Measuring Grounding Lines with QDInSAR

A. Hogg

~~Measuring Grounding Lines with QDInSAR~~

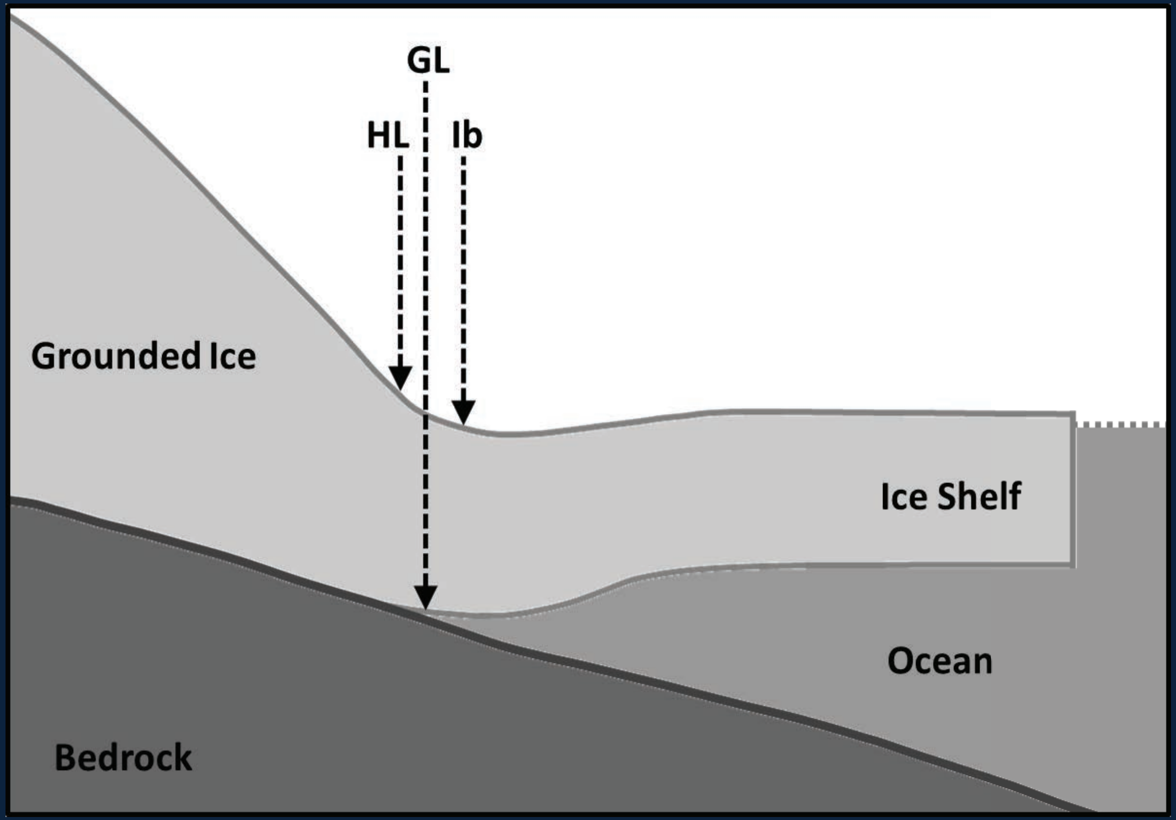
SAR Applications – many things, but not ice velocity!

A. Hogg

Contents

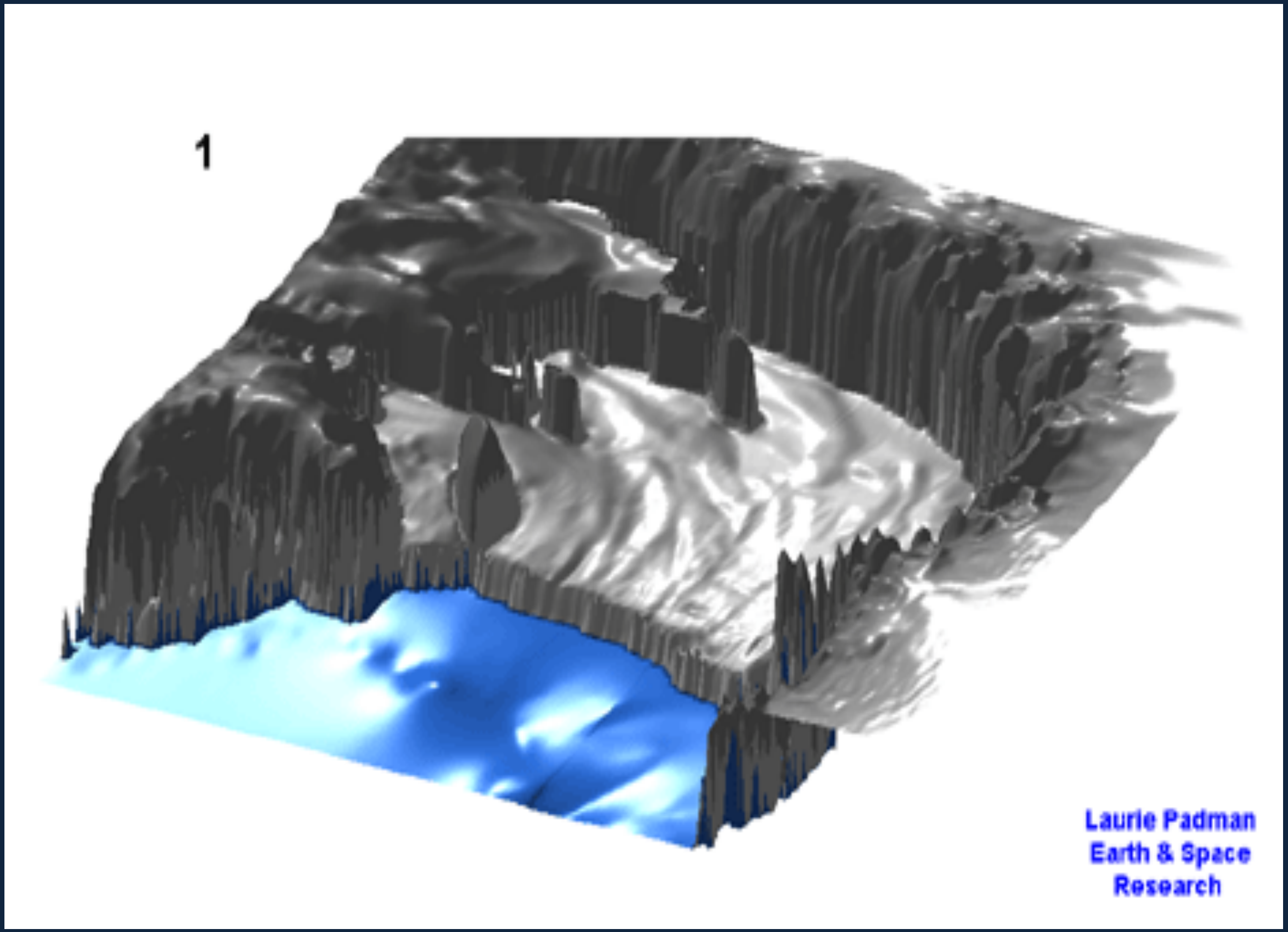
Importance of Grounding Lines

Grounding line is boundary between ice, bedrock and the ocean



Cross-section of an ice sheet grounding zone showing the relative position of the grounding line (GL), the hinge line (HL) and the break in surface slope (Ib)

Importance of Grounding Lines

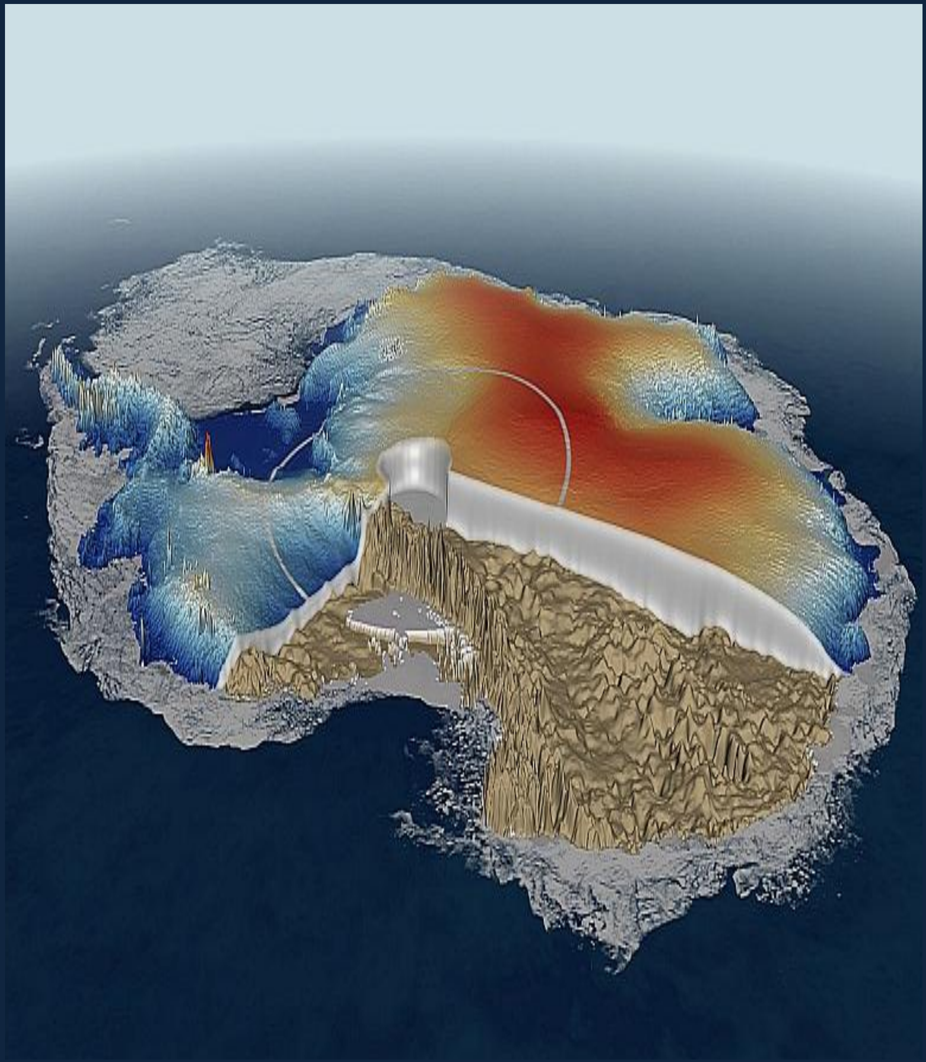


- Transitory feature that moves on:
  - short time periods, due to ocean tides, atmospheric pressure changes
  - long time periods, due to ice thinning and dynamic imbalance

Importance of Grounding Lines

Grounding lines are important because they:

(1) Mark the lateral extent of an ice sheet / ice stream

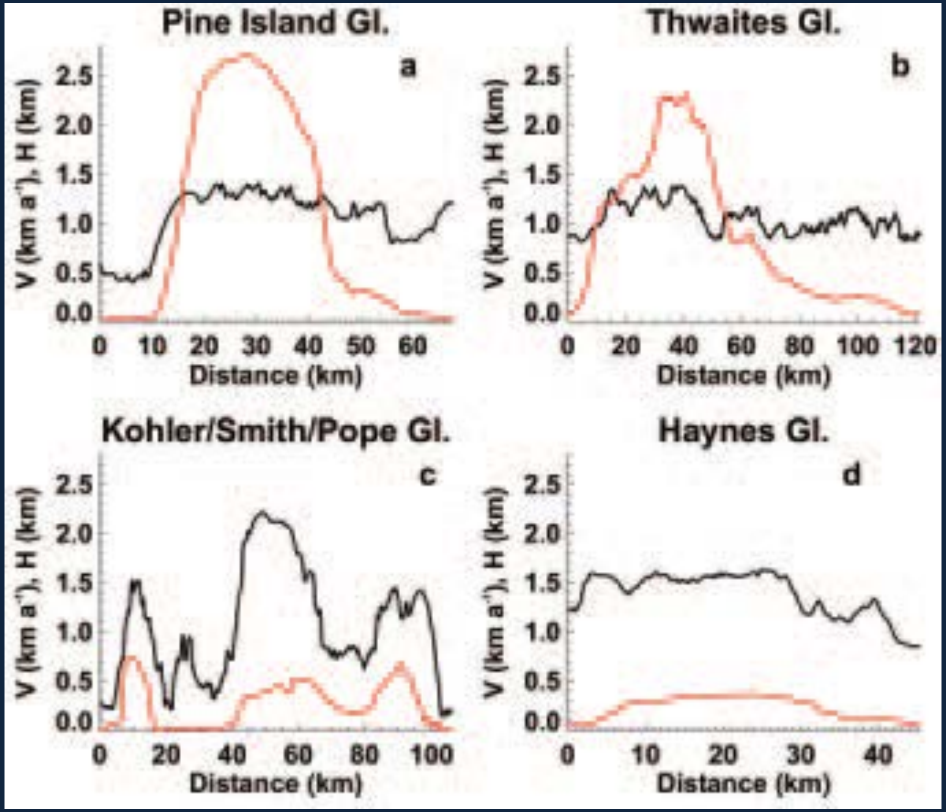


Importance of Grounding Lines

Grounding lines are important because they:

(1) Mark the lateral extent of an ice sheet / ice stream

(2) Are used to define flux gates for ice sheet mass budget estimates



Rignot et al., 2006

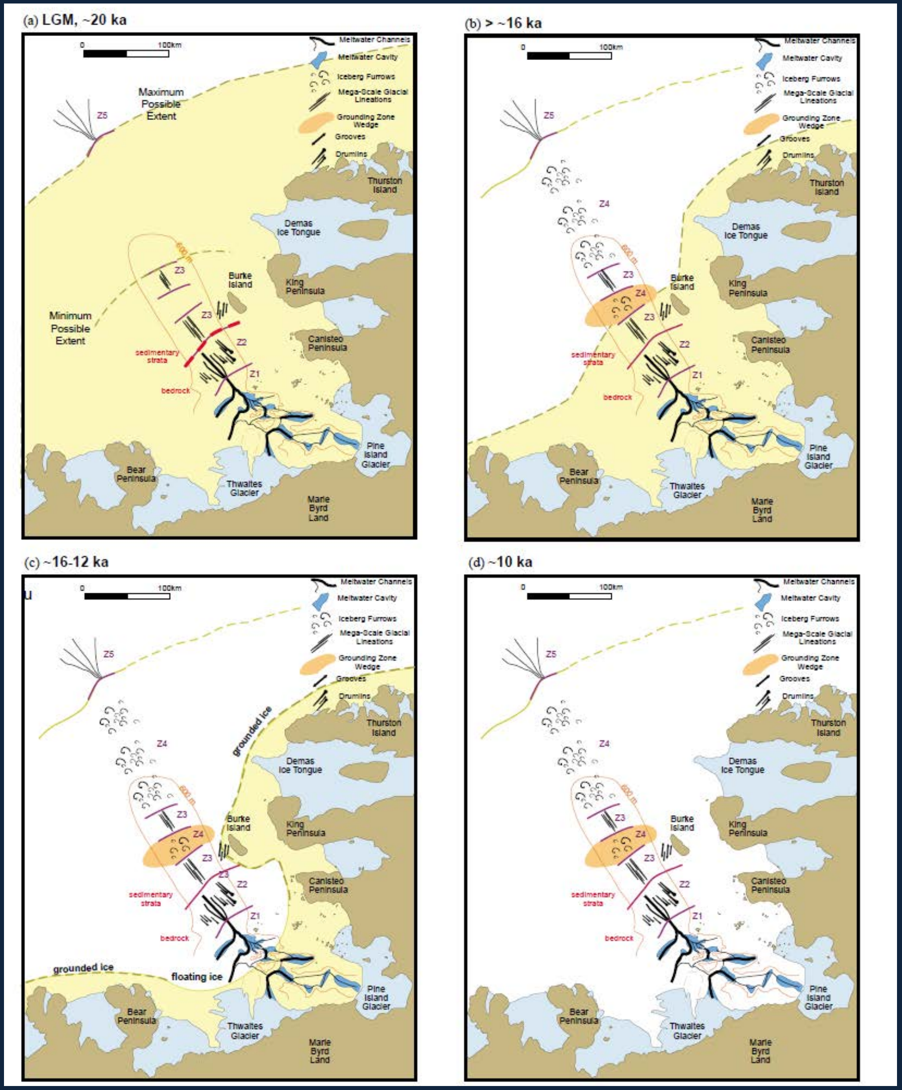
Importance of Grounding Lines

Grounding lines are important because they:

(1) Mark the lateral extent of an ice sheet / ice stream

(2) Are used to define flux gates for ice sheet mass budget estimates

(3) Detect ice sheet stability, advance, or retreat



Lowe and Anderson, 2009

Importance of Grounding Lines

Grounding lines are important because they:

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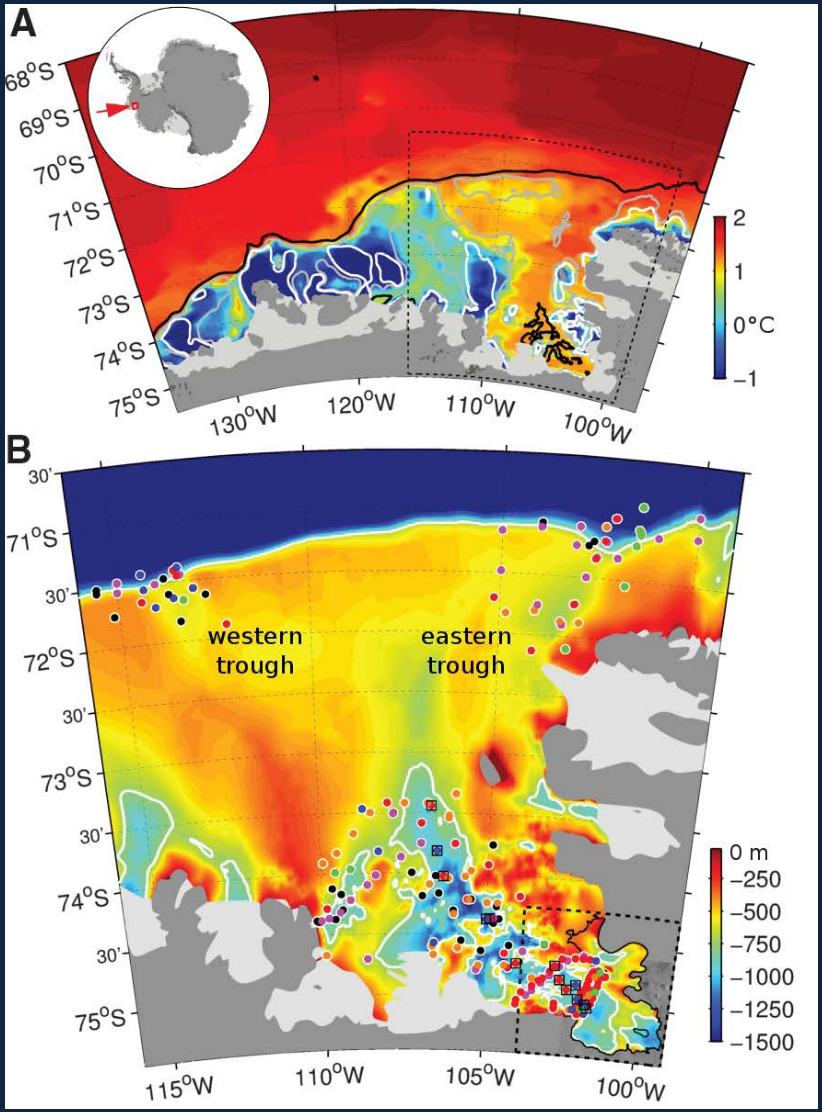
(3) Detect ice sheet stability, advance, or retreat

(4) Identify regions with ocean imbalance



Dutrieux et al., 2014

Importance of Grounding Lines

Grounding lines are important because th

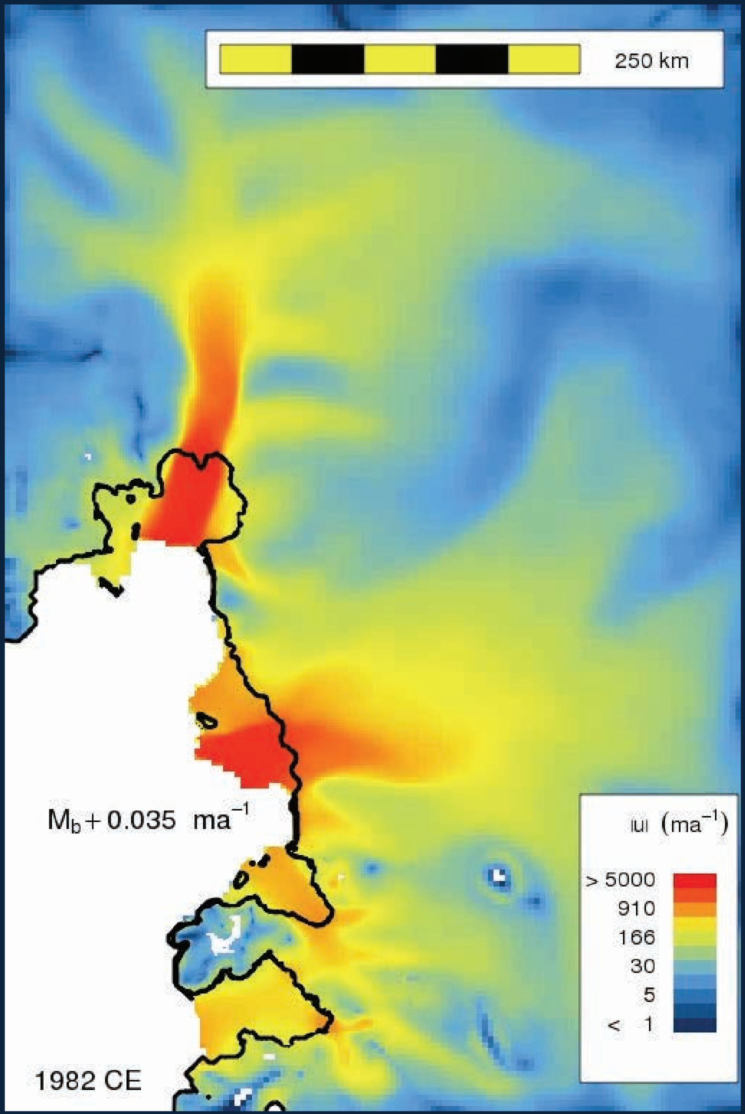
(1) Mark the lateral extent of an ice sheet / ice stream

(2) Are used to define flux gates for ice sheet mass budget estimates

(3) Detect ice sheet stability, advance, or retreat

(4) Identify regions with ocean imbalance

(5) Improve predictions of ice sheet evolution



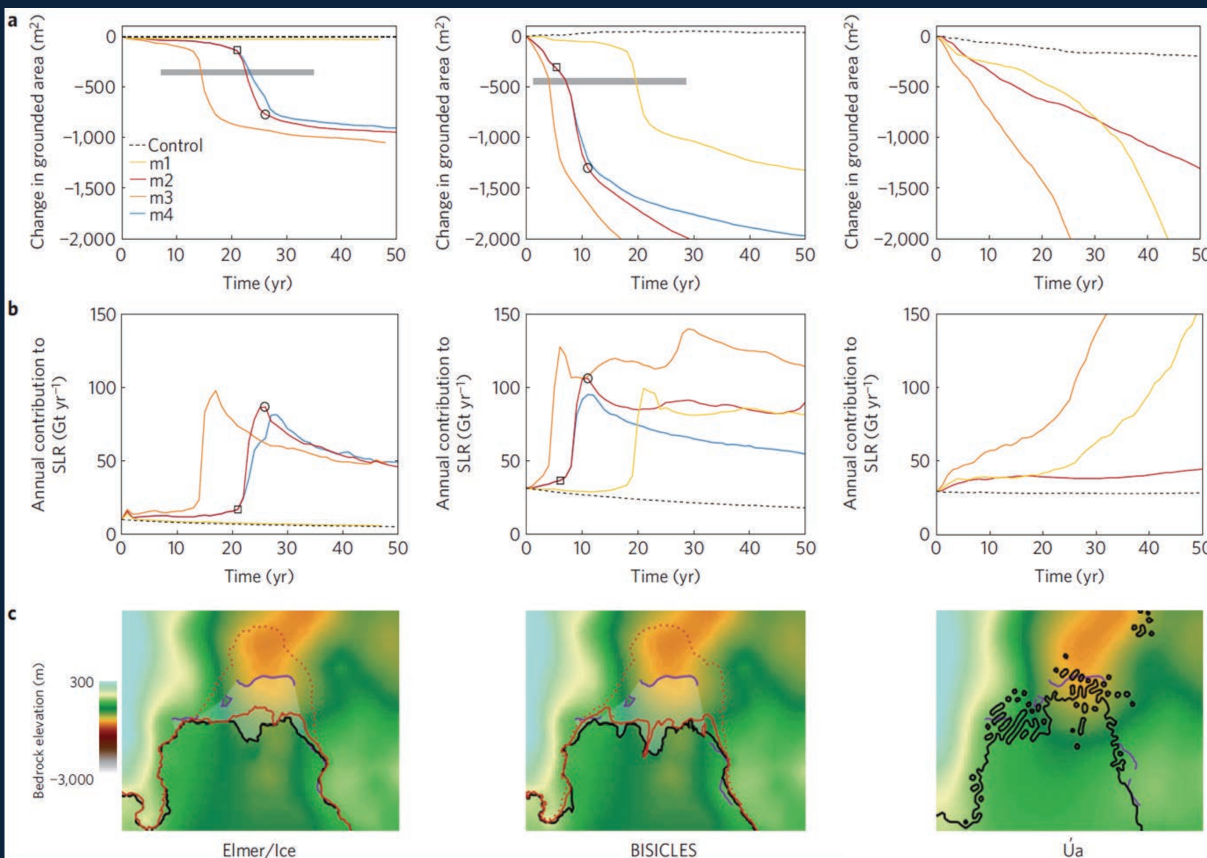
Cornford et al., 2013

Importance of Grounding Lines

(5) Improve predictions of ice sheet evolution….

