Recent Changes in Antarctic Mass Balance

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Important Facts/Terms

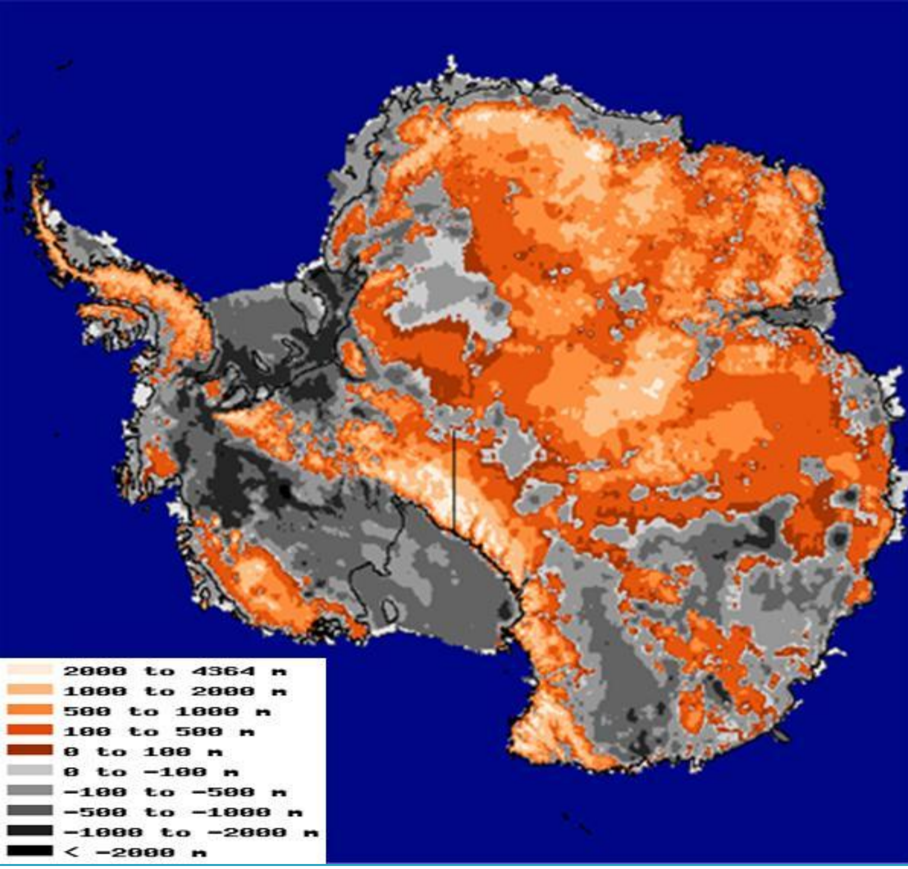
- Grounding Line: Point where glacier ice outflow begins to float and thus contribute to sea level rise (SLR)

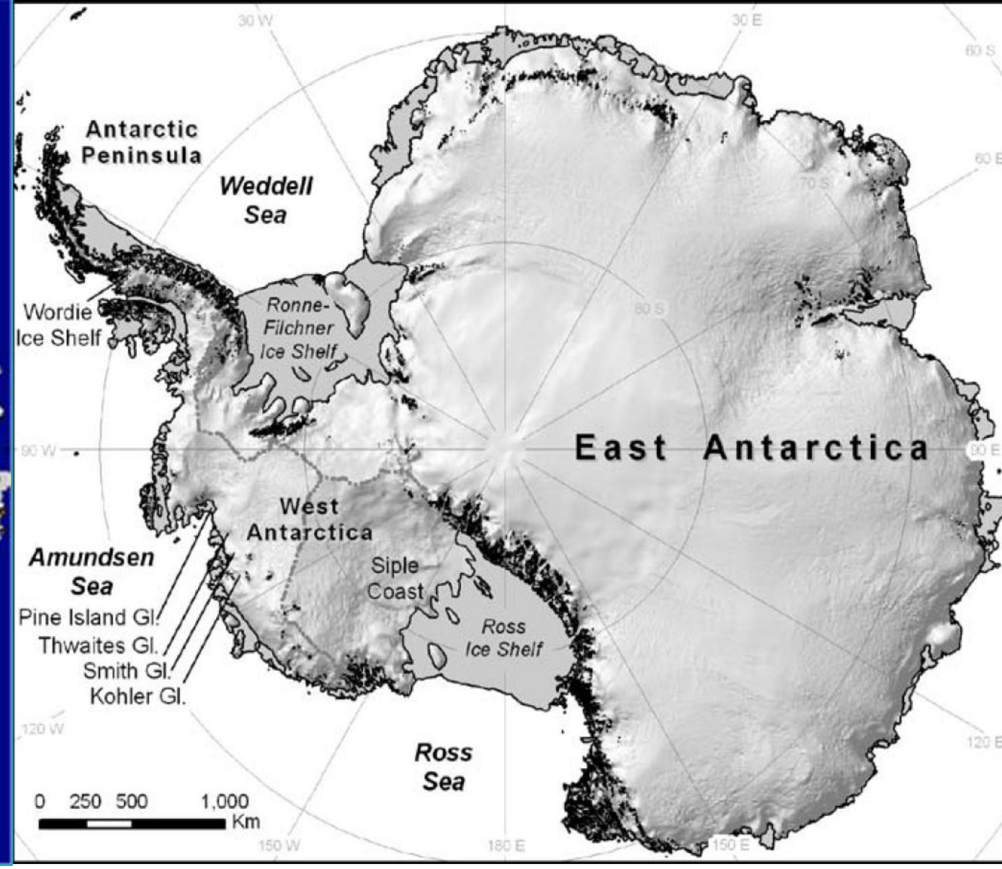
- Gigatonne (Gt): 1 Km^3= Lake Windermere
- 360 Gt= 1 mm SLR
- Glacial Isostatic Adjustment (GIA): Adjustment for rebound of the Earth's crust in response to present and historical changes in the weight of ice sheets

Ice Sheets

- There are three specific ice masses in Antarctica which can be treated independently.
- The East Antarctic Ice Sheet, the West Antarctic Ice Sheet and the Antarctic Peninsula.
- This is because of distinct topographic differences between the three regions.

