Funding Support:

# Larsen Ice Shelf Disintegrations:
## climate – ice – ocean interactions that led to break-up


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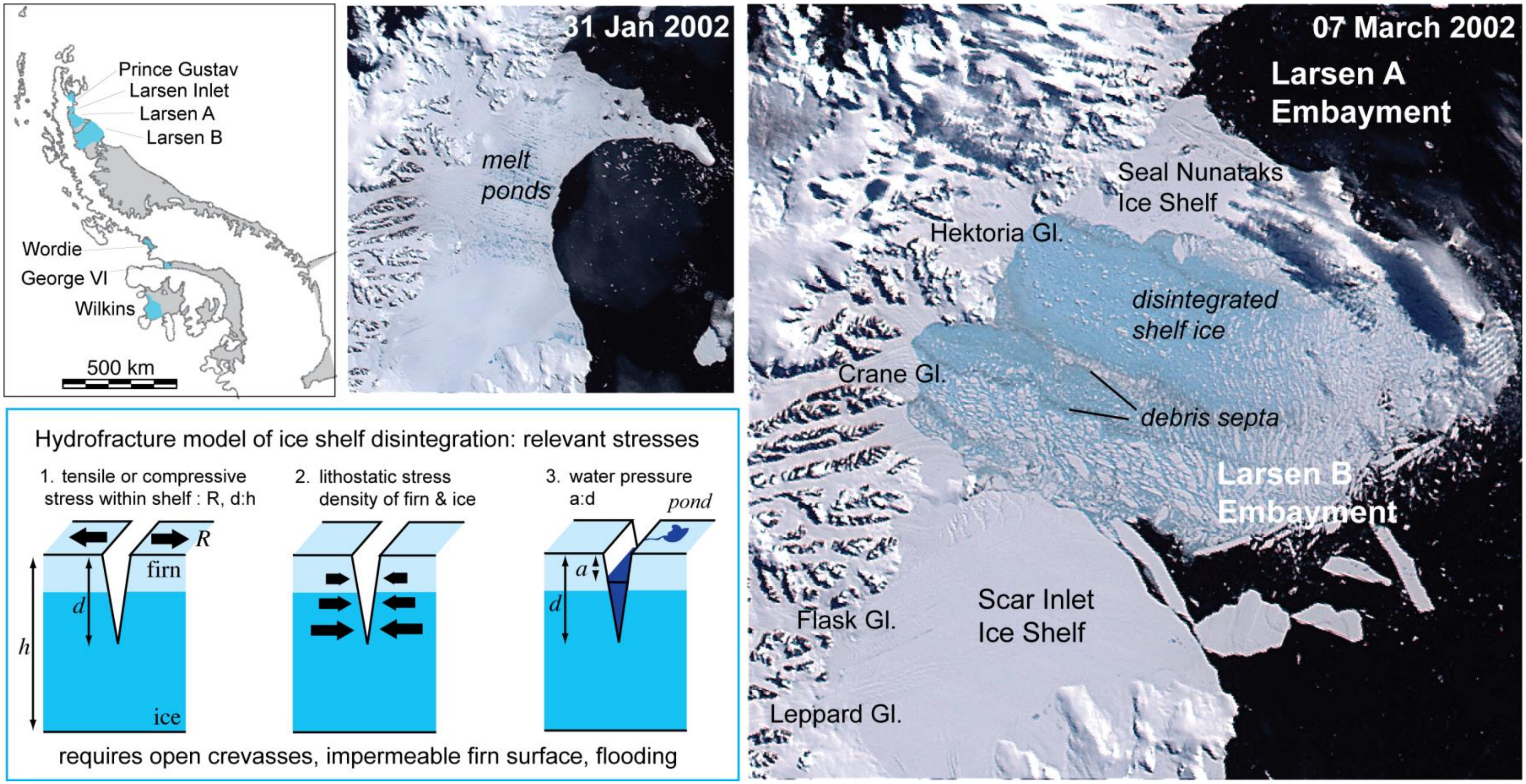
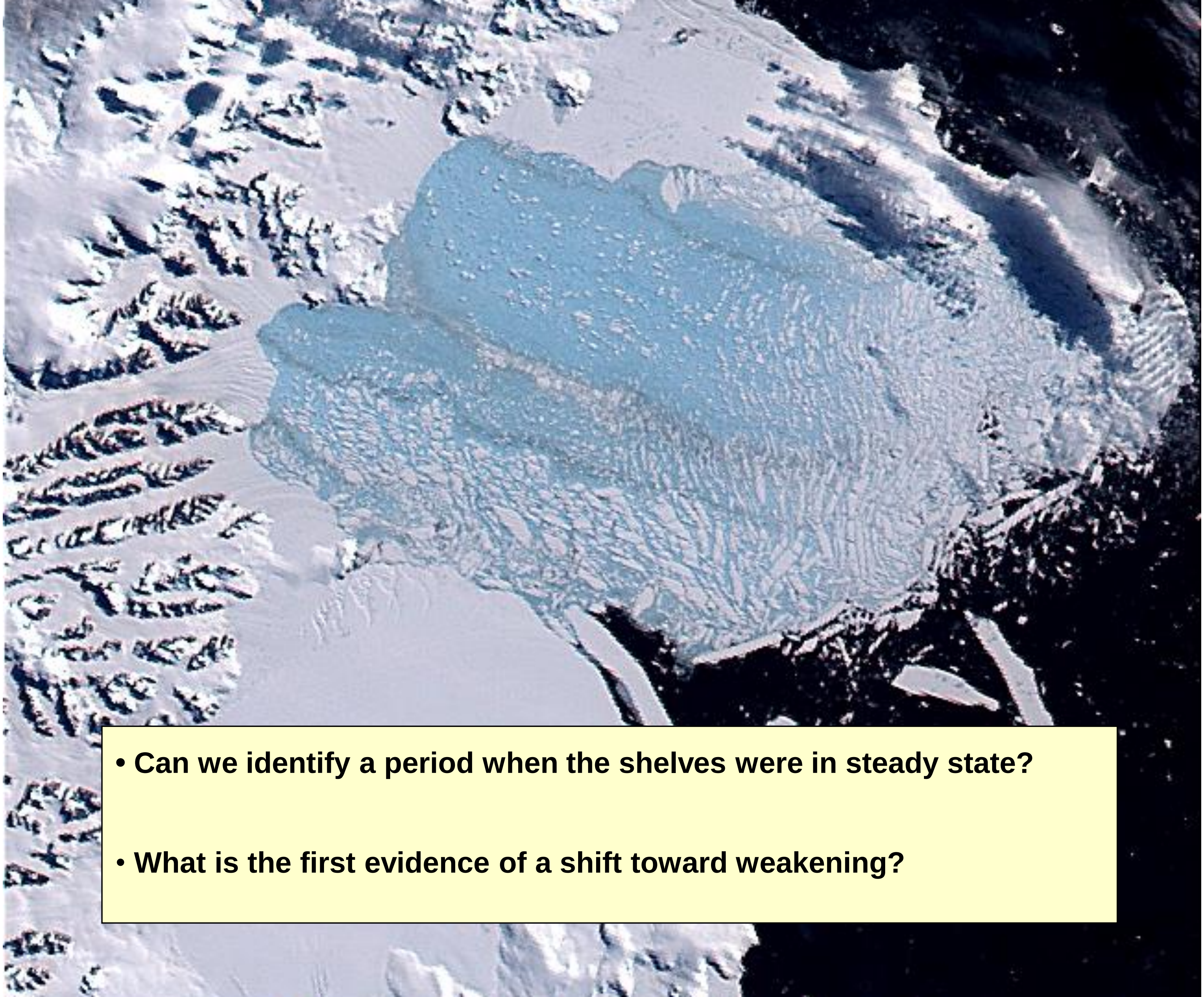
# *Antarctic ice shelf break-ups: how to disintegrate an ice shelf*



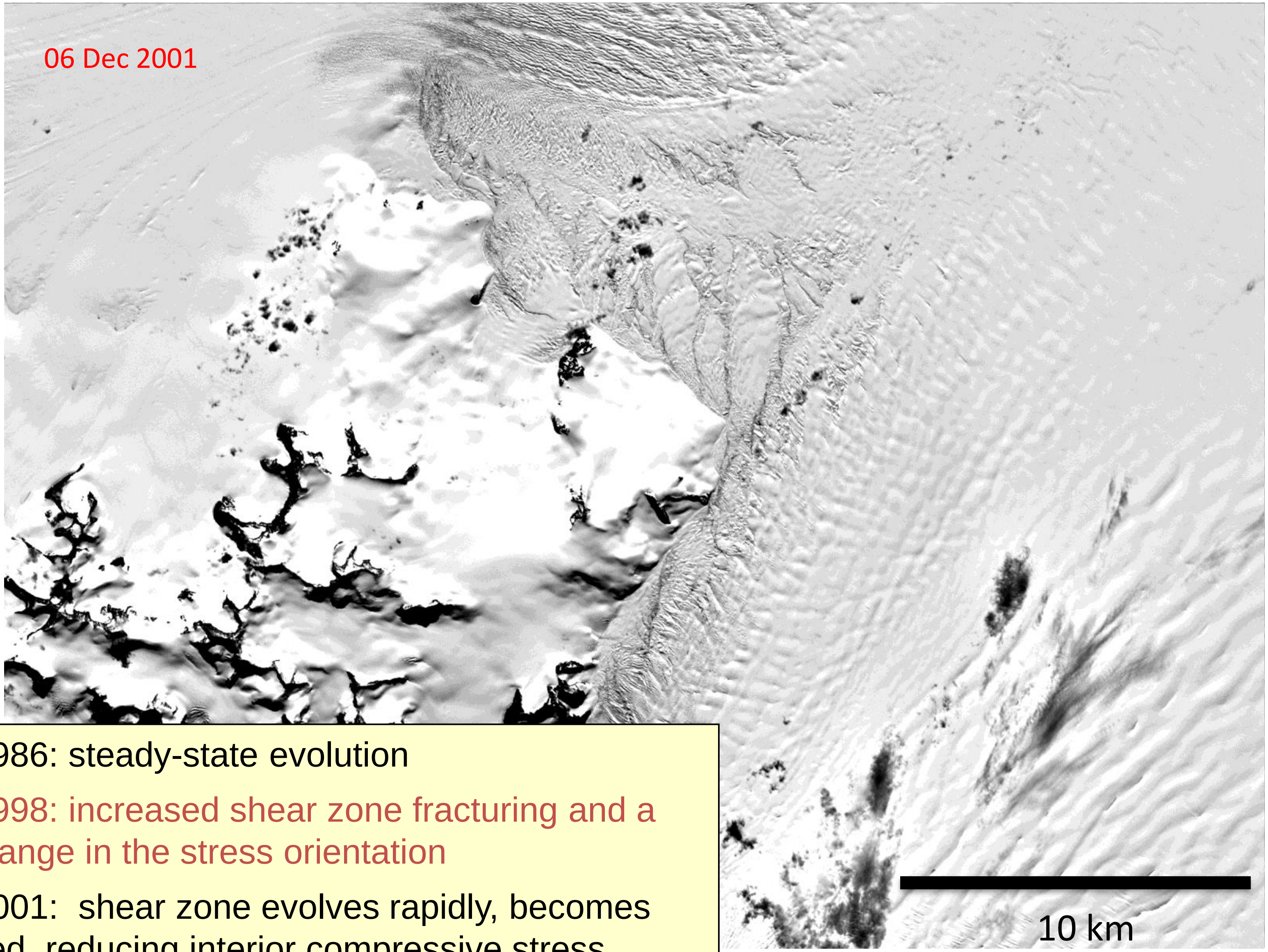

and, low interior compressive stress, dense icy firn, and a long melt season.

Scambos, Hulbe, and Fahnestock, 2003, Ant. Res. Series v.79



- **Can we identify a period when the shelves were in steady state?**
- **What is the first evidence of a shift toward weakening?**

# *Foyn Point margin evolution, 1963-2001*




1963-1986: steady-state evolution

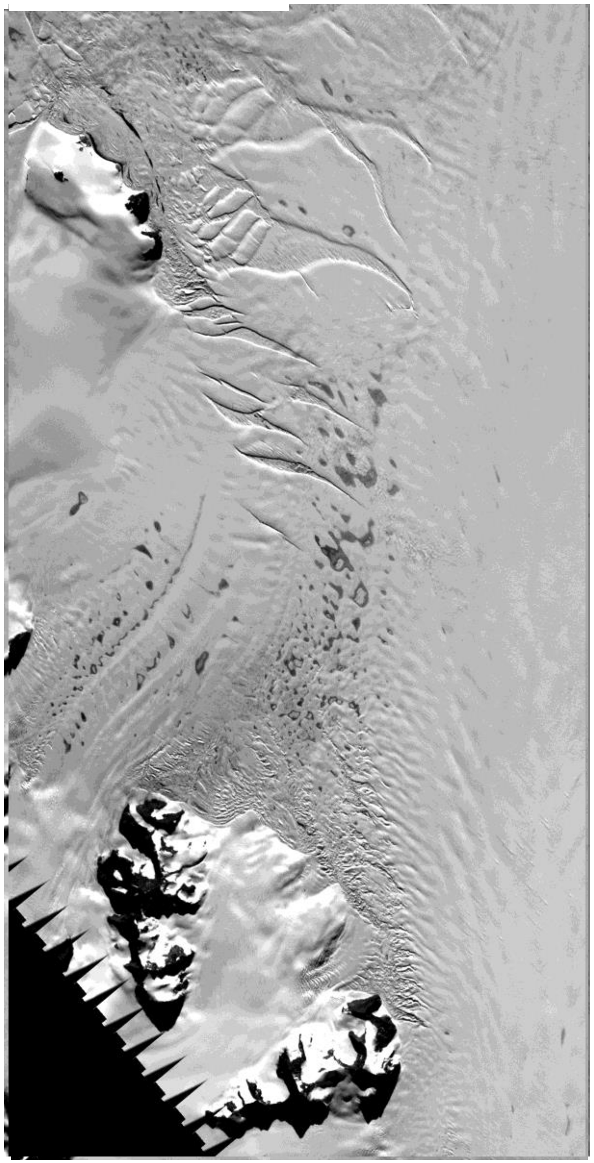
1986-1998: increased shear zone fracturing and a change in the stress orientation

1998-2001: shear zone evolves rapidly, becomes disrupted**,** reducing interior compressive stress.

Scambos et al., 2014 in prep.; see also Glasser and Scambos, 2008

## *Cape Disappointment margin evolution, 1963-2011*

21 Feb 2000



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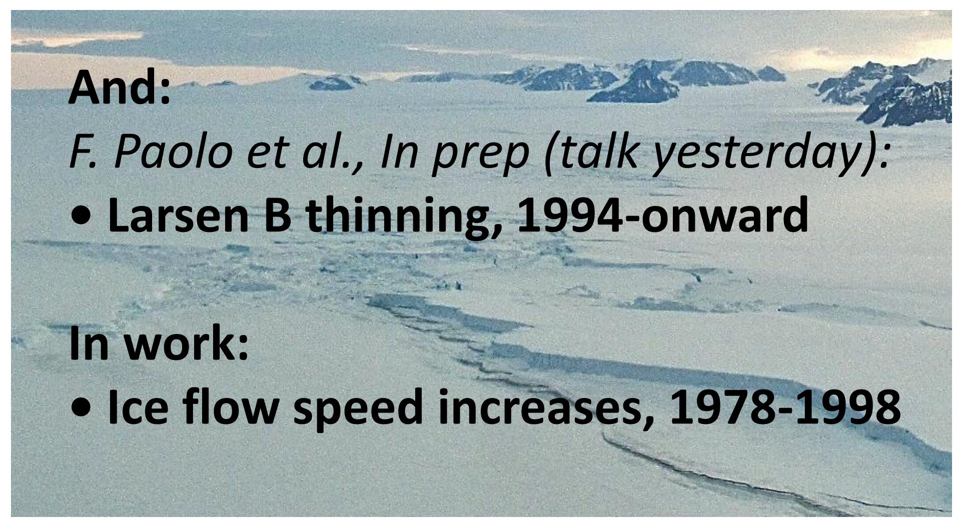



Scambos et al., 2014 in prep.; see also Glasser and Scambos, 2008

# *A conceptual model …*

**Peninsula climate, sea ice, and ocean conditions changed in the 1980s**

**Warming and increased westerlies**

- ***more frequent foehn wind events***
- ***sea ice cover declines in the NW Weddell***

**Greater wind traction on the ocean surface, especially at the ice shelf front**

**Change in ocean circulation at depth?**

- ***modified Weddell Deep Water (mWDW) entrained beneath the shelves?***

**Ice shelves weakened, especially at the margins**

**Increased surface melting on the Larsen ice**

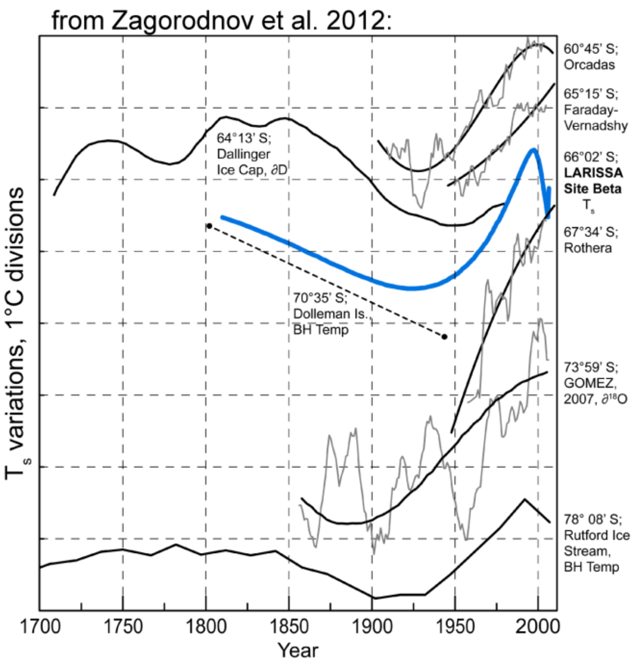
- ***increased susceptibility to hydrofracture***