…. But not all ice sheet models accurately reproduce grounding line retreat.

Response to the same climate forcing, simulated by three of the most sophisticated, independent ice sheet models:



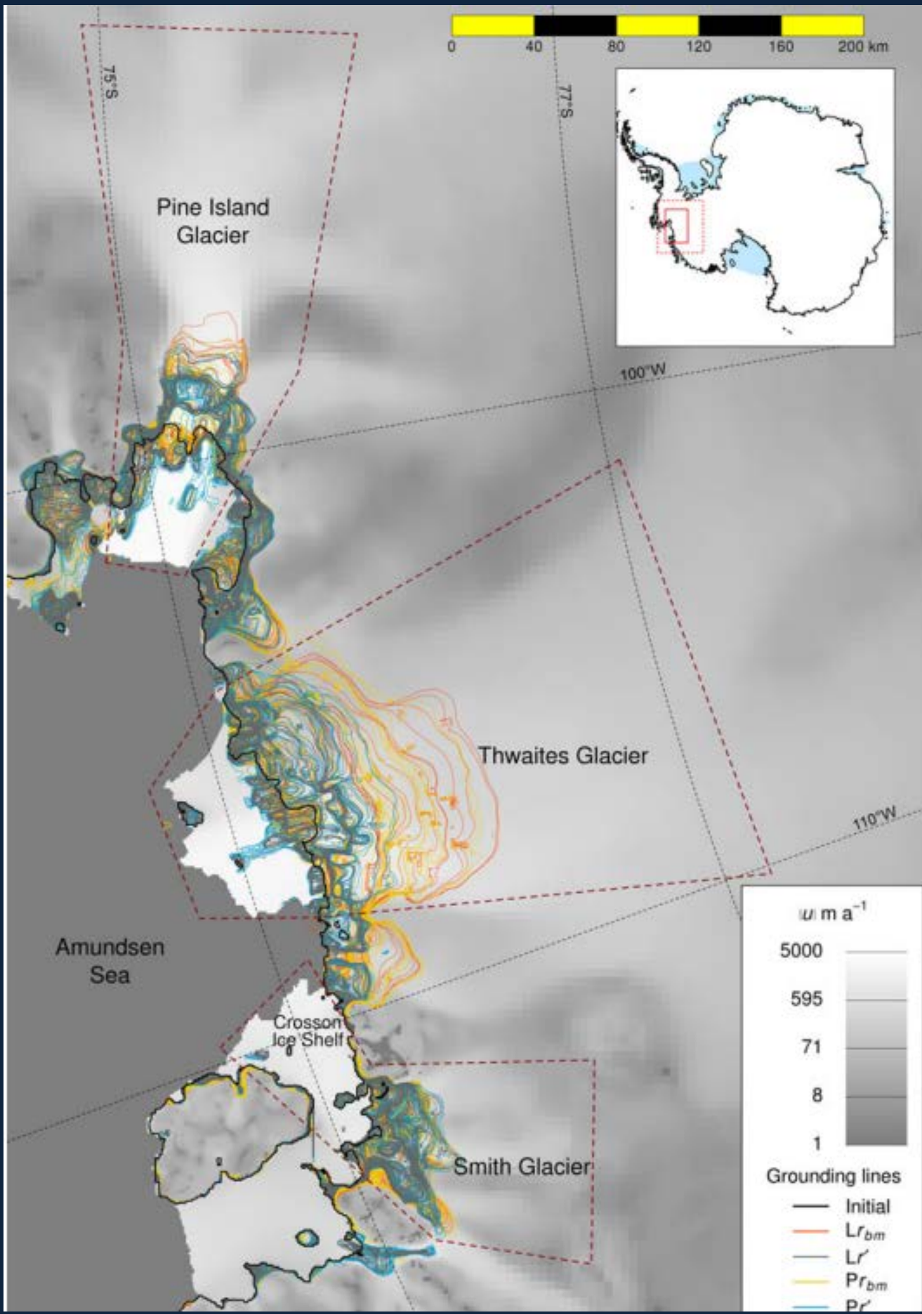
Change in grounded area

Contribution to sea level rise

Spatial pattern of grounding line retreat

(Favier et al., 2014)

Importance of Grounding Lines



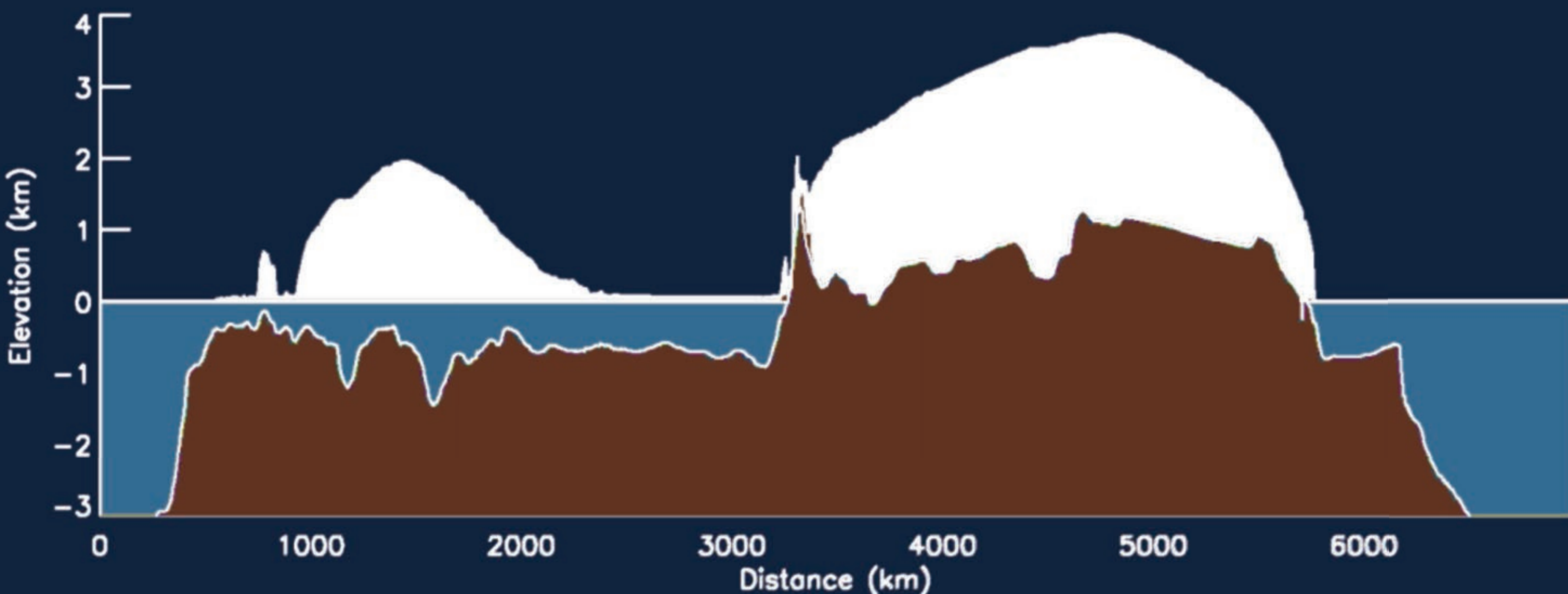
Under different climate scenarios, the same ice sheet model forecasts different retreat rates.

This is expected, but what's right?

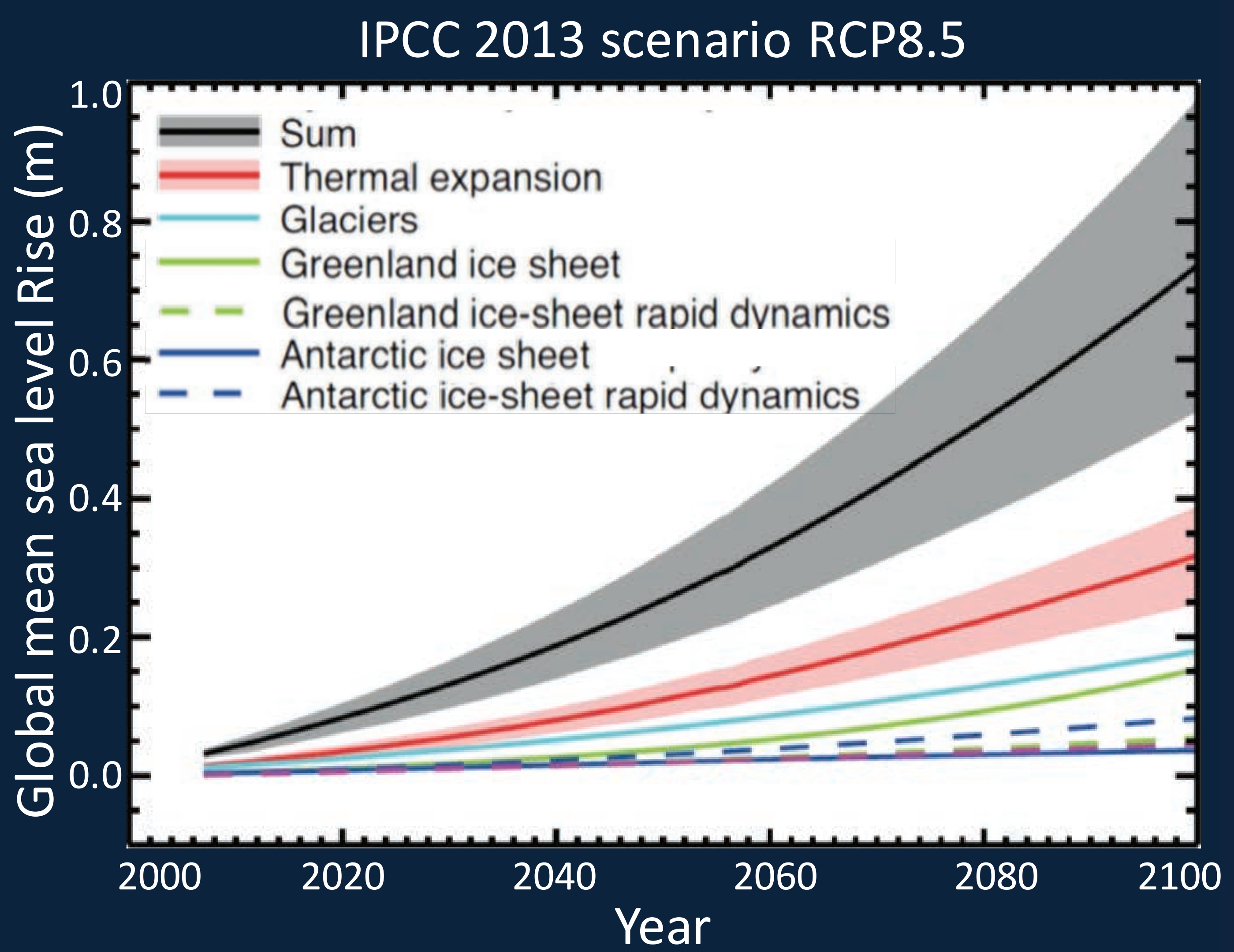
Need observations of real change to improve confidence.

(Nias et al., 2016)

Theoretical Instability

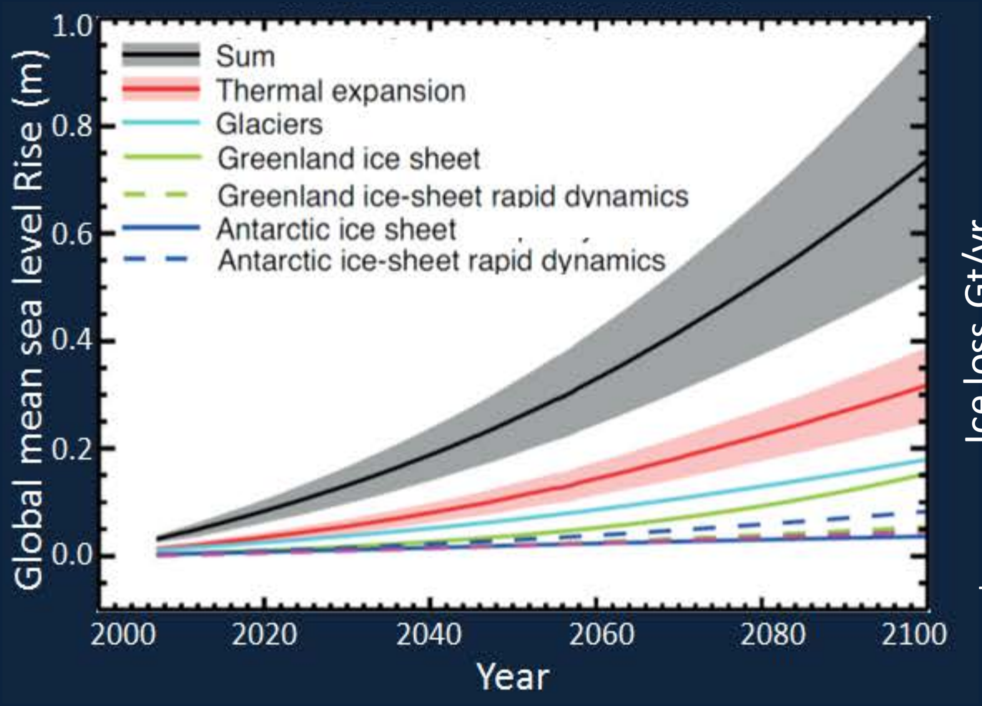


Contribution to Sea Level Rise



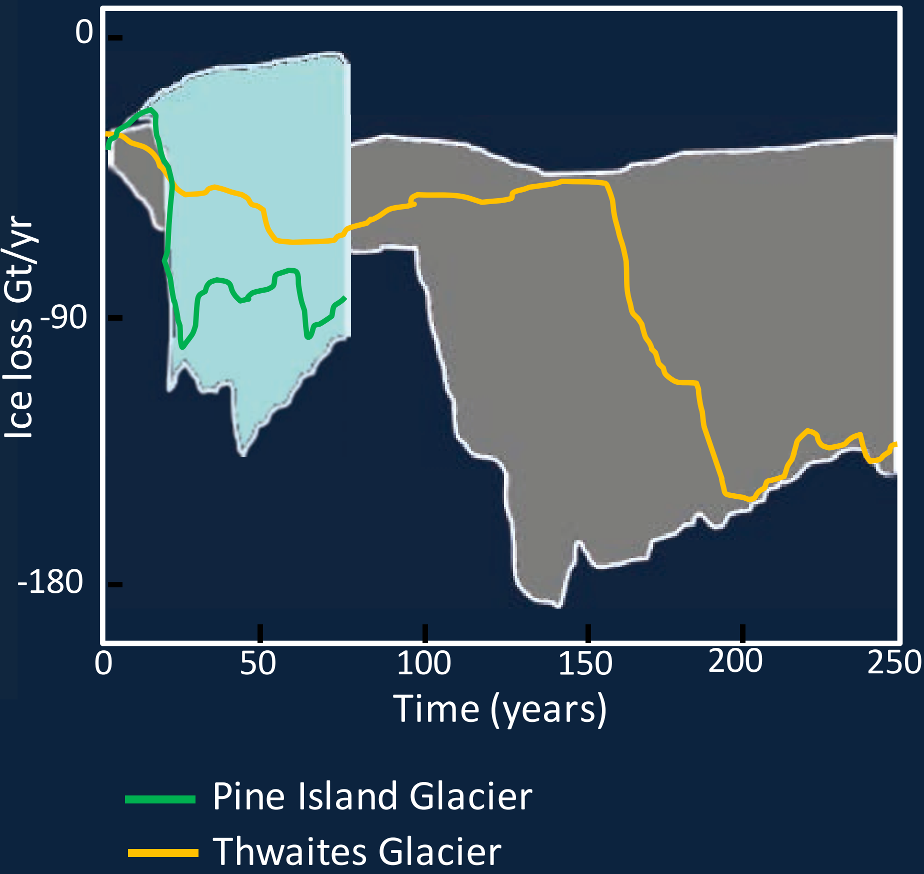
Contribution to Sea Level Rise

Predicting Future Global Change
IPCC 2013 scenario RCP 8.5



0.45 ± 0.14 mm/yr SLR

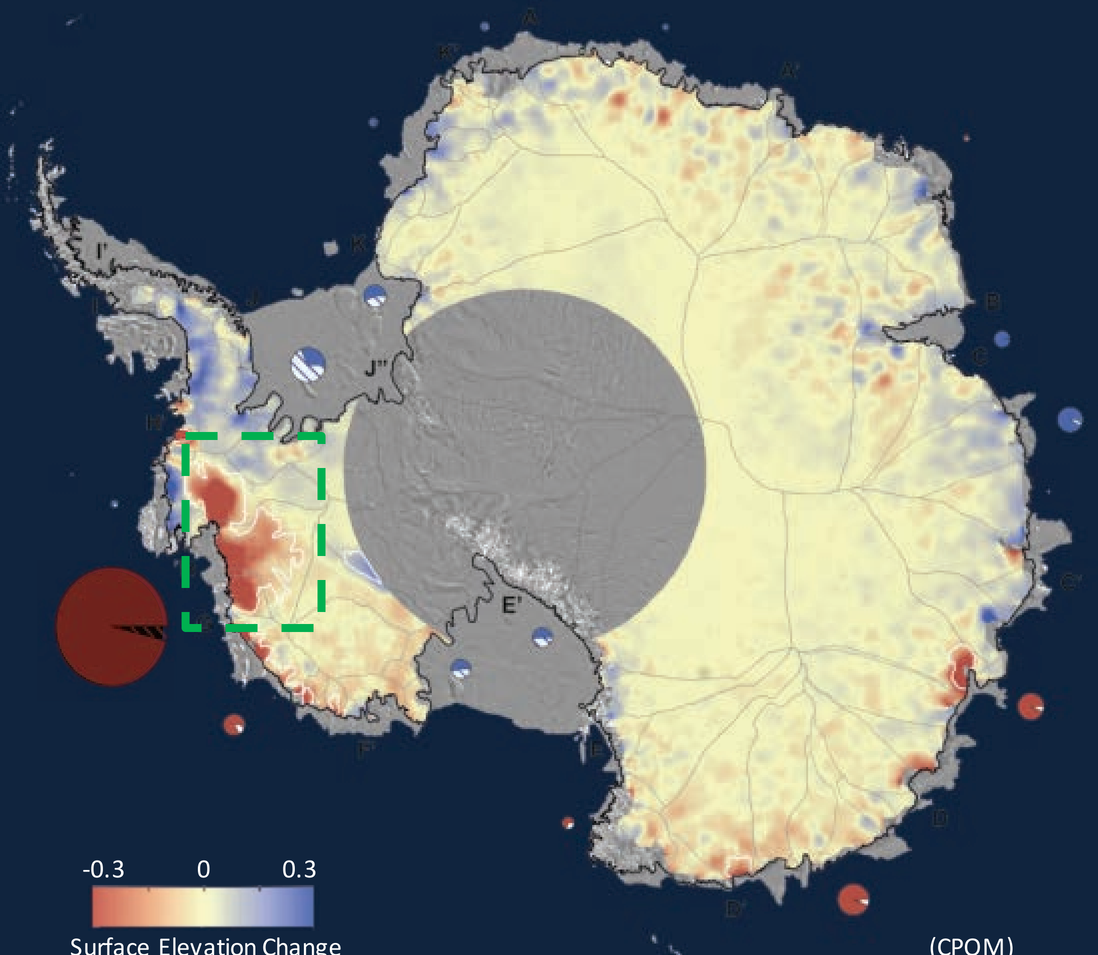
Future West Antarctic Ice Loss
Not spatially or temporally continuous



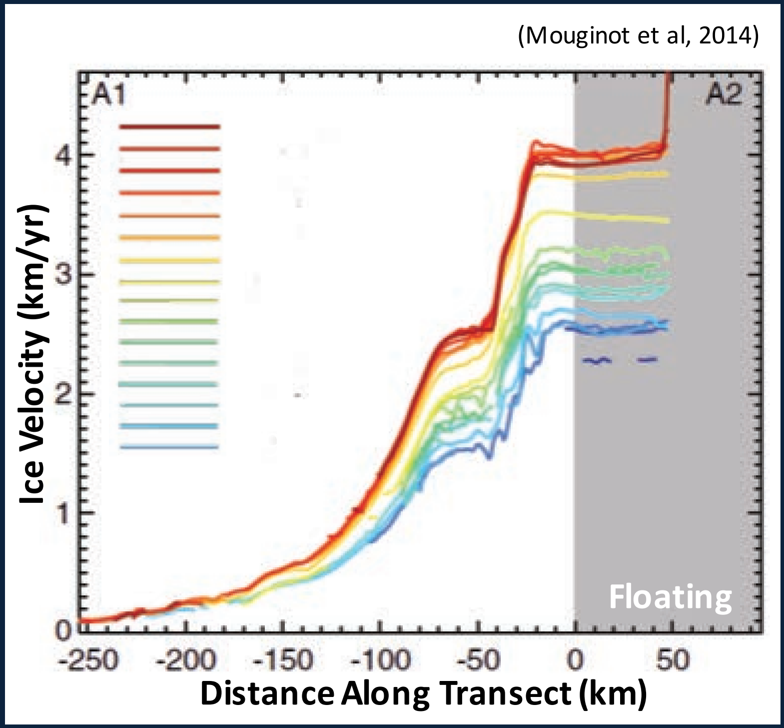
(Joughin et al, 2010)