Allison et al. 2009





East Antarctic Ice Sheet

- Largest Ice Sheet
- Holds 50 meter sea level potential (SLP)

Lythe et al. Bedmap Consortium 2000. Vaughan, D. 2008

West Antarctic Ice Sheet

- Grounded Below Sea Level (marine ice sheet)
- Holds 5 meter SLP
- Main Contributor to Antarctic Ice Mass losses

Antarctic Peninsula

- Mountainous region
- 0.3 meter SLP
- Warming in excess of 3°C over last 50 years
- Ignored from IPCC AR4 sea level predictions

Allison et al. 2009, Vaughan, D. 2008

Mass Balance Measuring

- The sum of the mass inputs and mass outputs result in the mass balance of the ice sheets
- Mass is continually added to the ice sheets through snowfall
- Mass is removed by iceberg calving and basal melting
- Size, topography and weather across the ice sheets require mass balance measurements to be done through remote sensing techniques
- This can be done through measuring elevation change, mass change and ice flux.

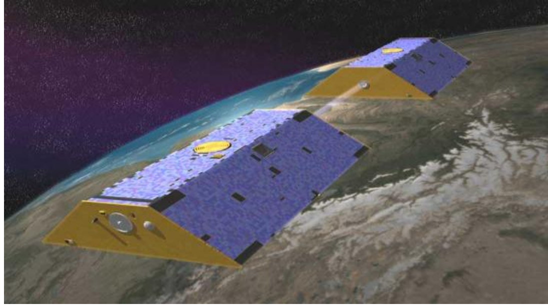
Allison et al. 2009

Elevation change: Radar and Laser Altimetry

- Measure the distance from the sensor to the surface and thus elevation of the surface
- Radar Altimeter signals are easily affected by snow properties and have a large bias over narrow and rough/sloping terrain
- Laser Altimeters have better resolutions but are affected by cloud cover
- Correction for GIA must be done for precise results

Allison et al. 2009, Ekholm et al. 2002

MassChanges: GRACE

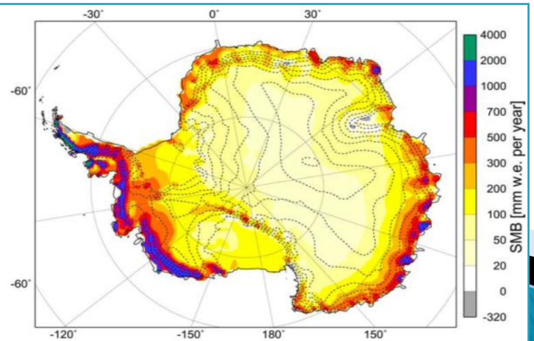


- Measures the change in regional gravitational fields caused by ice sheet mass changes
- Done by precise measurement of separation between a pair of satellites in identical orbits
- Very sensitive to GIA therefore significant error potential
- Can however measure mass loss acceleration effectively[1]

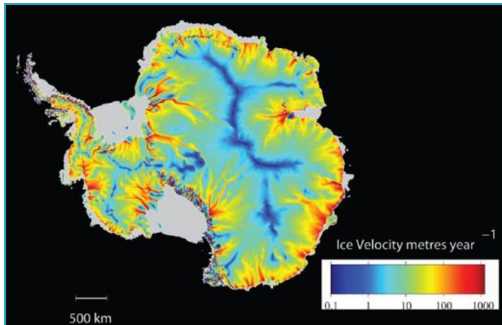
Allison et al. 2009, Bevis et al. 2009,
Chen et al. 2006, [1]Velicogna. 2009

Ice Mass Flux: SAR Interferometry

- Estimates the sum of the mass inputs to a glacier and the mass outputs
- Inputs are determined through precipitation modelling
- Outputs are determined by measuring the depth of ice and velocity of ice as it crosses the grounding line
- Done using Ground Penetrating Radar, Differential SAR Interferometry and Speckle Tracking



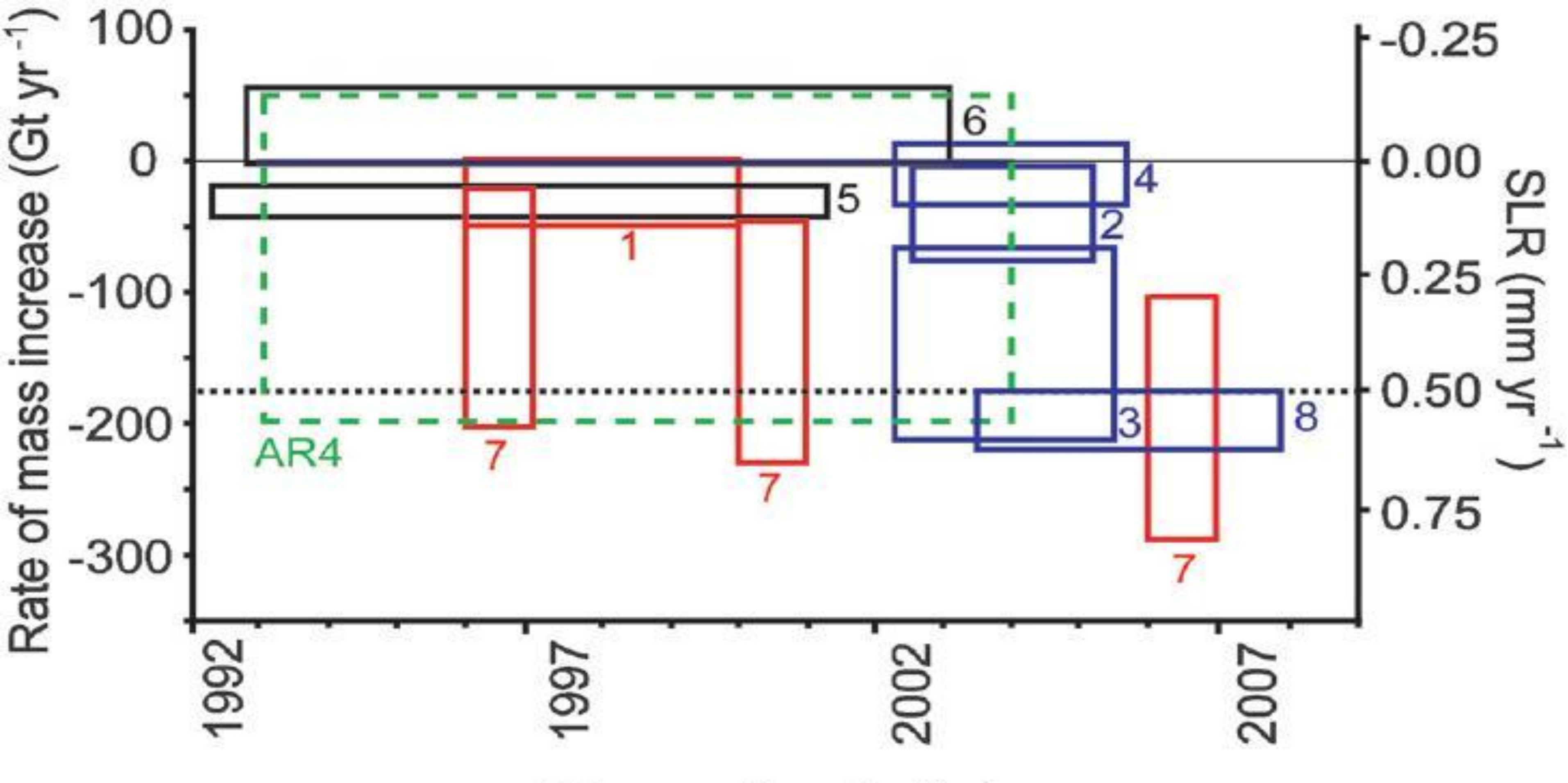
Allison et al. 2009, Rignot et al. 2008, Van de berg et al. 2006




