MASS BALANCE

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Overview:

-Why do we care ?

-Contribution to Sea Level

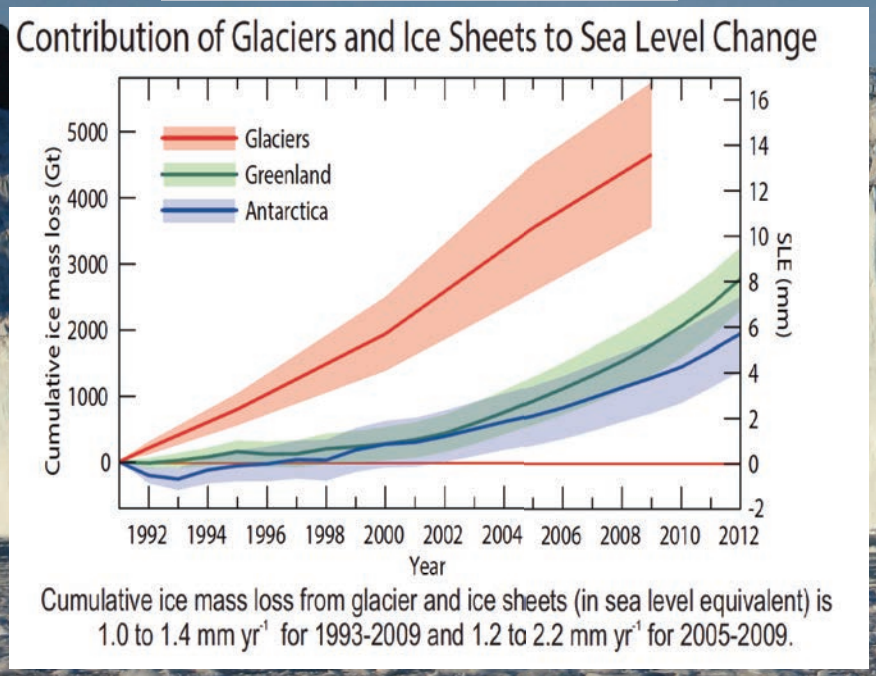
-Methods to determine Mass Balance: Pros and Cons

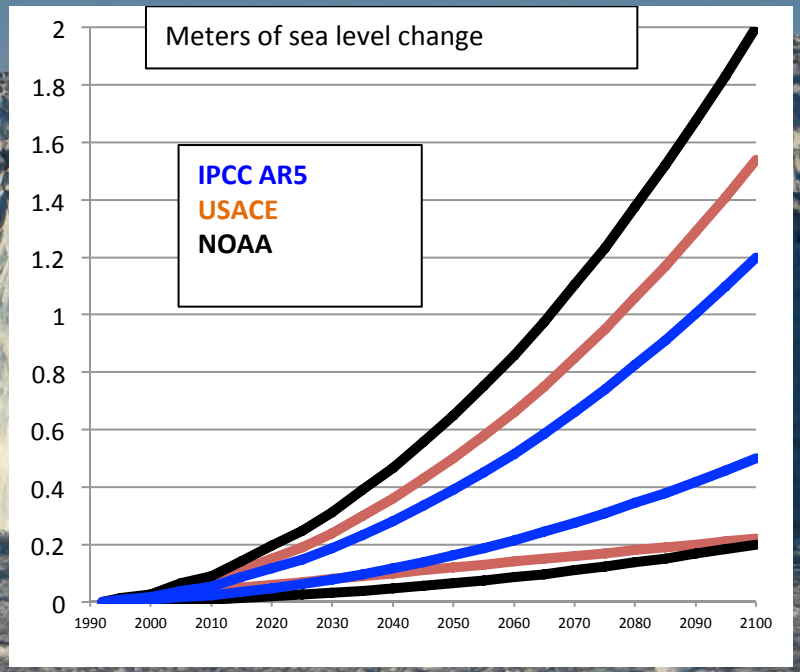
-Synergy between observations to improve understanding of Physical processes that control the mass balance

What sea level rise in a warming climate?

4 m/century 14 kyr ago, 1 m/century today, SL 6-9 m higher 125 kyr ago

Present: 1 m/century



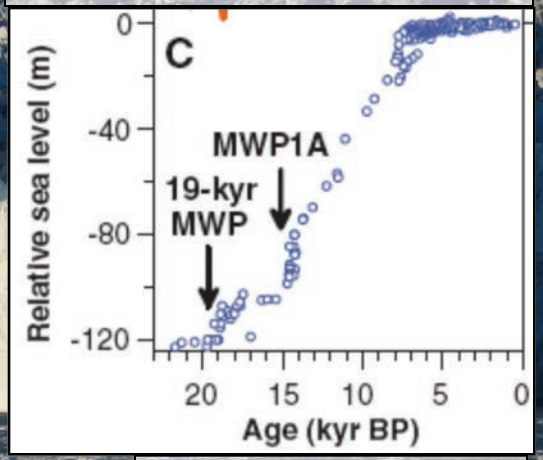


IPCC AR5 Ch 4, 2013

Ice Sheet Mass Balance

Antarctica:
Average precip. 17 cm/yr w.e.
SLR equivalent ~60 m
Annual turn over of mass 2,480 Gt/yr = 6.1 mm/yr SLR

MWP1a: SLR > 40 mm/yr

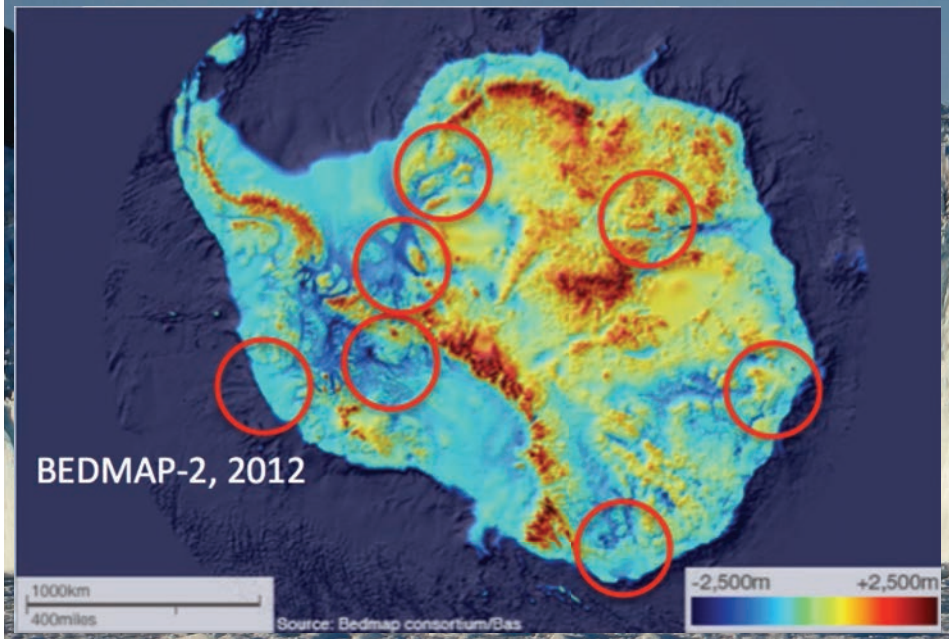


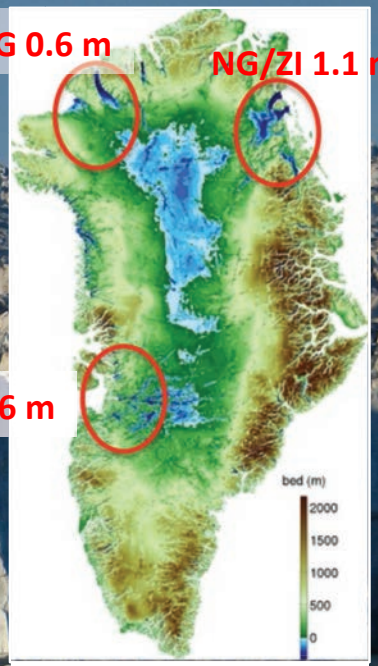
Alley et al., Science 2005

GREENLAND:
Average precip. 24 cm/yr
SLR equivalent ~7 m
Annual turn over 510 Gt/yr = 1.4 mm/yr SLR

Ice sheet Mass Balance

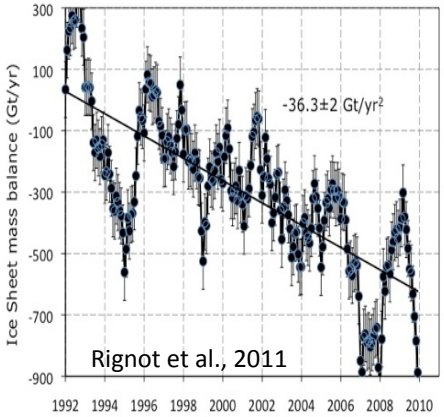
WAIS: 4 m SLR (3 m marine)
EAIS: 53m (19 m marine);
Greenland: 7 m (2 m marine).





Morlighem et al., 2014

Ice Sheet Mass Balance



Current rate: 44Gt/yr^2

Glaciers, ice sheets, ice caps, thermal expansion → 1 m by 2100

Mass Balance

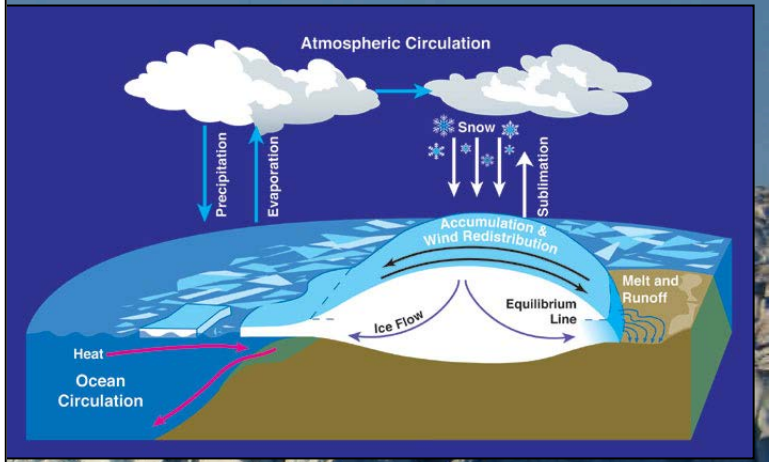
Physical processes:

-Surface Mass Balance (SMB):

due to processes that affect the surface of the ice sheet (precipitation, Evaporation, runoff, blowing snow etc.)

-Ice Dynamics:

fracturing/melting of ice at ice sheet margins AND sliding of ice on its bed toward the sea.



MASS BALANCE

= total mass change

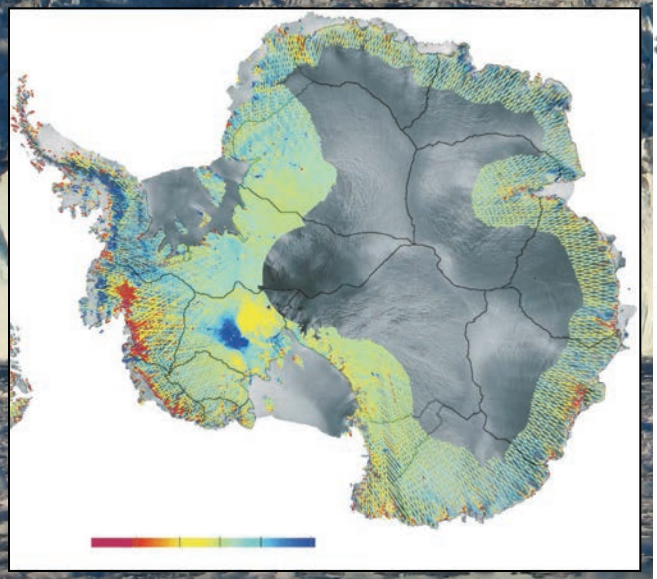
= Input(accumulation) – output (ablation)

= SMB - Ice Discharge

How to measure mass balance?

Measure volume changes

Altimetry survey

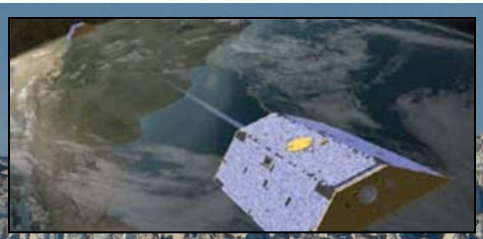


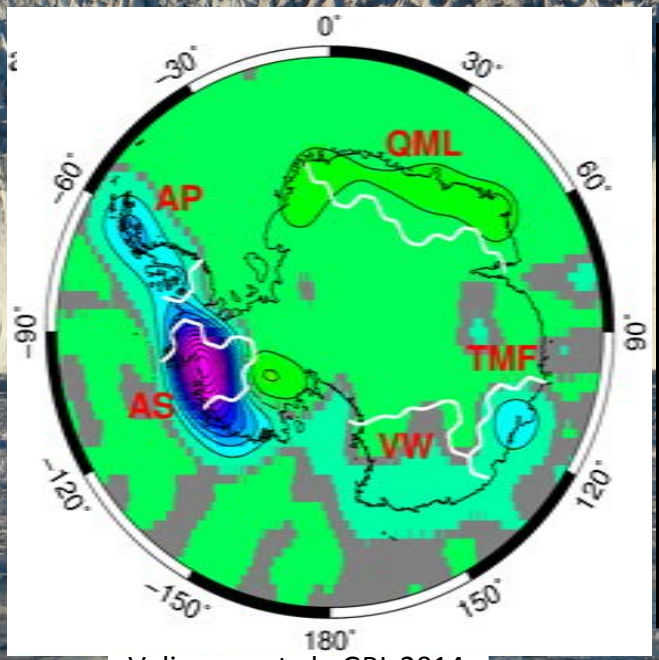
Pritchard et al., Nature 2009

Long time series, but unknown density and limited spatial sampling.