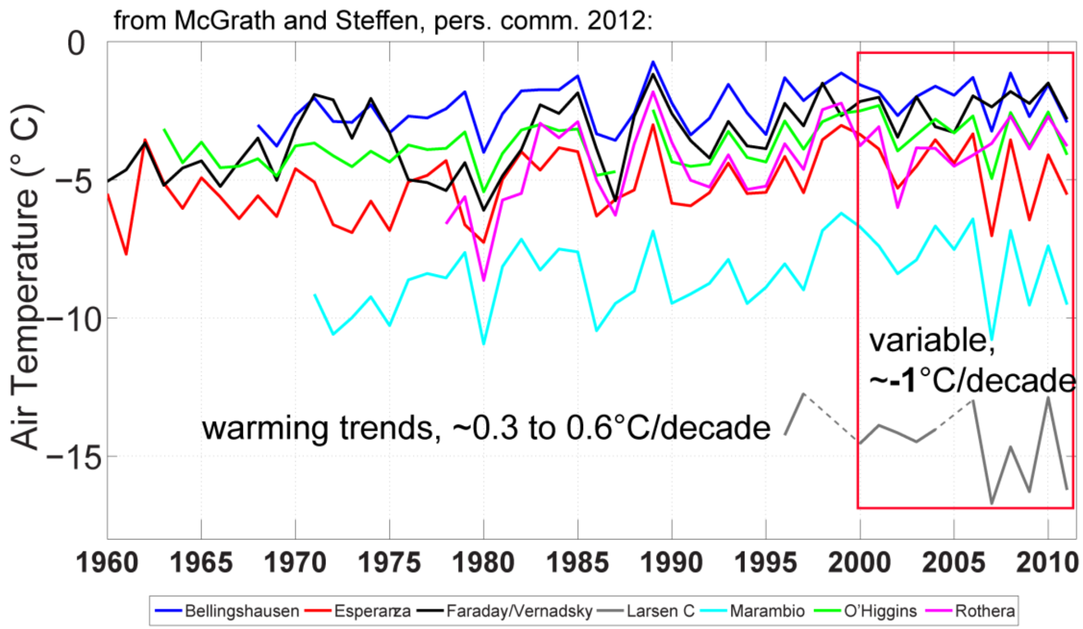
**Greater exposure to wave action at ice front**

- ***wave train flexed shelf to trigger event?***

# Climate trend for the Antarctic Peninsula

Warming conditions since ~1930 until 2006
slight cooling in recent years



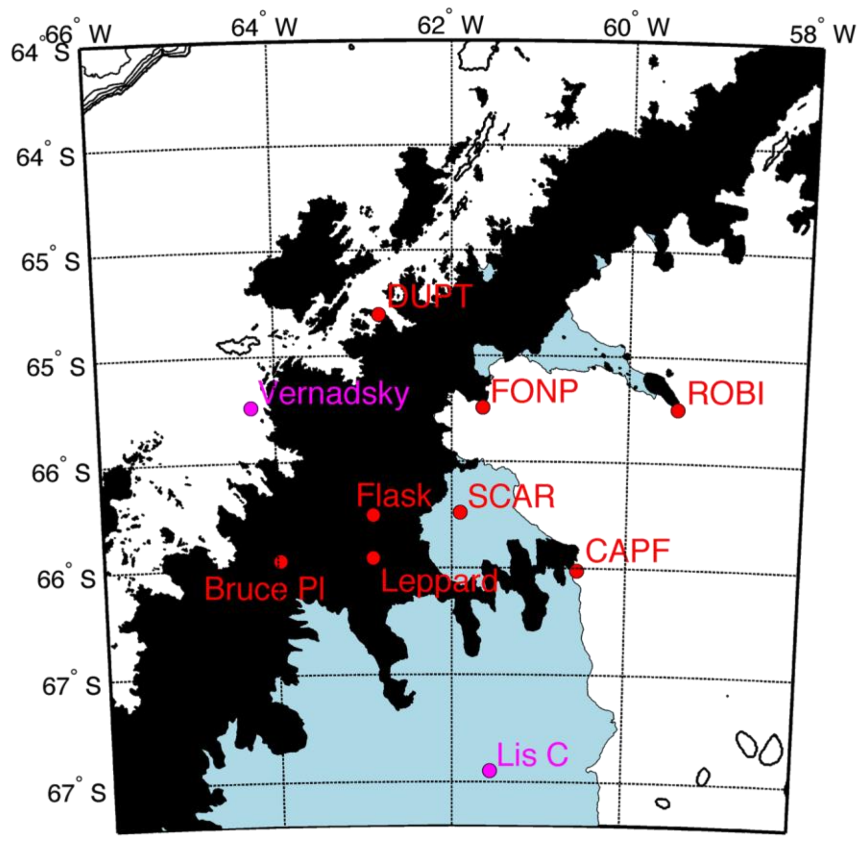

Borehole temperatures and ice cores

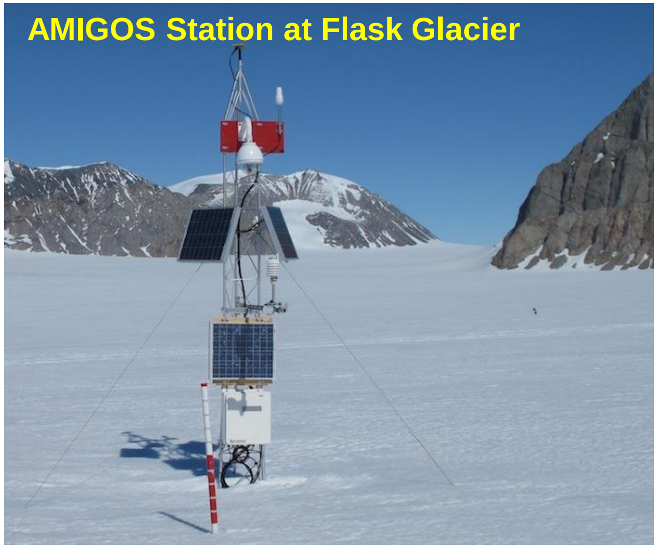
Weather station records

Bull. Am. Met. Soc., 2012, State of the Climate 2011: Antarctica

# *Linking weather to climate: LARISSA AMIGOS and PoleNet stations*

Map of LARISSA weather station locations (red)

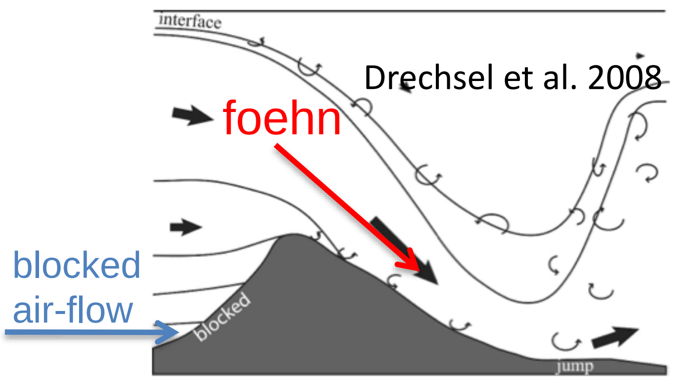


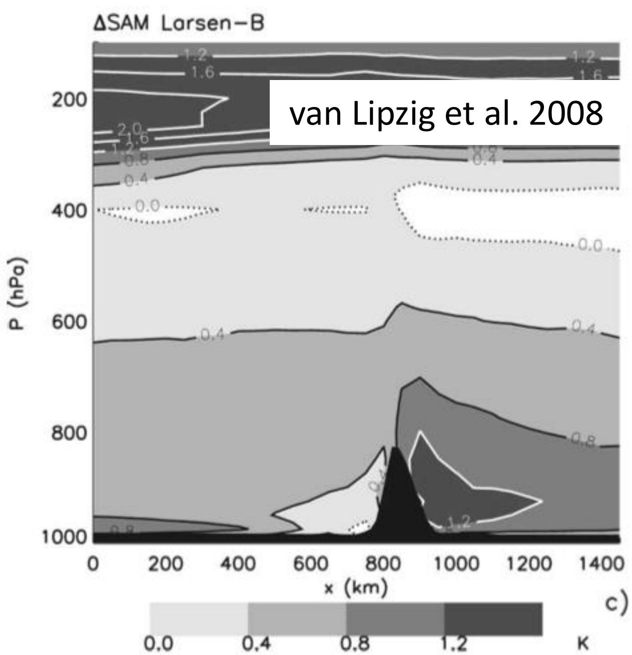



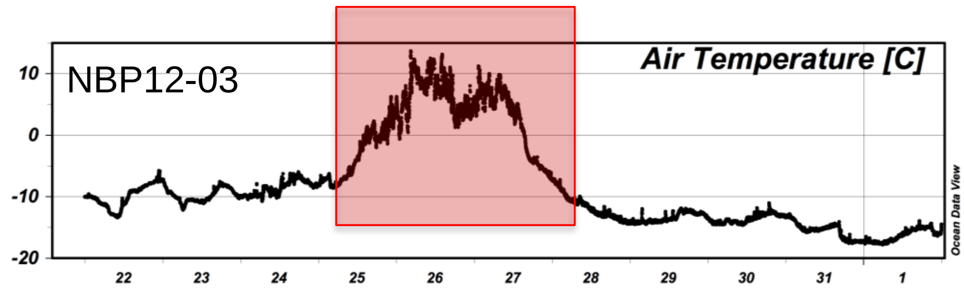


M. Cape, M. Vernet et al., 2014 in prep.

# *Foehn Winds* *(or 'chinooks')*




- Synoptic forcing leads to higher incidence of air flow over the peninsula
    - SAM+, stronger low-level westerlies
- Orographically induced ascent of westerlies -> advection of warm, dry air to the surface on the leeward side
- Foehn events persistent over days – weeks

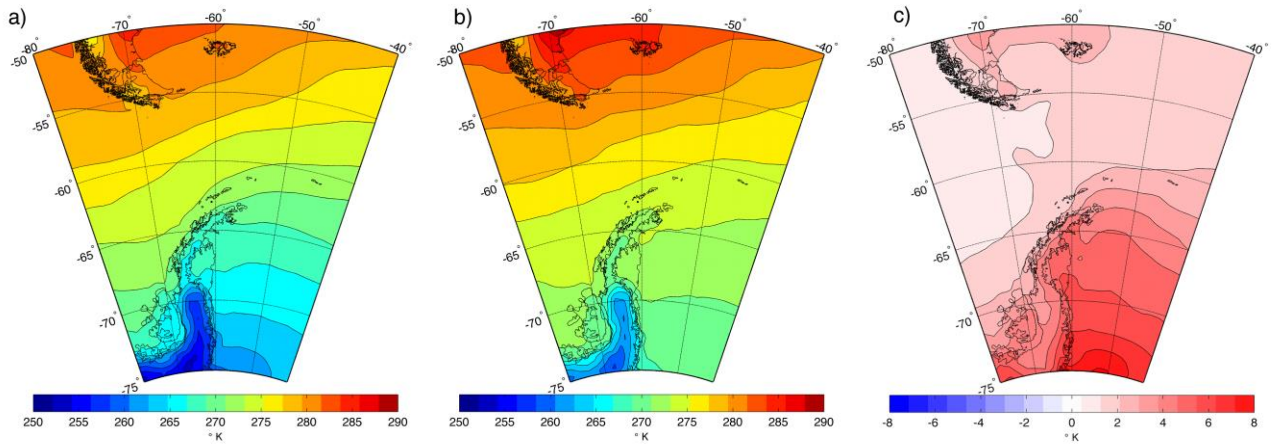
M. Cape, M. Vernet et al., 2014 in prep.

# Regional climate pattern during foehn events

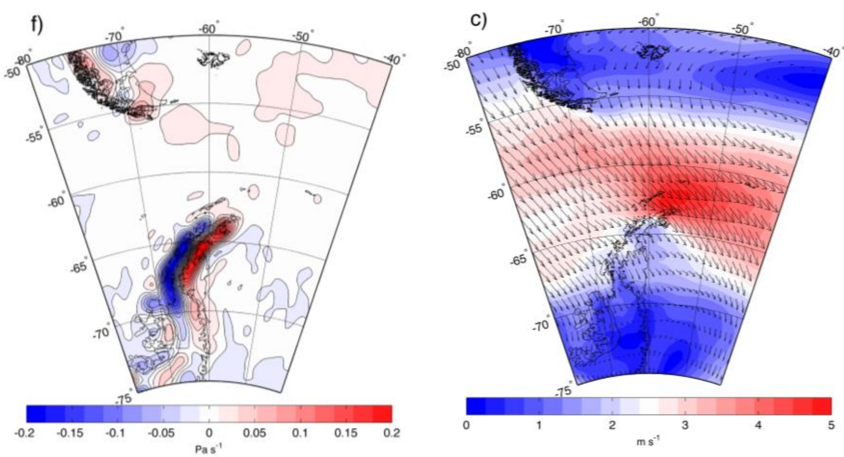
Temperature and wind from ECMWF ERA-Interim reanalysis

Temperature (K)

**Normal conditions** **Foehn conditions** **Difference**




Wind anomaly (m/s)




Vertical wind velocity anomaly (850 hPa)

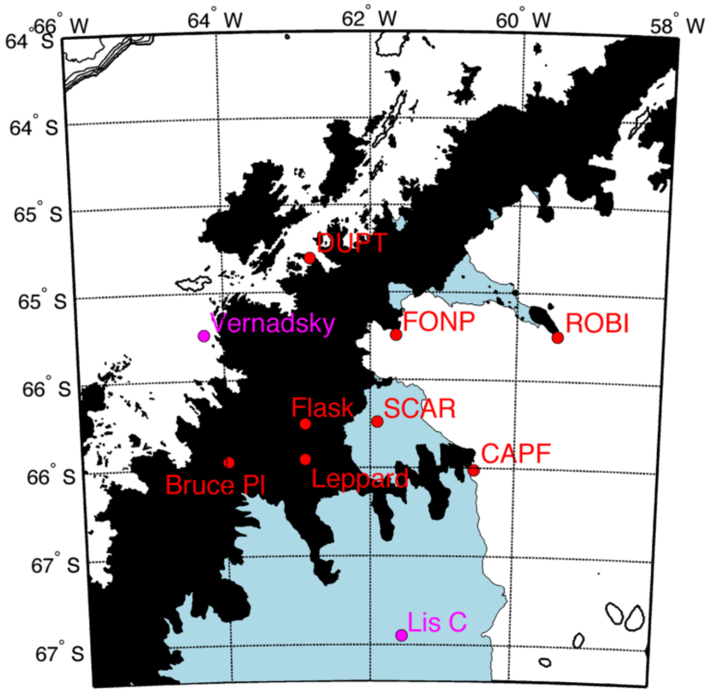
Surface wind velocity anomaly (10 m)

- Open water periods linked to:
  - stronger SLP gradient
  - higher surface air temperature
  - enhanced cross-peninsula flow from NW

M. Cape, M. Vernet et al., 2014 in prep.

# Warmth and foehn events correlate with El Niño and +SAM for autumn

Map of ground station locations



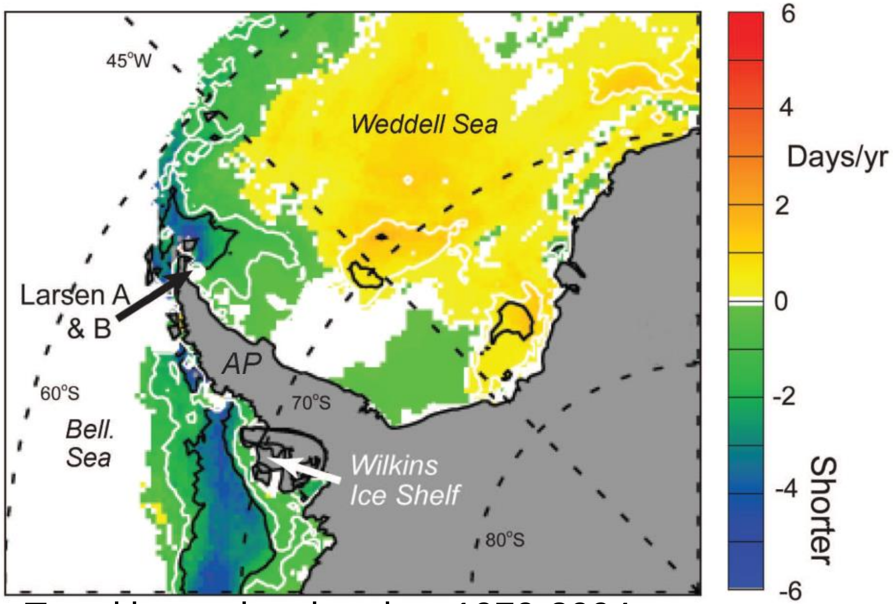

**2010 - 2013**

**Correlation between seasonally averaged SAM and Nino3.4 and datasets.** Significant values in red.

| Observation | Season | Nino3.4 (rho) | SAM (rho) |
|---|---|---|---|
| Foehn Days (%) | **DJF** | -0.32 | 0.3 |
| | **MAM** | 0.035 | 0.4 |
| | **JJA** | 0.14 | **0.54** |
| | **SON** | **-0.62** | **0.79** |
| Mean temp (ºC) | **DJF** | -0.36 | 0.25 |
| | **MAM** | -0.3 | **0.72** |
| | **JJA** | -0.24 | **0.72** |
| | **SON** | -0.29 | **0.8** |

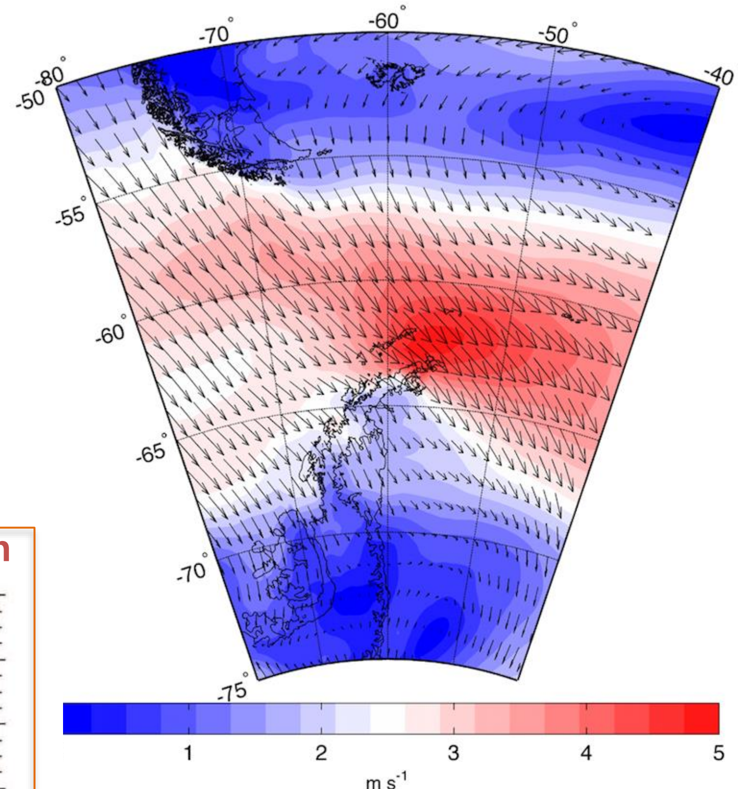
M. Cape, M. Vernet et al., 2014 in prep.

