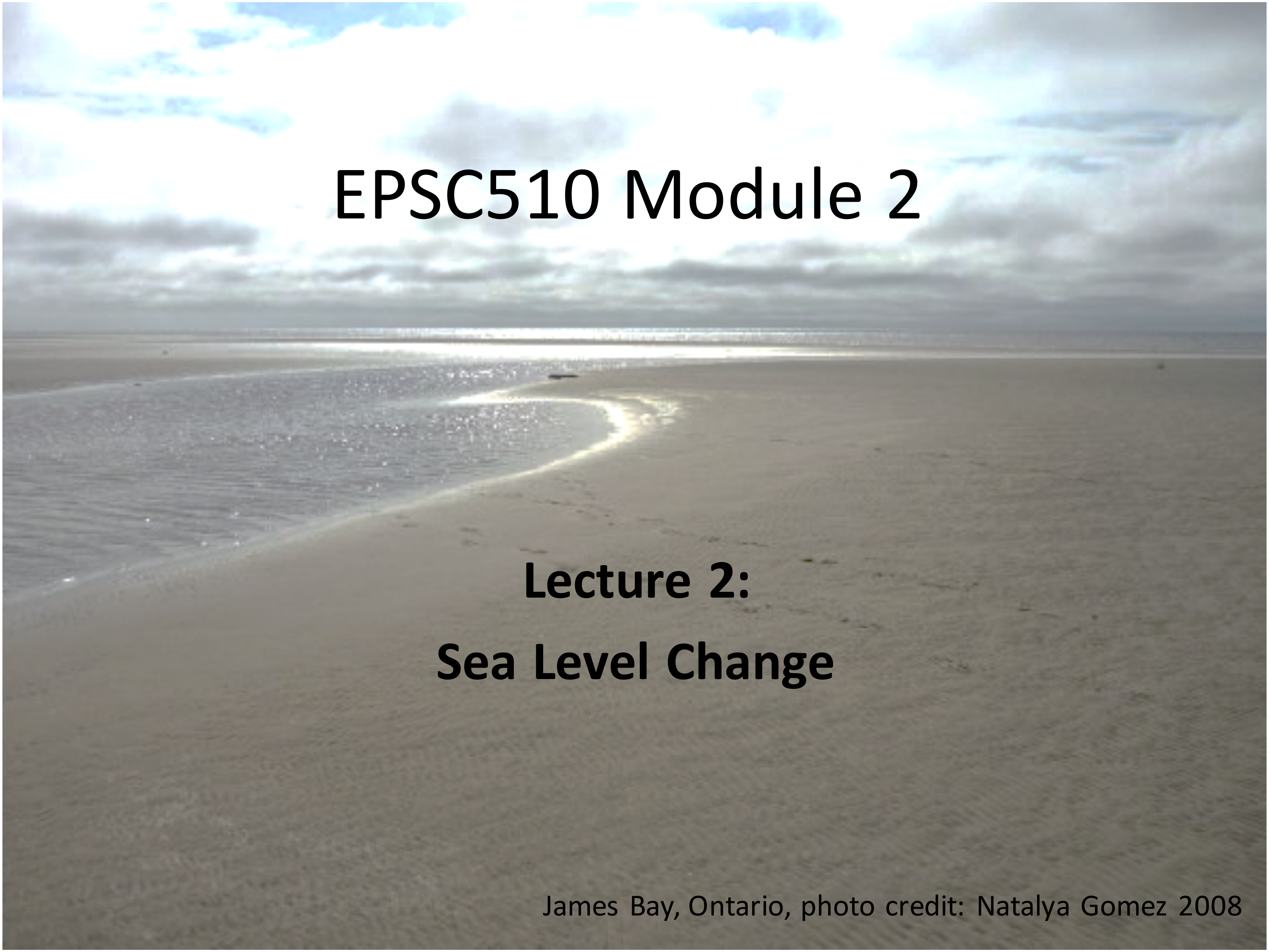
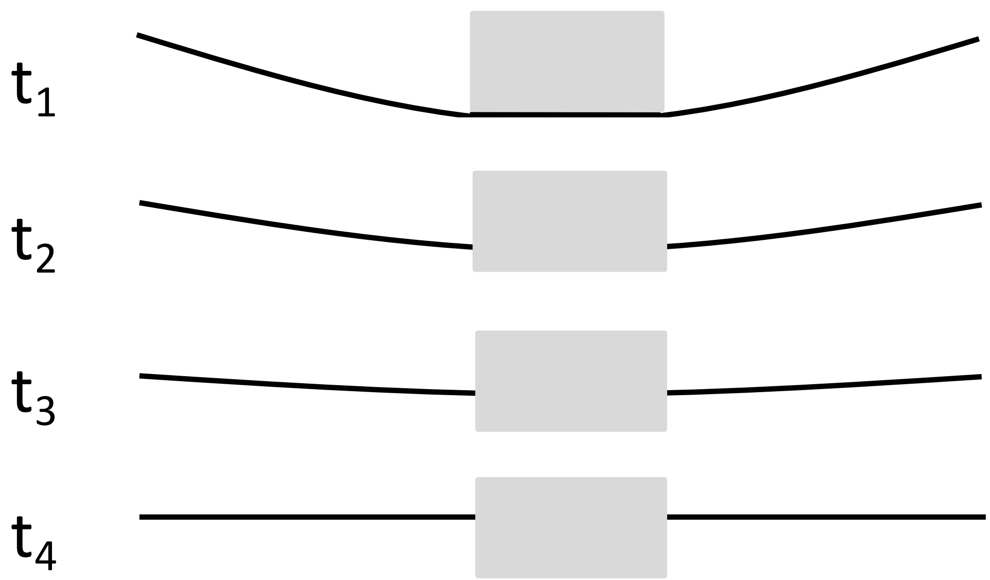


EPSC510 Module 2

Lecture 2:
Sea Level Change

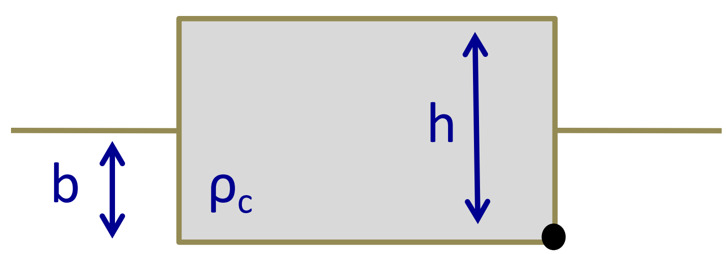
James Bay, Ontario, photo credit: Natalya Gomez 2008

Last Class: Isostasy and Rheology



Rheology
(The macroscopic response of a material to an applied stress)
|
|
V
Isostasy

Isostasy:
Archimedes Principle / Hydrostatic Equilibrium applied to the Earth.



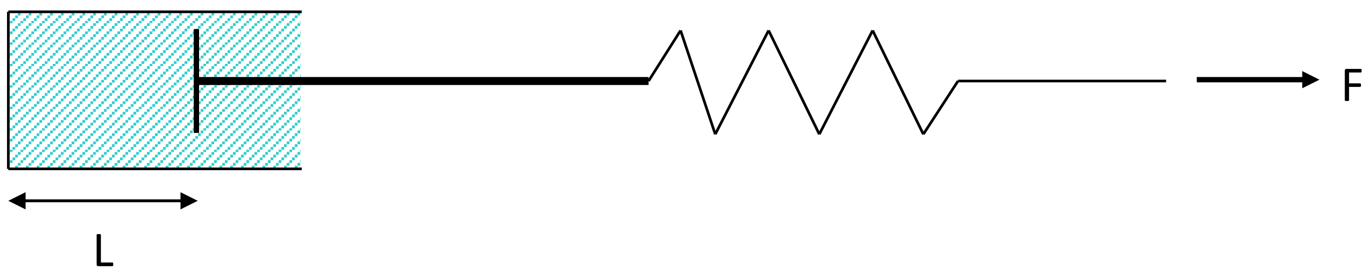
$$\frac{b}{h} = \frac{\rho_c}{\rho_m}$$

Last Class: Isostasy and Rheology

1-D MODELS OF RHEOLOGY

3) Viscoelastic Body

- many ways to define such a material
- assume the following 1-D linear response: "Maxwell Body"



- constitutive equation:

$$\dot{e} = \frac{1}{k}\dot{F} + \frac{1}{\eta}F$$

End members:

$k \rightarrow \infty$ Viscous body

$\eta \rightarrow \infty$ Elastic body

Last Class: Isostasy and Rheology

ENVIRONMENT DEPENDENCIES

.

$$\dot{e} = \frac{1}{k}\dot{F} + \frac{1}{\eta}F$$

- Both k & η are functions of pressure P & temperature T
- ν is a much stronger function of P,T (in general)
- to a first approximation: $\eta = \eta(P,T) = \eta(T)$
- experiments have shown: $\eta(T) = \eta_0 \exp(-a[T - T_0])$

  $\eta(T_0) = \eta_0$

- "a" is a complex function of thermodynamic properties
- thus, small changes in temperature produce exponentially large changes in viscosity!!!

$$\dot{e} = \frac{1}{k}\dot{F} + \frac{1}{\eta_0 \exp(-a[T - T_0])}F$$

Cases:

(1) Cold … means η large so: $\dot{e} \cong \frac{1}{k}\dot{F}$ Elastic response

(2) Hot … means η small so: $\dot{e} \cong \frac{1}{\eta}F$ Viscous response

(3) Warm … intermediate T so: viscoelastic response … similar to tar

Outline

This Class: Sea Level Change

1. Sea-level records and definitions

2. Sea-level changes in response to ice cover variations

   a. The sea-level equation

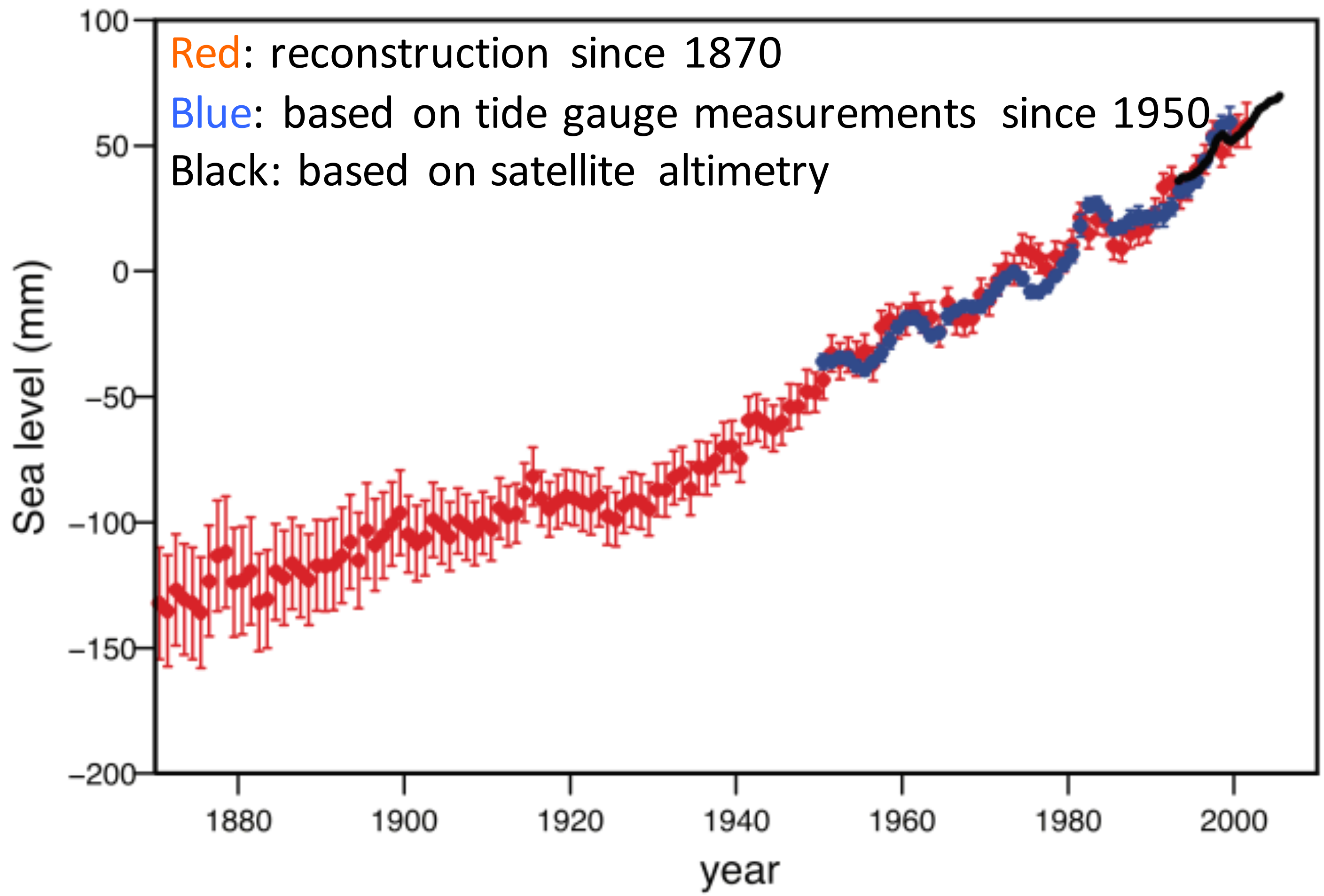
   b. Physics

3. Example

Future Sea-Level Rise?

1. Sea – level records

Annual averages of global sea level



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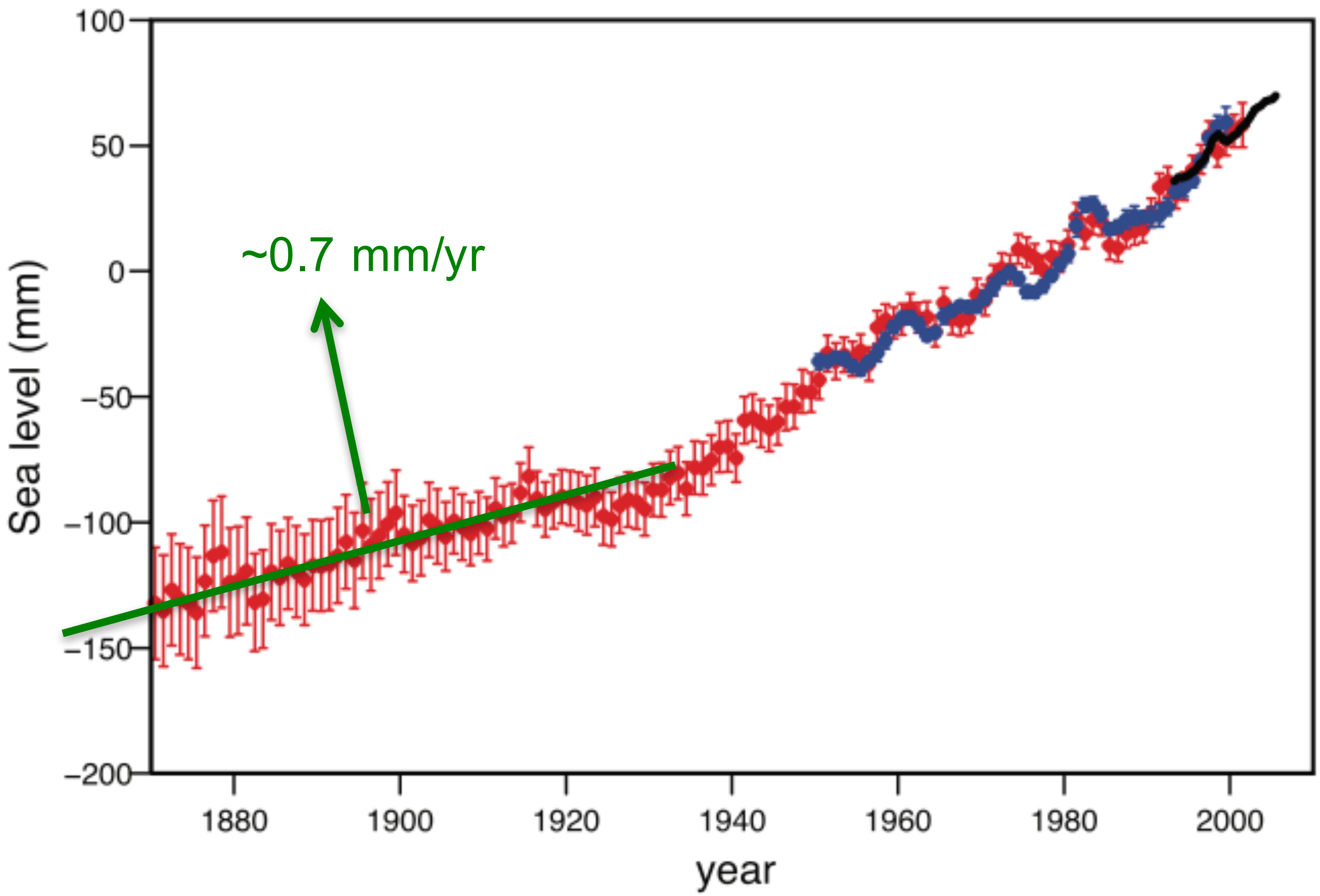
1. Sea – level records

Annual averages of global sea level



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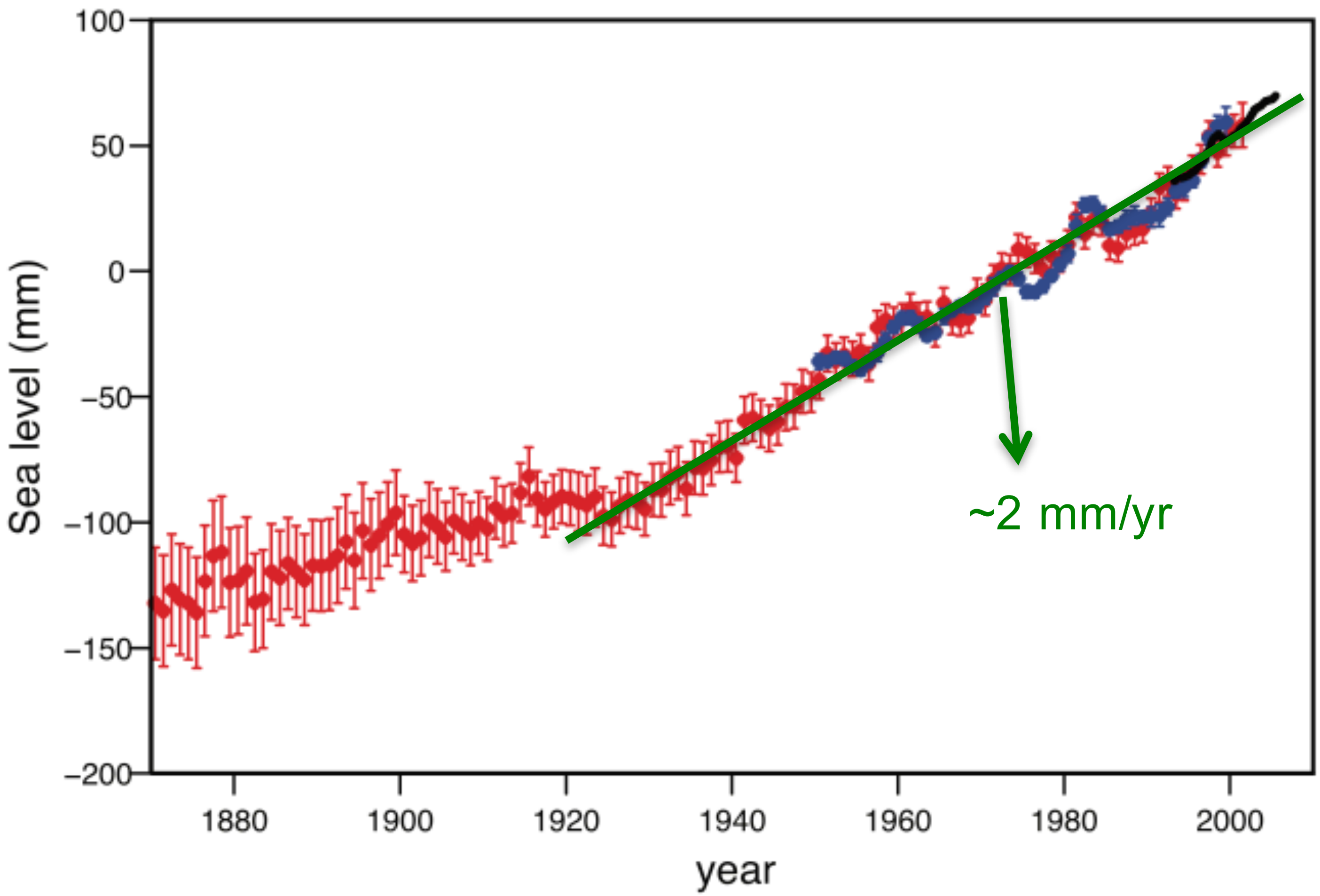
Annual averages of global sea level



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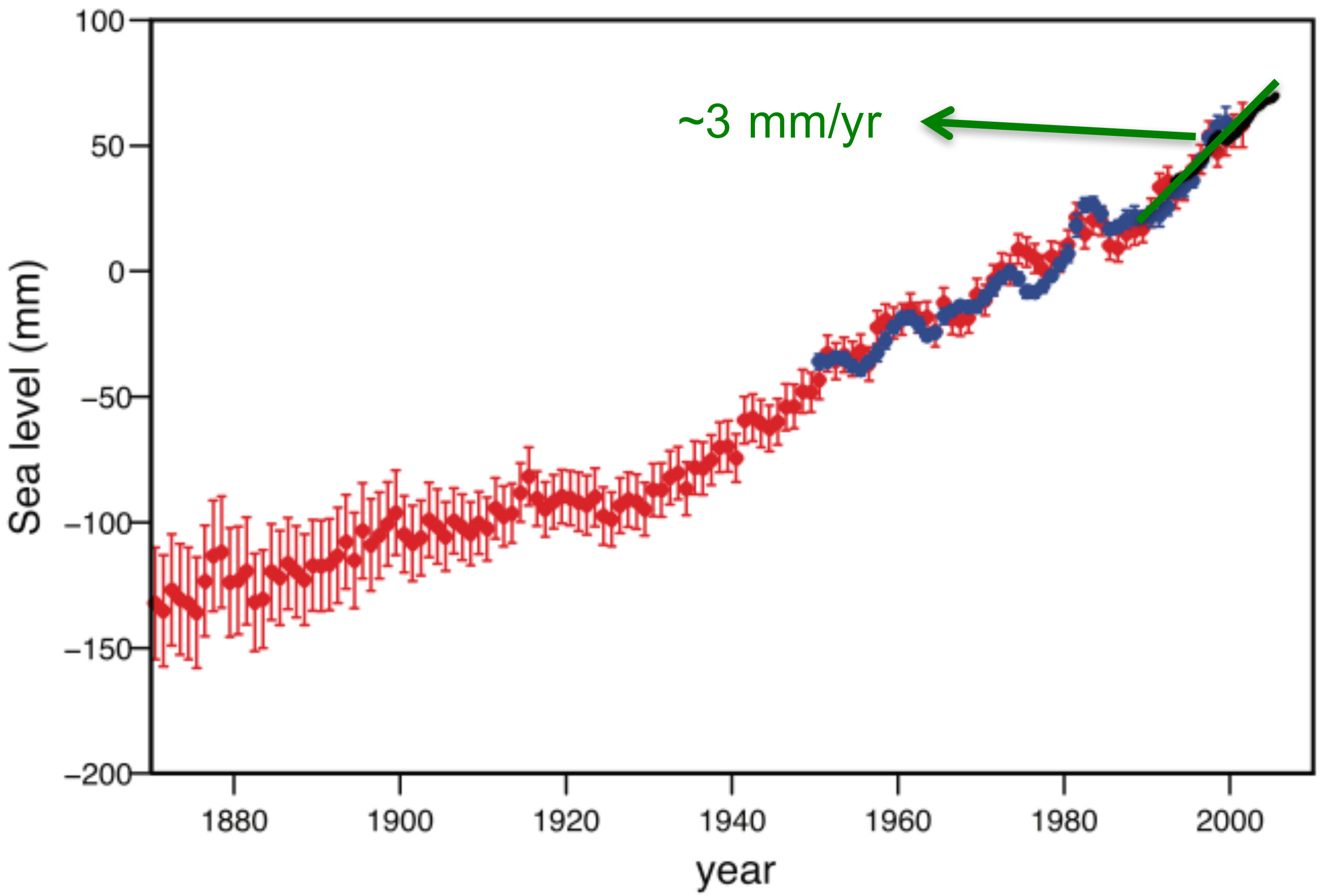
Annual averages of global sea level



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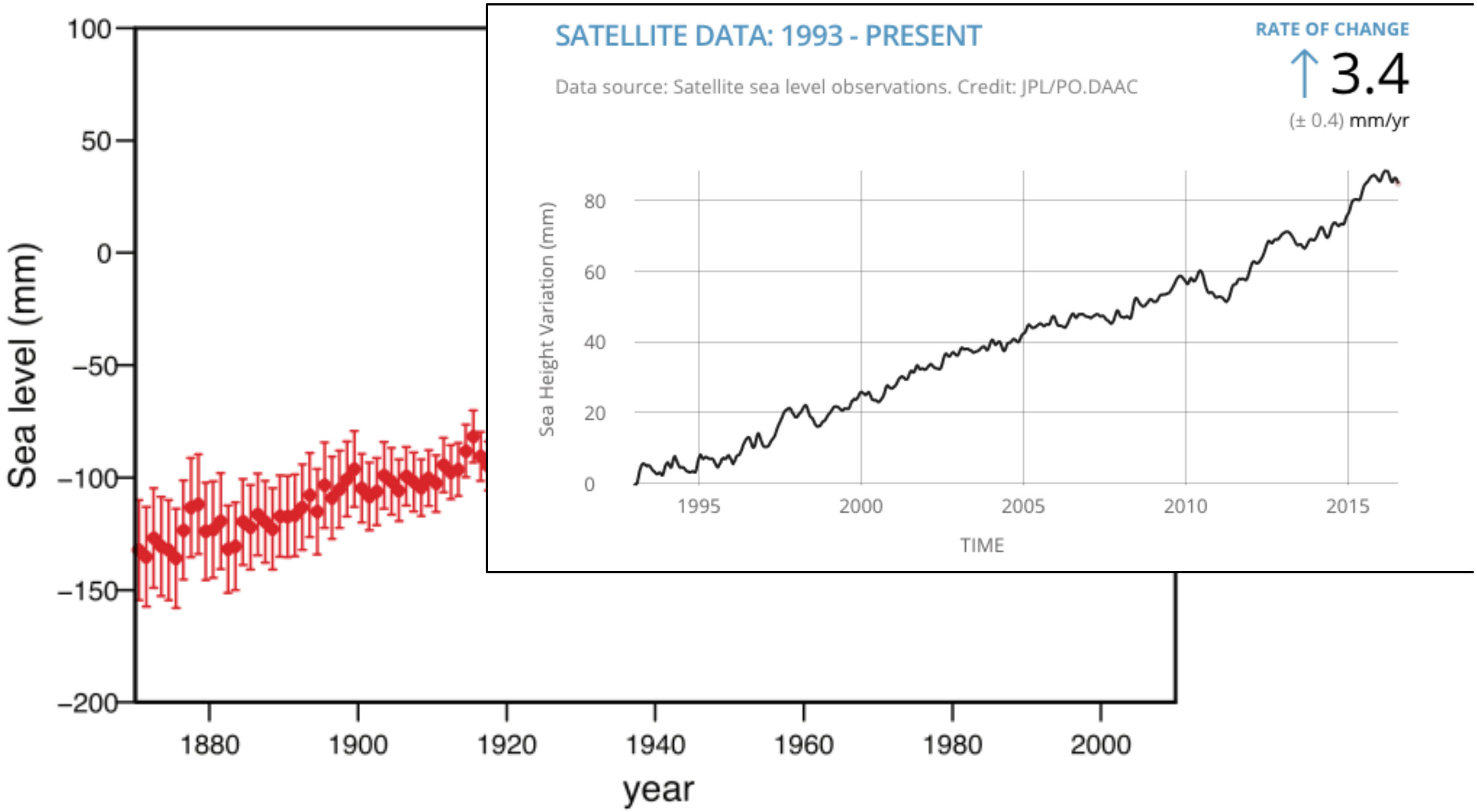
1. Sea – level records