Measure mass balance

Time-variable gravity

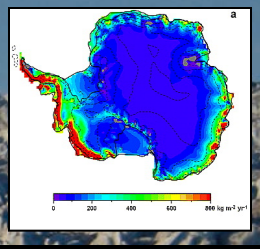


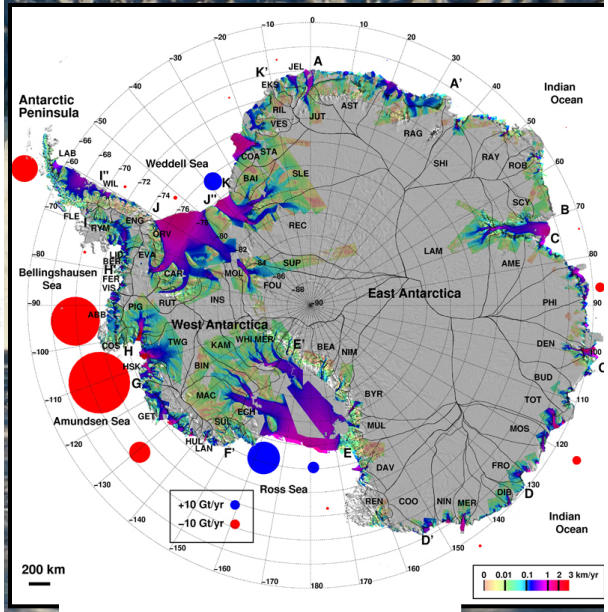


Velicogna et al., GRL 2014

Direct measurement, but short time series, GIA correction and resolution

Ice motion + regional climate modeling





Rignot et al., NatGeo, 2008

Detects glacier speed up but requires high precision components. Coverage

Volume change from altimetry surveys (laser, radar)

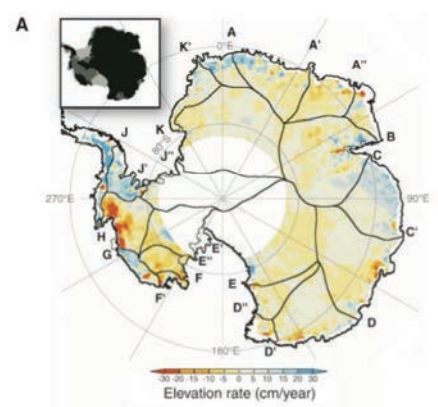
Pros:

- Good time series since 1992 with ERS, prior data not reliable enough.
- Indicates areas of change (changes in interior snowfall, how fast some glaciers are thinning and others are not, important for testing ice flow numerical models)

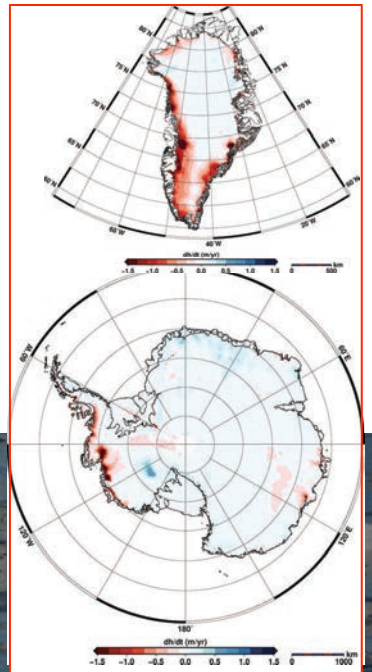
Cons:

- Transformation of volume into mass = 50% uncertainty (0.3 to 0.9).
- Sparse sampling of coastal regions (nadir tracks)
- Long time series needed to detect trends (> 10 years).
- Unknown penetration depth (radar)
- Laser pointing errors (laser).
- Significant impact of slopes.

