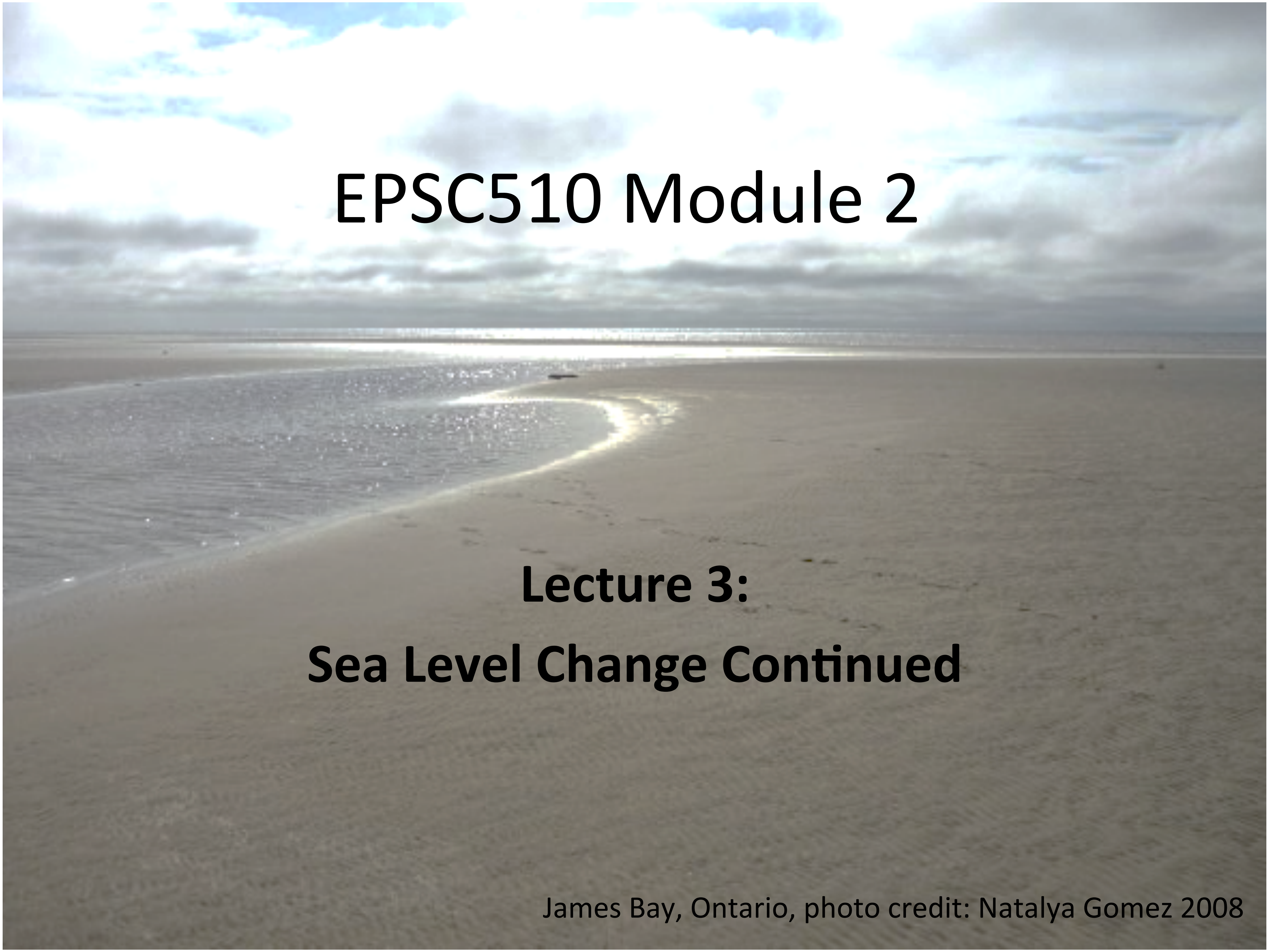
EPSC510 Module 2

Lecture 3:

Sea Level Change Continued



James Bay, Ontario, photo credit: Natalya Gomez 2008

Sea Level Records and Definitions

Tamisiea et al. (2014):
Sea Level Records and Definitions

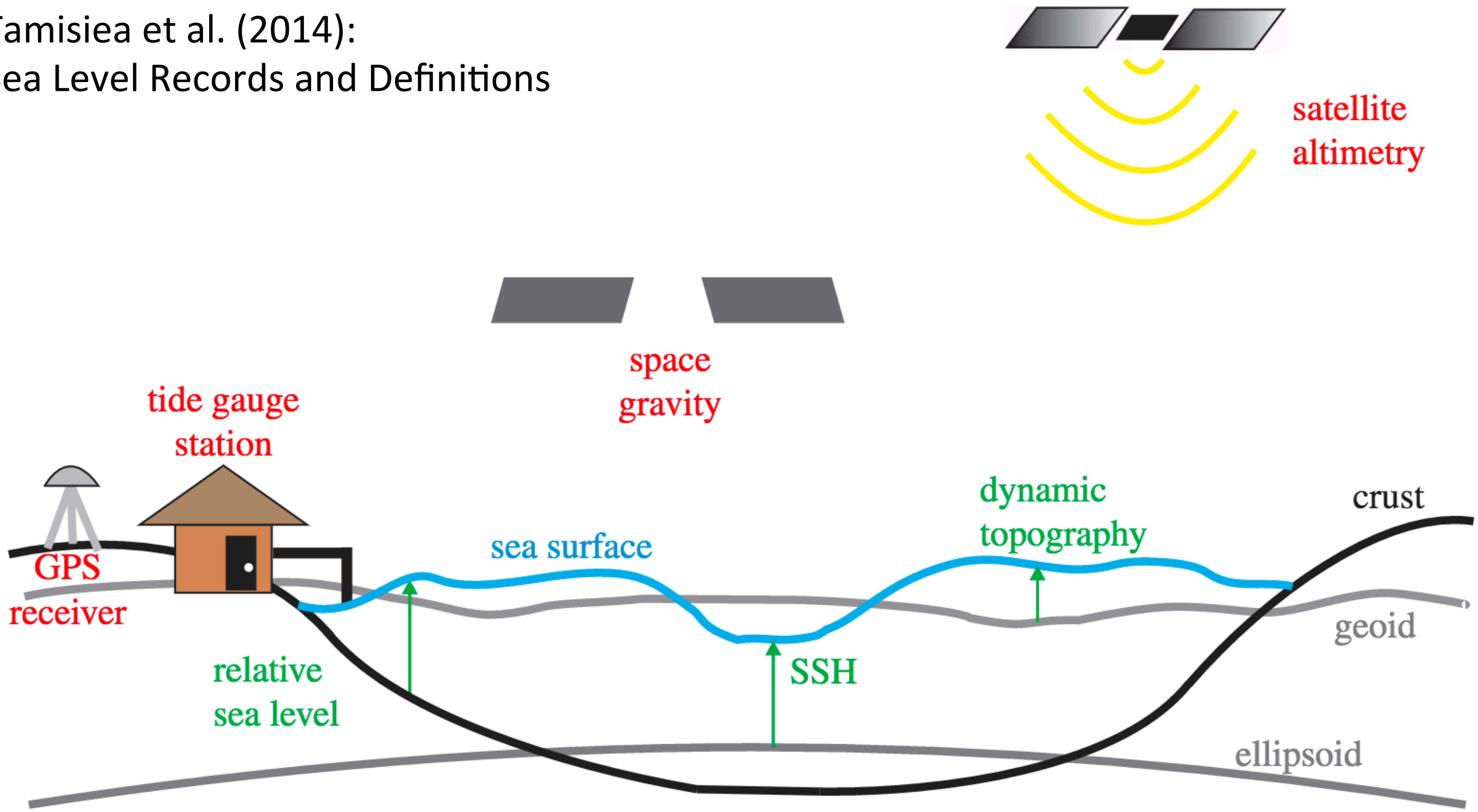
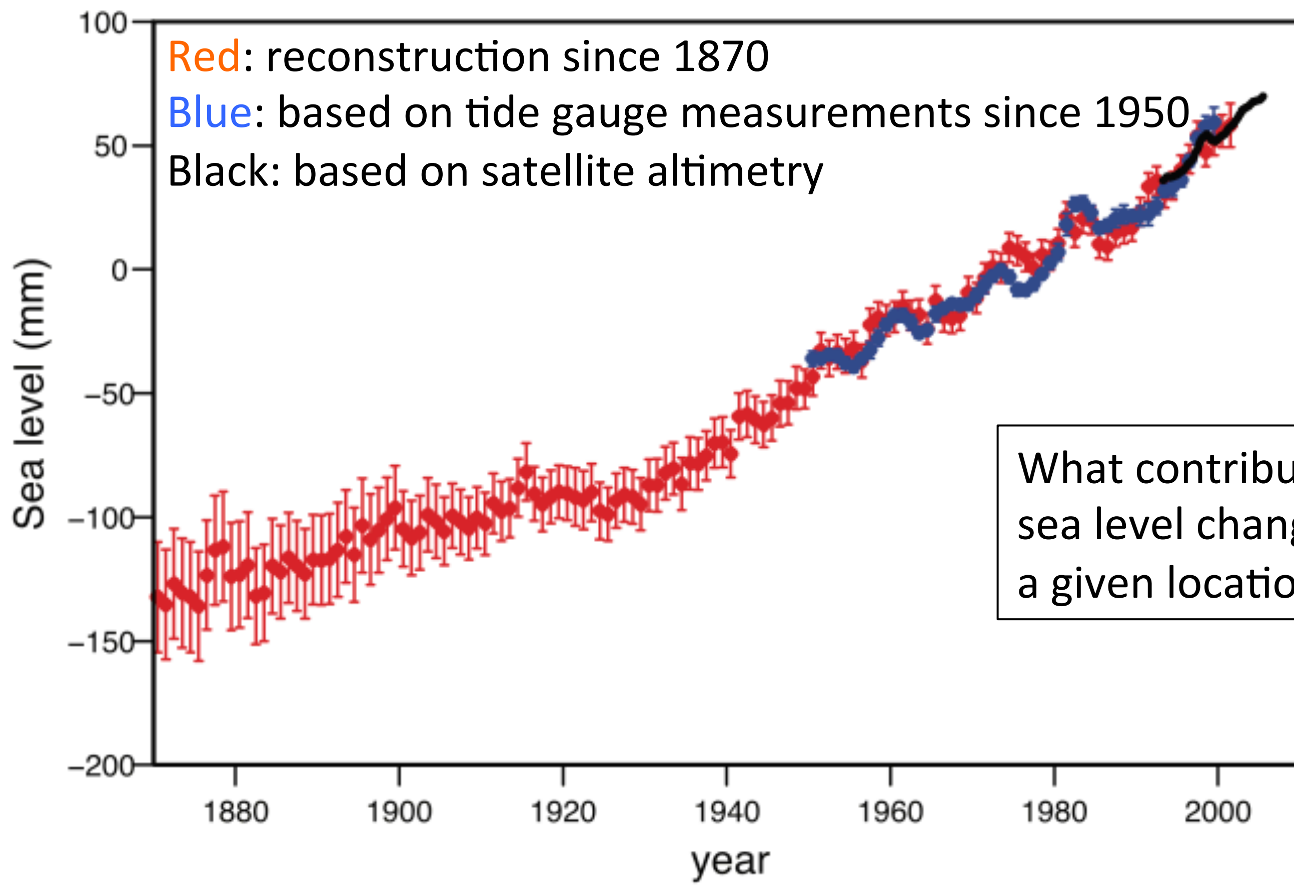


Figure 1. Simple schematic illustrating the relationship between sea surface height (SSH), the geoid, and dynamic topography. Included on the figure are representations of different components of the observing system and their respective measurement: GPS (or GNSS) for crustal deformation, satellite gravity for the geoid, altimetry for SSH and tide gauges for relative sea level.

Global Average Sea Level Change

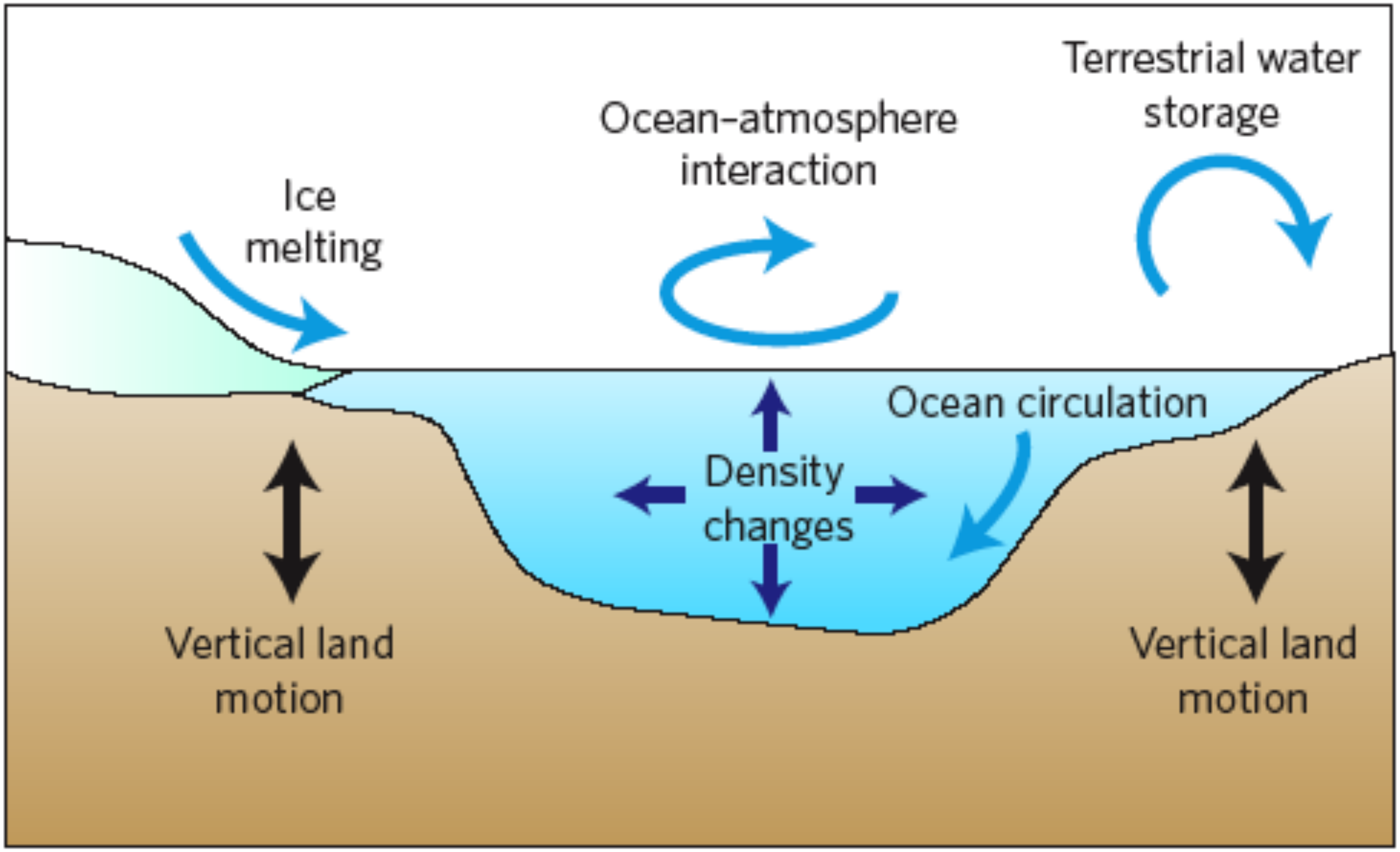
Annual averages of global sea level



What contributes to sea level changes at a given location?

Bindoff et al., (2007). Observations: Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of WG1 to the 4th Assessment Report of the IPCC*. USA

Sea Level Change: Physical Processes



Contributions to Modern Sea Level Change

Milne et al. (Nature Geosci., 2009)

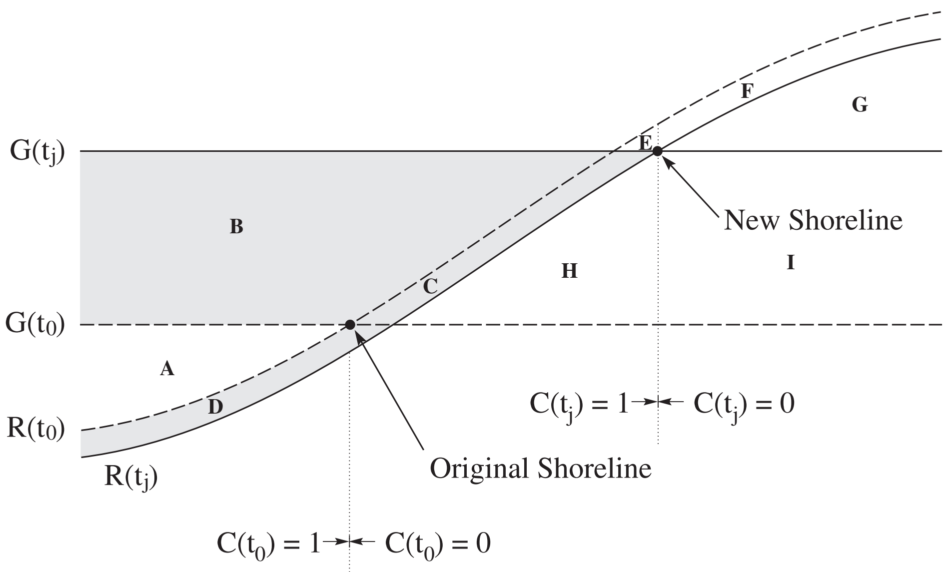
The Sea Level Equation

Generalized Sea-Level Equation

Projection of sea-level change at t_j onto the ocean function at time t_j

$$\Delta S(\theta,\psi,t_j) = \left[\Delta\mathcal{SL}(\theta,\psi,t_j) + \frac{\Delta\Phi(t_j)}{g}\right] C(\theta,\psi,t_j)$$
$$- T(\theta,\psi,t_0)\left[C(\theta,\psi,t_j) - C(\theta,\psi,t_0)\right]$$

A topographic correction term to account for shoreline migration



The Sea Level Equation

SEA LEVEL MODEL INGREDIENTS

$$\Delta\mathcal{SL}(\theta,\psi,t) = \Delta\mathcal{SL}(\Delta I, \Delta S, \Delta\omega)$$

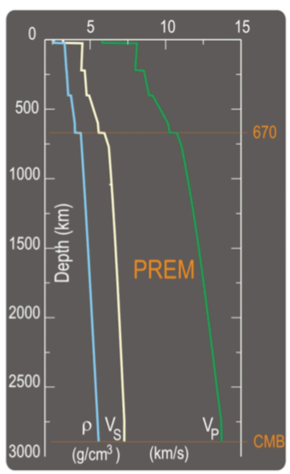
EARTH FORCING

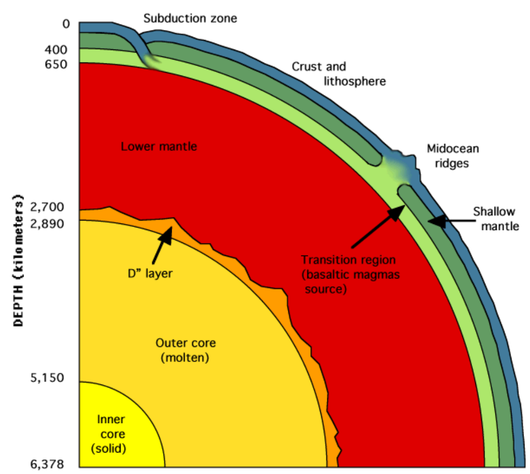
Ice location and thickness (inferred from modeling GIA data, e.g. sea level)

EARTH MODEL

Earth geometry and elastic, density and viscosity** structure (PREM, GIA data)

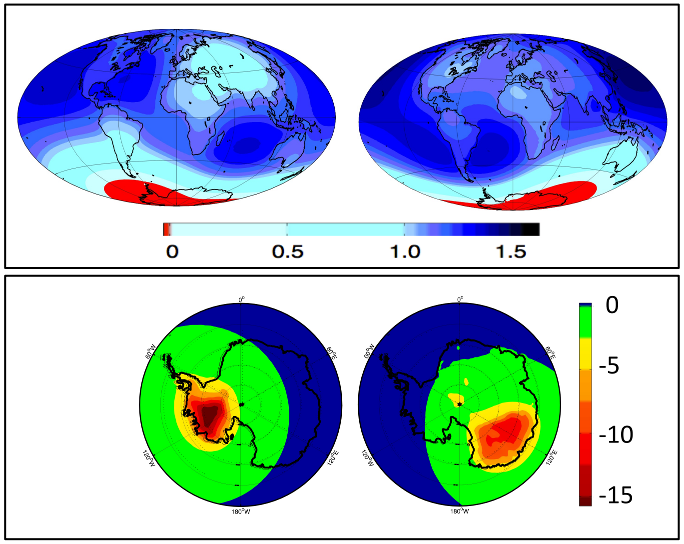
Physics…





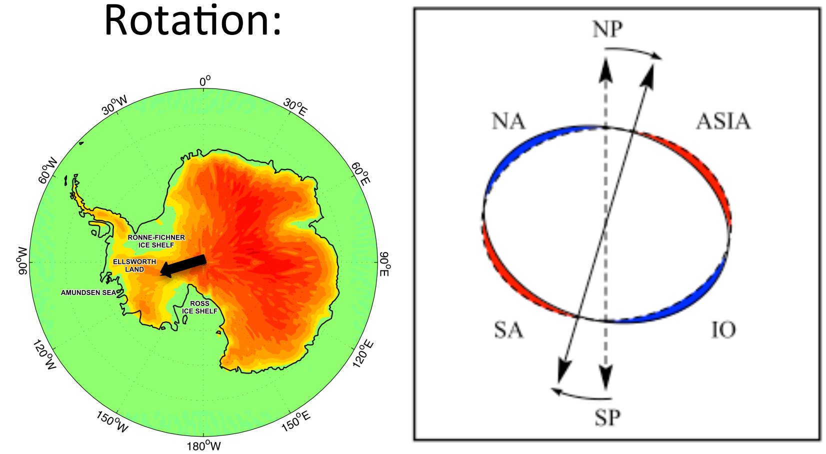
**strong temperature dependence, not well constrained

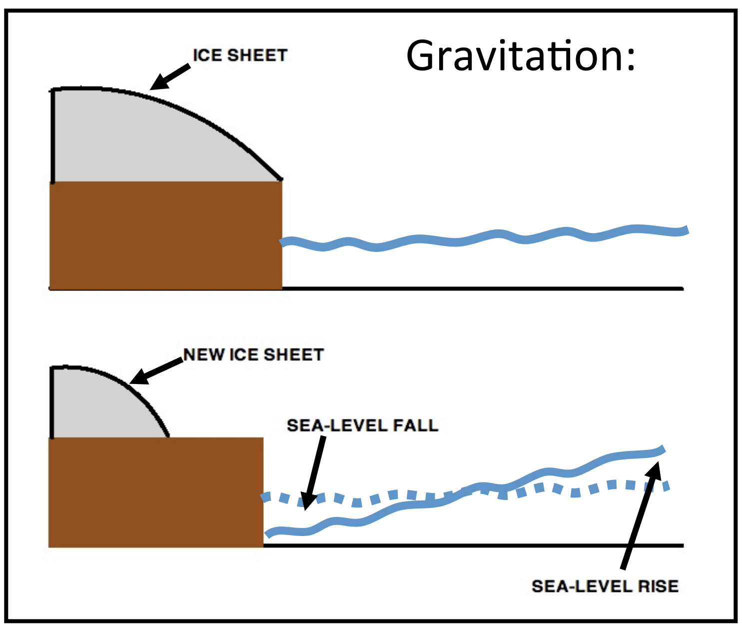
Sea Level Physics: short timescales

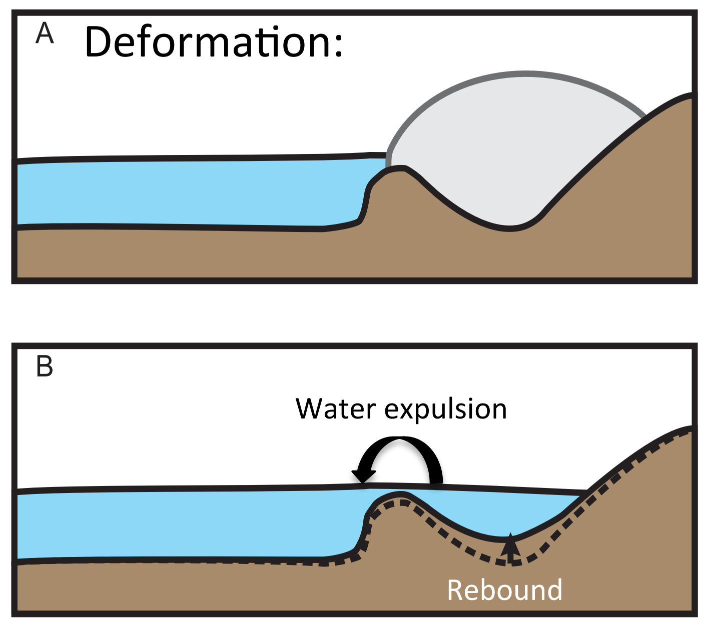


Gomez et al., GJI, 2010

Rotation:







A bit of history

[Woodward (1888)]

On Postglacial Sea Level

W. E. Farrell*

Cooperative Institute for Research in Environmental Sciences, University of Colorado/NOAA, Boulder, Colorado 80302, USA

J. A. Clark

Institute of Arctic and Alpine Research and Dept. Geological Sciences, University of Colorado, Boulder, Colorado 80302, USA

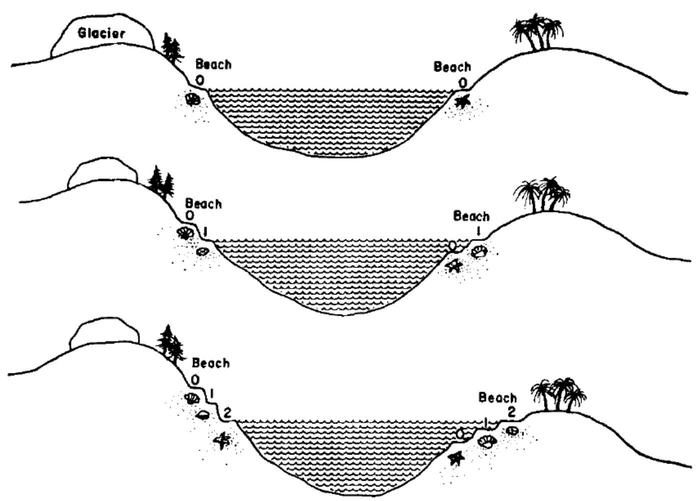


FIG. 6. Schematic illustration of the sea level changes occurring on a viscoelastic earth model. (a) The situation in the isostatic state before any melting of the ice.

Geophys. J. R. astr. Soc. (1976) **46,** 647–667.

… Next major developments by:
Richard Peltier,
Kurt Lambeck,
Jerry Mitrovica,

From Farrell & Clark, 1976: spherically symmetric, rigid Earth

density field. The gravitational potential on and outside the Earth's surface is

$$\phi(r) = \frac{\Gamma M_E}{r}, \qquad r \geqslant a$$

where Γ is Newton's gravitational constant and M_E is the Earth's total mass. Suppose we extract a mass M_I, representing an ice sheet, from a thin spherical shell (the ocean) at $r = a$ and locate M_I at a point on the Earth's surface. ($M_E - M_I$ is still spherically symmetric.) If θ measures the angular distance away from the point mass, the new gravitational potential field with reference to origin 0 is

$$\phi^*(r, \theta) = \frac{\Gamma(M_E - M_I)}{r} + \frac{\Gamma M_I}{\sqrt{(r^2 + a^2 - 2ar\cos\theta)}}.$$

Along the Earth's surface the new potential field

$$\phi^*(a, \theta) = \frac{\Gamma(M_E - M_I)}{a} + \frac{\Gamma M_I}{2a\sin(\theta/2)}$$

is not constant and hence the spherical surface $r = a$ is not a possible sea level. There is a nearby equipotential, however, at a radial distance $\varepsilon(\theta)$ away from a on which

$$\phi^*(a + \varepsilon, \theta) = \phi(a).$$

Since $M_I \ll M_E$, we expect $\varepsilon \ll a$ and, to first order in ε,

$$\phi^*(a+\varepsilon, \theta) = \phi^*(a, \theta) + \varepsilon \frac{\partial \phi^*(a, \theta)}{\partial r}.$$

But to sufficient accuracy, $\partial \phi^*/\partial r = \partial \phi/\partial r = -g$, the acceleration of gravity at the Earth's surface, hence

Writing $g/\Gamma = M_E/a^2$, we have

$\Delta S\mathcal{L}$ →

$$\varepsilon(\theta) = \frac{M_I a}{M_E}\left(\frac{1}{2\sin(\theta/2)} - 1\right).$$

Along the surface $r = a+\varepsilon$, ϕ^* is constant, and thus the surface represents a possible sea level, but it is not the actual sea level because we have not allowed for the volume lost from the ocean and added to the ice. If $a+\varepsilon$ is an equipotential, then for any constant $c \ll a$, $a+\varepsilon+c = a+\varepsilon^*$ is also an equipotential, and c can be found by conserving the total mass in the system. It is easy to show that the volume contained between the two surfaces $r = a$ and $r = a+\varepsilon$ is zero, so to conserve mass we must have

$$\int_0^\pi 2\pi\rho_\omega c a^2 \sin\theta \, d\theta + M_I = 0$$

where ρ_ω is the density of sea water. This yields

$\frac{\Phi}{g}$ →

$$c = -\frac{M_I}{M_E}\frac{a\rho_E}{3\rho_\omega}$$

$$\varepsilon^*(\theta) = \frac{M_I a}{M_E}\left(\frac{1}{2\sin(\theta/2)} - 1 - \frac{\rho_E}{3\rho_\omega}\right). \quad (1)$$

Since $\phi^*(a+\varepsilon^*, \theta)$ is constant, and the mass lost by the ocean (that contained between the surface $r = a$ and $r = a+\varepsilon^*$) equals the mass of the point ice cap ε^* is the correct change in sea level for this idealized example. ε^* is the change in sea level because it is the difference between the radial distance to the final sea surface and the radial distance to the initial sea surface.

Table 1

Relative sea level change on a rigid Earth when water from the ocean is frozen at a point

	θ (degrees)	R
	1	+30·54
	10	+1·65
~2200 km	20	+0·05
	45	−0·83
	60	−1·00
	90	−1·16
	180	−1·28

back

Outline

This Class: Sea Level Change Continued...

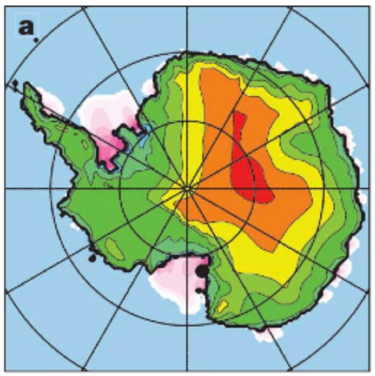
1. Sea level change and GIA on ice age timescales.

