Sea level effects from prehistoric and present-day ice changes on land

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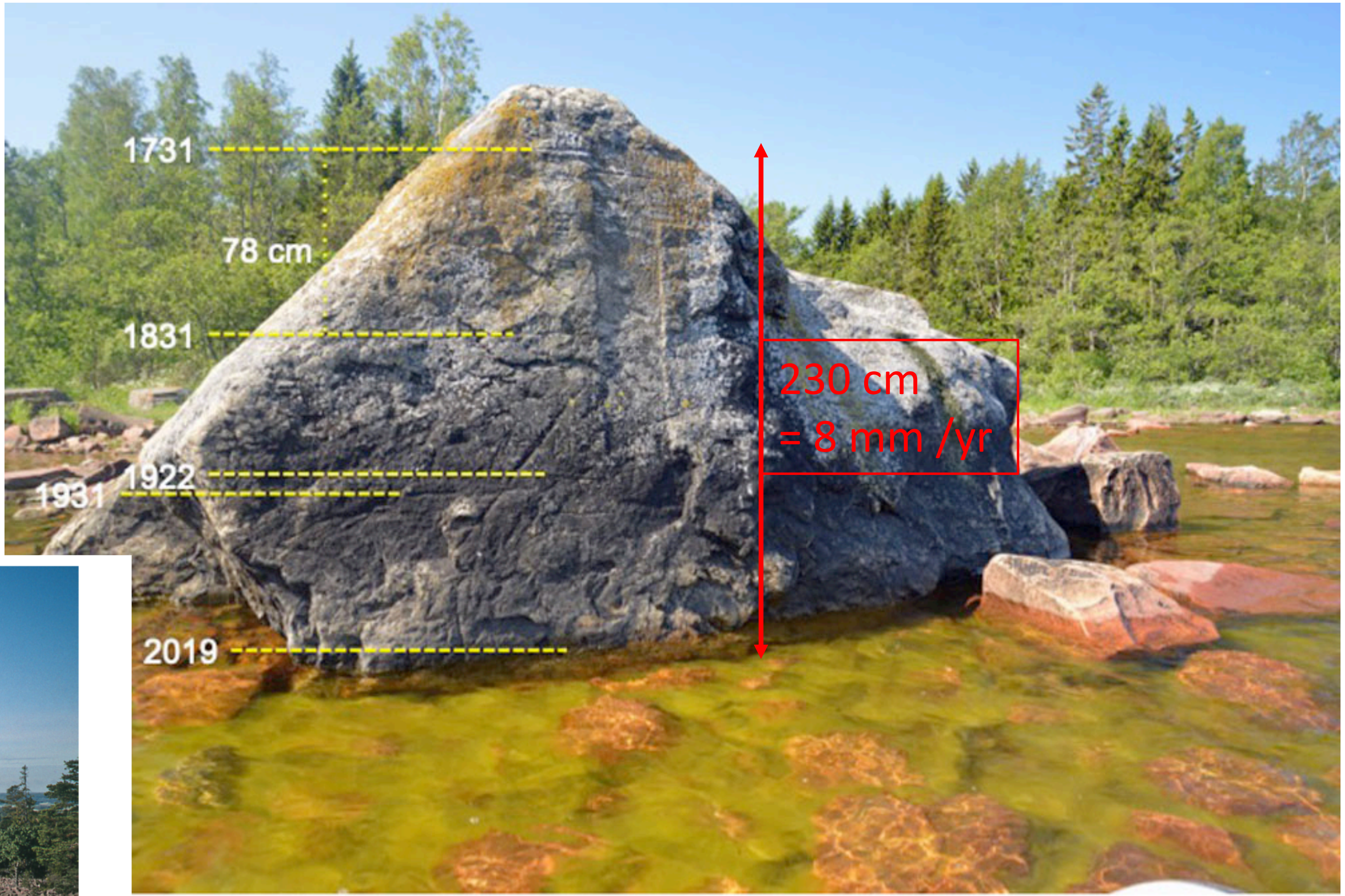
Outline

- What happens to Earth's surface when ice melts?
- The 'Sea Level Equation'
- Prehistoric and present ice and sea level changes
- Vertical land movement and importance for coastal sea level

Background

The solid Earth surface moves vertically as ice melts. And continues to do so for many years.