Elevation rate (1992 - 2003)
ERS radar altimetry

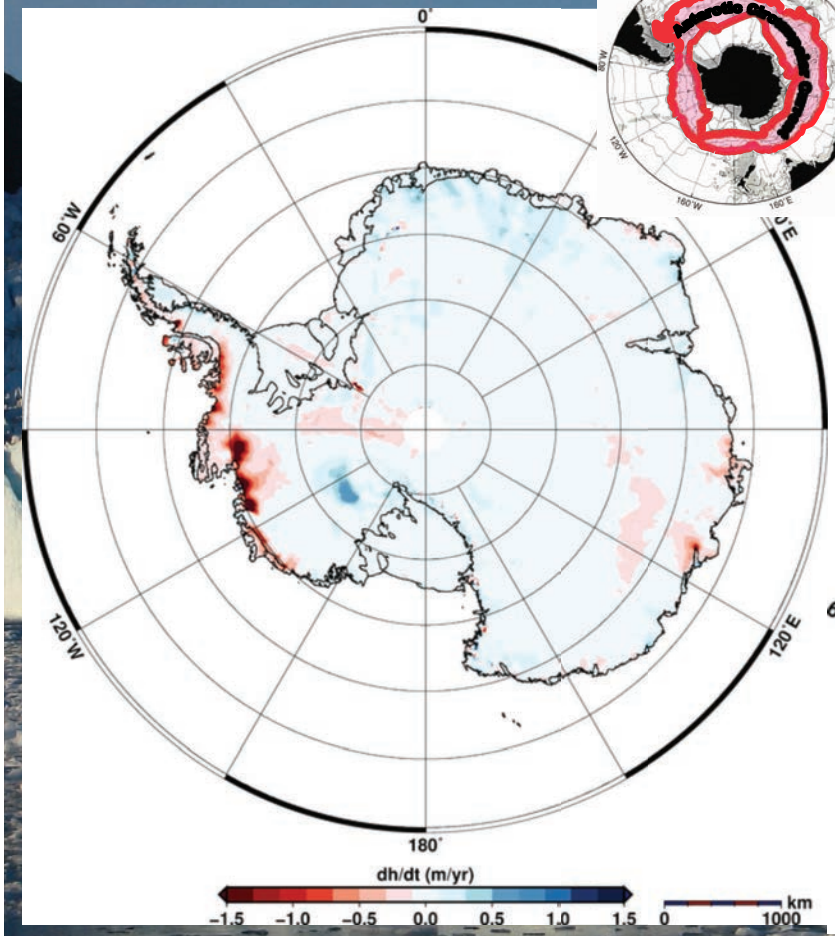


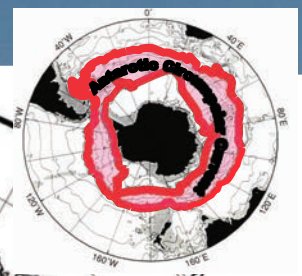
Shepherd and Whingam 2007

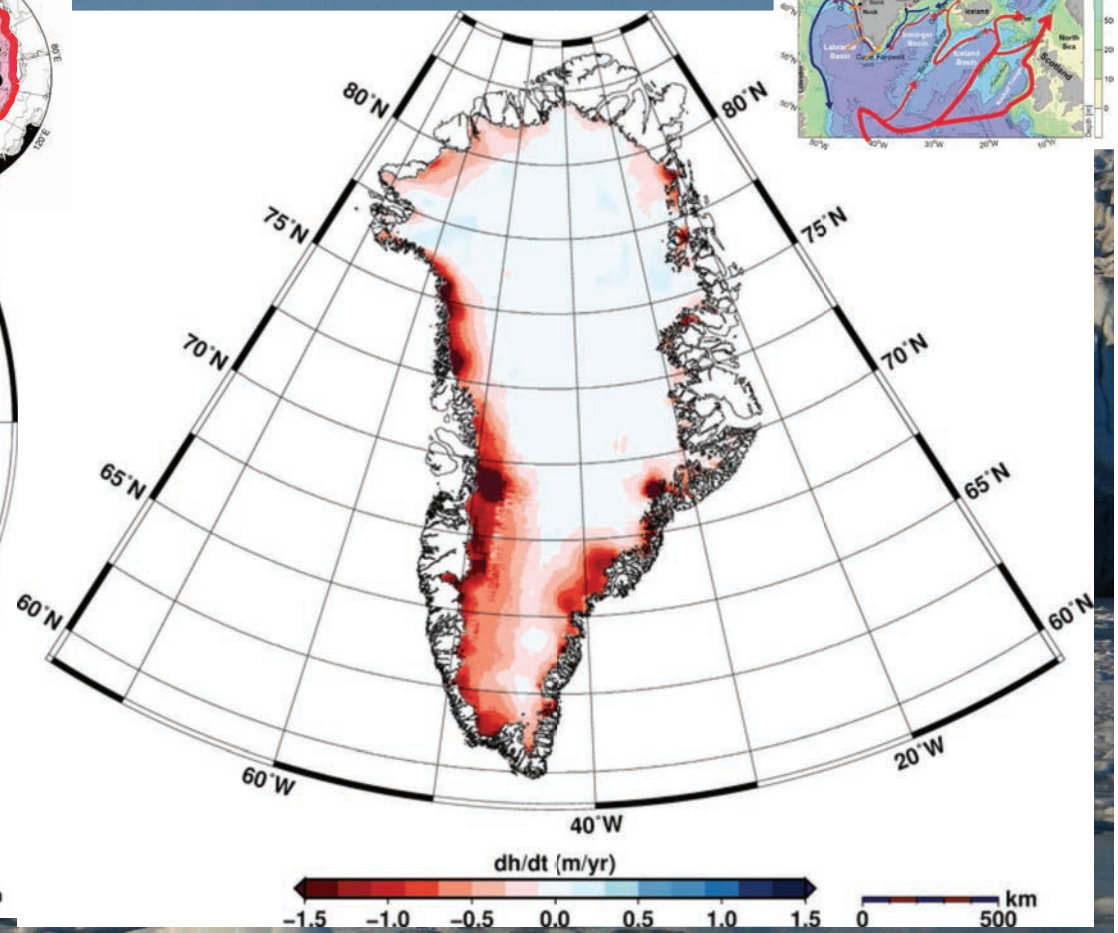


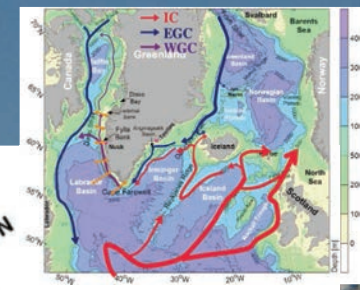
McMillan et al., 2014

Ice Sheet Mass Balance



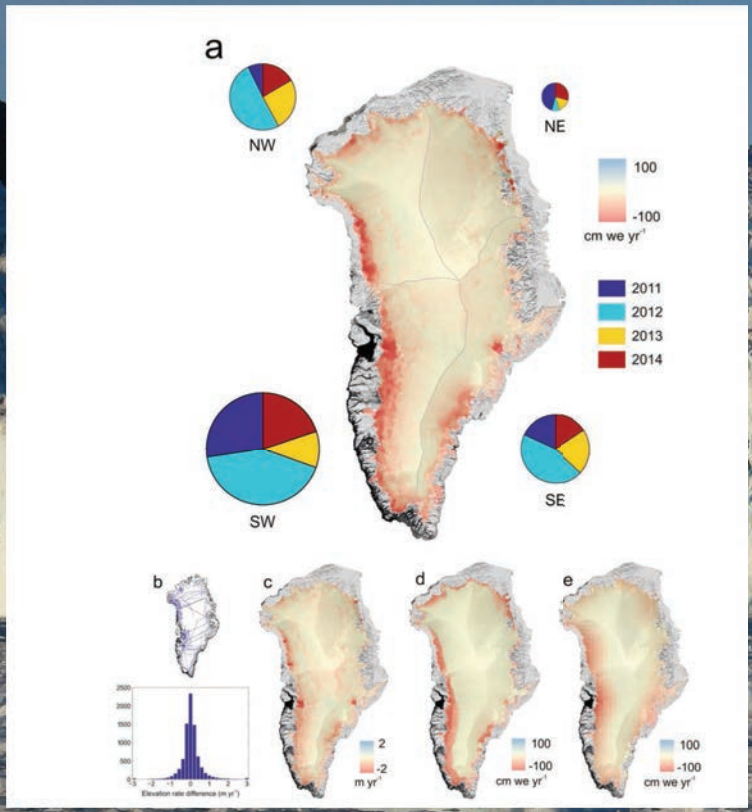




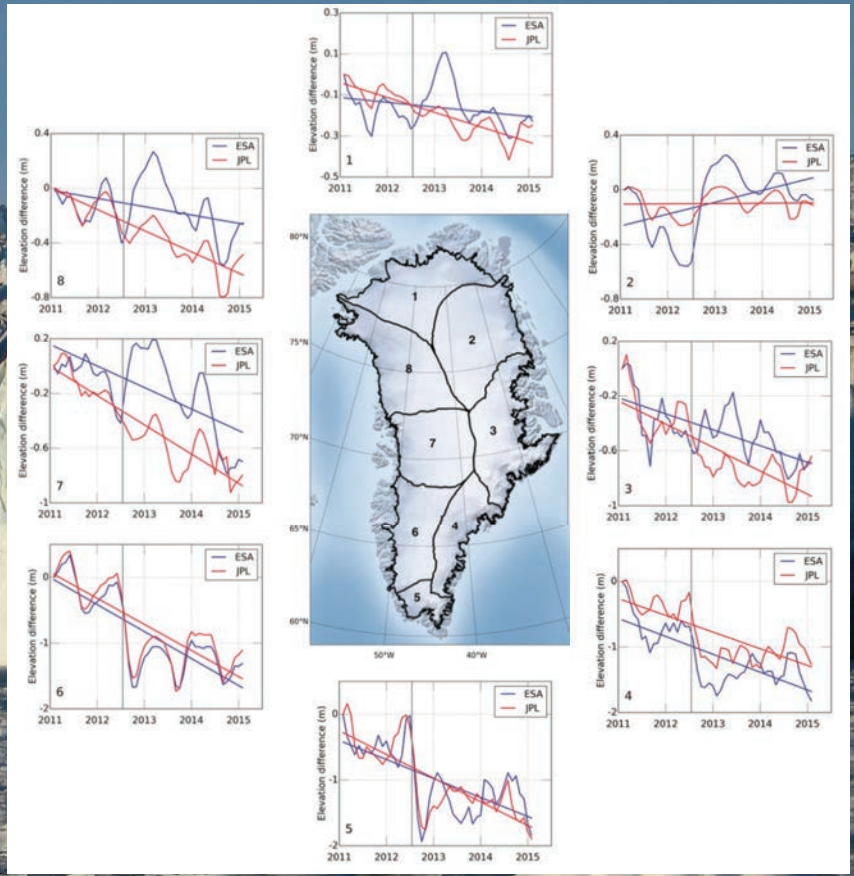


McMillan et al., GRL, 2014

Ice Sheet Mass Balance

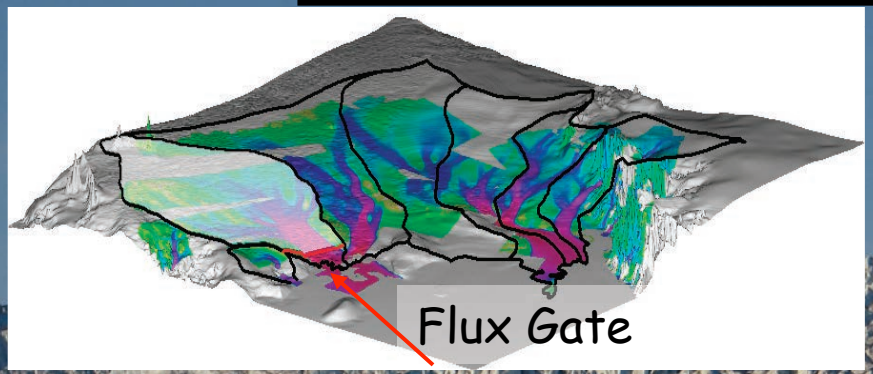


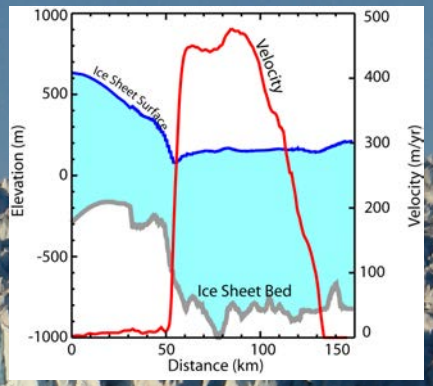
McMillan et al., GRL, 2016



Nilson et al., TC, 2016

Mass budget





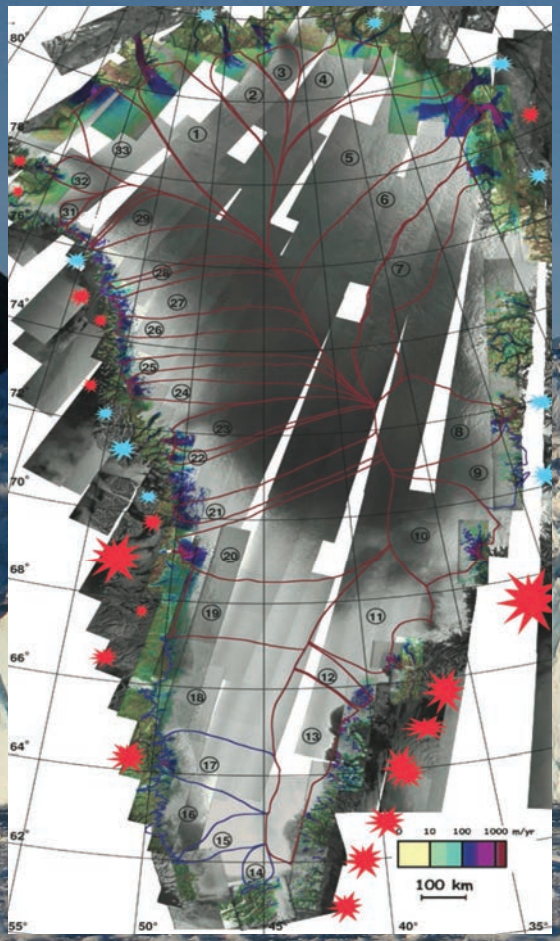
Mass balance = Accumulation – Discharge

Accumulation : Regional climate model RACMO/MAR (precision 5-20%)
Ice thickness : radio echo sounding, hydrostatic equilibrium at glacier grounding line (precision 10-50 m)
Ice velocity: InSAR velocity (precision 1-10 m/yr).

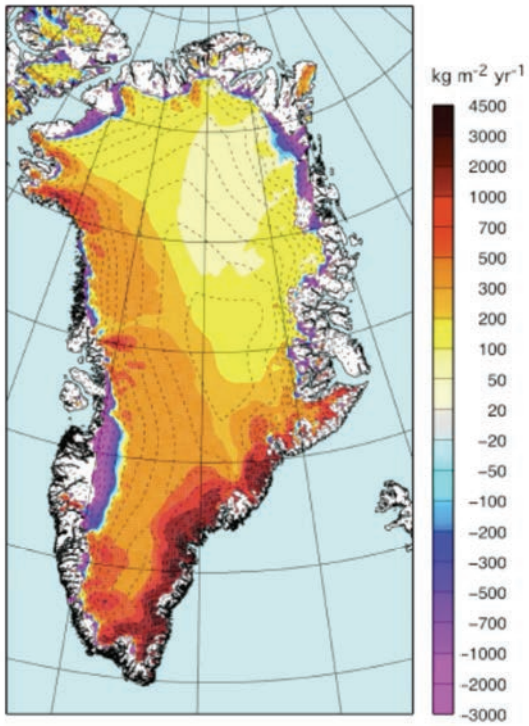
Pros: Examine the partitioning of mass balance (surface vs ice dynamics), tracks individual glaciers, surface mass balance available before satellite record, old velocity records, comprehensive method.

Cons: Compares two large numbers with errors to get mass balance, data gaps in ice thickness, unknown errors in runoff from SMB models, data gaps in velocity coverage, processing intensive.

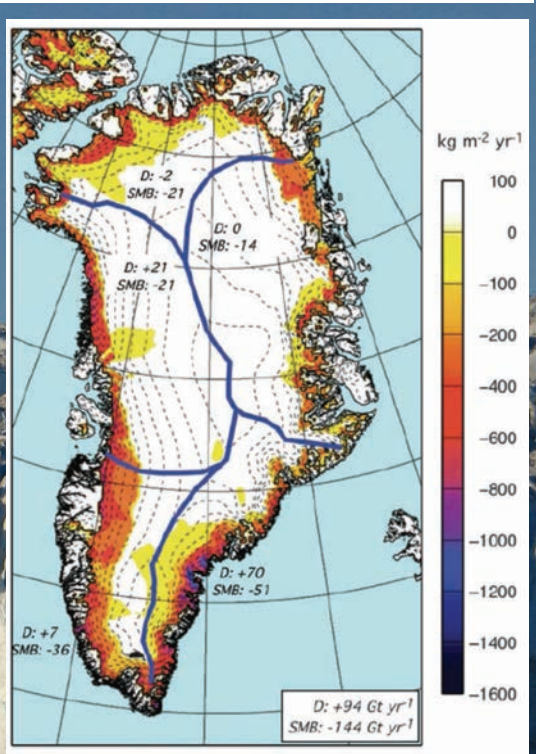
Greenland mass balance from InSAR/RACMO2



Rignot et al. GRL 2008.

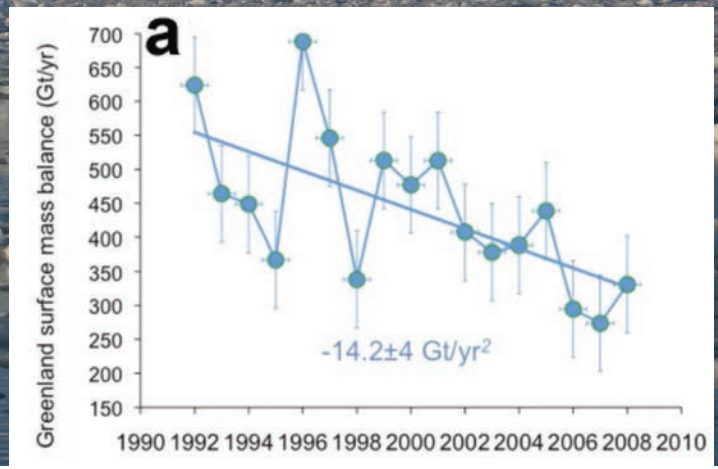


SMB 1961-1990



dM/dt 2003-2008

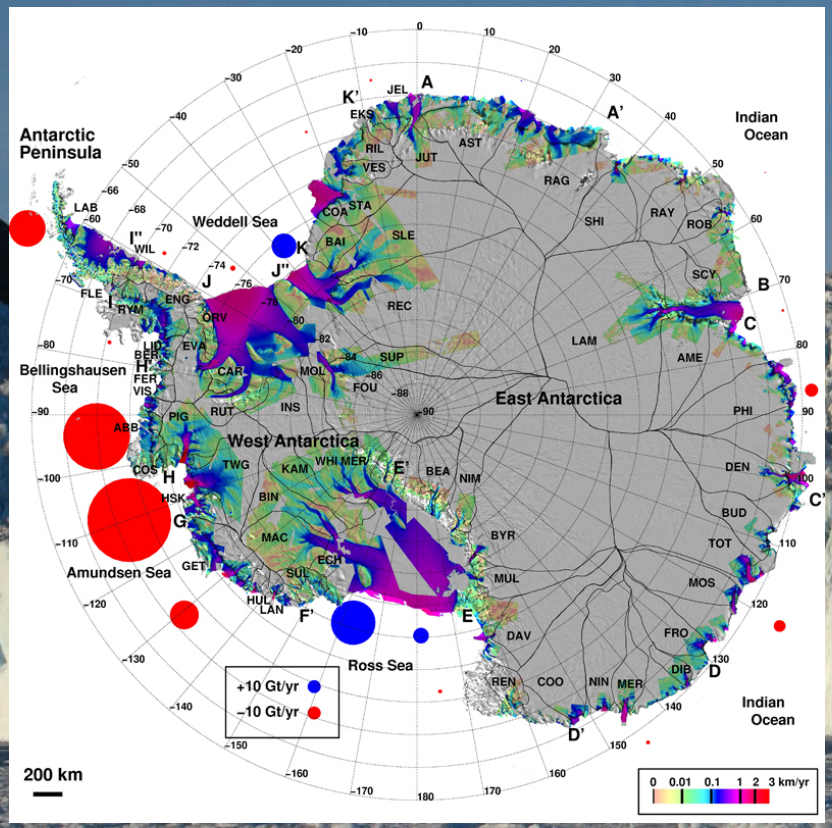
Van den Broeke et al., Science 2009

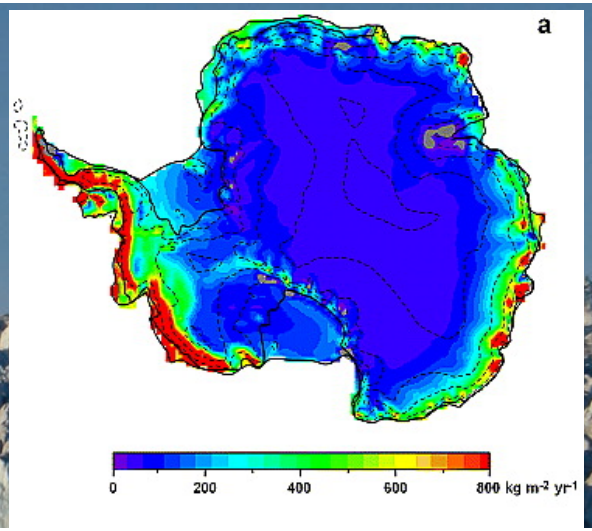


9% precision or +/- 41 Gt/yr.

