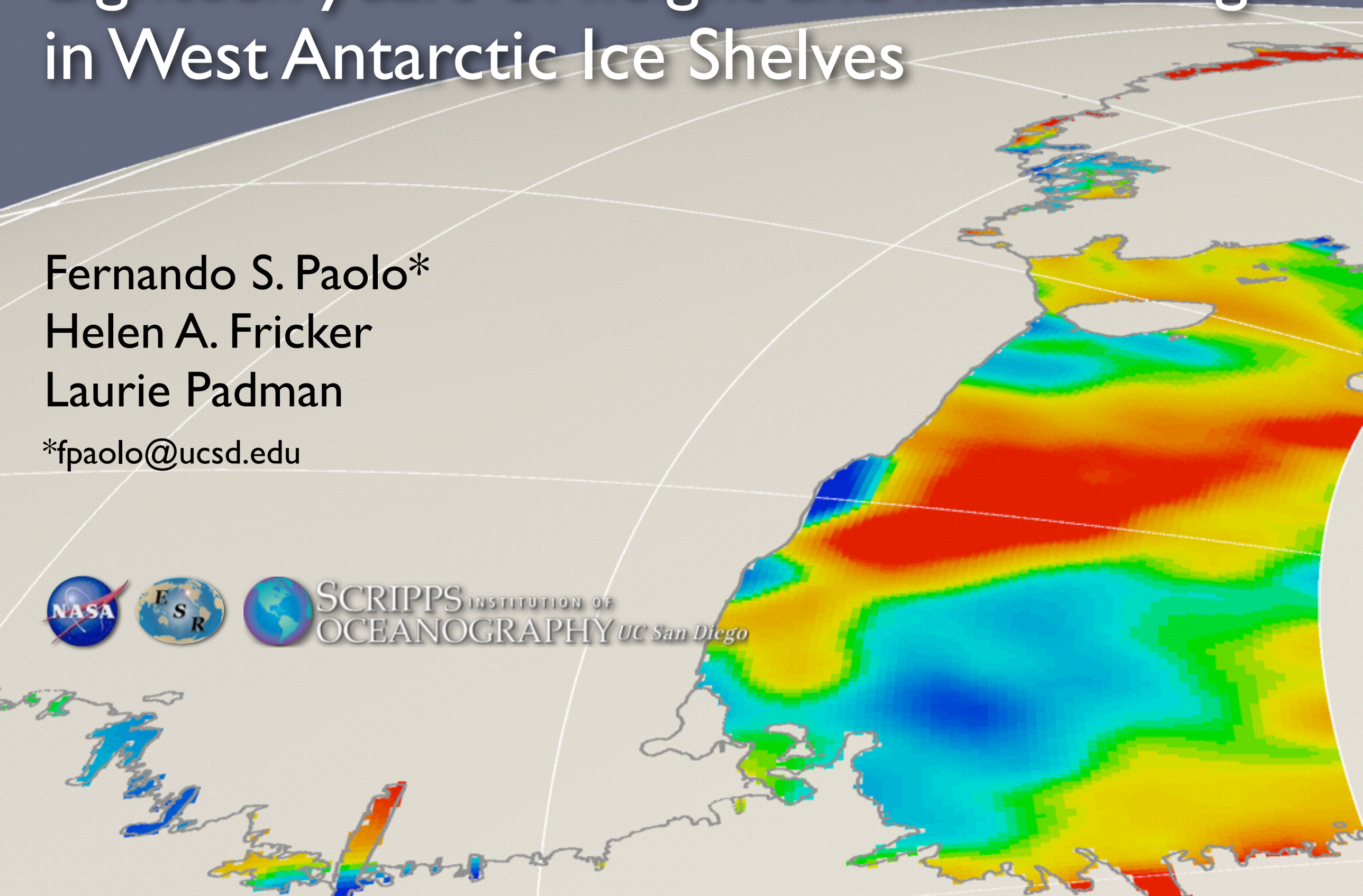
Eighteen years of height and mass changes in West Antarctic Ice Shelves

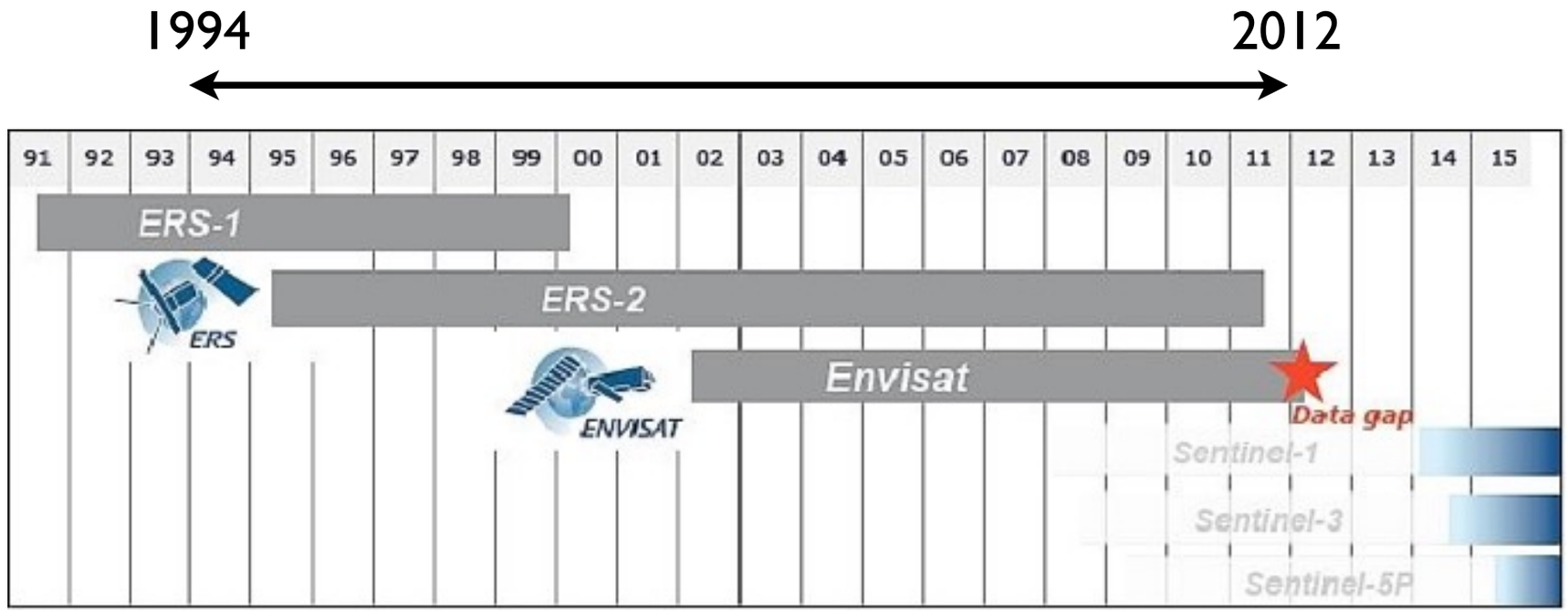
Fernando S. Paolo*
Helen A. Fricker
Laurie Padman

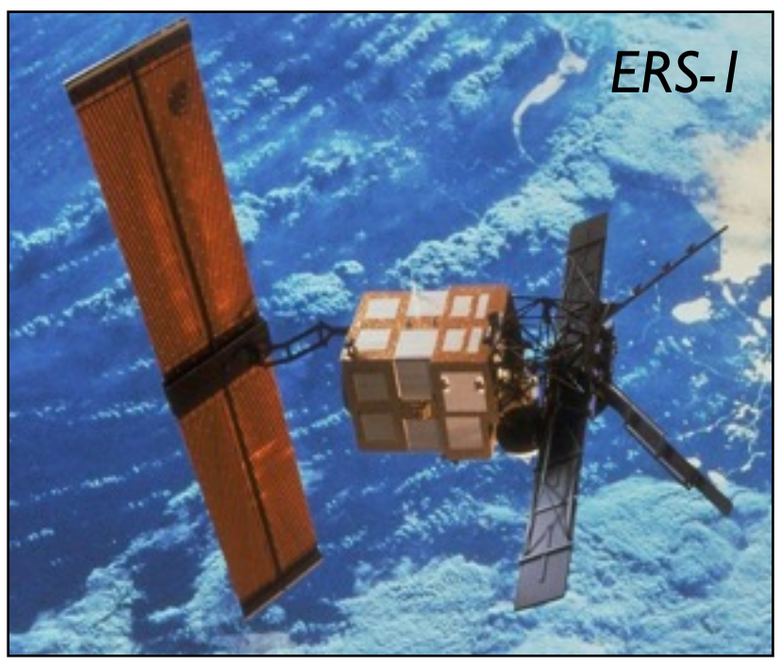
*fpaolo@ucsd.edu



Can we obtain **long** and **continuous** observational records for the Antarctic ice shelves?