# Did a decrease in sea ice cover at the Larsen fronts trigger NW Weddell ocean circulation changes?

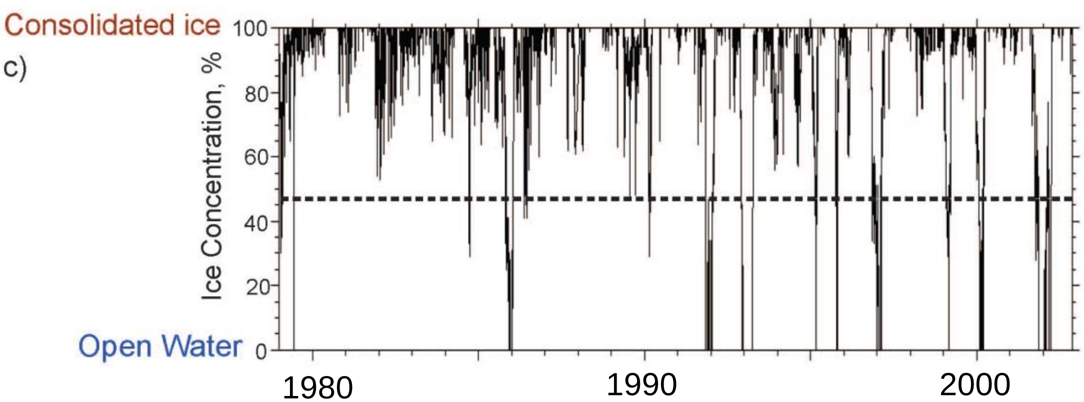



Trend in sea ice duration, 1979-2004

Wind anomaly during foehn events

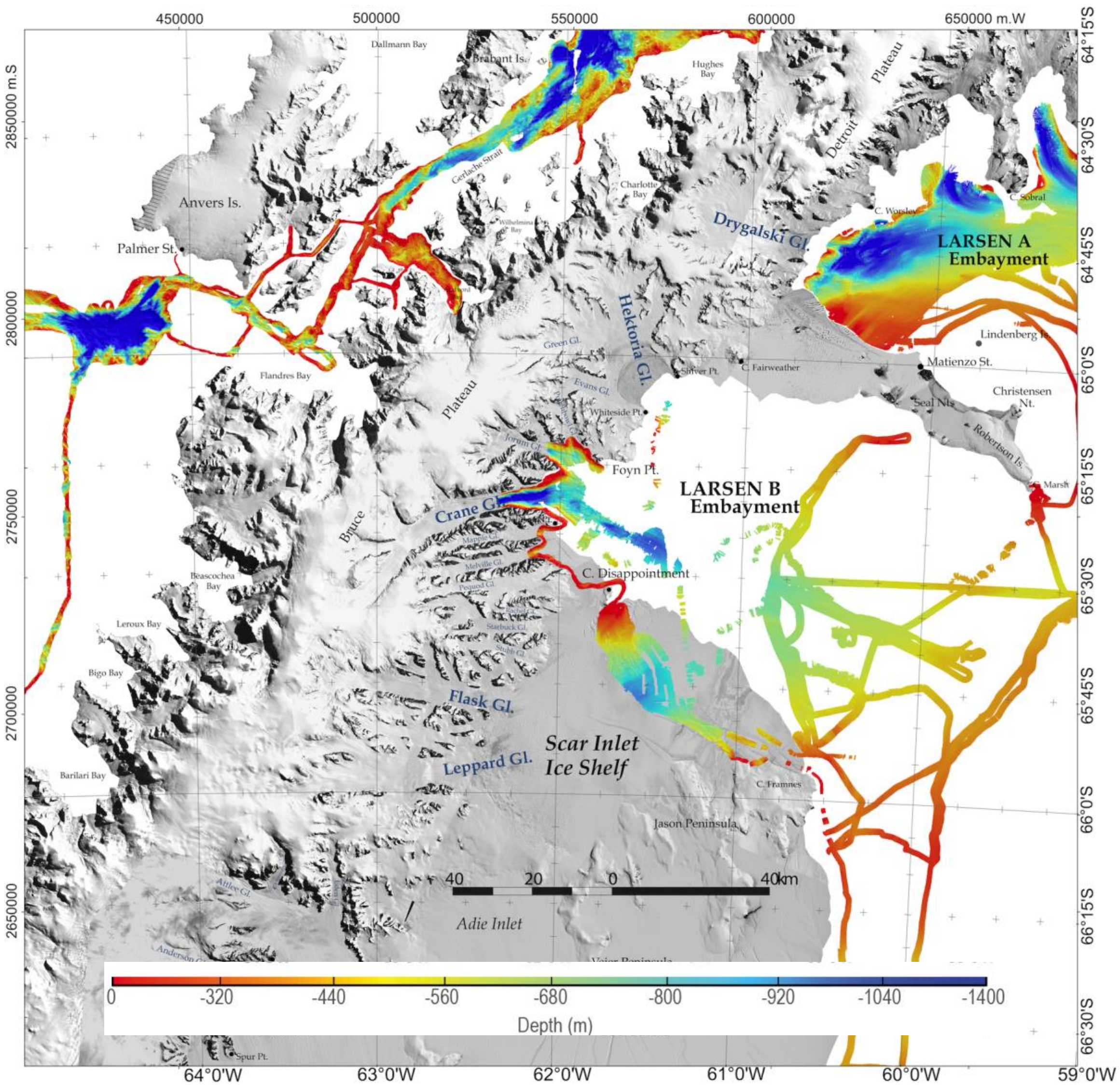



**Sea ice concentration in NW Weddell: less ice is more traction**

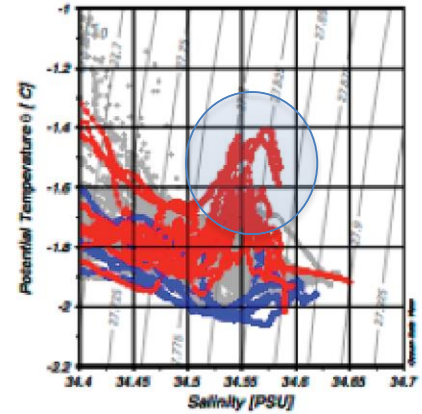



Stammerjohn et al., 2008 JGR-C; Massom, Scambos et al, in prep.; M. Cape, M. Vernet et al., 2014 in prep.

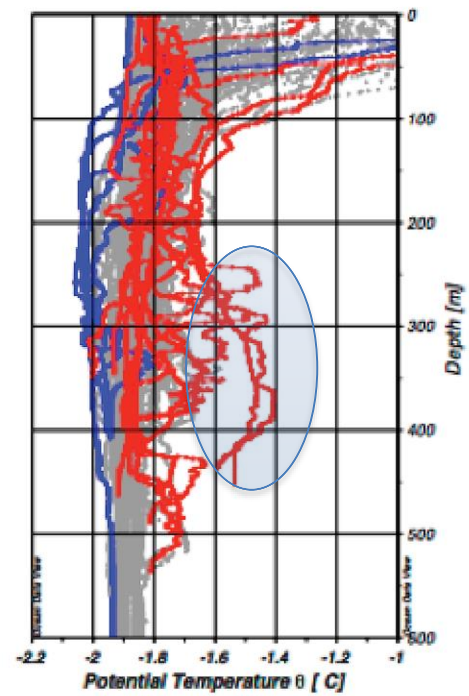
# *Ocean data for the region: presence of 'warm' mWDW at depth*




Modified Weddell Deep Water




Warm, Saline, Dense

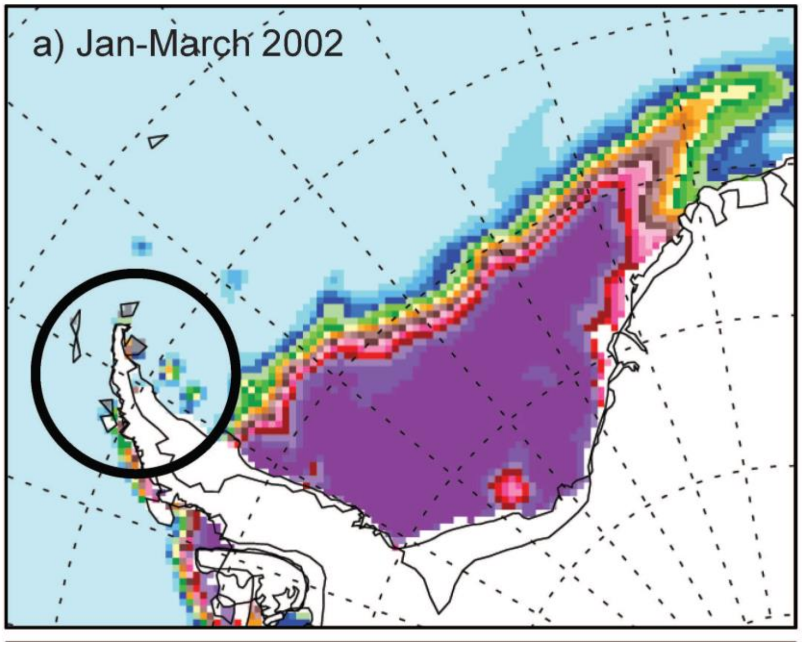



Below the ice shelf keels

# *Wave action: pulling the trigger?*

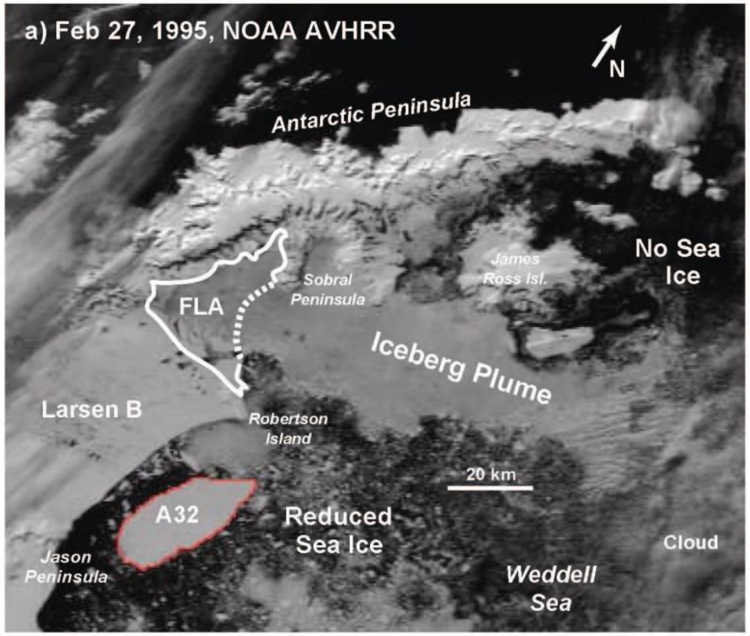
Open water in the NW Weddell allows ocean swell to reach the ice shelf front

2002




SSM/I data

1995

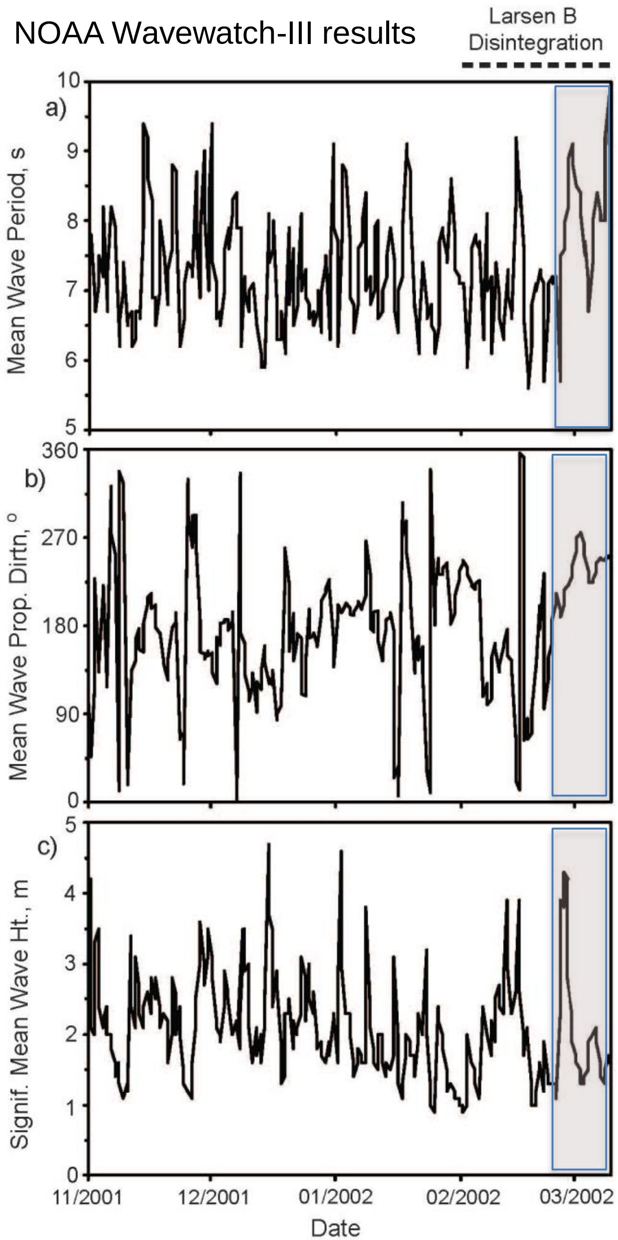



AVHRR image

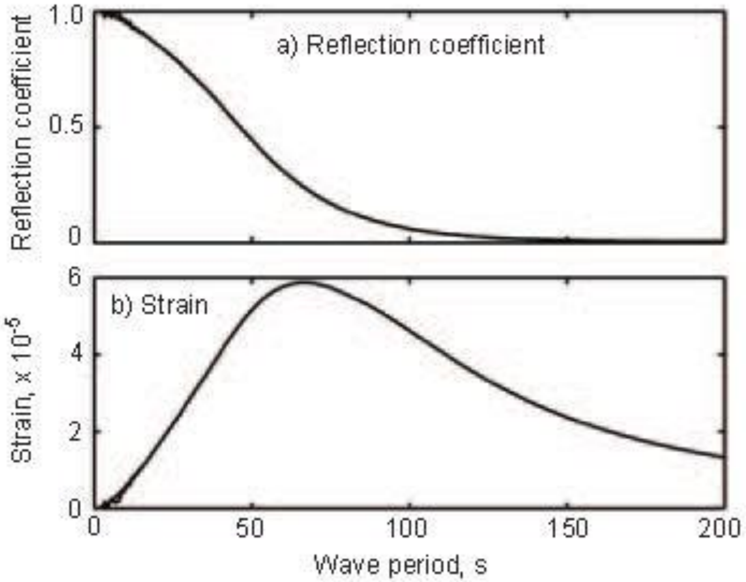
Massom, Scambos et al, in prep.

# Wave action: pulling the trigger?

NOAA Wavewatch-III results




Model results for 250 m –thick shelf

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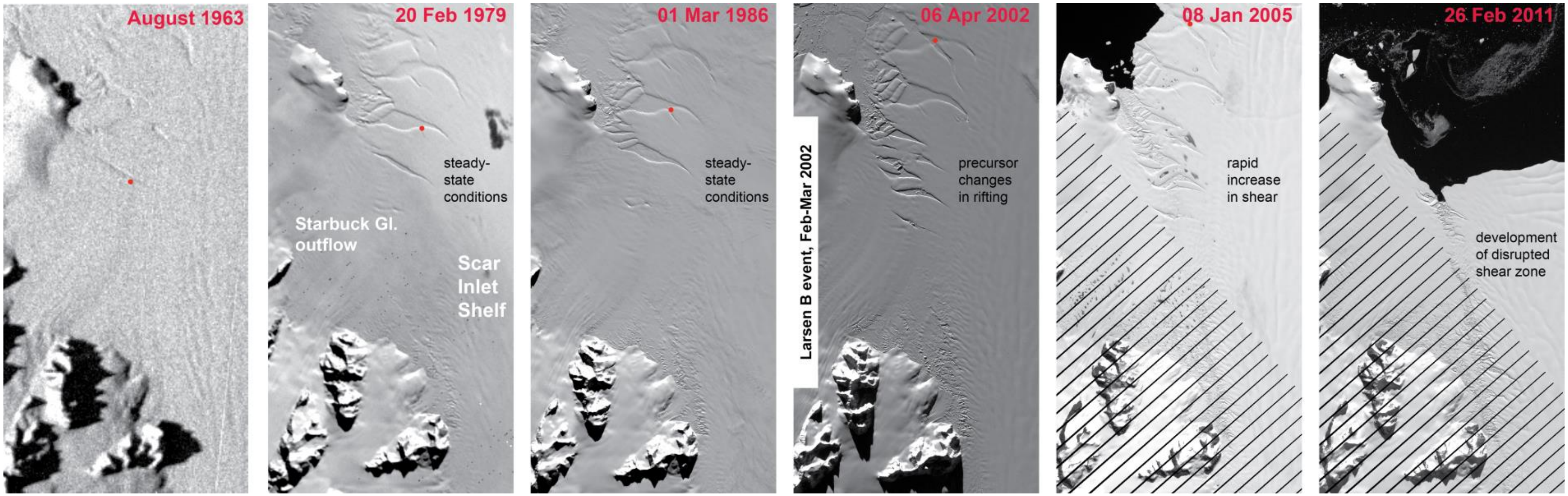
Thank you.

## *Cape Disappointment margin evolution, 1963-2011*




1963-1986: steady-state evolution (or nearly so)

1986-2002: an expansion of the shear zones and a change in the stress directions

2002-present: shear zone evolves rapidly, becomes disrupted, reducing interior compressive stress.

The shelf is now more susceptible to hydro-fracture.

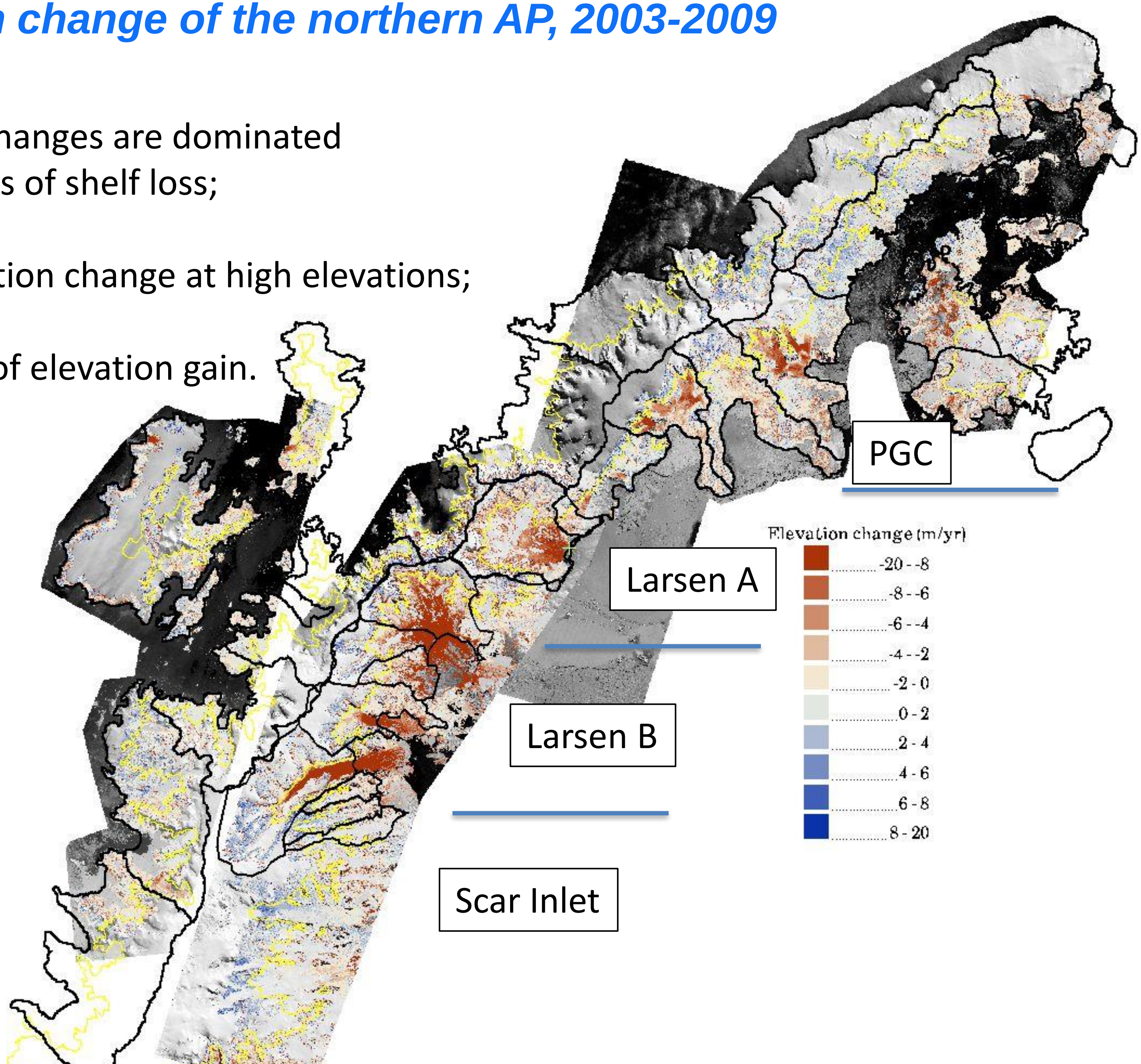

Scambos et al., 2014 in prep.; see also Glasser and Scambos, 2008

# *Elevation change of the northern AP, 2003-2009*

Elevation changes are dominated
by the areas of shelf loss;

Little elevation change at high elevations;

Few areas of elevation gain.