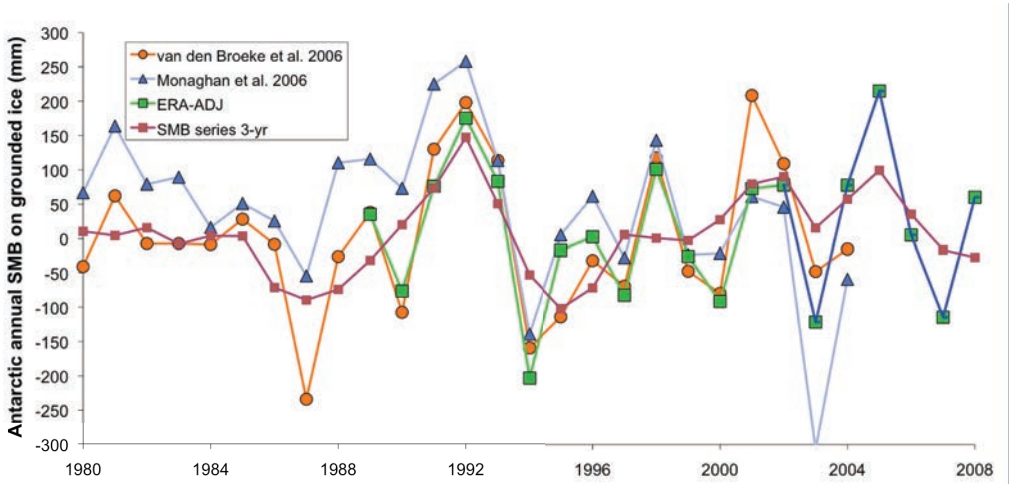
SMB dominated by an increase in surface runoff

Antarctic mass balance from InSAR/RACMO2





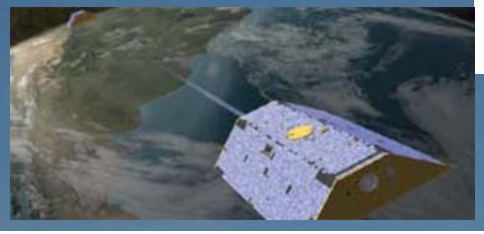
Yearly time series of SMB from RACMO2 (van den Broeke et al. GRL 2006)



- Ongoing acceleration in flow in the Amundsen Sea (exponential increase for PIG) from 1996 (ERS-1/2) to present (ALOS PALSAR).
- High flow speeds in northern Peninsula consecutive to ice shelf collapse.
- **No acceleration in ice flow** in East Antarctica.

±5 to 20% precision, or ±72 Gt/yr on average
Large interannual variations (±300 Gt/yr)
No detectable change in SMB in Antarctica.

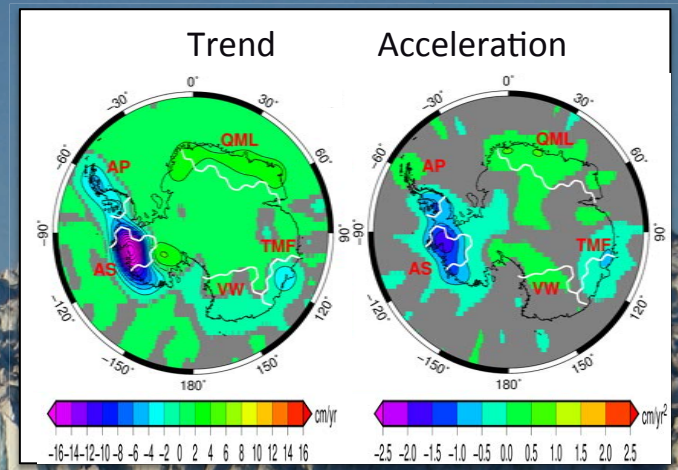
Gravity

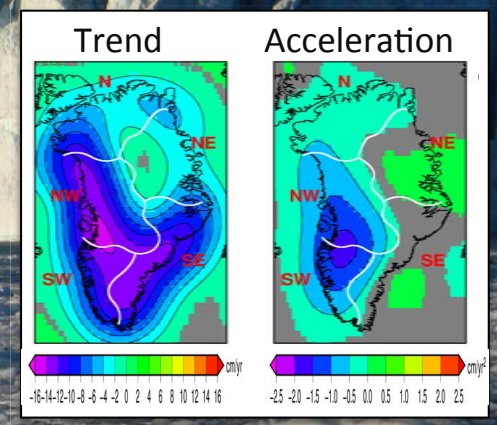


Measure of changes in the Earth gravity field.

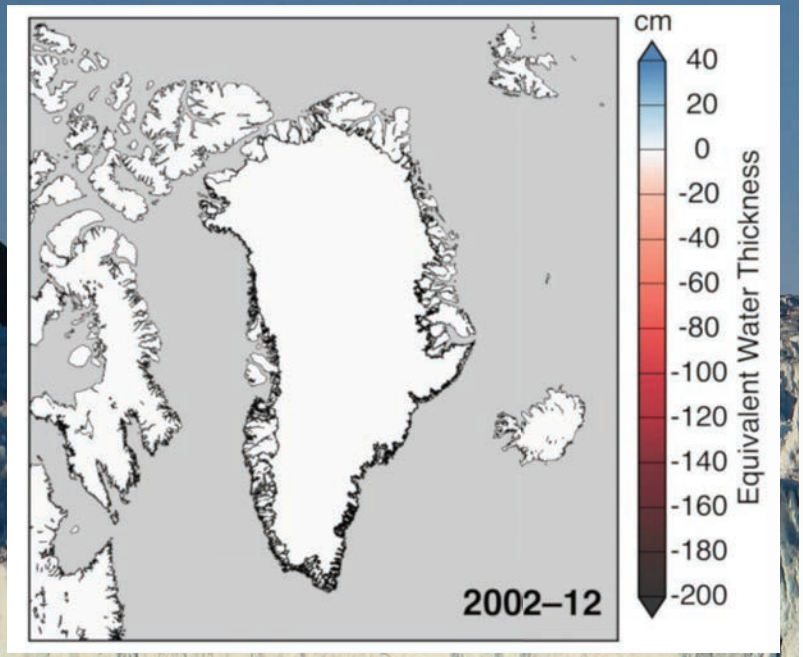
Pros:
-Monthly updates,
-direct measurement of mass,
-comprehensive (includes all peripheral glaciers), monthly updates.

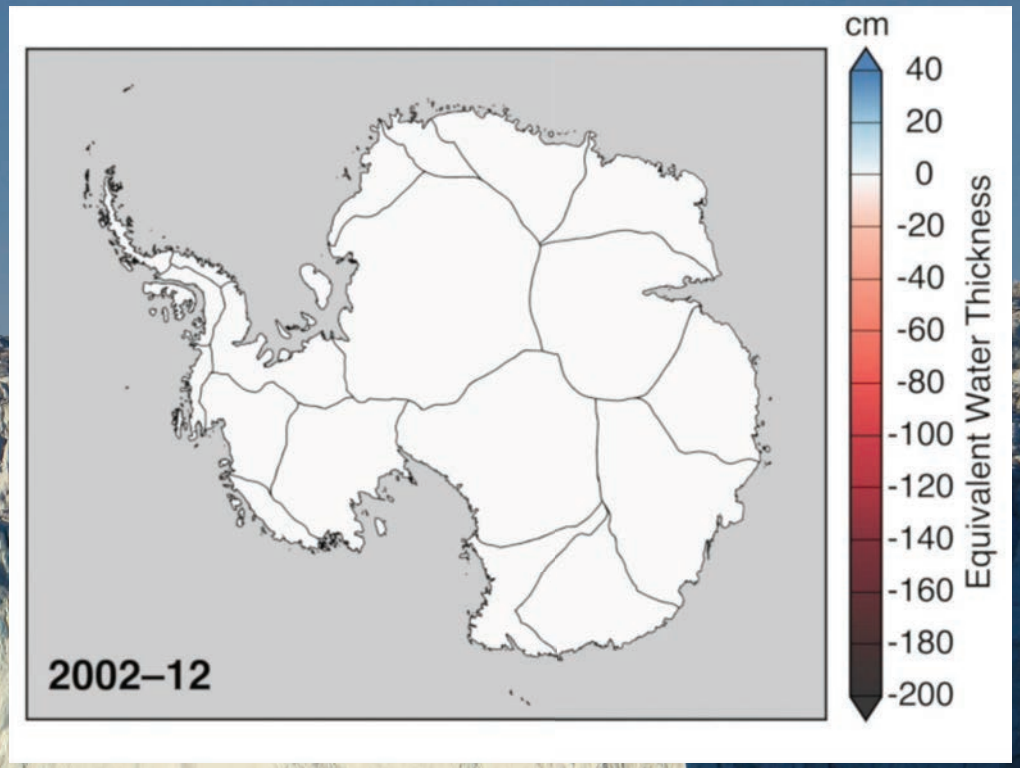
Cons:
-Spatial resolution of a few hundred kilometer scale (does not provide details at the glacier leve)l ,
- Does not provide details about partitioning into physical processes.
-correction for GIA (Glacial Isostatic Adjustment)





Velicogna et al 2014, updated

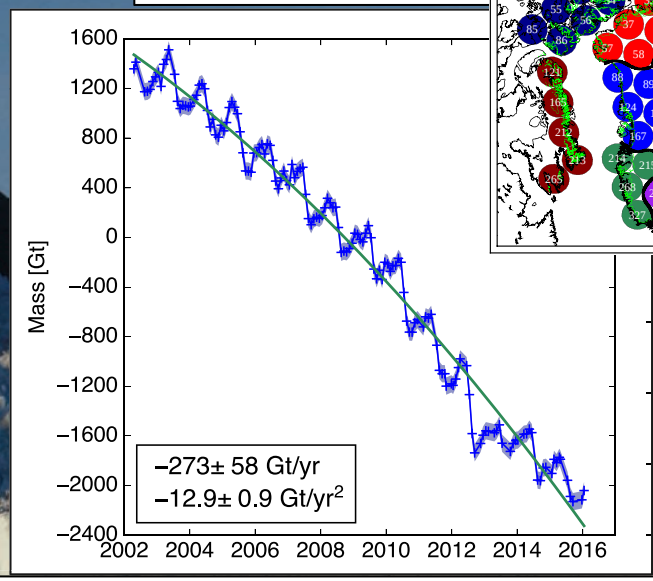


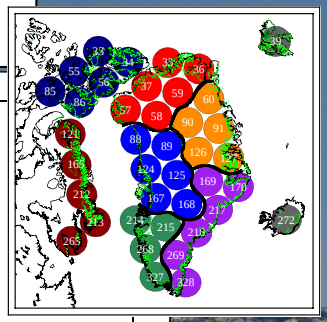


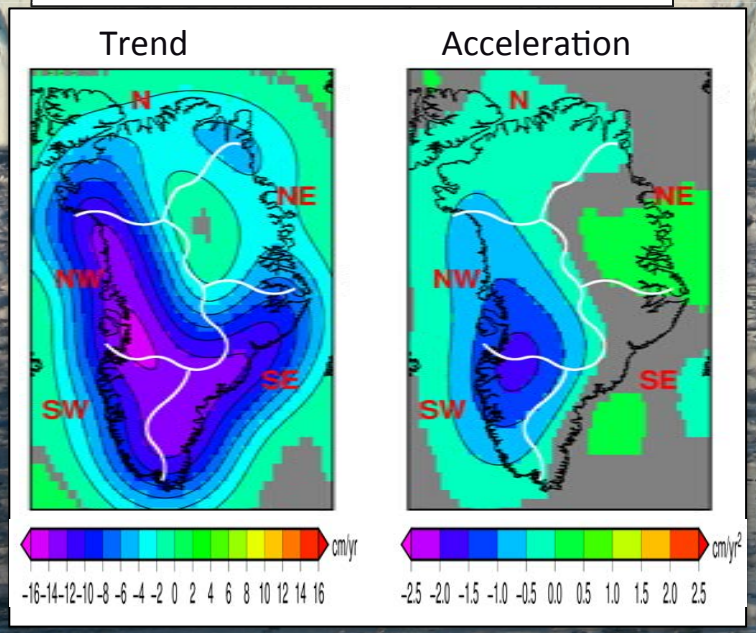
http://faculty.sites.uci.edu/velicogna/animations/

Ice Sheet Mass Balance(Apr 2002-Jan 2016)

