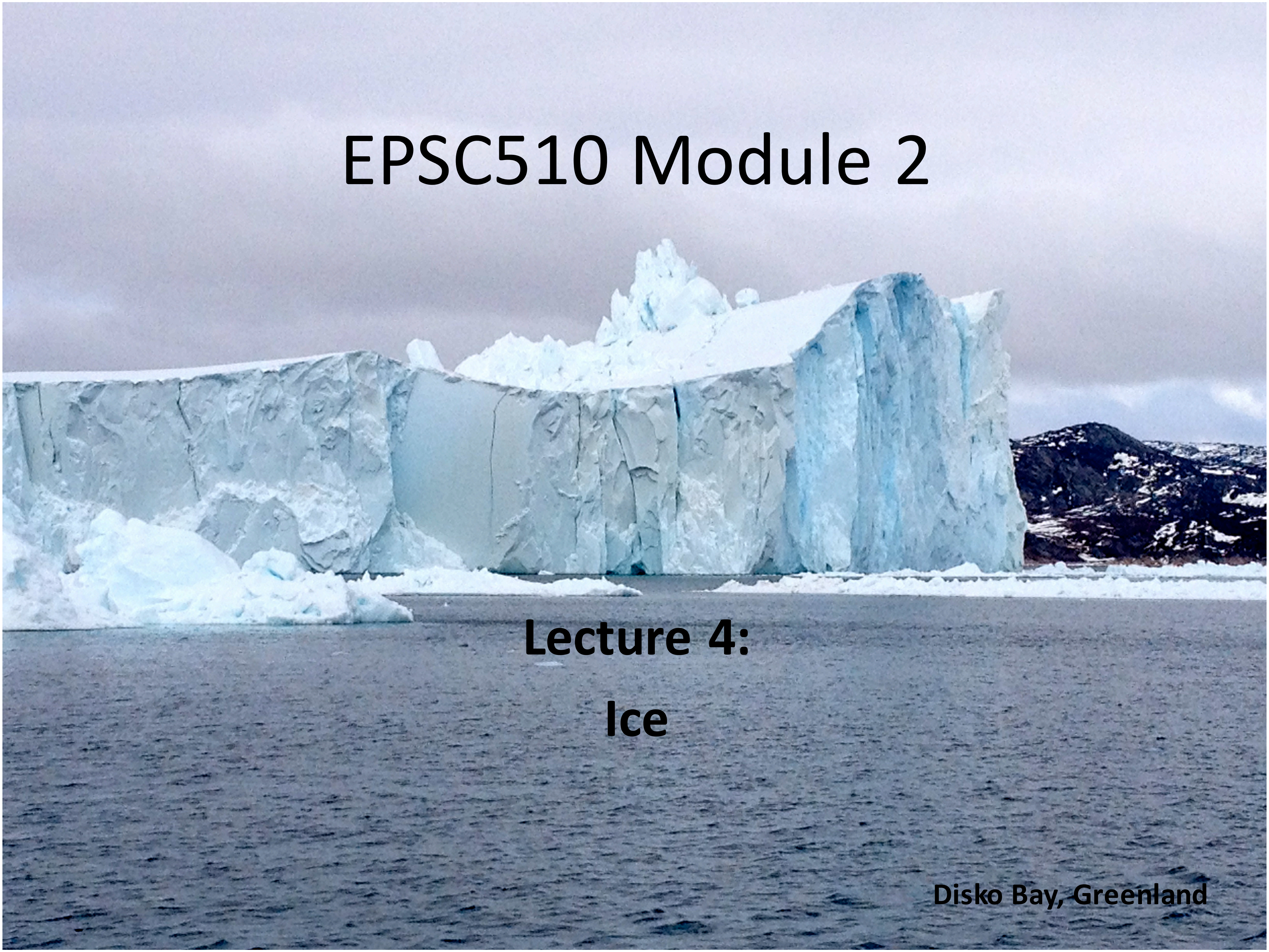
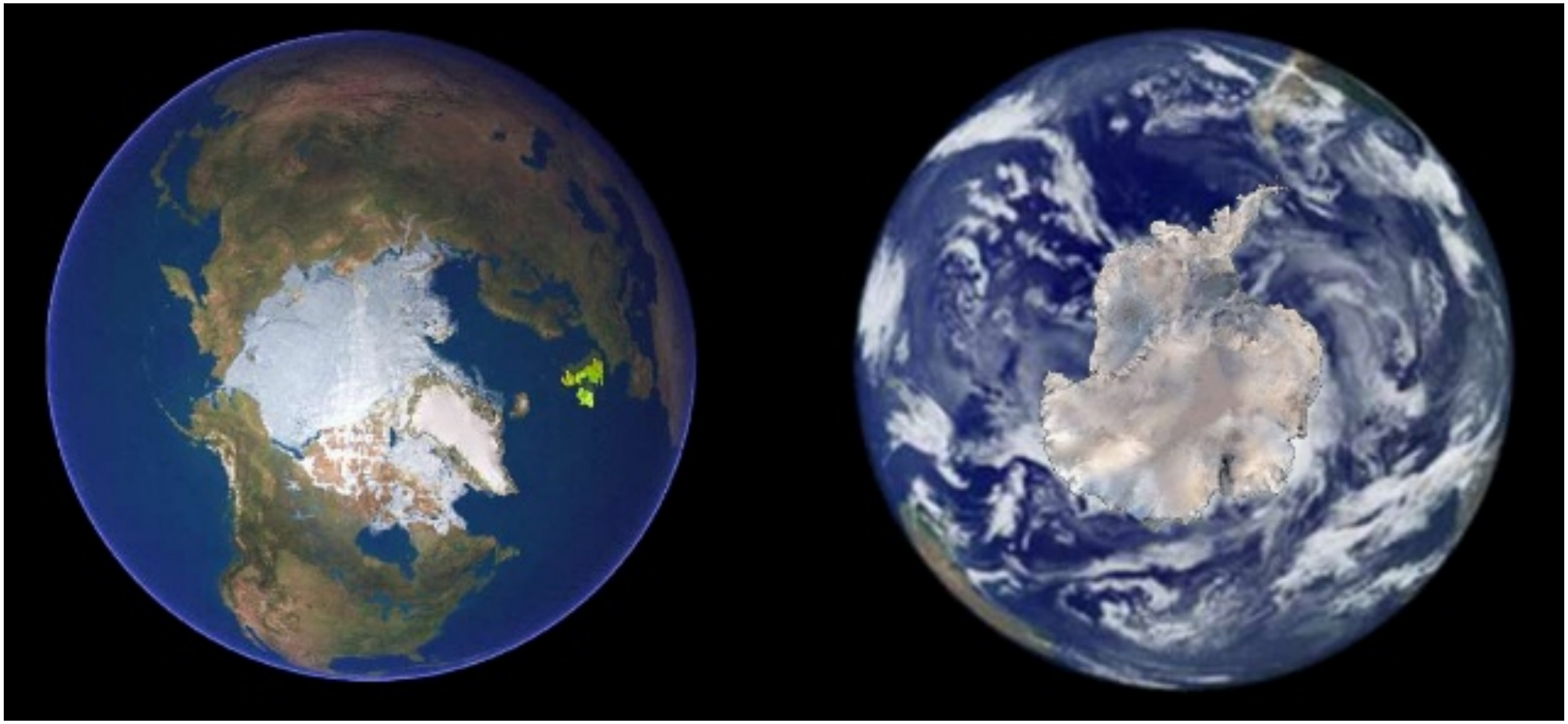
EPSC510 Module 2



Lecture 4:
Ice

Disko Bay, Greenland

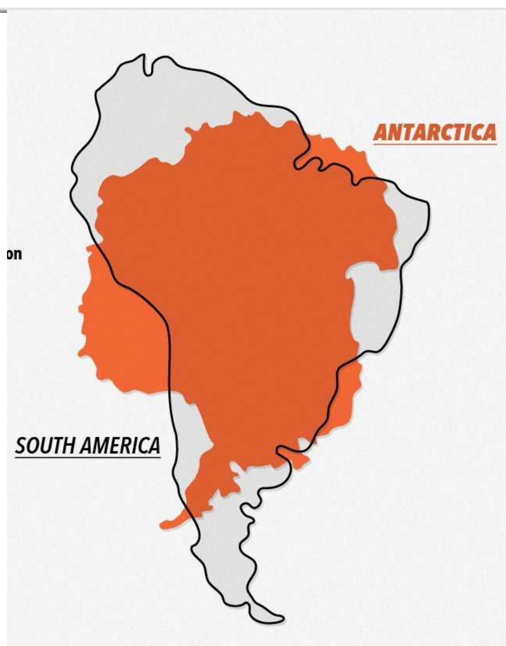
Today's Ice Sheets



Greenland ice would raise sea level by ~ 7 meters

Antarctic ice would raise sea level by ~ 57 meters

Today's Ice Sheets

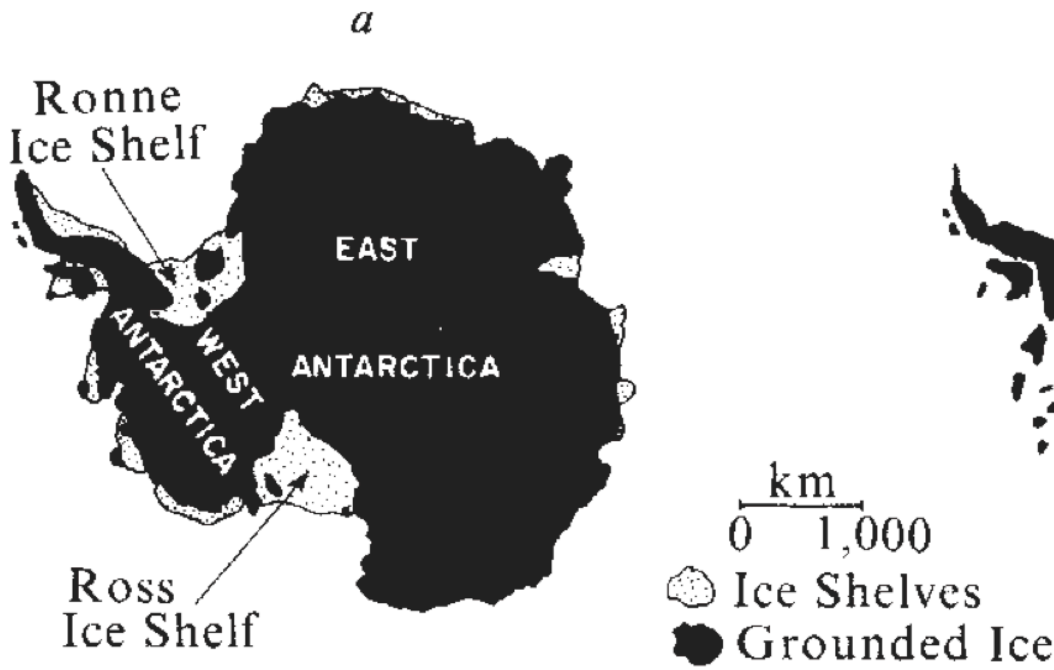


Antarctic ice would raise sea level by ~ 57 meters

West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

J. H. Mercer

Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210

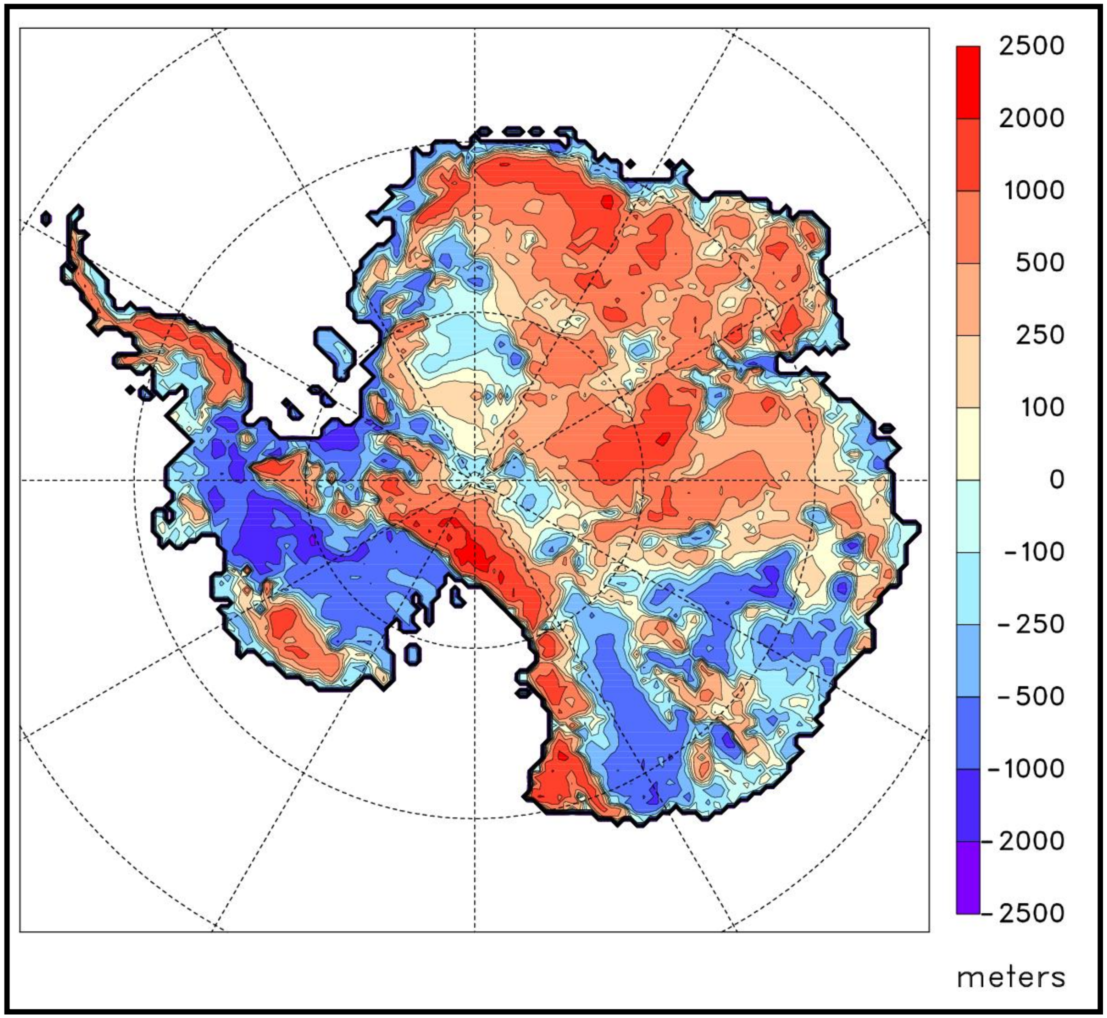


Stability of Antarctic ice

from J. Weertman

Today's Ice Sheets: Marine Ice Instability

Marine-based sectors of the Antarctic Ice Sheet (blue)
are potentially unstable and could retreat rapidly in a warming climate.



Elevation of the Bedrock beneath the ice sheet
marine-based regions (blue)

BEDMAP

Uncertainty in Future Sea Level Change

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley

www.sciencemag.org SCIENCE VOL 344 16 MAY 2014

RESEARCH LETTER
10.1002/2014GL060140

Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011

E. Rignot[1,2], J. Mouginot[1], M. Morlighem[1], H. Seroussi[2], and B. Scheuchl[1]

[1]Department of Earth System Science, University of California, Irvine, California, USA, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Key Points:
- Fast grounding line retreat of the entire Amundsen Sea sector of West Antarctica
- Observations are a signature of a marine ice sheet instability in Antarctica

Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models

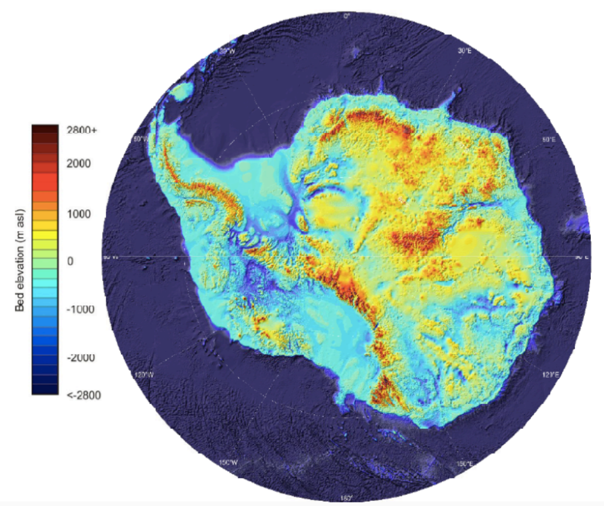
A. Levermann[1,2], R. Winkelmann[1], S. Nowicki[3], J. L. Fastook[4], K. Frieler[1], R. Greve[5], H. H. Hellmer[6], M. A. Martin[1], M. Meinshausen[1,7], M. Mengel[1], A. J. Payne[8], D. Pollard[9], T. Sato[5], R. Timmermann[6], W. L. Wang[3], and R. A. Bindschadler[3]

Earth Syst. Dynam., 5, 271-293, 2014
www.earth-syst-dynam.net/5/271/2014/
doi:10.5194/esd-5-271-2014

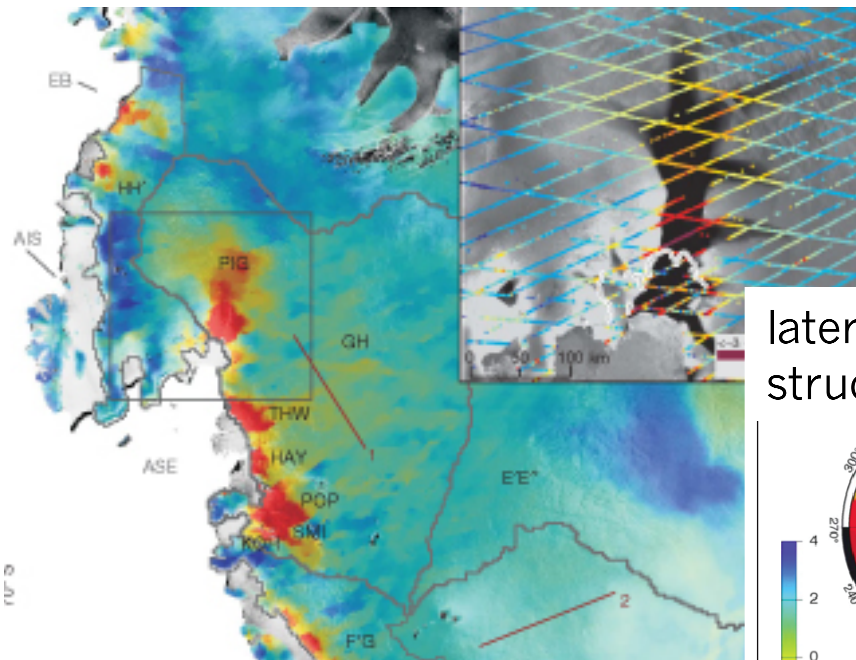
Antarctica's Response to Climate Warming is complicated

IPCC 5th Assessment Report: "Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the likely range during the 21st century."

marine-based regions

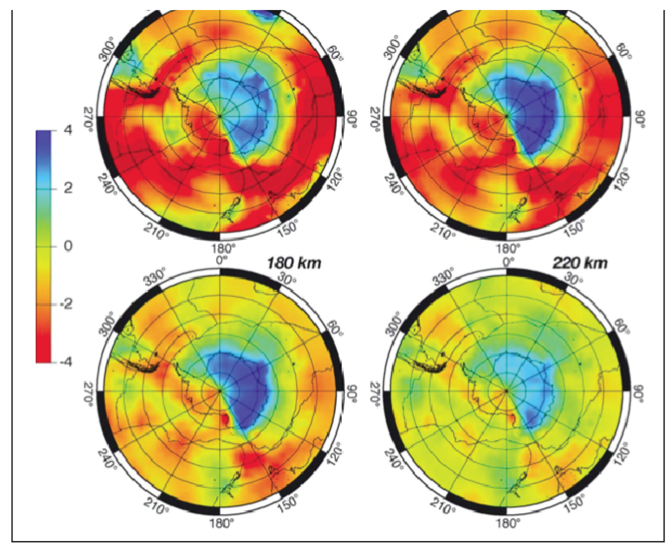


BEDMAP2



Past and ongoing ice mass changes contributing to Earth deformation

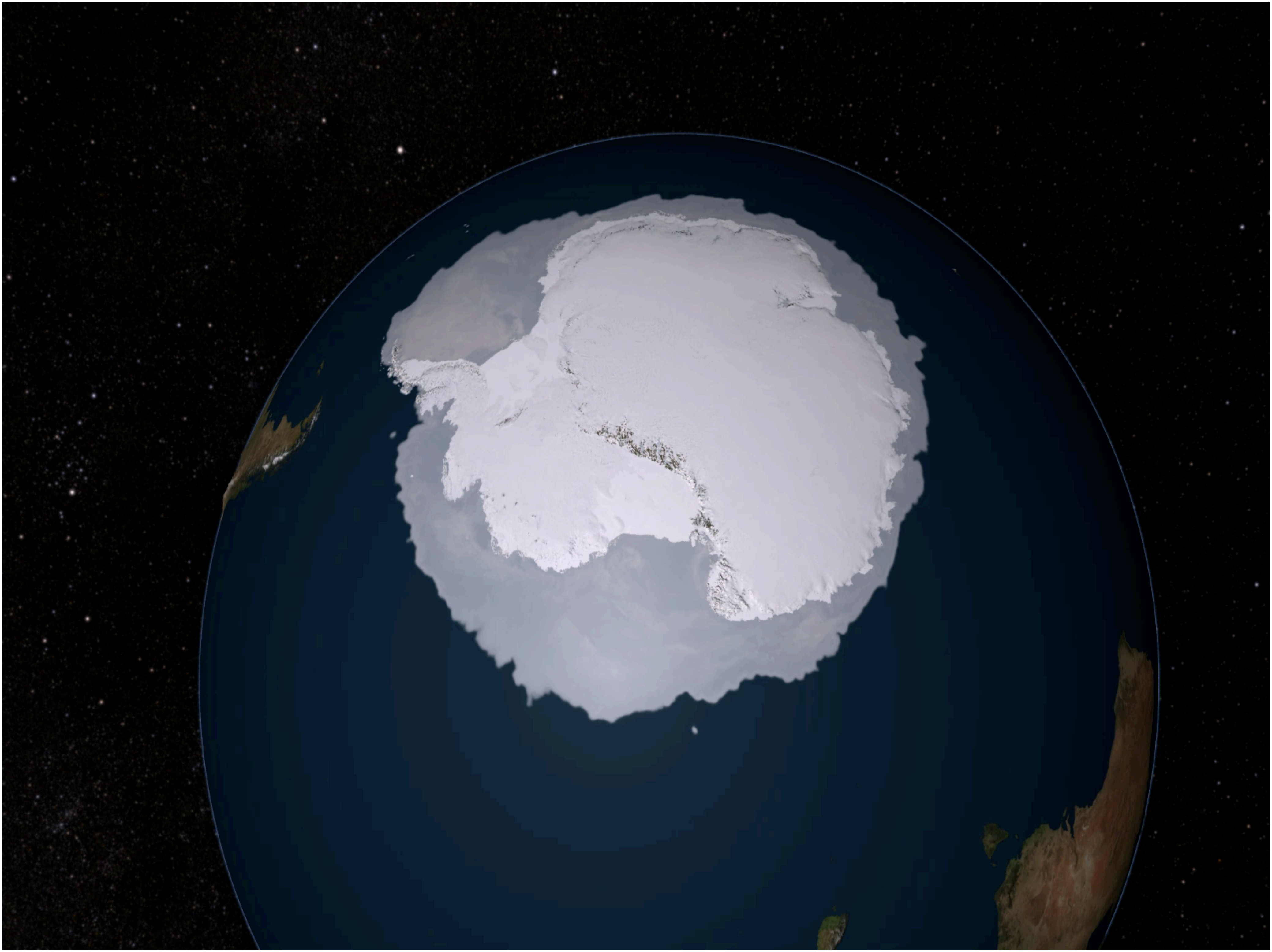
lateral variations in Earth structure



Seismic Tomography, Morelli & Danesi (2004)

Marine Ice In Antarctica is Vulnerable

- Antarctic Ice has responded rapidly to climate change in the past.



