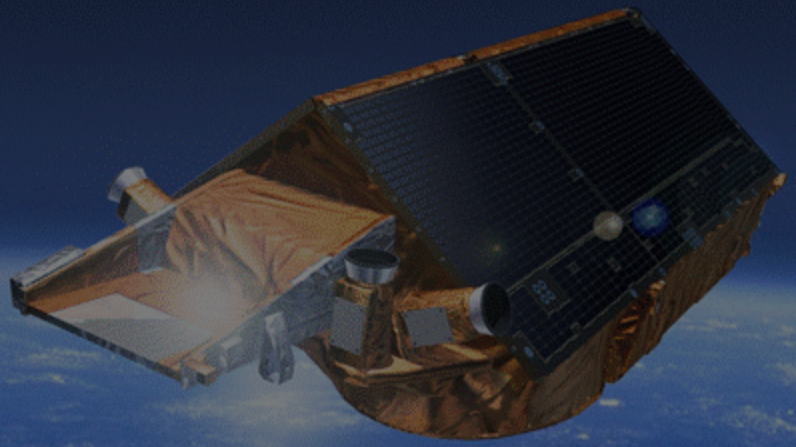
How to measure 3 trillion tons of ice

Andrew Shepherd



cpom

esa

UNIVERSITY OF LEEDS

- Ice and climate
- Measuring ice loss
- Satellite altimetry
- Ice sheet mass balance

cpom

esa

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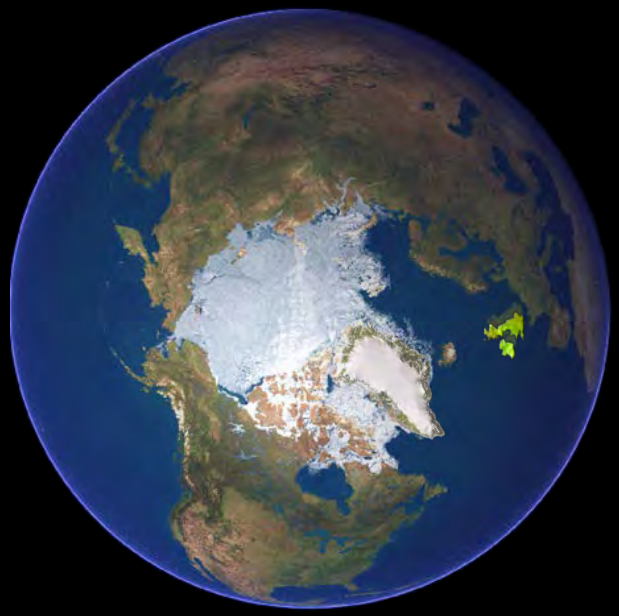
Ice and climate

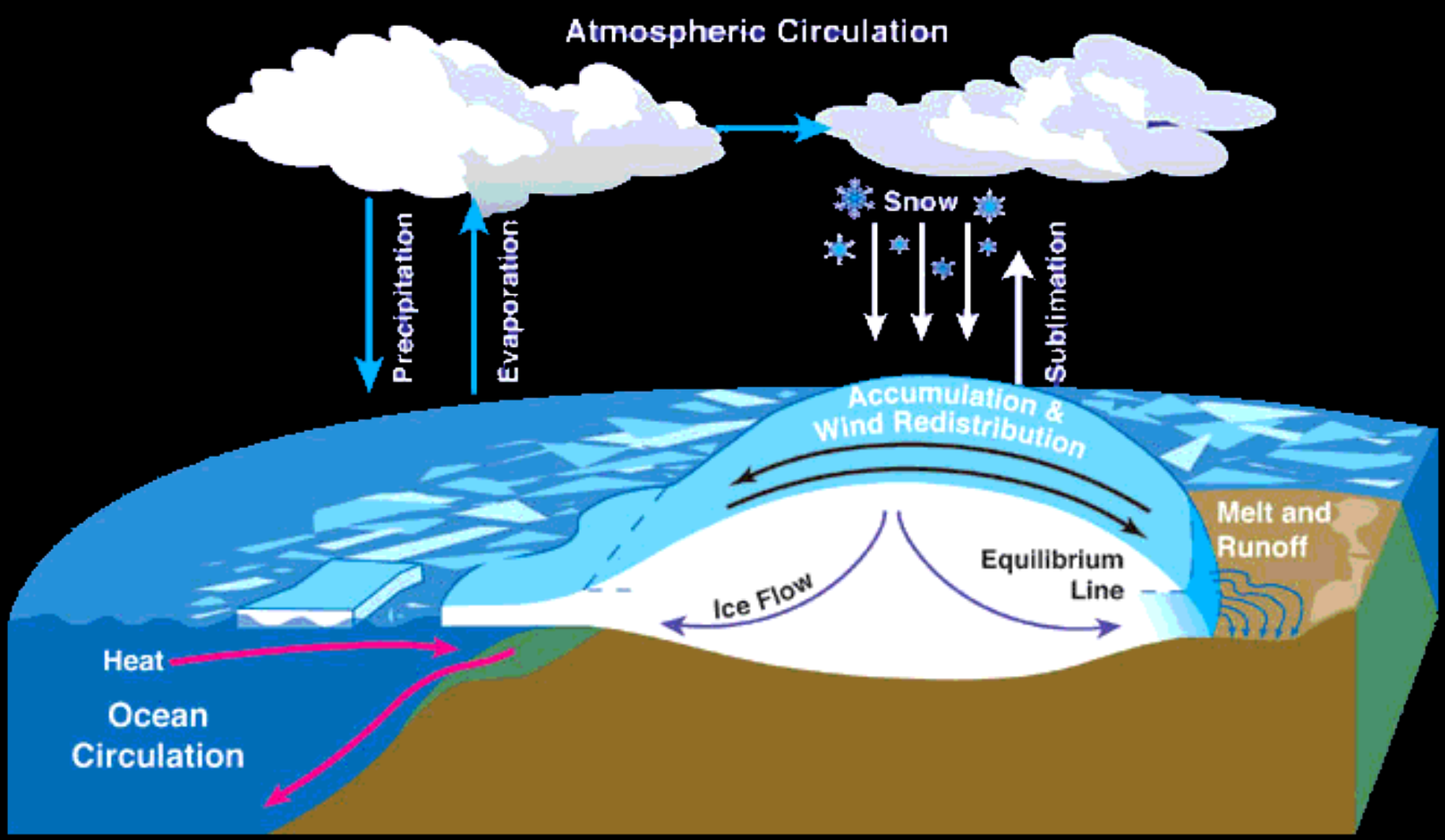
Ice and climate



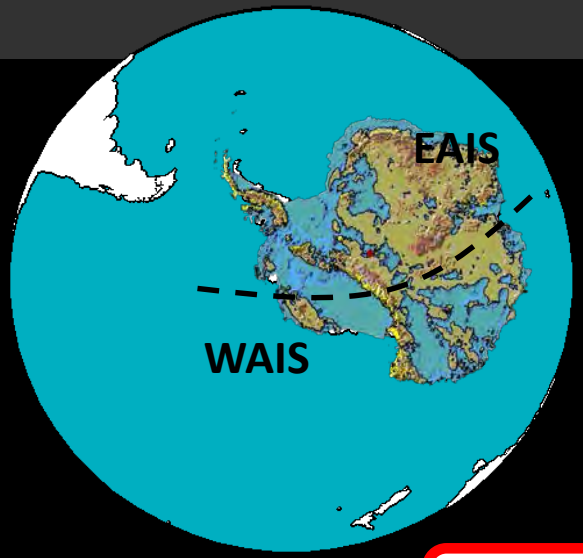
Greenland contains enough ice to raise sea levels by 7m

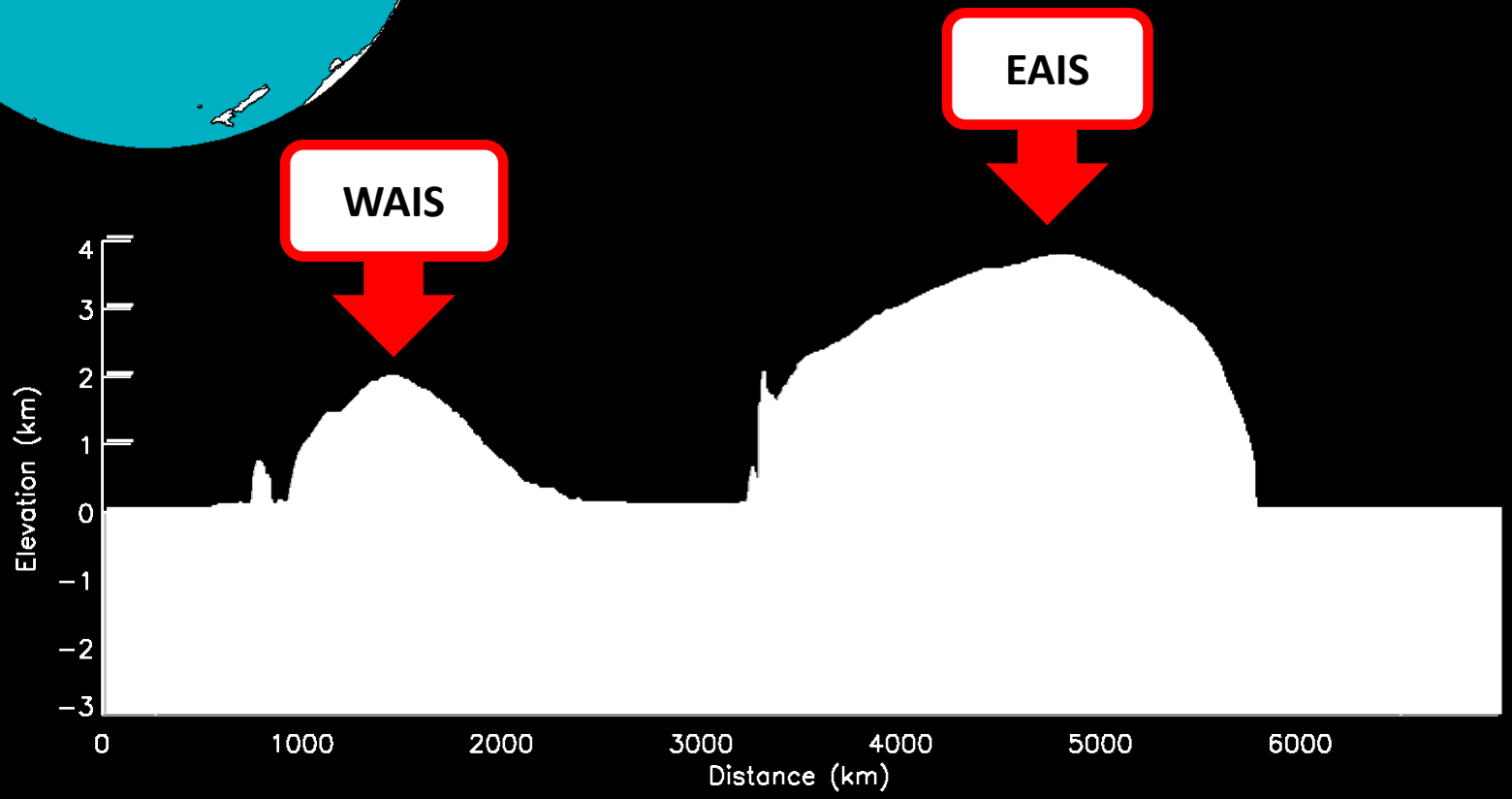
Antarctica contains enough ice to raise sea levels by 57m

Ice and climate

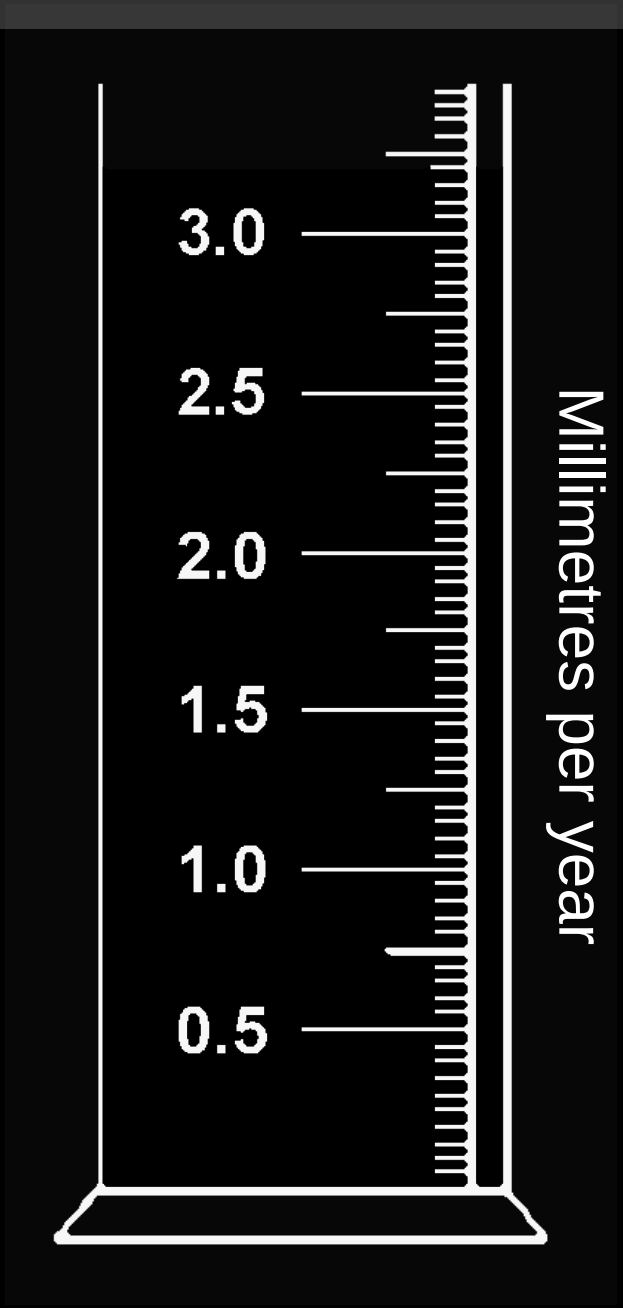


Ice and climate



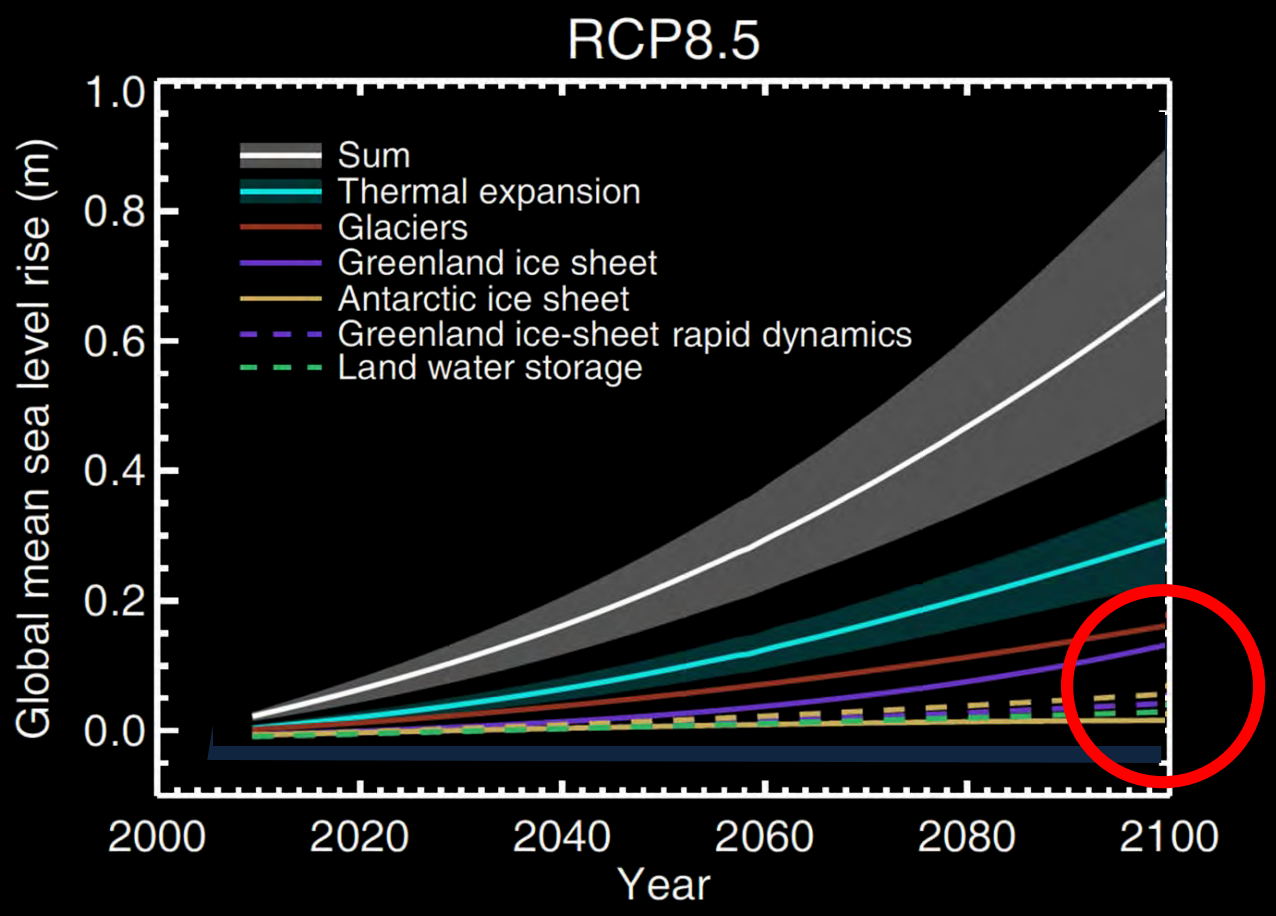


Ice and climate

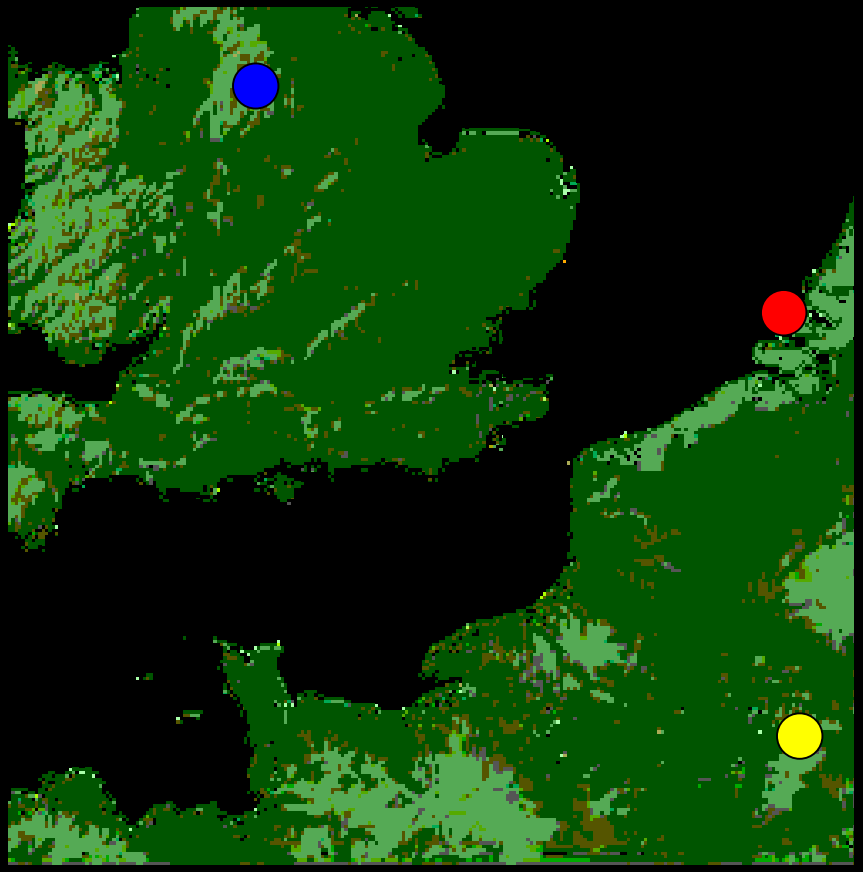


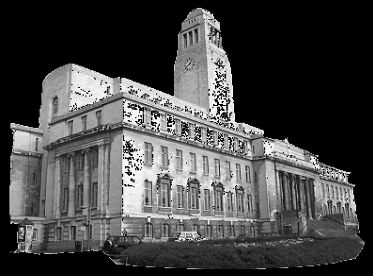
- Thermal expansion
- Glaciers & ice caps
- Greenland
- Antarctica

