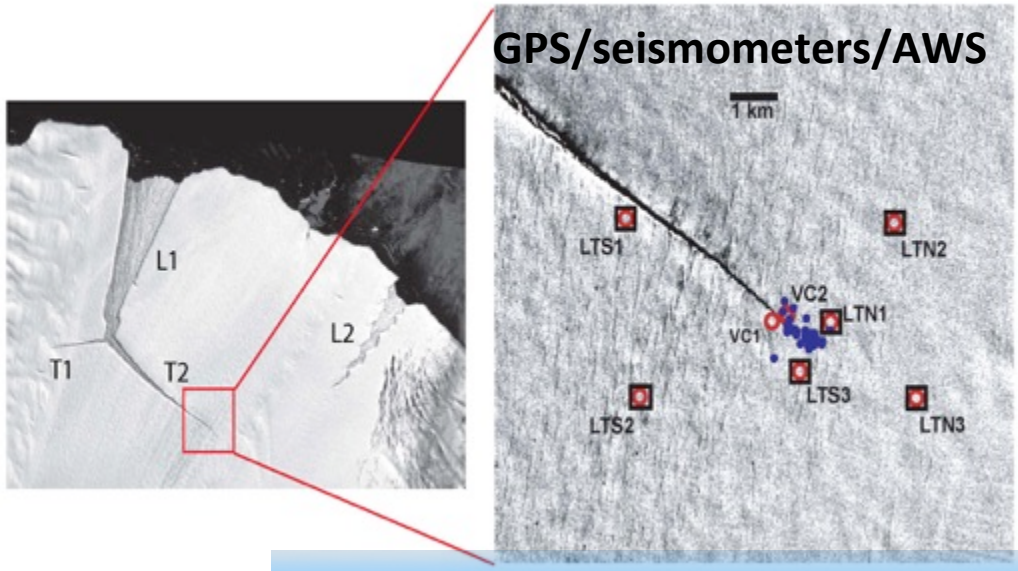
Iceberg calving

Recurrence interval of large calving events is decades

Seismic detection of iceberg calving

Episodic “icequakes” associated with rift motion detected with GPS & seismometers

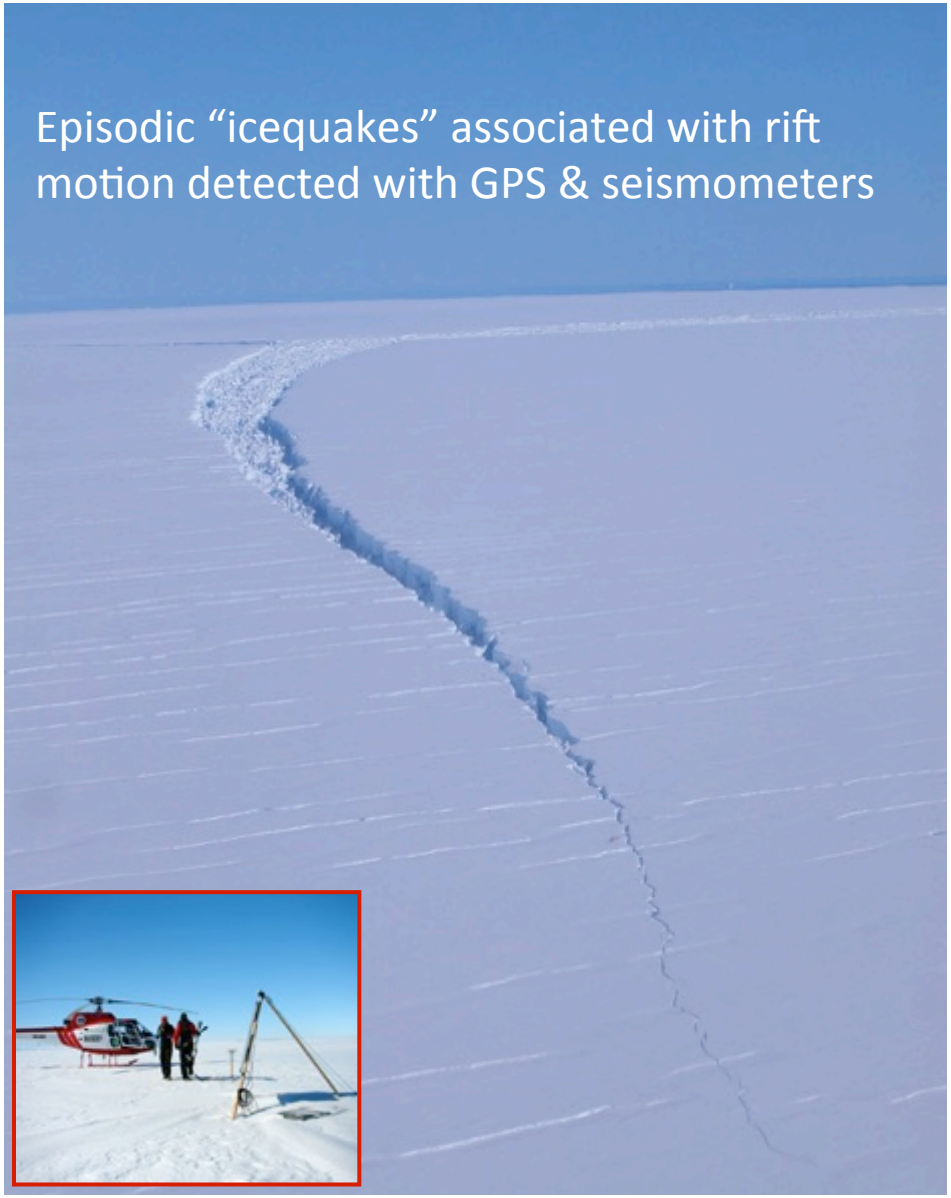
Four year field program funded by NSF in collaboration with Australian Antarctic Division