Working in Antarctica


Getting there….


Living there…

Ice Sheet Dynamics Overview

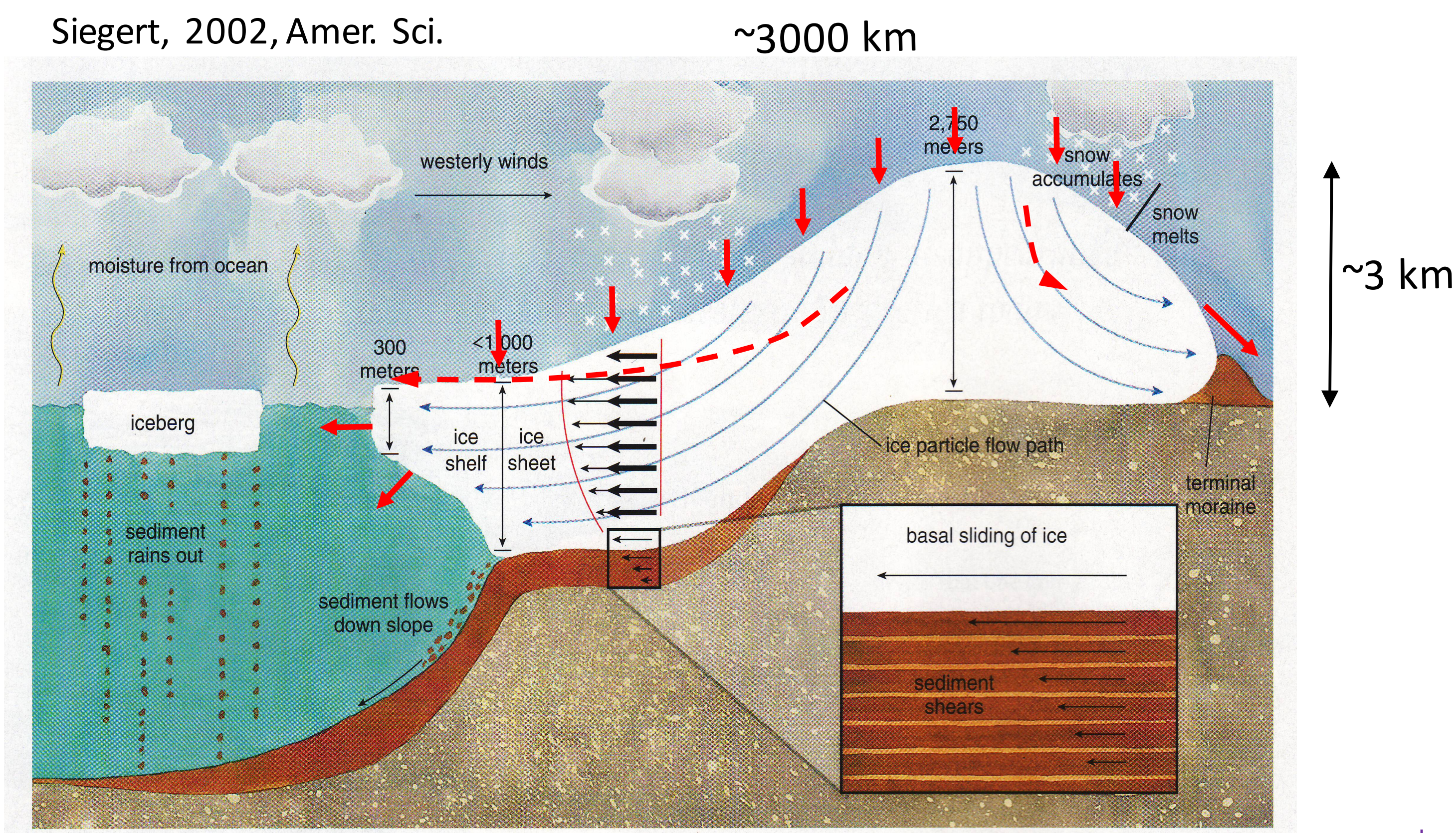
Much of the following overview of ice dynamics and ice sheet modeling comes from the introductory website: www.antarcticglaciers.org

And from notes, slides and discussions with David Pollard at Pennsylvania State University.

Ice Sheet Dynamics

- Glacier flow (velocity and motion) is controlled by several factors including:
  - ice geometry (thickness, steepness)
  - Ice properties (temperature, density)
  - Valley geometry
  - Bedrock conditions (hard, soft, frozen bed...)
  - Subglacial hydrology (water at the bed)
  - Terminal environment (land, sea, ice shelf, sea ice)
  - Mass balance (rate of accumulation and ablation)

Siegert, 2002, Amer. Sci.



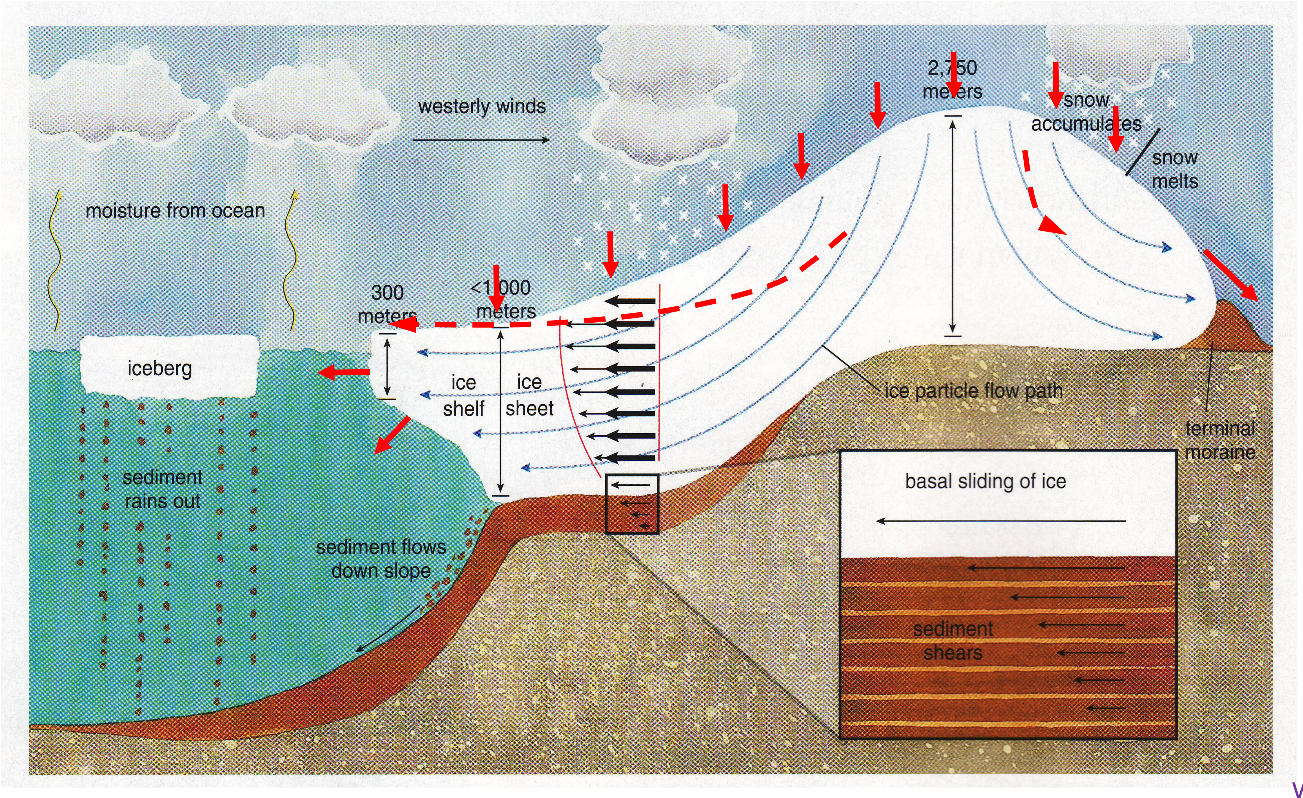
www.antarcticglaciers.org

Ice Sheet Dynamics

- Glaciers flow by creep under gravitational driving stress, through the processes of:
  - internal deformation (creep)
  - basal sliding (ice sliding on bed below)
  - soft bed subglacial deformation (bed deforming, transporting overlying ice)
- Driving Stress controlled by gravity, ice density and temperature, ice thickness and ice surface slope.
- Resistive stresses include basal drag, lateral drag against valley walls, or buttressing of ice shelves (which themselves are experiencing drag from below or their sides)

Siegert, 2002, Amer. Sci.

~3000 km



~3 km

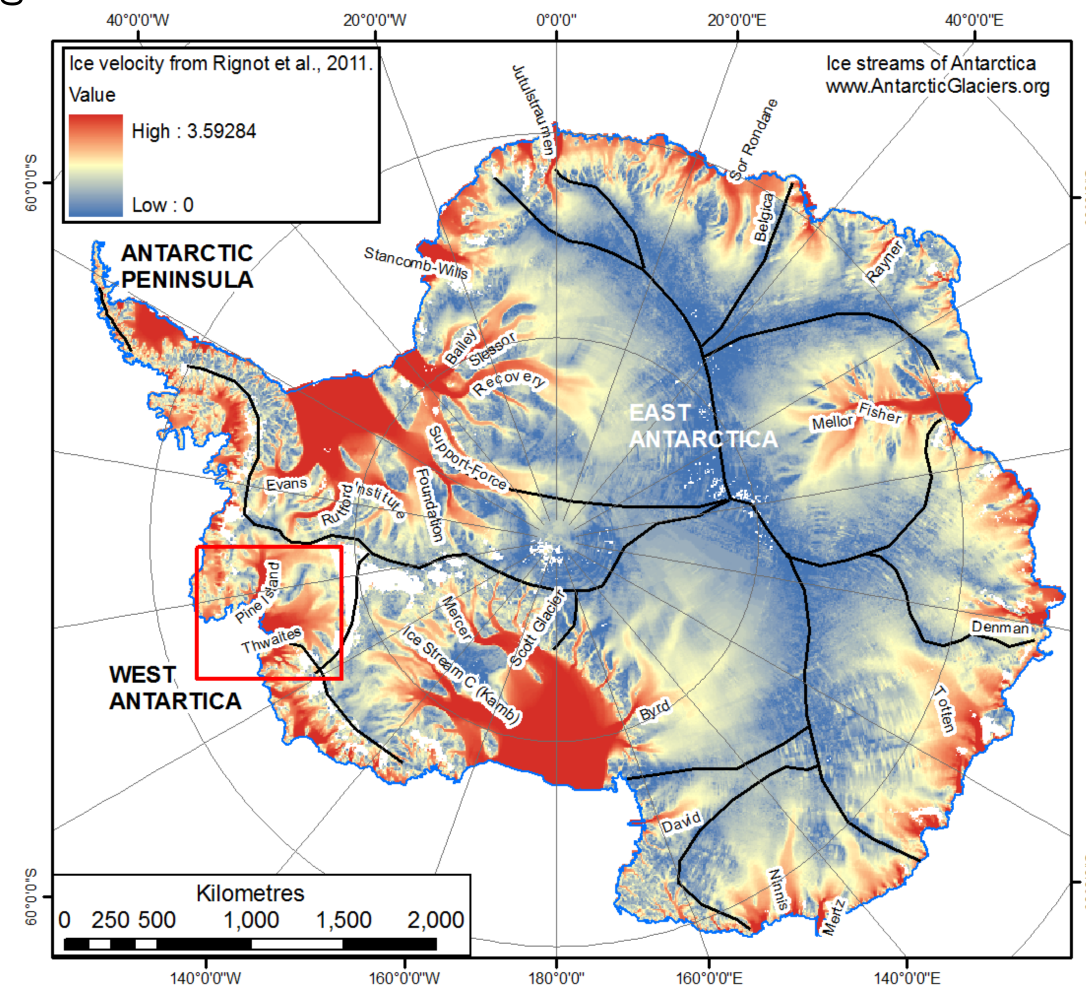
www.antarcticglaciers.org

Ice Sheet Dynamics

- Glaciers flow by creep under gravitational driving stress, through the processes of:
  - internal deformation (creep)
  - basal sliding (ice sliding on bed below)
  - soft bed subglacial deformation (bed deforming, transporting overlying ice)
- **Ice Streams:** corridors of fast ice flow on wet, slippery bed that drain the ice sheet
  - 90% of discharge occurs through ice streams in Antarctica.

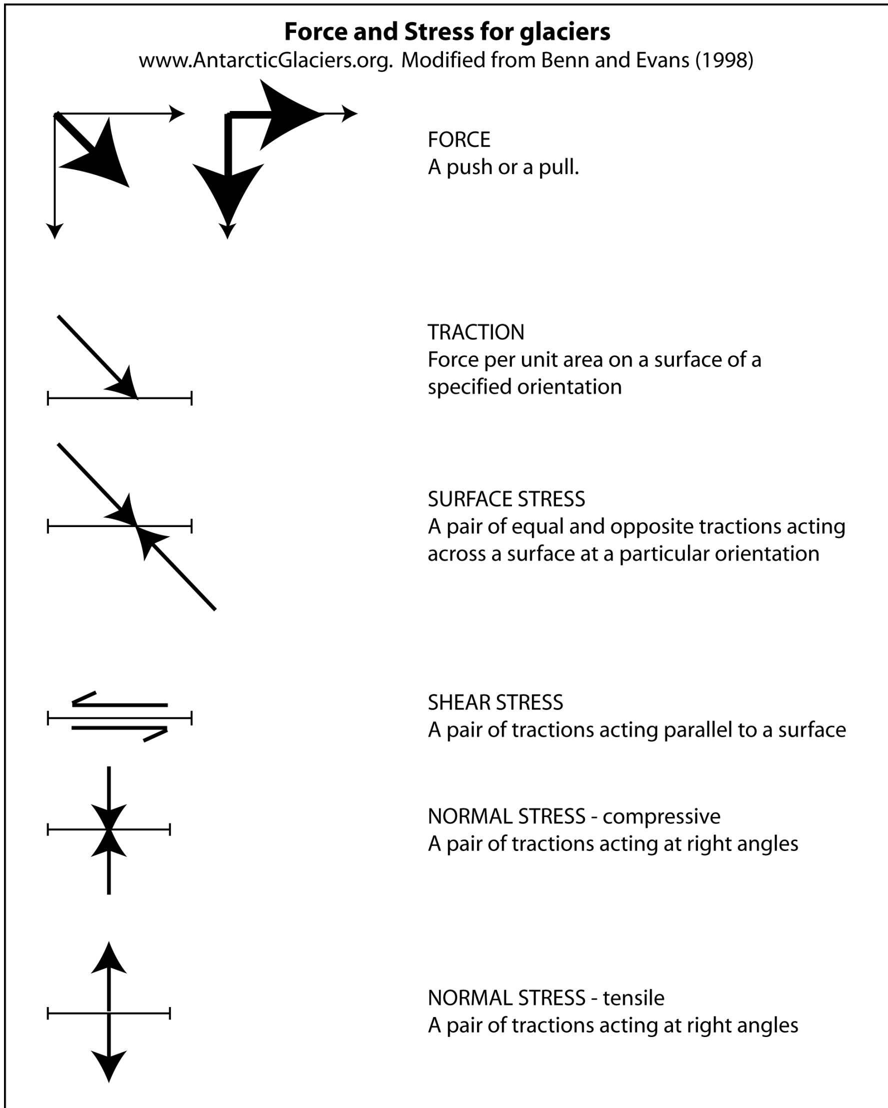
NASA Animation of Rignot et al. (2011) ice velocity

Ice stream scale:
- > 20 km in width
- > 150 km in length
- 100s m/y (where surrounding ice flows at <10s m/y)



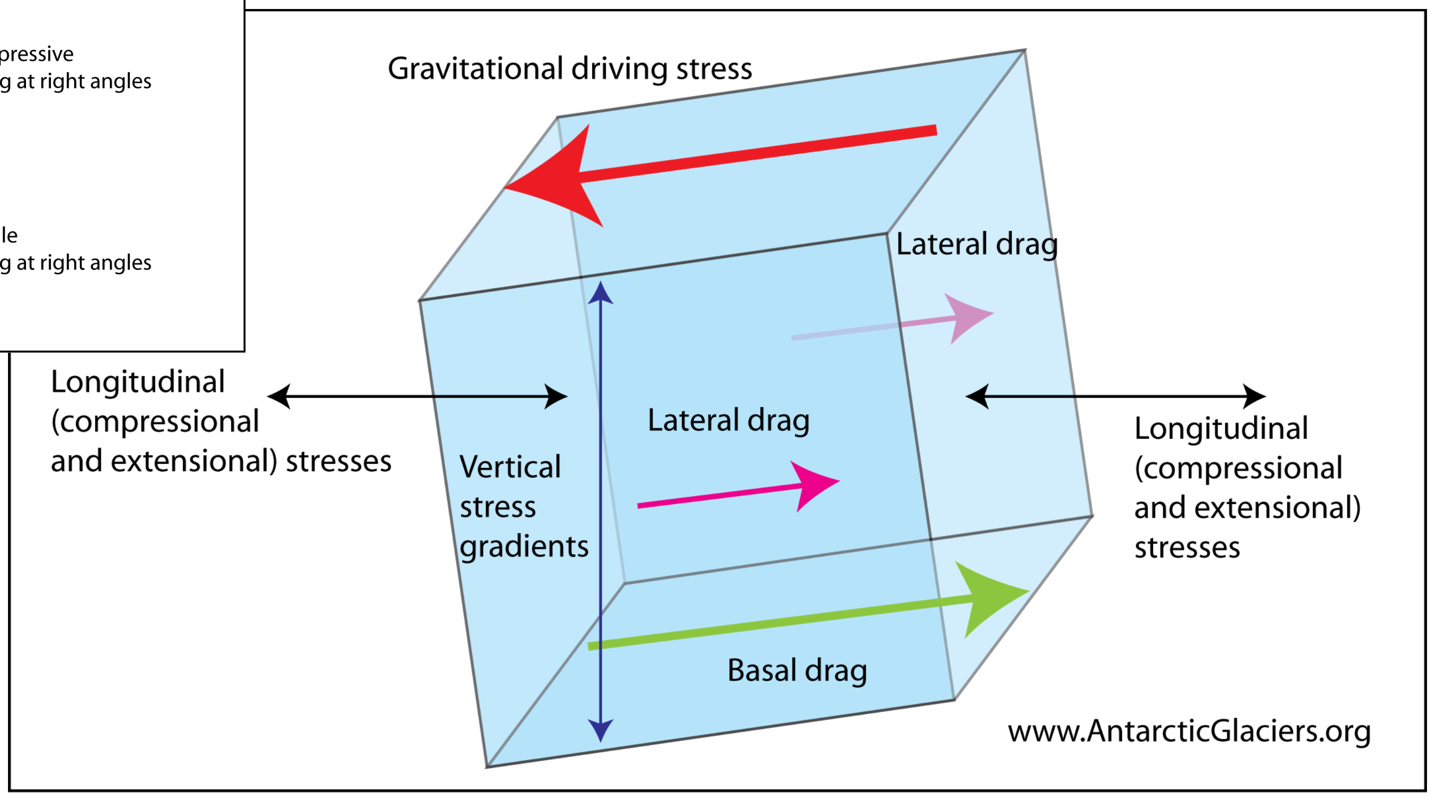
www.antarcticglaciers.org

Ice Sheet Dynamics: Stress



Driving and resisting stresses operating on a block of ice on an inclined slope.

www.antarcticglaciers.org



Ice Sheet Model Ingredients

1) Ice Conservation (Continuity) Equation

$$\frac{\partial H}{\partial t} = \frac{\partial (uH)}{\partial x} + B$$

2) Glen's Law – non-Newtonian fluid

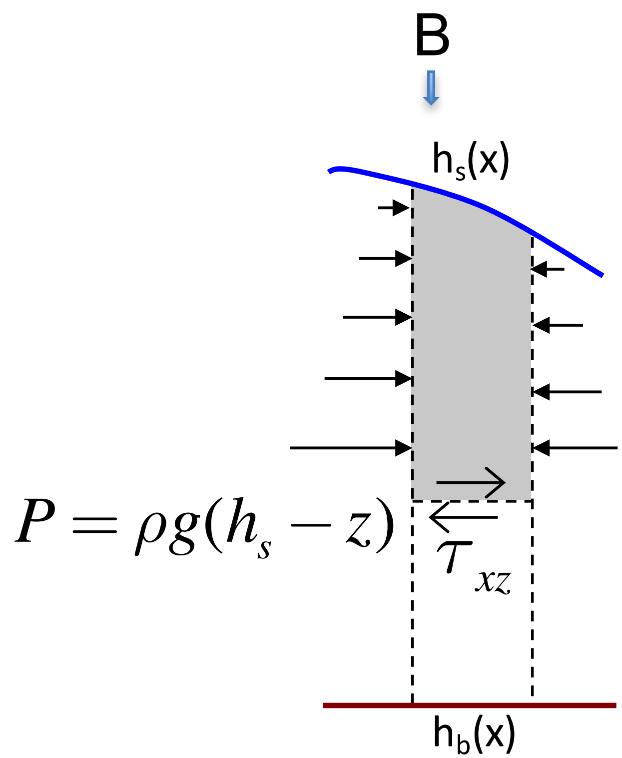
$$\varepsilon_{ij} = A|\tau|^{n-1}\tau_{ij} \qquad \text{(Glen's Law)}$$

3) Flow Equations

E.g. The shallow-ice approximation

- Valid for H<< L, sticky base
- Asserts that (a) hydrostatic pressures are the dominant driving force, and (b) vertical shear is the dominant mode of deformation.