Ice and climate



Ice and climate



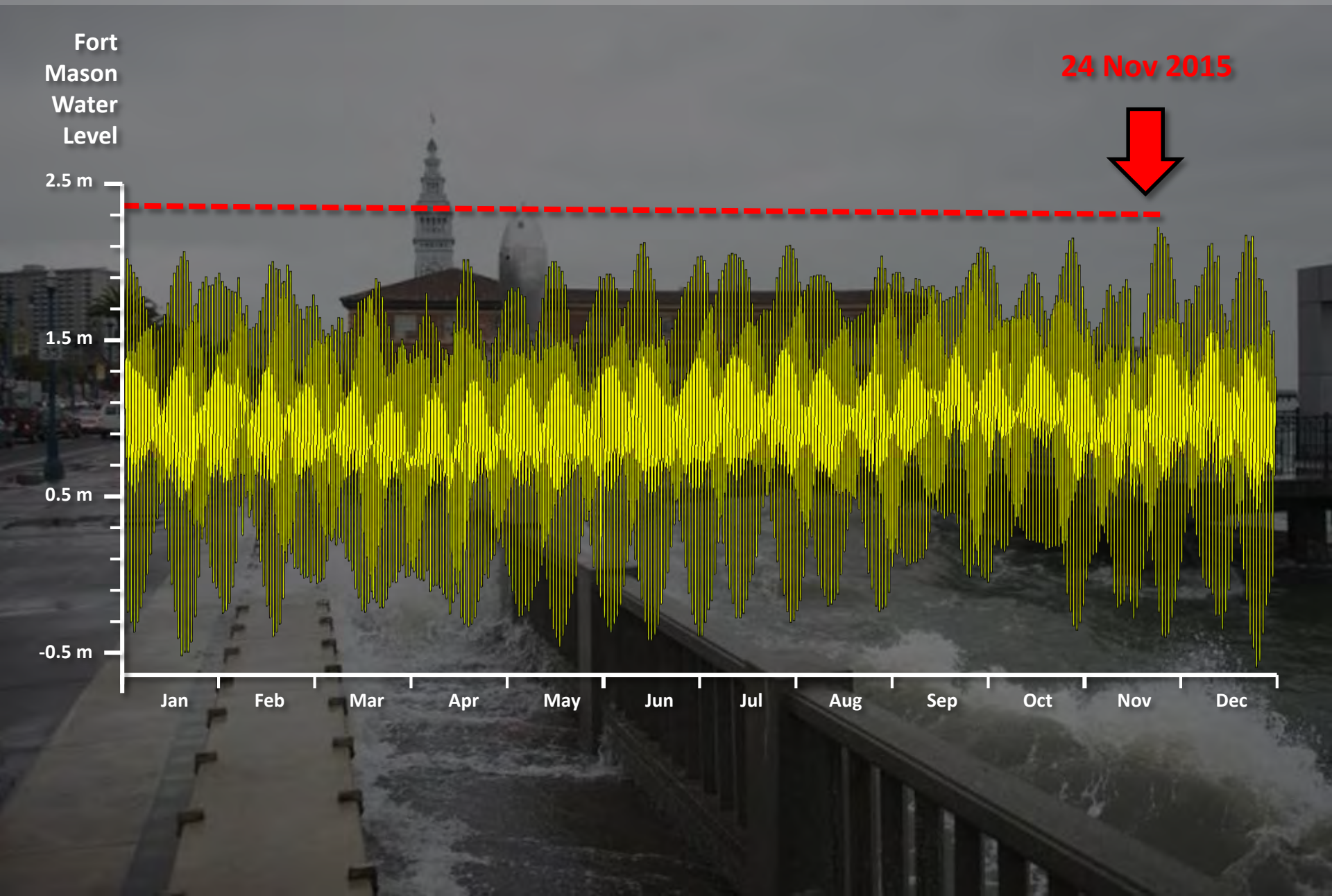


86 m.a.s.l.

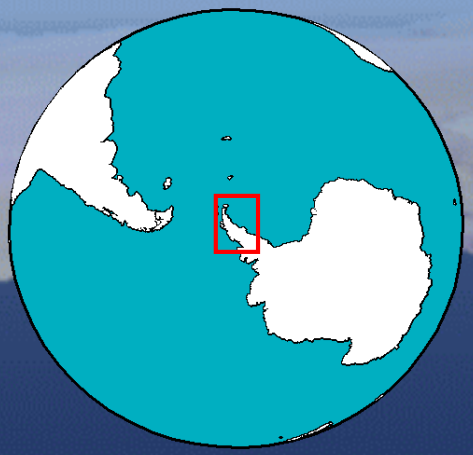
35 m.a.s.l.

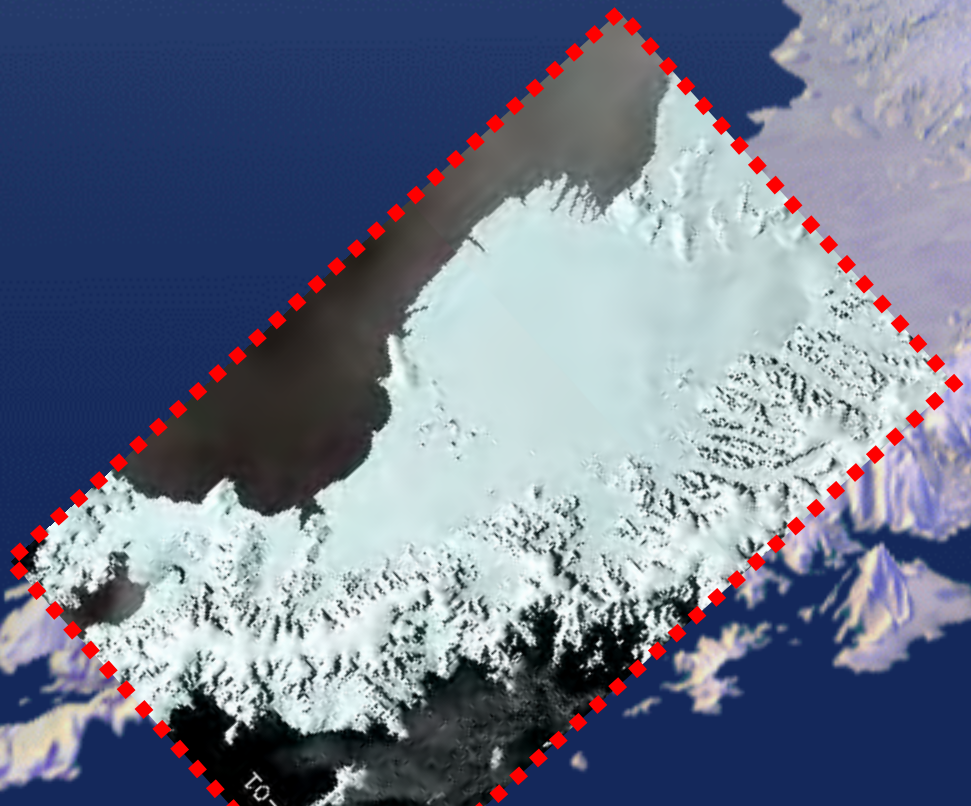
10 m.a.s.l.

