Hot Topics in Glaciology

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NCEO - Nottingham 2019

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NERC SCIENCE OF THE ENVIRONMENT
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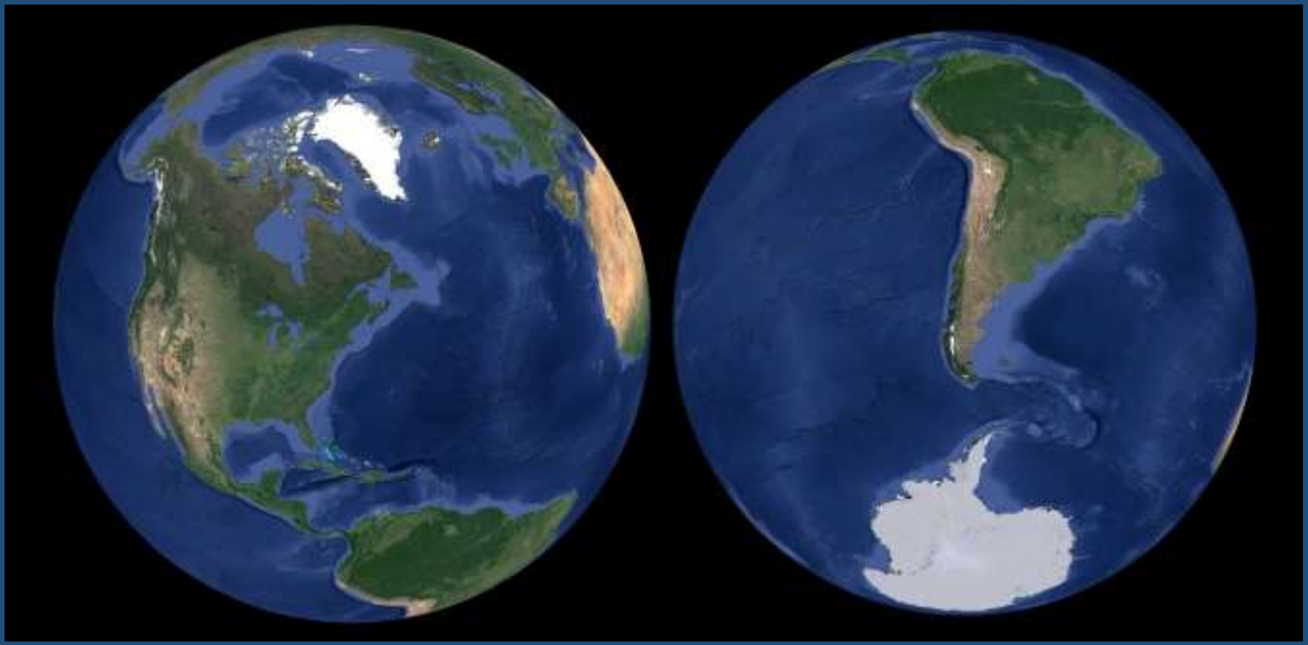
Importance of Ice Sheets

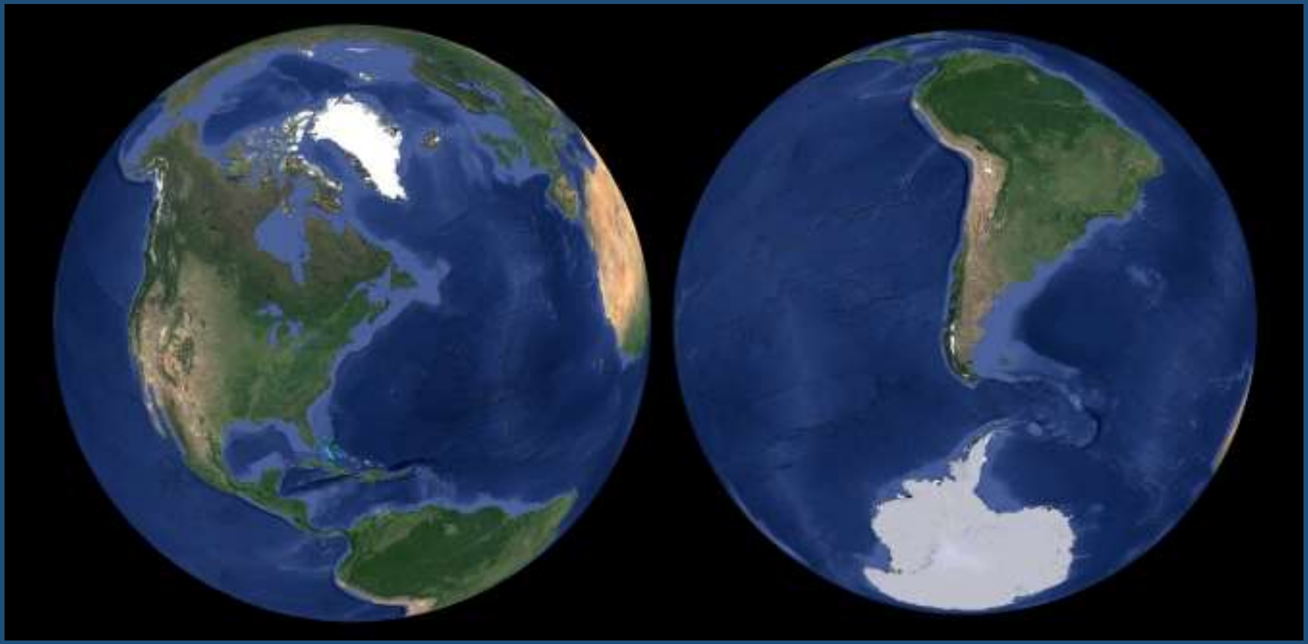
- Ice sheets are the largest reservoirs of fresh water on the planet.
- Together, the Antarctic and Greenland ice sheets contain more than 99 % of the freshwater ice on Earth.
    - 58 m global sea level stored in Antarctica.
    - 6 m global sea level stored in Greenland.



Importance of Ice Sheets

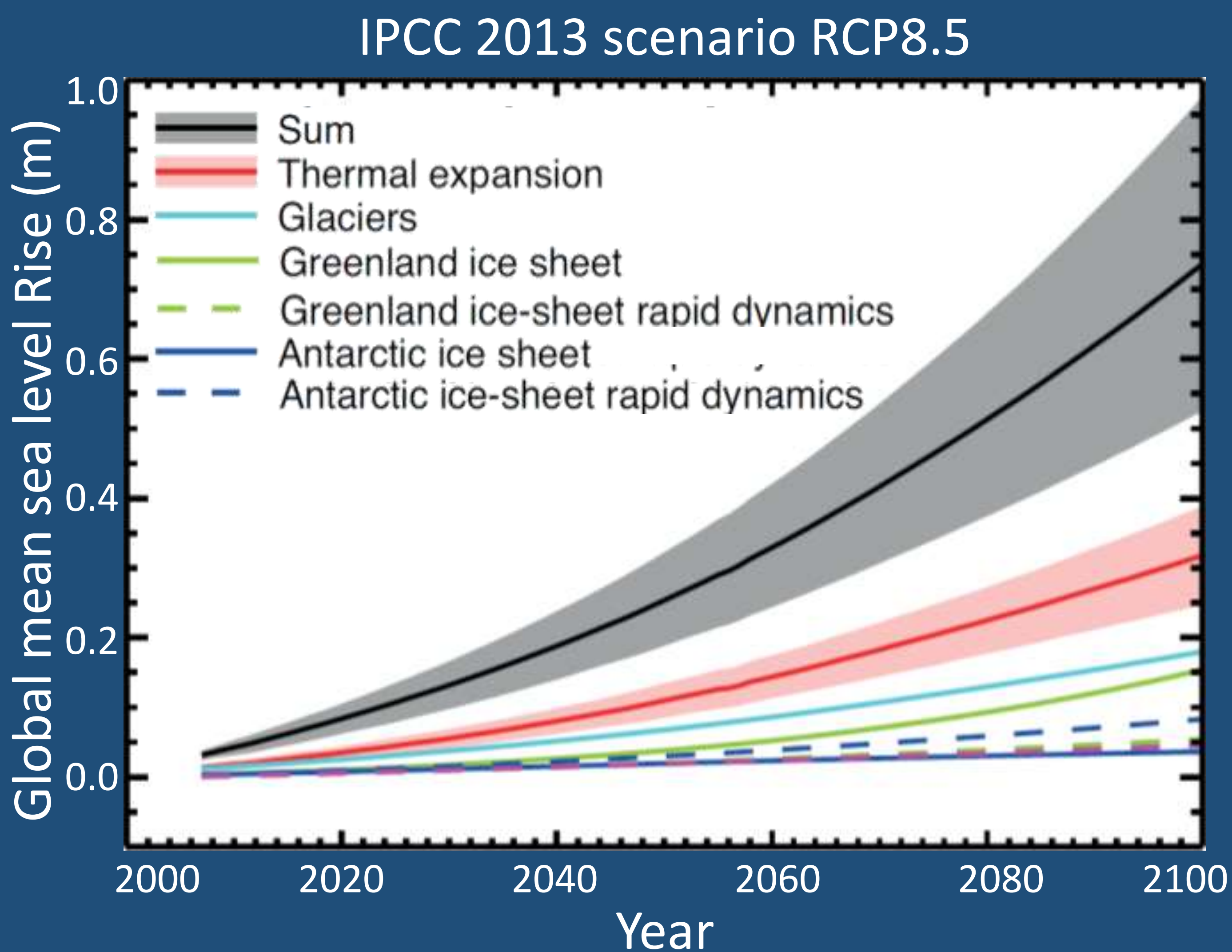
Ice sheets are a key component of the present day Earth System. The transfer of energy and mass influences:

- Global sea level => impacting coastal communities.
- Atmospheric circulation => cold, high elevation land masses.
- Ocean circulation => delivery and uptake of cold, fresh water to the ocean.
- Earth's polar albedo => proportion of reflected incoming solar radiation.



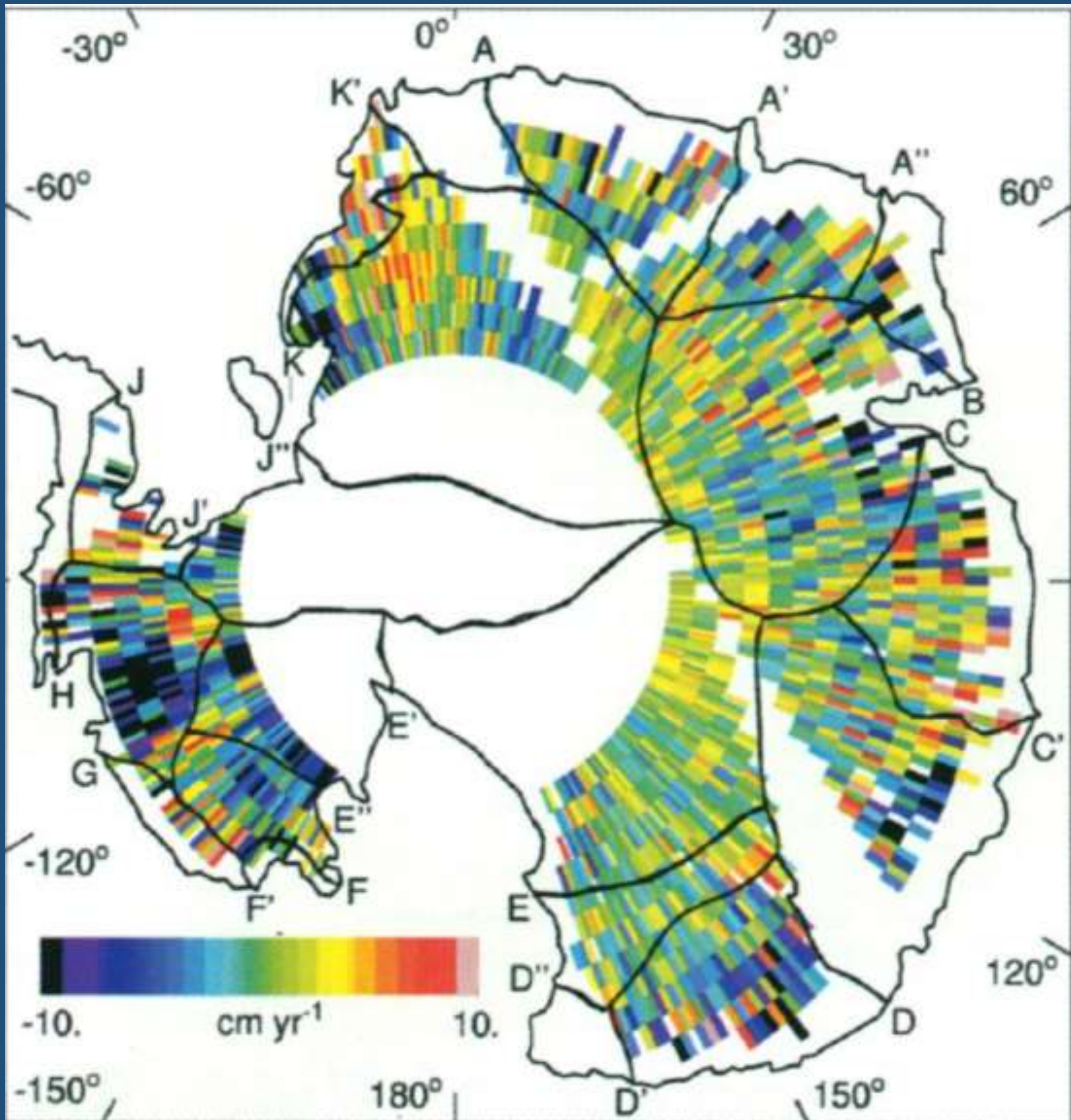
Credit: NASA

Contribution to Sea Level Rise



Present day sea level rise (SLR)
3.4 mm/yr

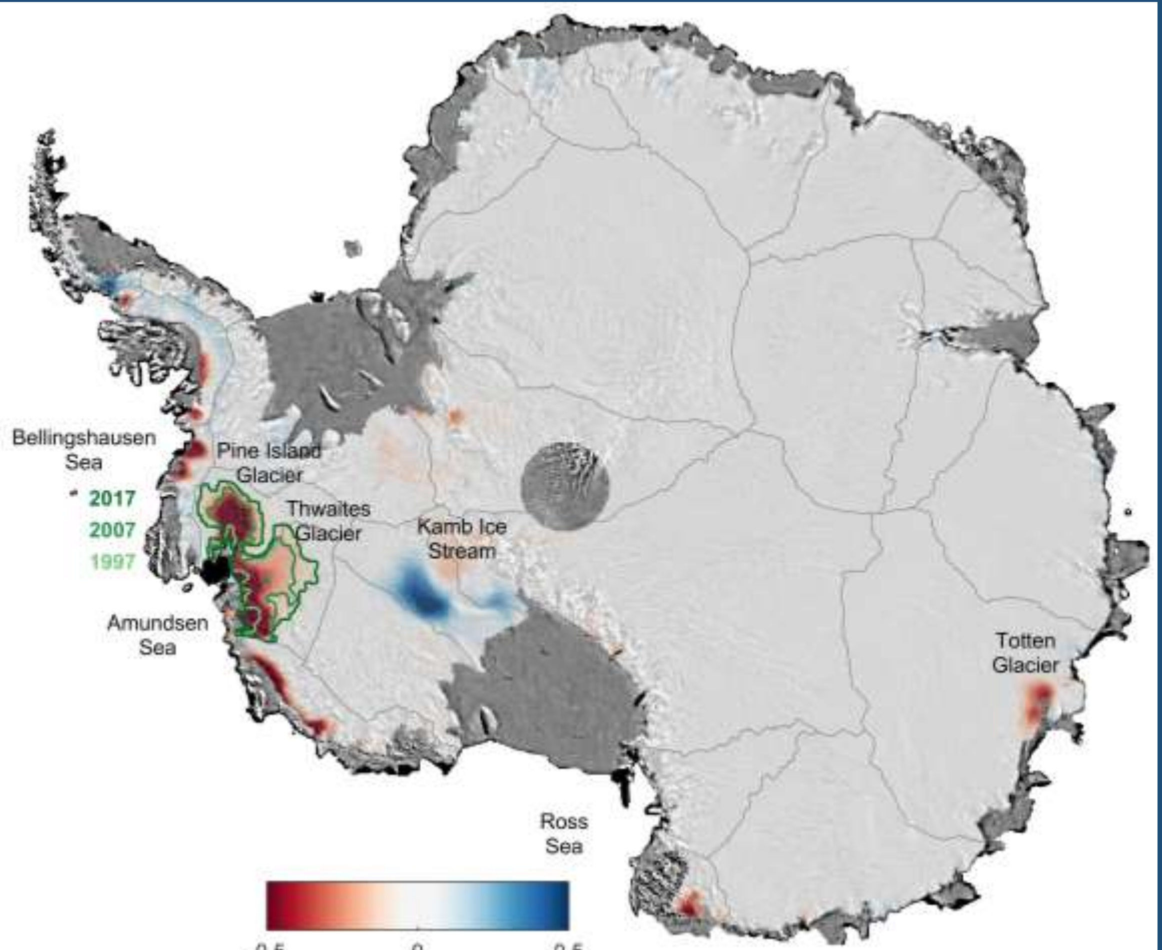
25-year long satellite record



(Wingham et al., 1998)