$$\varepsilon_{xz} \approx \frac{1}{2}\frac{\partial u}{\partial z} \qquad \tau_{xz} \approx -\rho g(h_s - z)\frac{\partial h_s}{\partial x}$$



h_s = ice surface elevation

h_b = ice base elevation

H = ice thickness h_s - h_b

4) Interactions with ocean, bed and climate

Ice Sheet Model Ingredients

1) Ice Conservation (Continuity) Equation

$$\frac{\partial H}{\partial t} = \frac{\partial (uH)}{\partial x} + B$$

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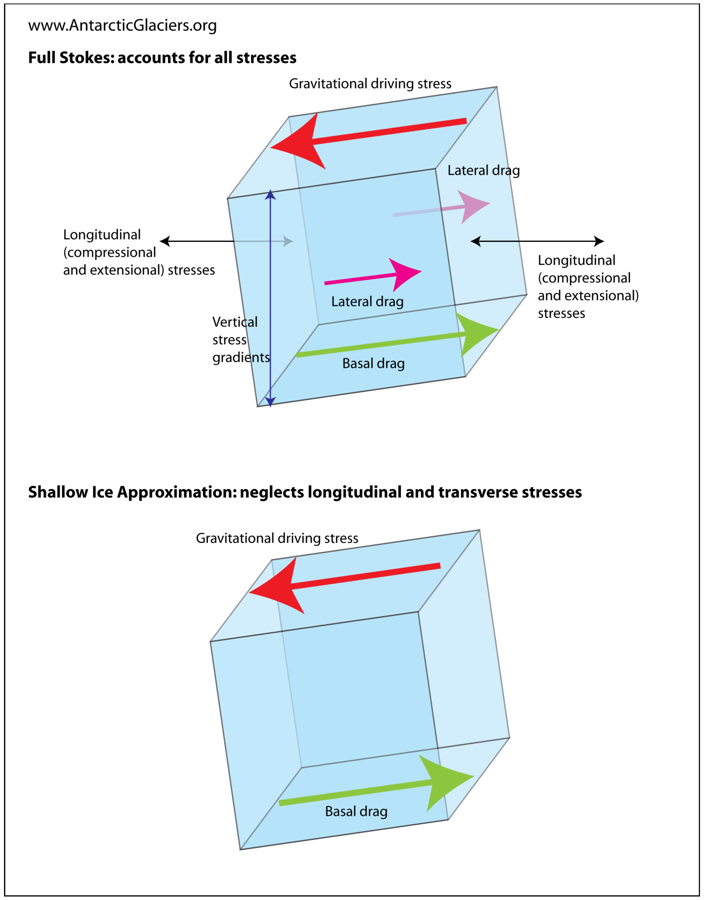
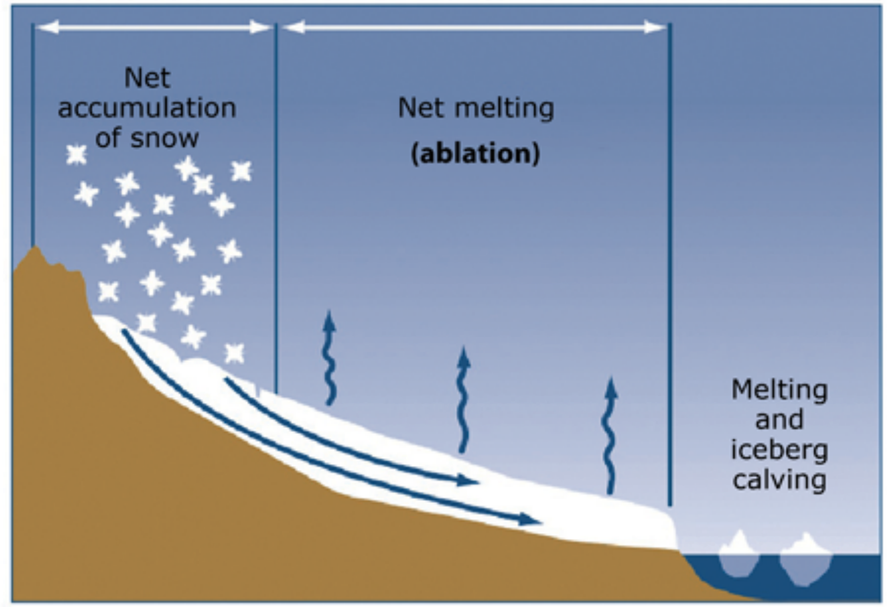
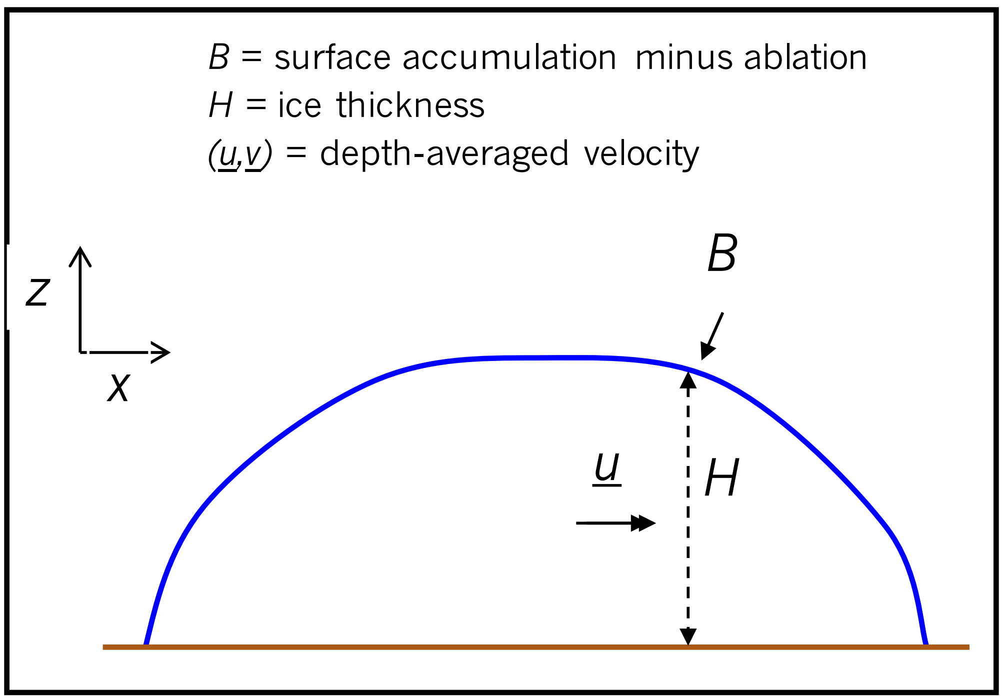


Ice Sheet Model Ingredients: Continuity Equation

Surface snowfall accumulates on interior, is compacted to ice (upper ~100 m) and is transported by ice flow to lower marginal regions (taking ~10^4 to 10^5 years).

Grounded ice is lost as surface melt, or discharged to floating ice shelves or bergs.





P. Hoffman, www.snowballearth.org/slides

Ice Conservation (Continuity) Equation:

$$\frac{\partial H}{\partial t} = -\frac{\partial(\bar{u}H)}{\partial x} - \frac{\partial(\bar{v}H)}{\partial y} + B$$

Pollard & DeConto (2009, 2012)

Ice Sheet Model Ingredients

2) Glen’s Law – non-Newtonian fluid

$$\varepsilon_{ij} = A\left|\tau\right|^{n-1}\tau_{ij} \qquad \text{(Glen's Law)}$$

Glacier Deformation

Glaciers flow because permanent deformation occurs as a result of strain in response to stress. Strain may include deformation of the ice or the sediments at the ice-bed interface, or sliding at the ice-bed interface. Resistance to strain depends on ice temperature, crystal structure, bed roughness, debris content, water pressure and other factors.

Creep is the deformation of ice crystals. Movement can occur between or within ice crystals (Cuffey & Paterson 2010). The relationship between creep and stress can be given by **Glen’s Flow Law:**

$$\varepsilon = A\tau^n$$

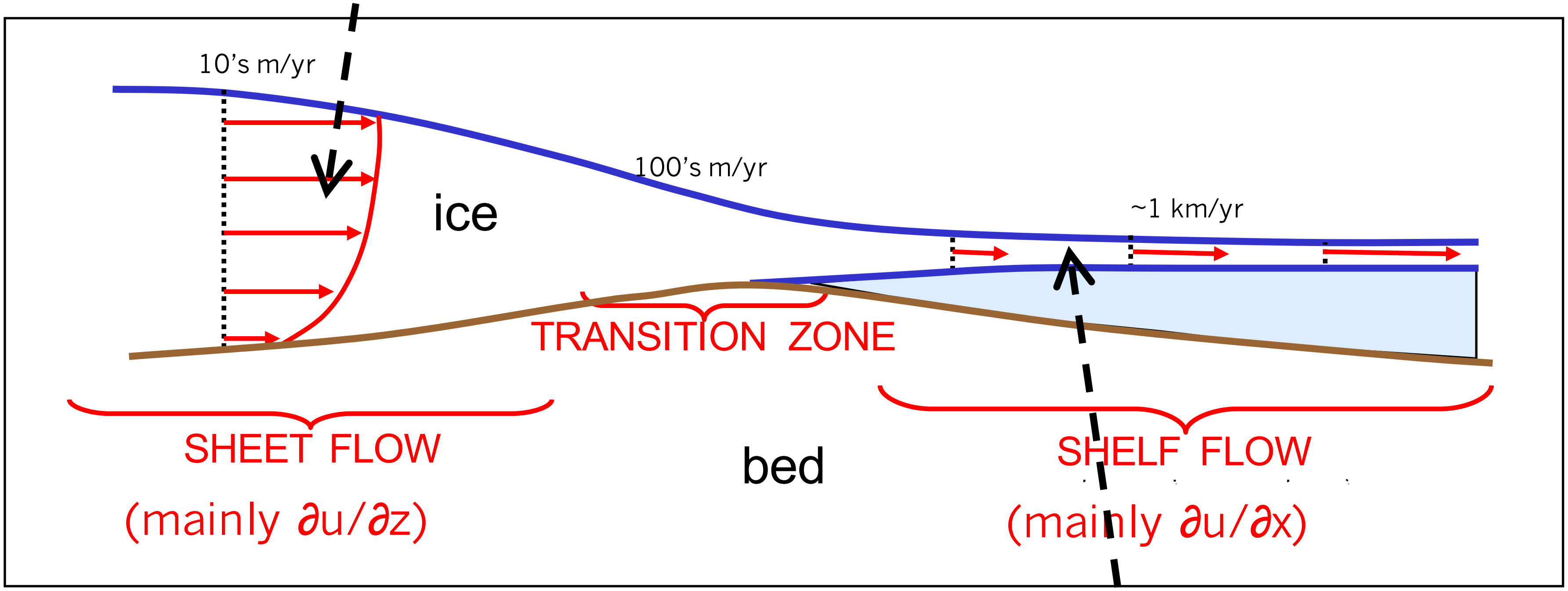
Where ε is the strain rate, *A* and *n* are constants, and τ is the basal shear stress. The constant $n = 3$, and the value of *A* is dependent on ice temperature, crystal orientation, debris content and other factors. Glacier ice may form beautiful folds or structures in response to creep.

Ice Sheet Model Ingredients: Flow Equations

Two different modes of flow, two different scaled equations:

Sheet flow (grounded, sticky or frozen base), shearing:

$$\bar{u} = -\frac{2A(\rho g)^n}{n+2} H^{n+1} |\nabla h_s|^{n-1} \frac{\partial h_s}{\partial x}$$



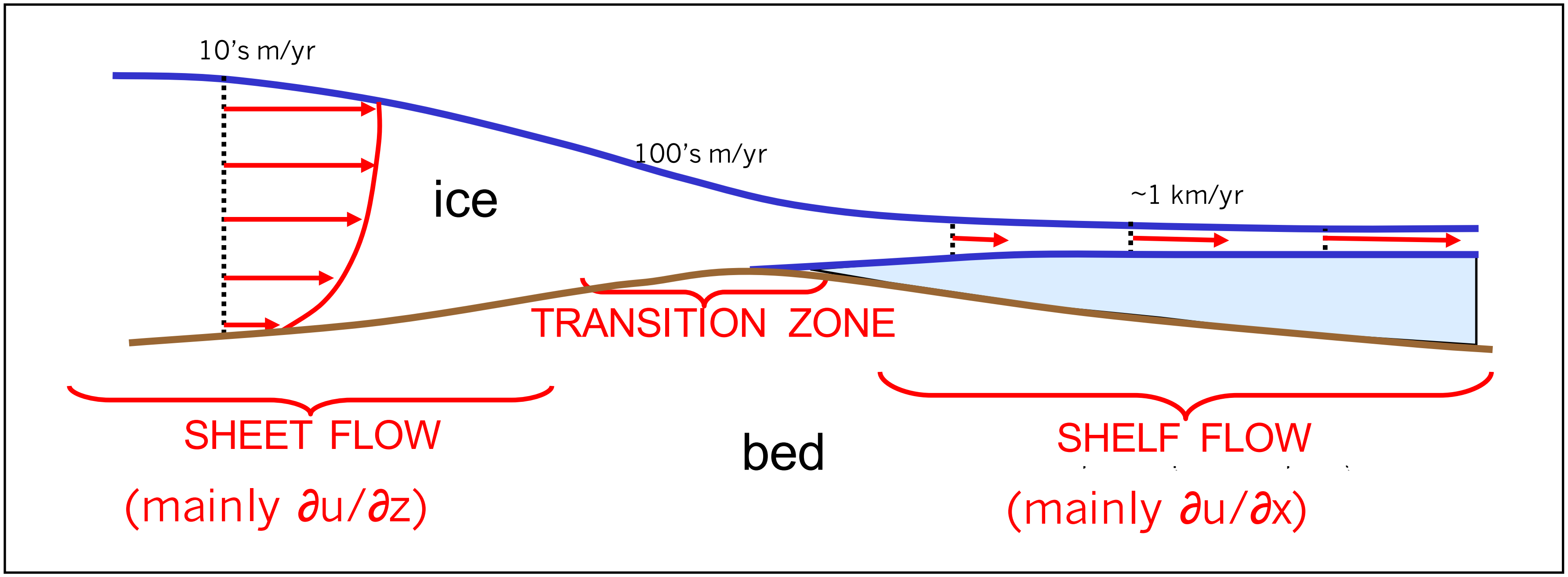
Shelf (floating) or stream (slippery base) flow, stretching:

$$\frac{\partial}{\partial x}\left[\frac{2\mu H}{\bar{A}^{1/n}}\left(2\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}\right)\right] + \frac{\partial}{\partial y}\left[\frac{\mu H}{\bar{A}^{1/n}}\left(2\frac{\partial \bar{u}}{\partial y}+\frac{\partial \bar{v}}{\partial x}\right)\right] = \rho g H \frac{\partial h_s}{\partial x} + \frac{k}{B^{1/m}} | u_b^2 + v_b^2 |^{\frac{1-m}{2m}} u_b$$

Ice Sheet Model Ingredients: Flow Equations

What about the transition zone (or "grounding zone") where longitudinal and vertical stresses are both important?

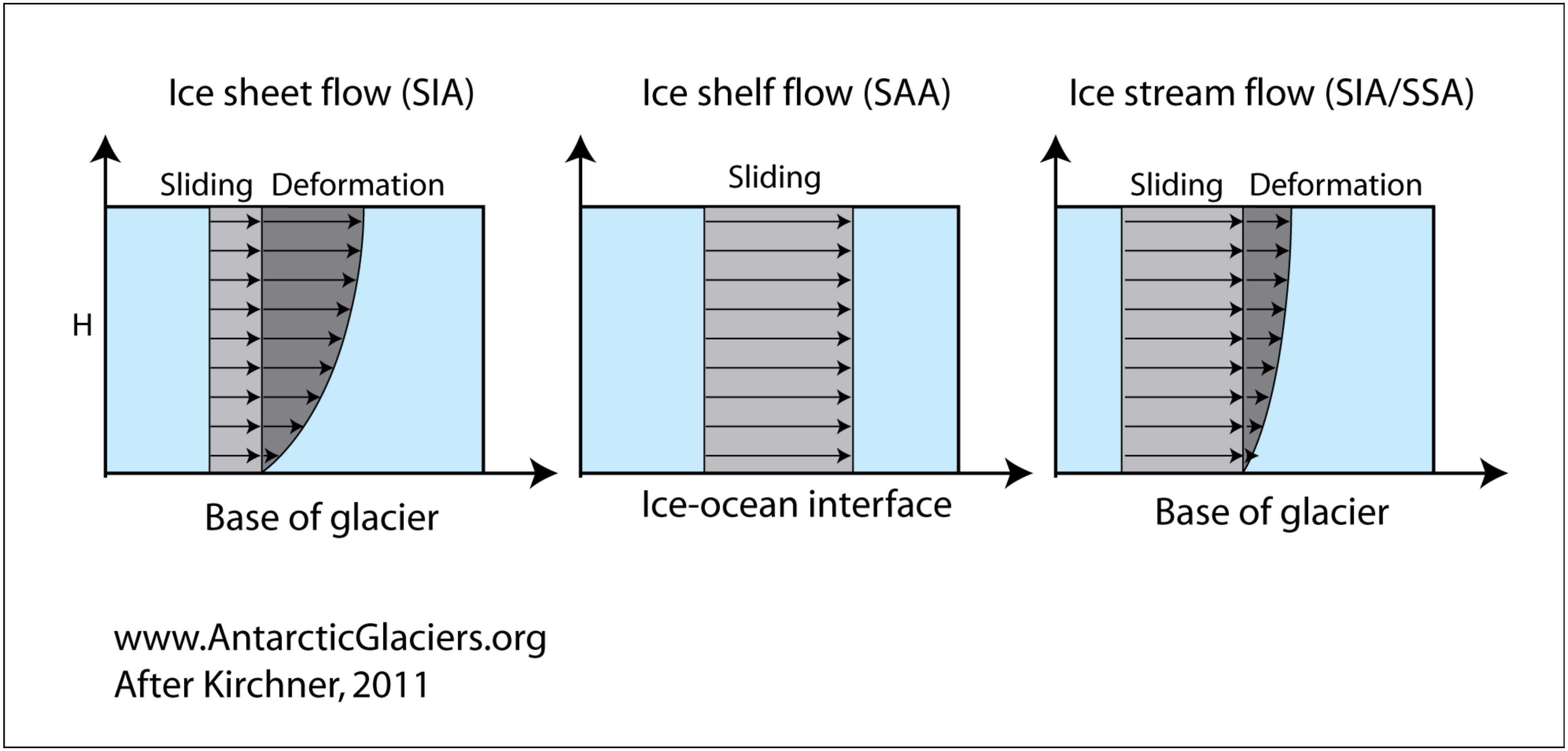
- Full stokes (requires high resolution, computationally expensive)
- Shallow Ice Approximation (SIA) and Shallow Shelf Approximation (SSA) plus parameterization across the grounding line.
- Hybrid (e.g. neglecting higher order terms + Schoof parameterization)



- Other standard components: ice temperatures, bedrock response to ice load

Pollard & DeConto (2009, 2012)

Ice Sheet Model Ingredients: Flow Equations



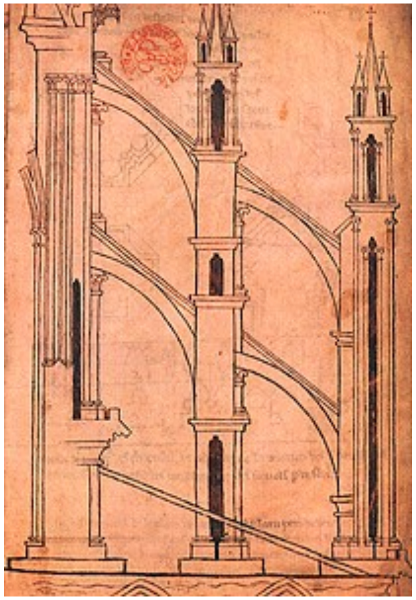
Ice Sheet Model Ingredients: Grounding Zone

Schoof's (2007, JGR) parameterization of flux across grounding lines, and buttressing:

$$q_B(x_g) = \left(\frac{\bar{A}(\rho_i g)^{n+1}(1-\rho_i/\rho_w)^n}{4^n C} \right)^{\frac{1}{m+1}} \theta^{\frac{n}{m+1}} h^{\frac{m+n+3}{m+1}}.$$

Ice thickness at grounding line

Ice shelf buttressing

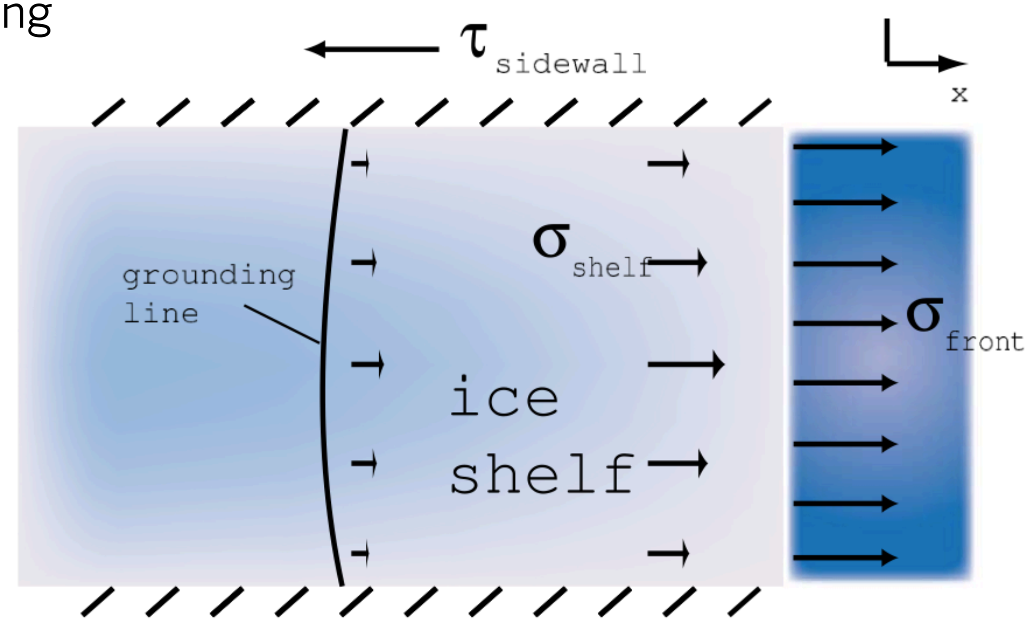


Flying buttress schematic
Riems Cathedral,
France, 1320-1335 AD

Table 1. List of the Parameter Values Used[a]

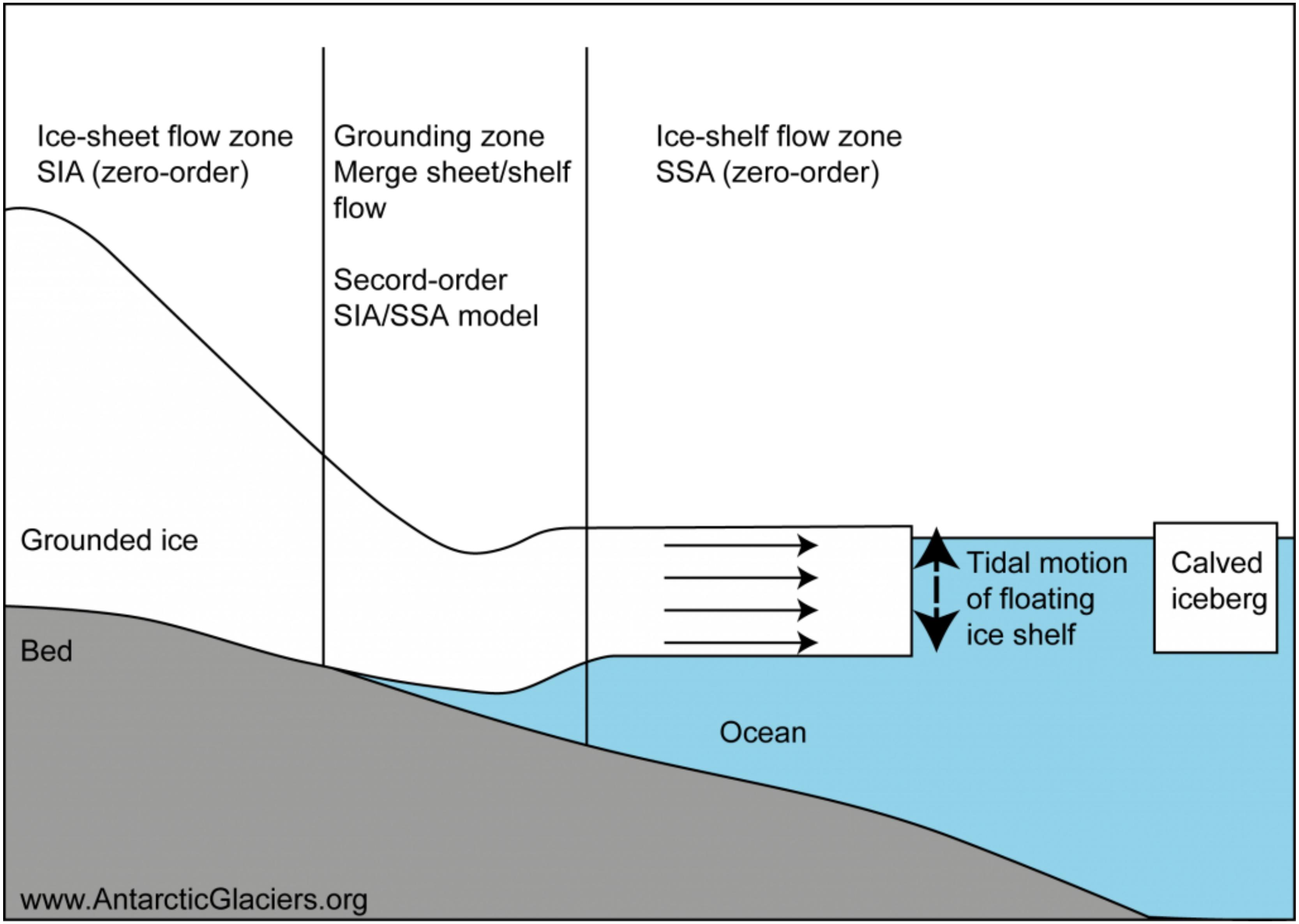
Parameter	Value
ρ_i	900 kg m^{-3}
ρ_w	1000 kg m^{-3}
g	9.8 m s^{-2}
n	3
m	1/3
C	7.624 × 10^6 Pa m$^{-1/3}$ s$^{1/3}$
a	0.3 m a^{-1}

[a]Values for $\bar{A}$ are given in Table 2. With the chosen value of C, a basal shear stress of 80 kPa corresponds to a sliding velocity of about 35 m a^{-1}.