Satellite Observations of Change

Surface elevation change
1992 - 2010

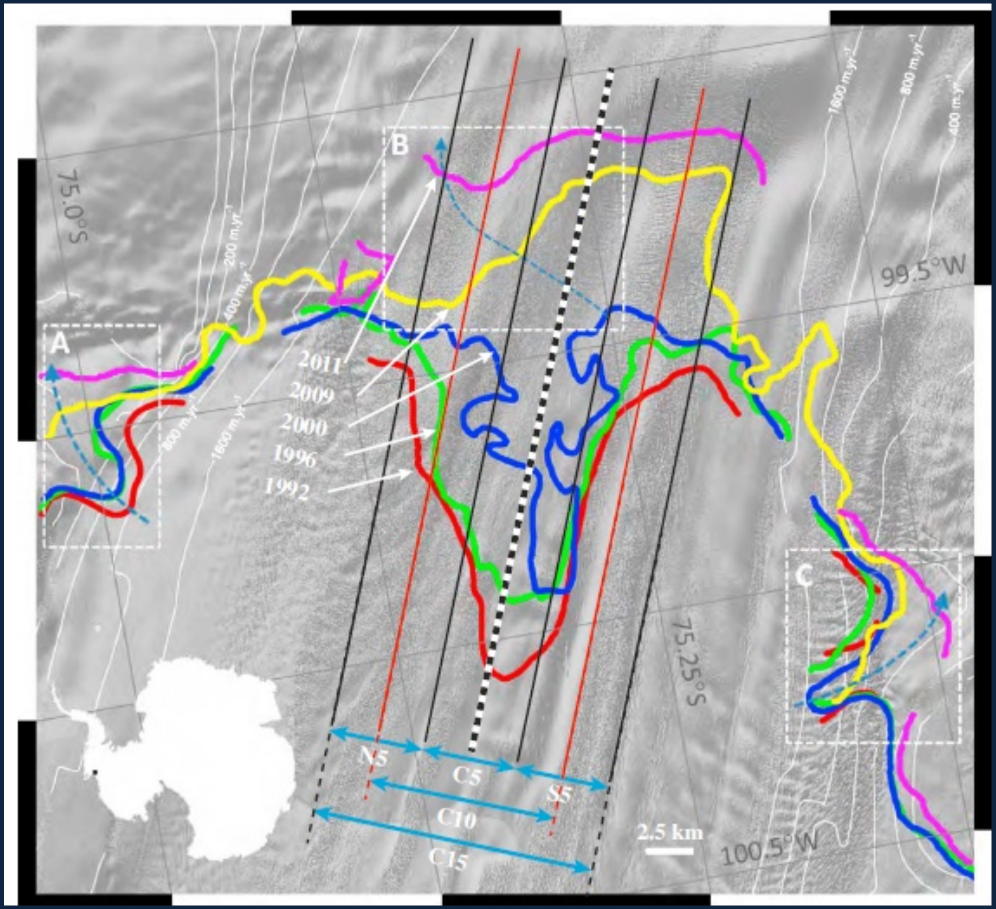


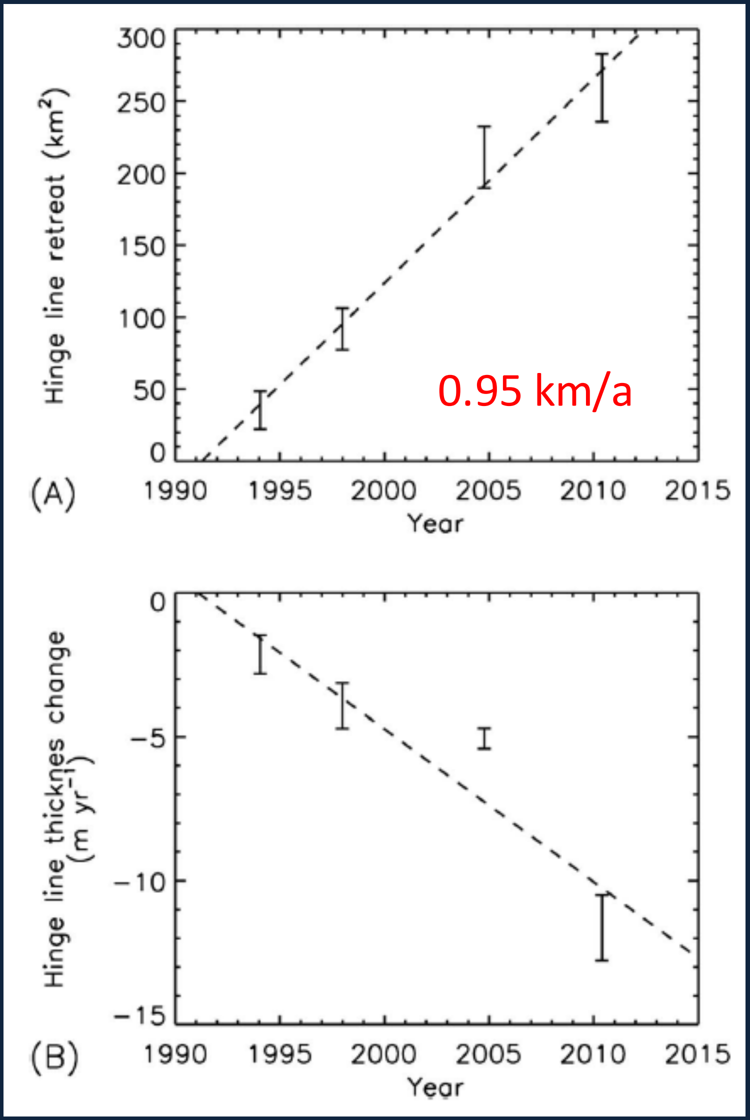
Ice velocity speed-up
1994 – 2010



Observations of Grounding Line Retreat

Individual ice streams – Pine Island Glacier



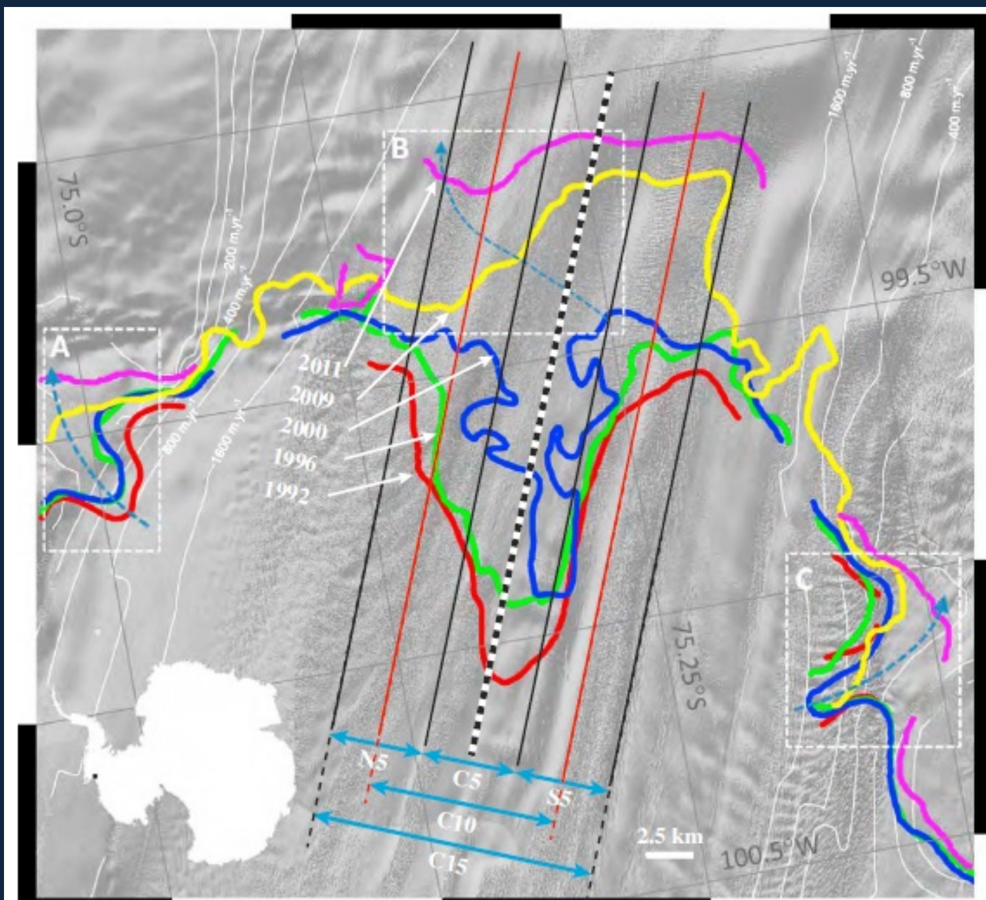


Grounding line retreat correlated with ice thinning

(Park et al., 2013)

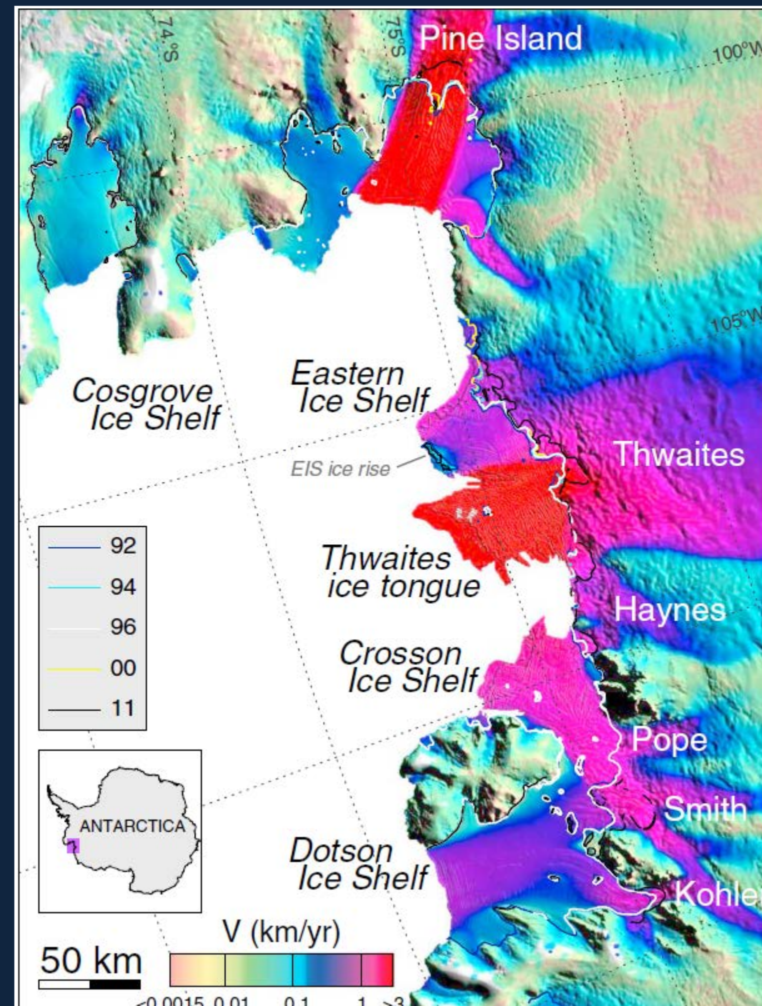
Observations of Grounding Line Retreat

Individual ice streams – Pine Island Glacier



(Park et al., 2013)

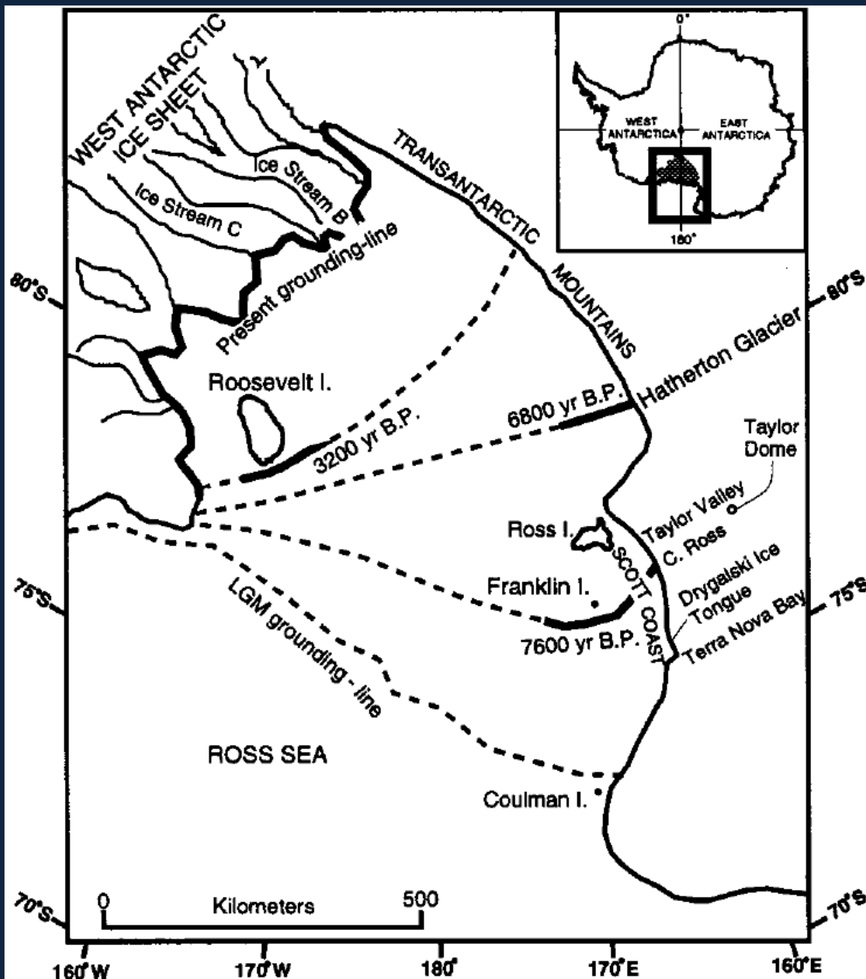
Whole sectors of Antarctica – Amundsen Sea Embayment



(Rignot et al., 2014)

Observations of Grounding Line Retreat

How do 'present day' observations of GL retreat compare with historical records?



Estimate of dated grounding line retreat on the Ross ice shelf during the Holocene (Conway et al., 1999).

Estimated by dating shells and diatoms in marine sediment cores and incorporated in raised beaches, radiocarbon dates of algae from ice dammed lakes and using paleoclimate model simulations

Retreated nearly 1300 kilometres since the Last Glacial Maximum (LGM) 20,000 years ago

- McMurdo Sound on the Ross Ice Shelf retreat rate ~0.12 km per year over last 7500 years
- Ice Stream C on the Ross ice shelf 0.03 km per year between 1974 and 1984
- neighbouring ice Stream B the retreat over the same time period was larger, at 0.45 km per year

Methods for Detecting GL Retreat

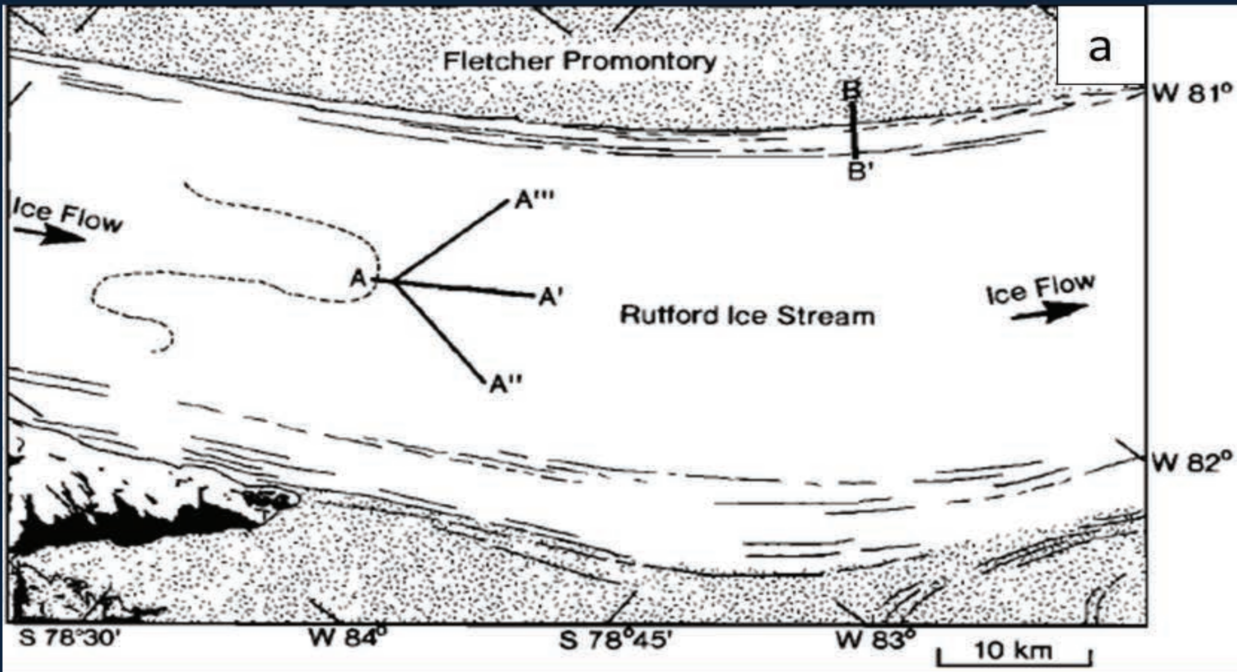
Methods broadly fall into 2 categories:

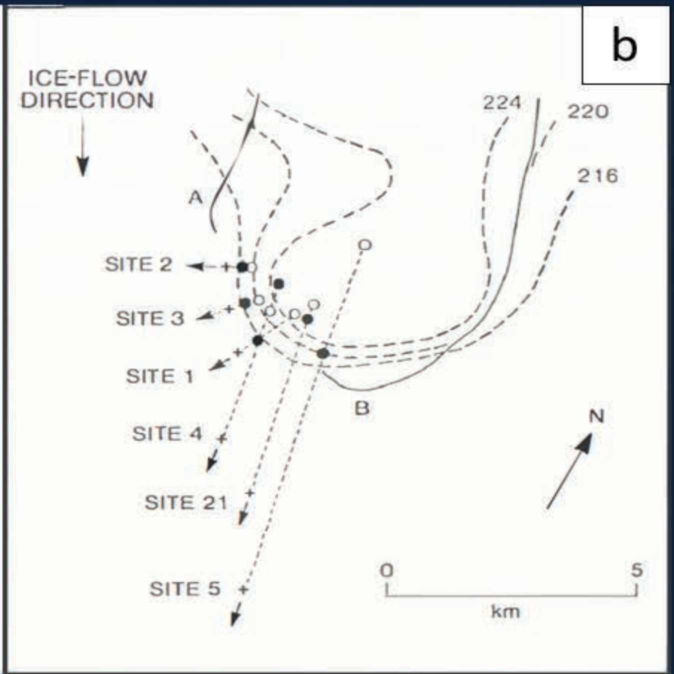
a) Detecting real tidal displacement of the ice shelf
   - Advantage – grounded ice sheet definitely does not move with ocean tides so high confidence measurement
   - Disadvantage – tricky to measure, especially if tide amplitude is small

b) Using the prominent break in surface slope that occurs at the boundary between the flat ice shelves, and topographically heterogeneous grounded ice
   - Advantage – prominent feature that is easy to measure with a range of datasets
   - Disadvantage – break in surface slope can occur in other locations, for other reasons

Methods for Detecting GL Retreat

Field measurements – in situ kinematic GPS, tilt meters, in situ interferometers also exist

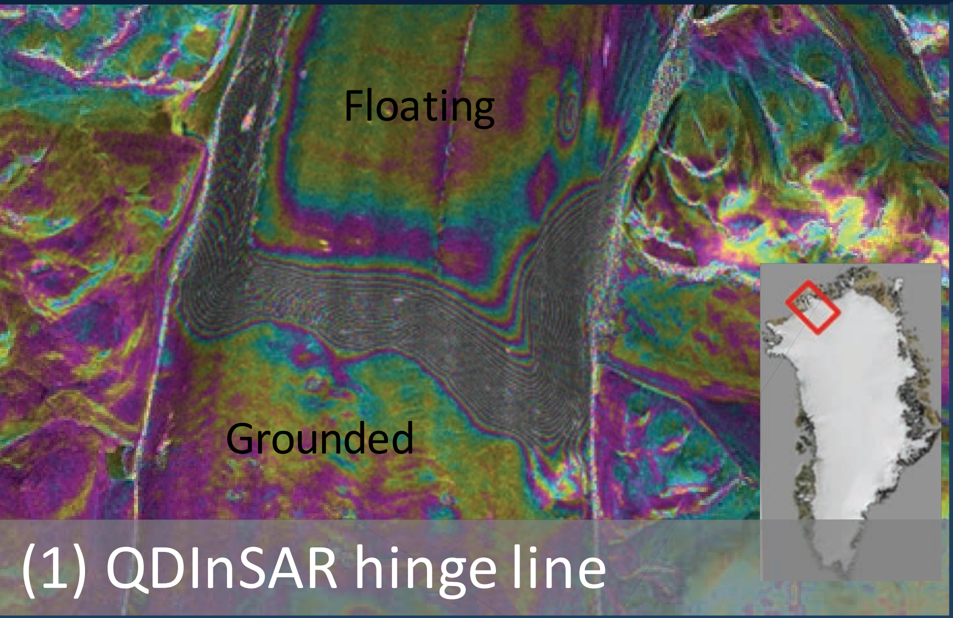




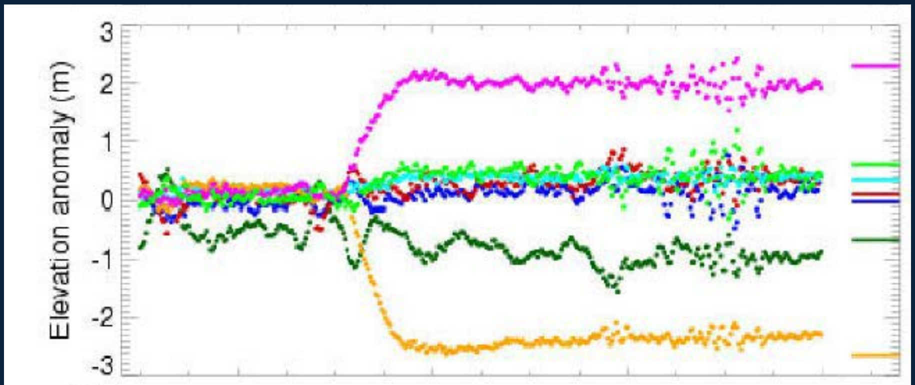
in situ kinematic GPS on the Rutford ice stream on the Filchner-Ronne ice shelf (Vaughan, 1995)

tilt meters Doake Ice Rumples (Smith, 1991)

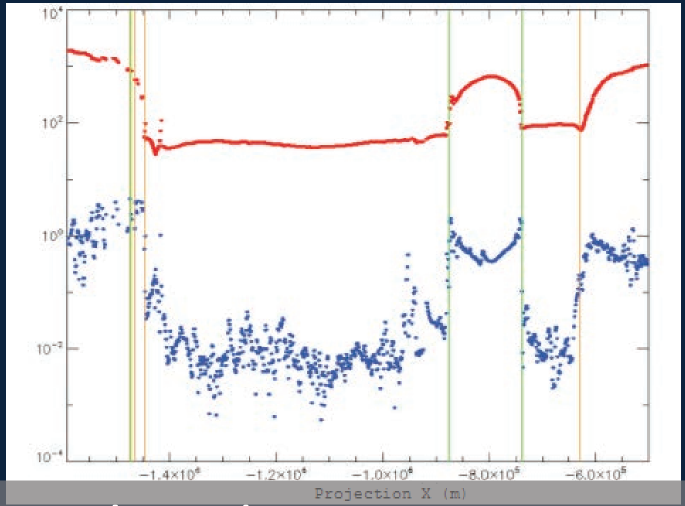
Methods for Detecting GL Retreat



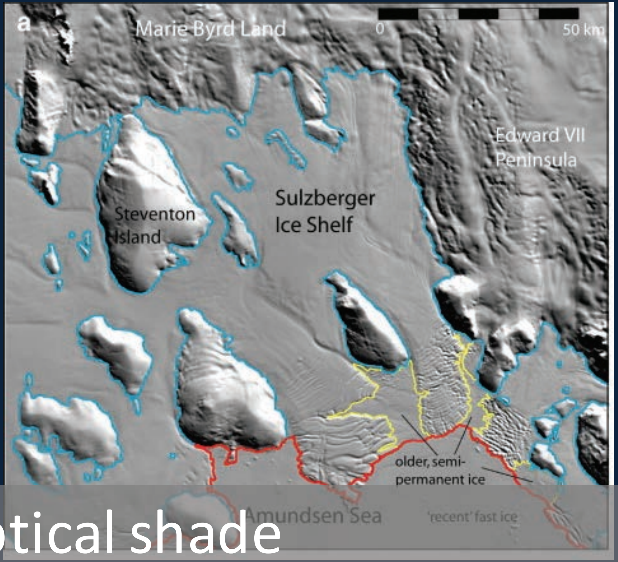
(1) QDInSAR hinge line



(2) Altimetry hinge line



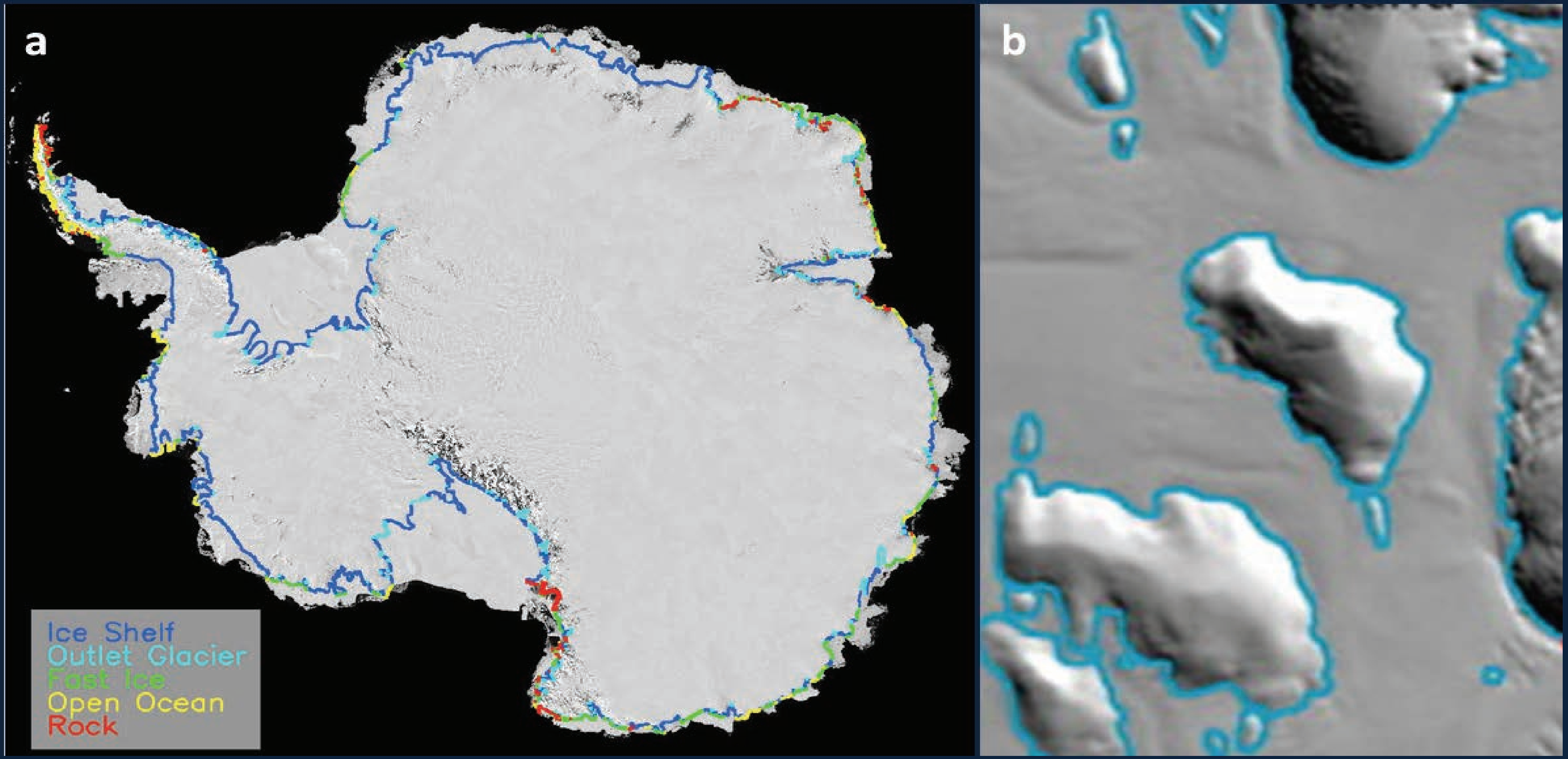
(3) Break in slope



(4) Optical shade

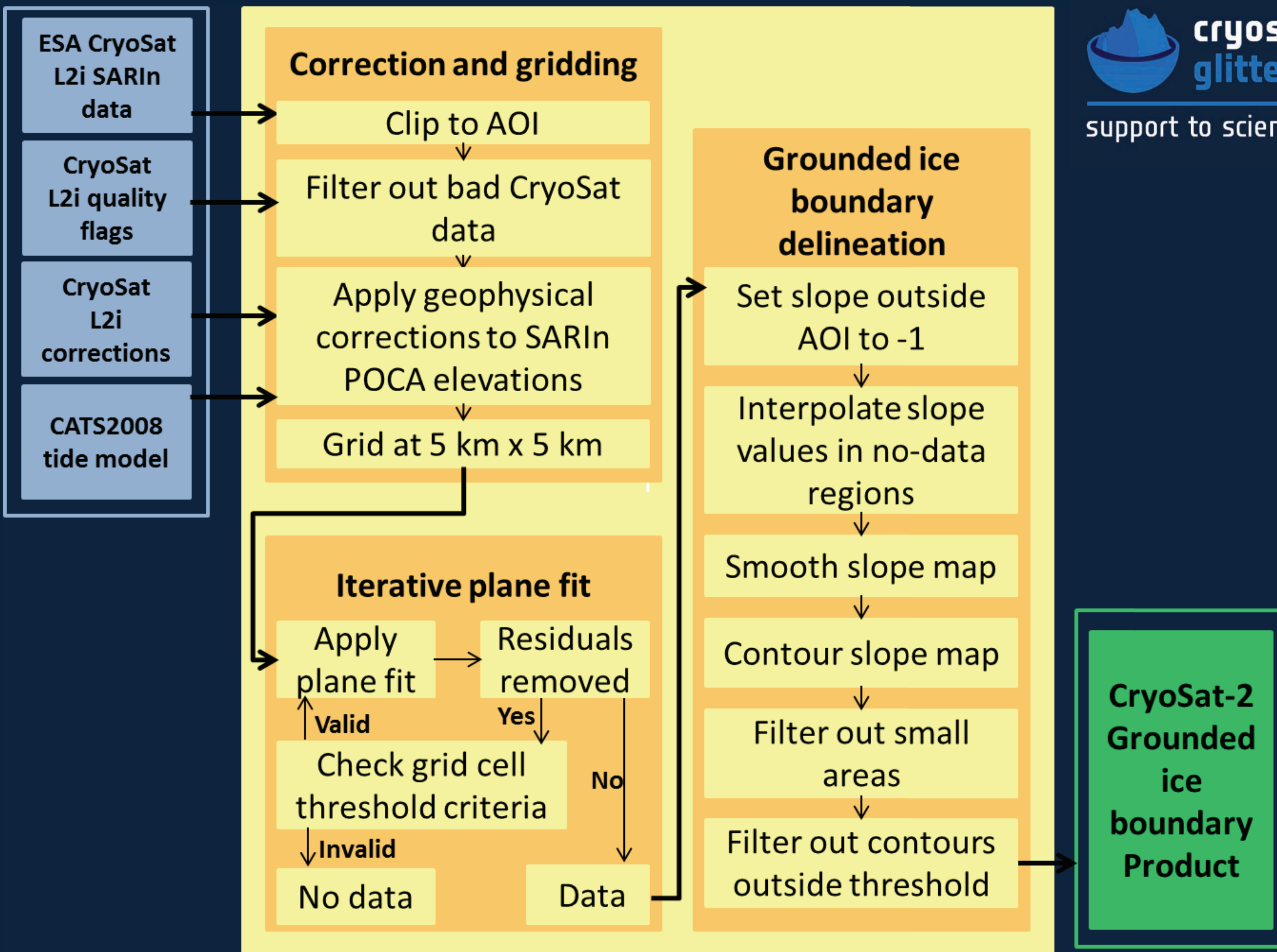
Methods which use the break in surface slope