Scambos, Berthier, Haran, Shuman et al, 2014 in review The Cryosphere

# Summary of results

**33 major basins and islands**

**AP <66°S: -24.8 ± 4.9 Gt a$^{-1}$**

**AP West: -4.3 ± 0.8 Gt a$^{-1}$**

**AP East: -17.7 ± 3.5 Gt a$^{-1}$**

Eastern 'Shelf Loss' Glaciers*:
-15.0 ± 3.0 Gt a$^{-1}$

Below 1000 m, both sides:
-20.8 ± 4.1 Gt a$^{-1}$

Above 1000 m, both sides:
-3.0 ± 0.6 Gt a$^{-1}$

***Larsen A tributary glaciers ~4.9 Gt a$^{-1}$**
**Larsen B tributary glaciers ~7.9 Gt a$^{-1}$**

…assuming 0.9 density for all ice volume, and 20% errors, based on previous work.

Table S1. Mass balance and volume change estimates from combined satellite image and altimetry analysis
Area (km$^2$), Mean dM/dt (Gt a$^{-1}$), Number of Measurements, Mean dh/dt (m a$^{-1}$), Mean dV/dt (km$^3$ a$^{-1}$)

| | Ice-Covered | Total | Ice Front Retreat | | | Below 1000 masl | | | | | Above 1000 masl | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Area | dM/dt[a] | Area | dH/dt[b] | dV/dt[c] | Area | dDEM[d] | ICESat[e] | dH/dt[f] | dV/dt | Area | ICESat[e] | dH/dt[f] | dV/dt |
| **AP >66°S, 1-33** | **34059.5** | **-24.2** | **248.3** | **-3.5** | **-0.8** | **23096.5** | **56.4** | **9980** | **-1.00** | **-23.1** | **10985.7** | **2642** | **-0.27** | **-3.0** |
| **AP West, 1-11** | **14337.3** | **-4.3** | **6.1** | **-5.3** | **-0.0** | **9014.3** | **39.2** | **2999** | **-0.27** | **-2.4** | **5322.8** | **893** | **-0.59** | **-2.4** |
| **AP East, 15-33** | **15721.6** | **-17.7** | **241.3** | **-2.5** | **-0.8** | **10397.9** | **74.5** | **6981** | **-1.75** | **-18.2** | **5319.1** | **1775** | **-0.10** | **-0.7** |
| 1 Bigo-Barilari B. | 1737.4 | -1.37 | 2.5 | -3.8 | -0.00 | 825.4 | 38.6 | 210 | -0.88 | -0.72 | 912.0 | 152 | -0.88 | -0.80 |
| *1a Cadman Gl.* | *309.6* | *-0.37* | *2.5* | *-3.8* | *-0.00* | *101.4* | *53.8* | *297* | *-2.23* | *-0.23* | *208.2* | *(0)* | *(-0.88)* | *-0.18* |
| 2 Trooz-Lever Gl. | 1479.7 | 0.50 | | | | 771.5 | 71.5 | 425 | 0.72 | 0.56 | 708.3 | 19 | -0.0 | -0.00 |
| 3 Flandres B. | 1123.7 | -0.45 | | | | 403.8 | 57.8 | 156 | -0.14 | -0.06 | 720.0 | 60 | -0.61 | -0.44 |
| 4 Anvers Is. | 2155.9 | -0.33 | 2.5 | -6.0 | -0.01 | 1965.2 | 40.4 | 844 | -0.16 | -0.32 | 191.7 | (0) | | -0.05 |
| *4a Ricke B.* | *83.3* | *-0.21* | *2.5* | *-6.0* | *-0.01* | *83.3* | *44.5* | *120* | *-2.71* | *-0.23* | *0.0* | | | |
| 5 Andvord B. | 1163.2 | -0.06 | | | | 641.6 | 23.9 | 80 | -0.06 | -0.04 | 521.5 | 85 | -0.33 | -0.03 |
| 6 Brabant Is. | 916.7 | -0.43 | 1.1 | -6.2 | -0.00 | 672.4 | 28.7 | 14 | -0.61 | -0.41 | 244.4 | (2) | | -0.07 |
| *6a Rush Gl.* | *43.6* | *-0.07* | *1.1* | *-6.2* | *-0.00* | *28.2* | *96.3* | *3* | *-2.64* | *-0.08* | *14.7* | *(0)* | | *-0.00* |
| 7 Charlotte B. | 505.5 | -0.50 | | | | 316.7 | 13.6 | (0) | -1.57 | -0.50 | 188.8 | (0) | | -0.05 |
| 8 Cayley Gl. | 1512.6 | -0.75 | | | | 817.4 | 28.1 | 255 | -0.81 | -0.66 | 695.2 | 221 | -0.25 | -0.17 |
| 9 Wright Ice Pied. | 1370.1 | -1.22 | | | | 845.6 | 57.8 | 314 | -1.35 | -1.14 | 524.3 | 209 | -0.40 | -0.21 |
| 10 Charcot B. | 800.9 | -0.37 | | | | 437.2 | 57.9 | 159 | 0.14 | 0.06 | 363.7 | 140 | -1.30 | -0.47 |
| 11 West Trinity | 1571.5 | 0.68 | | | | 1317.7 | 17.1 | 542 | 0.63 | 0.83 | 253.8 | (5) | | -0.07 |
| 12 Mott Snowfield | 987.7 | -1.12 | 0.9 | -3.3 | -0.0 | 984.0 | 14.6 | 536 | -1.26 | -1.24 | 3.7 | (0) | | 0.00 |
| *12a North Duse B.* | *242.9* | *-0.45* | *0.9* | *-3.3* | *-0.0* | *239.2* | *17.7* | *230* | *-2.0* | *-0.49* | *3.6* | *(0)* | | *0.00* |
| 13 Tabarin Pen. | 363.9 | -0.65 | | | | 363.9 | 43.8 | 140 | -1.98 | -0.72 | | | | |
| 14 Joinville-Du.-D'U. Is. | 2336.4 | -0.53 | | | | 2336.4 | 0.0 | 1528 | -0.25 | -0.58[g] | 0.0 | | | |
| 15 Vega Is. | 175.7 | -0.25 | | | | 175.7 | 70.1 | 34 | -1.58 | -0.28 | 0.0 | | | |
| 16 Snow Hill Is. | 312.5 | -0.27 | | | | 312.5 | 0.0 | 163 | -0.96 | -0.30[g] | 0.0 | | | |
| 17 North JRI | 524.6 | -0.64 | | | | 389.6 | 37.2 | 70 | -2.00 | -0.78 | 134.9 | 96 | 0.05 | 0.07 |
| 18 South JRI | 568.5 | -0.24 | 8.1 | -1.1 | -0.01 | 364.8 | 60.3 | 169 | -0.78 | -0.29 | 203.7 | 119 | 0.13 | 0.03 |
| **19 West JRI** | **707.7** | **-1.52** | **39.0** | **-3.8** | **-0.07** | **625.6** | **69.4** | **178** | **-2.56** | **-1.60** | **82.1** | **(0)** | | **-0.02** |
| 20 East Trinity | 1347.0 | 0.55 | | | | 1119.2 | 64.0 | 850 | 0.67 | 0.75 | 227.8 | (0) | | -0.06 |
| **21 Sjögren Gl.** | **1177.3** | **-1.16** | **8.7** | **-3.0** | **-0.01** | **852.8** | **81.9** | **297** | **-1.64** | **-1.40** | **324.6** | **123** | **0.34** | **0.12** |
| **22 Larsen Inlet** | **807.9** | **-0.42** | **3.9** | **-2.8** | **-0.01** | **582.5** | **87.8** | **342** | **-0.85** | **-0.50** | **225.4** | **51** | **0.17** | **0.04** |
| **23 D-B-E Gl.** | **822.7** | **-0.94** | **11.3** | **-2.2** | **-0.01** | **502.8** | **95.1** | **302** | **-1.91** | **-0.96** | **320.0** | **166** | **-0.23** | **-0.07** |
| **24 Nordenskjöld Cst.** | **590.4** | **-0.73** | **4.5** | **-3.1** | **-0.01** | **391.5** | **95.5** | **190** | **-2.14** | **-0.84** | **198.9** | **69** | **0.22** | **0.04** |
| ***24a Fothergill*** | ***227.6*** | ***0.07*** | | | | ***143.8*** | ***96.4*** | ***179*** | ***0.41*** | ***0.06*** | ***83.8*** | ***27*** | ***0.11*** | ***0.01*** |
| ***24b Arrol Icefld.*** | ***363.6*** | ***-0.77*** | ***4.5*** | ***-3.1*** | ***-0.01*** | ***248.1*** | ***94.9*** | ***11*** | ***-3.68*** | ***-0.91*** | ***115.5*** | ***42*** | ***0.41*** | ***0.05*** |
| **25 Drygalski Gl.** | **963.4** | **-2.39** | **2.6** | **-2.2** | **0.00** | **618.0** | **69.1** | **760** | **-4.14** | **-2.56** | **345.4** | **43** | **-0.29** | **-0.10** |
| 26 Seal Nunataks | 665.3 | -0.80 | | | | 575.3 | 59.5 | 292 | -1.52 | -0.87 | 90.0 | (4) | | -0.02 |
| *26a Fairweather Gl.* | *491.7* | *-0.56* | | | | *401.7* | *85.2* | *125* | *-1.52* | *-0.60* | *90.0* | *(4)* | | *-0.02* |
| ***26b Robertson Is.*** | ***173.6*** | ***-0.24*** | | | | ***173.6*** | ***0.0*** | ***167*** | ***-1.54*** | ***-0.27*** | ***0.0*** | | | |
| **27 Hektoria-Green Gl.** | **1146.2** | **-3.96** | **85.9** | **-12.4** | **-0.53** | **714.4** | **62.1** | **506** | **-5.05** | **-3.60** | **431.8** | **18** | **-0.63** | **-0.27** |
| **28 Evans Gl.** | **299.1** | **-0.77** | **53.6** | **-2.8** | **-0.08** | **259.2** | **57.2** | **116** | **-2.92** | **-0.76** | **39.9** | **(1)** | | **-0.01** |
| **29 Jorum-Punchbl. Gl.** | **596.8** | **-0.51** | **10.7** | **-3.8** | **-0.02** | **313.2** | **80.4** | **179** | **-1.93** | **-0.60** | **283.6** | **143** | **0.19** | **0.05** |
| **30 Crane Gl.** | **1314.8** | **-2.10** | **1.3** | **-3.9** | **-0.00** | **409.3** | **60.1** | **430** | **-5.78** | **-2.36** | **905.5** | **318** | **0.03** | **0.03** |
| 31 Cape Disappt. | 1098.5 | -0.36 | 11.7 | -1.1 | -0.00 | 958.5 | 47.2 | 713 | -0.45 | -0.43 | 140.0 | 58 | 0.35 | 0.05 |
| ***31a M-M-P Gl.*** | ***662.4*** | ***-0.23*** | ***11.7*** | ***-1.1*** | ***-0.00*** | ***588.0*** | ***45.2*** | ***436*** | ***-0.38*** | ***-0.23*** | ***75.4*** | ***(9)*** | | ***-0.02*** |
| *31b Starbuck-Stubb Gl.* | *435.3* | *-0.17* | | | | *370.5* | *50.4* | *283* | *-0.56* | *-0.21* | *64.8* | *49* | *0.36* | *0.02* |
| 32 Flask Gl. | 1247.3 | 0.12 | | | | 714.2 | 58.2 | 782 | 0.32 | 0.23 | 533.1 | 150 | -0.19 | -0.10 |
| 33 Leppard Gl. | 1841.9 | -1.31 | | | | 1005.1 | 36.6 | 900 | -1.00 | -1.00 | 836.8 | 416 | -0.54 | -0.45 |

Abbreviations for place names : AP, Antarctic Peninsula; B., Bay; Cst., Coast; Disappt., Disappointment; Du., Dundee; D'U., D'Urville; Gl., Glacier; Is., Island; Icefld., Icefield; JRI, James Ross Island; M-M-P, Mapple-Melville-Pequod; Pen., Peninsula ; Pied., Piedmont; Punchbl., Punchbowl.

[a]Assuming mean density of 900 kg/m$^3$ for all dV/dt measurements.

[b]Rate of elevation loss measured just above area of grounded ice retreat.

[c]Volume loss assumes floatation was reached midway between 2003 – 2010 (period of observations).

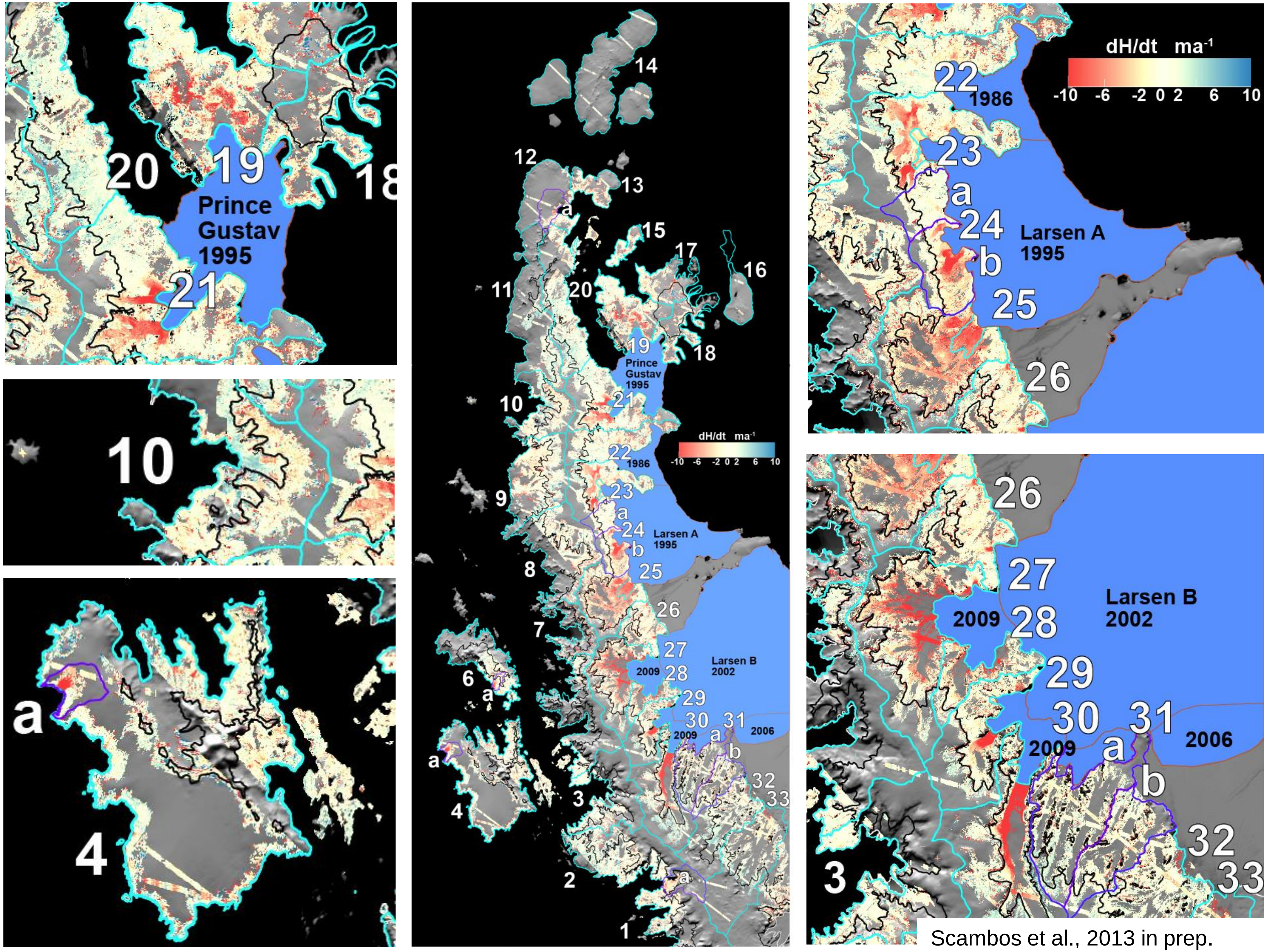
[d]Percent area covered by differential DEM satellite stereo-image data.

[e]Number of repeat-track point measurements used. If <10 ICESat dH/dt measurements are available, the regional mean ICESat dH/dt (-0.27 m a$^{-1}$) or, for sub-basins, the main basin mean, is used.

[f]Hypsometric weighting for areas below 1000 m elevation; weighted by number of ICESat measurements for areas above 1000 masl elevation.

[g]For these regions, dH/dt was determined by ICESat only.