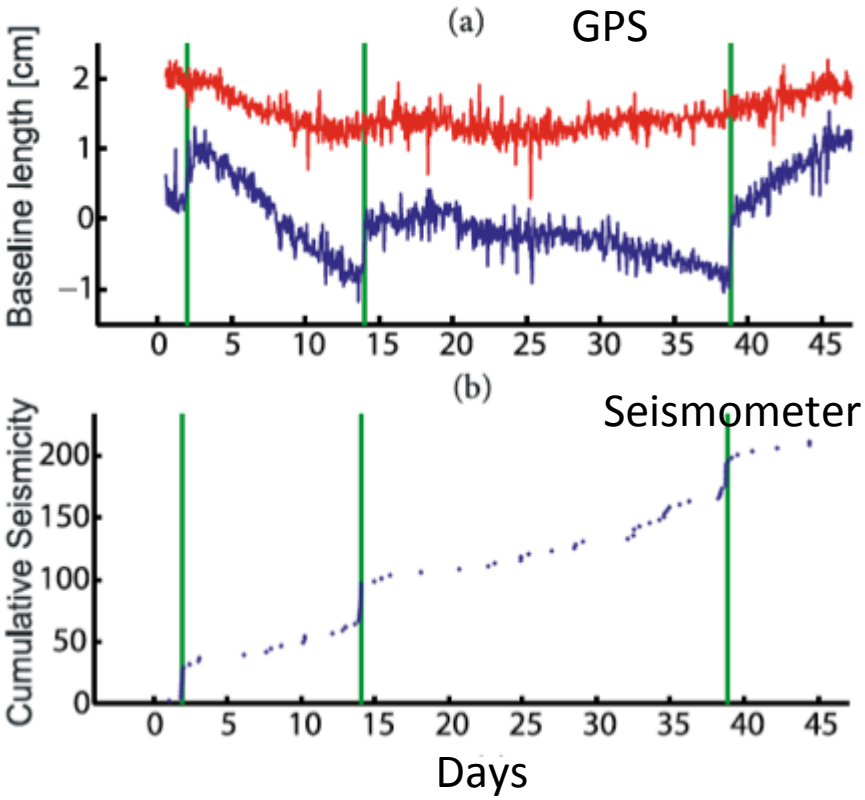


Bassis, Fricker et al., GRL, 2005

Seismic detection of iceberg calving