We have integrated 18 years of observations





Ice-shelf thinning
West Antarctica
1994-2012

meters
0
-20
-40
-60

Year 1994.0

Outline

The challenge in obtaining long observational records

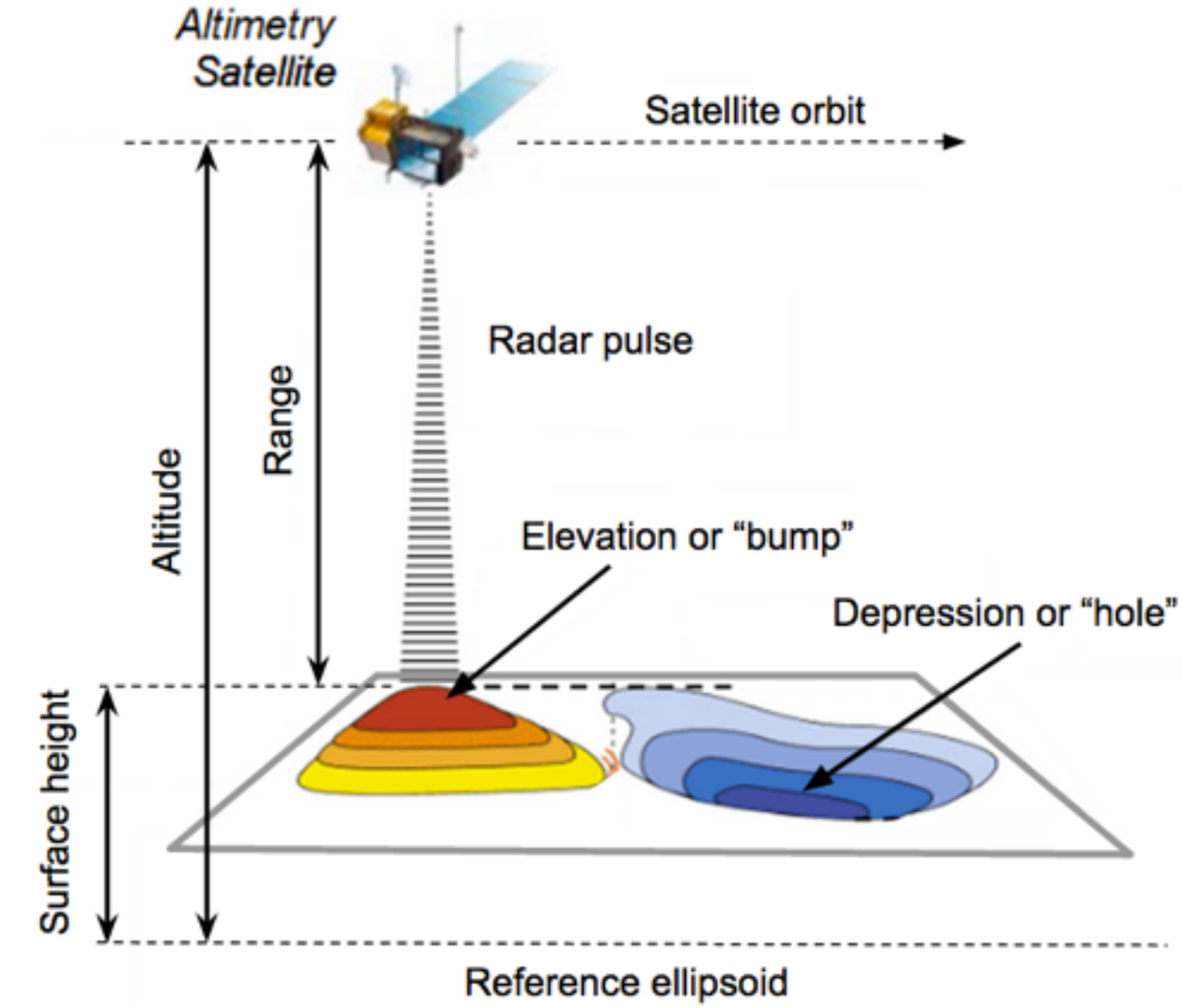
Two key points of our methodology

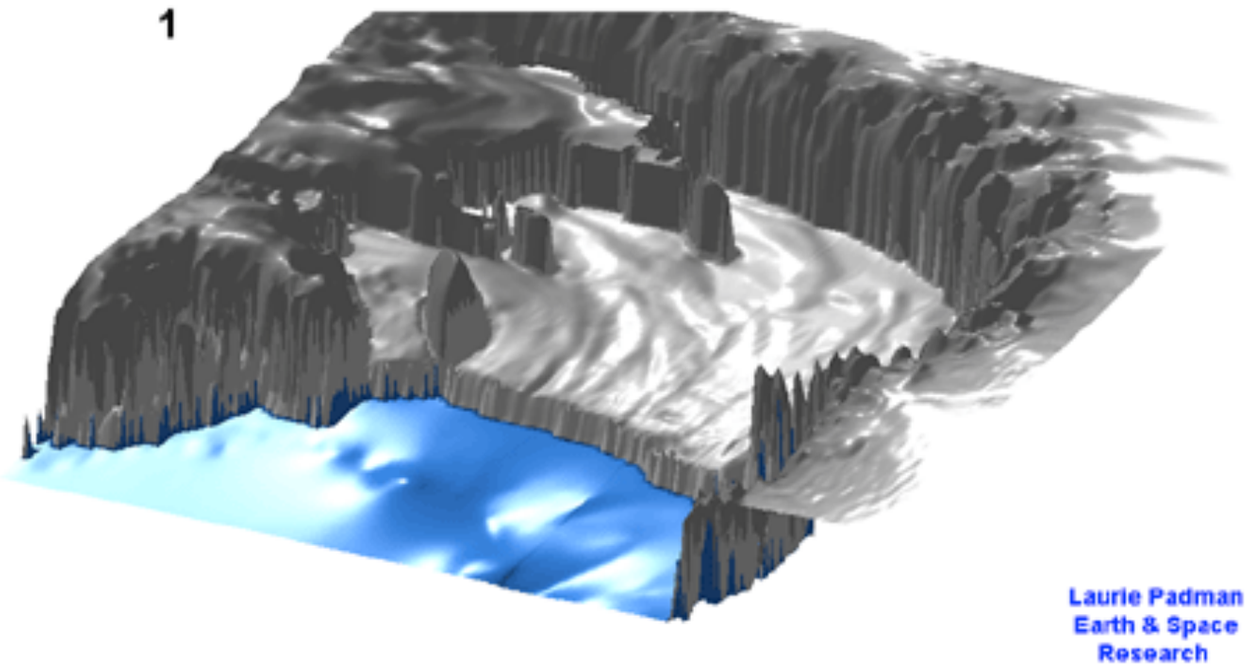
Show some results: 18 years of change

Summary

Problem:

Low signal-to-noise ratio

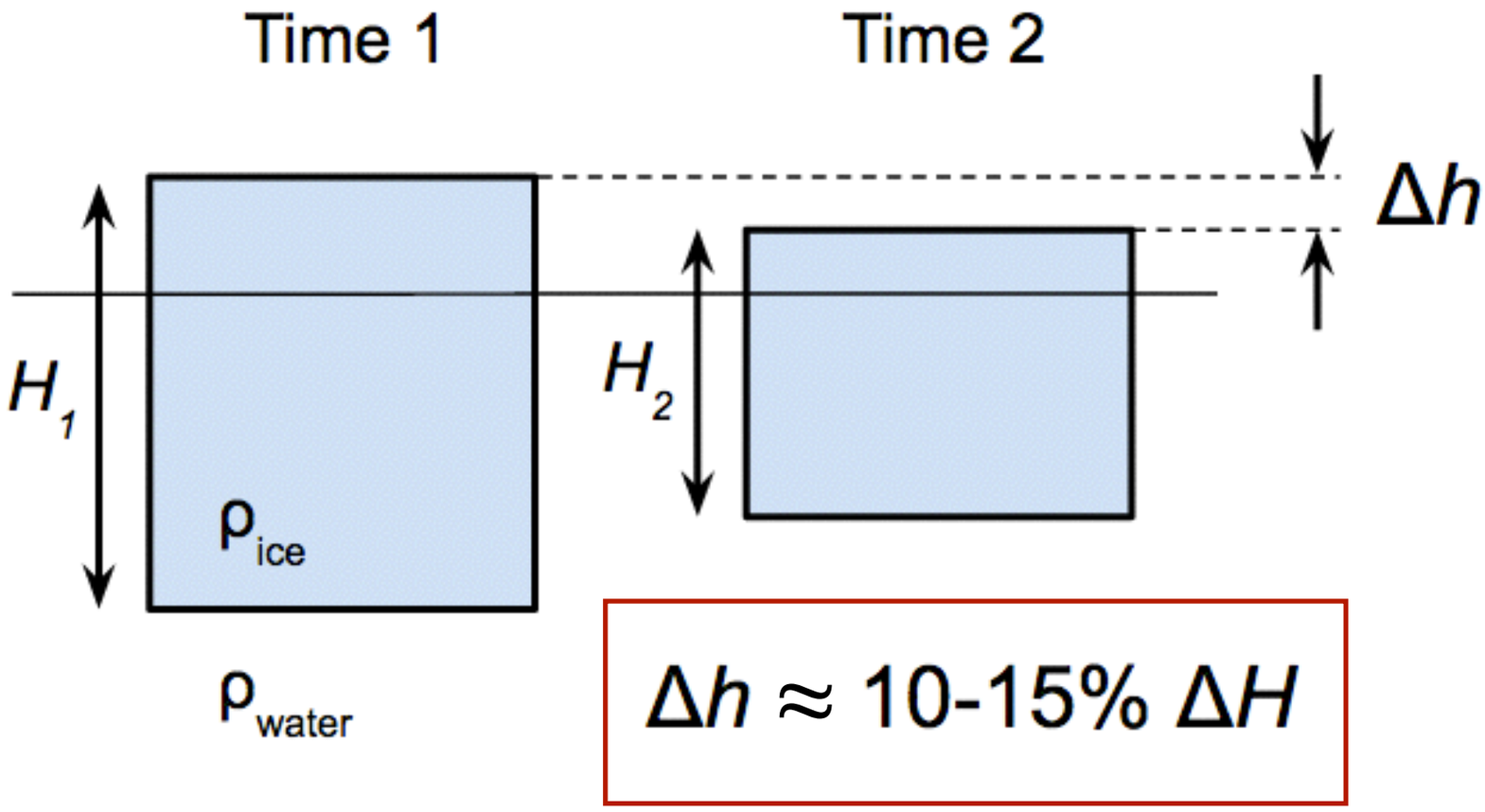




$$\partial h/\partial t = func($$

tides,
penetration,
backscatter,
pressure,
sea-level rise,
dynamic topo.,
…,
thickness)

As a consequence of hydrostatic balance...



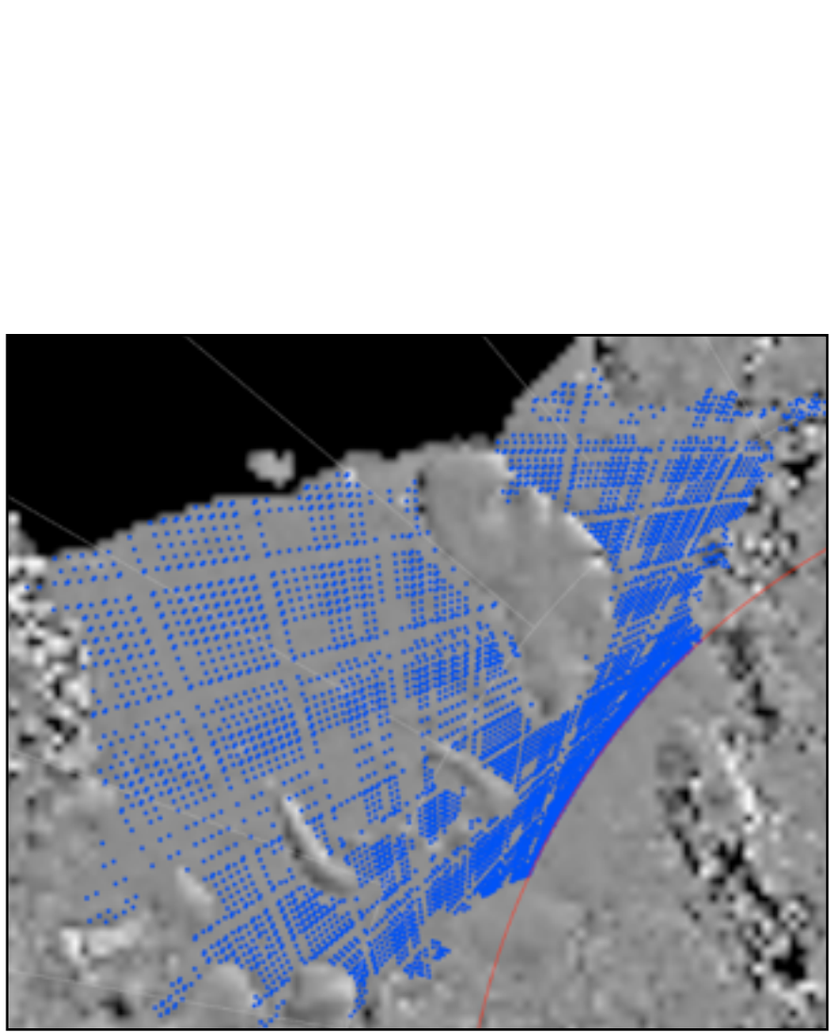
This limits detection of changes in the vertical component

Solution:

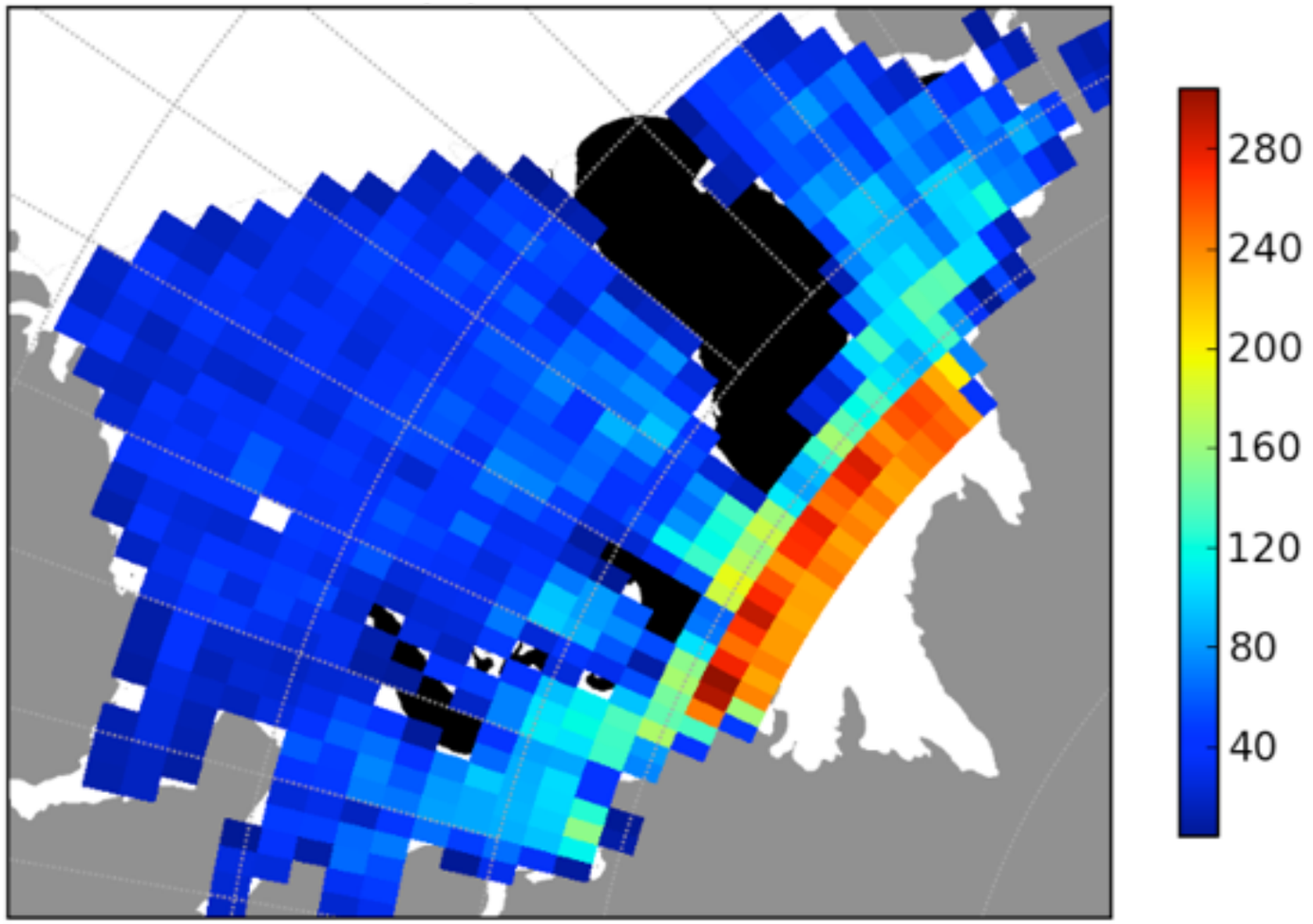
Averaging tens-to-hundreds of observations