Annual averages of global sea level

https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level



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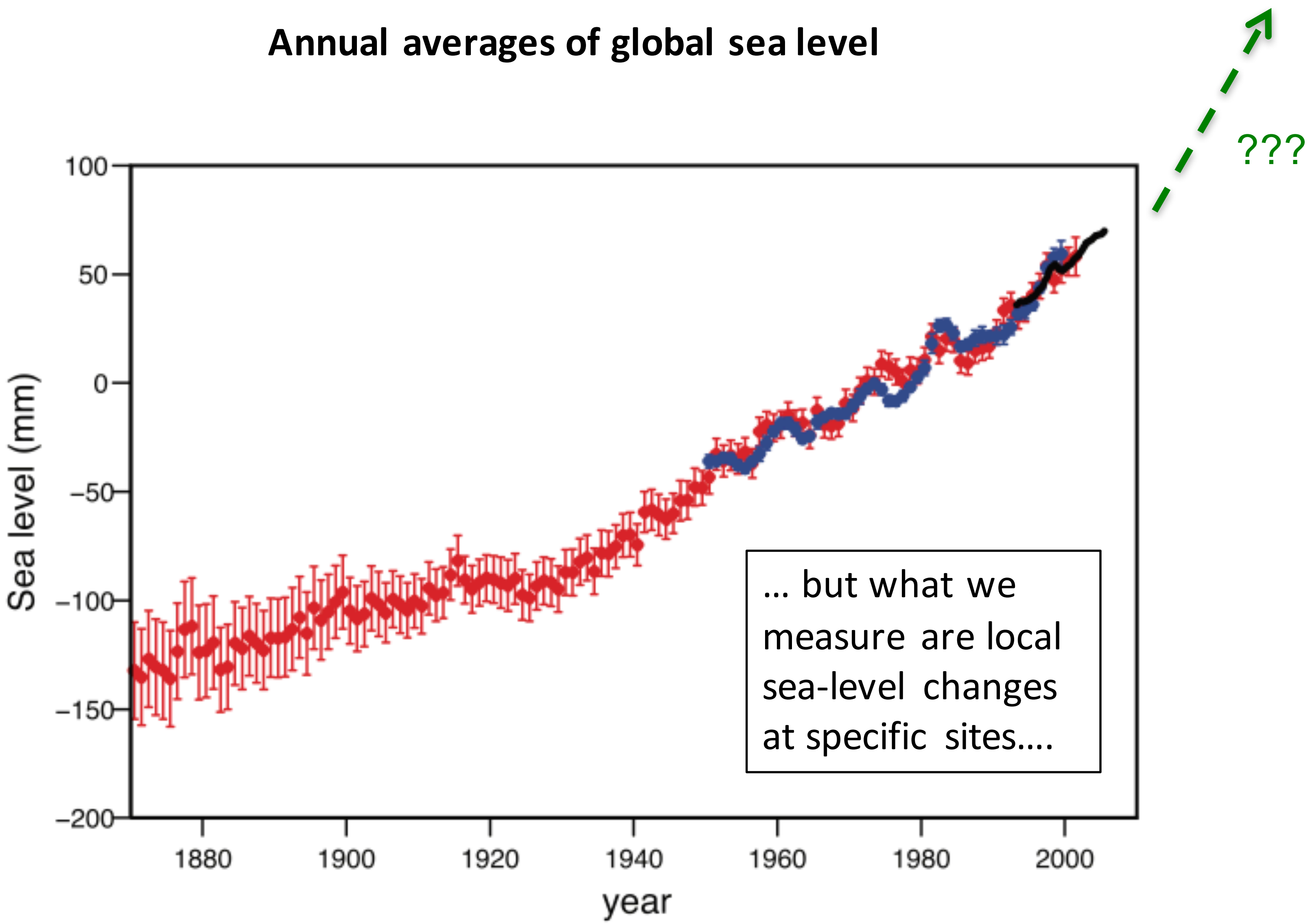
1. Sea – level records

Annual averages of global sea level



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

1. Sea – level records

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

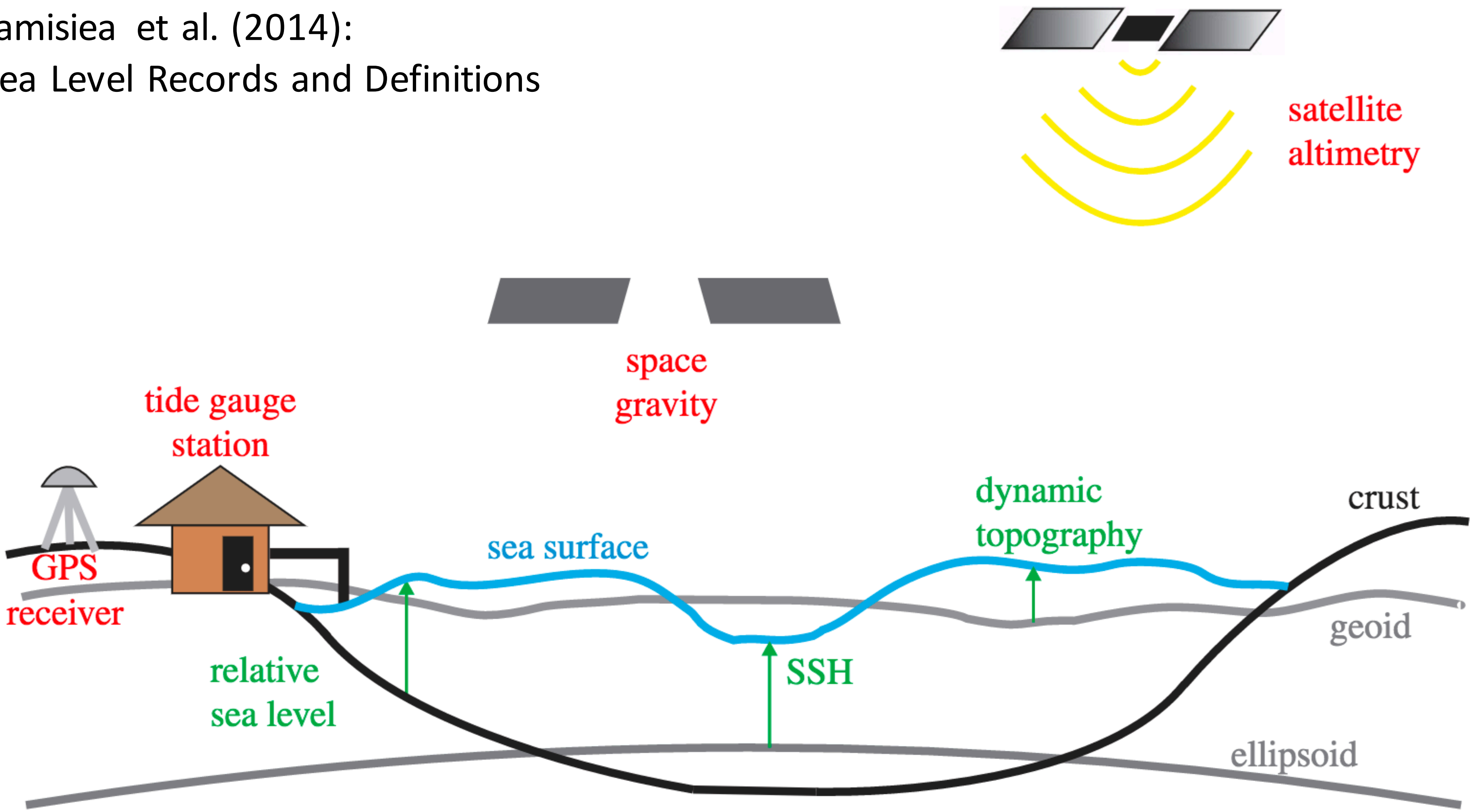
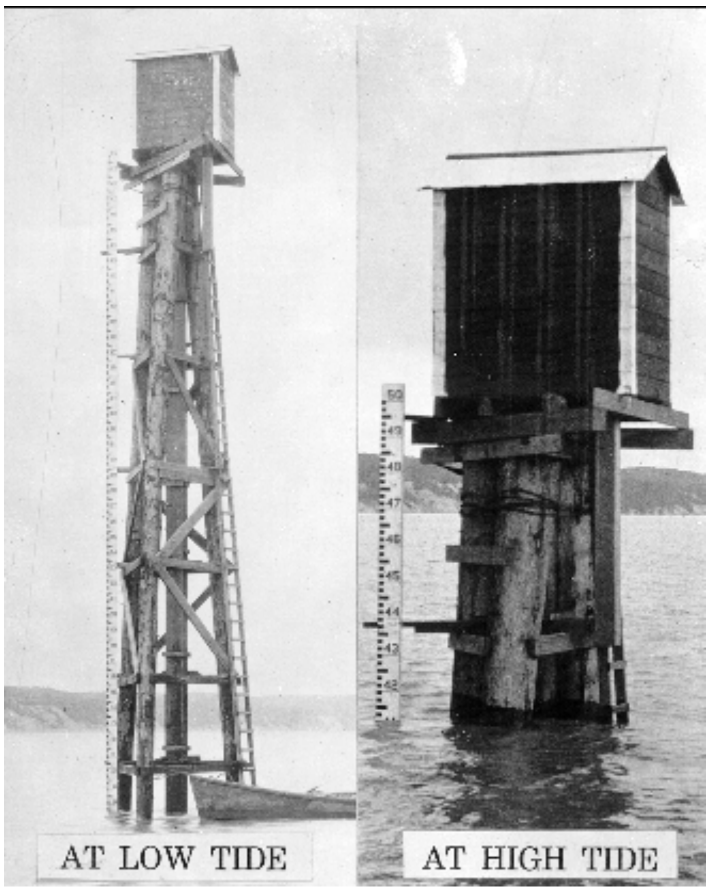


Figure 1. Simple schematic illustrating the relationship between sea surface height (SSH), the geoid, and dynamic topography. Included on the figure are representations of different components of the observing system and their respective measurement: GPS (or GNSS) for crustal deformation, satellite gravity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

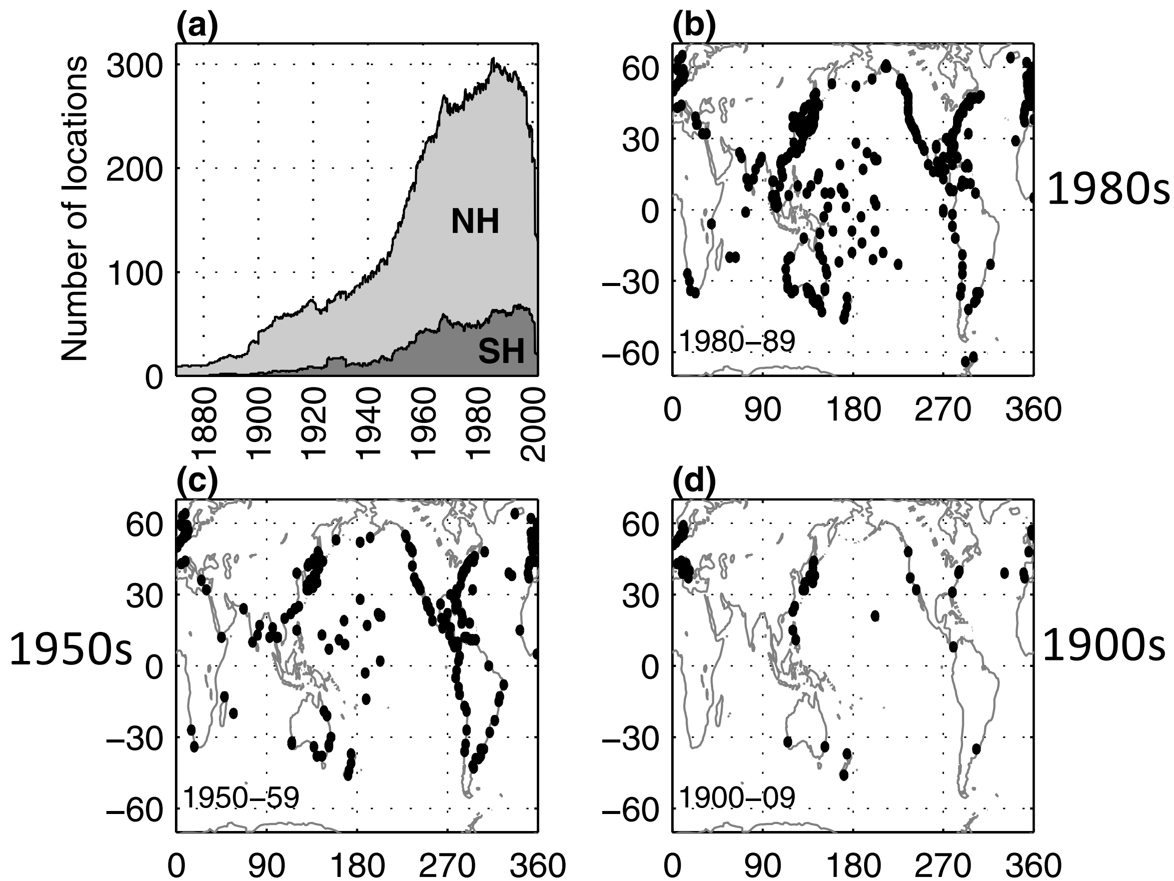
1. Sea – level records

Tide Gauges measure:
(Relative) Sea Level = ocean surface – ocean floor

*caution: "relative sea level" can also refer to the sea level at some time in the past relative to the present.



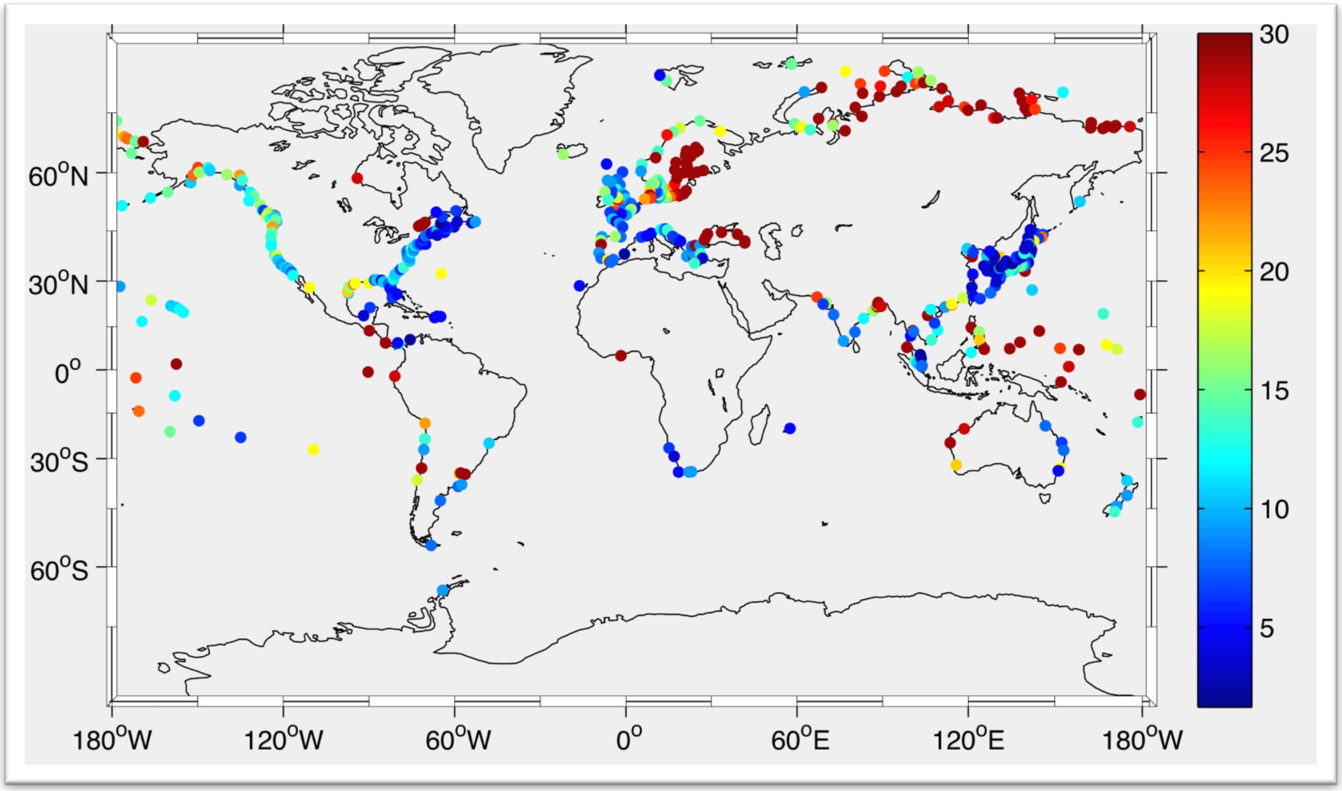
http://co-ops.nos.noaa.gov/about2.html



Church and White (2006)

1. Sea – level records

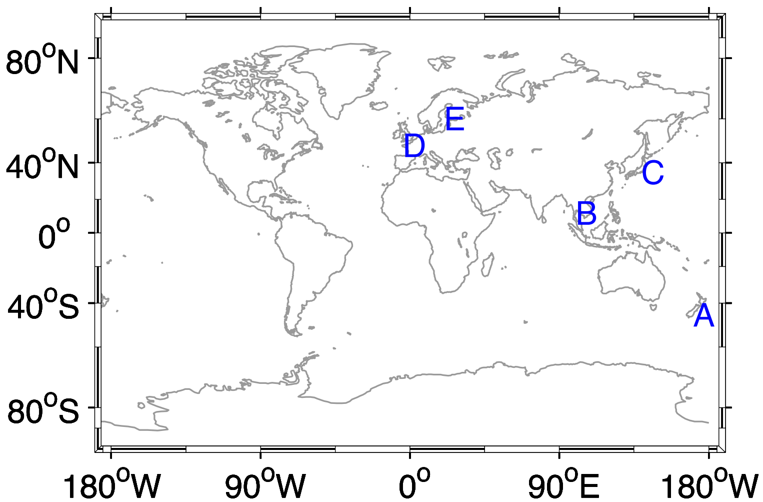
Variance (cm^2) in Annual Tide Gauge Records

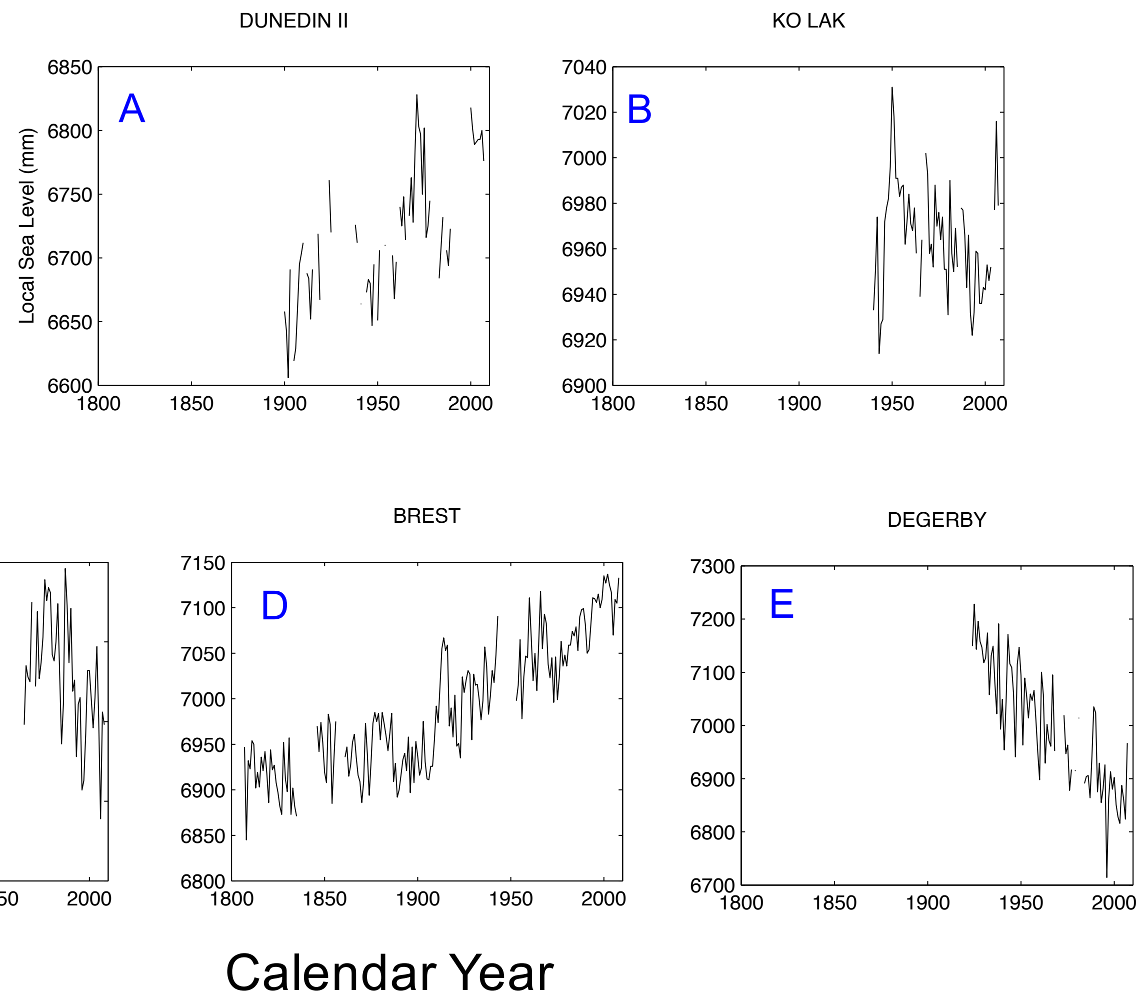


1157 tide gauges in the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference (RLR) database

1. Sea – level records

You can get these yourself from:
http://www.psmsl.org/

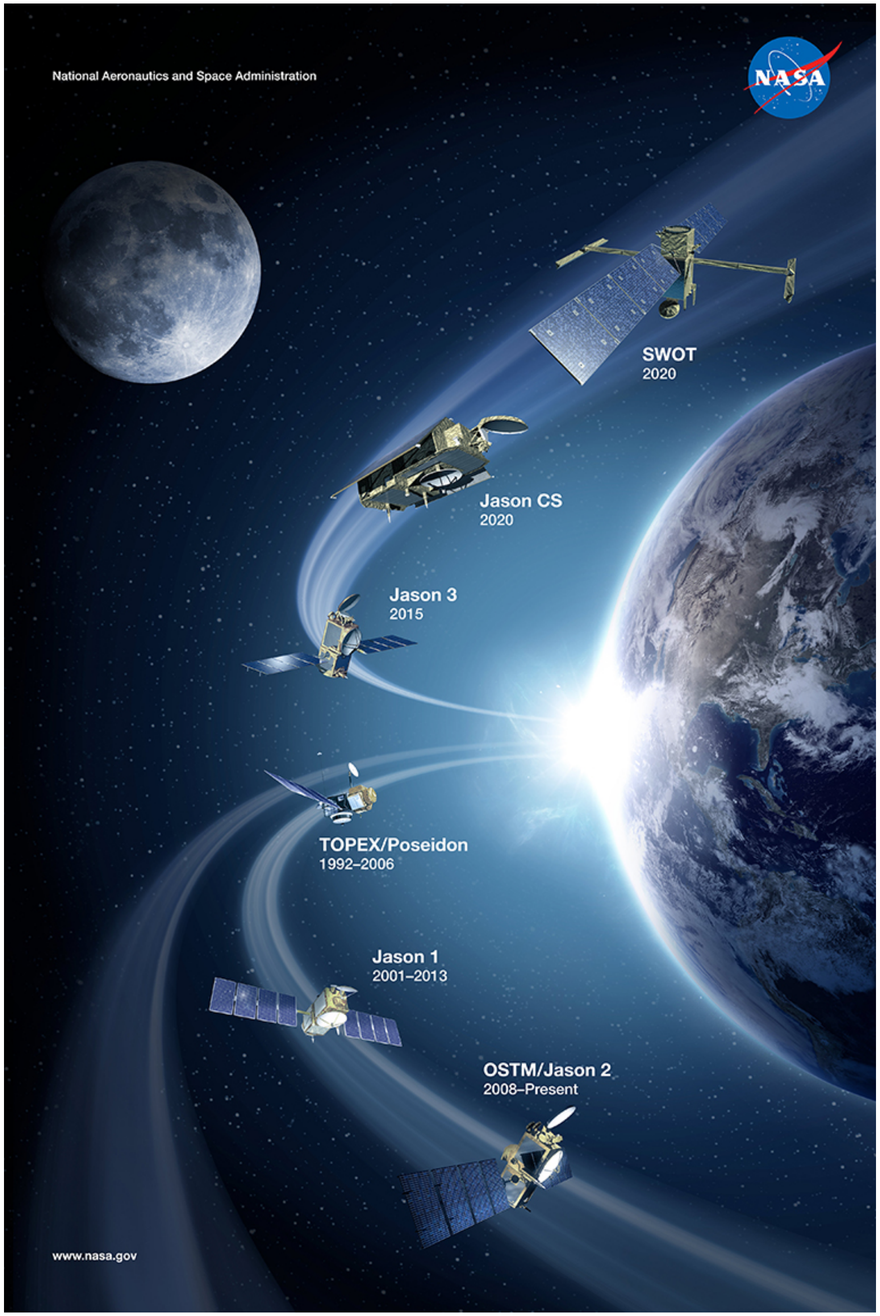




1. Sea – level records

Satellite Altimetry

"Since 1992 NASA, NOAA and European partners have been tracking global ocean surface topography with joint ocean altimeter satellite missions from an orbit 1,336 km above the ocean surface. The spacecrafts' radar altimeters measure the precise distance between the satellite and sea surface. This record began with TOPEX/Poseidon, followed by Jason-1 and the Ocean Surface Topography Mission on Jason-2, and will be continued by Jason-3." - NASA

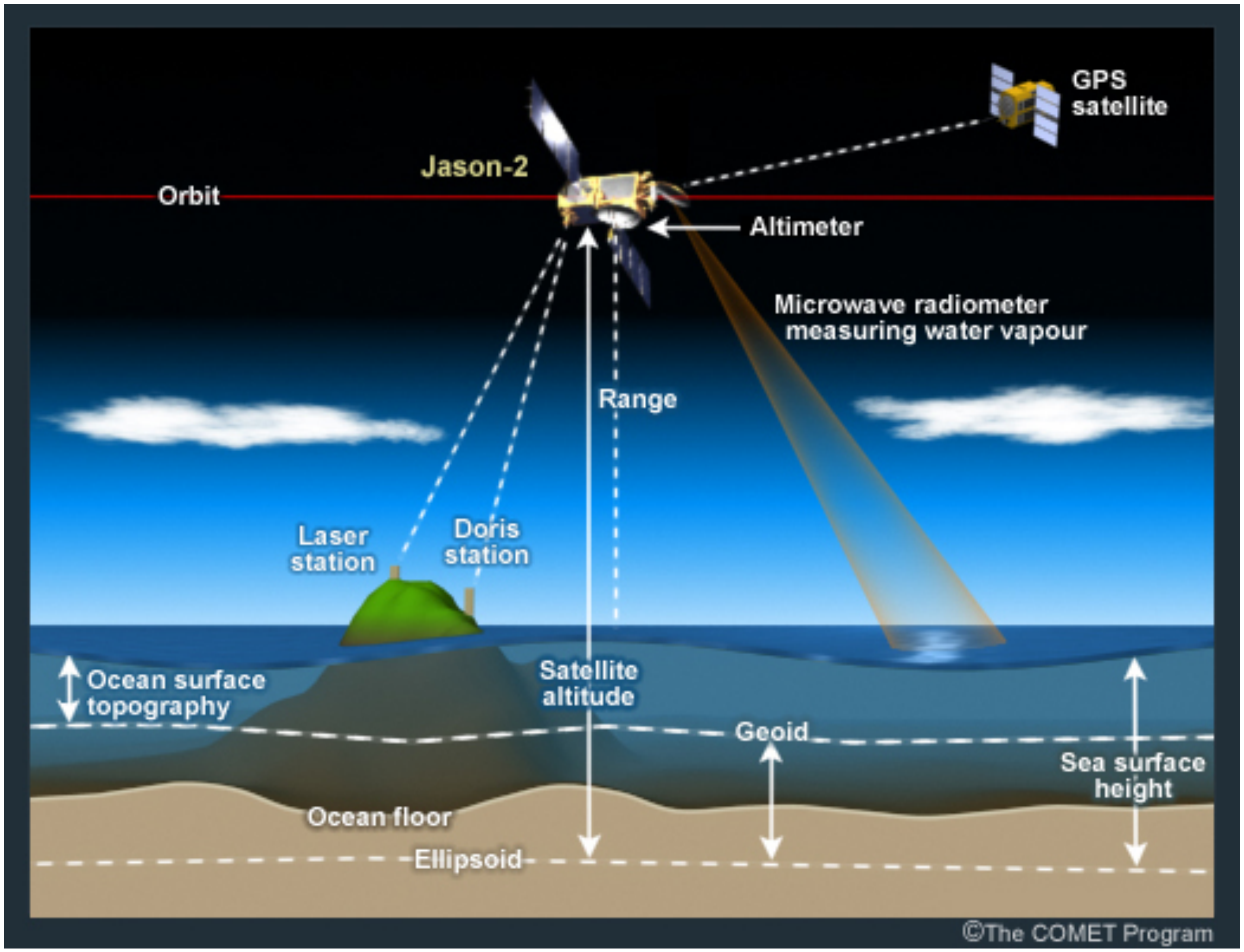


http://www.eumetsat.int/jason/print.htm

1. Sea – level records

Satellite Altimetry measures:
Sea Surface Height = ocean surface – reference ellipsoid