Antarctic Mass Balance


Overall Mass Balance

Ref.	Antarctica (Fig. 3)
1	Rignot & Thomas 2002
2	Ramillien *et al.* 2006
3	Velicogna & Wahr 2006b
4	Chen *et al.* 2006b
5	Zwally *et al.* 2005
6	Wingham *et al.* 2006b
7	Rignot *et al.* 2008b
8	Cazenave *et al.* 2009
AR4	Solomon *et al.* 2007



Allison et al. 2009, Chen et al. 2008

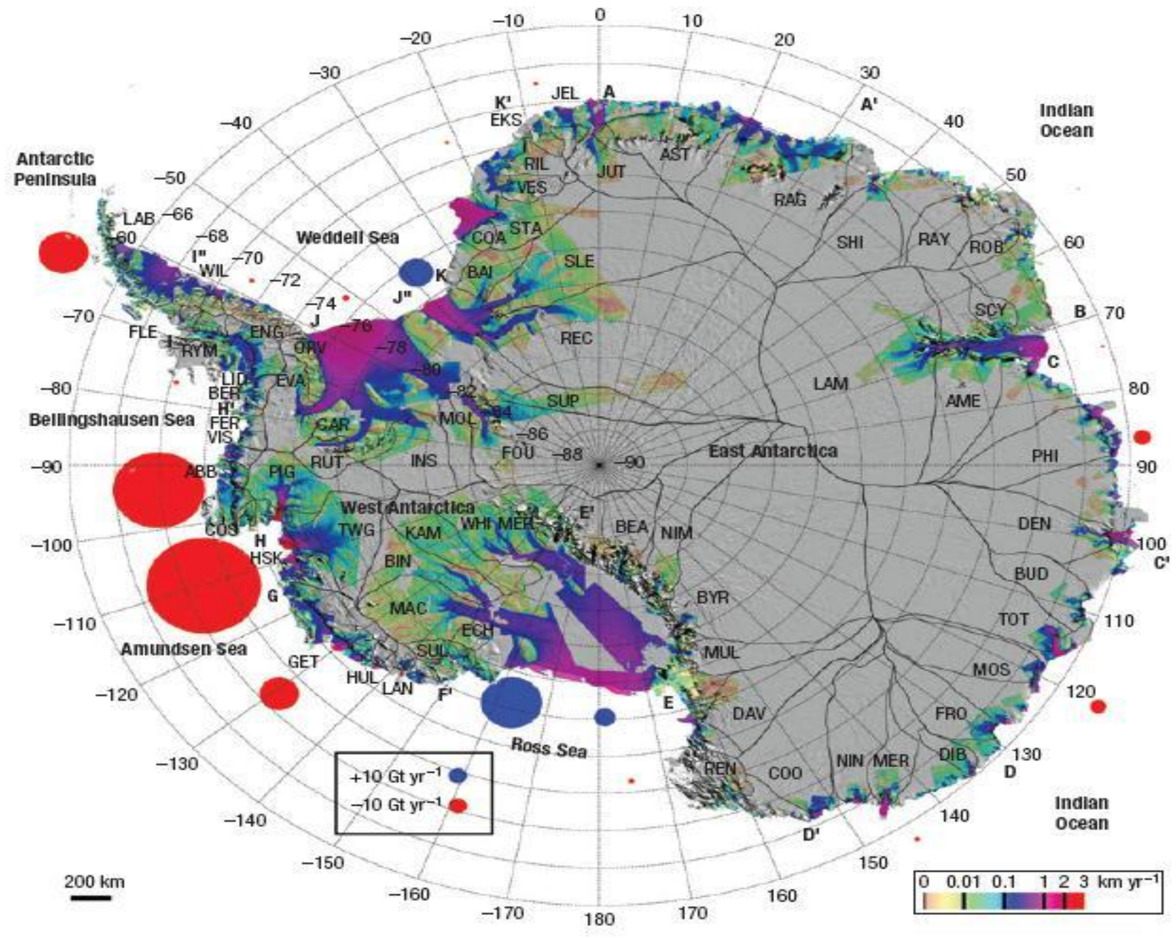
Regional Mass Balance

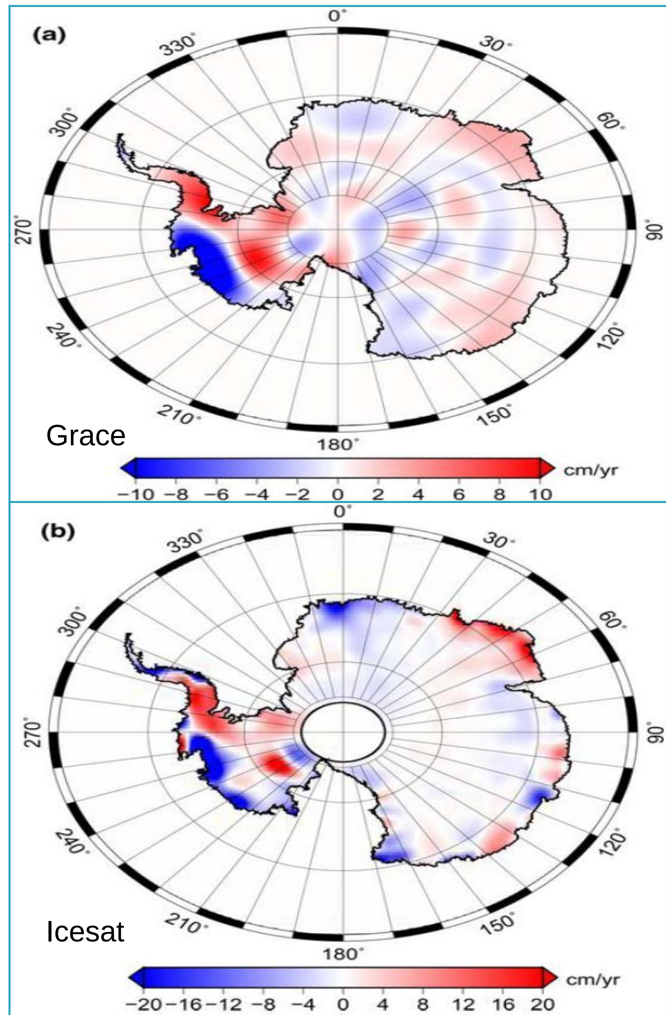
- Strong East-West Gradient
- Significant Regional Variations
- Higher Elevations show accumulation
- EAIS showing some increases of precipitation

Table 2 Mass balance in gigatonnes (10^{12} kg) per year for 1996 and 2006 of basins II″ and G H, West Antarctica, the Peninsula and the entire Antarctic ice sheet.

Sector	Outflow (Gt yr^{-1})	Net (Gt yr^{-1})	Net+ (Gt yr^{-1})
GH Pine Is. Thwaites 1996	215 ± 3	−39 ± 25	−41 ± 27
GH Pine Is. Thwaites 2006	261 ± 4	−85 ± 26	−90 ± 27
West Antarctica 1996	654 ± 22	−66 ± 53	−83 ± 59
West Antarctica 2006	700 ± 23	−112 ± 54	−132 ± 60
II″ Graham Land 1996	20 ± 3	−5 ± 6	−12 ± 7
II″ Graham Land 2006	49 ± 3	−34 ± 6	−47 ± 9
Peninsula 1996	107 ± 8	−13 ± 23	−25 ± 45
Peninsula 2006	136 ± 10	−42 ± 24	−60 ± 46
Antarctica 1996	1,546 ± 30	−78 ± 78	−112 ± 91
Antarctica 2006	1,621 ± 32	−153 ± 78	−196 ± 92