Averaging #1

3-month time bins
27-km spatial cells

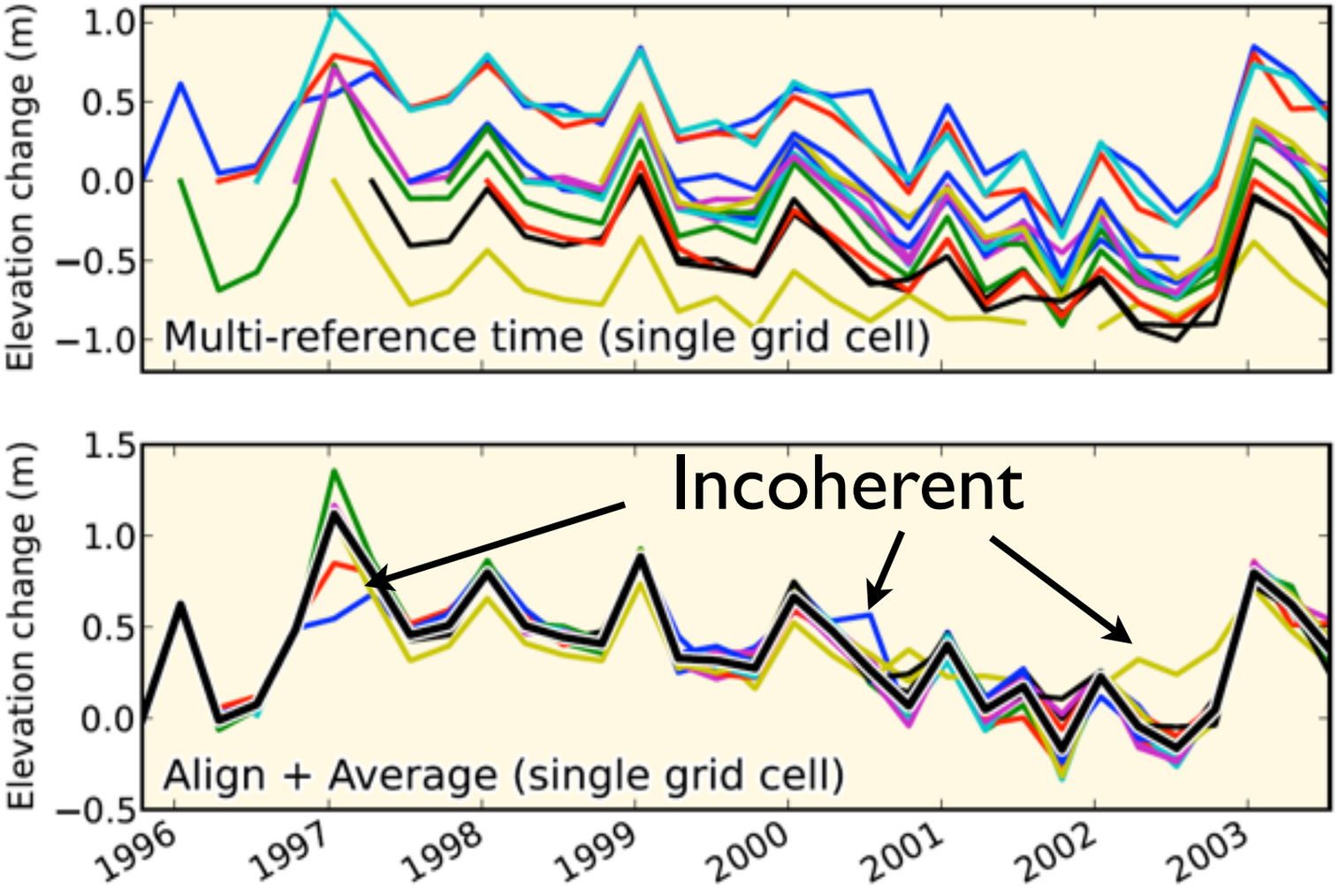


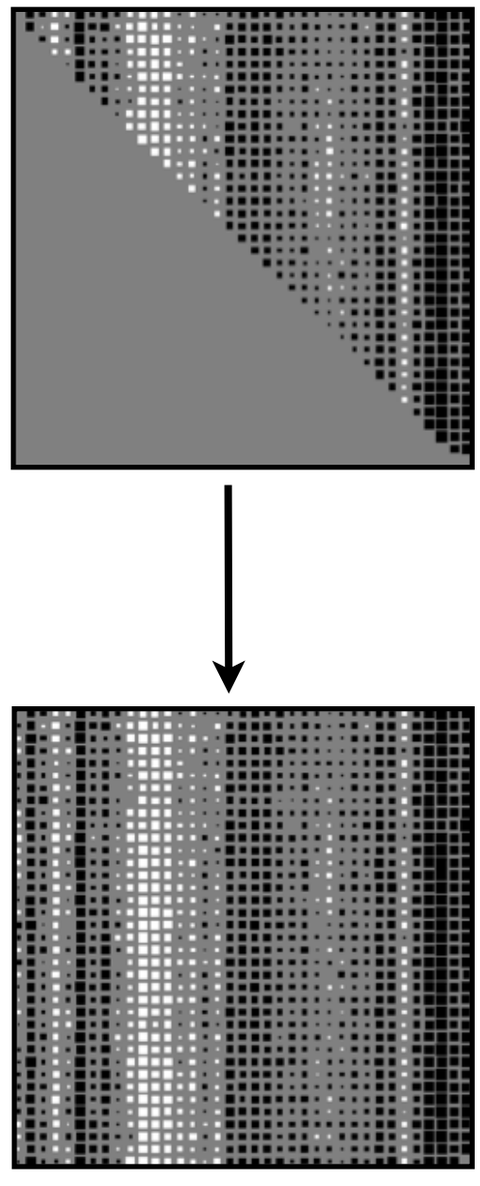
High crossover density



Averaging #2

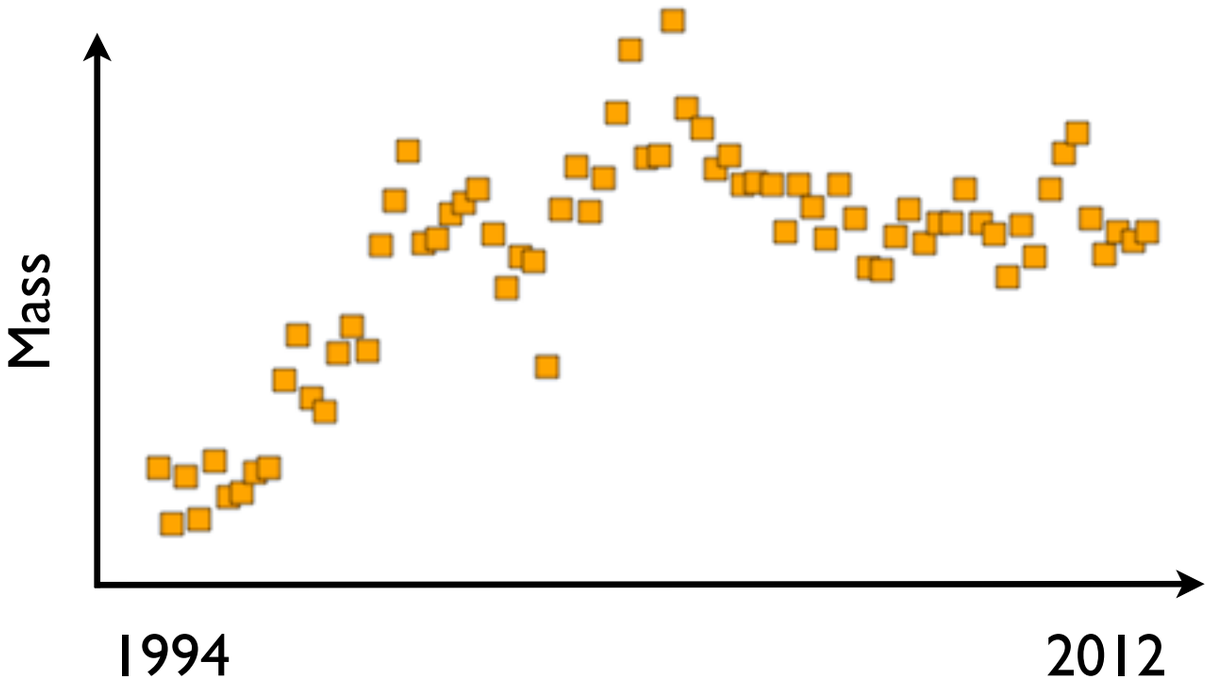
Coherent vs Incoherent signal



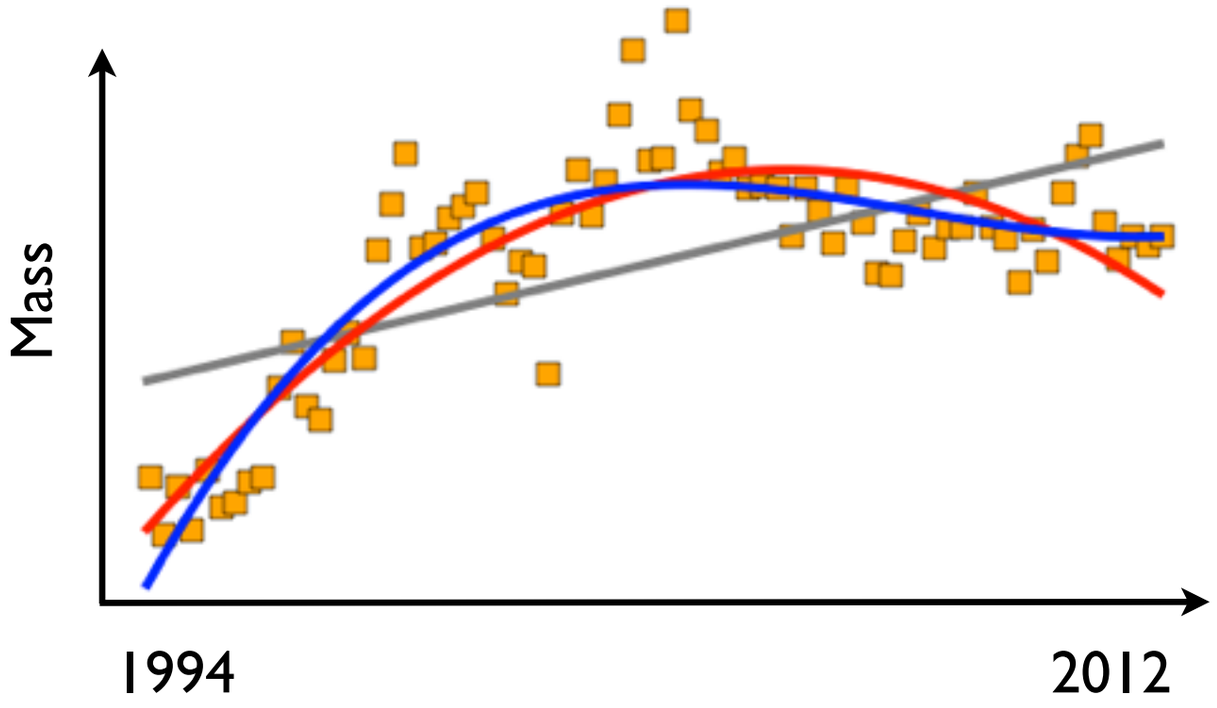


Problem:

Nonlinear (in time) underlaying trends



18 years of Mass change in East Antarctic ice shelves



Is the trend a

Line?