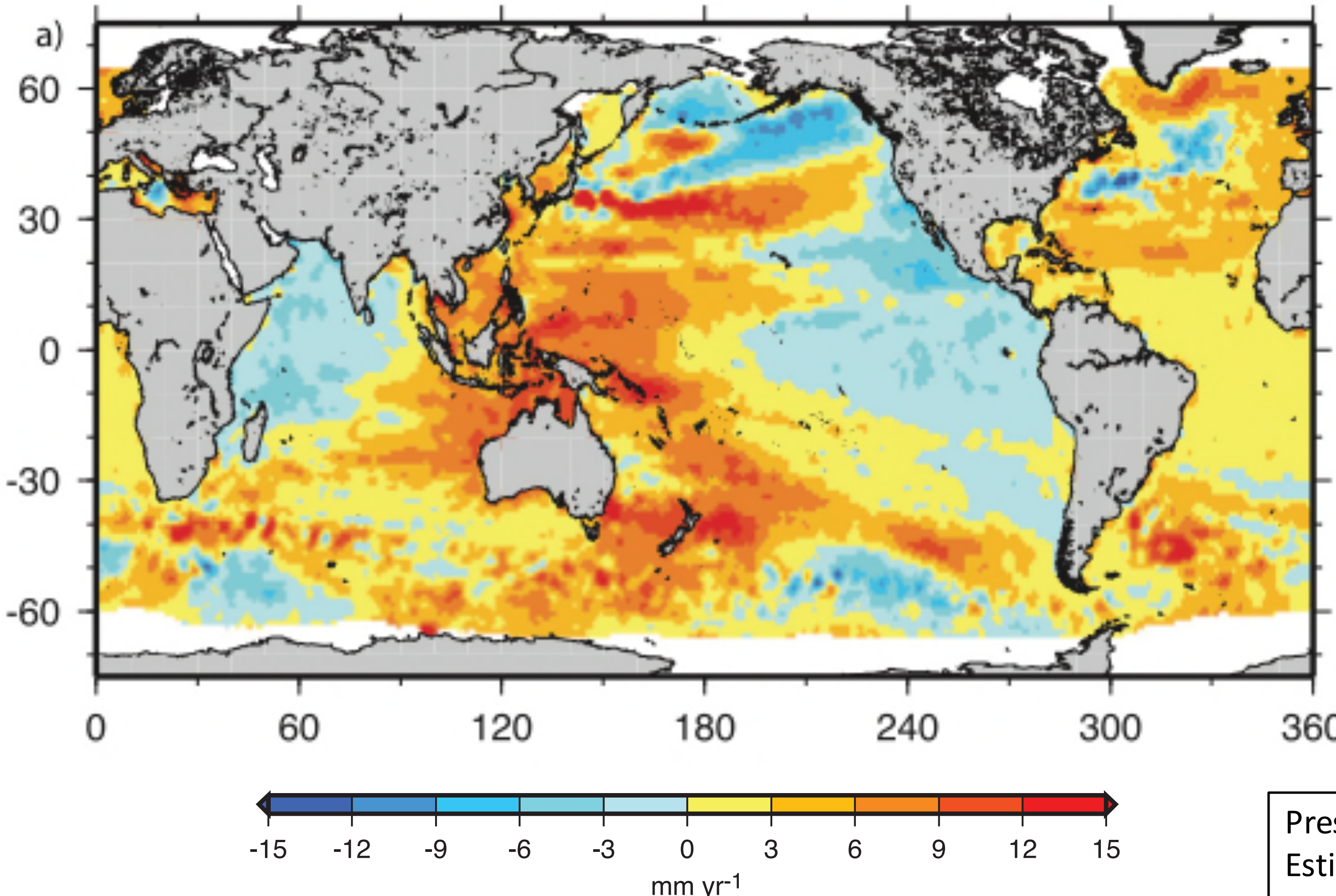
*caution: "sea level" and "sea surface height" are used interchangeably in some literature. In this talk, they are different.



http://www.eumetsat.int/jason/print.htm

1. Sea – level records

Sea Level trend (mm/year) from 1993-2003 from satellite altimetry



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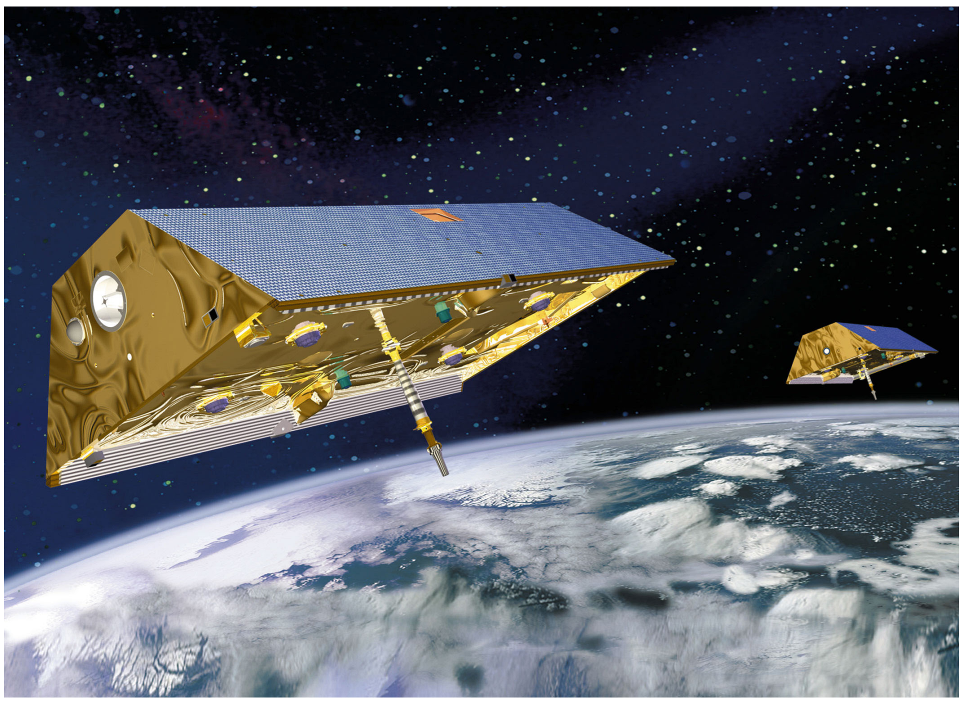
Presentation topic: Estimating contributions to this signal

1. Sea – level records

GRACE – Gravity Recovery and Climate Experiment (since 2002)

2 satellites orbit the Earth together, and their speed changes according to the mass below them. The distance between satellites is measured to produce global maps of mass variations.



Data, info and related studies available here: http://www.csr.utexas.edu/grace/

1. Sea – level records

GRACE – Gravity Recovery and Climate Experiment (since 2002)

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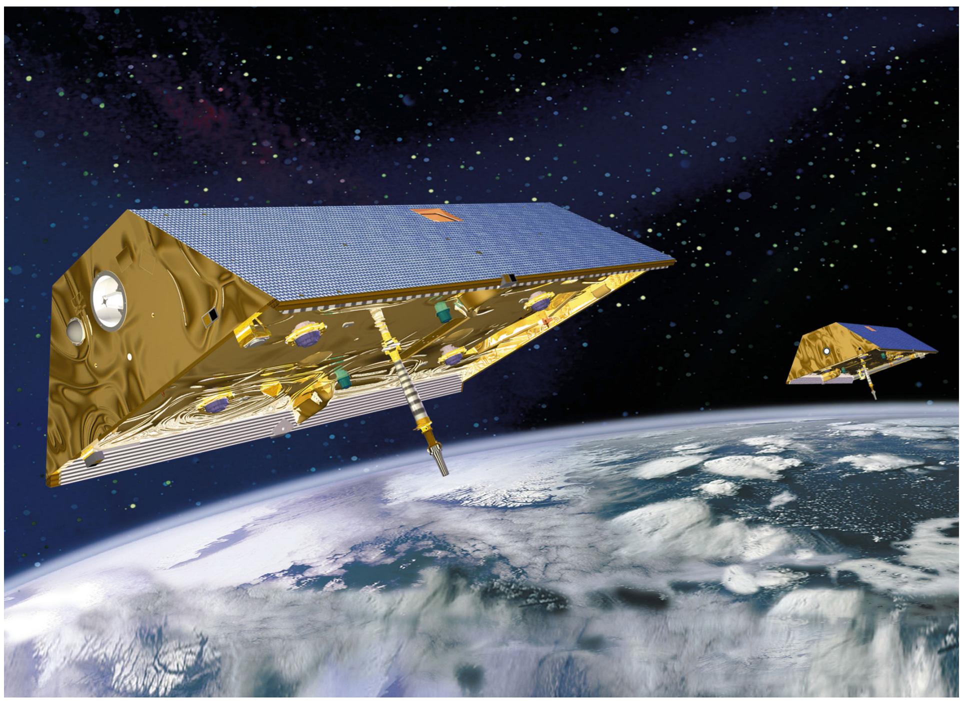


Challenges:

Low Resolution

- Combine with other datasets, develop data processing techniques (e.g. Slepian functions - https://eos.org/project-updates/a-suite-of-software-analyzes-data-on-the-sphere-2)

Separating sources - Observed changes mass distribution across the Earth's surface are associated with a combination of:

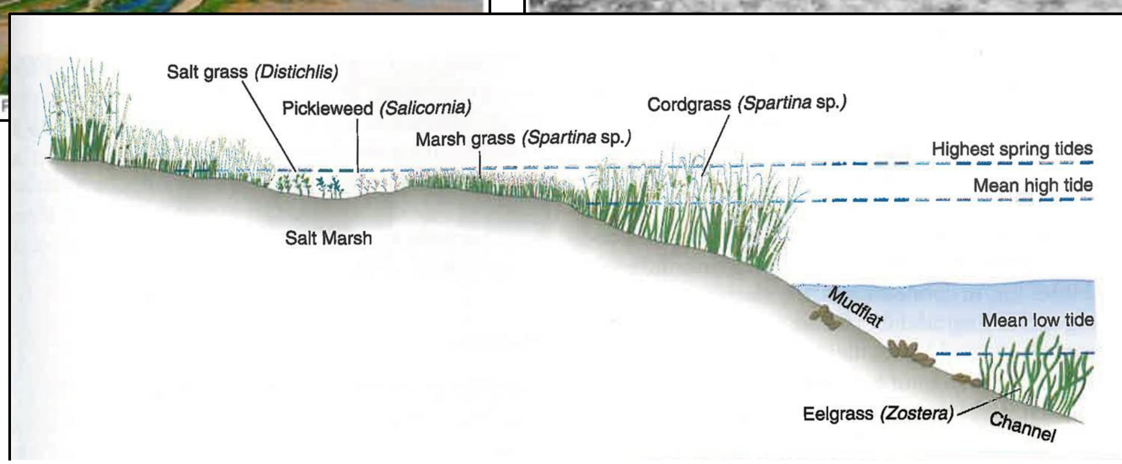
- Solid Earth changes
- Ocean circulation
- Groundwater storage
- Exchange of mass between ice sheets and mountain glaciers and the ocean
- Atmospheric circulation
- … other effects, e.g., forest fires!

Data, info and related studies available here: http://www.csr.utexas.edu/grace/

1. Sea – level records

Paleo sea-level records – biological and geological, e.g.,

- Past shoreline markers
- Corals (grow up to just below the surface, then are exposed to sunlight above water when sea level falls.)
- Salt Marshes (last ~ky)



1. Sea – level records

Paleo sea-level records – Oxygen Isotope Record

A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records

Lorraine E. Lisiecki
Department of Geological Sciences, Brown University, Providence, Rhode Island, USA

Maureen E. Raymo
Department of Earth Sciences, Boston University, Boston, Massachusetts, USA

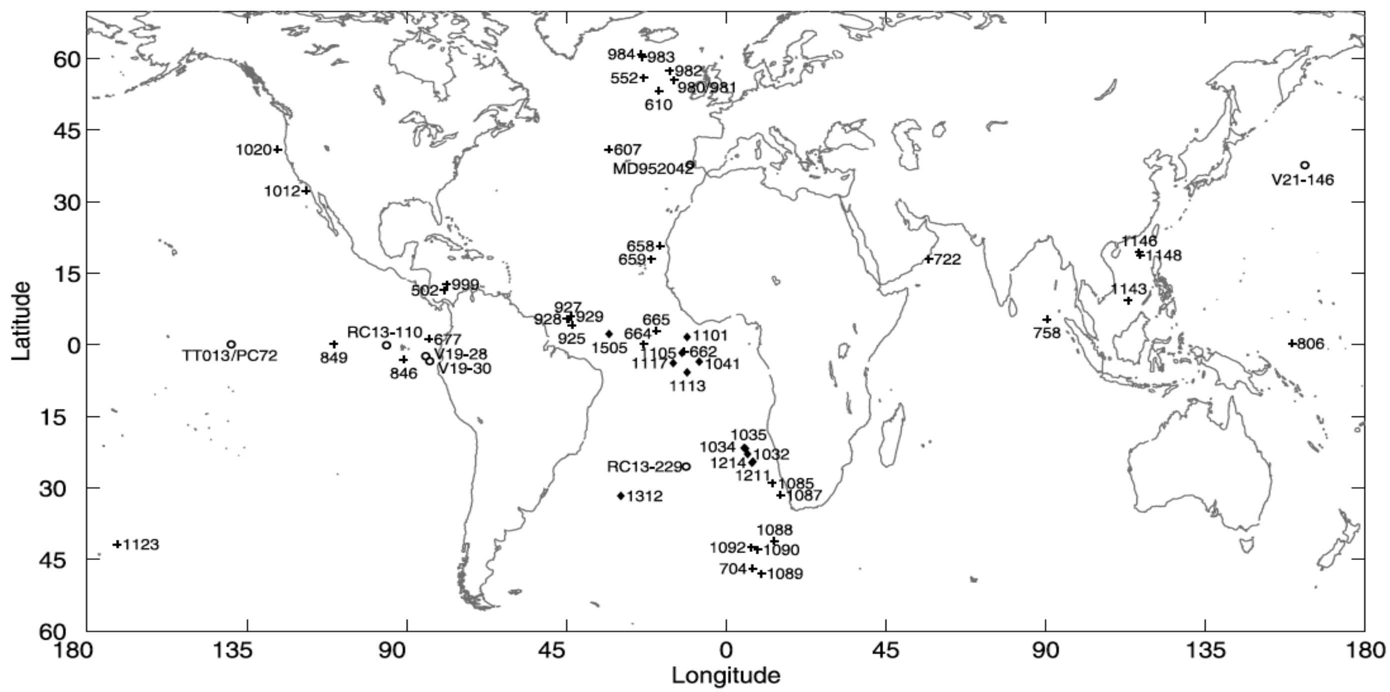
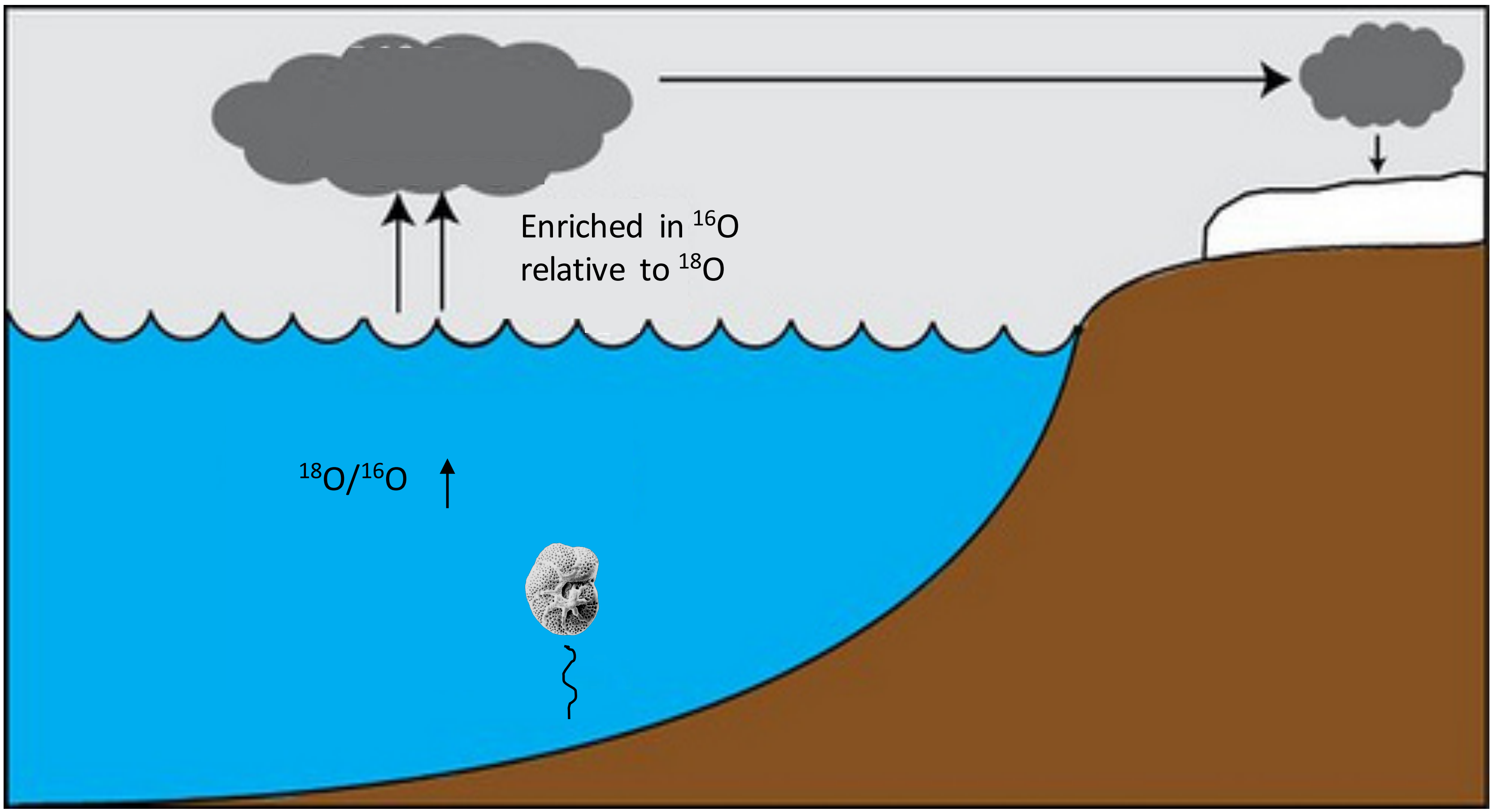


Figure 1. Location of the cores used in this study. Benthic $\delta^{18}O$ data are taken from Deep-Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sites (crosses), GeoB sites (diamonds), and others (circles).

1. Sea – level records

Oxygen Isotope Fractionation (in 1 slide): Ice has a lower d^{18}O value than seawater, so oxygen isotope values provide a proxy for contribution from ice to sea level changes.



1. Sea – level records

MORE ICE

PA1003 LISIECKI AND RAYMO: PLIOCENE-PLEISTOCENE BENTHIC STACK PA1003

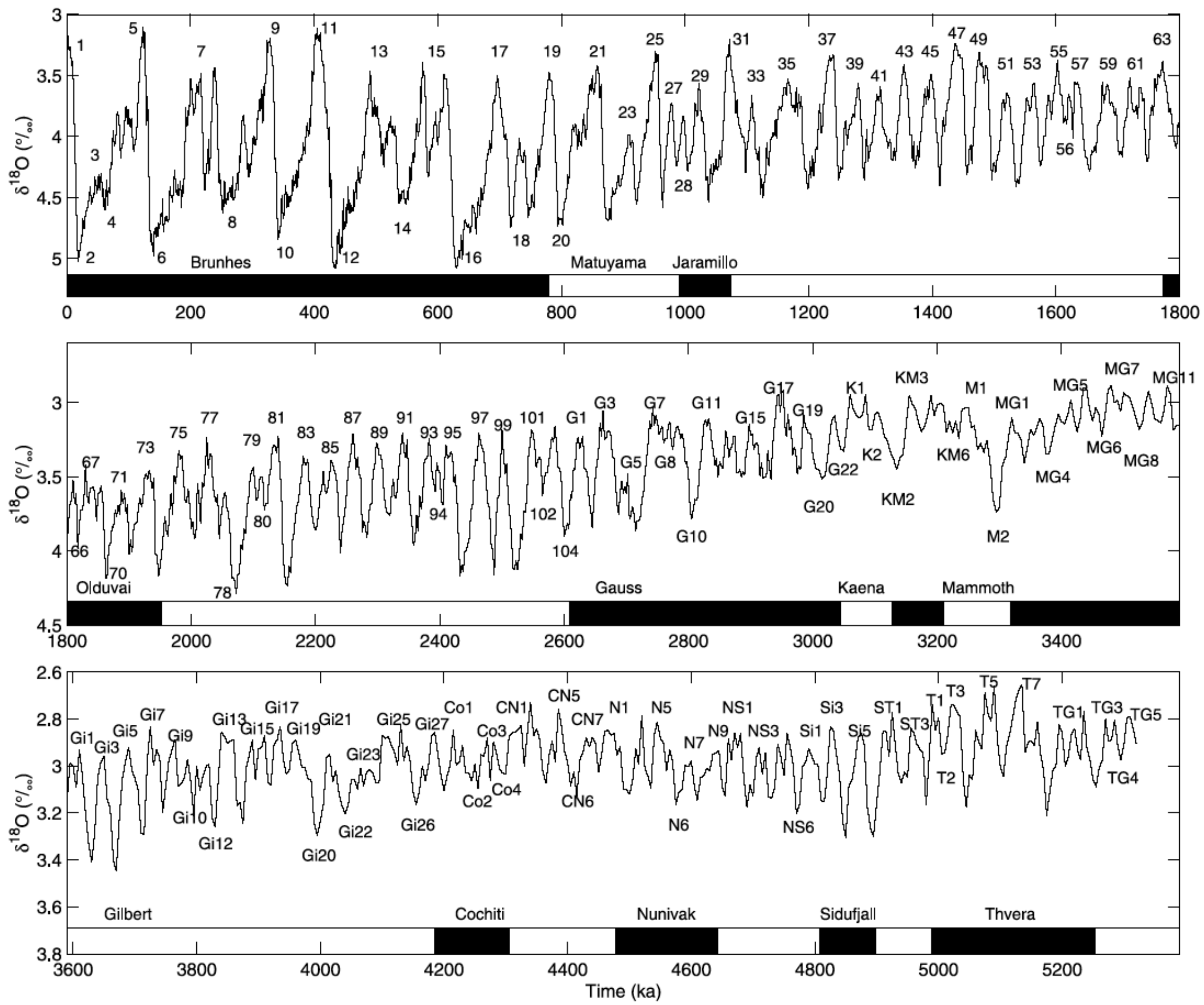


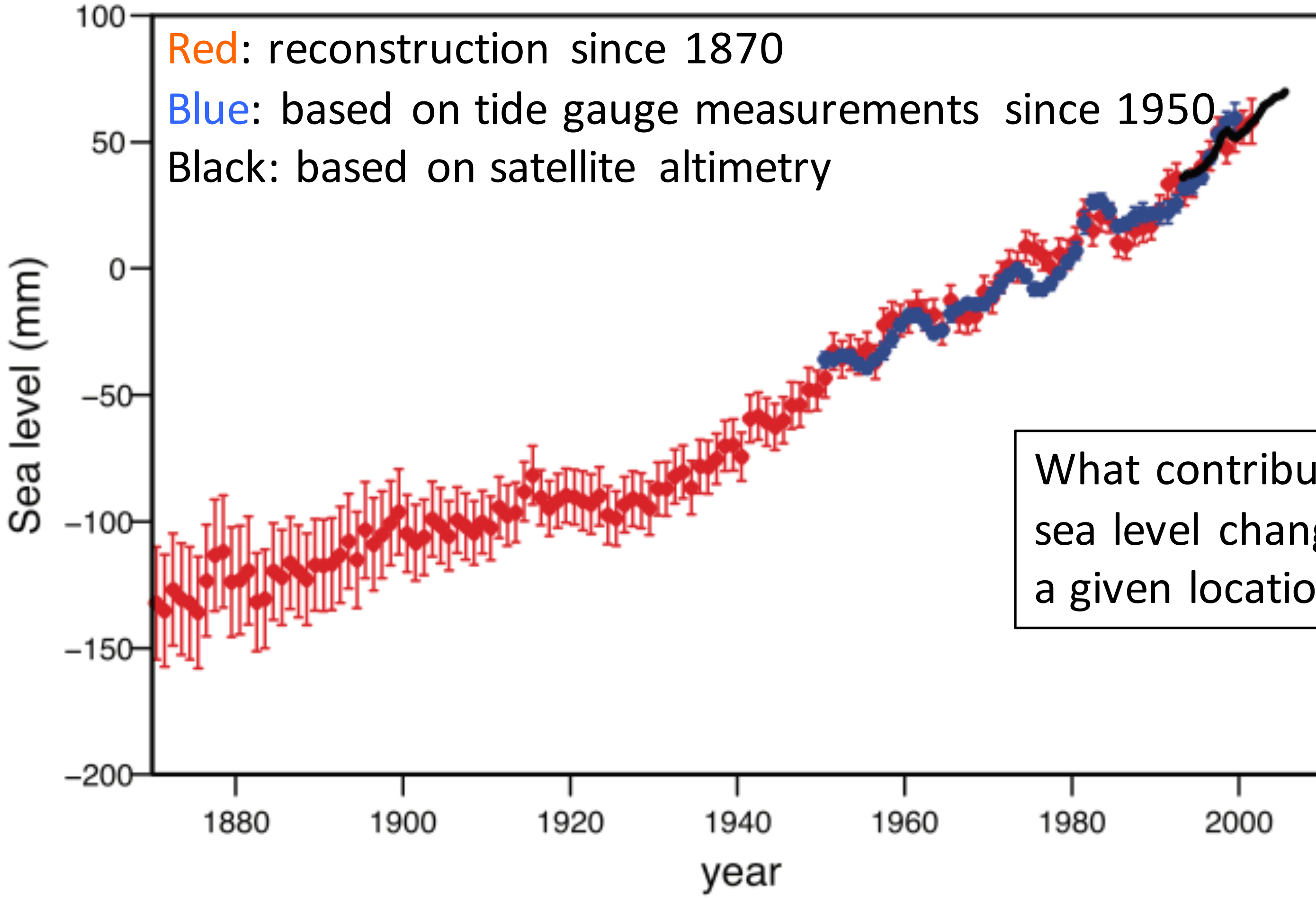
Figure 4. The LR04 benthic $\delta^{18}O$ stack constructed by the graphic correlation of 57 globally distributed benthic $\delta^{18}O$ records. The stack is plotted using the LR04 age model described in section 5 and with new MIS labels for the early Pliocene (section 6.2). Note that the scale of the vertical axis changes across panels.

PALEOCEANOGRAPHY, VOL. 20, PA1003, doi:10.1029/2004PA001071, 2005

We will come back to this…

1. Sea – level records

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

2a. The Sea – level Equation

Local sea-level changes are the result of the combination of various effects:

1) Dynamic Effects
   long term: thermal expansion of the ocean
   short term: ocean dynamics, air-sea interactions, temperature and salinity variations, tides…

2) Static Effects
   the advance and retreat of ice sheets and mountain glaciers produce distinct patters of sea level change called "sea level fingerprints"

3) Glacial Isostatic Adjustment
   the ongoing adjustment of the land and sea surface do to ice cover changes that occurred in the past

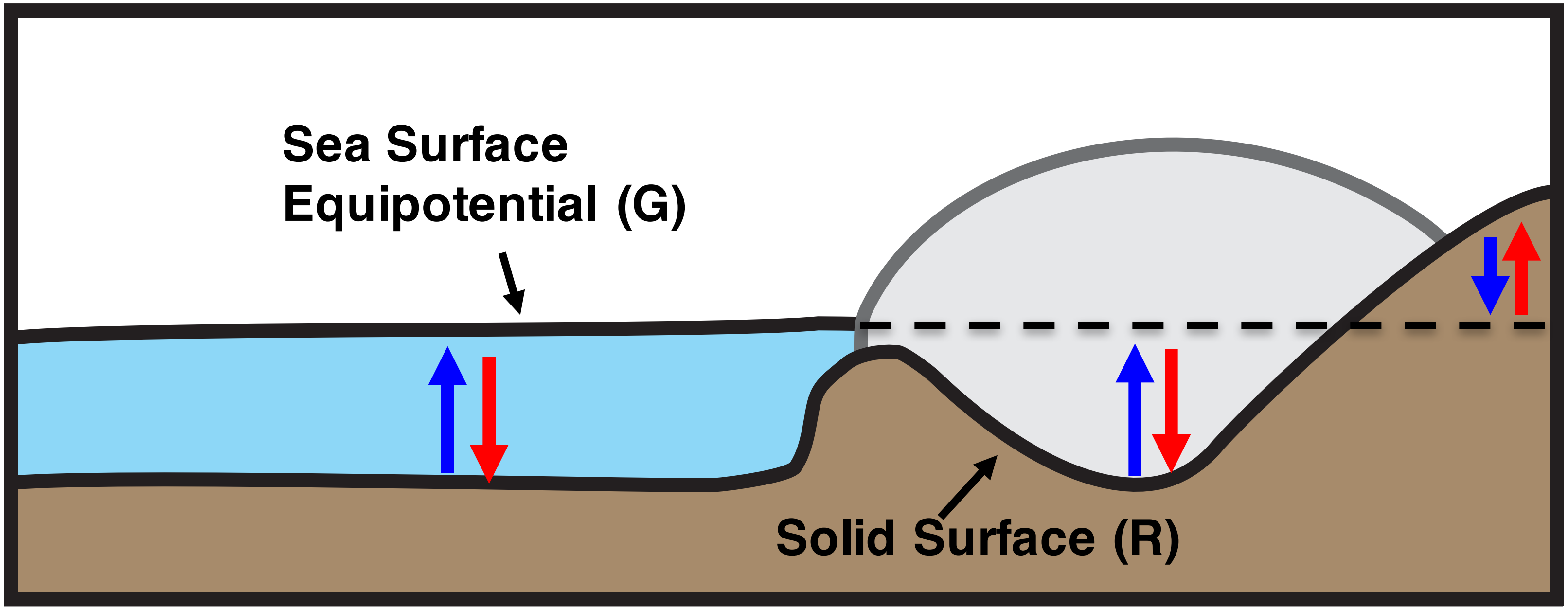
4) Long term affects (as we discussed last week, we may come back to this)

Sea – level changes associated with ice!