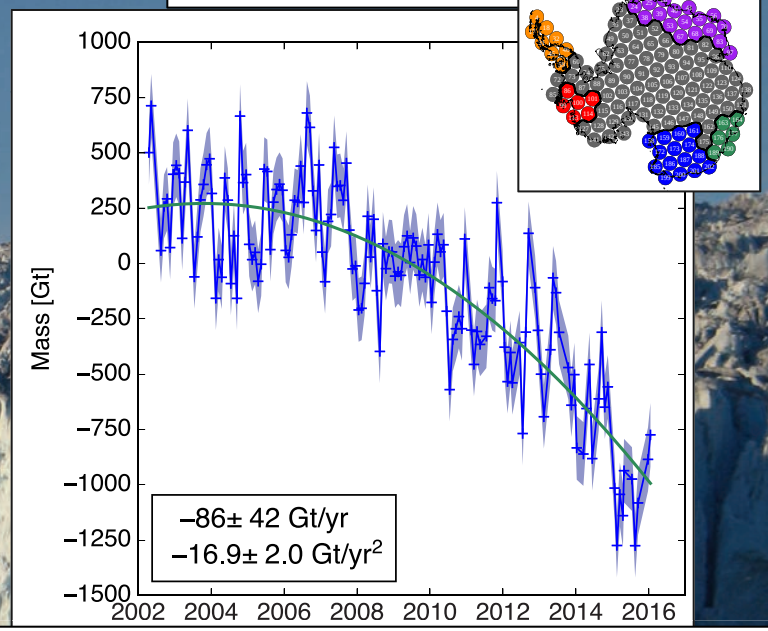
Greenland

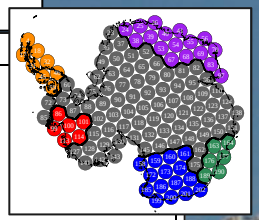


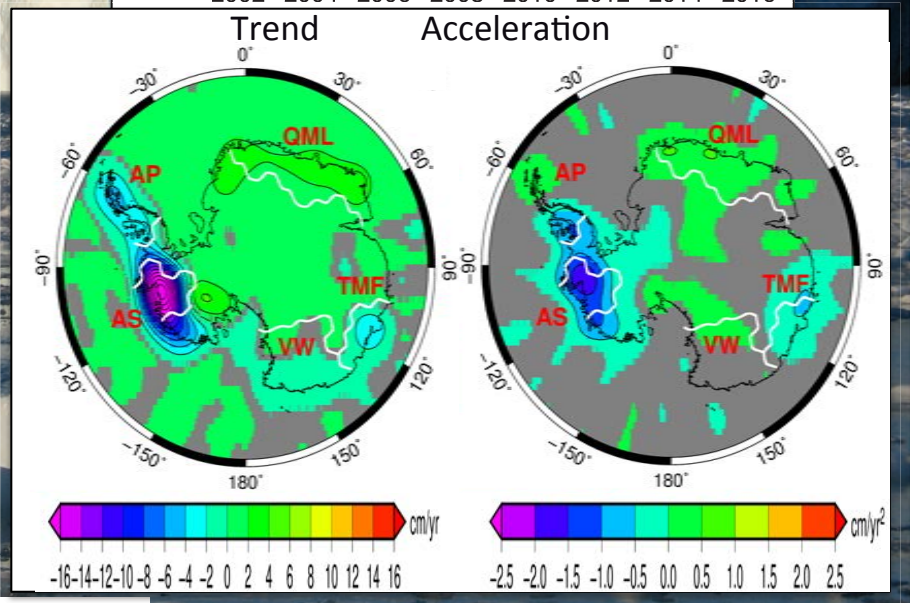




Antarctica







Velicogna et al., 2014, updated.

Synergy of observations

GRACE, Altimetry, InSAR are not competing techniques, but complementary techniques of mass balance.

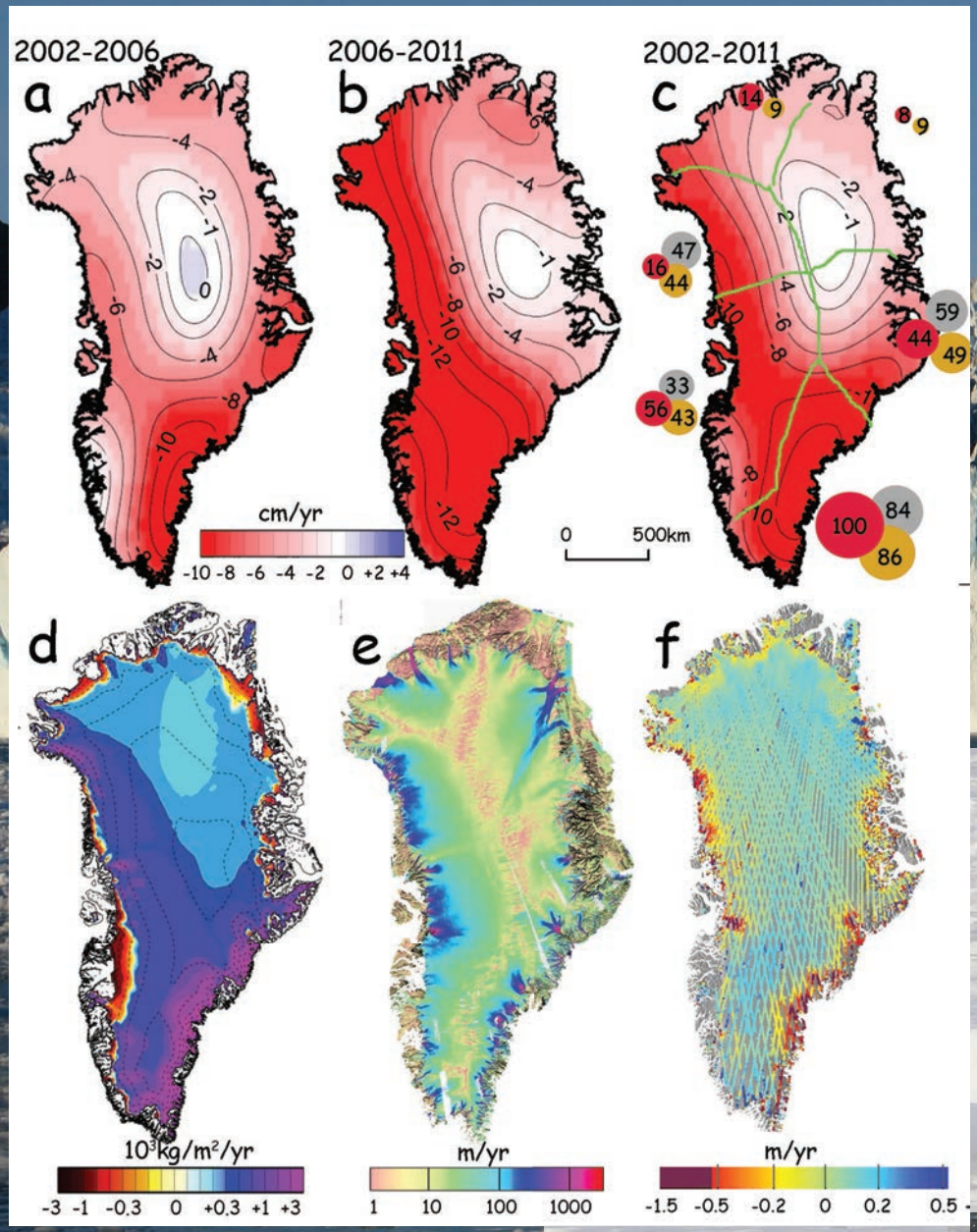
GRACE: direct, monthly updated, mass changes, but with no spatial details at the glacier scale, partitioning, and links to physics.

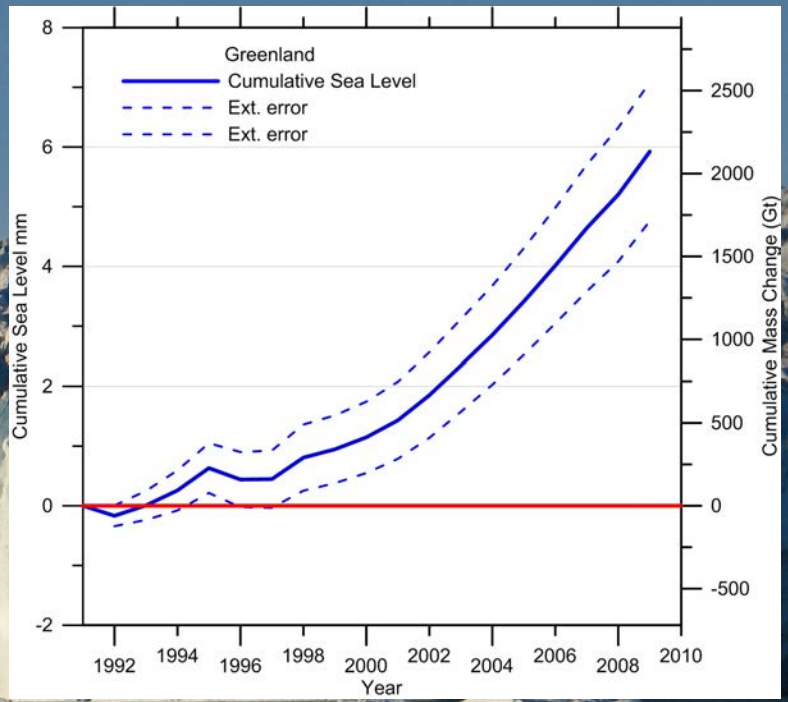
Altimetry: least-well fit for mass balance assessment, but critical for spatial details on thinning/thickening (early warning), and numerical models.

InSAR: Ice dynamics (and SMB) is key to interpret changes, partition of losses, and constrain numerical flow model.

Other data needed: Ice thickness, bathymetry, AWS (in situ), rheology, ocean thermal forcing, etc.

Greenland mass balance



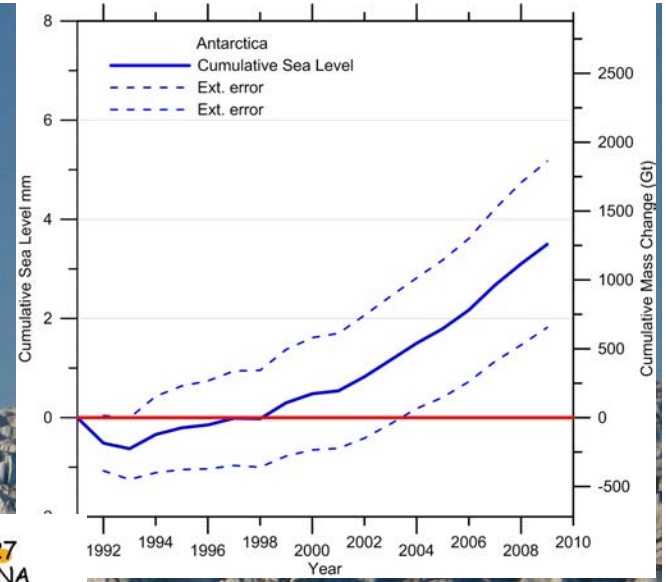


- Upper panel: Contribution to sea from Greenland based on 12 studies.
- 50% of the loss if from increased surface melt, 50% from increased glacier flow.
- Left panel: (a-c) Mass loss from GRACE for three periods; (d) RACMO SMB for 1989-2004; (e) Ice velocity for 2007-2009; and (f) Surface elevation changes from ICESat for 2003-2008.

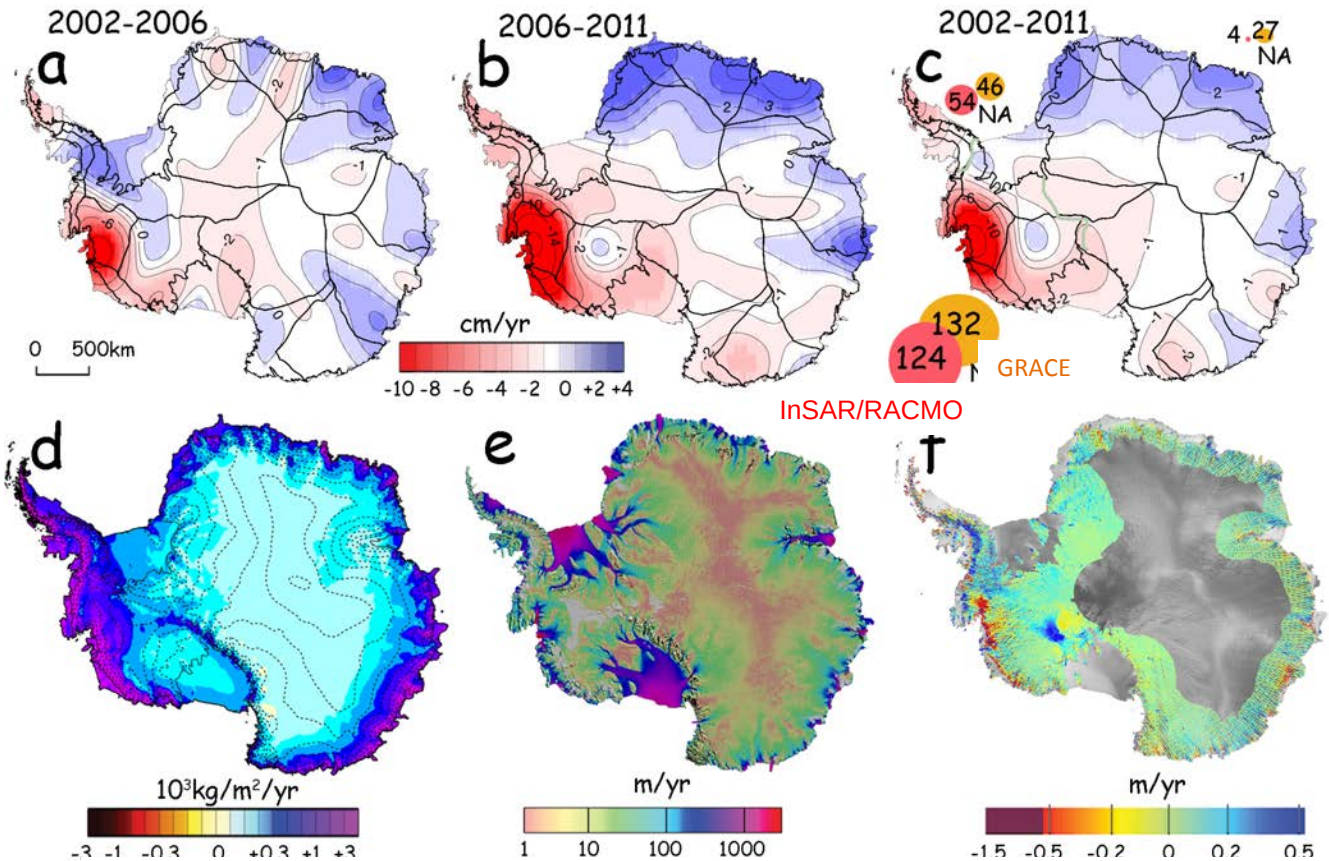
IPCC AR5 Ch 4, 2013

Antarctic mass balance

Right panel: C Synthesis of 12 studies, 3 techniques, for Antarctica. Ice loss dominated by glacier flow.