- record of surface elevation change from ERS-1

25-year long satellite record

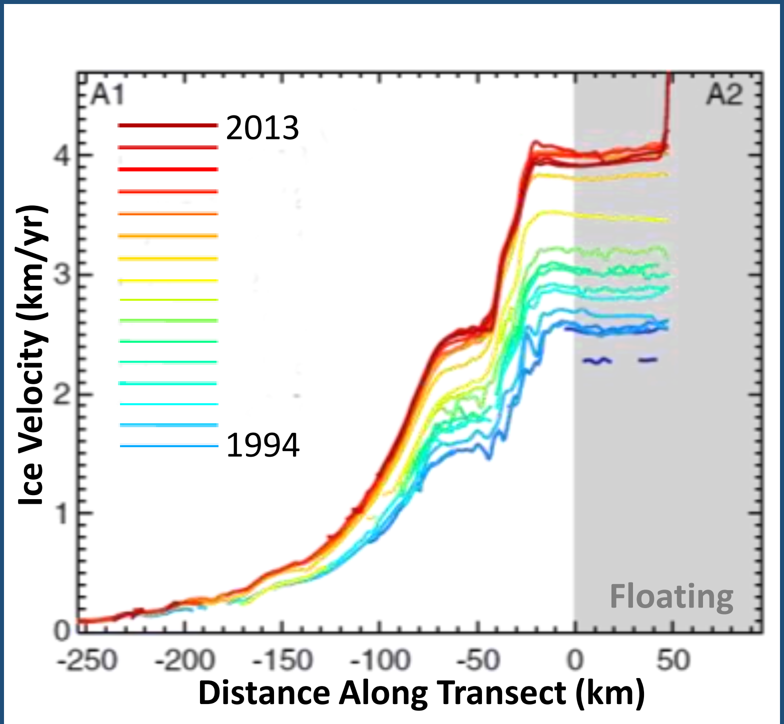


(Shepherd et al., 2019)

- 25-year record of surface elevation change
- Elevation change strongest in West Antarctica
- Occurring at rates of up to 9m/yr on Smith Glacier
- Dynamically imbalanced surface lowering corresponds with ice speedup and grounding line retreat

Dynamic Imbalance in Antarctica

Ice velocity speed-up
1994 – 2010



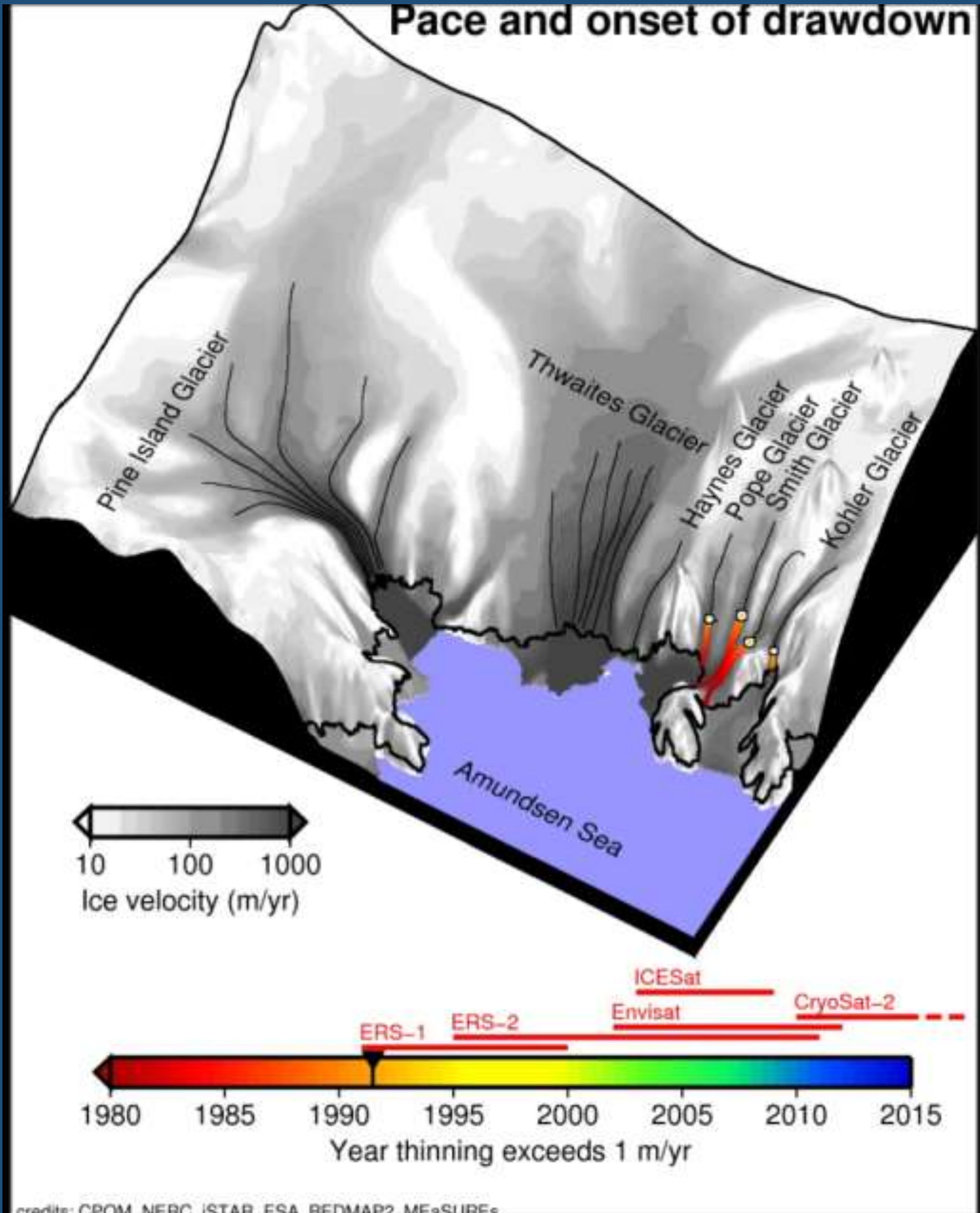
(Mouginot et al, 2014)

- Elevation change strongest in West Antarctica
- Occurring at rates of up to 9m/yr on Smith Glacier
- Dynamically imbalanced surface lowering corresponds with ice speedup and grounding line retreat
- All Amundsen sea glaciers have sped up since the 1990's
- 42 % increase in ice velocity observed on Pine Island Glacier
- Over 30 km of grounding line retreat on Smith Glacier

Observing Present Day Change

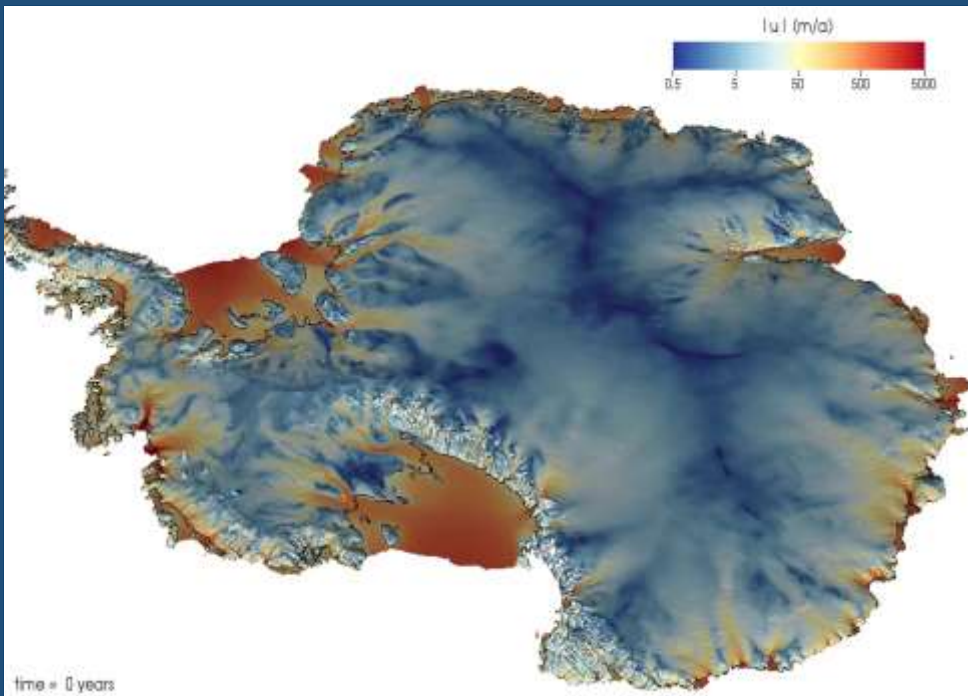
- Observations have shown that the pattern of dynamic imbalance is spatially and temporally variable

- 25 years of dynamic imbalance in Amundsen sea sector shows that onset occurs at different times on neighbouring glaciers

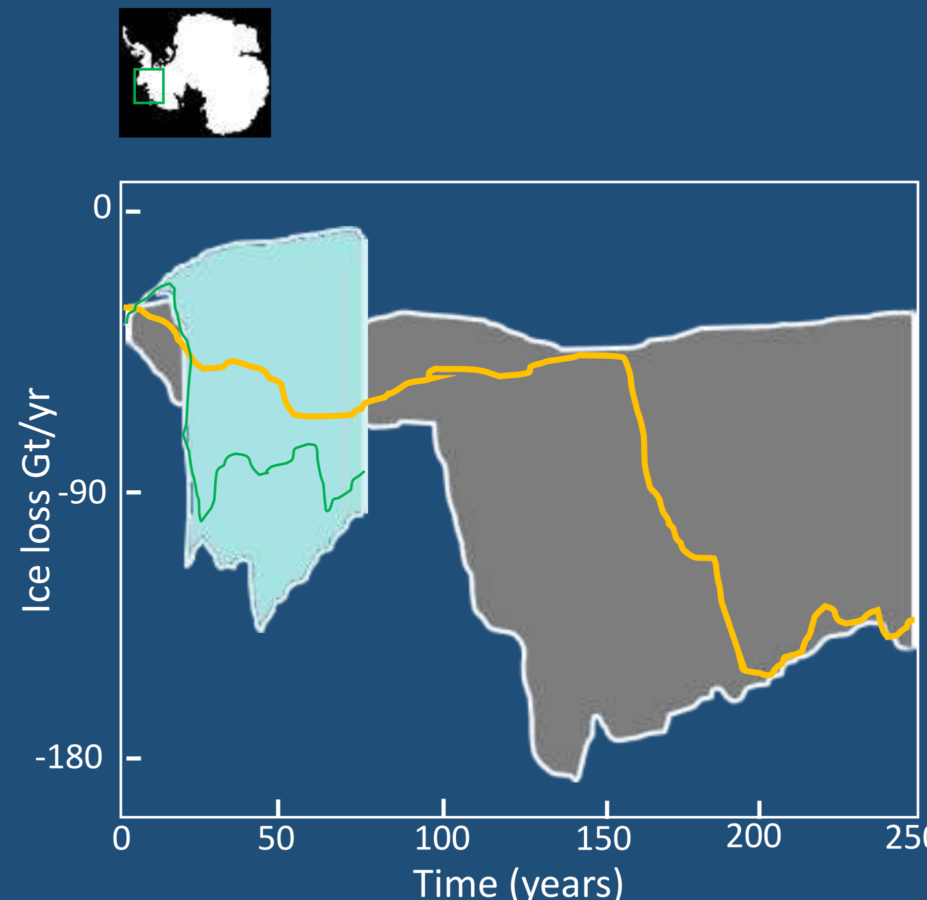


(Konrad et al, 2016)

Predicting Future Change



(Cornford et al, 2013)

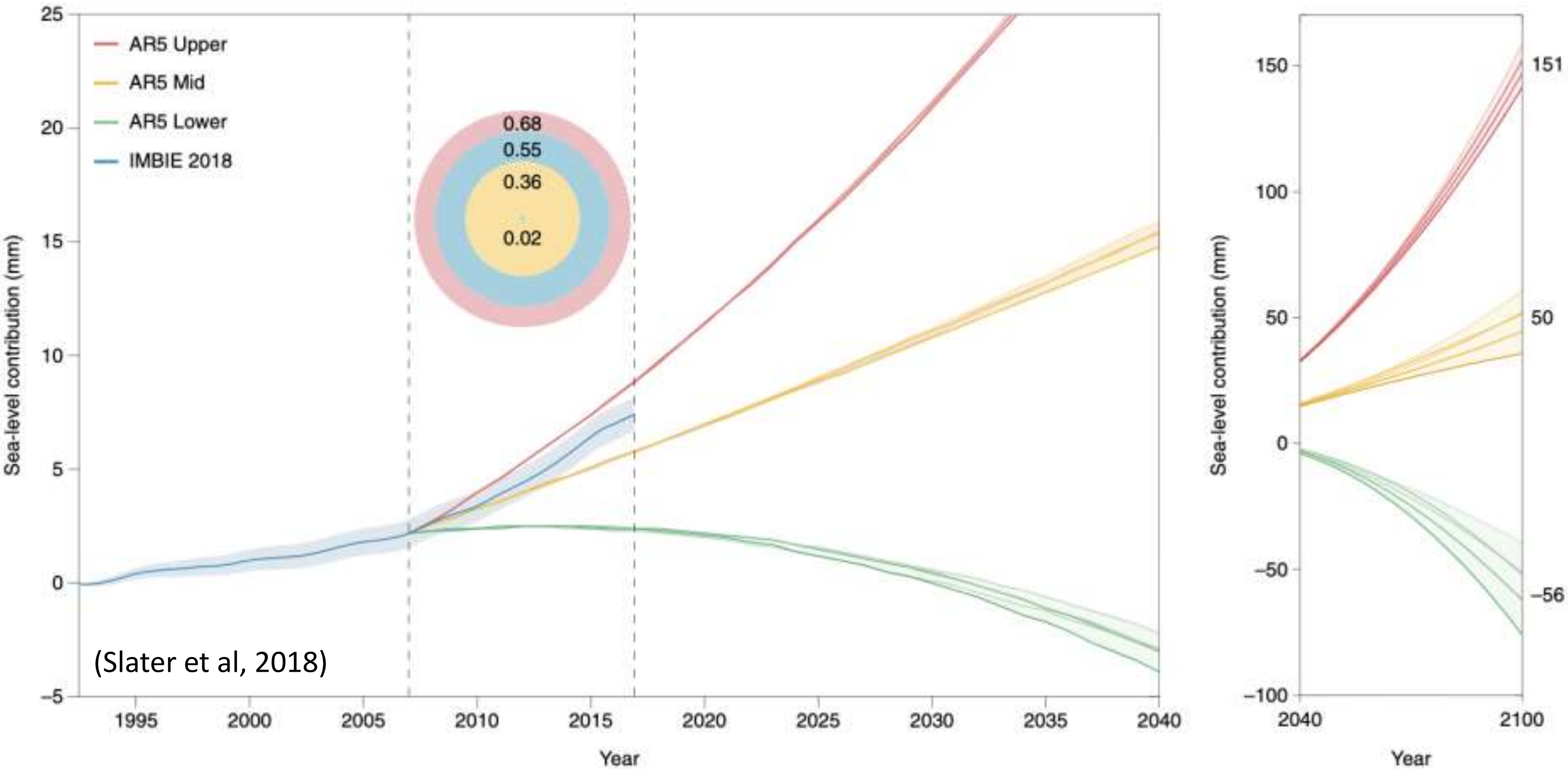


(Joughin et al, 2014)