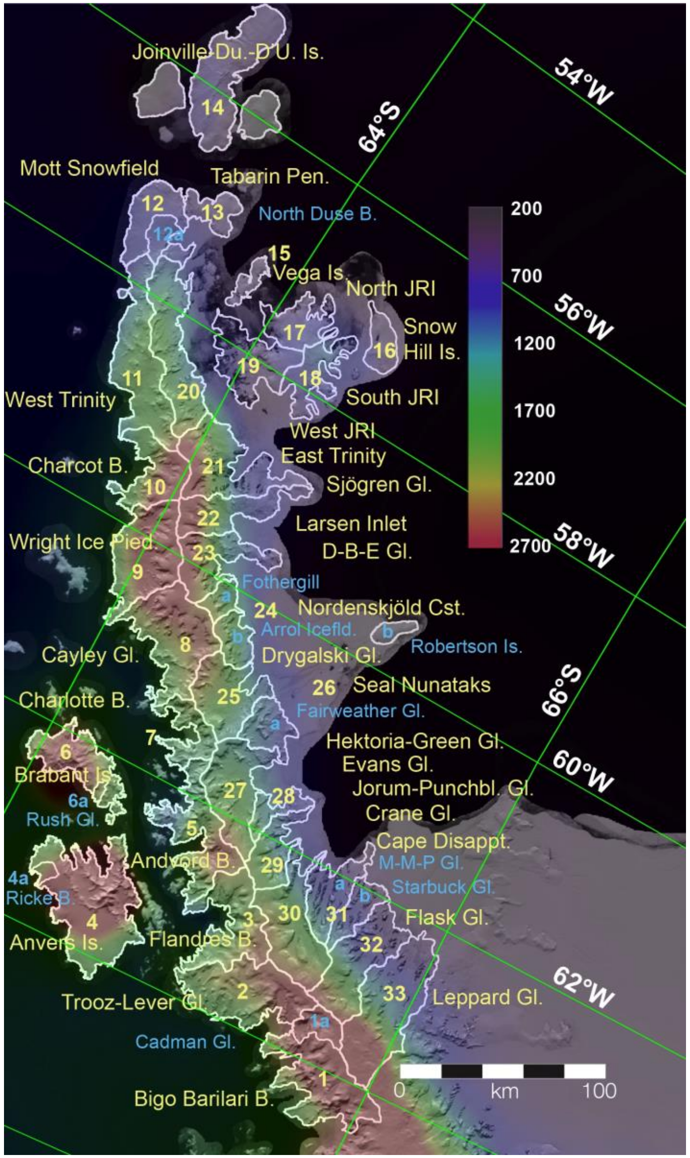
Scambos et al., 2013 in prep.



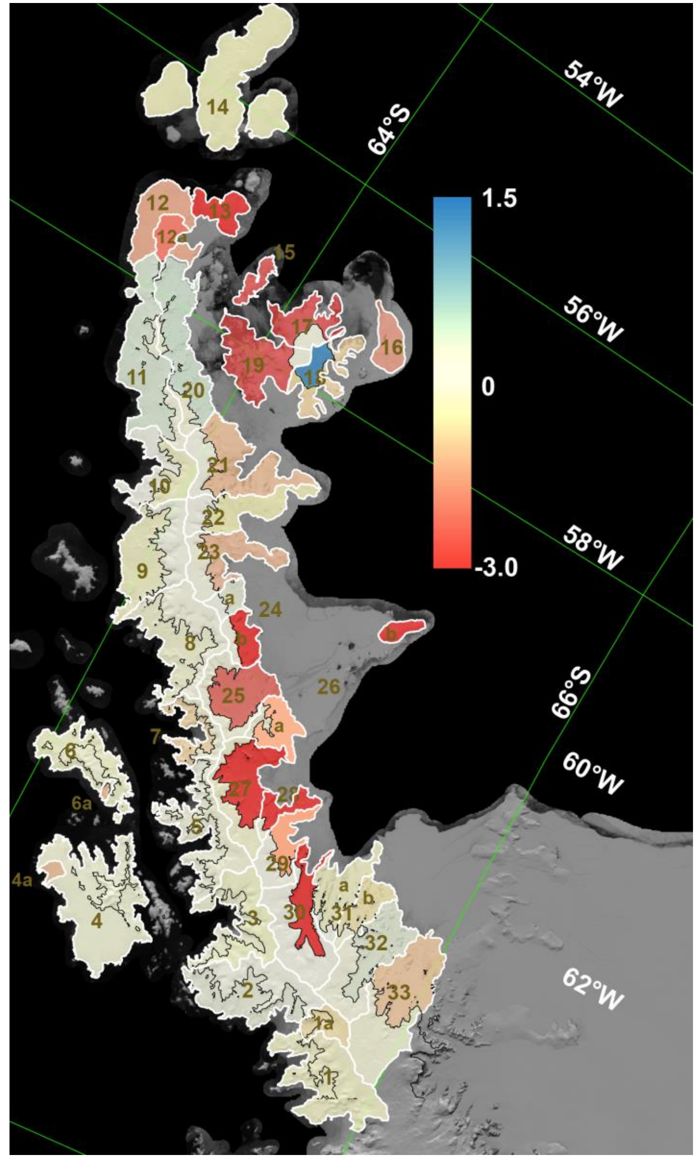

Scambos et al., 2013 in prep.

# Accumulation map and 'Imbalance Ratio'

Red: **>2700** kg m$^{-2}$ a$^{-1}$; Purple: **<200** kg m$^{-2}$ a$^{-1}$




'Imbalance Ratio', dM/dt / dMi/dt

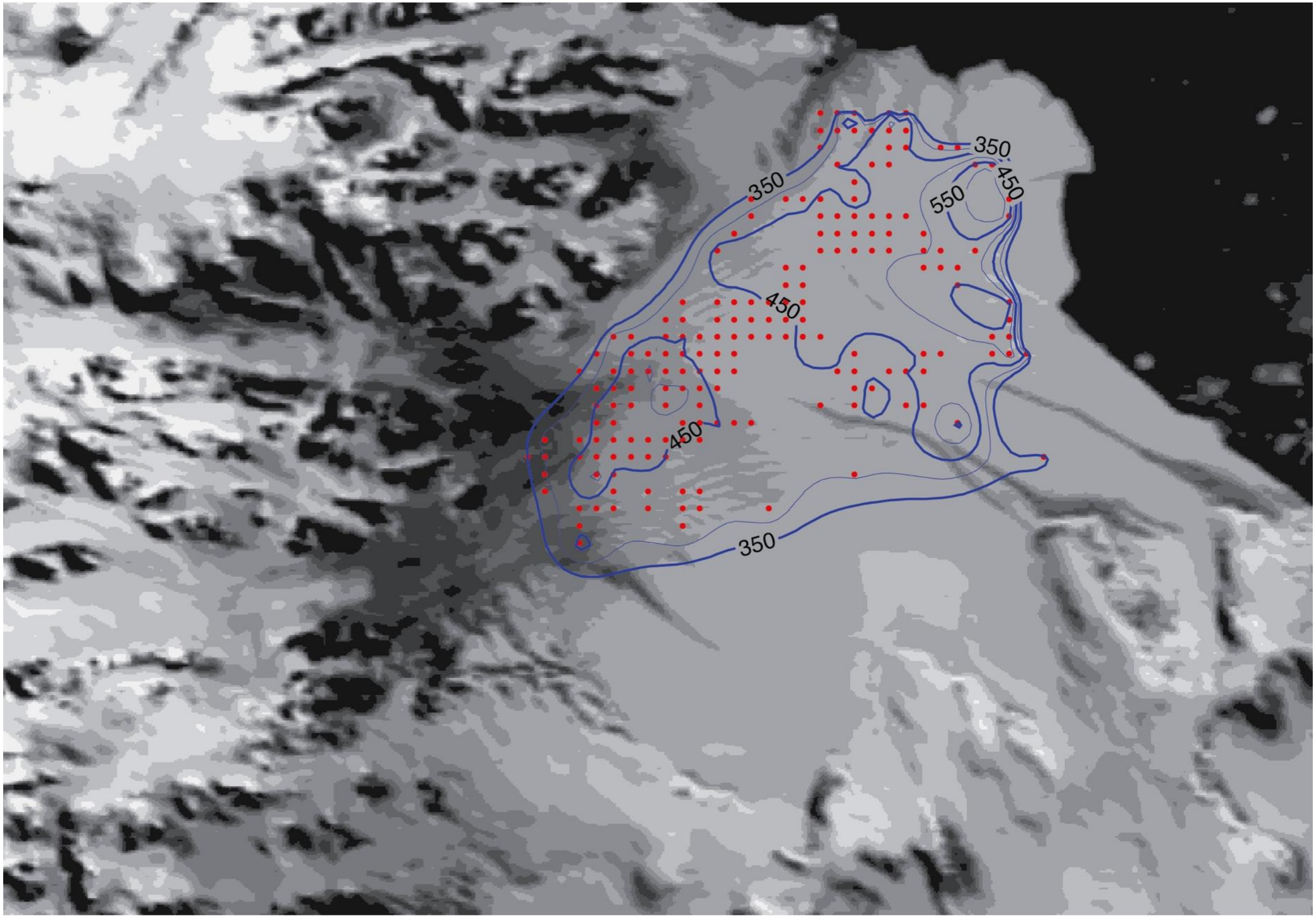



Lenaerts et al., 2012; Scambos et al., 2014 The Cryo.

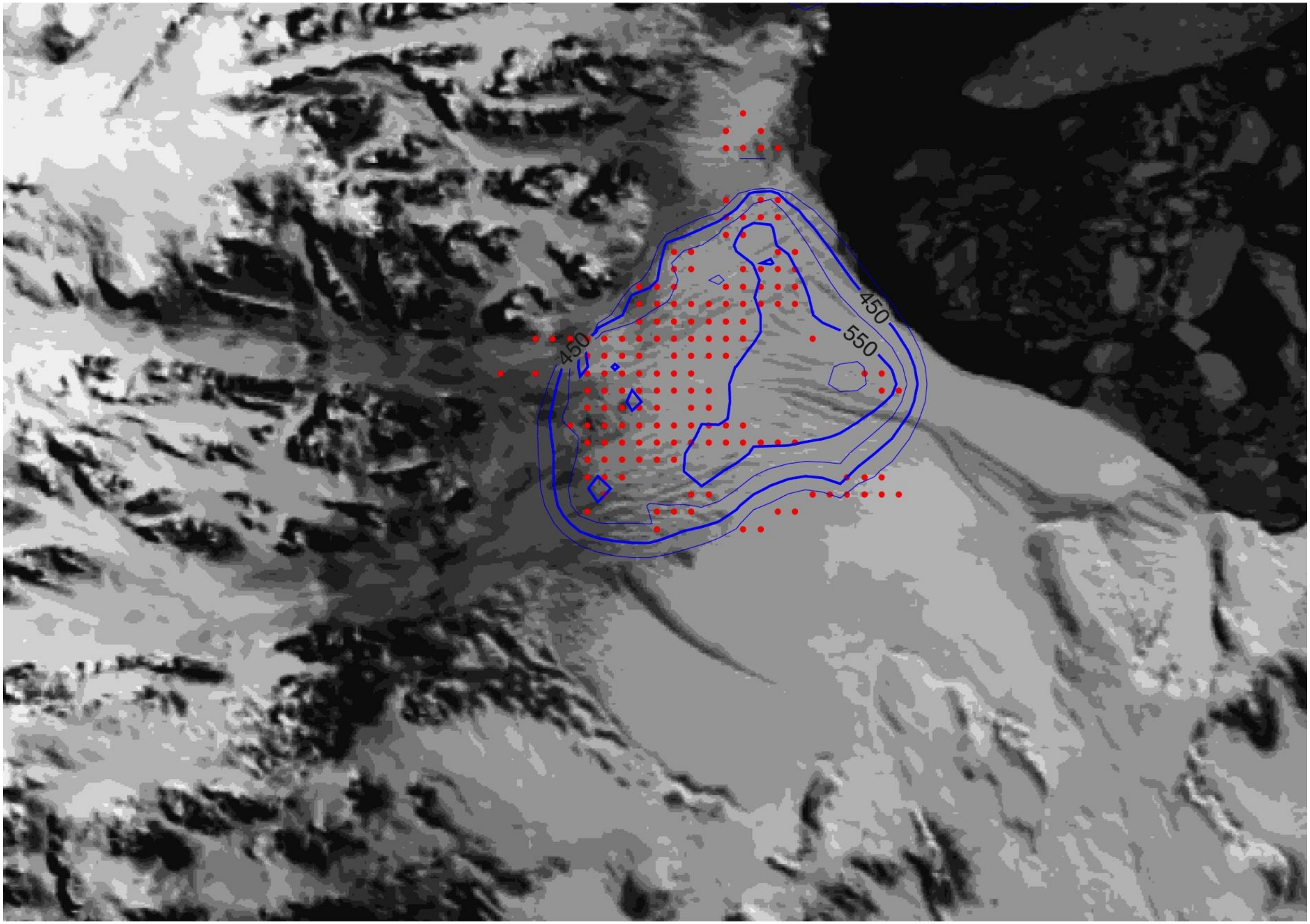

Scar Inlet Ice Shelf in 2006 – the last intense melt season
Iceberg A-54
Remnant Larsen B Ice Shelf --
Scar Inlet
11 February 2006


Scar Inlet Shelf is riddled with narrow crevasses;
Spacing is << ice thickness;
Accumulation rate is near zero (2010-2012).