← GRACE →

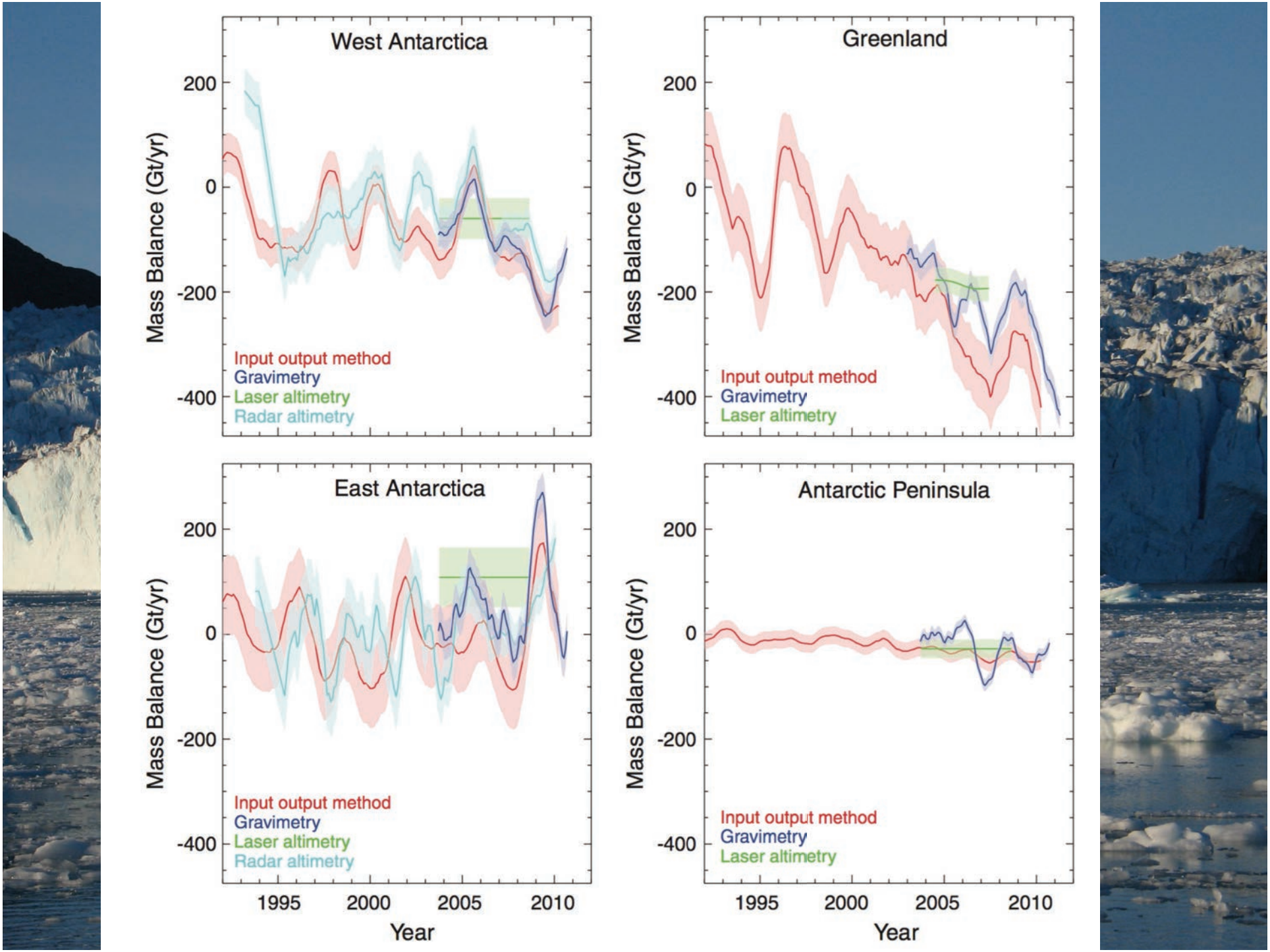


SMB Velocity Height change

IPCC AR5 uses all studies

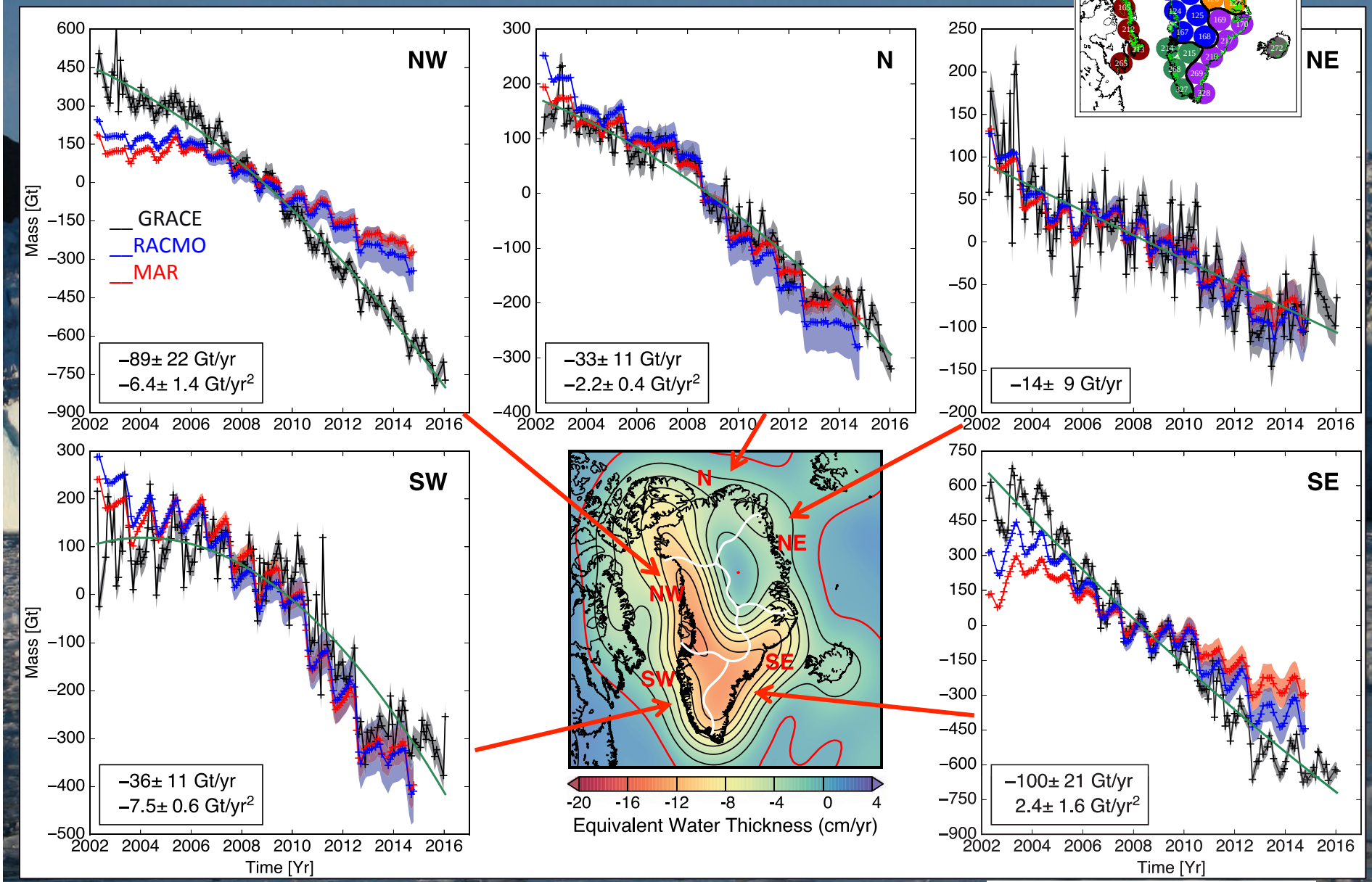
Left panel: (a-c) Mass loss from GRACE; (d) RACMO/SMB for 1989-2004; (e) Ice velocity for 2007-2009; and (f) ICESat surface elevation changes for 2003-2008.

IPCC AR5 Ch 4, 2013


West Antarctica
Greenland
East Antarctica
Antarctic Peninsula
Mass Balance (Gt/yr)
200
0
-200
-400
Input output method
Gravimetry
Laser altimetry
Radar altimetry
1995
2000
2005
2010
Year

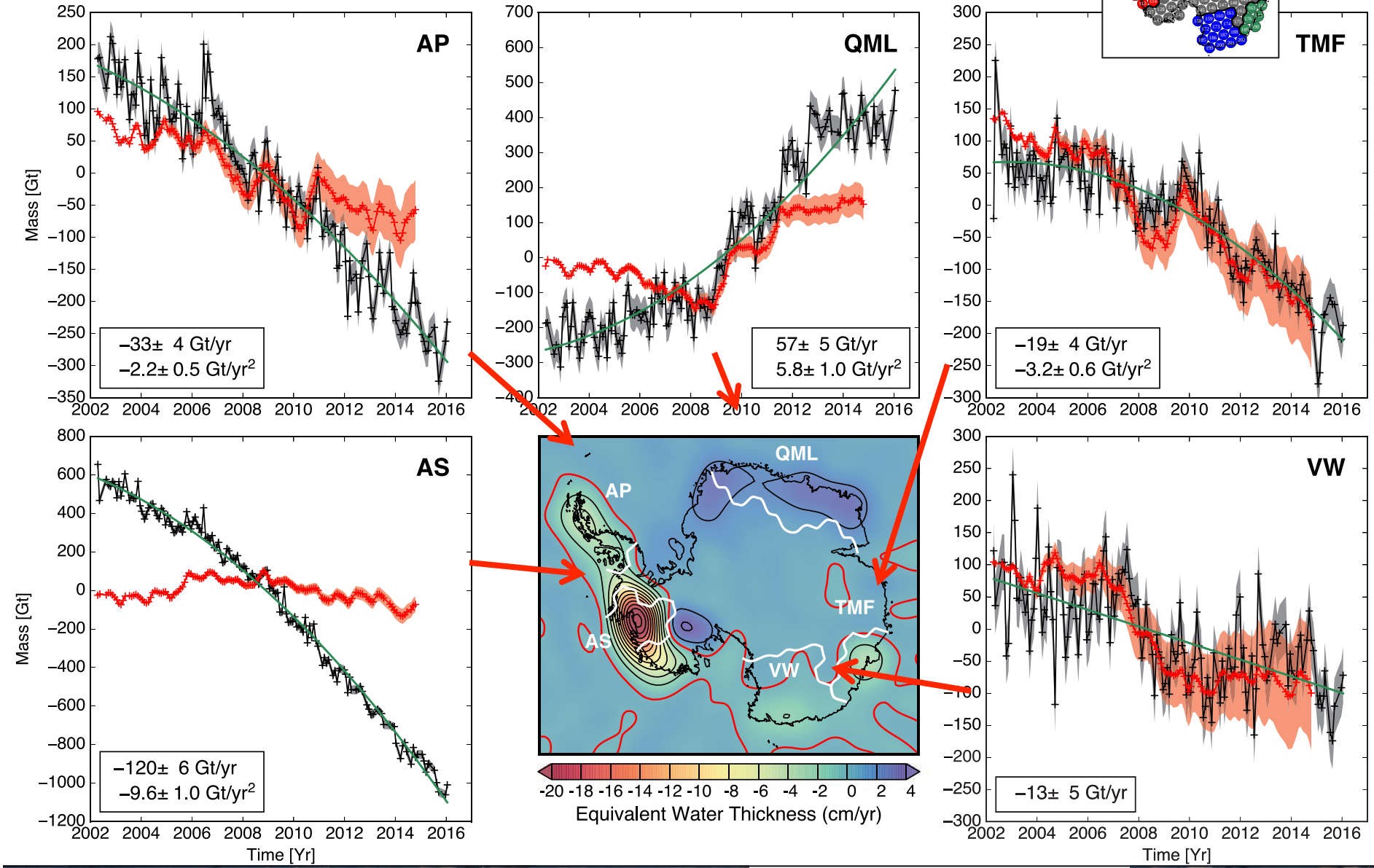
Synergistic use of independent observations to improve understanding of Physical processes