Pine Island Glacier
Thwaites Glacier

- PIG increase ice loss by 80% in next 20 years
- Thwaites increases in ice loss are lower over next century, increasing rapidly thereafter
- Large spatial and temporal variability in glacier response will continue – monitoring essential

IPCC Reports link to satellite observations



- Since 1992 Antarctica has contributed 7.6 mm to global sea level rise, 40 % has occurred in the last 4 years
- During overlap period, rate of ice loss was 80 % higher than IPCC's central prediction, and is closest to the upper limit predicted loss

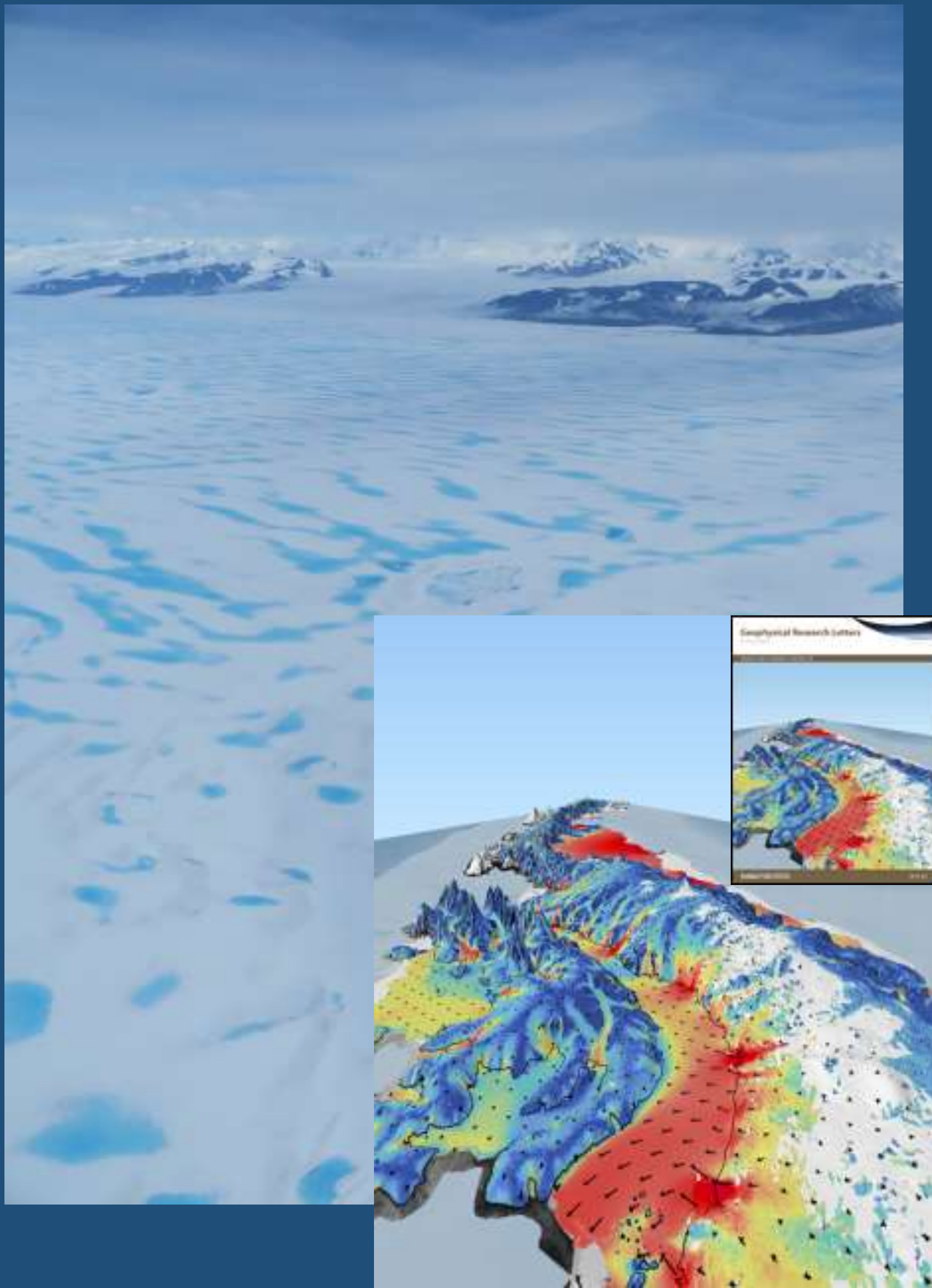
Questions worth answering

1. Is all ice thinning caused by dynamic imbalance?
    - If not what are the other causes, and can we partition the physical processes responsible for triggering change

2. Under what conditions does dynamic imbalance lead to instability?

3. Over what timescale can all these different processes act?
    - Is ice sheet change a long term signal or is it easier for it to start and stop than we might once have thought?

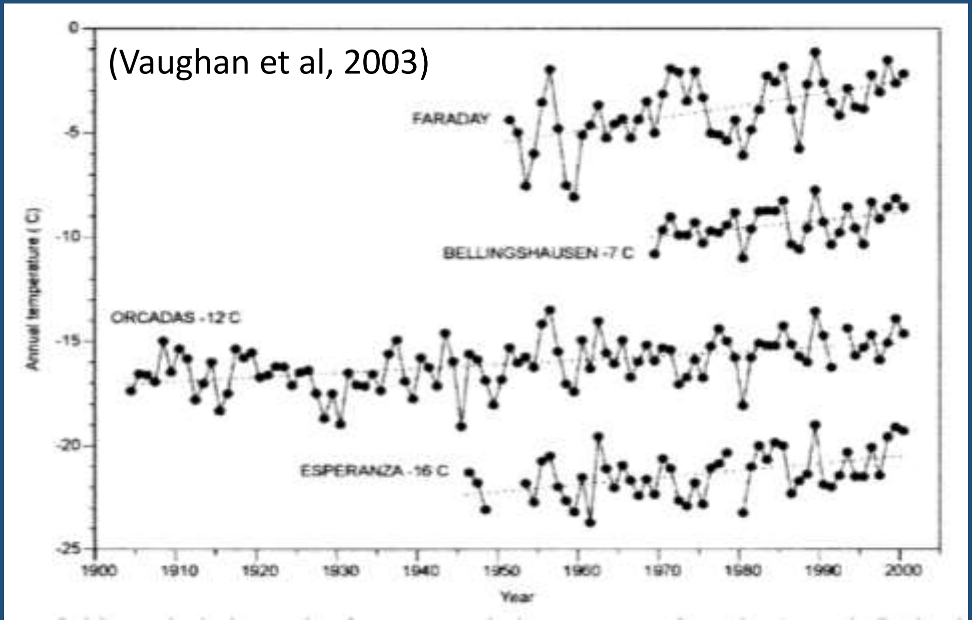
What do we know about the Antarctic Peninsula?



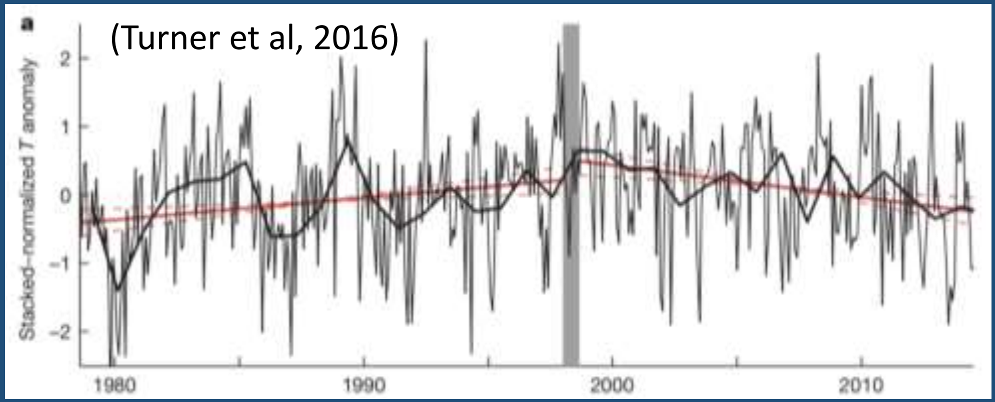
- Most Northerly tip of Antarctica
- Hundreds of small tributary glaciers flow out into the ocean or feed into ice shelves
- The mountainous spine is over 3000m in elevation
  - Has a strong precipitation gradient with high snowfall in the West and low snowfall in the East
  - Also influences strong temperature gradient with dry snow zone at inland Western Palmer Land, & wet snow and melt ponds forming at low elevations and on ice shelves

What do we know about the Antarctic Peninsula?

Air temperatures not simply increasing over time:



Decreased since the late 1990's:



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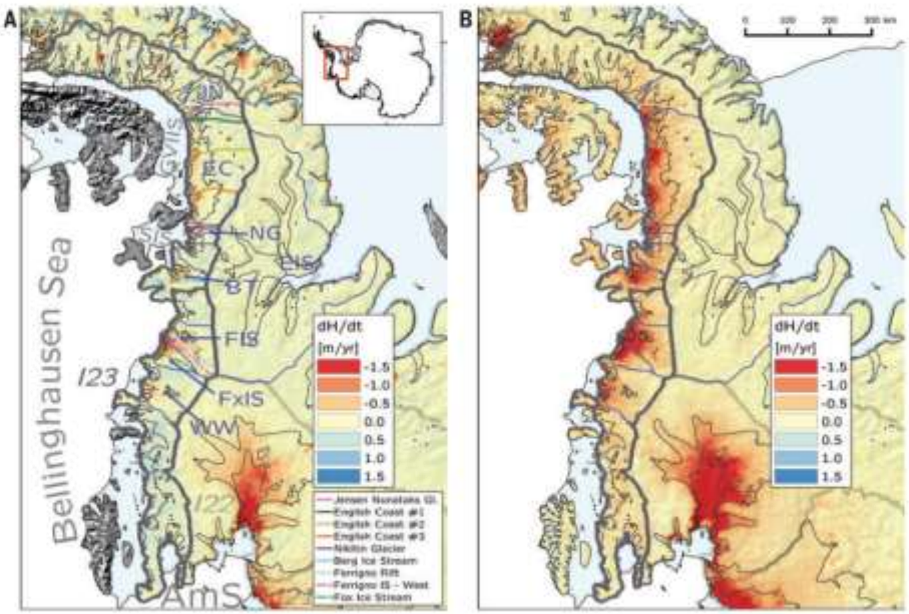
- Environmental change in region is complex

Western Palmer Land Imbalance

GLACIER MASS LOSS

Dynamic thinning of glaciers on the Southern Antarctic Peninsula

B. Wouters,[1*] A. Martin-Español,[1] V. Helm,[2] T. Flament,[3] J. M. van Wessem,[4] S. R. M. Ligtenberg,[4] M. R. van den Broeke,[4] J. L. Bamber[1]

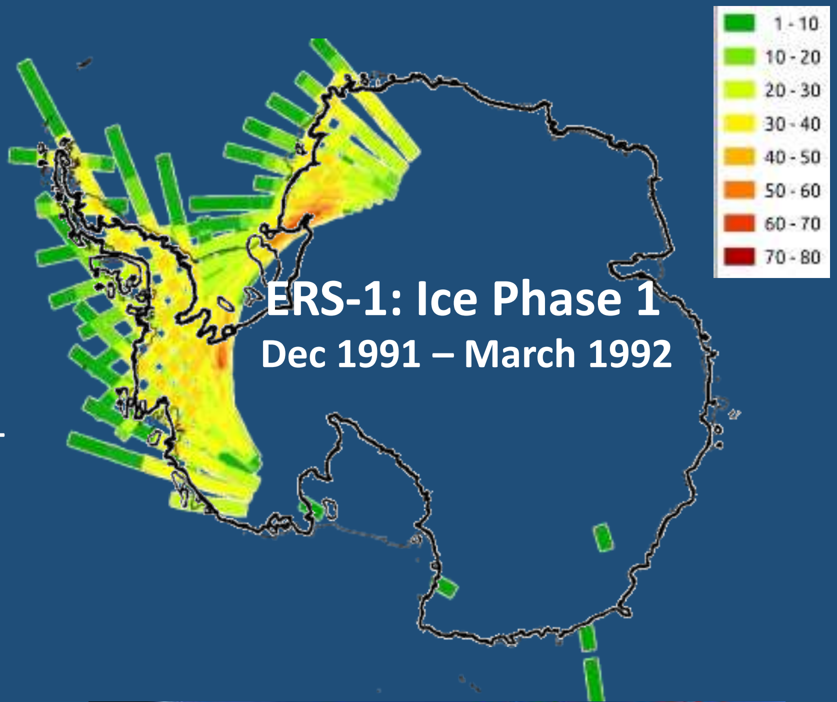


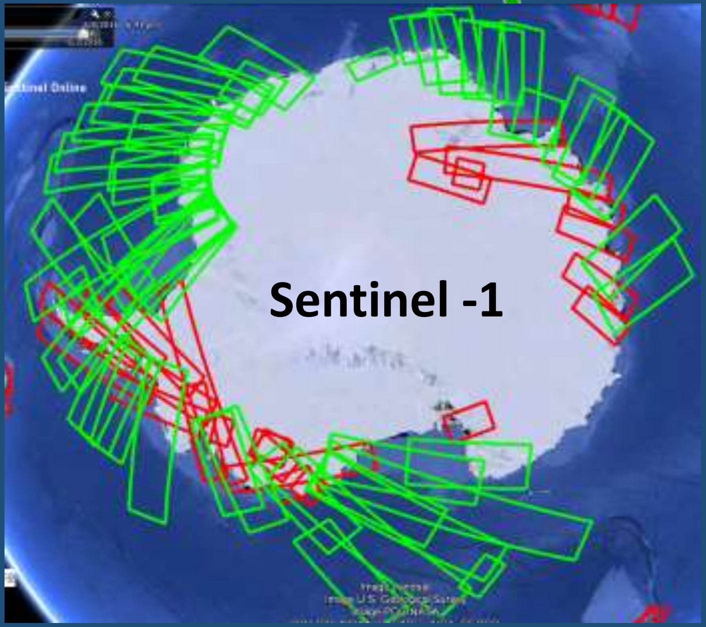
		2003–2005	2007–2009	2003–2009	2010–2014	
basin 23	GRACE	-11±7	-1±11	-6±3	-19±8	Gt/yr
	Altimetry	2±18	-4±8	1±11	-24±5	Gt/yr
basin 24	GRACE	3±20	-11±13	-5±7	-34±12	Gt/yr
	Altimetry	13±18	-6±13	2±19	-35±7	Gt/yr
basin 23+24	GRACE	-8±13	-12±17	-11±5	-52±14	Gt/yr
	Altimetry	15±25	-10±15	3±22	-59±10	Gt/yr

- Compute changes in mass balance from ENVISAT & CryoSat-2 volume changes and GRACE
- Estimated 35 Gt/yr loss of ice
- Attributed to dynamical imbalance
- Raised the prospect that a flow instability is occurring in this marine-based sector of Antarctica
- But, no direct observations of ice flow