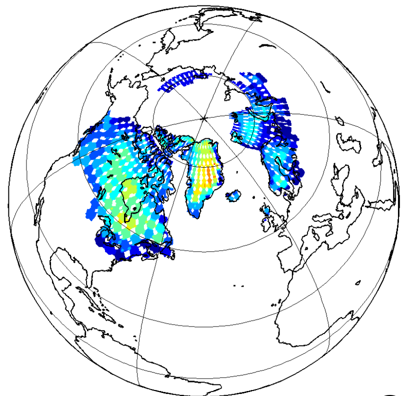
2. An Example Calculations

3. 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)

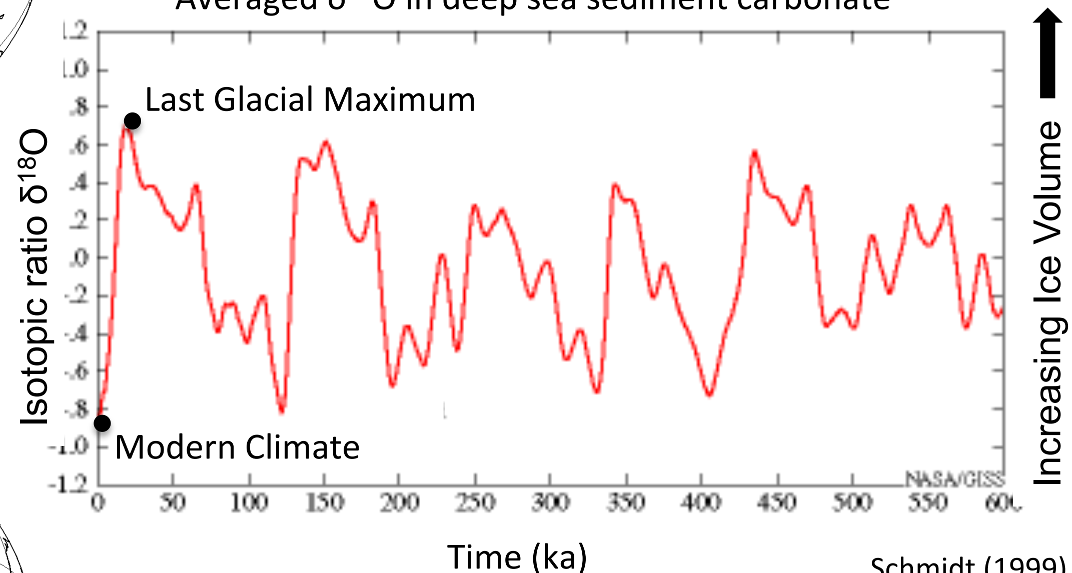
Sea Level Physics: Ice-Age Timescales

Last Glacial Maximum



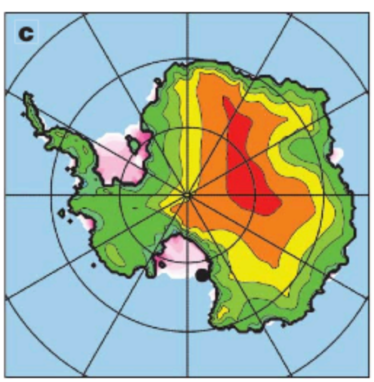


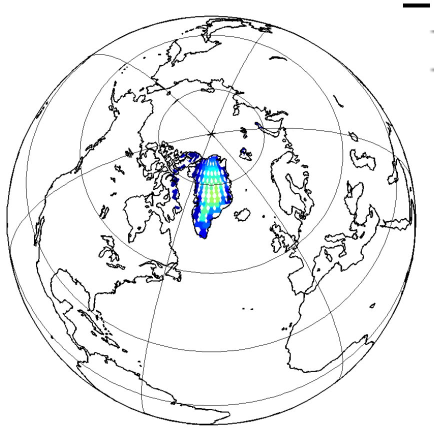
Averaged δ18O in deep sea sediment carbonate



Schmidt (1999)

Modern Climate



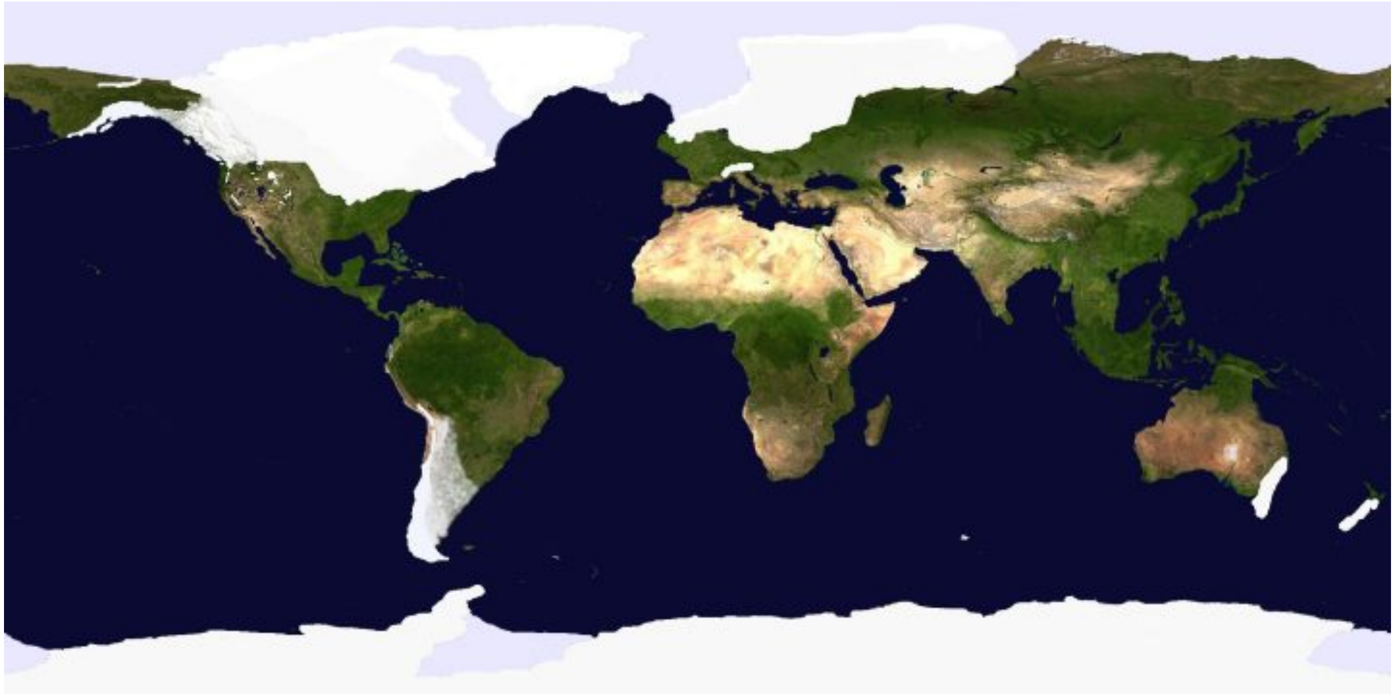


Pollard & DeConto (2009)

Peltier (2004) ICE5G

Sea Level Physics: Ice-Age Timescales

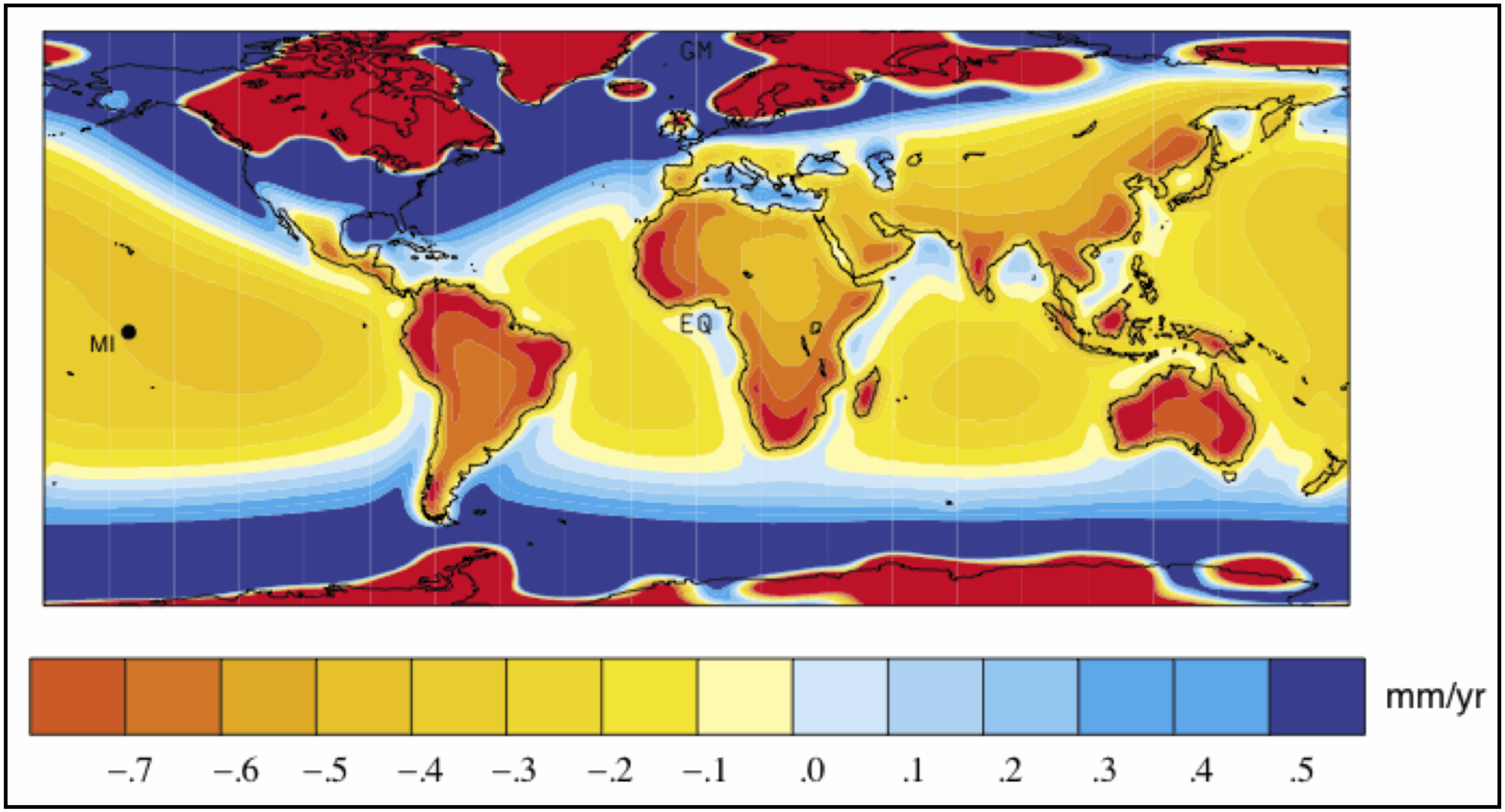
LGM



… difference in ice volume relative to the present-day is sufficient to raise globally averaged sea level by ~130 m (~ ½ of this is associated with the Laurentide ice sheet)

2b. Sea Level Physics: Ice-Age Timescales

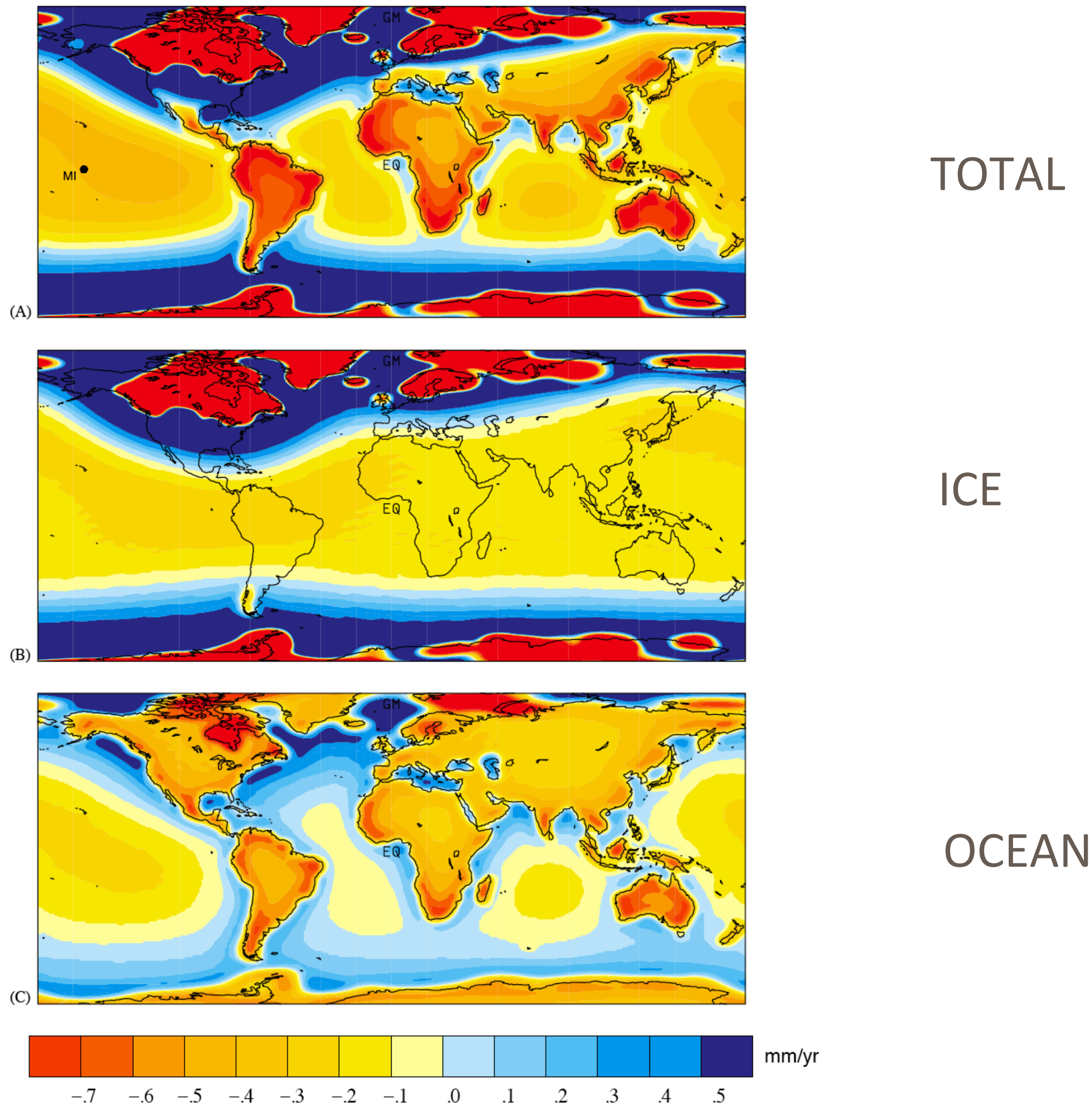
Numerical prediction of the present-day rate of change of global sea level due to ongoing GIA effects from the last ice age



Mitrovica and Milne (2002)

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA



Mitrovica and Milne (2002)

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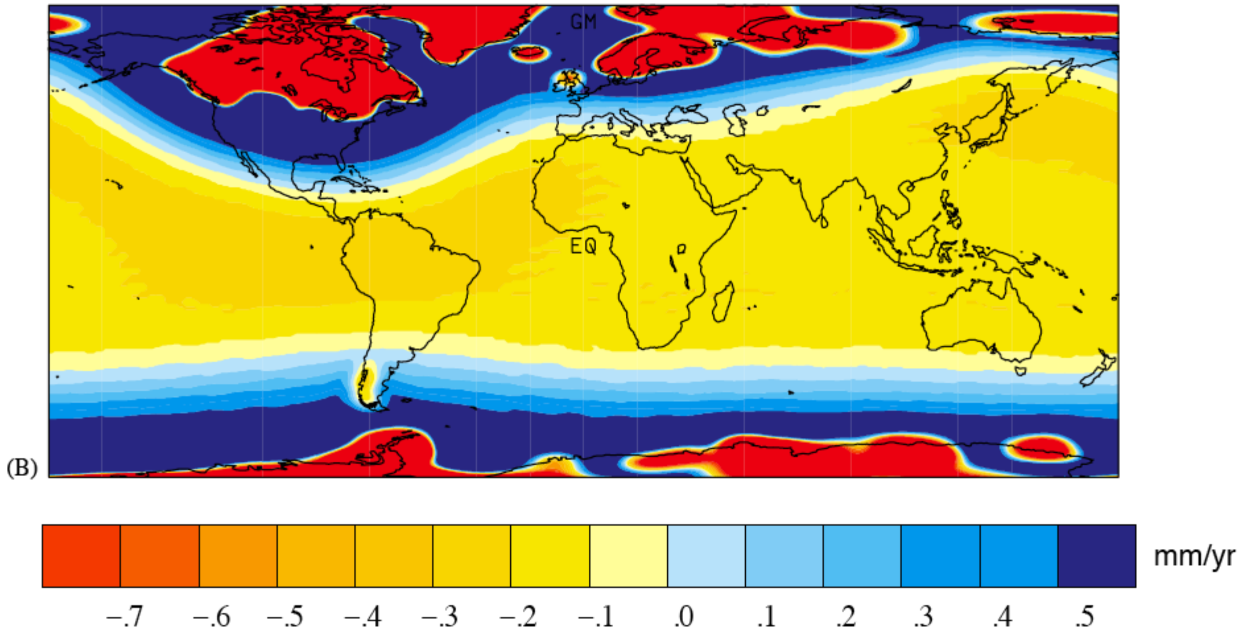
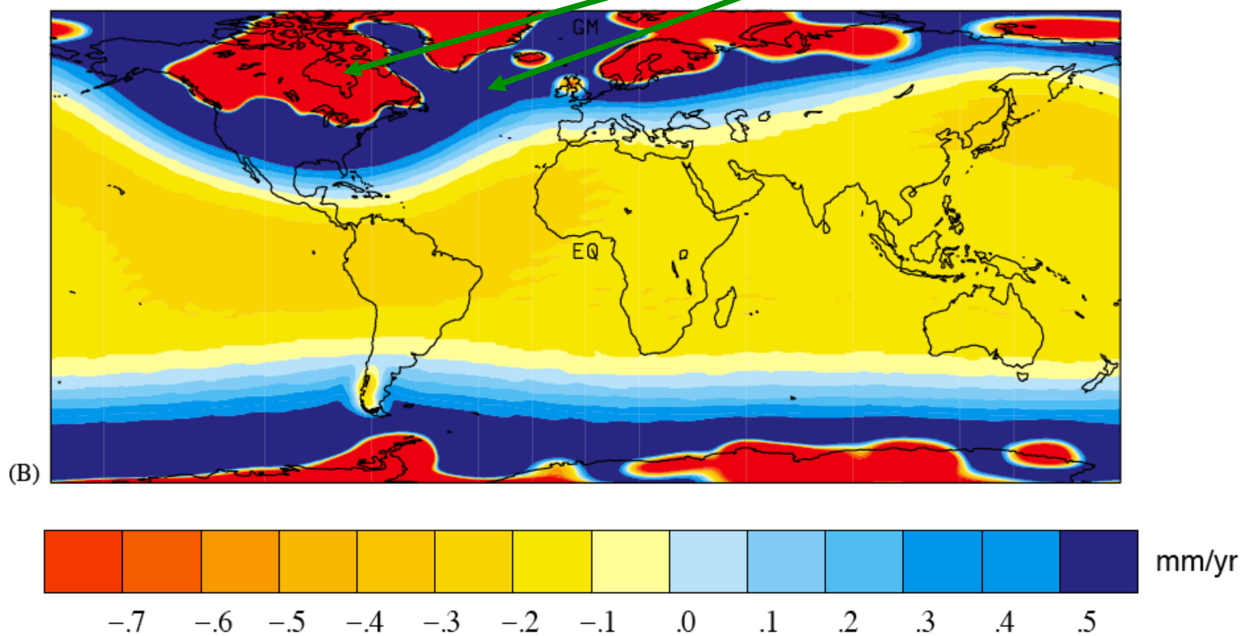


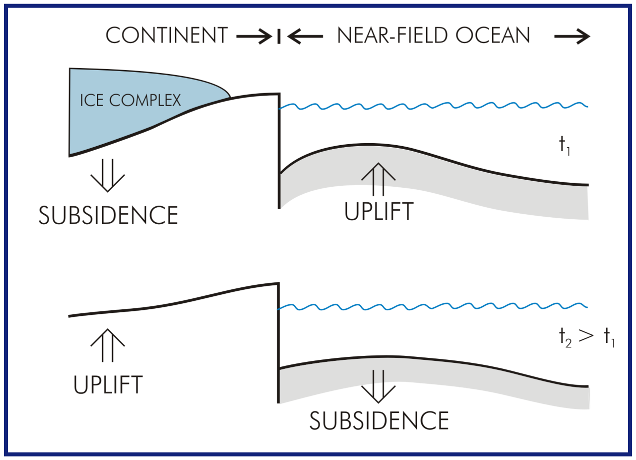
Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA



NEAR FIELD



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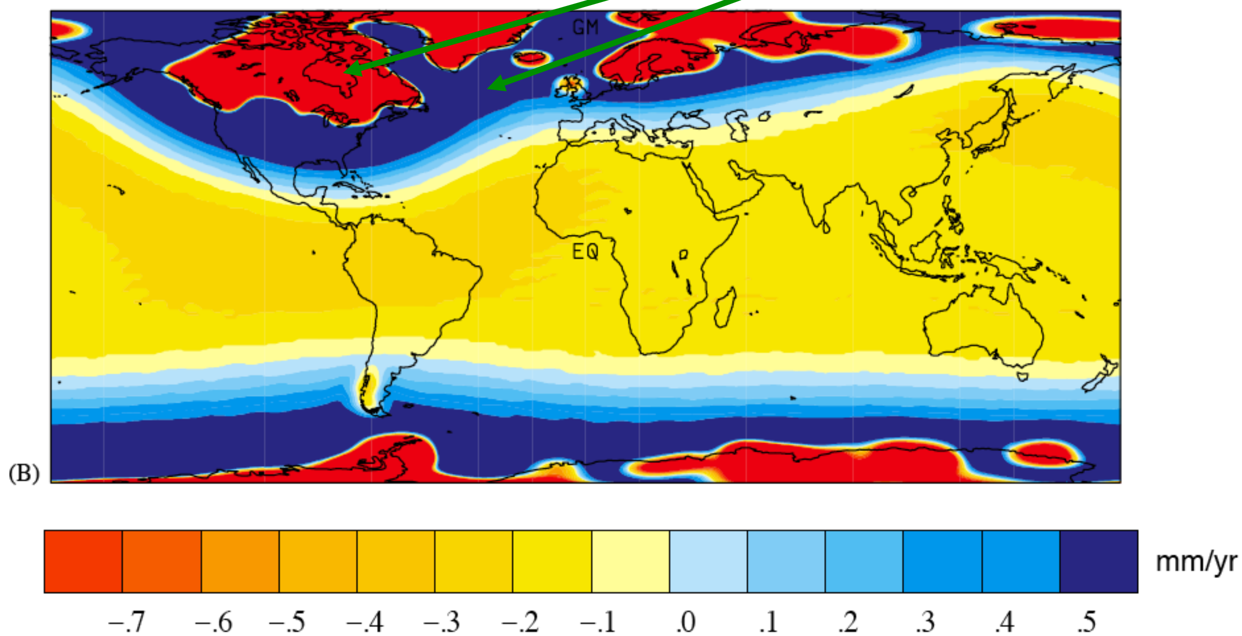

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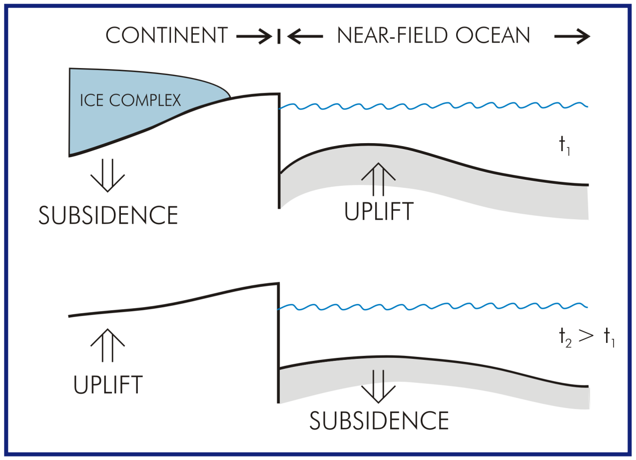

Ice Signal

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Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA

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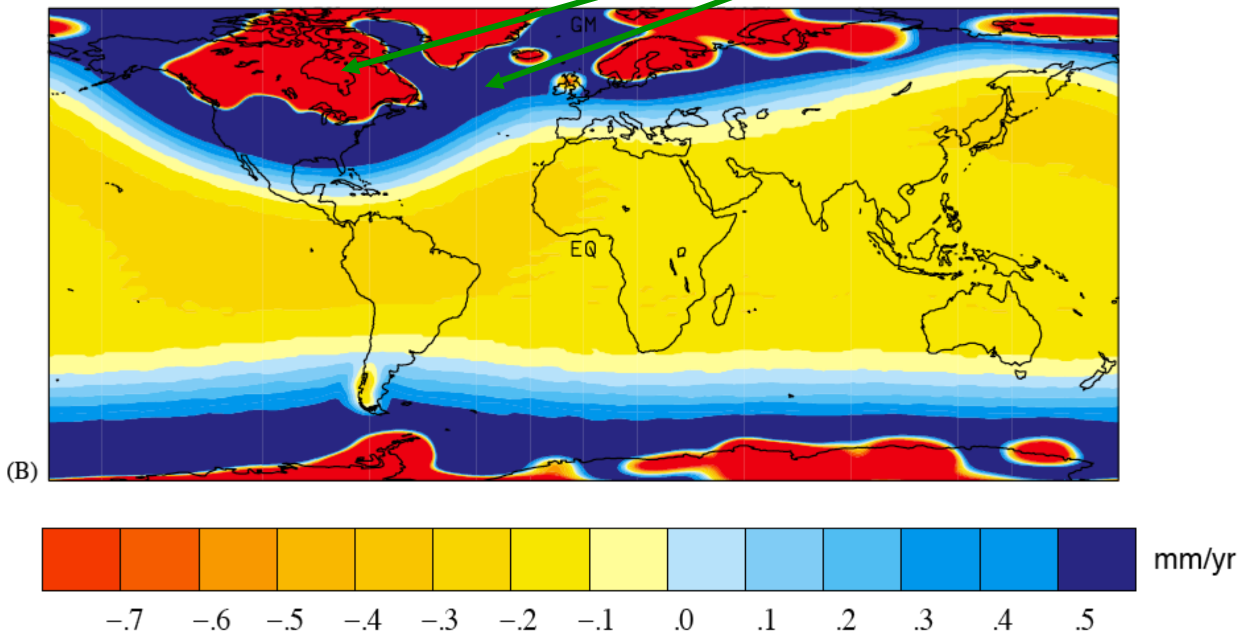

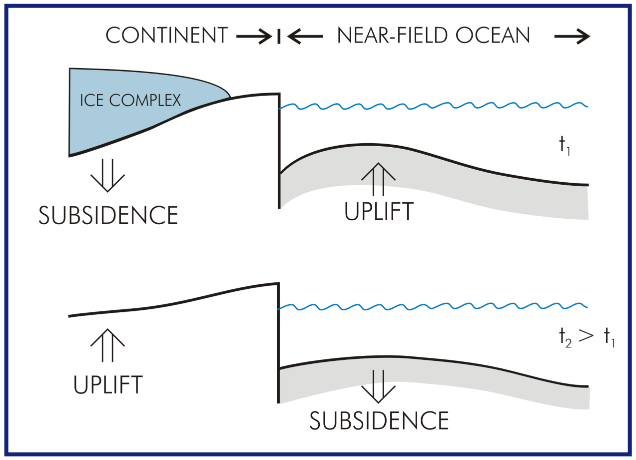

Ice Signal

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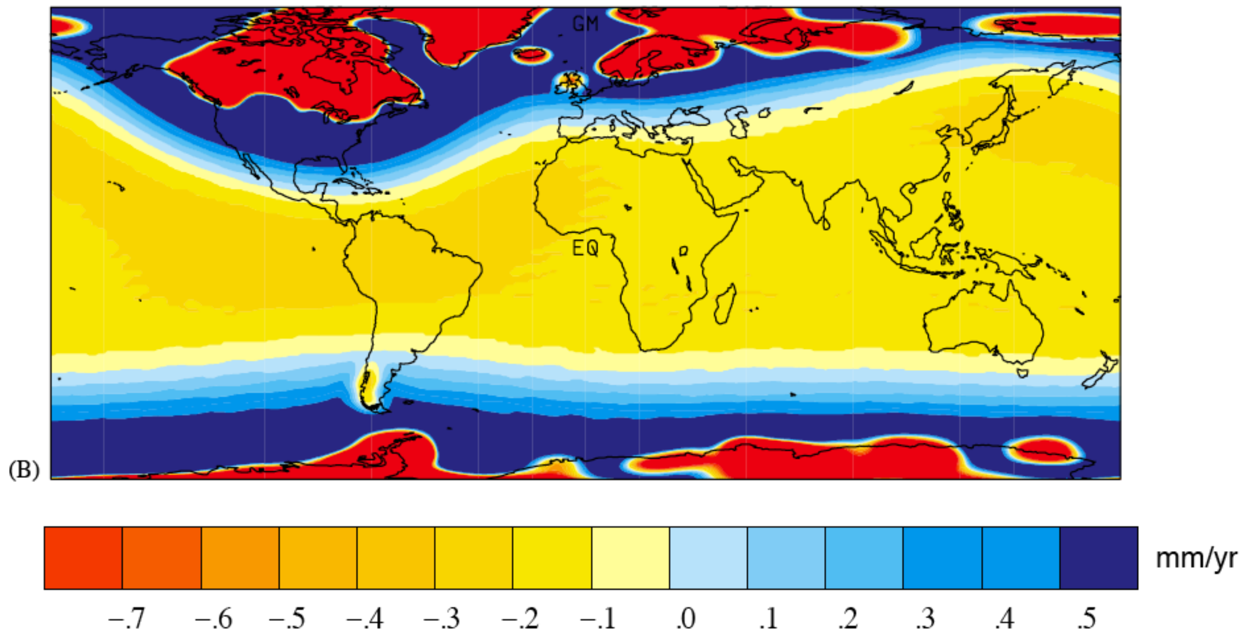

Ice Signal

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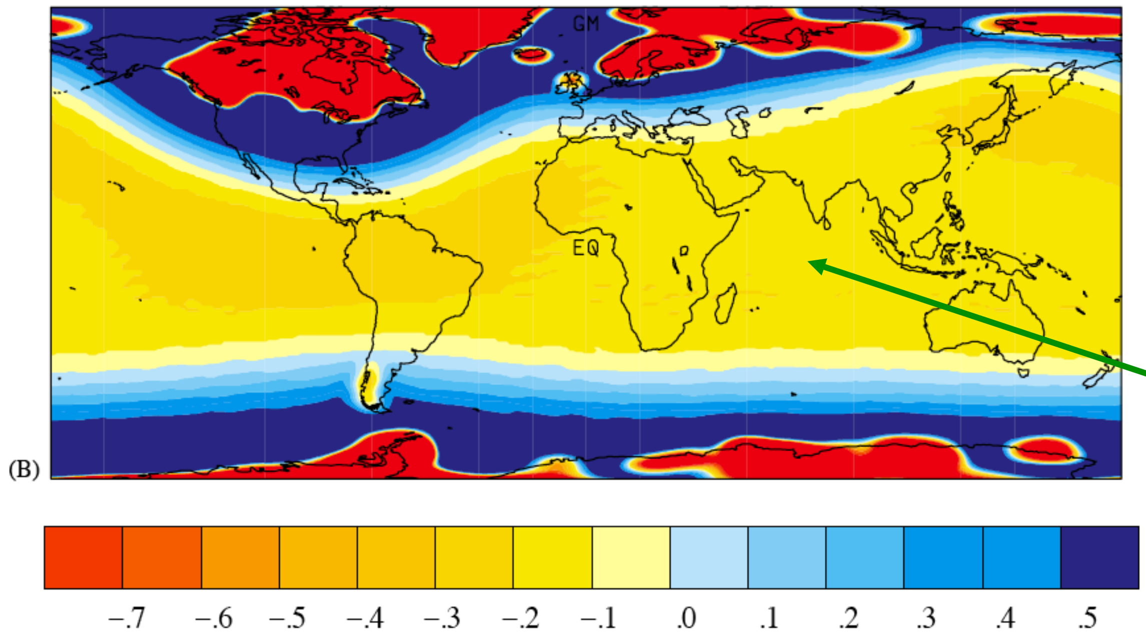
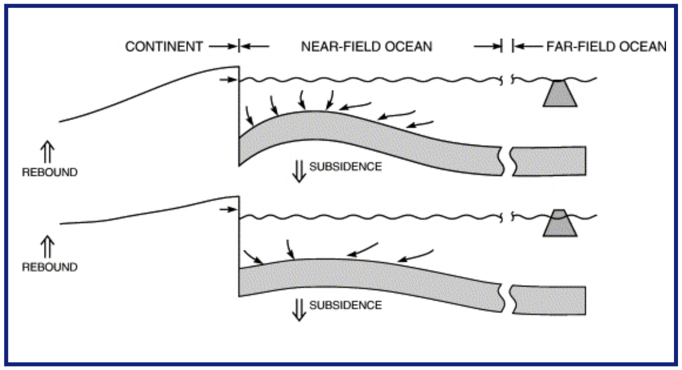


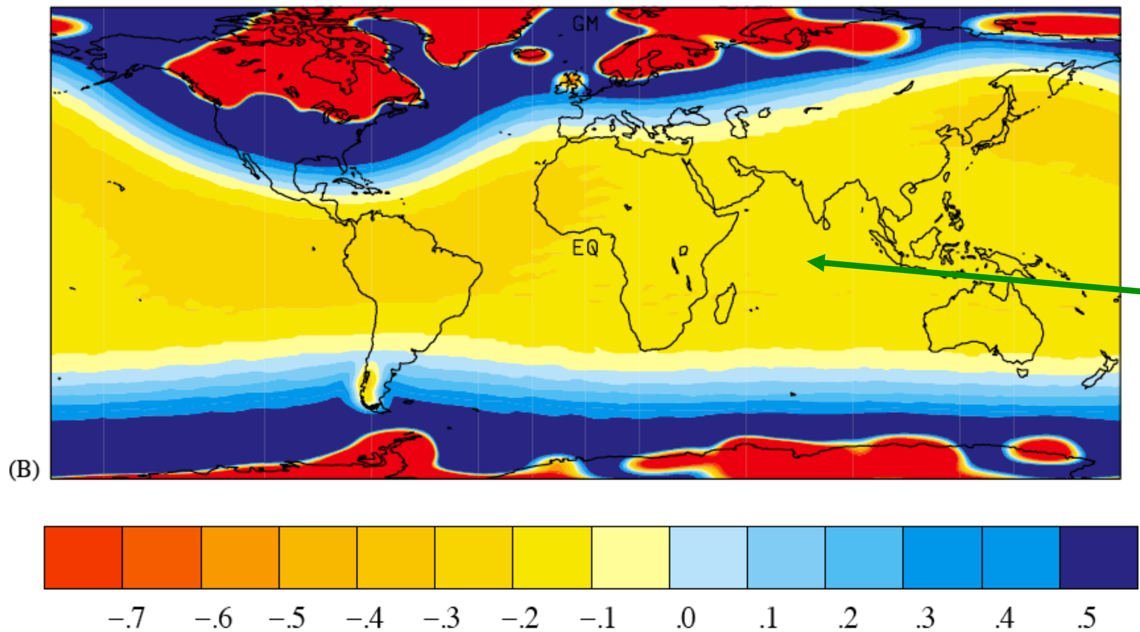


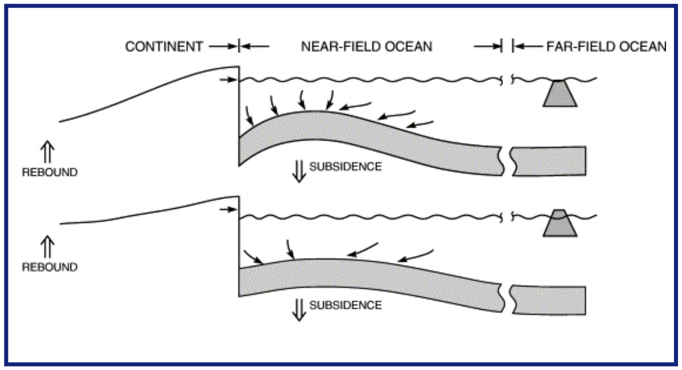
FAR FIELD

Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA





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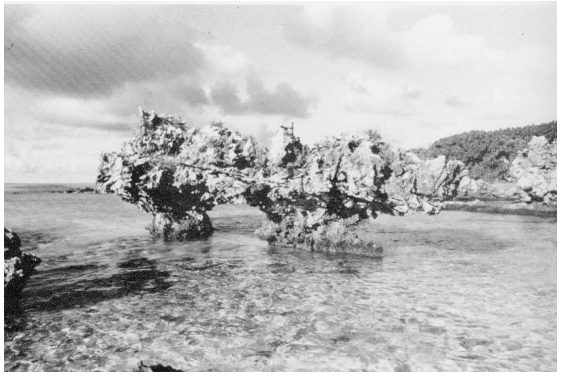
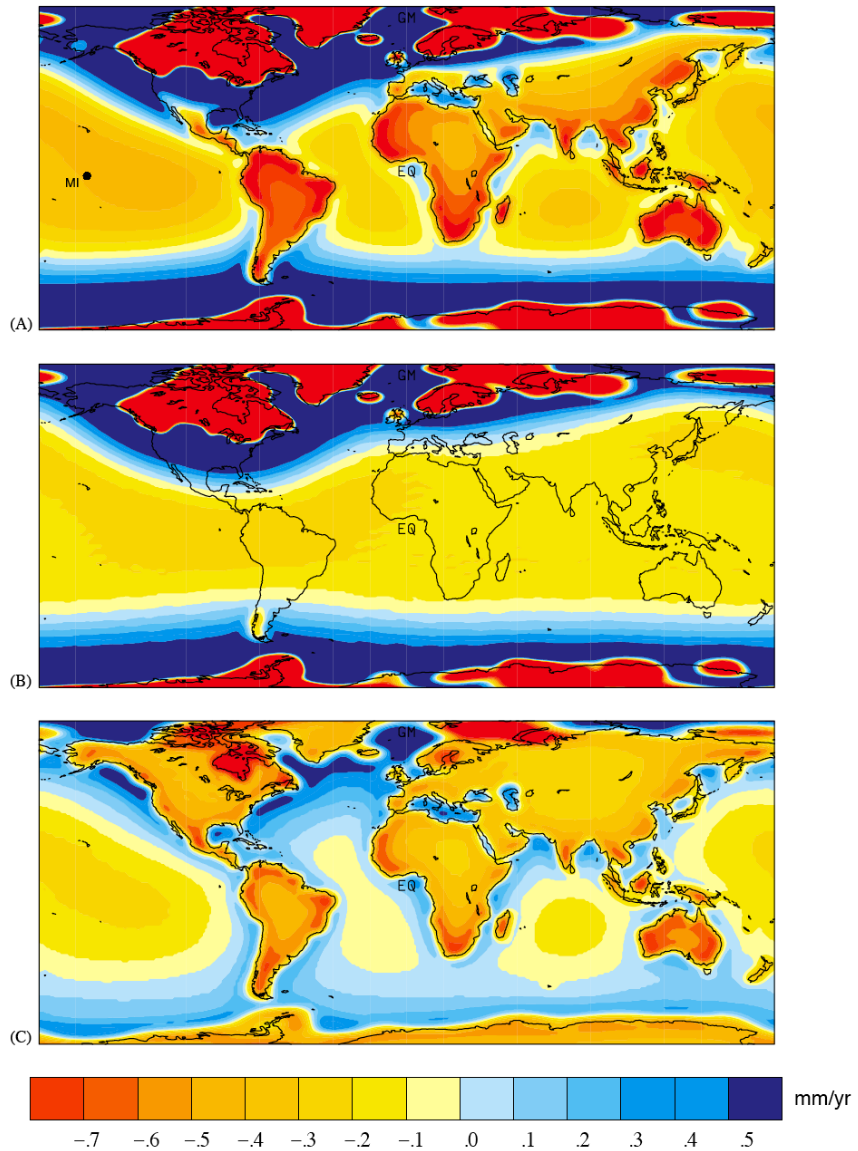


Ice Signal

Equatorial Ocean Syphoning!