Detecting Grounding Lines: Optical Shadow



- Break in surface slope at the ice shelf/ice sheet boundary causes shadow
- Shadow can be observed in optical data
- Manual delineation of the shadow boundary can be used as a proxy for grounding line position

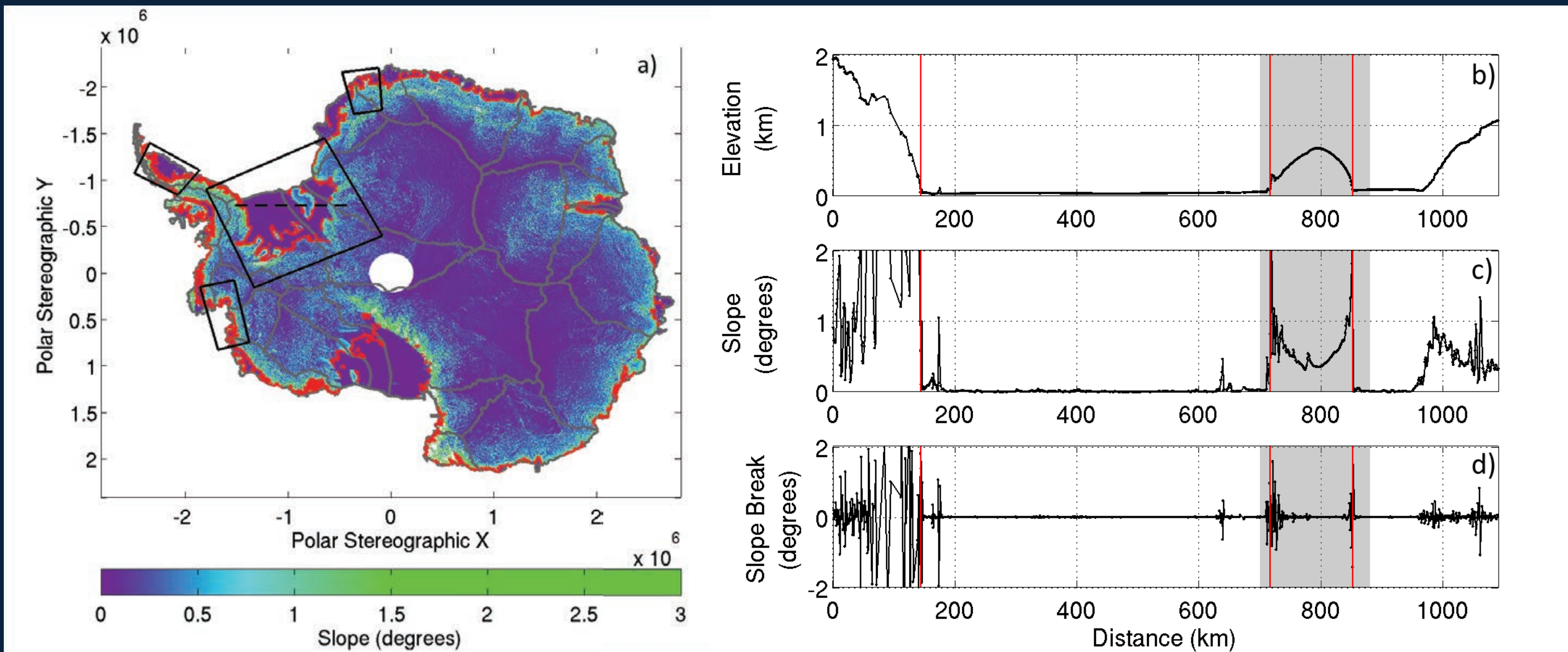
Detecting Grounding Lines: Topographic slope



cryosat+ glitter
support to science element

Detecting Grounding Lines: Topographic slope

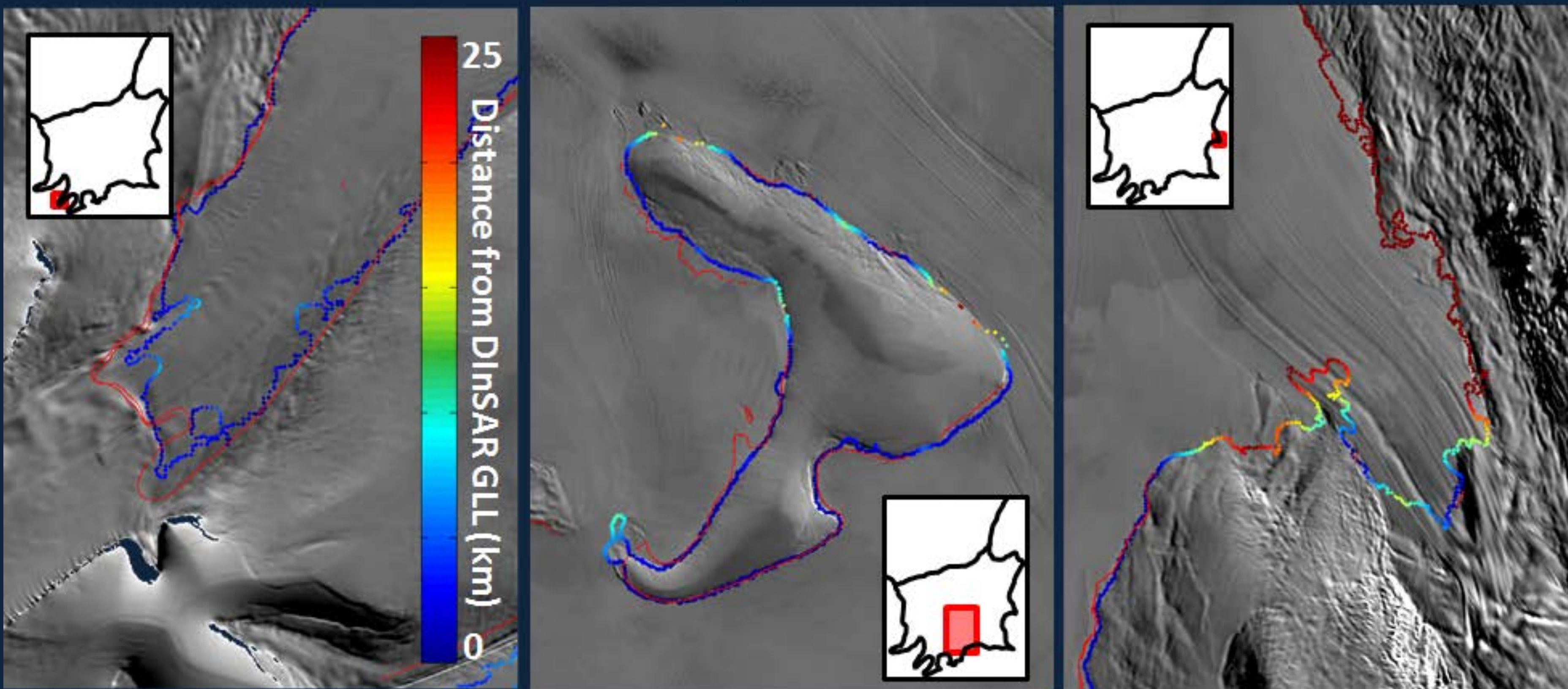
Topographic slope from CryoSat-2



Break in slope corresponds to grounding line from QDInSAR (red)

Detecting Grounding Lines: Topographic slope

Carson Inlet | Henry Ice Rise | Support Force



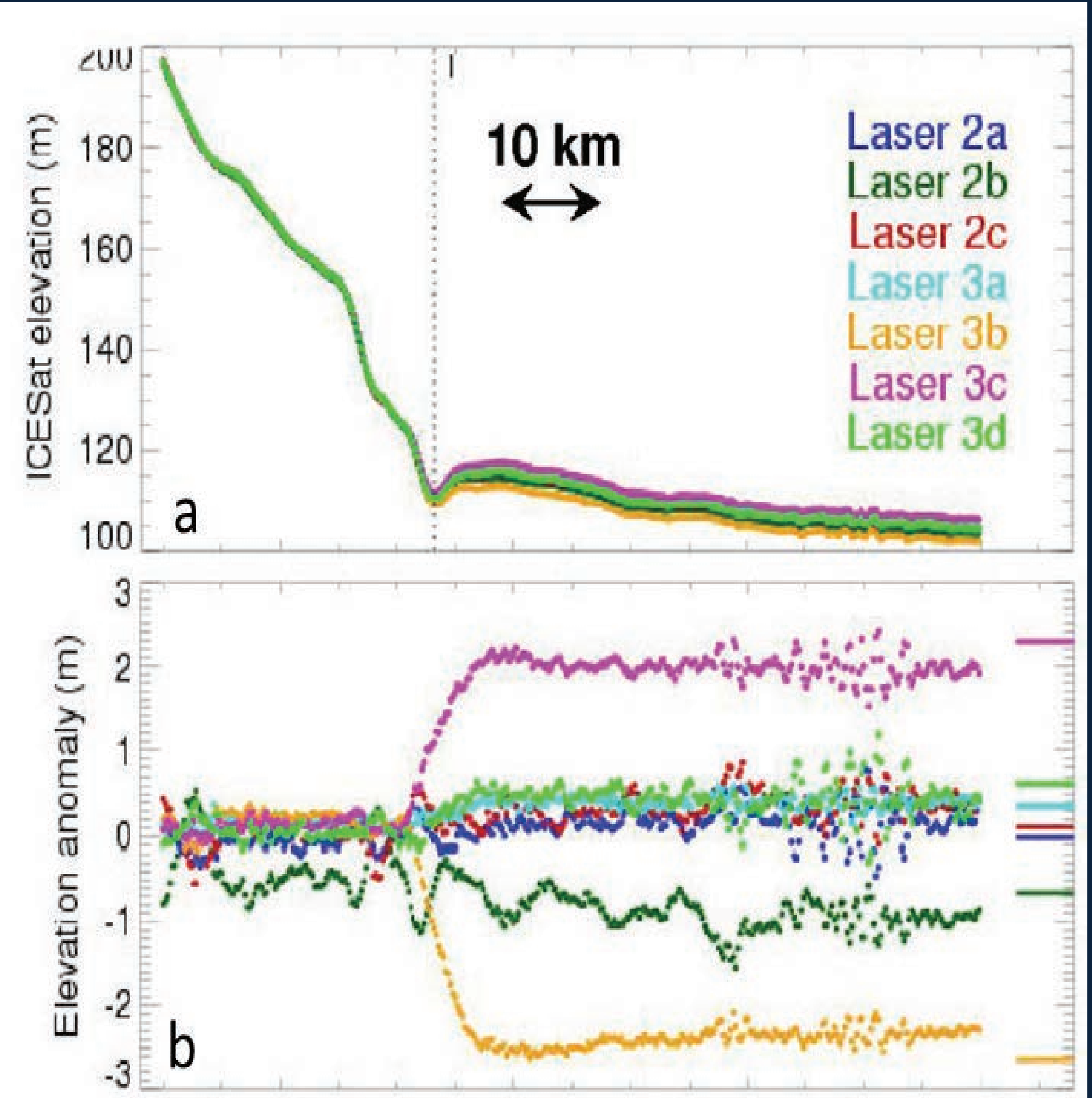
- Good GLL across many ice streams
- Good GLL product on islands
- CS2 grounding line in areas with no DInSAR

Methods which detect real tidal displacement

Detecting Grounding Lines: Laser Altimetry

- Obtain geolocated footprint locations and ocean and load tide corrections from ICESat laser altimetry L2 Antarctic dataset (GLA12 product)
- Filter out cloud affected data, and radiometrically calibrate the return energy and receiver gain using the GLA01 product
- ‘Re-tide’ dataset using GOT99.2 tidal model correction originally applied to the ICESat data
- Apply saturation correction to elevation data where return energy is greater than receiver gain
- Interpolate each transect of elevation onto a common set of evenly spaced latitude values for each repeated track
- Calculate the mean elevation profile for all repeats
- Calculate the elevation anomaly for each repeat track by differencing the absolute elevation of each track from the mean profile

Detecting Grounding Lines: Laser Altimetry

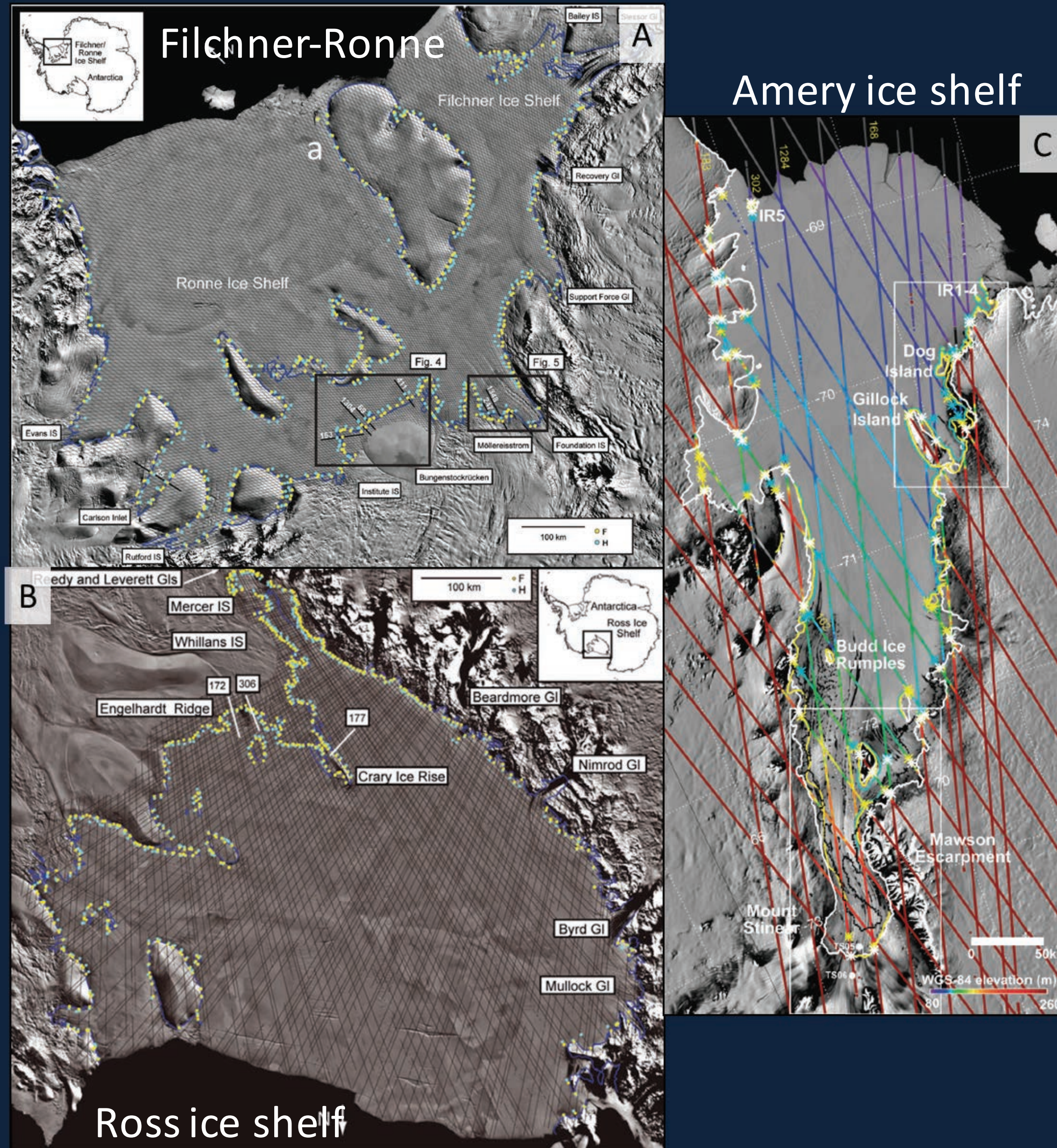


Absolute ice surface elevation measured along an ICESat track

Elevation anomaly measured along the same track

(Fricker and Padman, 2006).

Detecting Grounding Lines: Laser Altimetry

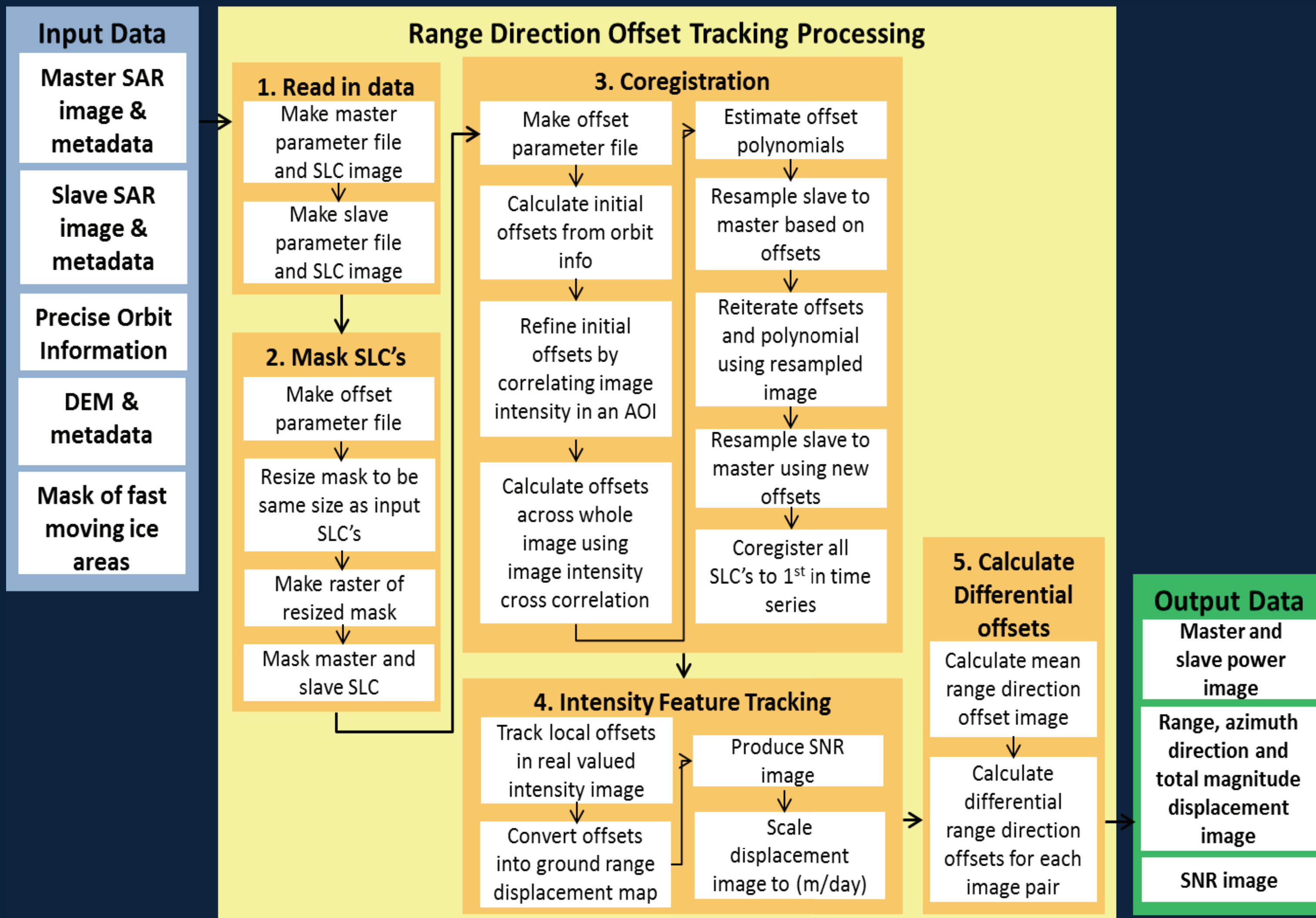


grounding line (blue dot)
point of floatation (yellow dot)

(Brunt et al., 2010)
(Brunt et al., 2011)
(Fricker et al., 2009)

Detecting Grounding Lines: DRDOT

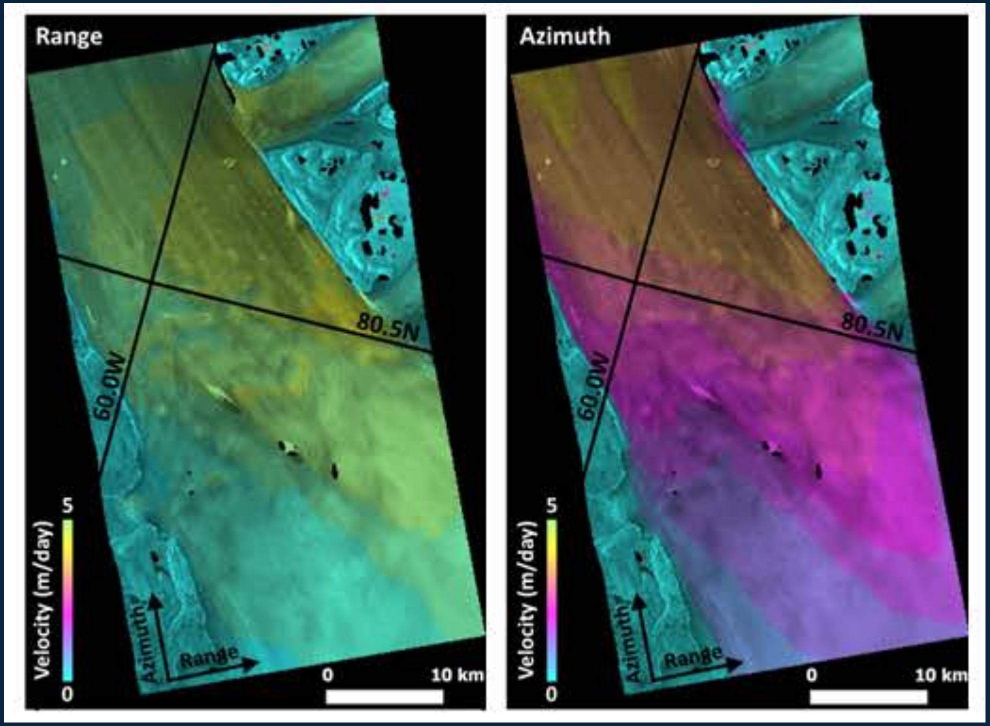
Differential Range Direction Offset Tracking (DRDOT)

