

Lecture 10: Sea level

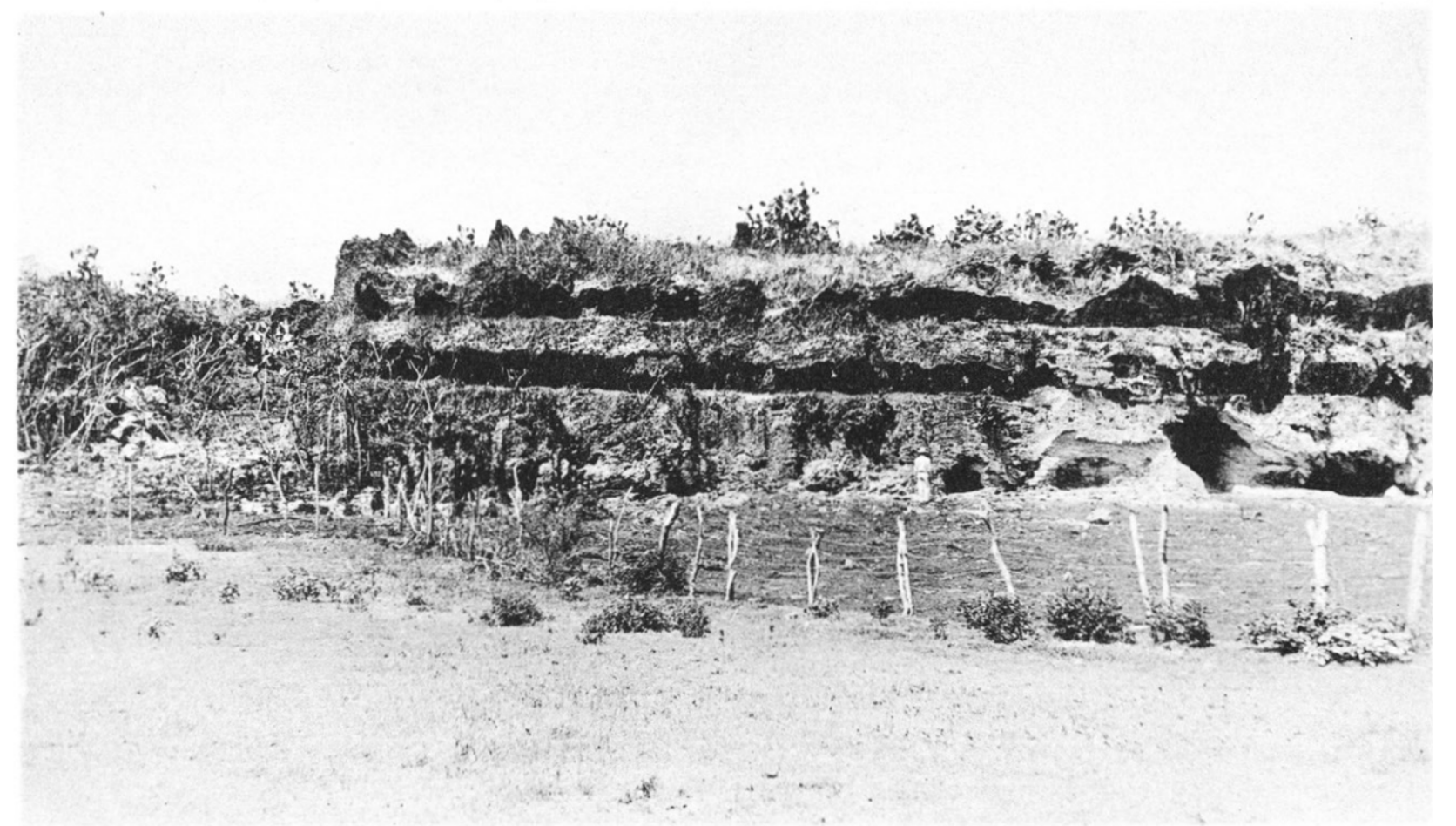
- Hypsometry
- Relative sea level
- Glacial isostatic adjustment
- Viscoelasticity
- Earth as a viscoelastic solid
 - Elastic response (ongoing melt)
 - Fingerprints of ice melt
 - Viscous response (after melting ends)



We acknowledge and respect the $lək^wəŋən$ peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