Quadratic?

Cubic?

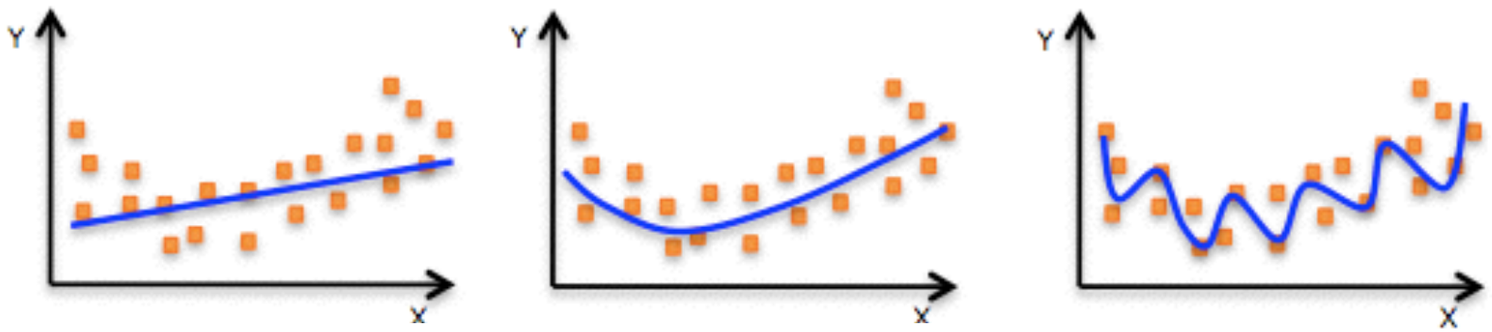
Solution:

Regularized regression

+

Cross-validation

Why do we fit straight lines to short records?



Underfitting Just right! Overfitting

Simple model ⟷ Complex model

High bias *High variance*

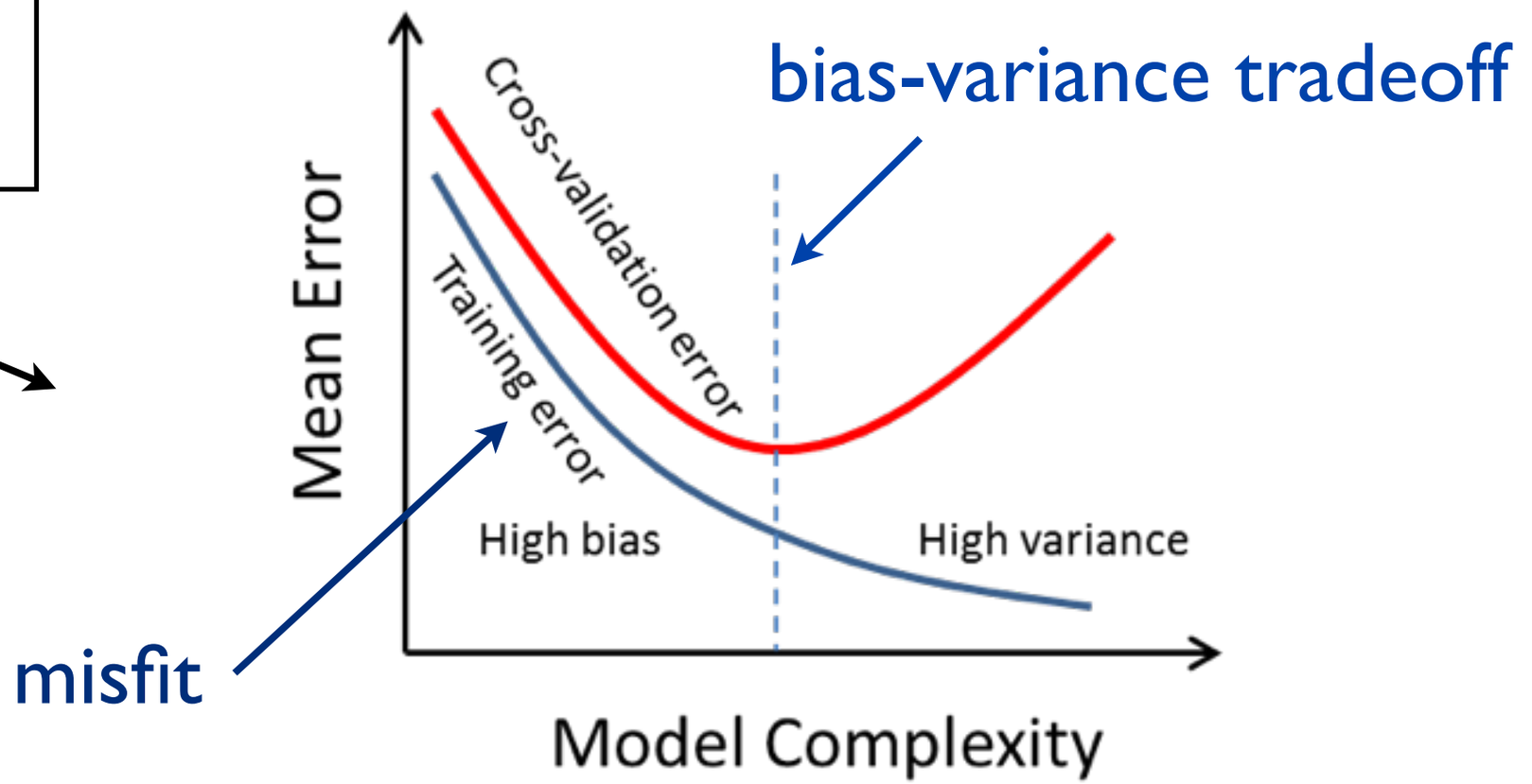
We fit polynomials: $\hat{h}(t) = \sum \beta_n t^n + \varepsilon$

Using Lasso: $min \; || h - t\,\beta ||_2 + \lambda || \beta ||_1$

constrains bias

constrains variance

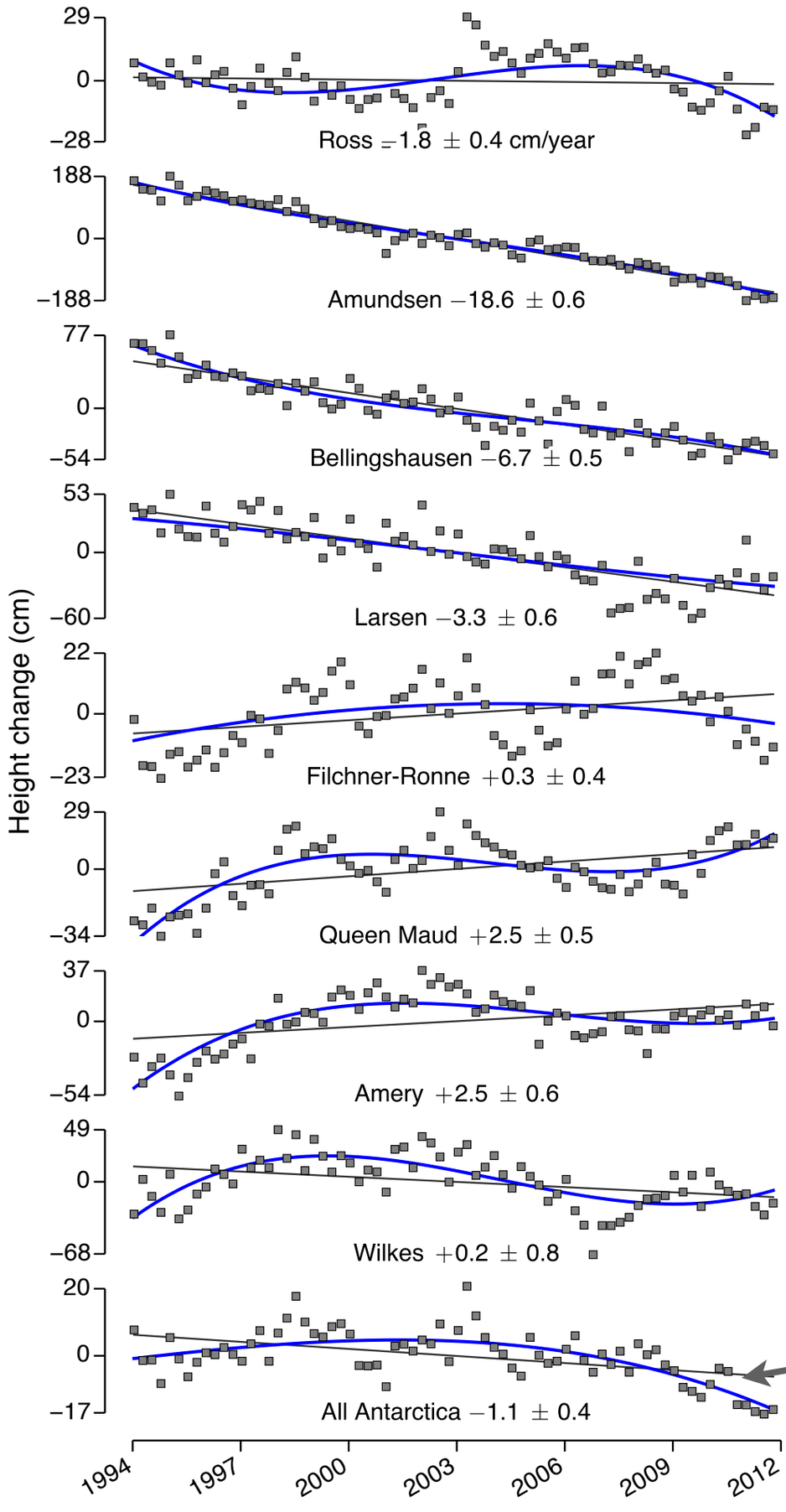
λ defines the shape of the fit!



Tibshirani, 1996

So what do we get after all?

Regional time series of surface-height change



Sustained ice loss since 1994

East ice-shelf regions in phase?

Ice-loss acceleration

These are long-term trends!