Discovered in the 18th century by Anders Celcius



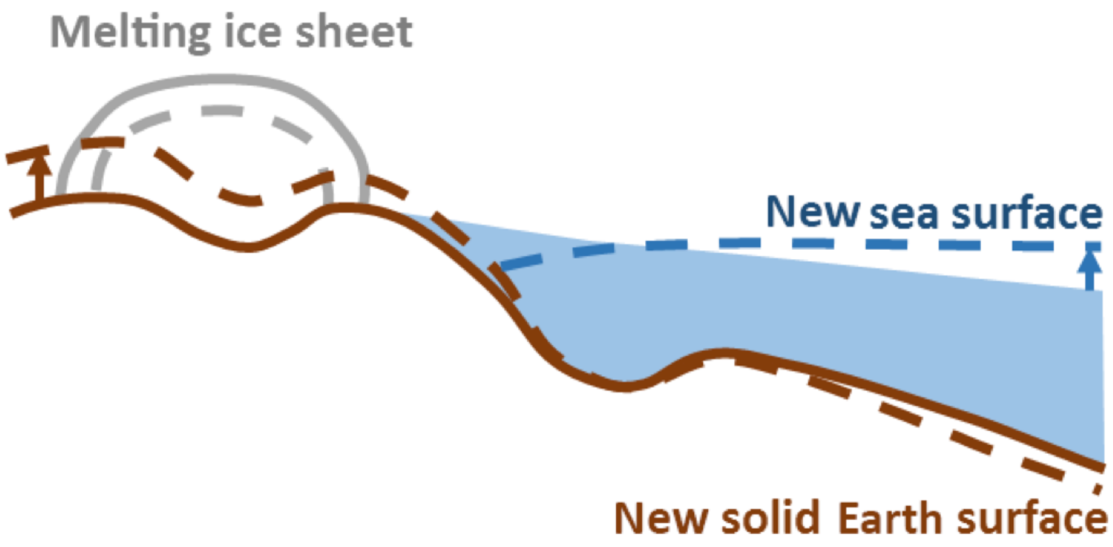
Celcius-rock
Iggön, Sweden

Figure 3-7. Ancient boulder shore that is situated high above sea level because of the postglacial rebound (northern part of the Åland Islands).

What happens when ice melts?

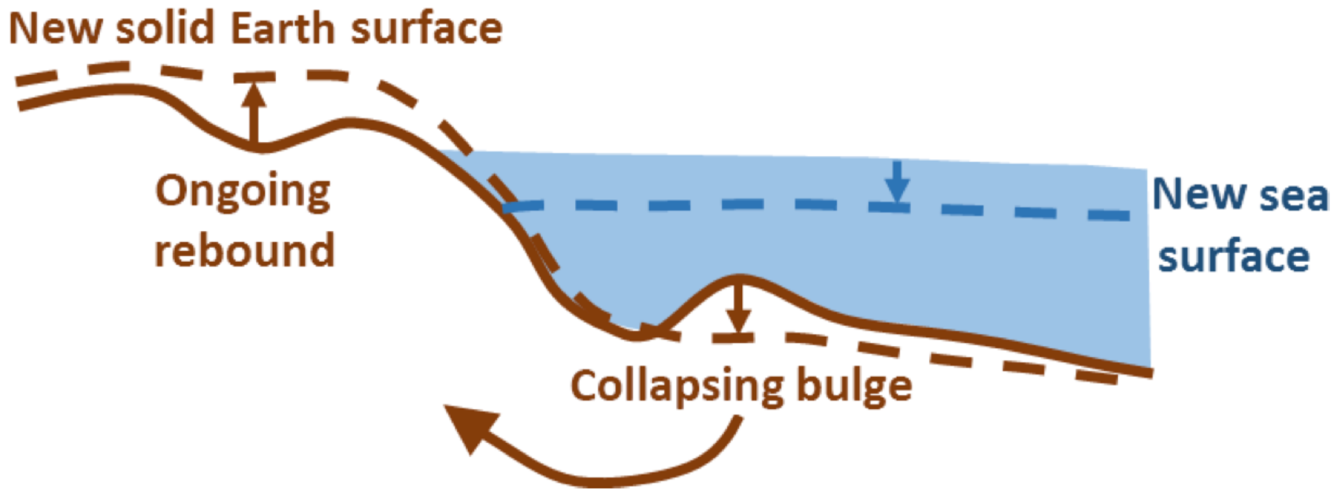
Immediate

- **elastic** solid Earth deformation
- gravitational change due to land-to-ocean mass redistribution
- global mean sea level rise



Long term/GIA (>1 kyr)

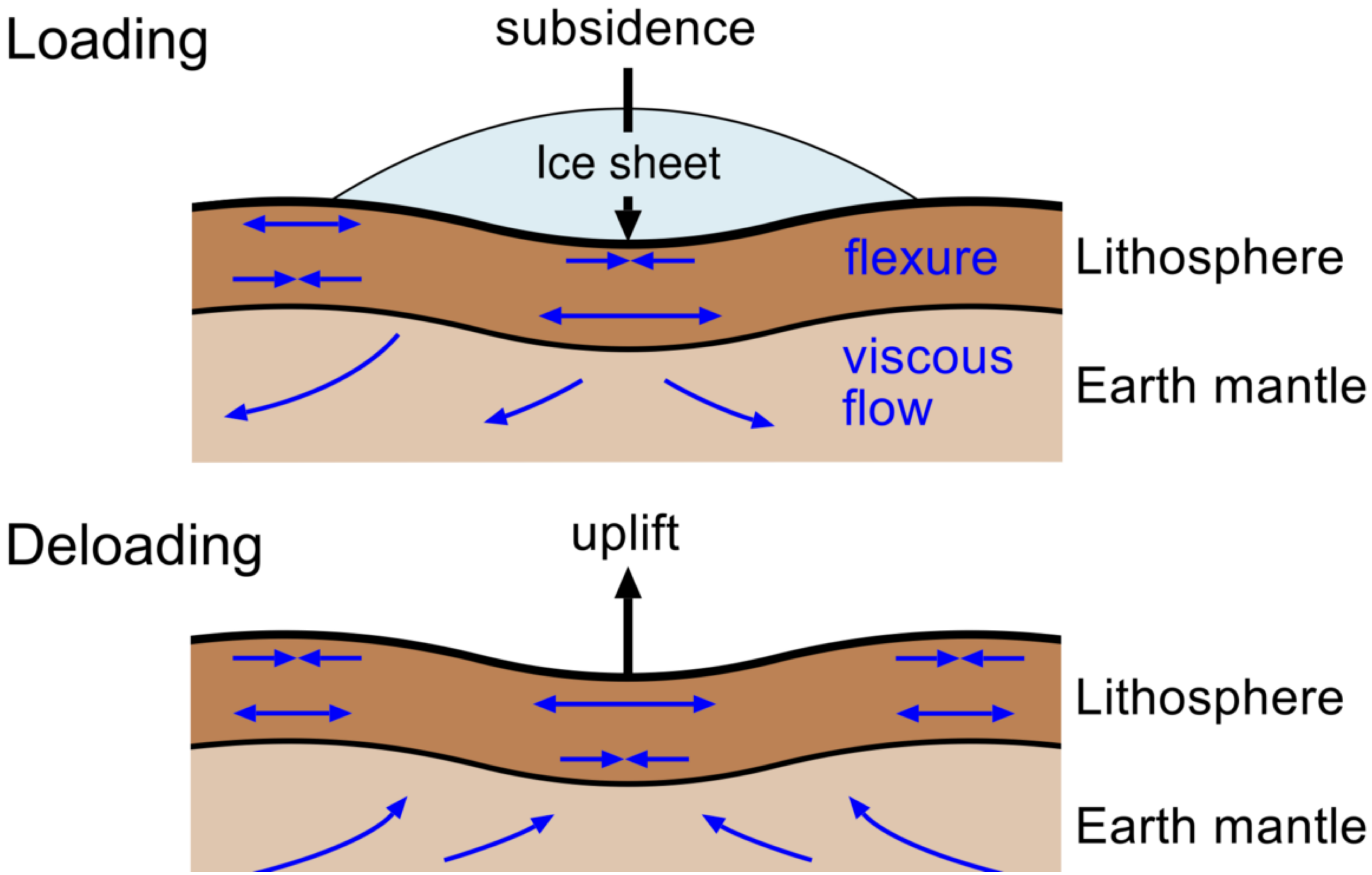
- continued **viscoelastic** solid earth deformation (GIA)
- gravitational change due to mantle mass redistribution below
- global mean sea level rise or fall