Ice Sheet Model Ingredients: Flow Equations

Hybrid Model example



Ice Sheet Model Ingredients: Flow Equations

What about the transition zone (or "grounding zone") where longitudinal and vertical stresses are both important?

- Full stokes (requires high resolution, computationally expensive)
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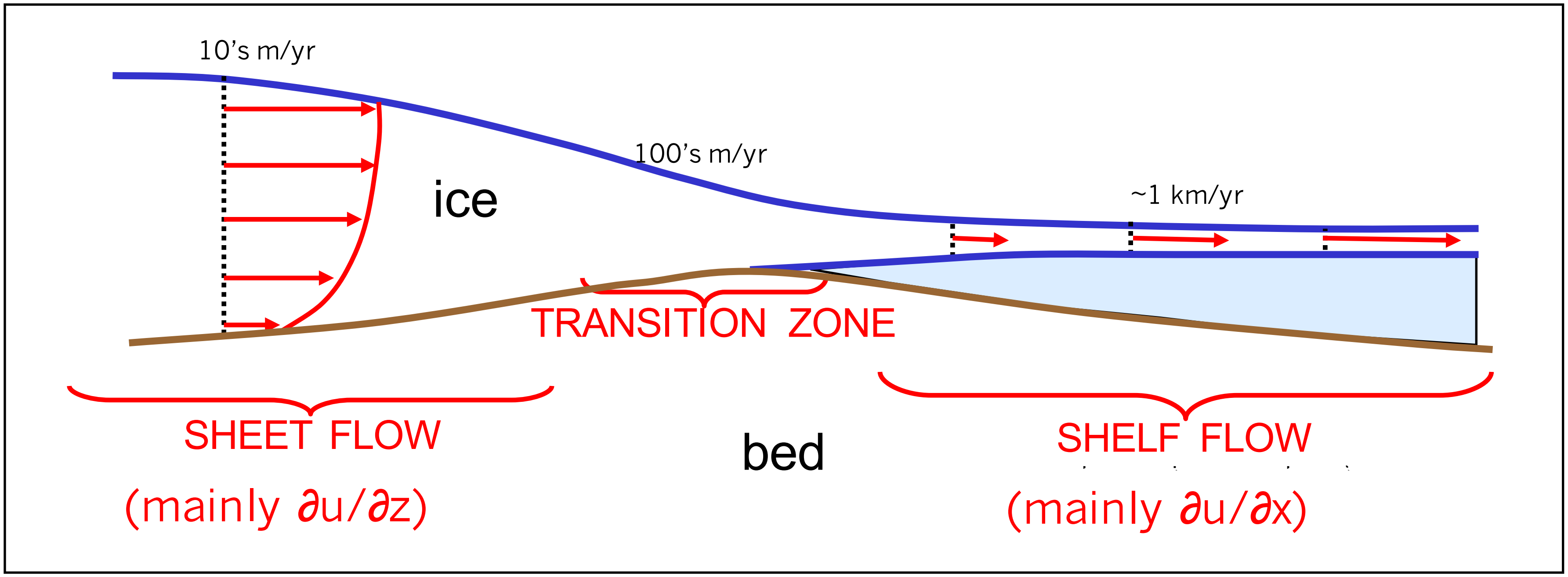
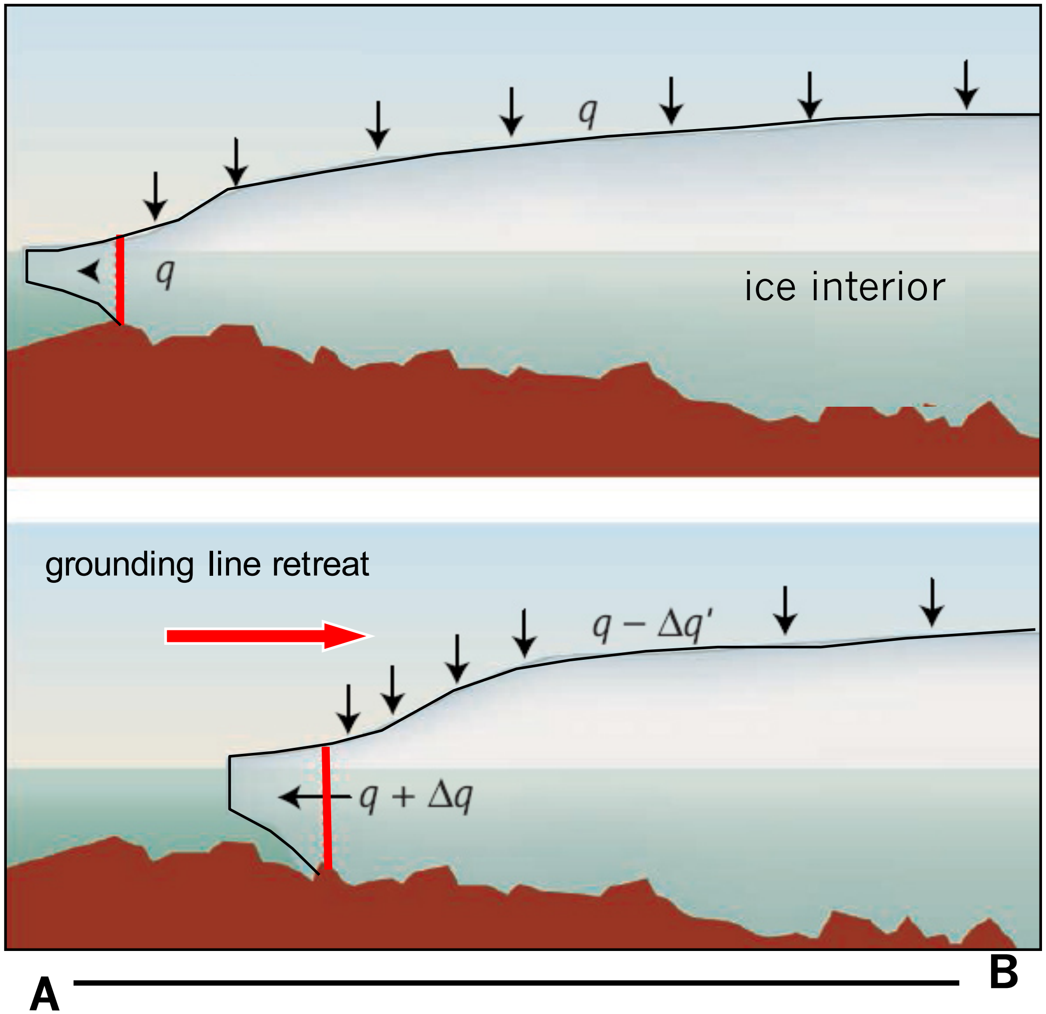
- Hybrid (e.g. neglecting higher order terms + Schoof parameterization)



- Other standard components: ice temperatures, bedrock response to ice load

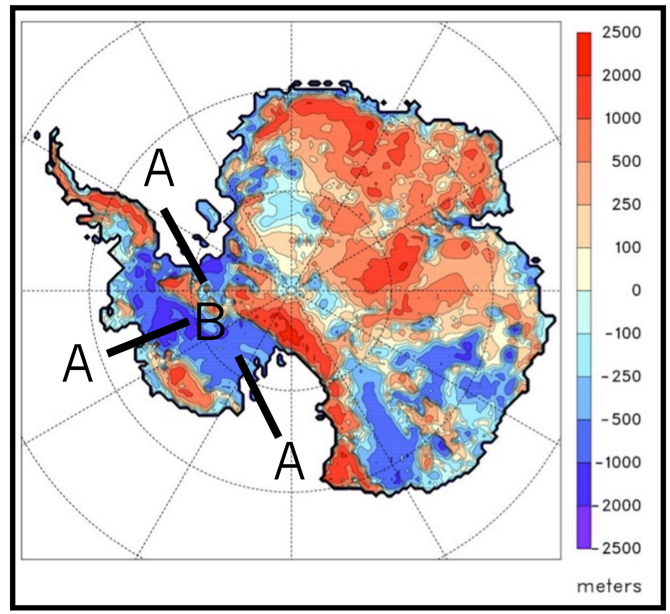
Pollard & DeConto (2009, 2012)

Marine Ice Sheet Stability and Dynamics



Vaughan and Arthern (2007)

If the bed of a marine ice sheet deepens upstream from the grounding line, then there is a possibility of runaway retreat.



BEDMAP

**BUT! This implies viscoelastic deformation of the solid Earth and sea level changes at the grounding lineinfluence ice sheet stability.

Ice Sheet Model Ingredients

Known inputs

- Temperature data
- Precipitation data
- Annual temperature range
- Sea level
- Sea surface temperature
- P/T lapse rate
- Geothermal heat flux

Model constants

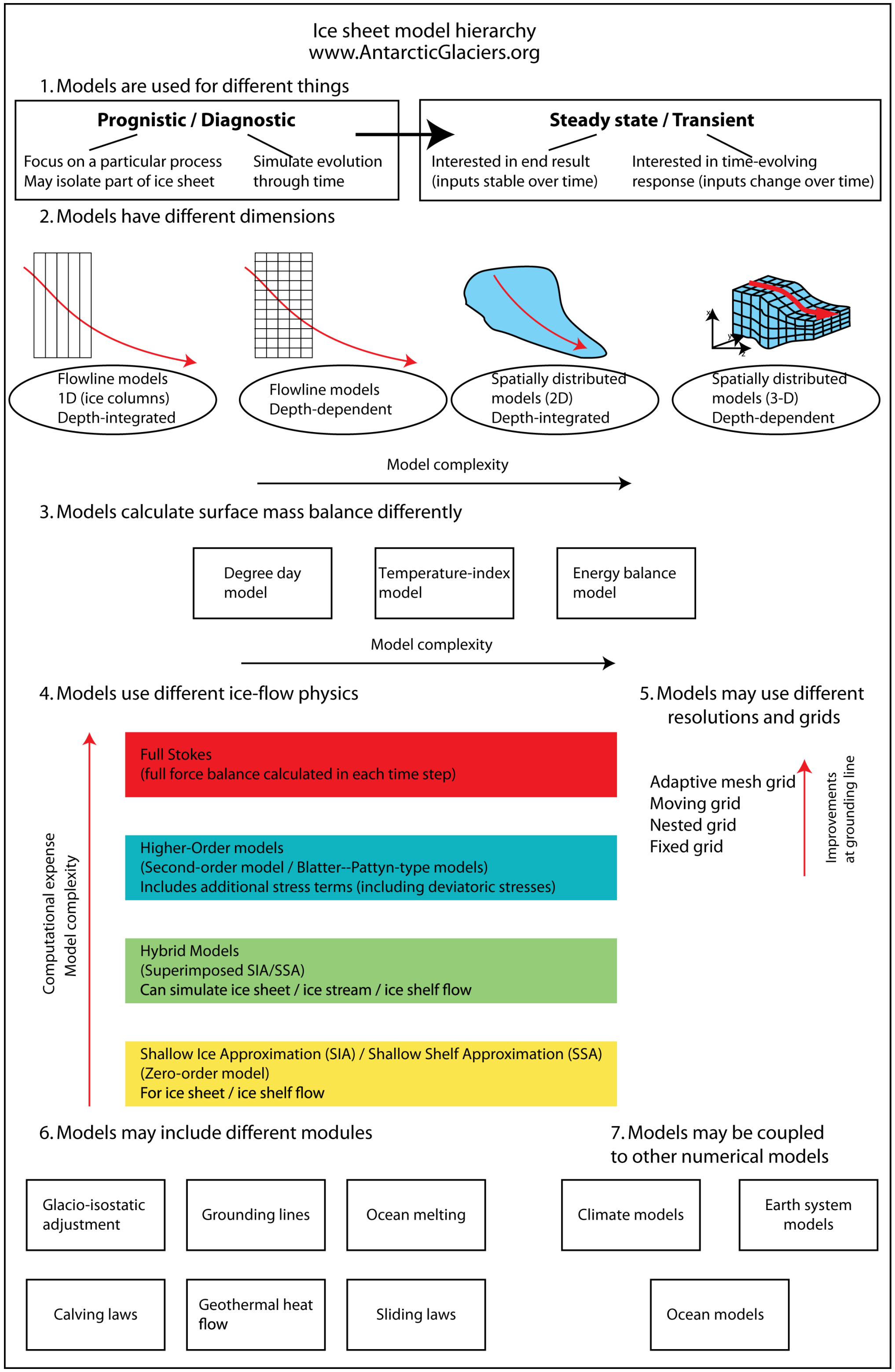
- Ice density
- Sea water density
- Gravitational acceleration
- Sliding exponent
- Density of mantle
- Thermal conductivity of ice

Tuned parameters

- Degree day factors snow/ice
- Sliding exponent
- Calving rate coefficient
- Deformation coefficient
- Refreezing

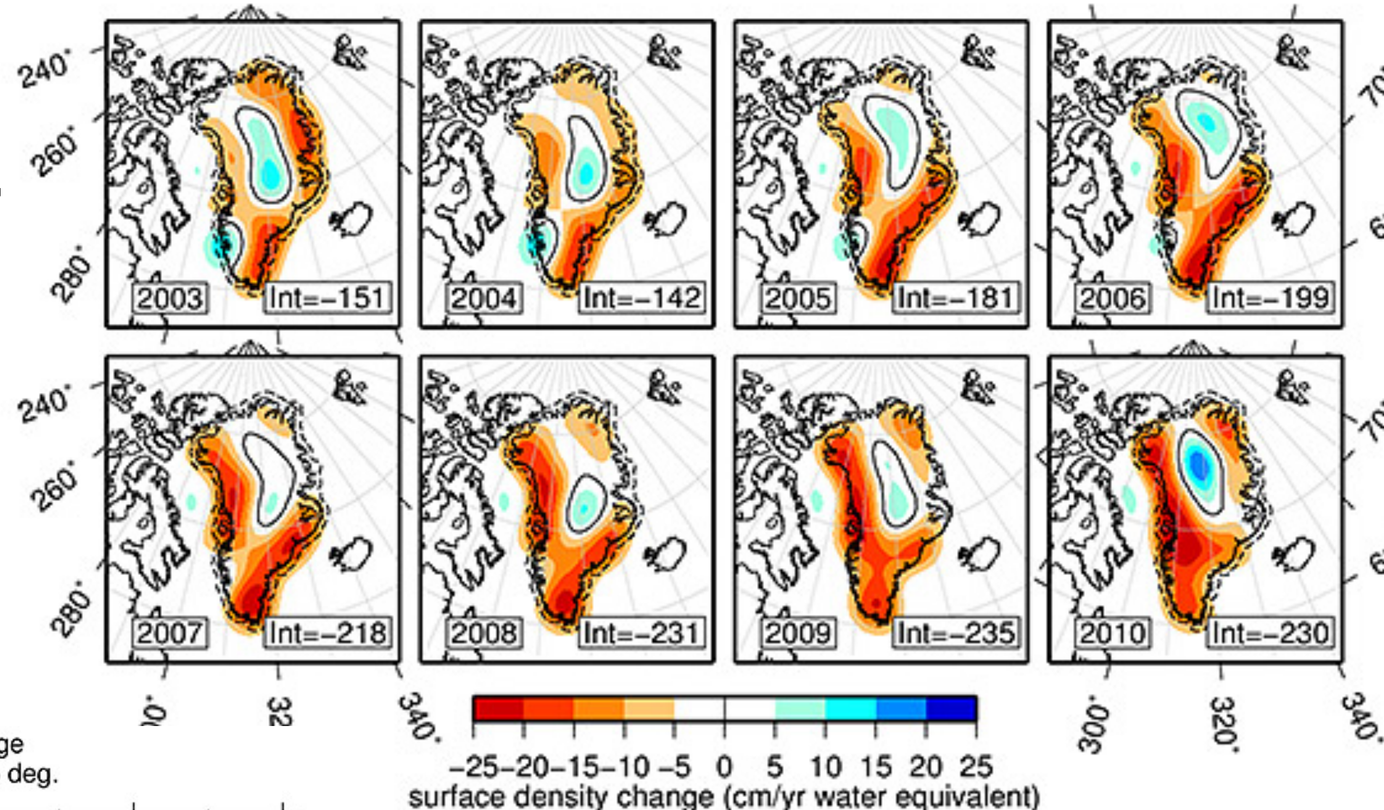
To match observations

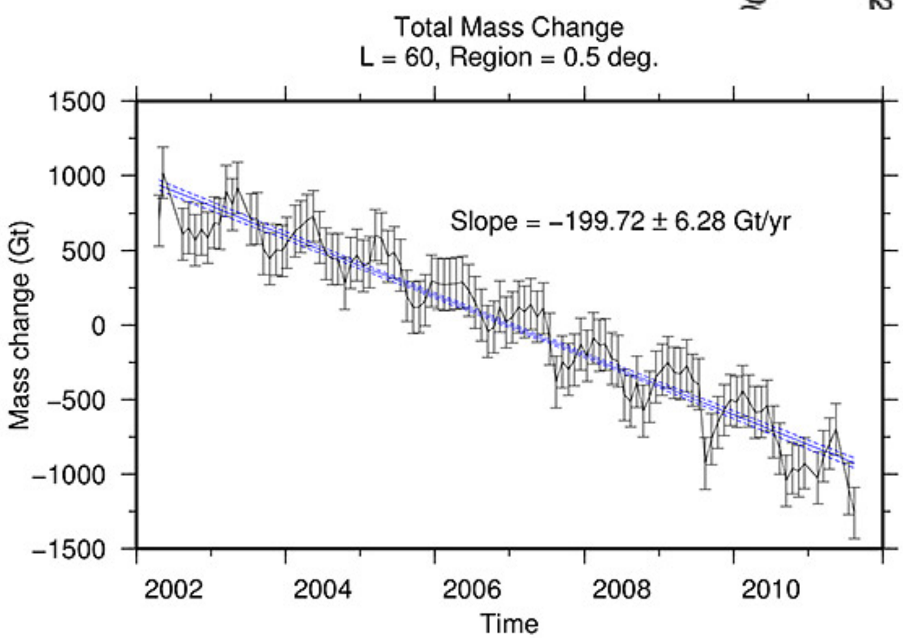
- Observed glacier length
- Observed glacier geometry
- Observed glacier volume
- Observed glacier velocity


Ice sheet model hierarchy
www.AntarcticGlaciers.org
1. Models are used for different things
Prognistic / Diagnostic
Focus on a particular process
May isolate part of ice sheet
Simulate evolution
through time
Steady state / Transient
Interested in end result
(inputs stable over time)
Interested in time-evolving
response (inputs change over time)
2. Models have different dimensions
Flowline models
1D (ice columns)
Depth-integrated
Flowline models
Depth-dependent
Spatially distributed
models (2D)
Depth-integrated
Spatially distributed
models (3-D)
Depth-dependent
Model complexity
3. Models calculate surface mass balance differently
Degree day
model
Temperature-index
model
Energy balance
model
Model complexity
4. Models use different ice-flow physics
Computational expense
Model complexity
Full Stokes
(full force balance calculated in each time step)
Higher-Order models
(Second-order model / Blatter--Pattyn-type models)
Includes additional stress terms (including deviatoric stresses)
Hybrid Models
(Superimposed SIA/SSA)
Can simulate ice sheet / ice stream / ice shelf flow
Shallow Ice Approximation (SIA) / Shallow Shelf Approximation (SSA)
(Zero-order model)
For ice sheet / ice shelf flow
5. Models may use different
resolutions and grids
Adaptive mesh grid
Moving grid
Nested grid
Fixed grid
Improvements
at grounding line
6. Models may include different modules
Glacio-isostatic
adjustment
Grounding lines
Ocean melting
Calving laws
Geothermal heat
flow
Sliding laws
7. Models may be coupled
to other numerical models
Climate models
Earth system
models
Ocean models

Other Ice

Greenland Ice Sheet:
Strong seasonal variations,
Surface Melting
Topography driven flow
... and more!