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA



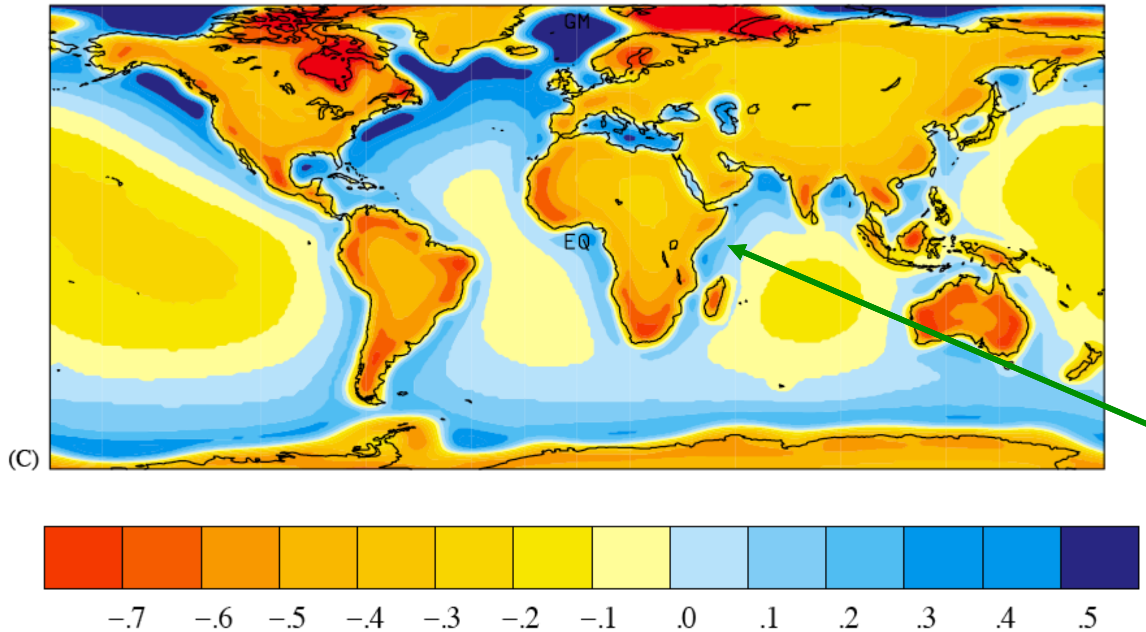
TOTAL

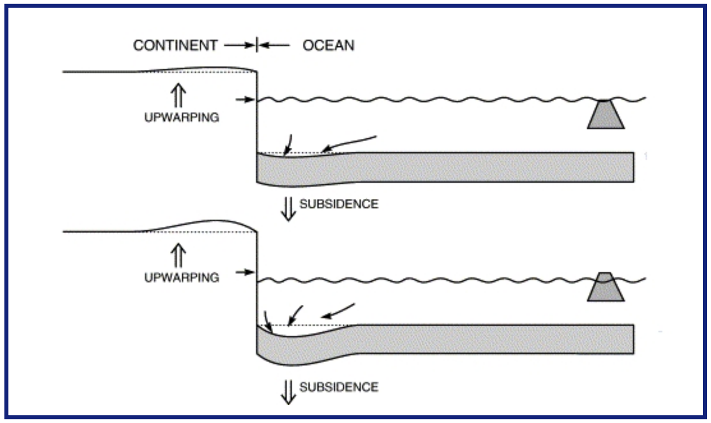
ICE

OCEAN

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA





Continental Levering!

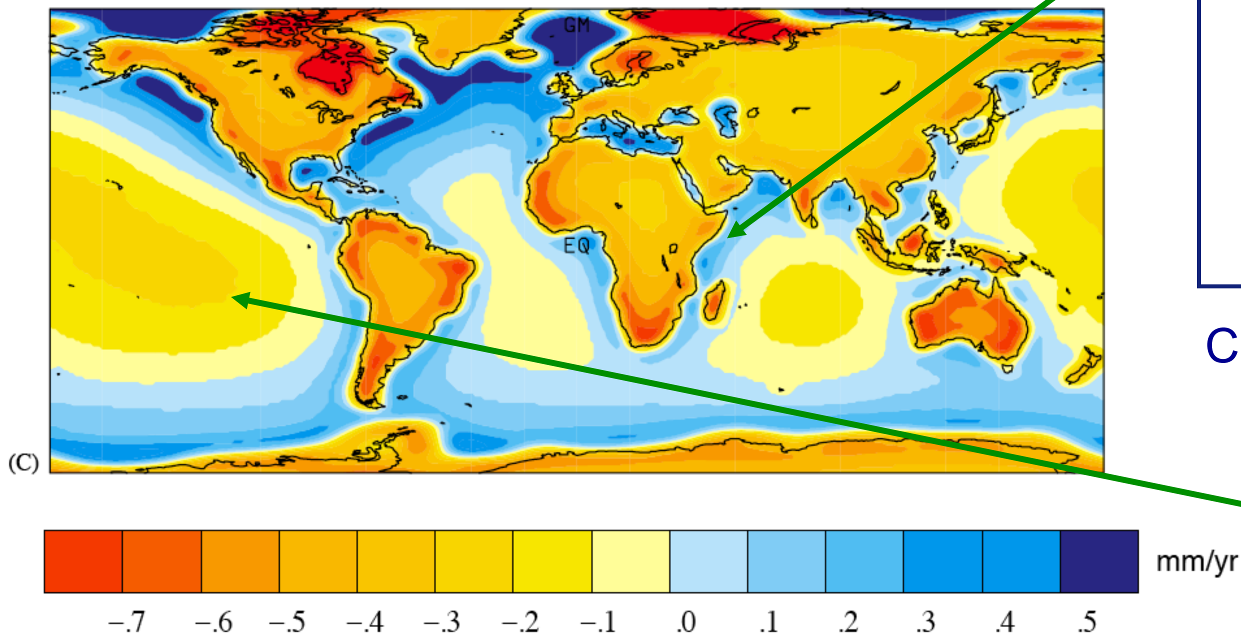
FAR FIELD

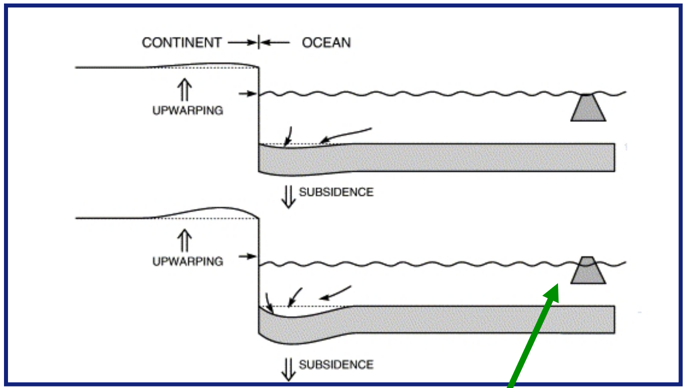
Ocean Signal

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA

FAR FIELD





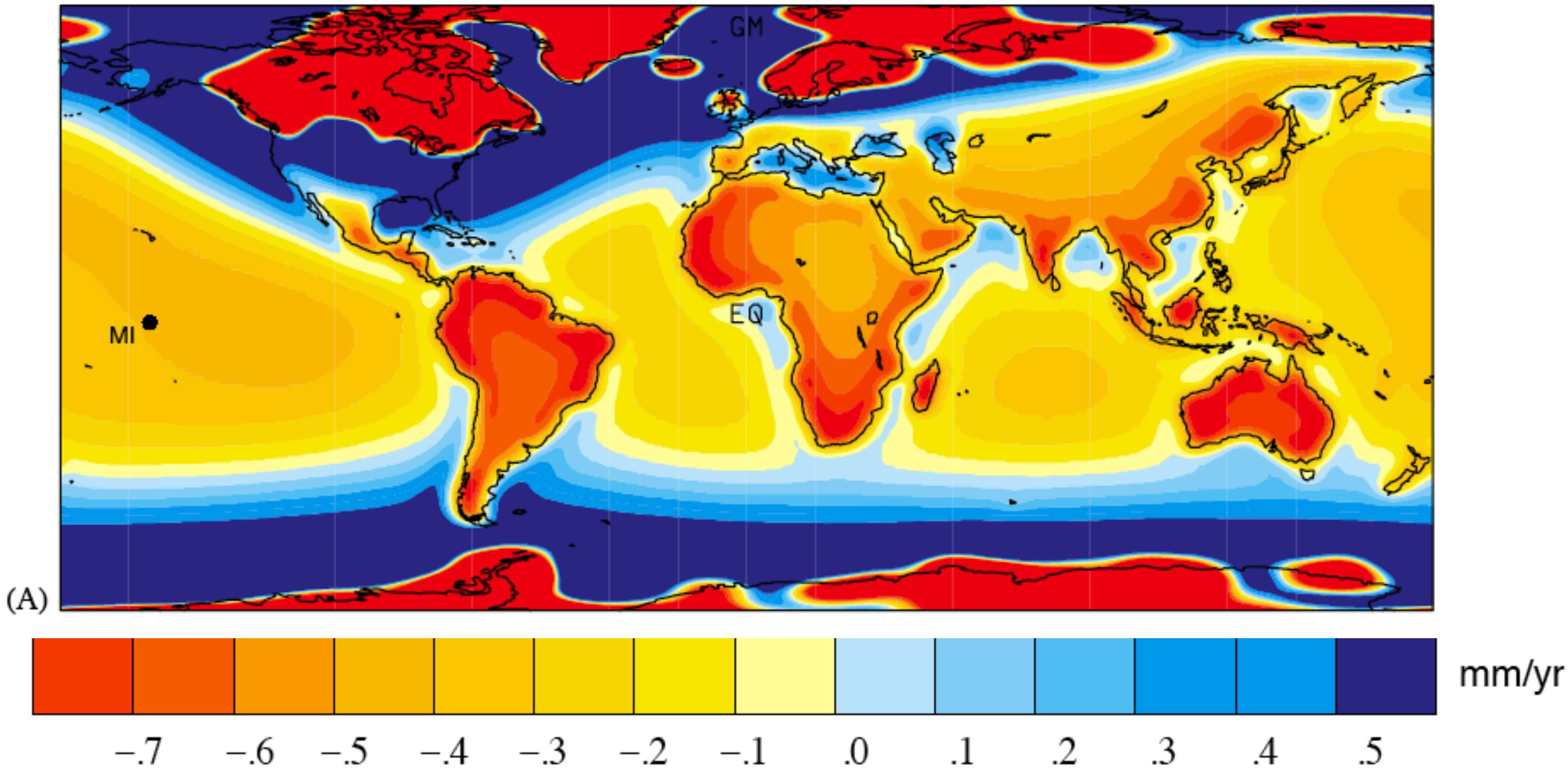
Continental Levering!

2nd contribution to equatorial ocean syphoning

Ocean Signal

2b. Sea Level Physics: Ice-Age Timescales

Numerical Prediction of Present-Day Rate of
Global Sea-Level Change Due to Ongoing GIA

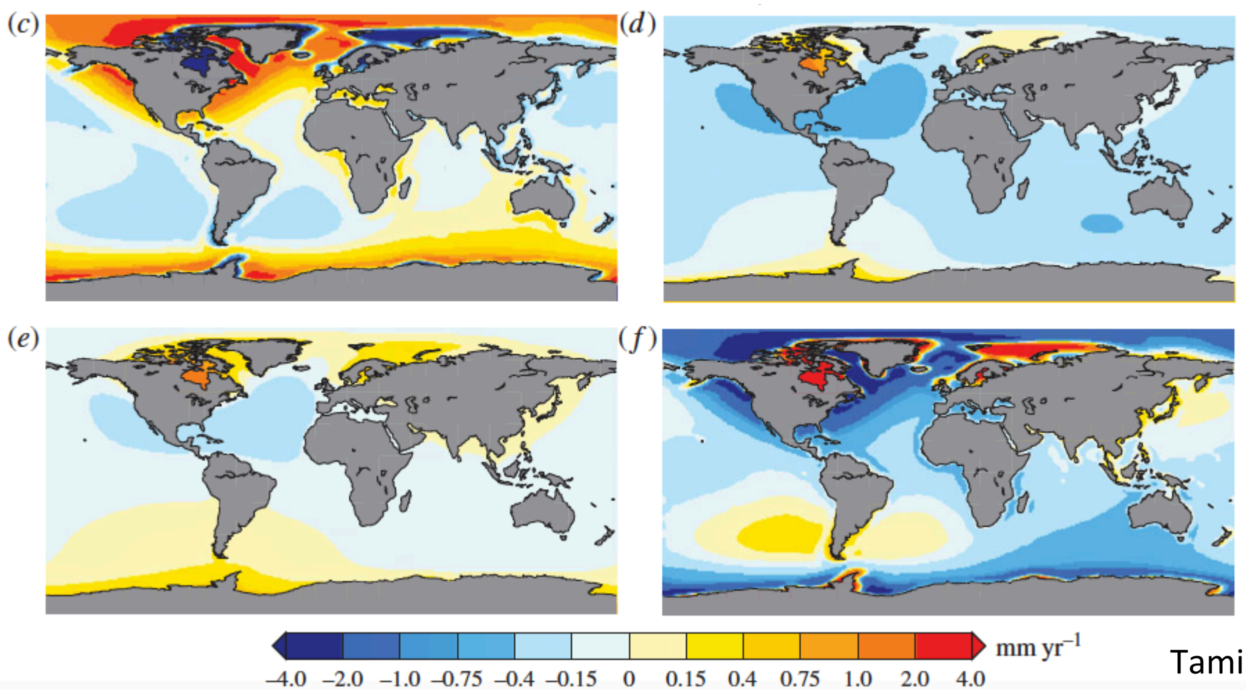


2b. Sea Level Physics: Ice-Age Timescales

Expressions of GIA in modern sea-level records

Sea level (tide gauges)

Sea surface height (altimetry)



Geoid height (GRACE)

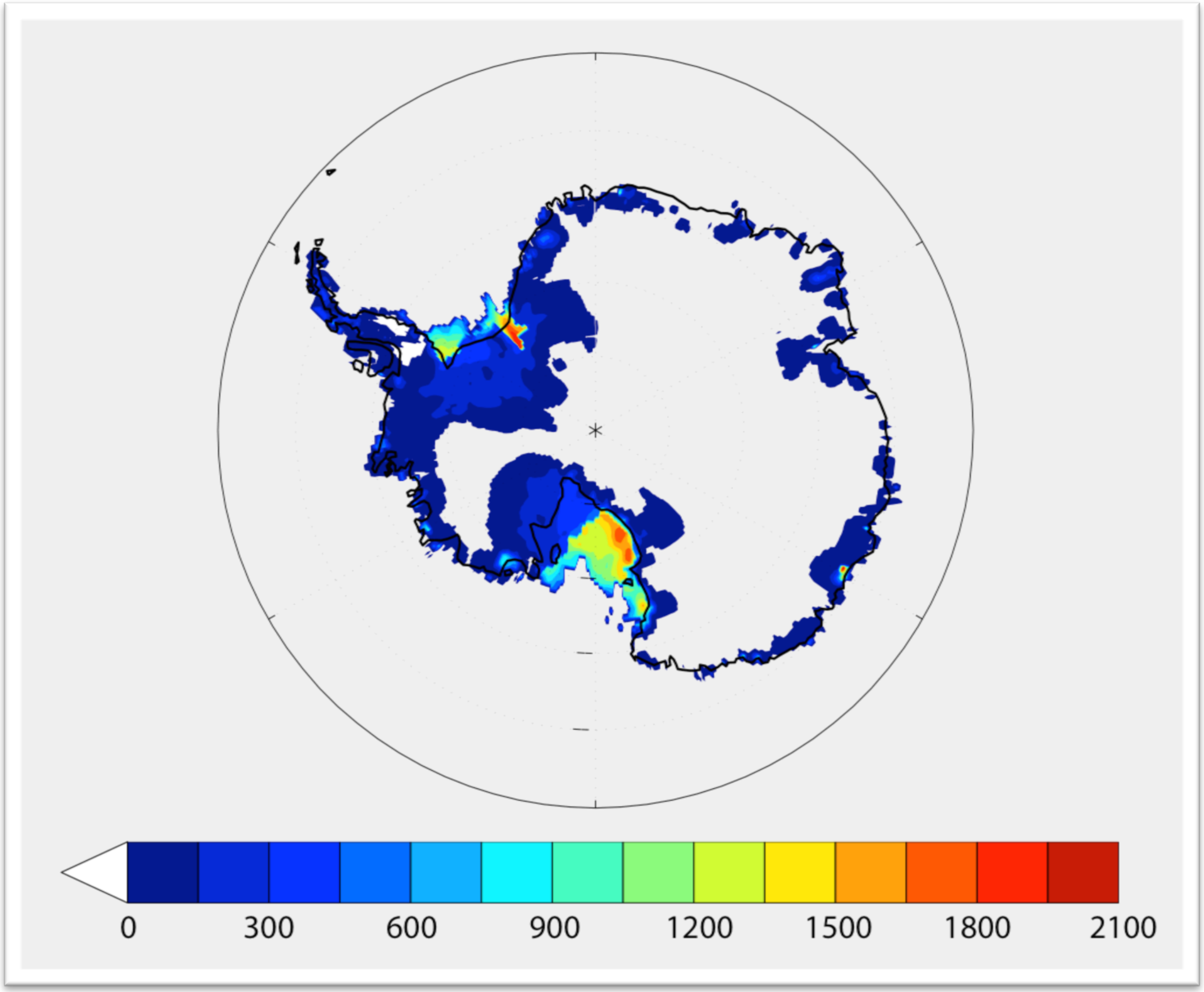
Crustal motion (GNSS)

Tamisiea et al. (2014)

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

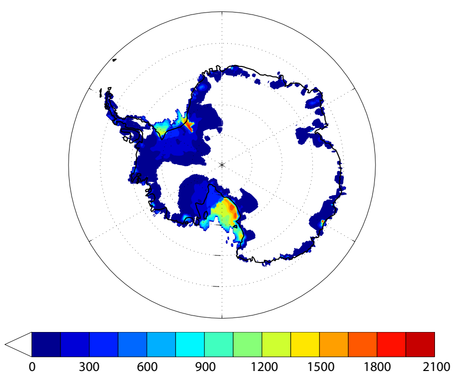
3. Sea Level Change Example

Ice Loss Scenario:
eustatic value = 1.8 m (after filling the holes)

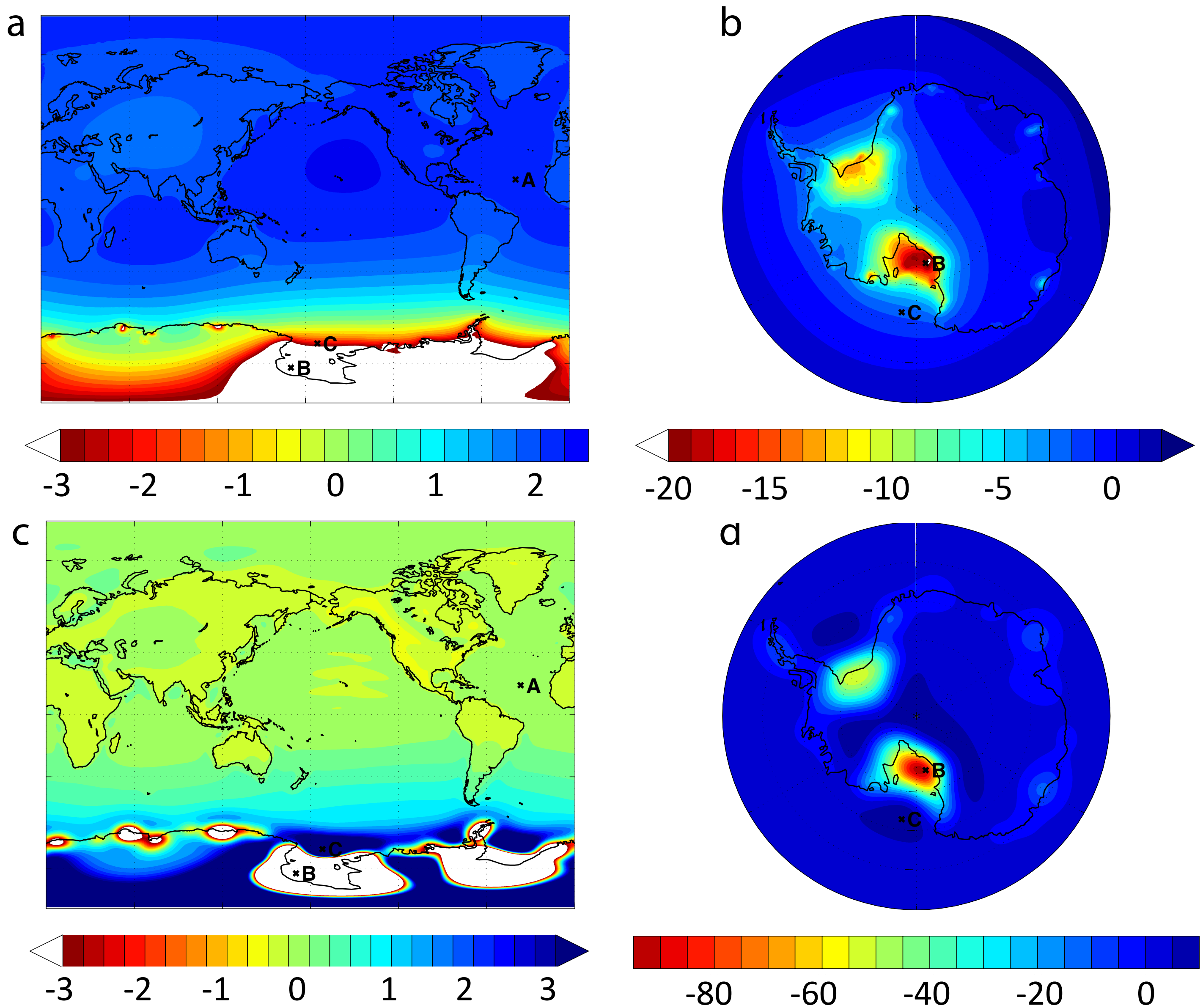


3. Sea Level Change Example

Elastic SL change immediately after ice sheet retreat



SL change over next 10 ky (ice remains constant)



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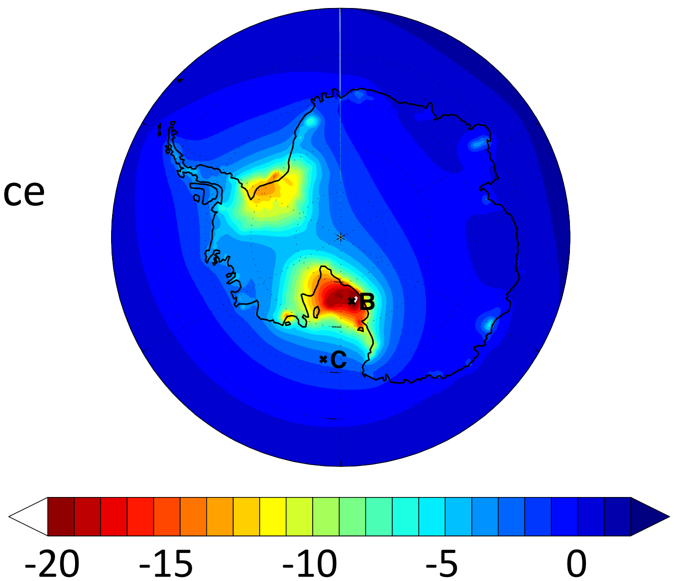

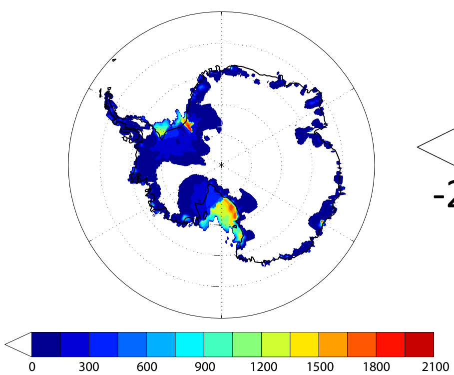

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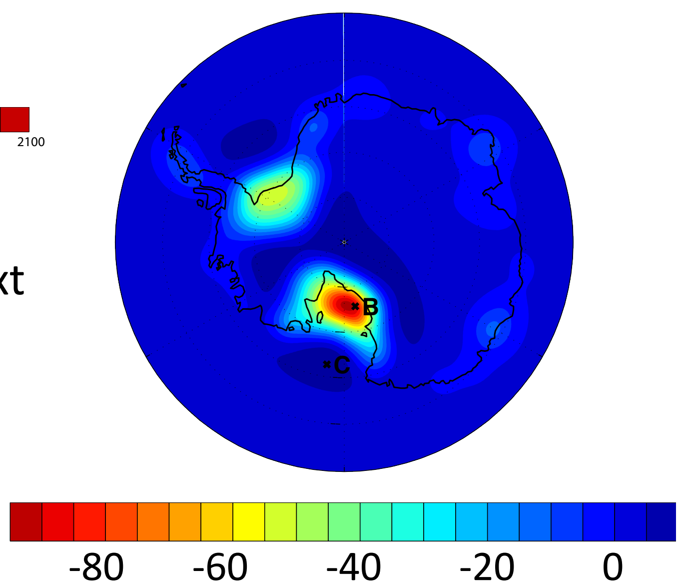

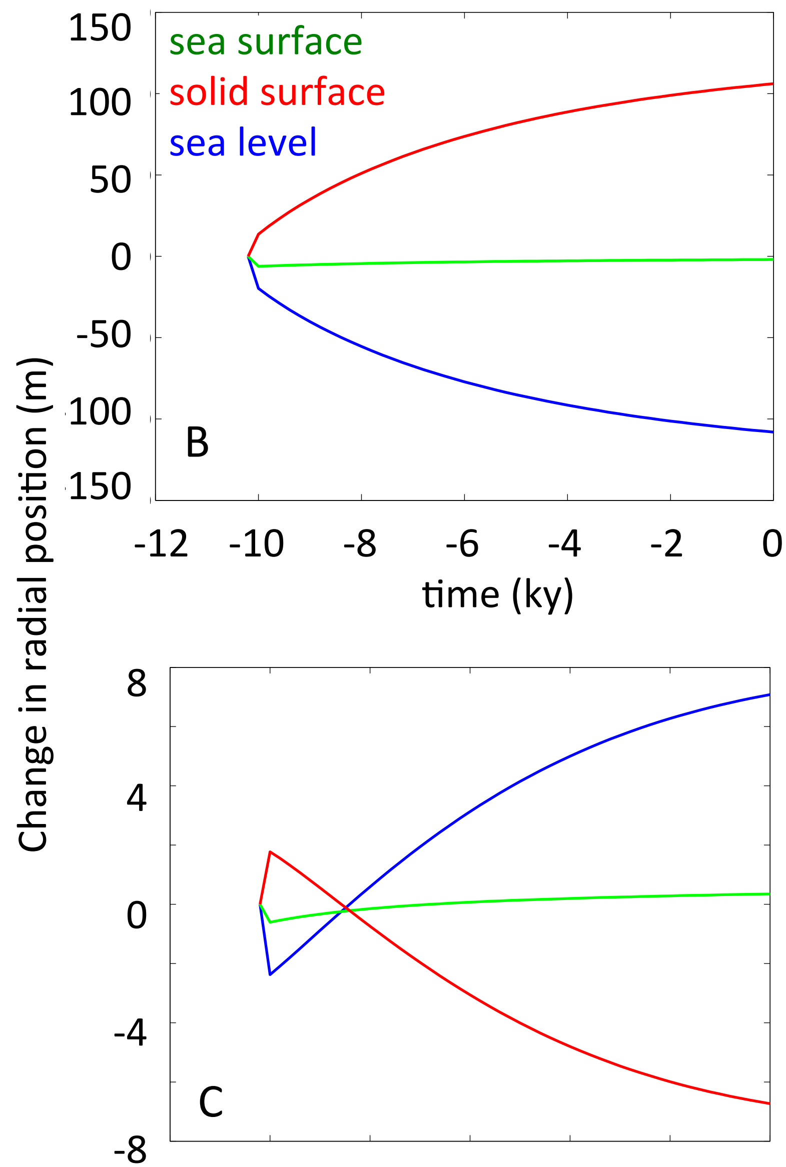

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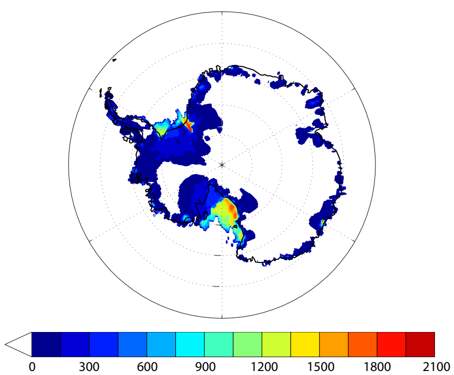
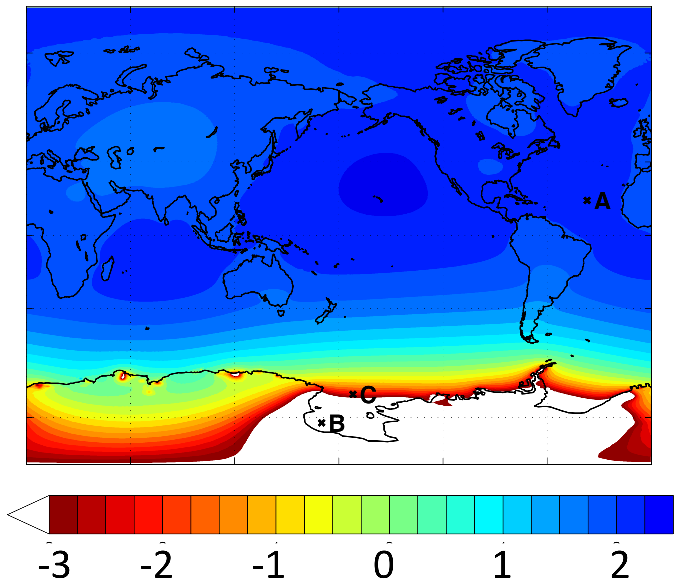
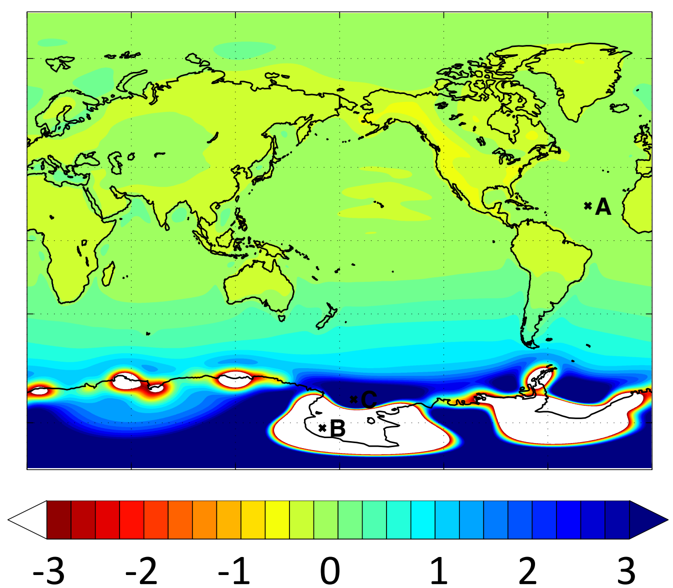
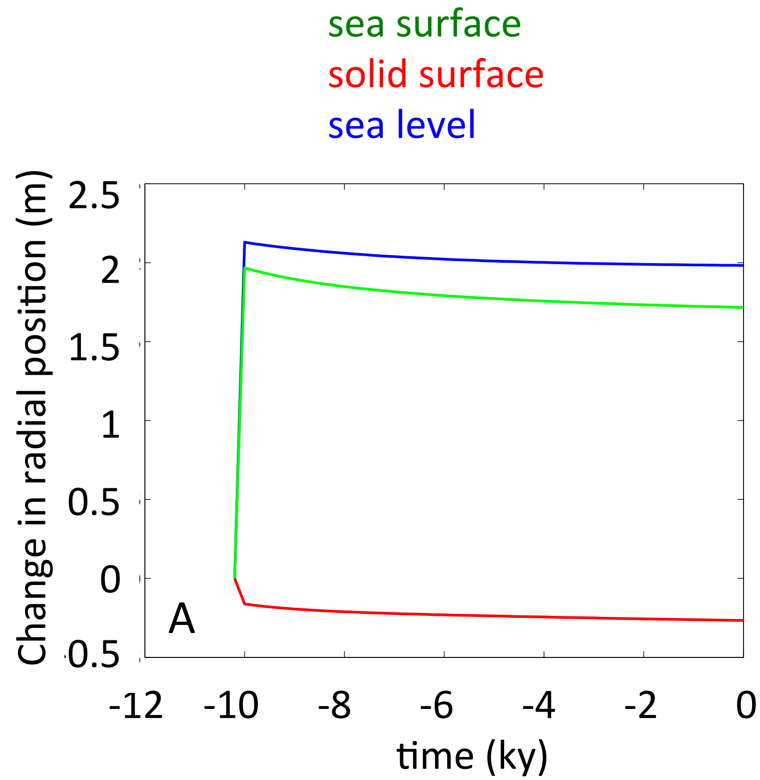




SL change over next 10 ky (ice remains constant)





Quick Mental Break!