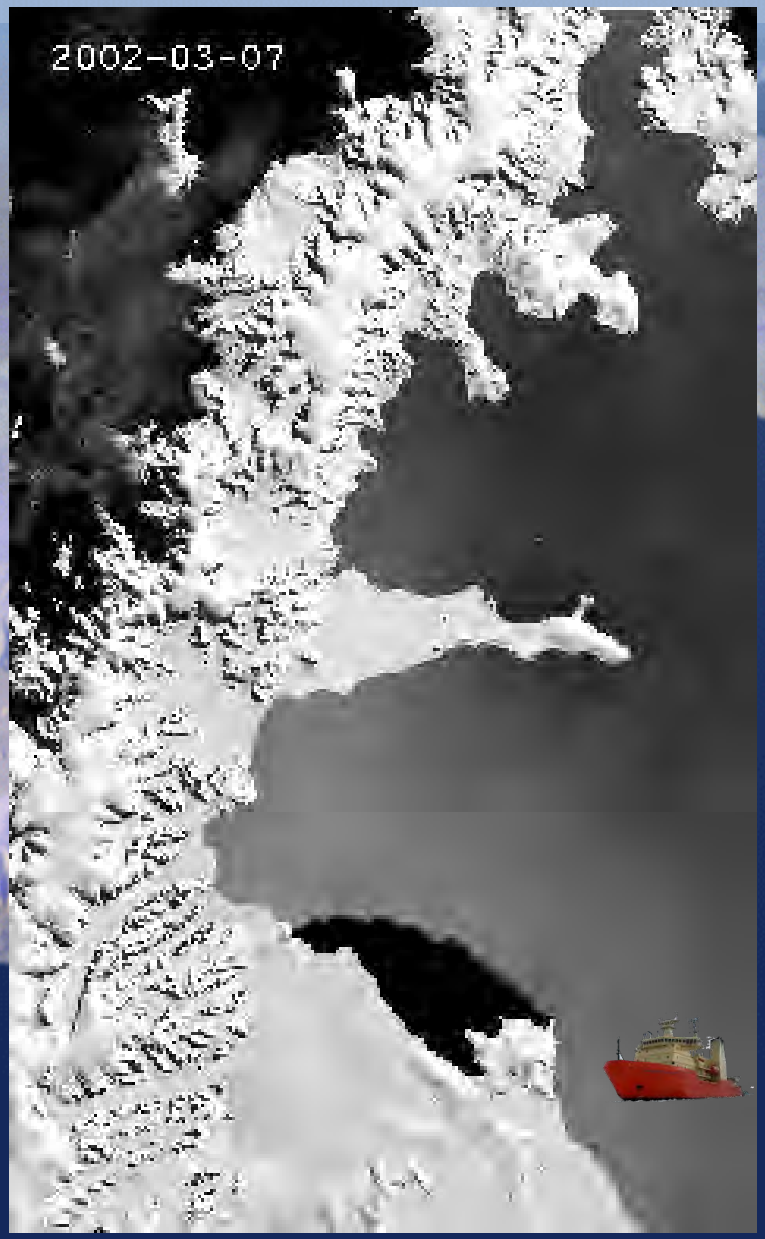
Ice and climate



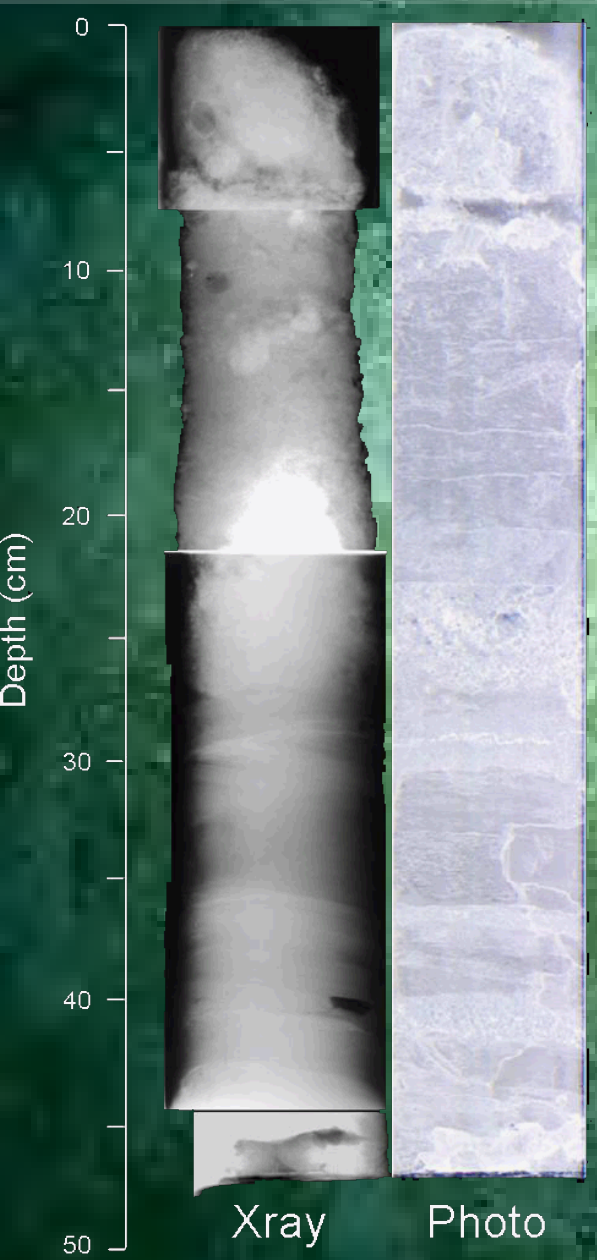
Ice and climate

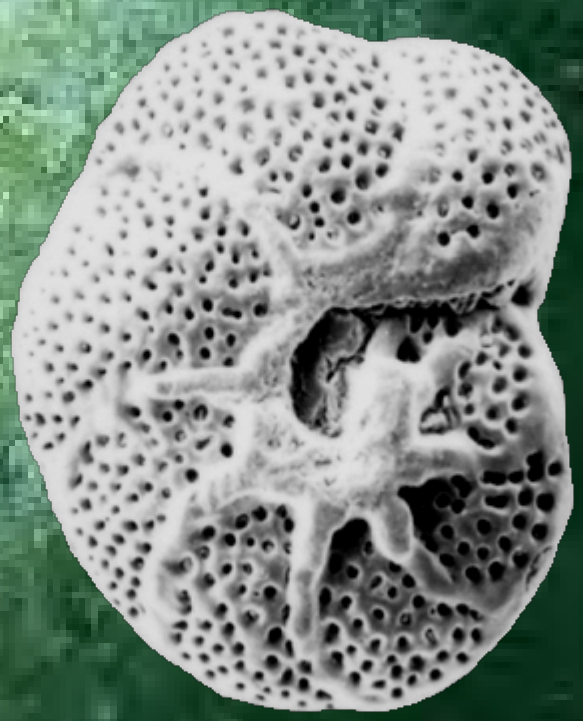




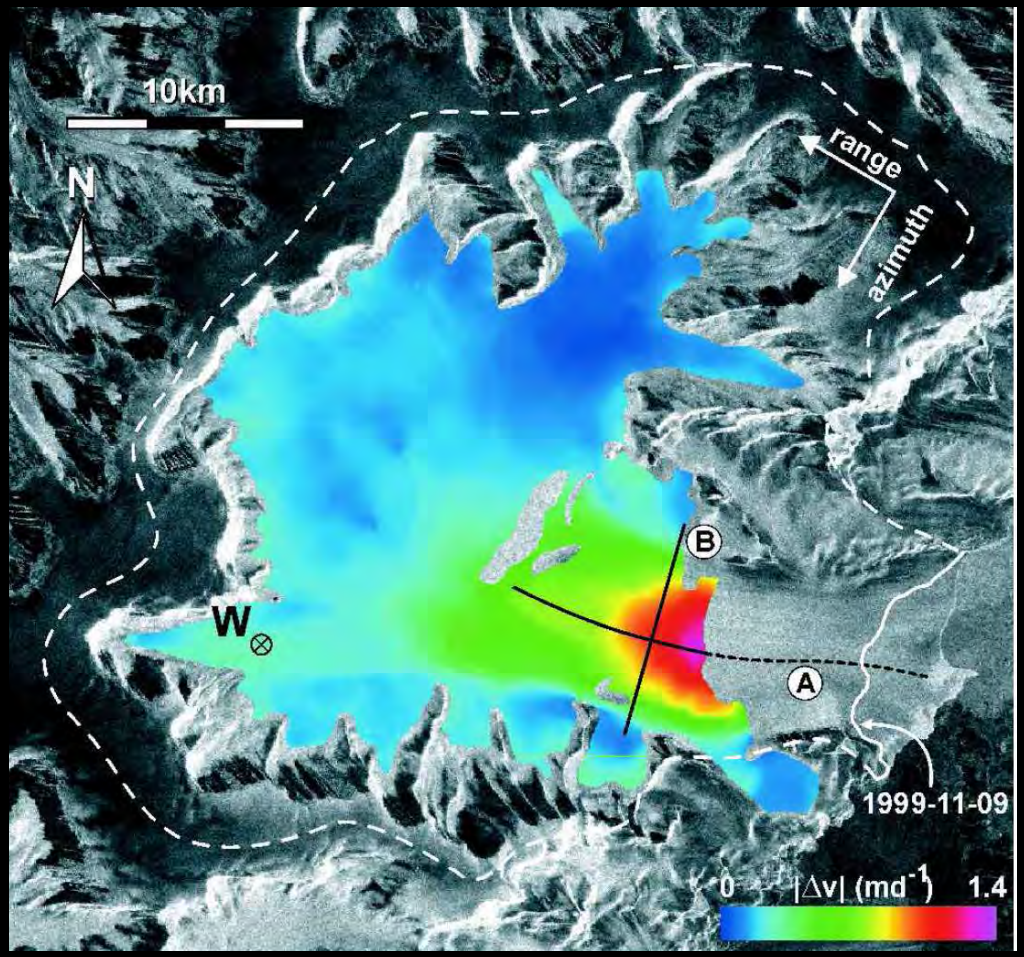


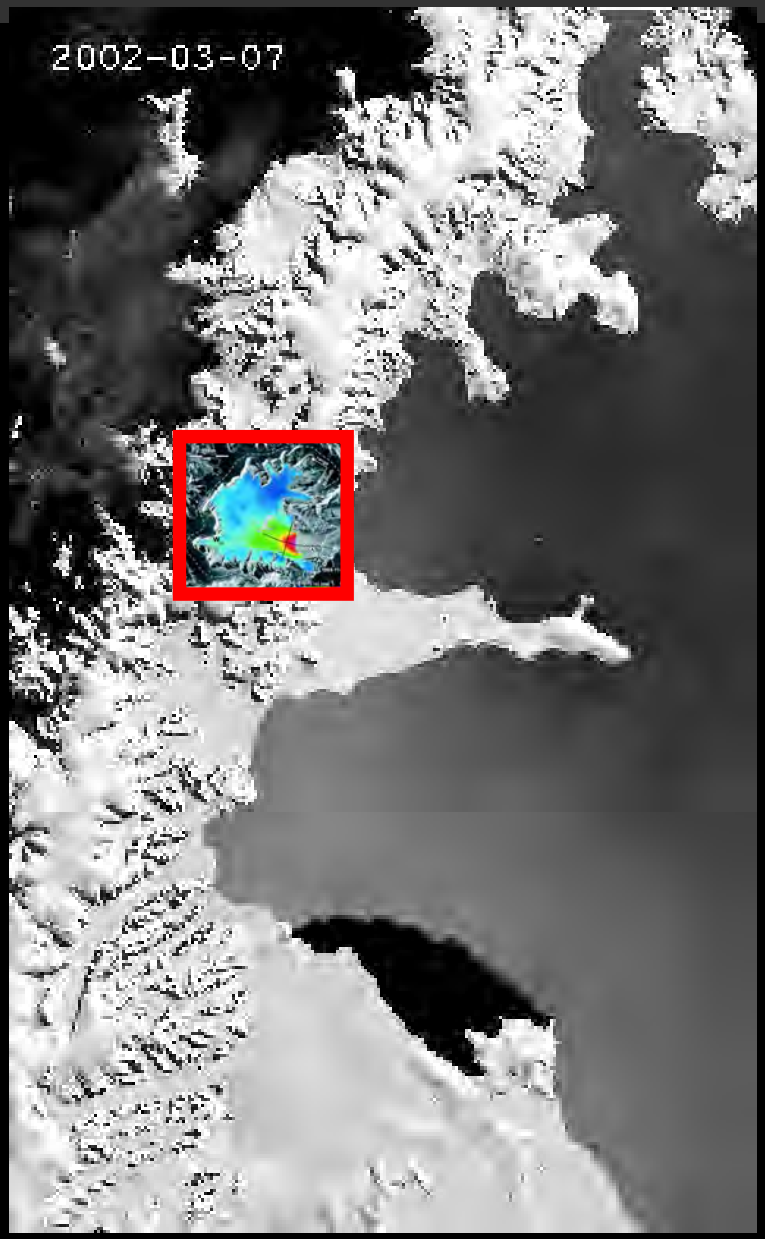
Ice and climate





Ice and climate





Measuring ice loss

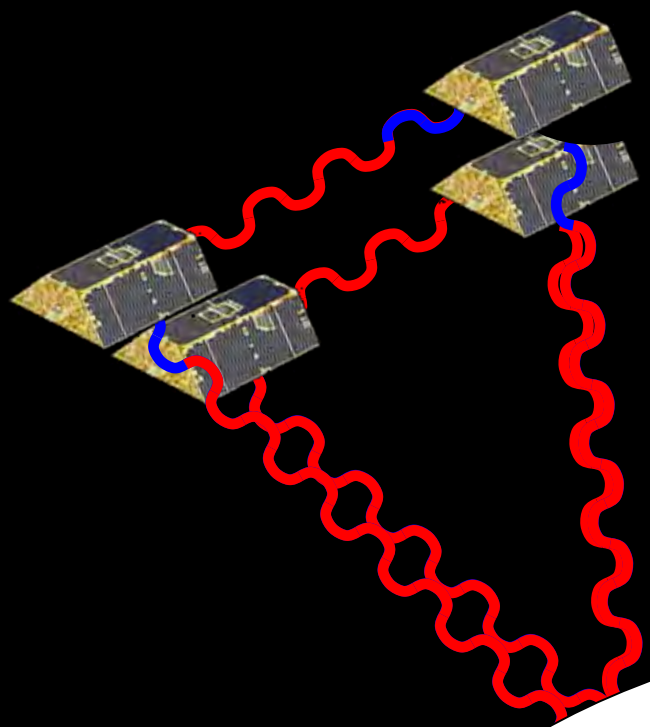
Measuring ice loss

Altimetry measures changes in ice sheet shape

Mass budget differences ice sheet flow and snowfall

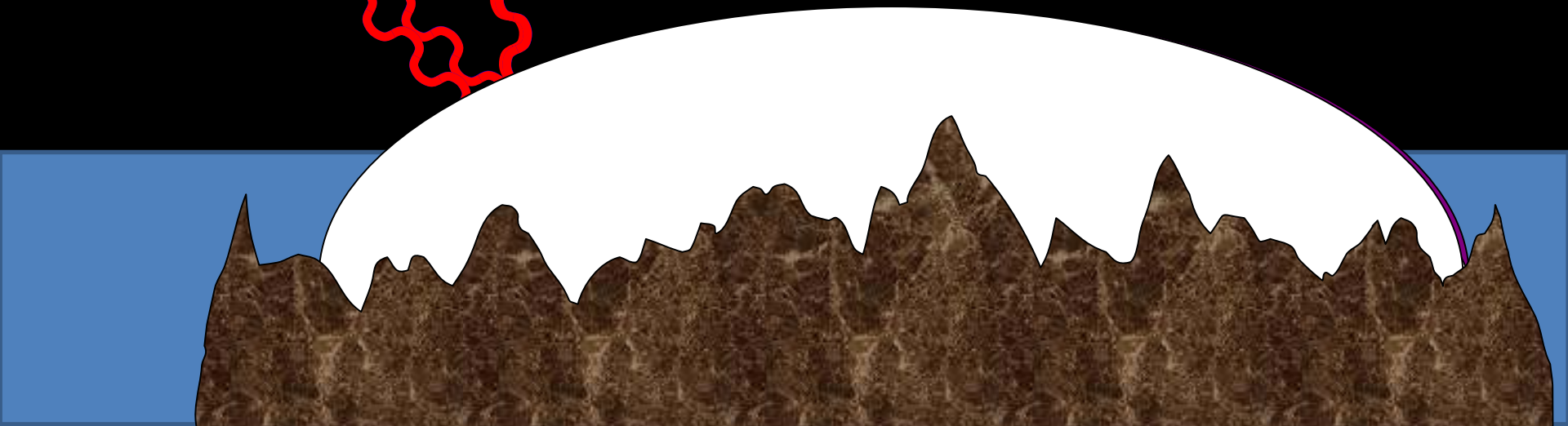
Gravimetry measures changes in ice sheet weight

Measuring ice loss



GRACE **Gravimetry** measures changes in Earth's gravitational attraction through orbital separation

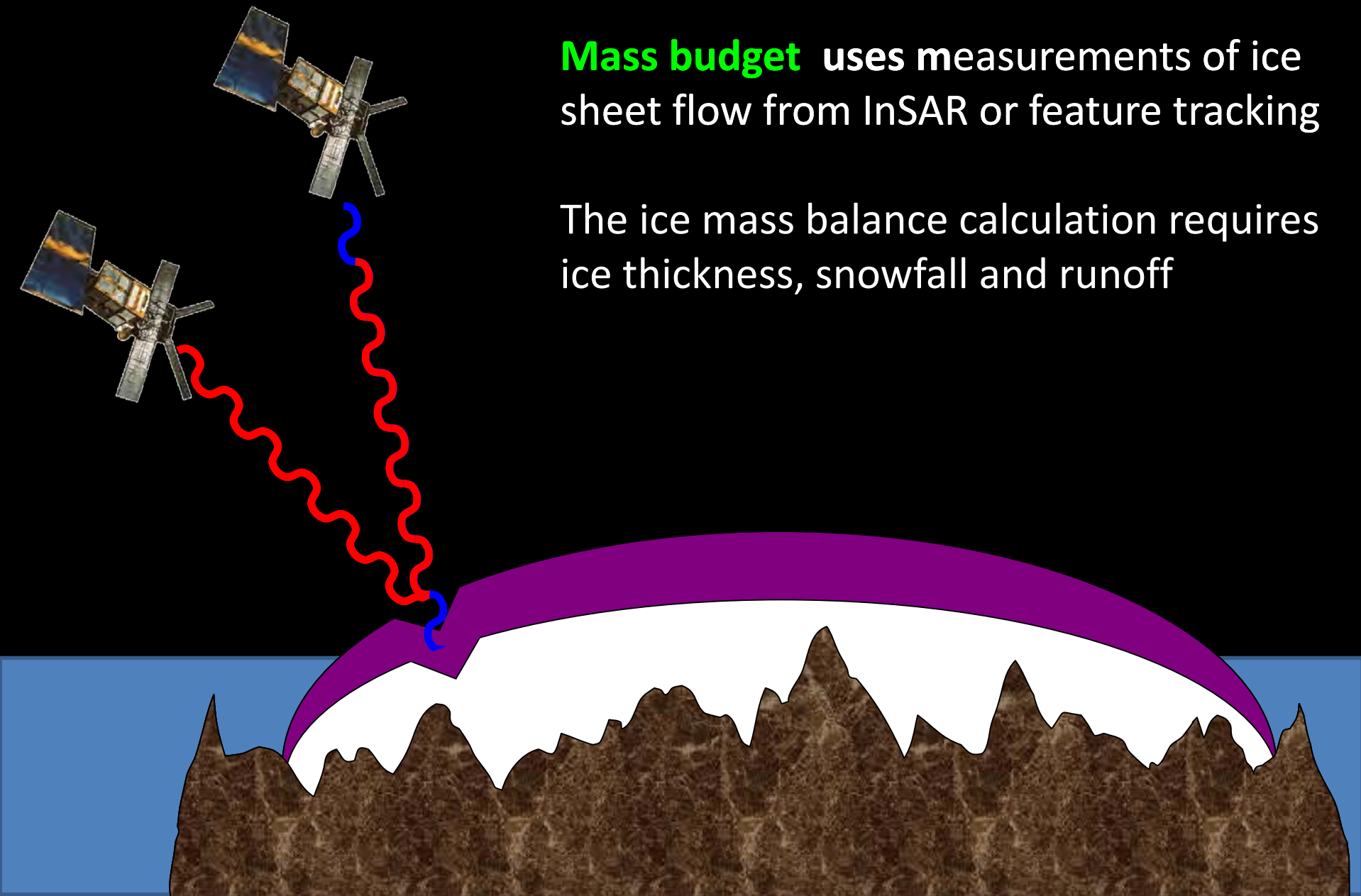
The ice mass balance calculation requires glacial isostatic adjustment, snowfall, and runoff



Measuring ice loss

Luthcke et al., 2013

Measuring ice loss



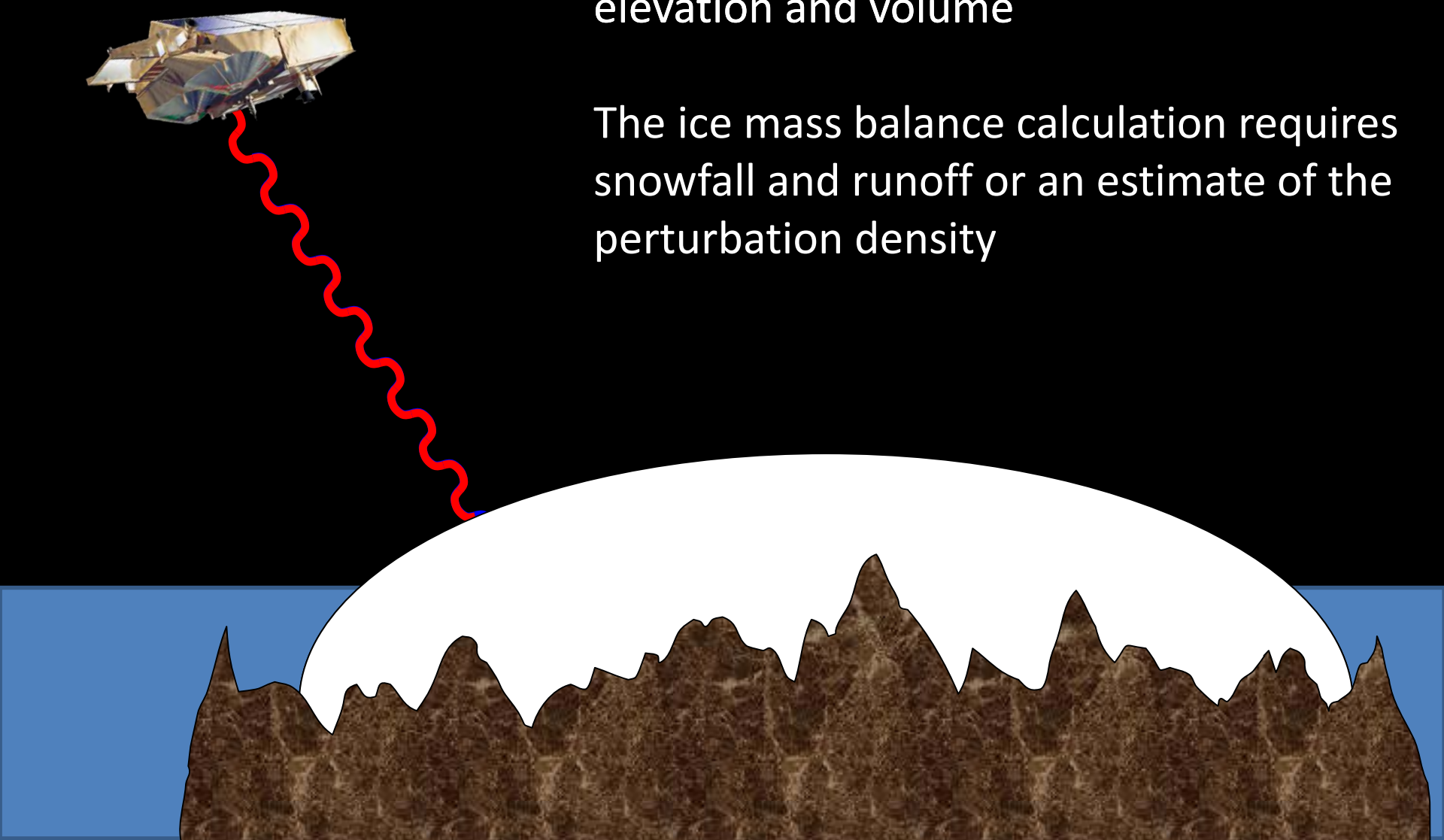
Mass budget **uses m**easurements of ice sheet flow from InSAR or feature tracking

The ice mass balance calculation requires ice thickness, snowfall and runoff

Measuring ice loss

Rignot et al., 2011

Measuring ice loss



Altimetry **m**easures changes in ice sheet elevation and volume

The ice mass balance calculation requires snowfall and runoff or an estimate of the perturbation density