Davis et al. 2005, Gunter et al. 2009, Rignot et al. 2008

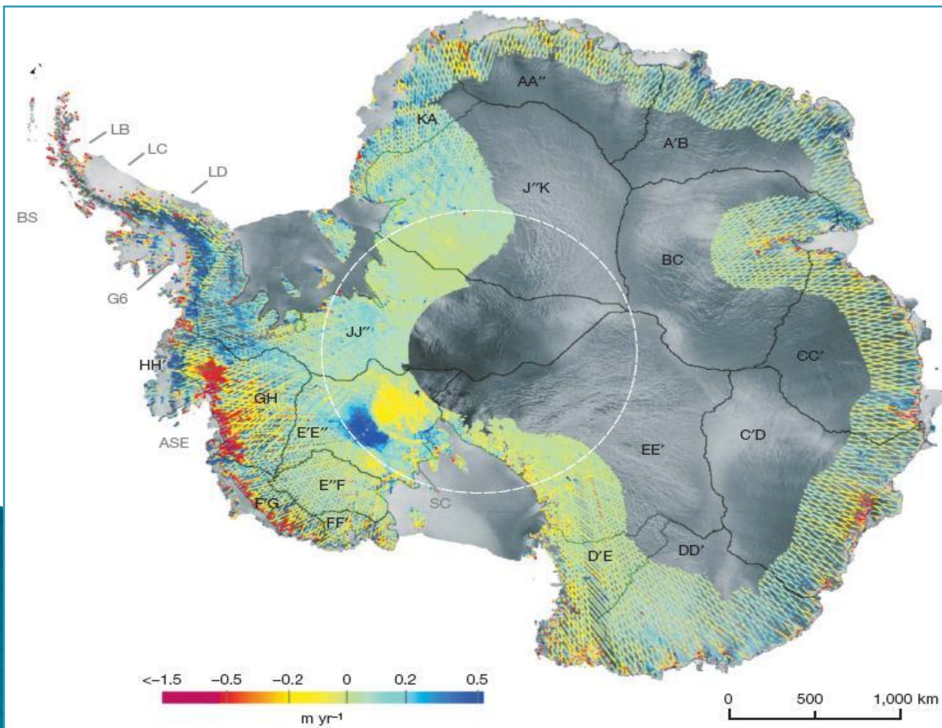


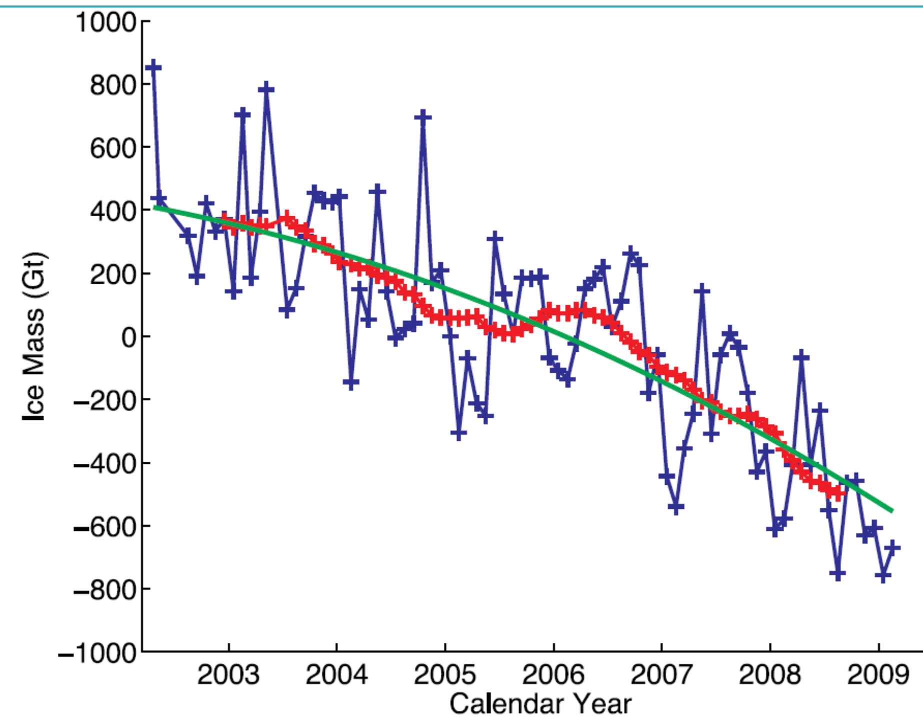


[1]Pritchard et al. 2009, [2]Velicogna, I. 2009

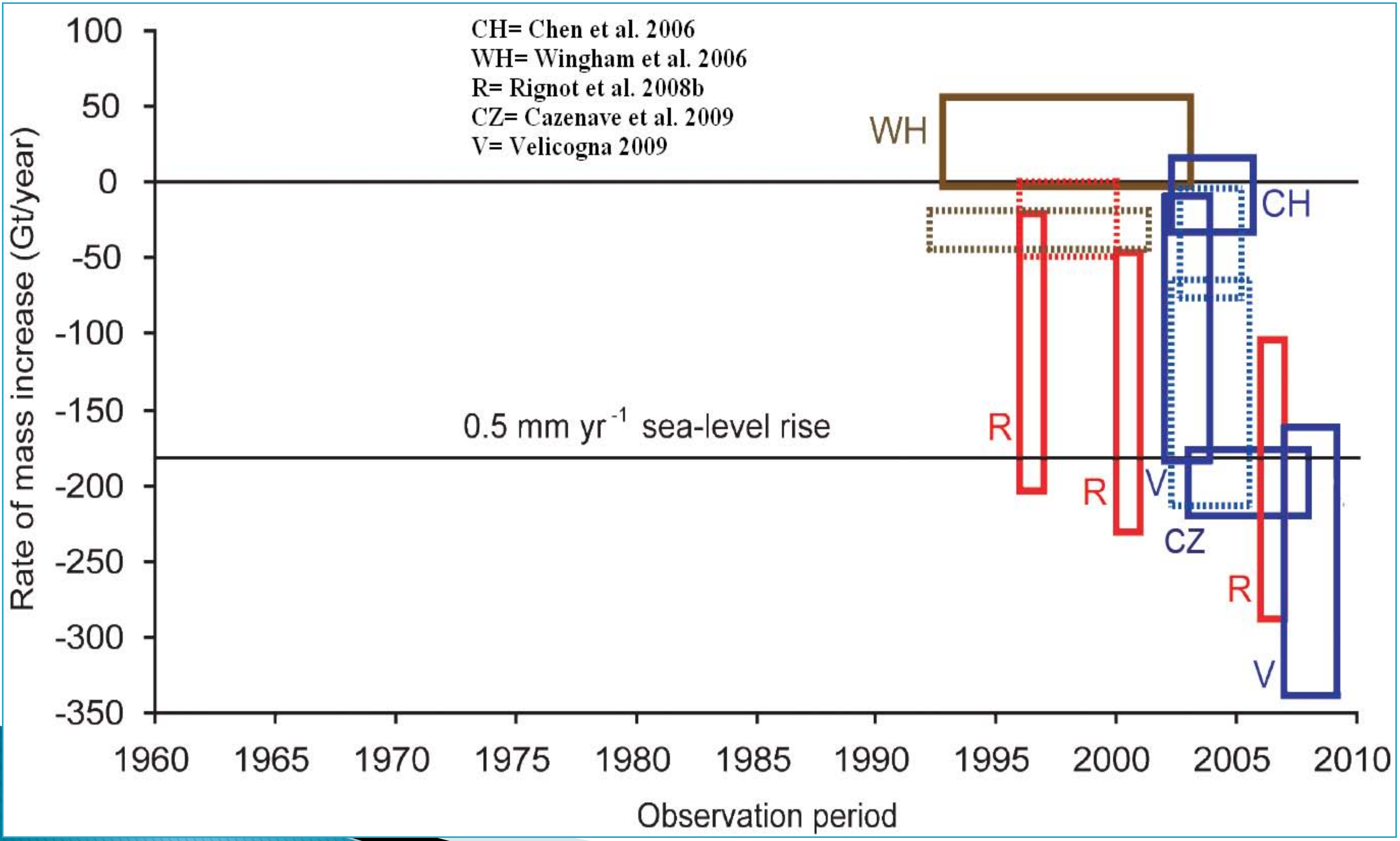
Recent and Dynamic Changes

- Dynamic thinning occurring at Antarctic margins[1]
- Ice mass loss has accelerated by 140%
- 99% confidence in acceleration of loss
- Current loss estimated at **246 Gt year^{-1}** (2009)[2]