Quick Mental Break!

King Penguins,
Photo credit: Leslie Frost, Environmental Manager at Australia Antarctic Division
(Acquired in an NYC taxi cab)

2a. The sea level equation



Static Sea Level

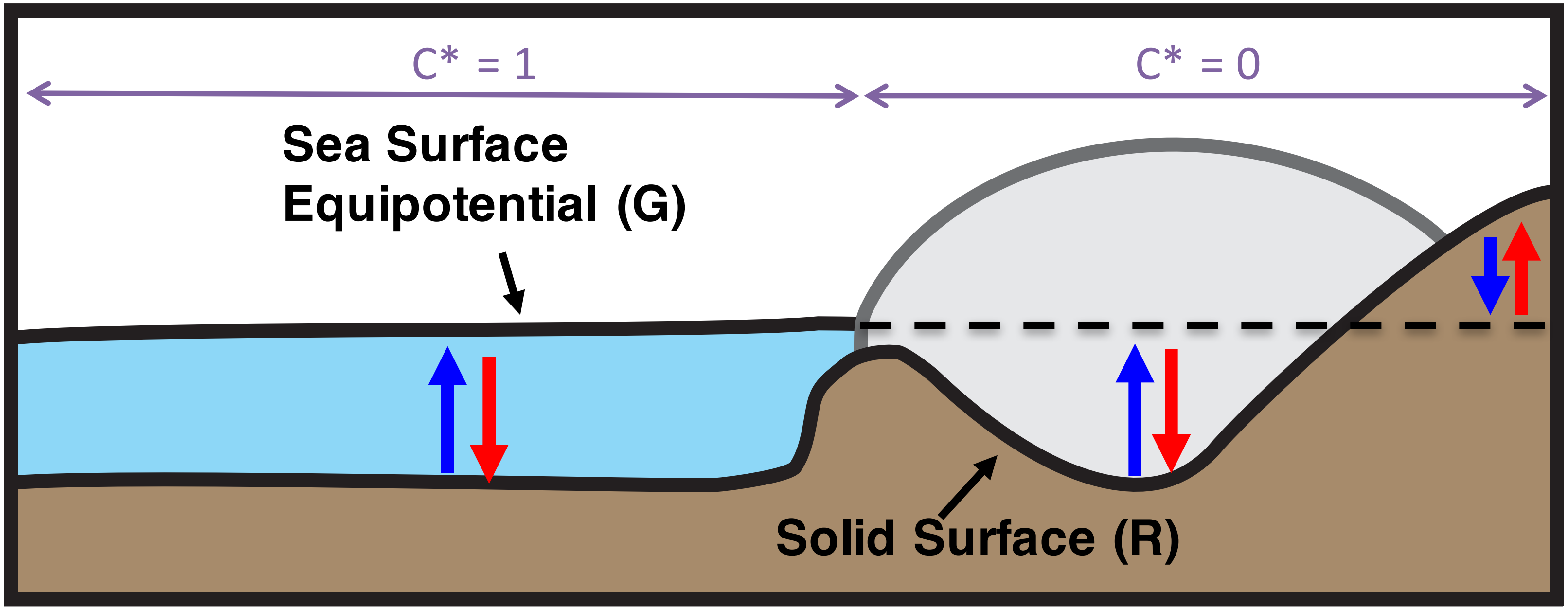
$$SL(\theta, \psi, t) \equiv G(\theta, \psi, t) - R(\theta, \psi, t).$$

Land Elevation (Topography)

$$T(\theta, \psi, t) \equiv R(\theta, \psi, t) - G(\theta, \psi, t),$$
$$= -SL(\theta, \psi, t).$$

One more definition….

2a. The Sea Level Equation



Static Sea Level $$SL(\theta, \psi, t) \equiv G(\theta, \psi, t) - R(\theta, \psi, t).$$

Land Elevation (Topography) $$T(\theta, \psi, t) \equiv R(\theta, \psi, t) - G(\theta, \psi, t), \\ = -SL(\theta, \psi, t).$$

Ocean Depth: $$S(\theta, \psi, t_j) = SL(\theta, \psi, t_j)\, C^*(\theta, \psi, t_j)$$

Ocean Function: $$C^*(\theta, \psi, t_j) = \begin{cases} 1 & \text{if } SL(\theta, \psi, t_j) > 0 \text{ and there is no grounded ice} \\ 0 & \text{elsewhere,} \end{cases}$$

2a. The Sea Level Equation

Consider a change from the initial state at time t_o to a new state at time t_j:

$$G(\theta, \psi, t_j) = G(\theta, \psi, t_0) + \Delta G(\theta, \psi, t_j),$$

$$R(\theta, \psi, t_j) = R(\theta, \psi, t_0) + \Delta R(\theta, \psi, t_j),$$

$$SL(\theta, \psi, t_j) = SL(\theta, \psi, t_0) + \Delta SL(\theta, \psi, t_j),$$

$$T(\theta, \psi, t_j) = T(\theta, \psi, t_0) + \Delta T(\theta, \psi, t_j),$$

With some algebra, we can find and expression for ΔS …

2a. The Sea Level Equation

Generalized Sea-Level Equation:

$$\Delta S(\theta, \psi, t_j) = \Delta SL(\theta, \psi, t_j) C(\theta, \psi, t_j) - T(\theta, \psi, t_0)[C(\theta, \psi, t_j) - C(\theta, \psi, t_0)],$$

$$C^*(\theta, \psi, t_j) = \begin{cases} 1 & \text{if } SL(\theta, \psi, t_j) > 0 \text{ and there is no grounded ice} \\ 0 & \text{elsewhere,} \end{cases}$$

2a. The Sea Level Equation

Generalized Sea-Level Equation

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

$$\Delta S(\theta, \psi, t_j) = \boxed{\Delta SL(\theta, \psi, t_j) C(\theta, \psi, t_j)}$$
$$- T(\theta, \psi, t_0)[C(\theta, \psi, t_j) - C(\theta, \psi, t_0)],$$

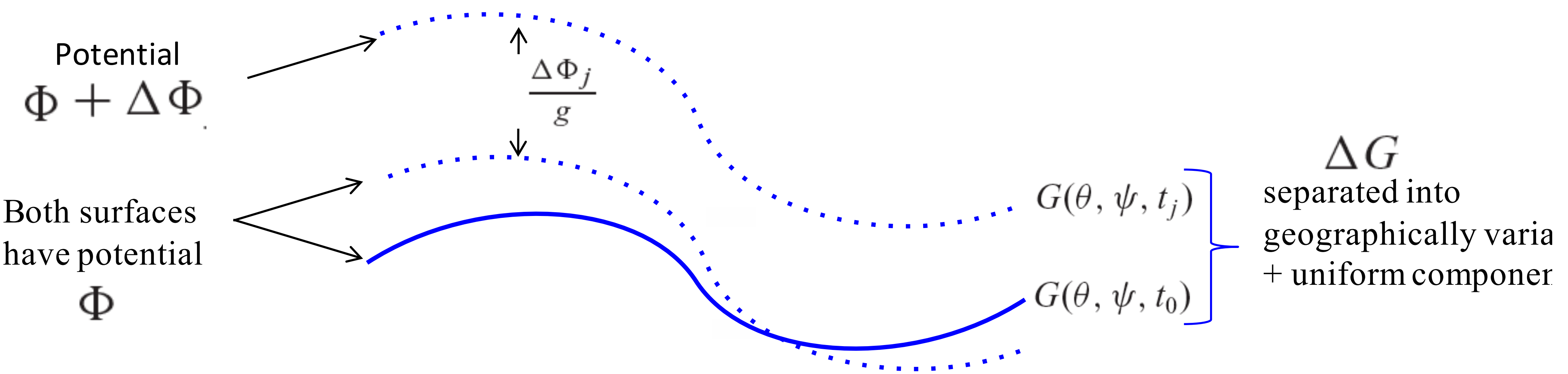
$$C^*(\theta, \psi, t_j) = \begin{cases} 1 & \text{if } SL(\theta, \psi, t_j) > 0 \text{ and there is no grounded ice} \\ 0 & \text{elsewhere,} \end{cases}$$

2a. The Sea Level Equation

Generalized Sea-Level Equation

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

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



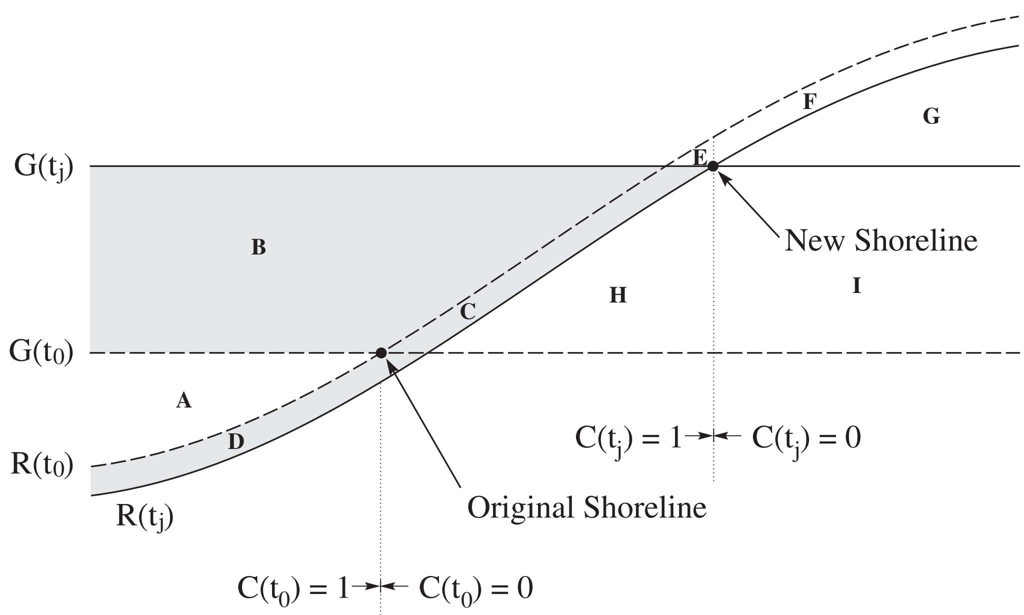
2a. The Sea Level Equation

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



2a. The Sea Level Equation

Generalized Sea-Level Equation

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

Integral equation – RHS depends on ocean depth changes :

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

Ocean depth changes

2a. The Sea Level Equation

SEA LEVEL MODEL INGREDIENTS

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

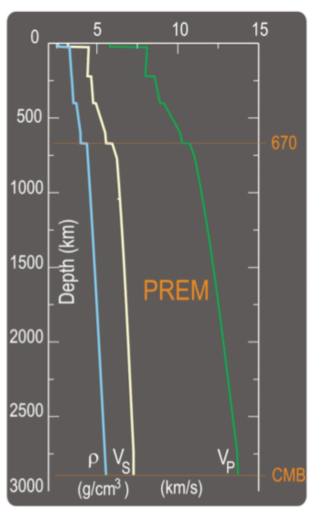
EARTH FORCING

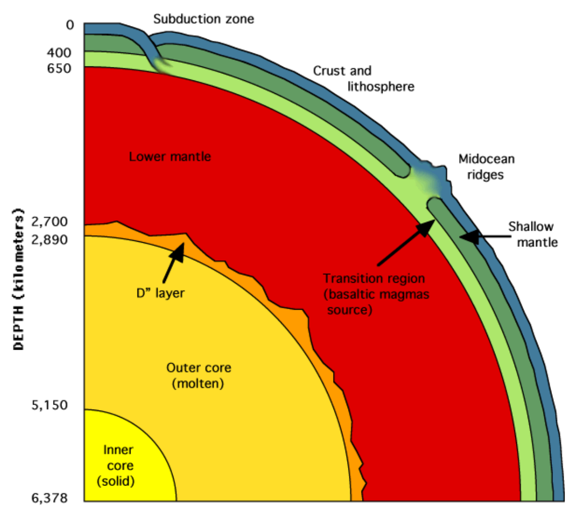
Ice location and thickness (inferred from modeling GIA data, e.g. sea level)

EARTH MODEL

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

Physics…

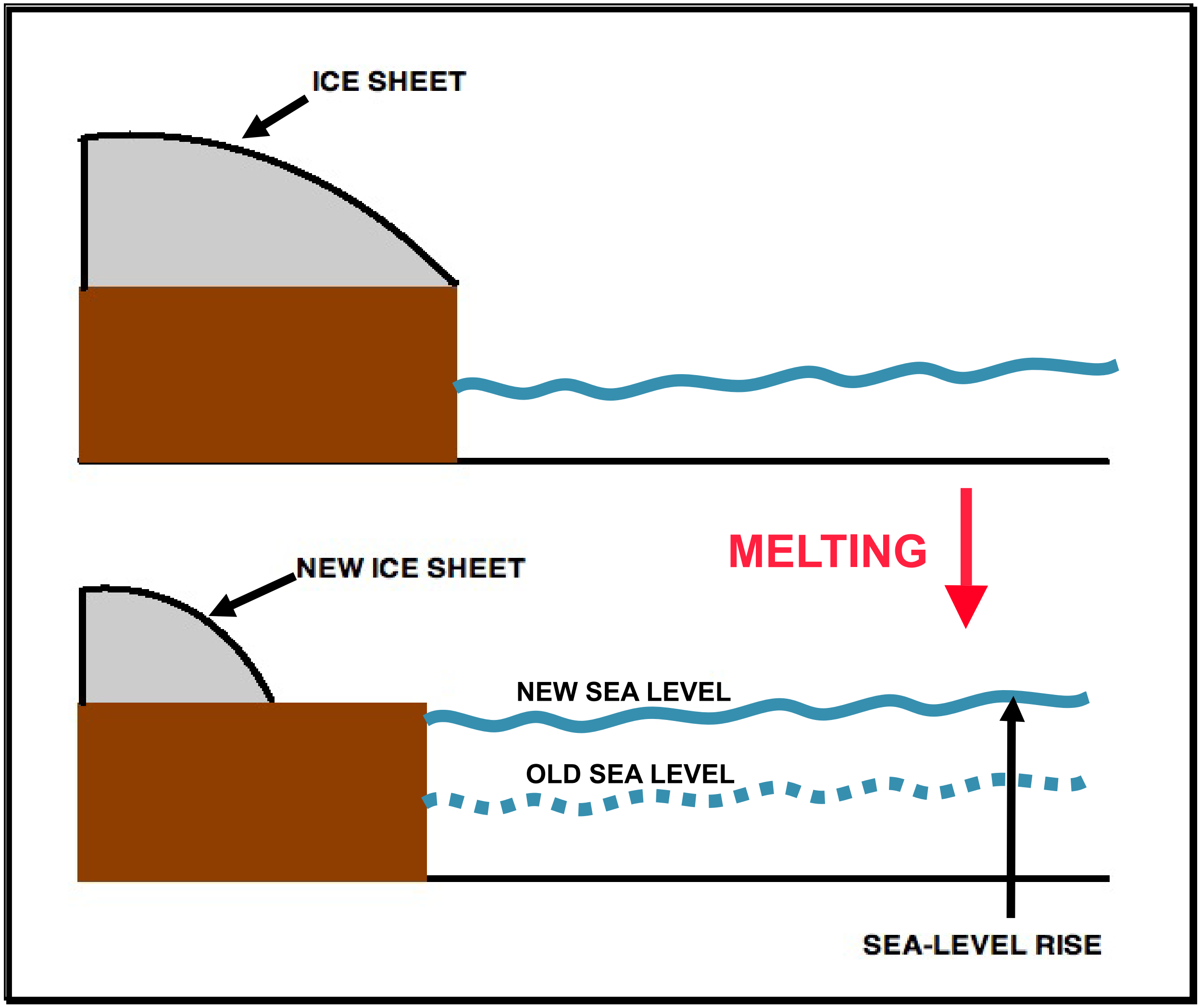




**strong temperature dependence, not well constrained

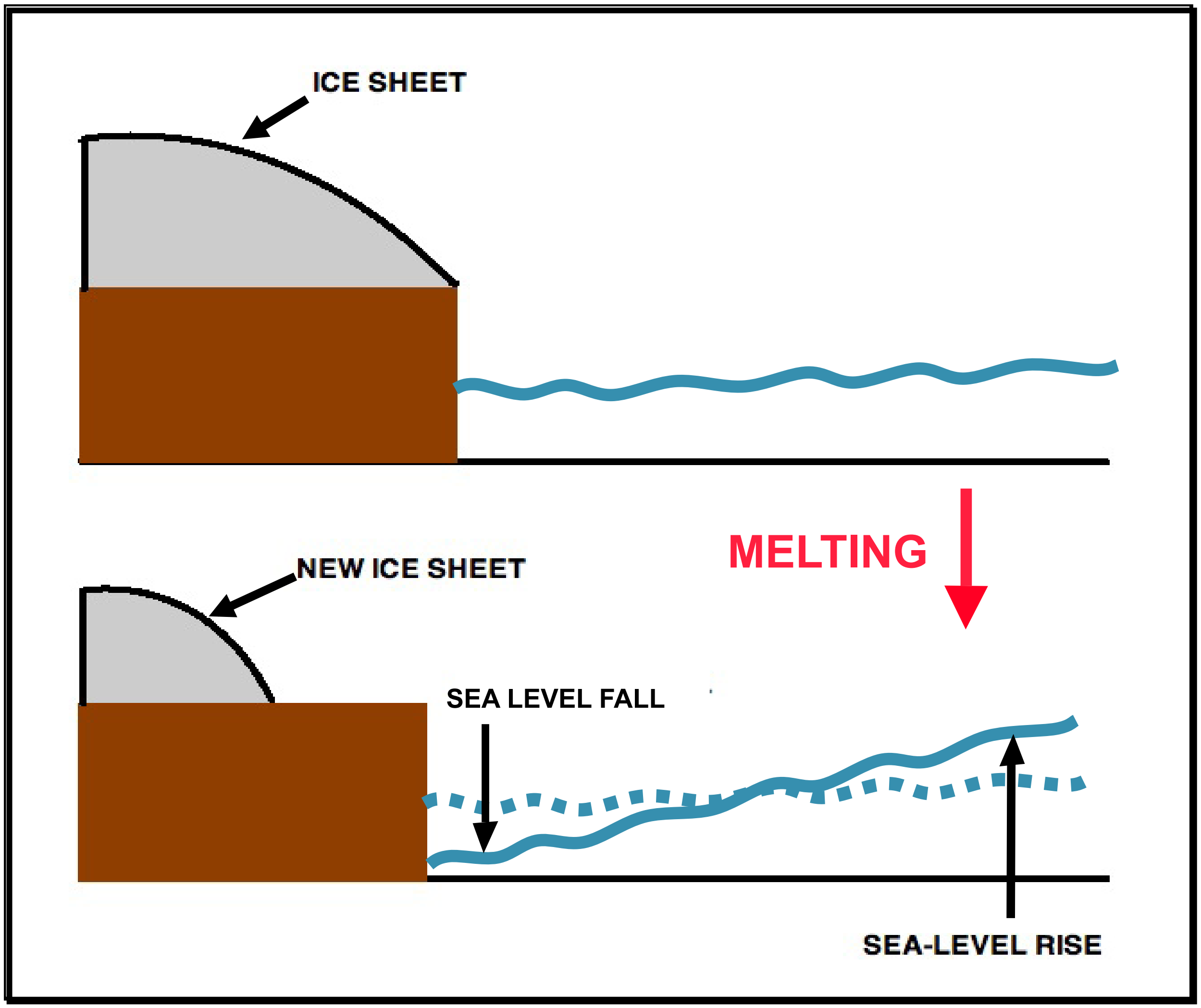
2b. Sea Level Physics

Eustatic Sea Level Change
(a.k.a. the "bath tub" model)



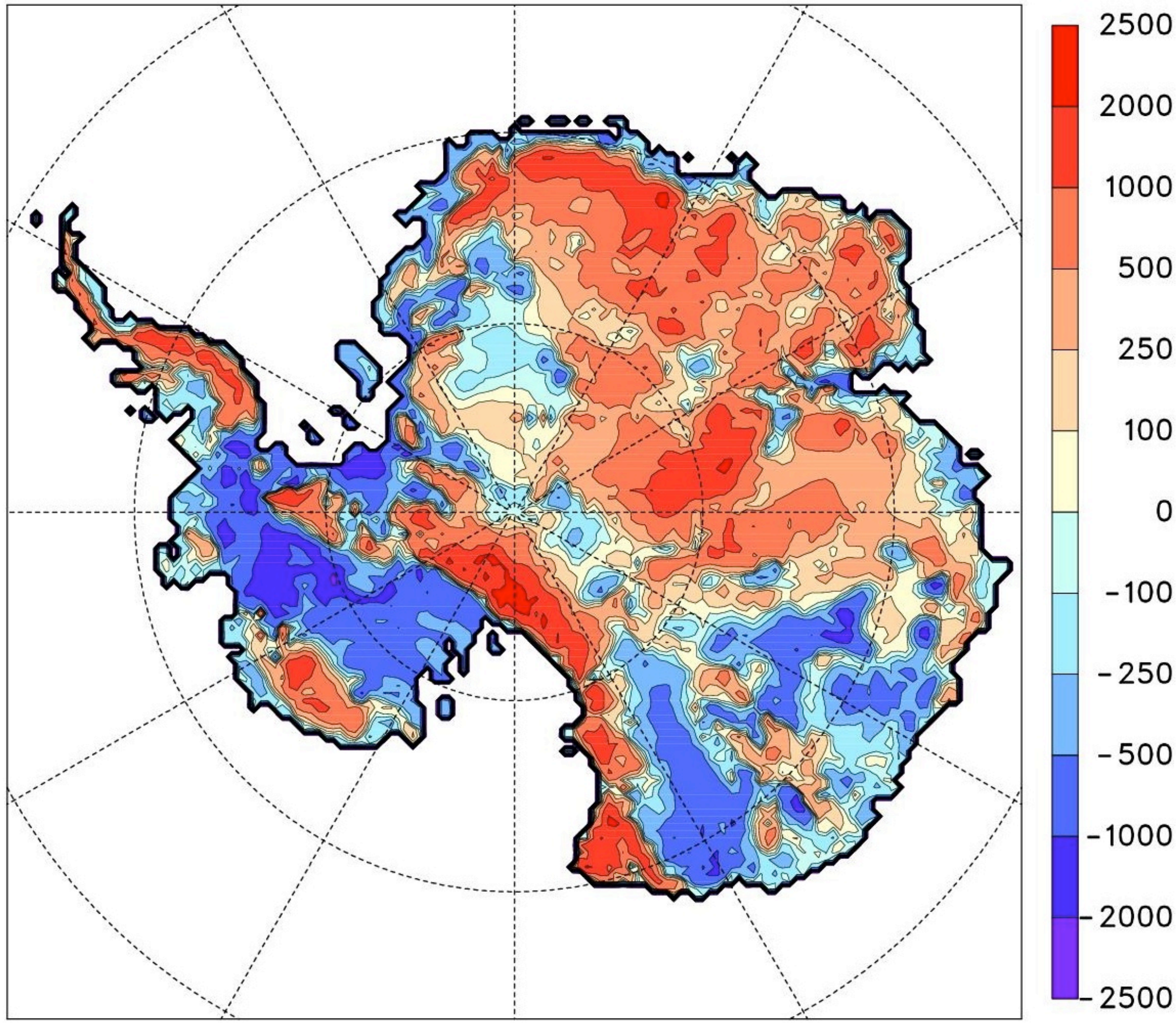
2b. Sea Level Physics

Gravitational Effect on
Sea Level Change

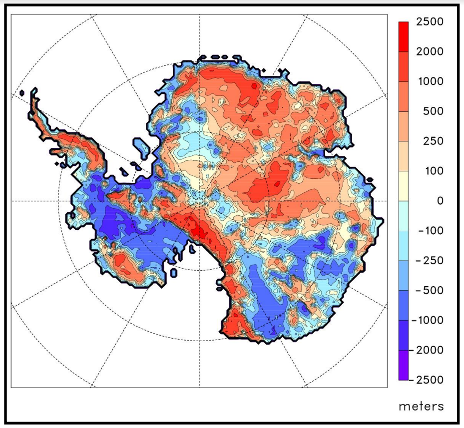


2b. Sea Level Physics

Bedrock Elevation (BEDMAP)



2b. Sea Level Physics: short timescales

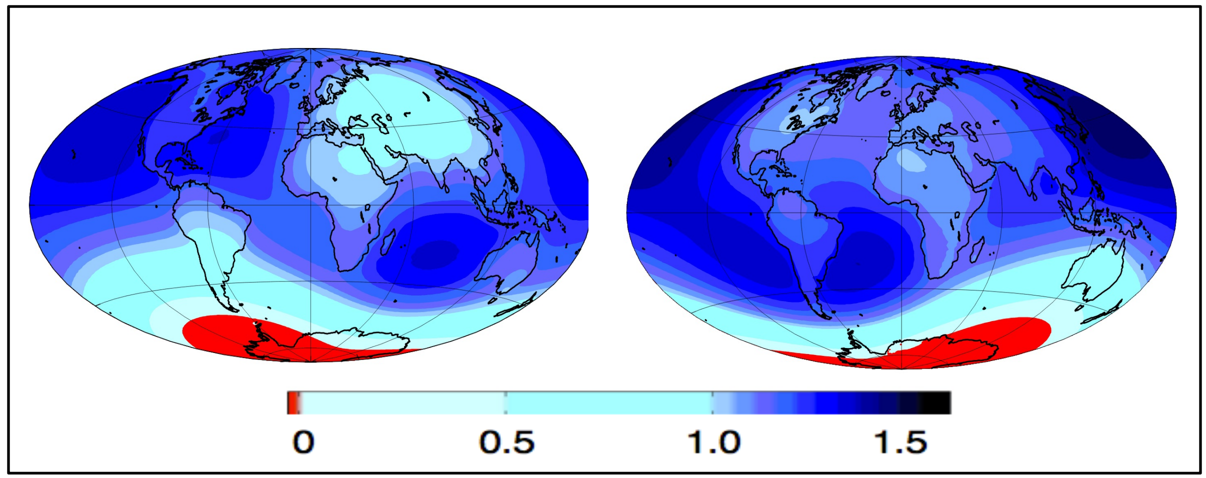


Bedrock Elevation (BEDMAP)

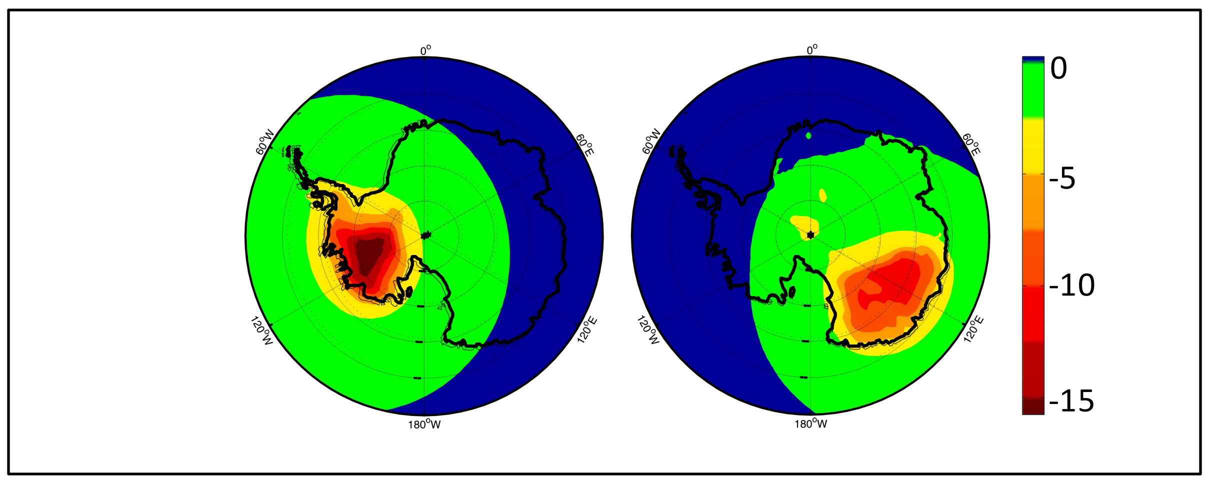
Normalized sea-level change following collapse of marine-based sectors of the Antarctic Ice Sheet