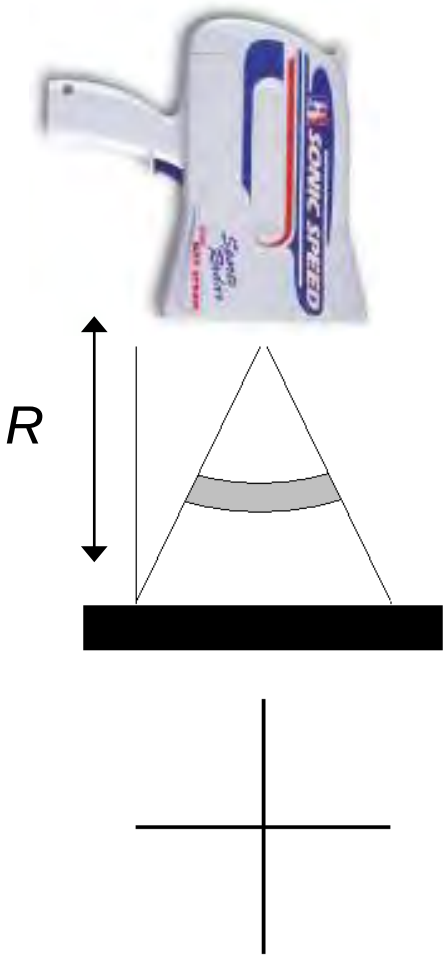
Measuring ice loss

McMillan et al., 2014, 2016; Sandwell et al., 2014; Tilling et al., 2015

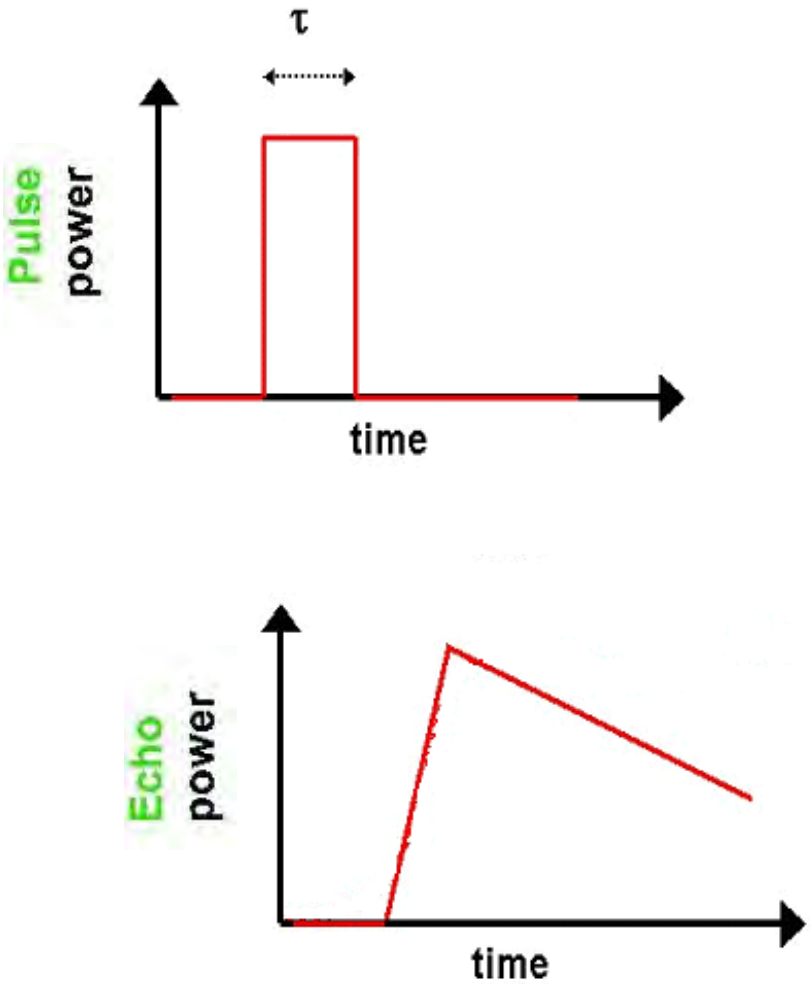
Radar altimetry

Radar altimetry

Side view

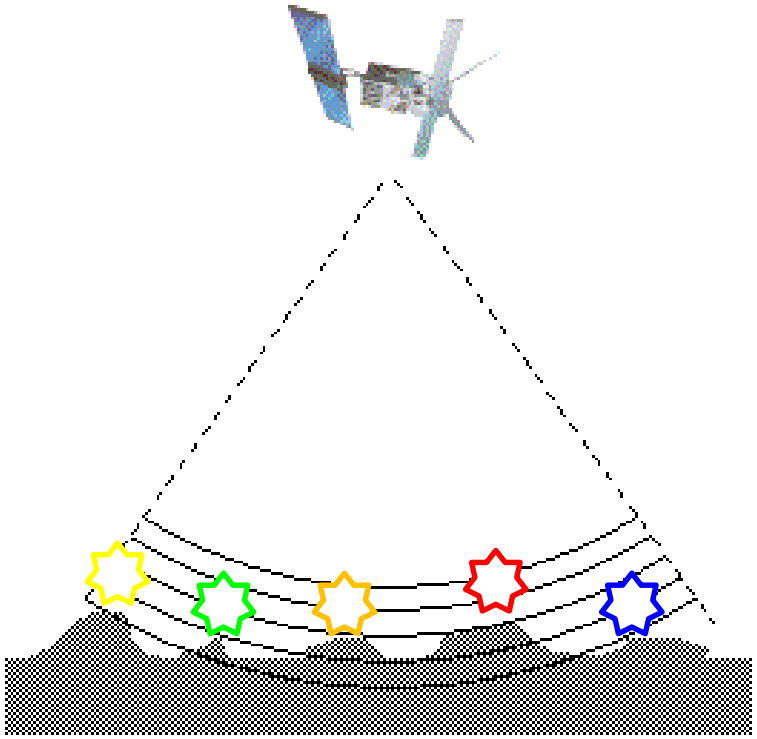


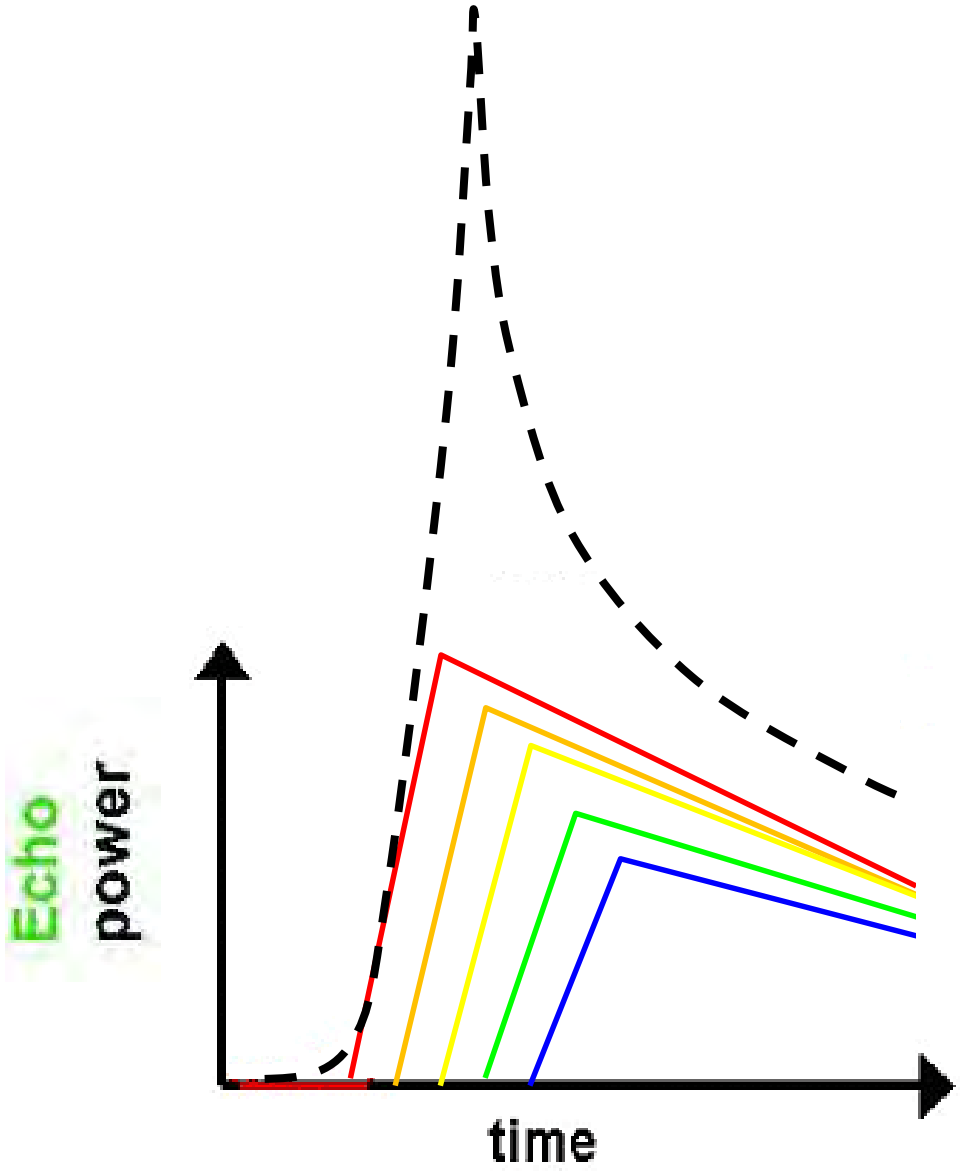
Plan view



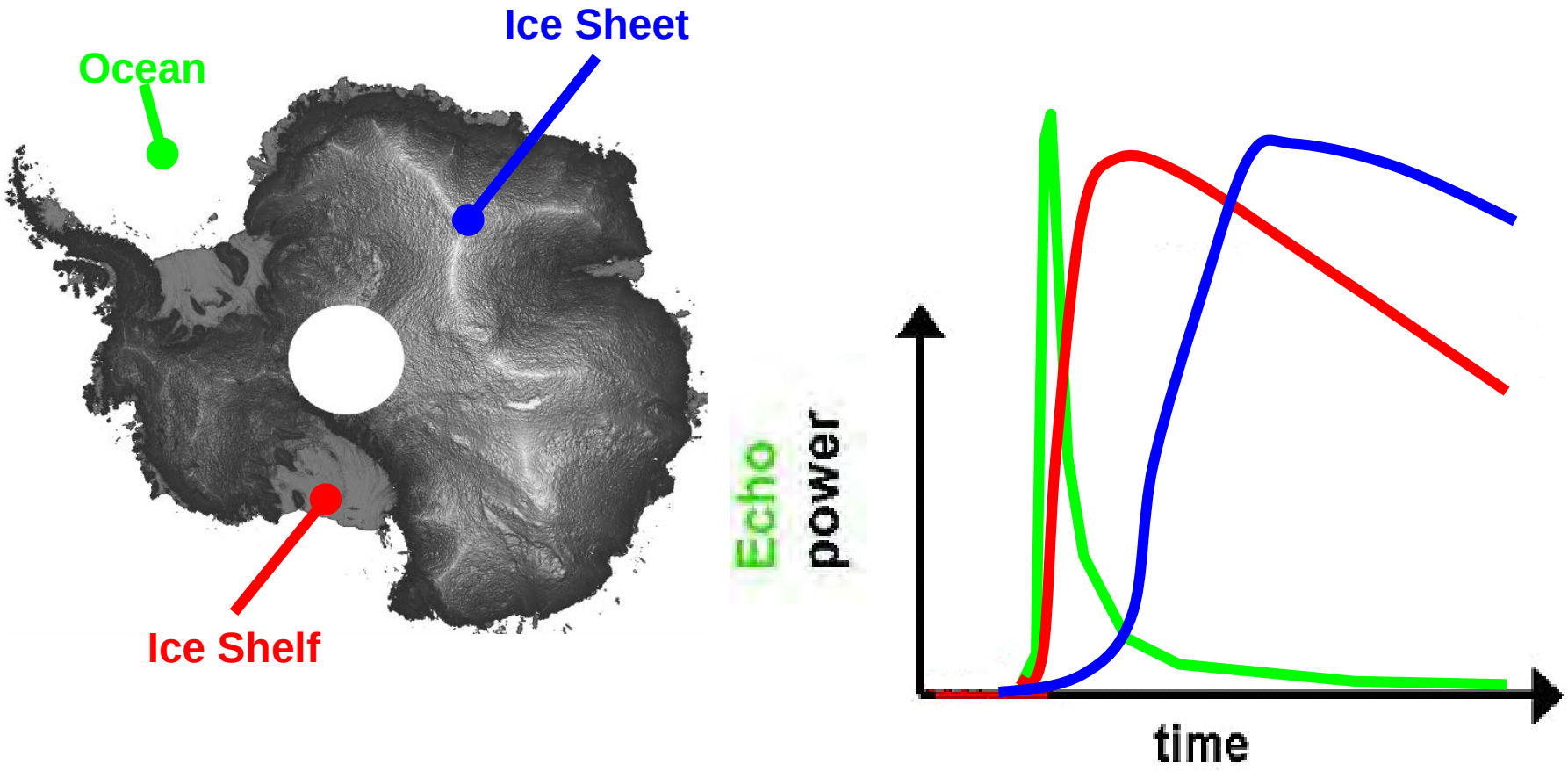
Travel time

Radar altimetry

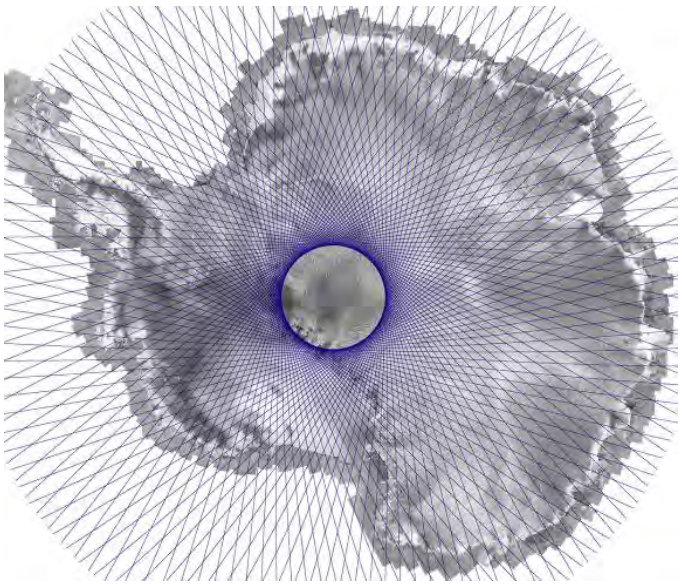


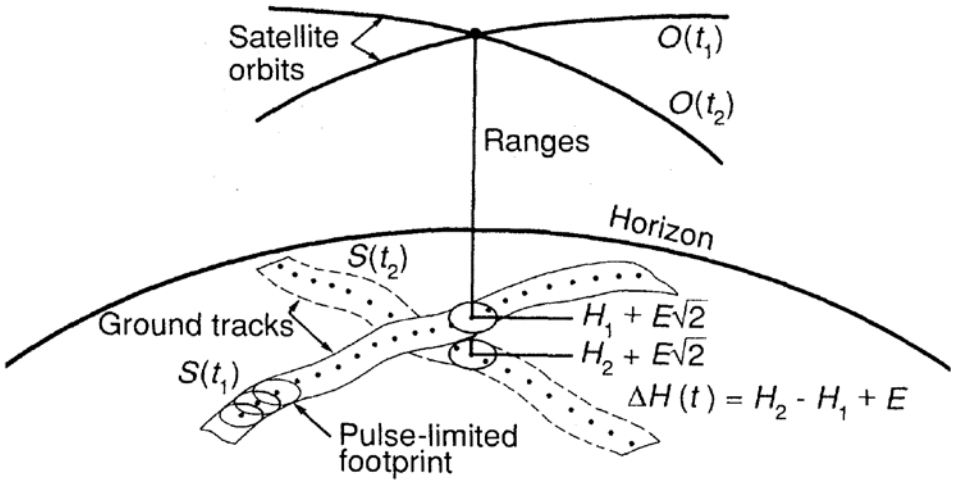


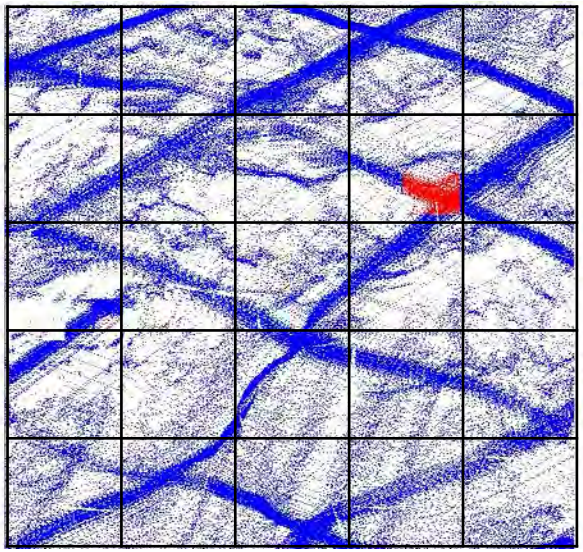
Radar altimetry

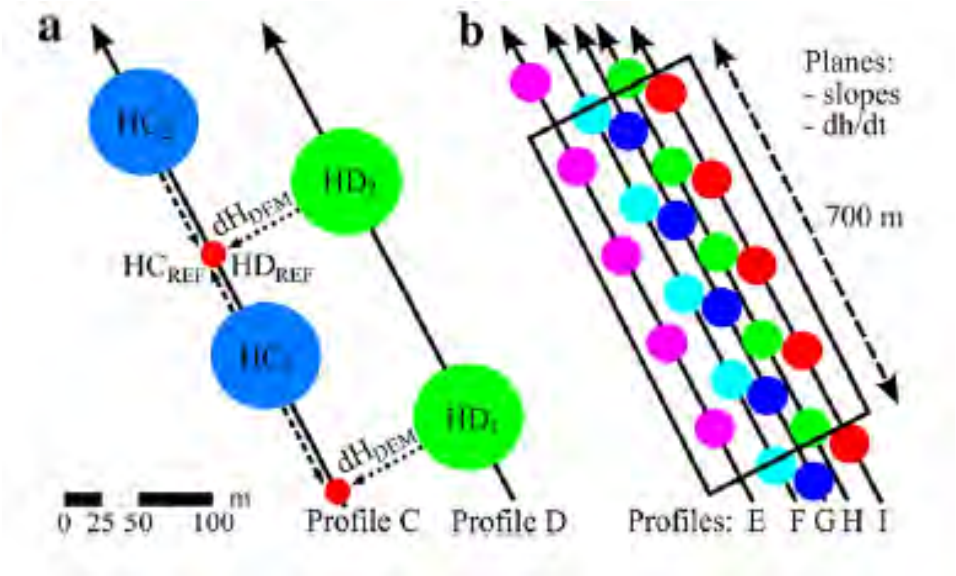


Radar altimetry

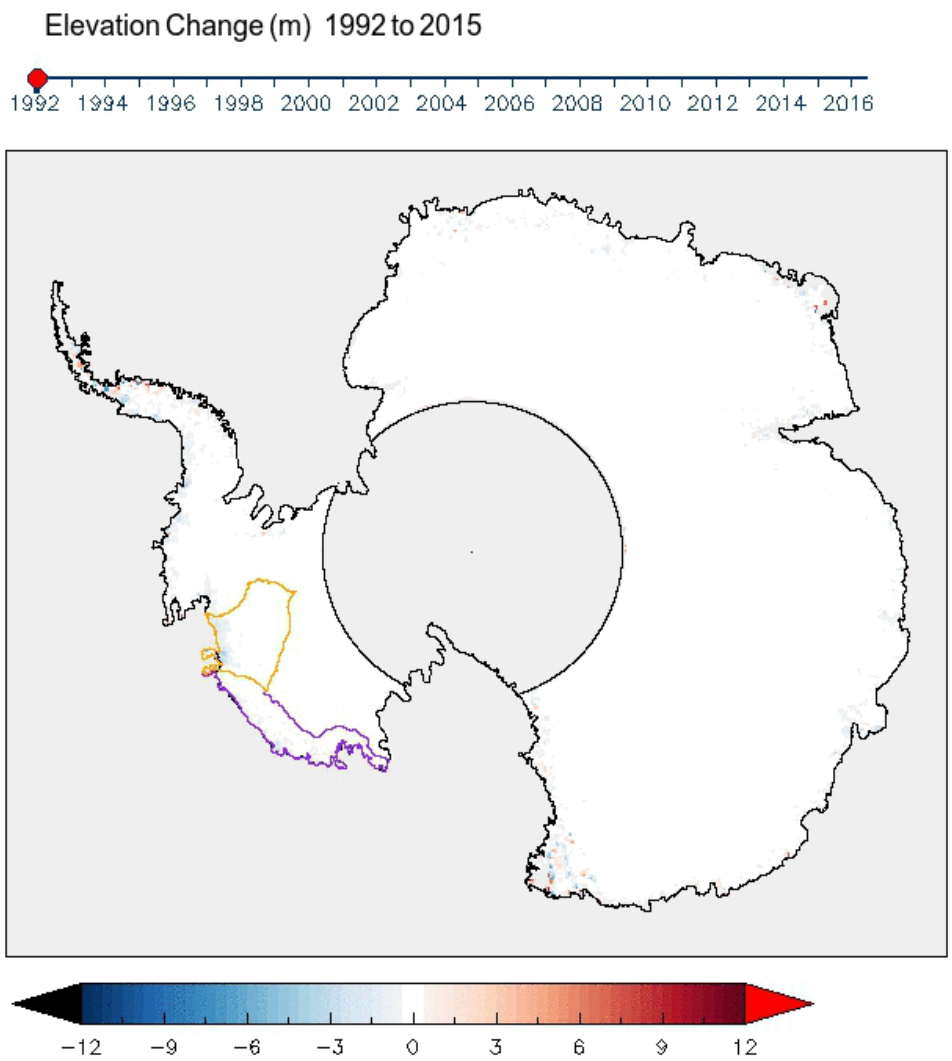


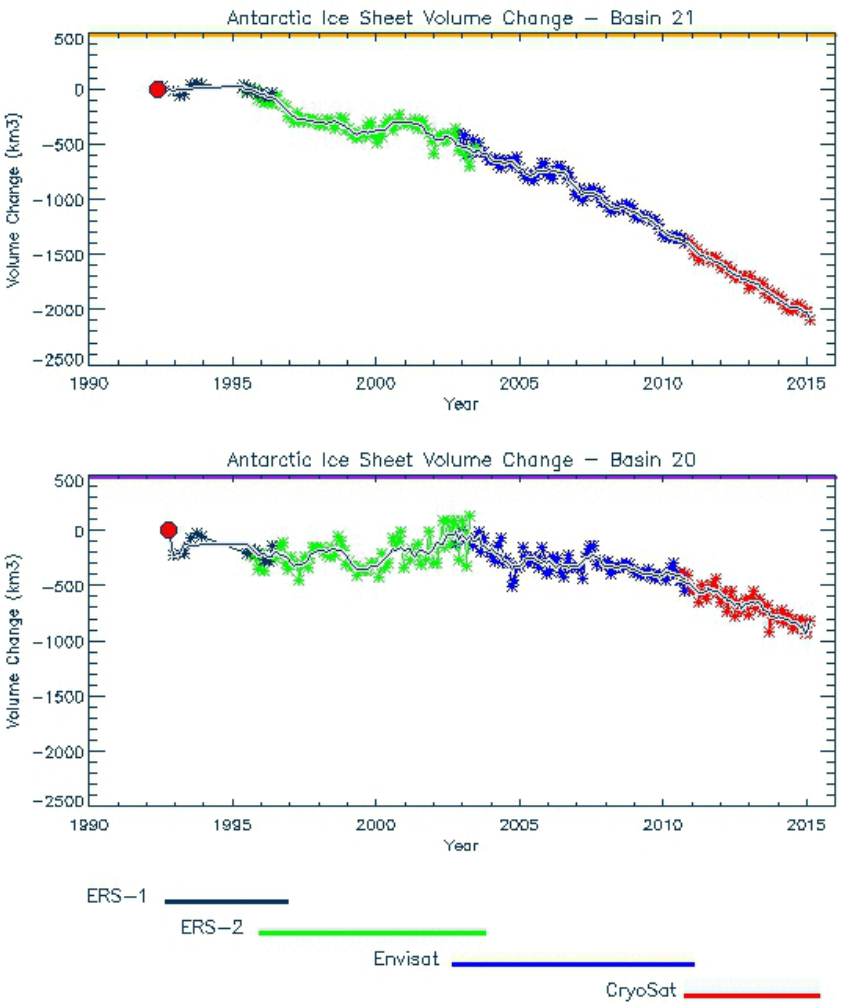






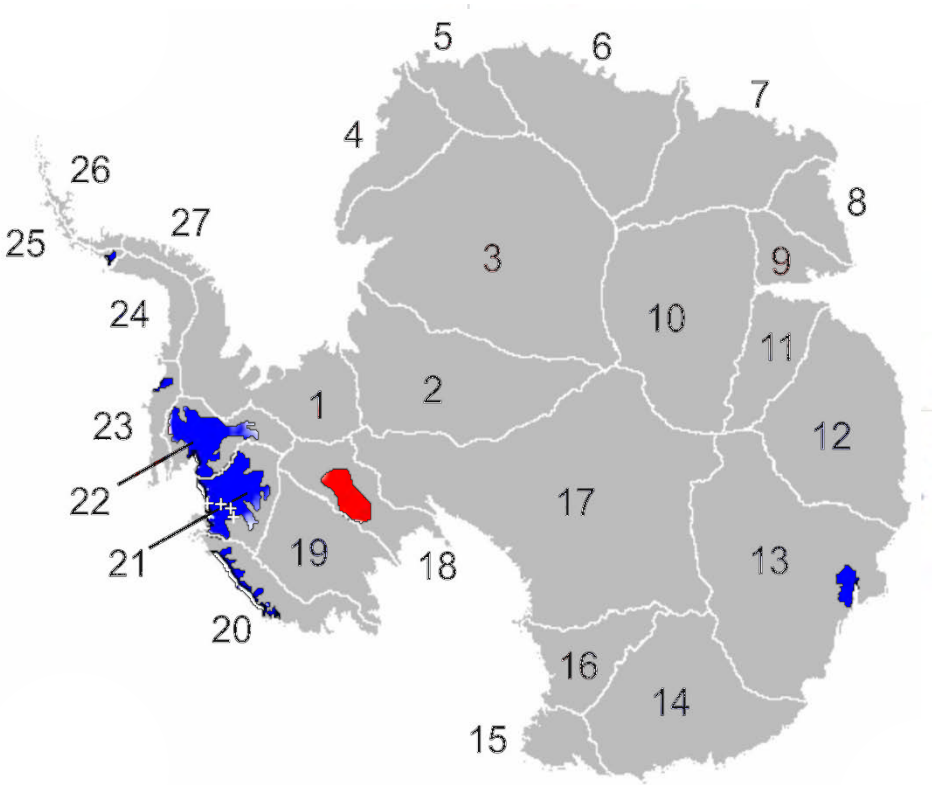
Radar altimetry



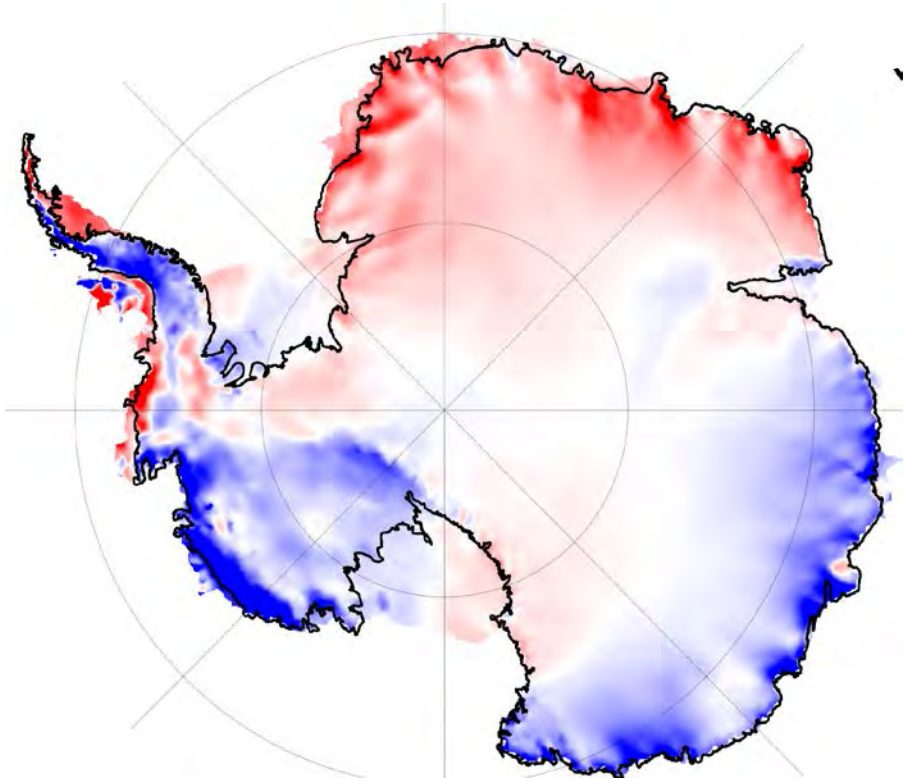


Radar altimetry

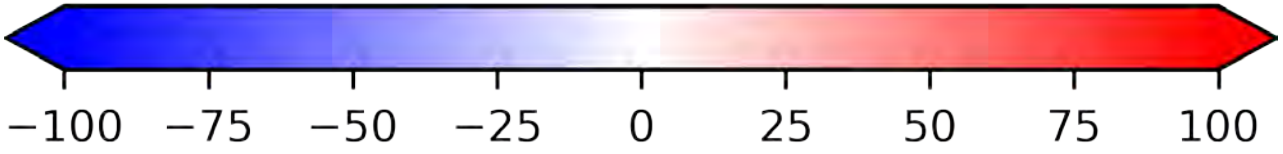
Altimetry



Firn model



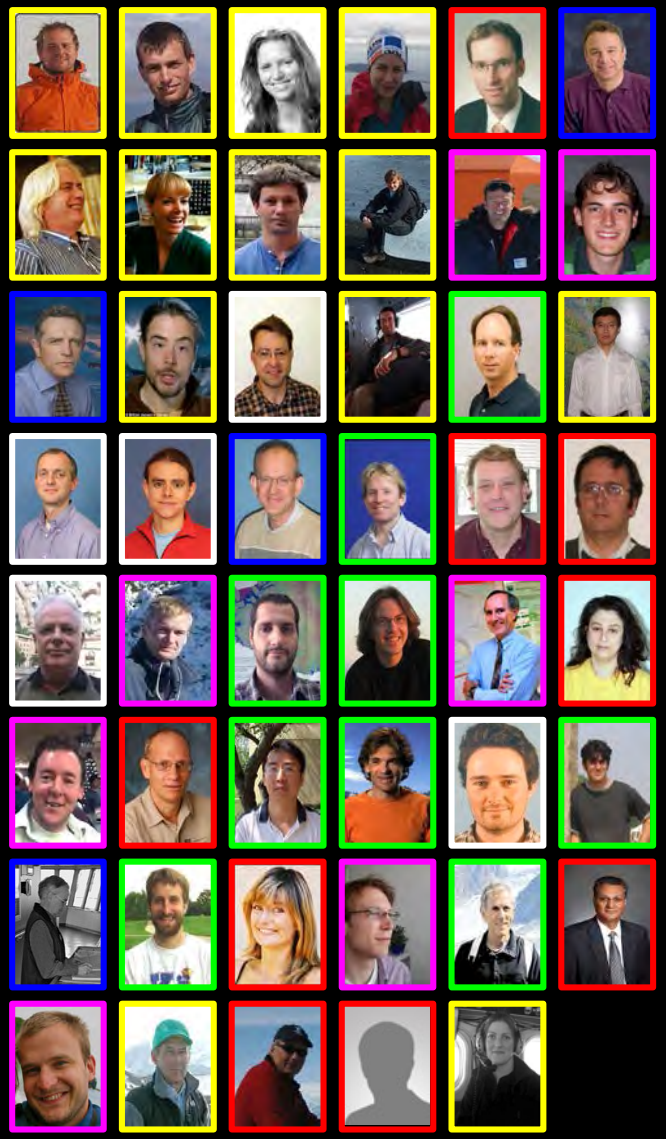
Elevation change (mm/yr)