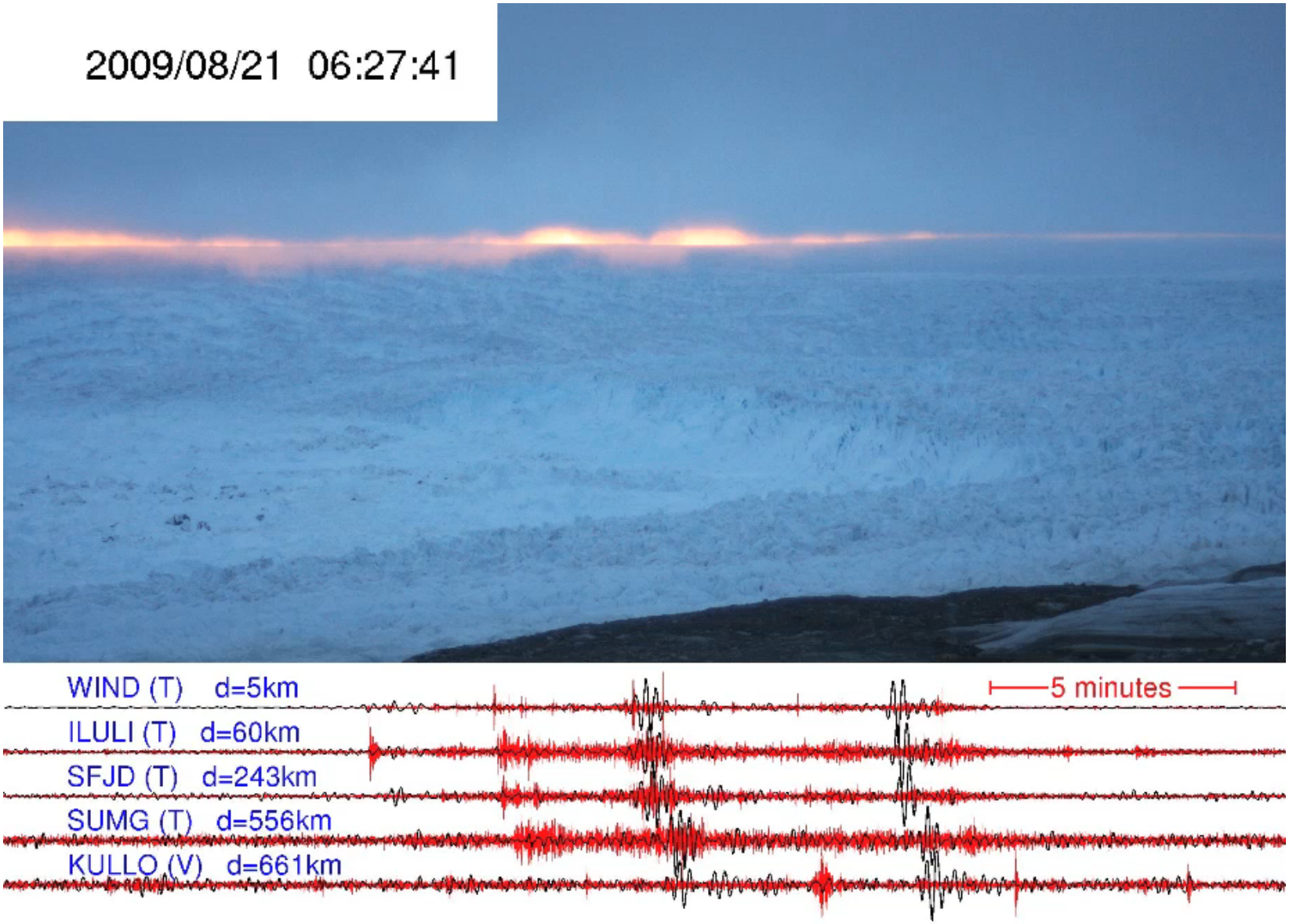
Episodic “icequakes” associated with rift motion detected with GPS & seismometers