Outline

This Class: Sea Level Change Continued…

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

2. An Example Calculations

3. Applications
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    2. Short timescale paleo: Meltwater Pulse 1A (~14ky ago)
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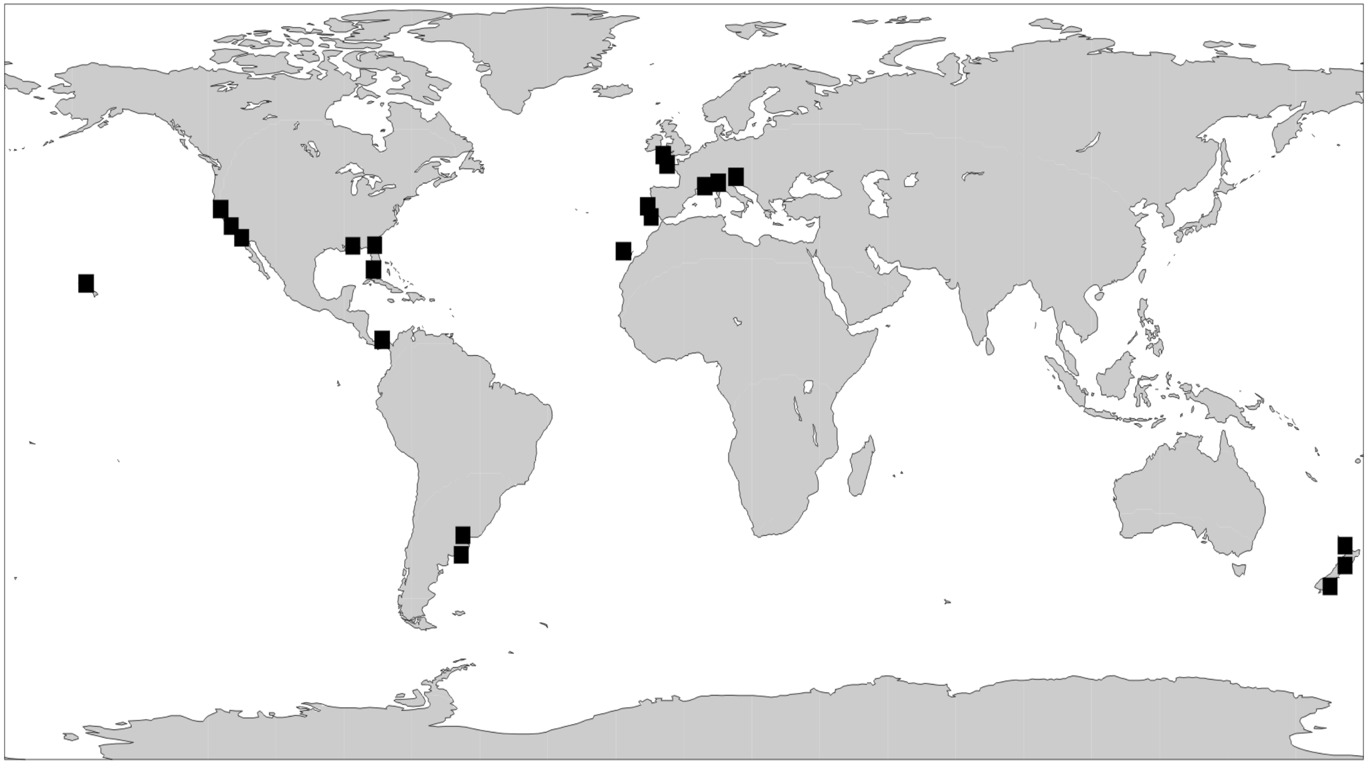
Application to 20th century tide gauge analysis

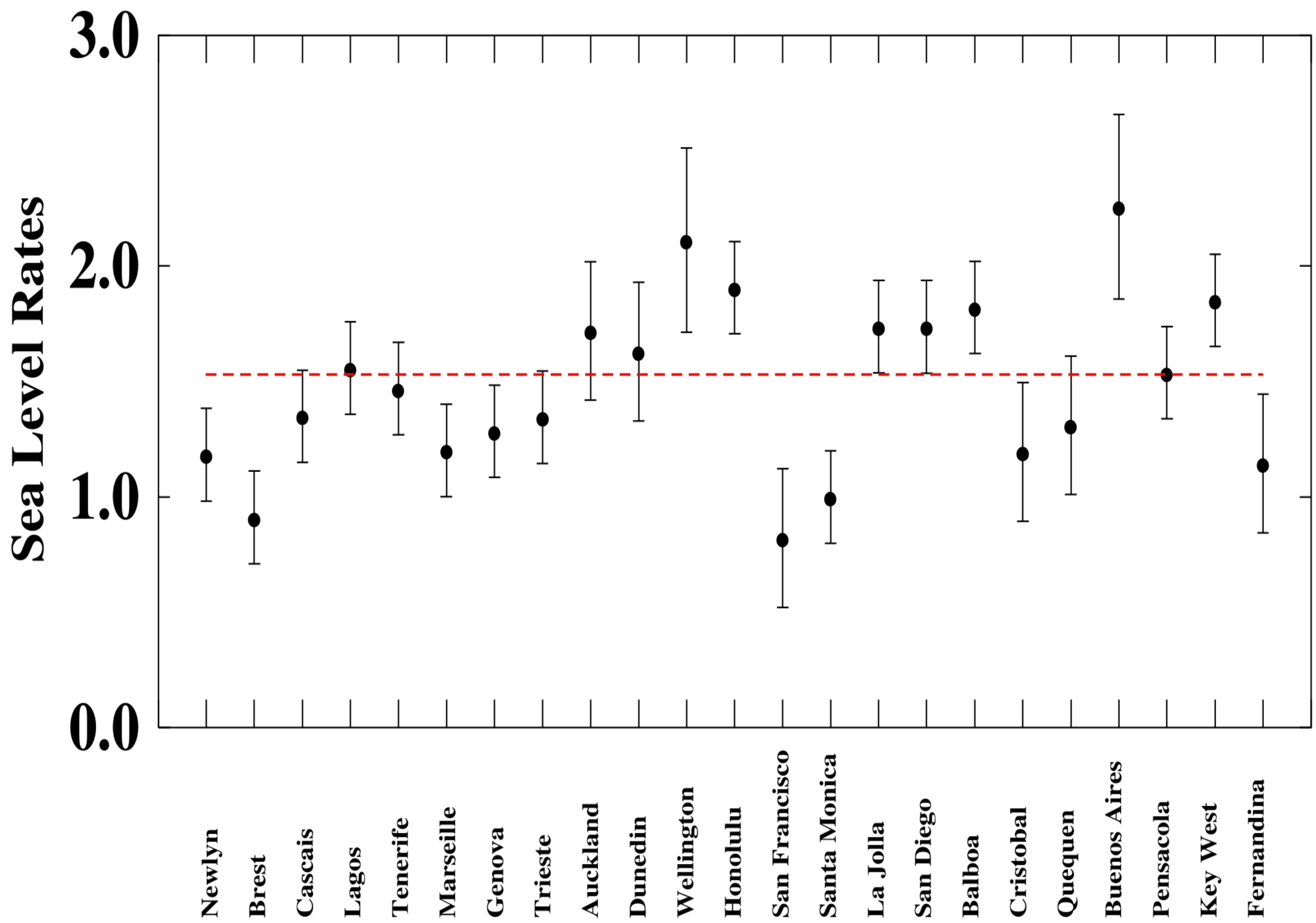
Recent mass balance of polar ice sheets inferred from patterns of global sea-level change

Jerry X. Mitrovica*, Mark E. Tamisiea*, James L. Davis†
& Glenn A. Milne‡

(2001)

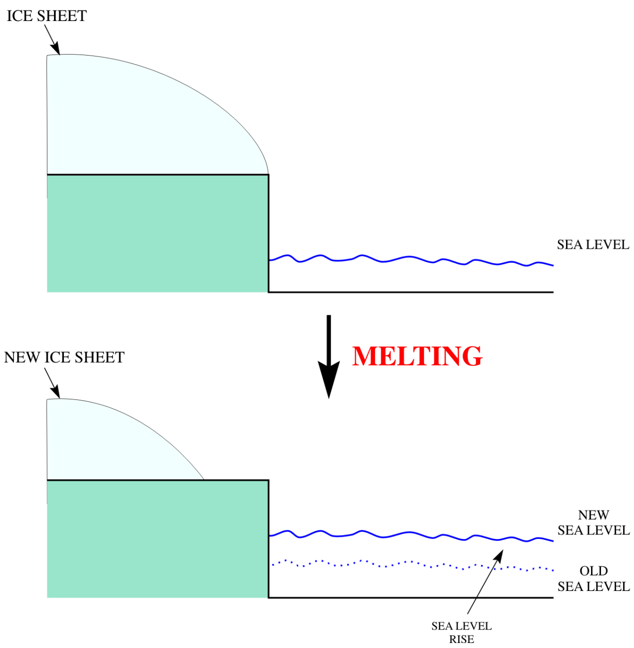


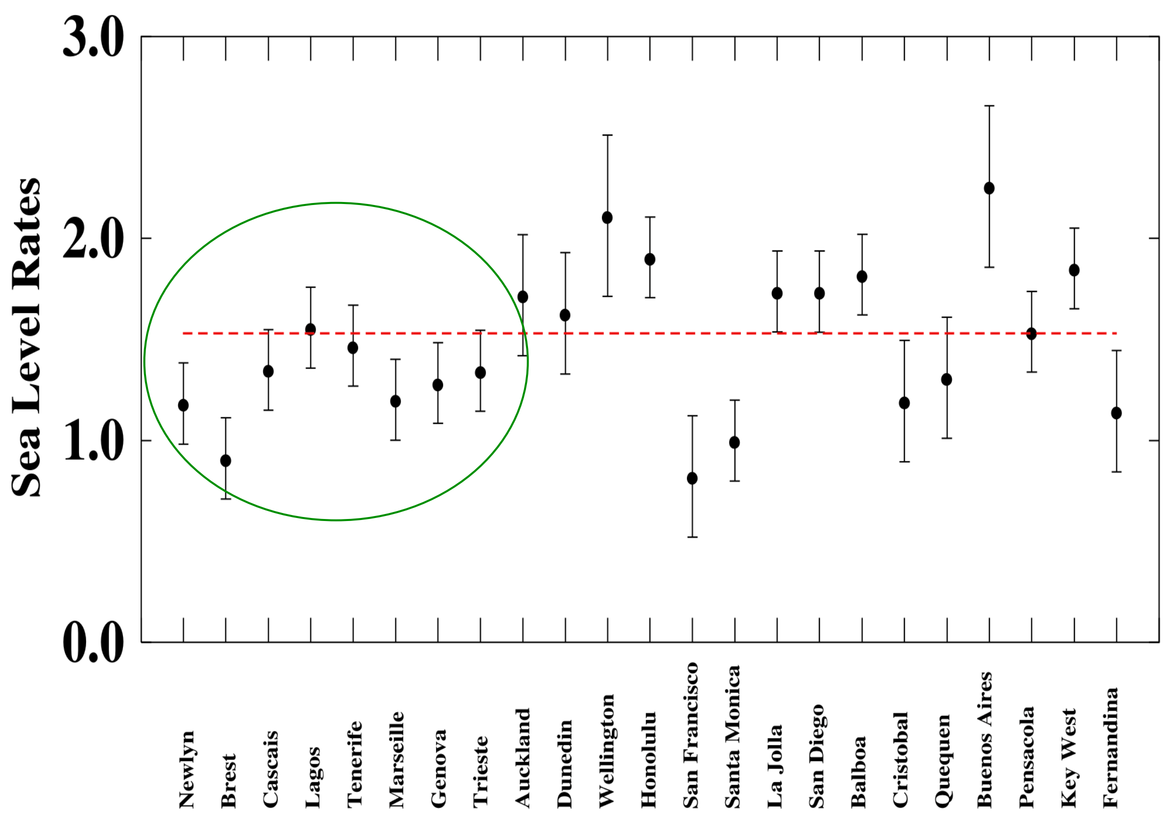
Application to 20th century tide gauge analysis



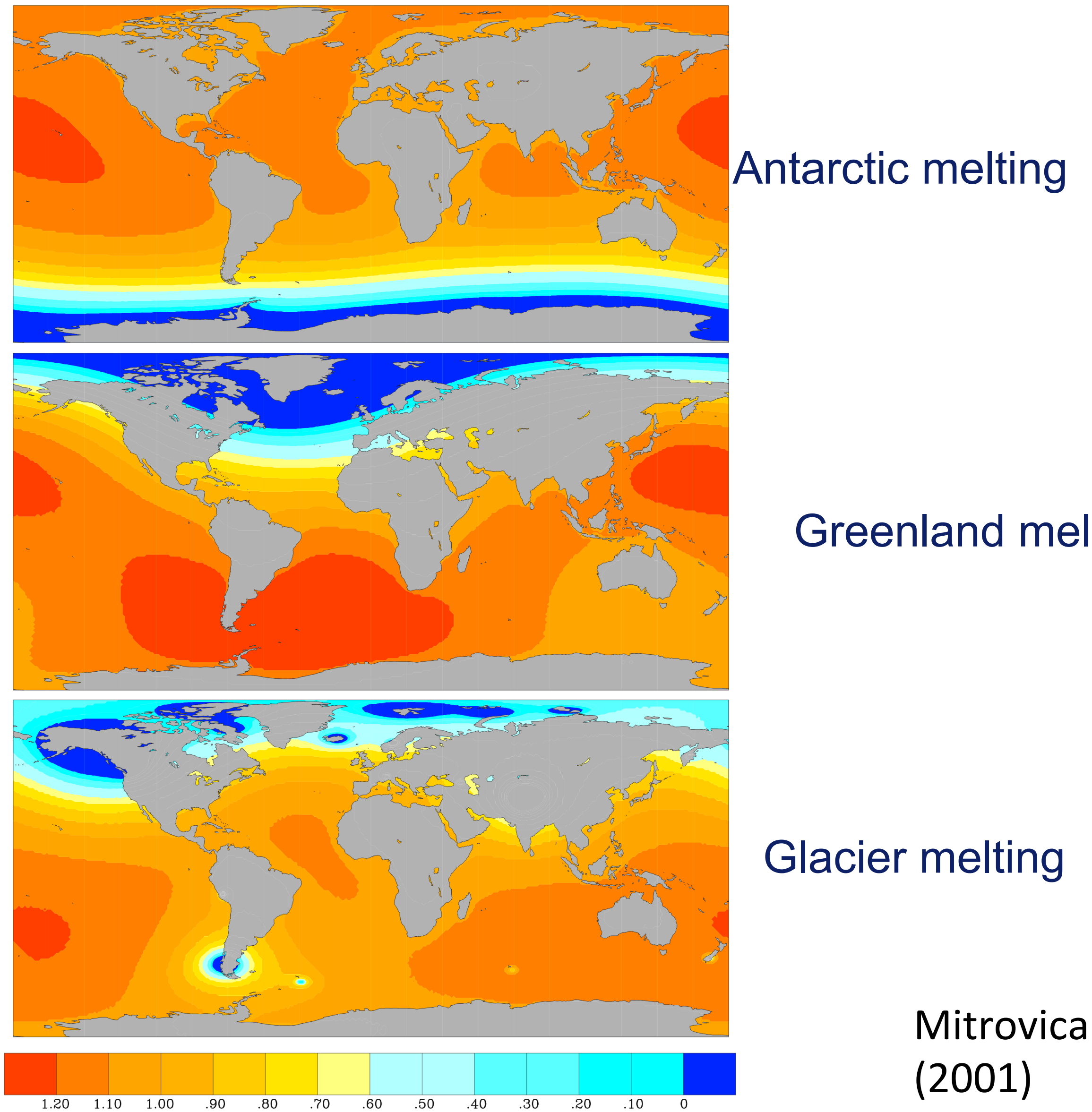
Application to 20th century tide gauge analysis

The Bathtub Model?



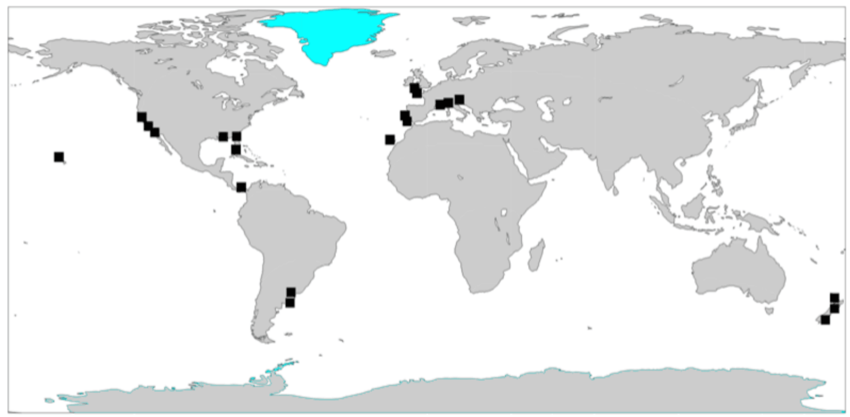


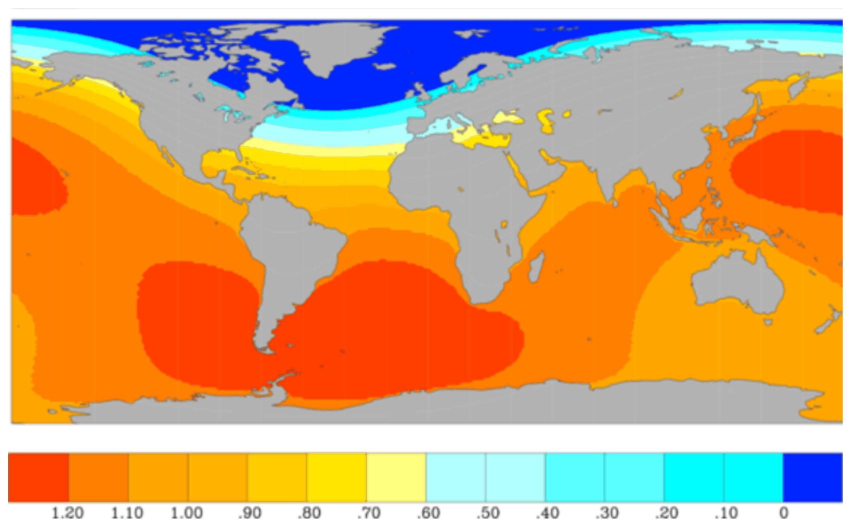
Application to 20th century tide gauge analysis



Mitrovica et. al. (2001)

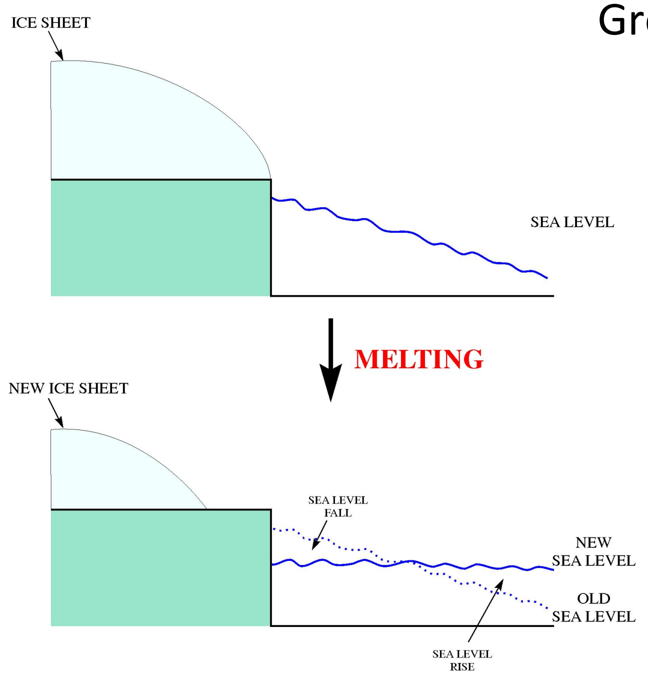
Application to 20th century tide gauge analysis



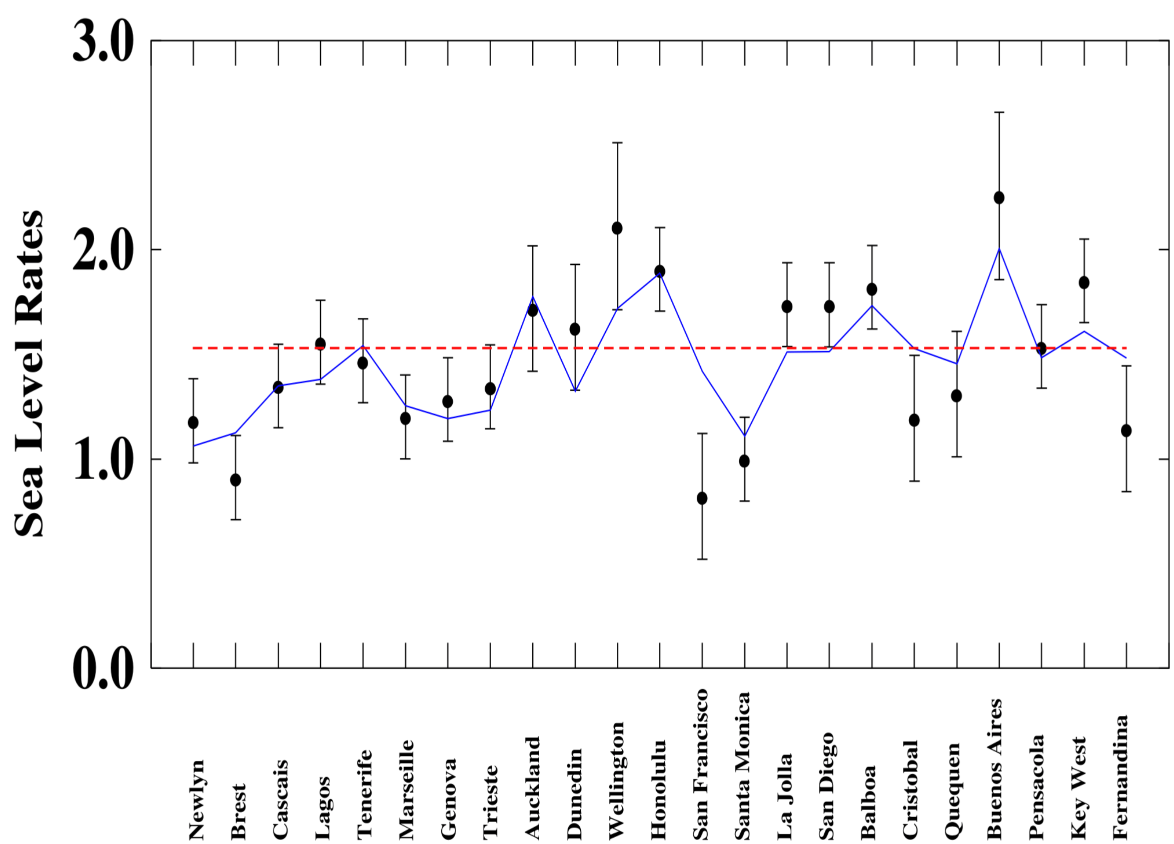


Application to 20th century tide gauge analysis

The Correct Physics …

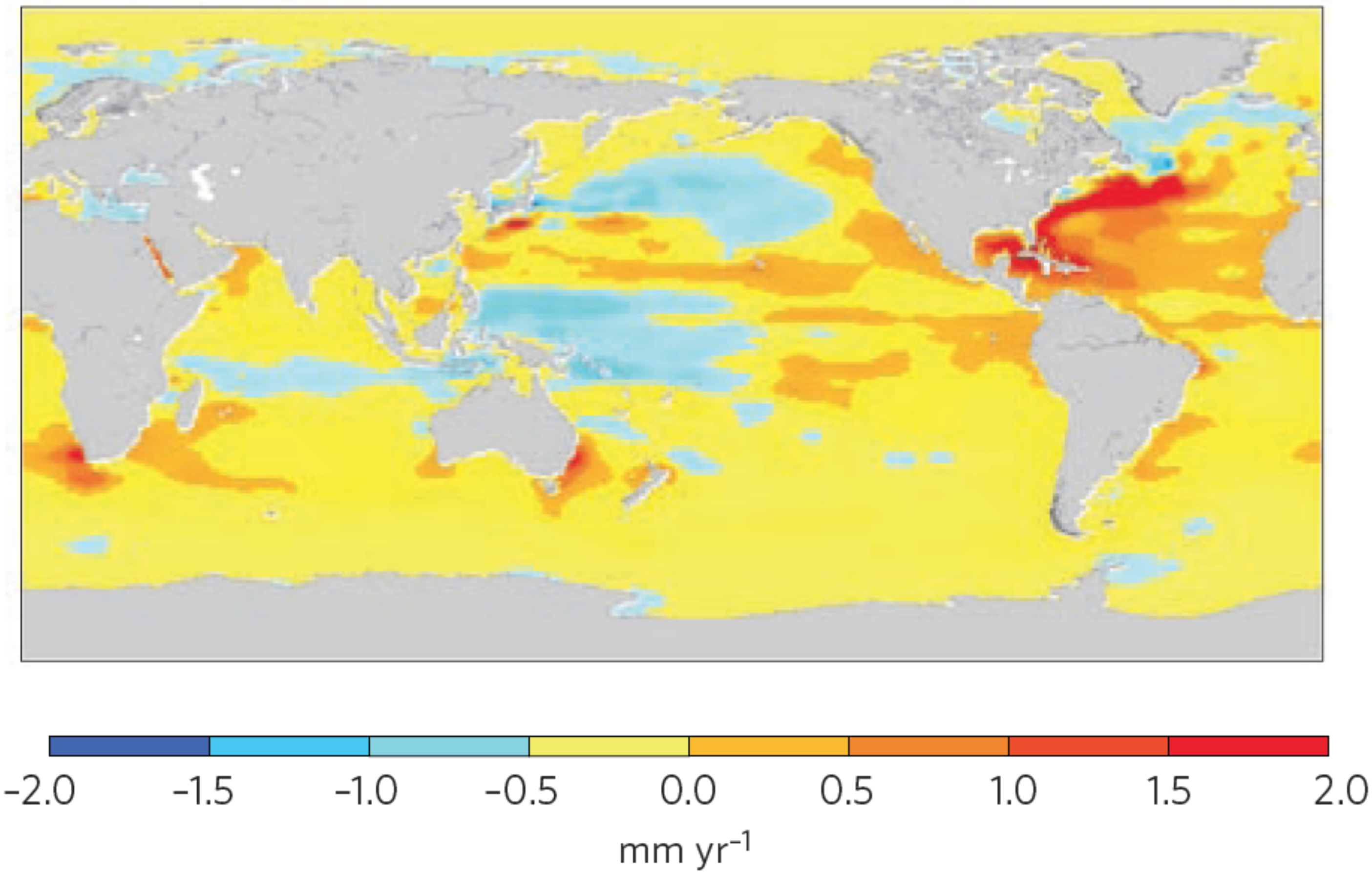


This analysis:
Sea Level Change =
Greenland + Antarctica + mountain glaciers + the rest



Application to 20th century tide gauge analysis

Issue: We need another fingerprint!



Steric effects (ocean temperature and salinity changes) – 1950-2003: Berge-Nguyen et al. [Glob. Planet. Change, 2008]

Application to 20th century tide gauge analysis

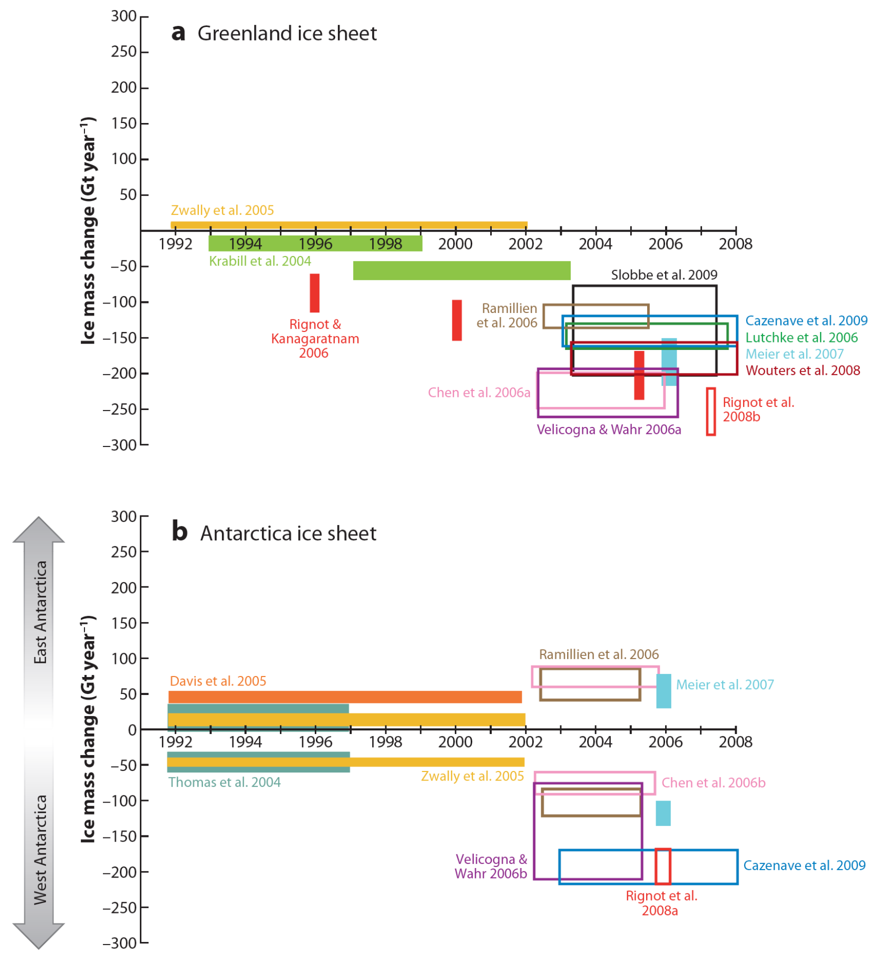


Figure 5

(*a*) Compilation of Greenland ice sheet mass loss based on remote-sensing observations between 1992 and 2008. (*b*) Same as (*a*) but for the Antarctica ice sheet (redrawn from Cazenave 2006).

A note on estimating ice loss over the 20th century and beyond.

Next class: ICE!

Cazenave & Llovel (Ann. Rev. Marine Sci., 2009)

Application to 20th century tide gauge analysis

- Next slides on the current state of the art in tide guage analysis [Hay et al., Nature, 2015] are from Dr. Carling Hay (Harvard University).

Estimating Sea Level

- Combine observations with models of the underlying physics of sea-level change.
- "Fingerprint" tide gauge records to estimate the individual contributions to 20th century sea-level change.