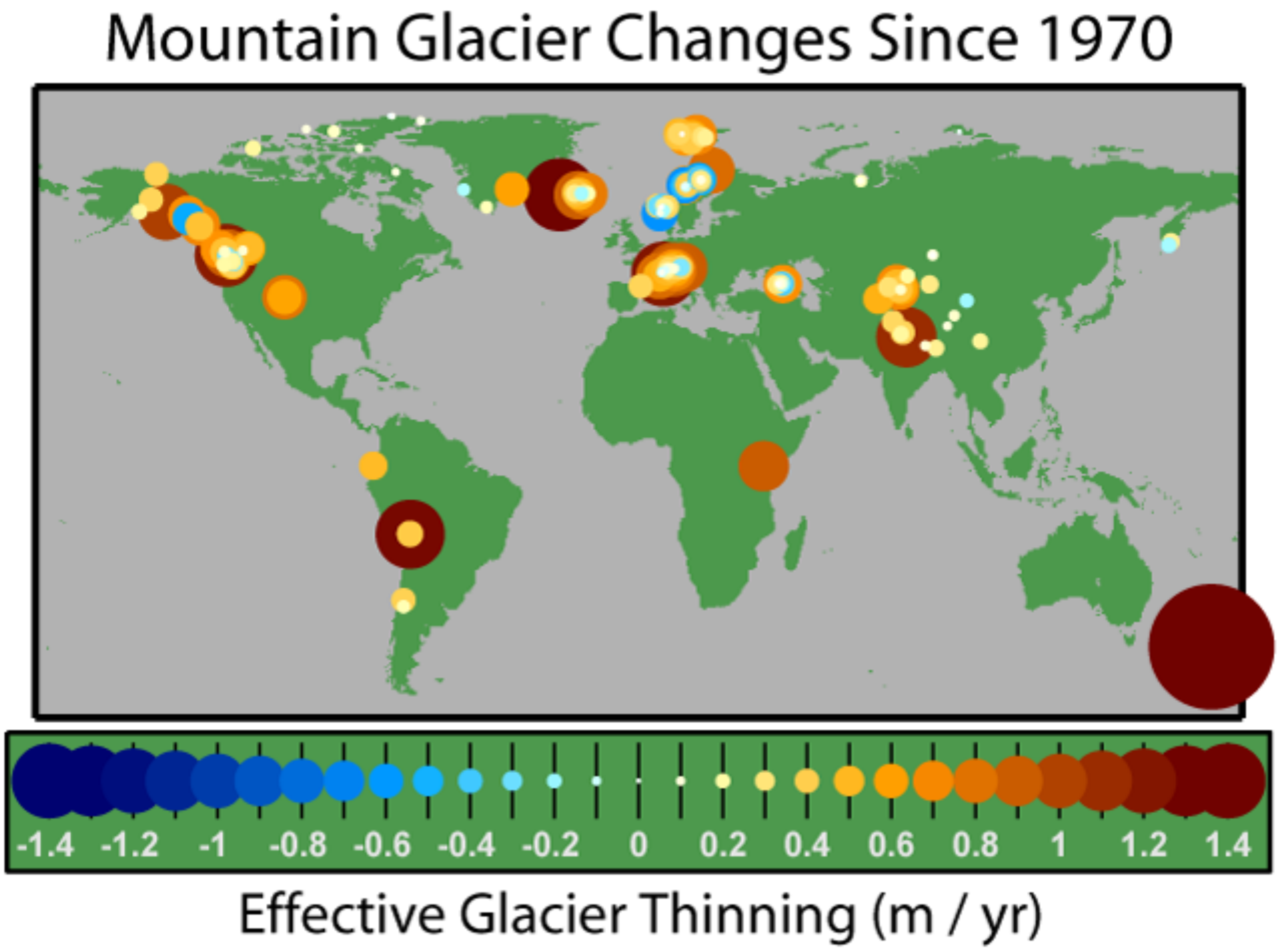




Other Ice

Mountain Glaciers: Mountain glaciers have been thinning and receeding significantly in recent decades

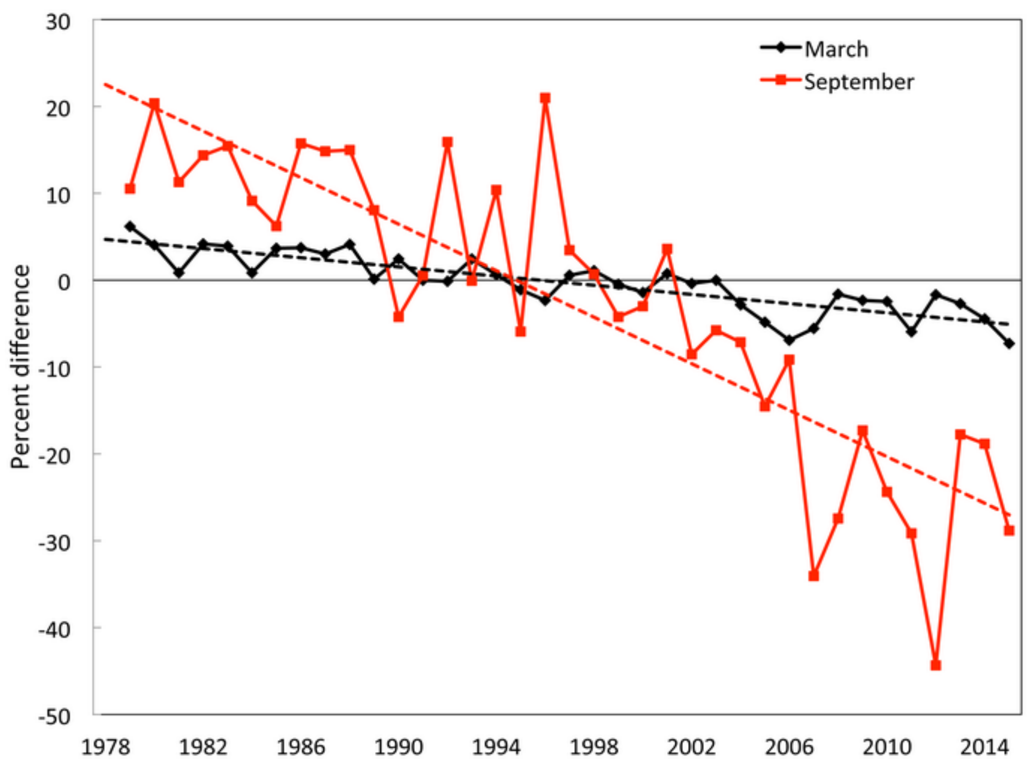
- see the movie "Chasing Ice" for visually impactful demonstration of climate change.



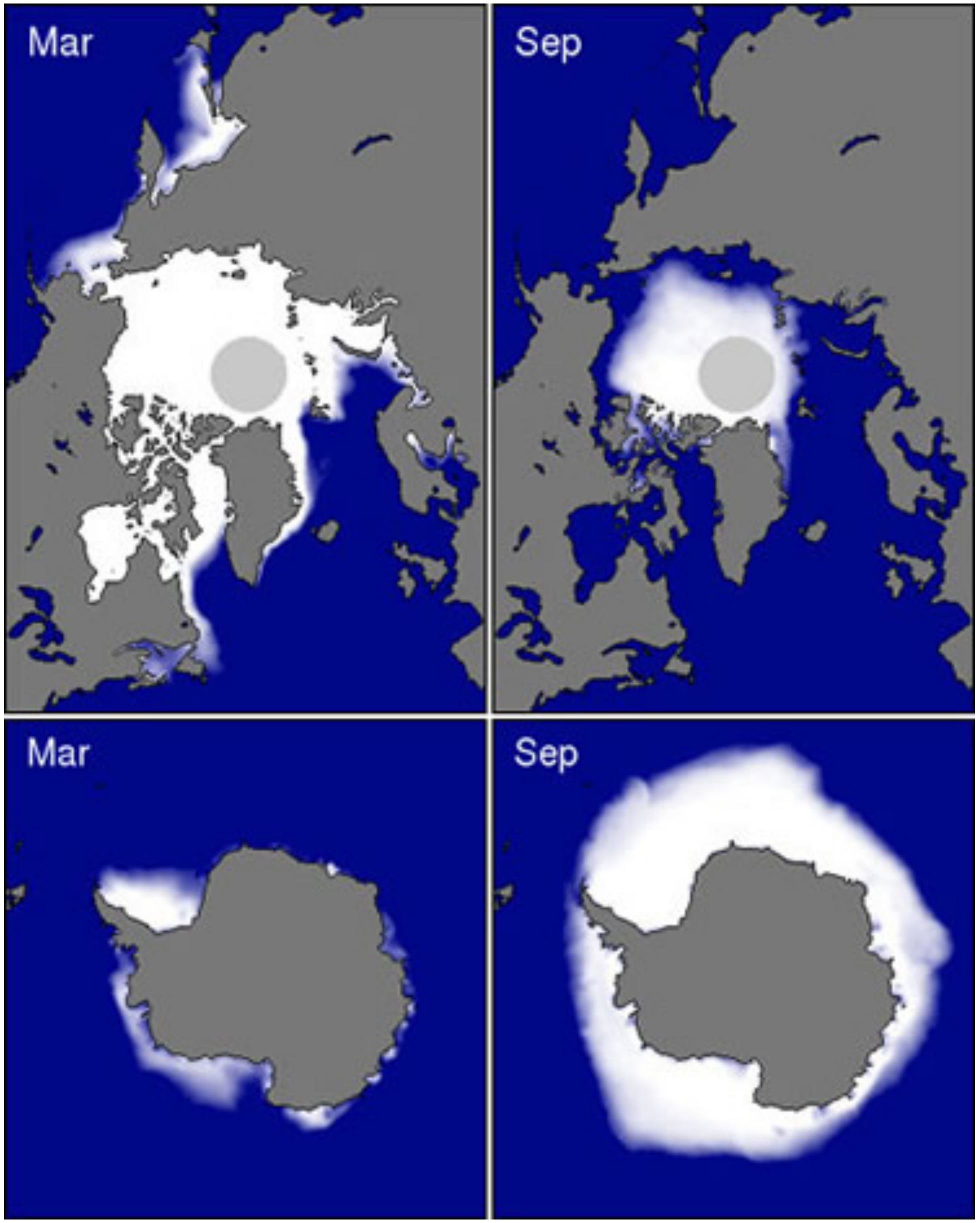
Other Ice

Sea Ice: Frozen water that forms, grows and melts in the ocean. Impacts climate and ocean circulation.

Northern Hemisphere sea ice extent anomalies in March (max) and September (min) relative to the mean values for the period 1981-2010.

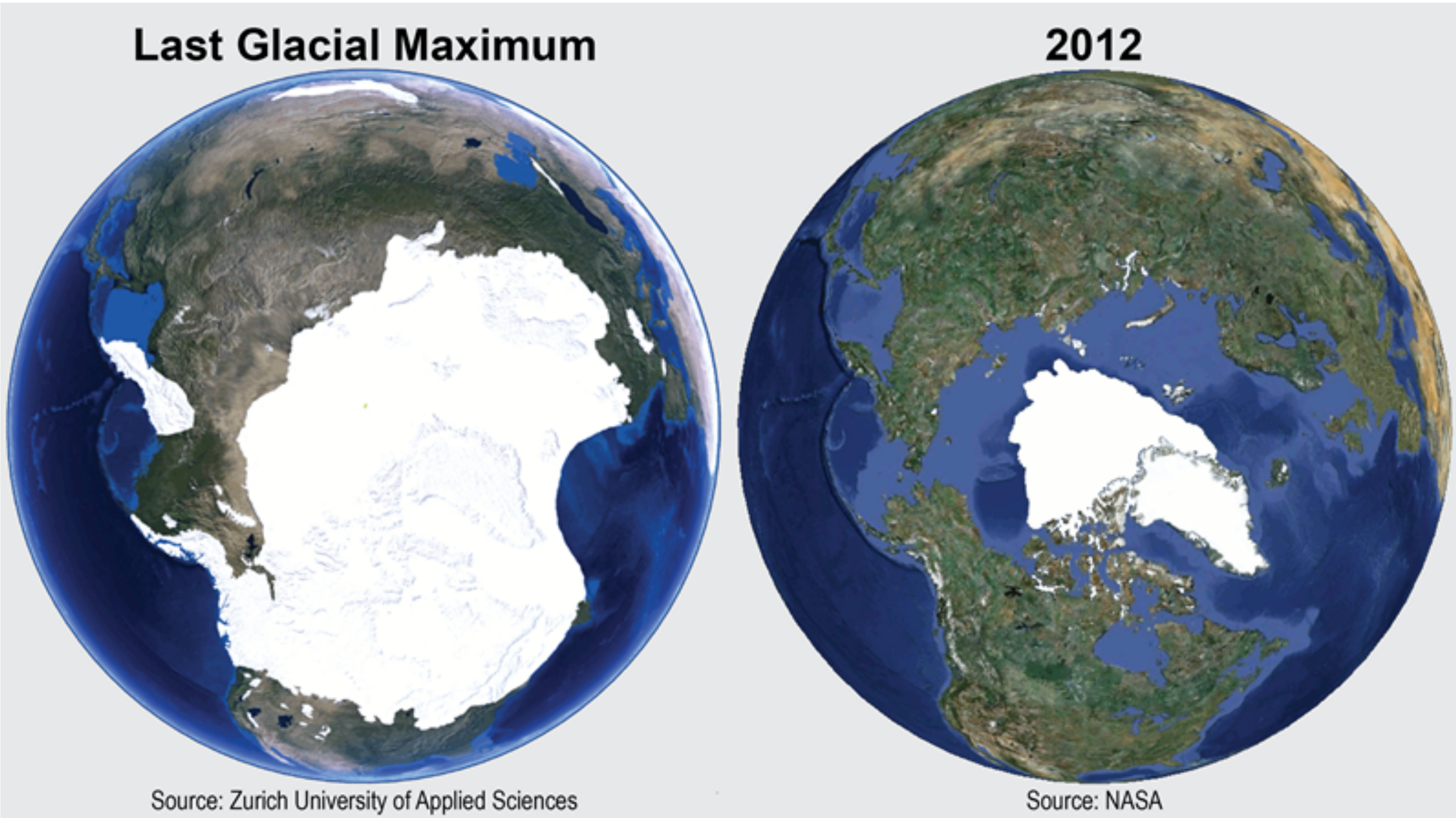


Average sea ice extent in 2015.



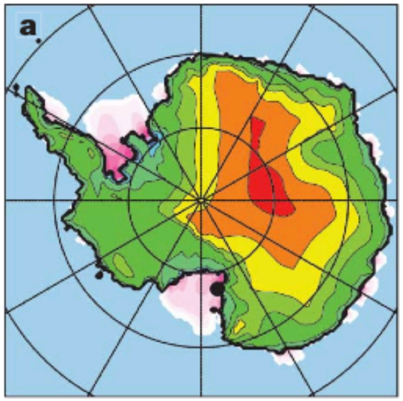
Other Ice

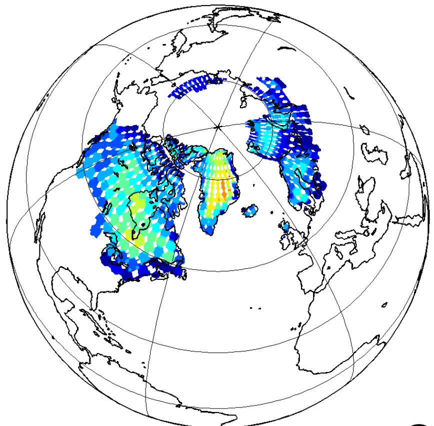
Past Ice Sheets:



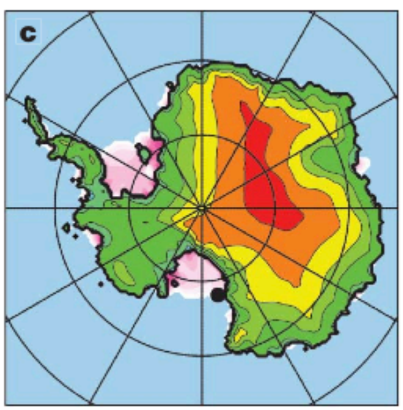
Sea Level Physics: Ice-Age Timescales

Last Glacial Maximum

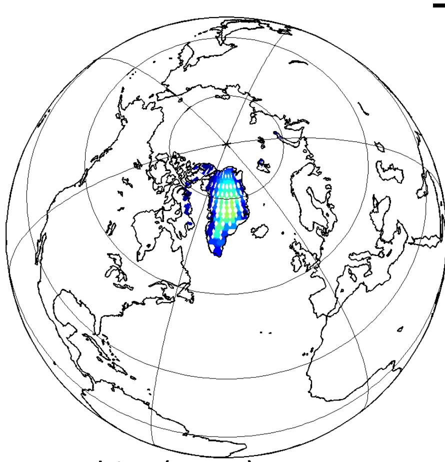




Modern Climate

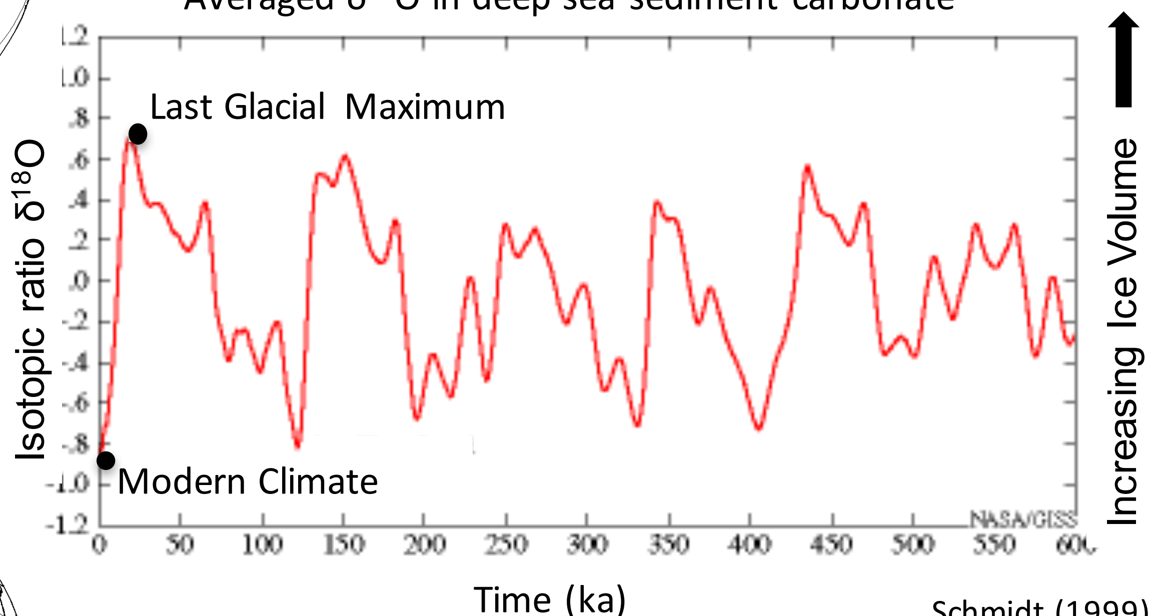


Pollard & DeConto (2009)



Peltier (2004) ICE5G

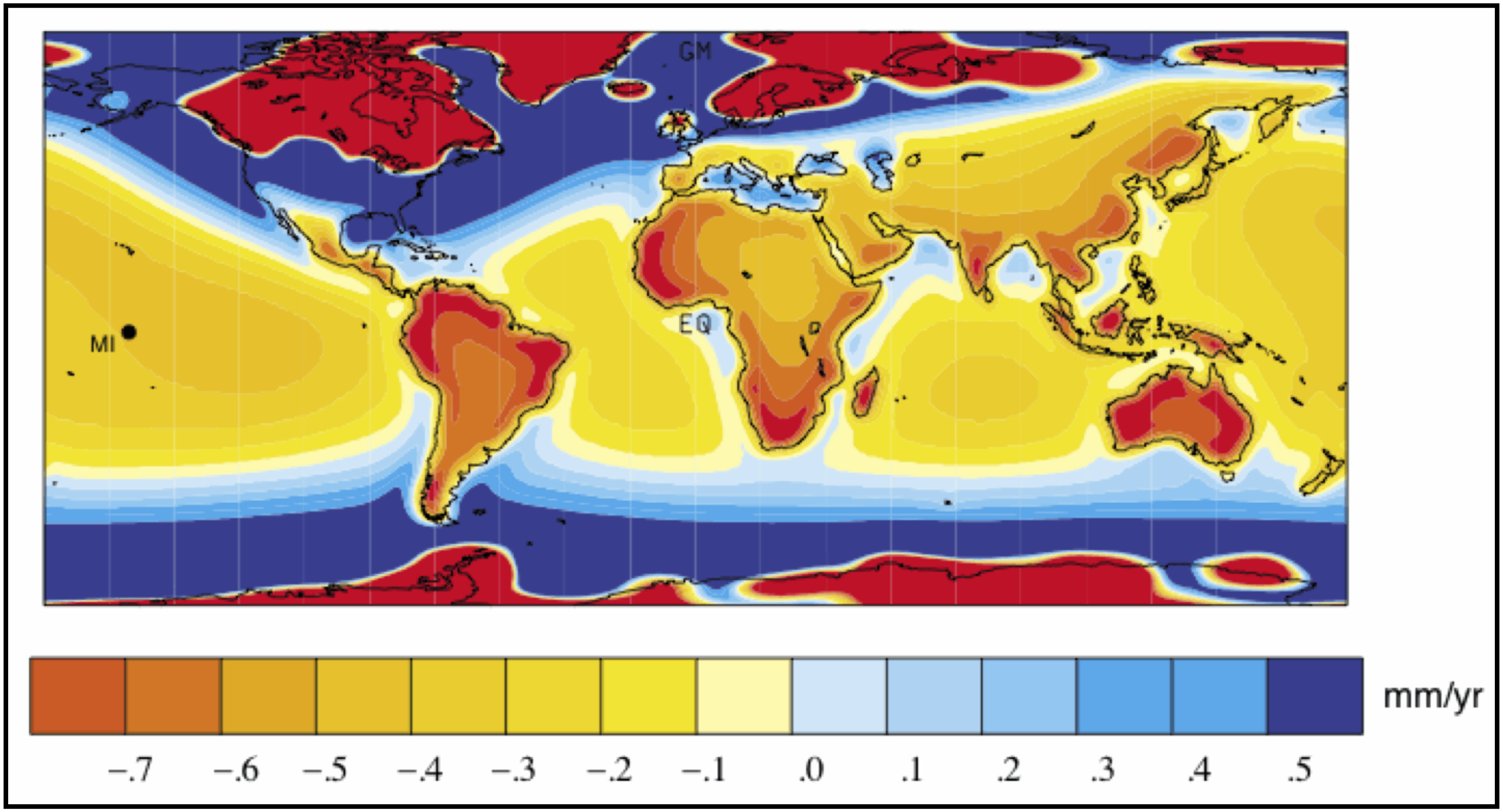
Averaged $\delta^{18}O$ in deep sea sediment carbonate



Schmidt (1999)

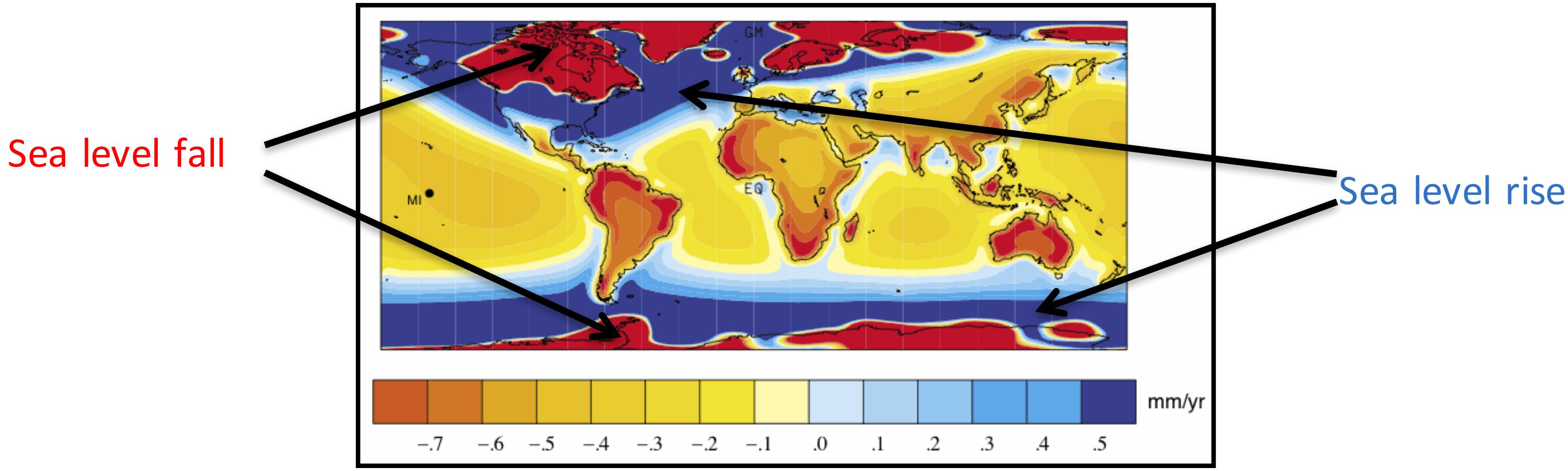
Sea Level Physics: Ice-Age Timescales

Numerical prediction of the present-day rate of change of global sea level due to ongoing GIA effects from the last ice age