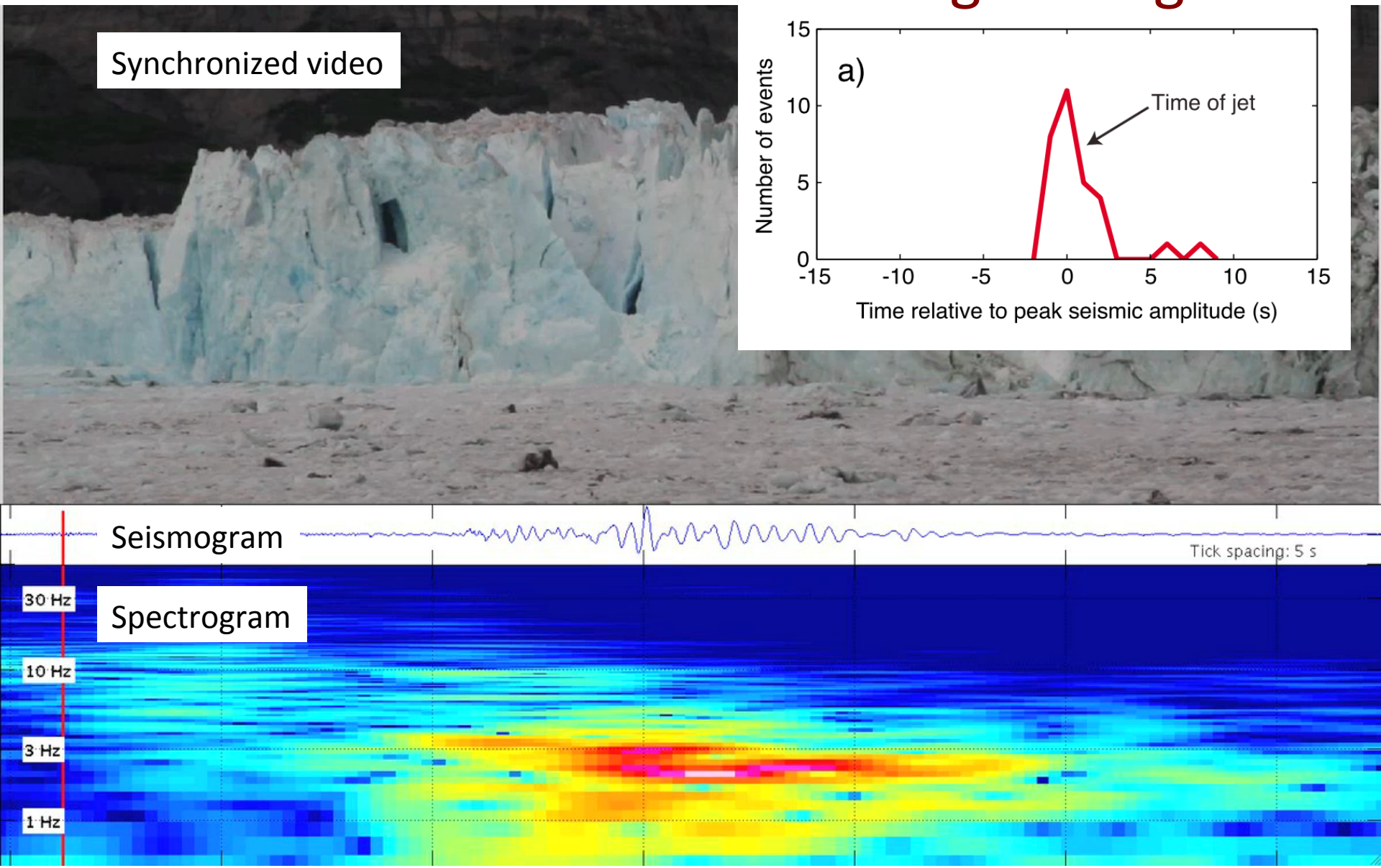


Bassis, Fricker et al., GRL, 2005

Seismic detection of iceberg calving

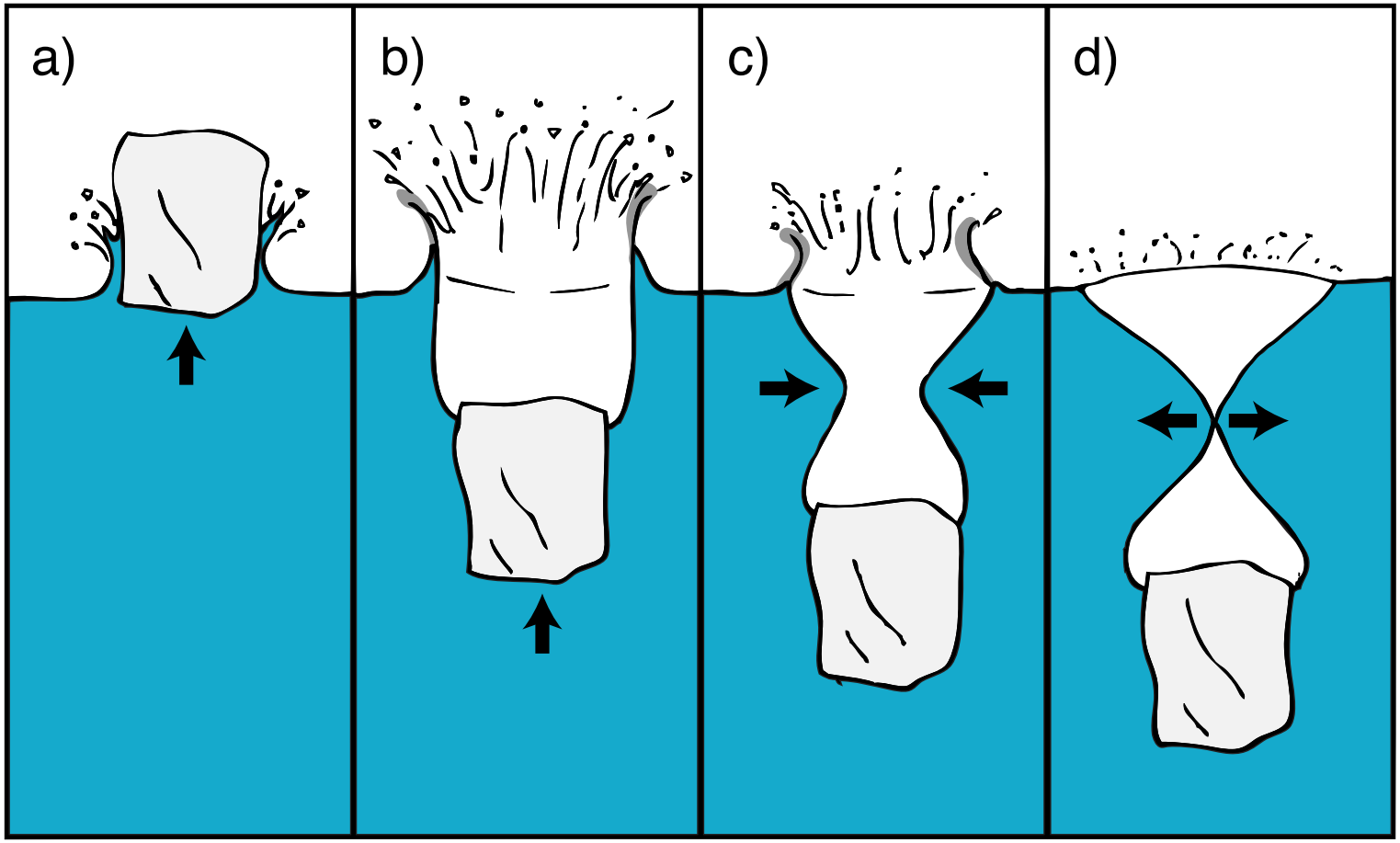


Seismic detection of iceberg calving



Bartholomaus et al., 2012, JGR

Seismic detection of iceberg calving

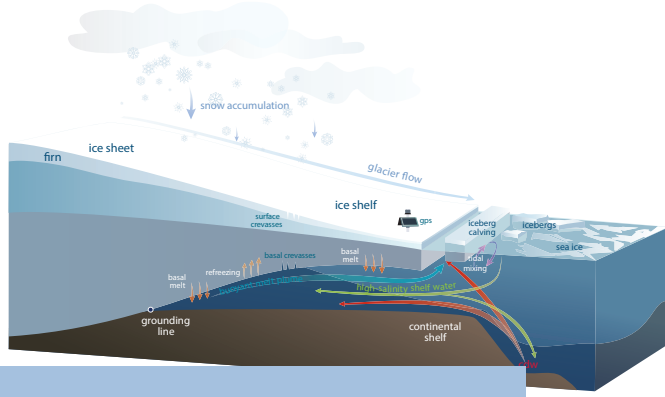


Iceberg-sea surface interactions

Bartholomaus et al., 2012, JGR

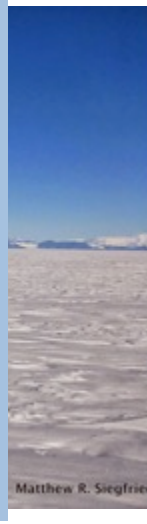
Summary

- Ice sheets are changing & have large potential contribution to sea-level rise (SLR) & freshwater flux to the oceans