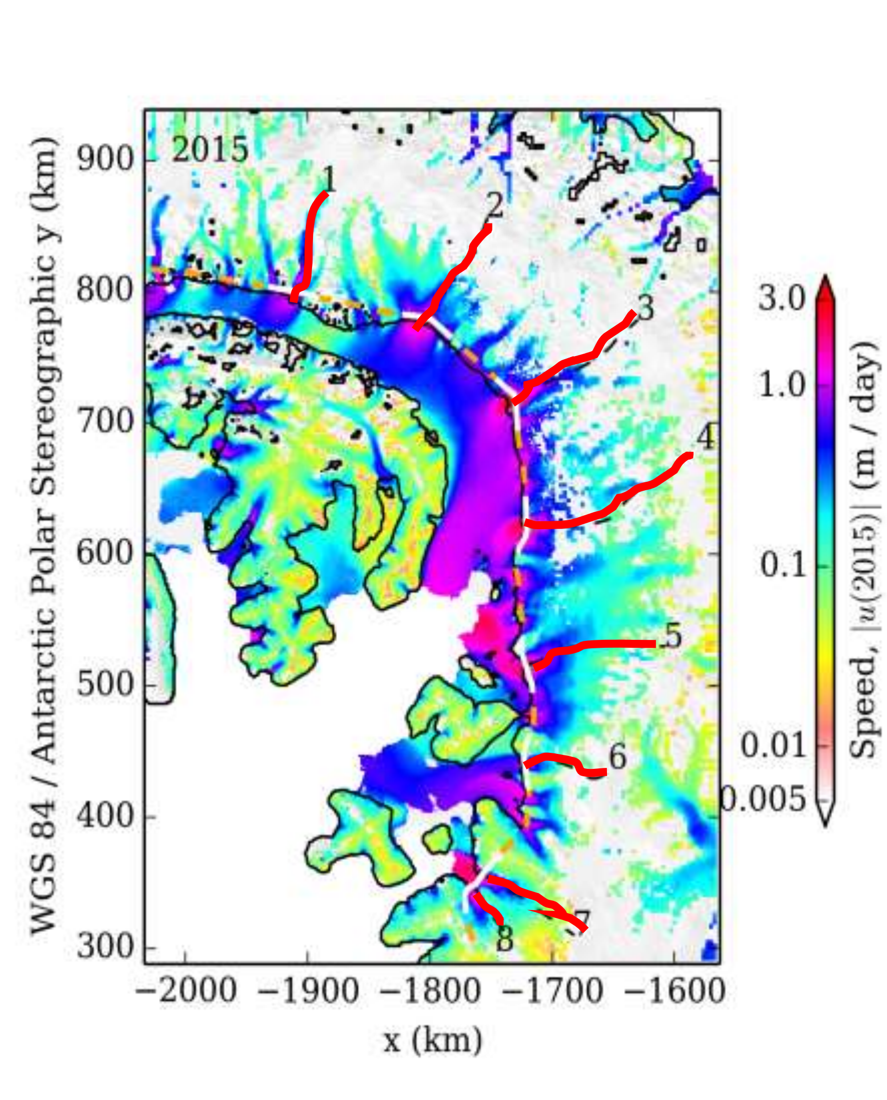
SAR Data

- Historical data from ERS-1/2 & ALOS PALSAR
- Landsat-8 compliments Sentinel data
- Sentinel-1 launched 3rd April 2014, Sentinel1-b launched 25th April 2016
- C-band SAR sensor, all year, day/night, all weather monitoring capability
- 12 day repeat period and large swath provided for the first time the opportunity to routinely monitor ice speed in near real time
- Both satellites combined will provide 6-day repeat coverage
- More data acquired in 1 week by Sentinel-1 than ~ 20 years of ERS combined!



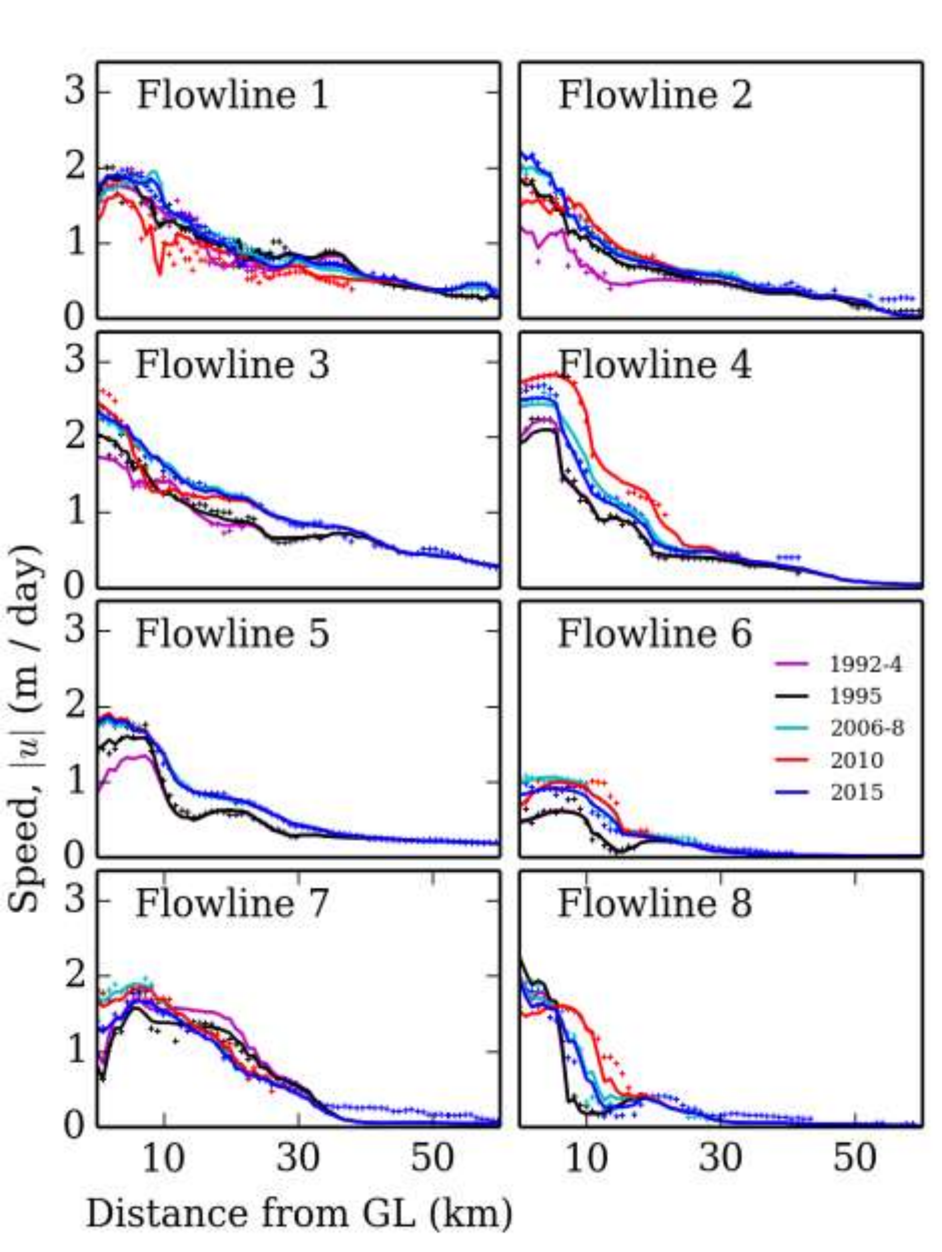


Change in Ice Speed



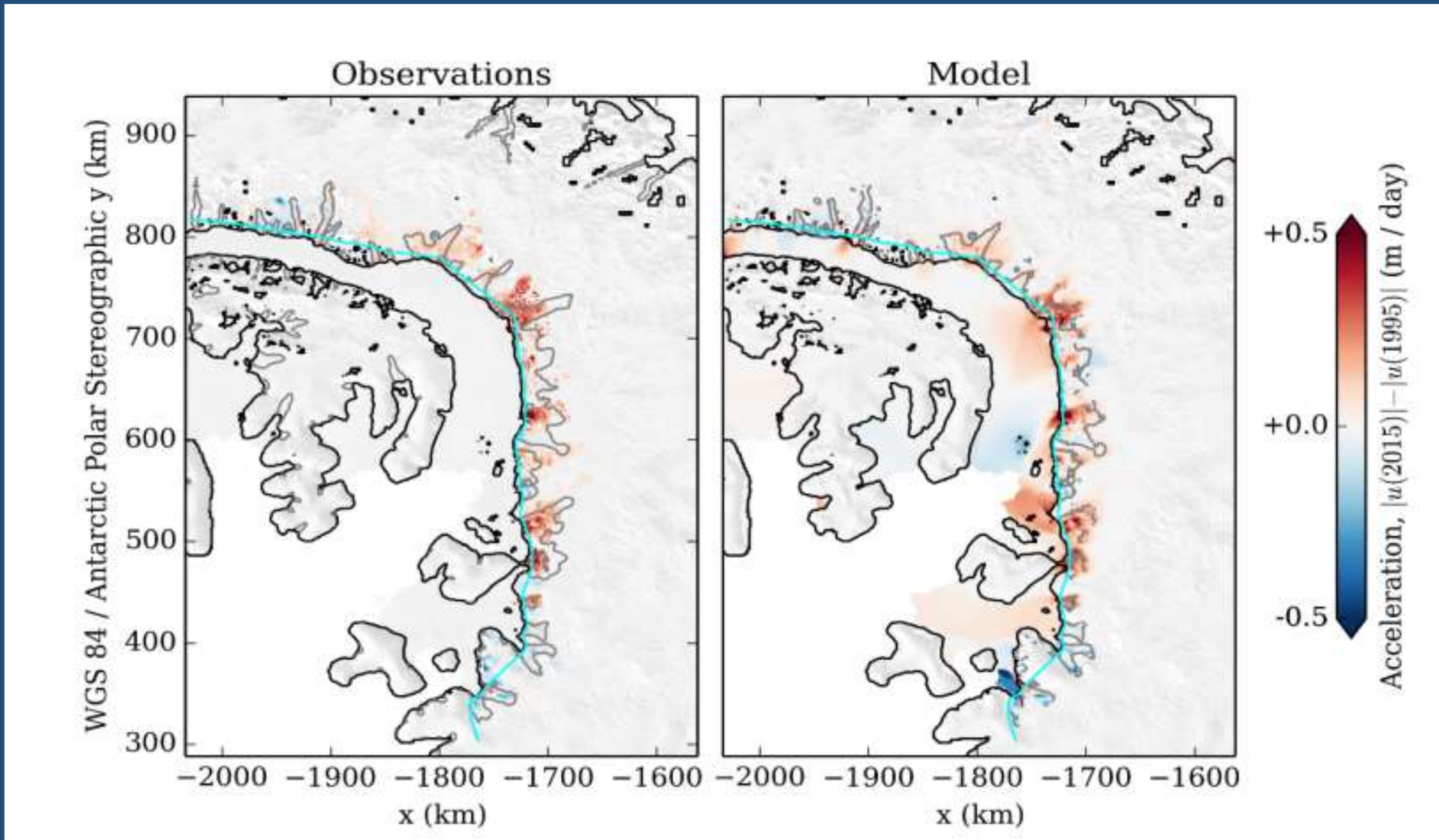
- 30+ glaciers apparent in our velocity data
- 10 reach maximum speeds in excess of 1.5 m/day
- Region of fast flow does not extend far inland
  - at distances greater than 100 km from the coast few areas of ice move at speeds greater than 0.25 m/day
- Generated flow-lines up 8 major flow units along coastline
- Extracted observed and modelled ice speed along each transect

Change in Ice Speed



- Results show good agreement between observed (dots) and modelled (line) spatial and temporal pattern
- Most glaciers have accelerated along their central trunks by between 0.25 - 0.5 m/day since the early 1990’s
- Largest accelerations occurred within the central portion of WPL - where ice flow is fastest
- The speedup represents a net loss of ice from the sector because it extends to the coast

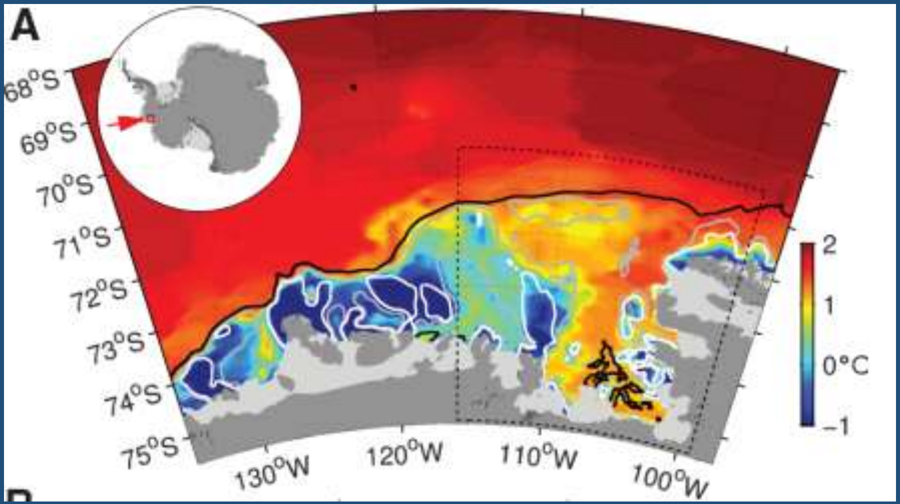
~~20~~ Years of Change in Ice Speed



- Ice speed difference map computed between 1995 and 2015
- Ice flow increased by 13 % over 20 year period
- Ice discharge has increased by 15 km^3/yr

Causes of Dynamic Imbalance

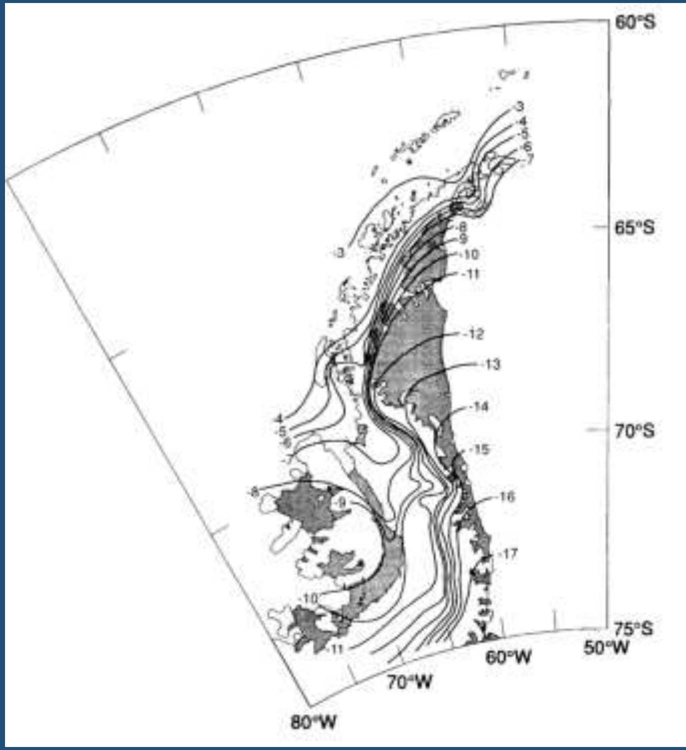
(Dutrieux et al., 2014)