Extract global information from sparse records.

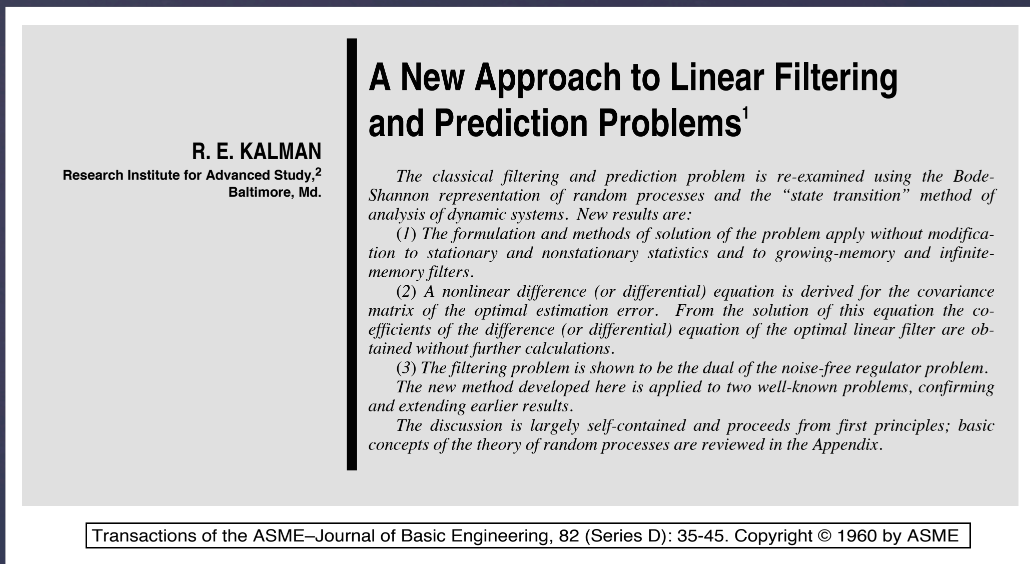
Multi-Model Kalman Smoother

Estimating Sea Level

Multi-Model Kalman Smoother (KS)

- Both algorithms are Bayesian in nature.
- Naturally accommodate measurements with data gaps.
- Allow the estimation of sea level at sites with and without observations.
- Compute GMSL by first estimating the equivalent global mean value of the individual contributions from their unique temporal-spatial fingerprints.
- The resulting uncertainties in our estimates of global mean sea level reflect the data sparsity over time.

Kalman Filter



A New Approach to Linear Filtering and Prediction Problems[1]

R. E. KALMAN
Research Institute for Advanced Study,[2]
Baltimore, Md.

The classical filtering and prediction problem is re-examined using the Bode-Shannon representation of random processes and the "state transition" method of analysis of dynamic systems. New results are:

(1) The formulation and methods of solution of the problem apply without modification to stationary and nonstationary statistics and to growing-memory and infinite-memory filters.

(2) A nonlinear difference (or differential) equation is derived for the covariance matrix of the optimal estimation error. From the solution of this equation the coefficients of the difference (or differential) equation of the optimal linear filter are obtained without further calculations.

(3) The filtering problem is shown to be the dual of the noise-free regulator problem.

The new method developed here is applied to two well-known problems, confirming and extending earlier results.

The discussion is largely self-contained and proceeds from first principles; basic concepts of the theory of random processes are reviewed in the Appendix.

Transactions of the ASME–Journal of Basic Engineering, 82 (Series D): 35-45. Copyright © 1960 by ASME

It's a method of predicting the future state of a system based on the previous states.

trajectory estimation for the Apollo program

space shuttle navigation systems

ballistic missile navigation systems

weather forecasting

Kalman Filter

It's a method of predicting the future state of a system based on the previous states.

Iteratively performs a least squares analysis whenever observations are available, and in the absence of observations relies on the model dynamics to compute the best estimate of state variables.

Kalman Filter

It's a method of predicting the future state of a system based on the previous states.

Iteratively performs a least squares analysis whenever observations are available, and in the absence of observations relies on the model dynamics to compute the best estimate of state variables.

The state is a description of all the parameters we will need to describe the current system.

State vector at time k:

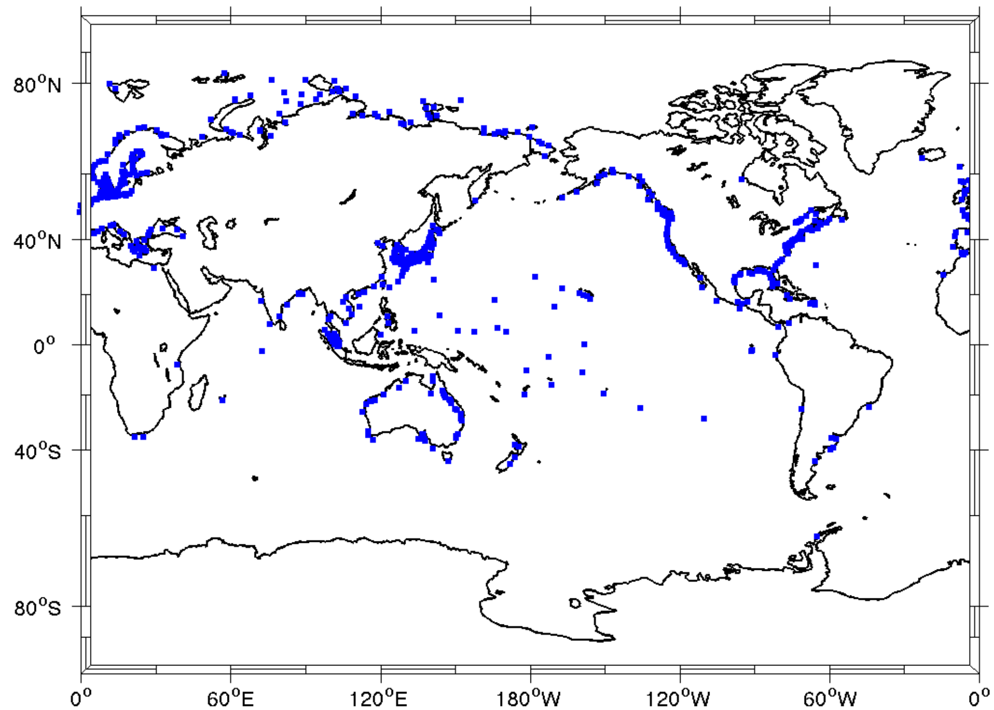
$$\vec{x}_k = \begin{bmatrix} \vec{S}_k & \vec{\beta}_k \end{bmatrix}^T$$

$\vec{S}_k$ = sea level at each tide gauge site

$\vec{\beta}_k$ = vector of ice sheet and mountain glacier melt rates

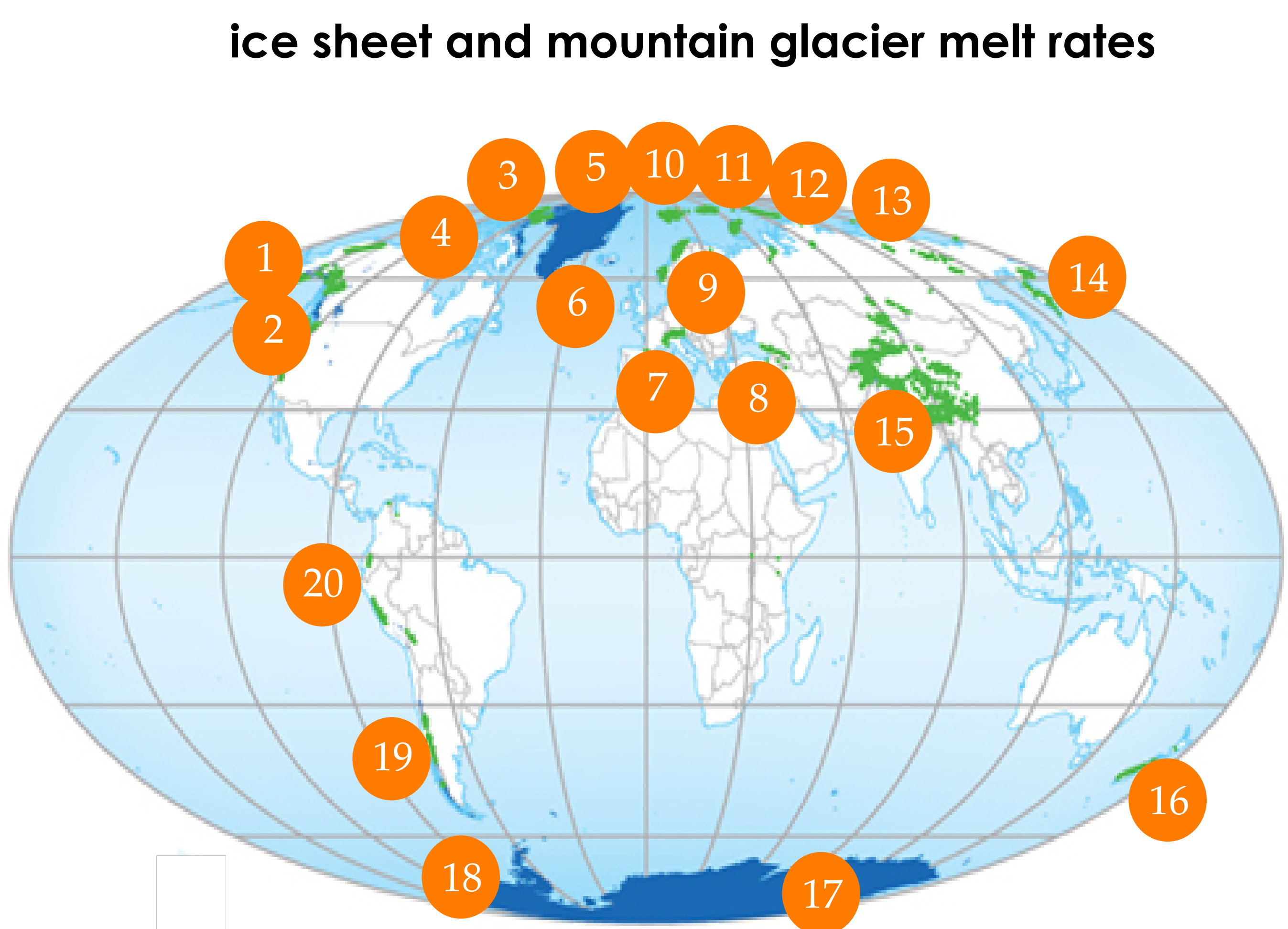
Kalman Filter

sea level at each tide gauge site



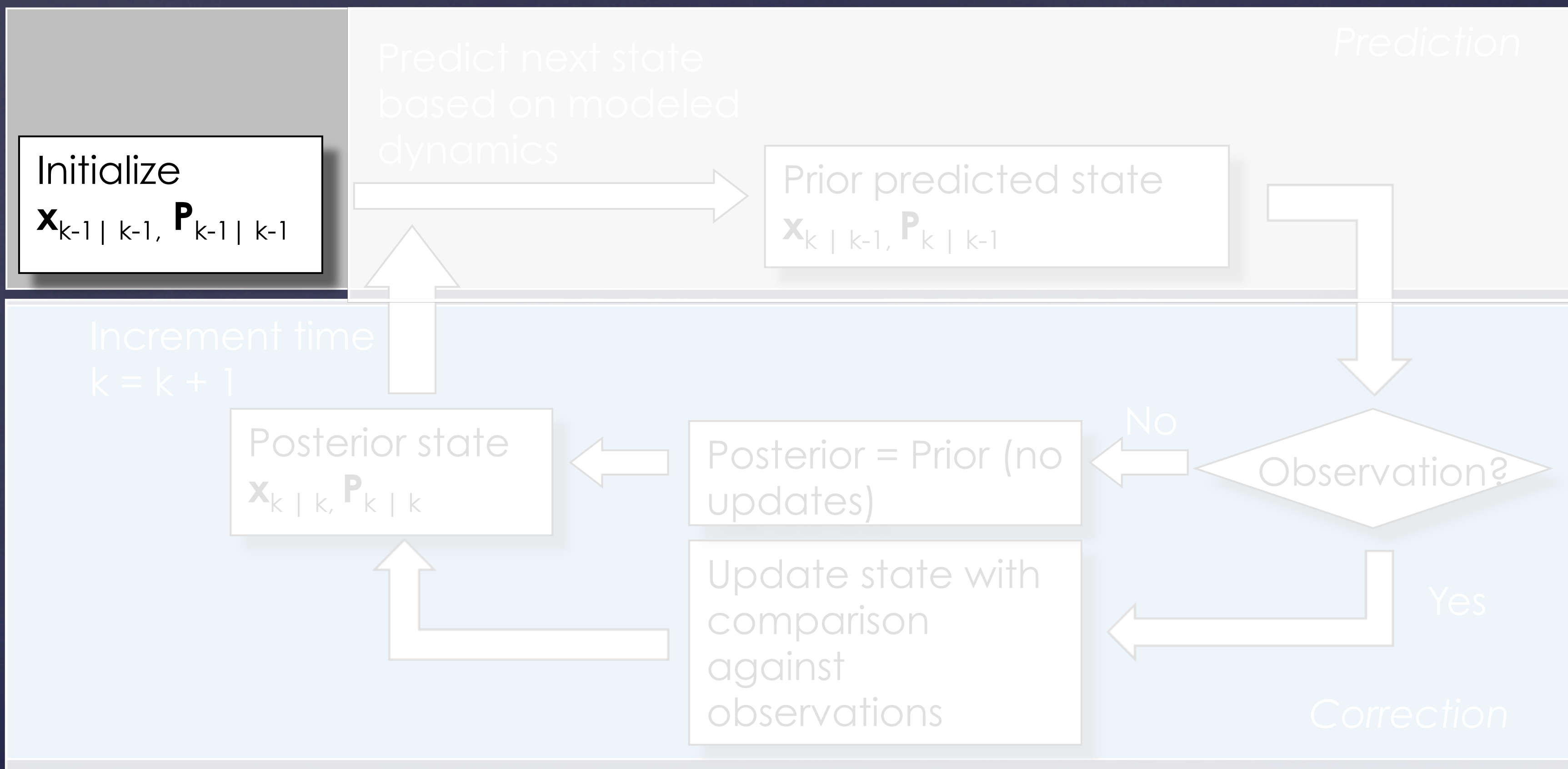
622 tide gauges

Kalman Filter



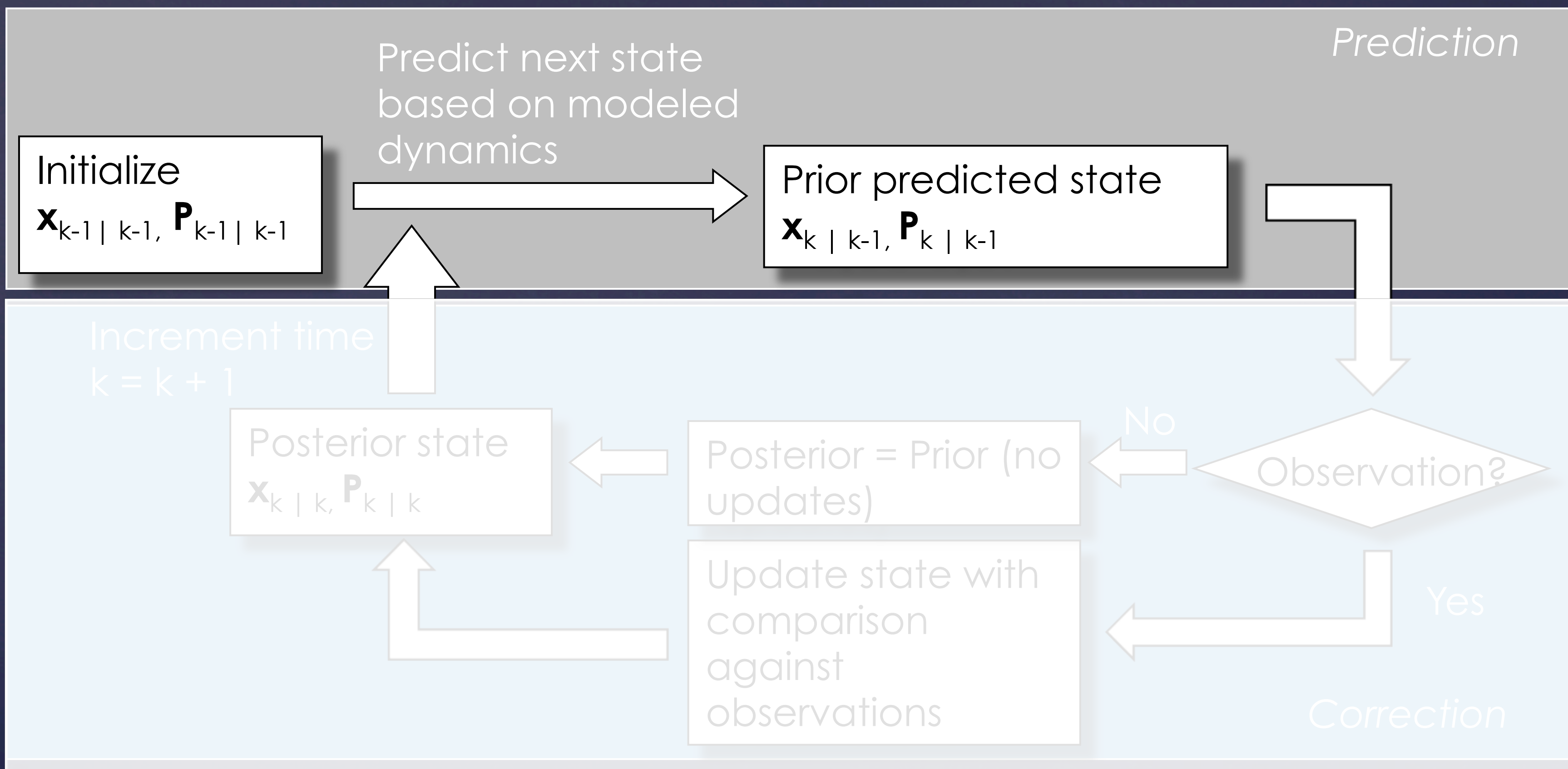
20 ice sheets and mountain glaciers
and a globally uniform term

Kalman Filter



Initialize our sea level and melt rates at the first time step (1900).

Kalman Filter



At each time step, we use a model to describe how we think the system behaves.

Kalman Filter

PREDICTION STEP

At each tide gauge:

Prescribed GIA & ocean models

$$\text{sea level}_k = \text{sea level}_{k\text{-}1} + \text{additional melt water}_{k\text{-}1} + \text{GIA} + \text{ocean dynamics} + \text{noise}$$

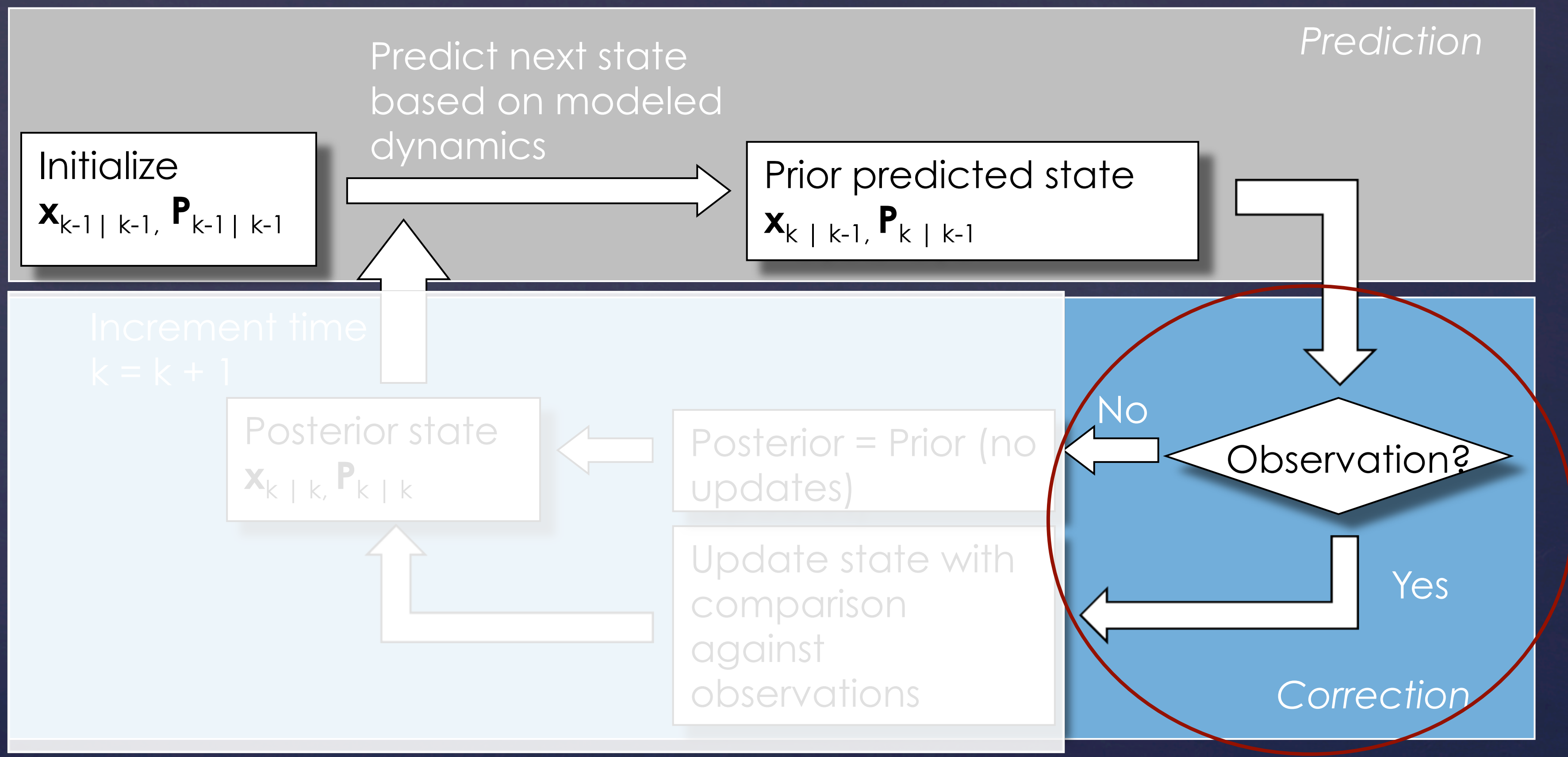
$$\text{additional melt water}_{k\text{-}1} = \sum_{\text{land ice}} \text{normalized fingerprints} \times \text{melt rate}_{k\text{-}1}$$

Normalized sea-level fingerprints

Each ice sheet and mountain glacier is modeled as an AR(1) process:

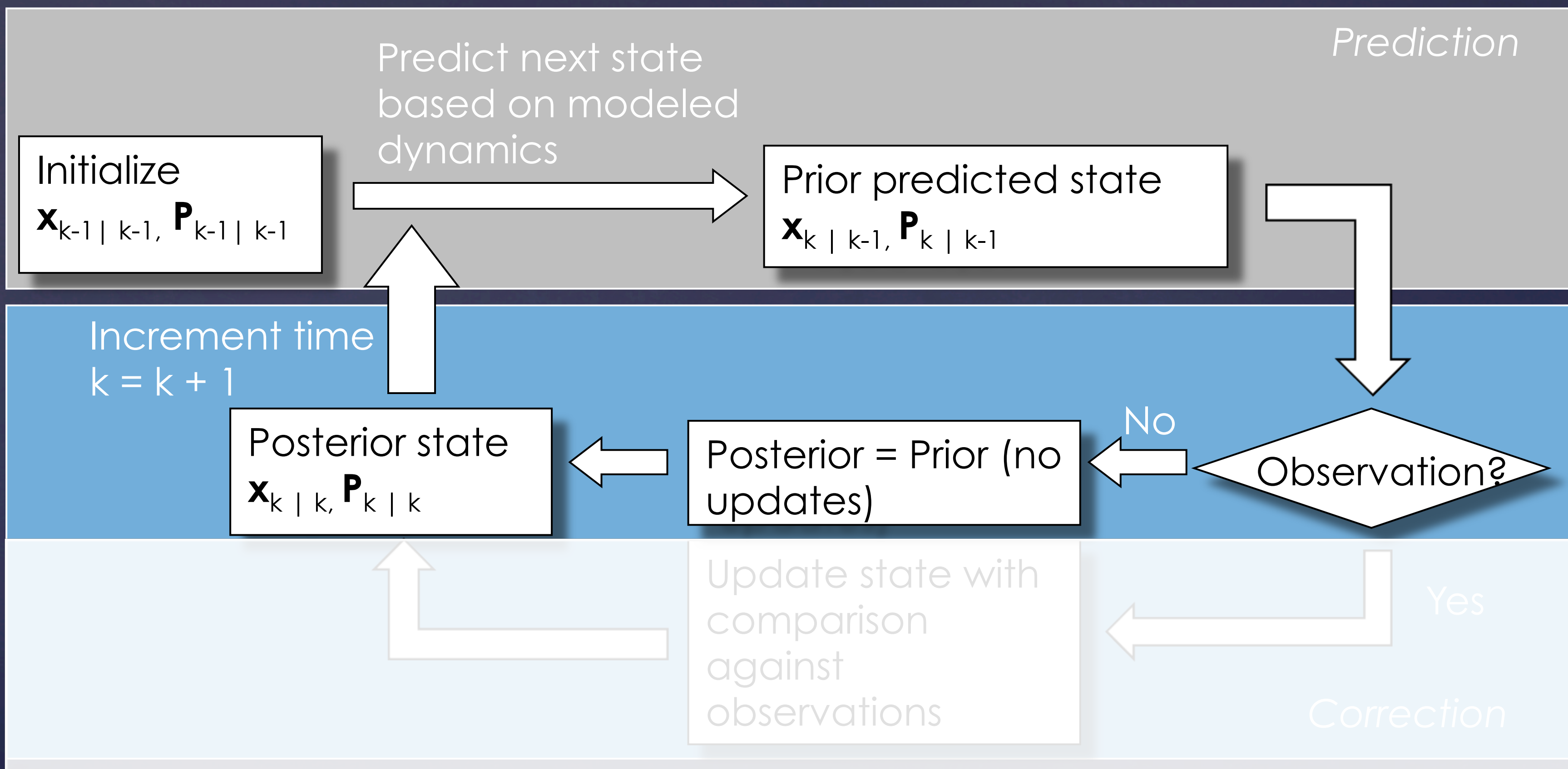
$$\text{melt rate}_k = \varrho \times \text{melt rate}_{k\text{-}1} + \text{noise}$$

Kalman Filter

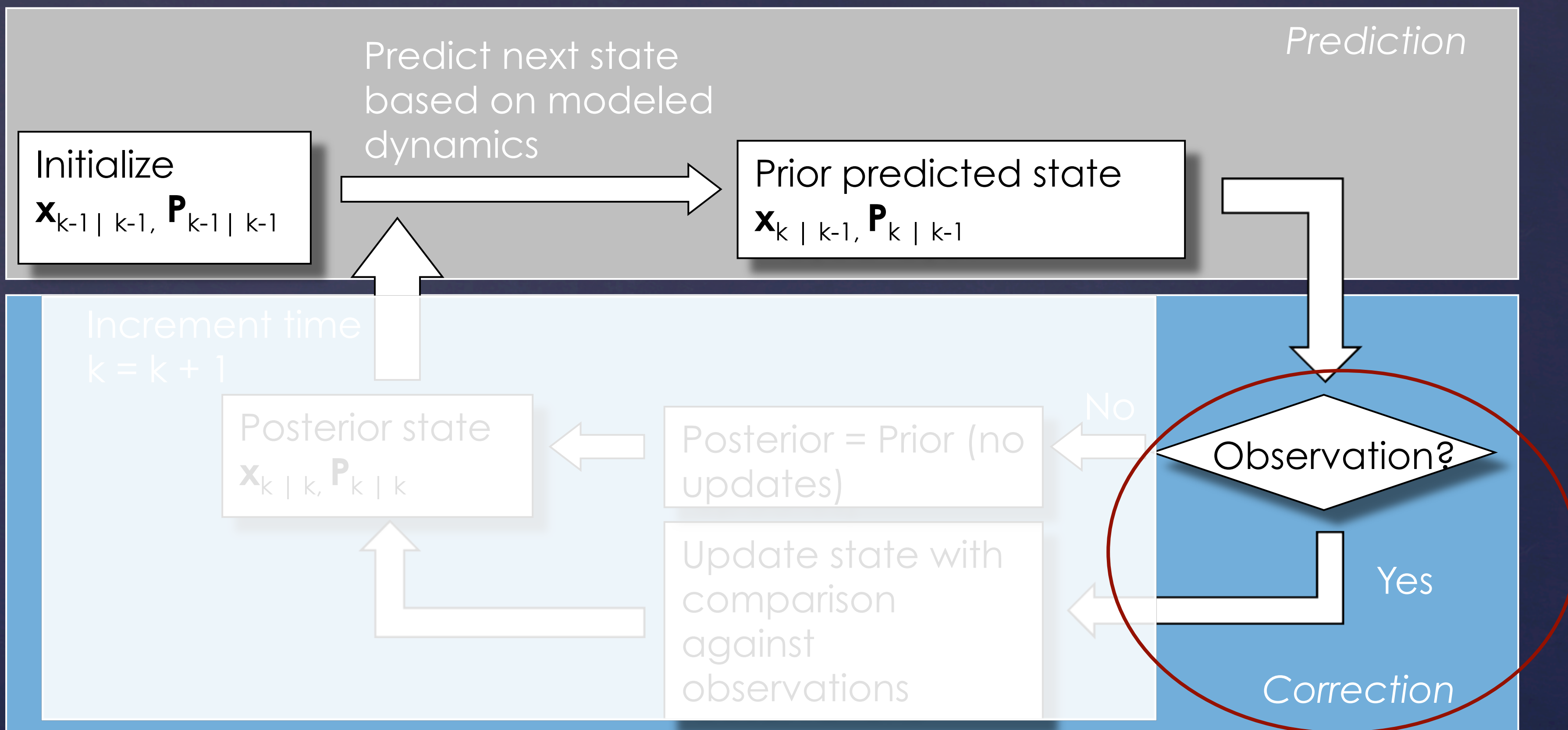


Kalman Filter

Option 1: No observations

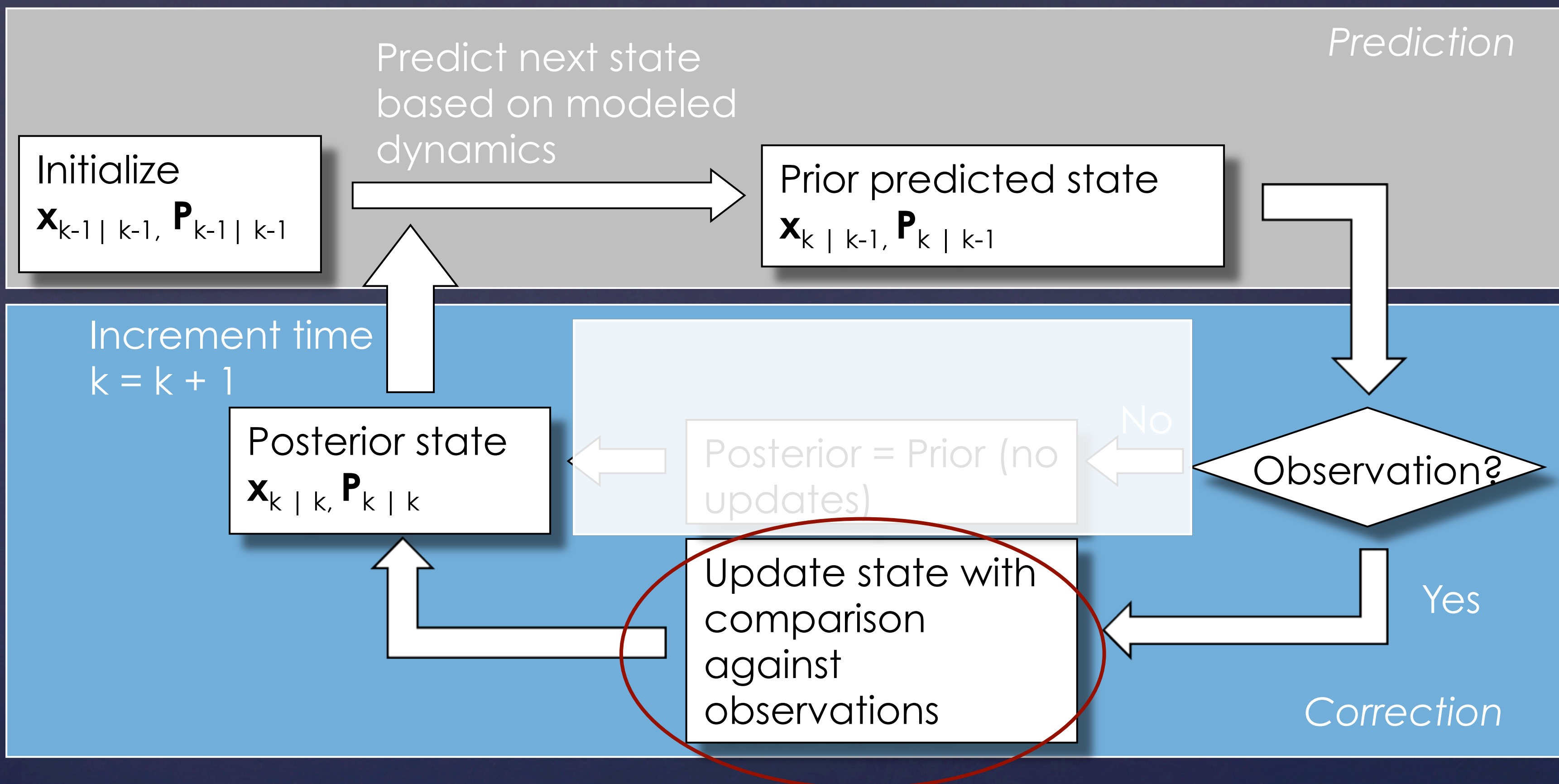


Kalman Filter



Kalman Filter

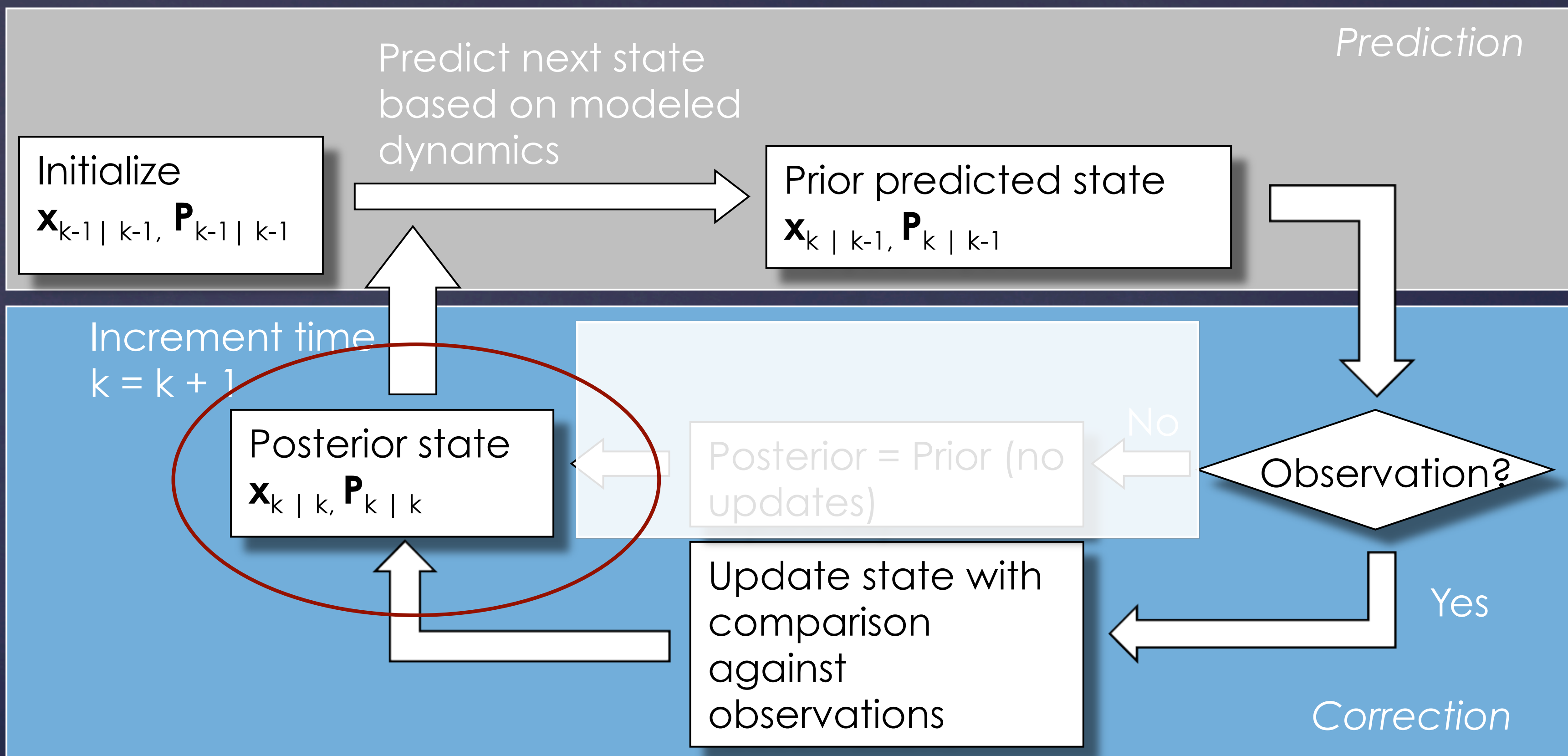
Correction Step



When we get new data, our state vector (sea level and melt rates) should change slightly to refine our current model.