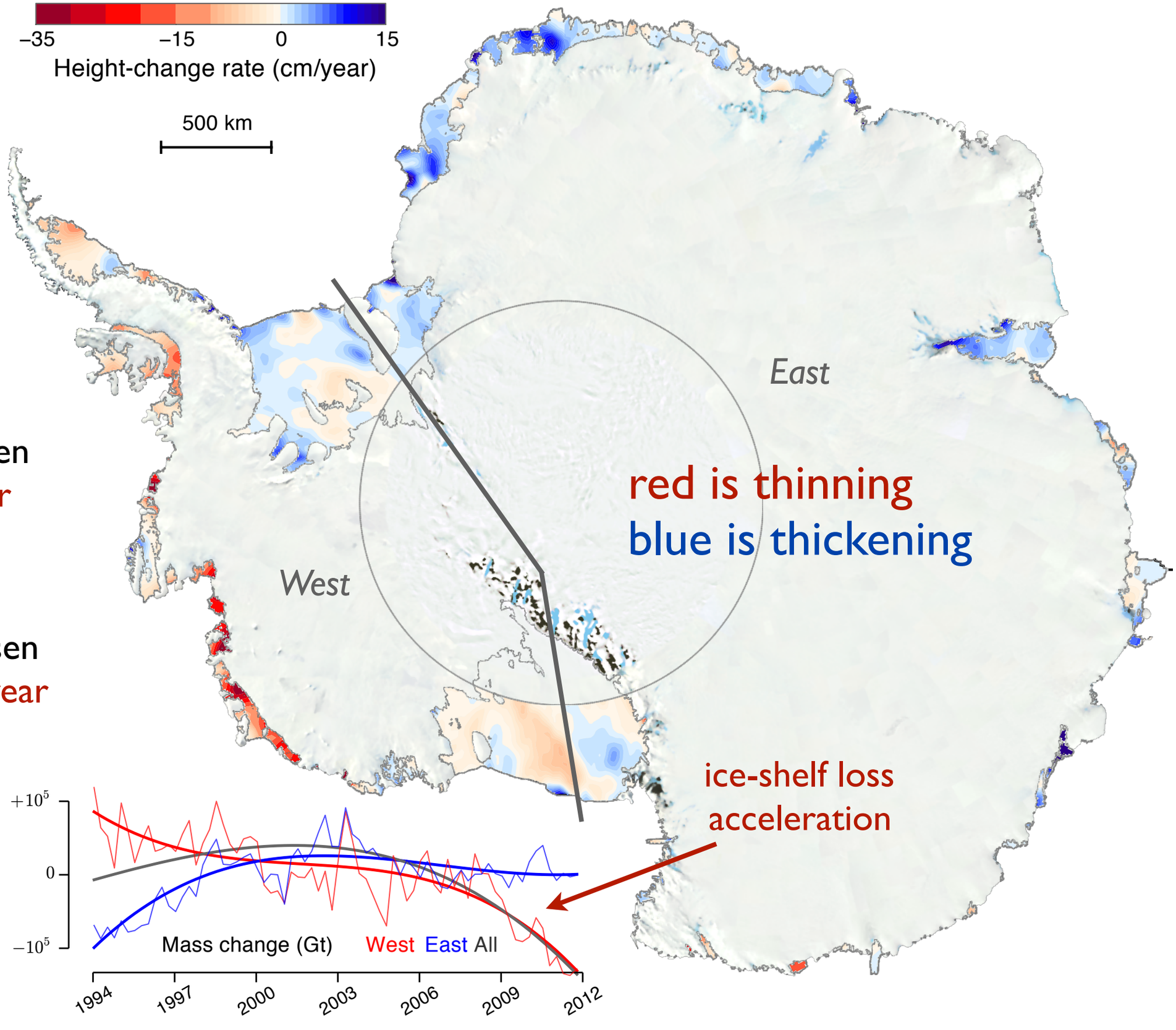
18-year rates of change

Regional thinning

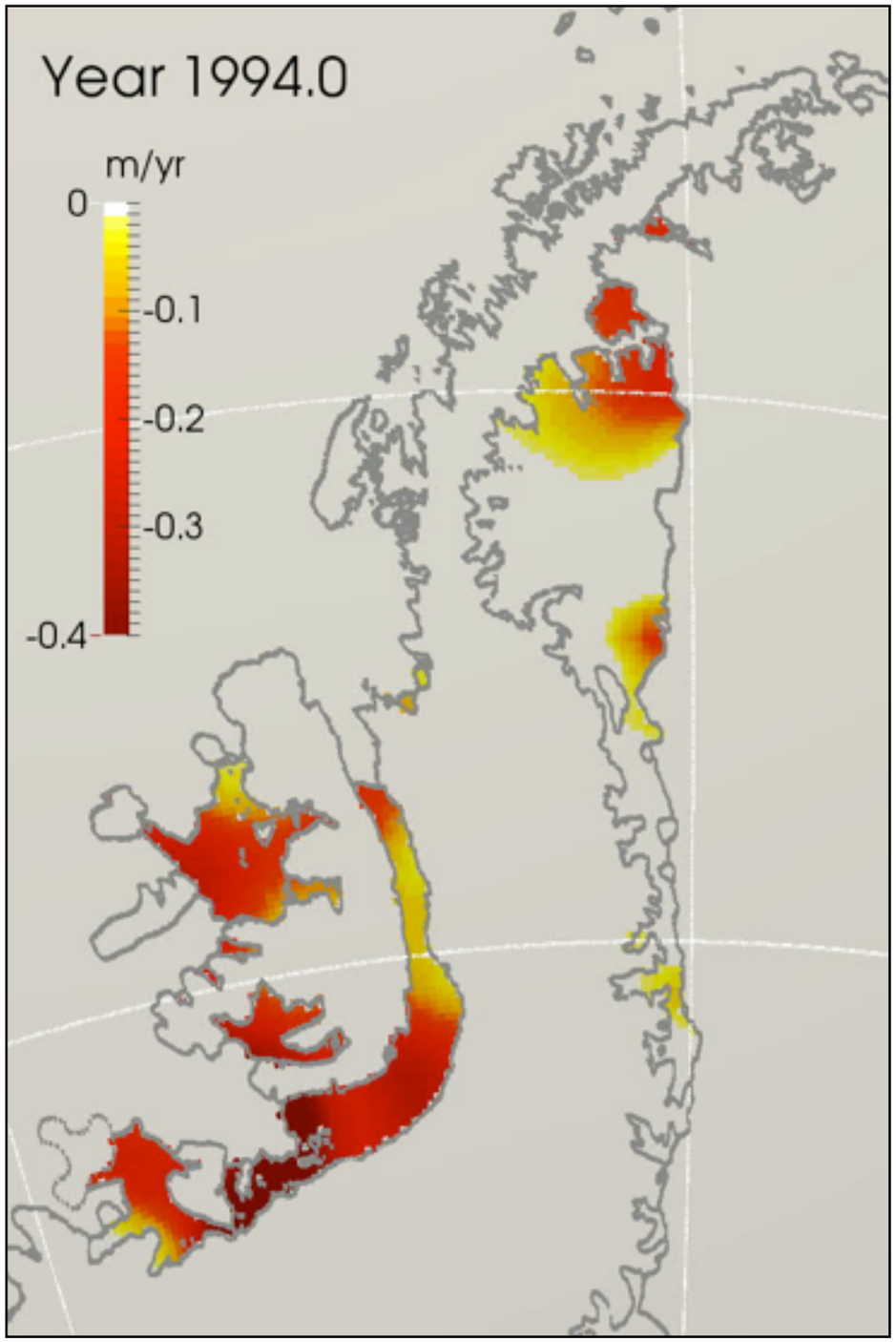
Larsen
~0.3 m/year

Bellingshausen
~0.7 m/year

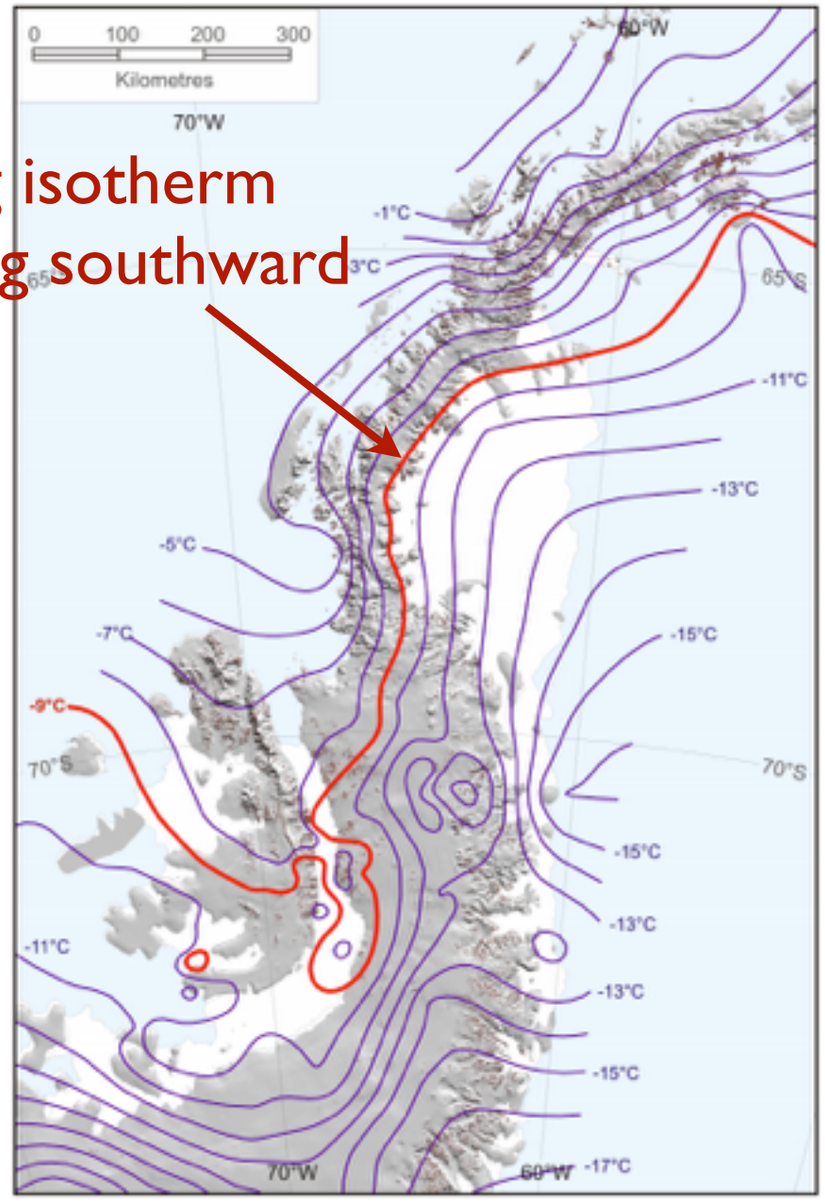
Amundsen
~1.9 m/year



Regional atmospheric warming trend?