- We
  mas
- In 2
  ice-
  wou
- We
  per
  responsible for ice sheet mass loss

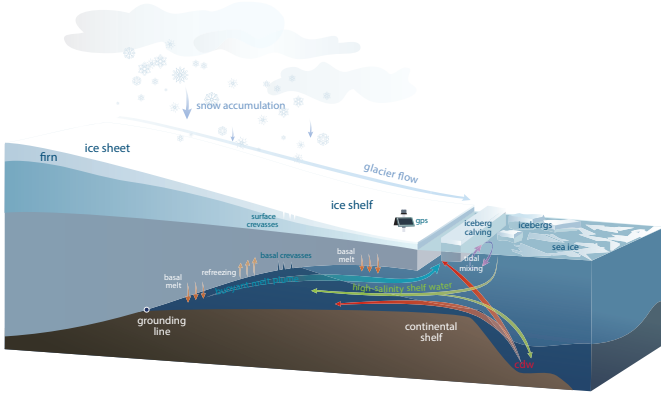
Ice sheet process	GPS	Seismometers
Flow rates	✔	
Subglacial water	✔	✔
Iceberg calving	✔	✔
Tidal motion	✔	
Mass balance	✔	

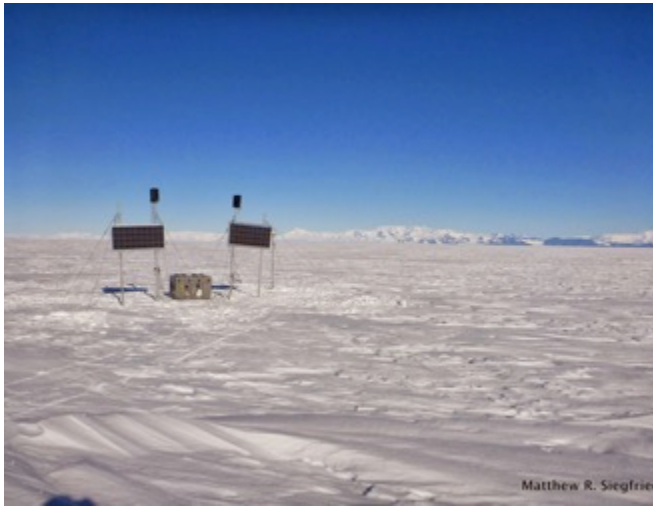


- Continued long-term GPS & seismic observations over the ice sheets are essential

Summary

- Ice sheets are changing & have large potential contribution to sea-level rise (SLR) & freshwater flux to the oceans
- We still have limited understanding of ice sheet mass loss processes
- In 20 years, we have learned a vast amount about ice-sheet processes from GPS & seismology, that would not have been possible via other methods
- We need to observe on short-time scales for long periods to fully understand the physical processes responsible for ice sheet mass loss
- Continued long-term GPS & seismic observations over the ice sheets are essential





We learn something every time we deploy a GPS or seismometer on a glacier!