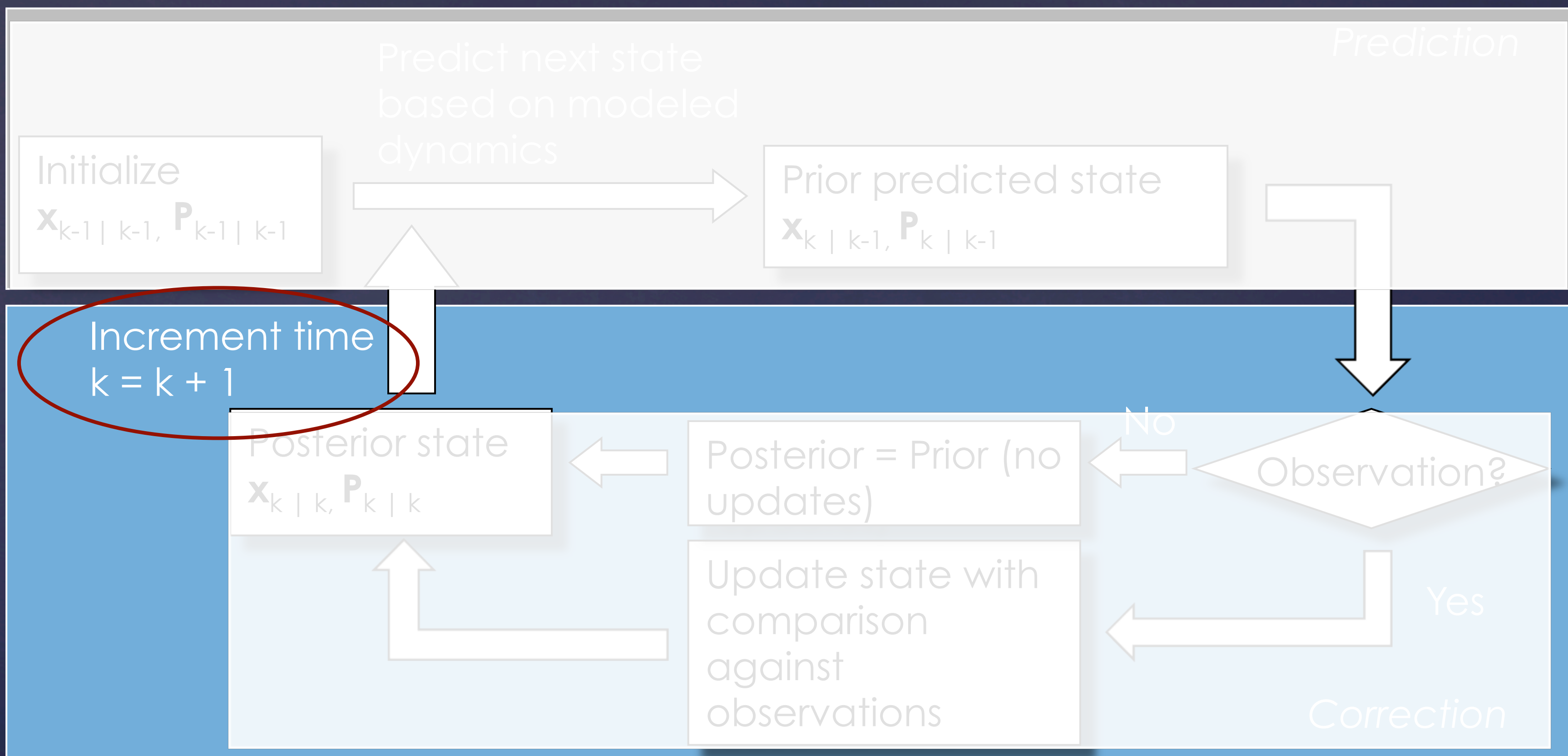
Kalman Filter

Correction Step



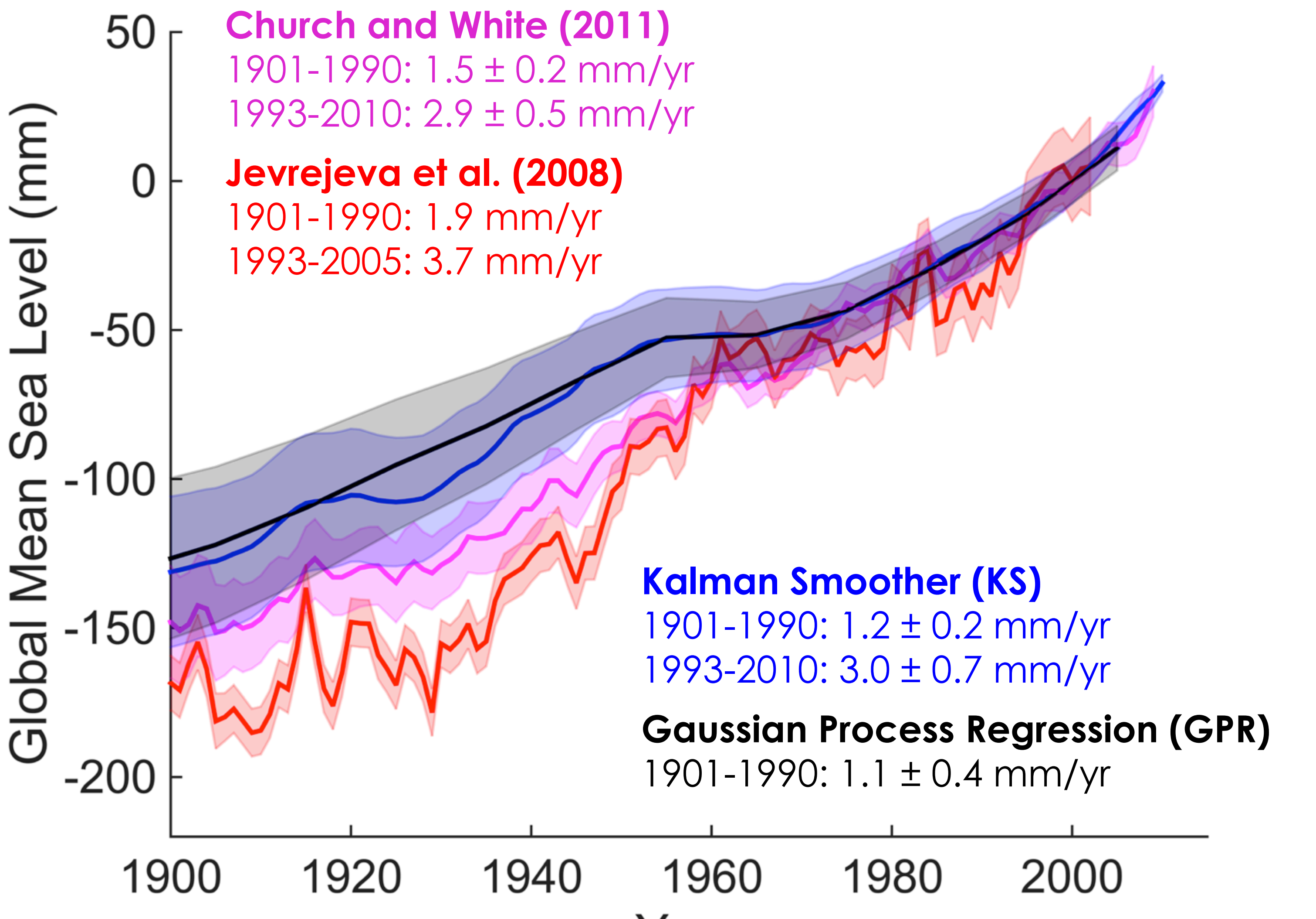
The result is a new state estimate that lies between the predicted and measured state, and has a better estimated uncertainty than either alone.

Kalman Filter



Step forward in time to make of a new prediction on the evolution of the state

Global Mean Sea Level



Hay et al., *Nature* (2015).

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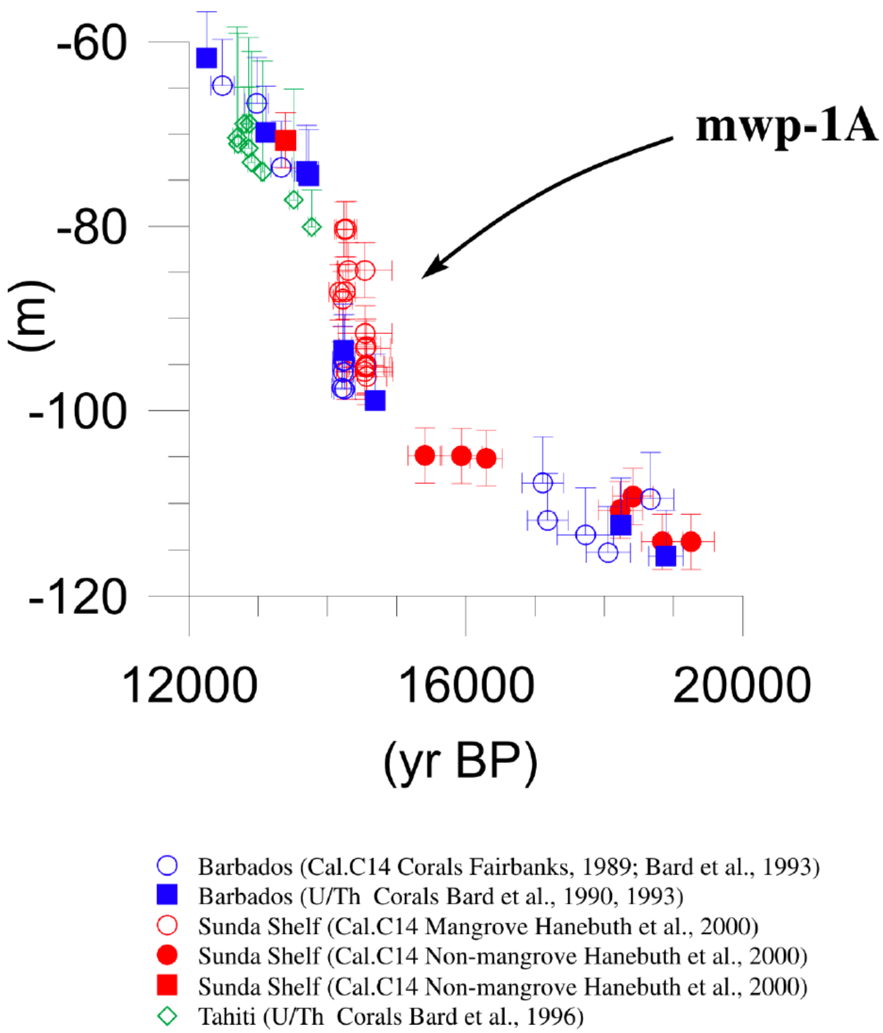
Meltwater Pulse 1A

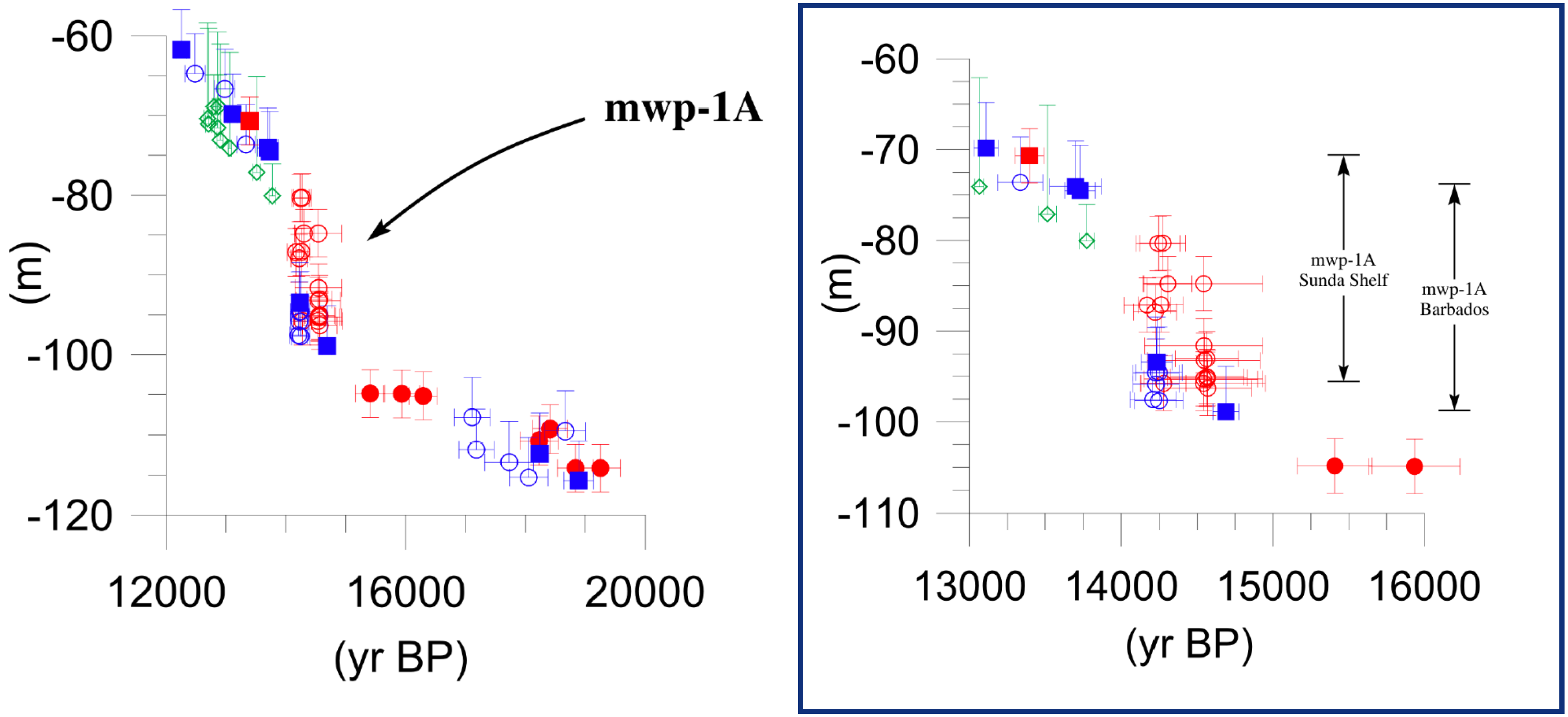


~ 15 meters of sea-level rise is < 350 years
(Deschamps et al. 2012)

Source(s) of mwp-1A???

Clark et al. (Science, 2002)

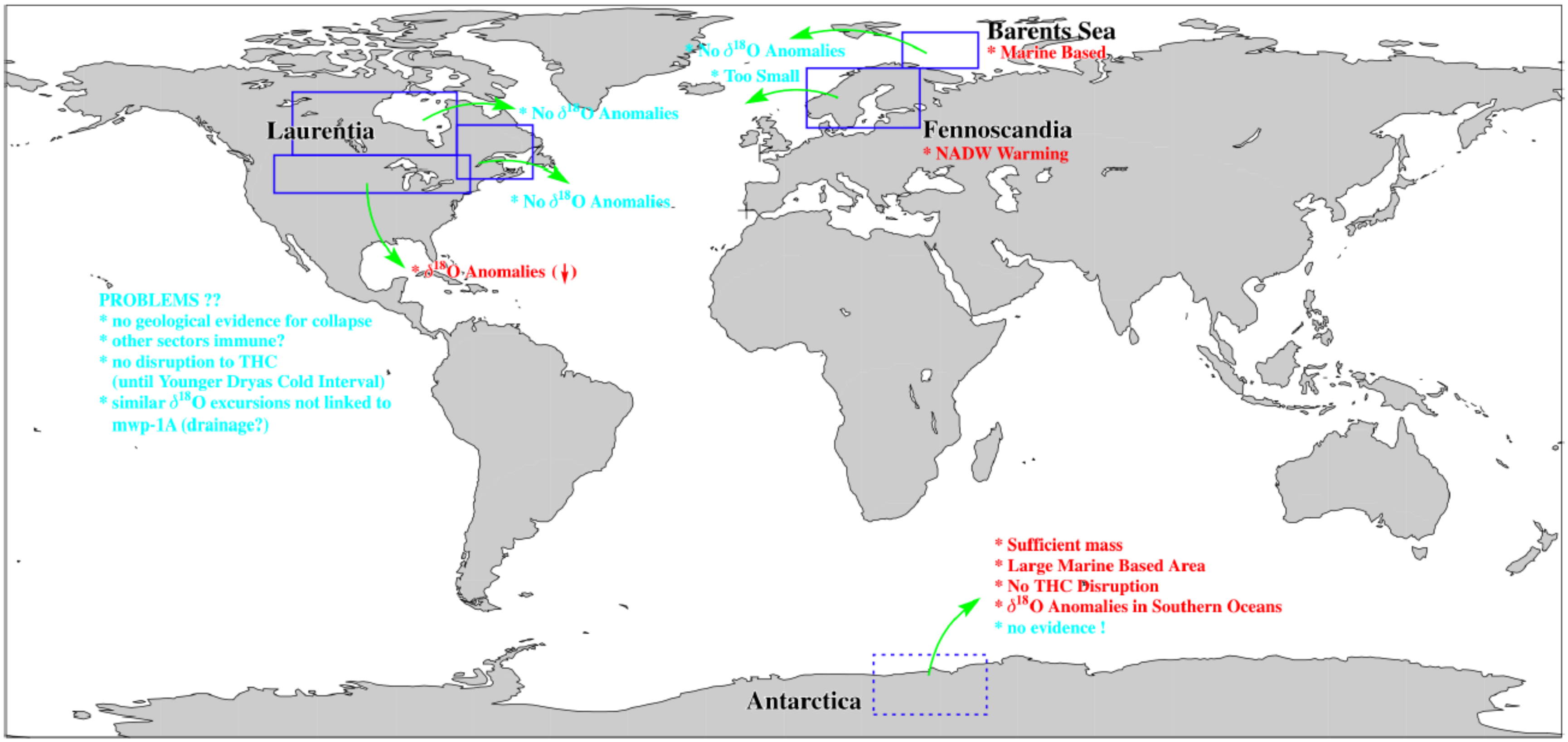
Meltwater Pulse 1A



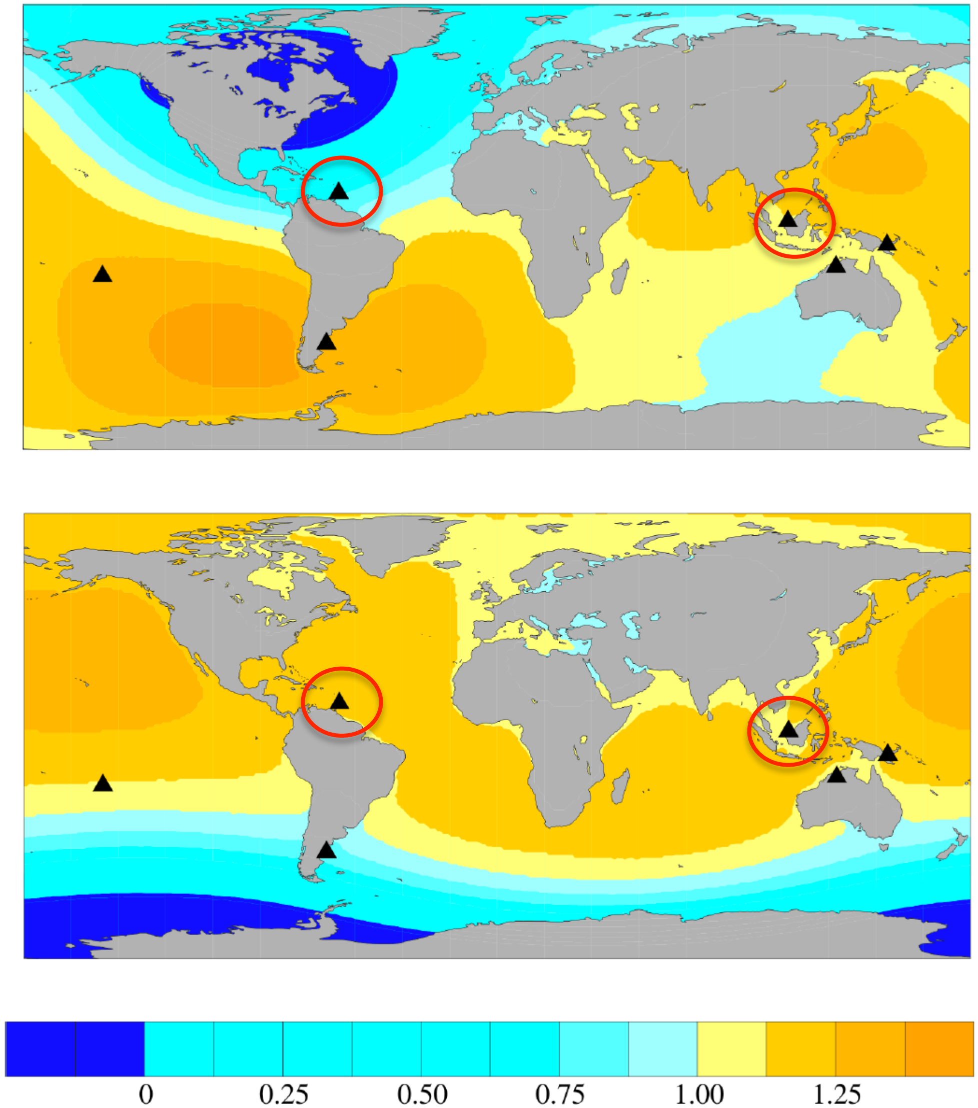
- ○ Barbados (Cal.C14 Corals Fairbanks, 1989; Bard et al., 1993)
- ■ Barbados (U/Th Corals Bard et al., 1990, 1993)
- ○ Sunda Shelf (Cal.C14 Mangrove Hanebuth et al., 2000)
- ● Sunda Shelf (Cal.C14 Non-mangrove Hanebuth et al., 2000)
- ■ Sunda Shelf (Cal.C14 Non-mangrove Hanebuth et al., 2000)
- ◇ Tahiti (U/Th Corals Bard et al., 1996)

Meltwater Pulse 1A

Possible melt scenarios:



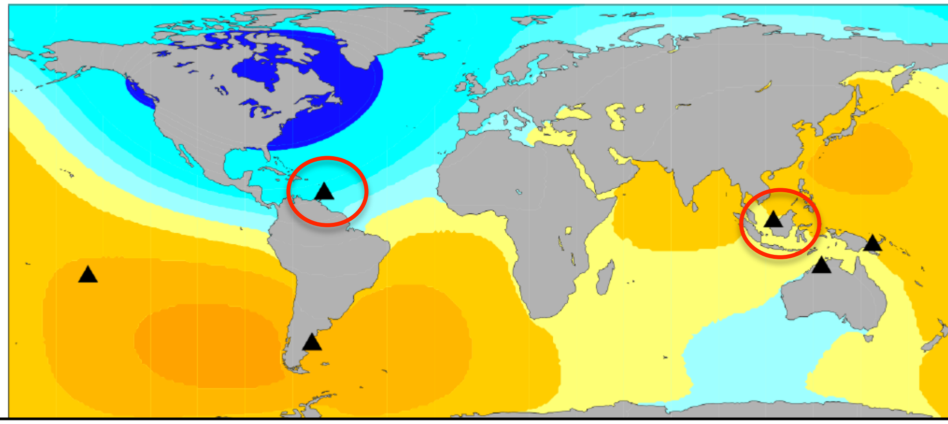
Meltwater Pulse 1A



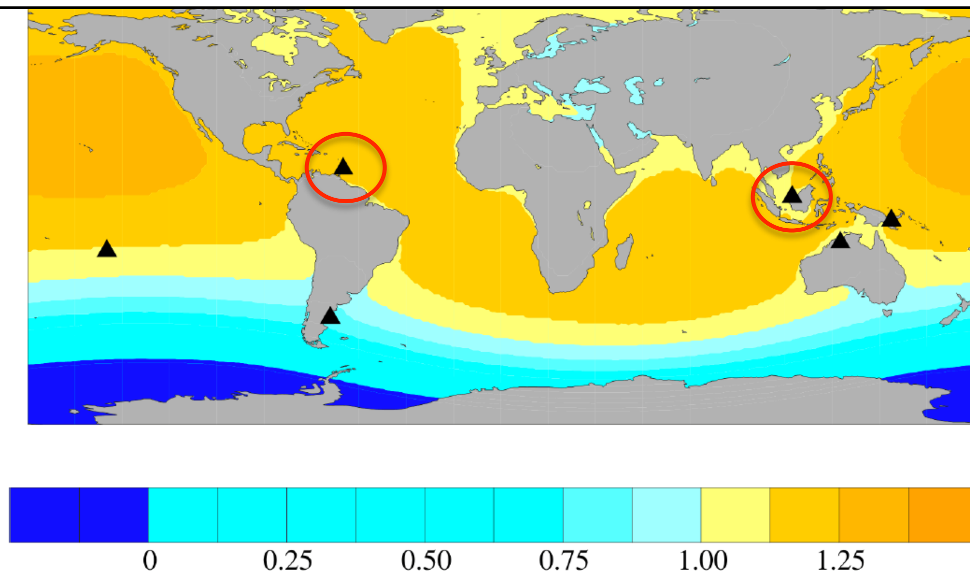
Southern Laurentian Source

West Antarctic Source

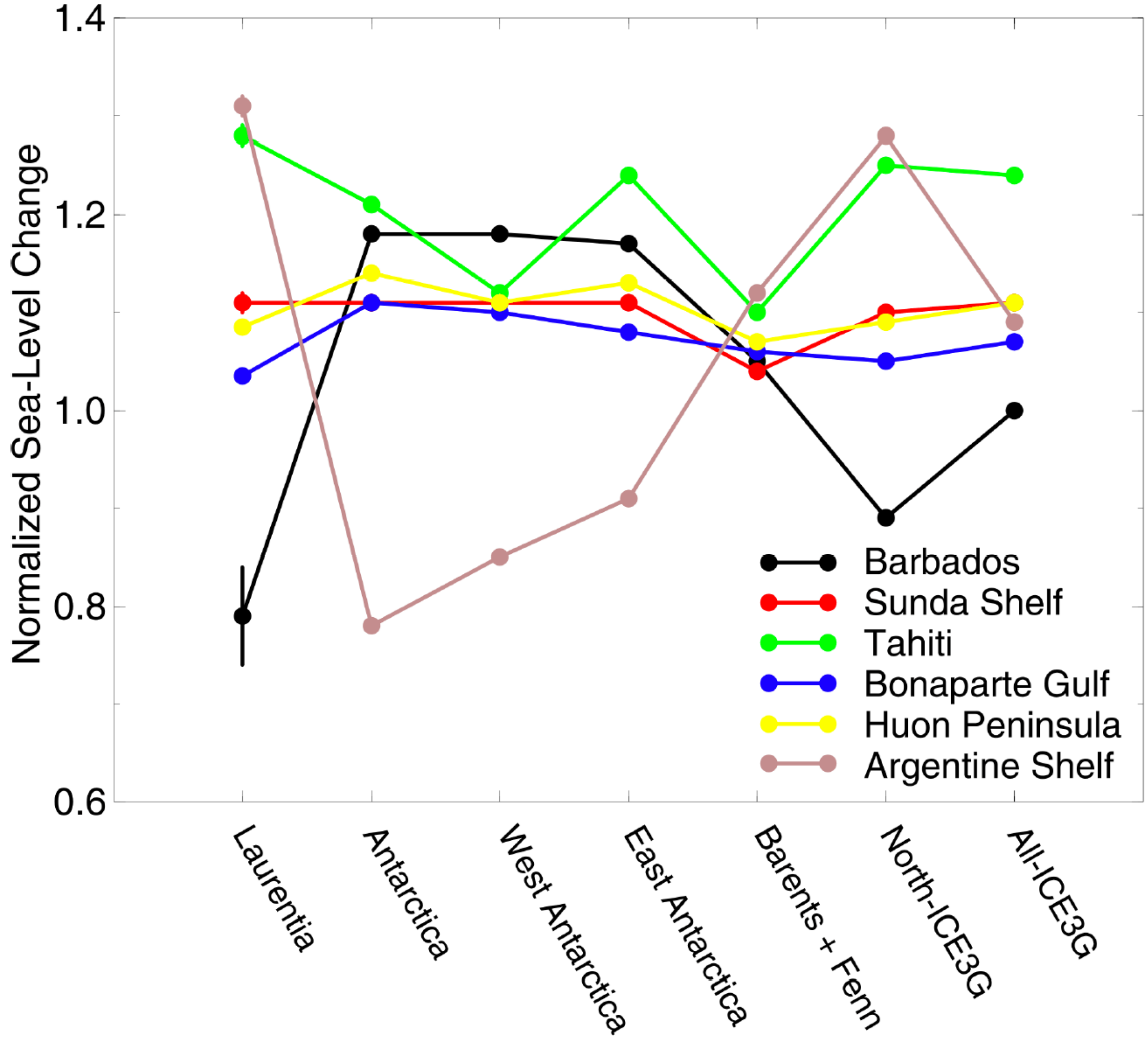
Meltwater Pulse 1A



… but Antarctic ice sheet modeling studies suggest that Antarctica contributed ~4-8 meters over the whole deglaciation. (e.g. Whitehouse et al., 2012, Pollard & DeConto, 2009, Gomez et al., 2013)



Meltwater Pulse 1A



Meltwater Pulse 1A

Climate implications?