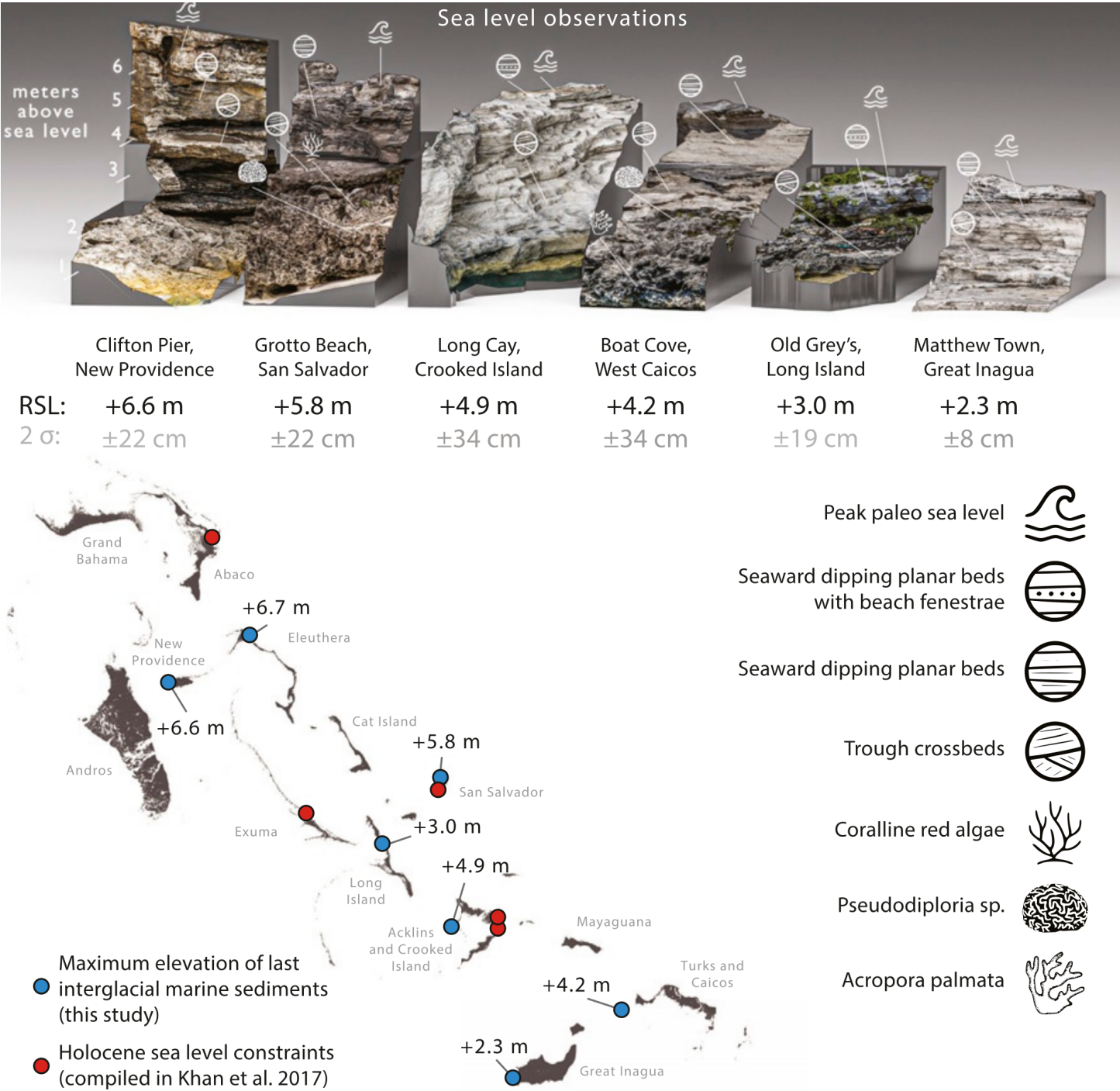


Hawaii

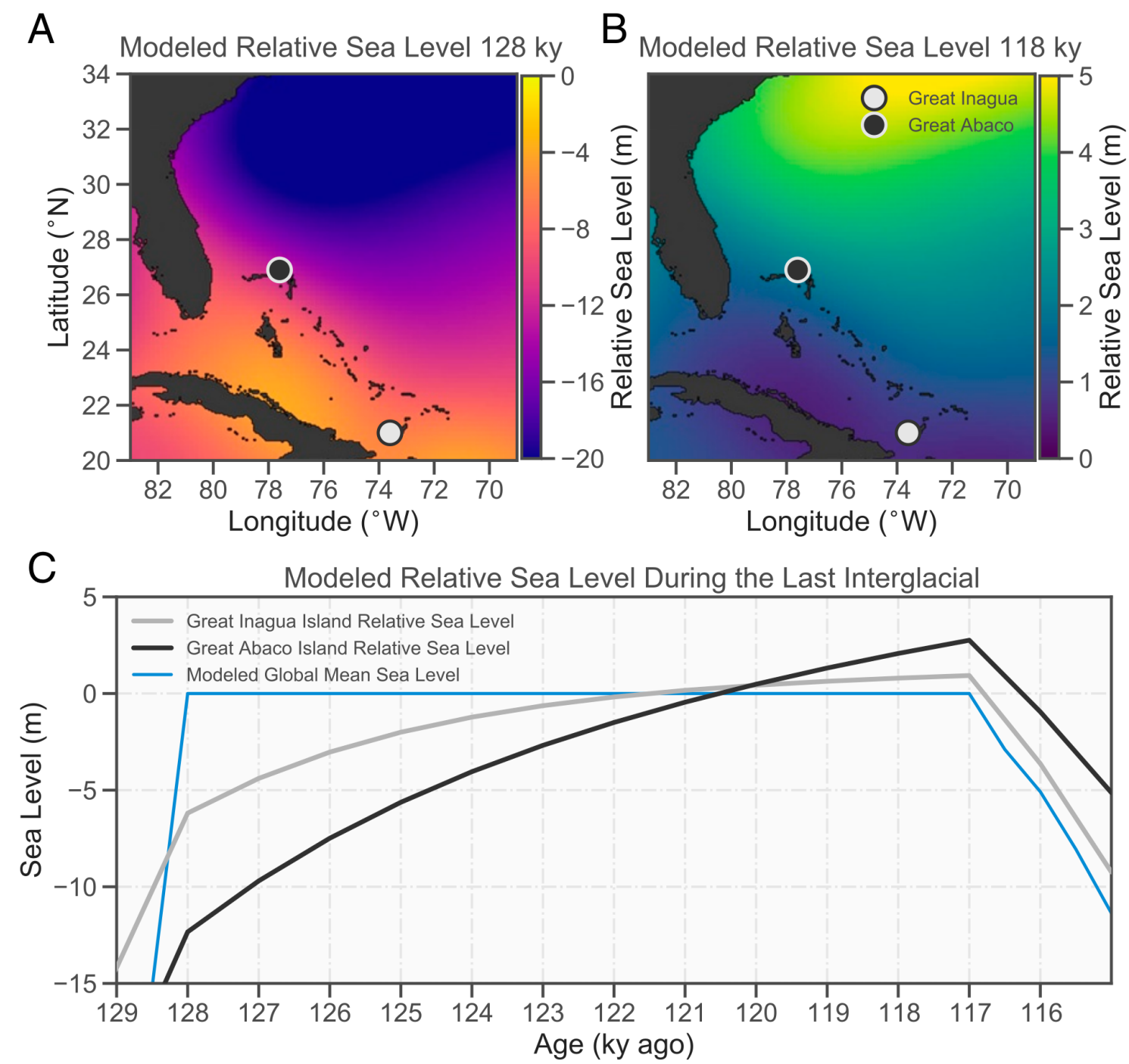


Linear features in lithified carbonate dunes at 6.7 meters and 8.2 meters

The Bahamas

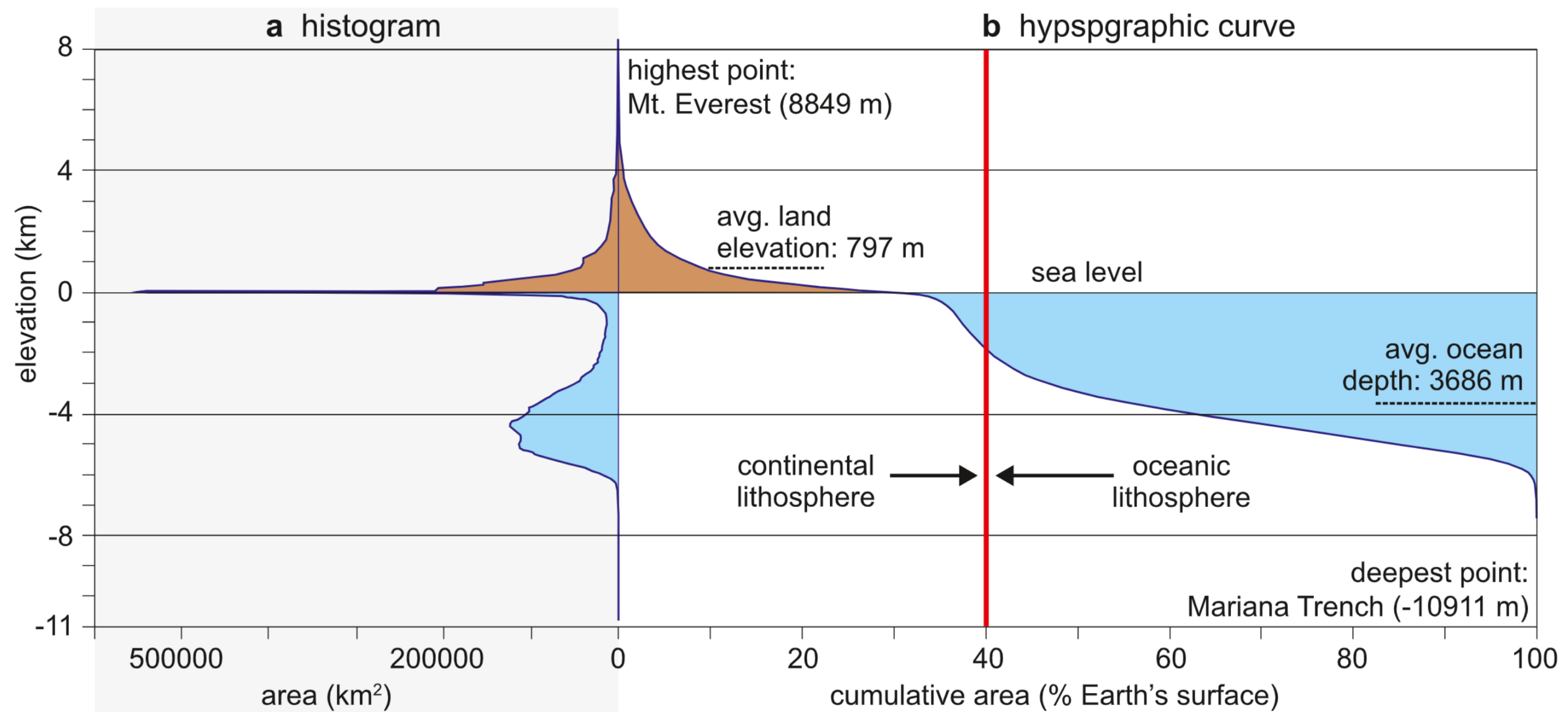


The Bahamas

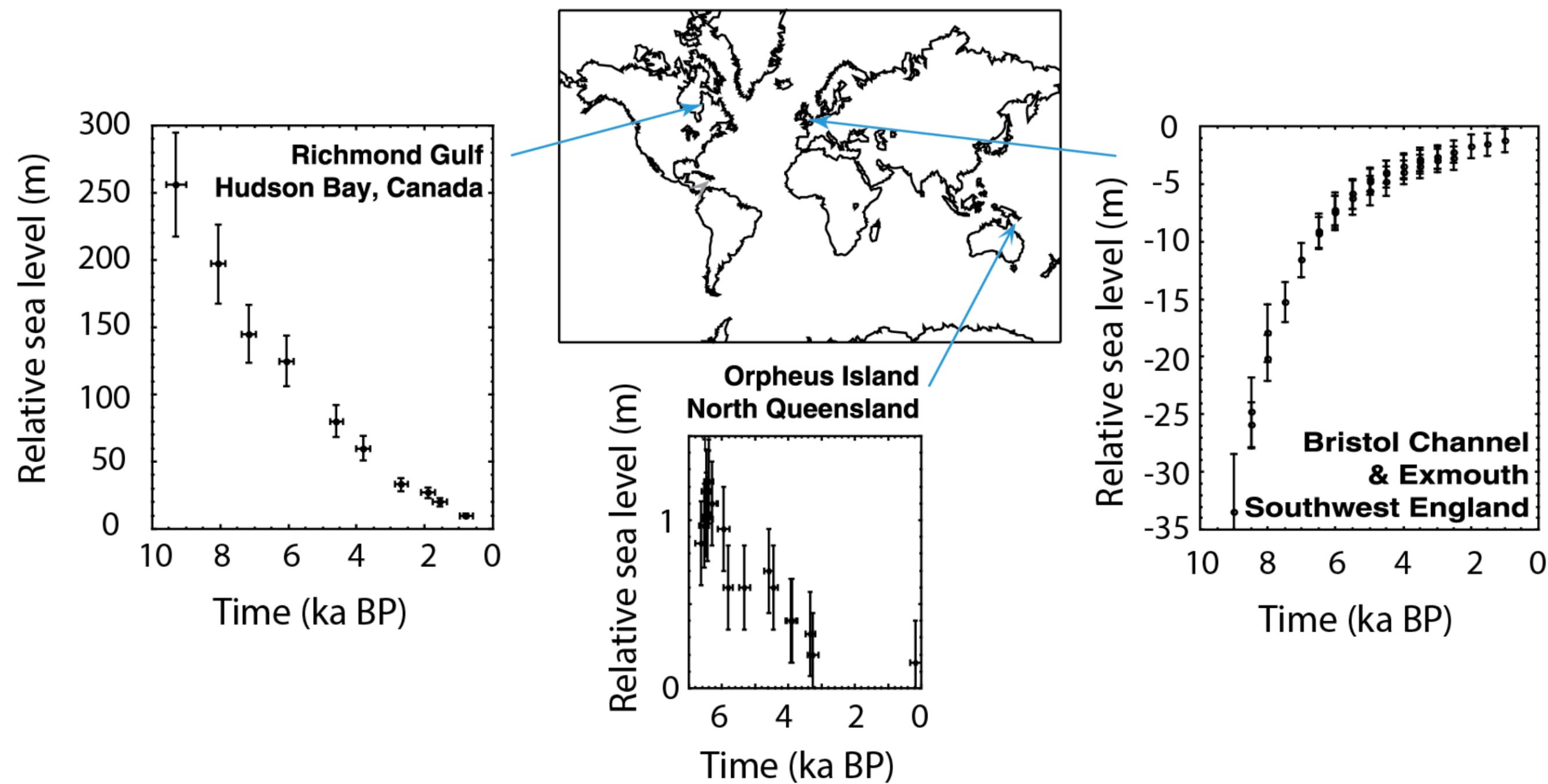


Back to hypsometry

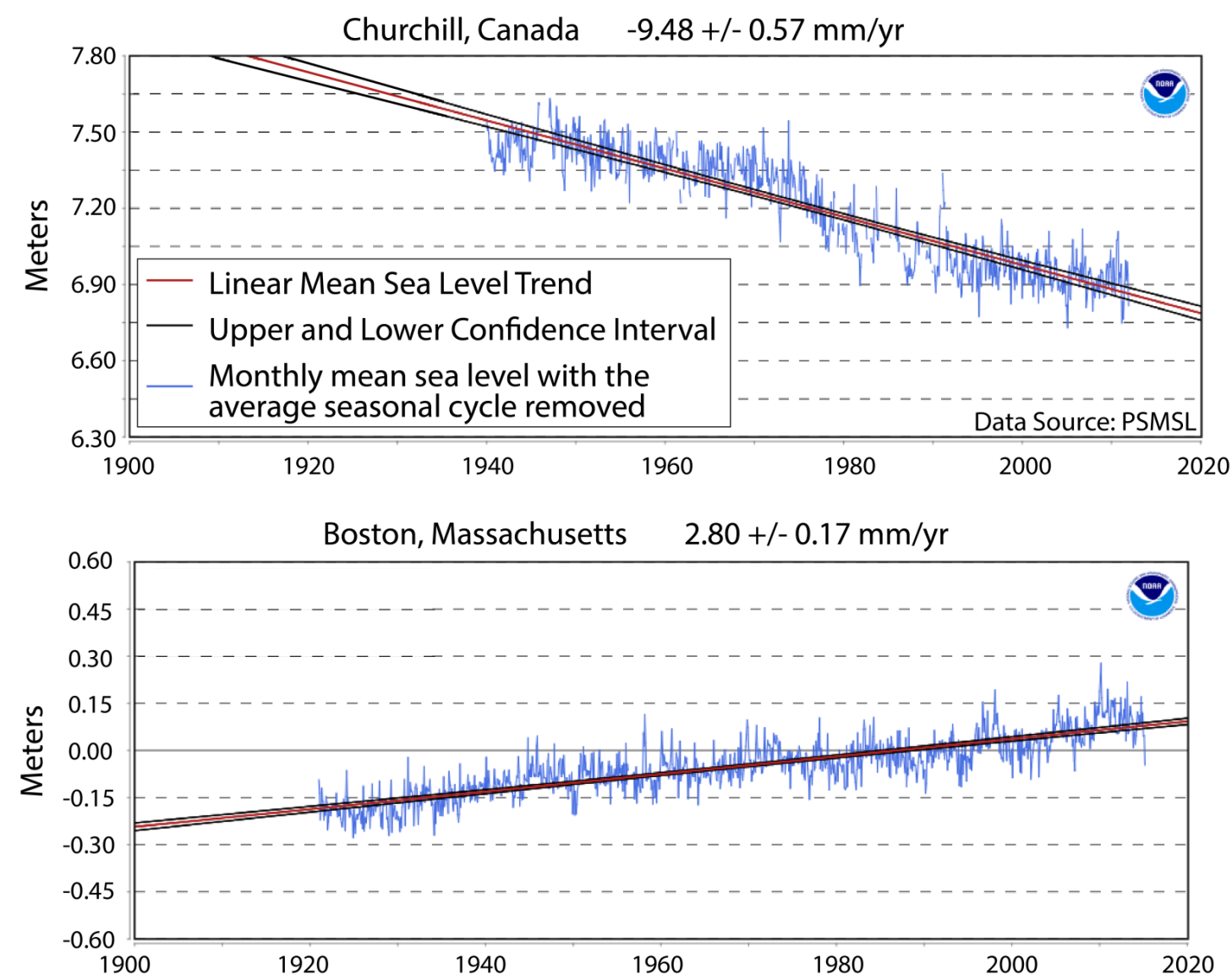
What is the relationship between water volume and sea level change? Consider 1 m sea level rise if sea level is +8848 m vs -3685 m