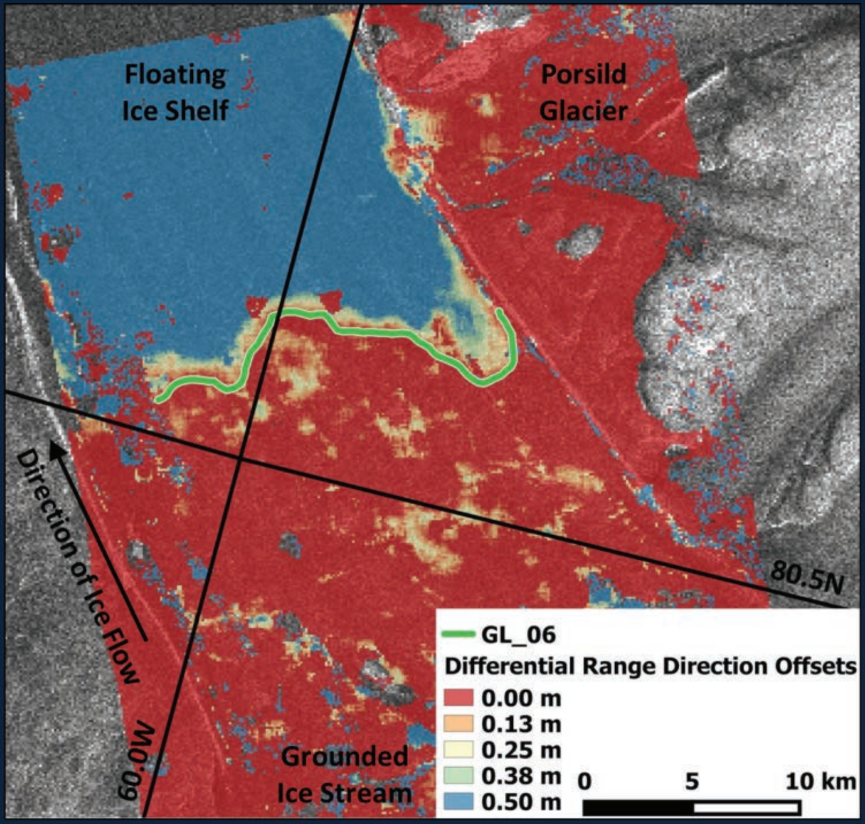


Detecting Grounding Lines: DRDOT

Differential Range Direction Offset Tracking (DRDOT)

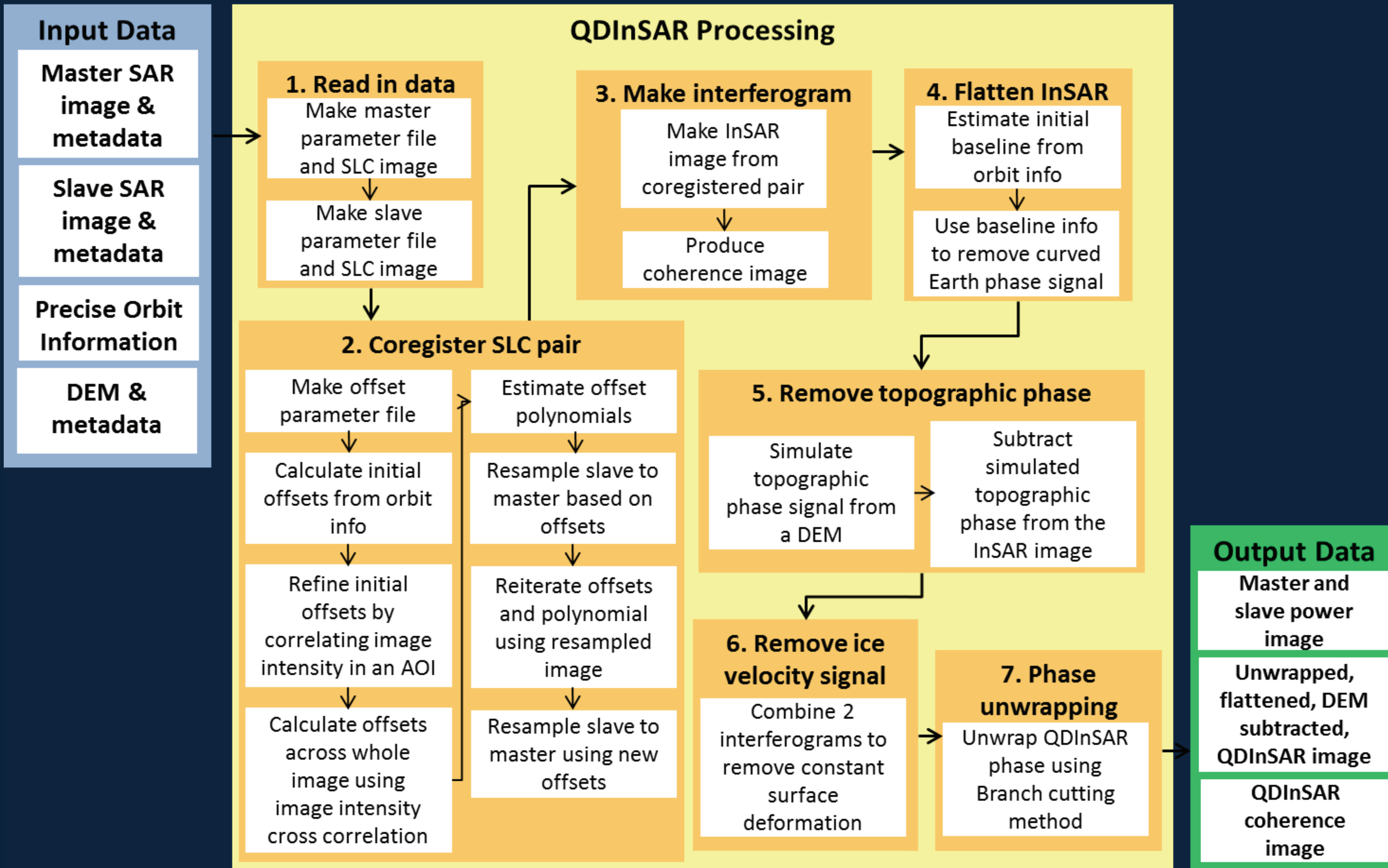
2D Ice speed





Take a time series and calculate difference from mean, high tide amplitude images show deformation caused by tides

Detecting Grounding Lines: QDInSAR



SAR Satellites

1990 → 2016

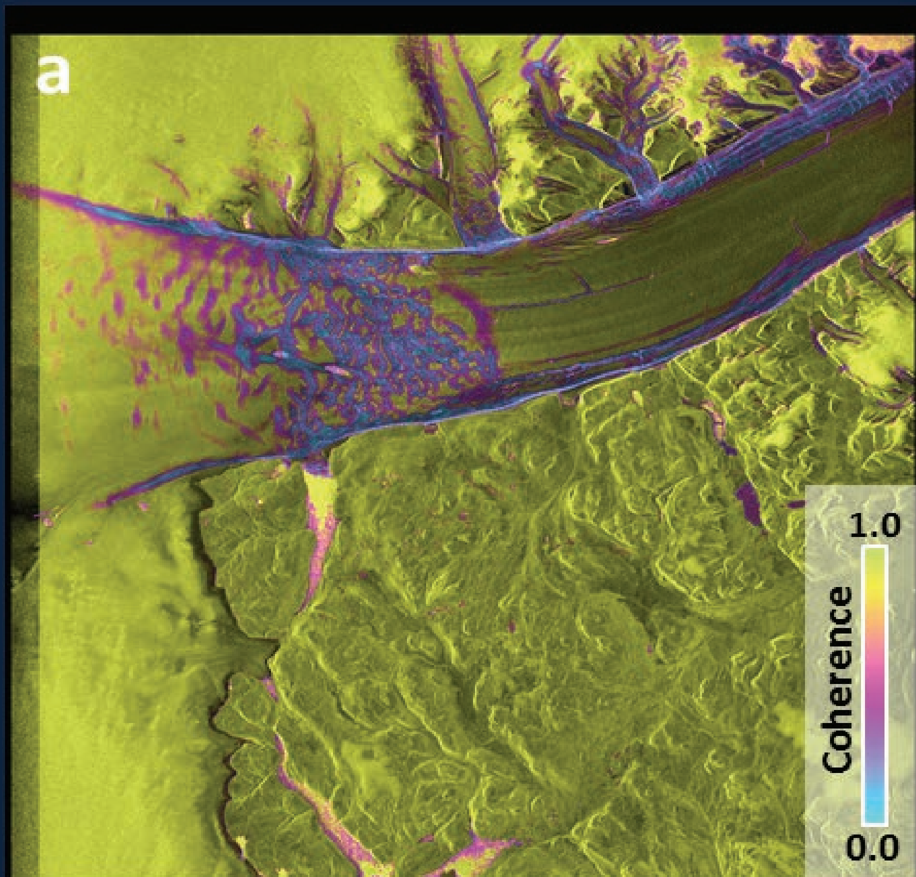
ERS-1 ERS-2 RADARSAT ENV ALOS TSX COSMO TDX S-1a S-1b

Detecting Grounding Lines: QDInSAR

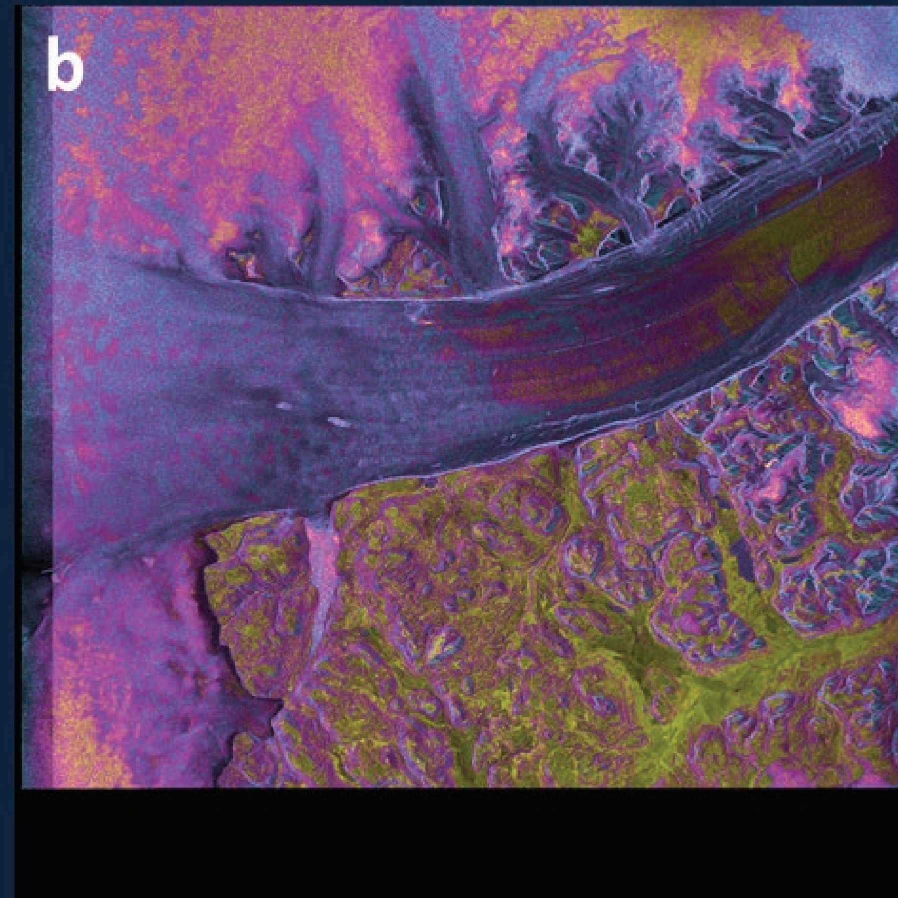
- Apply orbital corrections, instrument calibrations and image co-registration to SAR images
- Estimate the Interferometric baseline and perform common band filtering in order to generate a coherent interferogram

Detecting Grounding Lines: QDInSAR

Coherence Estimation



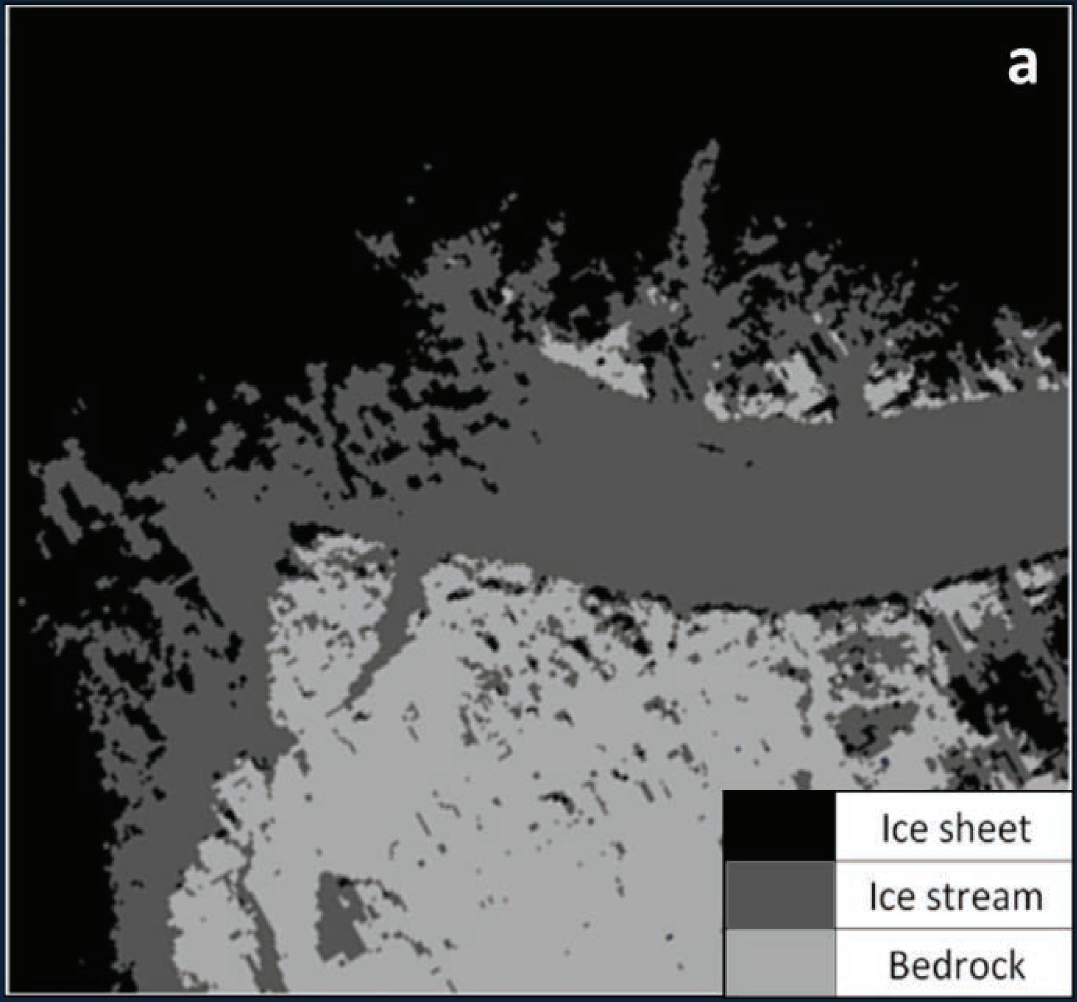
High coherence from 3-day temporal baseline pair



Low coherence from 12-day temporal baseline pair

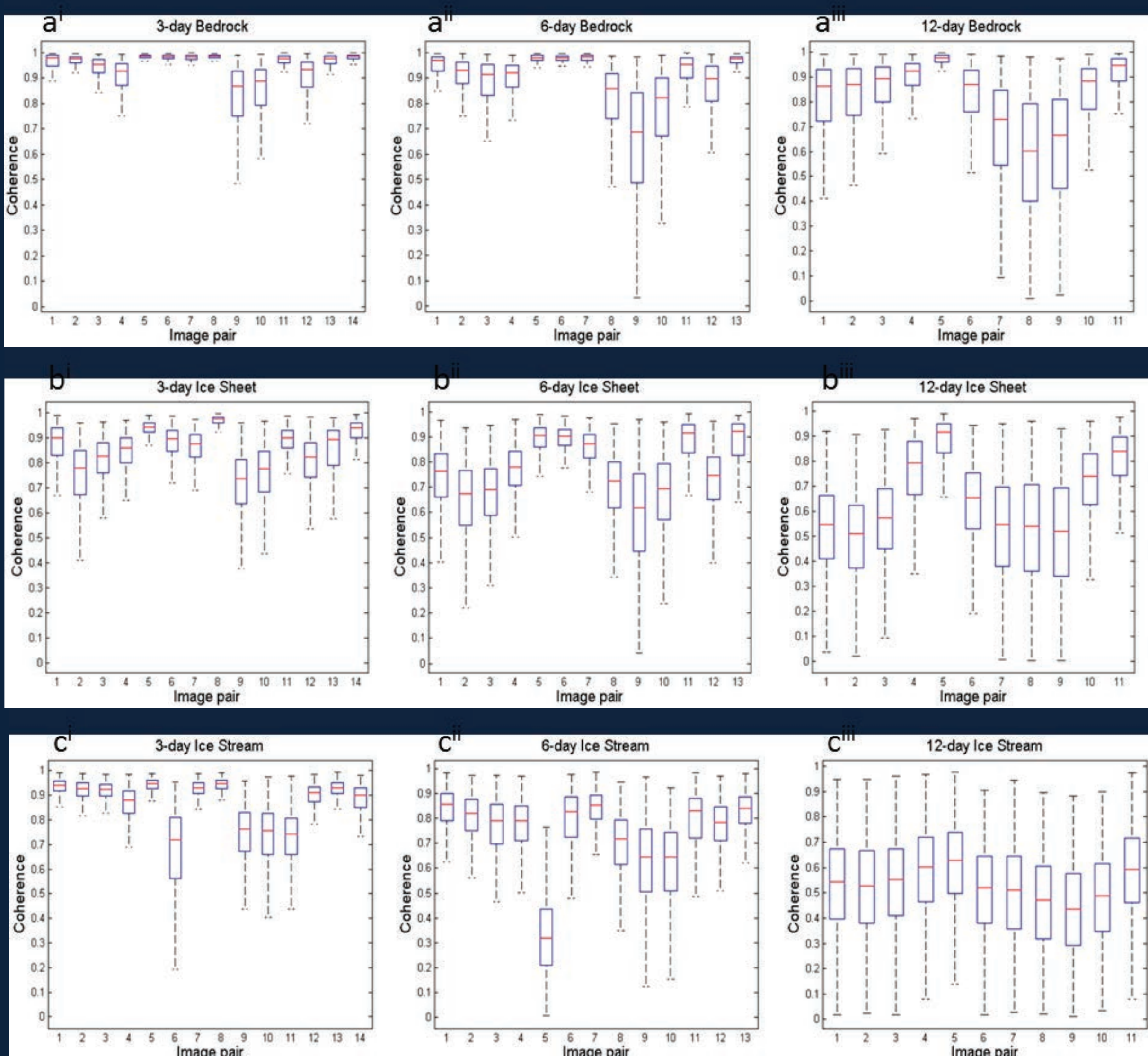
Detecting Grounding Lines: QDInSAR

Coherence Estimation



Detecting Grounding Lines: QDInSAR

Level of coherence



exposed rock

ice sheet

ice stream

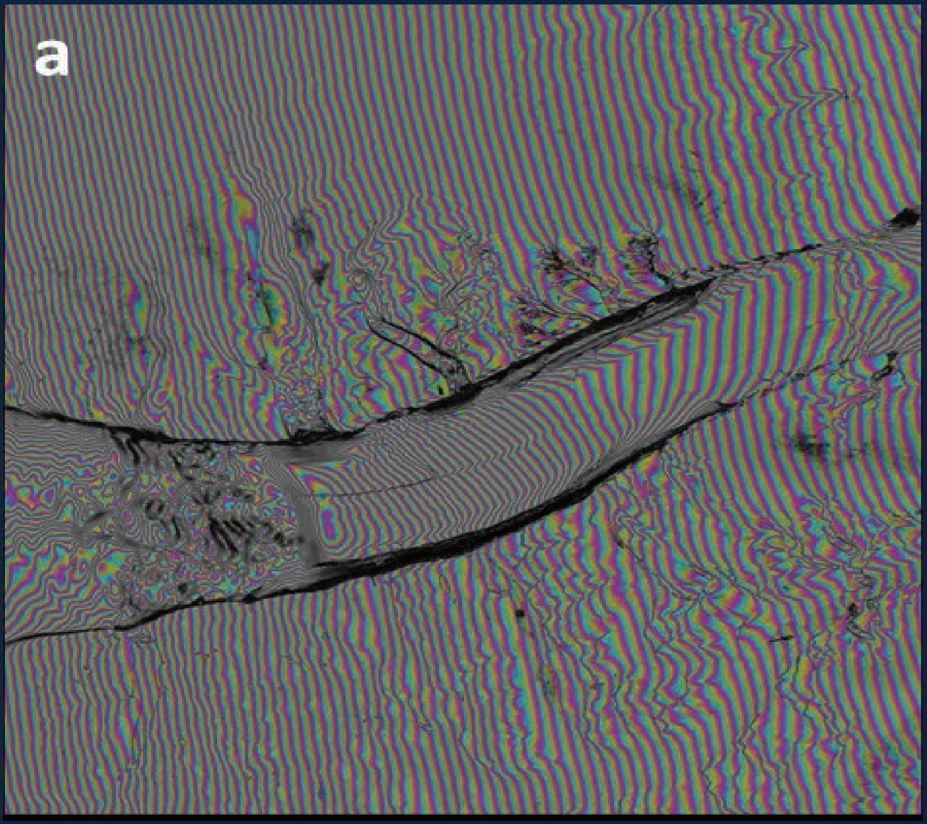
3 day

6 day

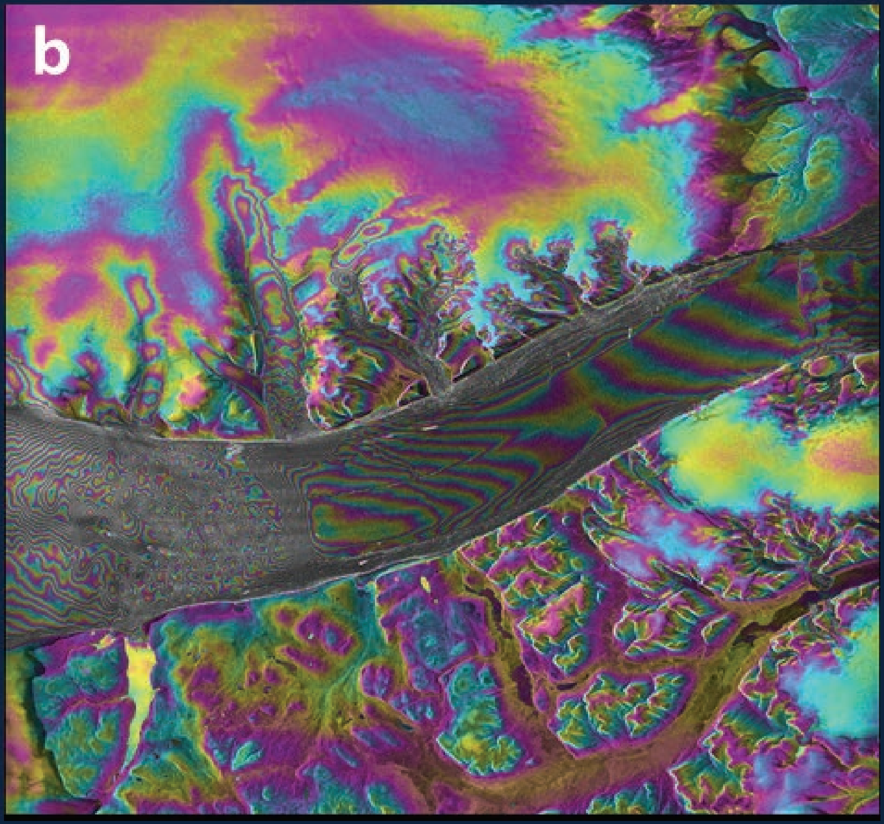
12 day

Detecting Grounding Lines: QDInSAR

Curved Earth Phase Signal Removal



Interferogram of Petermann Glacier with phase signal containing flat Earth, topographic, surface deformation and residual noise components

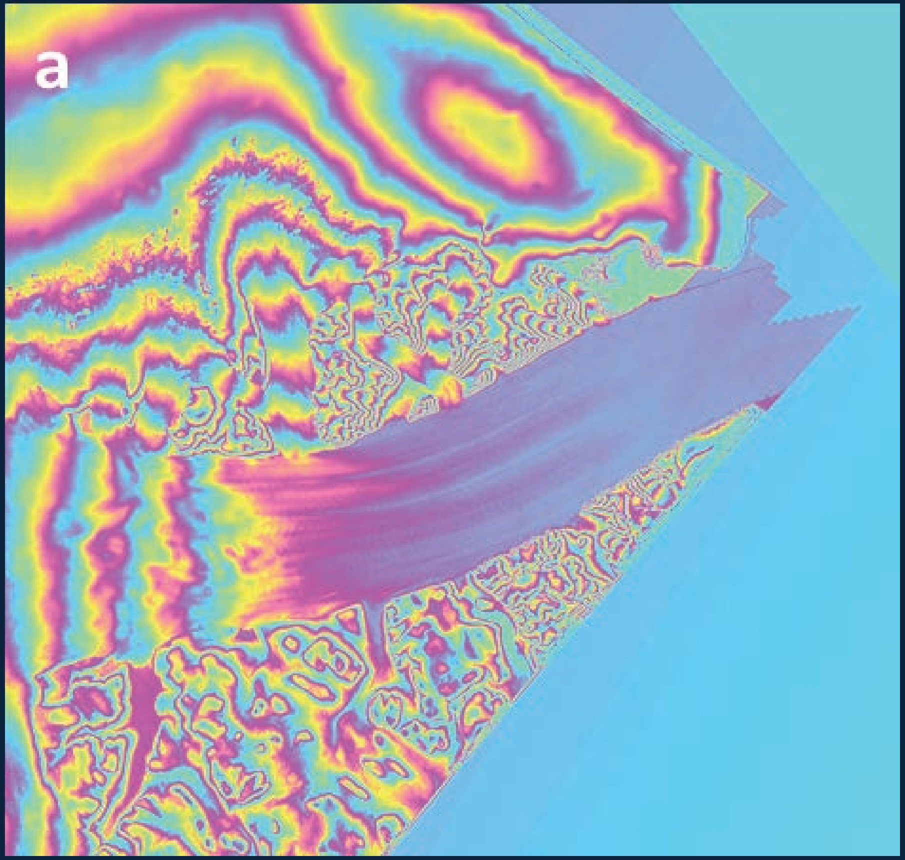


Interferogram once flat Earth phase signal has been removed.