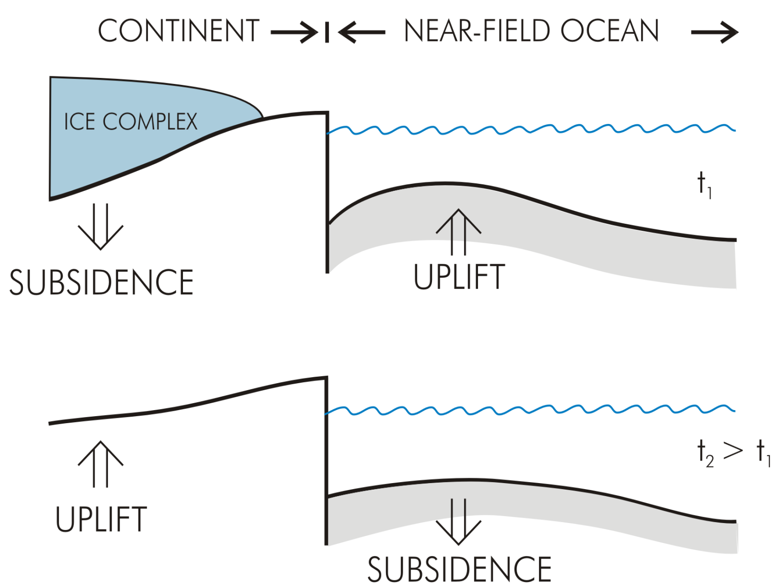


Mitrovica and Milne (2002)

Sea Level Physics: Ice-Age Timescales



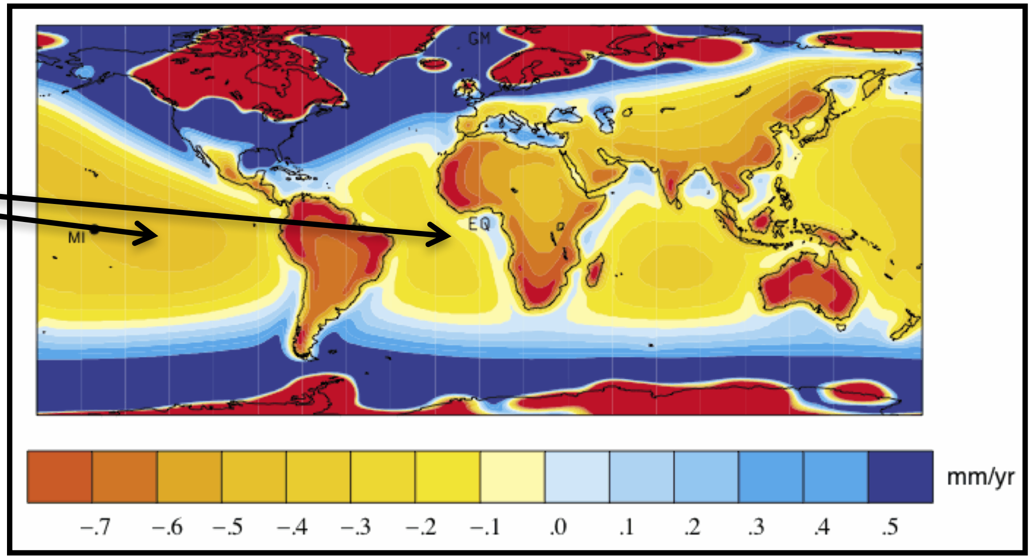
Mitrovica and Milne (2002)



Exposed beach lines in Hudson Bay

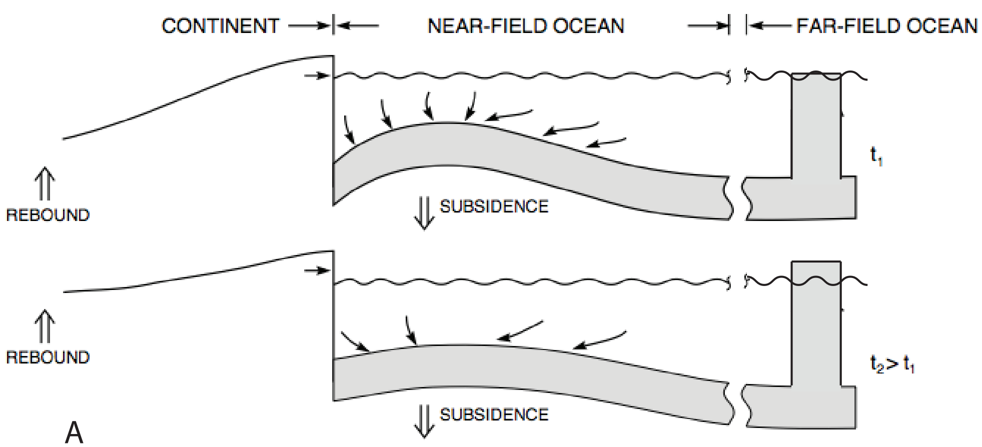
Sea Level Physics: Ice-Age Timescales

Sea level fall

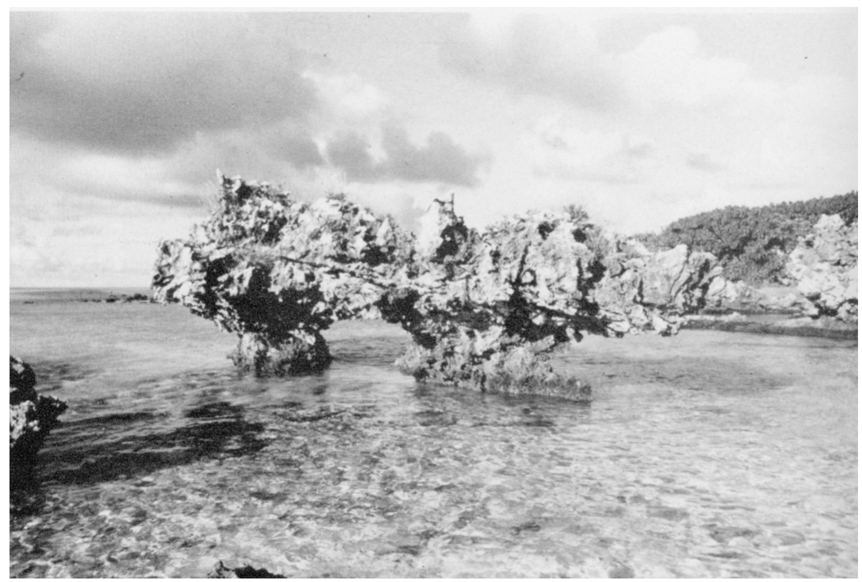


Mitrovica and Milne (2002)

Ocean Syphoning

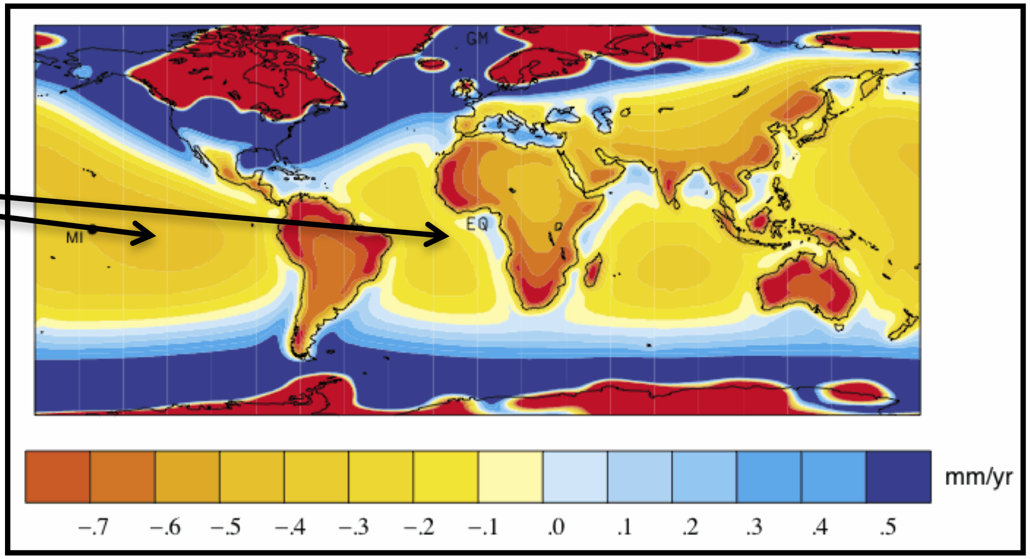


Exposed coral reef in equatorial regions



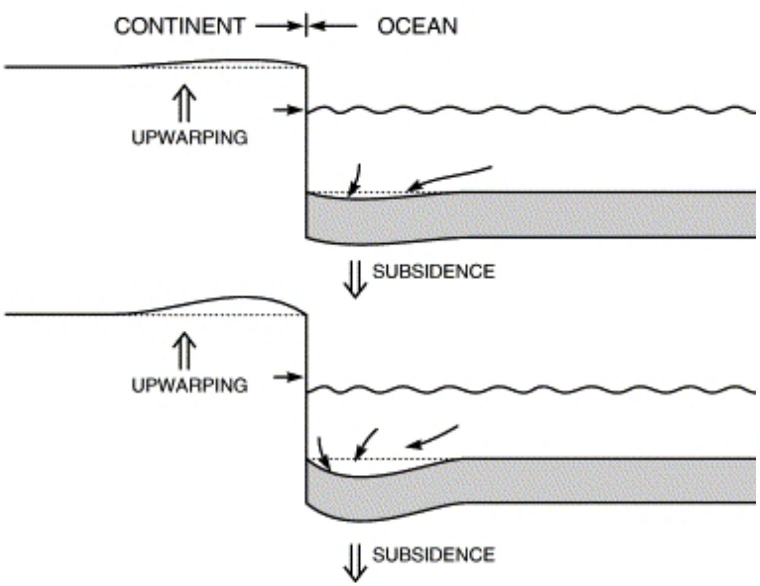
Sea Level Physics: Ice-Age Timescales

Sea level fall

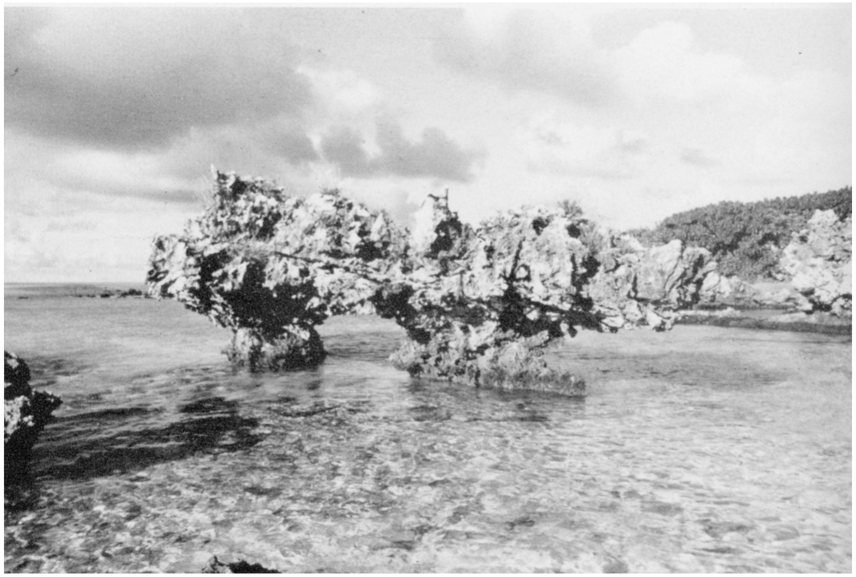


Mitrovica and Milne (2002)

Continential Levering



Exposed coral reef in equatorial regions

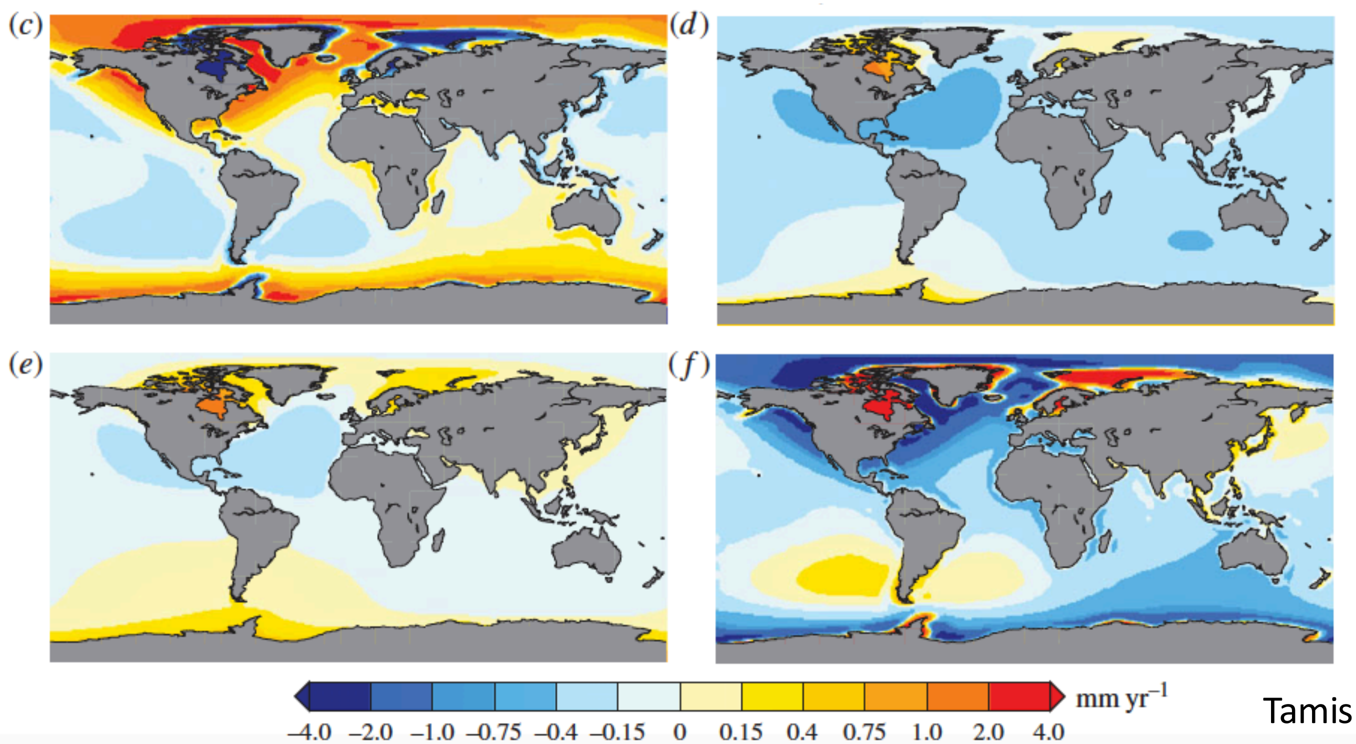


Sea Level Physics: Ice-Age Timescales

Expressions of GIA in modern sea-level records

Sea level (tide gauges)

Sea surface height (altimetry)



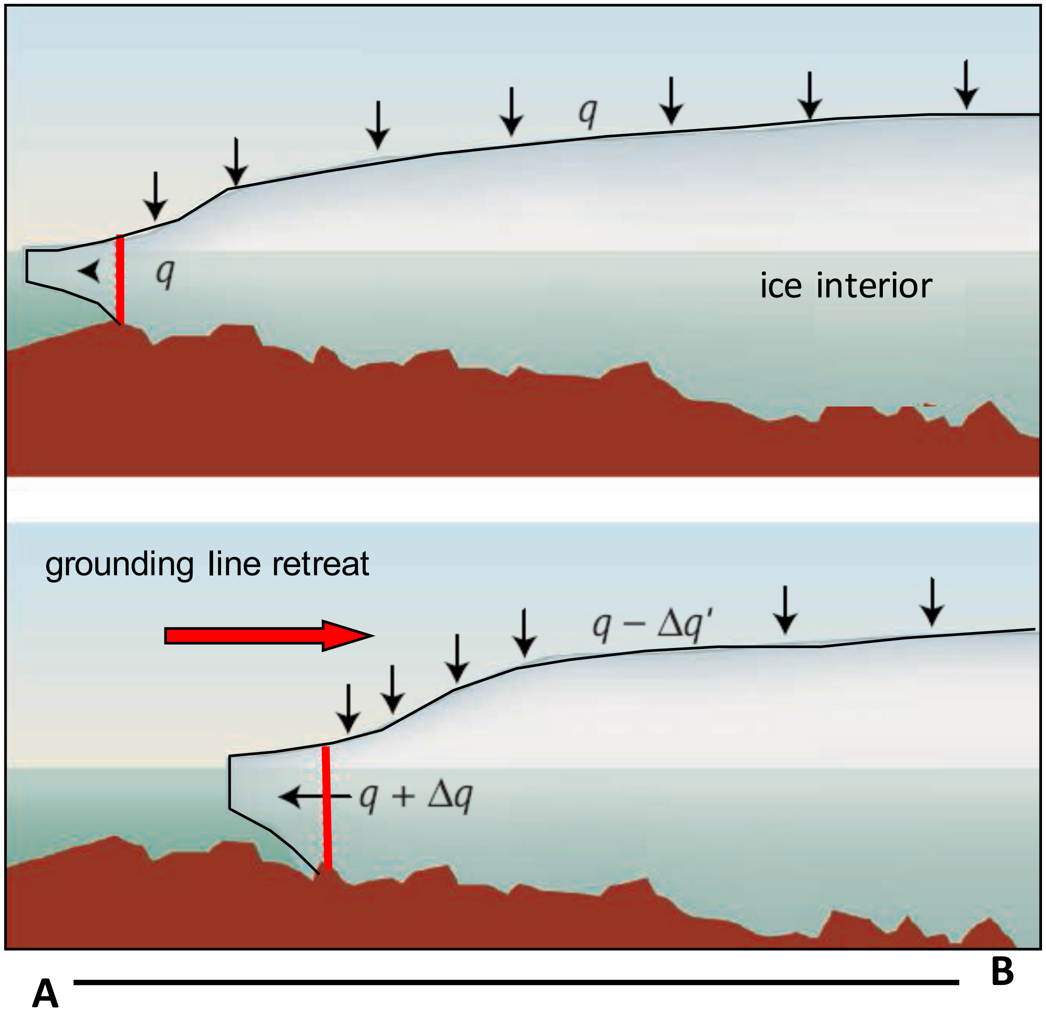
Geoid height (GRACE)

Crustal motion (GNSS)

Tamisiea et al. (2014)

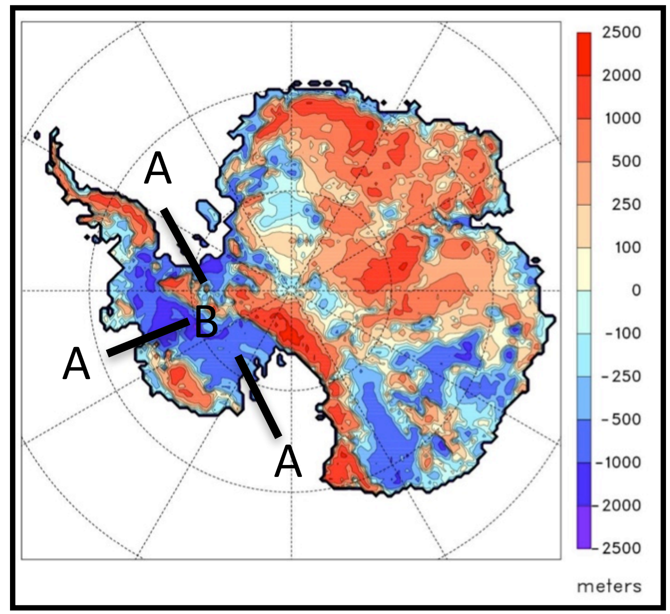
All modern observations of sea-level-related quantities are impacted by past ice and ocean loading changes!

Marine Ice Sheet Stability and Dynamics



Vaughan and Arthern (2007)

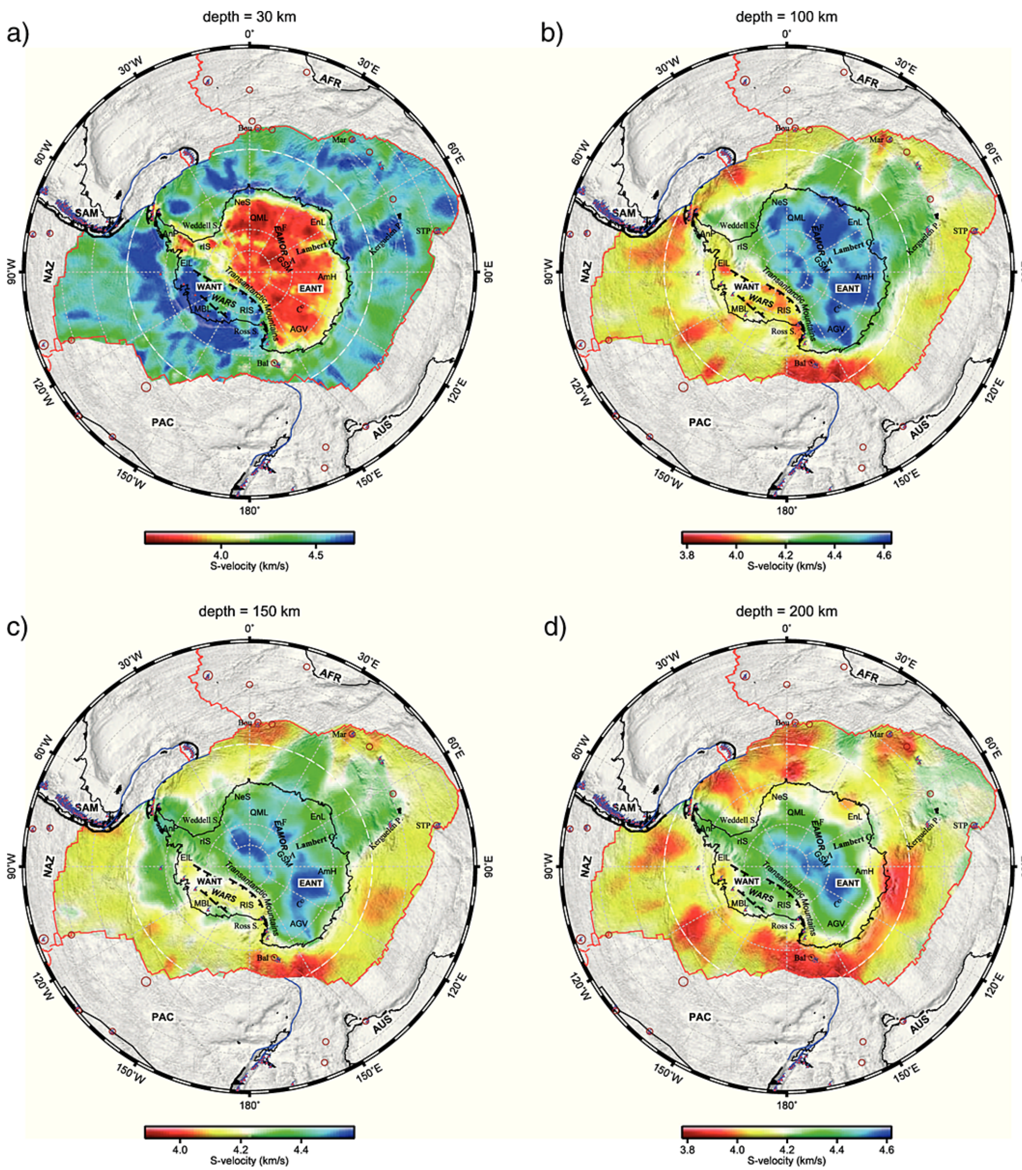
If the bed of a marine ice sheet deepens upstream from the grounding line, then there is a possibility of runaway retreat.