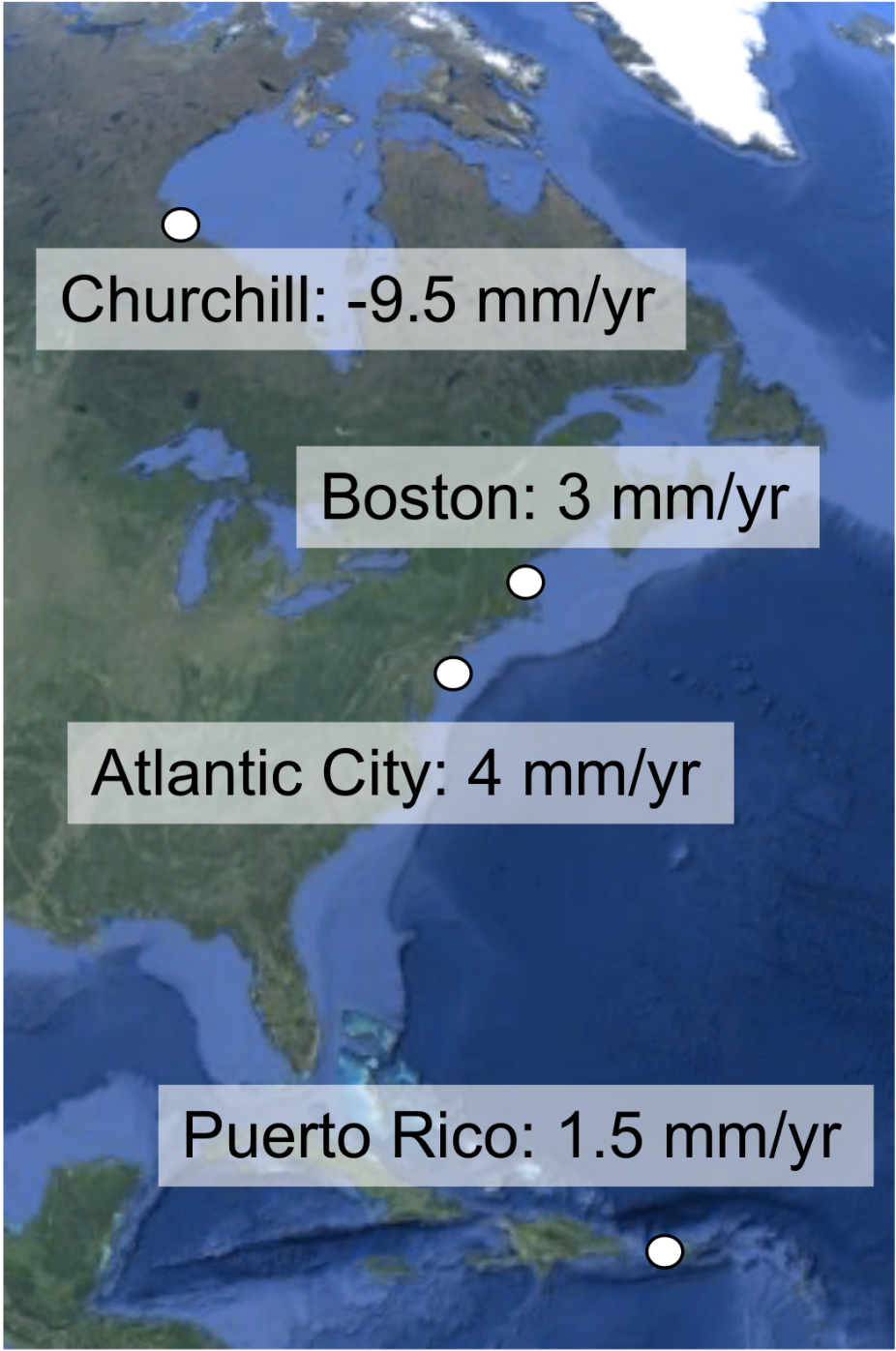
Relative Sea Level



Relative Sea Level

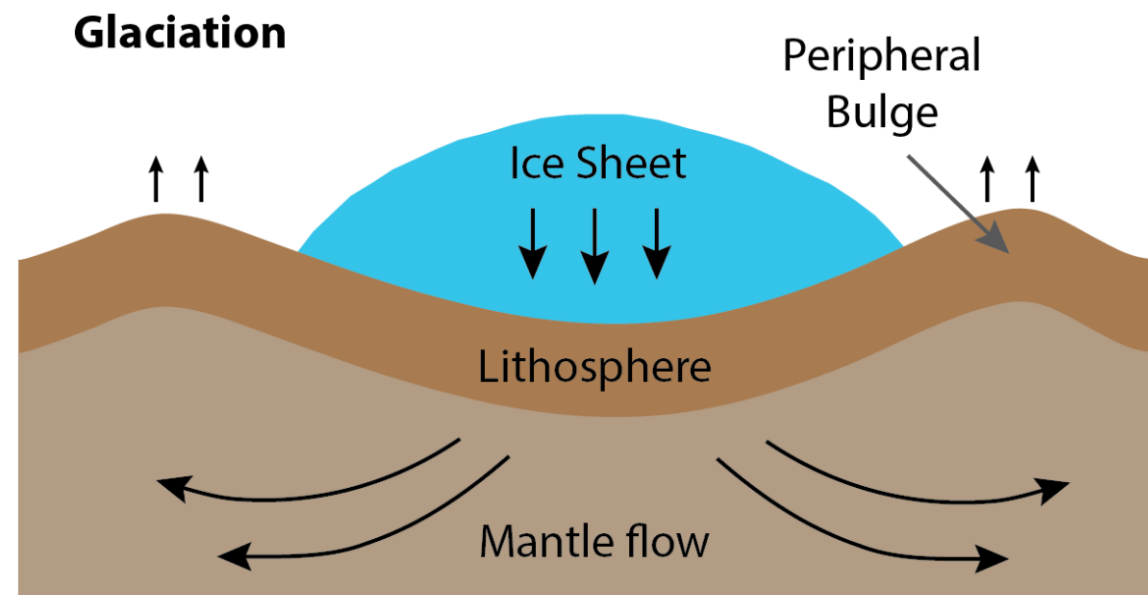


<http://tidesandcurrents.noaa.gov>



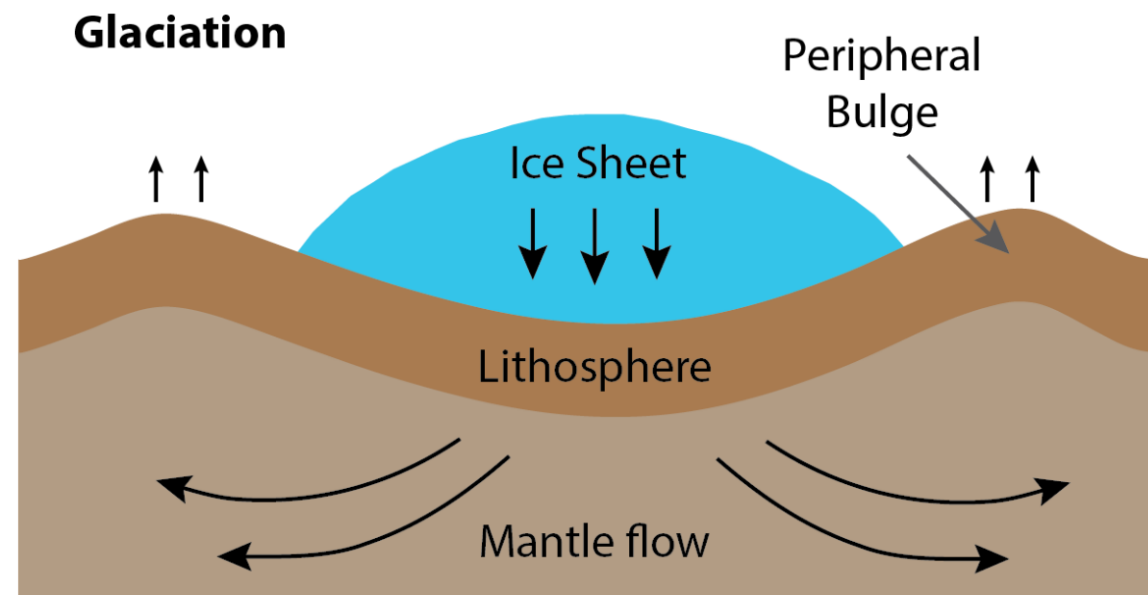
Glacial isostatic adjustment

During the glacial

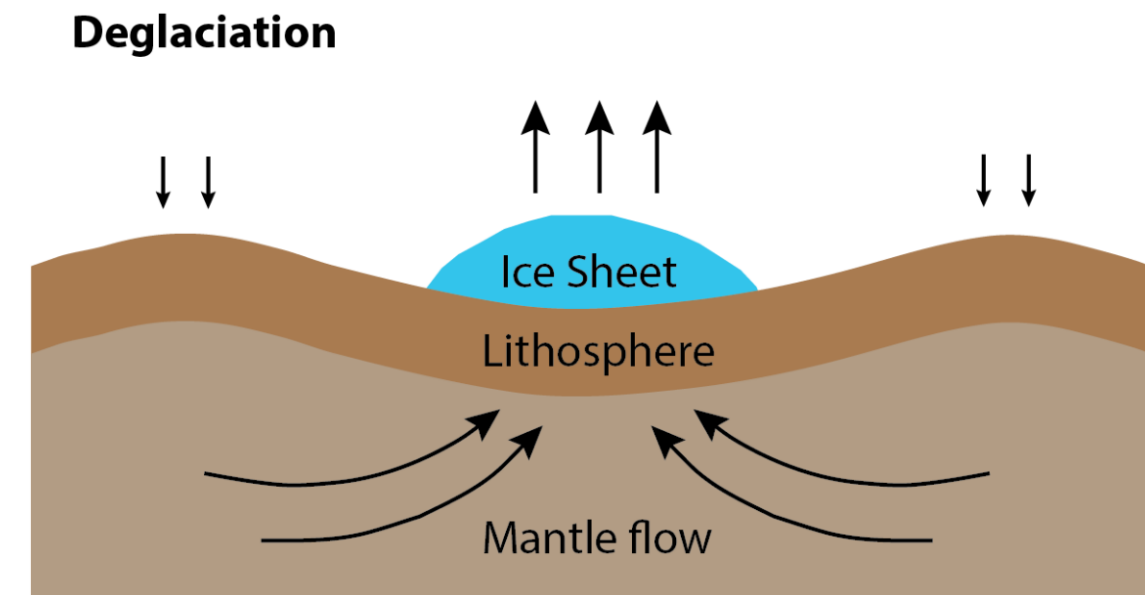


Glacial isostatic adjustment

During the glacial

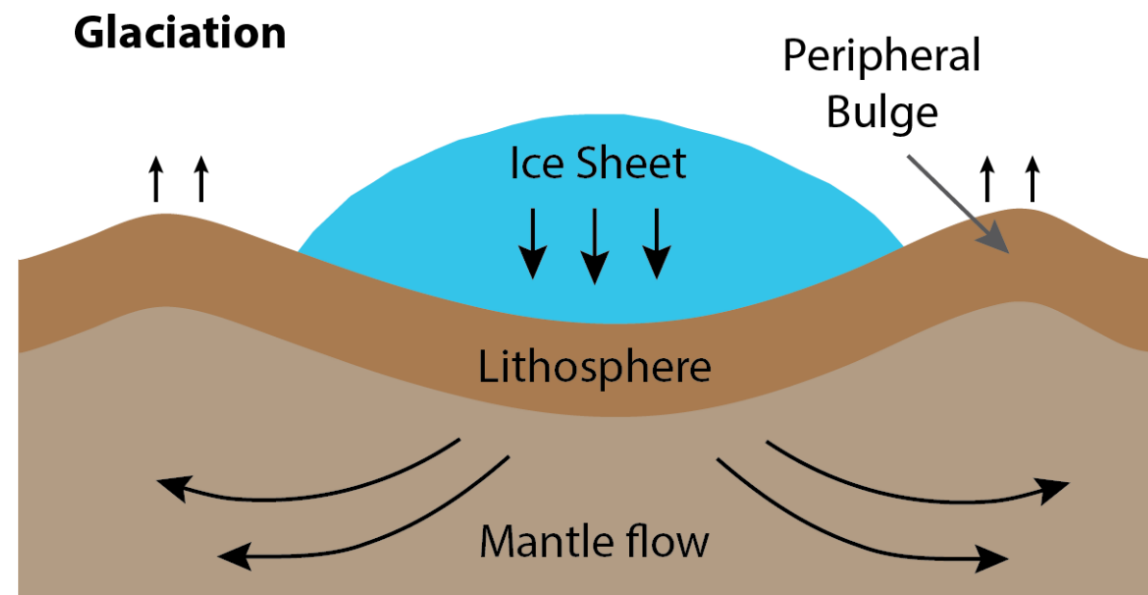


During the interglacial

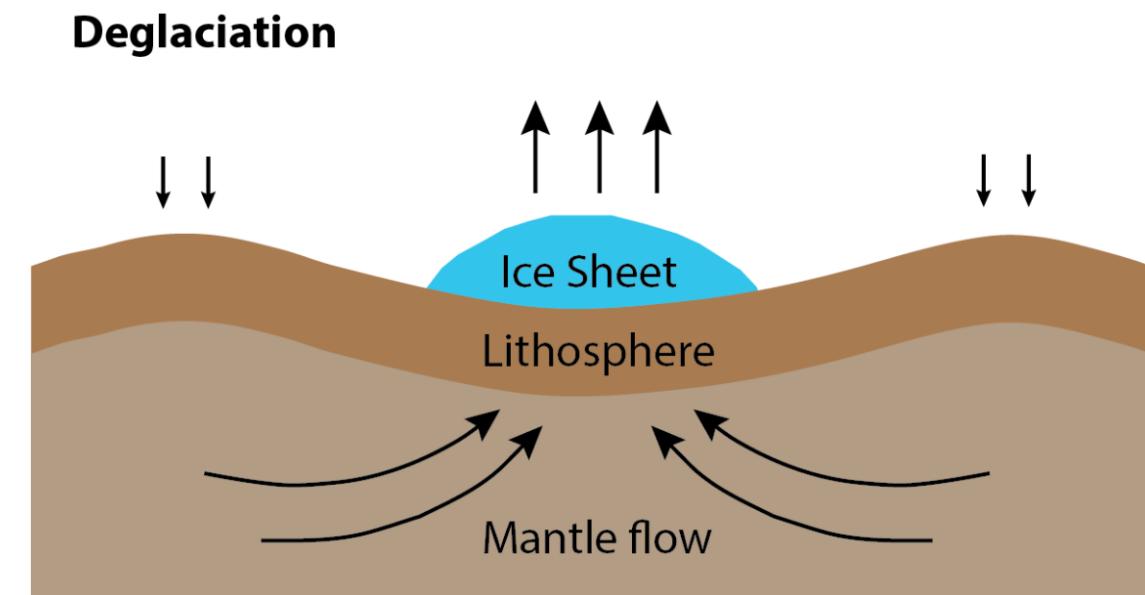


Glacial isostatic adjustment

During the glacial



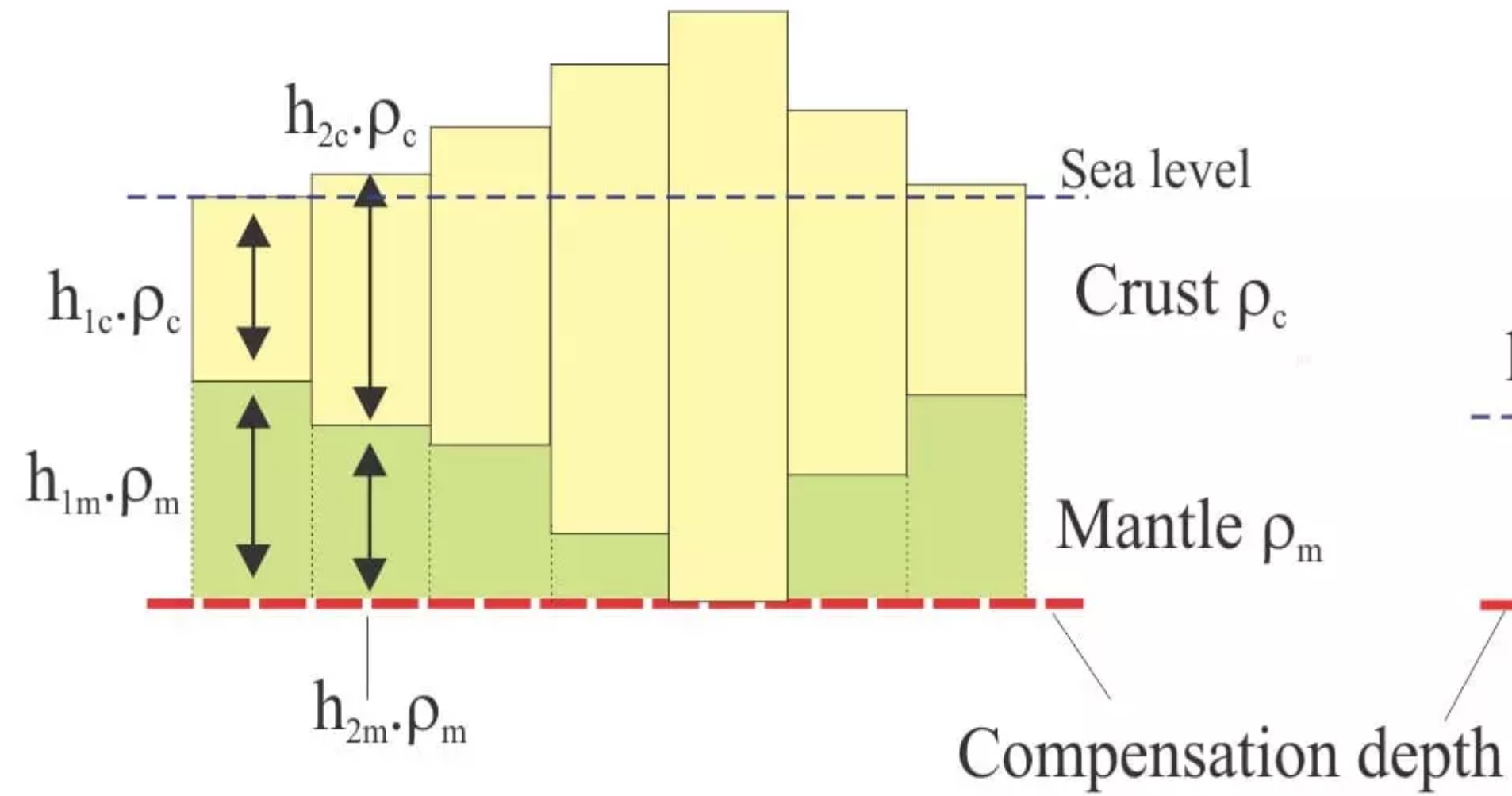
During the interglacial



- Postglacial rebound: **viscoelastic** response of the solid Earth after ice melt
- Glacial isostatic adjustment: the **viscoelastic** response of the Earth's solid surface, its gravity field, and rotation axis to changes in ice and ocean load

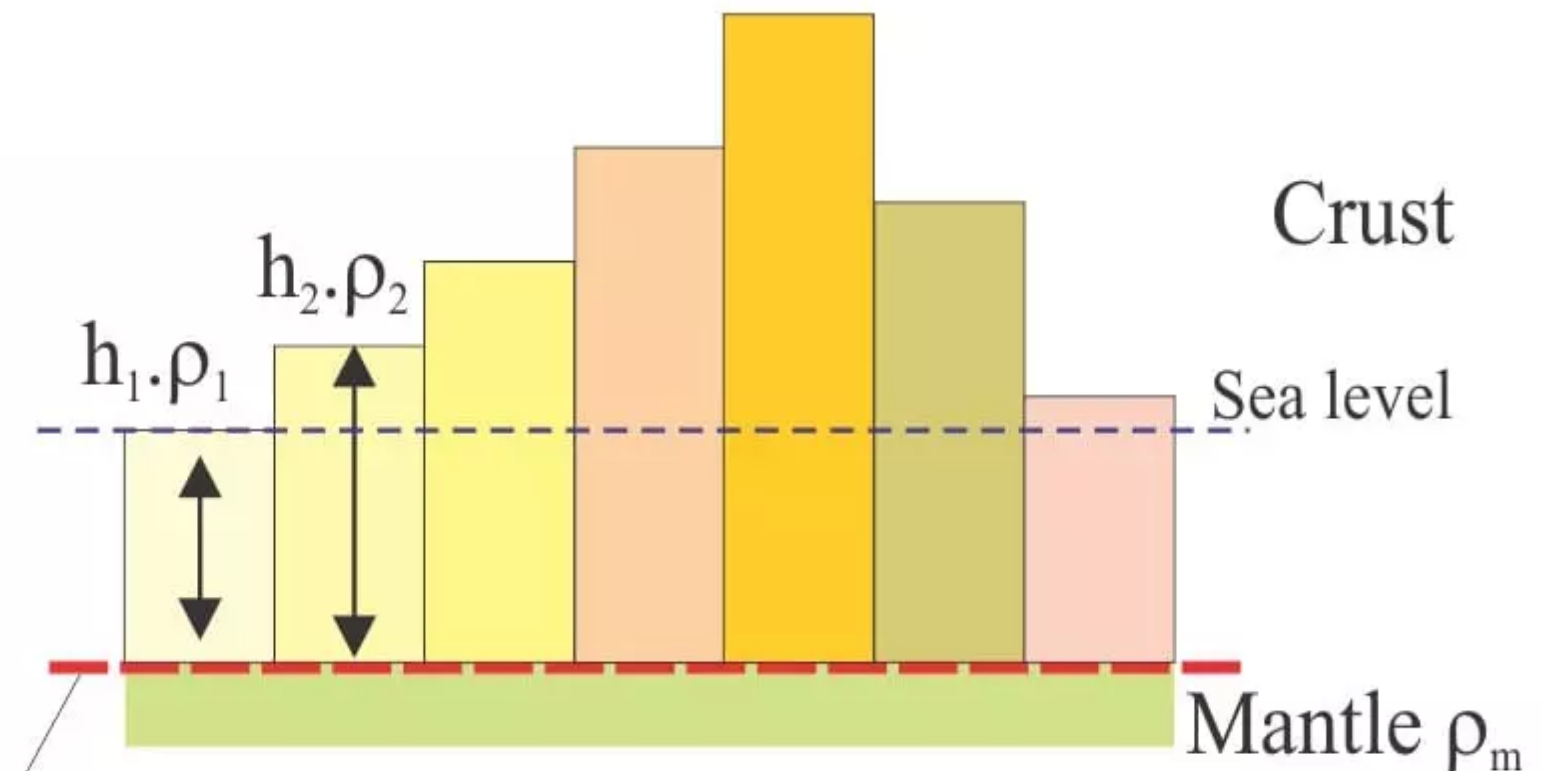
Our previous considerations of isostasy

Airy model of local isostasy



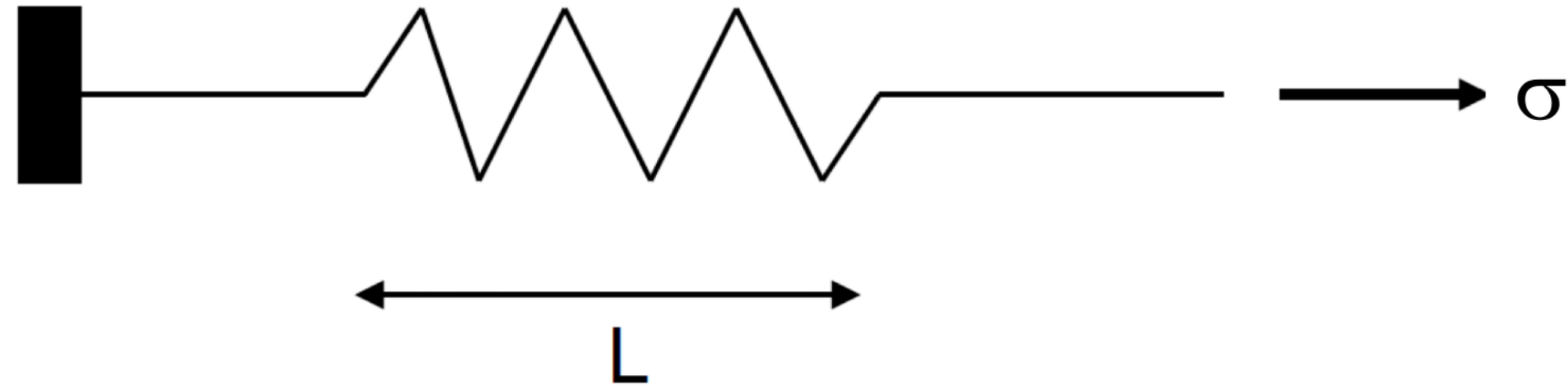
$$\mathbf{P} = (h_{1c} \cdot \rho_c \cdot g + h_{1m} \cdot \rho_m \cdot g) = (h_{2c} \cdot \rho_c \cdot g + h_{2m} \cdot \rho_m \cdot g) = \dots$$

Pratt model of local isostasy



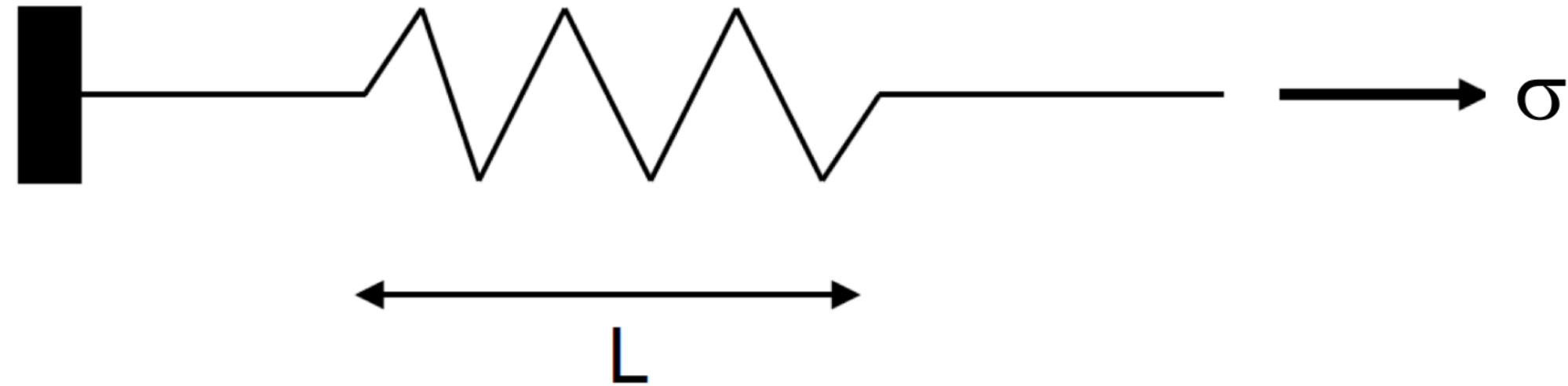
$$\mathbf{P} = (h_1 \cdot \rho_1 \cdot g) = h_2 \cdot \rho_2 \cdot g = \dots$$

Viscoelastic deformation



Stress is proportional to **strain** and a constant of proportionality (the Young's modulus or spring constant, k)

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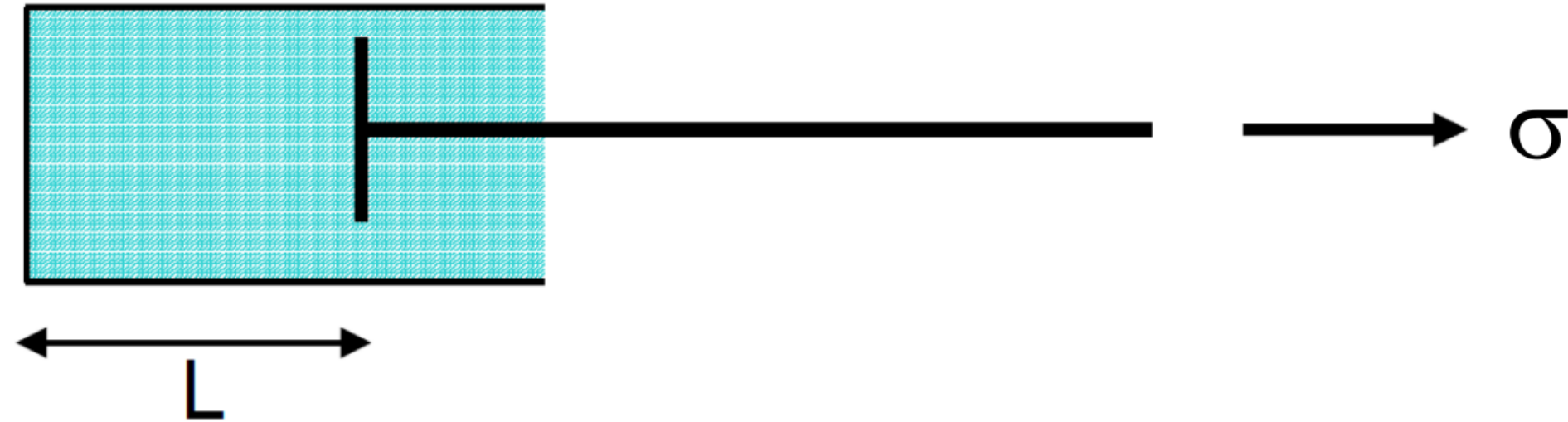
$$\sigma = k \frac{\Delta L}{L} = k e$$