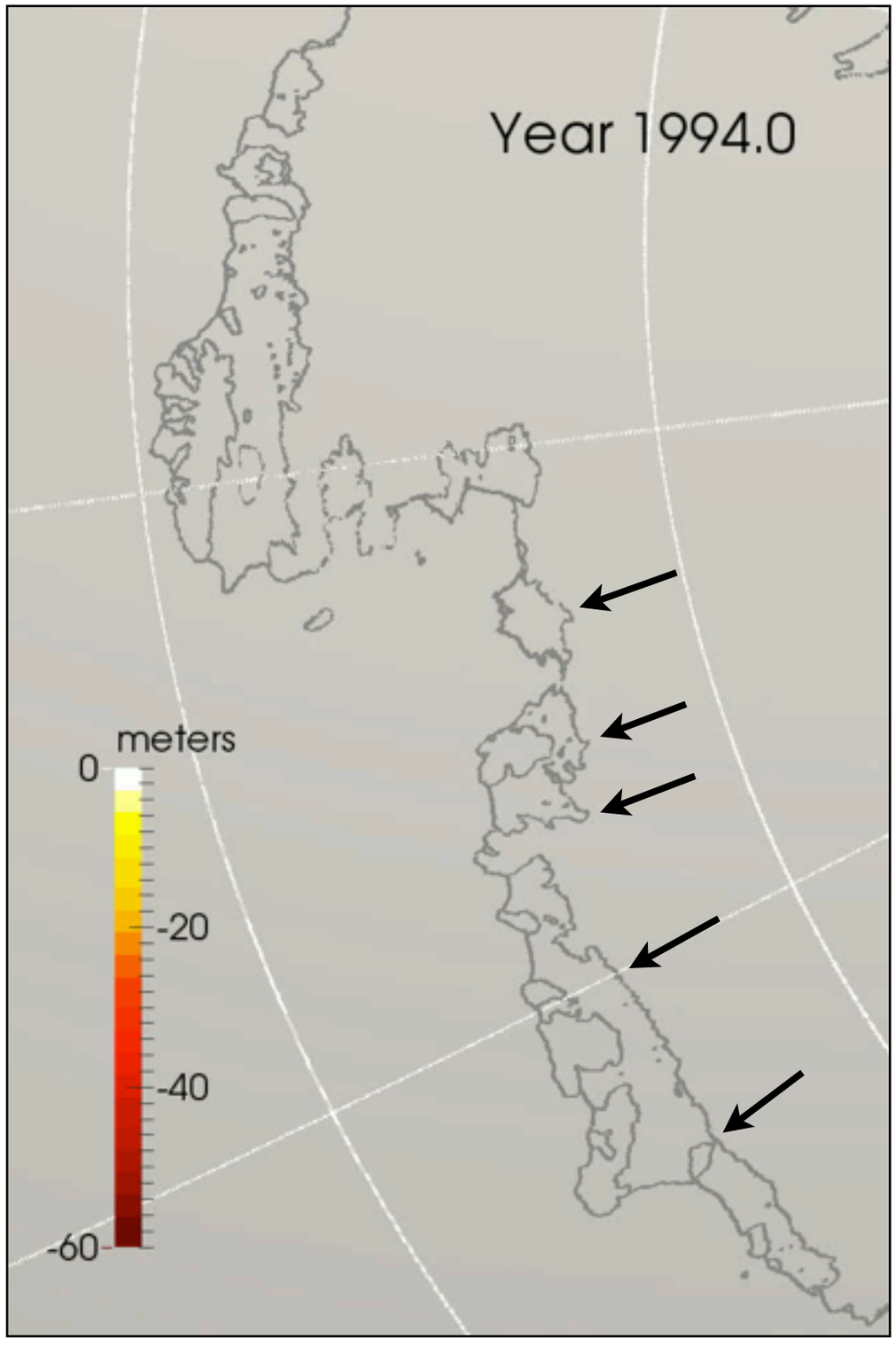
-9 deg isotherm moving southward

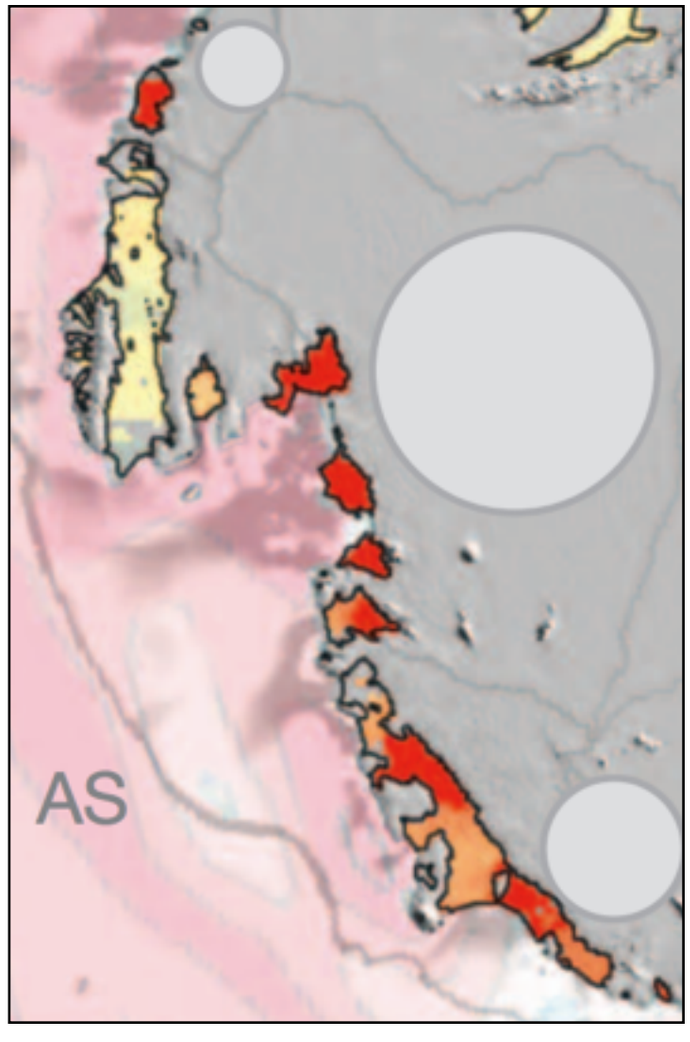


Cook & Vaughan, 2010

Different forcings within each environmental setting?

Characteristic signature of ocean-induced basal melting

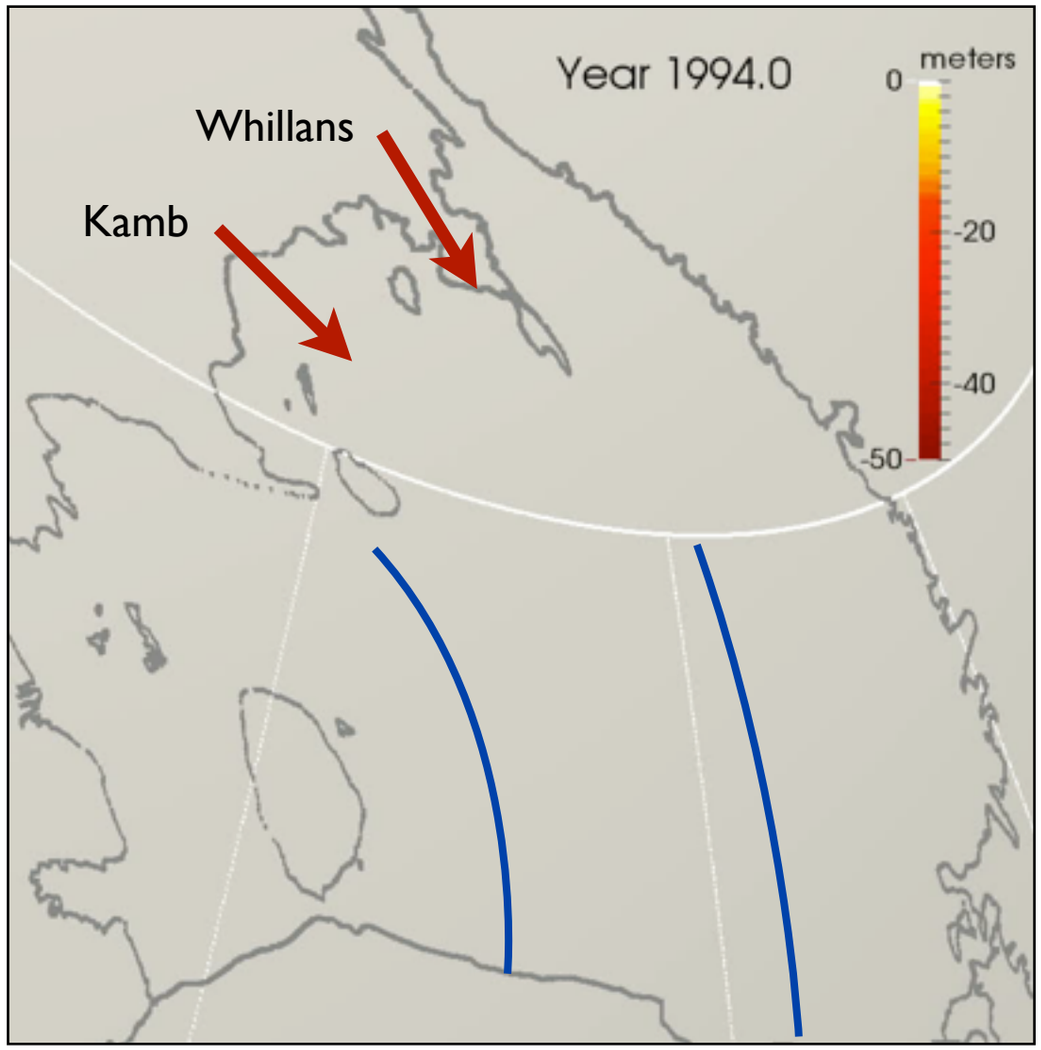


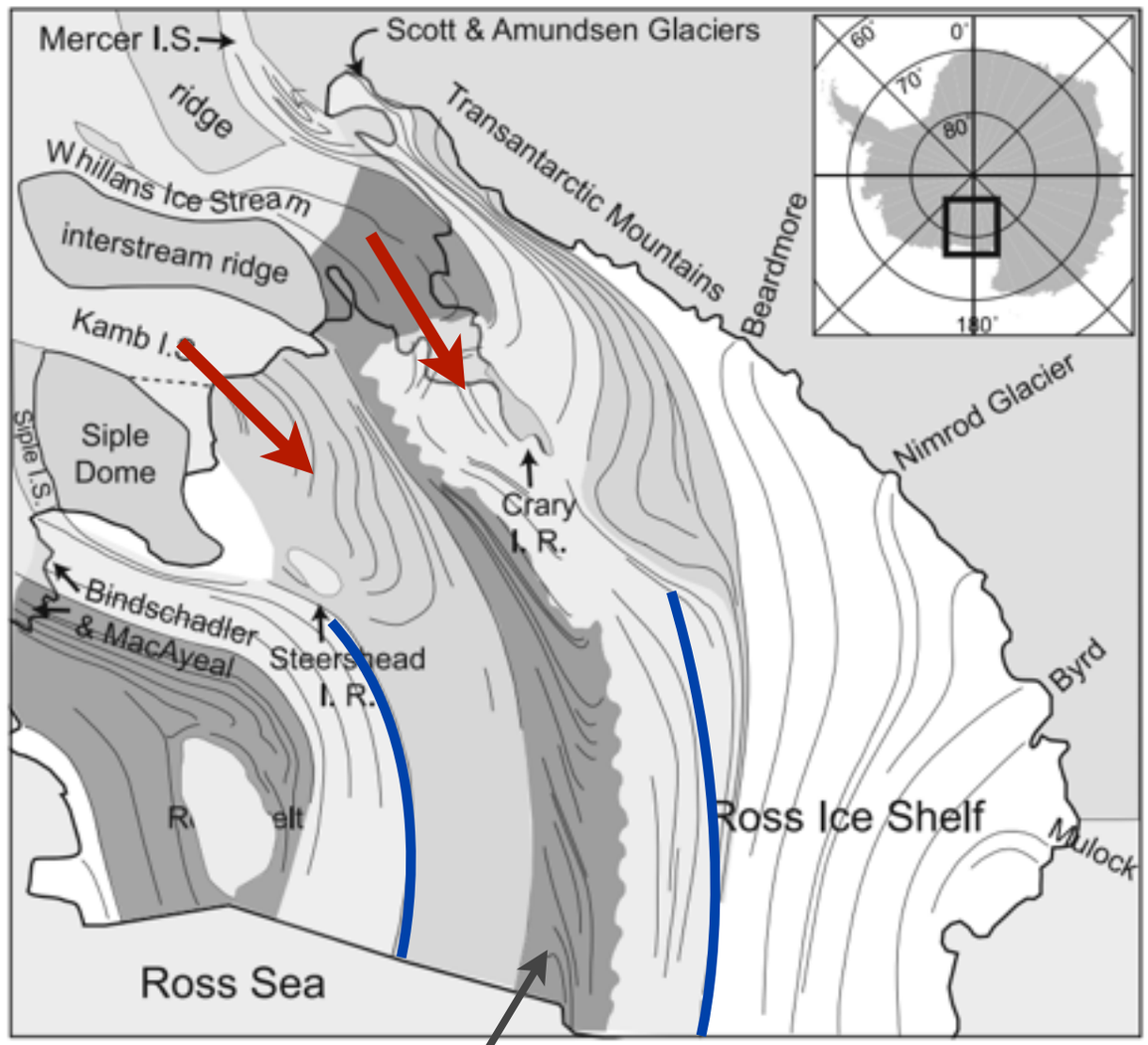


Lower melting point near the (deeper) grounding lines

Pritchard et al., 2012

Ice-stream stagnation/deceleration?



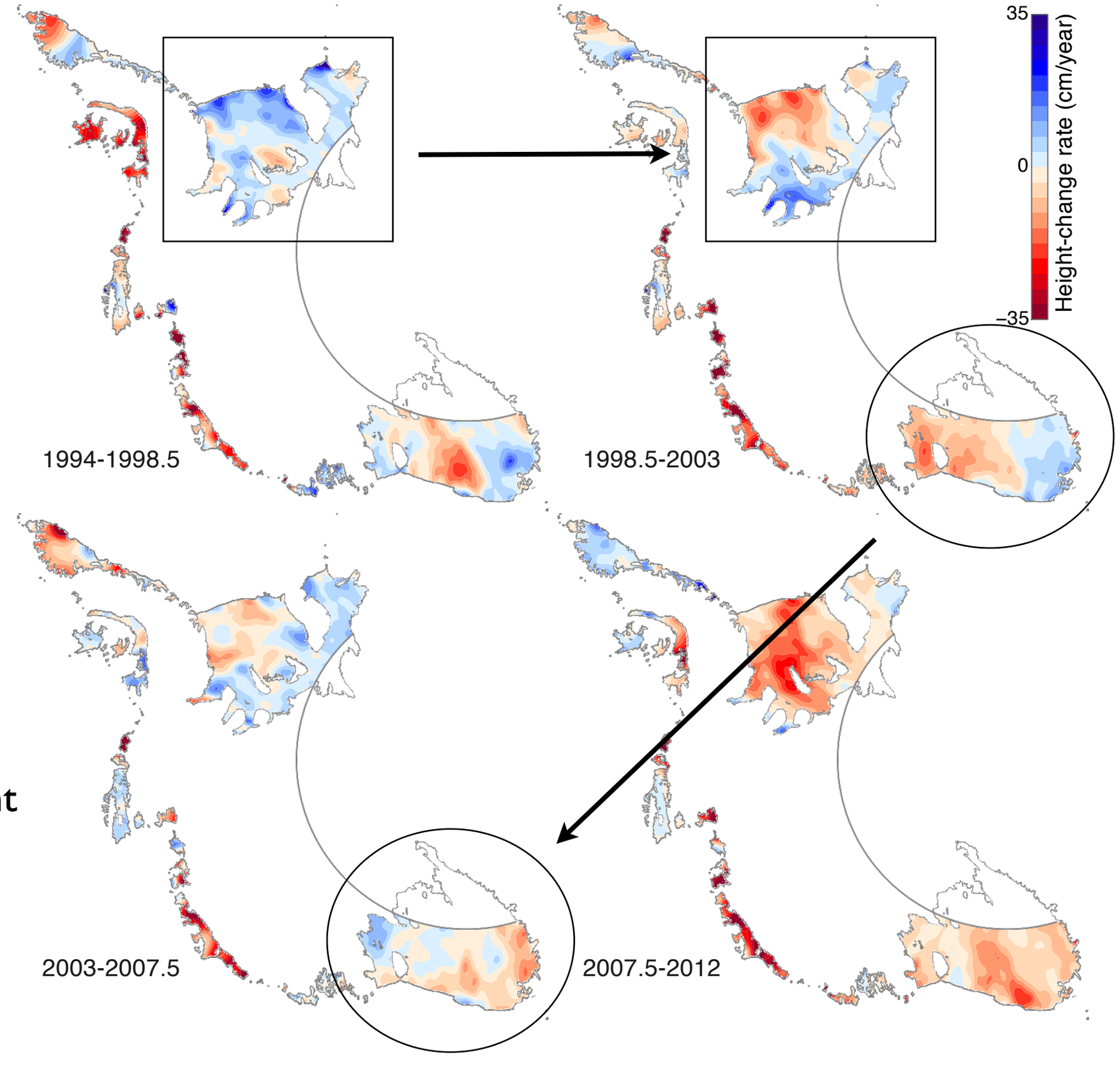


Hulbe & Fahnestock, 2007

Kamb and Whillans: provenance map from tracing flow features

How does the rate of change vary?