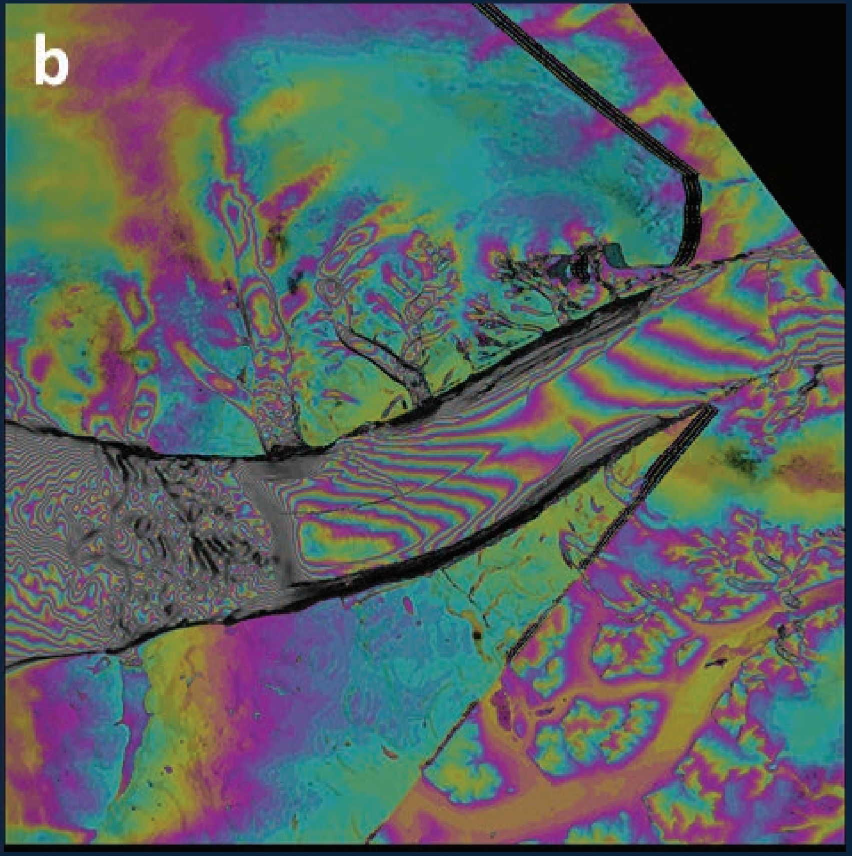
Detecting Grounding Lines: QDInSAR

Topographic Phase Signal Removal

- Topographic phase signal is simulated from an auxiliary Digital Elevation Model (DEM) and the SAR imaging geometry, and then is subtracted from the interferogram forming a differential interferogram (DInSAR).



Simulated topographic phase signal from the ASTER DEM



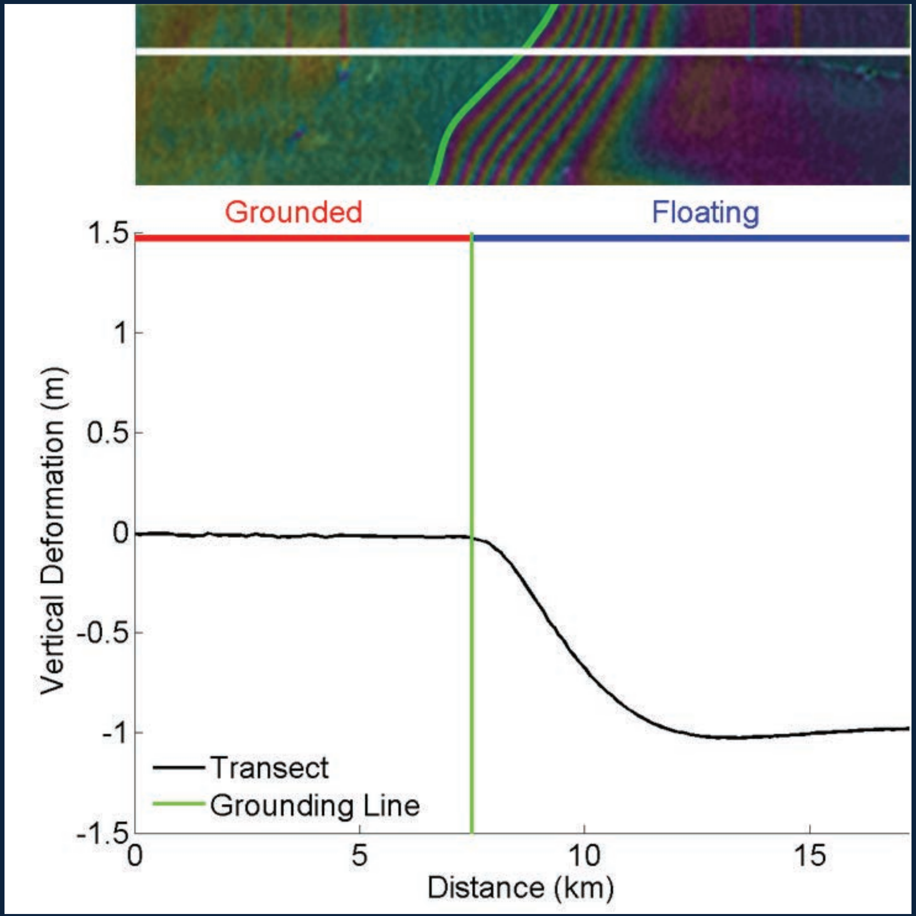
Interferogram with phase signal containing only the surface deformation and residual noise components

Detecting Grounding Lines: QDInSAR

QDInSAR Formation

- Surface deformation is caused by ice flow and, in floating sections, by ocean tides.
- Combine interferogram pairs to remove the common phase signal caused by constant ice flow, forming a quadruple difference interferogram (QDInSAR)

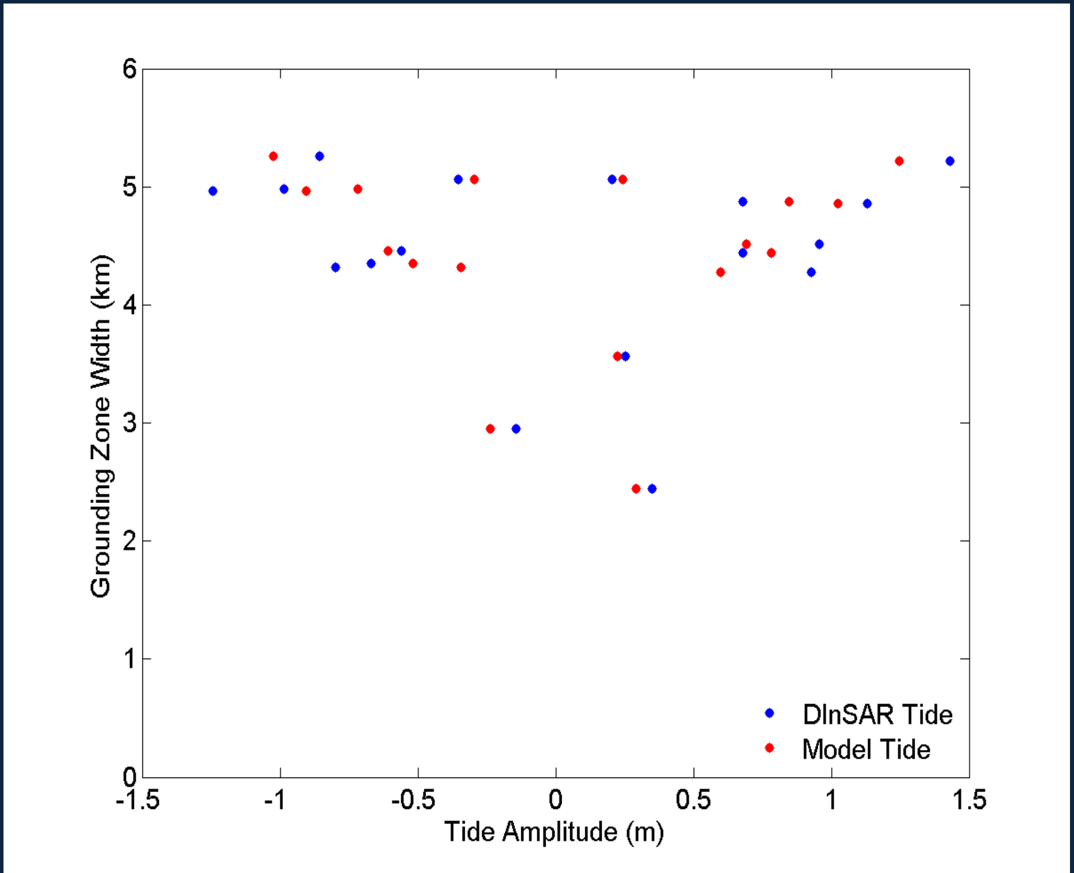
Picking the Grounding Line from a QDInSAR Image



- Quadruple difference interferometric fringe pattern across the grounding zone
- Profile of differential vertical displacement (black) extracted along a transect (white)
- The grounding line location (green) is identified as the inland limit of tidal flexure
- The QDInSAR image now contains the differential phase signal which on floating ice streams is largely caused by tidal motion, enabling the grounding line to be determined.

Detecting Grounding Lines: QDInSAR

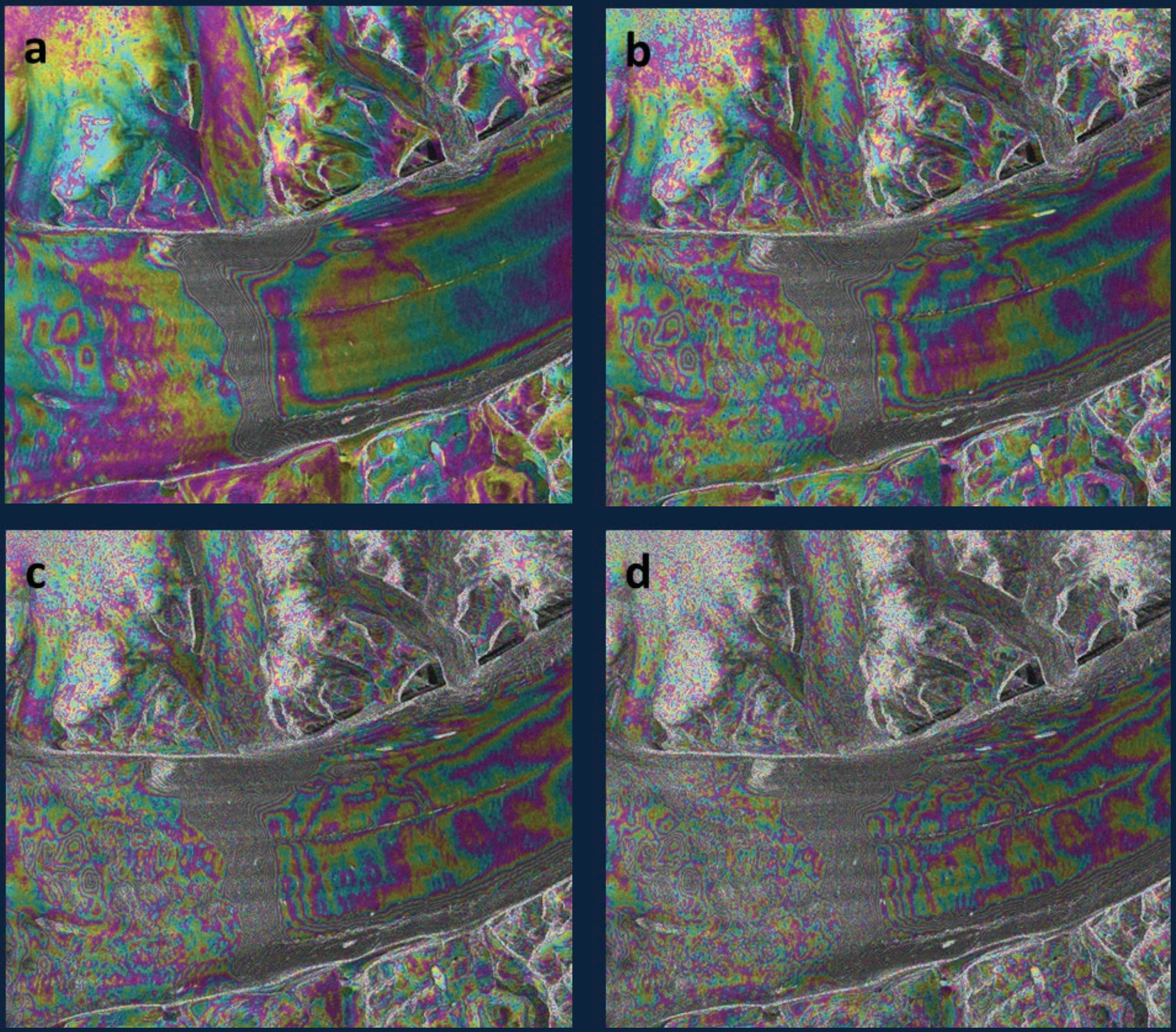
Grounding Zone Width



- The width of the grounding zone measured from the QDInSAR images, shown relative to the modelled differential tide and the relative displacement of the floating ice shelf measured in an unwrapped QDInSAR image.
- GZ width = ~4km
- Width doesn't vary too much with tide amplitude, although

Detecting Grounding Lines: QDInSAR

Grounding Zone Width

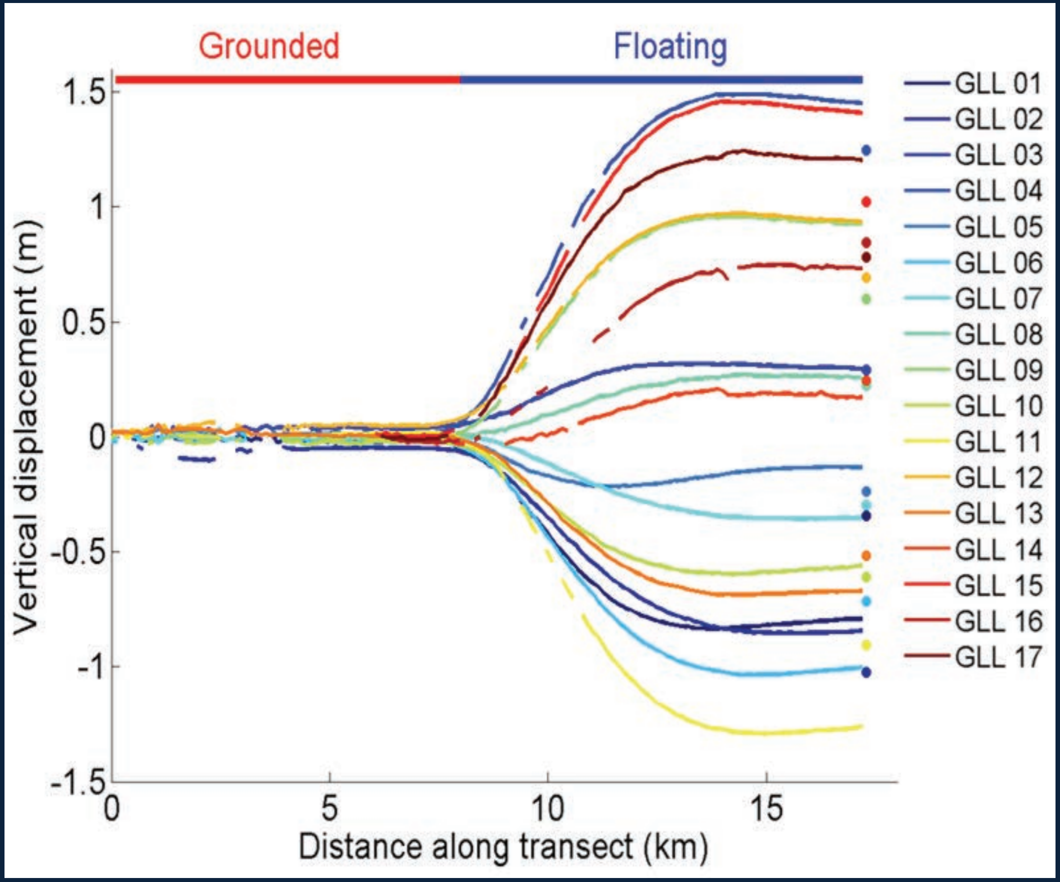


a) The original QDInSAR image, and the QDInSAR image with the phase signal multiplied by 2 (b), 3 (c) and 4 (c) times the original value.

Detecting Grounding Lines: QDInSAR

Phase Unwrapping – converting phase to absolute measure of deformation

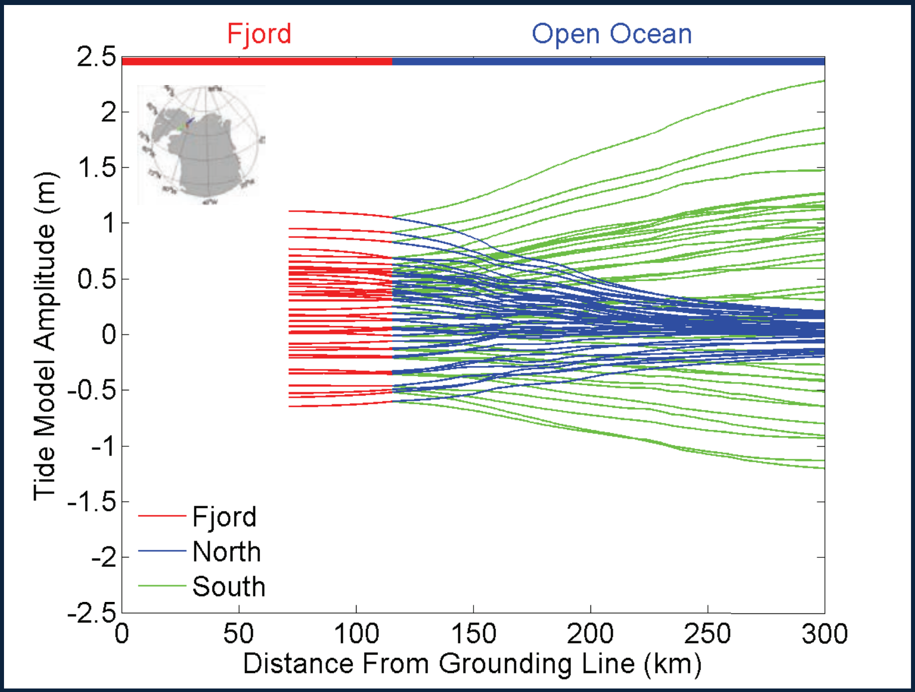
- The QDInSAR image can be unwrapping to retrieve the absolute phase difference



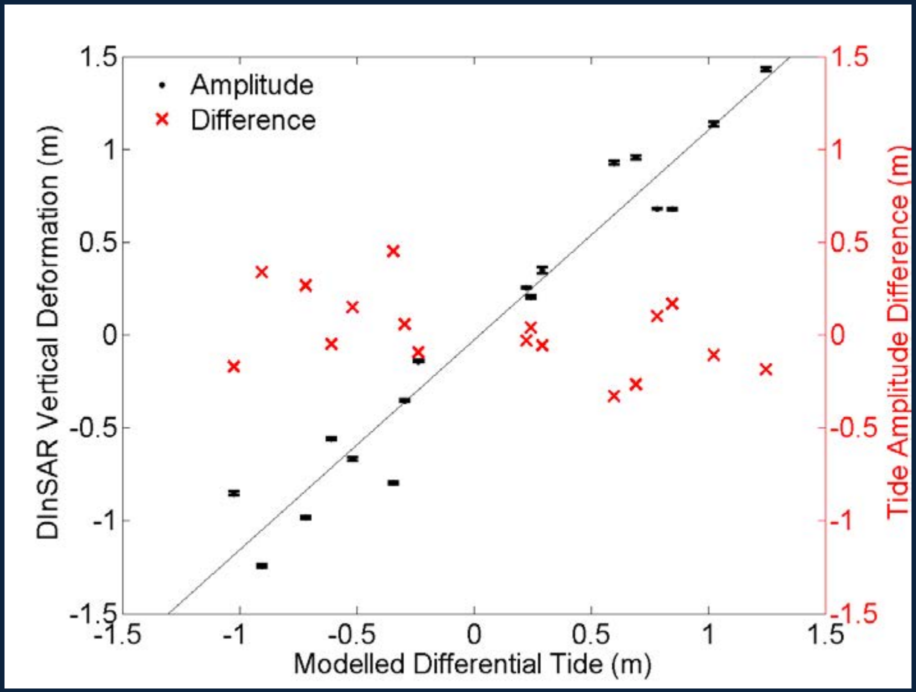
- Relative vertical displacement along a flow-line profile of a grounding zone
- Measured using 17 quadruple difference interferograms
- 0 and 8 kilometres: no vertical deformation = section of the glacier is grounded on bedrock
- 8 kilometres and farther seaward: up to 1.5 metres of relative deformation recorded = section of the glacier is influenced by the ocean tide and therefore floating

Detecting Grounding Lines: QDInSAR

Phase Unwrapping



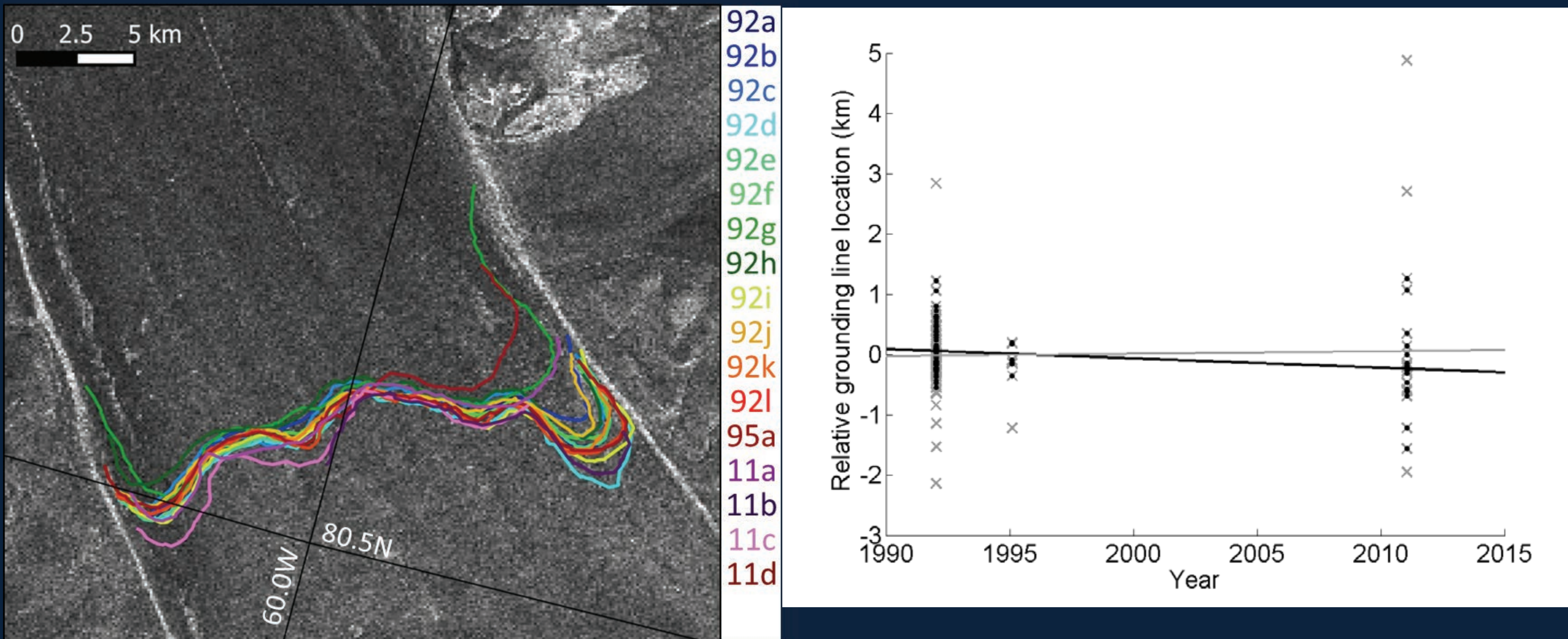
- Ocean tide amplitude in the Petermann Glacier:
- fjord (red), and to the North (blue) and South (green) of the fjord in Nares Strait
- AODTM-5 Arctic tide model. Each line shows tidal amplitude at the time of an ERS SAR acquisition
- The AODTM-5 tide model domain begins 71 km from the grounding line.



- Comparison between ocean tidal amplitude differences, as determined from the AODTM-5 Arctic tide model, and relative vertical displacement of the Petermann Glacier ice shelf, as determined from quadruple difference interferometry (black points).