Hooke's law

σ = stress
 e = strain

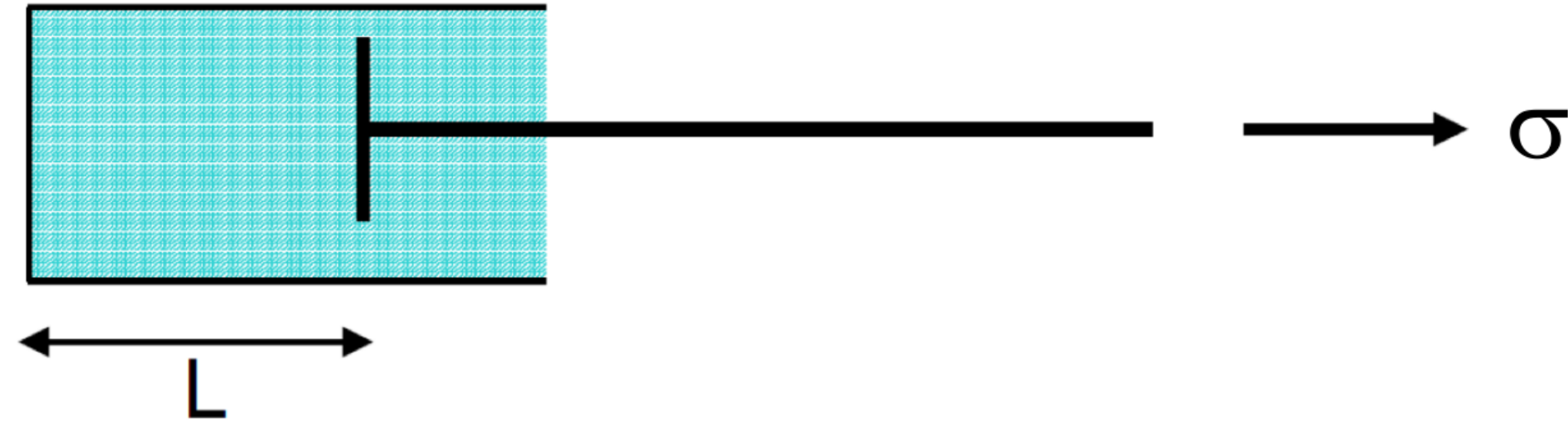


Viscoelastic deformation



Stress is proportional to **strain rate** and a constant of proportionality (the coefficient of viscosity, η)

Viscoelastic deformation



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$$\sigma = \eta \frac{d}{dt} \left(\frac{\Delta L}{L} \right) = \eta \frac{de}{dt}$$

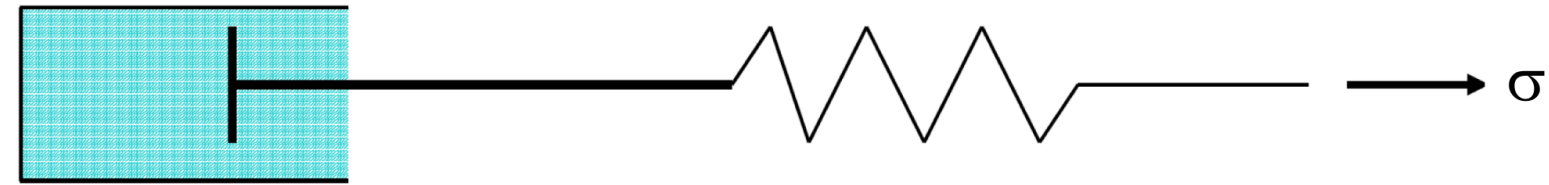
σ = stress

e = strain

For a fluid whose viscosity is not dependant on strain rate (Newtonian fluid)



Viscoelastic deformation



In the simplest model of viscoelastic deformation (a Maxwell body), the total strain is the sum of a viscous term and an elastic term that feel the same stress.

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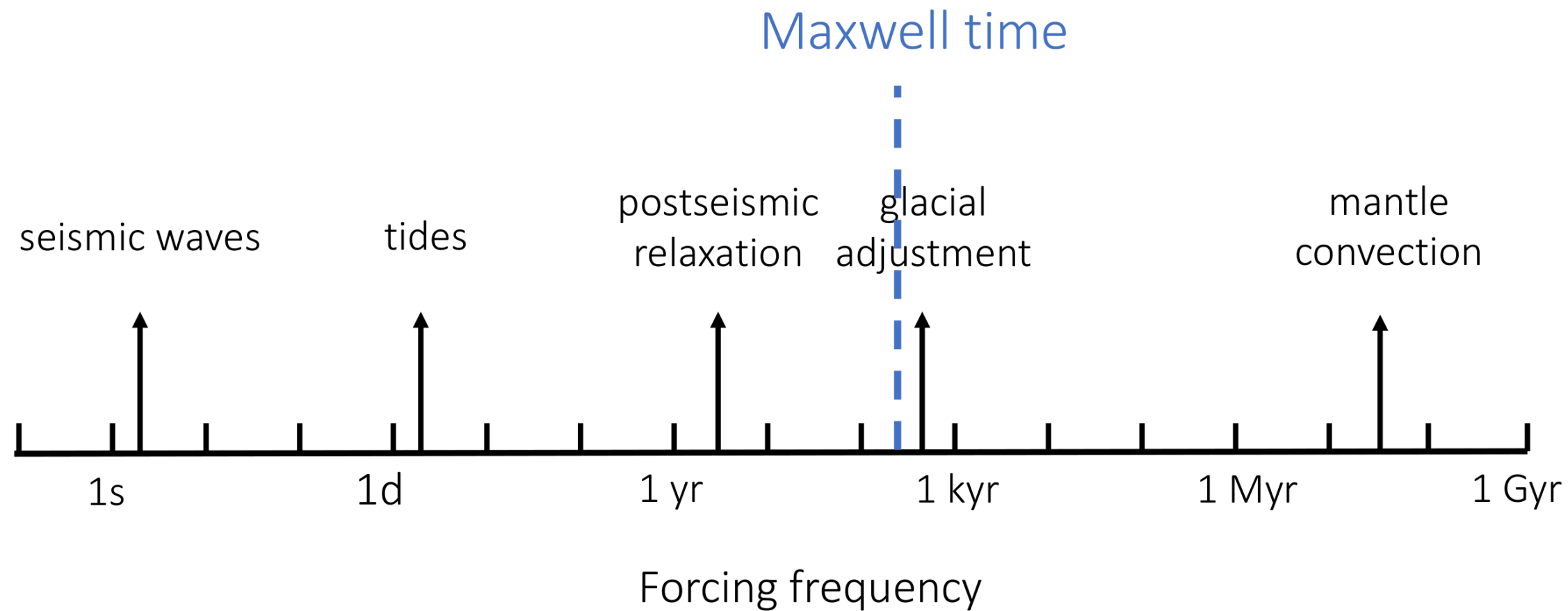
$$\frac{de}{dt} = \frac{1}{k} \frac{d\sigma}{dt} + \frac{1}{\eta} \sigma$$

σ = stress
 e = strain

An instantaneous elastic response and a time-dependant viscous response for a fluid whose viscosity is not dependant on strain rate (Newtonian fluid)



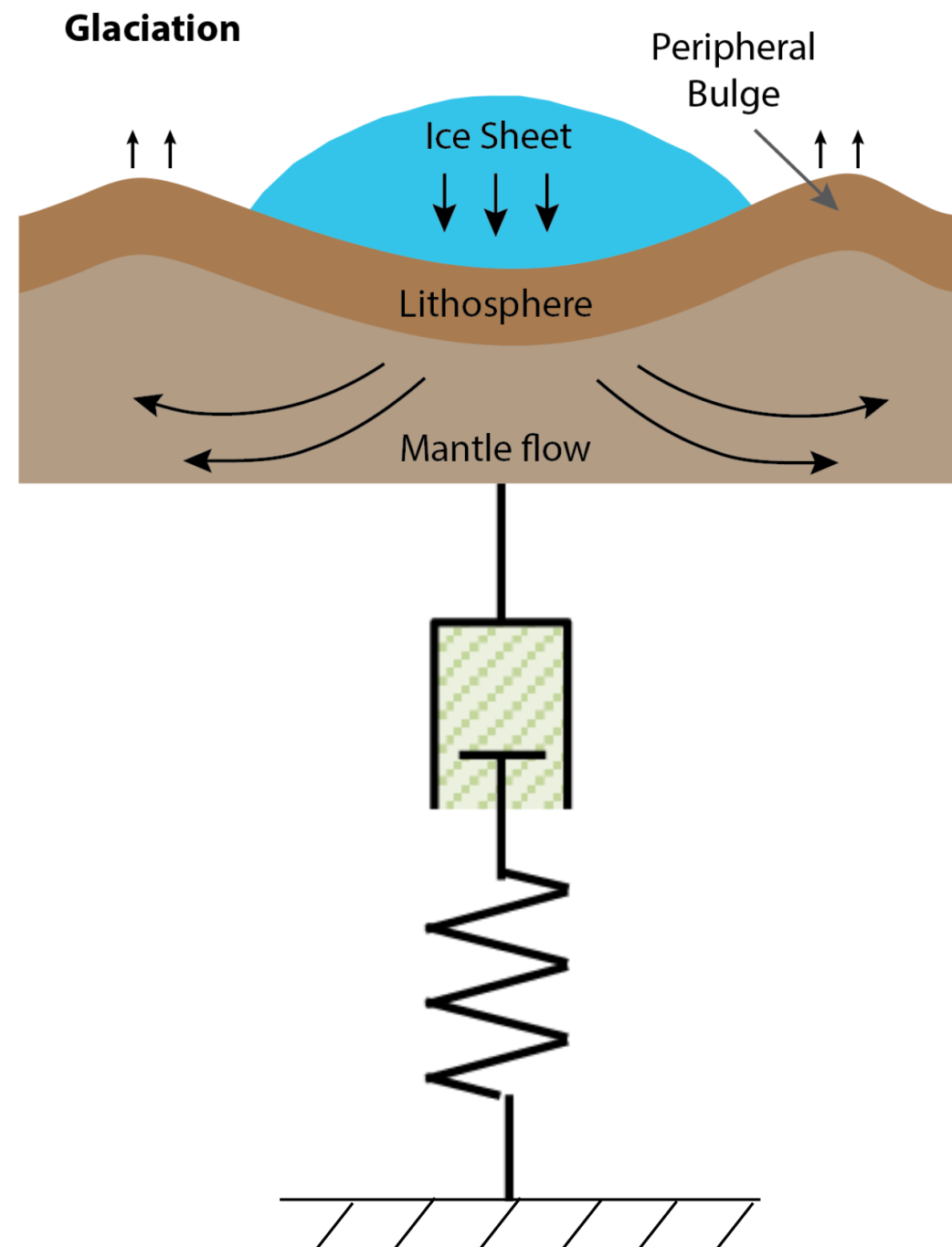
Earth as a viscoelastic solid



- Maxwell time: time after which half of the deformation is elastic and half is viscous. A body is often considered elastic for $t \ll t_{\text{Maxwell}}$ and mainly viscous for $t \gg t_{\text{Maxwell}}$.



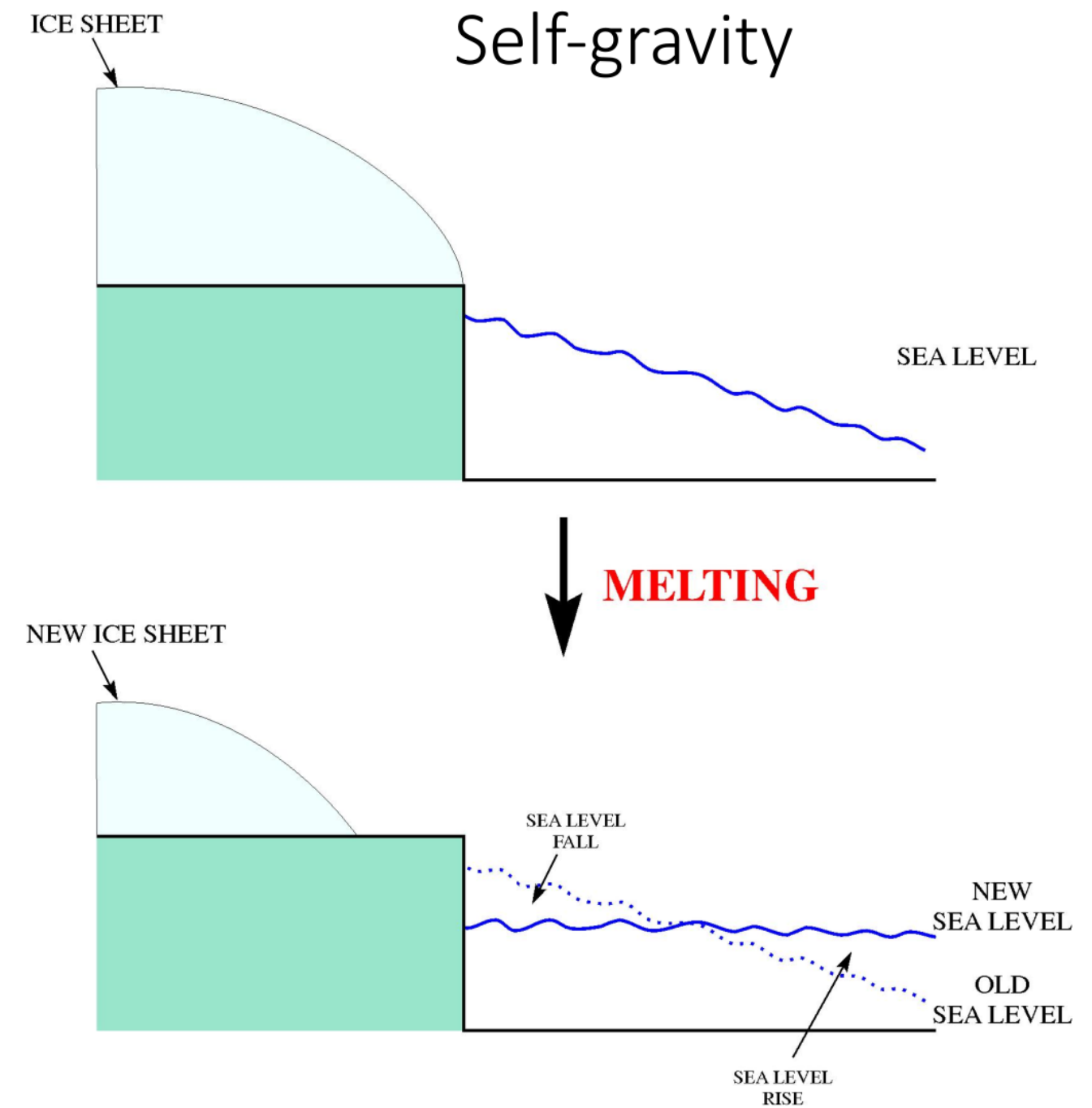
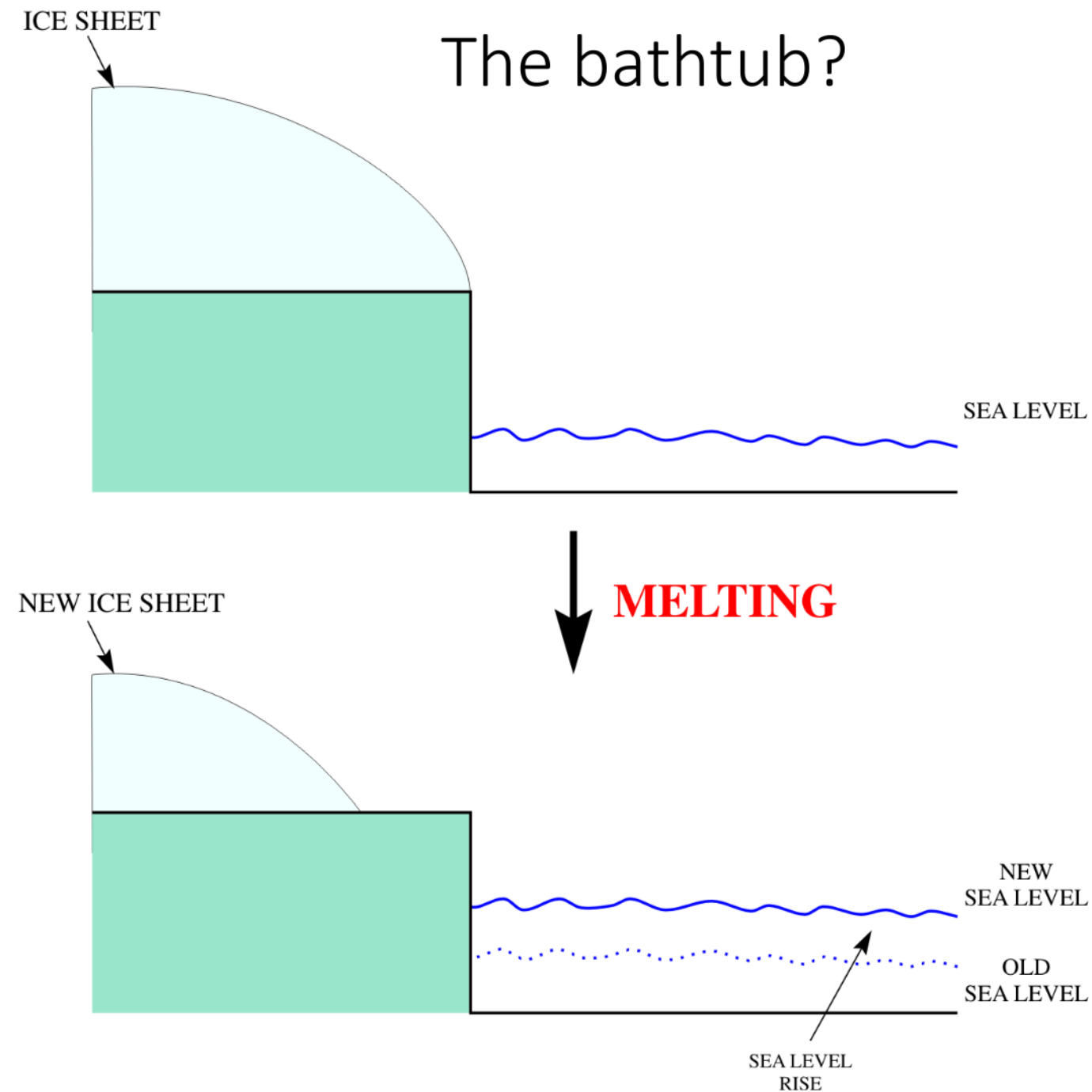
Earth as a viscoelastic solid