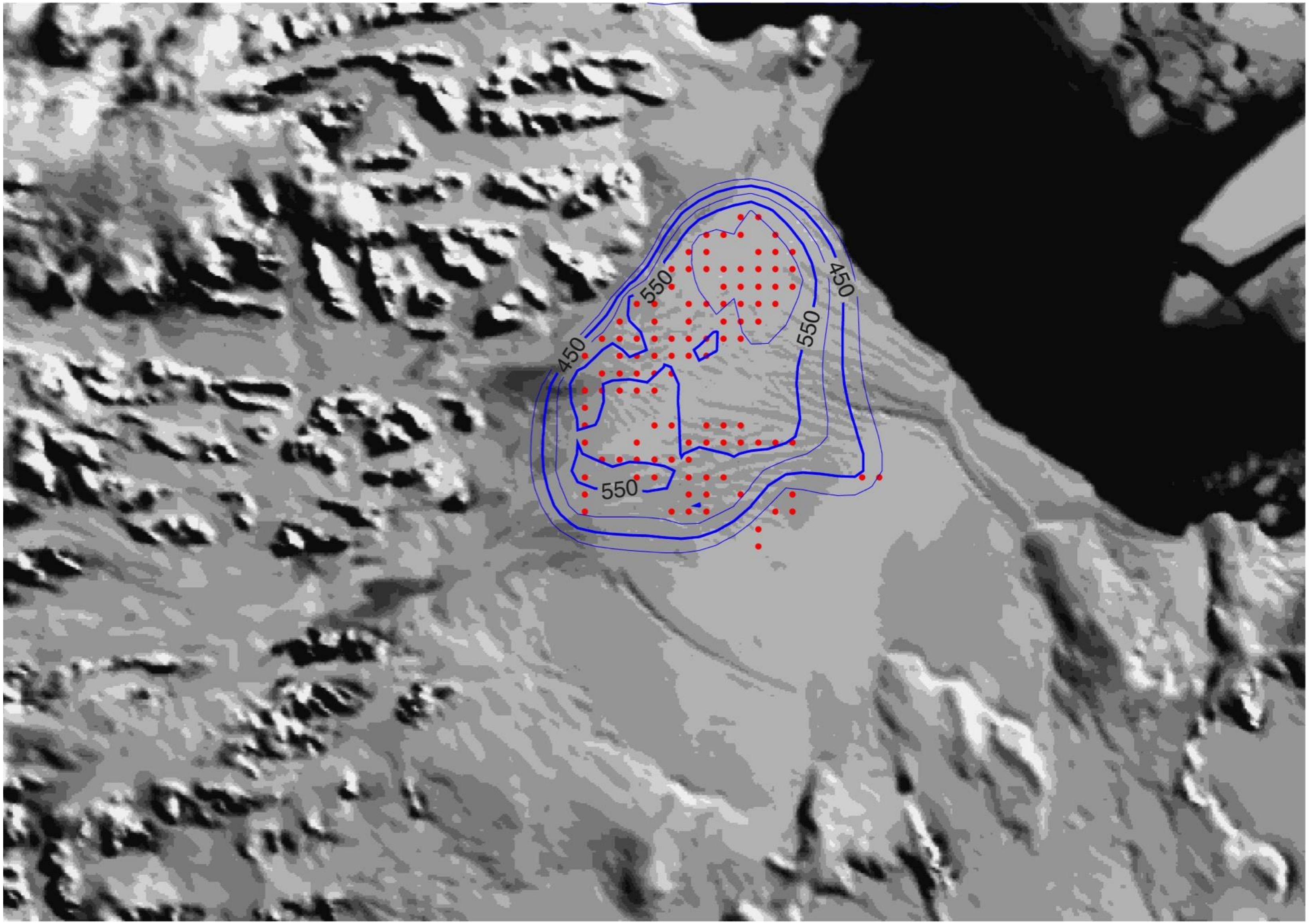
## *MODIS –pair flow speed, 2002-2004*



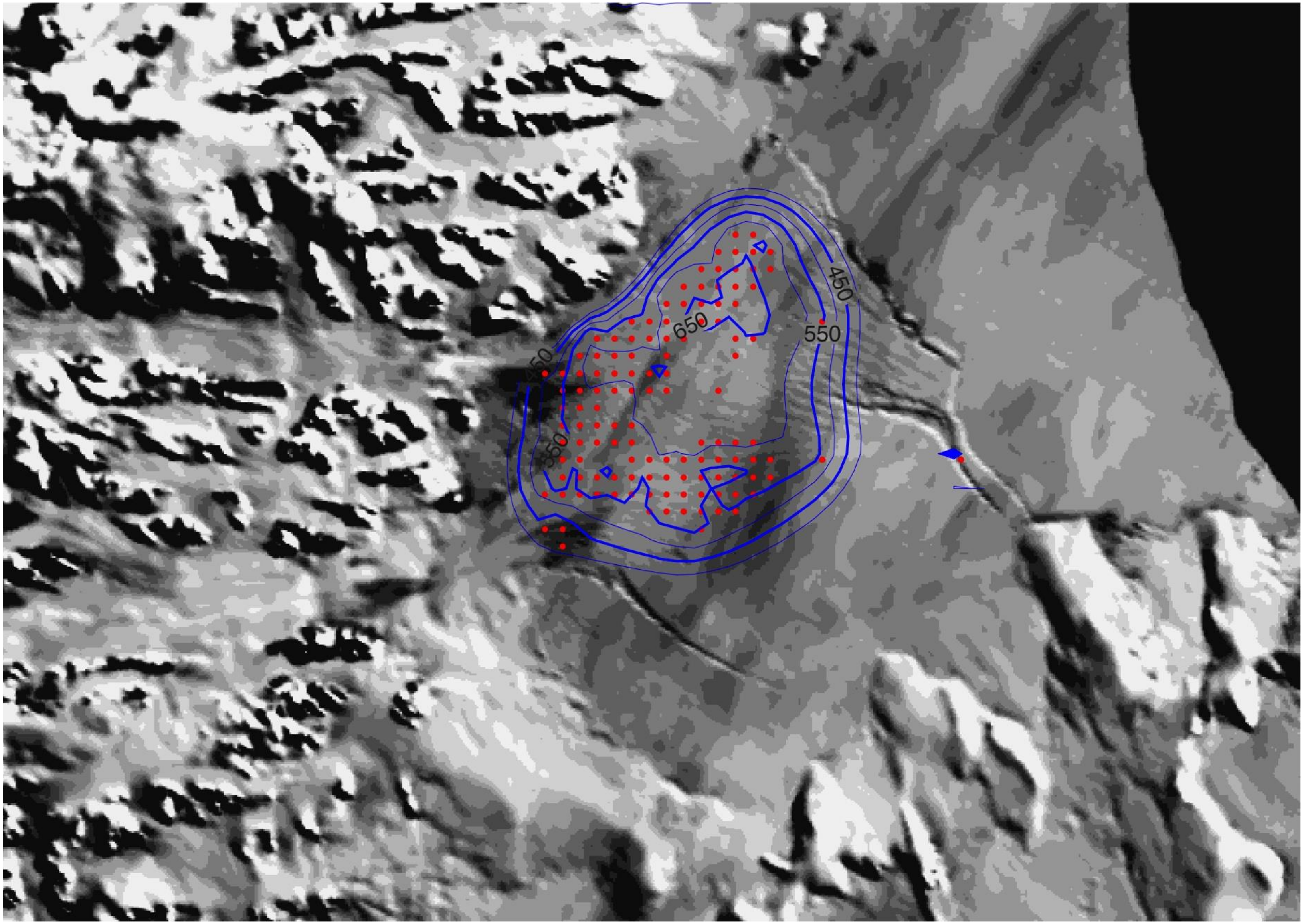
# MODIS –pair flow speed, 2004-2006



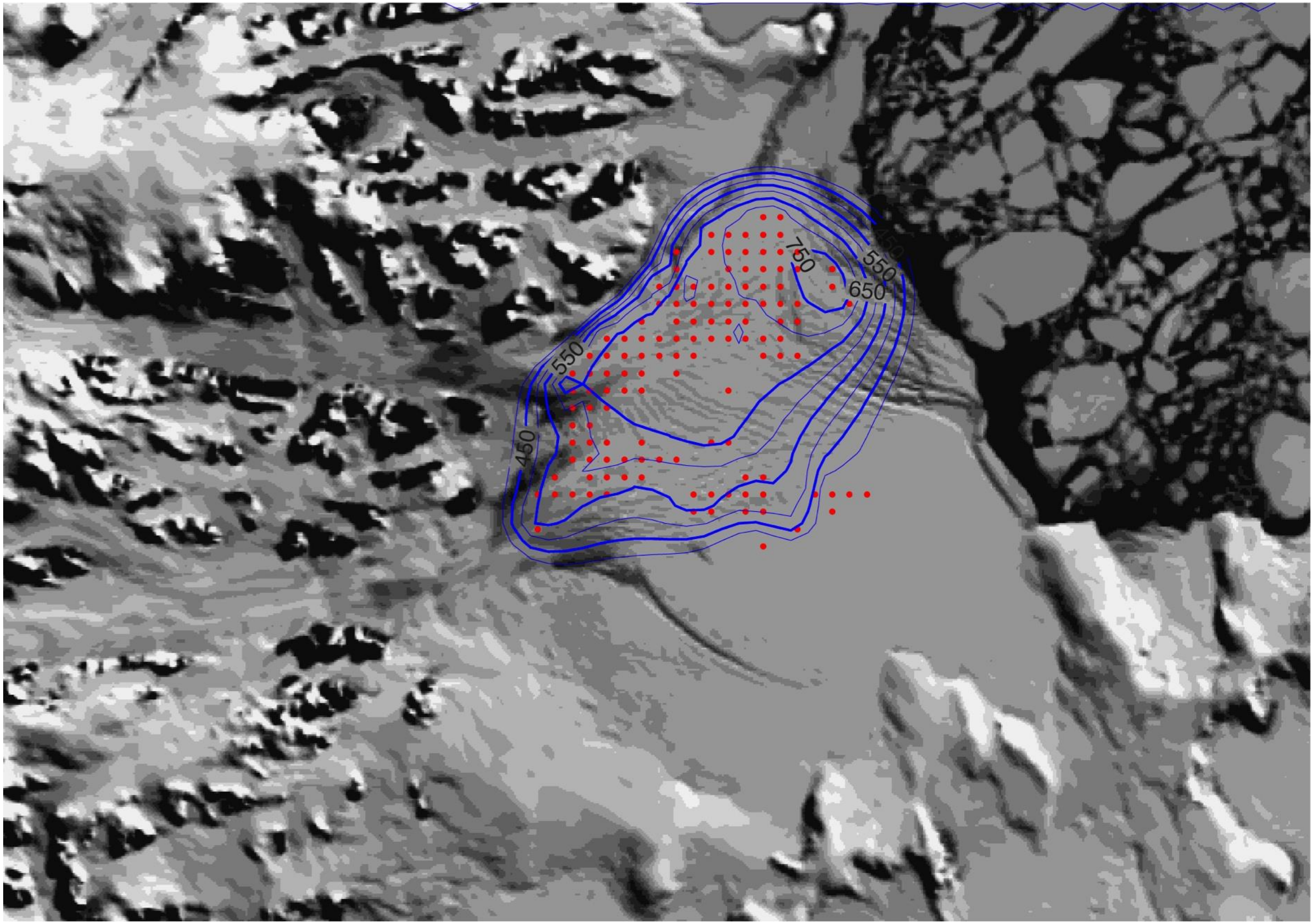
## *MODIS –pair flow speed, 2006-2008*



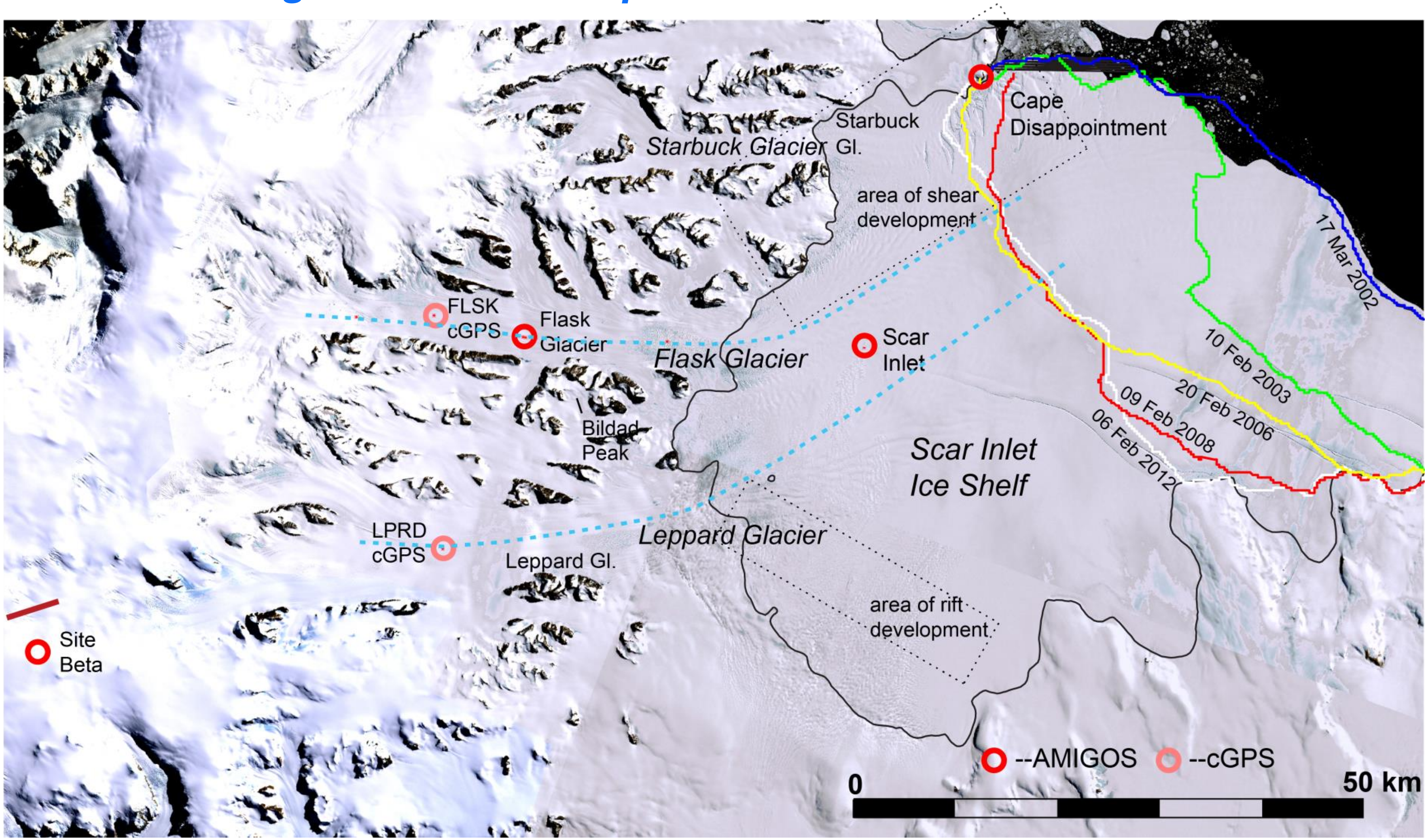
# *MODIS –pair flow speed, 2007-2009*



# MODIS –pair flow speed, 2010-2012



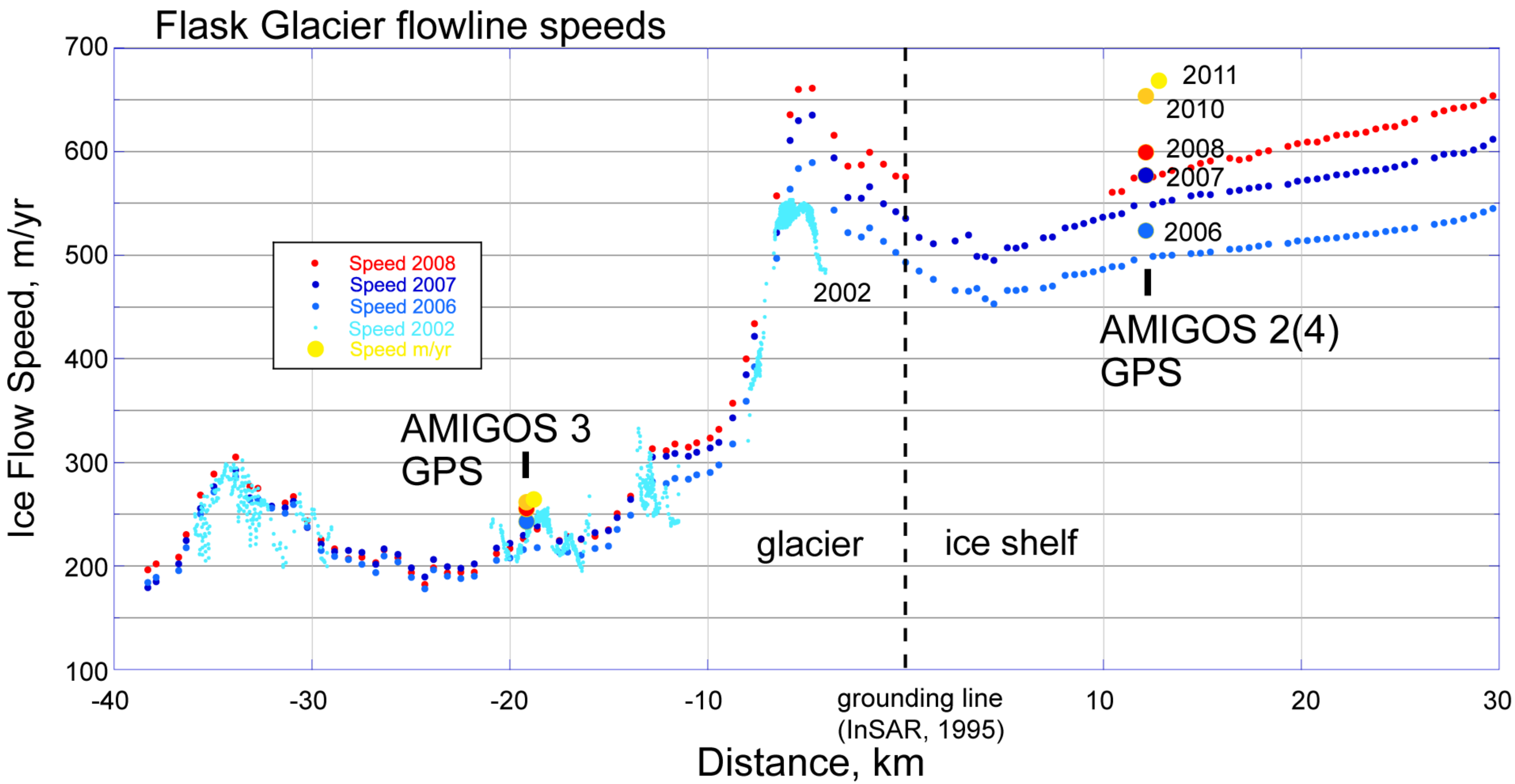
# *Scar Inlet Ice Shelf and tributary glaciers – evolving toward break-up*




LARISSA Project has installed several instruments since 2010 – GPS and AMIGOS – and has supported remote sensing and climate analysis.

# *Ice velocity mapping – Flask Glacier*

Significant speed-up of the shelf following the 2002 calving; confirmed by AMIGOS GPS




InSAR velocity mapping: Ian Joughin
GPS processing: Martin Truffer
ASTER image pair velocity: J. Bohlander and T. Scambos

# Project Conclusions

**Although a climate-driven hydro-fracture process triggered several shelf disintegrations, there are critical structural changes preceding events.**

– these appear to begin in the 1990s for Larsen B, Larsen A, and PGC shelves

– they may be related to sea ice cover and ocean circulation changes, or effects of increased melt water on the shelf and glacier surfaces.

**Elevation, volume, and mass losses in the northern A.P. are dominated by changes following ice shelf disintegration and evolving grounded ice loss**.

– total mass loss for study area is $24.2 \pm 4.8$ Gt $a^{-1}$

– elevation decline is pervasive, despite decadal increases in accumulation

– significant ice front changes continue in eastern Antarctic Peninsula

**Further retreat or disintegration at the Scar Inlet Ice Shelf is imminent**

– this may come from an intense melt season and hydrofracture, or

– existing large rifts and may fail structurally w/o a major melt season.

**The Larsen A and B ice shelves disintegrated by structural weakening and hydrofracture.**

- Hydrofracture was a result of extensive surface melting and melt ponds**.**

However, **satellite images** of the Larsen B **indicate early changes, preceding any shelf loss**

The **Peninsula climate during 1986-2006 saw frequent NW airflow**, +SAM and –ENSO

These climate patterns correlate with melt-producing, sea-ice-shifting **foehn winds**

**Sea ice trends for the Peninsula** area show **reduced summertime sea ice concentration** in the NW Weddell, ~1985 – 2006, particularly for the 1990s

**Conceptual Model -**

- **Reduced sea ice concentration in the NW Weddell allows wind stress to be transferred to the ocean surface layer;**

- **modified WDW was likely induced to flow into the sub-shelf cavities more frequently.**
  - **mWDW has sufficient heat to cause some minor basal shelf melting** and thinning, leading to structural changes, **reduced backstress**, and **facilitating hydro-fracture**.

- **Low sea ice cover allows wave action to contribute to shelf weakening and hydrofracture**

# Summary of results

Table 1. Summary of Mass Balance for the northern Antarctic Peninsula (>-66°S), 2001-2010
Units: Area ($km^2$), Mean dM/dt (Gt $a^{-1}$), Number of Measurements, Mean dh/dt (m $a^{-1}$), Mean dV/dt ($km^3$ $a^{-1}$)

| | Ice-Covered | Total | Ice Front Retreat | | | Below 1000 masl | | | | | Above 1000 masl | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Area | dM/dt[a] | Area | dH/dt[b] | dV/dt[c] | Area | dDEM[d] | ICESat[e] | dH/dt[f] | dV/dt | Area | ICESat[e] | dH/dt[f] | dV/dt |
| **AP >66°S, 1-33** | **34059.5** | **-24.2** | **248.3** | **-3.5** | **-0.8** | **23096.5** | **56.4** | **9980** | **-1.00** | **-23.1** | **10985.7** | **2642** | **-0.27** | **-3.0** |
| **AP West, 1-11** | **14337.3** | **-4.3** | **6.1** | **-5.3** | **-0.0** | **9014.3** | **39.2** | **2999** | **-0.27** | **-2.4** | **5322.8** | **893** | **-0.59** | **-2.4** |
| **AP East, 15-33** | **15721.6** | **-17.7** | **241.3** | **-2.5** | **-0.8** | **10397.9** | **74.5** | **6981** | **-1.75** | **-18.2** | **5319.1** | **1775** | **-0.10** | **-0.7** |
| Northwest AP Coast[g] | 5255.1 | -1.66 | -- | -- | -- | 3417.9 | 35.1 | 1270 | -0.27 | 0.91 | 1837.0 | 575 | -0.50 | -0.92 |
| **Western IFL Glaciers[h]** | **436.5** | **-0.68** | **6.1** | **-5.3** | **-0.03** | **212.9** | **55.7** | **410** | **-2.54** | **-0.54** | **222.9** | **(0)** | **(-0.84)** | **-0.19** |
| **Eastern ISL Glaciers[i]** | **9262.3** | **-14.97** | **233.2** | **-3.7** | **-0.76** | **6030.9** | **70.9** | **3903** | **-2.56** | **-15.68** | **3232.6** | **941** | **-0.01** | **-0.21** |
| James Ross Island[j] | 1800.8 | -2.40 | 47.1 | -3.3 | -0.08 | 1380.0 | 58.0 | 470 | -1.93 | -2.67 | 420.7 | 215 | 0.02 | 0.08 |
| Prince Gustav tributaries[k] | 1885.0 | -2.68 | 47.7 | -3.7 | -0.09 | 1478.4 | 76.6 | 475 | -2.03 | -3.00 | 406.7 | 123 | 0.23 | 0.94 |
| Larsen A tributaries[l] | 3184.4 | -4.48 | 22.3 | -2.7 | -0.03 | 2094.8 | 85.5 | 1594 | -2.32 | -4.86 | 1089.7 | 329 | -0.08 | -0.09 |
| Larsen B ISL tributaries[m] | 4192.9 | -7.81 | 163.2 | -3.9 | -0.64 | 2457.7 | 55.2 | 1834 | -3.18 | -7.82 | 1736.2 | 489 | -0.13 | -0.22 |
| Scar Inlet Ice Shelf trib.[n] | 3524.5 | -1.36 | -- | -- | -- | 2089.8 | 46.4 | 1965 | -0.47 | -0.98 | 1434.7 | 715 | -0.37 | -0.53 |

Abbreviations for place names : AP, Antarctic Peninsula; ISL, ice shelf loss; IFL, ice front loss.

[a]Assuming mean density of 900 kg/$m^3$ for all dV/dt measurements

[b]Rate of elevation loss measured just above area of grounded ice retreat.

[c]Volume loss assumes floatation was reached midway between 2003 – 2010 (period of observations).

[d]Percent area covered by differential DEM satellite stereo-image data

[e]Number of repeat-track point measurements used. If <10 ICESat dH/dt measurements are available, the regional mean ICESat dH/dt (-0.27 m $a^{-1}$) or, for sub-basins, the main basin mean, is used.

[f]Hypsometric weighting for areas below 1000 m elevation; weighted by number of ICESat measurements for areas above 1000 m elevation.

[g]Glacier basins 8 – 11 as shown in Figure 1.

[h]Glacier basins 1a, 4a, and 6a as shown in Figure 1.

[i]Glacier basins 19, 21-25, 26b, 27-30, and 31a as shown in Figure 1.

[j]Glacier basins 17, 18, and 19 as shown in Figure 1.

[k]Glacier basins 19 and 21 as shown in Figure 1.