1. Amundsen Sea Sector dynamic imbalance is due to ocean Circumpolar Deep Water (CDW) incursions onto continental shelf

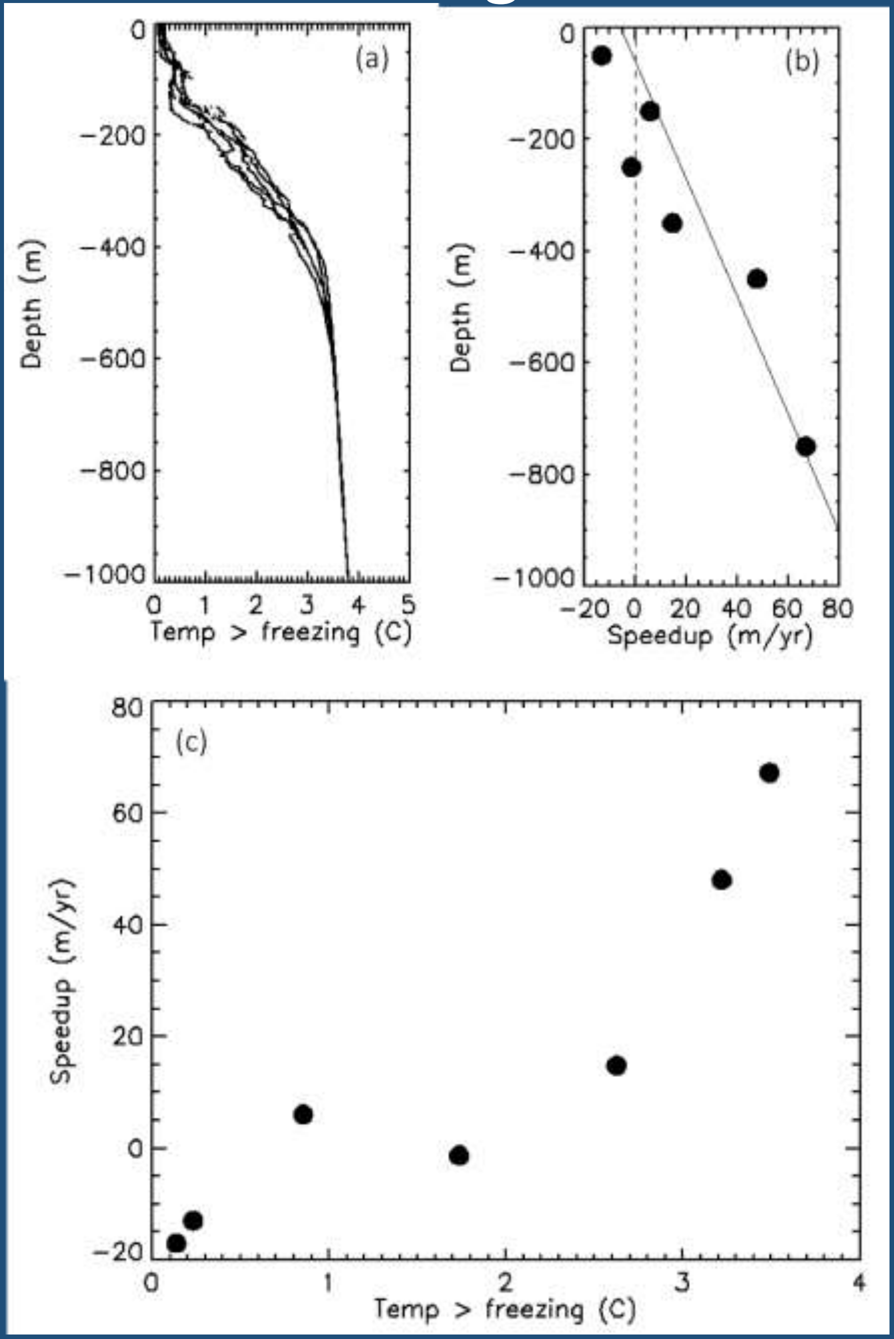
2. Antarctic Peninsula dynamic imbalance has been attributed to combination of atmospheric and oceanographic warming

- Is surface lowering in Western Palmer Land a southward progression of atmospheric warming or a northward progression of oceanographic warming?
    - Lies between the two…



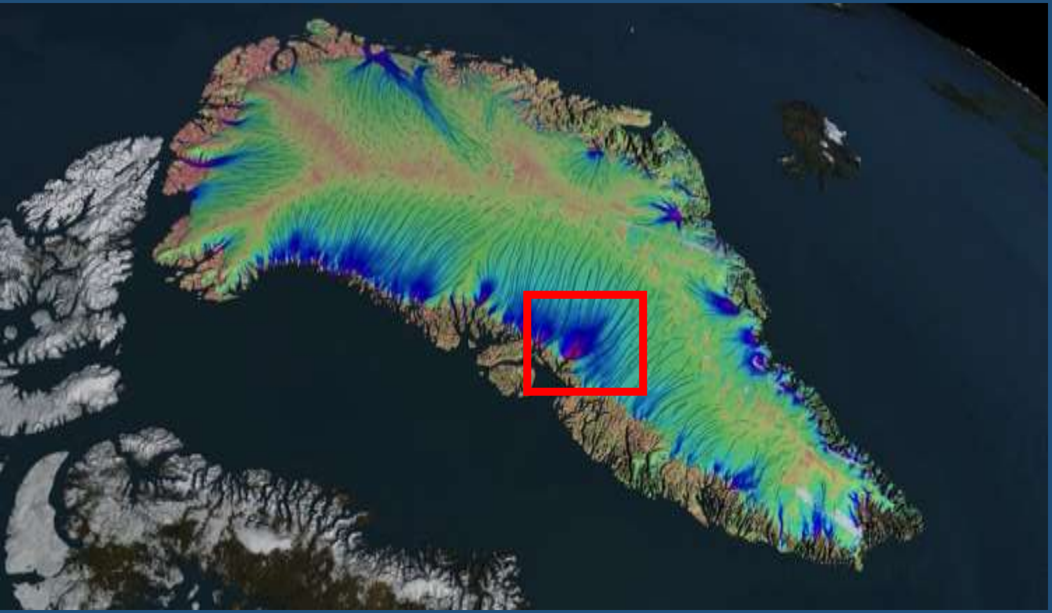
(Vaughan and Doake, 1996)

Ocean Forcing Cause of WPL Dynamics



- Within the sub-shelf cavity beneath George VI ice shelf show that ocean temperatures rise progressively at depths below 200 - 300 m
- Vertical distribution, correlates with the pattern of ice speedup – increased by 13%
- Speedup is greatest where glaciers are grounded more than 300 m below sea level
- Accounts for 35% of inland deflation observed, remainder is a snowfall shortfall

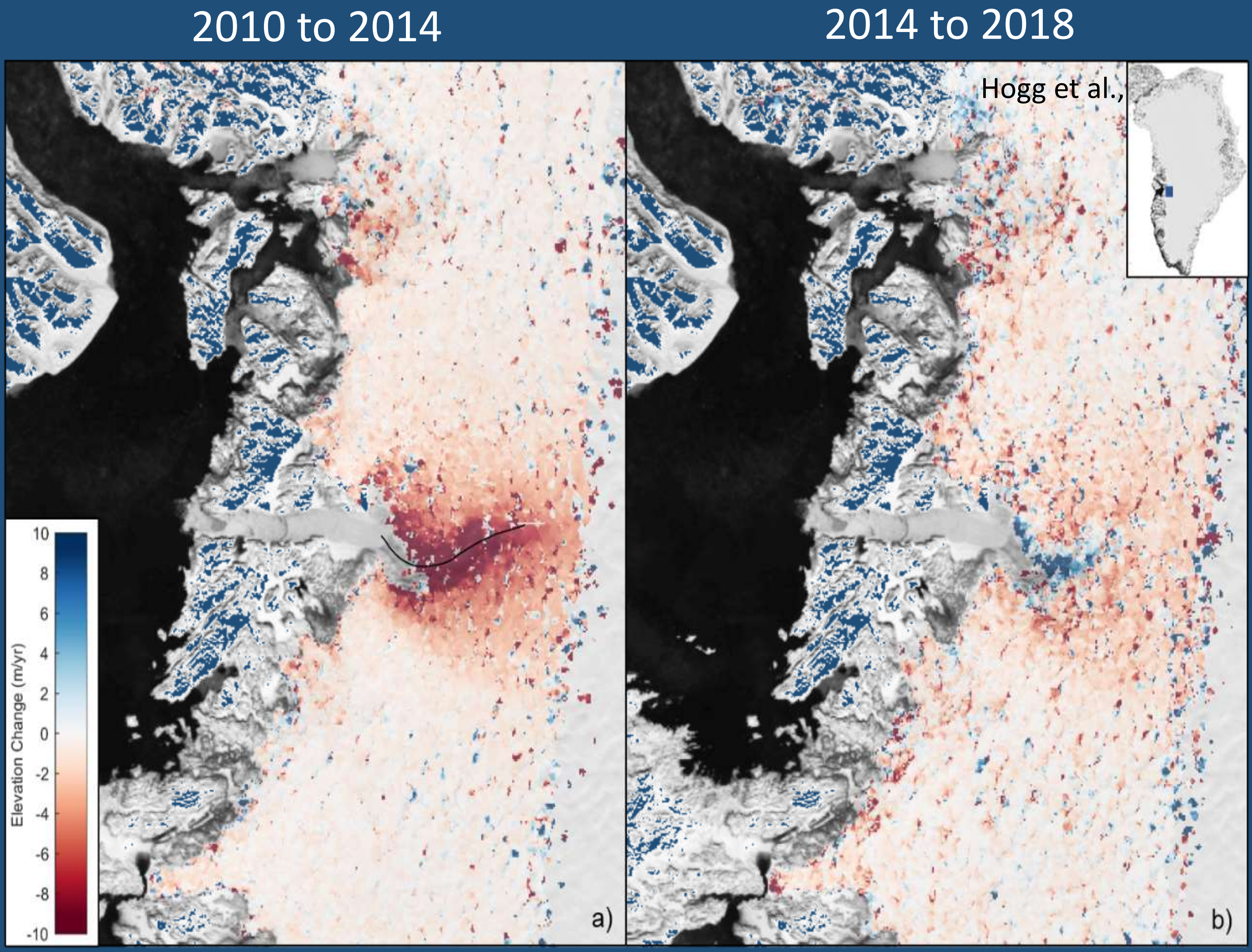
Jakobshavn Isbrae, Greenland



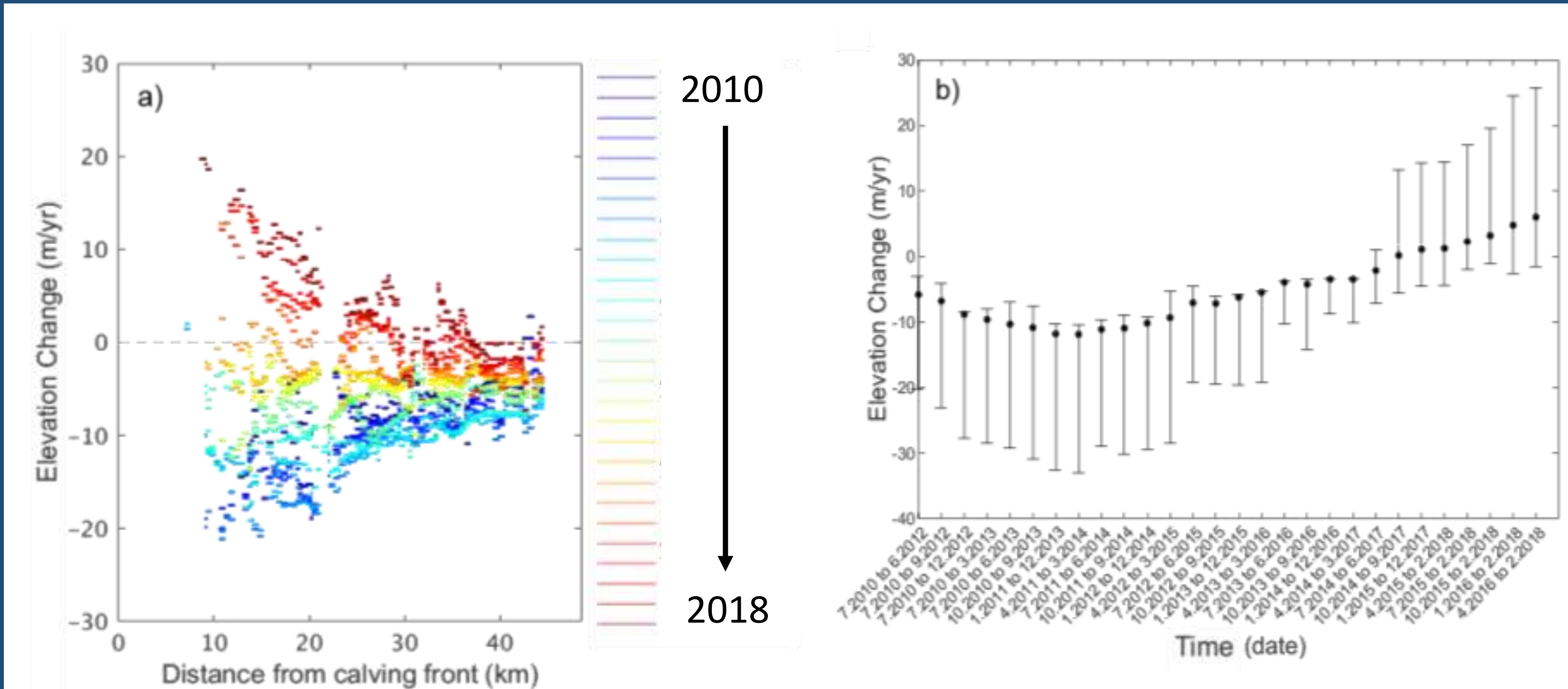
- One of the fastest flowing ice streams in the world
- 17 km/yr in 2012, 154 % increase since 1985
- Speedup of up to ~50 % recorded during the summer months

- Short and long-term changes in speed have coincided with the cycle of dynamic ice thinning
  - peak rates of over 50 m/yr
  - more rapid ice loss at low elevations and during the summer
- Sits on asymmetric bed topography, 1100 m below sea level, with retrograde bedrock slope
- Change triggered in 1997 by an influx of warm ocean water from the Irminger Sea, over a 400 m deep sill at the fjord mouth