- Load change at the top (a change in stress)
- instantaneous elastic response
- time-dependant viscous response

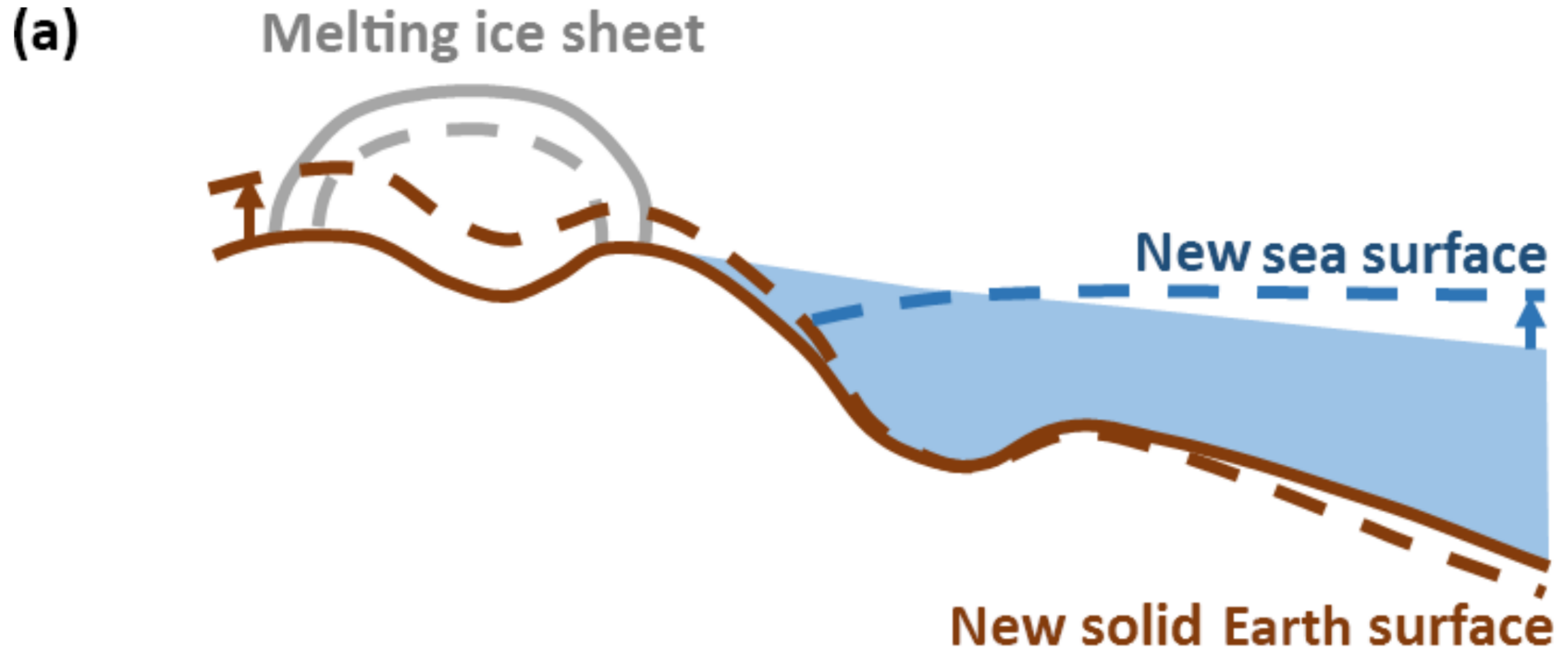
Elastic response

Sea level response to rapid melting of ice sheets and glaciers:



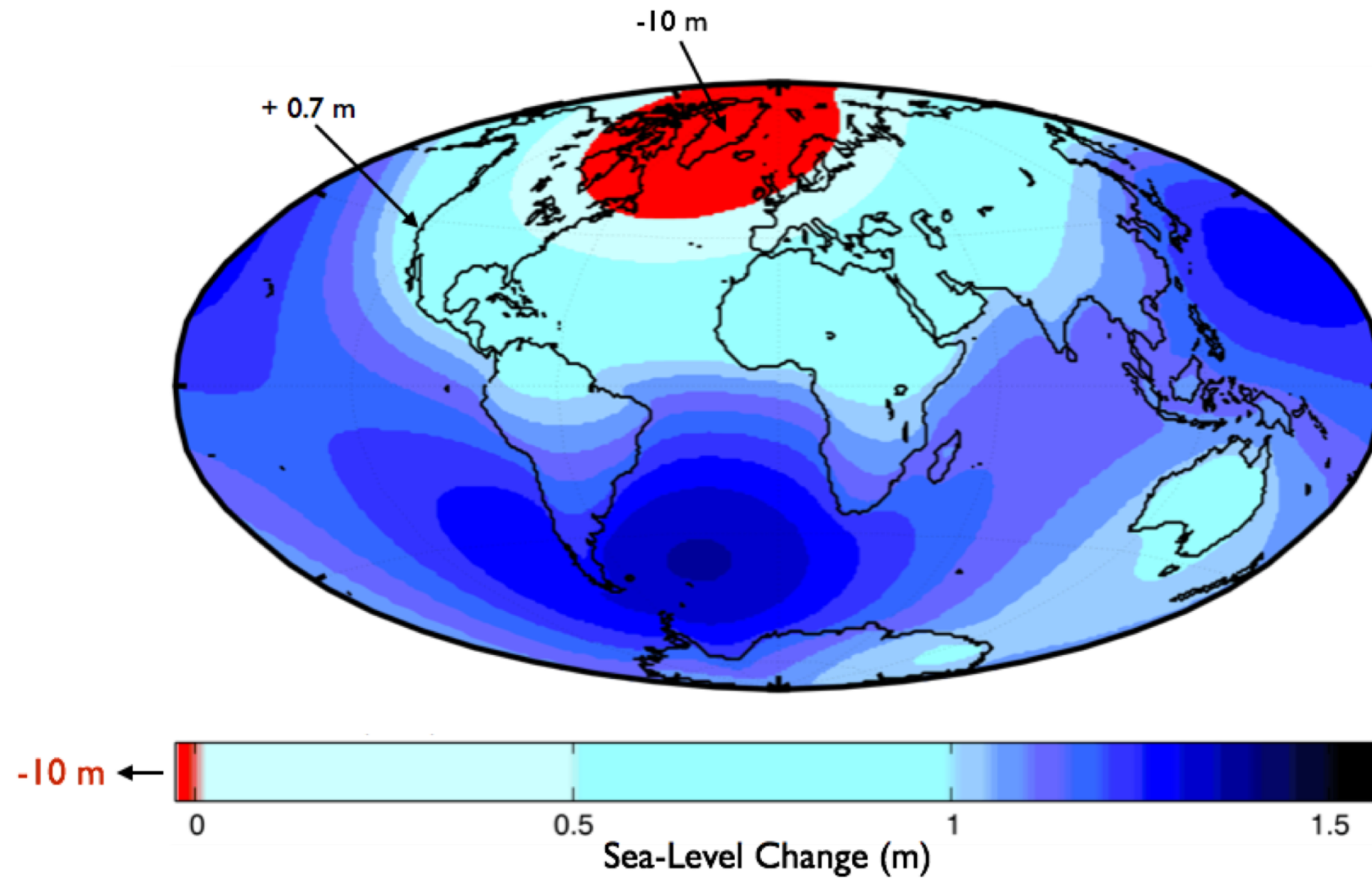
Elastic response

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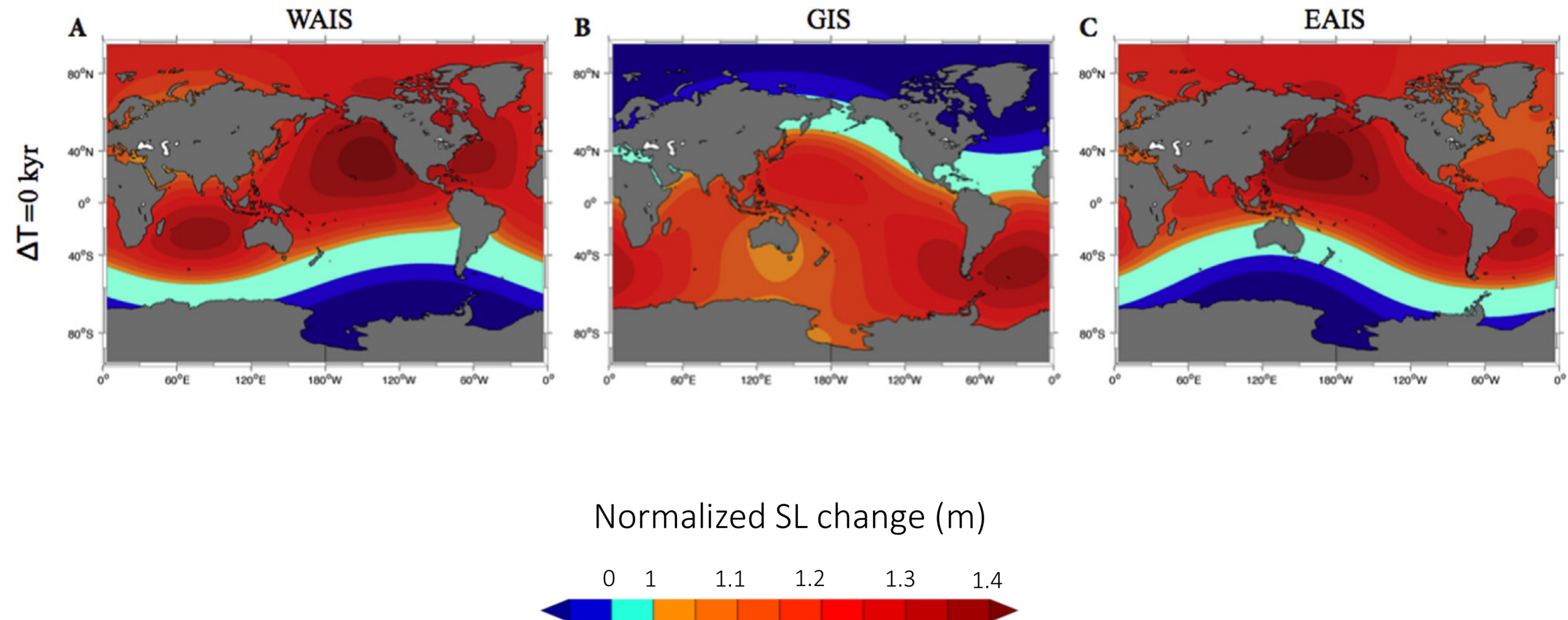
Sea level fingerprints

The instantaneous spatial pattern of sea level rise will be different depending on which ice sheet is melting



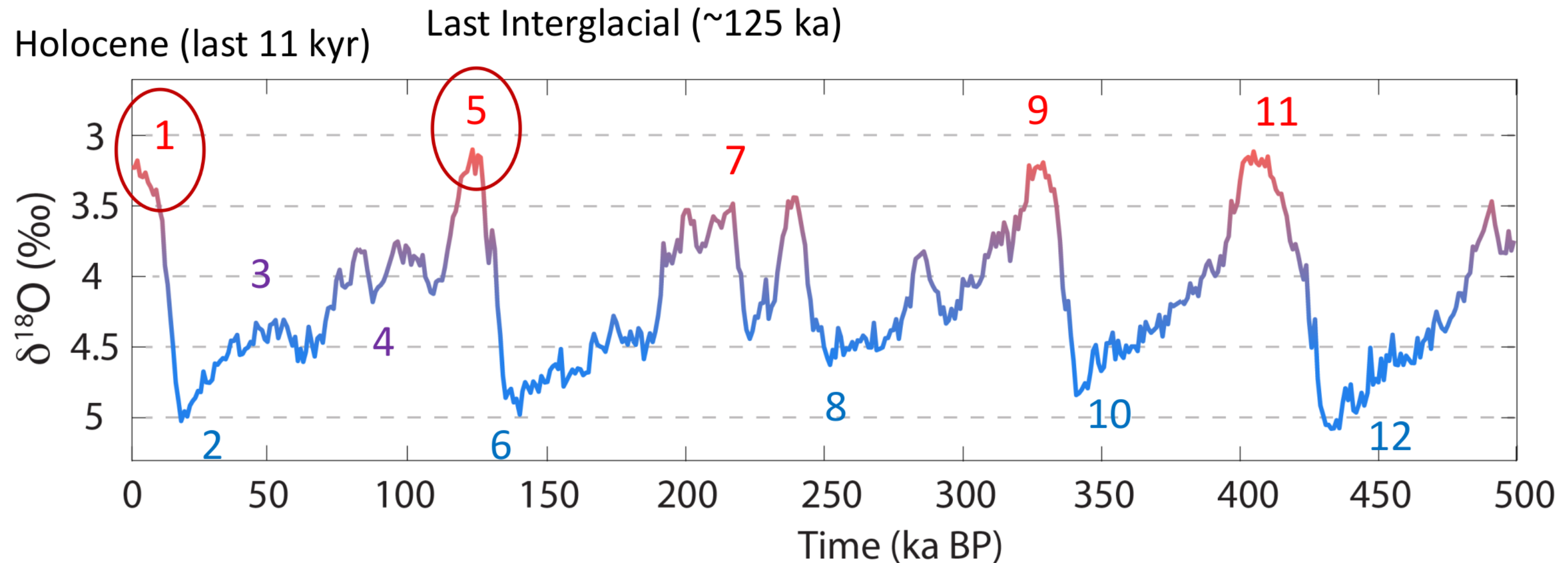
Sea level fingerprints

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Viscous response

What is the ongoing viscous response during an interglacial (after most ice melting is complete)?