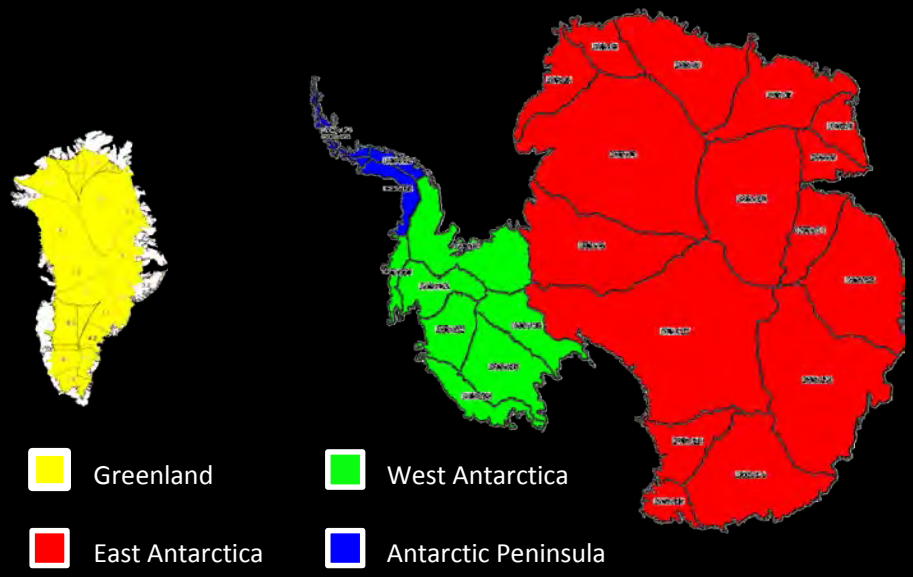


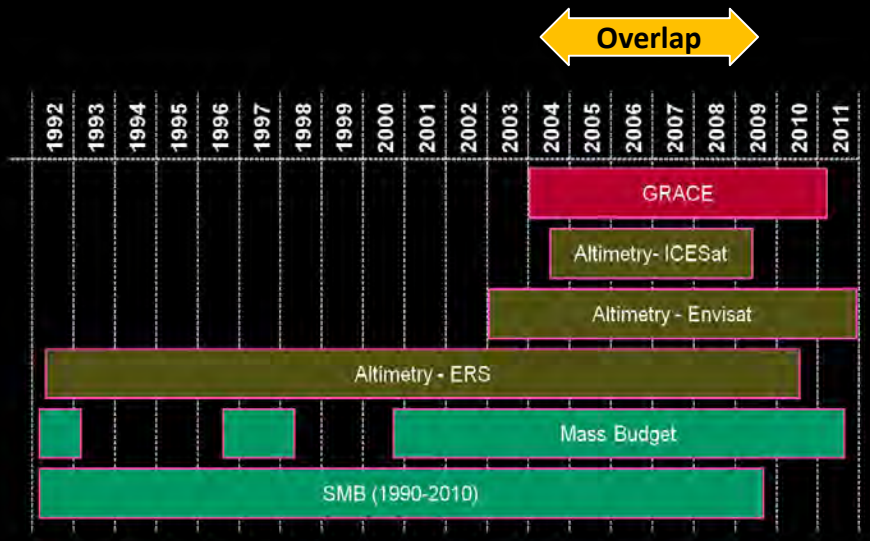
Ice sheet mass balance

imbie

imbie



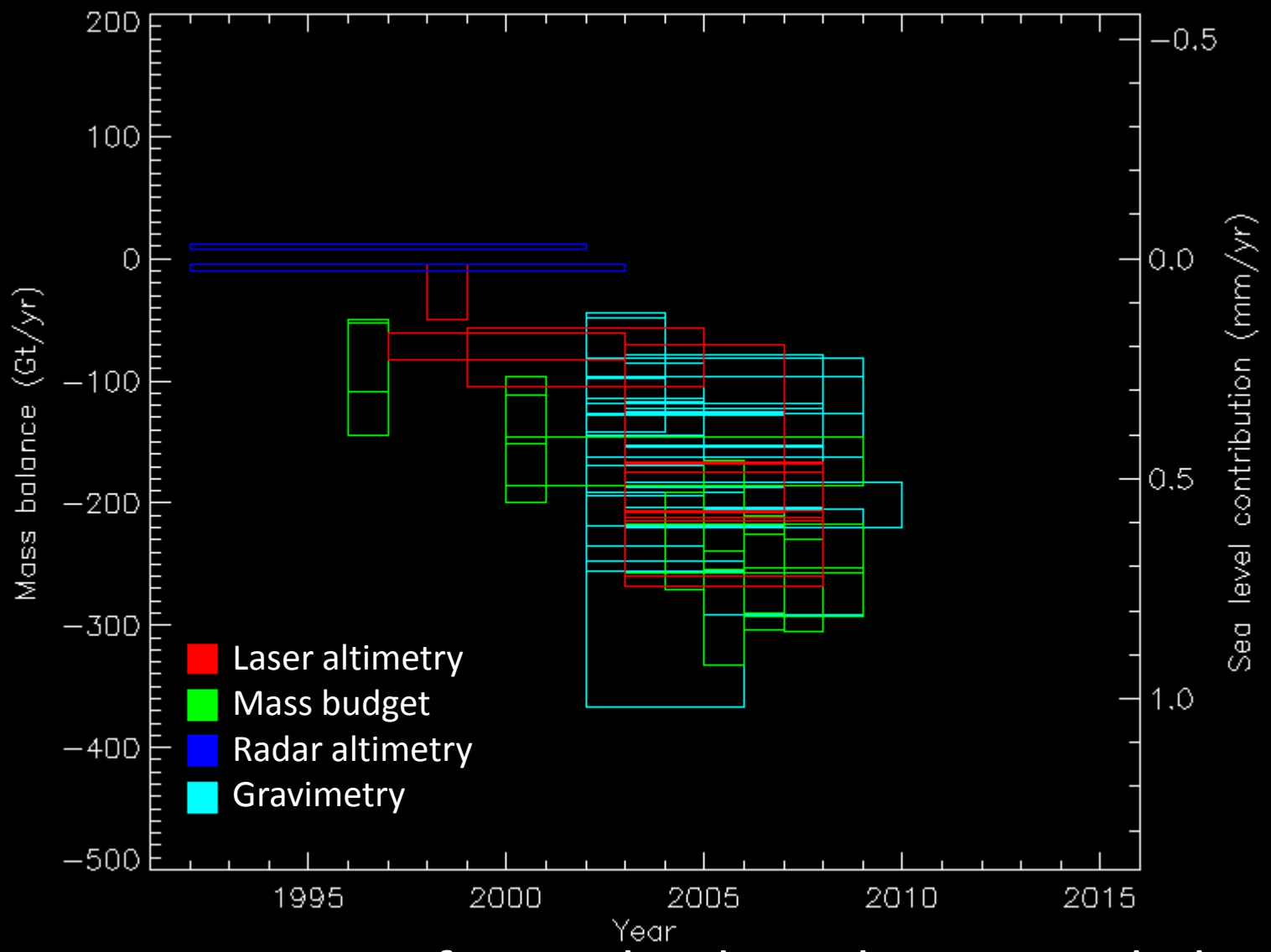

Greenland
West Antarctica
East Antarctica
Antarctic Peninsula


Overlap
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
GRACE
Altimetry- ICESat
Altimetry - Envisat
Altimetry - ERS
Mass Budget
SMB (1990-2010)

imbie-1

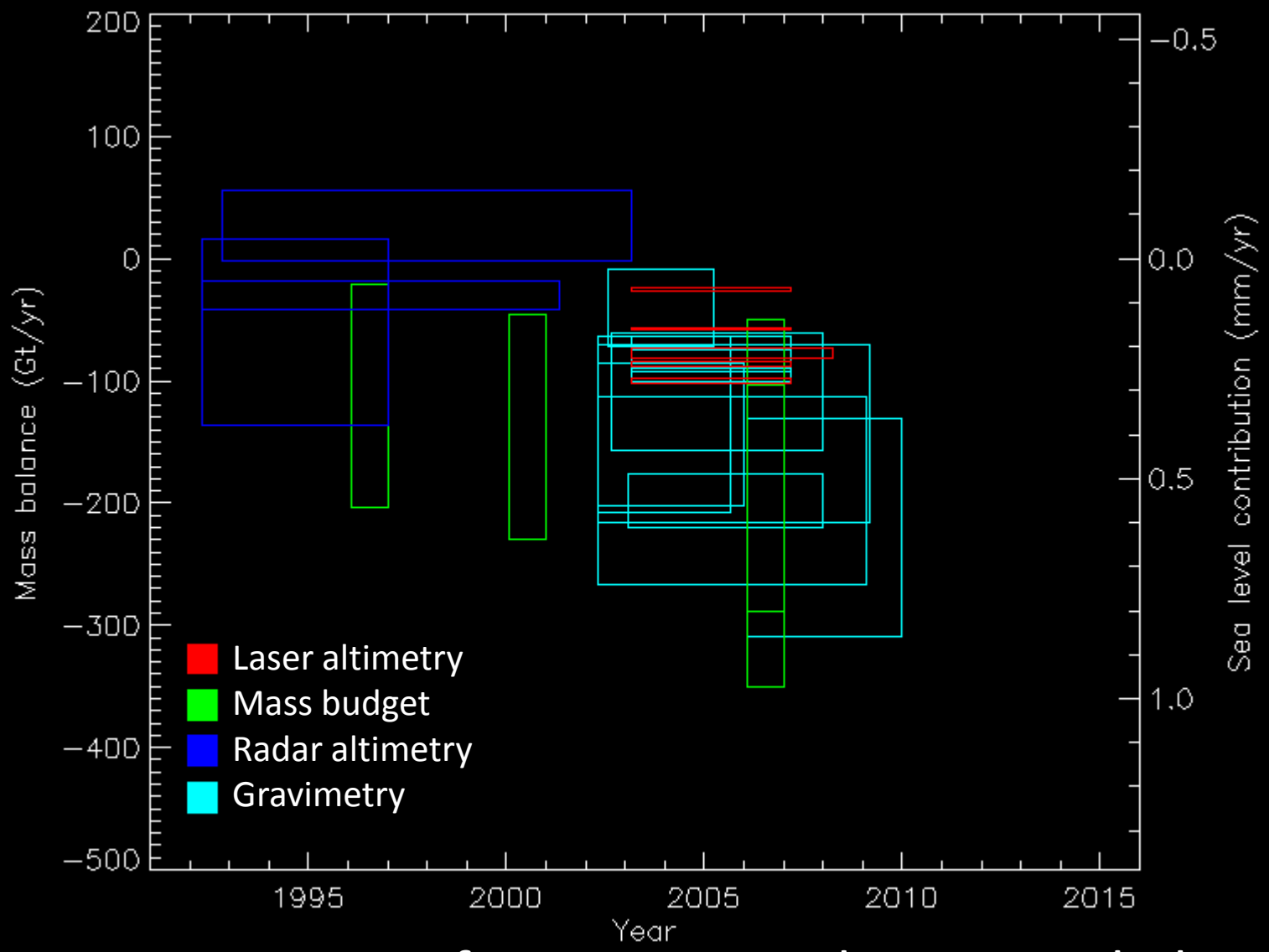
- Using common domains, techniques concur
- First community assessment
- 10 x more certain than spread of studies
- Ice sheets up from 10% to 30% of sea level trend
- Greenland five fold increase in rate of ice loss
- Antarctica constant rate of ice loss

Progress since imbie-1



52 new estimates of Greenland ice sheet mass balance!

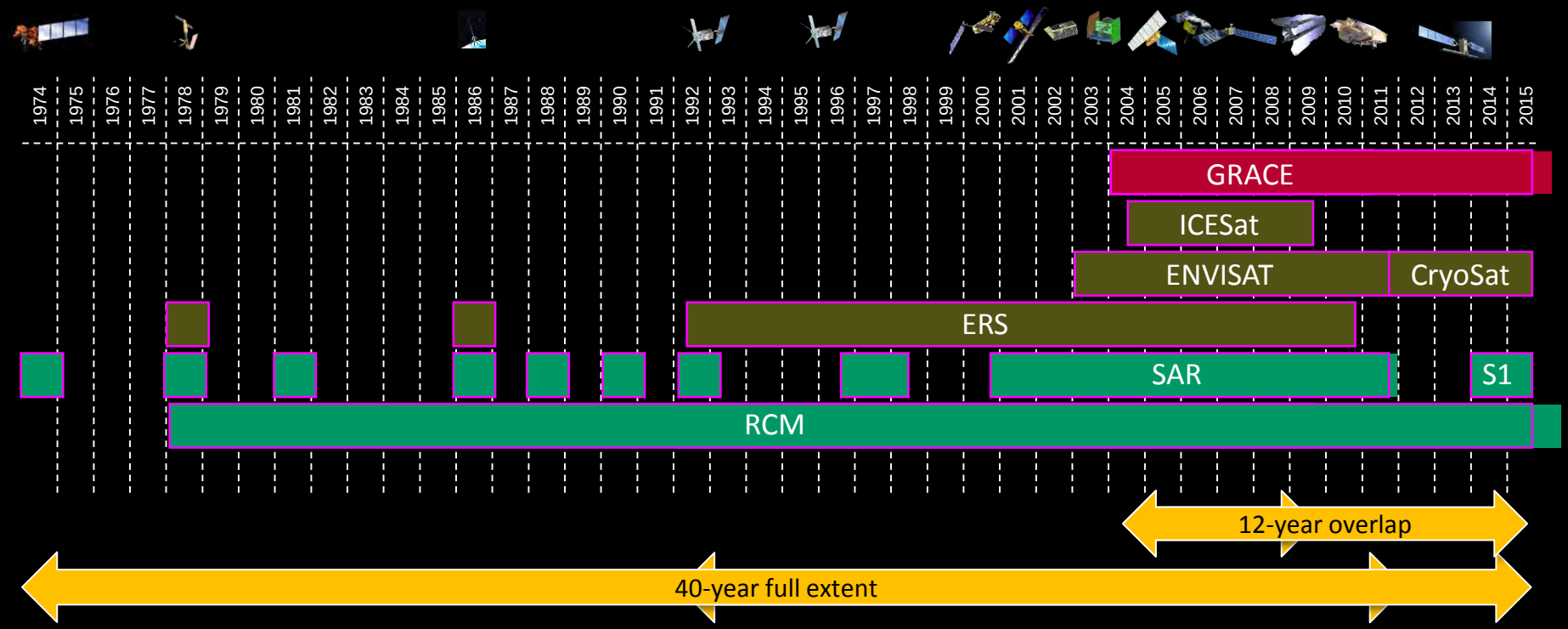
Progress since imbie-1



34 new estimates of Antarctic ice sheet mass balance!

Progress since imbie-1

- ~~10~~ 13 satellite missions, ~~54~~ 80+ years of data



imbie-2

Eric Rignot coordinates mass budget

Ben Smith coordinates altimetry

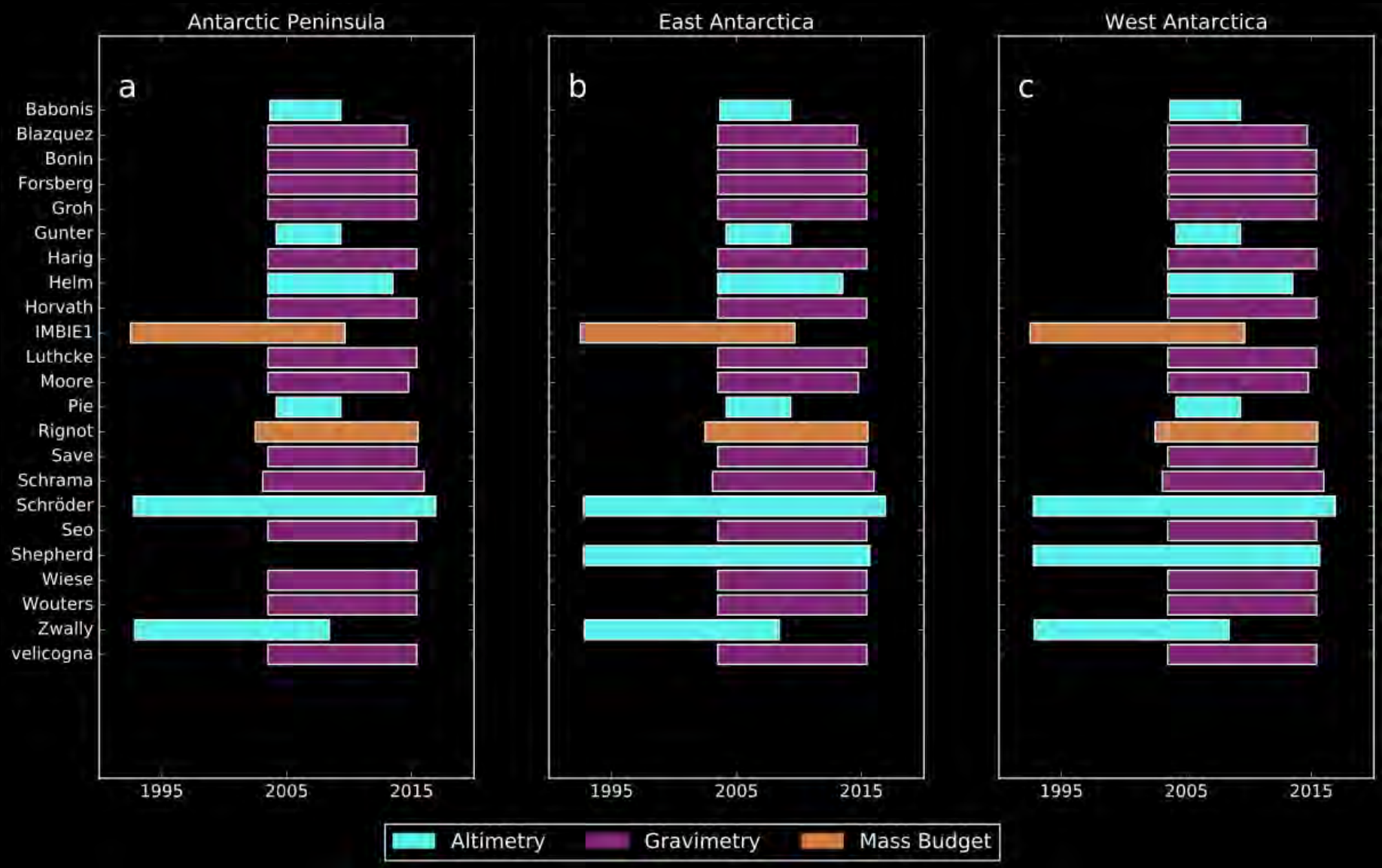
Isabella Velicogna coordinates gravimetry