Detecting Grounding Lines: QDInSAR

Grounding Line Change / Migration

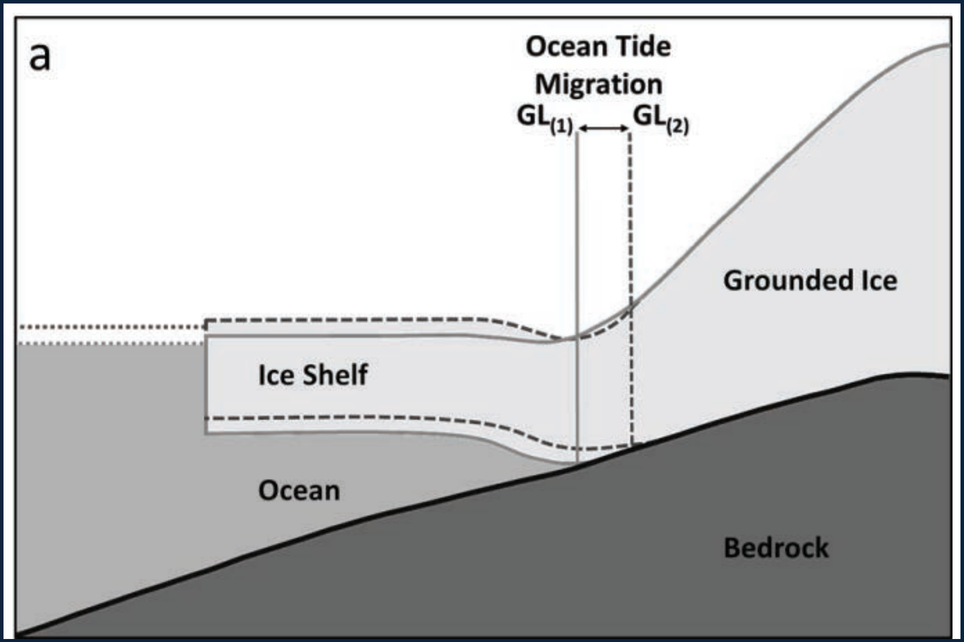


- Petermann Glacier grounding line measured between 1992 and 2011
- Each coloured line represents a grounding line produced from quadruple difference interferometry at distinct time periods
- Mean grounding line migration is 470 m
- Up to 7km motion on most variable section of the grounding zone

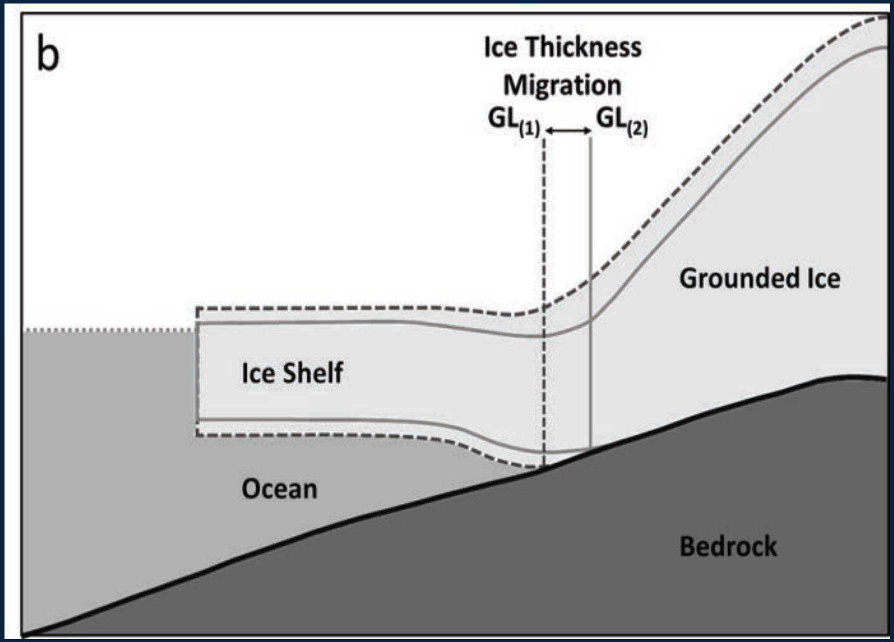
- But observed motion clearly not correlated with time..
- So what are the processes causing grounding line migration?

Detecting Grounding Lines: QDInSAR

Possible drivers of grounding line migration:



GL migration due to change in ocean tide amplitude

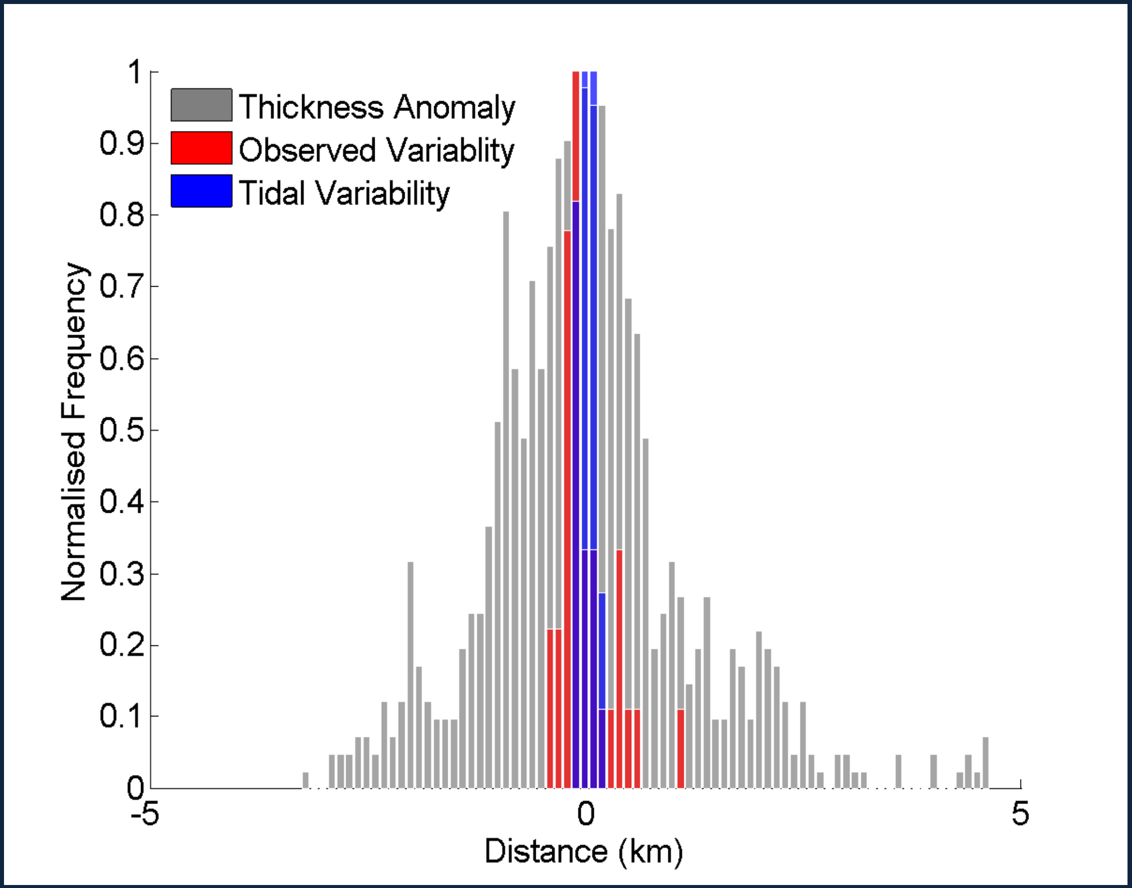


GL migration due to change in ice thickness

Does this influence grounding line location on long timescales only, or could it influence short tem change too?

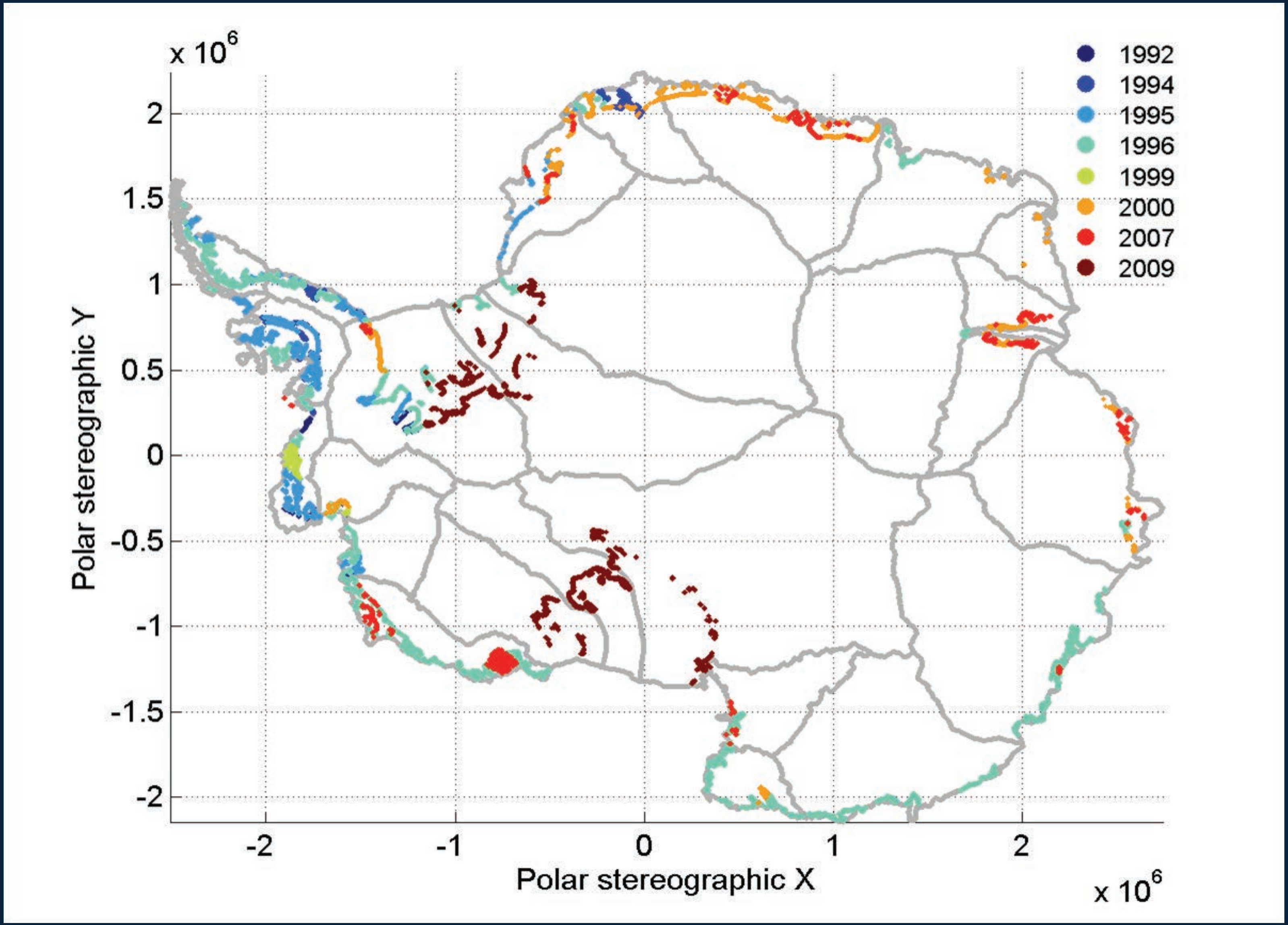
Detecting Grounding Lines: QDInSAR

Possible drivers of grounding line migration:



Normalised distribution of observed (red) changes in Peterman Glacier grounding line position and of the simulated change due to fluctuations in ocean tide (blue) and thickness anomaly (grey).

Detecting Grounding Lines: QDInSAR



Measurements of the grounding line position made by QDInSAR between 1992 and 2009 (NASA MEASURES, Rignot et al., 2011)

Sentinel-1 - The Next Generation of InSAR

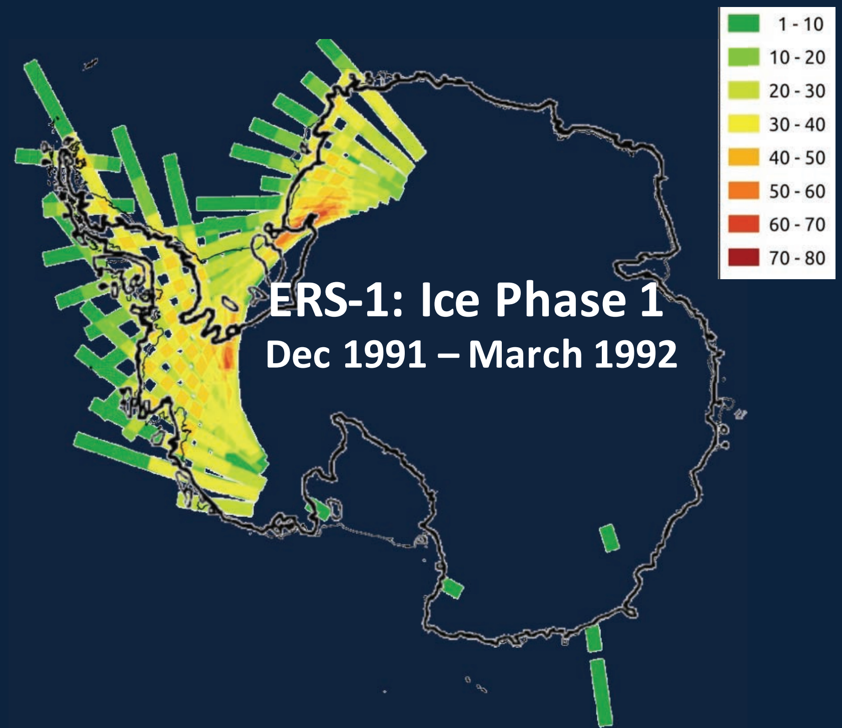
- Sentinel-1 launched 3rd April 2014
- First satellite in the Europe's Copernicus programme

- C-band SAR sensor, all year, day/night, all weather monitoring capability

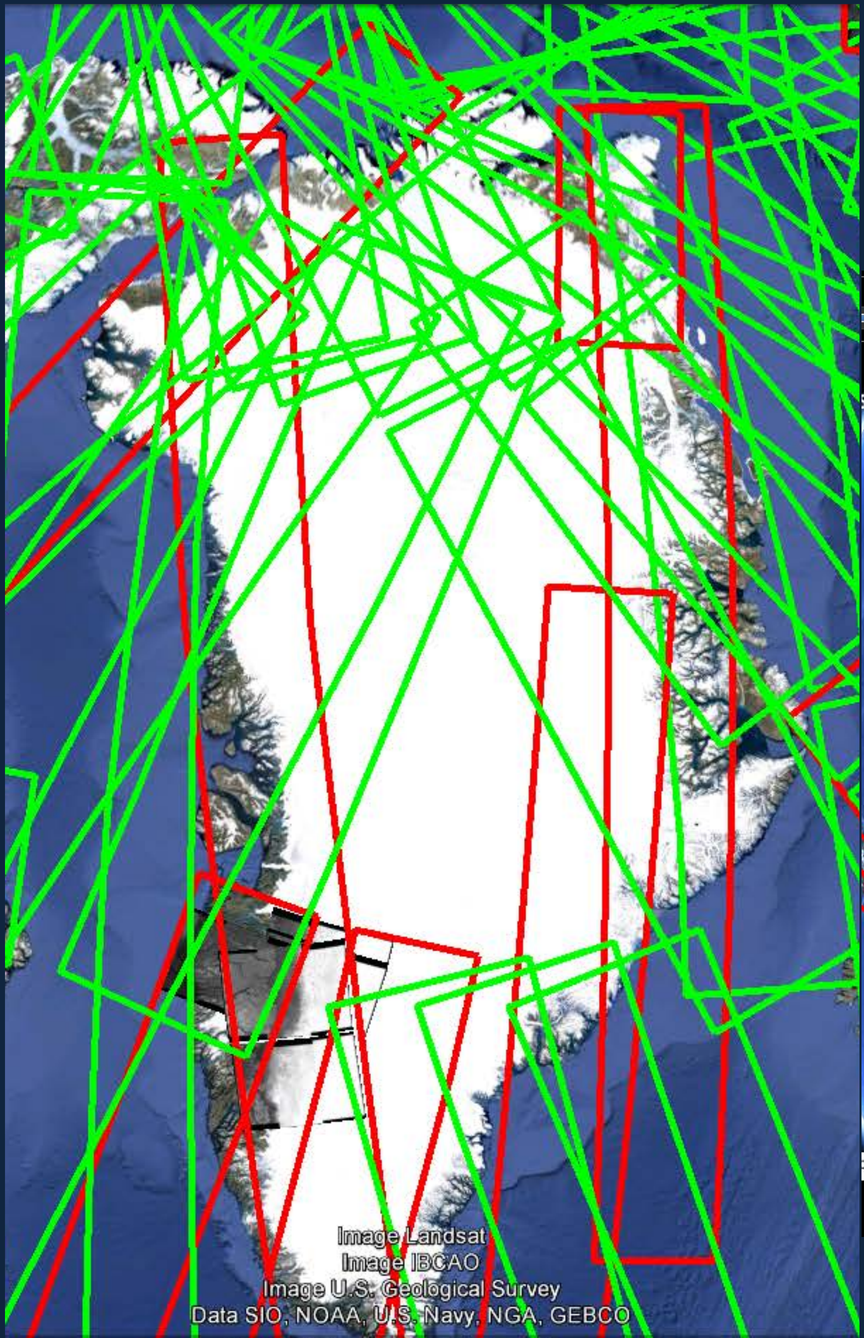
- 12 day repeat period and large swath provided for the first time the opportunity to routinely monitor ice speed in near real time

- Changes in ice flow
  - Changes can be temporary/routine – tidally induced, seasonal
  - Or permanent/long term – dynamic instability
  - Both important measure of sea level contribution from ice sheets to ocean

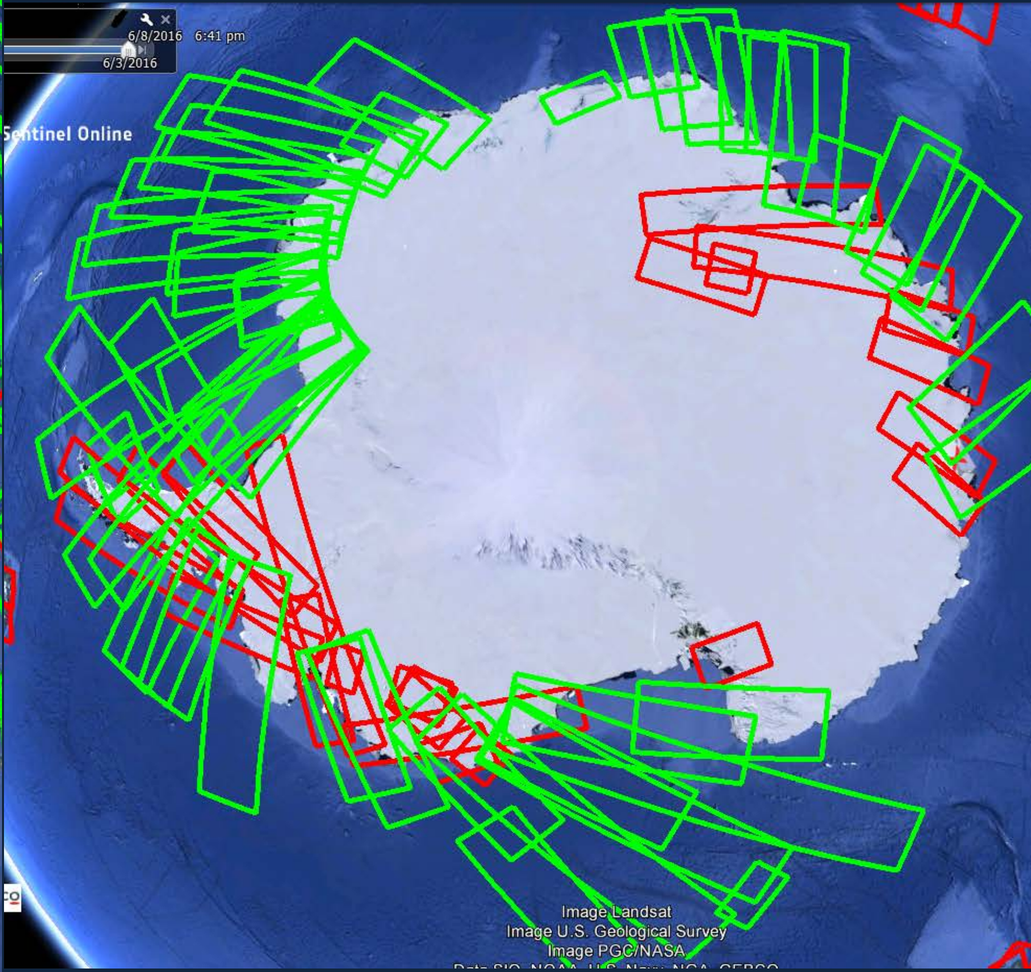
- Sentinel1-b launched 25th April 2016 – pair combined will provide 6-day repeat coverage



Sentinel-1 - The Next Generation of InSAR



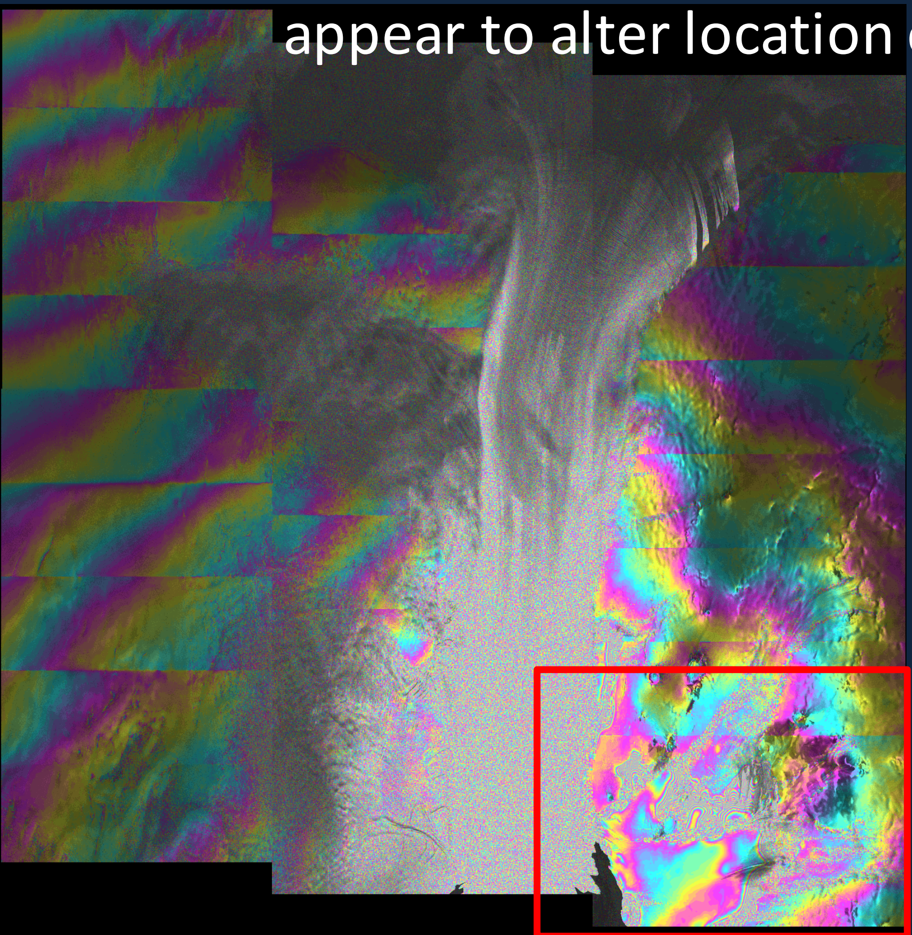
More data acquired in a week with S-1 than by years of ERS operation!