What happens when ice melts?

Glacial Isostatic Adjustment (GIA)

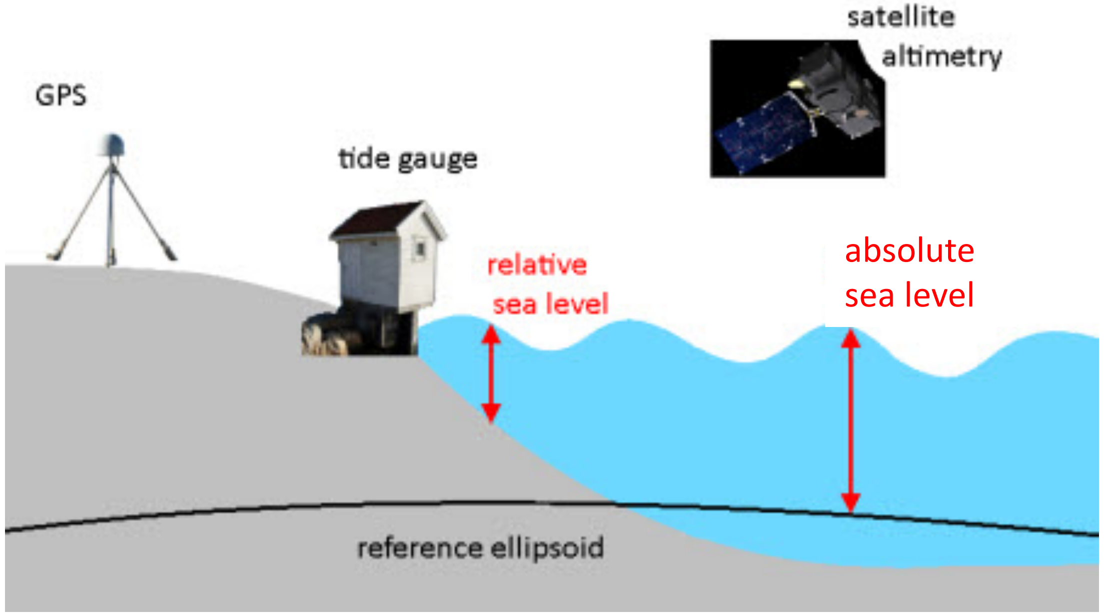
- Relevant on millenial timescales (1 – 100 kyr)
- smaller change rate than elastic uplift - but decays slowly over time.



The Sea Level Equation (SLE)

SLE in its simplest form:

S = N - U



S = relative sea level change (measured by tide gauges)

N = geoid / absolute sea level change (measured with satellite altimetry).

U = solid earth change (measured with GPS)

The Sea Level Equation (SLE)

SLE longer version: $$\Delta S(\theta, \psi, t) = \frac{\rho_{\mathrm{i}}}{\gamma} G_{\mathrm{S}} \otimes_i I + \frac{\rho_{\mathrm{w}}}{\gamma} G_{\mathrm{S}} \otimes_o \Delta S + C_{\mathrm{SL}}(t)$$

θ, ψ, t = co-latitude, longitude and time
ρ_i , ρ_w = density ice / water
γ = standard gravitational acceleration
G_S = Green's functions
I = ice mass loading change
C_{SL} = mean sea level change (spatially invariant)
$\otimes_i$,$\otimes_o$= convolution in time and space over ice loading / ocean loading

The Sea Level Equation (SLE)

$$\Delta S(\theta, \psi, t) = \frac{\rho_{\mathrm{i}}}{\gamma} G_{\mathrm{S}} \otimes_i I + \frac{\rho_{\mathrm{w}}}{\gamma} G_{\mathrm{S}} \otimes_o \Delta S + C_{\mathrm{SL}}(t)$$

ΔS on both sides. Integral equation that should be solved iteratively.