Michiel van den Broeke coordinates SMB

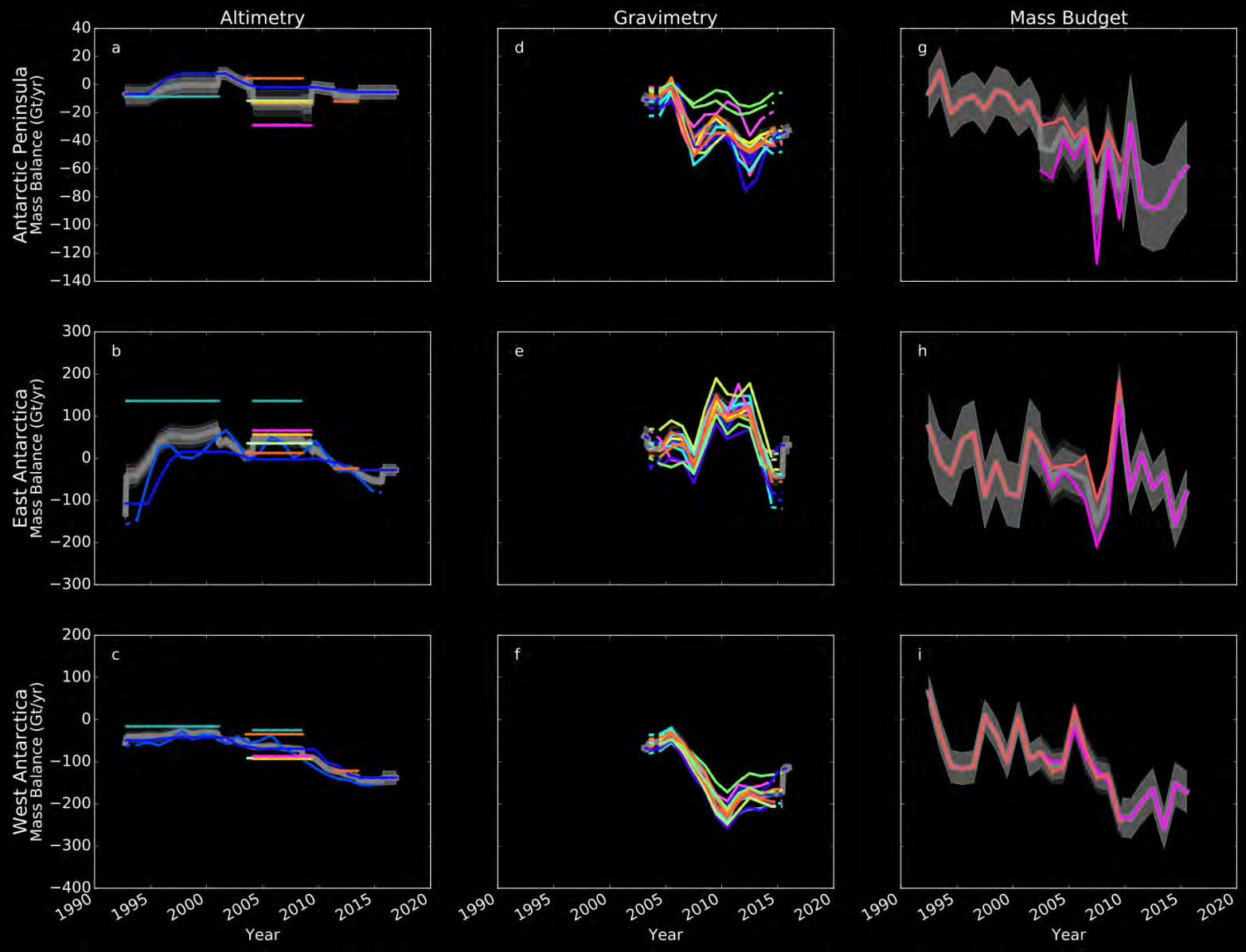
Pippa Whitehouse coordinates GIA

Country	Participants
USA	28
UK	13
Denmark	8
Germany	8
Netherlands	7
Canada	3
France	3
Austria	2
Belgium	2
Italy	2
Spain	2
Chile	1
Korea	1

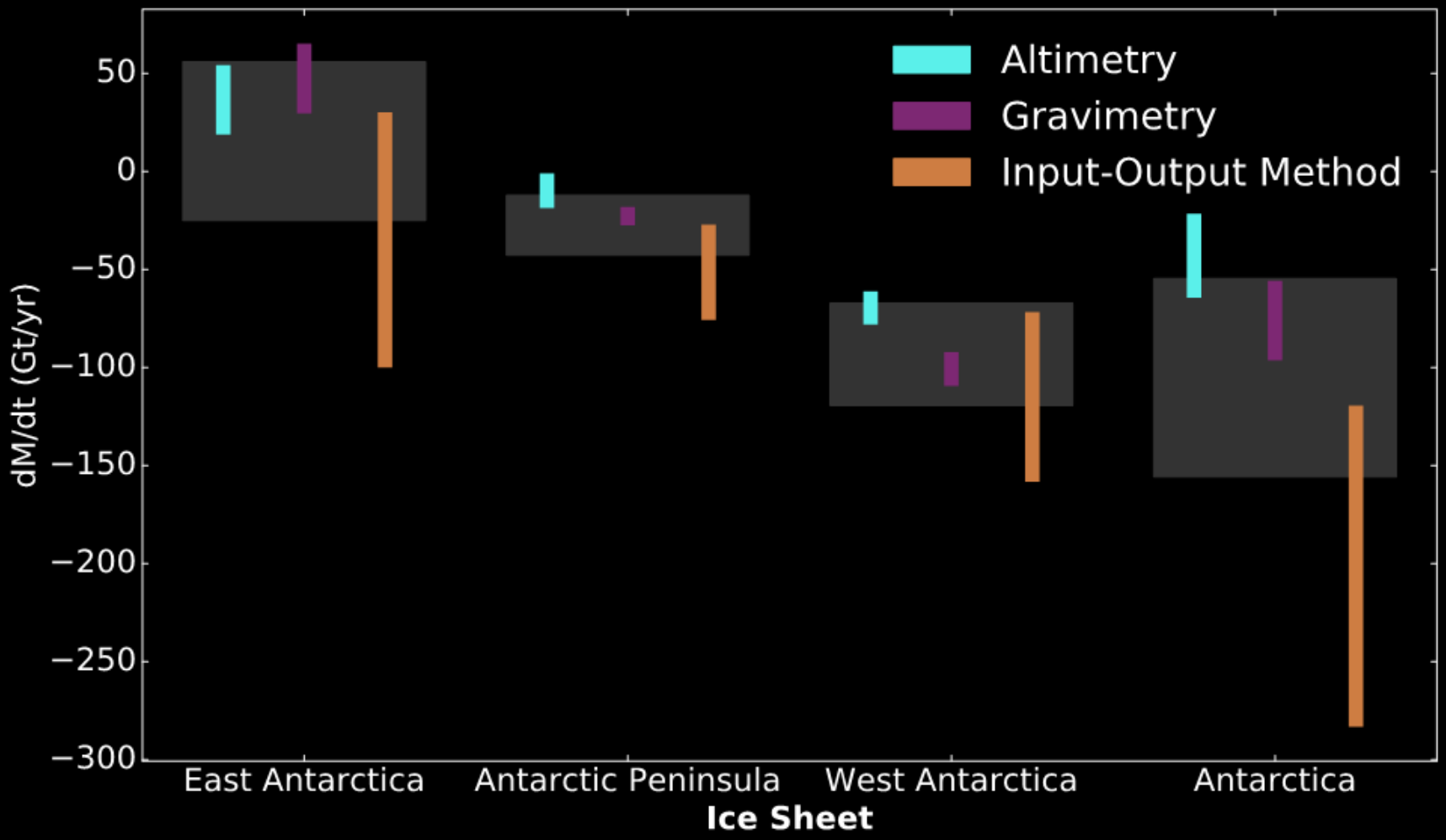
imbie-2


Antarctic Peninsula
East Antarctica
West Antarctica
a
b
c
Babonis
Blazquez
Bonin
Forsberg
Groh
Gunter
Harig
Helm
Horvath
IMBIE1
Luthcke
Moore
Pie
Rignot
Save
Schrama
Schröder
Seo
Shepherd
Wiese
Wouters
Zwally
velicogna
1995
2005
2015
Altimetry
Gravimetry
Mass Budget

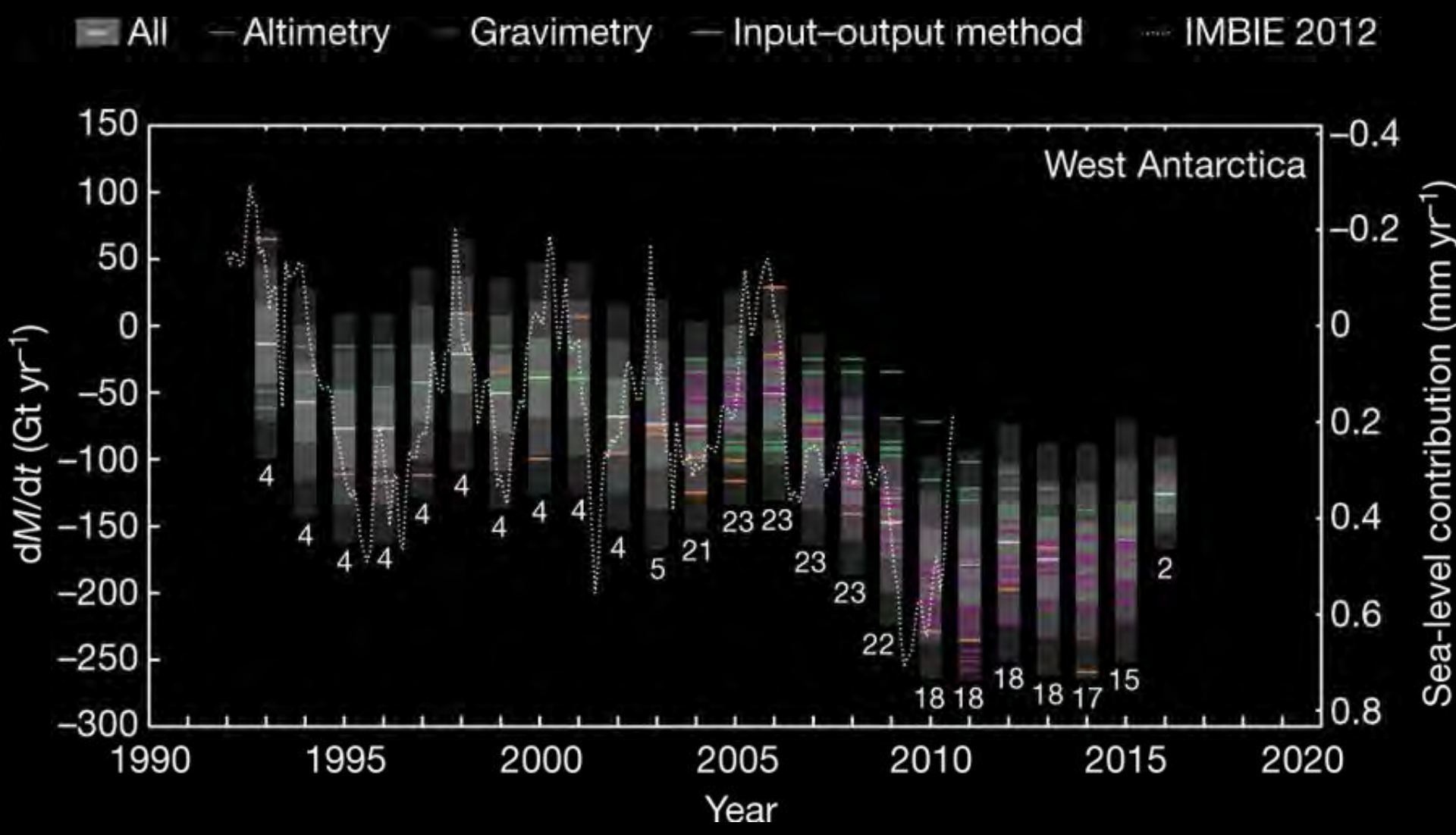
imbie-2


Altimetry
Gravimetry
Mass Budget
Antarctic Peninsula
Mass Balance (Gt/yr)
East Antarctica
Mass Balance (Gt/yr)
West Antarctica
Mass Balance (Gt/yr)
a
b
c
d
e
f
g
h
i
Year
Year
Year

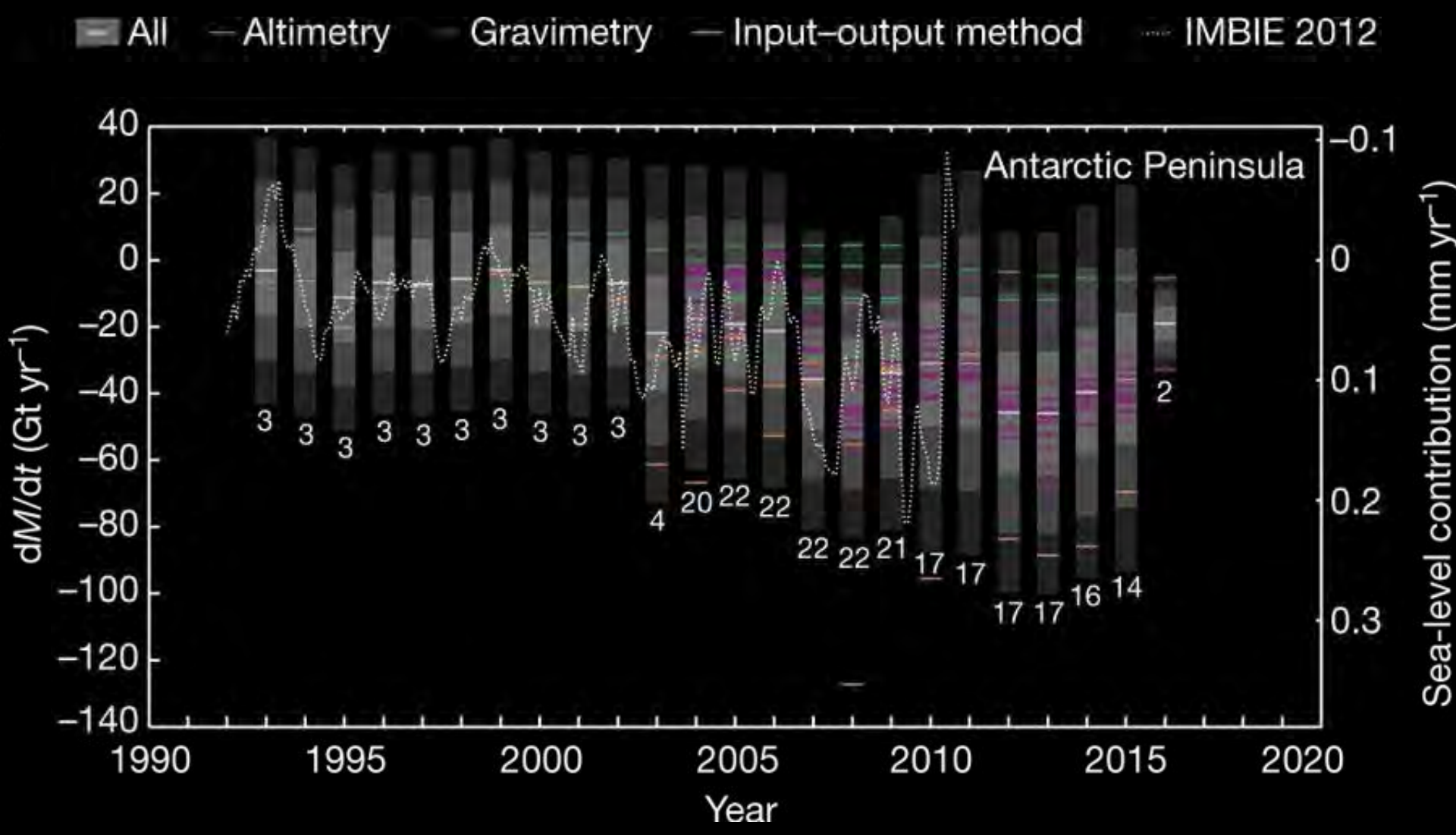
imbie-2


Altimetry
Gravimetry
Input-Output Method
50
0
−50
−100
−150
−200
−250
−300
dM/dt (Gt/yr)
East Antarctica
Antarctic Peninsula
West Antarctica
Antarctica
Ice Sheet

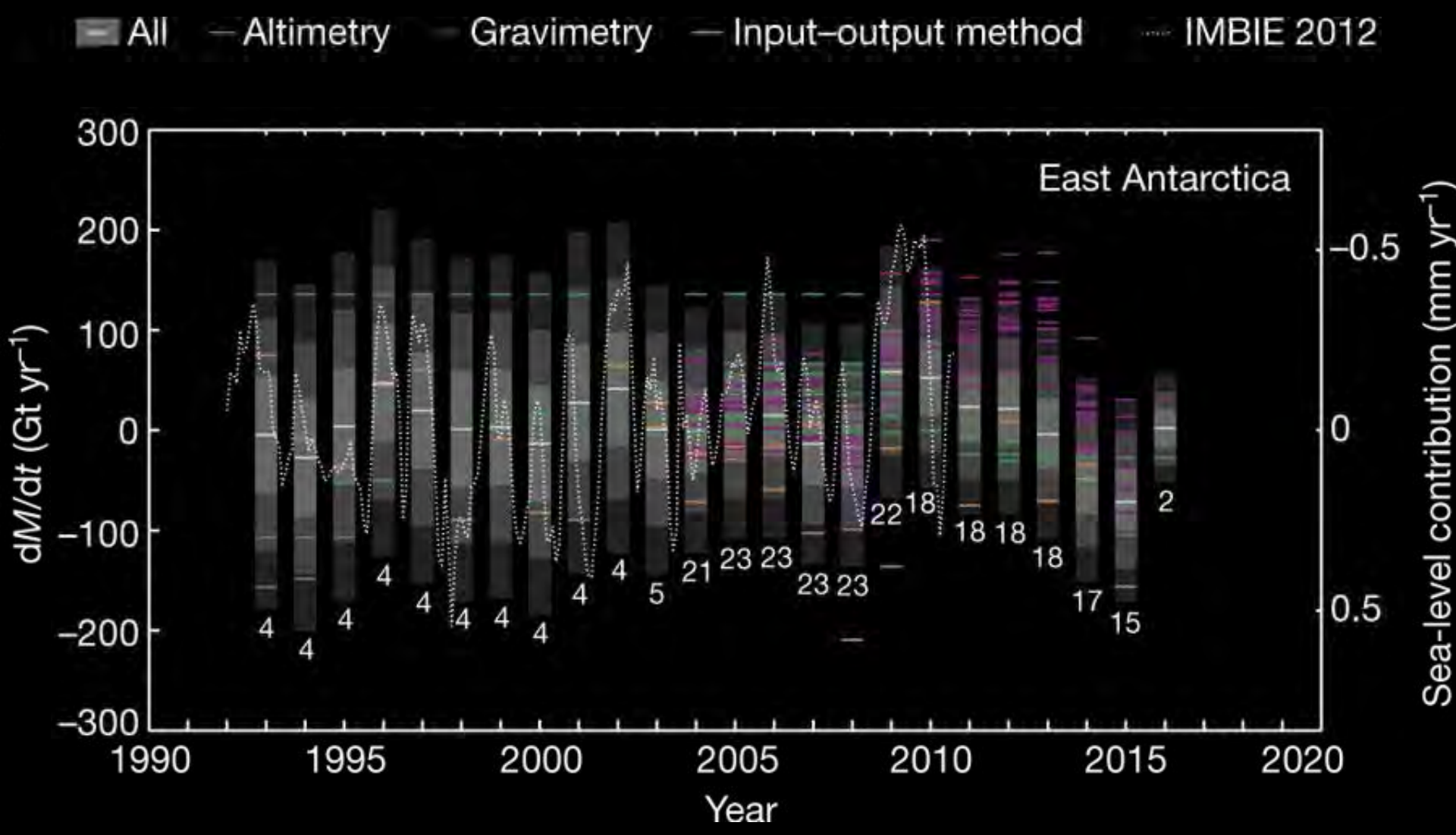
imbie-2


All
Altimetry
Gravimetry
Input–output method
IMBIE 2012
West Antarctica
dM/dt (Gt yr−1)
Sea-level contribution (mm yr−1)
Year
150
100
50
0
−50
−100
−150
−200
−250
−300
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1990
1995
2000
2005
2010
2015
2020
4
4
4
4
4
4
4
4
4
4
5
21
23
23
23
23
22
18
18
18
18
17
15
2