Greenland



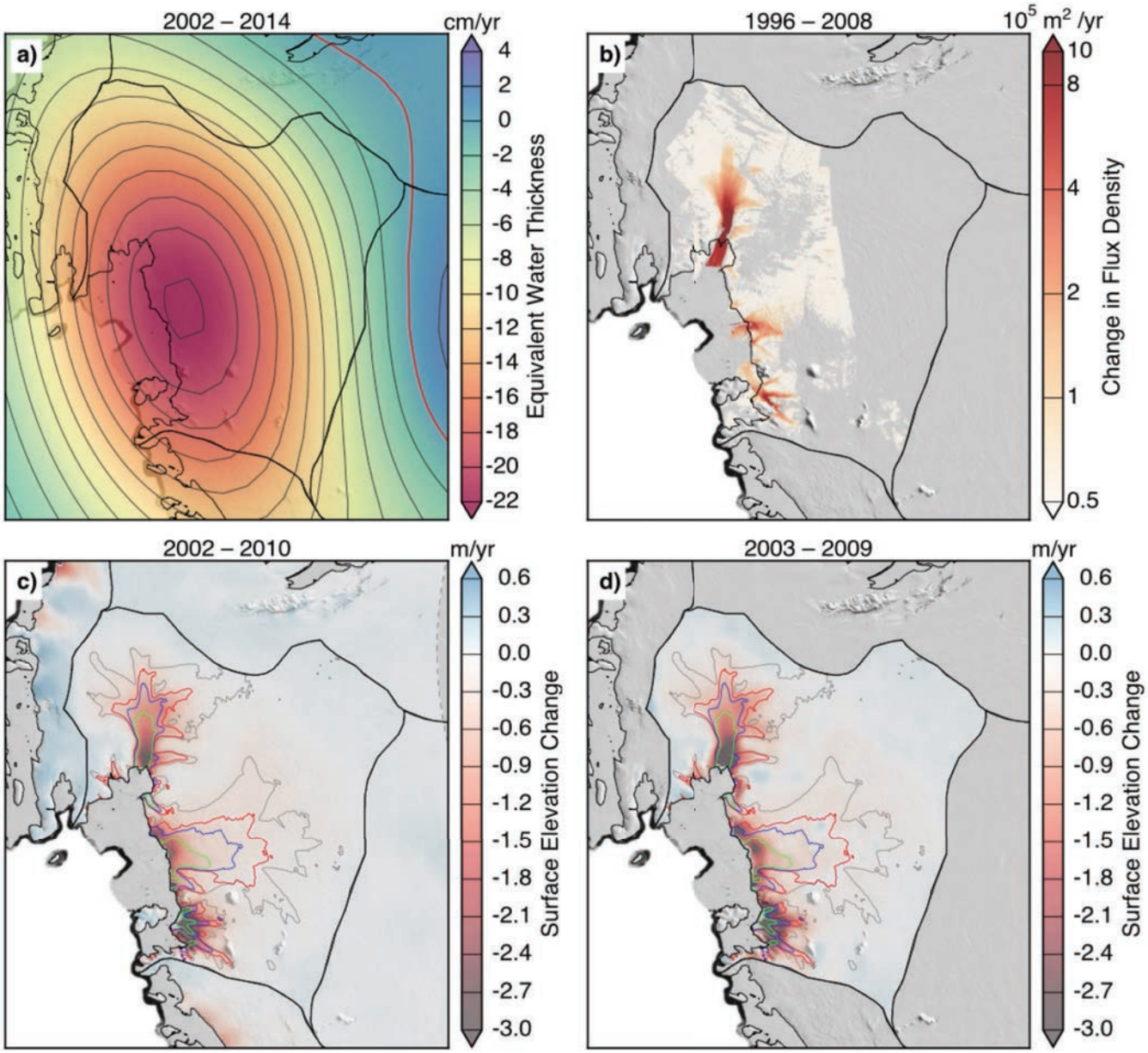
Velicogna et al., 2014, updated.

Antarctica



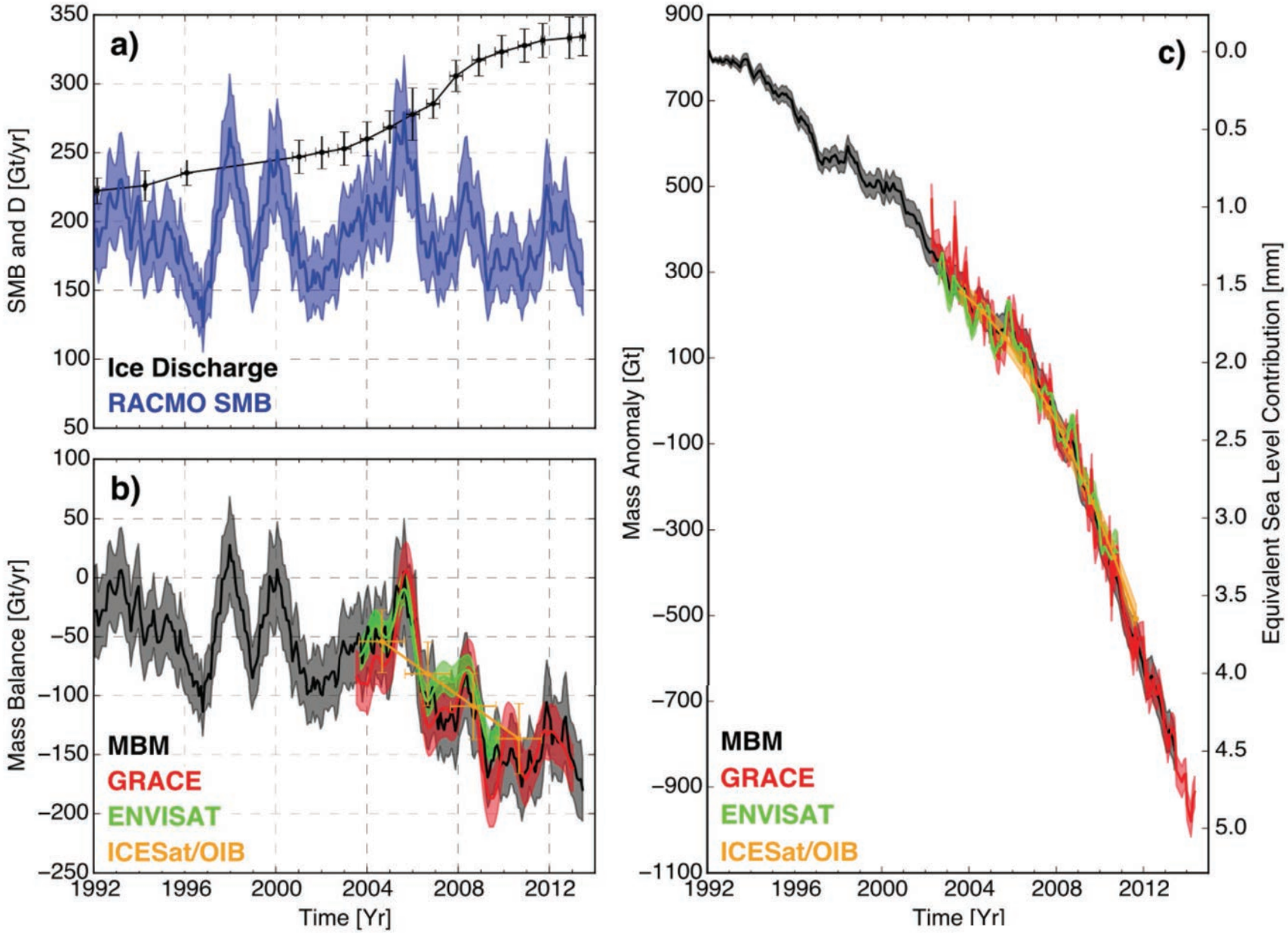
Velicogna et al., GRL, 2014; updated.

Mass Loss of the Amundsen Sea Embayment Glaciers



Sutterley et al., GRL, 2014

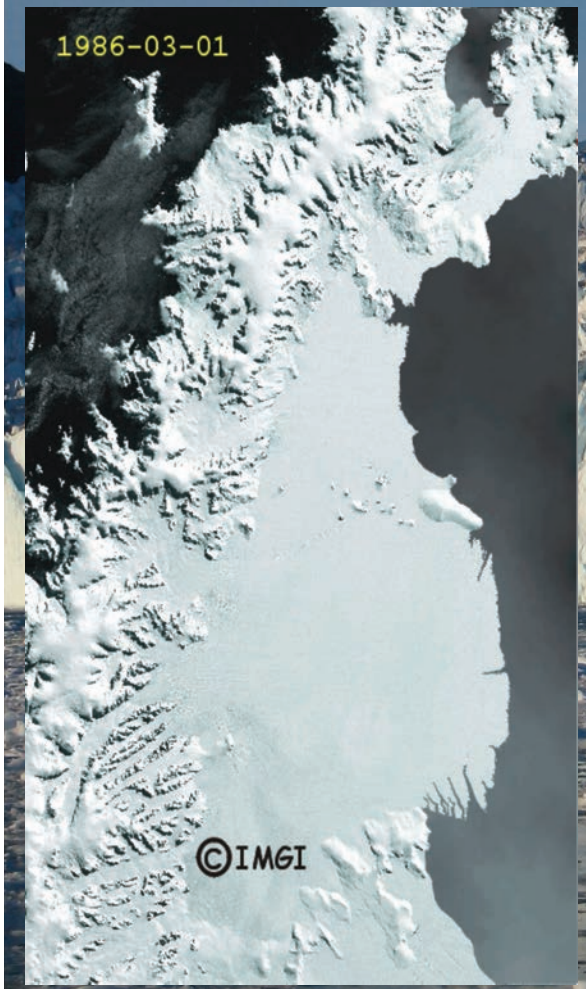
Mass Balance of the Amundsen Sea Embayment (ASE)