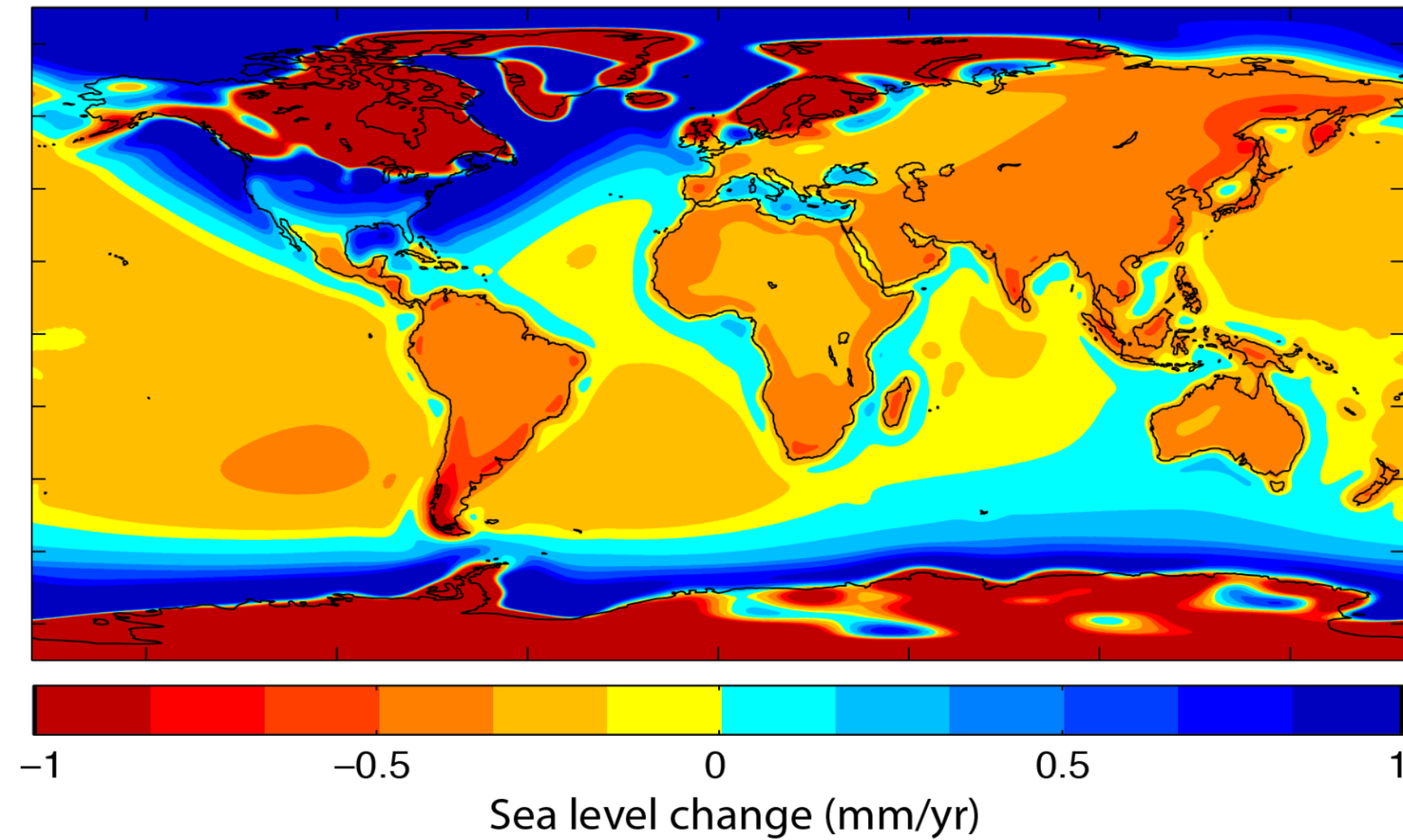


Interglacial = warm period between glacial maxima.



Viscous response

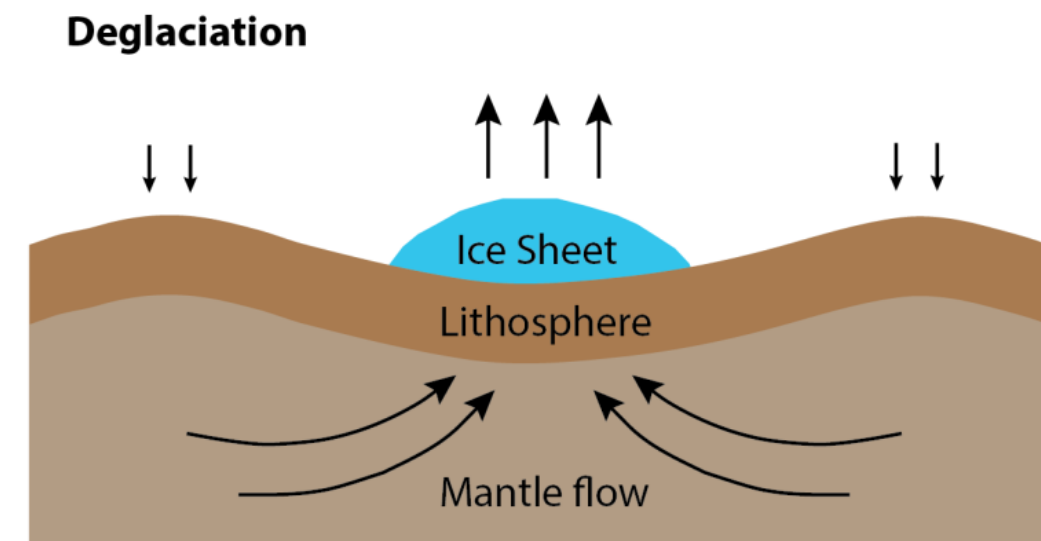
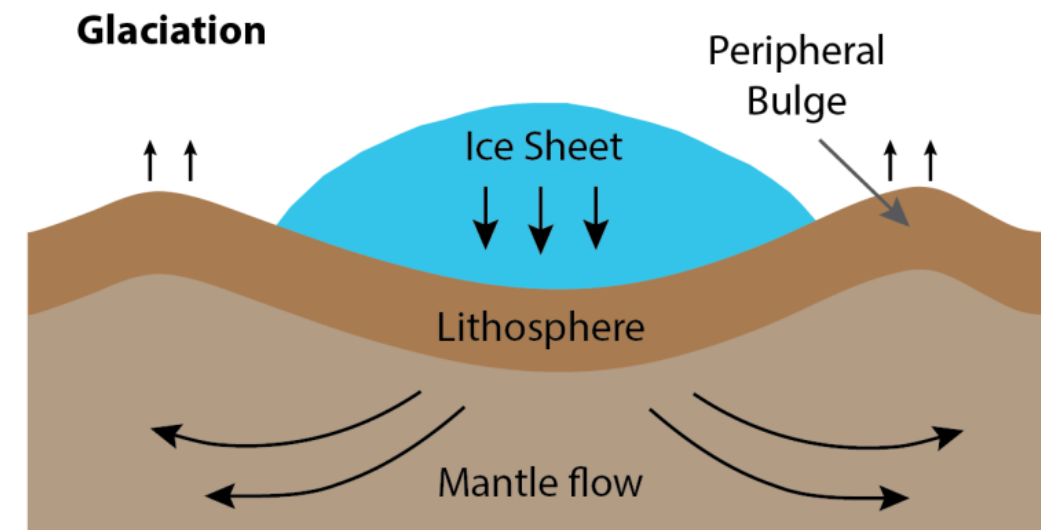
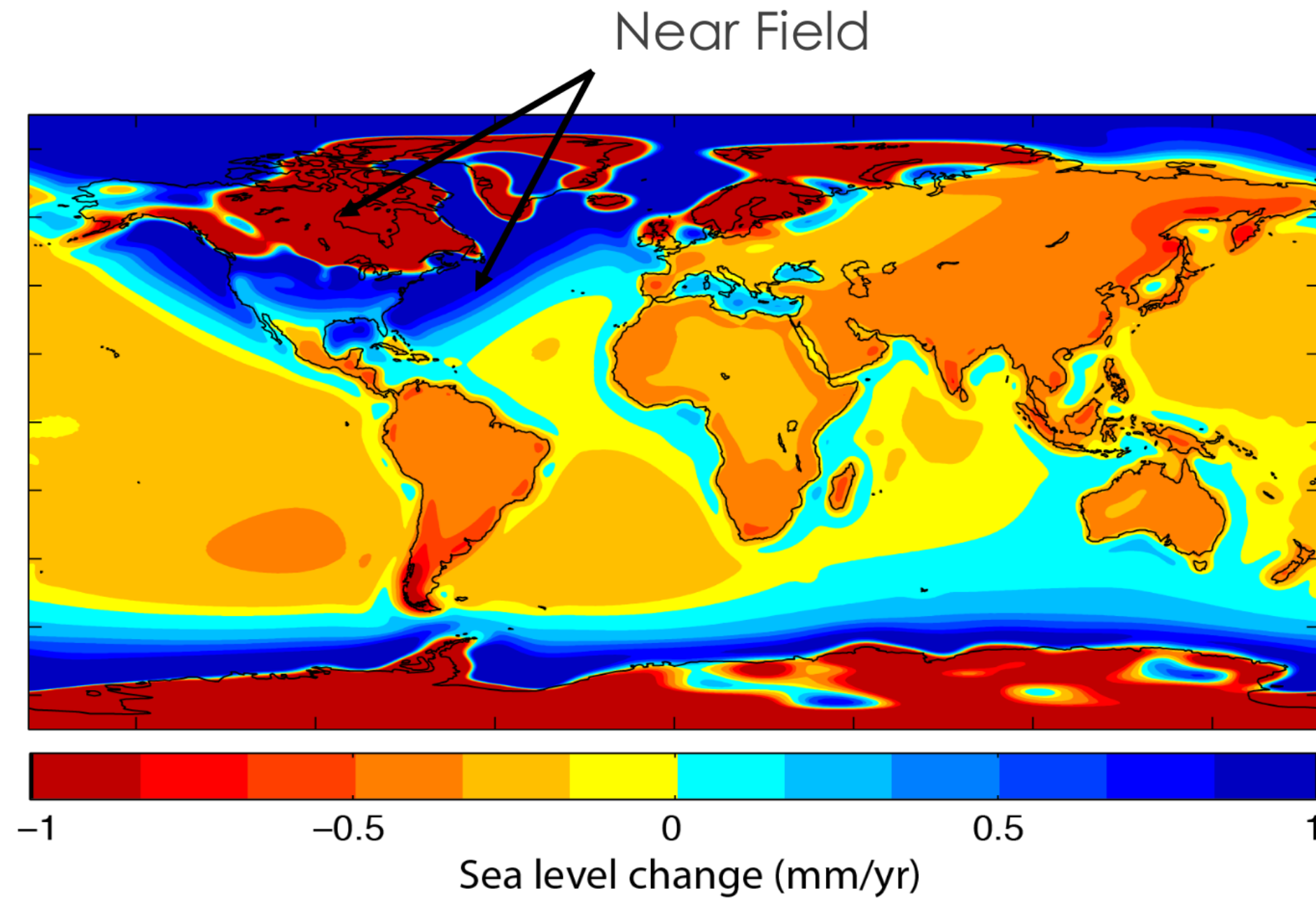
Numerical prediction of present-day rate of local sea-level change due to ongoing glacial isostatic adjustment



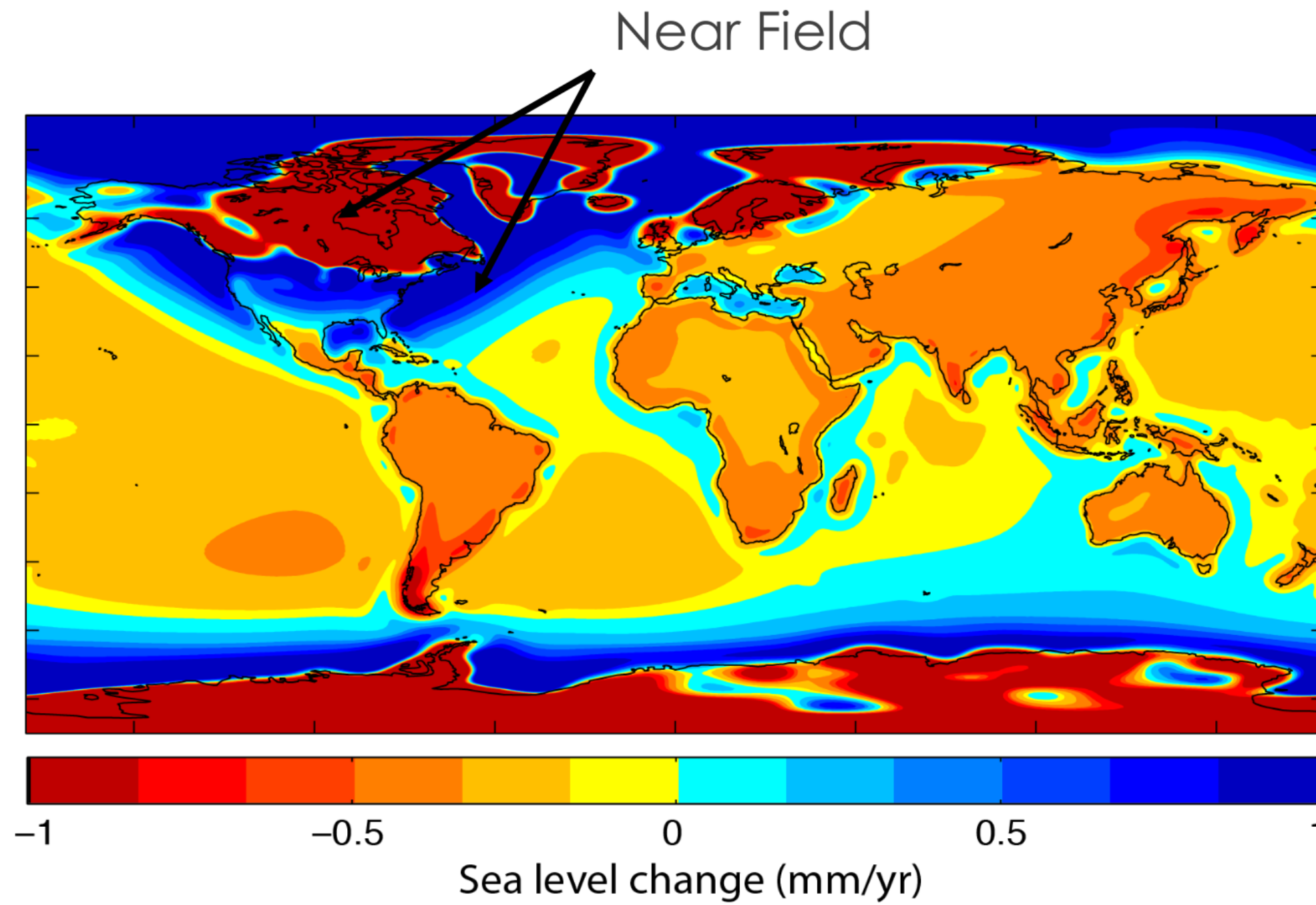
Describe the general pattern you see. What gives rise to this pattern?



Viscous response



Viscous response



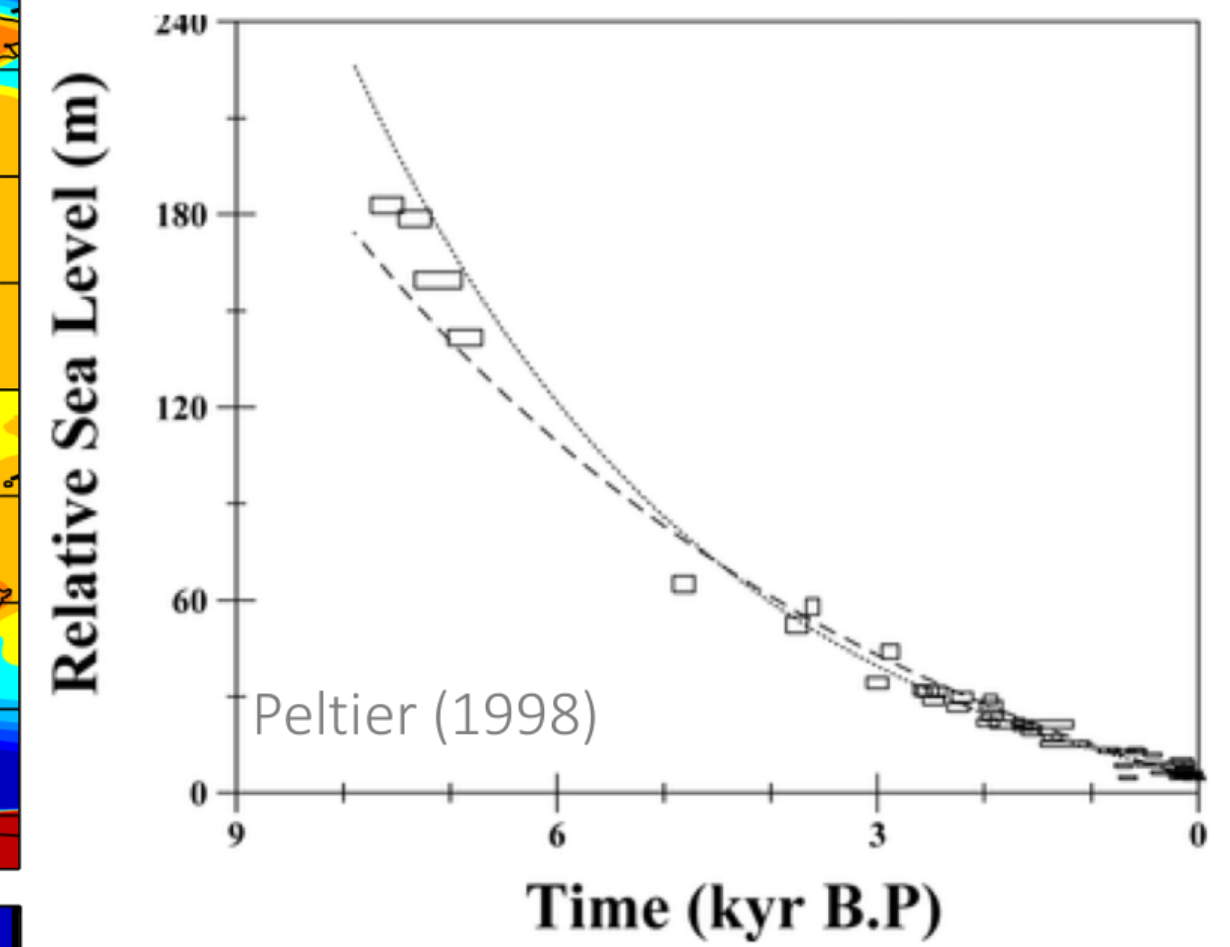
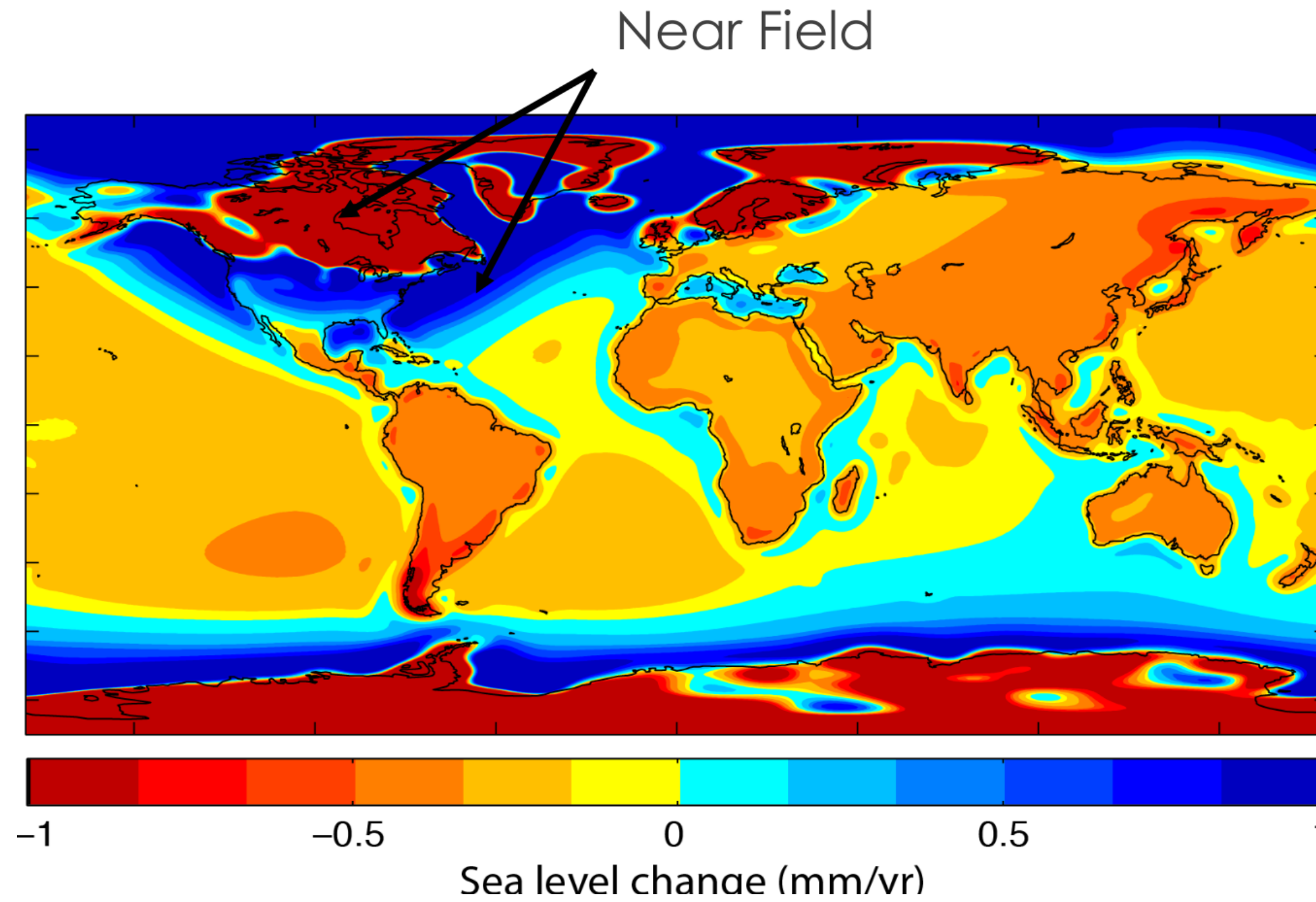
Nunavut - Canadian Arctic