Green's function (G_s) describes perturbations to the solid Earth displacement (U) and the gravitational potential (N) due to surface loading (I).

Free SLE-tool: SELEN = Sea Level Equation Solver (Spada and Stocchi, 2007). github.com/geodynamics/selen

The Sea Level Equation (SLE)

$$\Delta S(\theta, \psi, t) = \frac{\rho_{\rm i}}{\gamma} G_{\rm S} \otimes_i I + \frac{\rho_{\rm w}}{\gamma} G_{\rm S} \otimes_o \Delta S + C_{\rm SL}(t)$$

Mean sea level change due to surface loading (I) :

$$C_{\rm SL}(t) = -\frac{m_{\rm i}(t)}{\rho_{\rm w} A_0(t)} - \frac{\rho_{\rm i}}{\gamma} \overline{G_{\rm S} \otimes_{\rm i} I} - \frac{\rho_{\rm w}}{\gamma} \overline{G_{\rm S} \otimes_{\rm o} \Delta S}$$

Eustatic / Barystatic sea level change

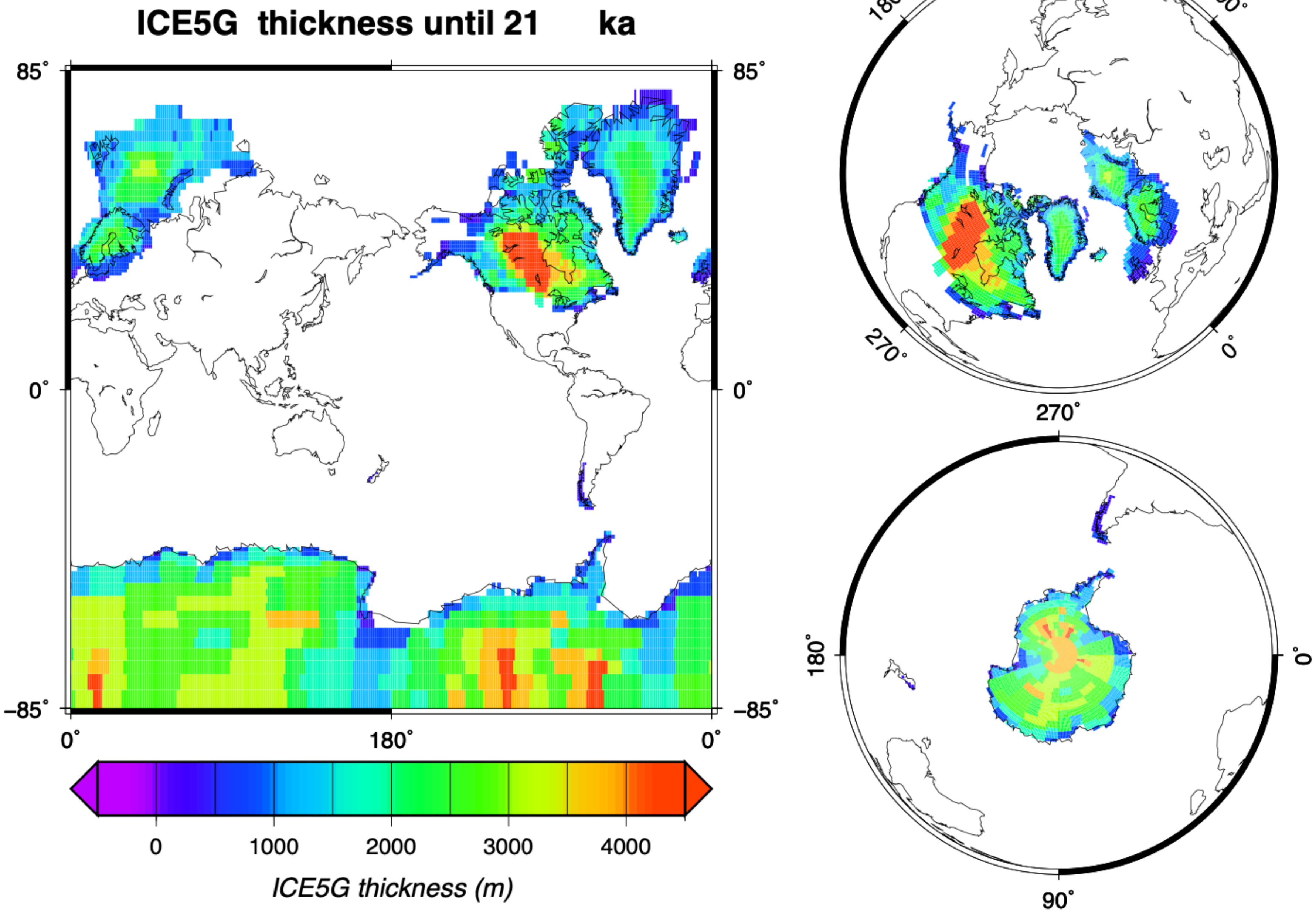
Average G_S for ice mass change

Average G_S from ocean mass change (small – often neglible)