Average rate for different 4.5-year intervals



Short-term rates are highly dependent on the “chosen” time interval!

Summary

18 years of **continuous** observations for (almost) all Antarctic ice shelves

Total ice-shelf loss has **accelerated** since the mid-2000s (due to WAIS)

Some "critical" regions have experience **sustained** significant ice loss since 1994

Short observational records **cannot** be used to infer the long-term state of the ice shelves

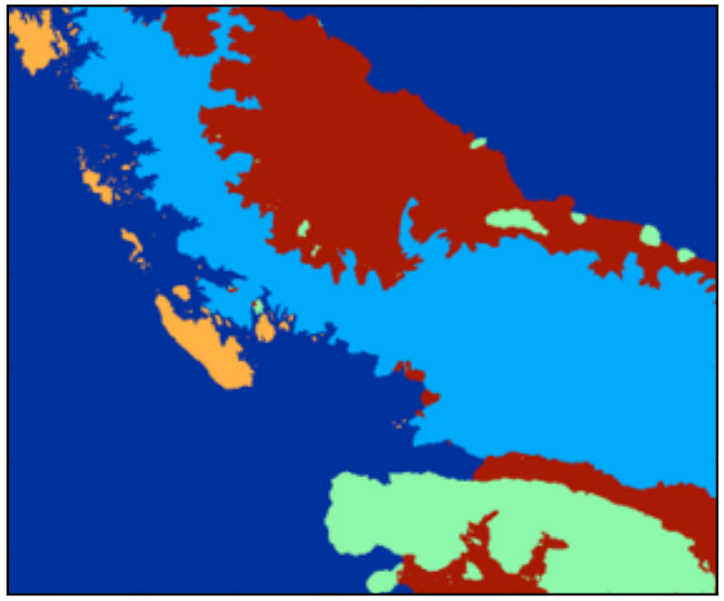
Height change (cm)

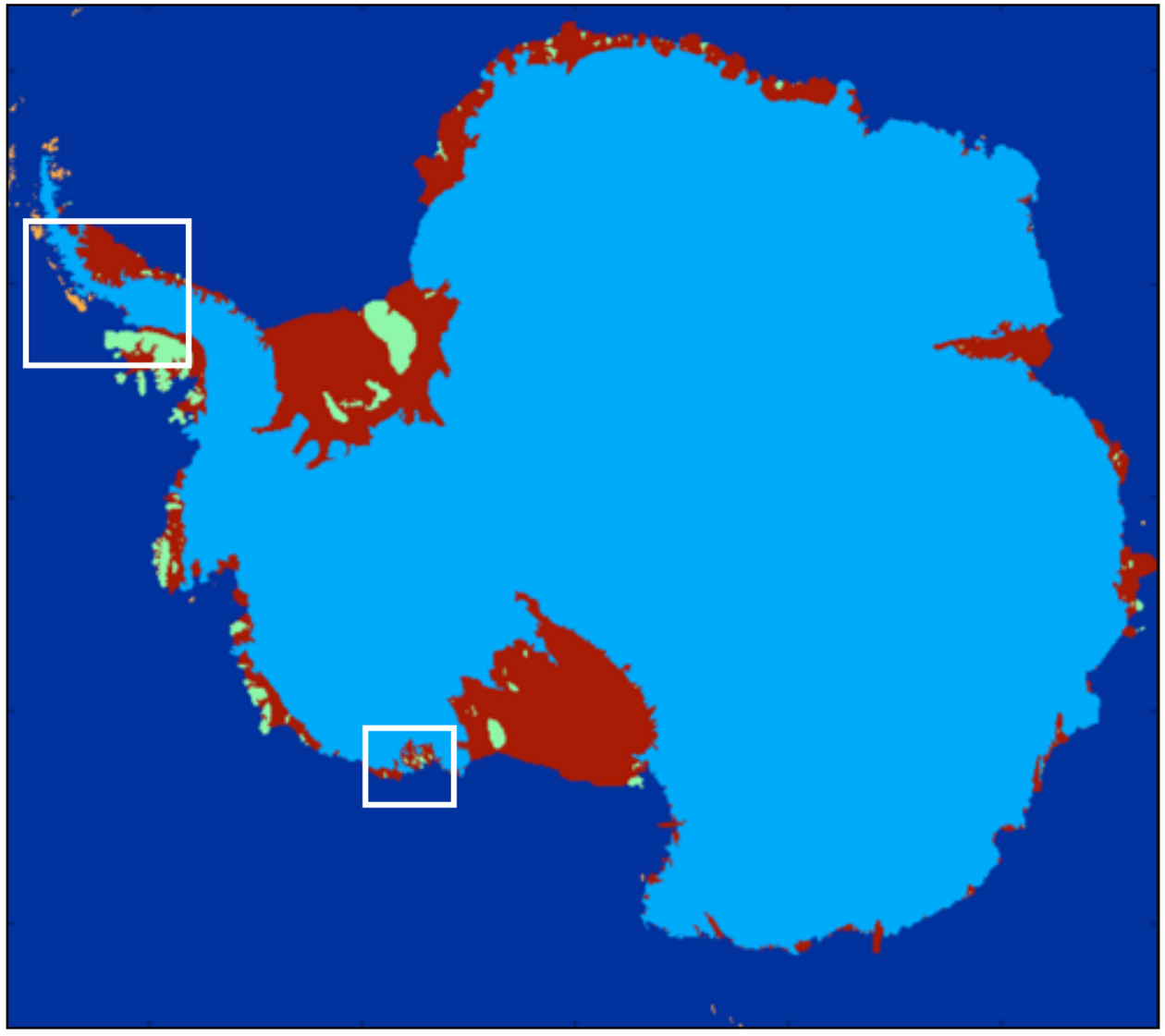
Brunt +4.7 ± 0.7 cm/year
Riiser +1.3 ± 0.5
Fimbul +3.4 ± 0.5
Lazarev −0.4 ± 0.6
Baudouin +0.7 ± 0.6
Prince Harald +7.2 ± 1.5
Amery +2.5 ± 0.6
West −3.6 ± 1.1
Shackleton −0.5 ± 0.6
Totten +25.6 ± 3.3
Moscow +3.7 ± 2.1
Holmes −0.4 ± 4.8
Dibble −8.3 ± 1.8

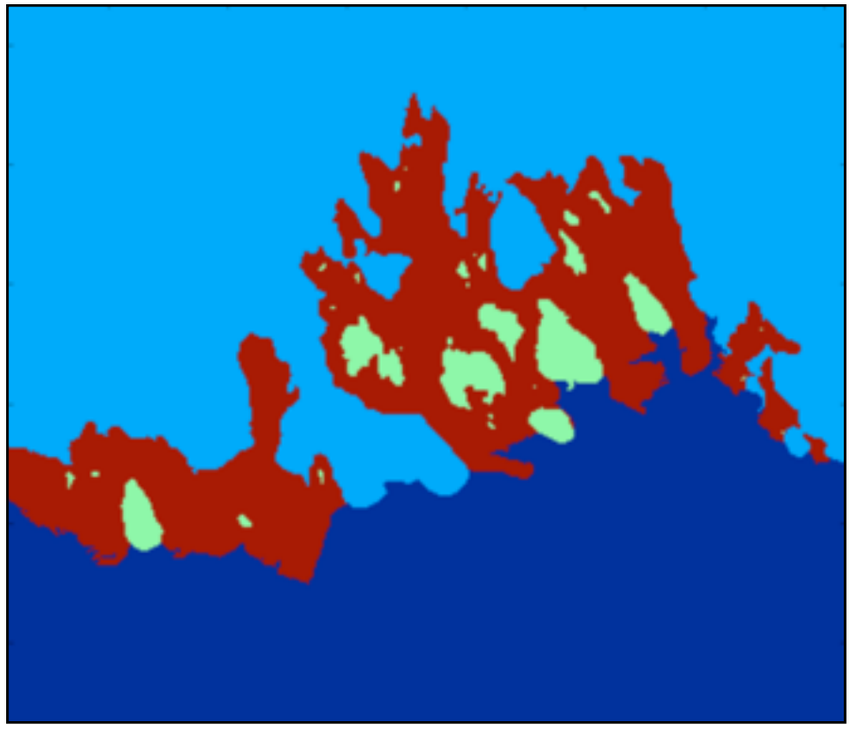
Mertz −0.7 ± 1.8 cm/year
Cook −20.1 ± 2.2
Rennick −5.2 ± 1.0
Mariner +1.8 ± 1.0
Drygalski +1.3 ± 2.5
Ross EAIS −0.9 ± 0.4
Ross WAIS −2.3 ± 0.4
Sulzberger +0.4 ± 0.7
Nickerson −1.6 ± 1.1
Getz −16.6 ± 0.6
Dotson −30.8 ± 1.3
Crosson −25.0 ± 2.1
Thwaites −23.7 ± 1.5

Pine Island −16.3 ± 1.1 cm/year
Cosgrove −6.0 ± 1.2
Abbot −1.9 ± 0.5
Venable −34.0 ± 1.4
Stange −4.2 ± 0.8
Bach −9.4 ± 0.9
Wilkins −5.2 ± 0.6
George VI −10.4 ± 0.7
Larsen B −6.6 ± 1.3
Larsen C −3.2 ± 0.5
Larsen D −3.0 ± 1.1
Ronne 0.0 ± 0.4
Filchner +1.5 ± 0.4