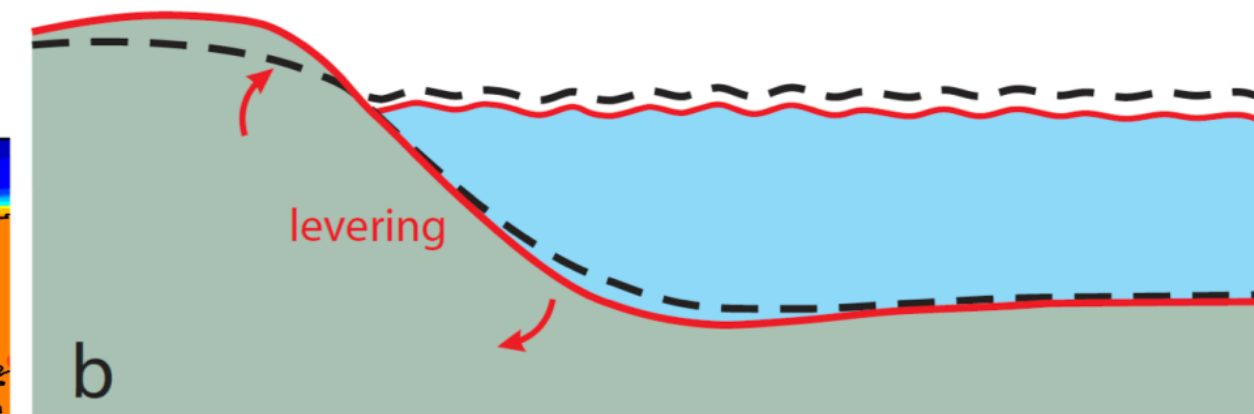
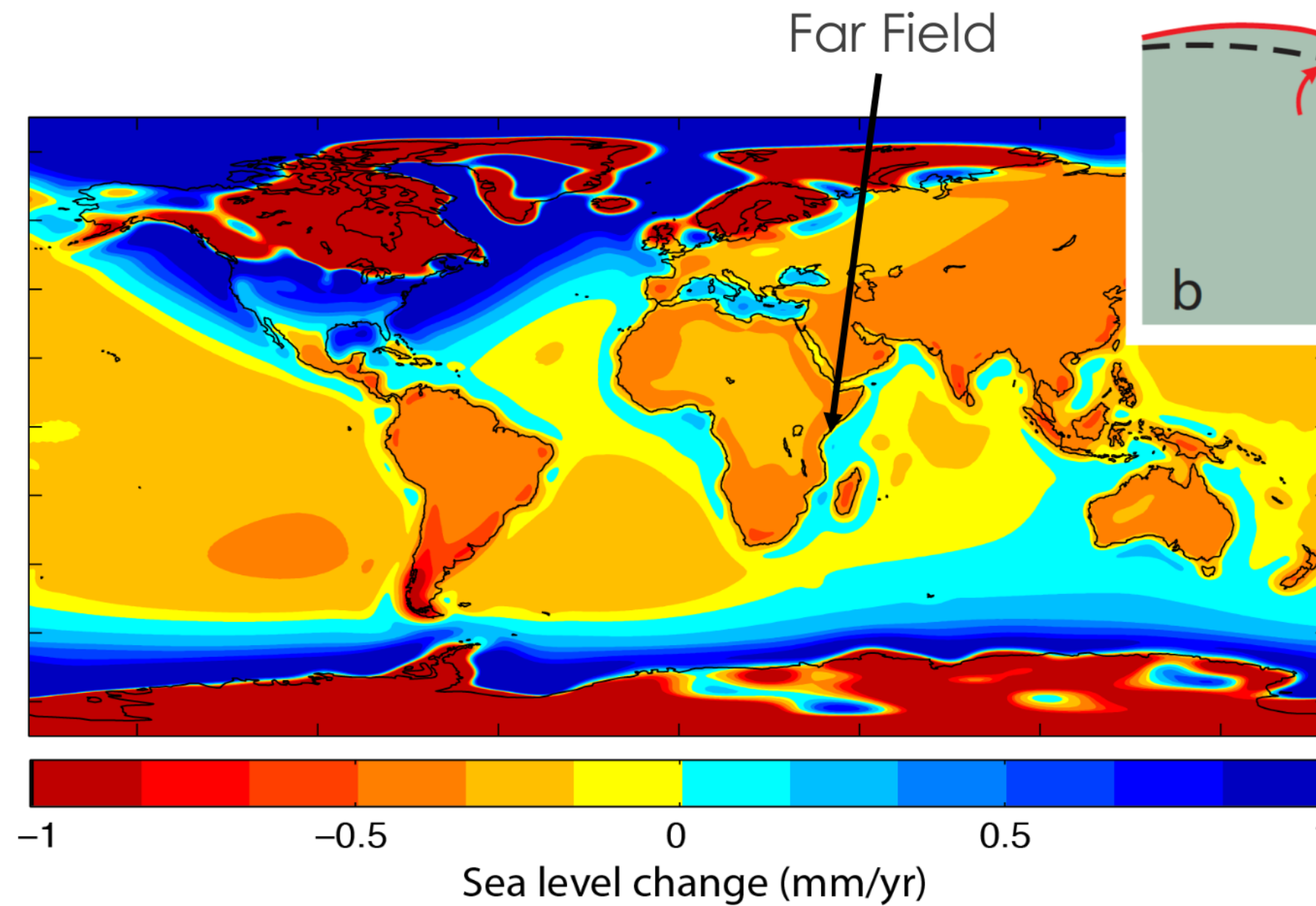
Image credit: Mike Beauregard



Viscous response



Viscous response

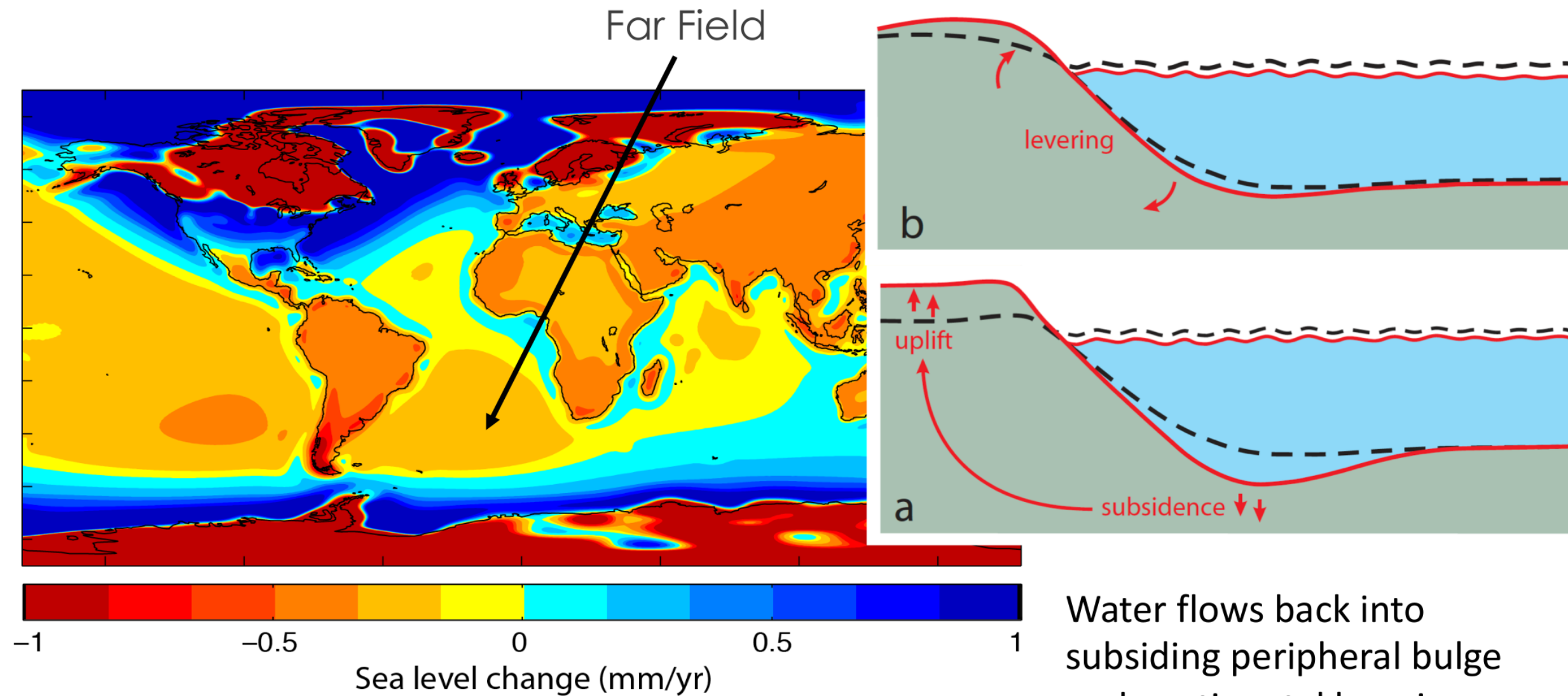


Water is added to the oceans during the deglaciation. Forces mantle to flow from oceans to continents (in the subsurface).

Does the sign of sea level change make sense?



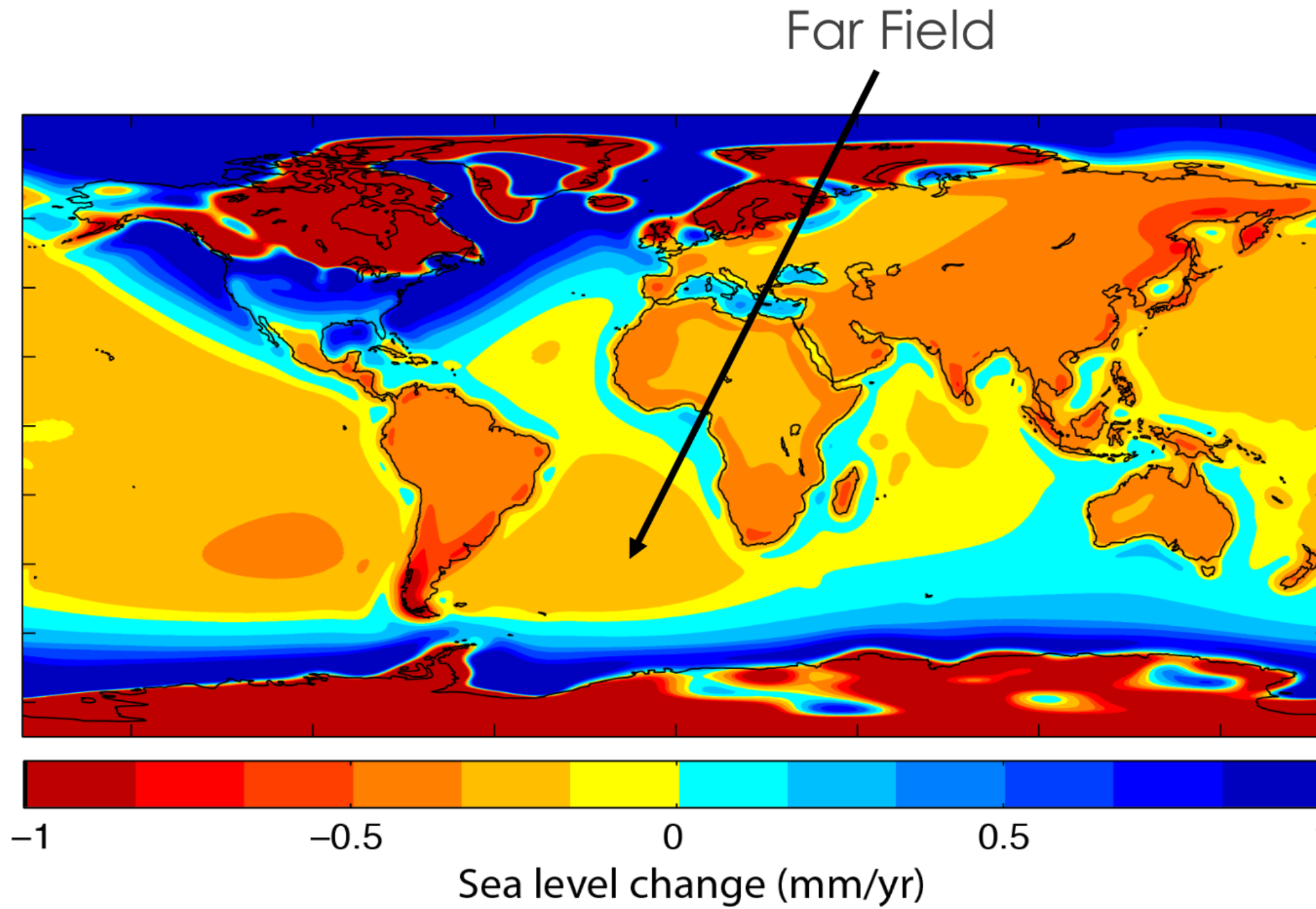
Viscous response



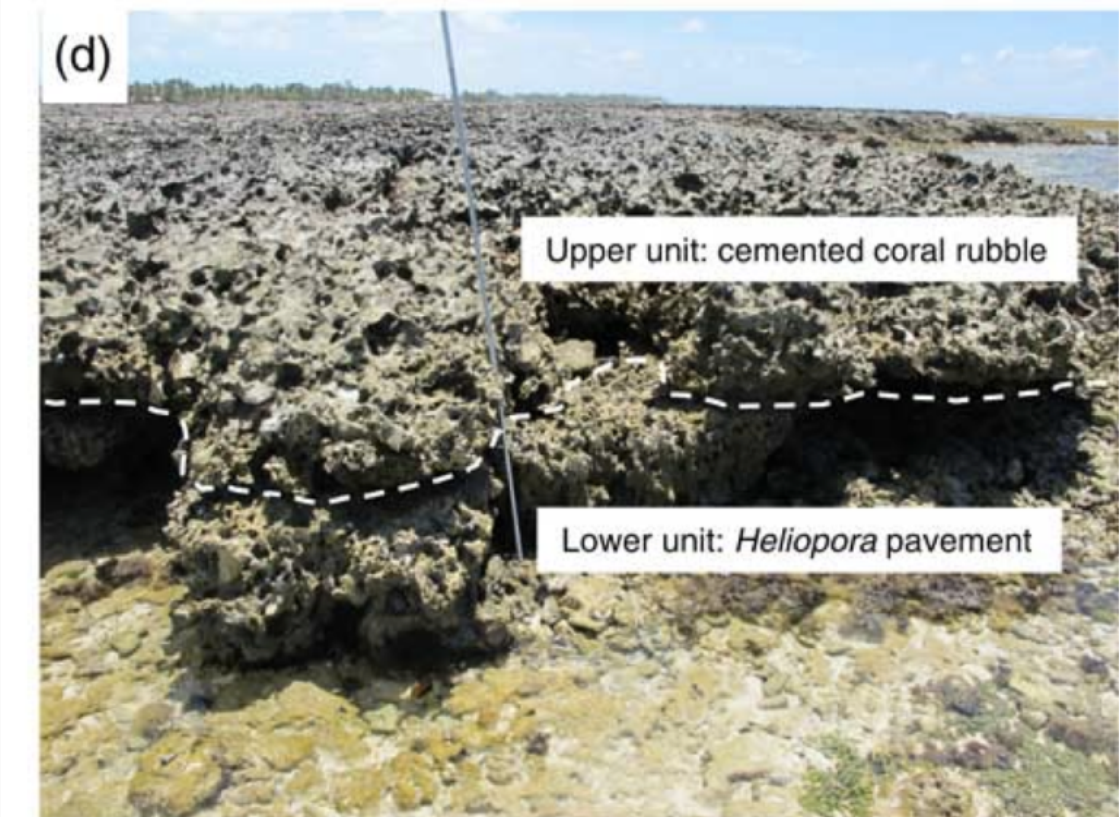
Numerical Prediction of present-day rate of global sea-level change due to ongoing GIA

Water flows back into subsiding peripheral bulge and continental levering areas, leading to overall sea level fall.