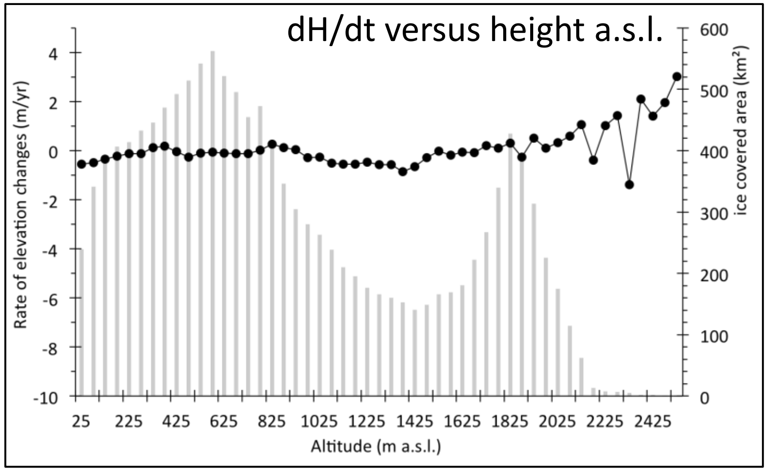
[l]Glacier basins 22-25 as shown in Figure 1.

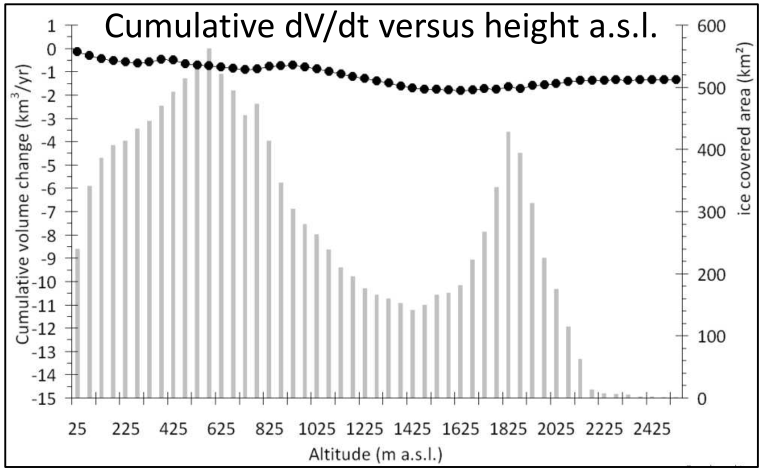
[m]Glacier basins 27-30, and 31a as shown in Figure 1.

[n]Glacier basins 31b, 32, and 33 as shown in Figure 1.

# *Summary of results: hypsometry of changes*

**West: basins with small ice front changes**



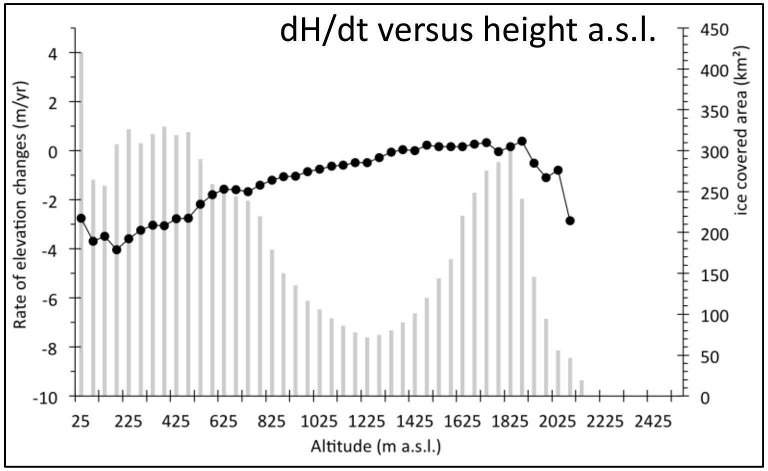



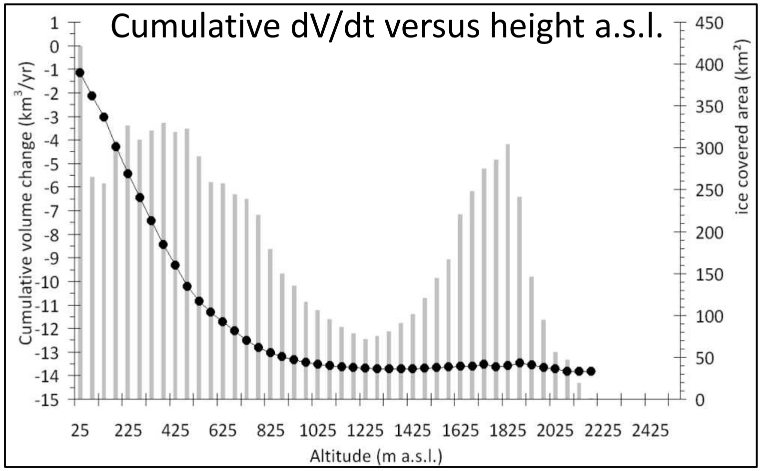

Pervasive small elevation loss, despite regional gradients in elevation, melt, and accumulation, and despite recent increases in accumulation

— Has warming increased firn compaction?

— or, residual effects of post-LIA ice shelf losses?

**East: basins with ice shelf and front retreat**




Elevation and volume losses greatest at low elev.

—Dominantly due to backstress reduction from shelf and ice front retreats

— Near-zero elevation change in upper catchments

Scambos et al., 2013a in prep.

# *Summary of results – error analysis*

**Comparison of dH/dt between the two methods (all co-located data)**

| | dDEM mean | ICESat mean | #points |
|---|---|---|---|
| entire study region | -1.77 m $a^{-1}$ | -2.09 m $a^{-1}$ | 6158 |
| <1000 m elevation | -2.08 m $a^{-1}$ | -2.42 m $a^{-1}$ | 5213 |
| >1000 m elevation | -0.06 m $a^{-1}$ | -0.23 m $a^{-1}$ | 945 |
| northern half of study area | -1.32 m $a^{-1}$ | -1.25 m $a^{-1}$ | 3206 |
| southern half of study area | -2.25 m $a^{-1}$ | -3.00 m $a^{-1}$ | 3286 |
| Western basins | -0.14 m $a^{-1}$ | -0.60 m $a^{-1}$ | 1195 |
| Eastern basins | -3.21 m $a^{-1}$ | -3.73 m $a^{-1}$ | 2820 |

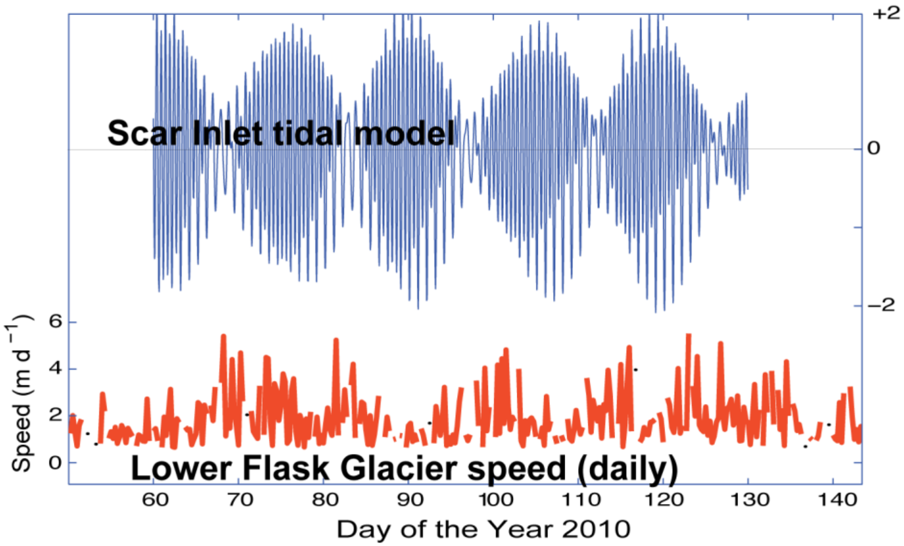
**Cross-over analysis (a check on agreement between methods, and ICESat correction)**

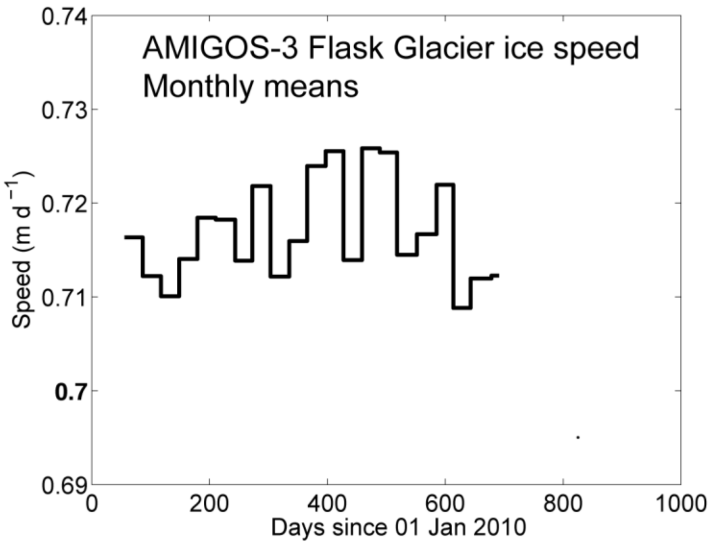
7 usable crossover regions in study area;

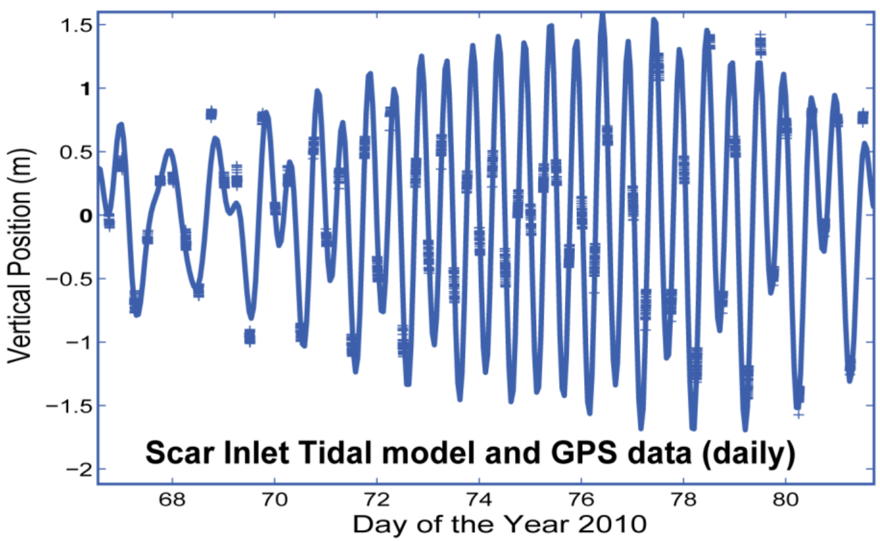
| | |
|---|---|
| **Mean difference between methods: dDEM – $\mathbf{ICESat_{corr}}$** | **+0.05 m $a^{-1}$** |
| Mean difference without correction: dDEM – $ICESat_{uncorr}$ | +0.96 m $a^{-1}$ |
| Mean absolute difference ascending vs $descending_{corr}$ | 1.28 m $a^{-1}$ |
| ascending vs $descending_{uncorr}$ | 1.96 m $a^{-1}$ |

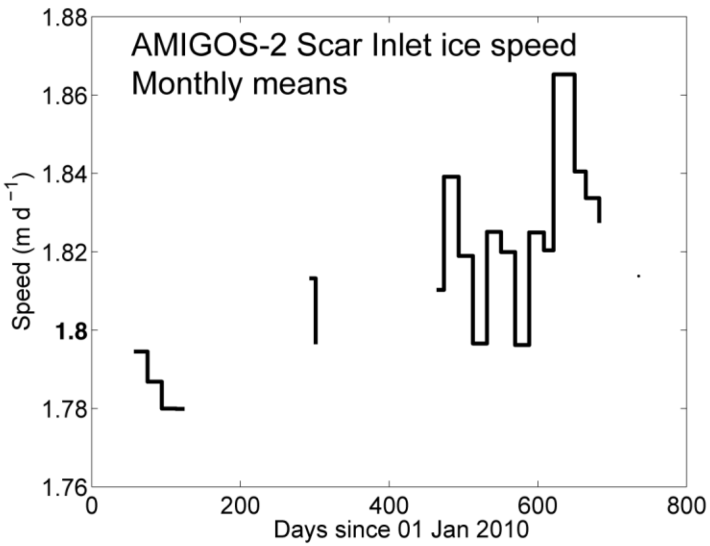
Scambos et al., 2013a in prep.

# Preliminary Results from AMIGOS precision GPS – continued shelf acceleration and glacier modulation by tides



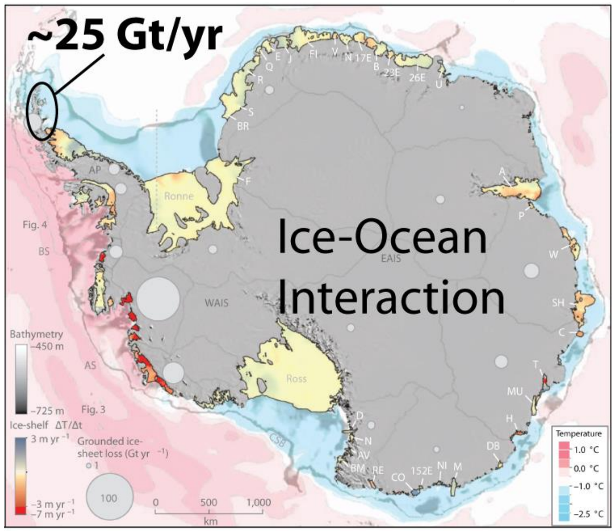



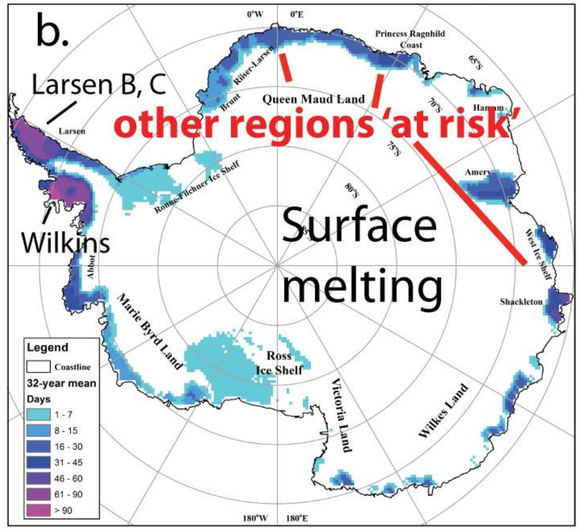

tide model, L. Padman; GPS processing, Martin Truffer

# *Ice shelf break-up has a large proportional effect on ice sheet mass balance*

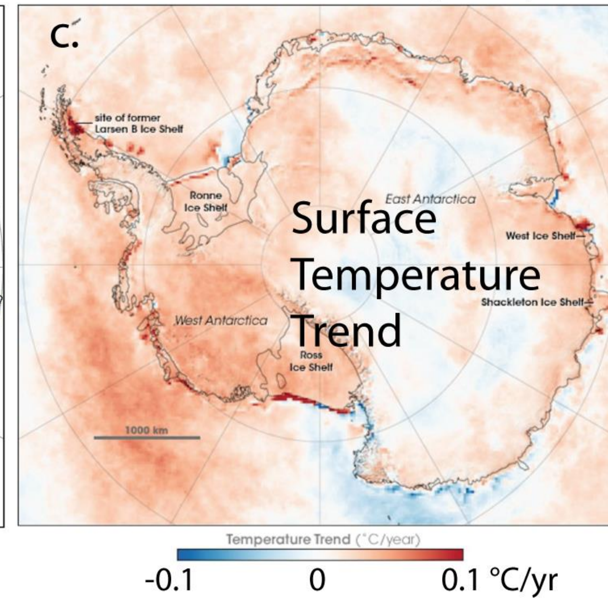
Prichard et al., 2012




Liu et al., 2006



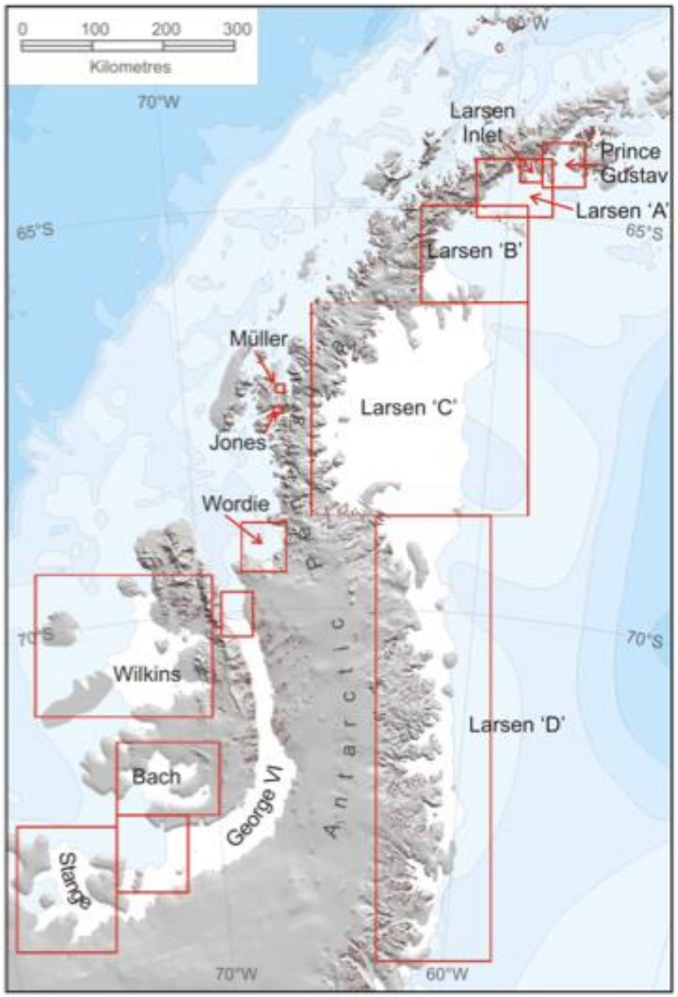

Kwok and Comiso, 2002, 2007




**Total Antarctic I.S. Mass Loss:**

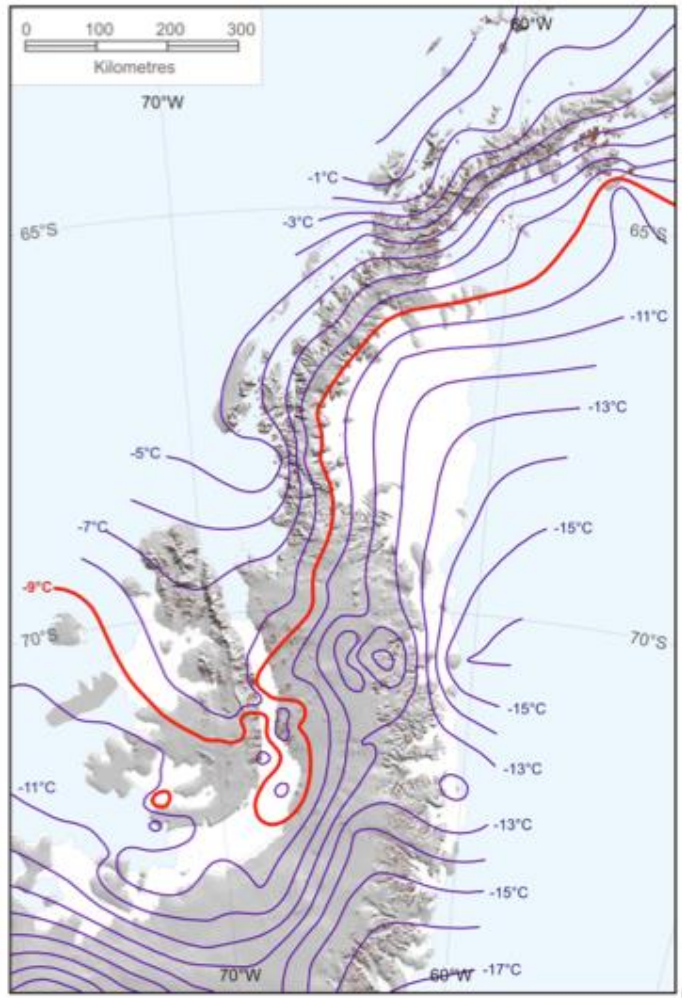
**-81 ± 43 Gt/yr**; Shepherd et al., 2012