BEDMAP

**BUT! This implies viscoelastic deformation of the solid Earth and sea level changes at the grounding lineinfluence ice sheet stability.

Earth Structure Beneath Antarctica



Variations in viscoelastic Earth structure can impact predictions of sea-level change and surface deformation following surface loading (ice cover changes) by:

1) Altering the timing and geometry of load-induced Earth deformation

2) Perturbing, via a sea-level feedback, the timing and extent of the ice-sheet retreat/advance

Outline

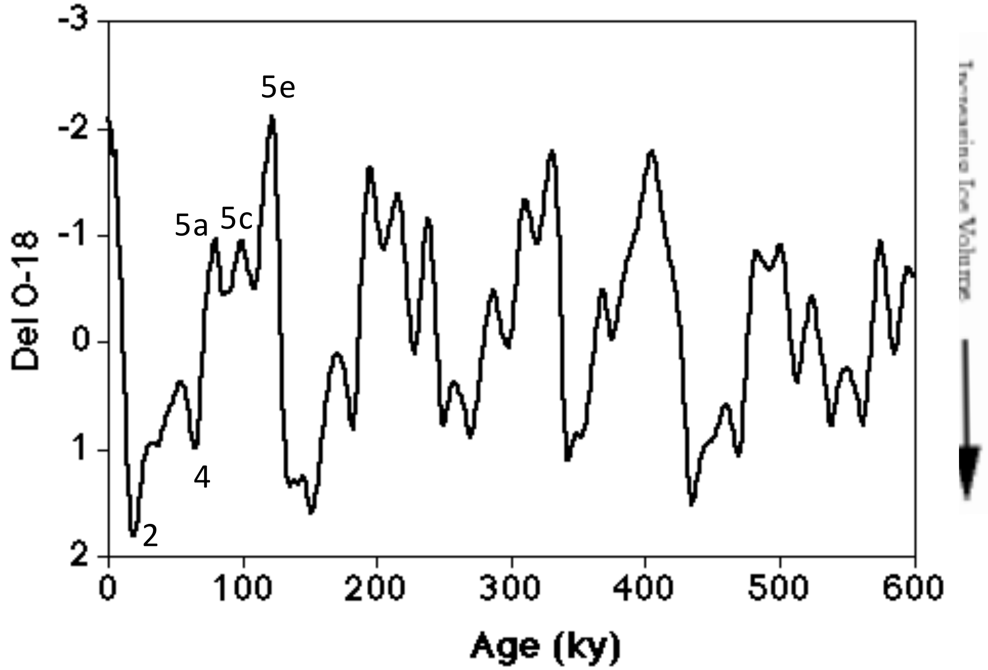
This Class: Sea Level Change Continued…

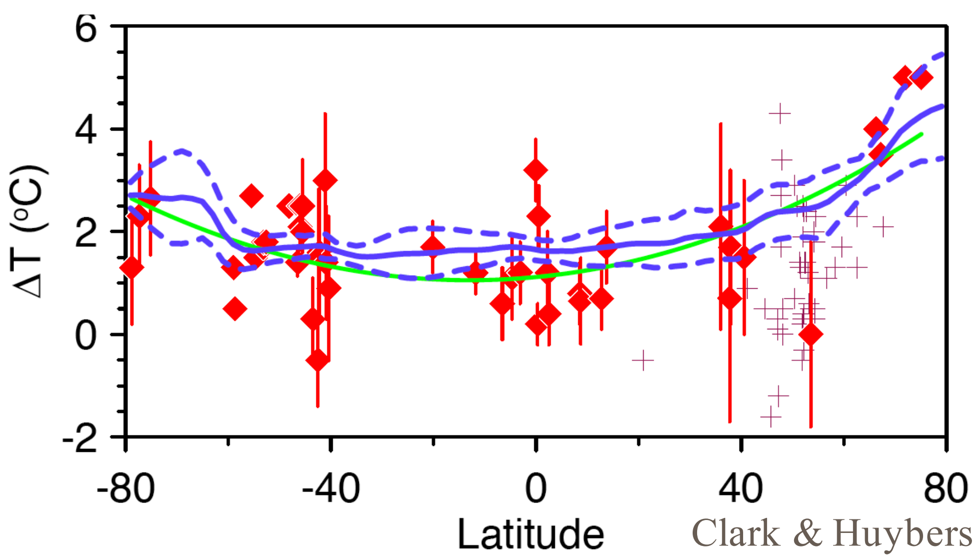
1. Sea level change and GIA on ice age timescales.

1. An Example Calculations

2. Applications
    1. Short timescale modern: 20th Century Tide Gauge Analysis
    2. Short timescale paleo: Meltwater Pulse 1A (~14ky ago)
    3. GIA: Archaeological evidence for recent acceleration in sea level rise (Holocene – last 2 ky)
    4. Ice age timescale: Sea Level during the Last Interglacial (~125 ky ago)

Ice Age Sea Level: The Last Interglacial

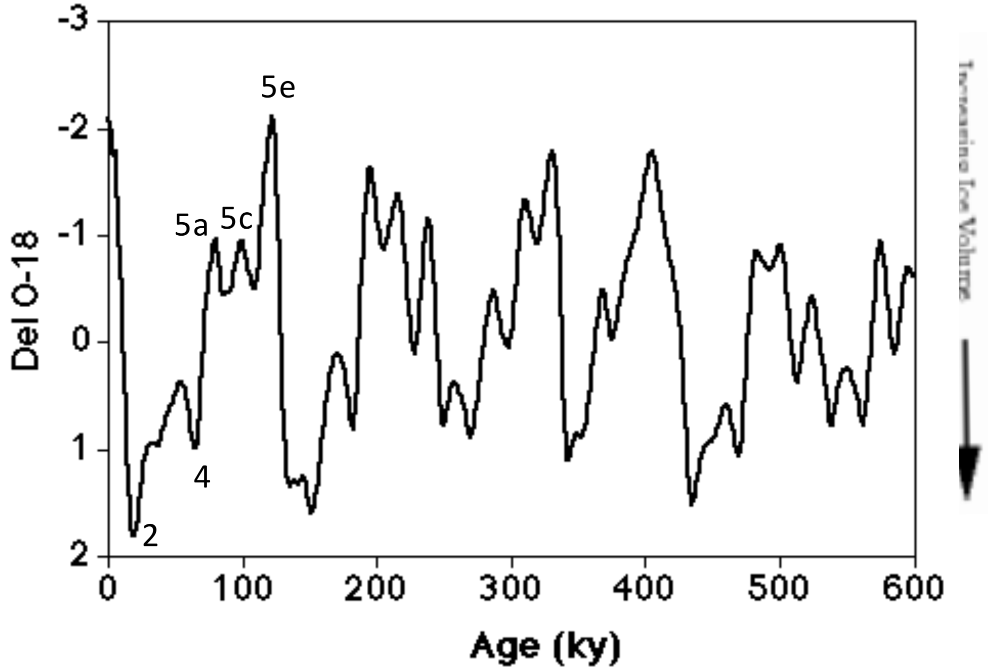


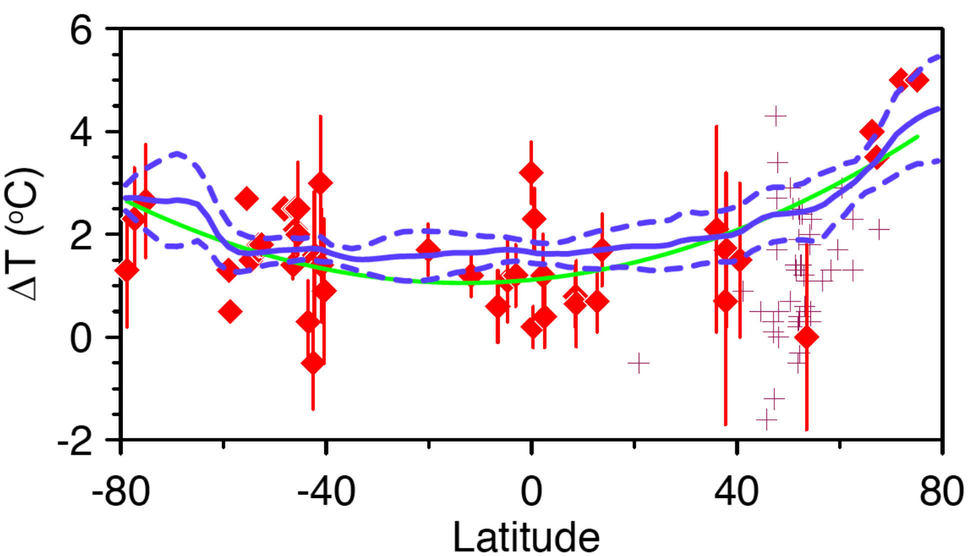


Clark & Huybers [2009]

- Marine Isotope Stage 5e (or the Eemian stage)
- ~125 kyr B.P.
- Polar temperatures were 3-5º higher than present (consistent with 1-2º of global warming)
- Current greenhouse gas concentrations are sufficient to raise global temperatures 1.4-3.2º
- Thus, LIG may be a good analogue for reasonable global warming scenarios

Ice Age Sea Level: The Last Interglacial





Interglacial outcrop Exmouth, W. Australia, *courtesy Bill Thompson (WHOI)*

Local LIG sea level markers ~4-6 m above present sea-level. What was globally averaged sea level at LIG?

Ice Age Sea Level: The Last Interglacial

Vol 000|00 Month 2009|doi:10.1038/nature08686 nature

ARTICLES

Probabilistic assessment of sea level during the last interglacial stage

Robert E. Kopp[1,2], Frederik J. Simons[1], Jerry X. Mitrovica[3], Adam C. Maloof[1] & Michael Oppenheimer[1,2]

With polar temperatures ~3–5 °C warmer than today, the last interglacial stage (~125 kyr ago) serves as a partial analogue for 1–2 °C global warming scenarios. Geological records from several sites indicate that local sea levels during the last interglacial were higher than today, but because local sea levels differ from global sea level, accurately reconstructing past global sea level requires an integrated analysis of globally distributed data sets. Here we present an extensive compilation of local sea level indicators and a statistical approach for estimating global sea level, local sea levels, ice sheet volumes and their associated uncertainties. We find a 95% probability that global sea level peaked at least 6.6 m higher than today during the last interglacial; it is likely (67% probability) to have exceeded 8.0 m but is unlikely (33% probability) to have exceeded 9.4 m. When global sea level was close to its current level (≥−10 m), the millennial average rate of global sea level rise is very likely to have exceeded 5.6 m kyr^{-1} but is unlikely to have exceeded 9.2 m kyr^{-1}. Our analysis extends previous last interglacial sea level studies by integrating literature observations within a probabilistic framework that accounts for the physics of sea level change. The results highlight the long-term vulnerability of ice sheets to even relatively low levels of sustained global warming.

Ice Age Sea Level: The Last Interglacial

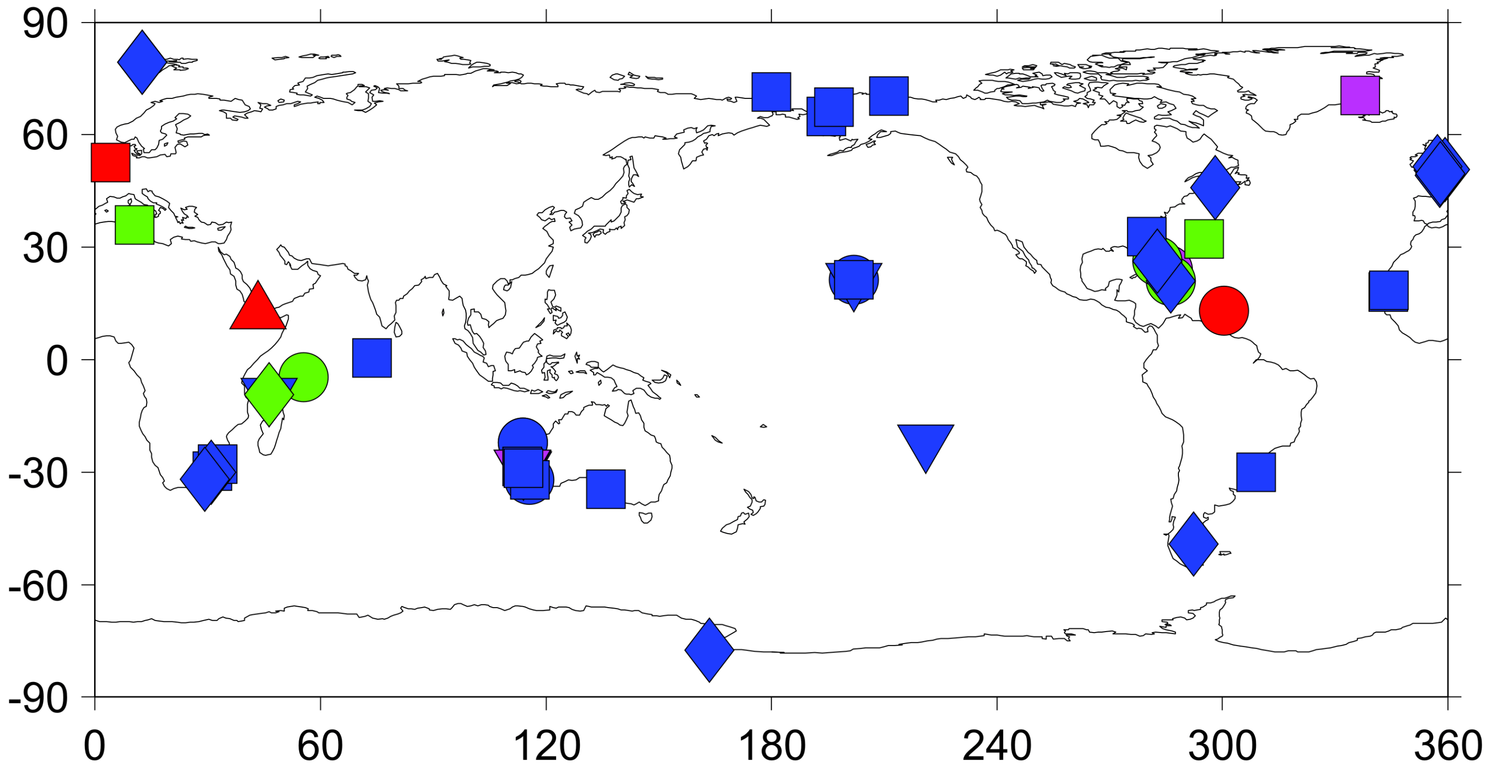


Figure 1 | Sites with at least one sea level observation in our database. The symbol shapes reflect the nature of the indicators (upward triangles, isotopic; circles, reef terraces; downward triangles, coral biofacies; squares, sedimentary facies and non-coral biofacies; diamonds, erosional). The colours reflect the number of observations at a site (blue, 1; green, 2; magenta, 3; red, 4 or more).

Ice Age Sea Level: The Last Interglacial

Statistical Method (Complicated)

SEA LEVEL DATABASE
(isotopic, coral, etc.)
Noisy (uncertainties in dates, tectonics), sparse

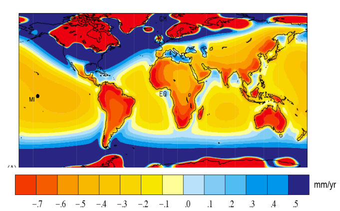
Empirical "data covariance"

BAYESIAN FRAMEWORK

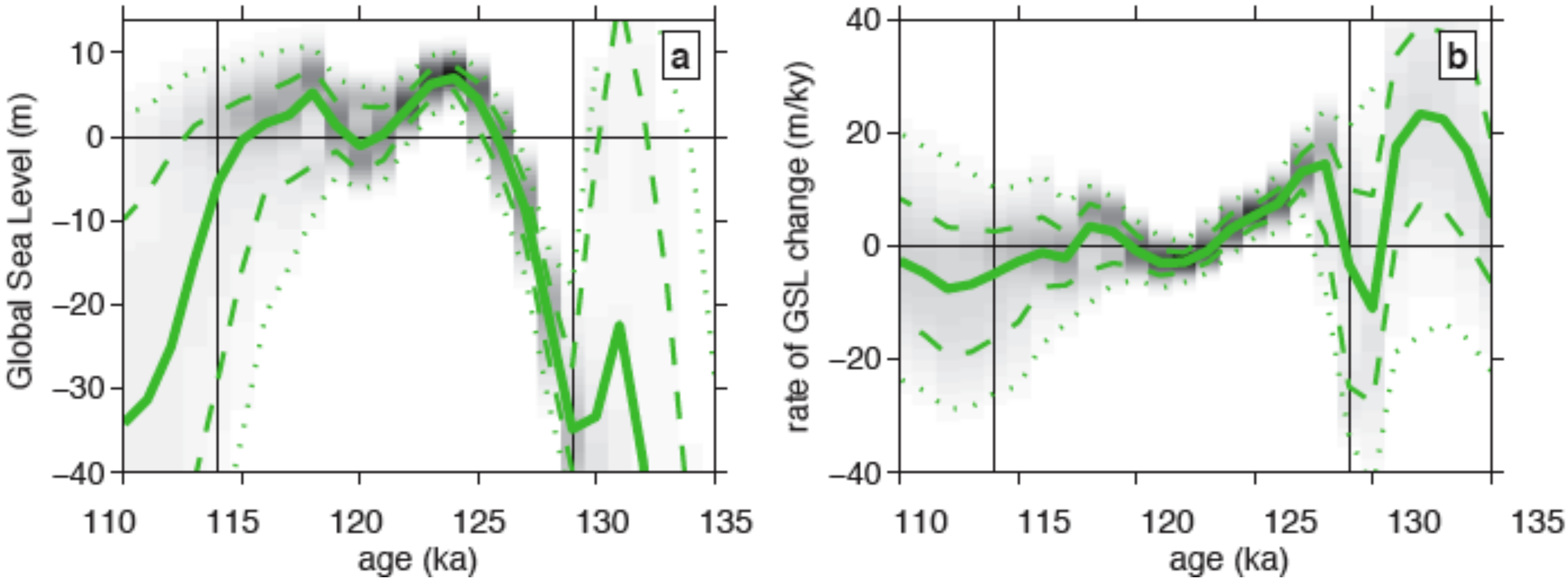
Posterior Probability Density Function of GSL(t)

MANY ICE AGE SEA LEVEL MODELS

Covariance between LSL and GSL



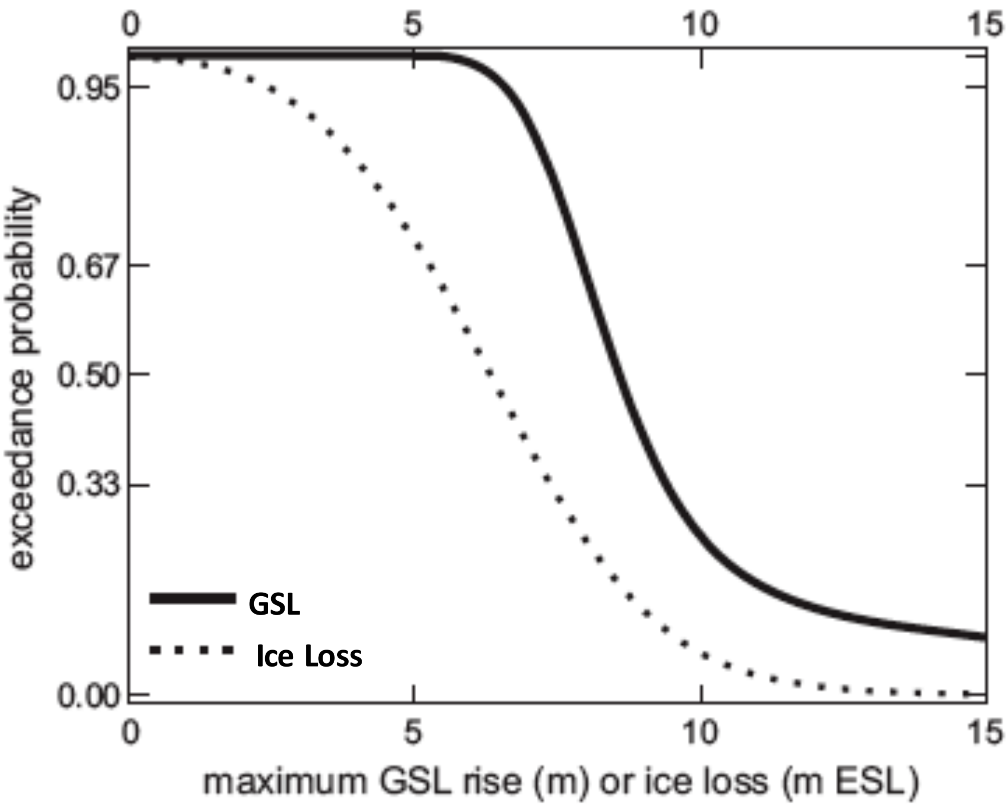
Ice Age Sea Level: The Last Interglacial



Posterior Probability Densities

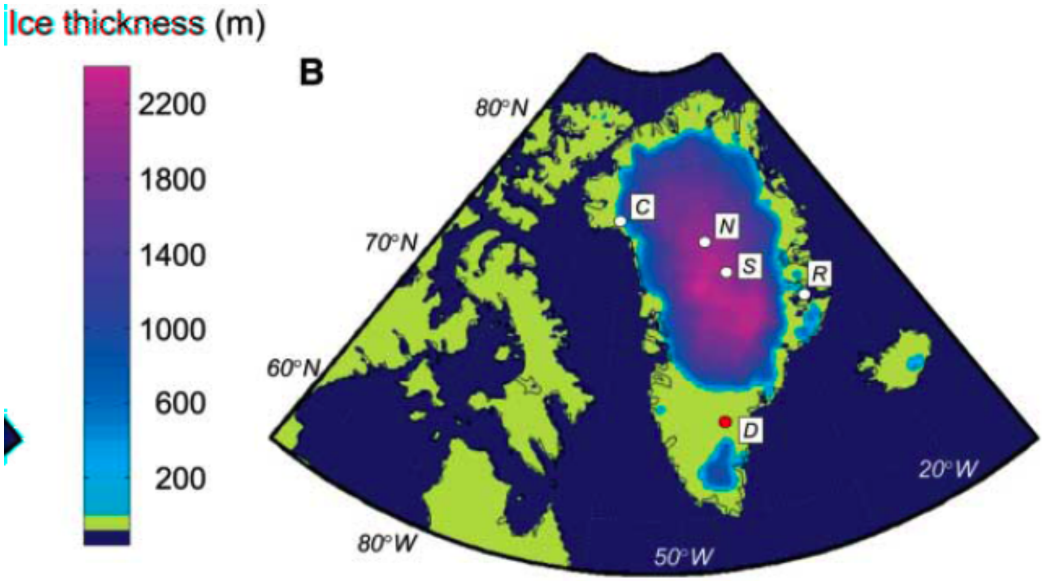
Use these to set up hypothesis tests and confidence intervals

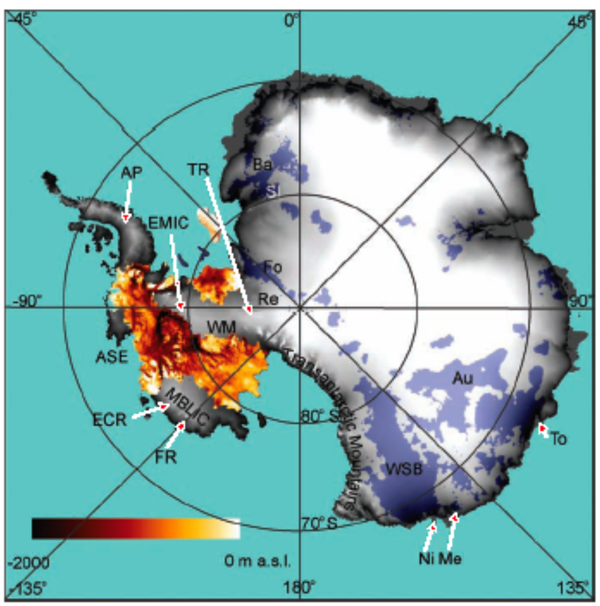
Ice Age Sea Level: The Last Interglacial



- 95% likely that globally averaged sea level at LIG peaked > 6.6 m above present level (67% likely that it exceeded 8.0 m; only 33% likely that it exceeded 9.4 m)
- 95% likely that both Antarctica and Greenland ice loss at LIG exceeded 2.5 m (equivalent sea level units) relative to present day (not necessarily at the same time)

Ice Age Sea Level: The Last Interglacial





The Greenland Ice Sheet

- Climate models (Otto-Bliesner et al., *Science*, 2006) suggest a maximum ice loss in the GIS and circum-Arctic ice fields at LIG = 3.4 m GSLR.