Viscous response

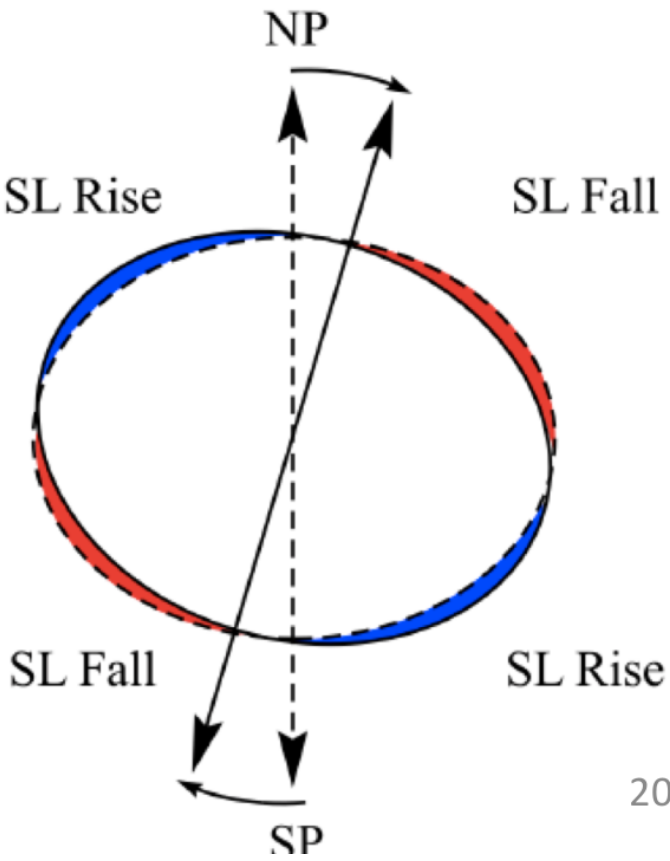
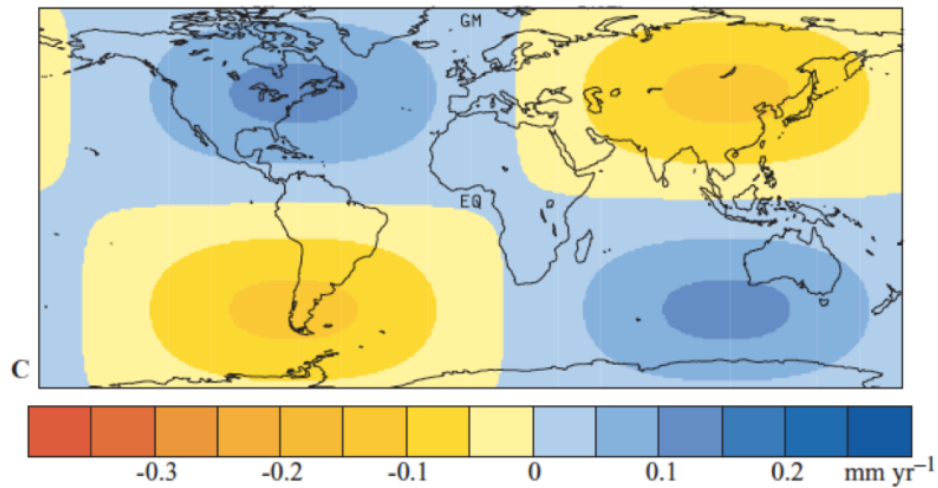
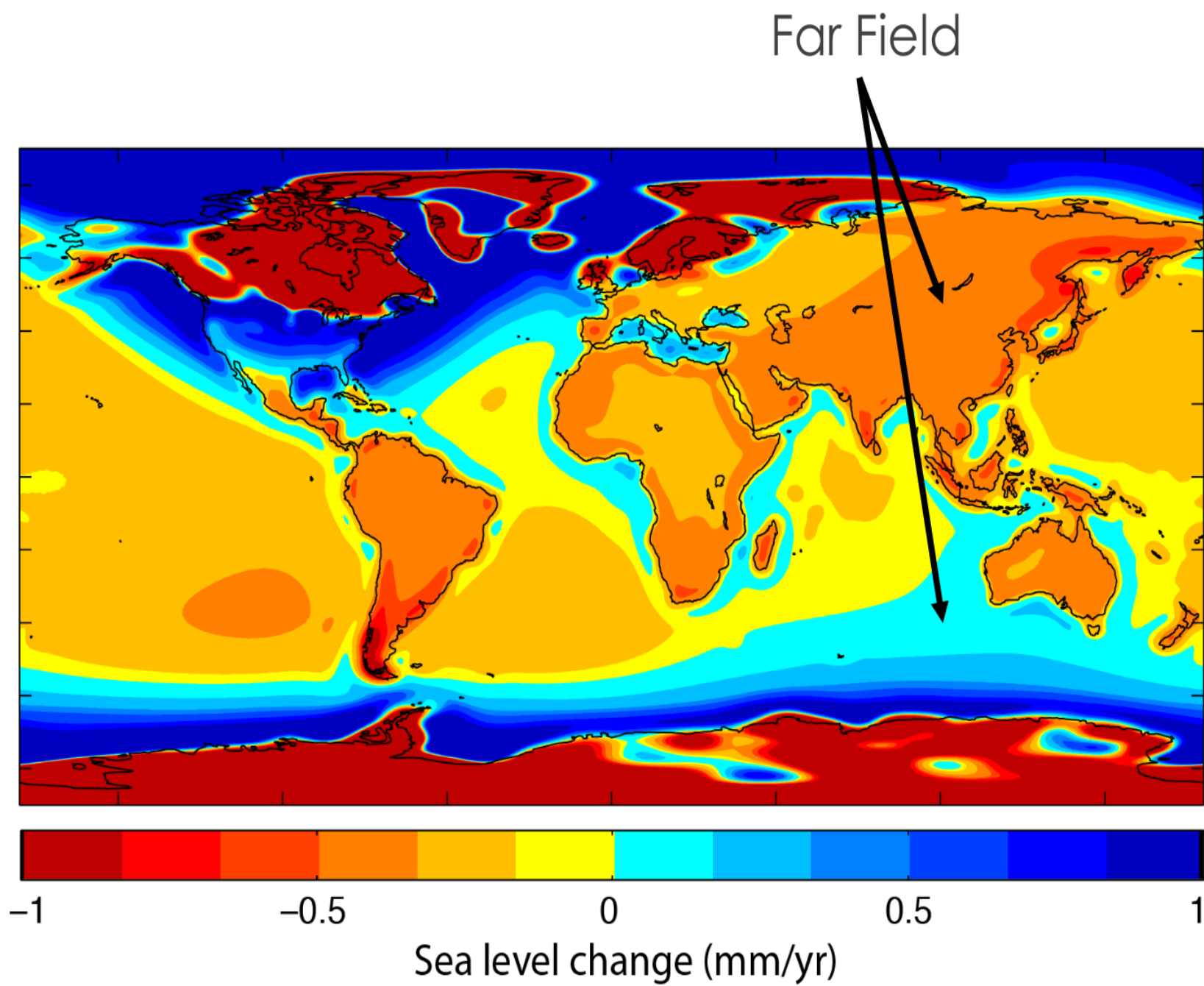


Exposed Holocene corals on Kiribati, west-central Pacific Ocean



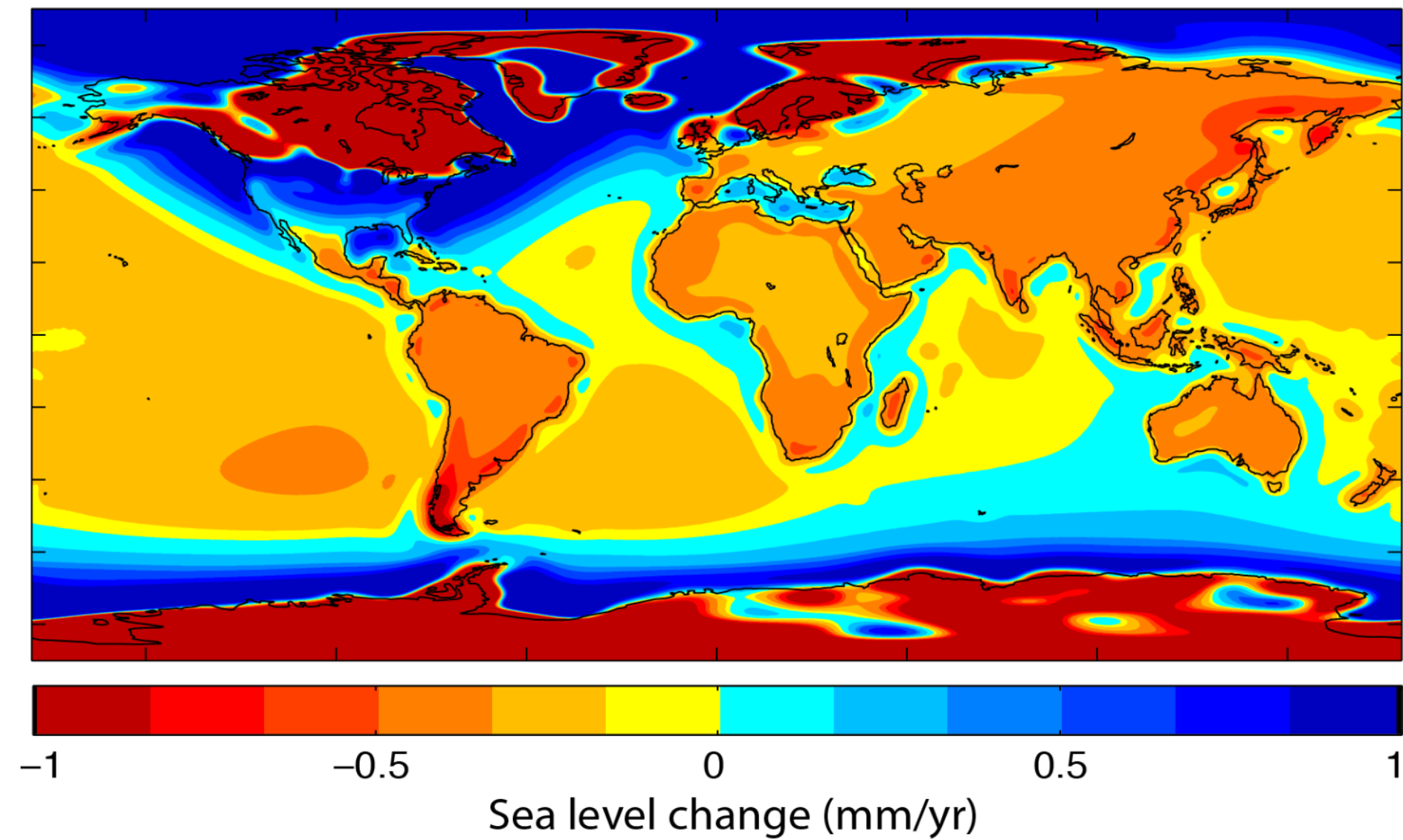
Yamano et al., 2017

Viscous response



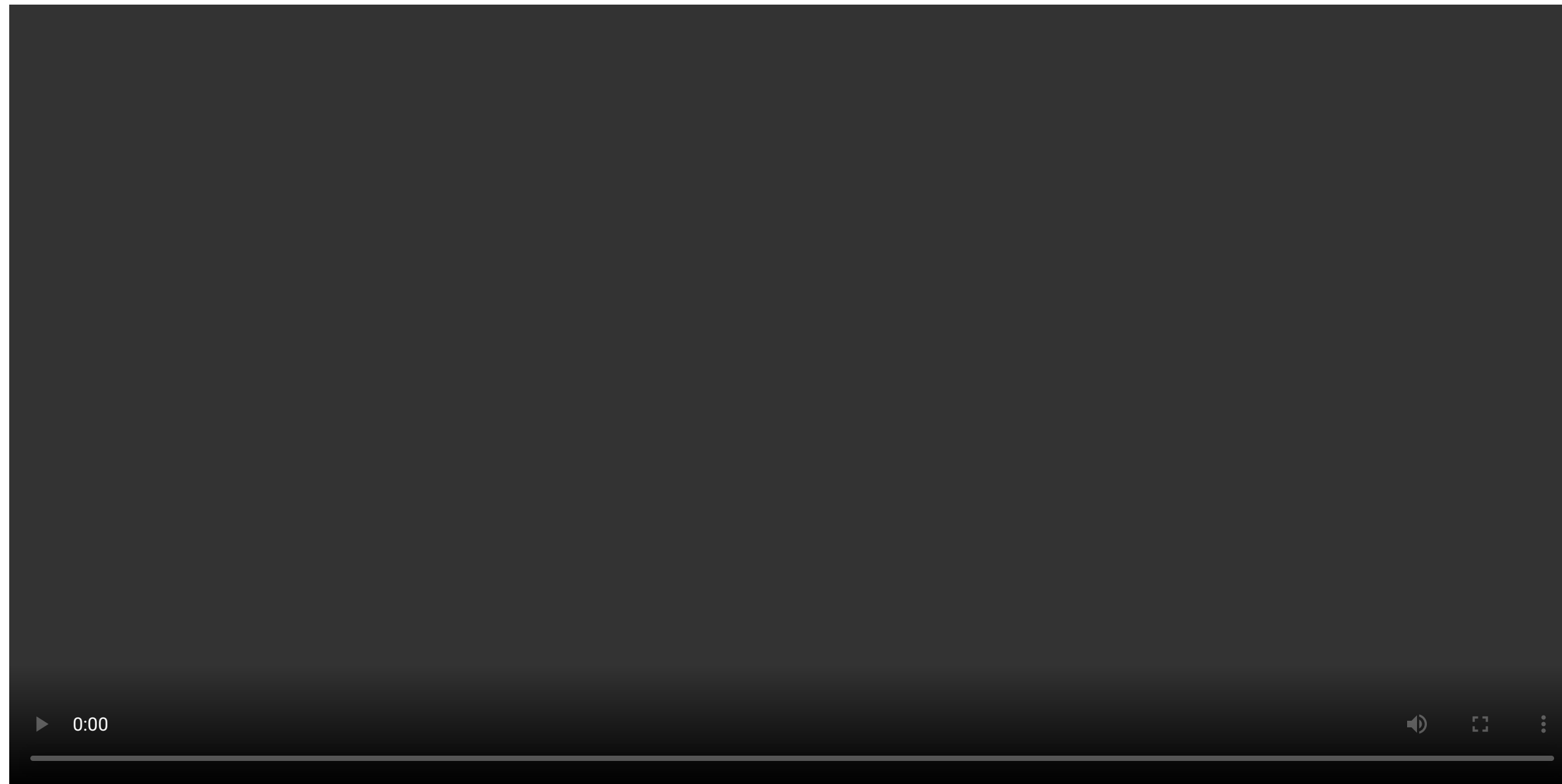
Viscous response

Test your intuition: try to draw the temporal evolution of sea level during an interglacial (with no excess melt) for Hawaii and The Bahamas.



Viscous response

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Past warm periods can tell us how sensitive ice sheets are to warming