West

East

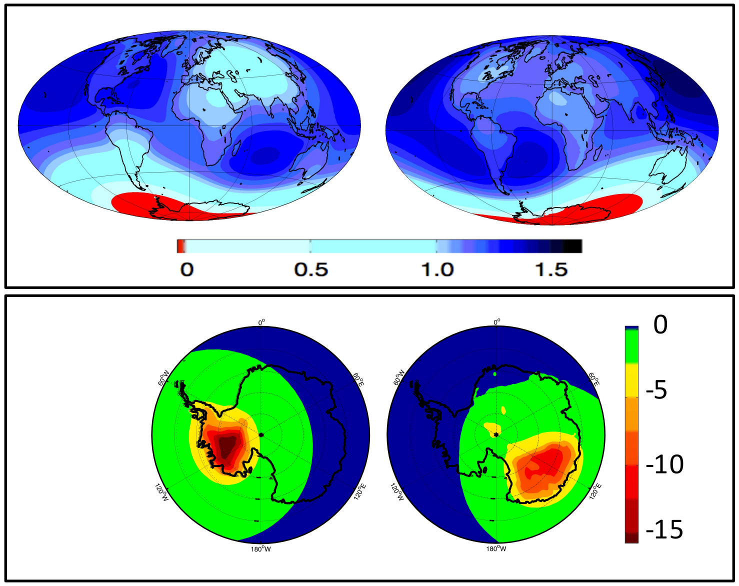


Polar projection focusing on sea level fall in the near-field



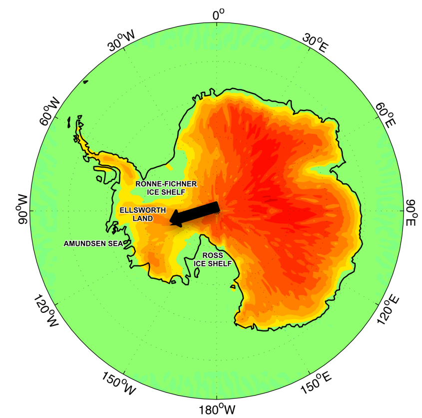
Gomez et al., GJI, 2010

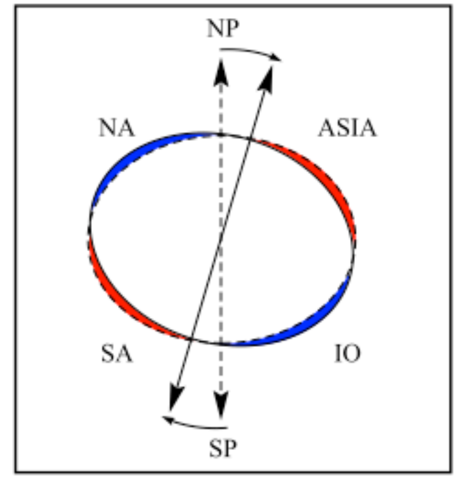
2b. Sea Level Physics: short timescales



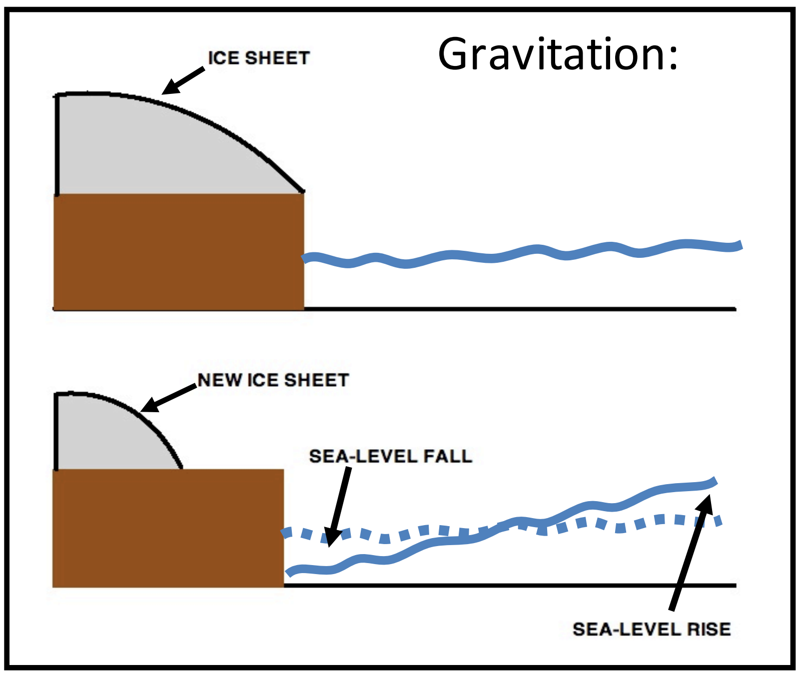
Gomez et al., GJI, 2010

Rotation:

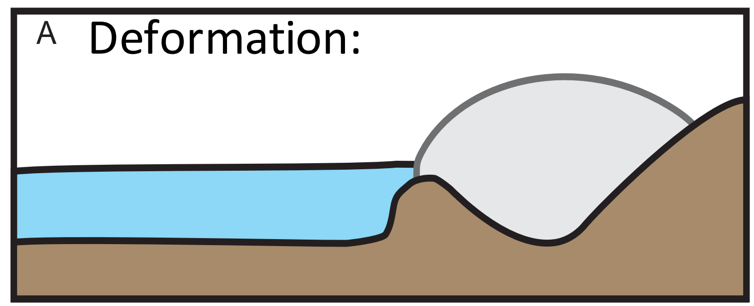


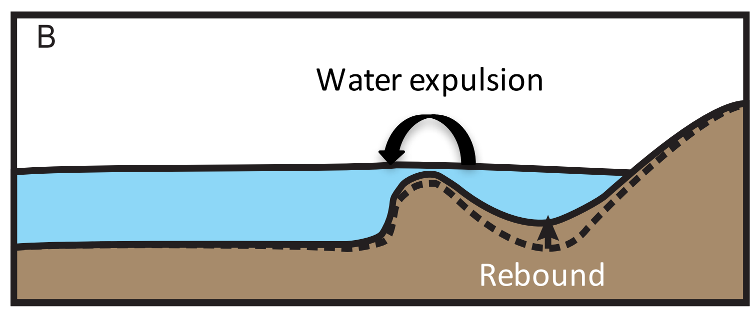


Gravitation:



Deformation:





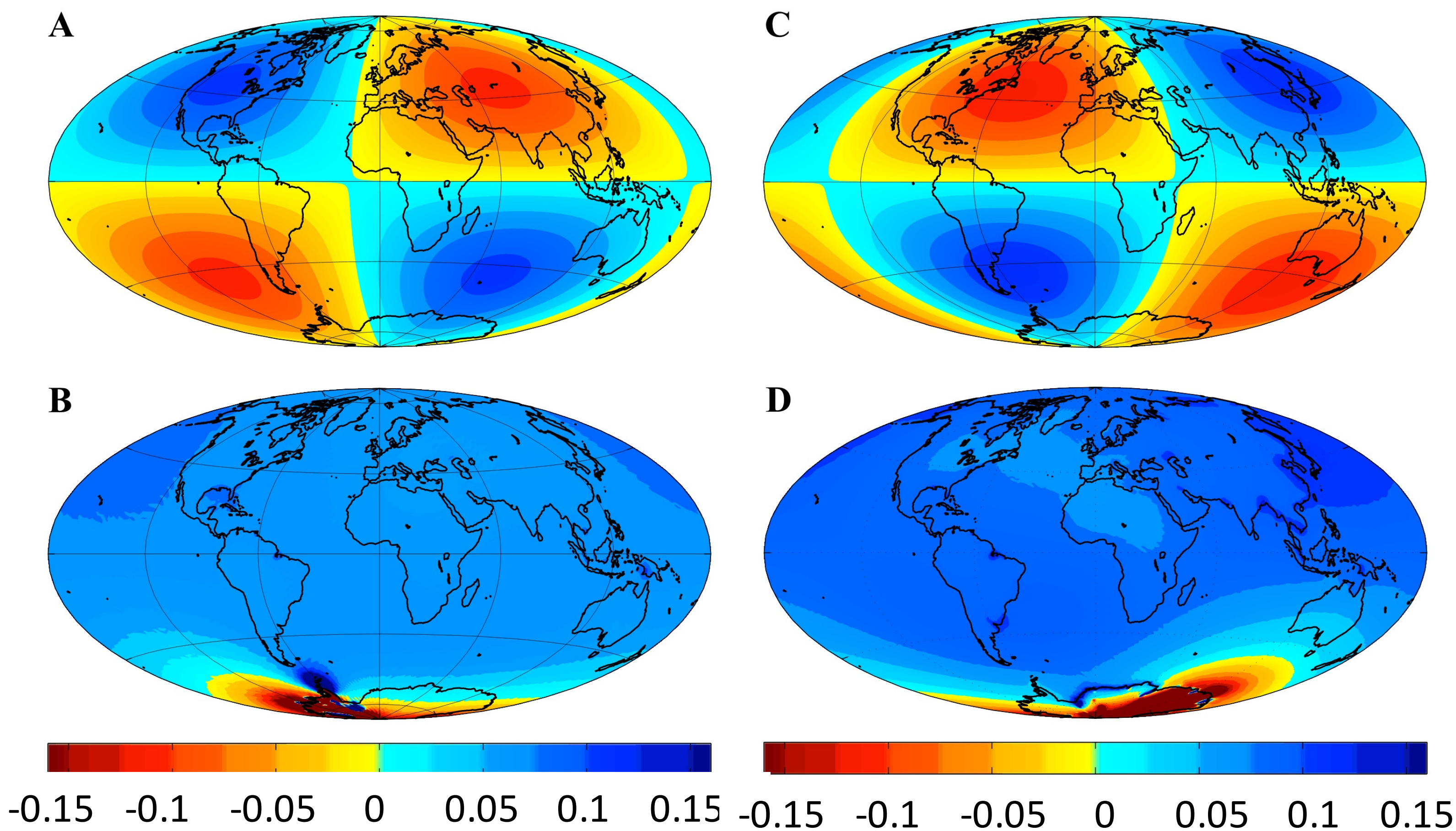
2b. Sea Level Physics: short timescales

WAIS

EAIS

Sea-level change due to rotation

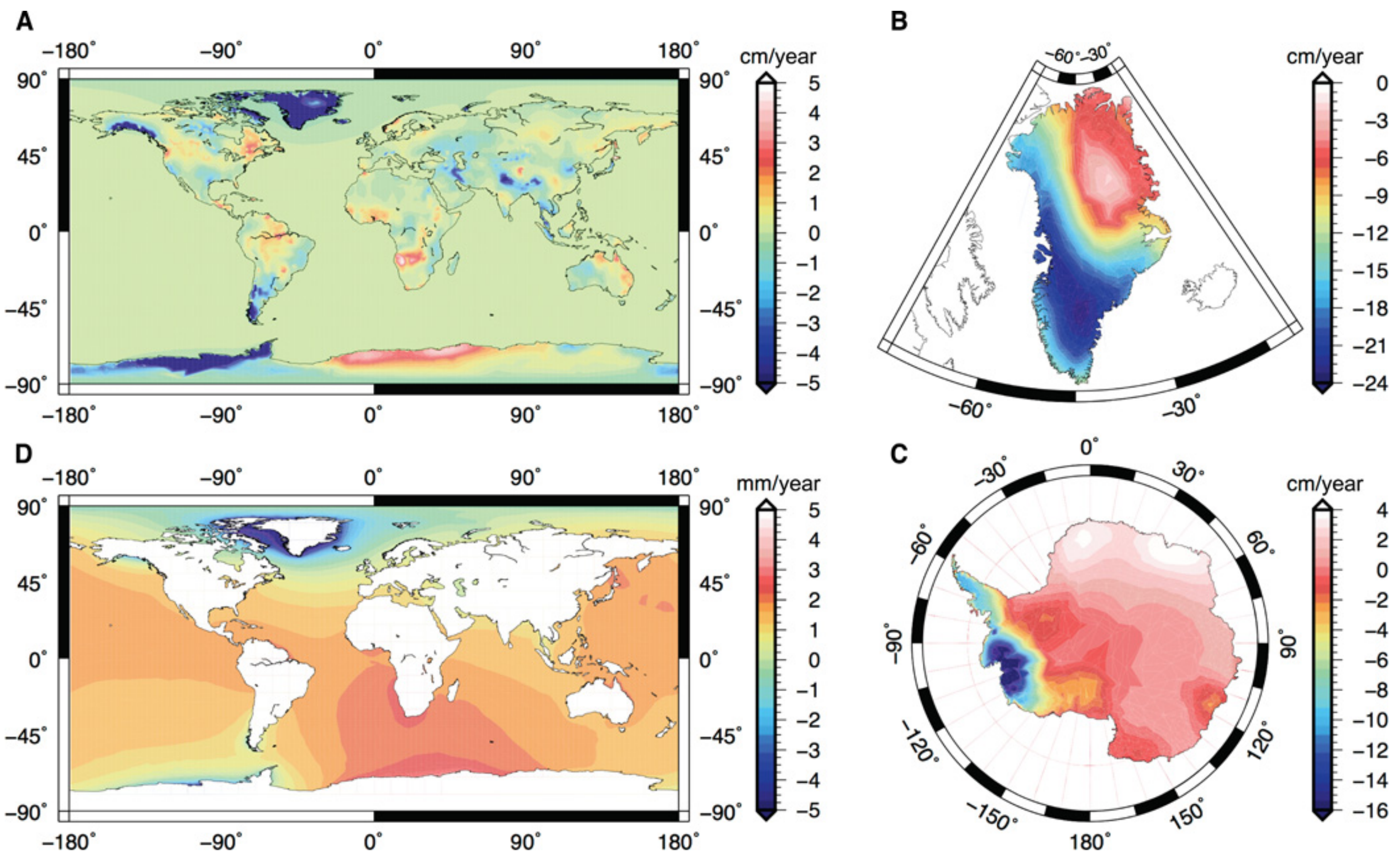
Sea-level change due to expulsion



Gomez et al. (2010)

2b. Sea Level Physics: short timescales

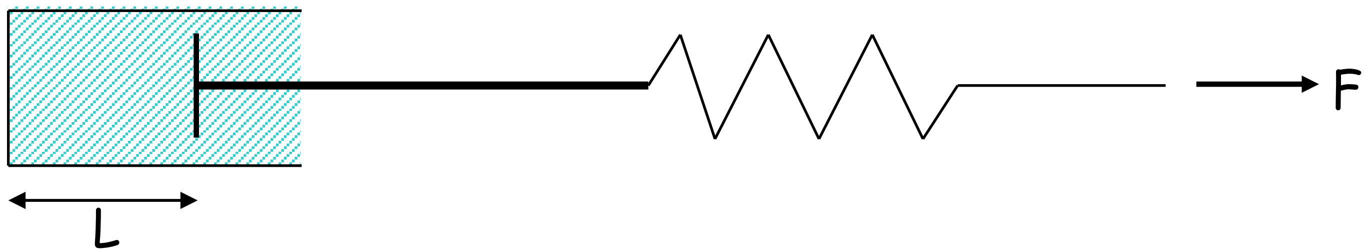
- https://sealevel.nasa.gov/resources/78/cumulative-sea-level-change-since-april-2002



2b. Sea Level Physics: Ice-Age Timescales

The Earth behaves like a visco-elastic body

- -many ways to define such a material
- -assume the following 1-D linear response: "Maxwell Body"



-apply stress: immediate elastic (E) response and then subsequent viscous (v) response:

-for a Maxwell Body:

$$\frac{\Delta L}{L} = \left(\frac{\Delta L}{L}\right)^{E} + \left(\frac{\Delta L}{L}\right)^{v} \Rightarrow$$

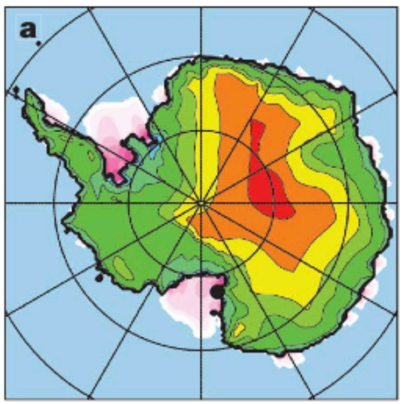
$$\frac{d}{dt}\left(\frac{\Delta L}{L}\right) = \frac{d}{dt}\left(\frac{\Delta L}{L}\right)^{E} + \frac{d}{dt}\left(\frac{\Delta L}{L}\right)^{v} \Rightarrow \frac{d}{dt}e = \frac{d}{dt}\left(\frac{F}{k}\right) + \frac{F}{\eta}$$

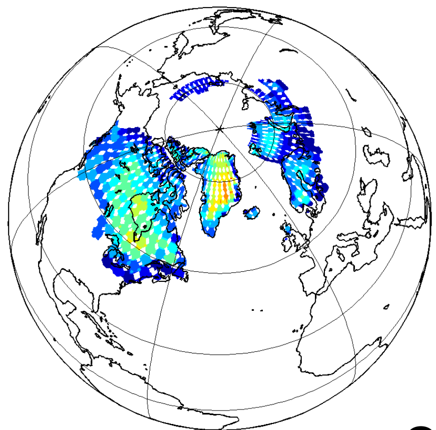
$$\dot{e} = \frac{1}{k}\dot{F} + \frac{1}{\eta}F$$

Constitutive equation (i.e. equation relating stress & strain) for a Maxwell visco-elastic 1-D body

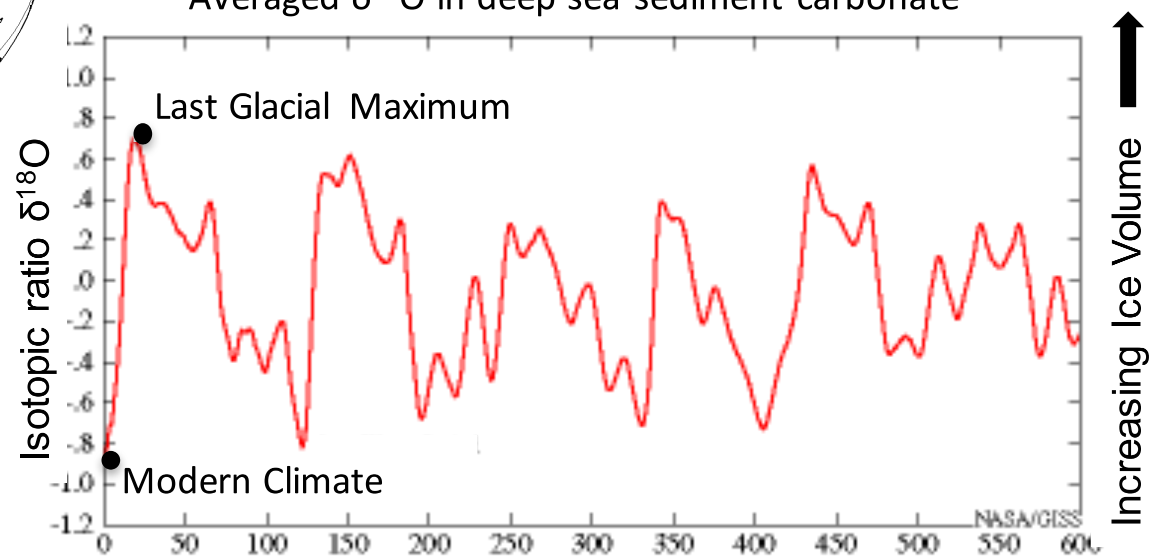
2b. Sea Level Physics: Ice-Age Timescales

Last Glacial Maximum



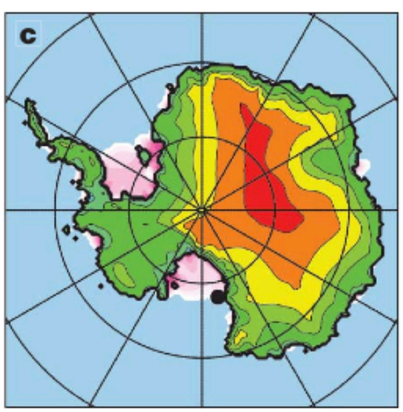


Averaged $\delta^{18}O$ in deep sea sediment carbonate

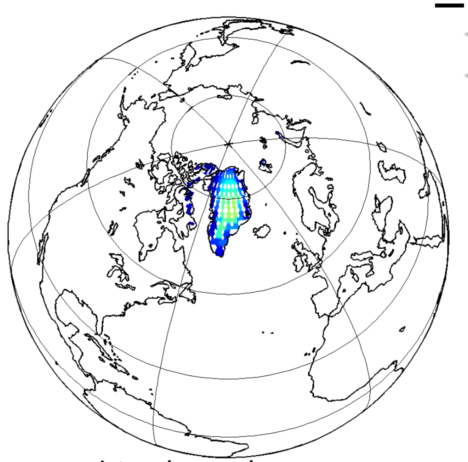


Schmidt (1999)

Modern Climate



Pollard & DeConto (2009)



Peltier (2004) ICE5G

2b. Sea Level Physics: Ice-Age Timescales

MORE
ICE

PA1003 LISIECKI AND RAYMO: PLIOCENE-PLEISTOCENE BENTHIC STACK PA1003

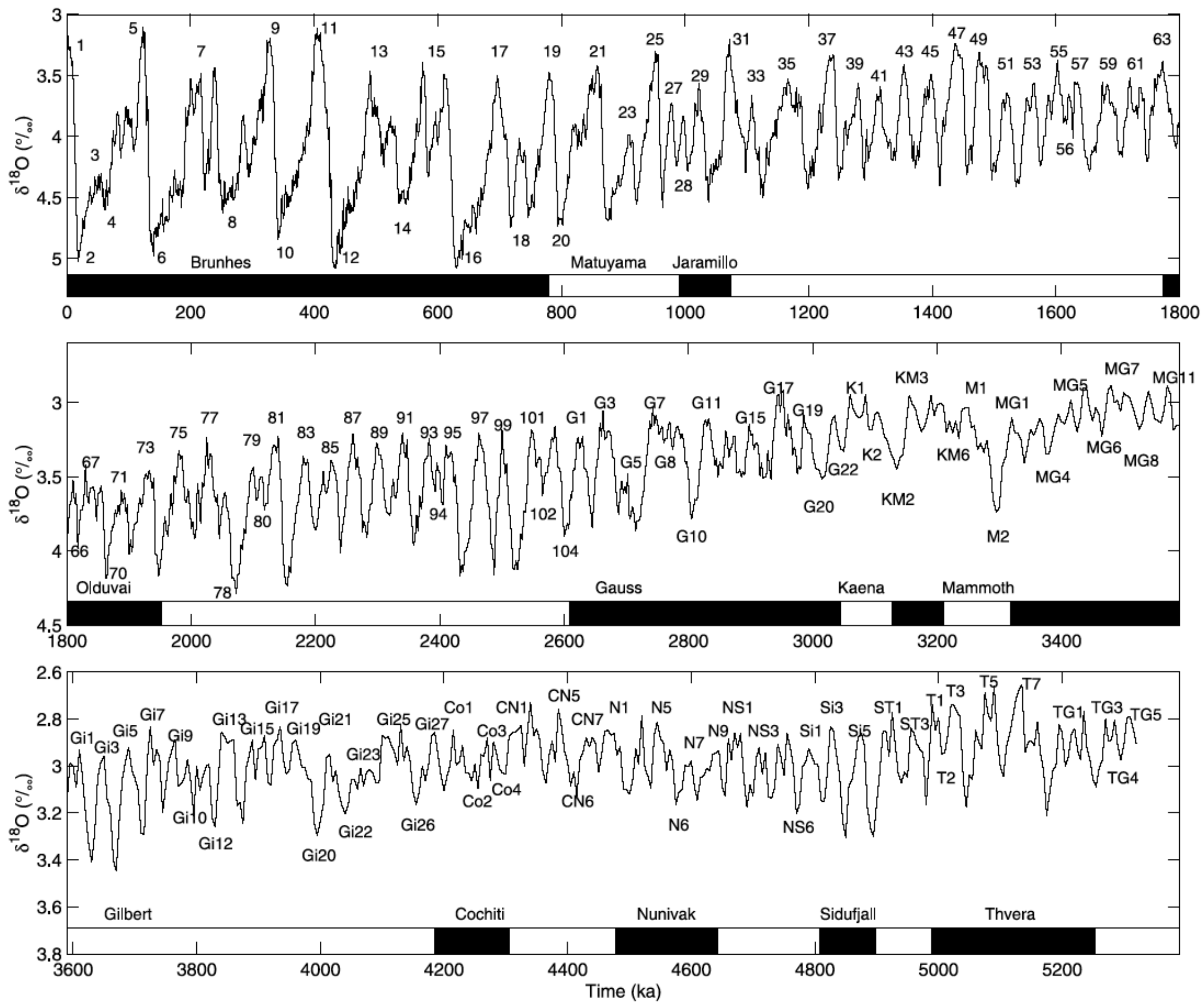
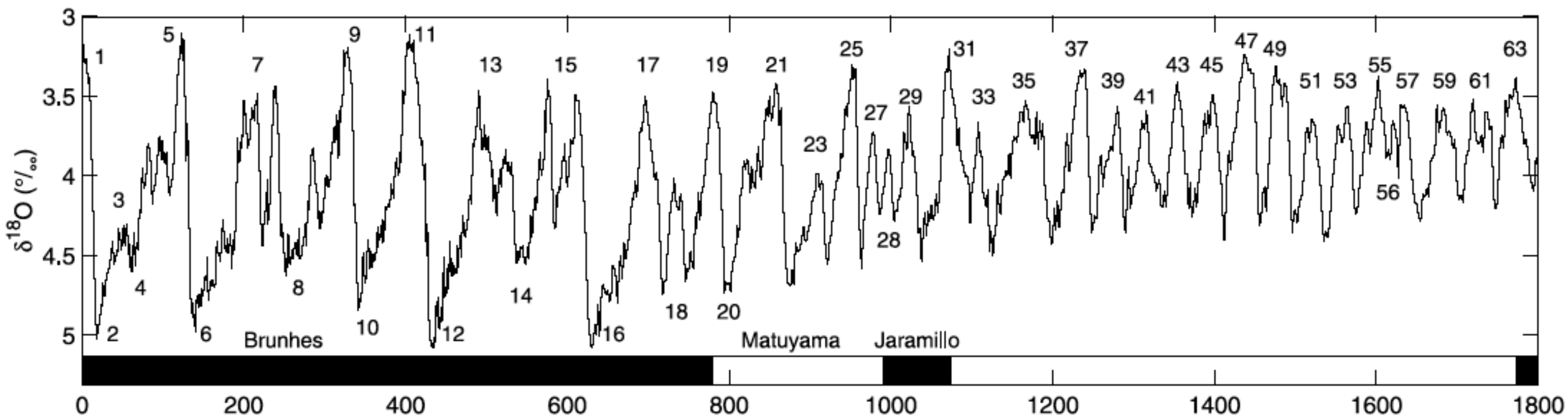


Figure 4. The LR04 benthic $\delta^{18}O$ stack constructed by the graphic correlation of 57 globally distributed benthic $\delta^{18}O$ records. The stack is plotted using the LR04 age model described in section 5 and with new MIS labels for the early Pliocene (section 6.2). Note that the scale of the vertical axis changes across panels.