Thermal expansion ~ 1 m GSLR

The West Antarctic Ice Sheet

- Collapse of marine-sectors = 3.2m GSLR (Bamber et al., *Science*, 2009)

Ice Age Sea Level: The Last Interglacial

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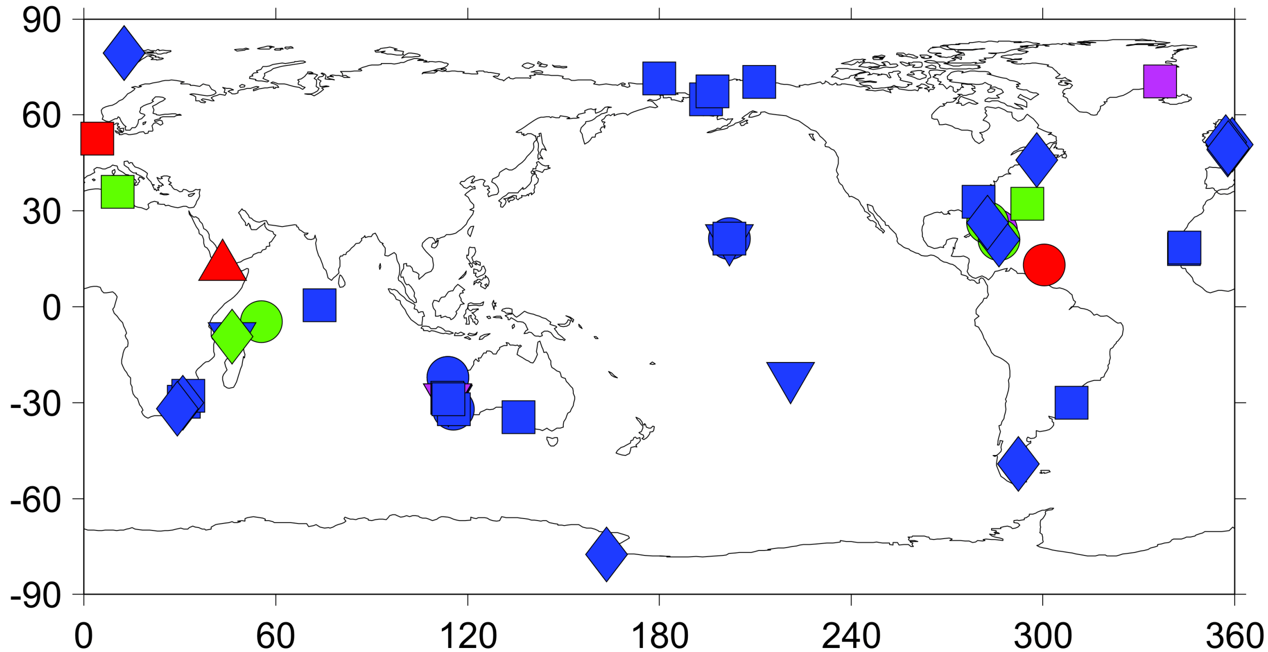

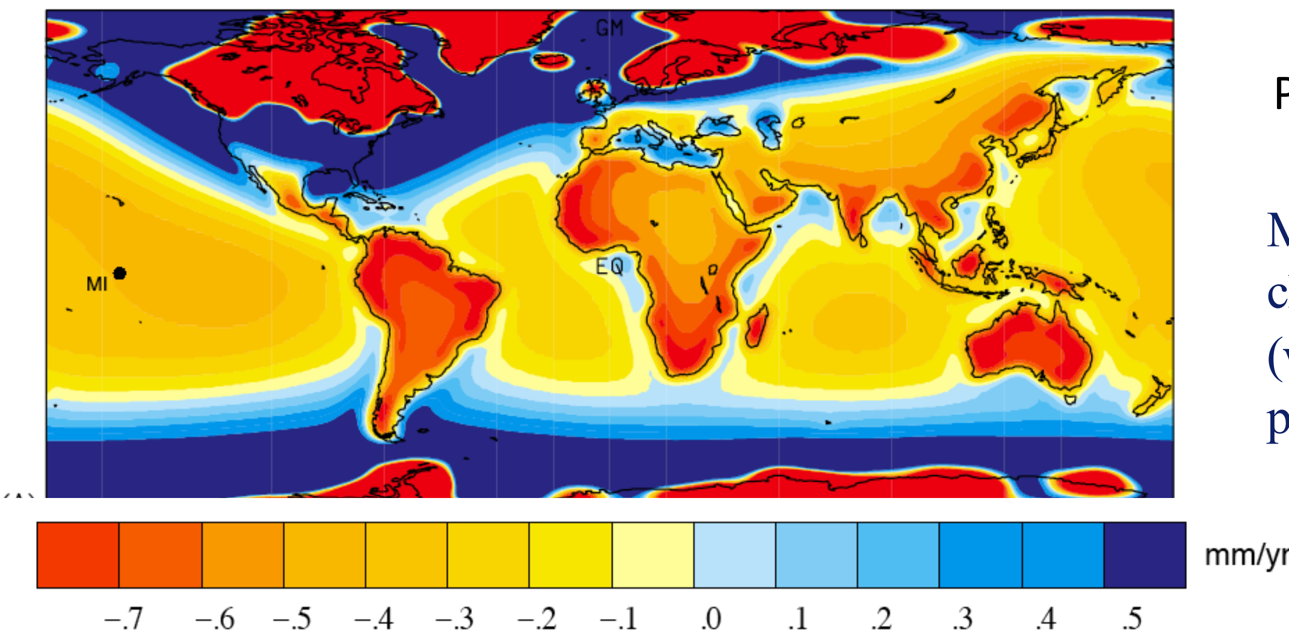

Physics of this result?

Mean prediction of sea-level change at these sites (weighted by number of data points)?

Ice Age Sea Level: The Last Interglacial

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Dynamic Topography

nature geoscience

LETTERS

PUBLISHED ONLINE: 23 JUNE 2013 | DOI: 10.1038/NGEO1859

Barbados-based estimate of ice volume at Last Glacial Maximum affected by subducted plate

Jacqueline Austermann[1]*, Jerry X. Mitrovica[1], Konstantin Latychev[2] and Glenn A. Milne[3]

Dynamic Topography

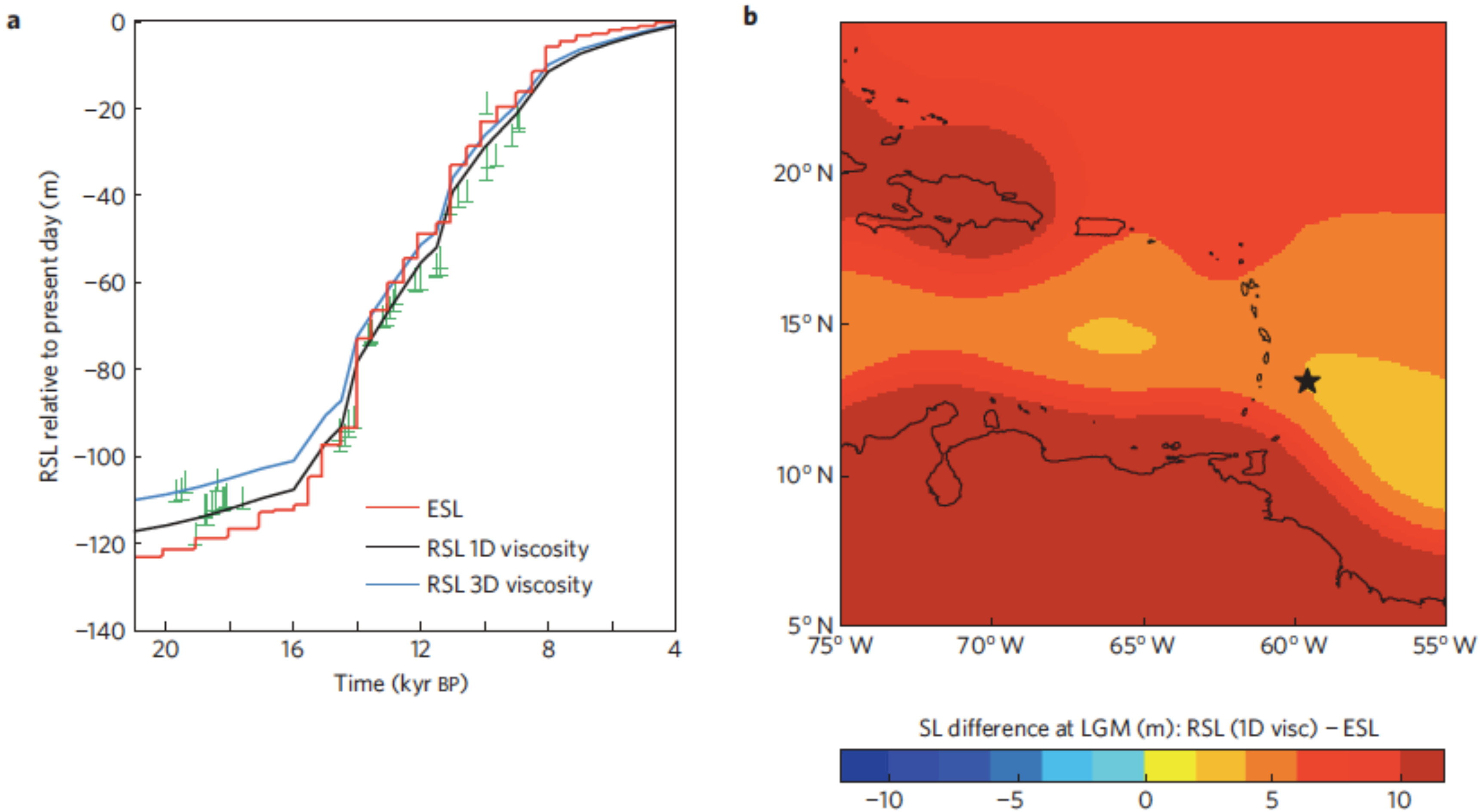

Figure 1 | RSL at Barbados from LGM to present. a, Black line: RSL prediction at Barbados (reproduced from ref. 3) computed using the X version of the ICE-5G/VM2 GIA model[3,13] (henceforth, called the ICE-5G model). Red line: ESL variation associated with the ICE-5G model, also from ref. 3. Blue line: analogous to black line, except that 3D variations in viscoelastic structure are incorporated (see text). The green symbols are U/Th-dated *A. palmata* samples[1-3] corrected for tectonic uplift[3]. **b**, Difference between predicted RSL and ESL at 21 kyr ago over the Caribbean region computed[20] using the ICE-5G/VM2 GIA model (star denotes Barbados).

Dynamic Topography

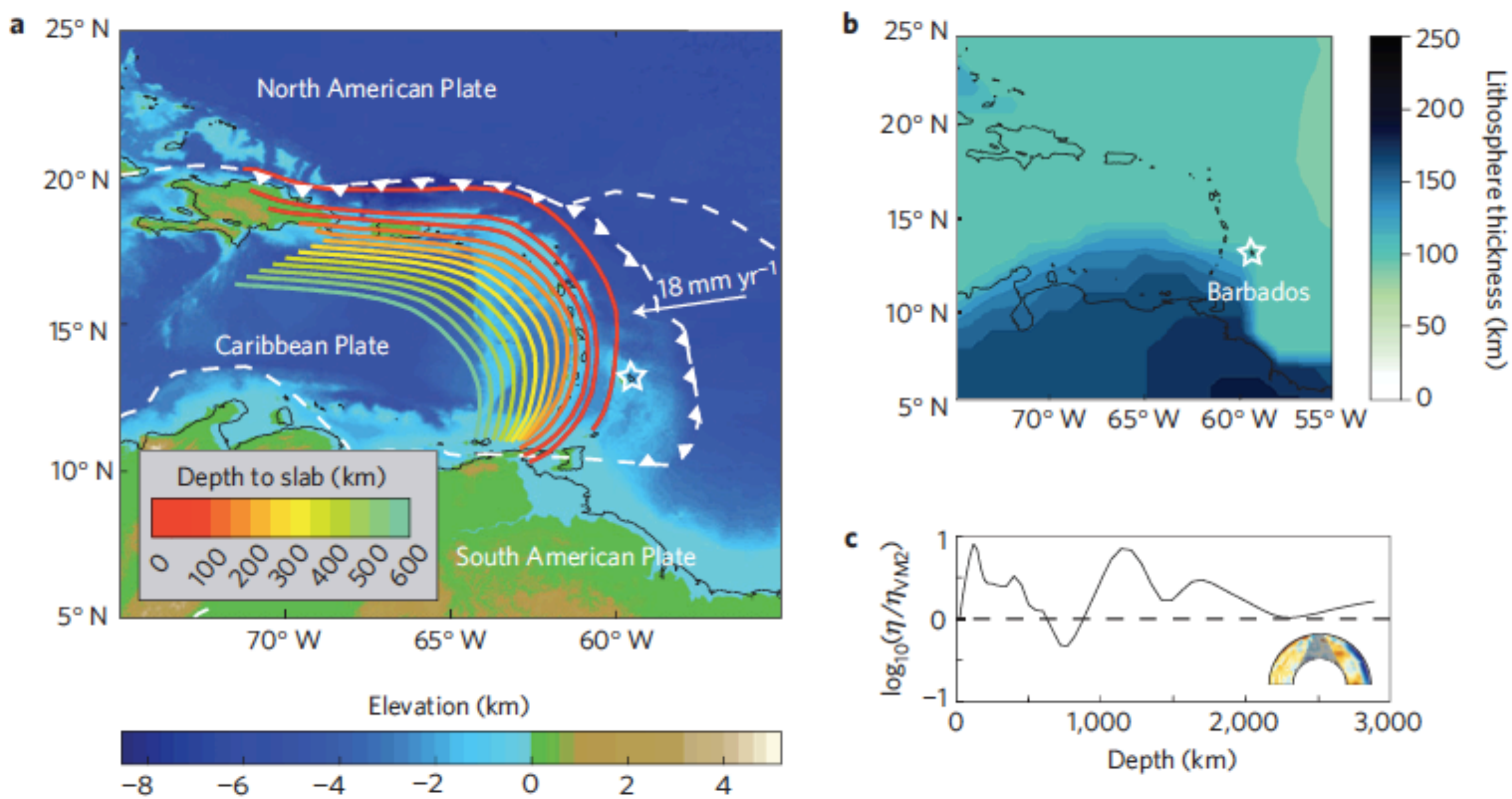

Figure 2 | Tectonic setting of the Caribbean and 3D Earth model. a, Crustal elevation with coastlines outlined in black. White dashed lines denote plate boundaries[22]. Red to green lines parallel to the trench are contours of depth (inset) from the surface down to the subducted slab[24]. **b**,**c**, The 3D viscoelastic Earth model adopted in GIA predictions. **b**, Thickness of elastic lithosphere[21]. **c**, Depth dependence of average logarithm of viscosity below Barbados, relative to the 1D VM2 profile, where the average is computed within a cone of diameter ranging from 300 km at the surface to 3,300 km at the core-mantle boundary (see inset).

Dynamic Topography

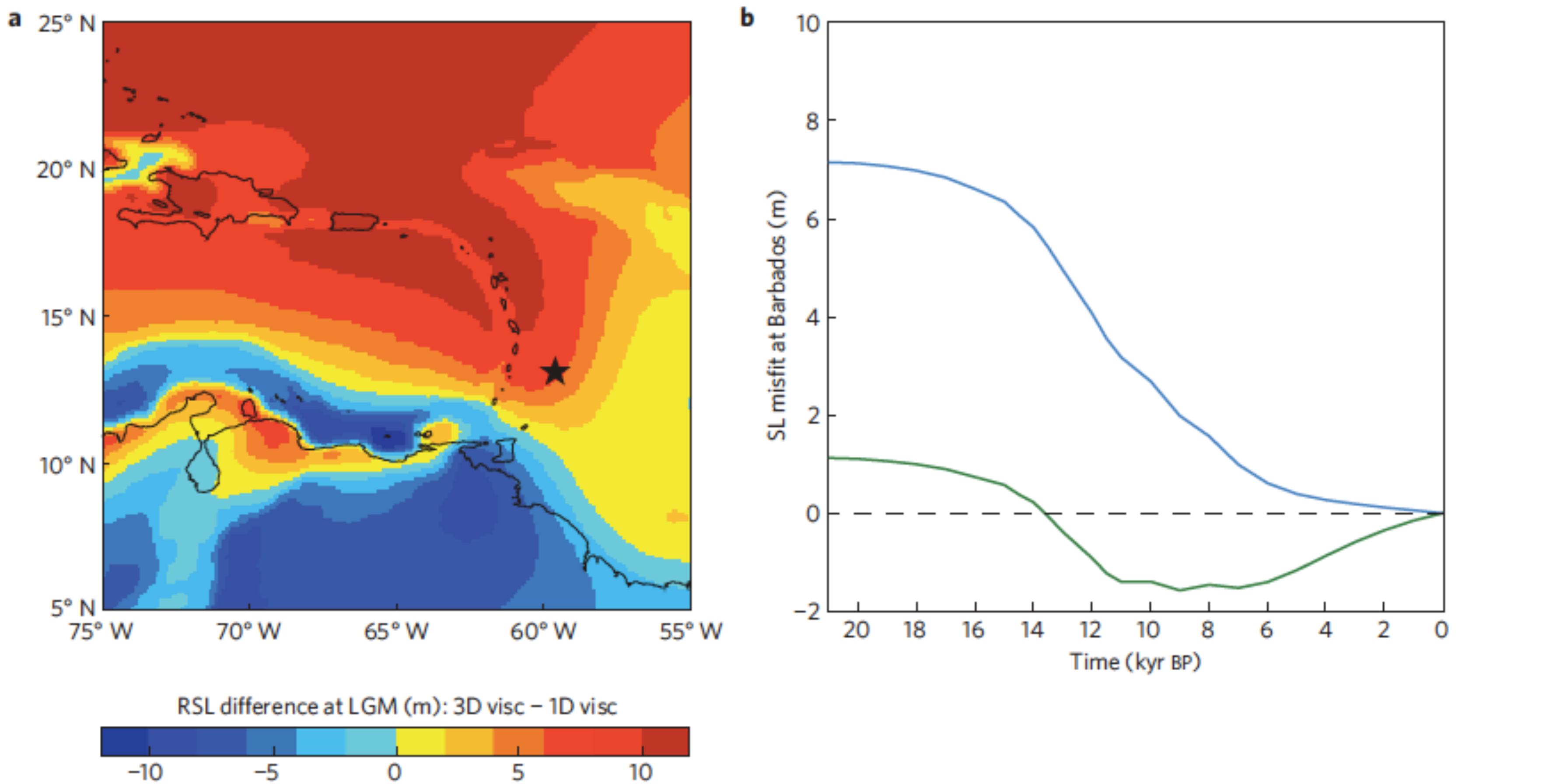

Figure 3 | Impact of lateral variations in mantle viscoelastic structure on predictions of RSL at Barbados. a, Perturbation in RSL at 21 kyr in the Caribbean due to 3D mantle viscoelastic structure (Fig. 2 and Supplementary Fig S1). The numerical prediction[20] adopts the ICE-5G model of ice geometry[3,13]. **b**, Blue line: perturbation in the predicted RSL at Barbados, as a function of time, associated with 3D mantle viscoelastic structure. Green line: same as blue, except the high viscosity slab in the upper mantle, associated with subduction under the Caribbean plate, is removed from the viscosity model.

Dynamic Topography

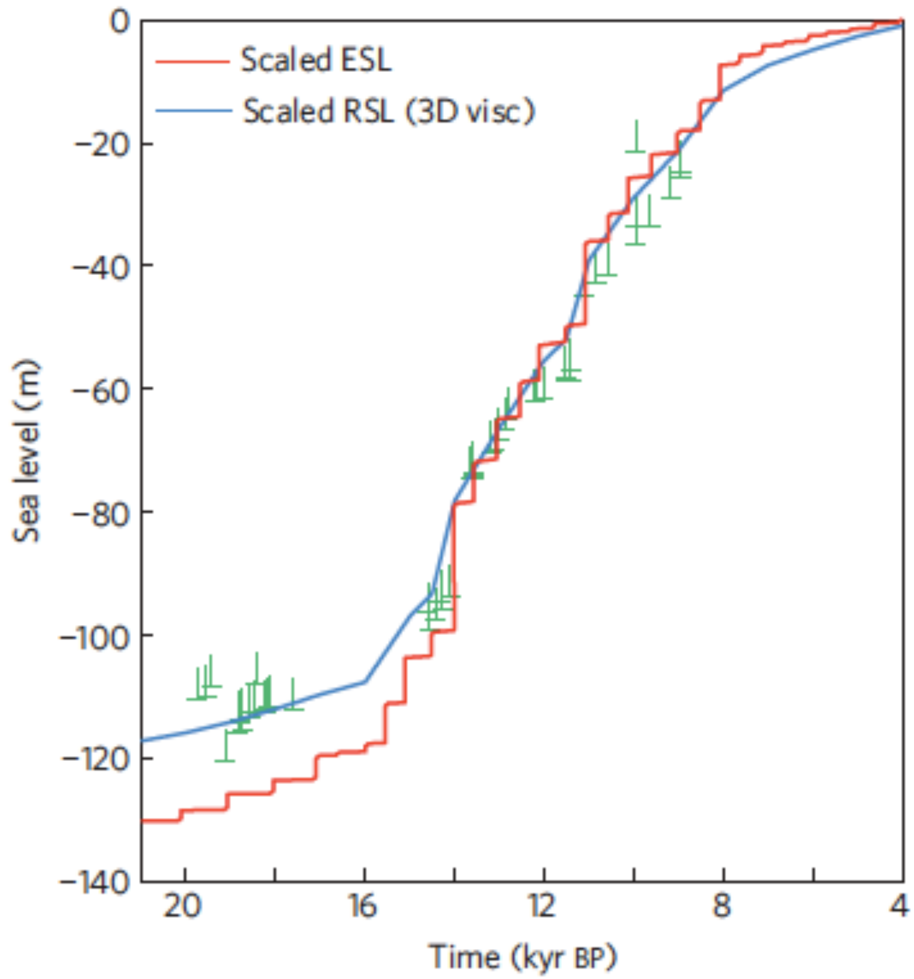

Figure 4 | Prediction of RSL at Barbados based on a 3D viscoelastic model. Blue line: RSL prediction at Barbados that accounts for 3D viscoelastic Earth structure (Fig. 1a, blue line), but scaled upwards to maintain a fit to the observations. Red line: ESL variation associated with the scaled ICE-5G model. Symbols are plotted as in Fig. 1a.