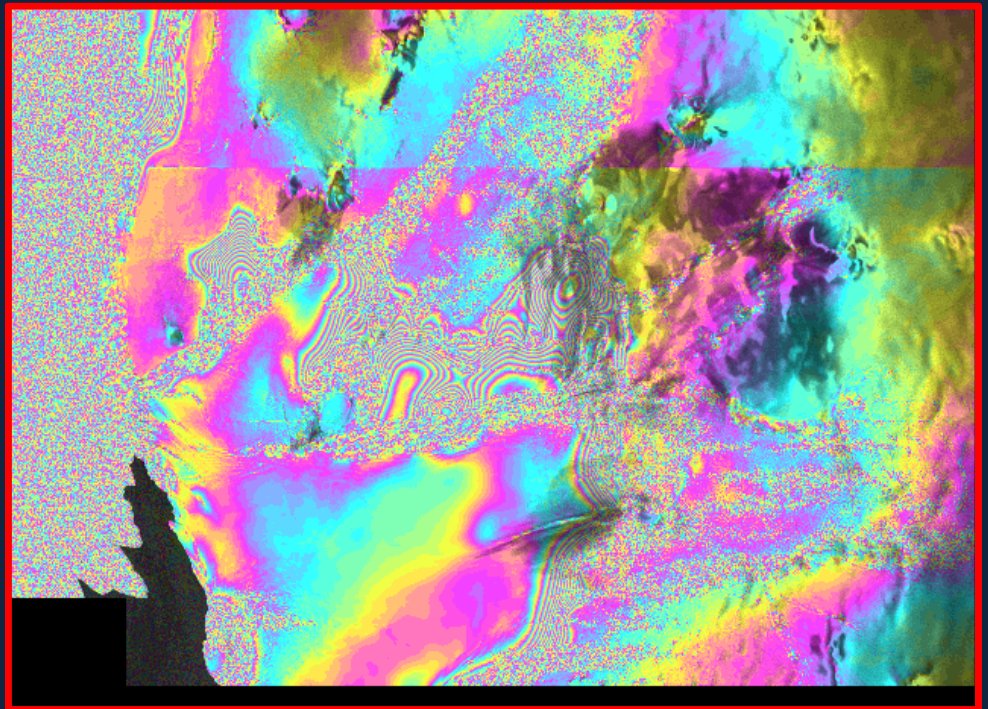


Sentinel-1 - The Next Generation of InSAR

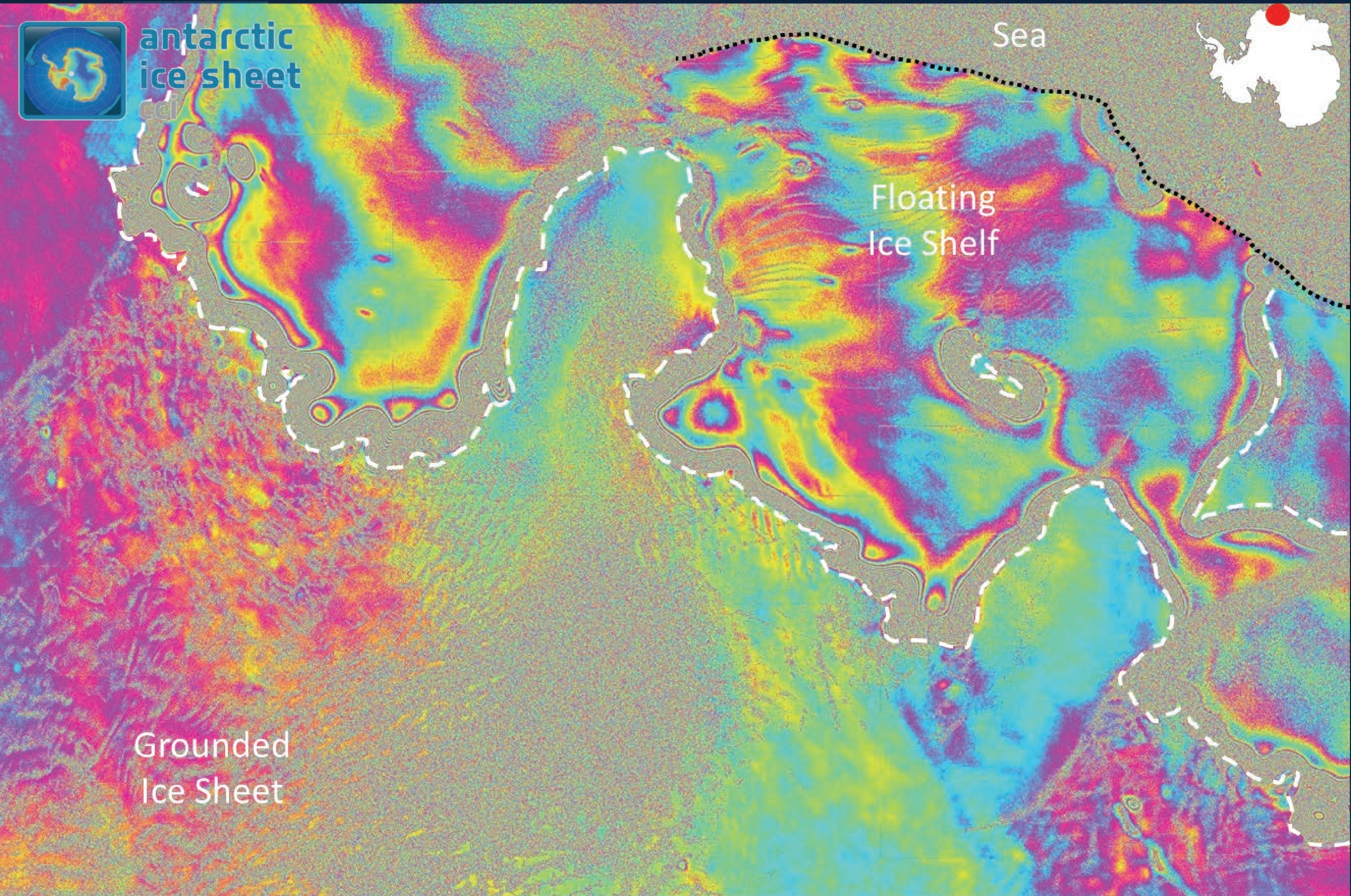
There are new challenges associated with TOPS mode interferometry

- Phase discontinuities can occur at the burst boundaries
- Definitely a problem for unwrapping interferograms to produce DEM or ice speed
  - May not be a large problem for grounding lines as doesn't appear to alter location of GZ fringes

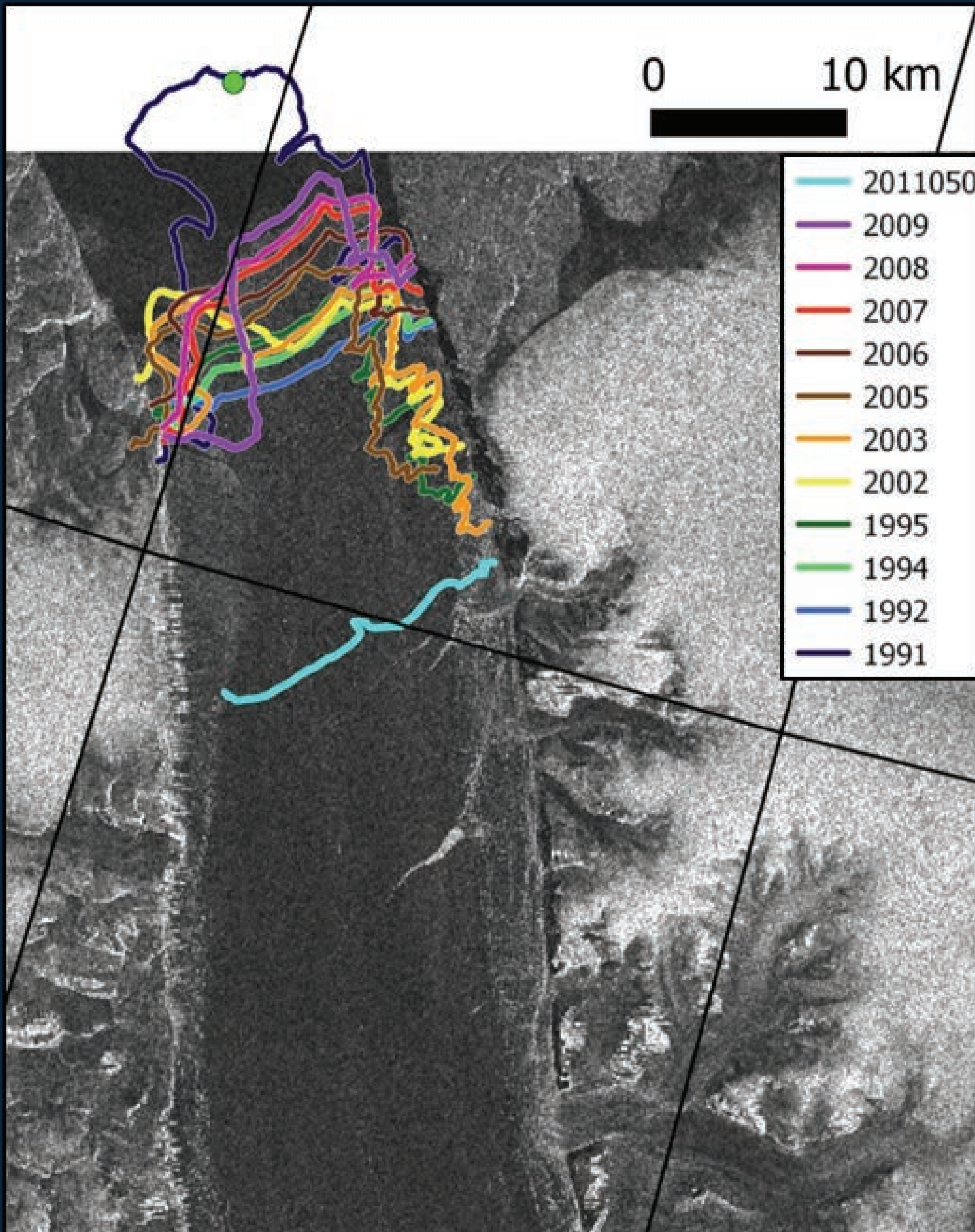




Sentinel-1 - The Next Generation of InSAR



SAR Applications: Calving Front Location



CFL's observed to change over long time scales and seasonally

CFL's Useful for:

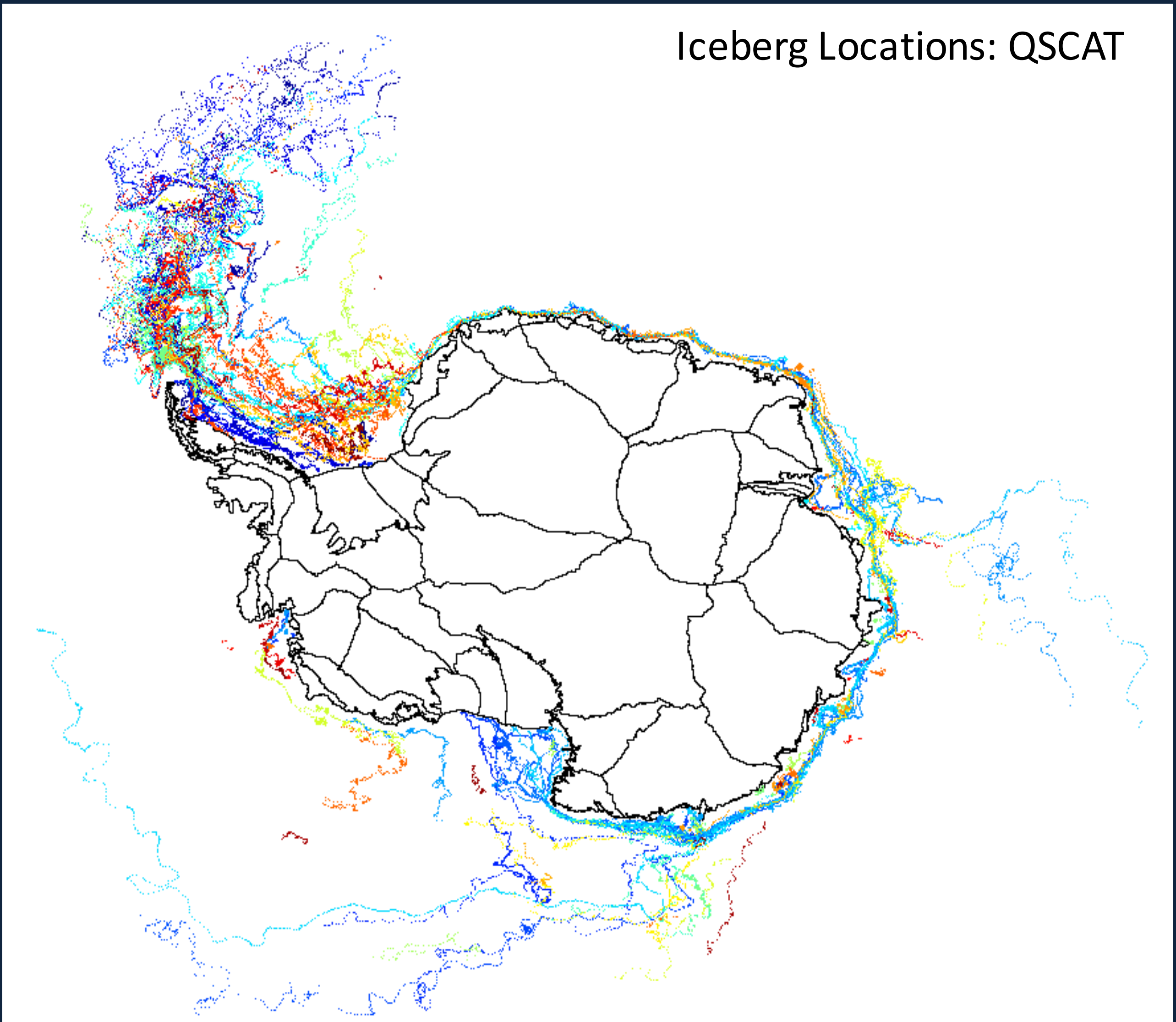
- Ice dynamic modelling
- Glacier area change

CFL's not limited to being produced from SAR data only, but is the best year round sensor

Data available from projects like Greenland Ice Sheet CCI

ice sheets greenland cci

SAR Applications: Iceberg Tracking



Iceberg locations tracked by a lots of sensors:

ERS

QSCAT

OSCAT

ASCAT

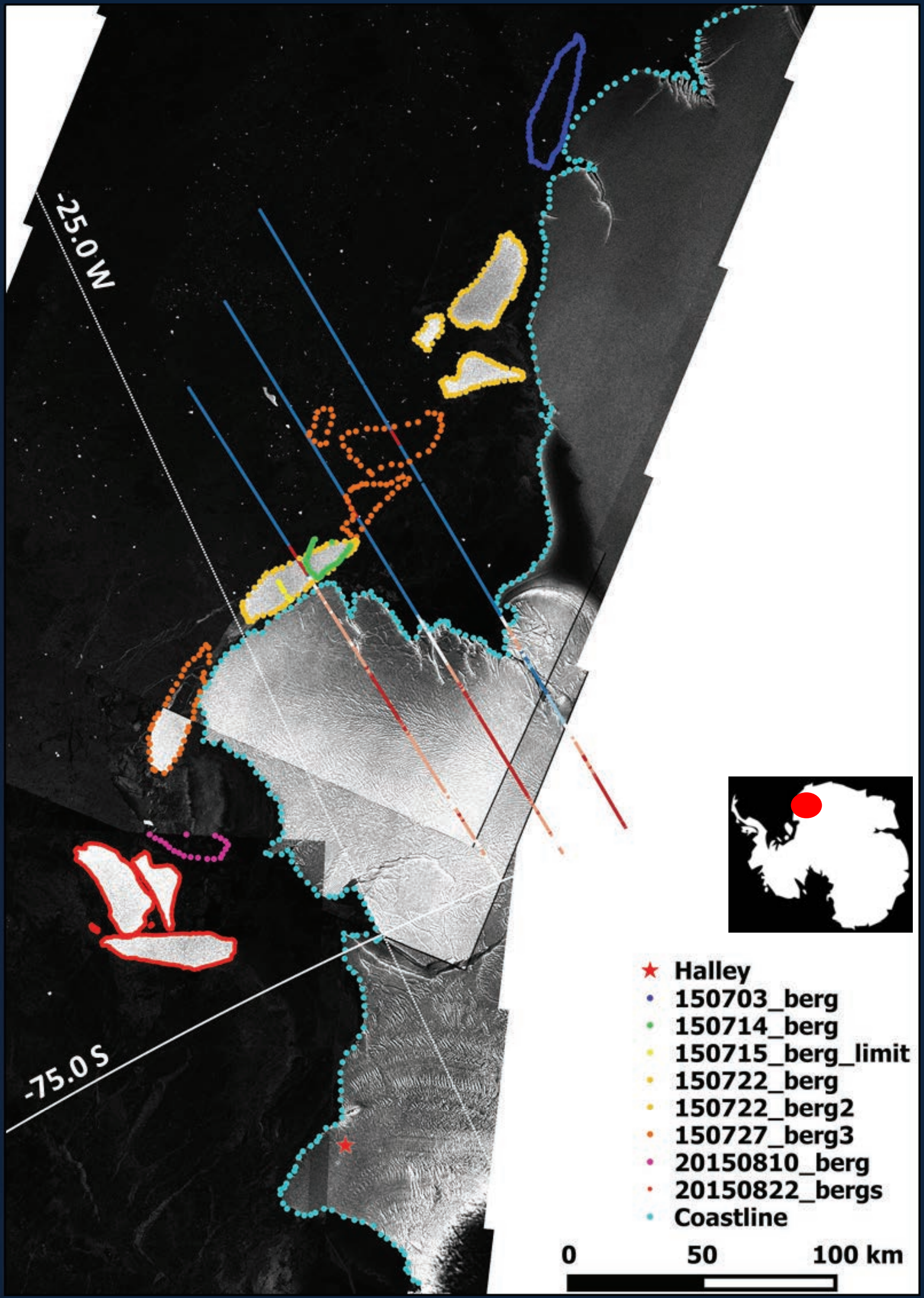
NSCAT

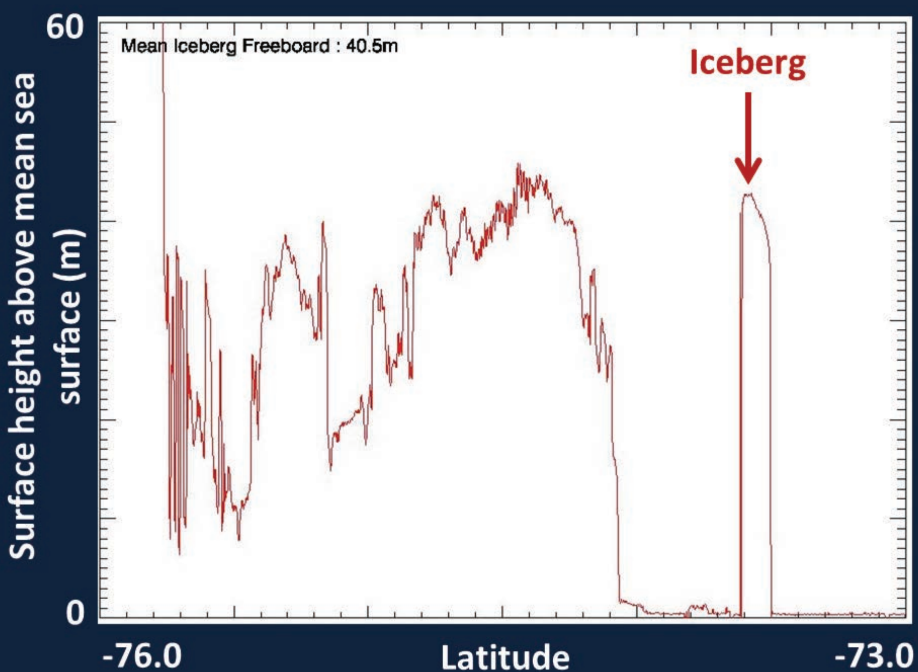
SASS

Locations available to download online: e.g. Antarctic iceberg tracking database

SAR Applications: Iceberg Tracking

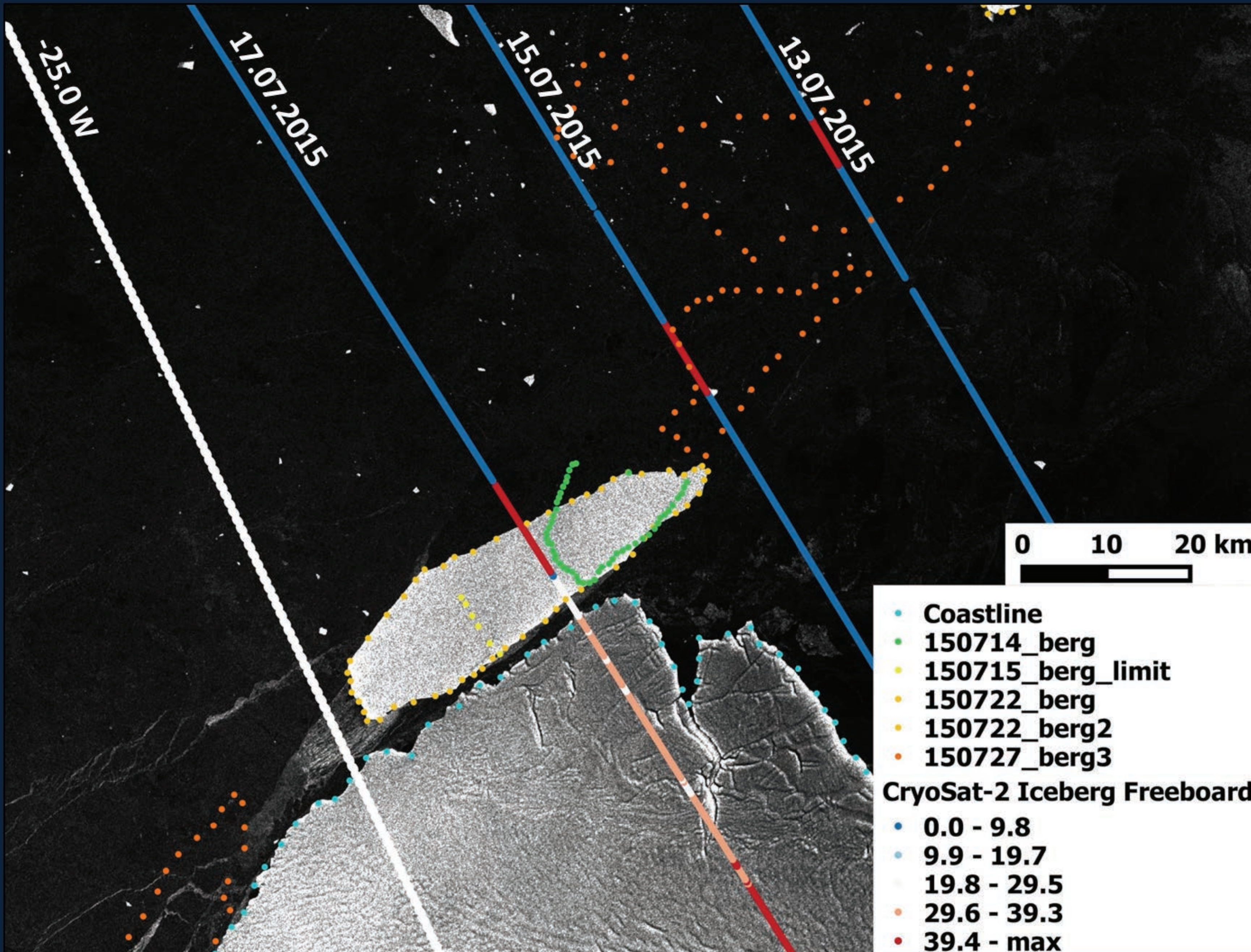
- Ice shelves calve icebergs
- Risk for ships and other infrastructure
- CryoSat-2 altimeter data used to measure ice freeboard
- Operational service for marine vessels and research stations



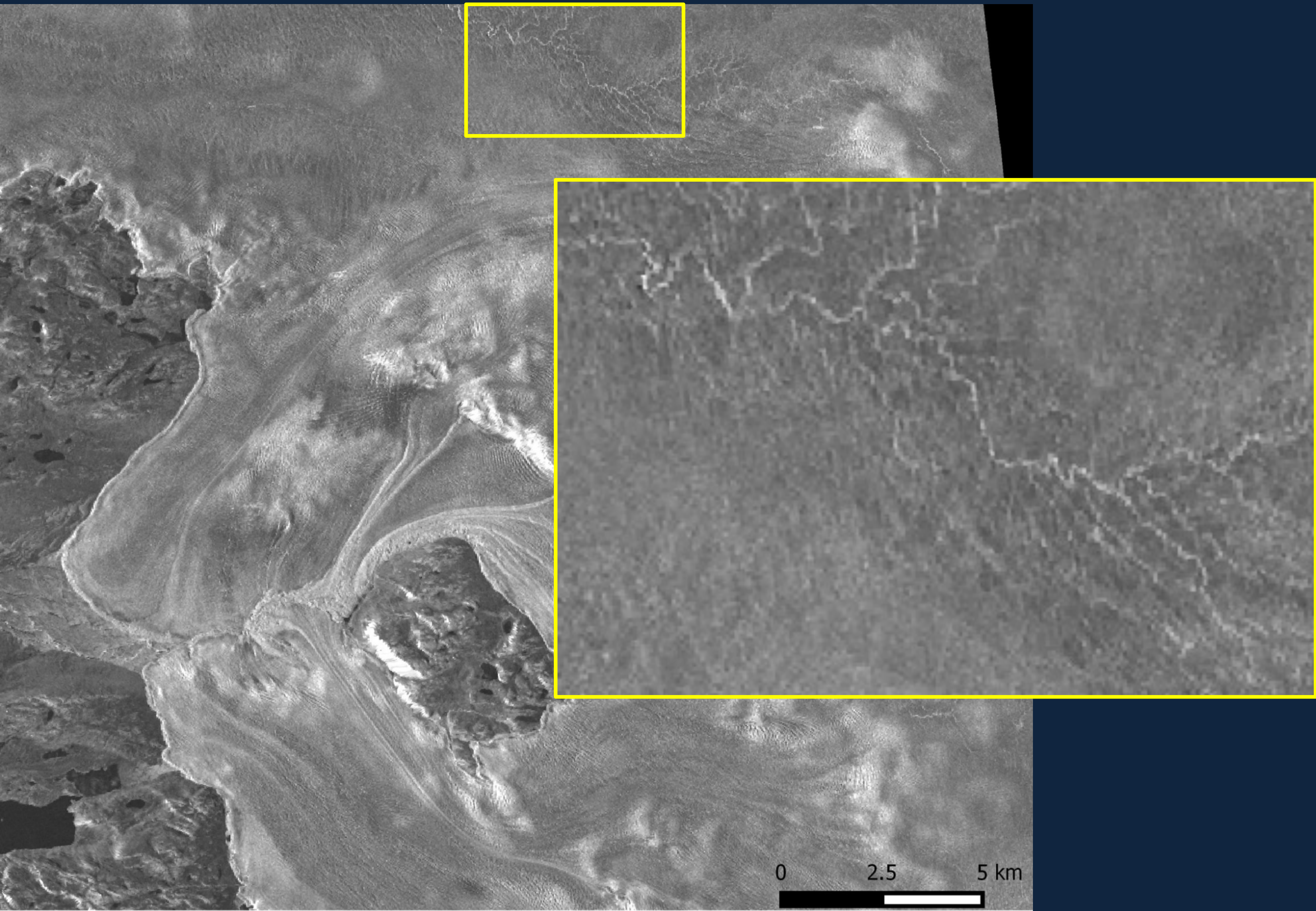


(Hogg and Ridout, CPOM)

SAR Applications: Iceberg Tracking



SAR Applications: Hydrology



Summary

(1) Grounding lines are important glaciological parameter

- Observations help us understand processes causing present day ice sheet change
- And, by modelling observed rates of grounding line retreat it will help us predict future change and associated sea level rise contribution with more confidence

(2) To date, QDInSAR is the best technique for precisely monitoring grounding line position – but it does have limitations, e.g. historically sparse spatial and temporal coverage

- we should continue to develop new techniques and methods to exploit all EO data archives
- New satellites such as S-1provide great opportunity for measuring grounding line more frequently, but scientific community must ask space agencies to acquire suitable data

Photo: A. Hogg – D. Vaughan collecting DELORES data, iSTAR traverse Pine Island Glacier 2013/14

Summary

(3) Dramatic long term (> annual/decadal) grounding line retreat has been observed in the Amundsen Sea sector over the last 25 years

(4) Short term (< annual) grounding line variability is still largely unknown as observations have been lacking

(5) Only the most sophisticated ice sheet models can accurately reproduce observed grounding line retreat.
- Initiatives like ISMIP6 are a great step forward for the next IPPC report

(6) SAR data is great
- there are many other useful applications!!

Photo: A. Hogg – D. Vaughan collecting DELORES data, iSTAR traverse Pine Island Glacier 2013/14