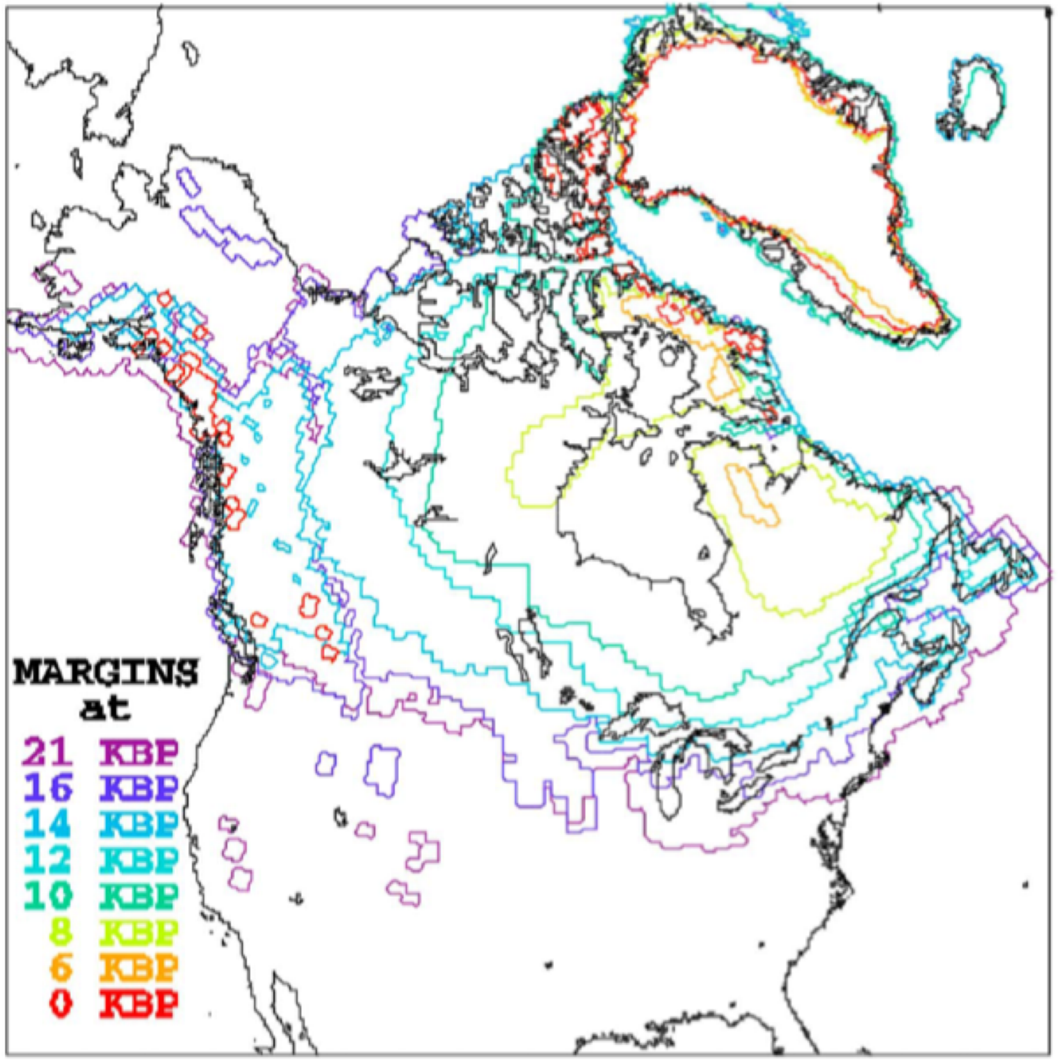
m_i = mass change of ice
A_O = global ocean area
ϕ = gravitational potential

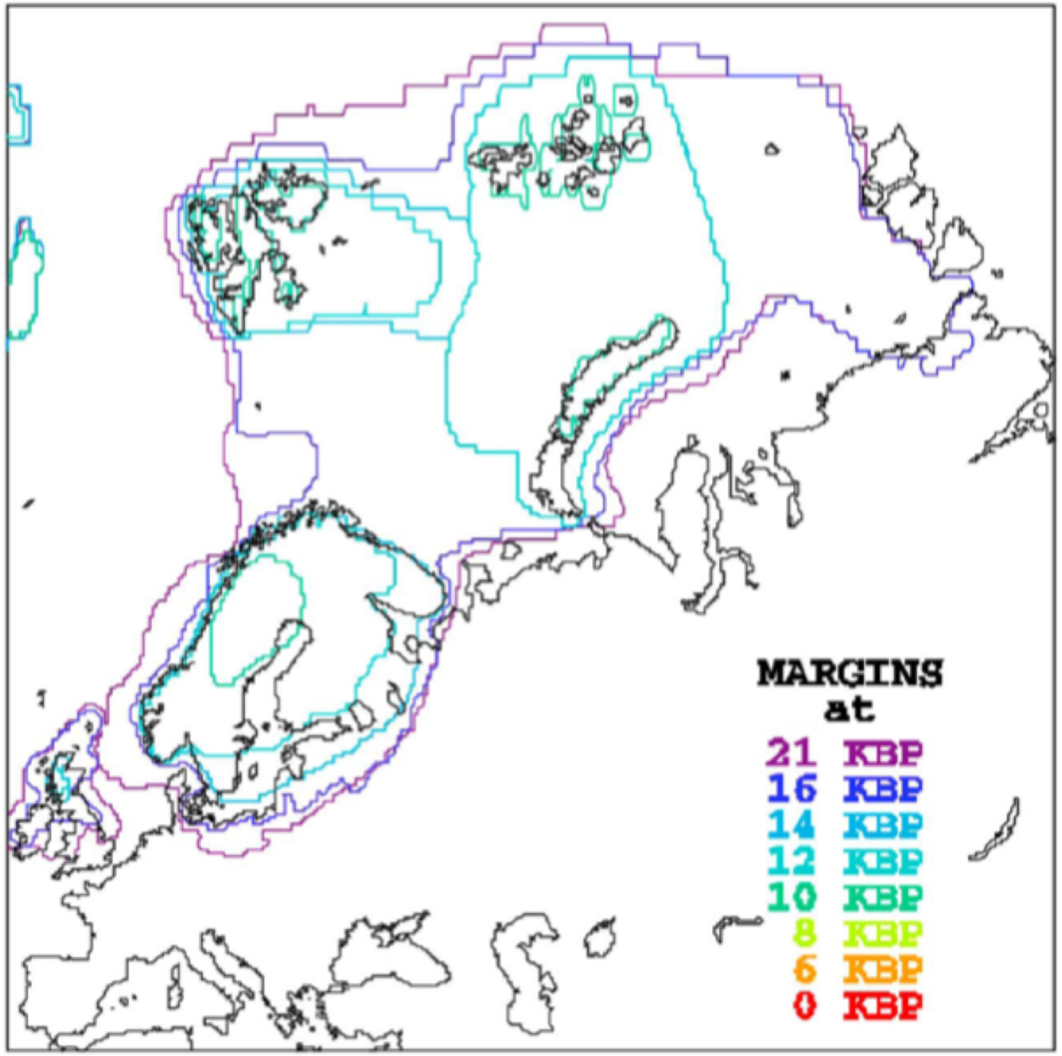
$$C_{\rm SL}(t) = -\frac{m_{\rm i}(t)}{\rho_{\rm w} A_0(t)} - \overline{\frac{\phi}{\gamma} - U}$$