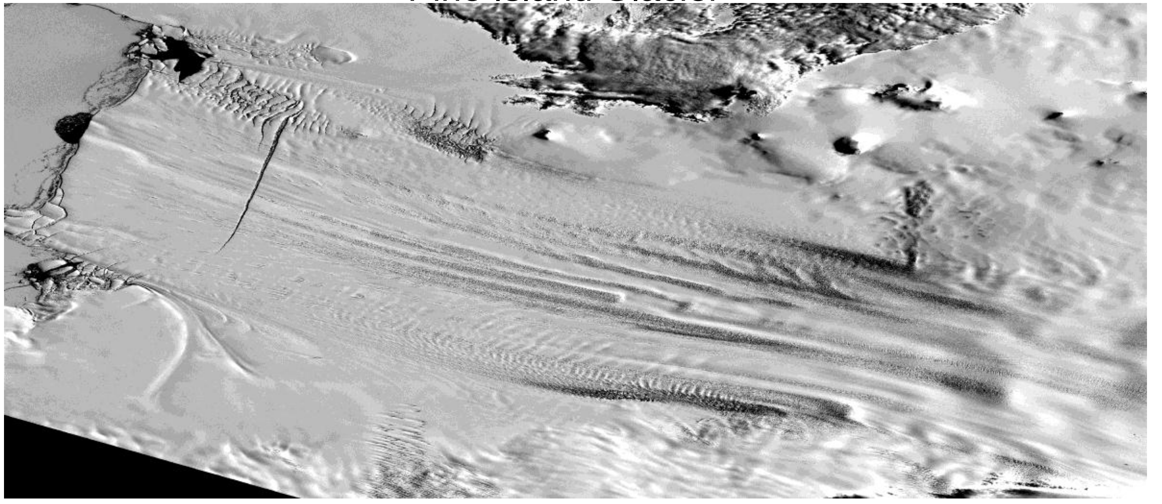


Recent Changes: Summary



The Copenhagen Diagnosis. 2009

Pine Island Glacier



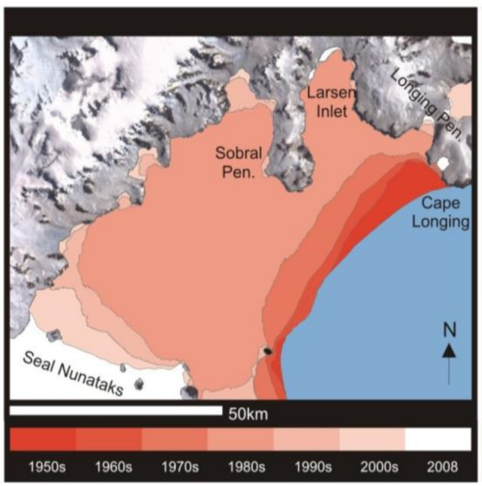
Dynamical Changes

Thwaites Glacier

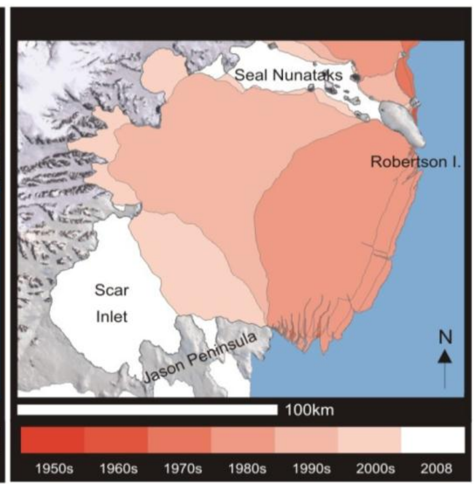
Ice Shelf Dynamics

J.H. Mercer, *Nature*, 1978

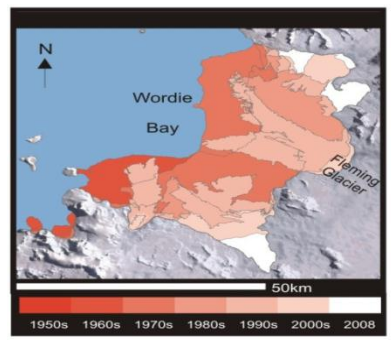
One warning sign that a dangerous warming is beginning in Antarctica will be the breakup of ice shelves in the Antarctic Peninsula just south of the recent January 0 °C isotherm; the ice shelf in Prince Gustav Channel on the east side of the peninsula, and the Wordie Ice Shelf, the ice shelf in George VI Sound, and the ice shelf in Wilkins Sound on the west side



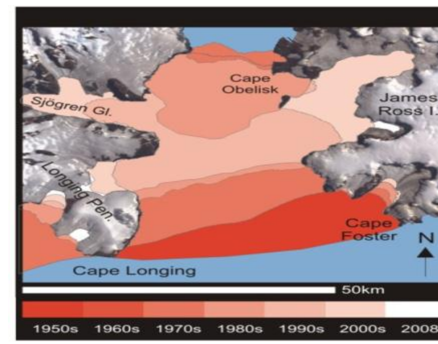
Larsen A



Larsen B

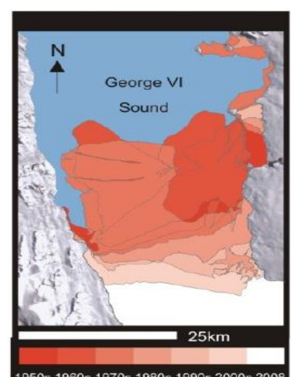


Wordie

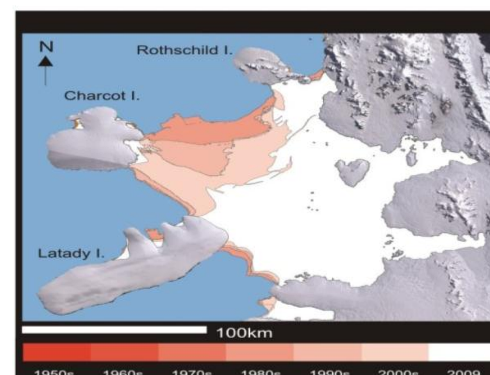


Prince Gustav

- **28,117 km² lost since 1950s**[1]



George VI North

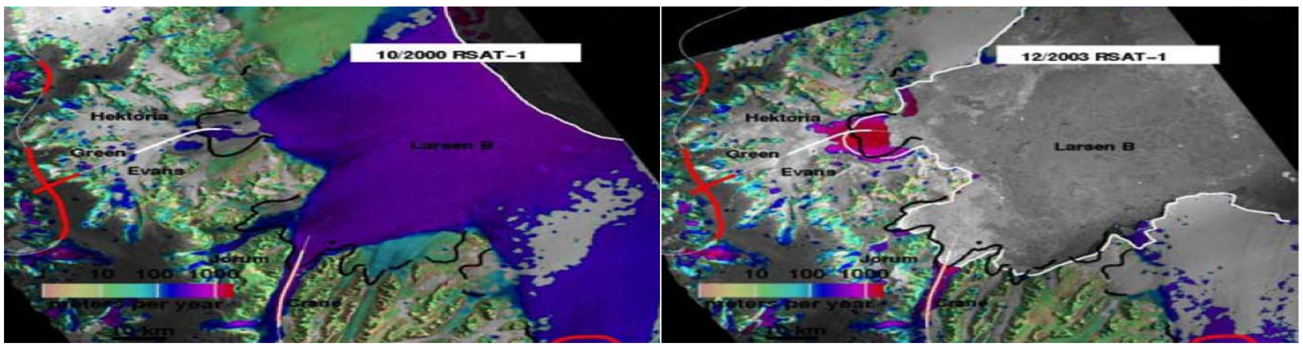


Wilkins

J.H. Mercer. 1978, [1]Cook and Vaughan, 2009.