Jakobshavn Isbrae

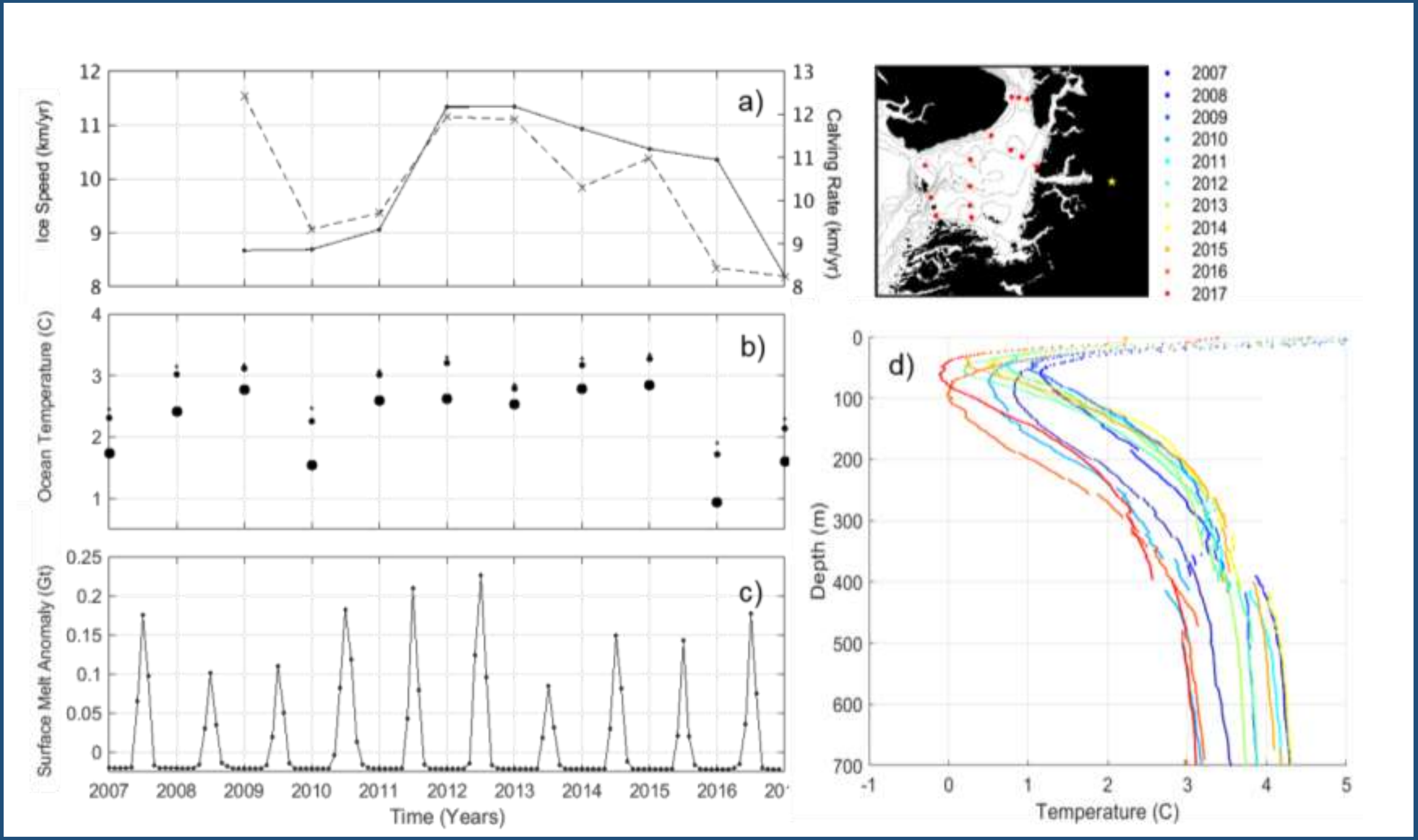


Jakobshavn Isbrae



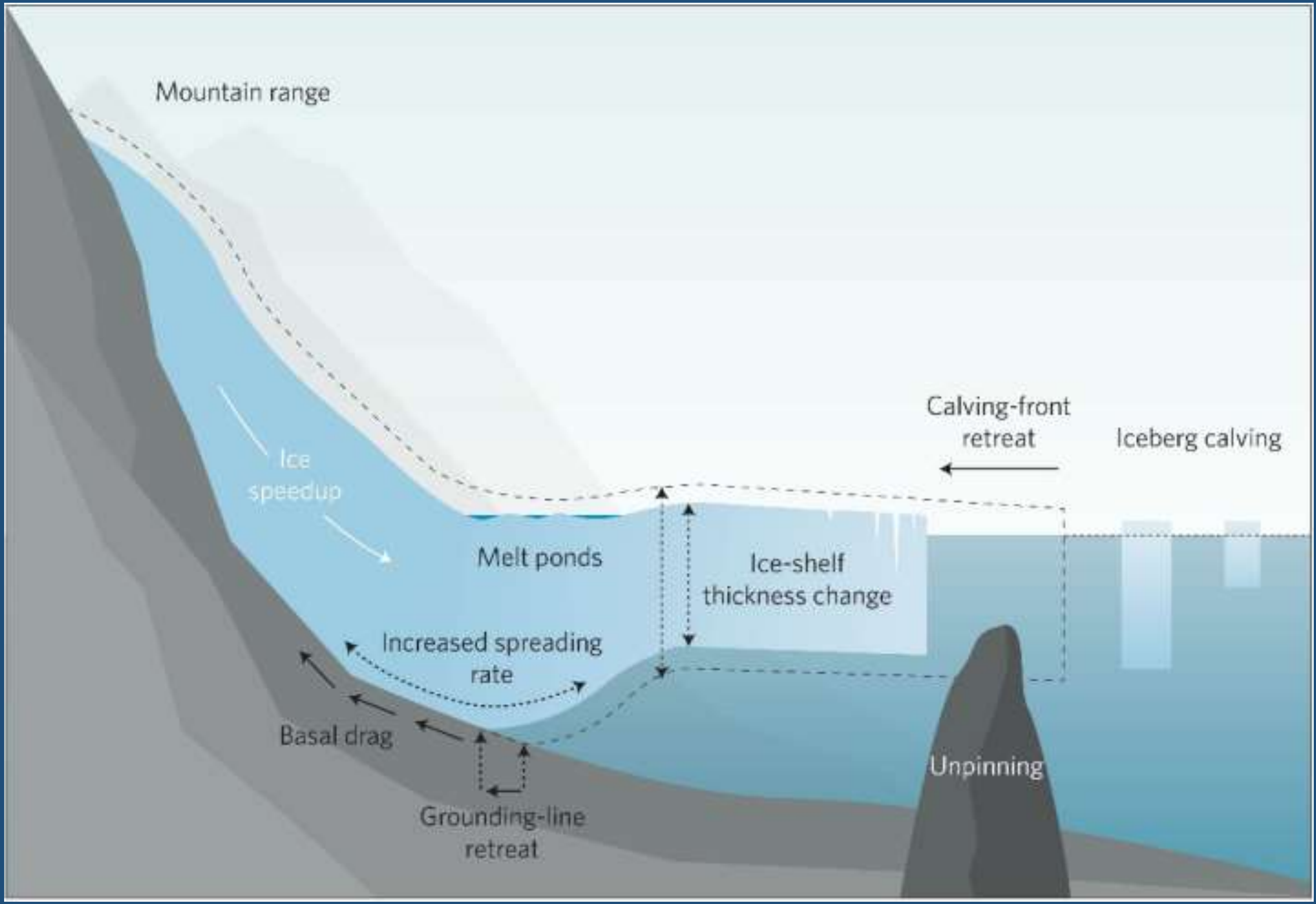
- Thinning has subsided, or reversed since 2014
- Has dynamic imbalance of Jackobshavn Isbrae paused, or even switched off since 2014?
- Is the same signal visible in the ice speed, or the possible forcing mechanisms?

Jakobshavn Isbrae



- Fast ice speeds occur at same time as high thinning rates.
- Slowdown in speed also observed after 2013
- Coincident with slowdown in thinning

Importance of ice shelves

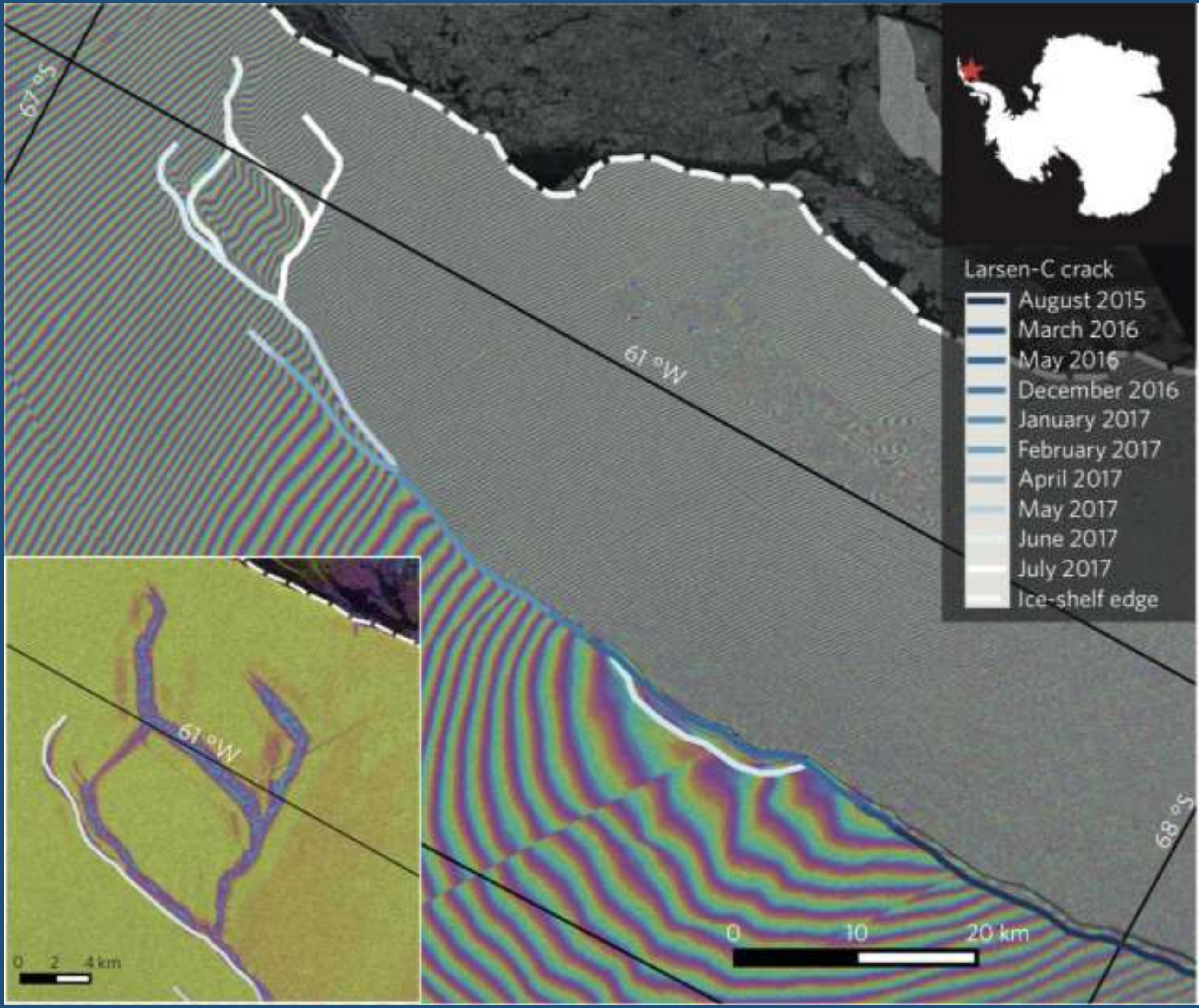


- Link grounded ice with the ocean which is important because:
  - Ice loss caused by atmospheric and oceanic forcing
  - Dynamic instability linked to ocean forcing