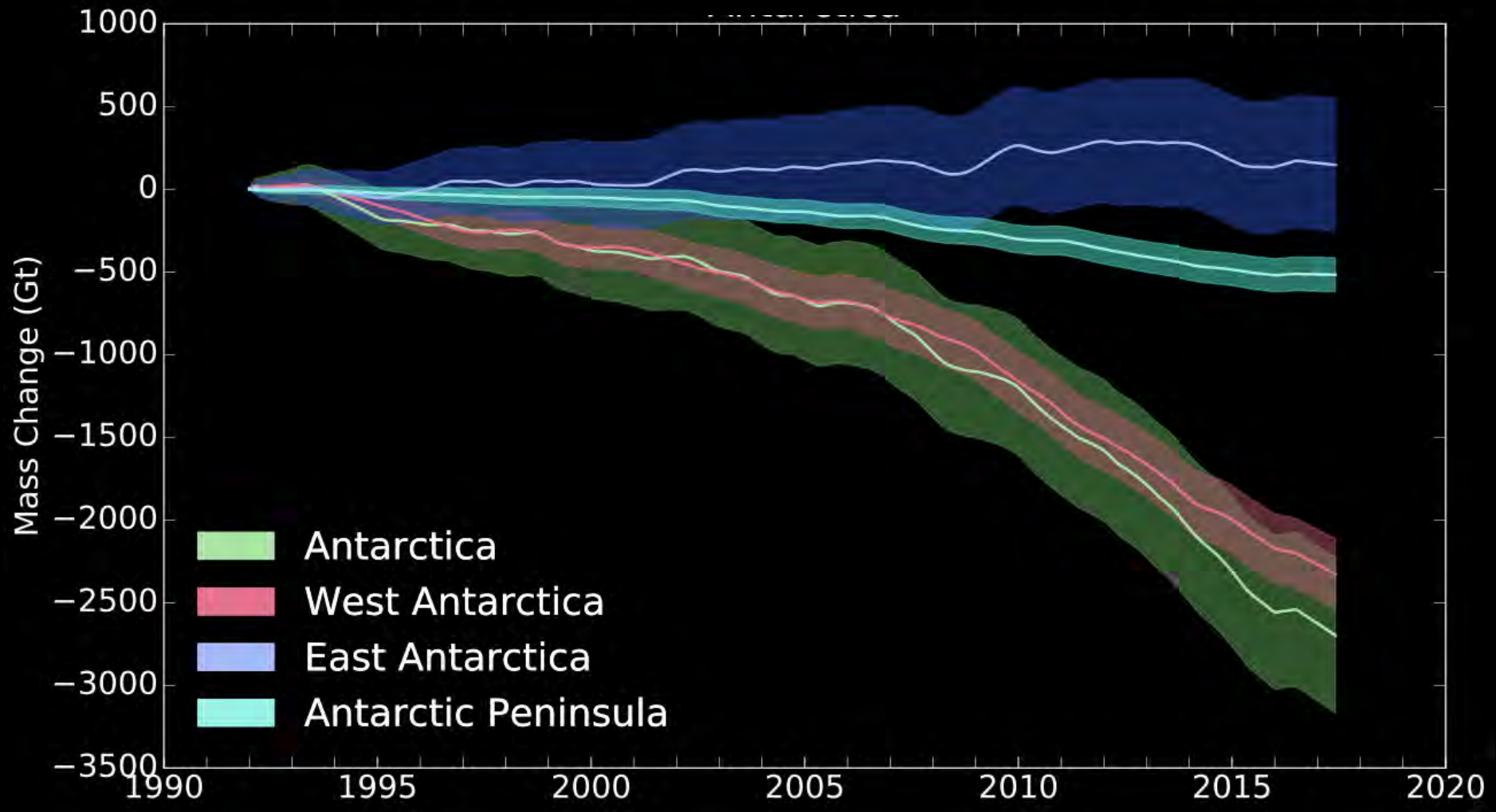
imbie-2


All
Altimetry
Gravimetry
Input–output method
IMBIE 2012
Antarctic Peninsula
dM/dt (Gt yr⁻¹)
Sea-level contribution (mm yr⁻¹)
Year
40
20
0
−20
−40
−60
−80
−100
−120
−140
−0.1
0
0.1
0.2
0.3
1990
1995
2000
2005
2010
2015
2020
3 3 3 3 3 3 3 3 3 3
4 20 22 22
22 22 21 17 17
17 17 16 14
2

imbie-2


All
Altimetry
Gravimetry
Input–output method
IMBIE 2012
East Antarctica
dM/dt (Gt yr−1)
Sea-level contribution (mm yr−1)
Year
300
200
100
0
−100
−200
−300
−0.5
0
0.5
1990
1995
2000
2005
2010
2015
2020
4
4
4
4
4
4
4
4
4
5
21
23
23
23
23
22
18
18
18
18
17
15
2

imbie-2


1000
500
0
−500
−1000
−1500
−2000
−2500
−3000
−3500
Mass Change (Gt)
1990
1995
2000
2005
2010
2015
2020
Antarctica
West Antarctica
East Antarctica
Antarctic Peninsula

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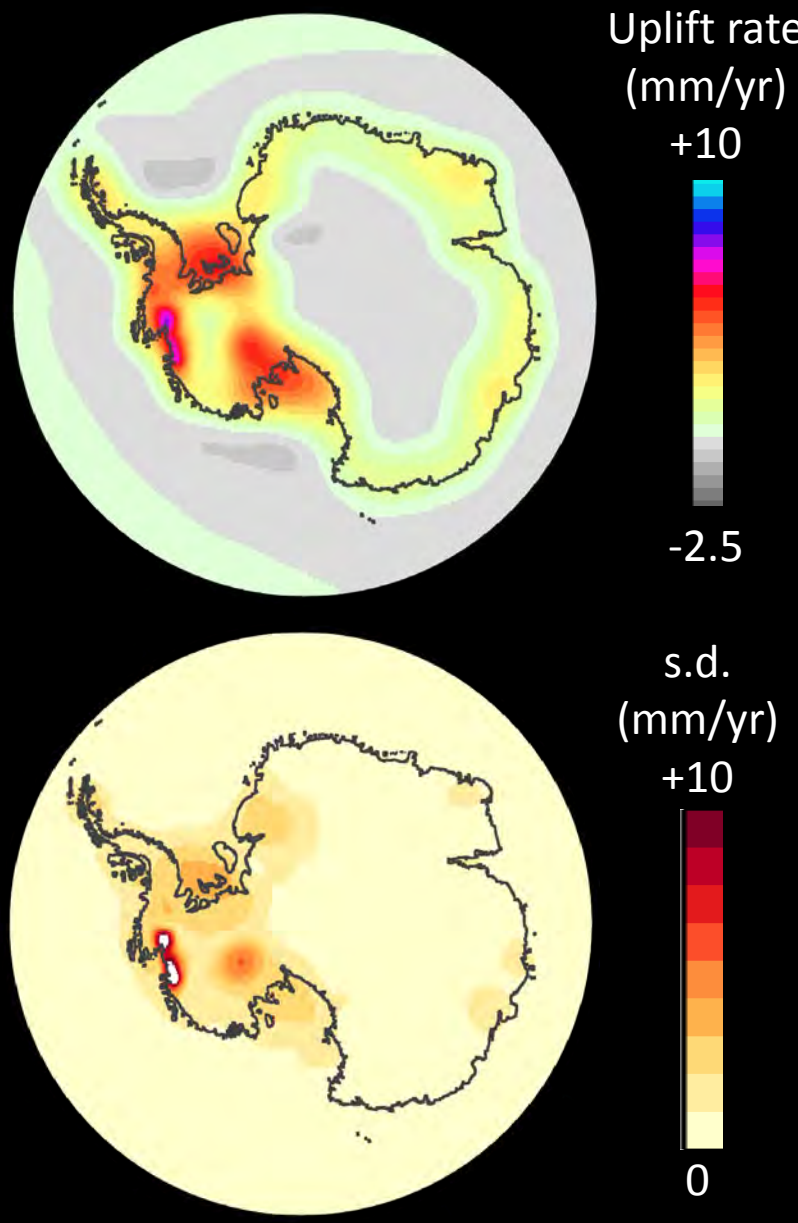
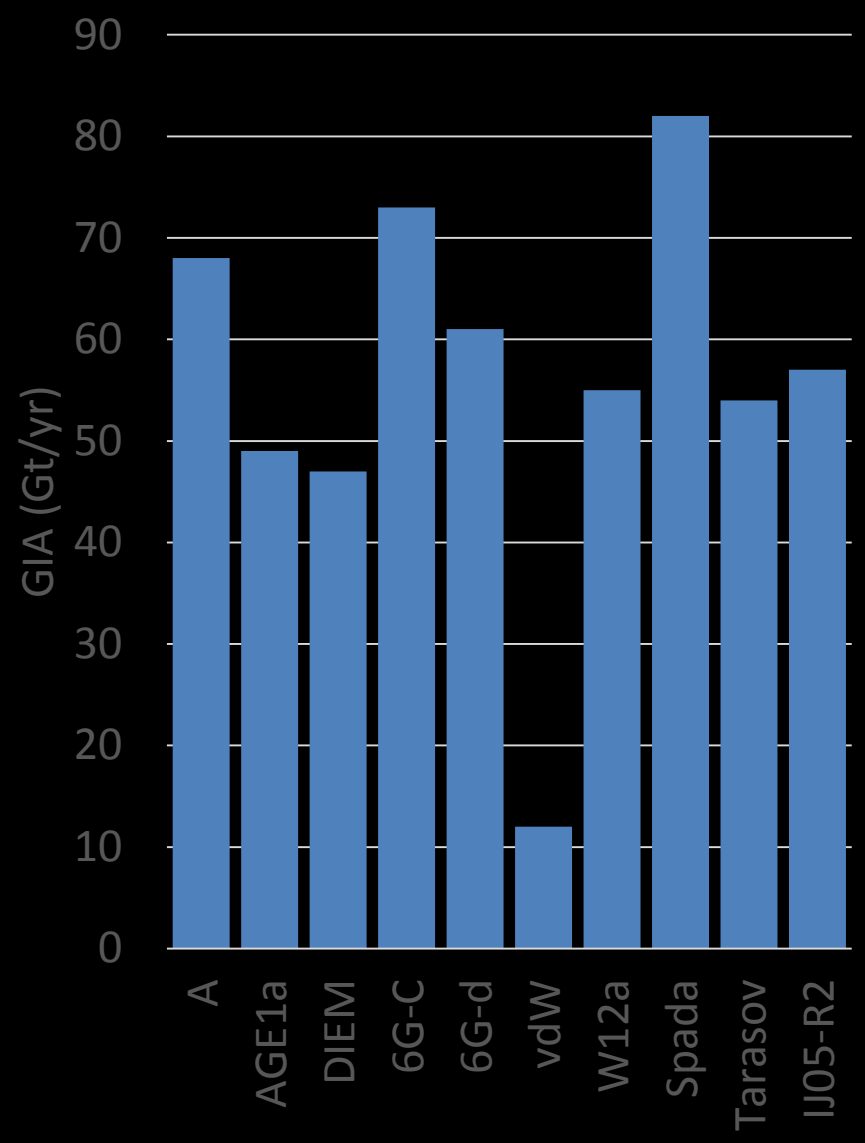
	1992–1997 (Gt yr^{-1})	1997–2002 (Gt yr^{-1})	2002–2007 (Gt yr^{-1})	2007–2012 (Gt yr^{-1})	2012–2017 (Gt yr^{-1})	1992–2011 (Gt yr^{-1})	1992–2017 (Gt yr^{-1})
EAIS	11 ± 58	8 ± 56	12 ± 43	23 ± 38	−28 ± 30	13 ± 50	5 ± 46
WAIS	−53 ± 29	−41 ± 28	−65 ± 27	−148 ± 27	−159 ± 26	−73 ± 28	−94 ± 27
APIS	−7 ± 13	−6 ± 13	−20 ± 15	−35 ± 17	−33 ± 16	−16 ± 14	−20 ± 15
AIS	**−49 ± 67**	**−38 ± 64**	**−73 ± 53**	**−160 ± 50**	**−219 ± 43**	**−76 ± 59**	**−109 ± 56**

imbie-2

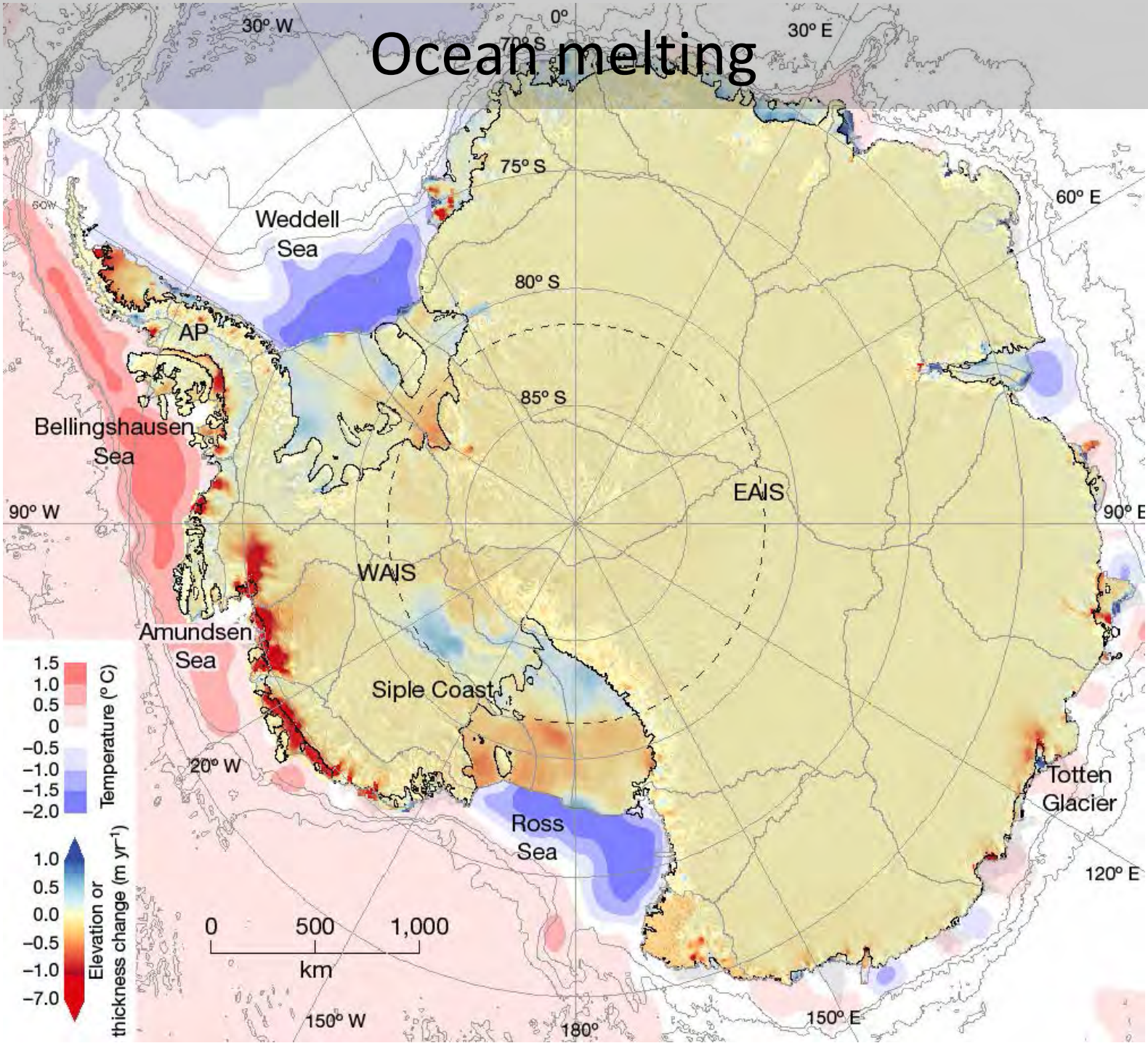
Model (1980-2012)	SMB Gt/y
RACMO2.3 **27km**	**2004**
RACMO2.4 **27km**	**2107**
MARv3.6.40 **35km**	**2150**
ERA-Interim **80km**	**1900**
JRA55 **55km**	**1807**

imbie-2

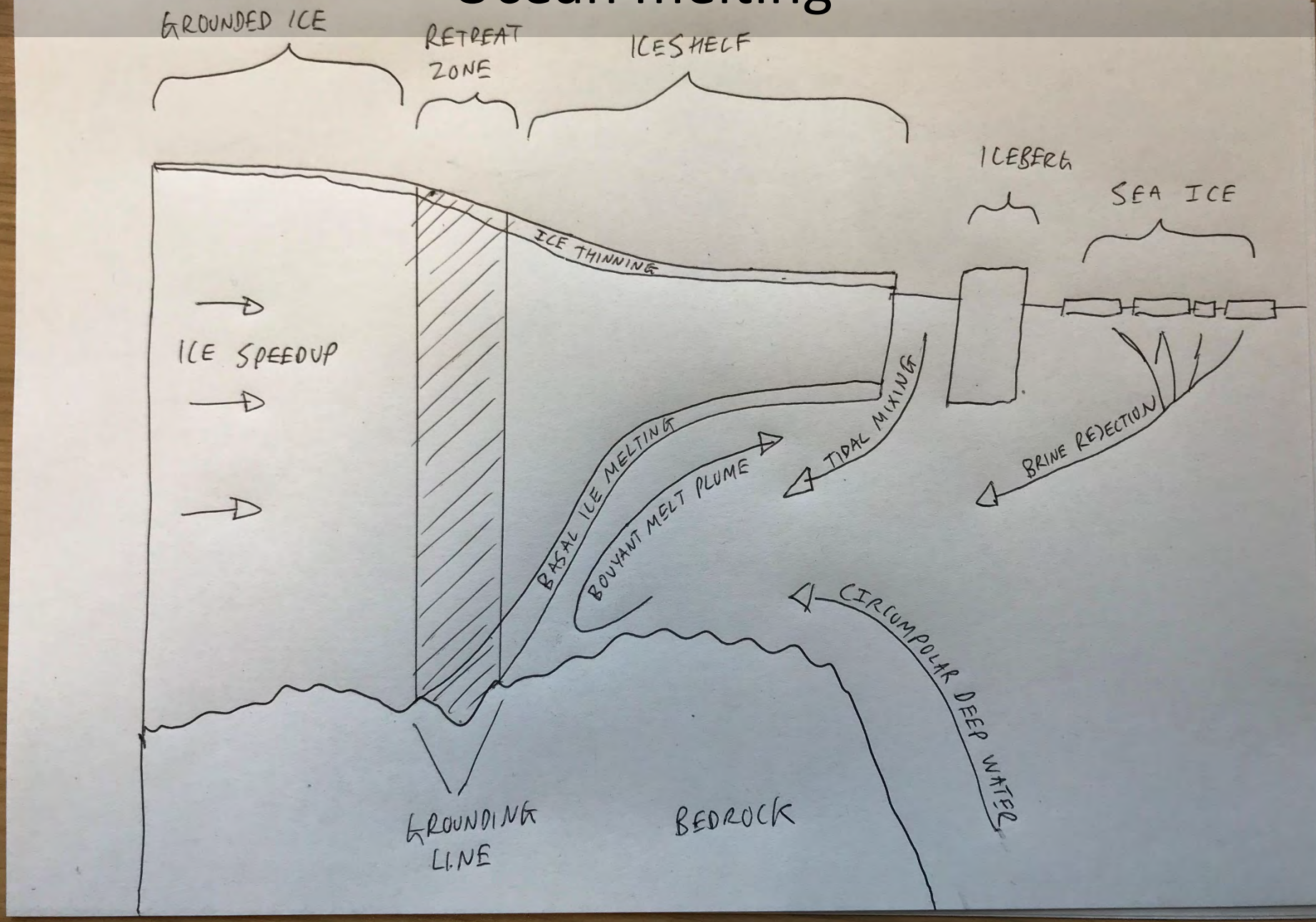

Uplift rate
(mm/yr)
+10
-2.5
s.d.
(mm/yr)
+10
0


GIA (Gt/yr)
90
80
70
60
50
40
30
20
10
0
A
AGE1a
DIEM
6G-C
6G-d
vdW
W12a
Spada
Tarasov
IJ05-R2