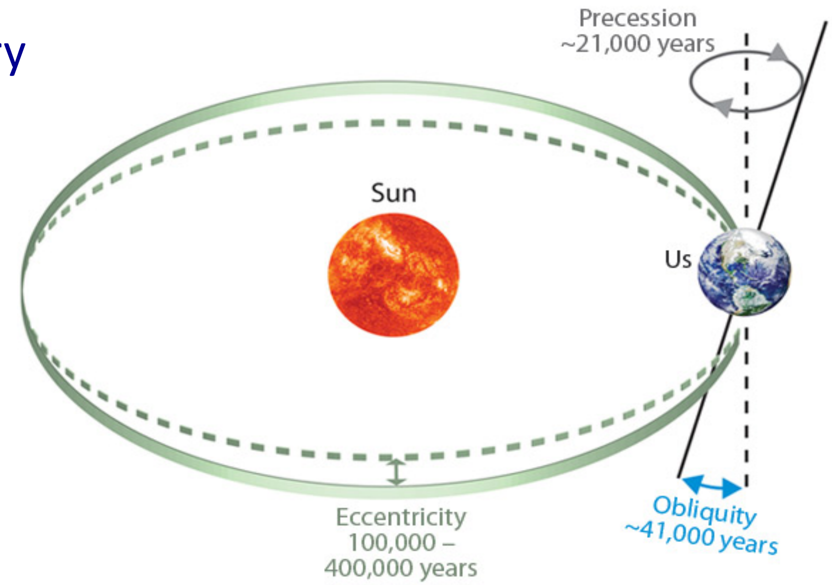
PALEOCEANOGRAPHY, VOL. 20, PA1003, doi:10.1029/2004PA001071, 2005

2b. Sea Level Physics: Ice-Age Timescales

MORE ICE

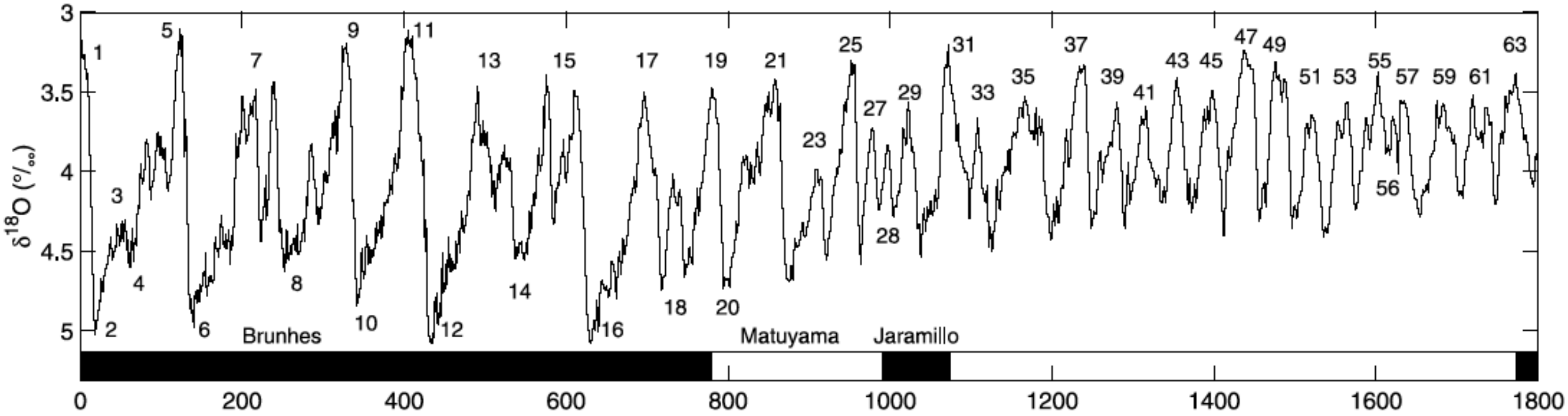


Milankovitch Theory



2b. Sea Level Physics: Ice-Age Timescales

MORE
ICE

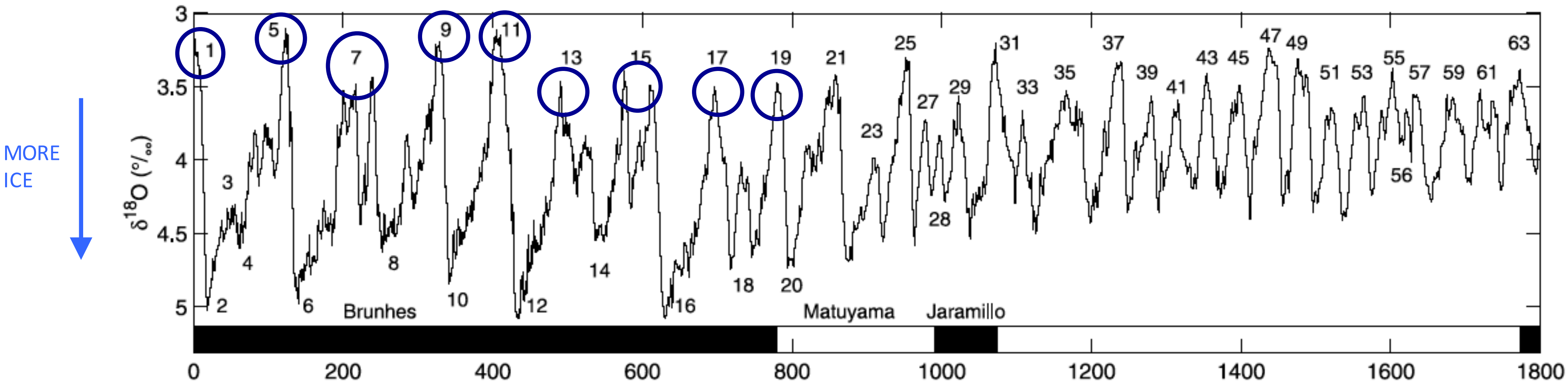


Transition from ice age cycles
with a dominant 40 kyr period to
cycles with a 100 kyr period.

Clark et al. (Paleoceanography, 1998)
Huybers (Science, 2006)
Raymo et al. (Science, 2006)

2b. Sea Level Physics: Ice-Age Timescales

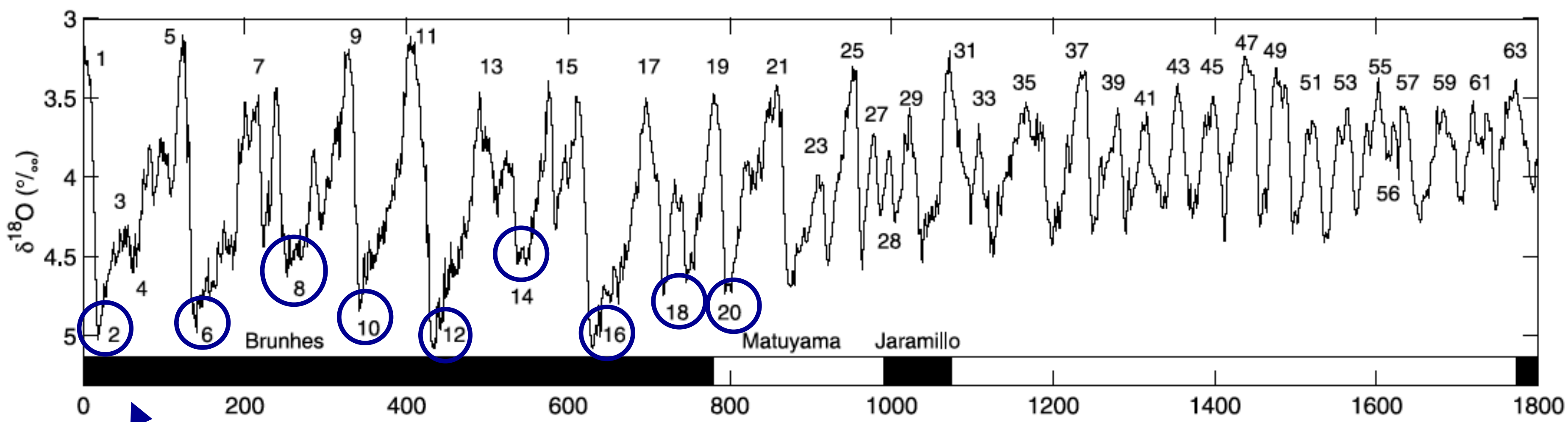
Interglacials …



2b. Sea Level Physics: Ice-Age Timescales

Glacial Maxima …

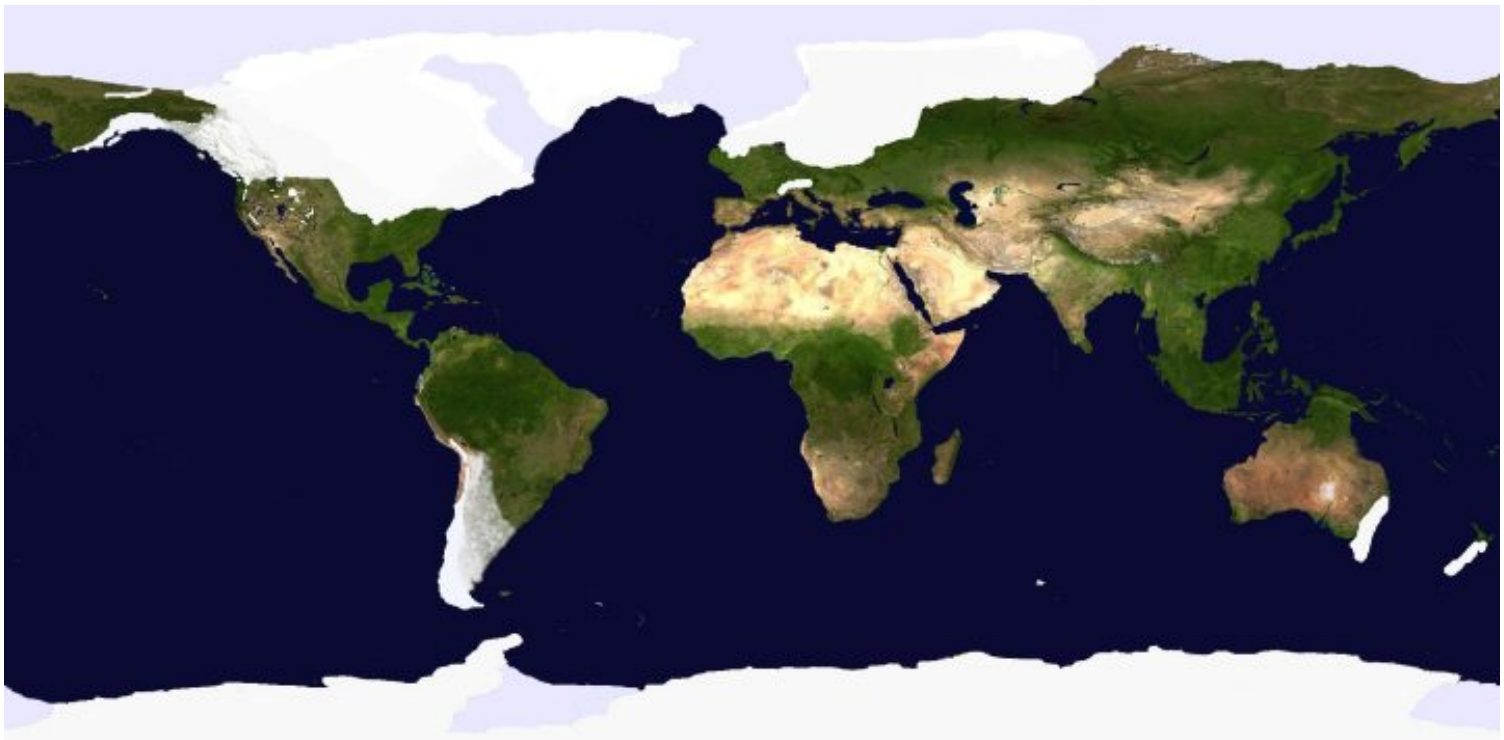
MORE
ICE



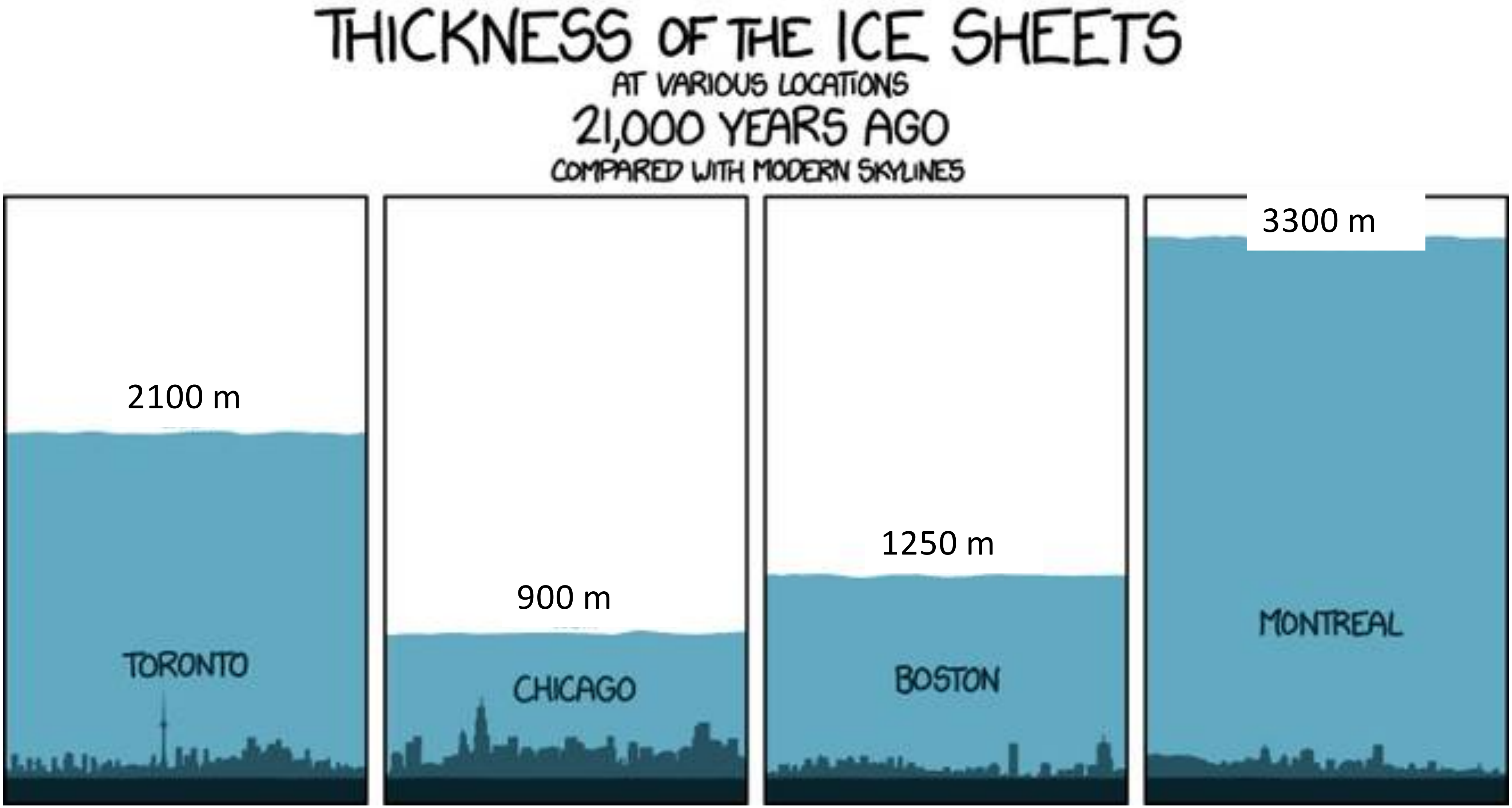
Last Glacial
Maximum (LGM)

2b. Sea Level Physics: Ice-Age Timescales

LGM



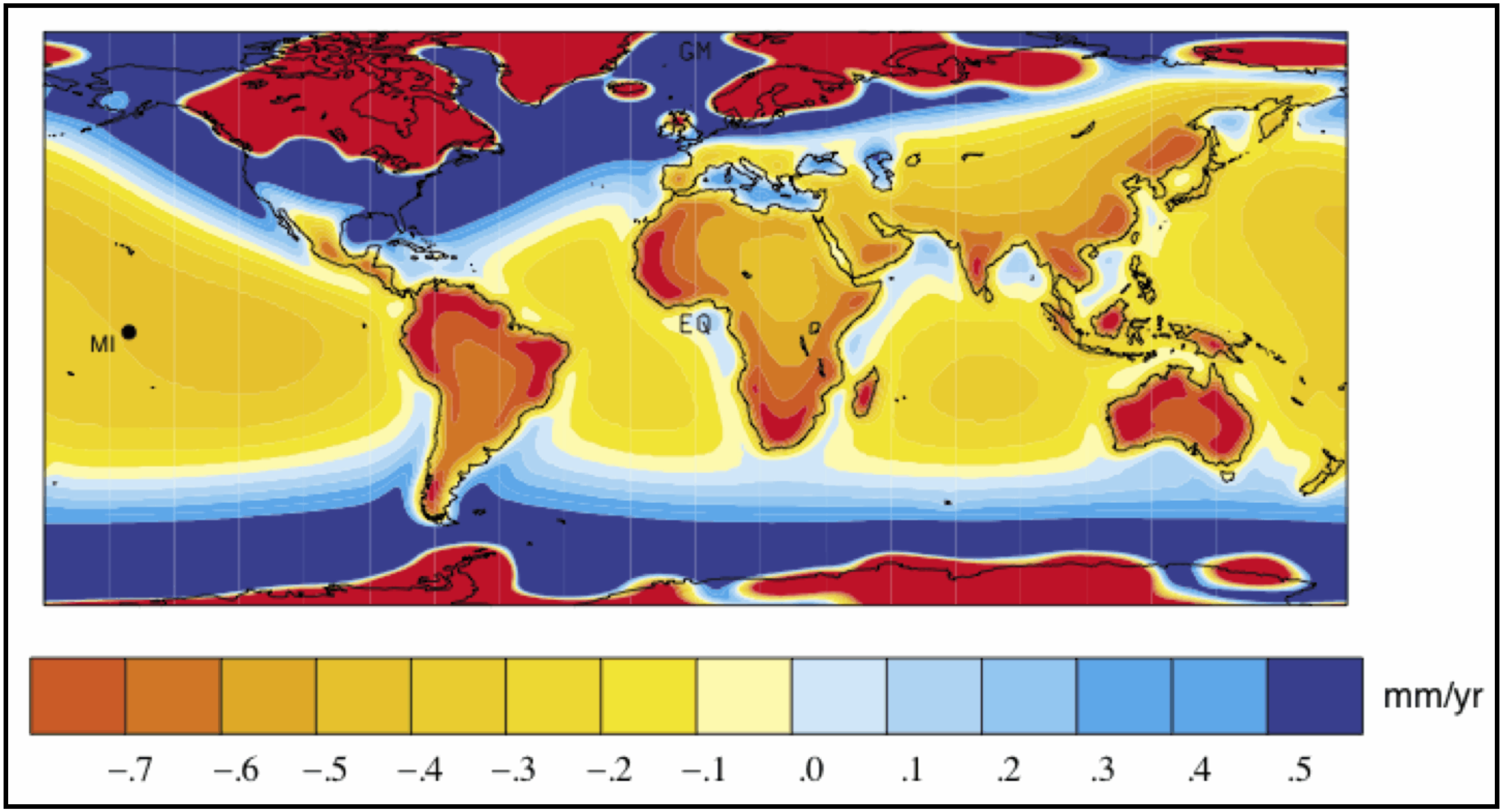
… difference in ice volume relative to the present-day is sufficient to raise globally averaged sea level by ~130 m (~ ½ of this is associated with the Laurentide ice


THICKNESS OF THE ICE SHEETS
AT VARIOUS LOCATIONS
21,000 YEARS AGO
COMPARED WITH MODERN SKYLINES
2100 m
TORONTO
900 m
CHICAGO
1250 m
BOSTON
3300 m
MONTREAL

xkcd

2b. Sea Level Physics: Ice-Age Timescales

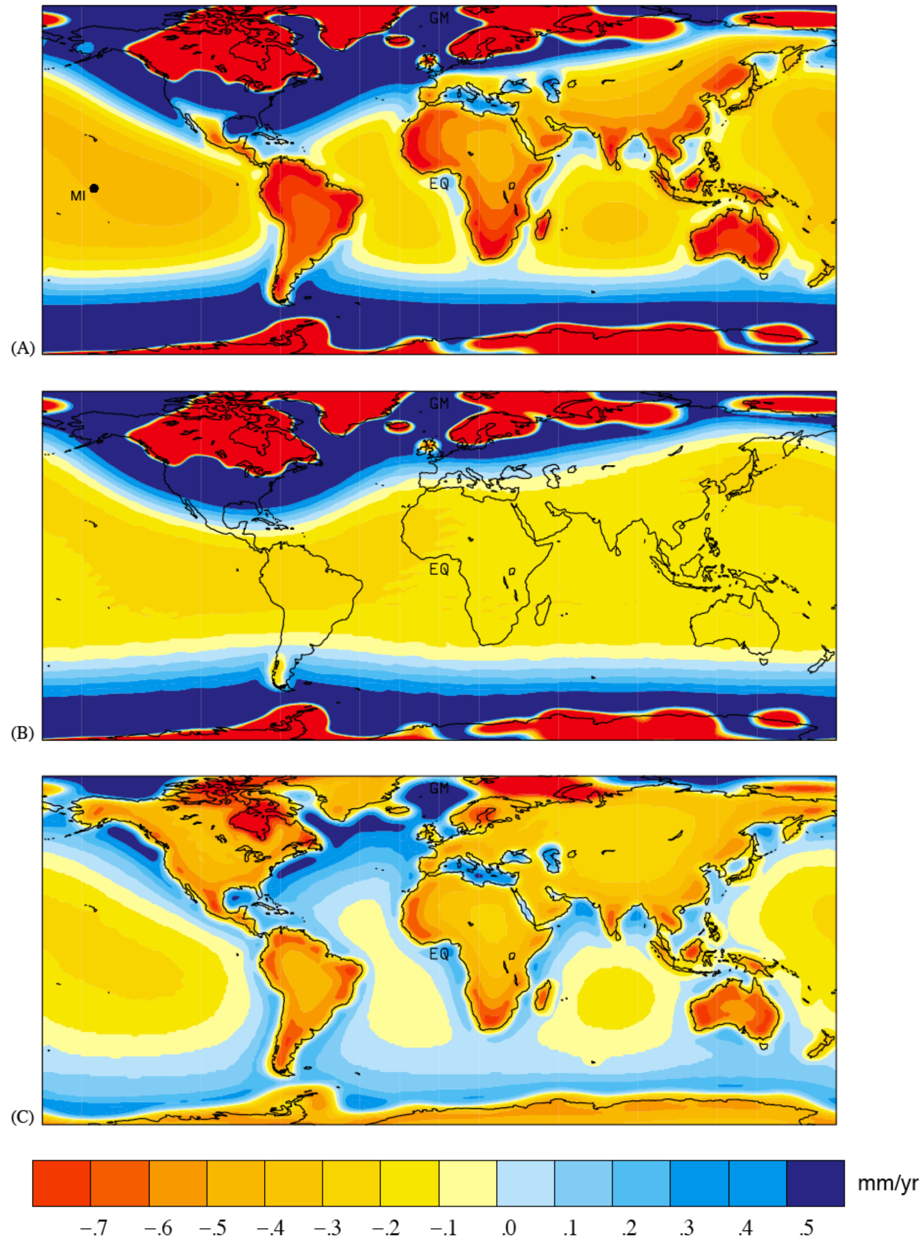
Numerical prediction of the present-day rate of change of global sea level due to ongoing GIA effects from the last ice age



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



TOTAL

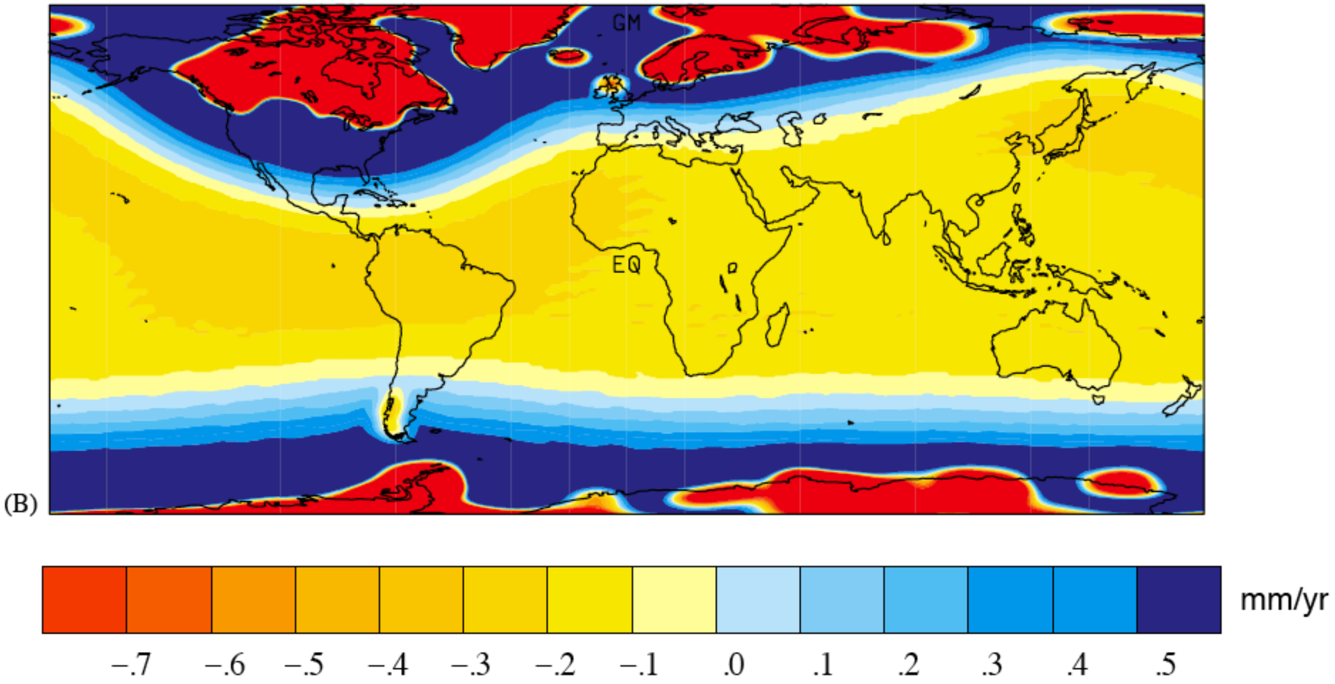
ICE

OCEAN

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

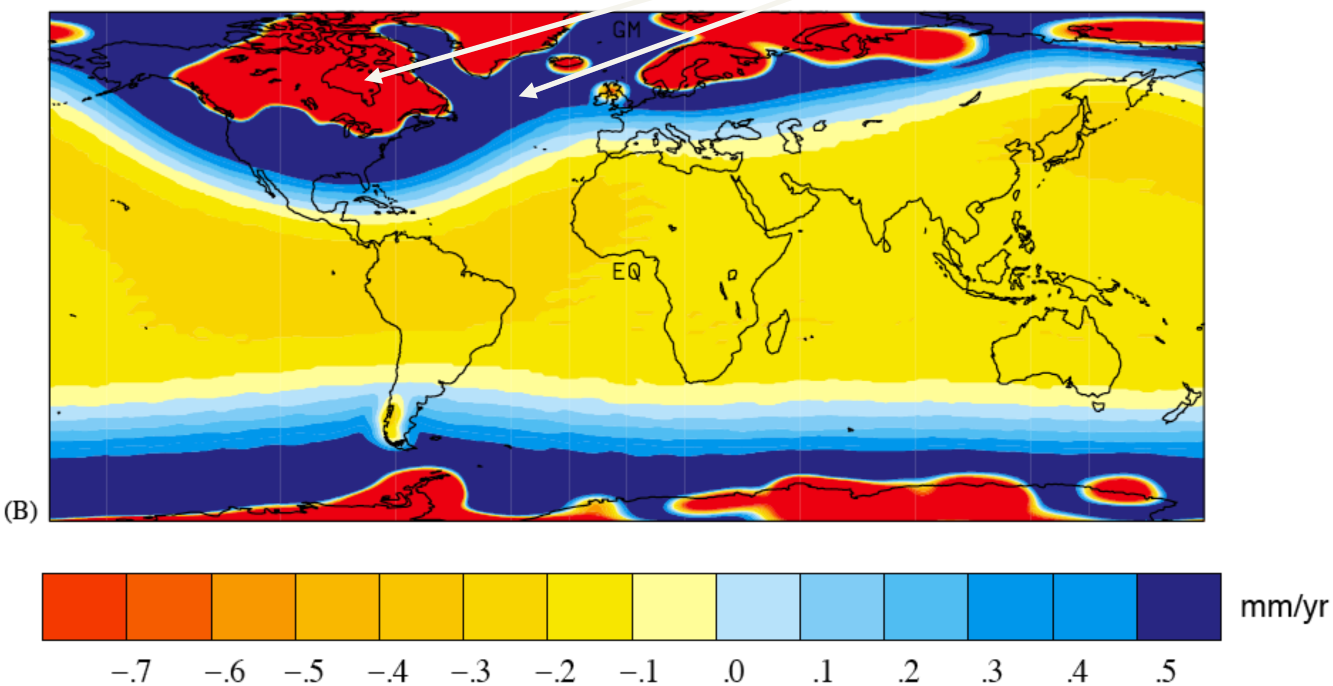


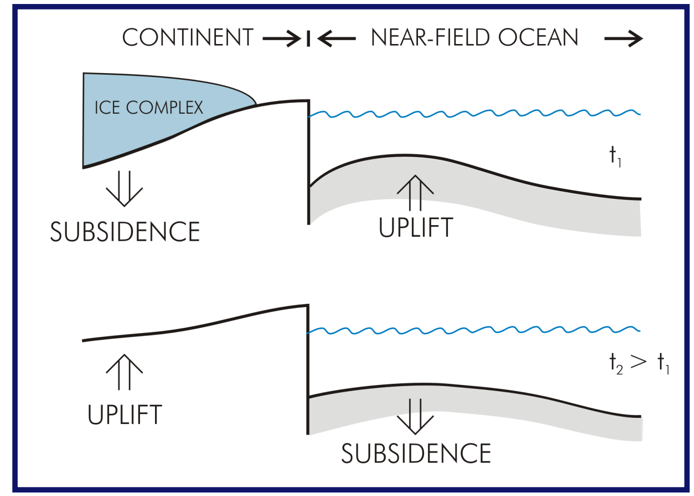
Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