Glacial Isostatic Adjustment (GIA)



Glacial Isostatic Adjustment (GIA)





Peltier et al. (2015)

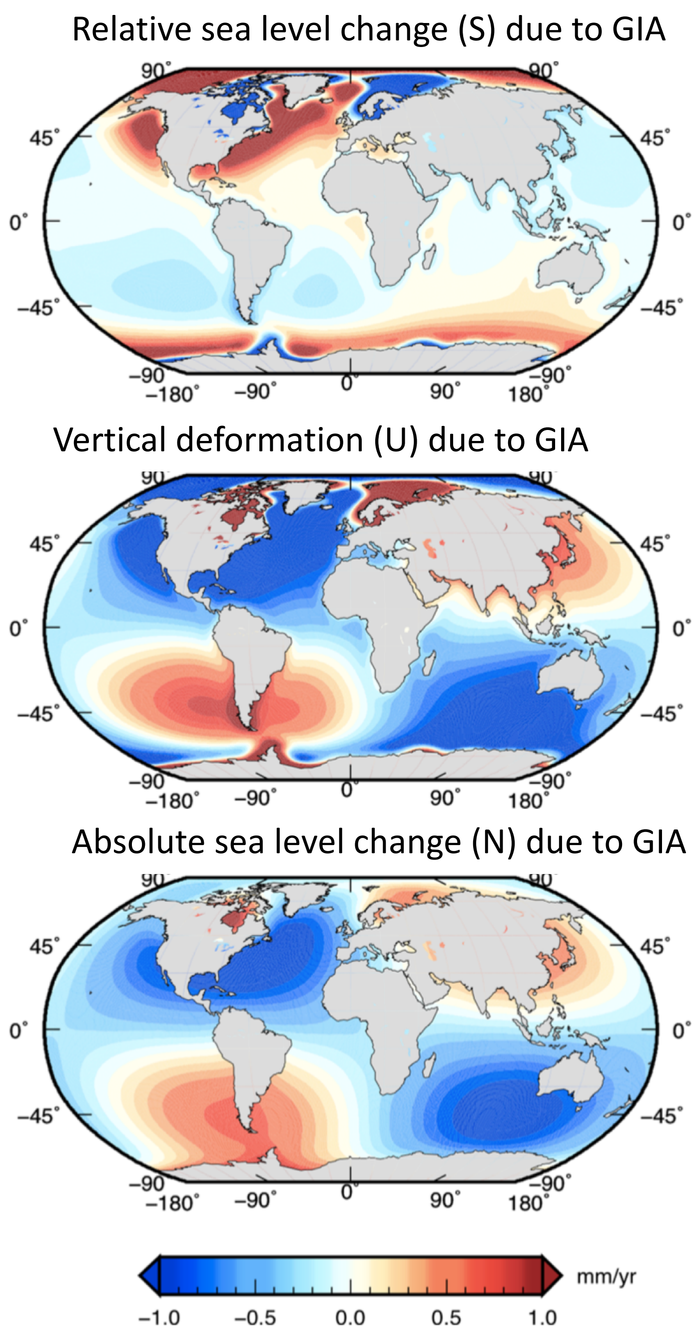
Sea level change due to Glacial Isostatic Adjustment (GIA)