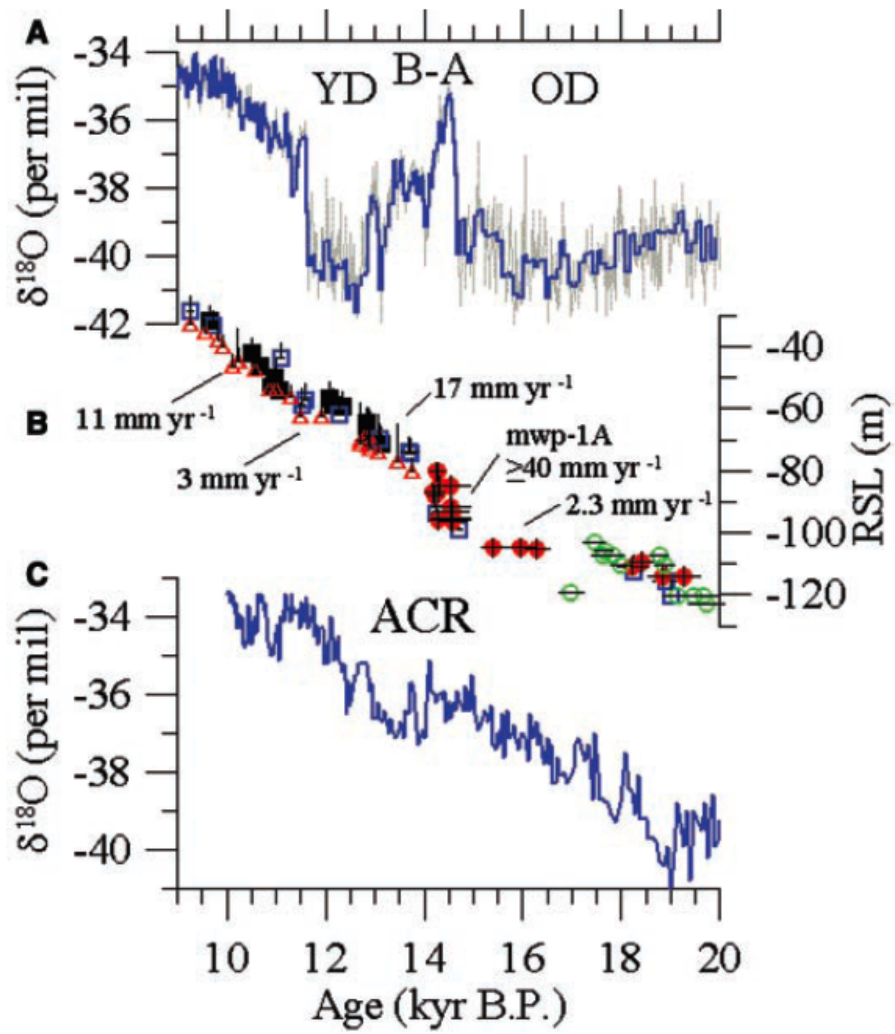
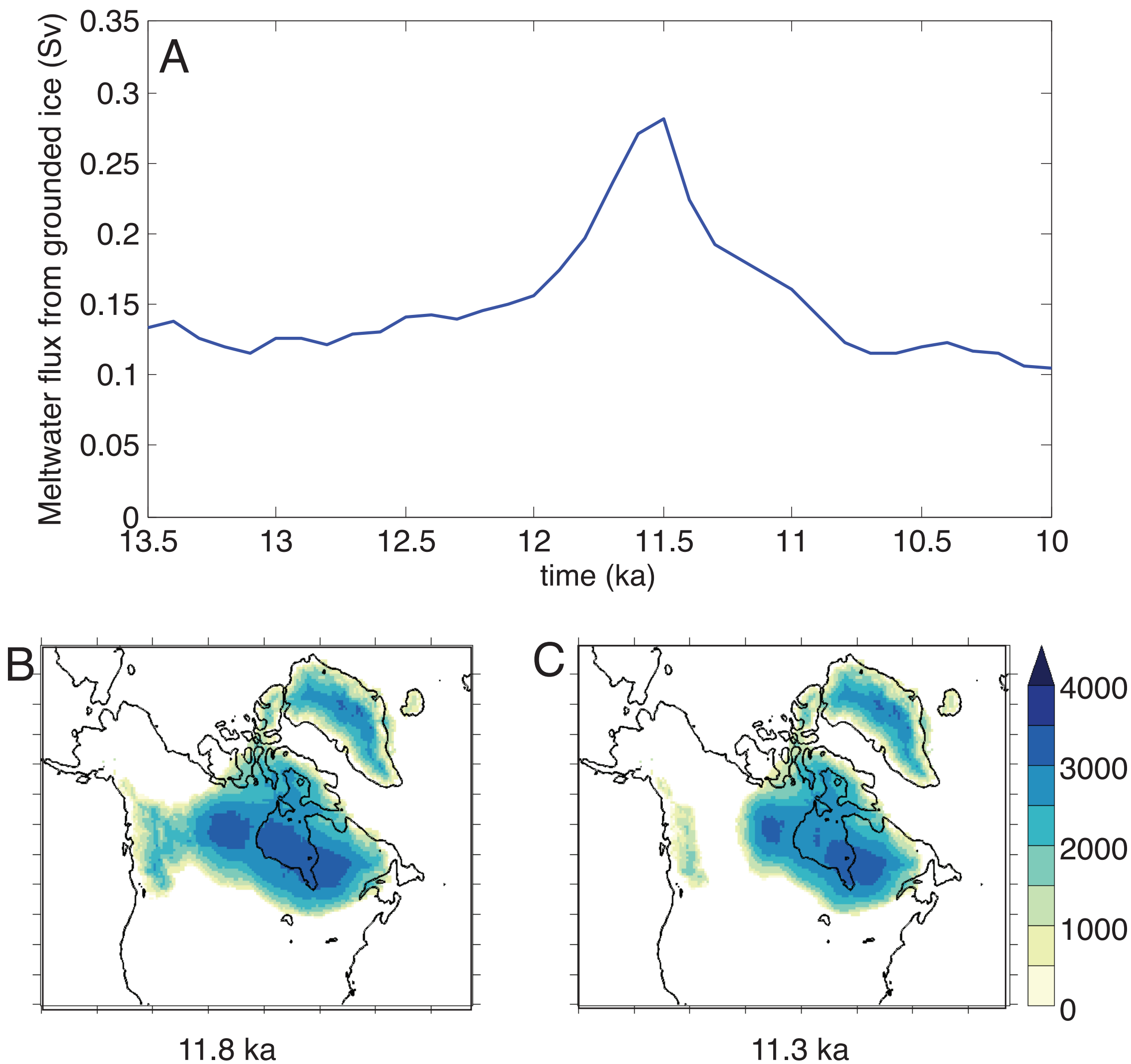


Fig. 5. Climate and sea-level records spanning the last deglaciation. (**A**) The Greenland Ice Sheet Project 2 (GISP2) oxygen isotope record (*40*, *41*). OD is the Oldest Dryas cold period, and YD is the Younger Dryas cold period. (**B**) Relative sea-level (RSL) records from far-field sites. Also shown are average rates of sea-level rise for the periods 19 to 14.6, 14.6 to 14.1, 14.1 to 12.9, 12.9 to 11.6, and 11.6 to 6 kyr B.P. Data are from Bonaparte Gulf (green open circles) (*42*), Barbados U/Th dated corals (open blue squares) (*5*), Sunda Shelf (*9*), Tahiti (open red triangles) (*5*), and New Guinea (closed black squares) (*43*). (**C**) The Byrd ice-core oxygen isotope record on the GISP2 time scale (*34*). ACR is the Antarctic Cold Reversal.

Weaver at al. (Science, 2003)

Meltwater Pulse 1A

Saddle Collapse Associated with Meltwater Pulse 1A in the Gregoire et al. (2012) model

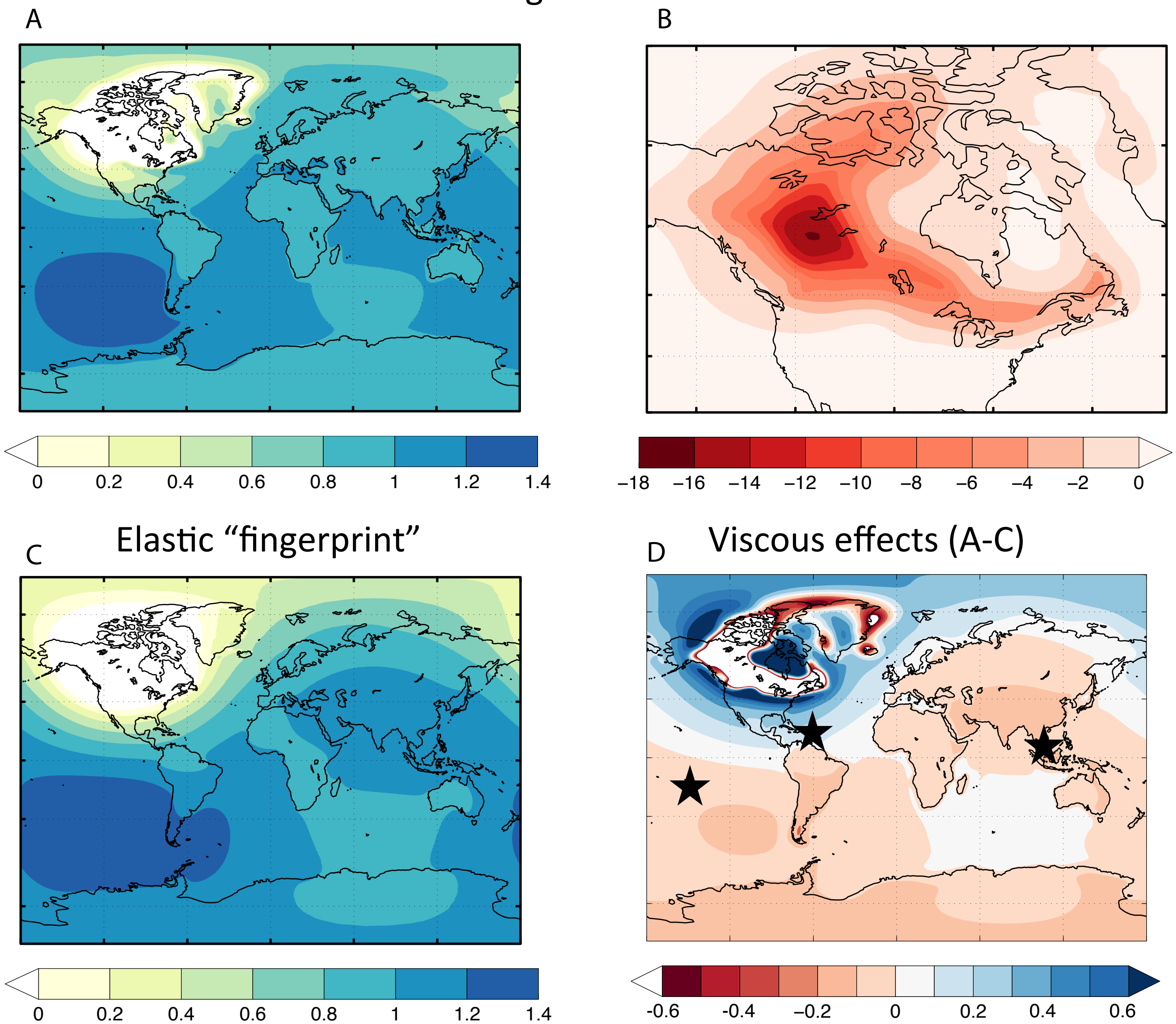


EEV =
10.5 meters

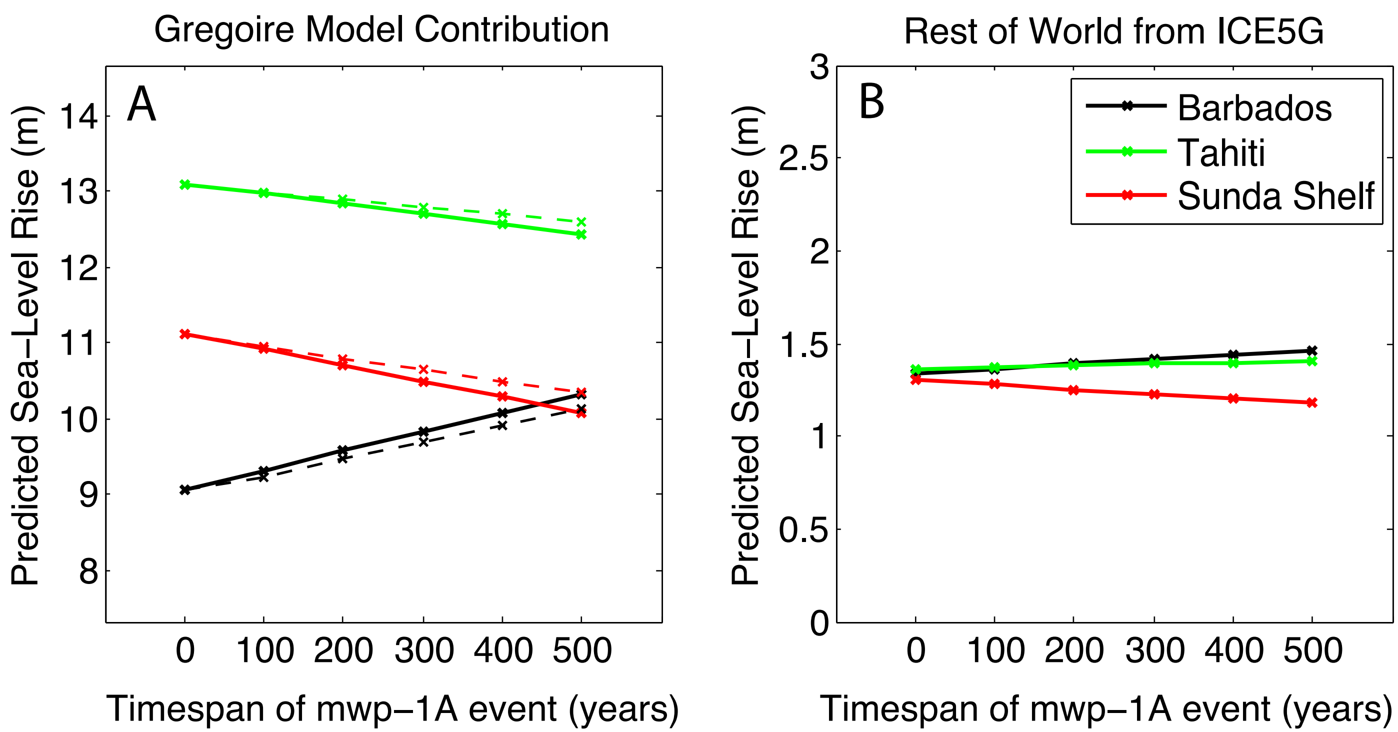
Meltwater Pulse 1A

Normalized sea-level change across the 500 yr mwp-1A time window

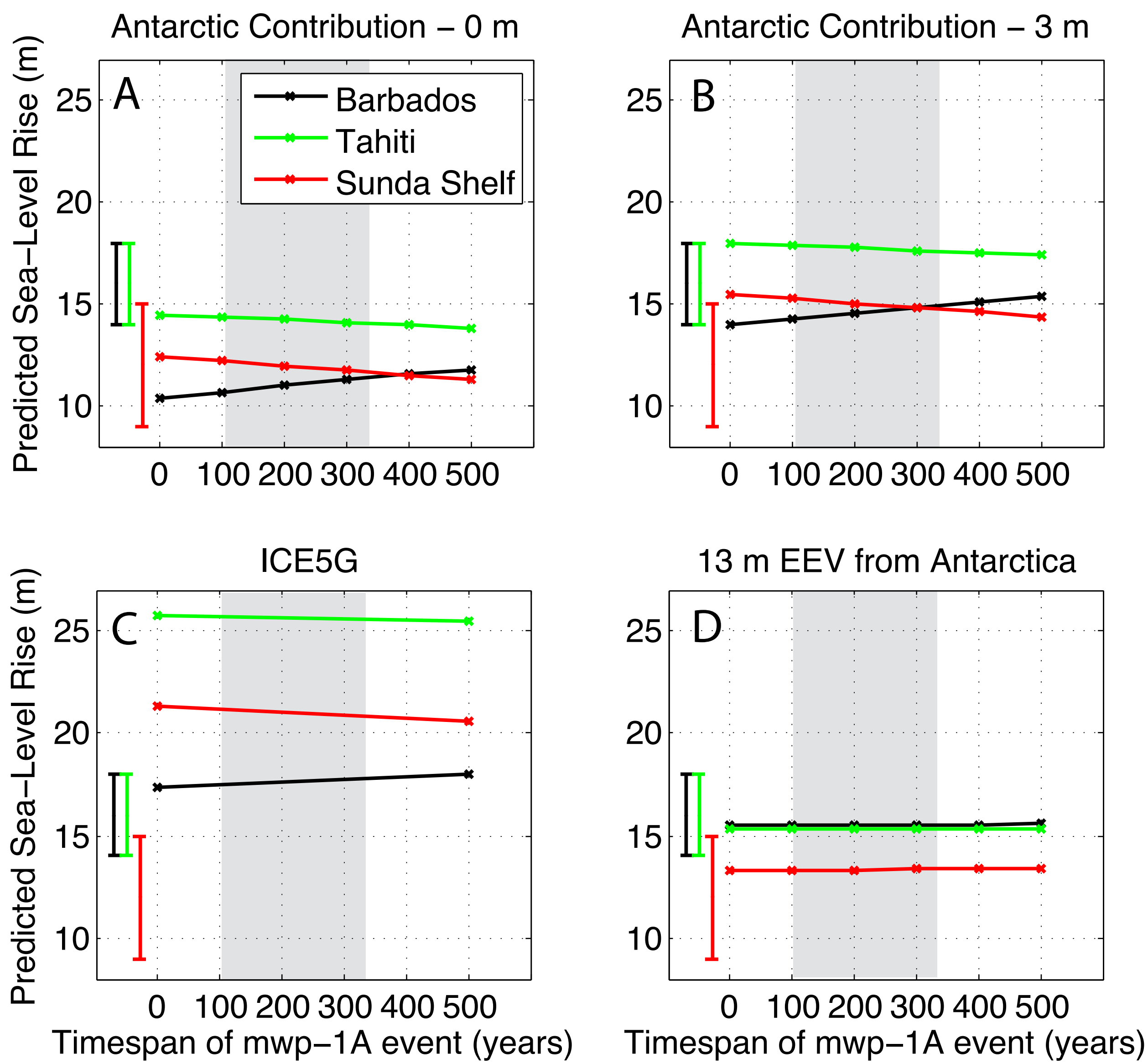
Calculated using a viscoelastic Earth model



Meltwater Pulse 1A

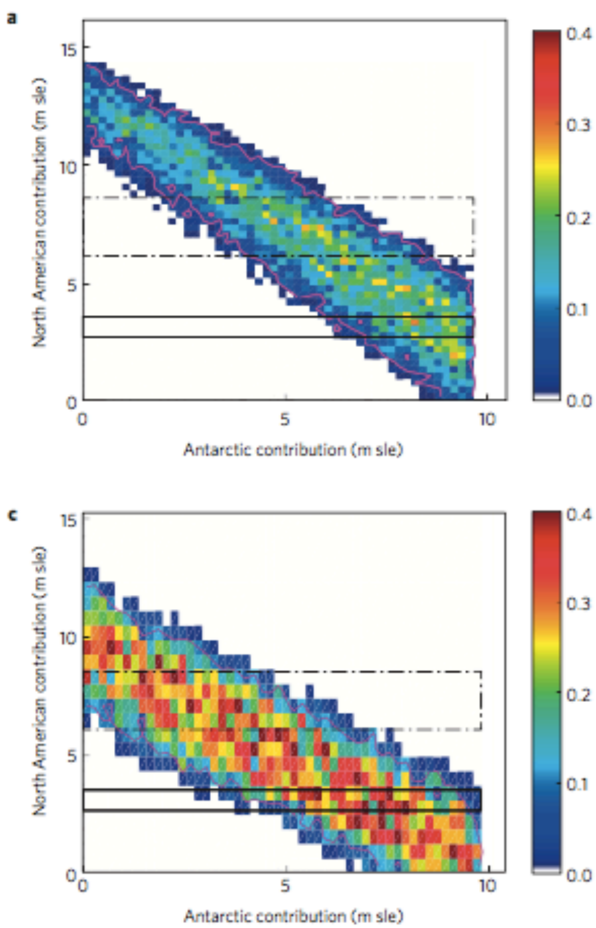


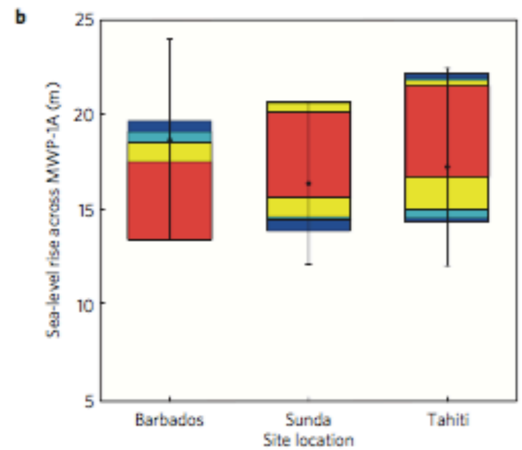
Meltwater Pulse 1A



Meltwater Pulse 1A

LETTERS NATURE GEOSCIENCE DOI: 10.1038/NGEO2616





Liu et al. (2015)

Note: there exists a large body of literature on the climate and ice dynamics associated with MWP-1A

Figure 3 | Posterior distribution of NAIS and AIS sea-level contributions conditioned
far-field MWP-1A amplitude estimates[1–3] (**a**) and for our revised amplitude estimates
magenta contour indicates the central 95% credible range. The black outlines indicate
near-field evidence: 2.8–3.7 m sle (solid line; ref. 11) and 6.4–9.0 m sle (dashed-dotted
the considered far-field sites (thin vertical bars) corresponding to **a** and **c**, respectively,
by scenarios that satisfy all far-field constraints. Cyan, yellow and red bars show the 9
(minimum to maximum) is represented by the dark blue bars. Note that the model-co
not visible.

Our analysis conclusively demonstrates that, when data and model uncertainties are carefully accounted for, the presently available far-field rsl reconstructions do not provide tightly bounded constraints on MWP-1A partitioning: specifically, the 95% credible AIS contribution to MWP-1A is 0–10.0 m sle when recent estimates of the NAIS contribution are considered[11,12]. Accordingly, our reassessment indicates that a significant AIS contribution may not be required, thus potentially reconciling the apparent inconsistency between near-field[10] and far-field evidence. At the same time, however, our results suggest that a dominant AIS contribution remains equally plausible. We note that any future improvements on the total NAIS contribution can be directly applied to our AIS–NAIS partitioning diagram (Fig. 3c) and anticipate that the approach taken here will provide the means to further constrain the source regions of MWP-1A as more geologic evidence becomes available. At present, uncertainty in the source distribution of MWP-1A remains a primary limitation in our understanding of the causes and consequences of this extreme event.

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Archaeological evidence for recent acceleration in sea level rise

Sea level in Roman time in the Central Mediterranean and implications for recent change

Kurt Lambeck[a,*], Marco Anzidei[b], Fabrizio Antonioli[c], Alessandra Benini[d], Alessandra Esposito[b]

[a] Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy
[c] ENEA, via Anguillarese 301, S. Maria di Galeria, 00060 Rome, Italy
[d] Deparment of World's Ancient Sciences, University of Tuscia, Viale Università, 01100 Viterbo, Italy

Earth and Planetary Science Letters 224 (2004) 563–575

Fish tanks (Piscinae) (generally carved directly in rock) used at the end of 2nd century and early 1st century BC

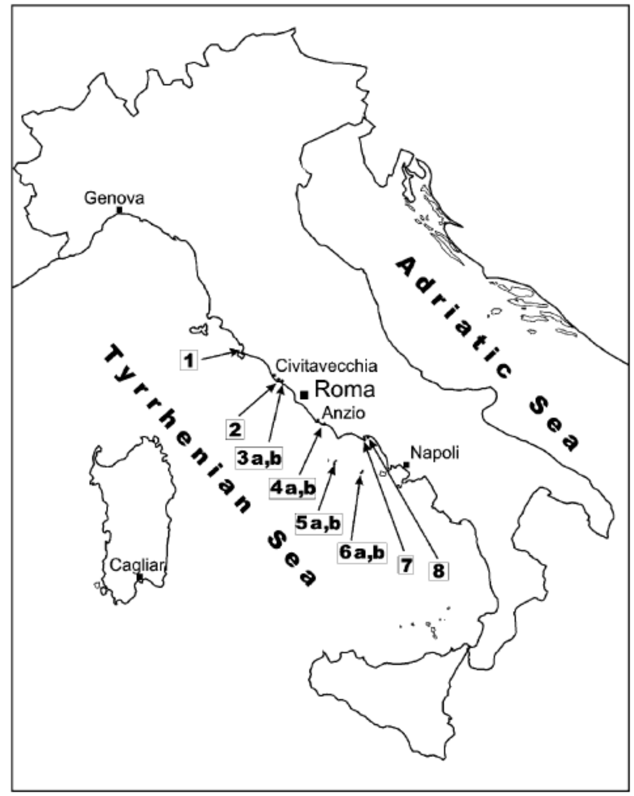
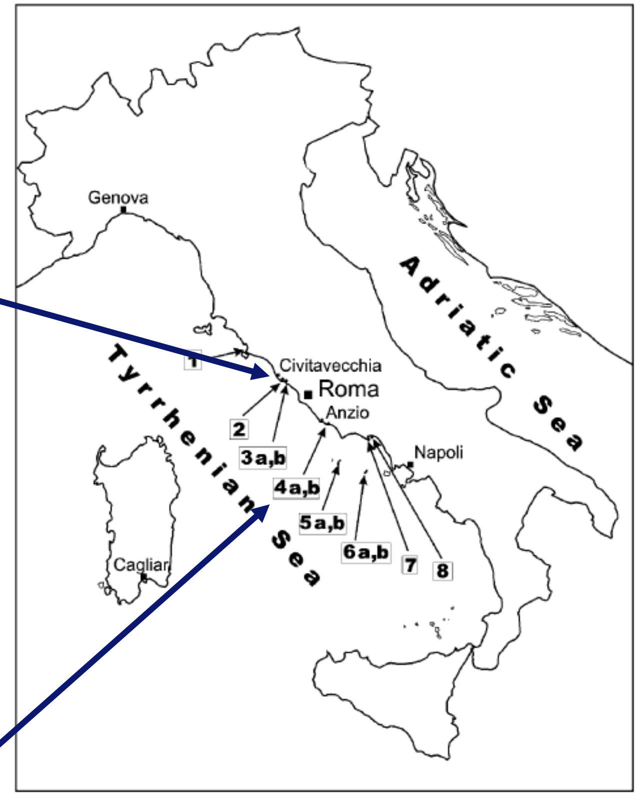


Fig. 1. Location map of the Roman epoch piscinae and tide-gauge sites along the central Tyrrhenian coast of Italy: (1) Santa Liberata, (2) Punta della Vipera, (3a) Santa Marinella Odescalchi, (3b) Santa Marinella Le Grottacce, (4a) La Banca, (4b) Torre Astura, (5a.b) Ponza (outdoor and indoor fish tank), (6a,b) Ventotene harbour and fish tanks, (7) Serapo and (8) Sarinola. The four tide gauge sites are located at Genoa, Civitavecchia, Naples and Cagliari.

Archaeological evidence for recent acceleration in sea level rise

B

A



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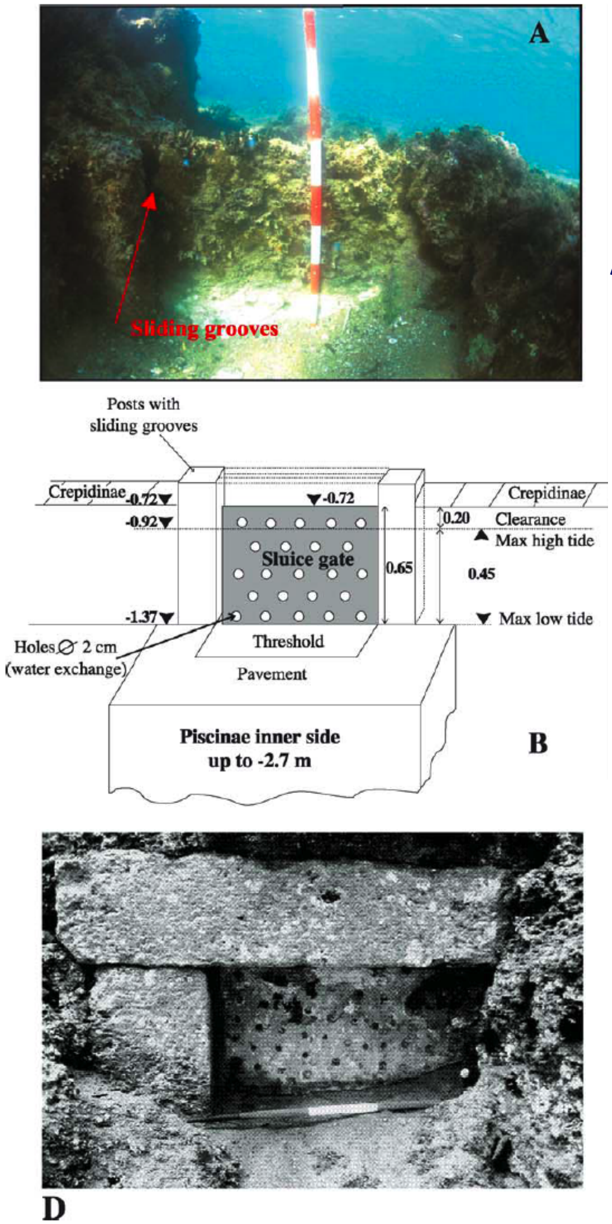
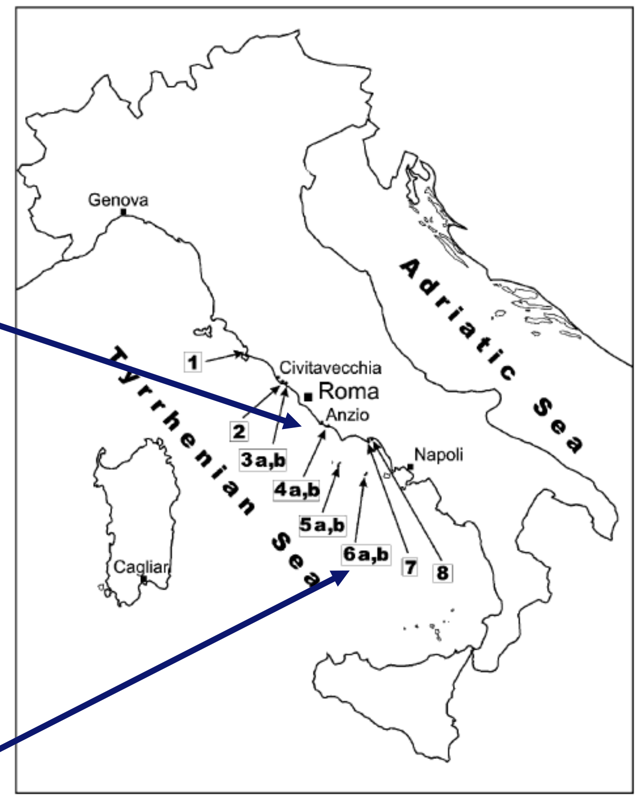
Archaeological evidence for recent acceleration in sea level rise





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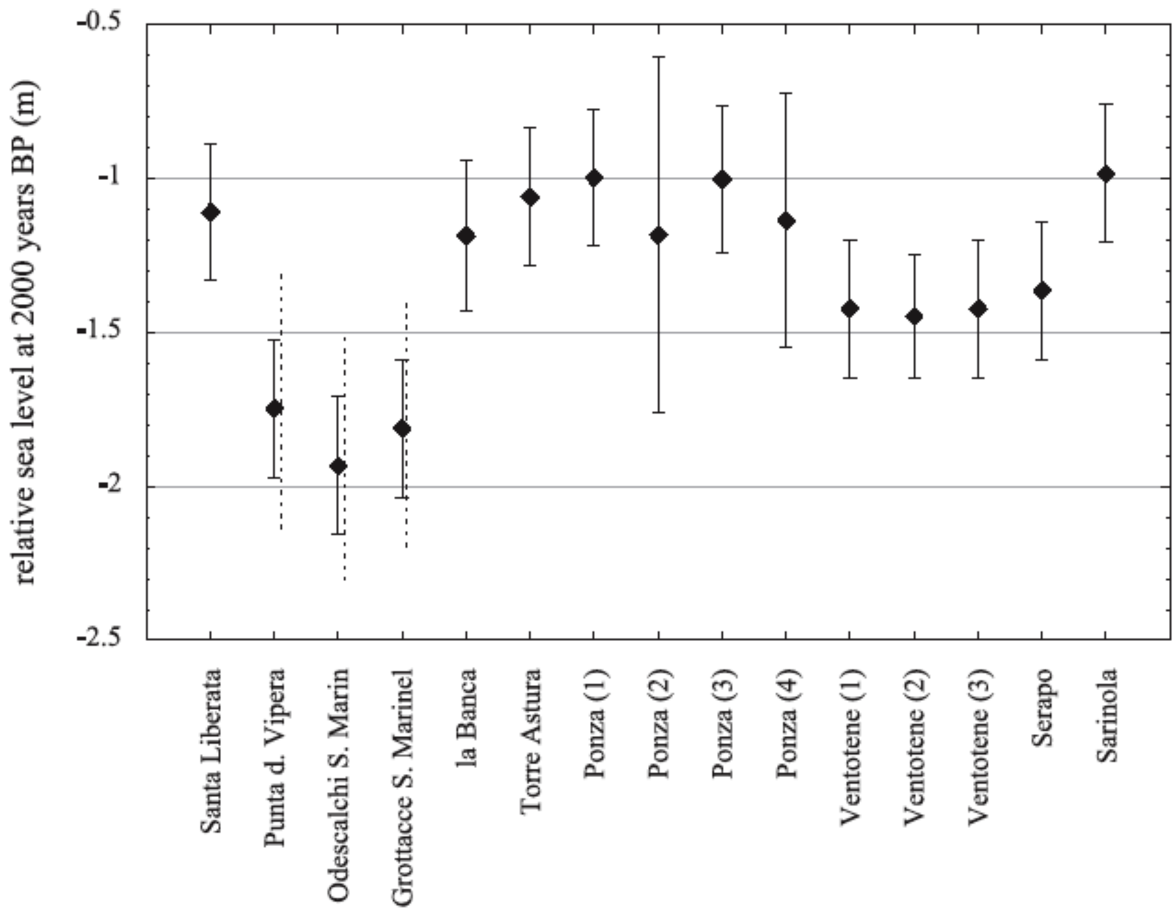
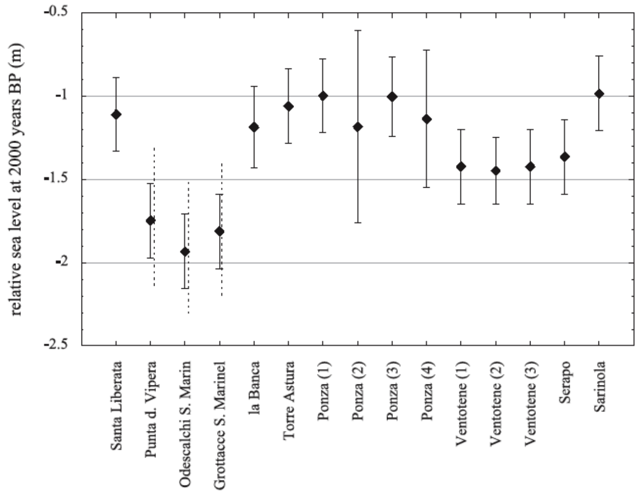
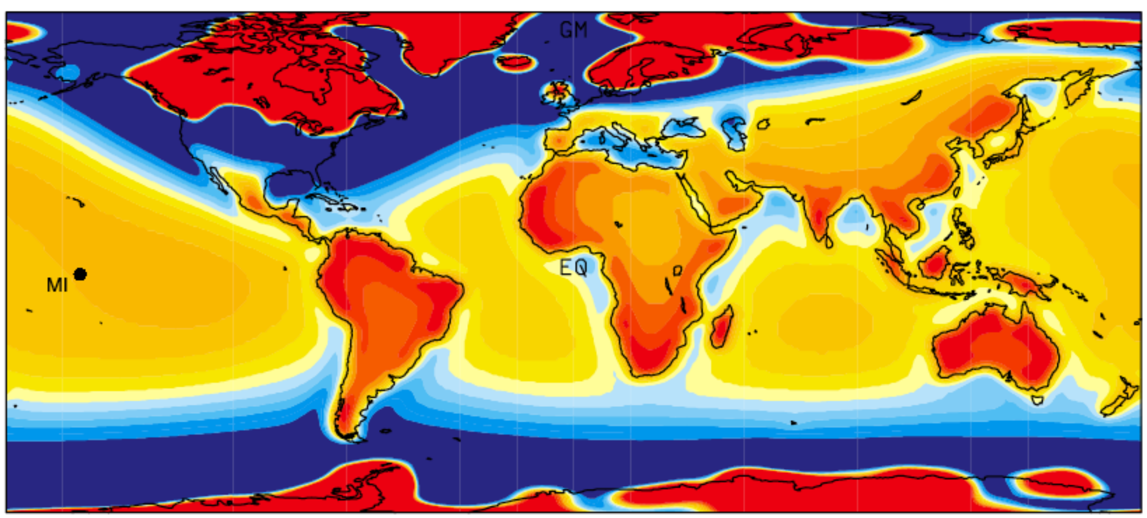