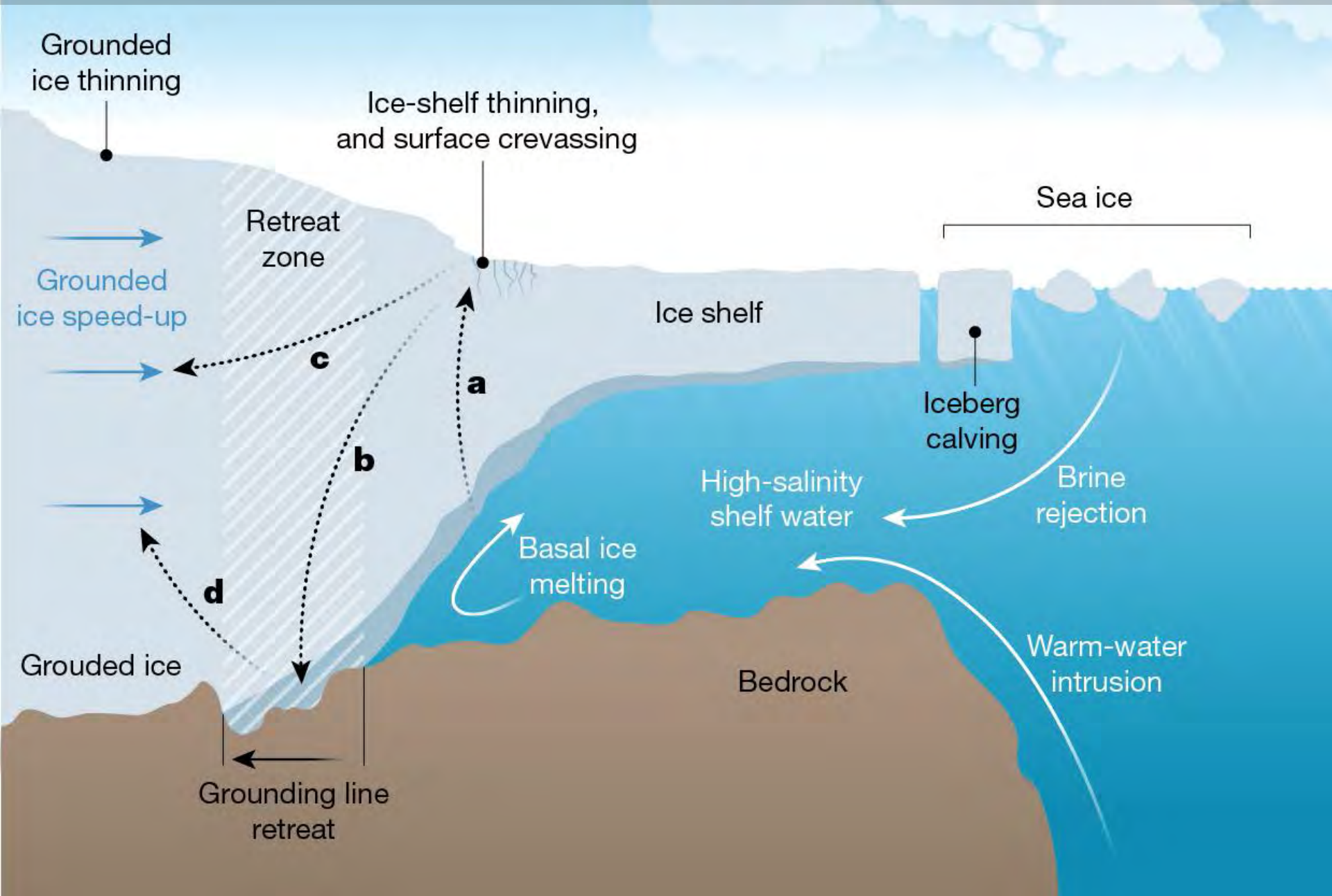
Ocean melting



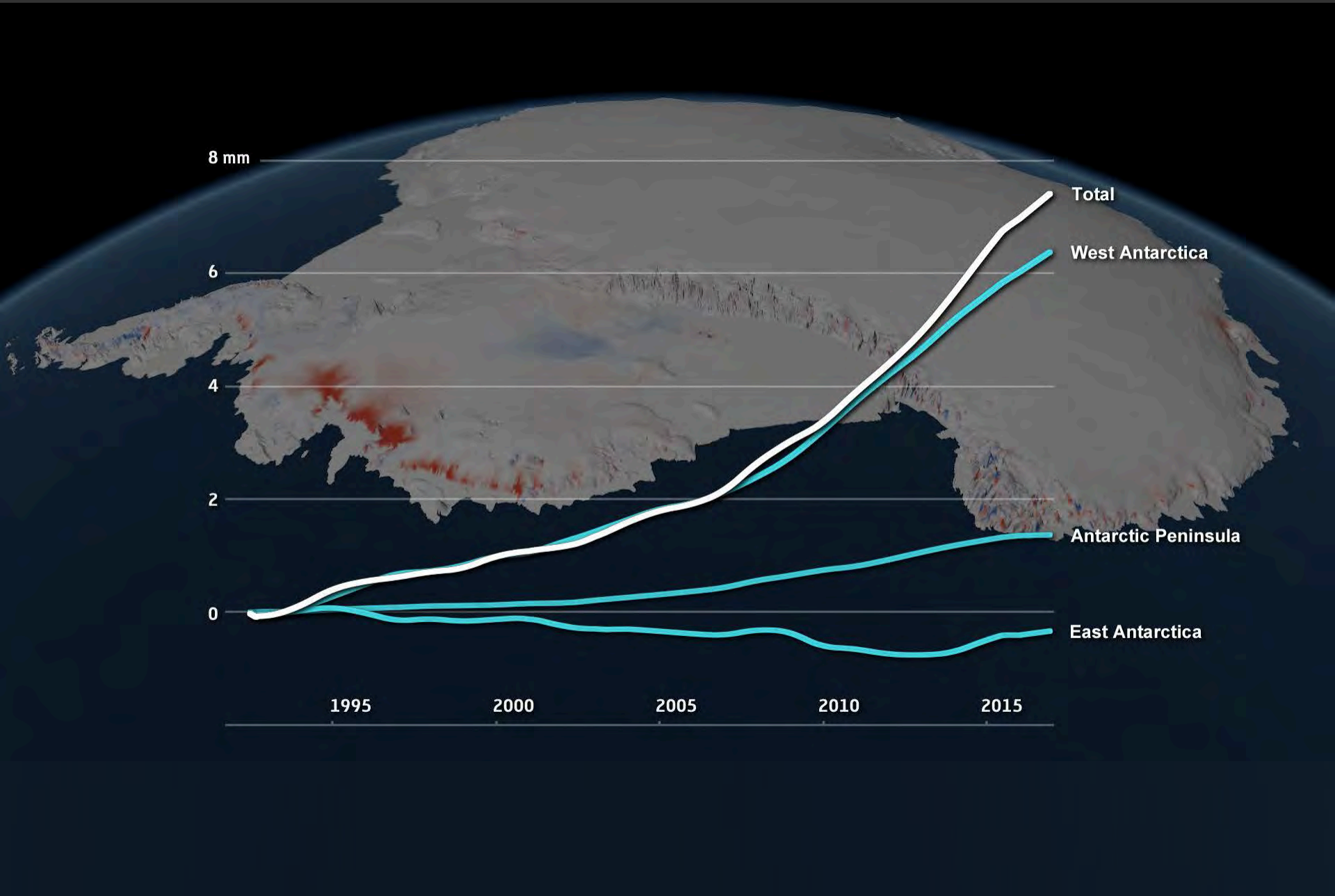
Ocean melting



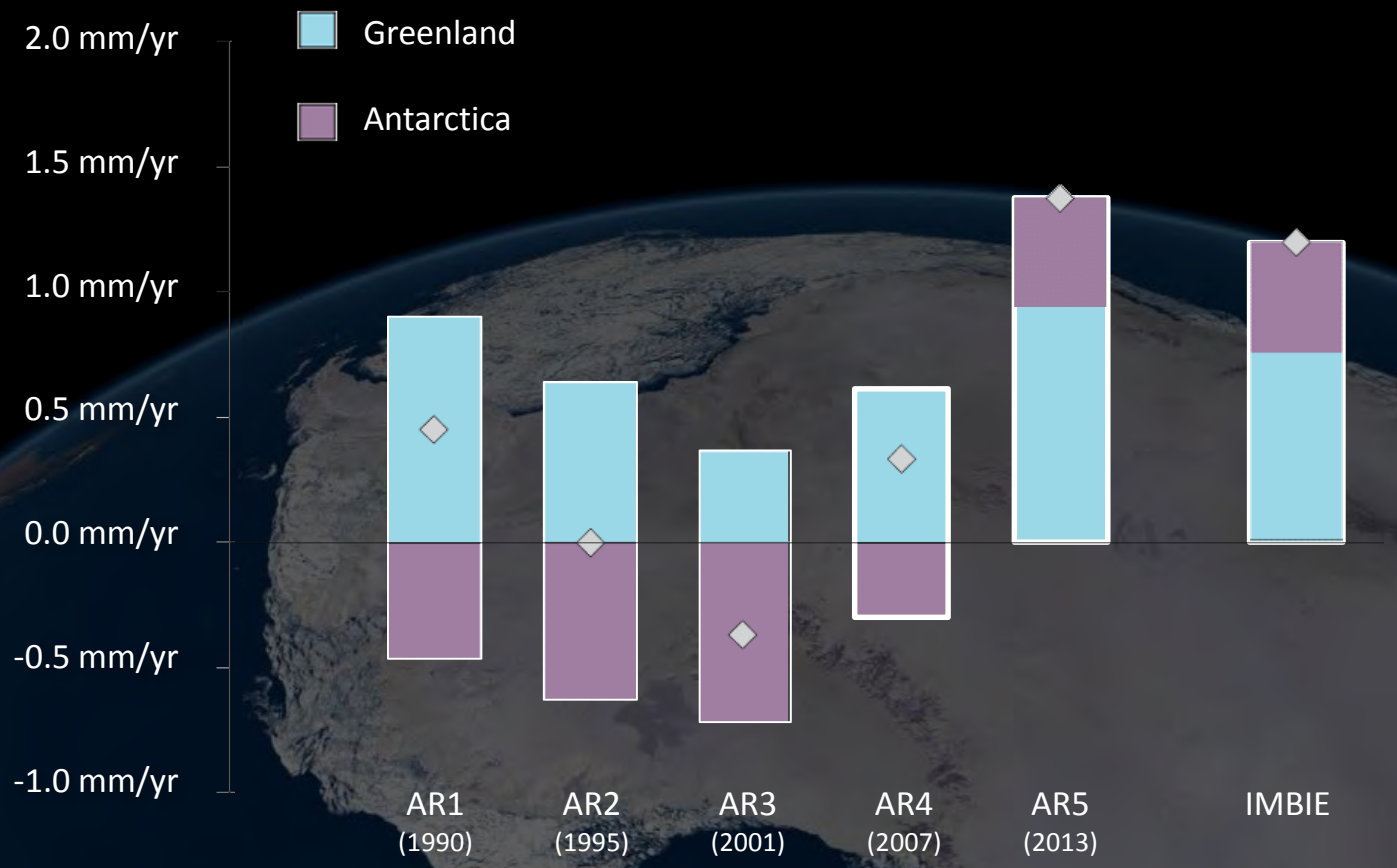
Ocean melting



Sea level contribution

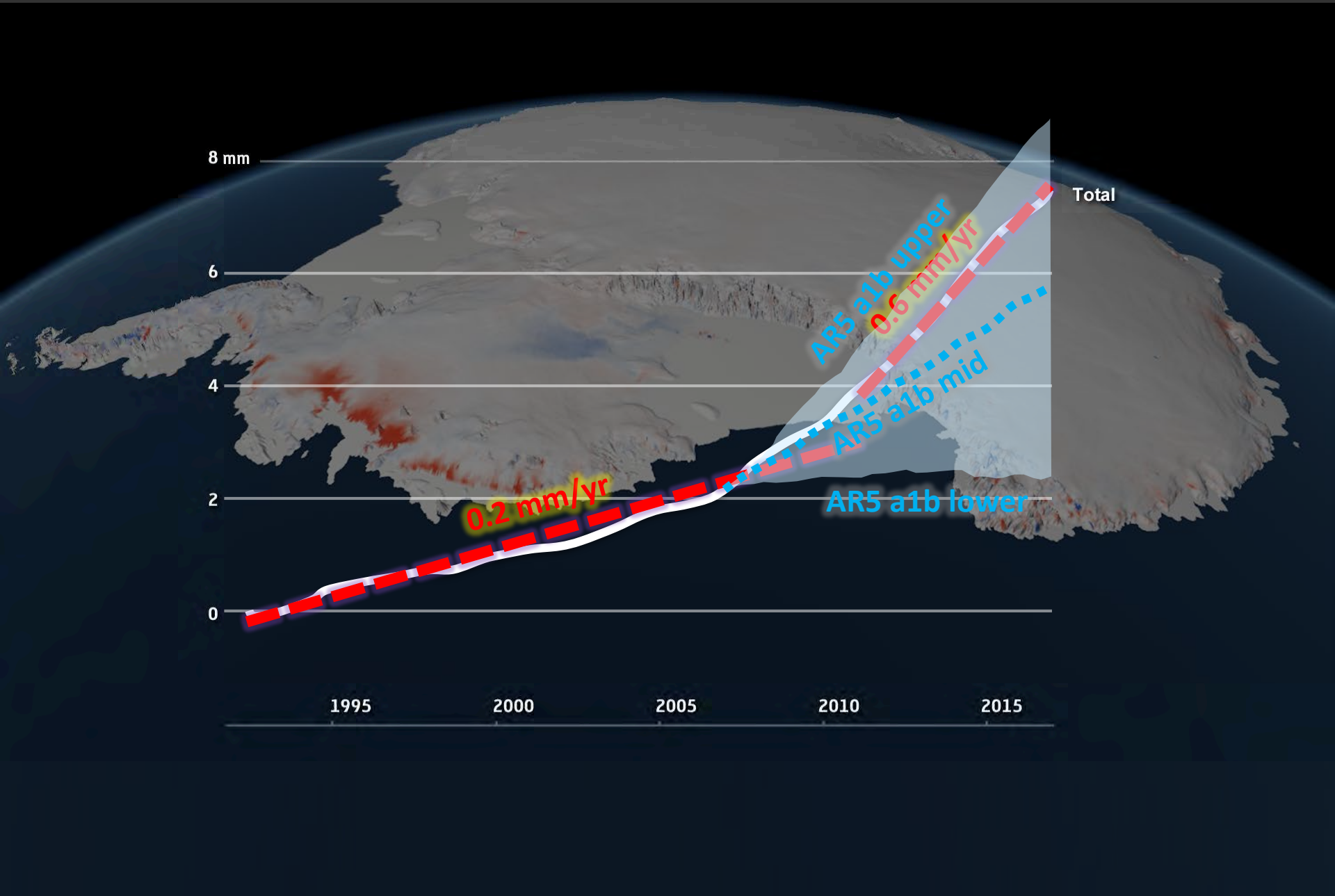


Sea level projections

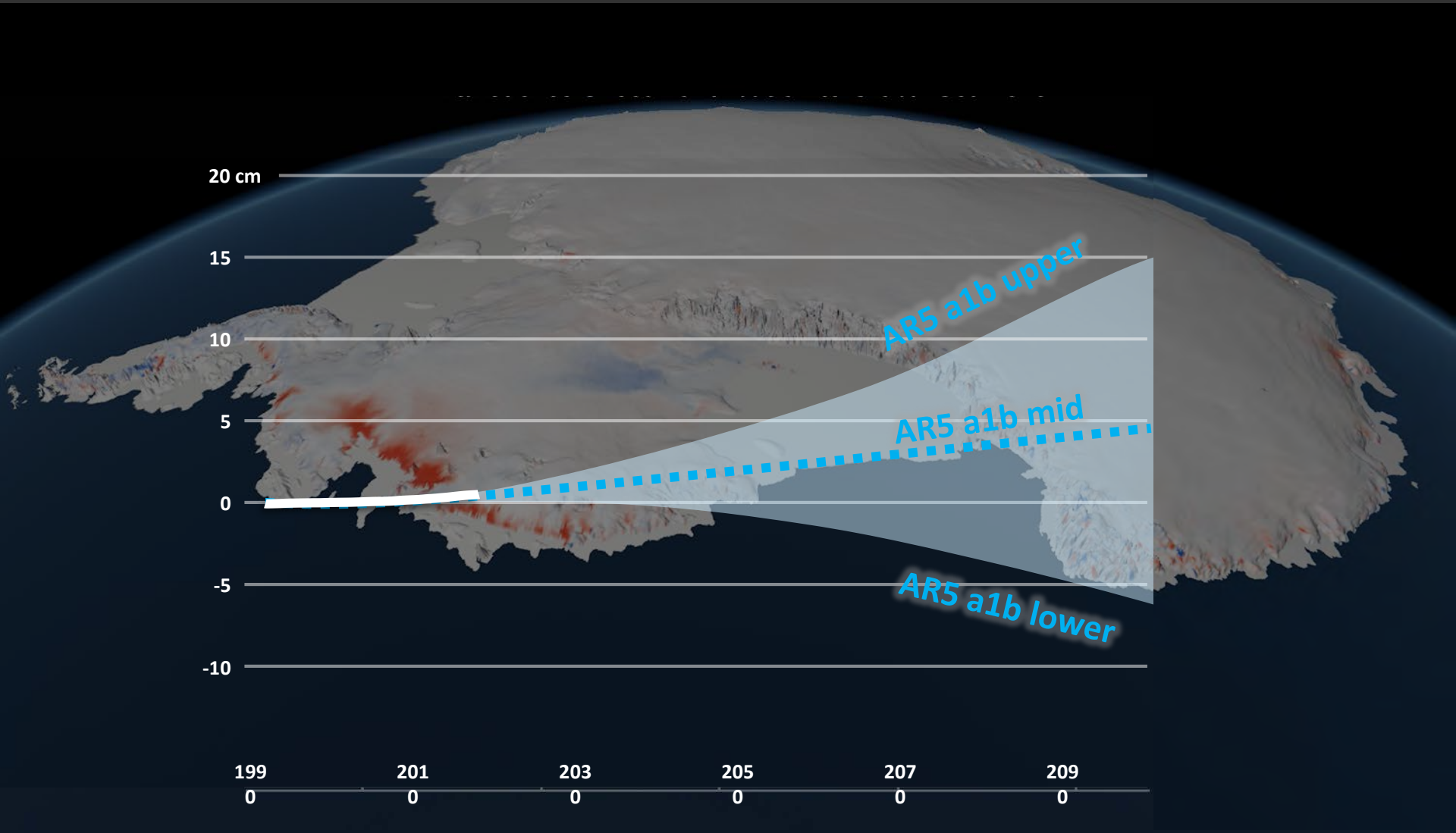


Shepherd and Nowicki, 2017

AR5 projections



AR5 projections



Summary

- 84 participants, 44 institutions, 13 nations
- 24 mass balance time series, 13 satellite missions
- 11 GIA models, 4 SMB models
- Sea level contribution up from 0.2 to 0.6 mm/yr
- Now tracking AR5 a1b upper scenario
- Dominated by WAIS, but increase at APIS also
- EAIS still shows departure
- Mass budget least certain and most negative

Next steps

- Greenland
- SMB, GIA
- Annual assessments
- Sentinel-3, GRACE-FO, ICESat-2, NISAR
- Model validation
- Glaciers

www.imbie.org

Article Metrics - Mass balance | Table 1 Rates of ice-sheet mass | imbie.org

imbie.org/data-downloads/

esa imbie NASA

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DATA DOWNLOADS

Home > Data downloads

This pages contains results of the imbie assesment and ancilliary data required to participate in the project. Ancilliary data will appear shortly.

Title	Date	Description	Download
IMBIE 2018 Antarctic Dataset	2018-06-08	This spreadsheet contains the IMBIE-2018 datasets for Antarctica (worksheet 1), Antarctic Peninsula (worksheet 2), East Antarctica (worksheet 3) and West Antarctica (worksheet 4). Each worksheet includes data on monthly cumulative ice sheet mass changes and their estimated uncertainty. The data are expressed in units of mass (Gigatons – columns B and C) and in units of equivalent mean global sea level rise (millimetres – columns D and E).	Download
IMBIE 2012 Dataset	2012-11-29	This spreadsheet contains the IMBIE-2012 datasets for Antarctica (worksheet 1) and Greenland (worksheet 2). Each worksheet includes data on monthly cumulative ice sheet mass changes and their estimated uncertainty. The data are expressed in units of mass (Gigatons – columns B and C) and in units of equivalent mean global sea level rise (millimetres – columns D and E).	Download