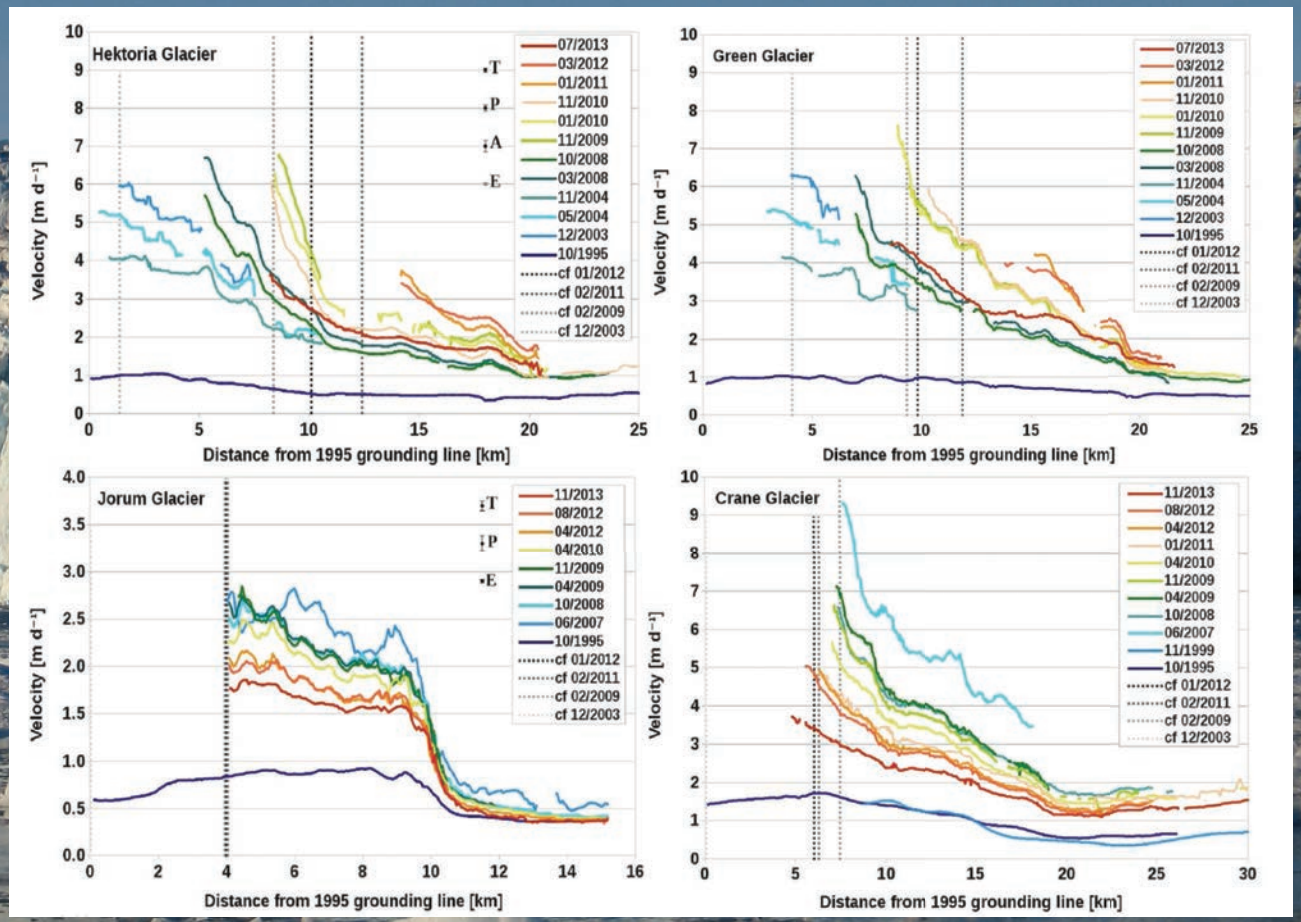


Sutterley et al., GRL, 2014

Ice shelf melting in Antarctica

An 8-fold increase in ice speed would raise sea level 4 m/century

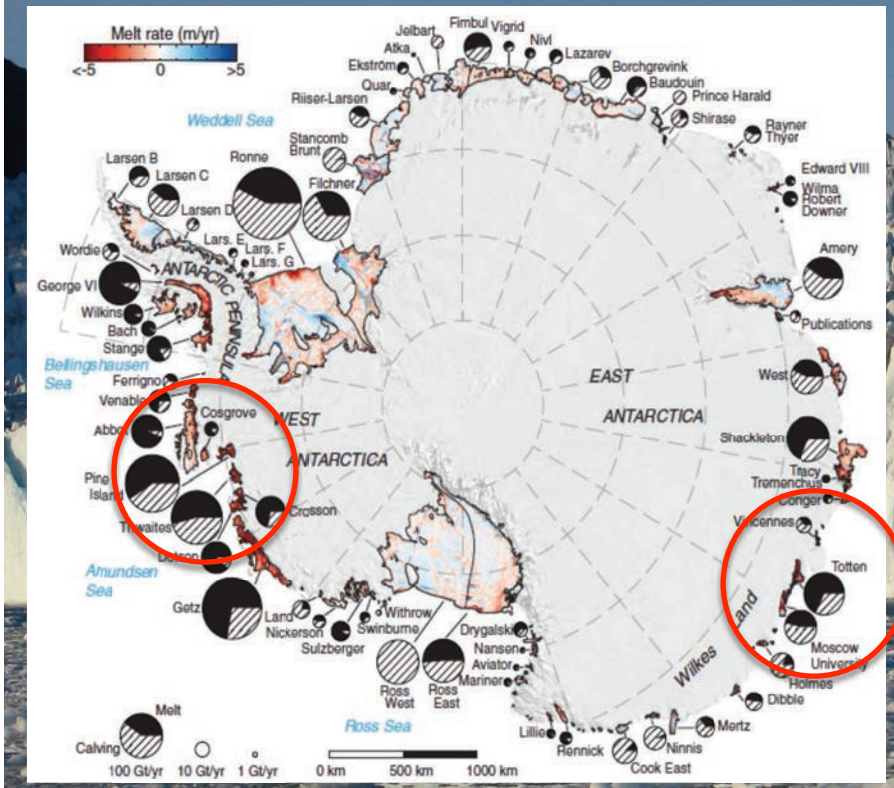


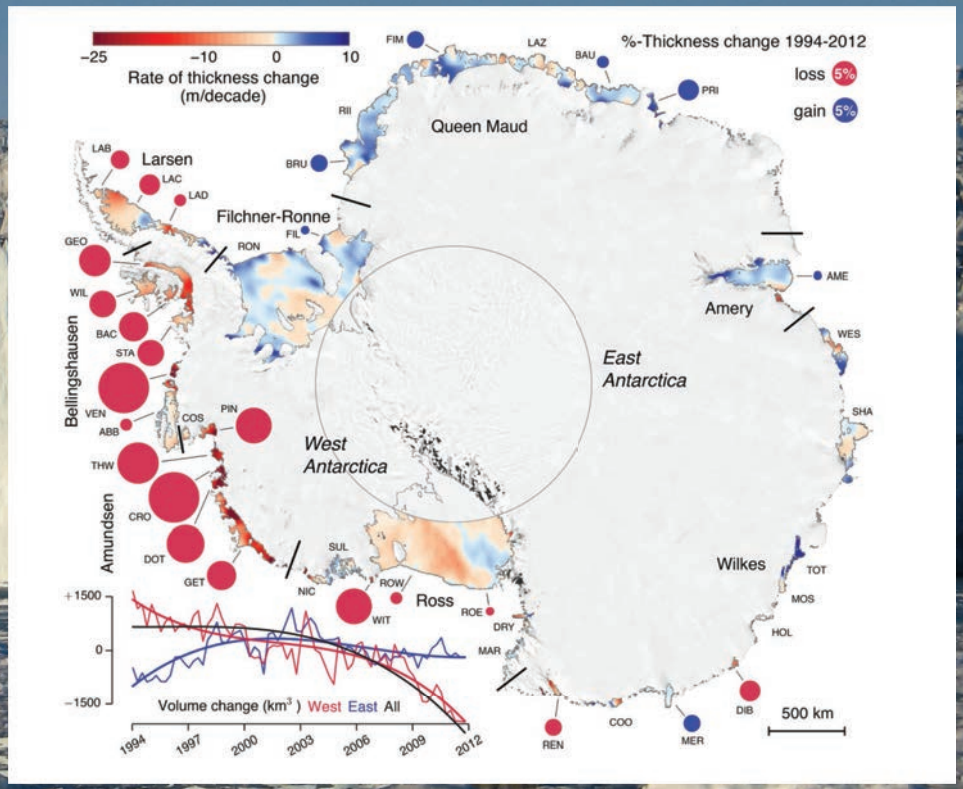


Wuite, J., et al, TC 2015

Ice shelf melting in Antarctica

Paolo et al., 2015

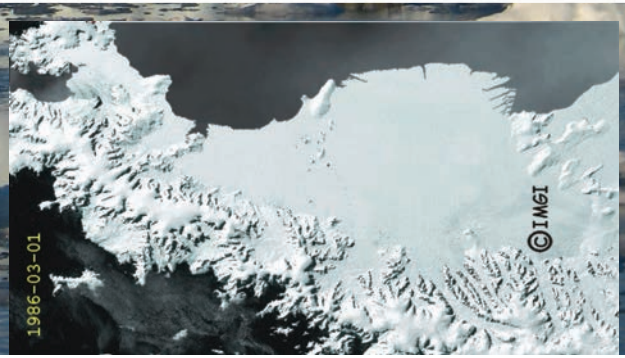




Bottom melt (black) vs calving (hatch)

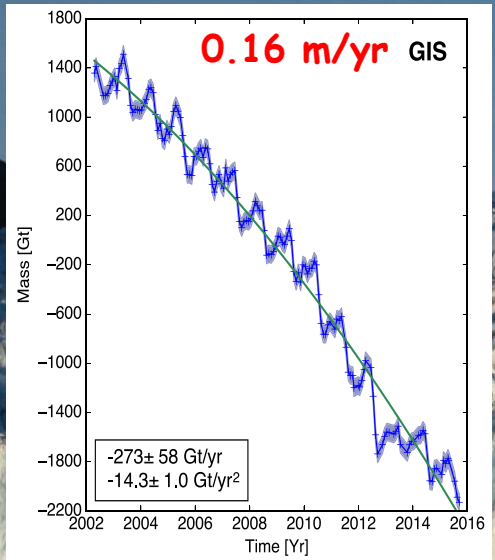
1,325 Gt/yr versus 1,089 Gt/yr

Half of the melt from SE Pacific (Rignot et al., 2013)

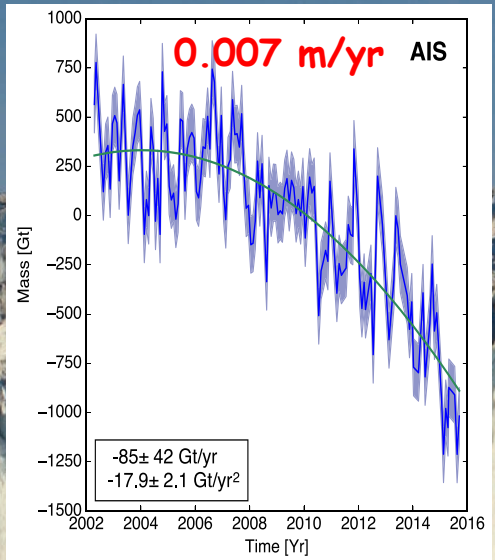


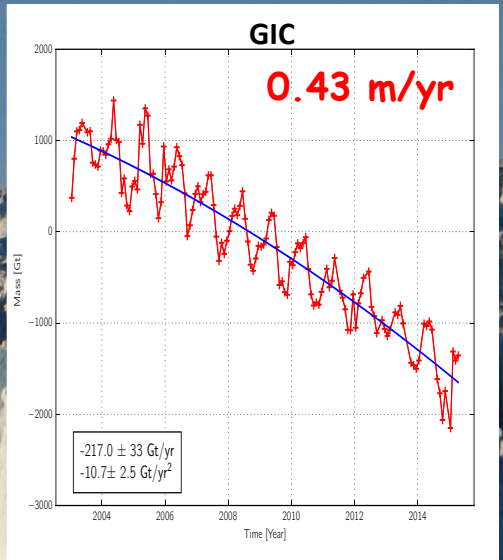
Ice sheets, glaciers and ice caps mass balance

Time period 2003-2015



(Velicogna, 2015)





(Ciraci et al., 2015)

Patagonia: 25±12 Gt/yr → 1.2 m/yr (21,000 Km²)
Alaska: 56±9 Gt/yr → 0.65 m/yr (85,000 km²)
Amundsen Sea sector: 104±7 Gt/yr → 0.26 m/yr (393,000 km²)
Antarctica: 85±42 Gt/yr (14 M km²)
Greenland: 273±58 Gt/yr (1.7 M km²)
GIC: 217±33 Gt/yr
Acceleration: 43 Gt/yr extra loss every year.
Mass loss increased from 575 Gt/yr in 2009 to 854 Gt/yr in 2015.

How to improve/continue ice sheet mass balance estimates

Mass Budget approach (Sentinel1a/b, NISAR, ALOS PALSAR-2, Cosmo Skymed, TerraSAR, RADARSAT, SAOCOM, OIB, RACMO/MAR/GEOS5):

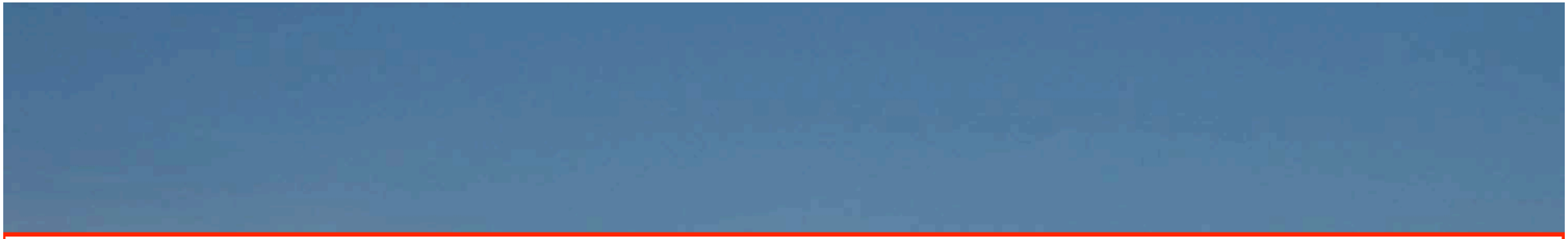
-- complete direct measurements of ice thickness at grounding lines
-- track grounding lines continuously (monthly).
-- continuous (monthly or lower) time series of ice velocity around the entire periphery.
-- Improved SMB models (higher resolution, more complete physics, improved melt models, faster turn around of output products.)

Altimetry, volume change estimate (Cryosat-2, OIB, ICESat-2, Sentinel-3)

-- denser coverage along the coast
-- better understanding of firn compaction and impact of density change on mass change estimates.
-- longer, continuous time series, especially in interior regions.

GRACE (GRACE follow-on, GRACE-2)

-- Longer time series
-- improved spatial resolution (GRACE follow-on)
-- improved GIA correction in Antarctica
-- benchmark for inter-comparison.



Conclusion

Tremendous progress, various techniques agree well and extend the data record, areas where they do not agree well are areas where the signal is complex (e.g. East Antarctica)

WE will witness an increase in capability in the future (GRACE F-O, ICESAt-2, InSAR, etc.), more resolution, more continuity, more comprehensive.

Independent provide additional constraints on numerical models and interpretation. Continuous, long time series are critical for models.

Understand the processes not jus mass balance why