1994 1997 2000 2003 2006 2009 2012

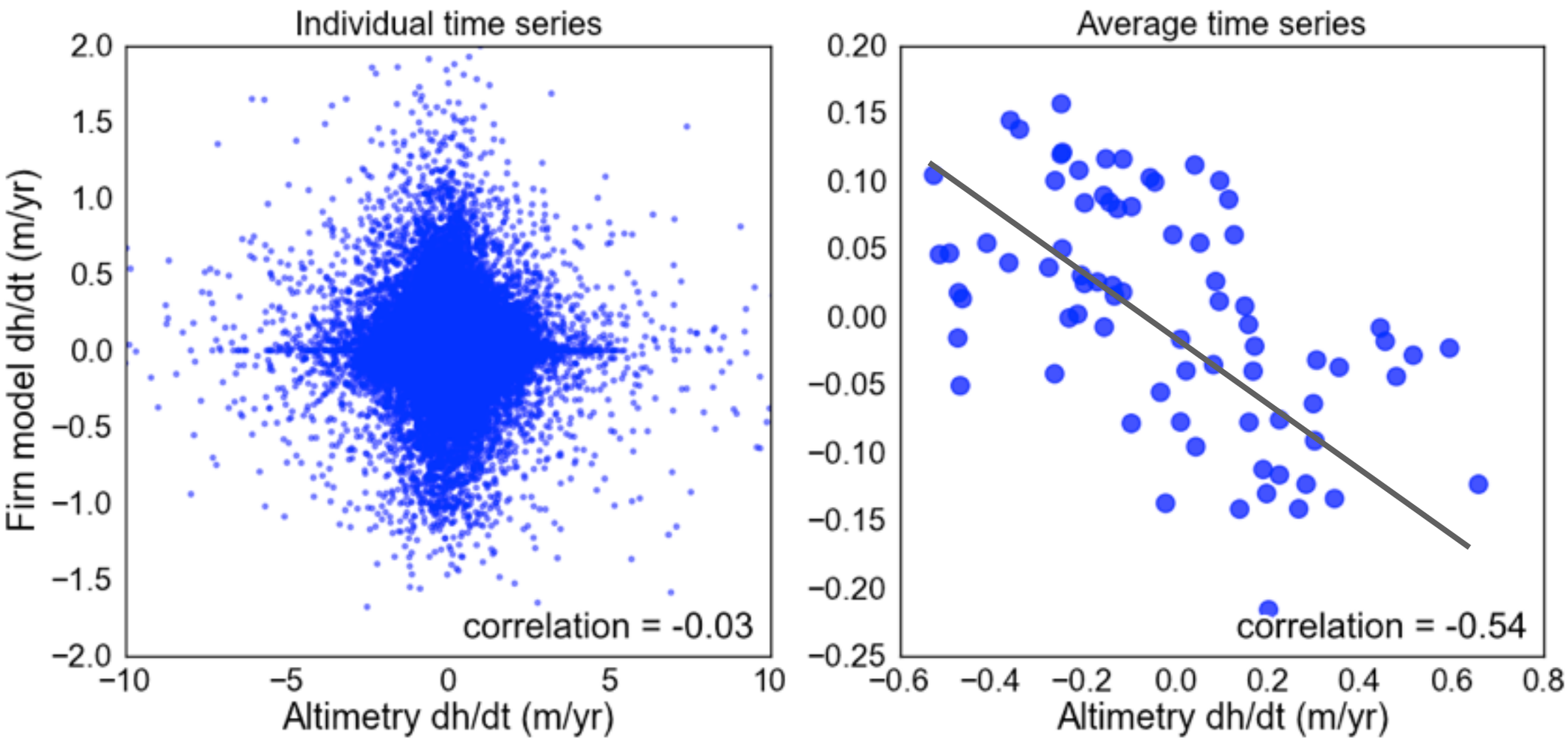






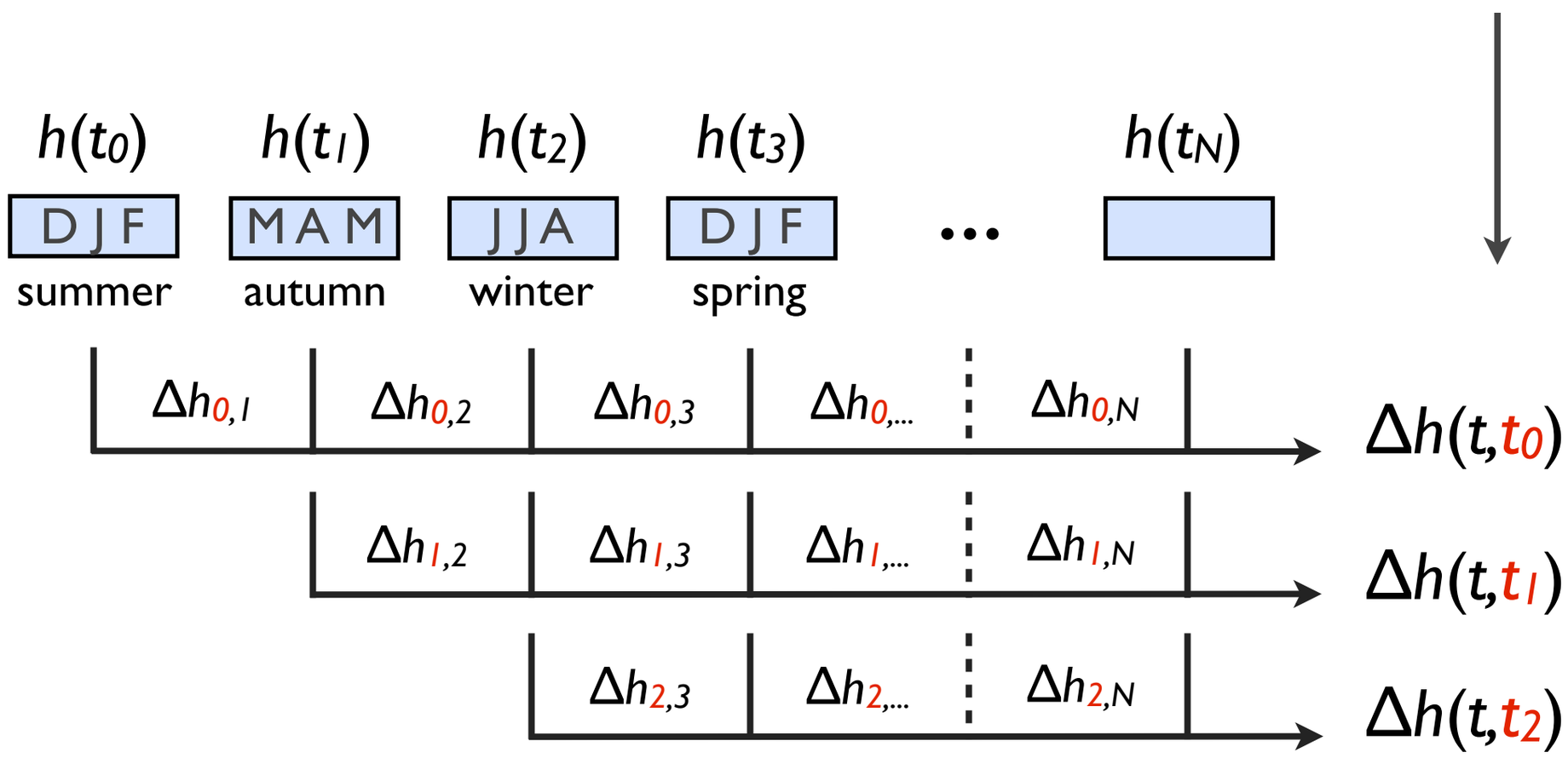
A reliable and complete ice shelf mask is a problem. So we (Geir Moholdt) created our own using all data available: MOA (Scambos et al. 2007), ASAID (Bindschadler et al. 2011), InSAR (Rignot et al. 2011), ICESat (Fricker/Brunt et al. 2006-10)

Firn model vs Altimeter observations

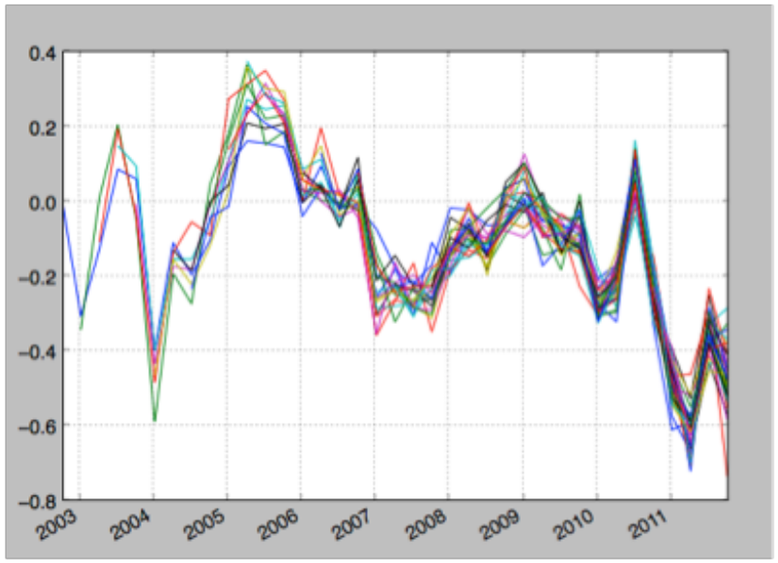


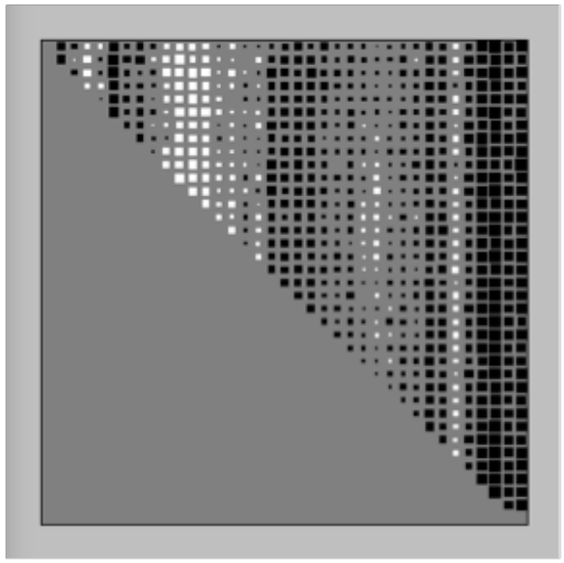
We explore all possible time combinations

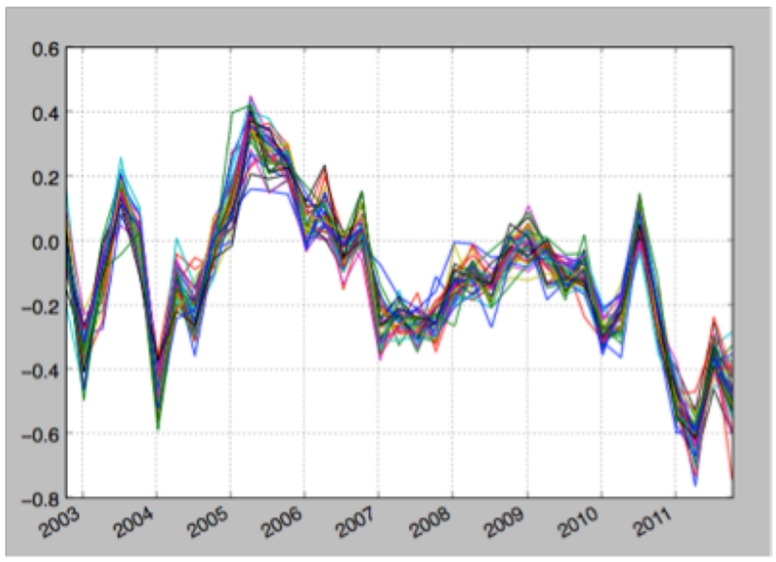
These are elevation changes with respect to different epochs

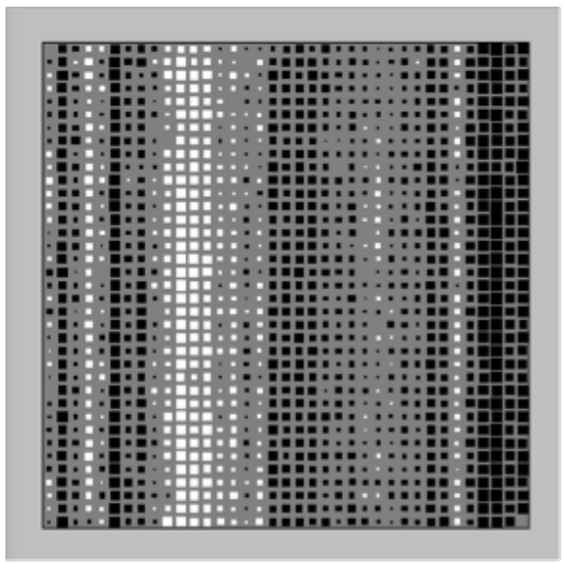


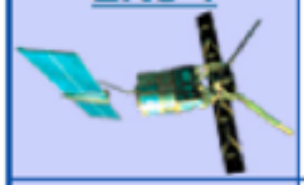
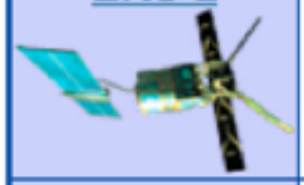
Why can we do this? → *The spatial distribution of crossovers changes with time*


0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2003
2004
2005
2006
2007
2008
2009
2010
2011




0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2003
2004
2005
2006
2007
2008
2009
2010
2011



Satellite	Agency	Launch	Altitude	Altimeter	Frequency used	Repetitivity	Inclination	Error budget (Open ocean)
ERS-1 	ESA	1991	785 km	RA	Ku-band	35 days (3 days ice phase, 168 days geodetic phase)	98.5°	Range: 3 cm; Orbit: 8-15 cm
ERS-2 	ESA	1995	785 km	RA	Ku-band	35 days	98.5°	Range: 3 cm; Orbit: 7-8 cm
Envisat 	ESA	2002	800 km	RA-2	Ku and S-band	35 days	98.5°	Range: 2-3 cm ; Orbit: 2-3 cm