Glacier Acceleration after break-up

- After ice shelf collapse, glaciers feeding Larsen A, B and Wordie Ice Shelves accelerated exponentially (up to 6x)[1,2]
- Mass loss increase from $3\pm1^{(1996)}$ to $\mathbf{31\pm9}$ Gt $\text{year}^{-1(2006)}$



- Wilkins Glacier accelerations next?
- Gilbert Glacier had advanced up to 2 km between 1990 and 2004 (prior to the most recent major break up events)[3]

[3]Braun et al. 2009, Cook and Vaughan, 2009, [1]Rignot et al. 2004, [2]Scambos et al. 2004

Amundsen Sea Embayment

- Glaciers in the Amundsen Sea Embayment have accelerated by up to **60%** since 1996
- 1.3m SLP (0.29mm/yr by 2007)[1] or **−105 Gt±27 year^{-1}** mass loss
- Pine Island Glacier, Thwaites Glacier and Smith Glacier are now contributing heavily to mass losses for all of Antarctica
- Region is grounded significantly below sea level therefore grounding line retreat is linked to hypothesized WAIS destabilization

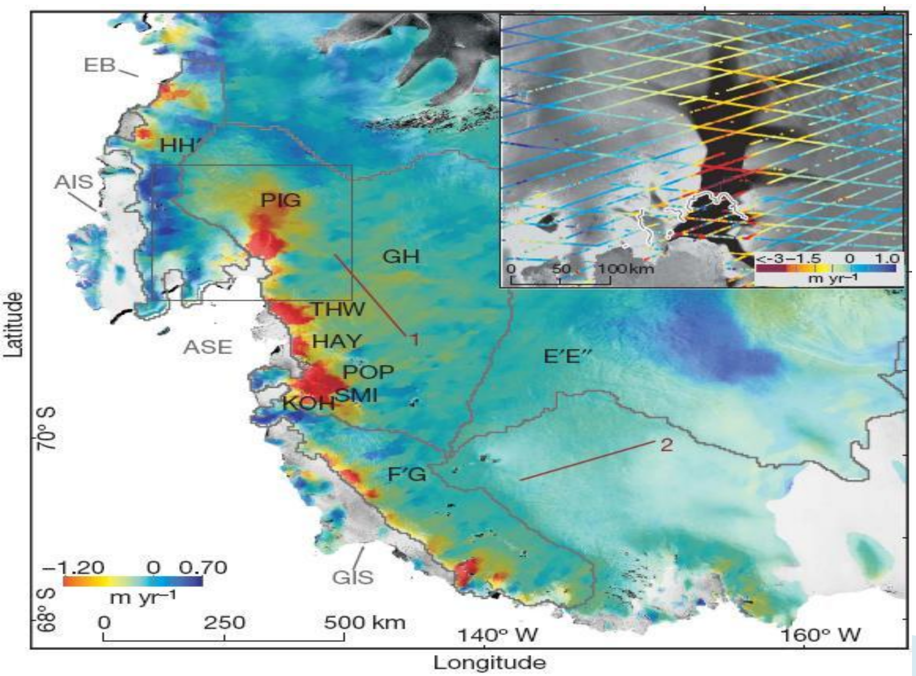
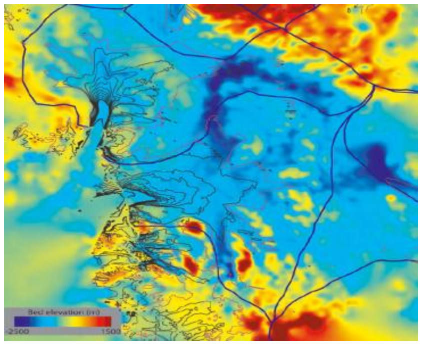


Table 1. Mass balance of West Antarctic Glaciers Draining Into the Amundsen Sea Between 1974 and 2007[a]

			Outflow, Gt/yr				
Glacier 2007	Area, × 10^6 km^2	Input, Gt/yr	1974	1996	2000	2006	2007
Pine Island	164	61 ± 9	65 ± 4	77 ± 2	85 ± 2	100 ± 5	107 ± 5
Thwaites	182	75 ± 11	80 ± 6	93 ± 2	97 ± 2	101 ± 5	109 ± 5
Interstream	11	9 ± 1	8 ± 1	8 ± 1	8 ± 1	10 ± 1	10 ± 1
Haynes, Smith, Kohler	37	31 ± 5	31 ± 4	37 ± 4	47 ± 4	50 ± 5	54 ± 6
Total Outflow	393	177 ± 25	184 ± 8	215 ± 7	237 ± 7	261 ± 9	280 ± 9
Mass Balance		−7 ± 26		−39 ± 26	−60 ± 26	−85 ± 26	−105 ± 27