Average = -1.35m +/- 0.07m

Corrected for vertical tectonic movement

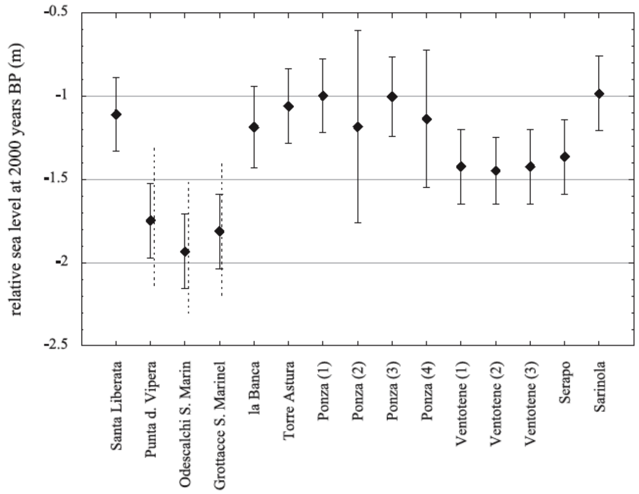
Archaeological evidence for recent acceleration in sea level rise



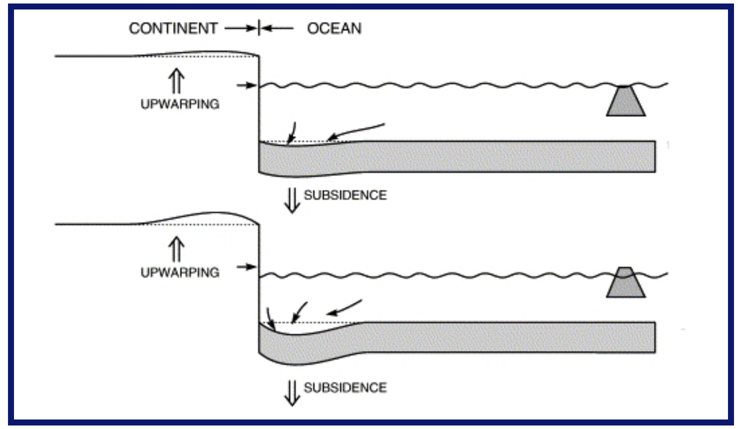


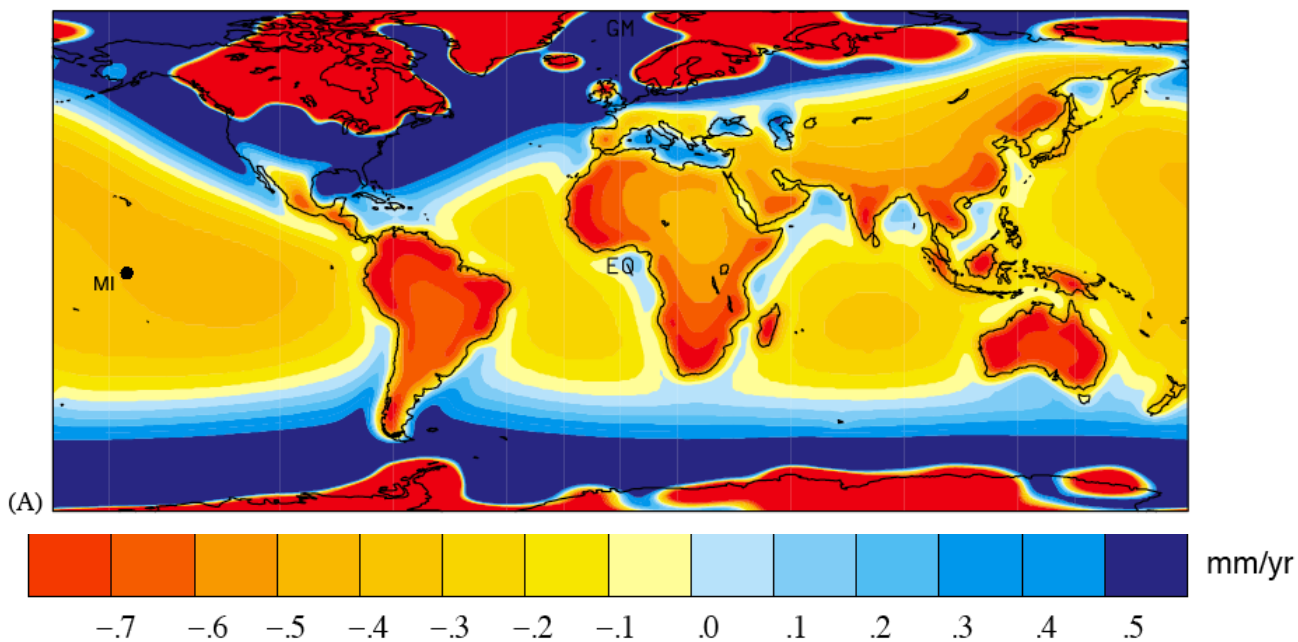
(A)

Archaeological evidence for recent acceleration in sea level rise



Dominated by continental levering!





Archaeological evidence for recent acceleration in sea level rise

Sea level in Roman time in the Central Mediterranean and implications for recent change

Kurt Lambeck[a,*], Marco Anzidei[b], Fabrizio Antonioli[c], Alessandra Benini[d], Alessandra Esposito[b]

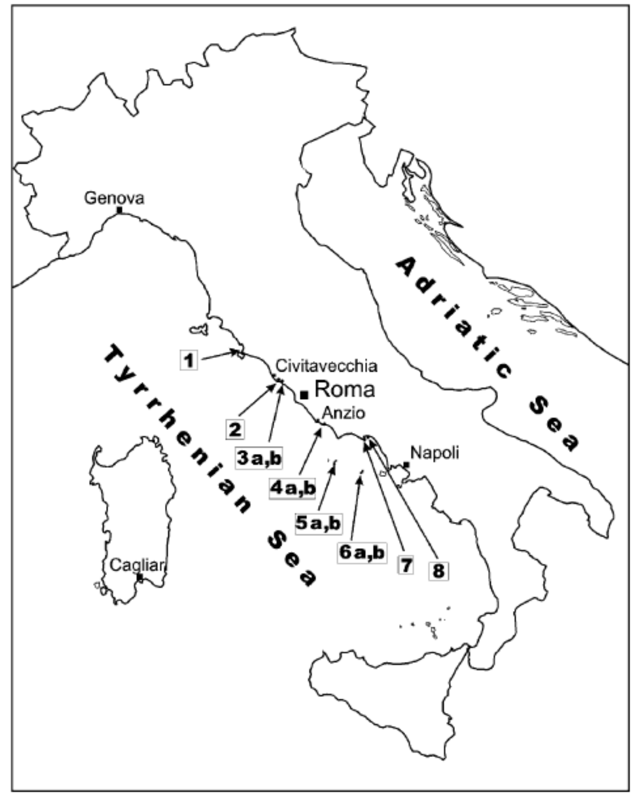
[a] Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy
[c] ENEA, via Anguillarese 301, S. Maria di Galeria, 00060 Rome, Italy
[d] Deparment of World's Ancient Sciences, University of Tuscia, Viale Università, 01100 Viterbo, Italy

Earth and Planetary Science Letters 224 (2004) 563–575

-1.37 +/- 0.07m → -0.13 +/- 0.09m

Relative sea-level of 2000 year old fish tanks

Correction for ice age effects



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Archaeological evidence for recent acceleration in sea level rise

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-1.37 +/- 0.07m → -0.13 +/- 0.09m

Conclude: little mass change of polar ice sheets in last 2000yrs!

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Outline

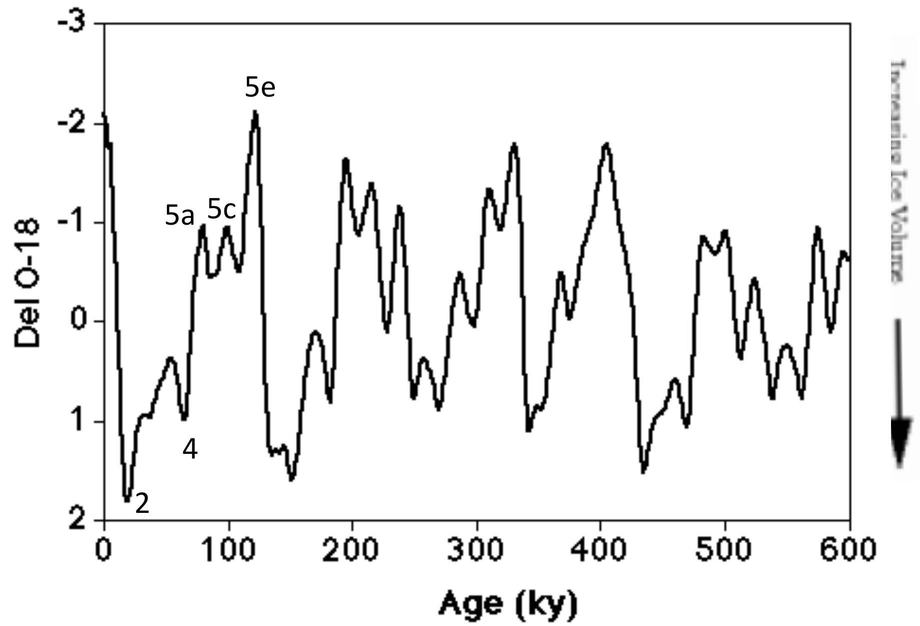
This Class: Sea Level Change Continued…

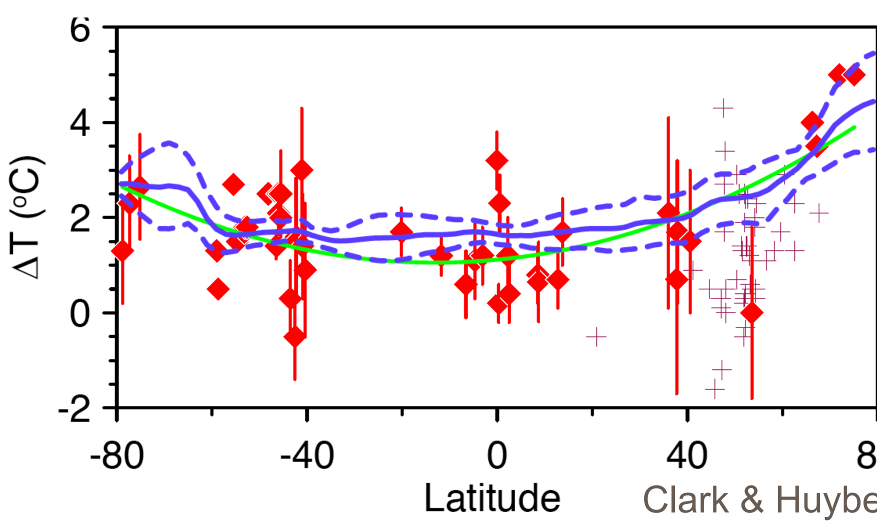
1. Sea level change and GIA on ice age timescales.

2. An Example Calculations

3. Applications
    1. Short timescale modern: 20^{th} 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

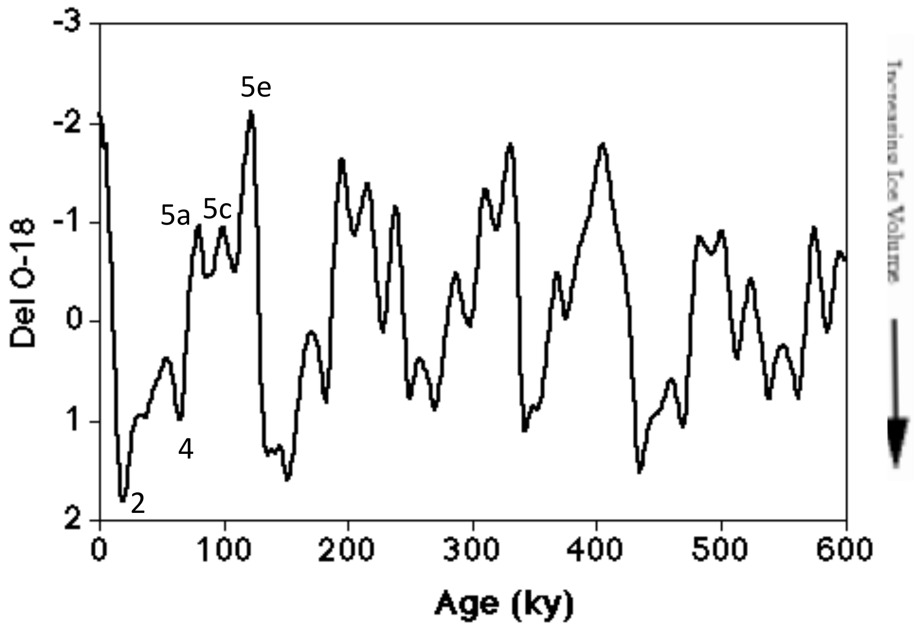


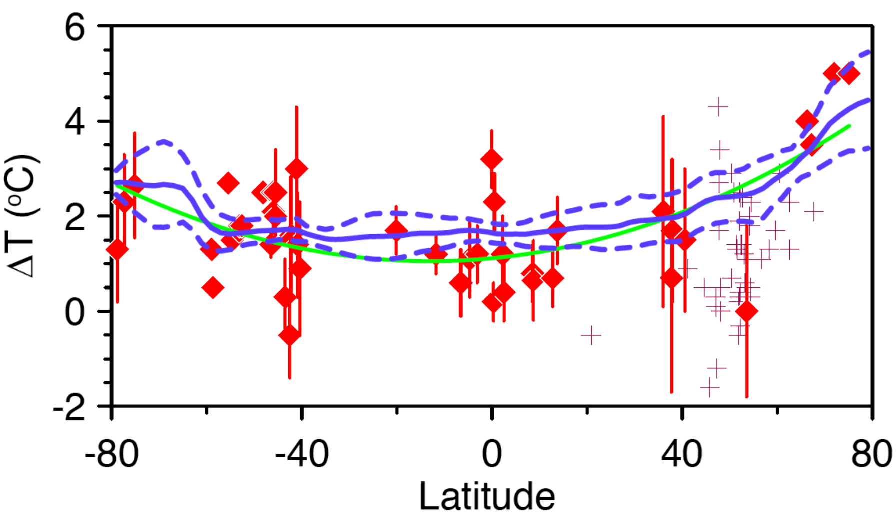


Clark & Huybers [2009]

- 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

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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

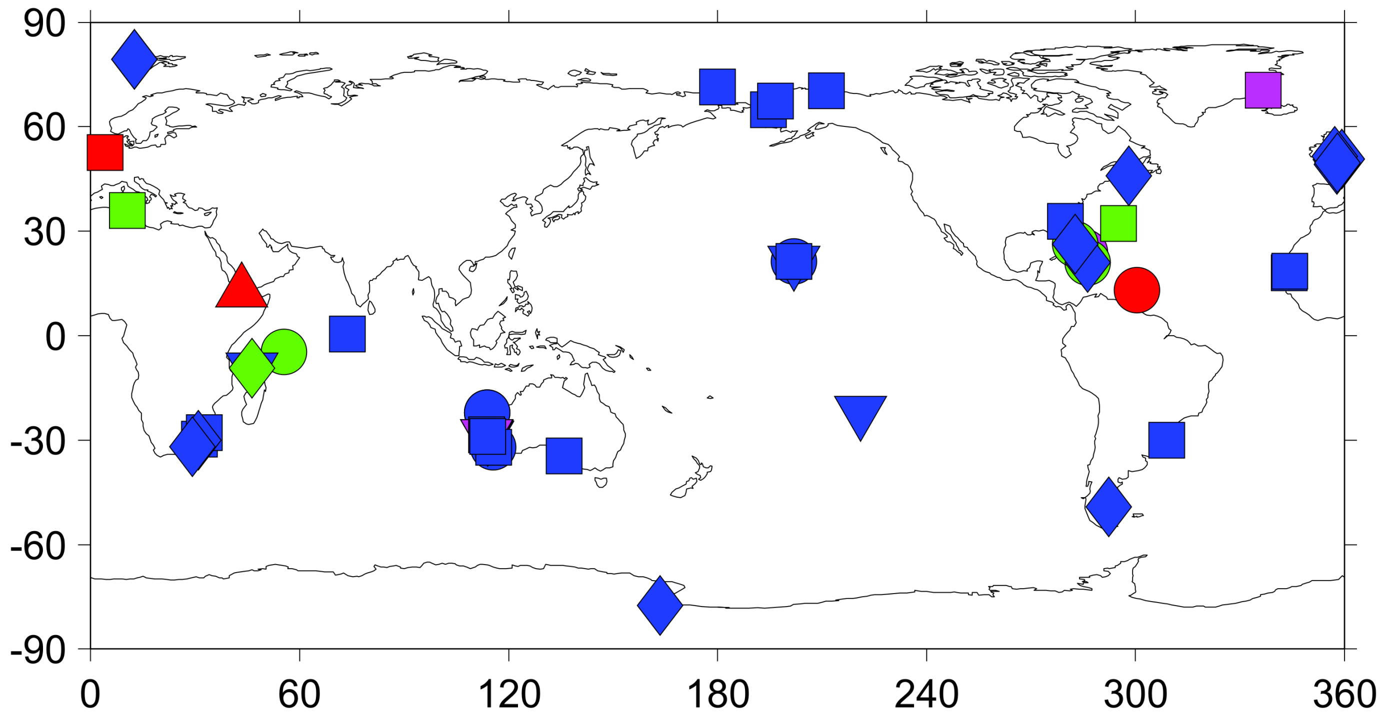


Figure 1 | Sites with at least one sea level observation in our database. The symbol shapes reflect the nature of the indicators (upward triangles, isotopic; circles, reef terraces; downward triangles, coral biofacies; squares, sedimentary facies and non-coral biofacies; diamonds, erosional). The colours 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

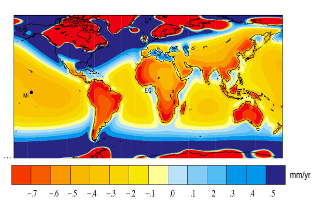
Statistical Method (Complicated)

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

Empirical "data covariance"

→ BAYESIAN FRAMEWORK → Posterior Probability Density Function of GSL(t)

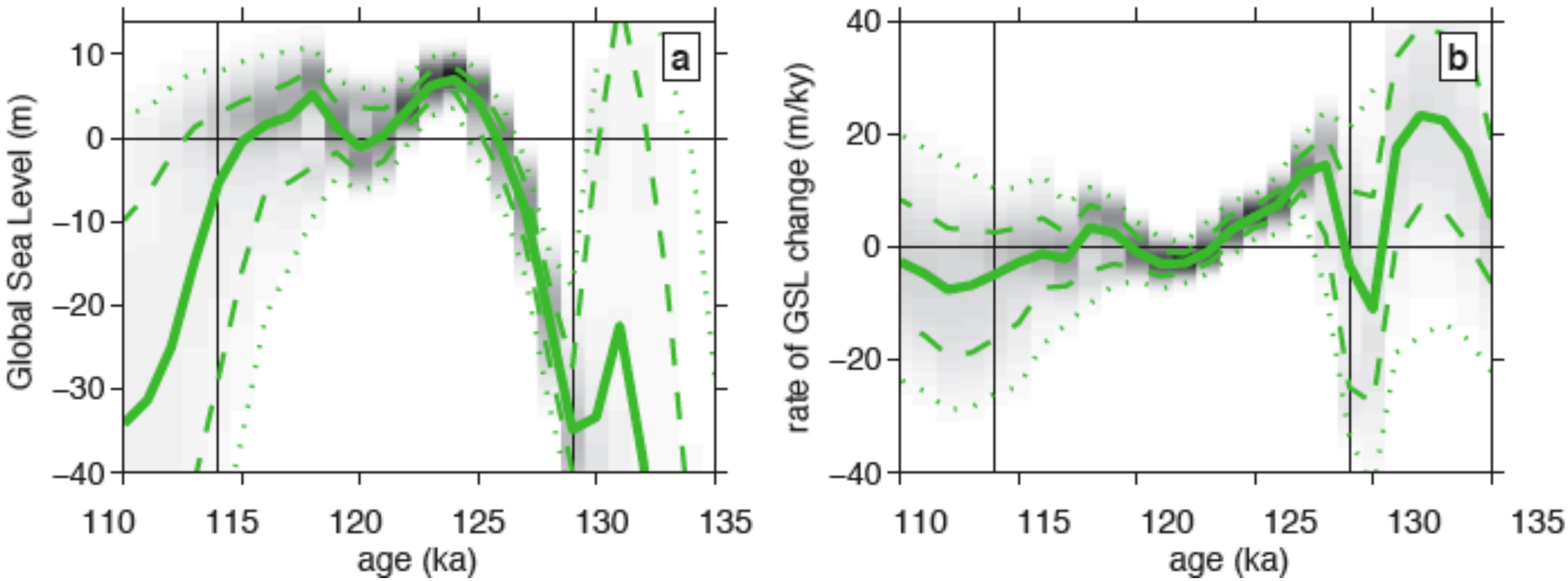
MANY ICE AGE
SEA LEVEL MODELS



Covariance between LSL and GSL

→ BAYESIAN FRAMEWORK

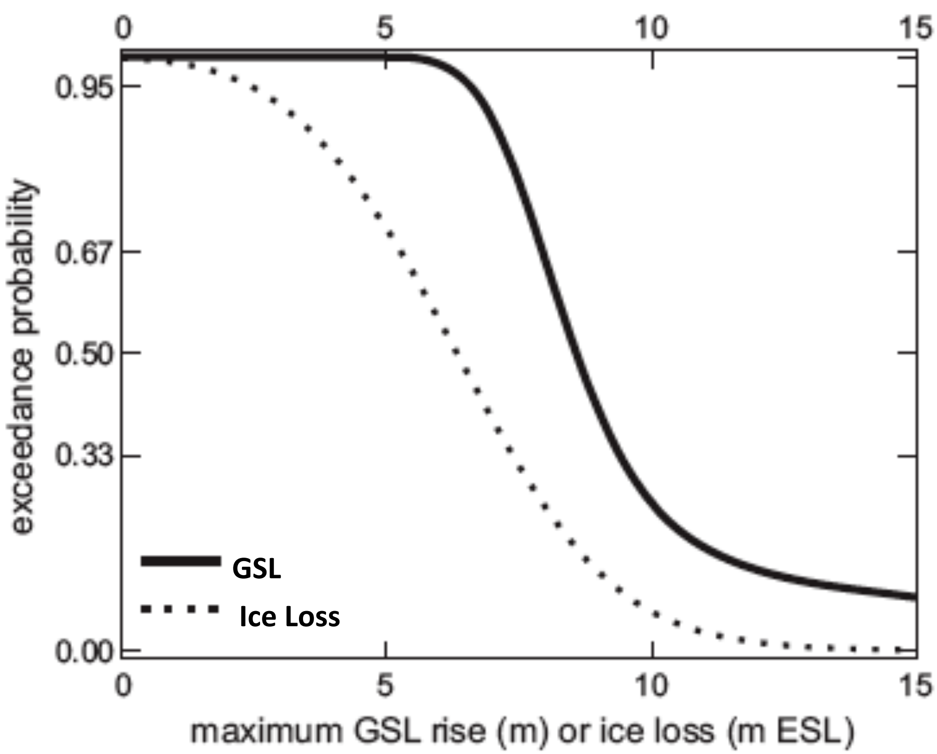
Ice Age Sea Level: The Last Interglacial



Posterior Probability Densities

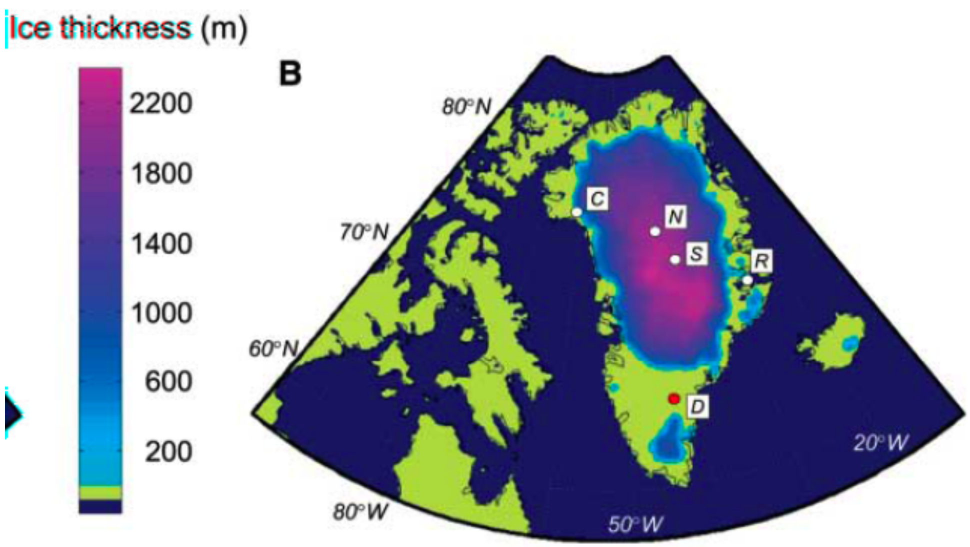
Use these to set up hypothesis tests and confidence intervals

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)

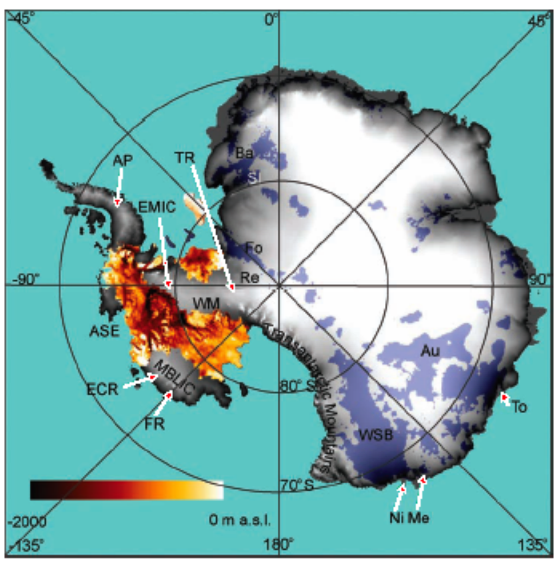
Ice Age Sea Level: The Last Interglacial



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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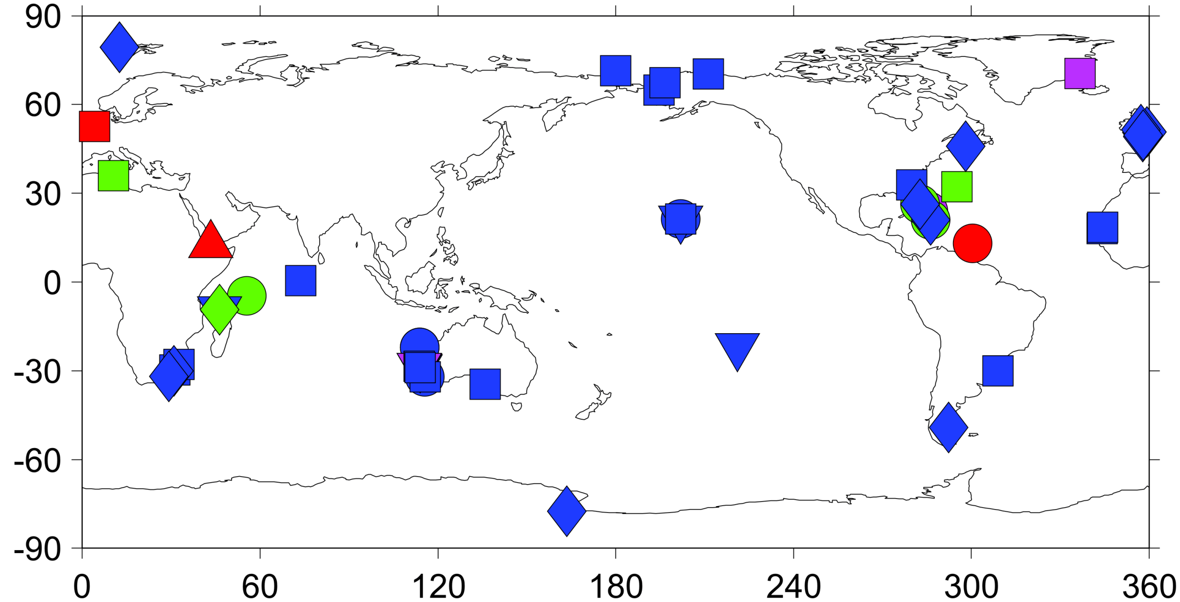

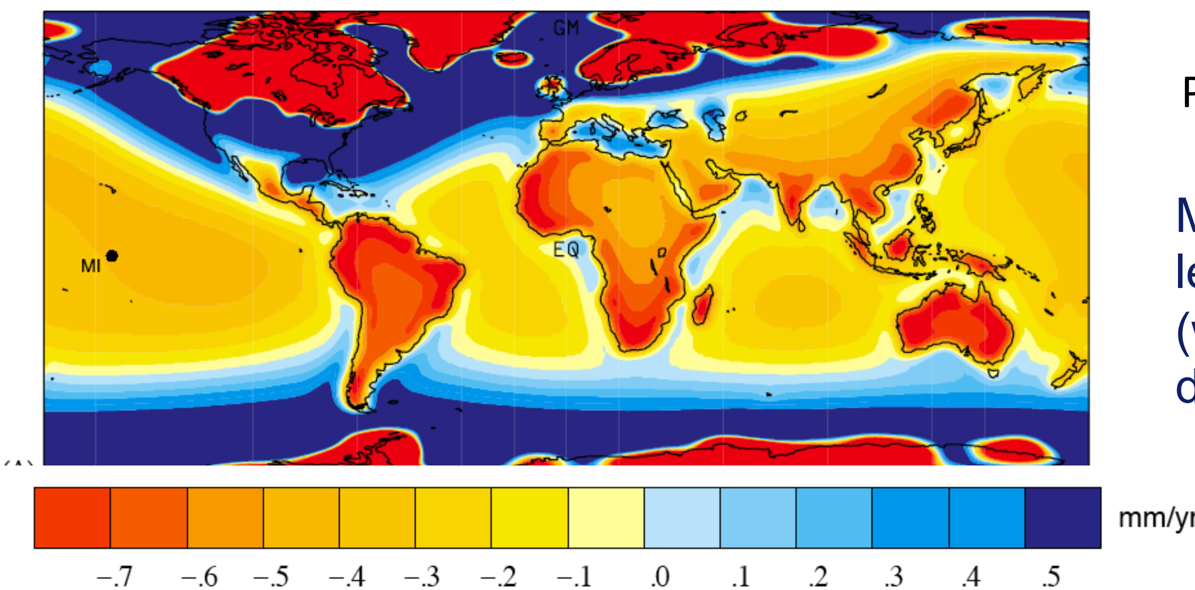

Physics of this result?

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

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