Ice Shelf Collapse and Calving

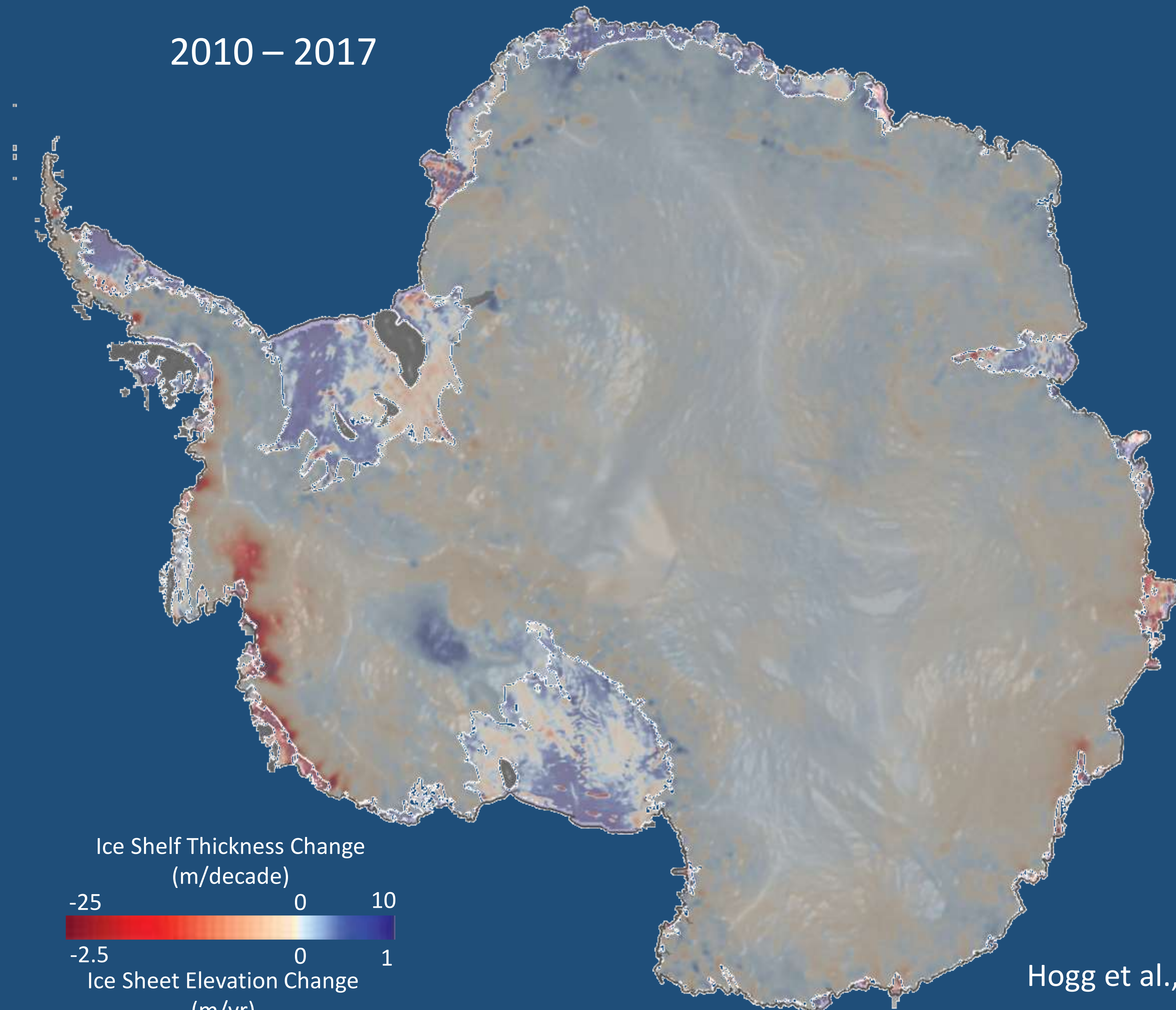
Larsen-A & B collapse

Larsen-C Iceberg Calving



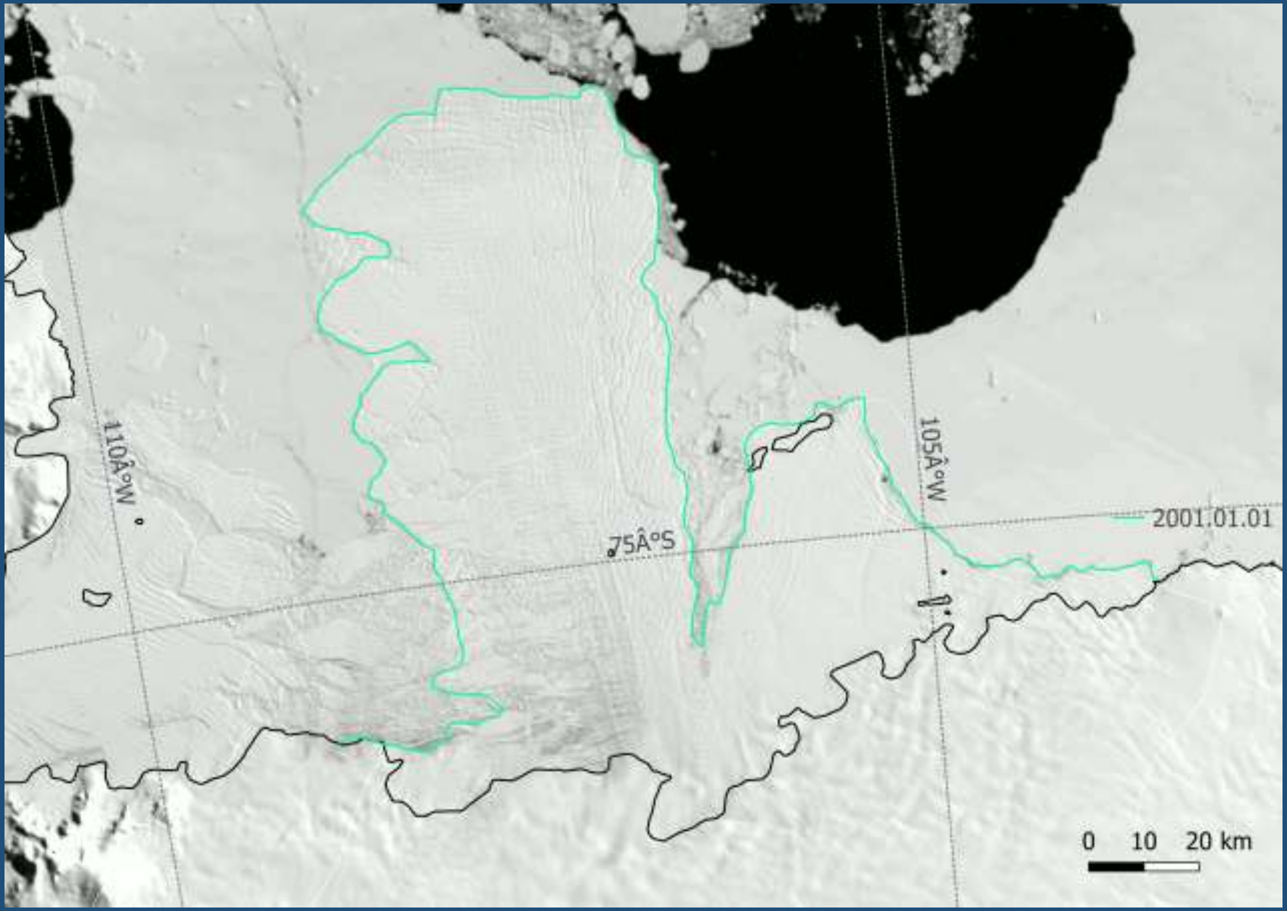
Hogg et al., 2017

Ice shelf Thickness Change



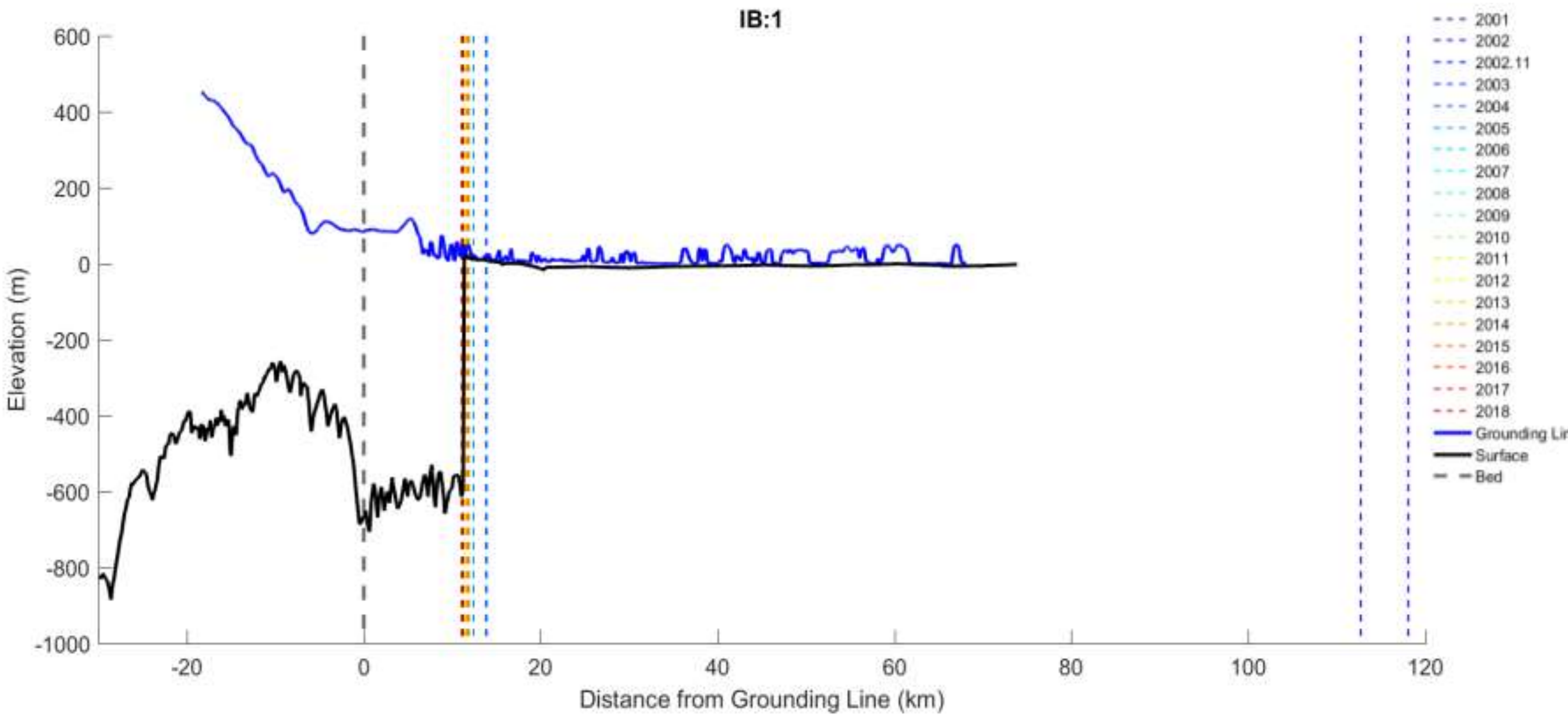
Hogg et al., 2019

Thwaites Glacier: Ice Shelf to tidewater transition



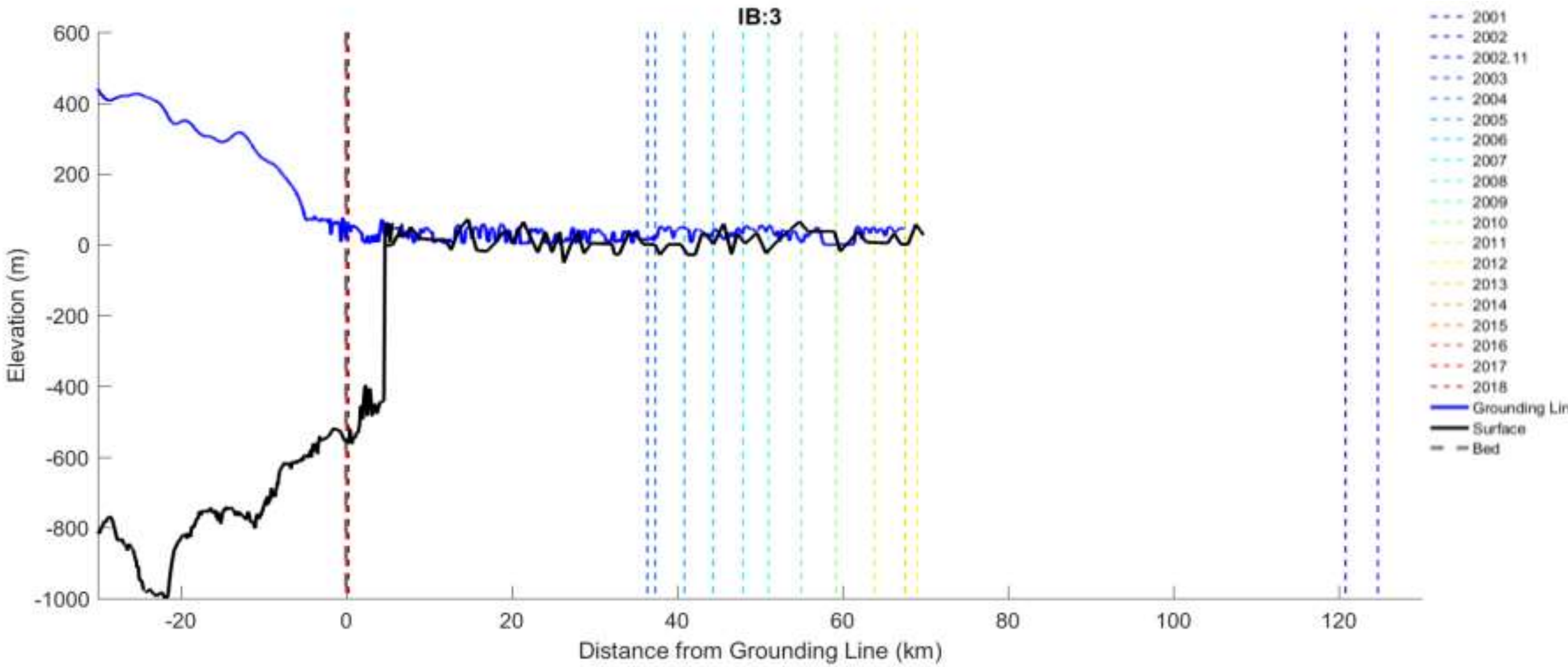
- After 39 years of cyclical growth and retreat, Thwaites Glacier calved a large section of its floating ice-shelf in 2012
- In the 6 years there has been no re-growth, and the ice-shelf remnant has continued to disintegrate.
- Now transitioned to a tidewater glacier, with rapid iceberg calving at the grounding line.

Thwaites Glacier: Ice Shelf to tidewater transition



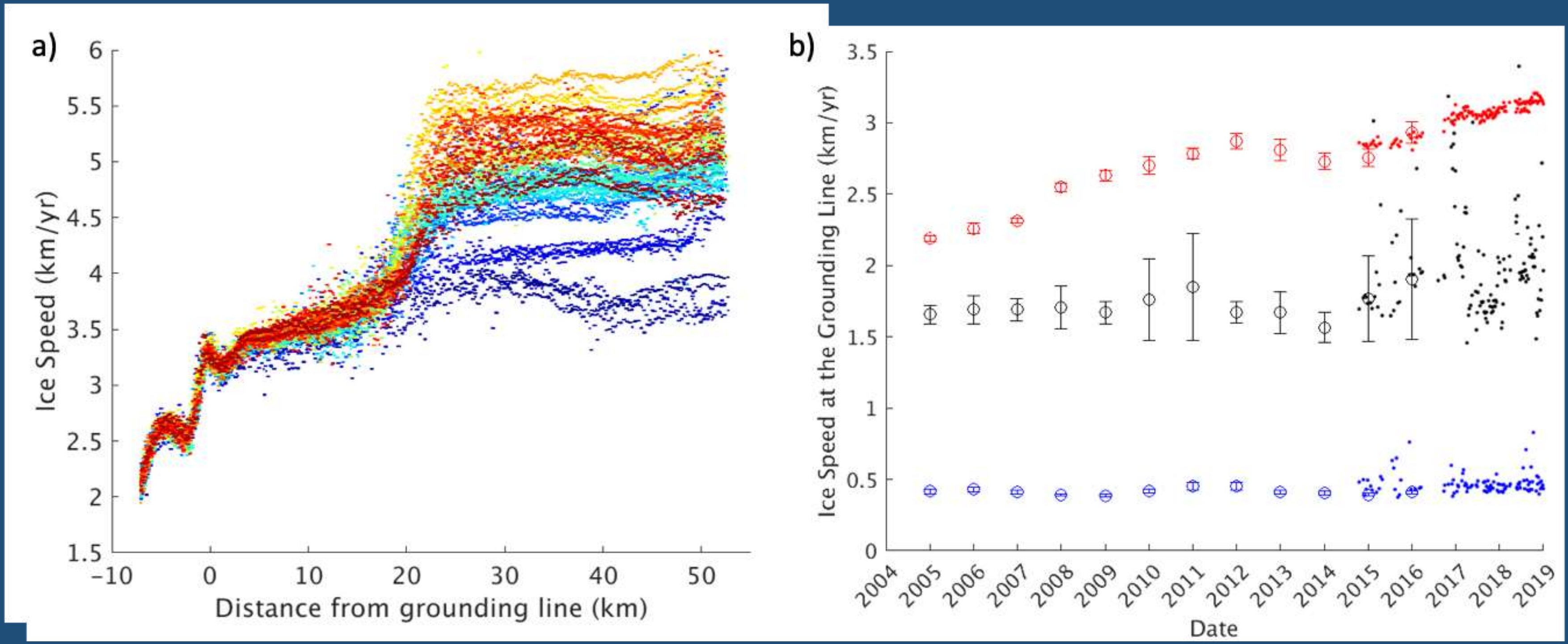
- On profile 1, the calving front retreated in 2002 leaving behind a small but stable shelf remnant
- Bedrock topography shows large hill which the grounding line is pinned to and can't retreat past

Thwaites Glacier: Ice Shelf to tidewater transition



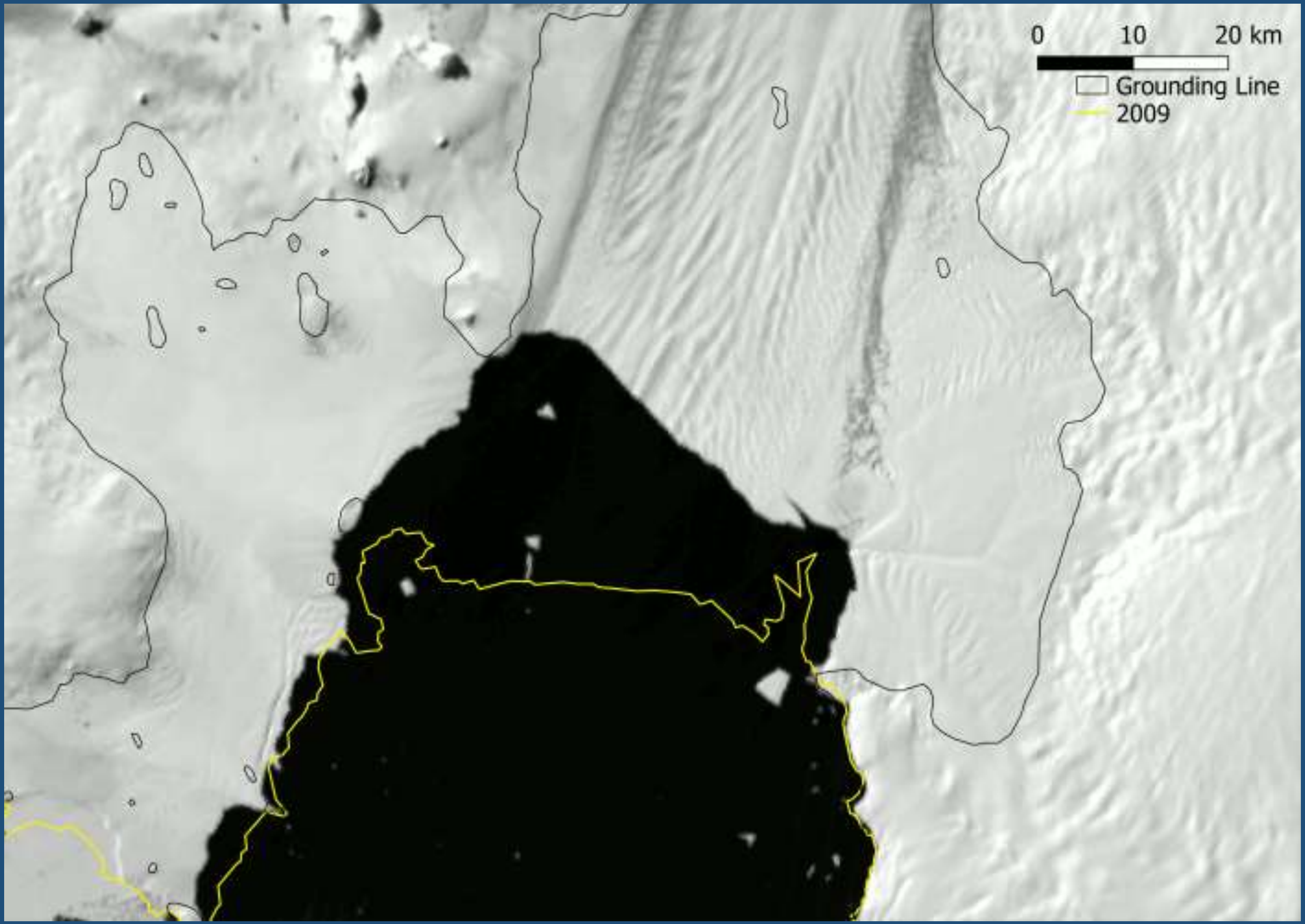
- On profile 2, the calving front retreat has been much more continuous
- Bedrock topography is a retrograde slope, providing favourable conditions for unstable retreat.
- Ice cliff is 90 m high, and ice 800 m thick