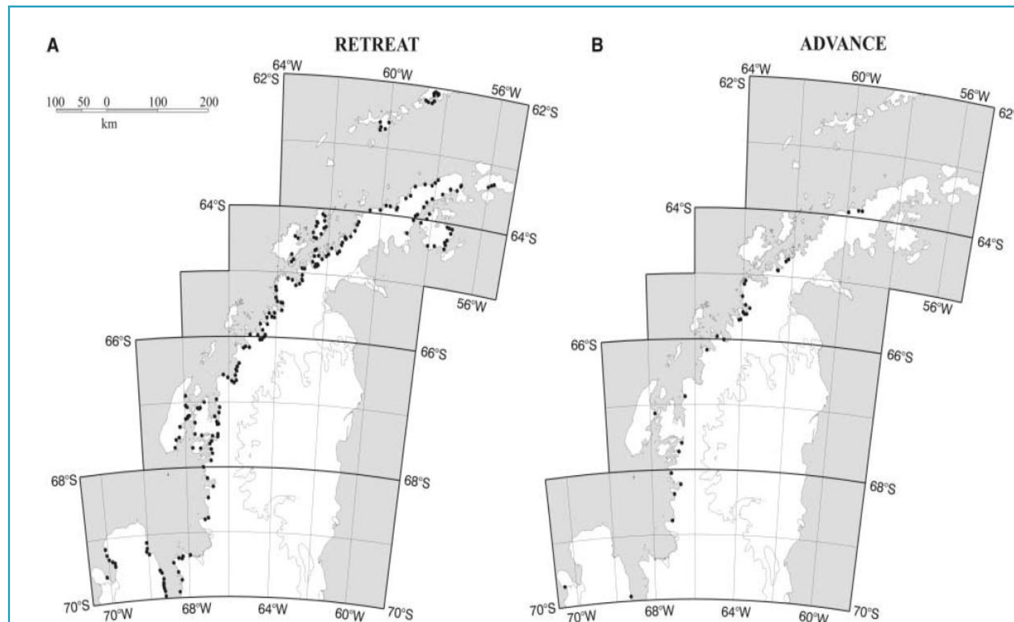
Hughes, T. 2009, Oppenheimer, M. 1998, Pritchard et al. 2009, [1]Rignot et al. 2008, Rignot, E. 2001 Rignot et al. 1996, Thomas et al. 2004



Antarctic Peninsula

- Losses increased by **140%** from 1992 to 2006
- **60 ± 21.6** Gt year^{-1}or 0.16 ⊞ 0.06 mm year SLR[1,2]
- Survey of 244 marine glaciers on the AP (2005)
- 87% retreat
- Region ignored in IPCC sea level predictions

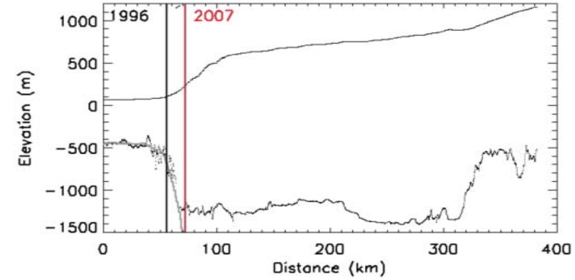
	Advance	Retreat
Less than 500 m	27	146
500–1000 m	2	35
1000–2000 m	3	17
2000–5000 m		13
More than 5000 m		1



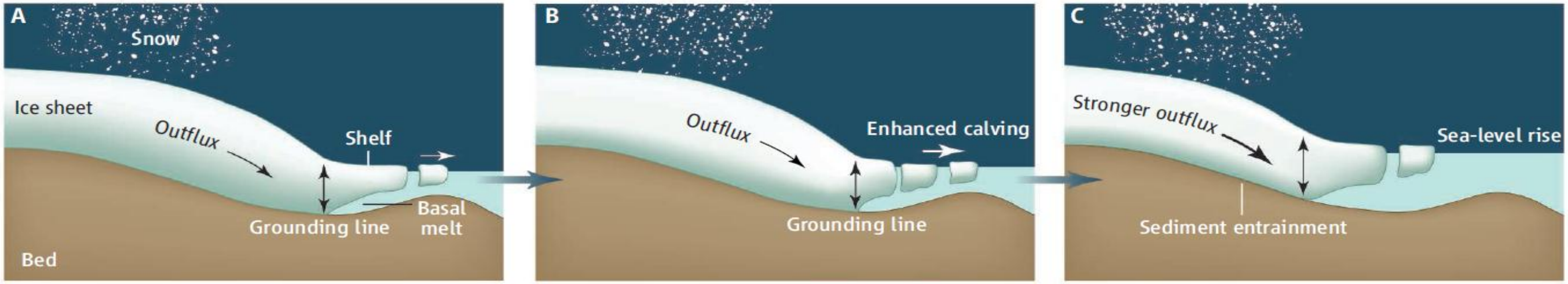
Cook et al. 2005, [1]Pritchard and Vaughan. 2007, [2]Rignot et al. 2008

Bamber et al. 2009, Mercer. 1978, Rignot. 2008, Schoof. 2007, Thomas et al. 2004, Vaughan. 2008

WAIS Destabilization



- WAIS has been argued to be inherently unstable and prone to systematic collapse
- Removal of fringe ice shelves and inland migration of grounding line would begin collapse
- Thwaites glacier and Pine Island Glacier are regions hypothesized to trigger this collapse
- Within the next 5 years there is evidence significant grounding line retreat will occur in these dynamic regions



Runaway instability. Currently the grounding line sits to the right, upslope just outside the marine-based basin (A). Warm thermal ocean upwelling beneath the ice shelf (*11*) and lubrication by wet sediment at the base may exacerbate the potential instability and aid in accelerating the outward ice flow. As ice thickens at the transition zone (near the vertical arrow at the grounding line), ice flow increases. The runaway instability (evolving from **A** to **C**) does not stop until a new stable position is found and ice that was once grounded to the floor of the submarine basin has been lost to the global oceans. [Adapted from (*5*)]

Mass Balance Overview:

- EAIS: In balance. Losses restricted to coastlines and gains are inherent to inland portions at higher elevations
- WAIS: Extremely Negative. Major ice losses occurring from glaciers in the Amundsen Sea Embayment and Bellinghausen Sea
- AP: Negative. Glacier retreats occurring throughout the AP and ice losses are accelerating quickly
- Overall Mass Balance (including error margin) between **−100 to −250 Gt year^{-1}** with most recent estimates being closer to **−200 Gt year^{-1}**
- IPCC AR4 result of +100 GT to −200 Gt year^{-1}
- Re-assessed sea level contribution at **0.56mm ± 0.06** per year (**18%** of total SLR)[1]
- 4x more than the IPCC mean value
- IPCC AR4 result of 0.14 ± 0.41mm per year

[1]Cazenave et al. 2009, Hock et al. 2009, IPCC 2007 AR4 Scientific Basis, Shepherd and Wingham, 2009

Conclusion

- Despite headlines such as:

- Antarctica is in fact losing ice extensively (100 to 250 Gt per year)
- Ice loss has rapidly increased and is accelerating
- Dynamical changes dominate ice losses