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

NEAR FIELD

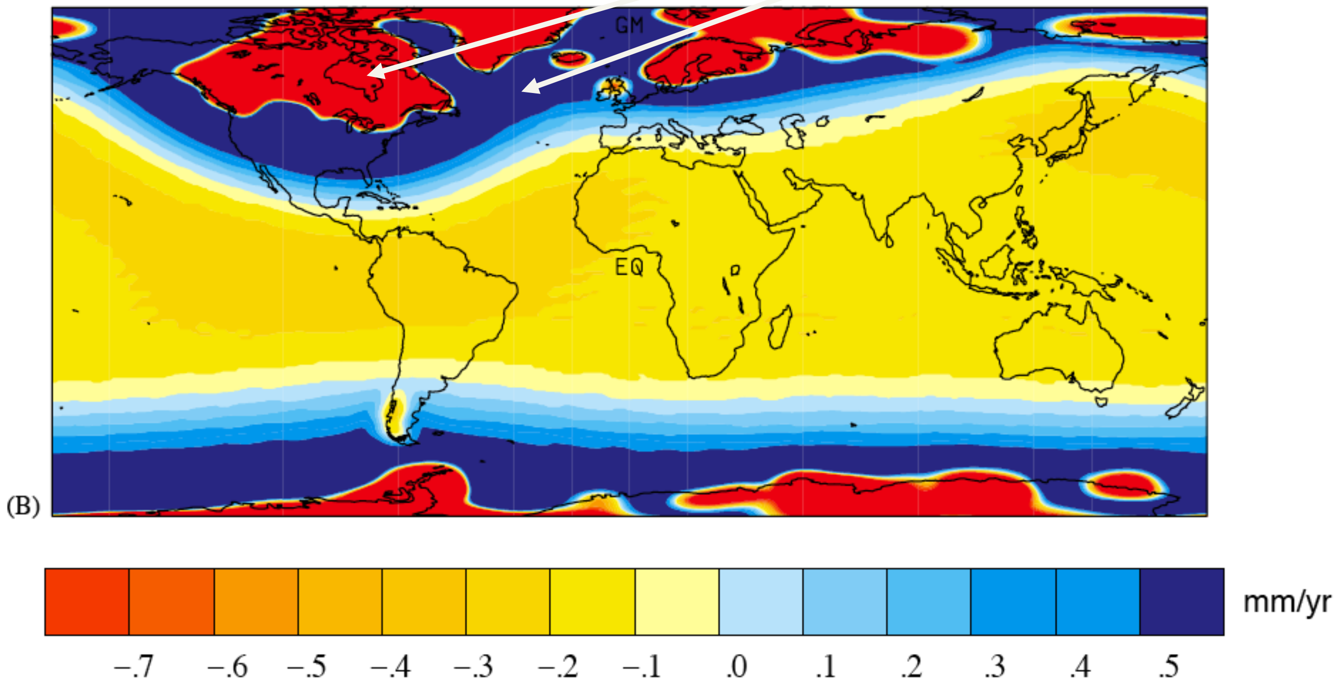




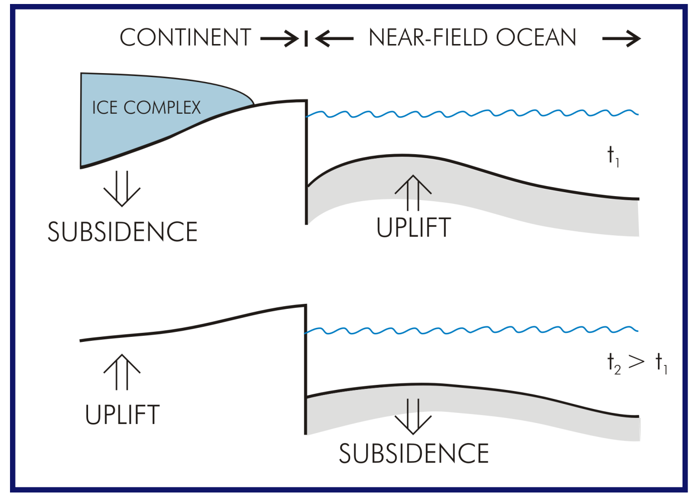
Ice Signal

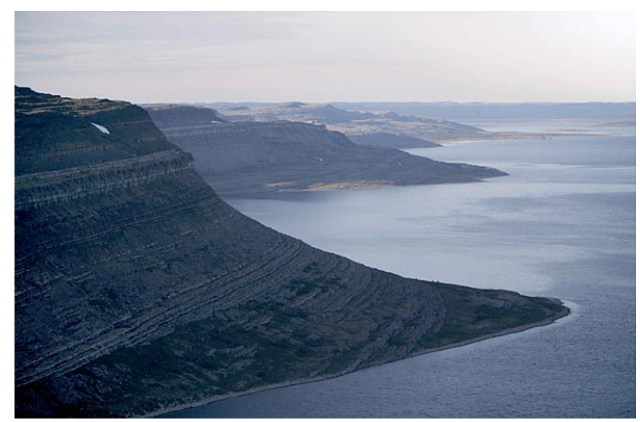
2b. Sea Level Physics: Ice-Age Timescales

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



NEAR FIELD

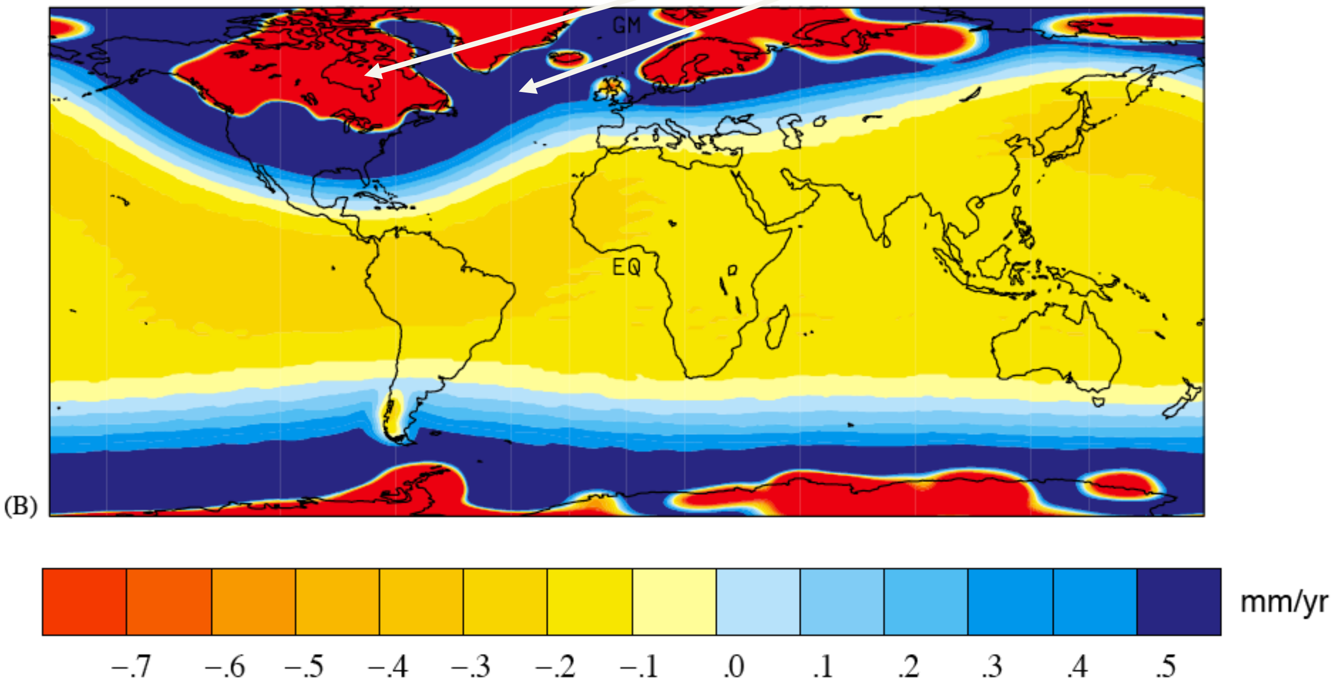




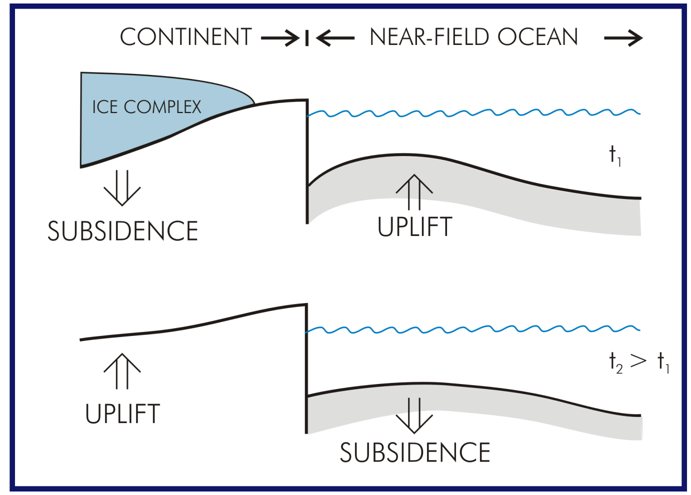
Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

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



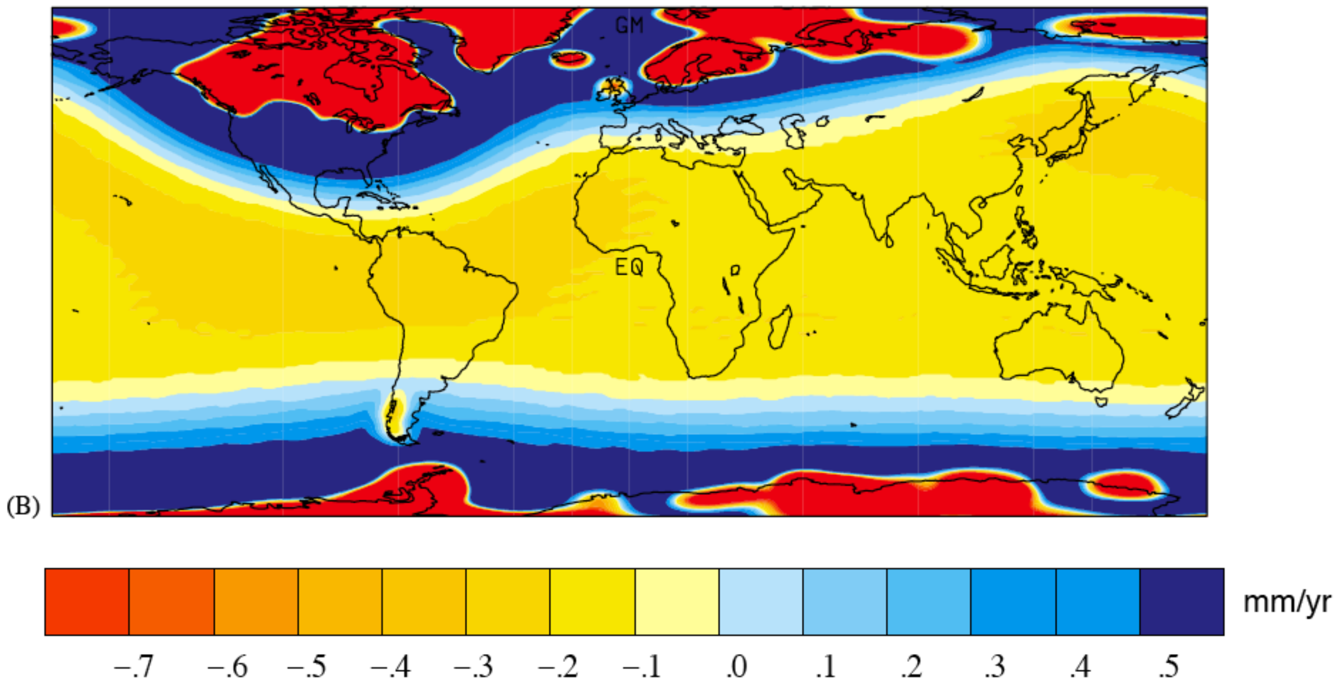
NEAR FIELD



Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

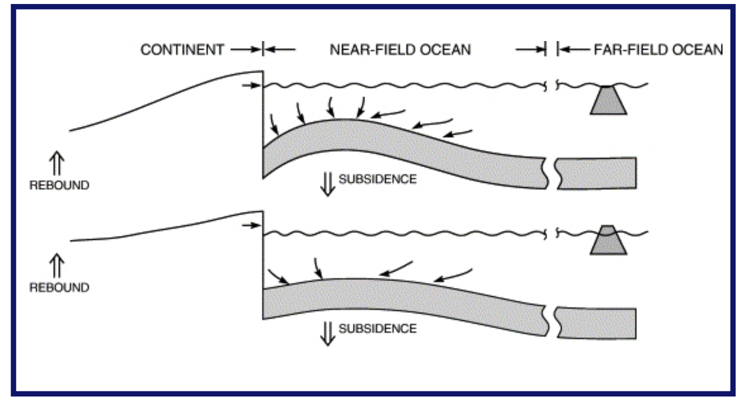
Numerical Prediction of Present-Day Rate of Global Sea-Level Change Due to Ongoing GIA



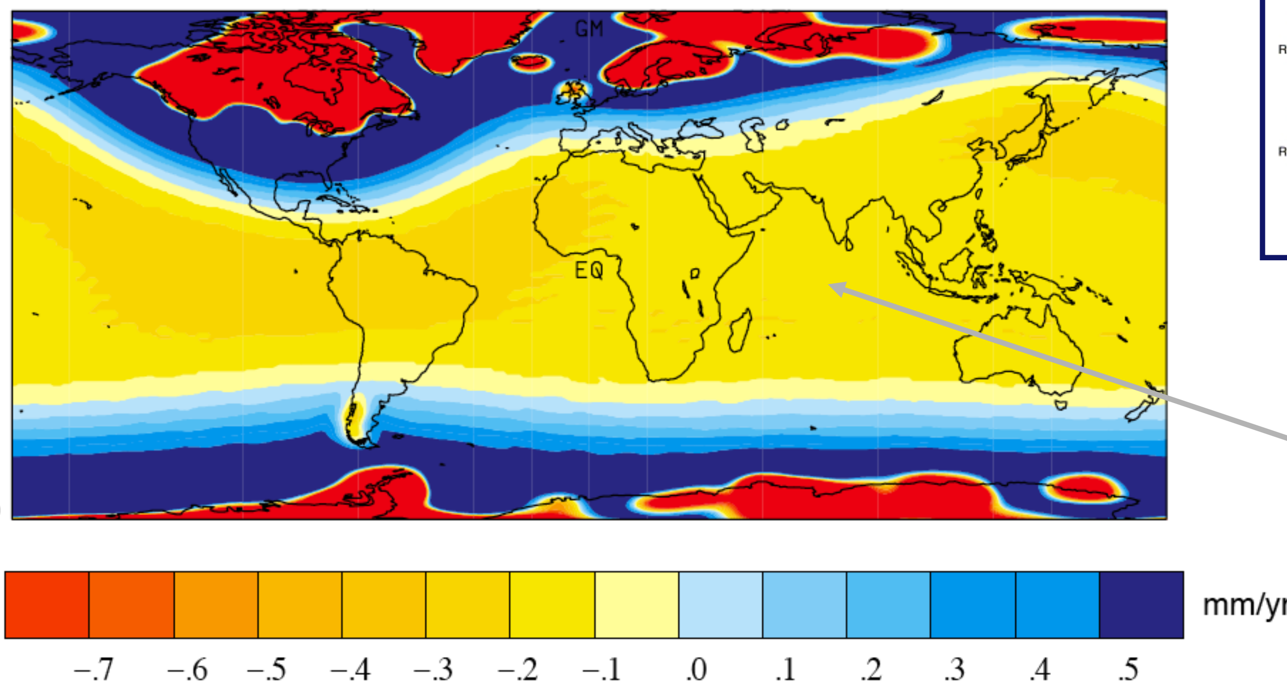
Ice Signal

2b. Sea Level Physics: Ice-Age Timescales

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



(B)

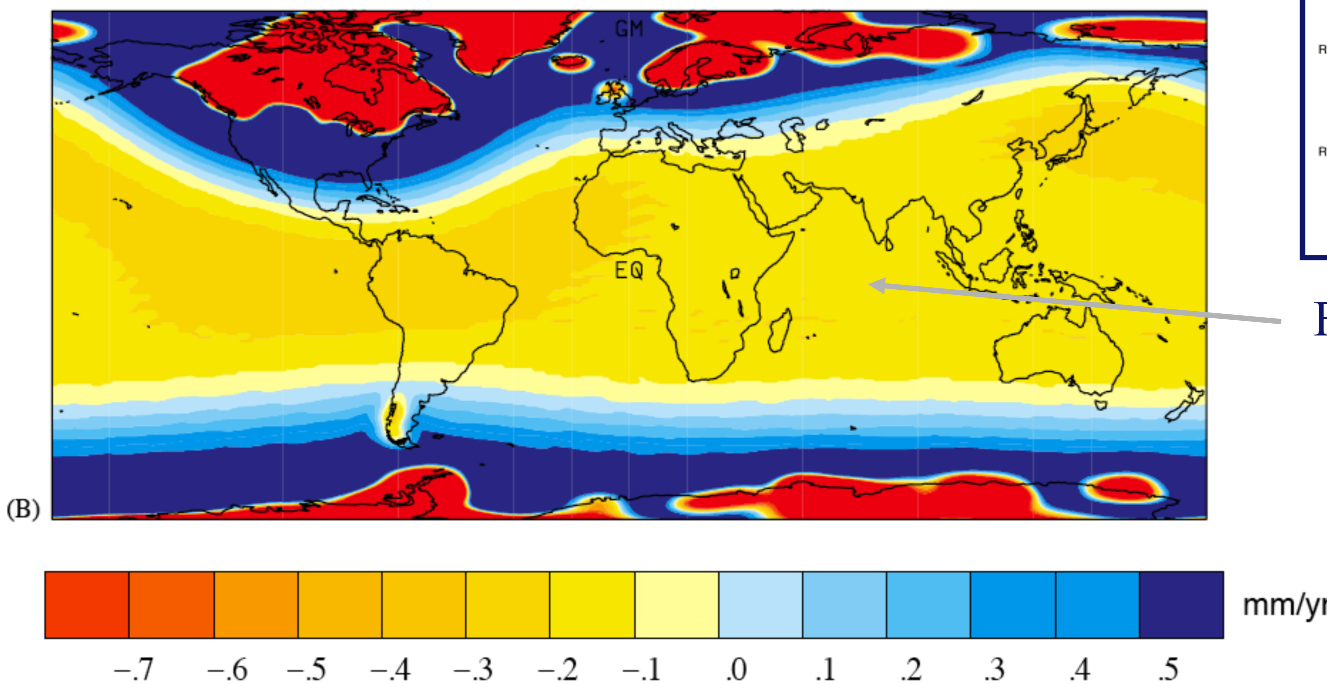


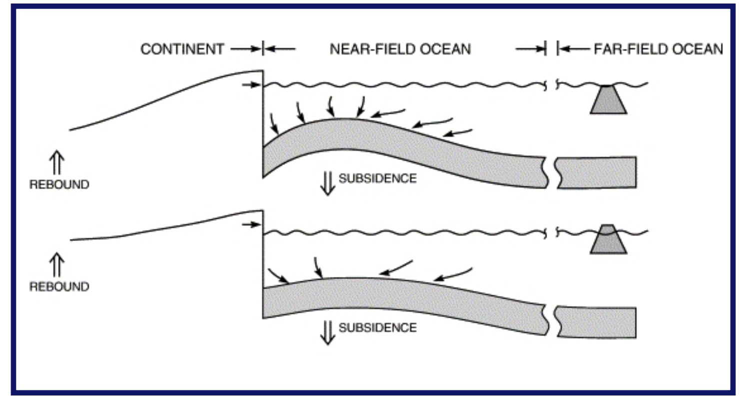
FAR FIELD

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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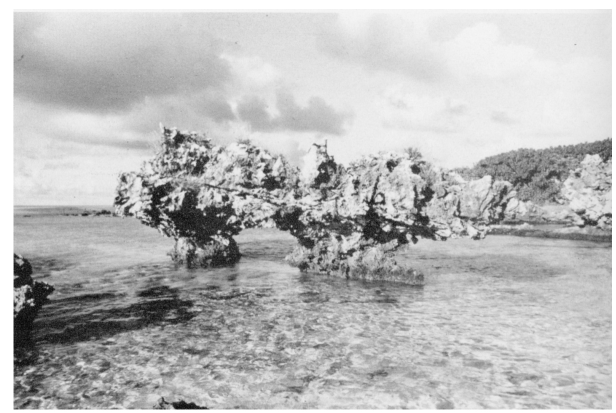
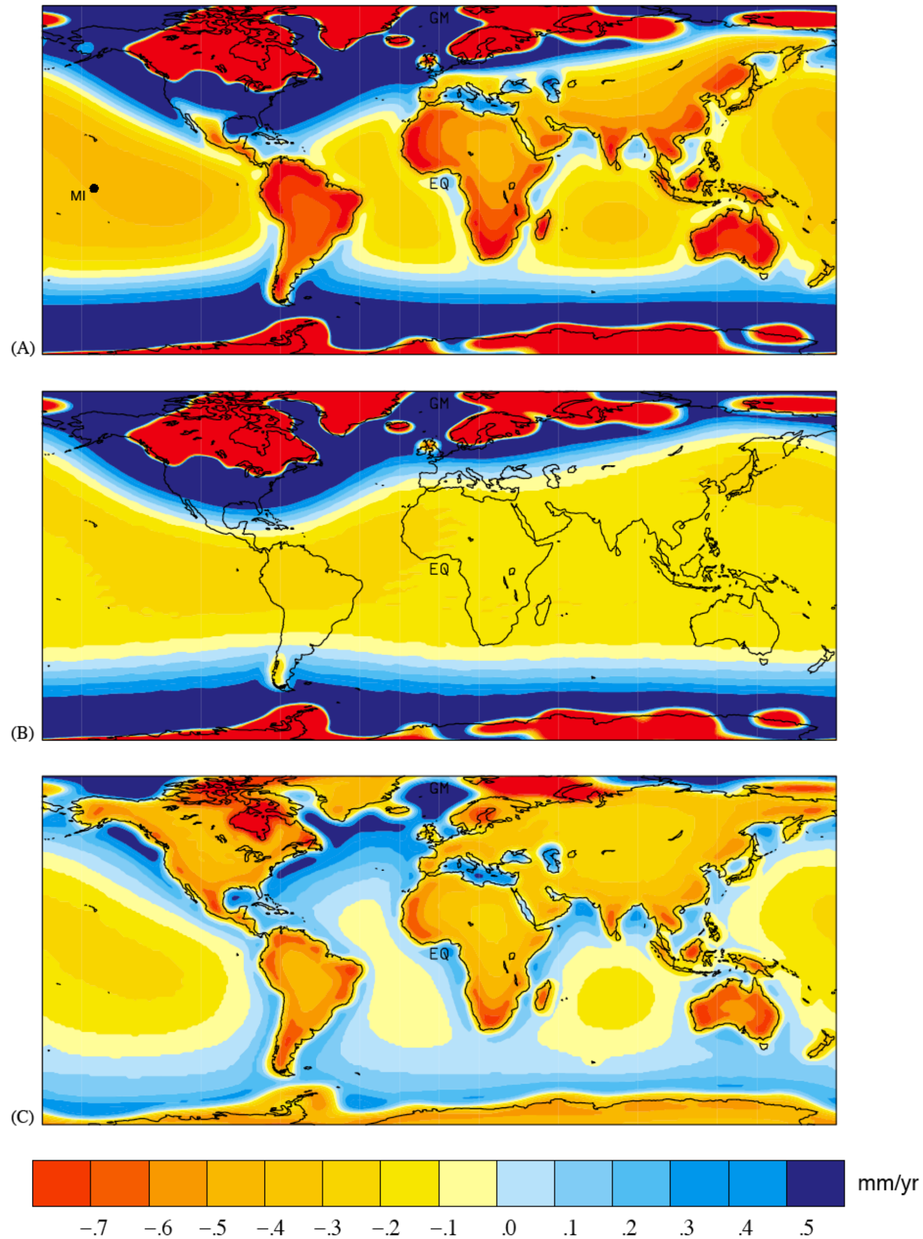


Ice Signal

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



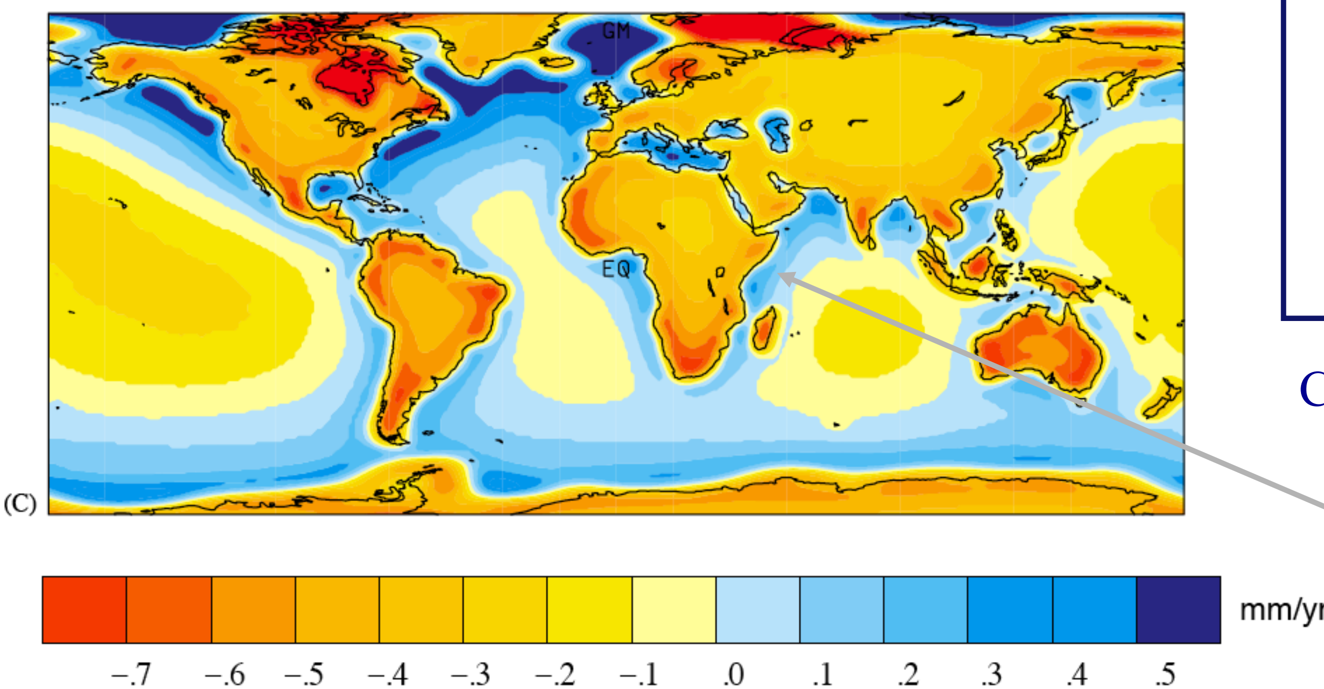
TOTAL

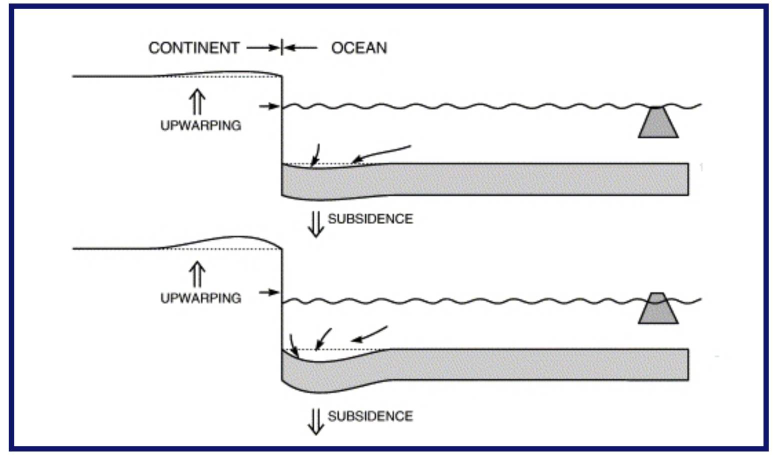
ICE

OCEAN

2b. Sea Level Physics: Ice-Age Timescales

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





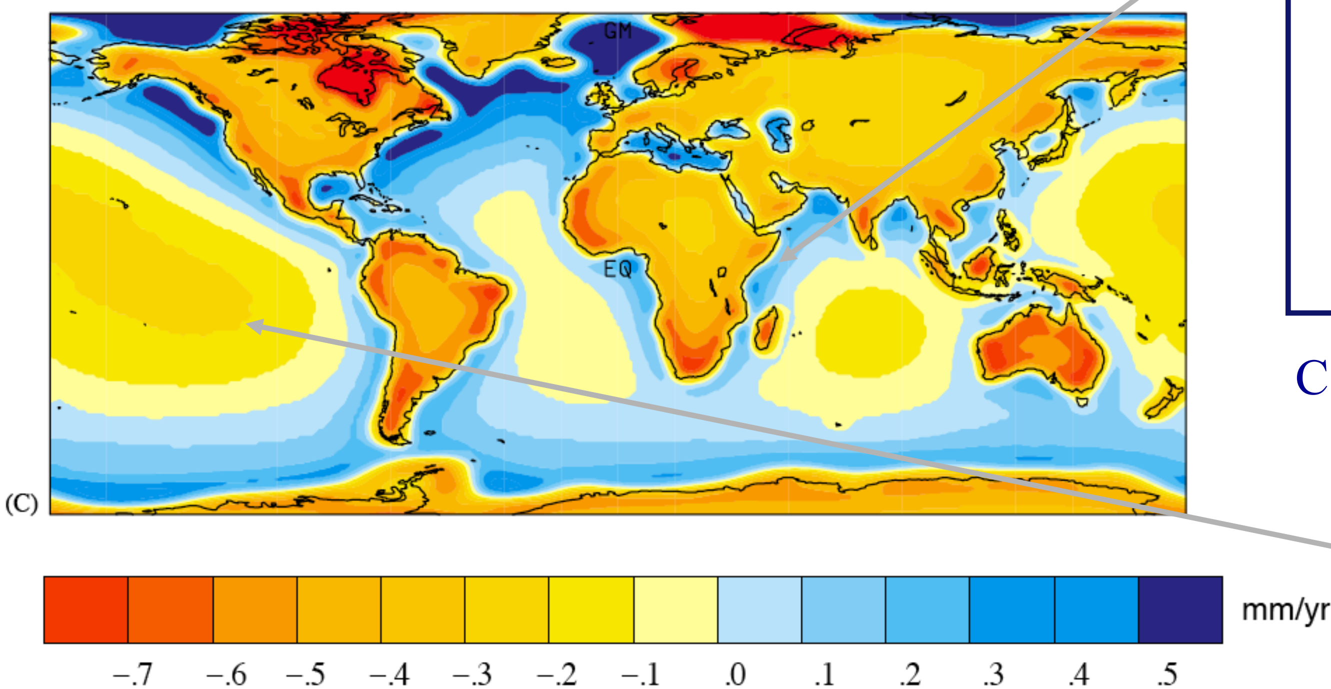
Continental Levering!