Sea level equation: $$S = N - U$$

Absolute sea level: $$N = \frac{\phi}{\gamma} + C_{SL}$$

$$\bar{S} \cong \bar{N} \cong C_{SL}$$
$$\bar{U} \cong 0$$

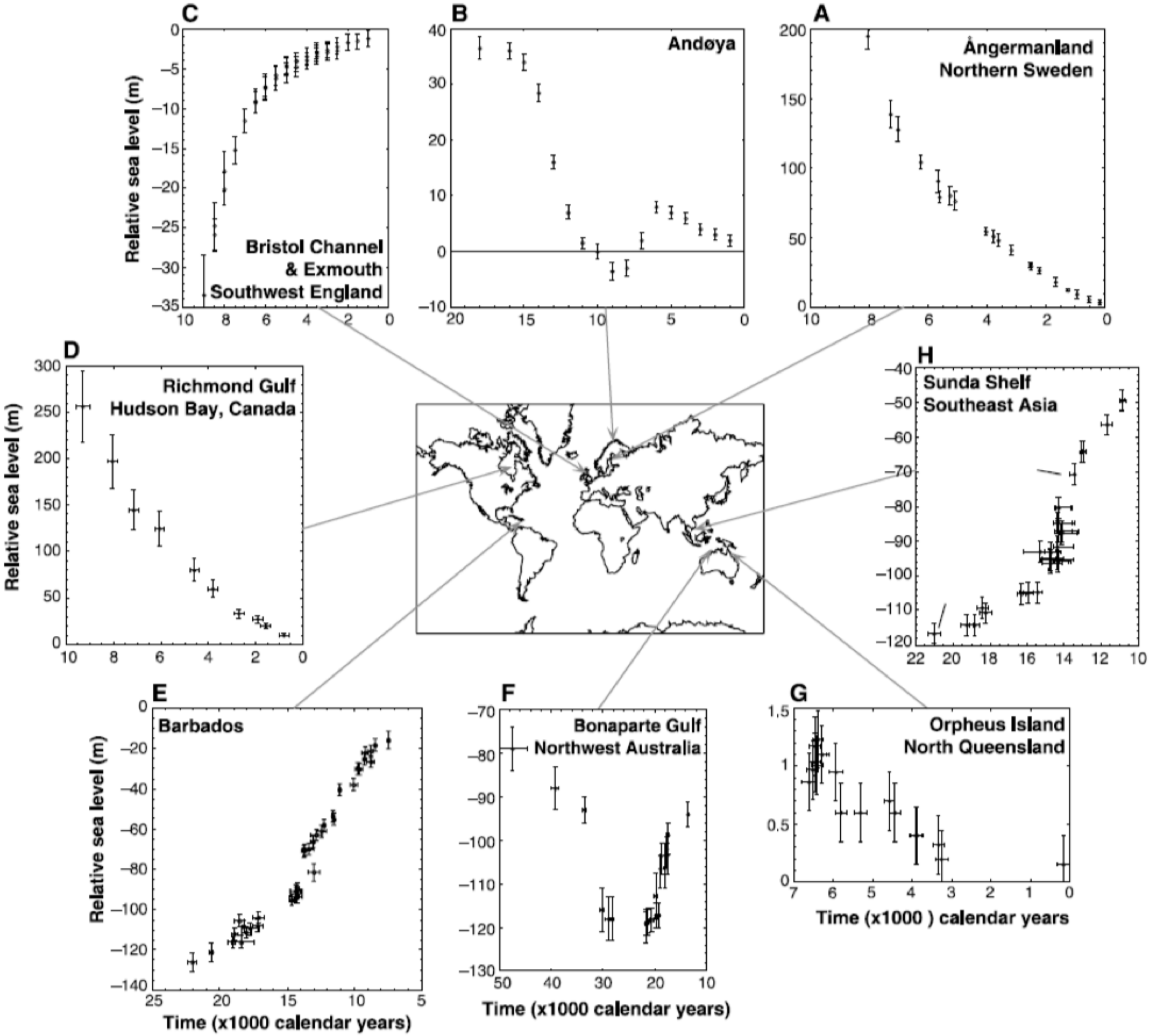
Fun fact: Present-day global sea level change due to GIA from last ice age (last glacial maximum 21 kyr ago): $C_{SL} \approx 0.3$ mm/yr (sea level rise) or ~10 % of global sea level change.