- ice mass loss of the northern Peninsula (<1 % of the ice sheet) is ~30% of the total mass imbalance for the continent;
- other regions show extended melt seasons and melt ponding at present;
- further warming could place far larger glacier systems 'at risk'



0 100 200 300
Kilometres
70°W
60°W
65°S
70°S
Larsen Inlet
Prince Gustav
Larsen 'A'
Larsen 'B'
Larsen 'C'
Larsen 'D'
Müller
Jones
Wordie
Wilkins
Bach
George VI
Stange
Antarctic

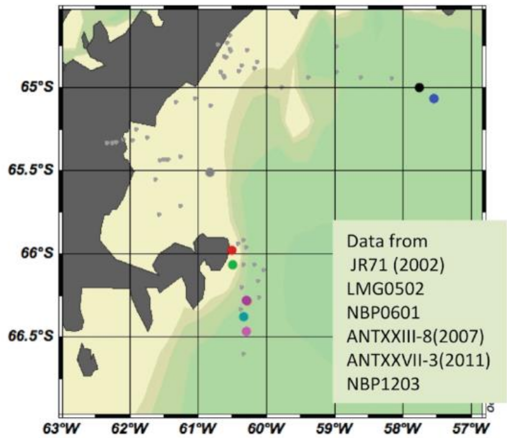

(a)

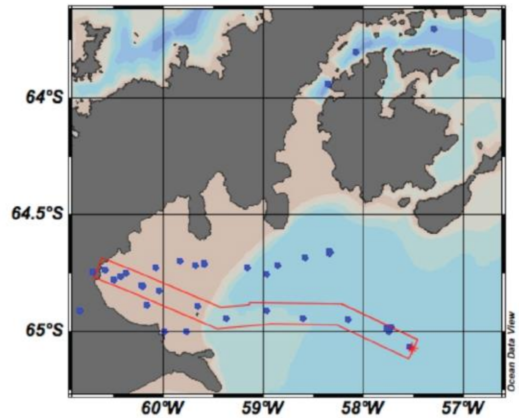


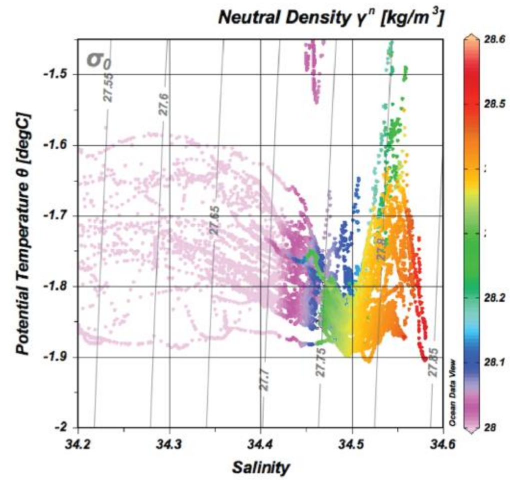
0 100 200 300
Kilometres
70°W
60°W
65°S
70°S
-1°C
-3°C
-5°C
-7°C
-9°C
-11°C
-13°C
-15°C
-17°C

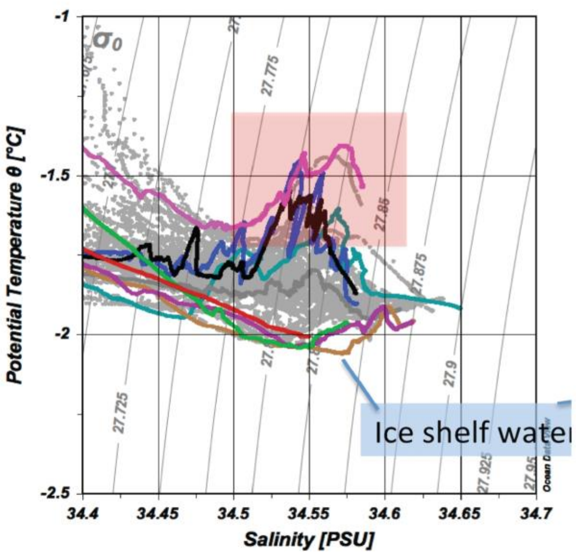

(b)

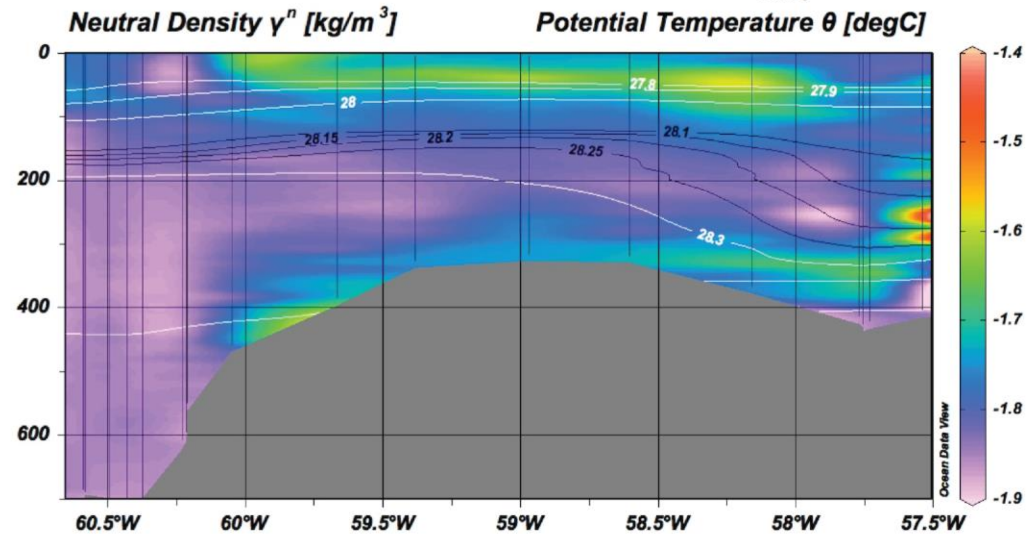
# *Ocean data for the region: 'warm' mWDW at depth, sometimes*



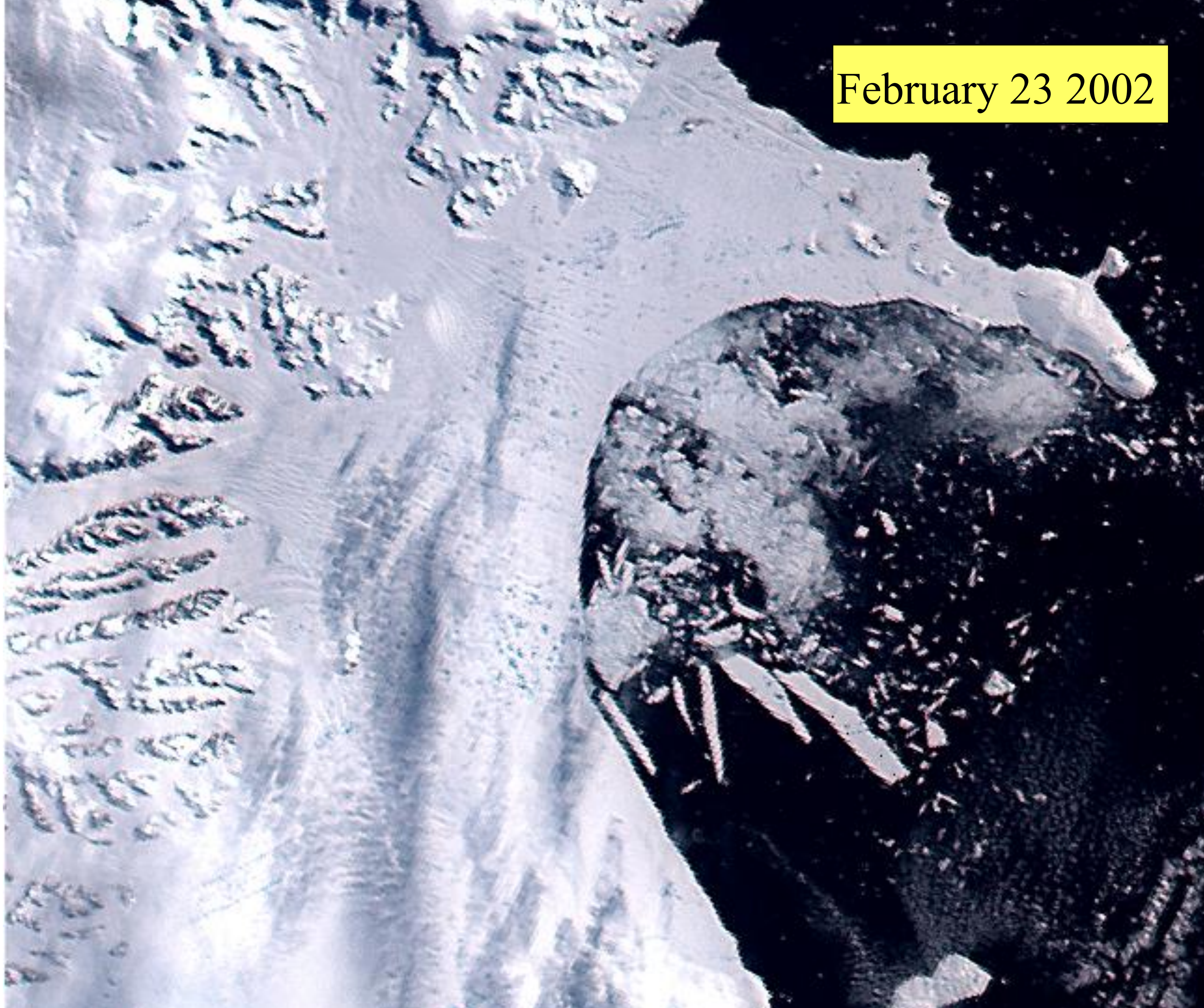



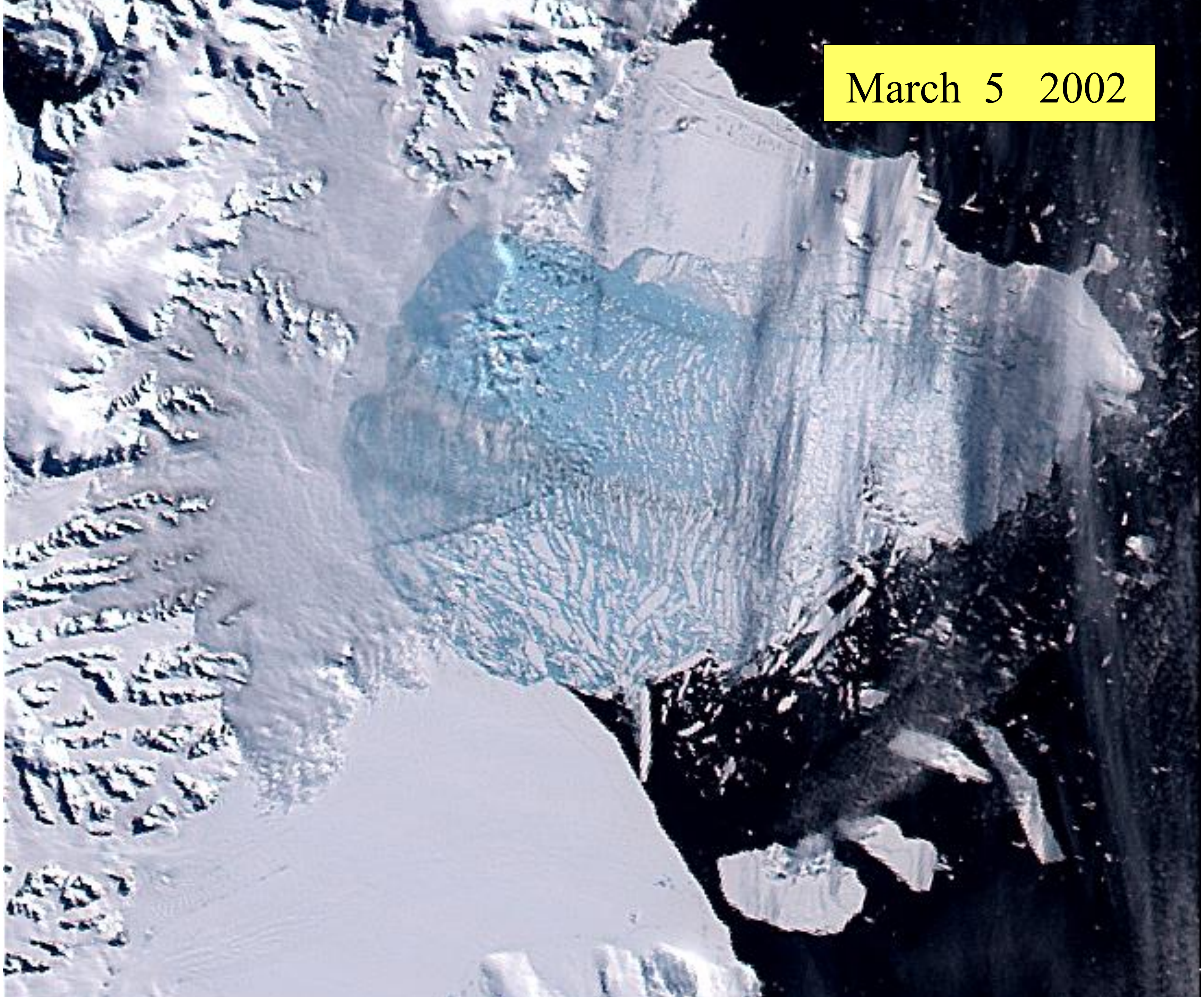



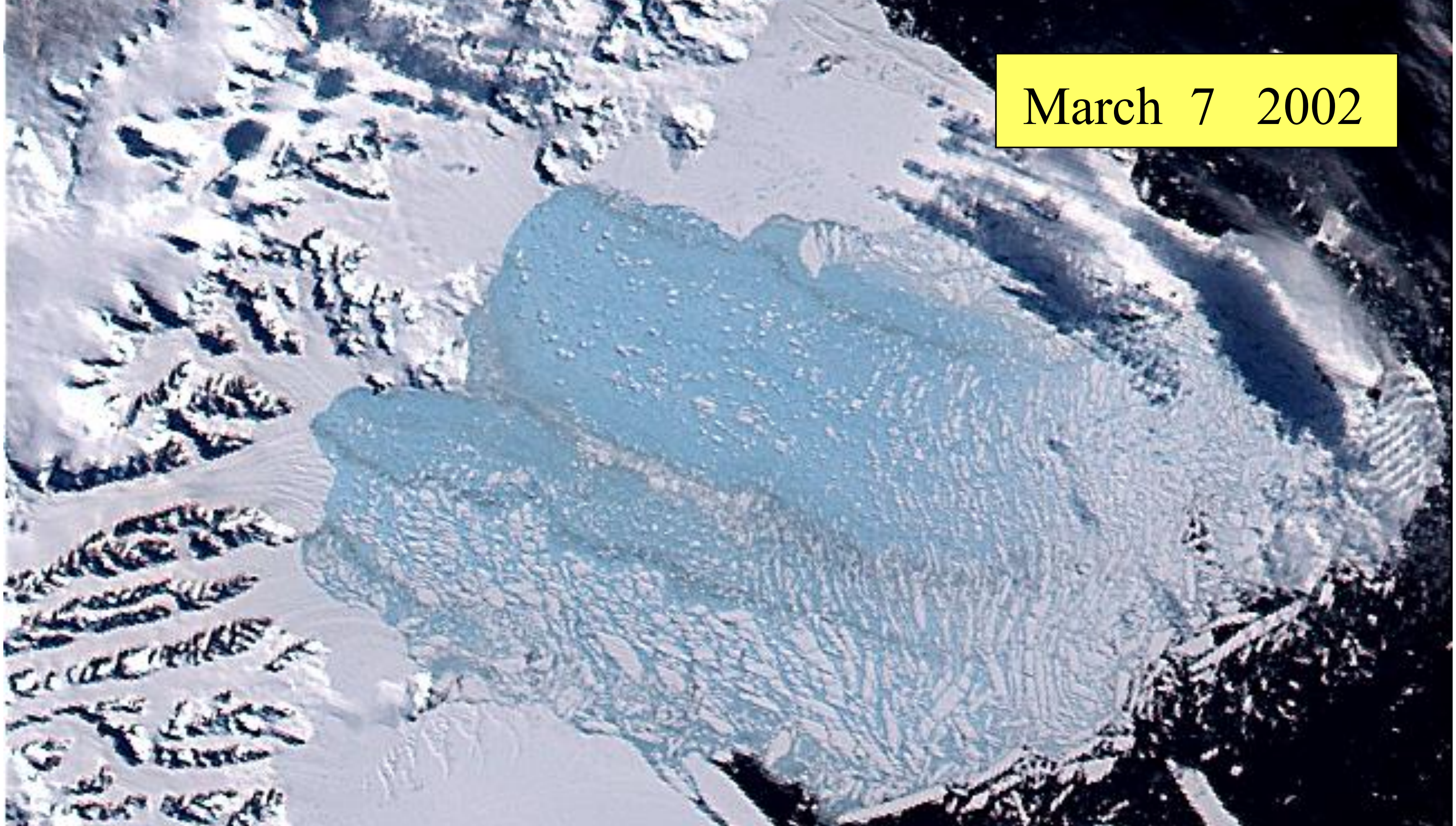

January 31 2002


January 31 2002


February 17 2002


February 23 2002


March 5 2002




- This is the end stage of a long process.
- Glasser and Scambos 2008 (and Viele et al., 2007 and Kazendhar et al., 2007) showed that there were precursors, but only looked at the period just before disintegration.
- **Can we identify:**

  **a period when the shelf was in steady state?**

  **the first evidence of a shift toward weakening?**