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



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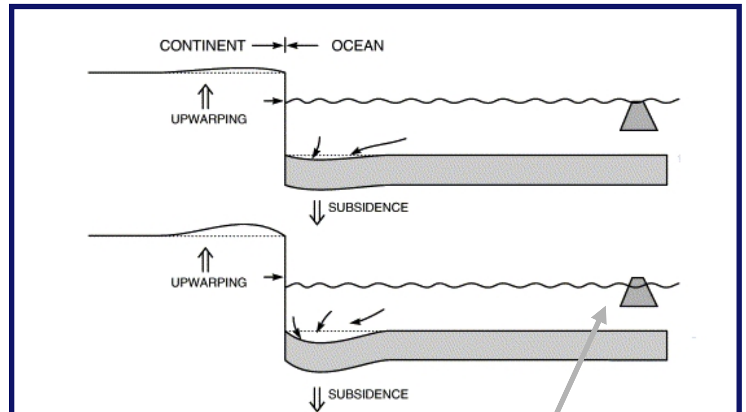


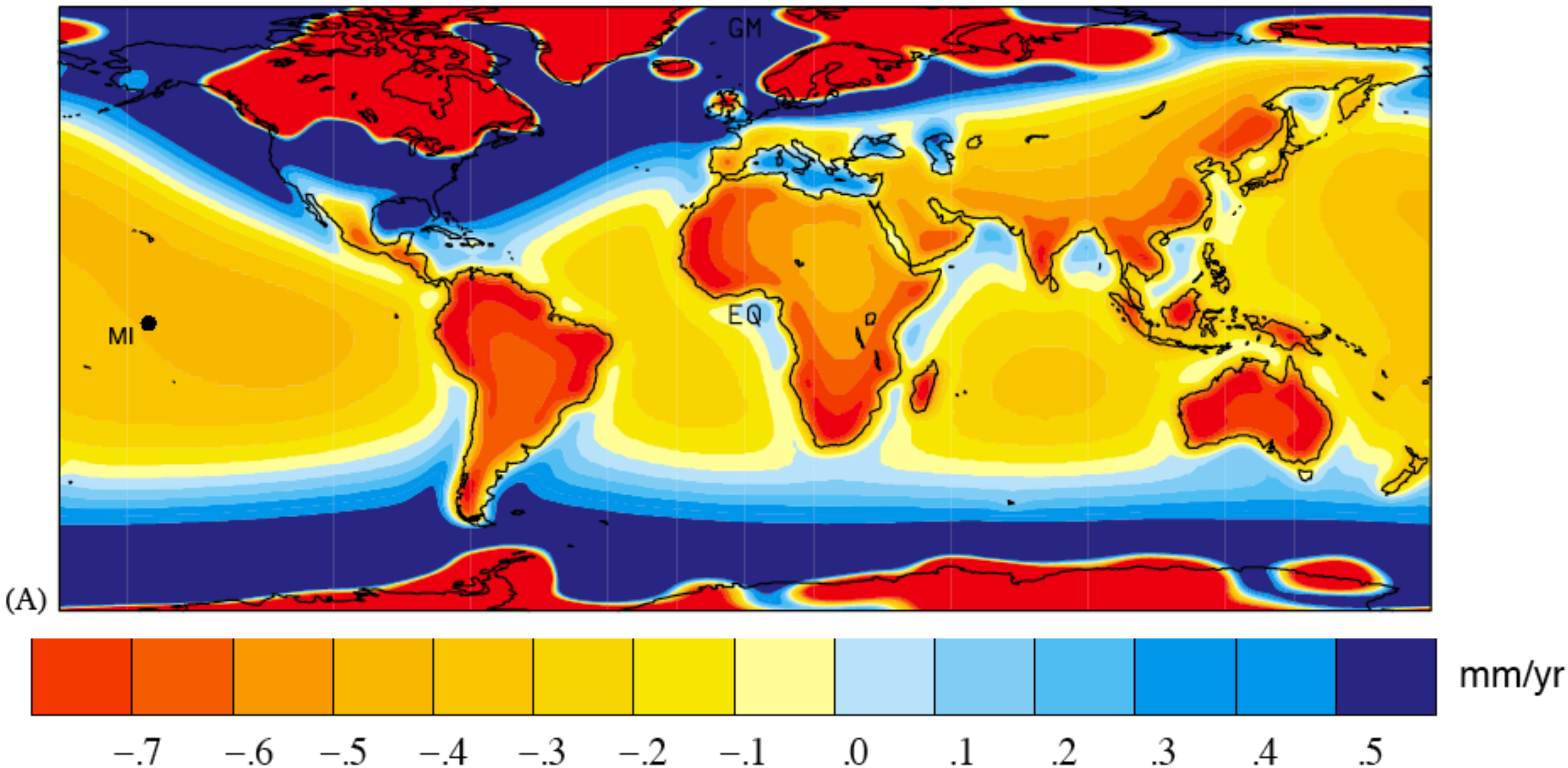
Continental Levering!

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

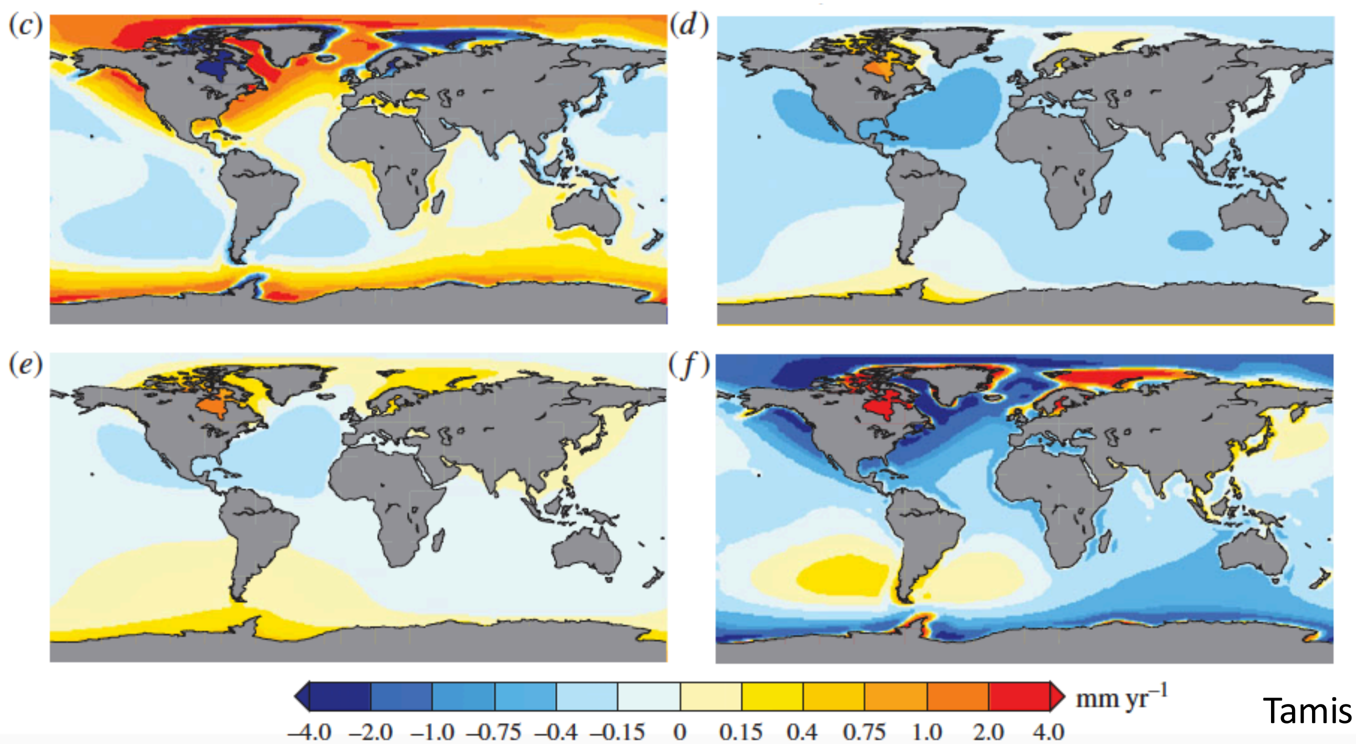
Expressions of GIA in modern sea-level records

Sea level (tide gauges)

Sea surface height (altimetry)

Geoid height (GRACE)

Crustal motion (GNSS)

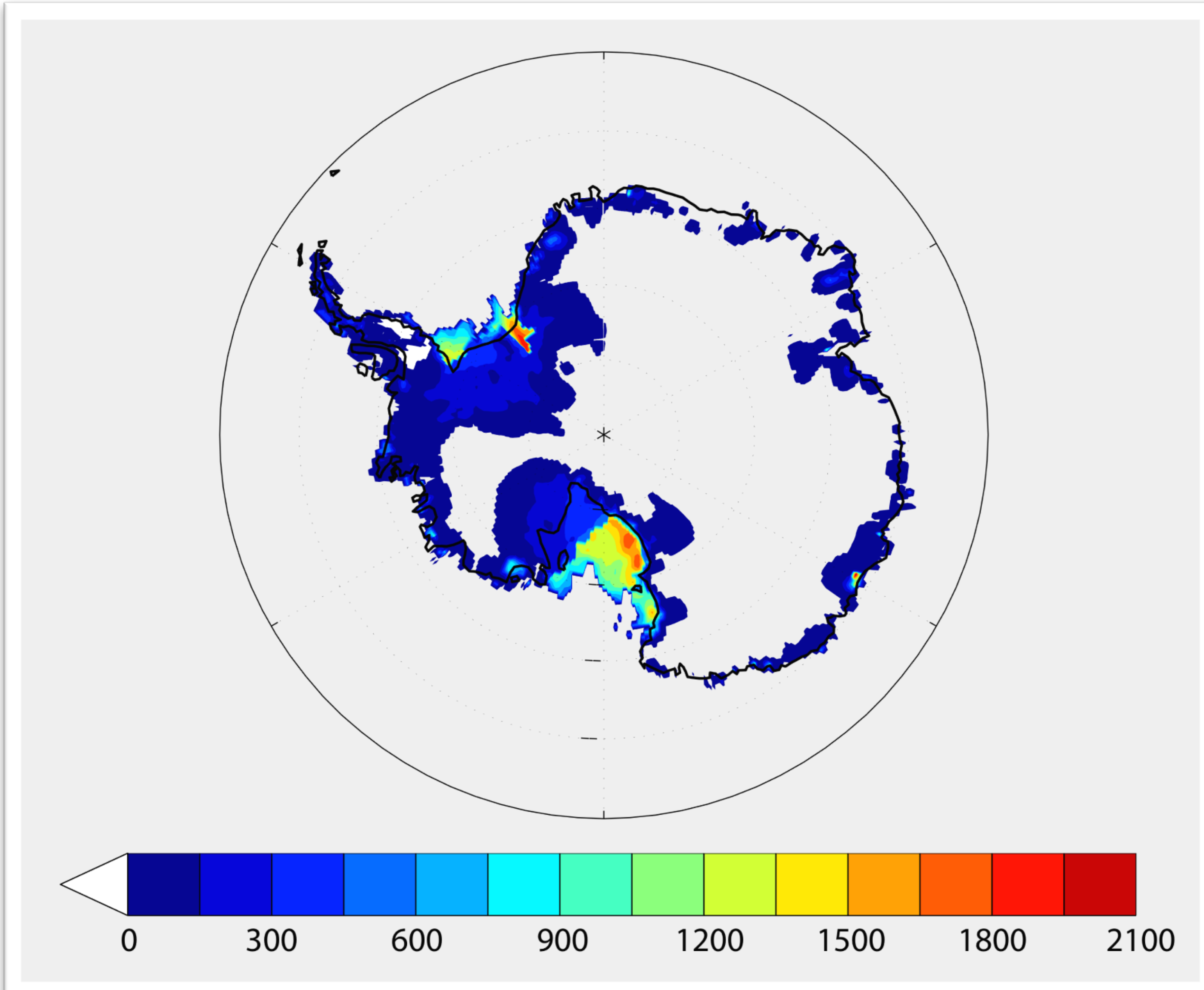


Tamisiea et al. (2014)

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

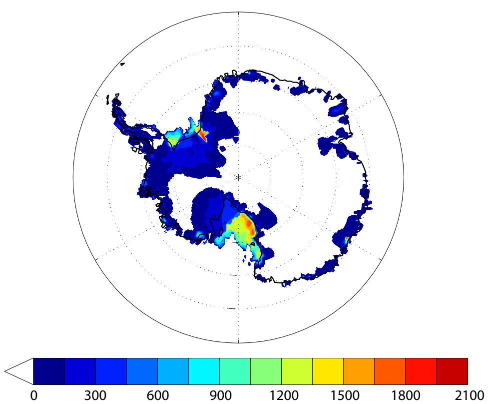
1b. Sea Level Change Example

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

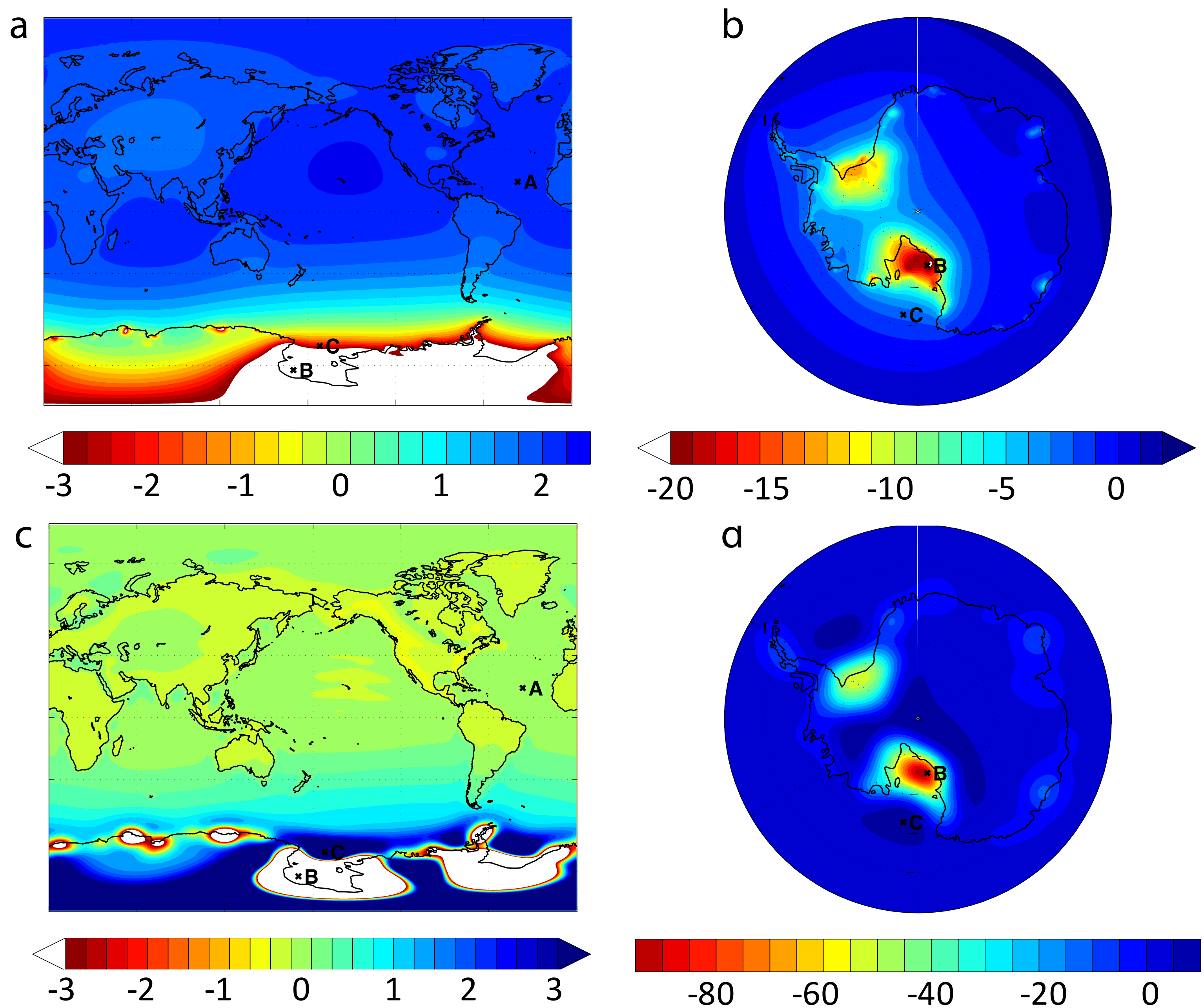


1b. Sea Level Change Example

Elastic SL change immediately after ice sheet retreat



SL change over next 10 ky (ice remains constant)



1b. Sea Level Change Example

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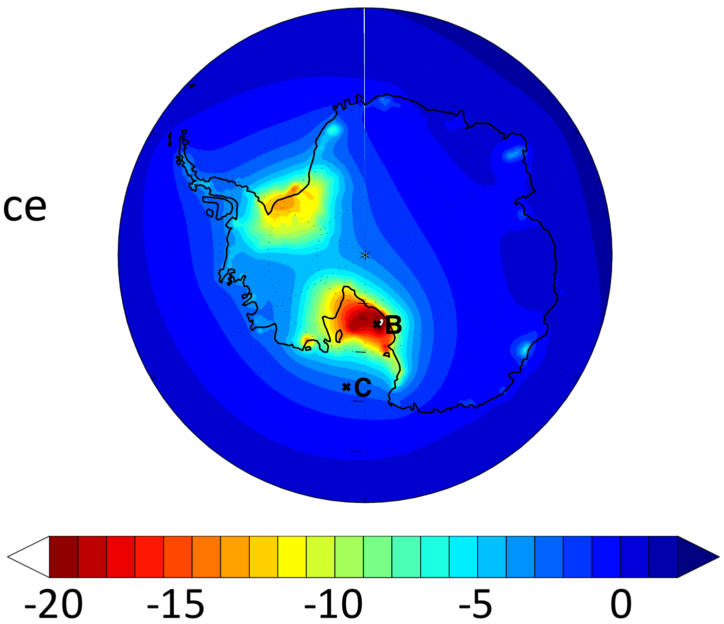

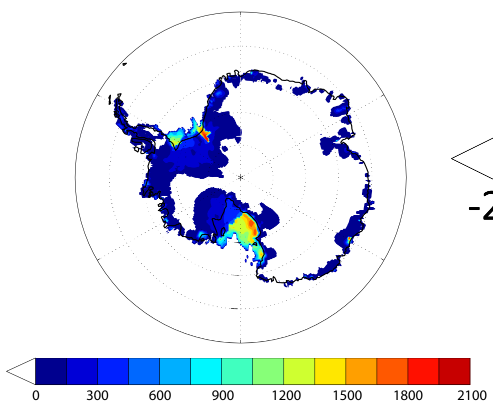

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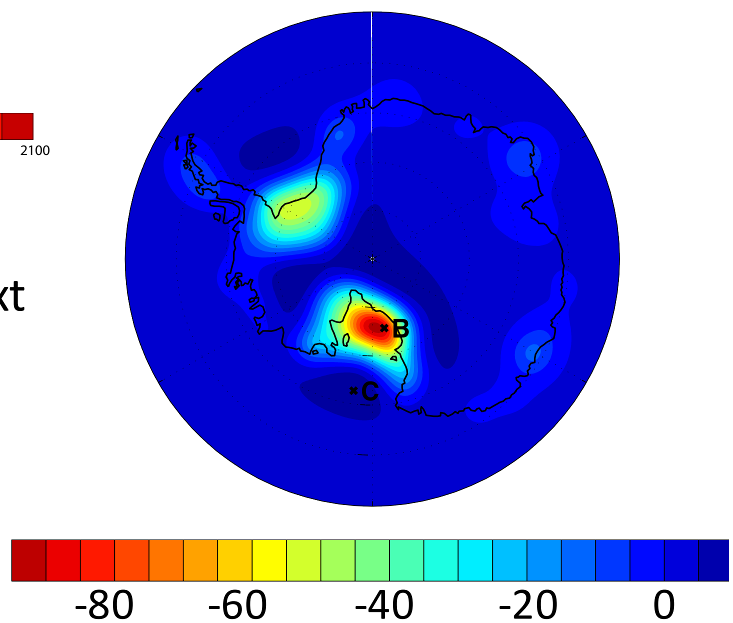

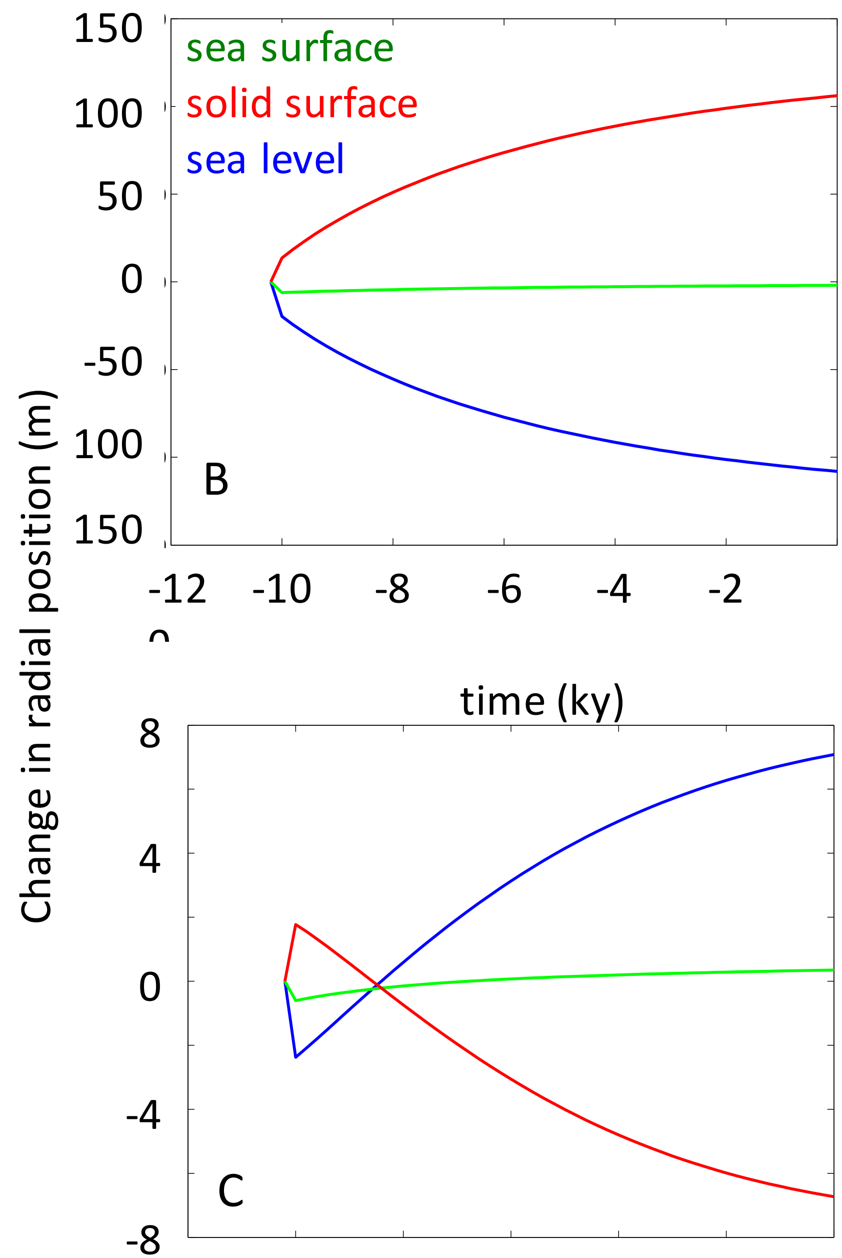

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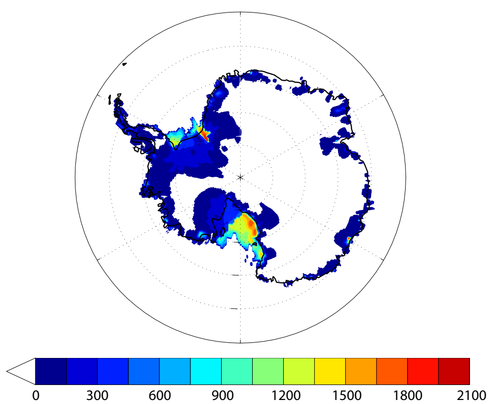

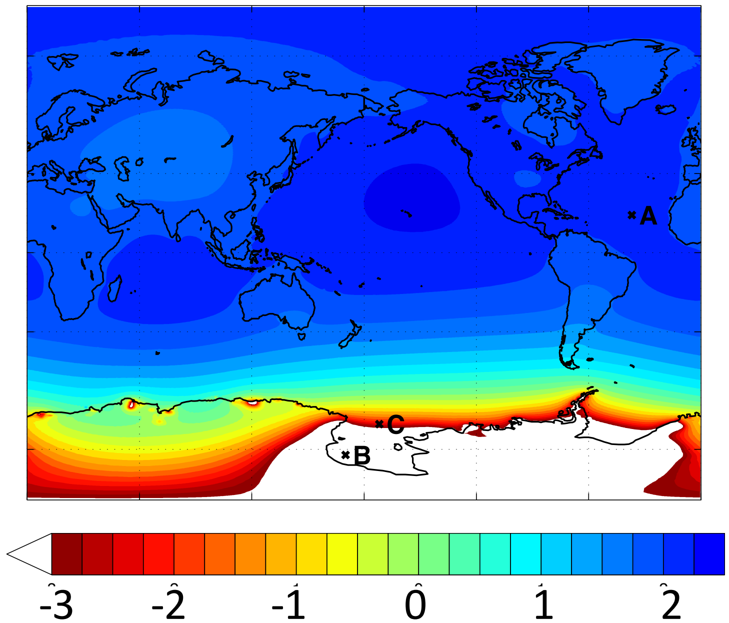

SL change over next 10 ky (ice remains constant)