Thwaites Glacier: Ice Shelf to tidewater transition



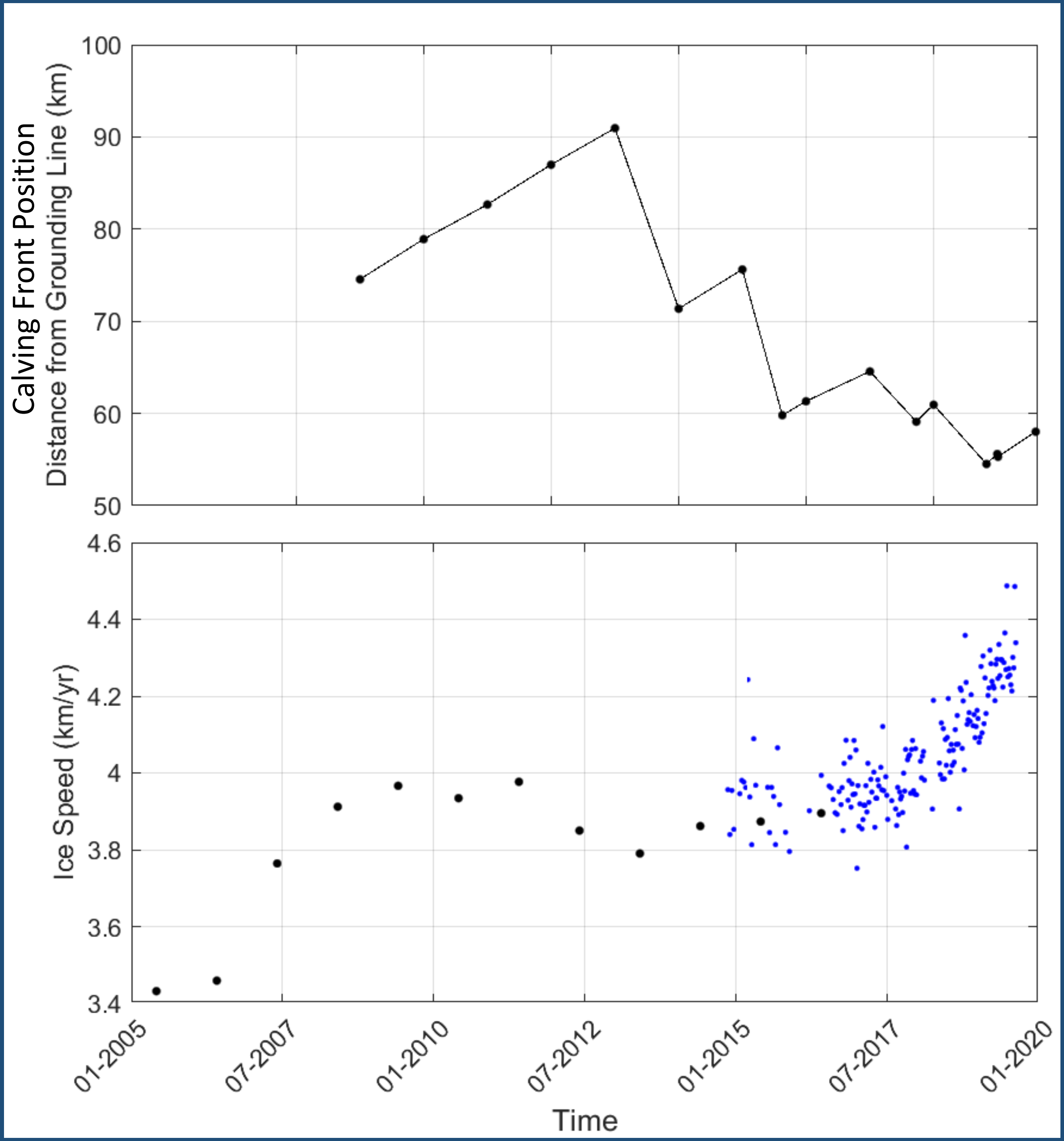
- Dynamic activity triggered in 2000 has controlled the pattern of ice loss on Thwaites Glacier, and since the ice cliff formed ice speeds have increased by a further 1000m/yr at the grounding line.

Pine Island Glacier: Renewed speedup



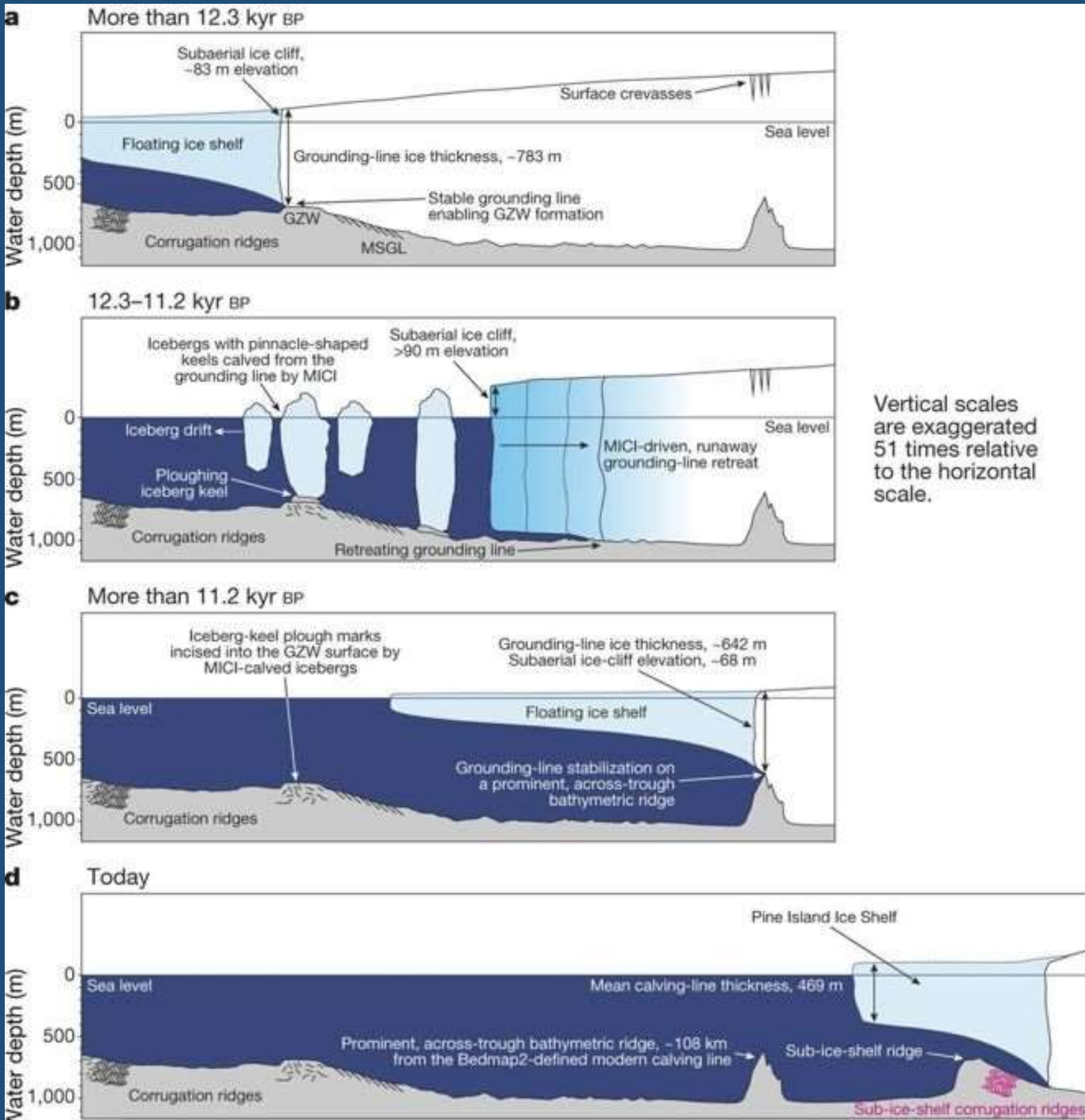
- Calving characterised by advance then iceberg calving ~ once per decade
- In last 4 years calving occurring with unprecedented frequency: 5 major events, with another large crack forming ~10 km inland

Pine Island Glacier: Renewed speedup



- Change in calving front position corresponds with recent changes in ice speed
- Specifically, the ice speed up started in earnest in mid ~2017 and continues through to the present day, when the calving front was the most receded on record.

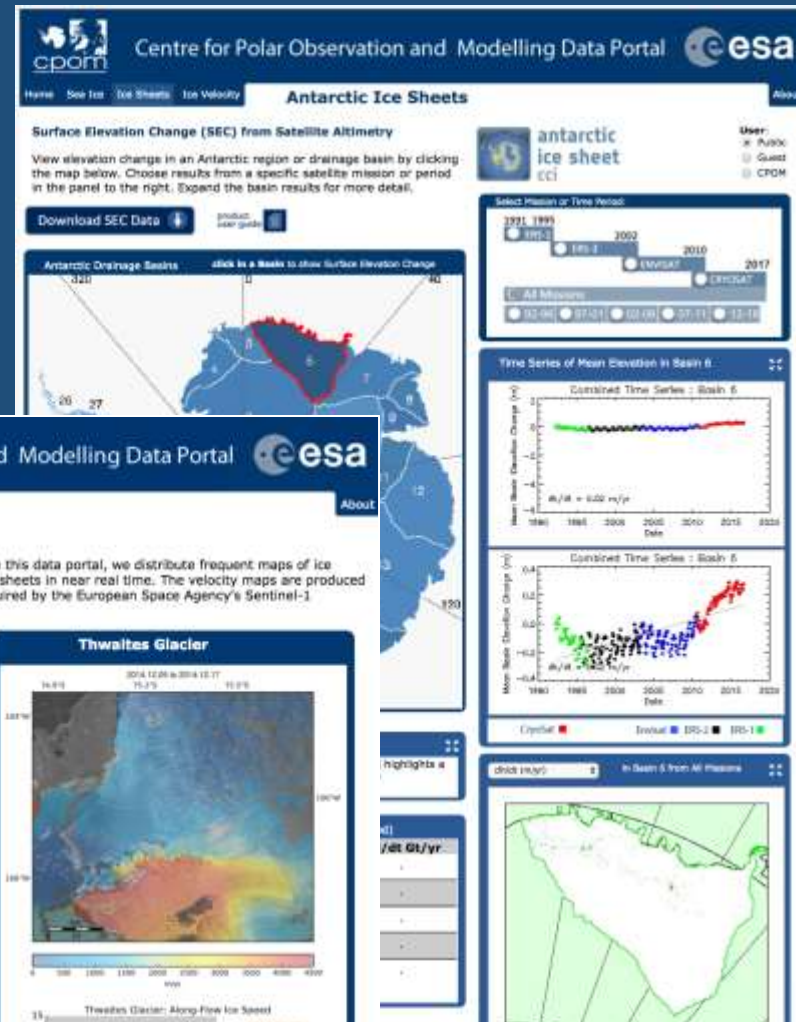
Marine Ice Cliff Instability

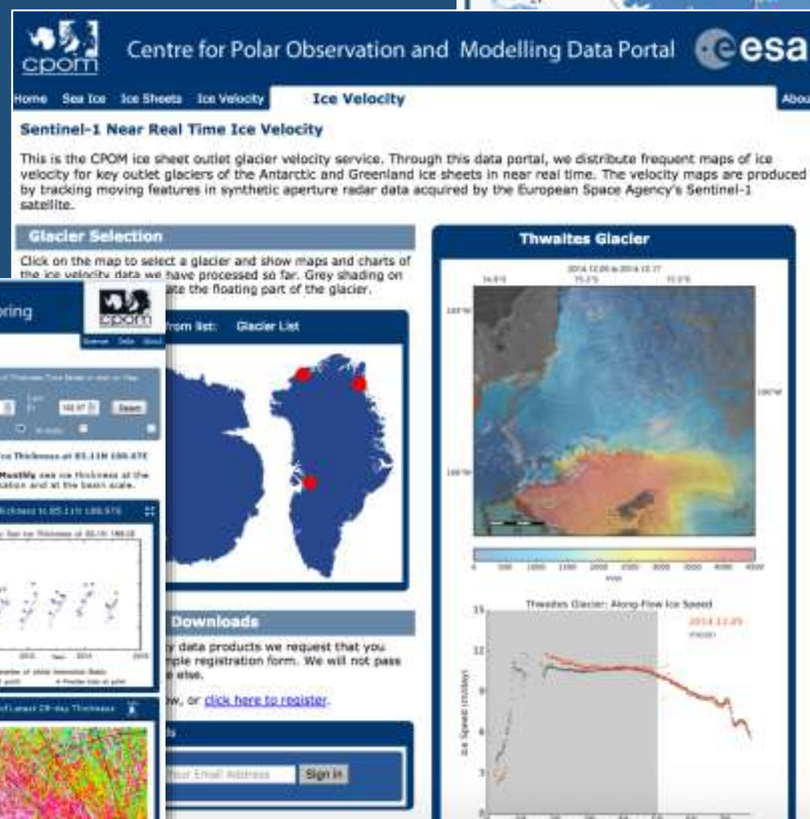


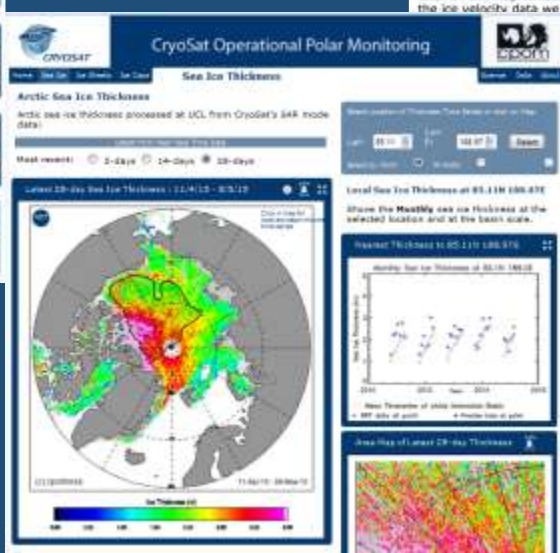
- All high end ice sheet sea level contribution scenarios rely on the ‘marine ice cliff instability’ mechanism (MICI)
- The western shelf of twaites appears to now meet the theoretical thresholds for MICI instability
- Imbalance is ongoing, but instability not triggered in last few years.
- Why?
- Dynamic activation of ice streams can switch on and off over short yearly time scales, so what's holding thwaites back?
- Can we rule out the high end sea level rise scenarios for the next IPCC?

CPOM EO Data Portals

- Processed satellite data - use products to answer open science questions
  - CPOM Data Portal
    - Sea ice thickness and ice velocity
    - http://www.cpom.ucl.ac.uk/csopr/iv/
  - ESA Climate Change Initiative (CCI)
    - Not just the cryosphere…
    - http://cci.esa.int/







Summary and Future Outlook

- Satellite remote sensing is a fascinating are of research that is complimentary to all areas of Earth science.
- The volume and quality of satellite data available has dramatically improved even within the last 5 years, revolutionising our ability to monitor the Earth surface and environmental change.
- Satellite EO has revolutionised our ability to observe changes in the cryosphere
- Sill more to be found out…
- Far too much data to analyse manually, so need to develop intelligent, semi automated computer solutions.
- Exciting challenge for the future!

Photo Credit: A. Hogg, Driving DELORES Radar on Pine Island Glacier with D. Vaughan