Paleo relative sea level records

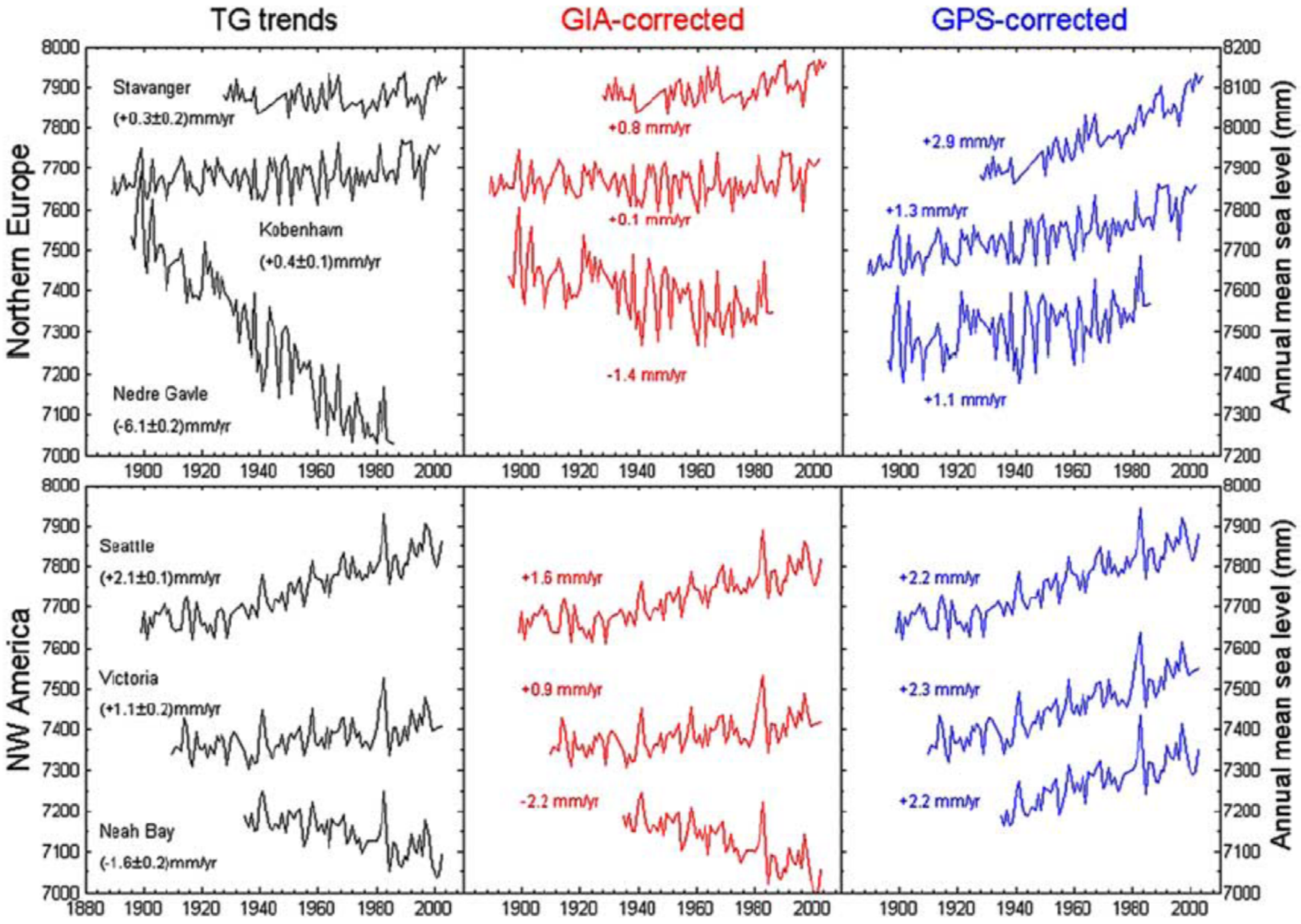
a

b



Tide Gauge sea level records

GIA can explain a large part of the GPS signal, but not everything.



Present-day ice changes

Present-day (climate change related) ice loss *also* changes Earts gravitational field (N) and solid earth surface (U).

Geophysical Research Letters

Research Letter | Open Access

Vertical Land Motion From Present-Day Deglaciation in the Wider Arctic

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Abstract

Vertical land motion (VLM) from past and ongoing glacial changes can amplify or mitigate ongoing relative sea level change. We present a high-resolution VLM model for the wider Arctic, that includes both present-day ice loading (PDIL) and glacial isostatic adjustment (GIA). The study shows that the nonlinear elastic uplift from PDIL is significant (0.5–1 mm yr^{-1}) in most of the wider Arctic and exceeds GIA at 15 of 54 Arctic GNSS sites, including sites in nonglaciated areas of the North Sea region and the east coast of North America. Thereby the sea level change from PDIL (1.85 mm yr^{-1}) is significantly mitigated from VLM caused by PDIL. The combined VLM model was consistent with measured VLM at 85% of the GNSS sites ($R = 0.77$) and outperformed a GIA-only model ($R = 0.64$). Deviations from GNSS-measured VLM can be attributed to local circumstances causing VLM.

Present-day ice changes

Mass loss (2003-2015)

Greenland	~250 Gt/yr
Glaciers	~300 Gt/yr
Antarctica	~100 Gt/yr
Total	~650 Gt/yr ≈ 1,8 mm/yr GMSL

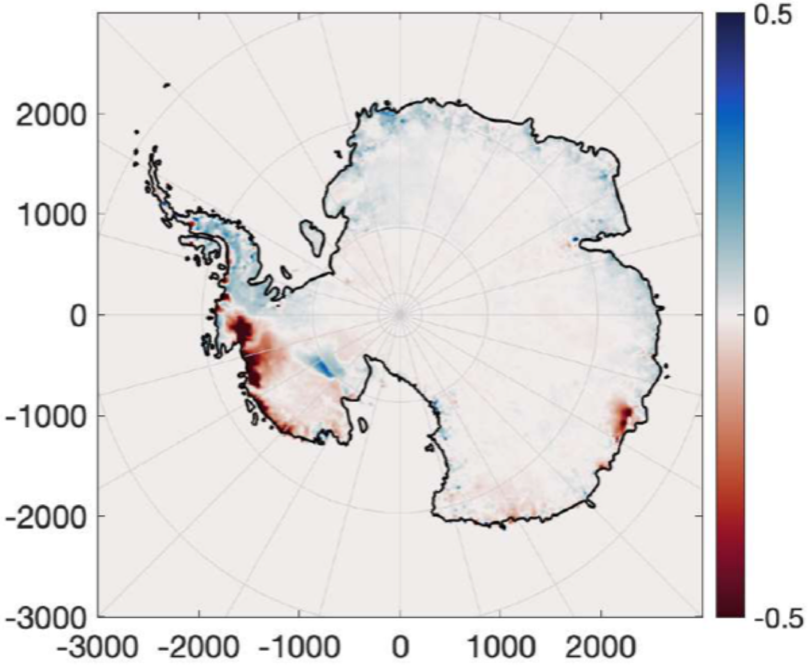


Figure 3.10: Average ice elevation change [m yr^{-1}] from 1995-2015 for Antarctic Ice Sheet.

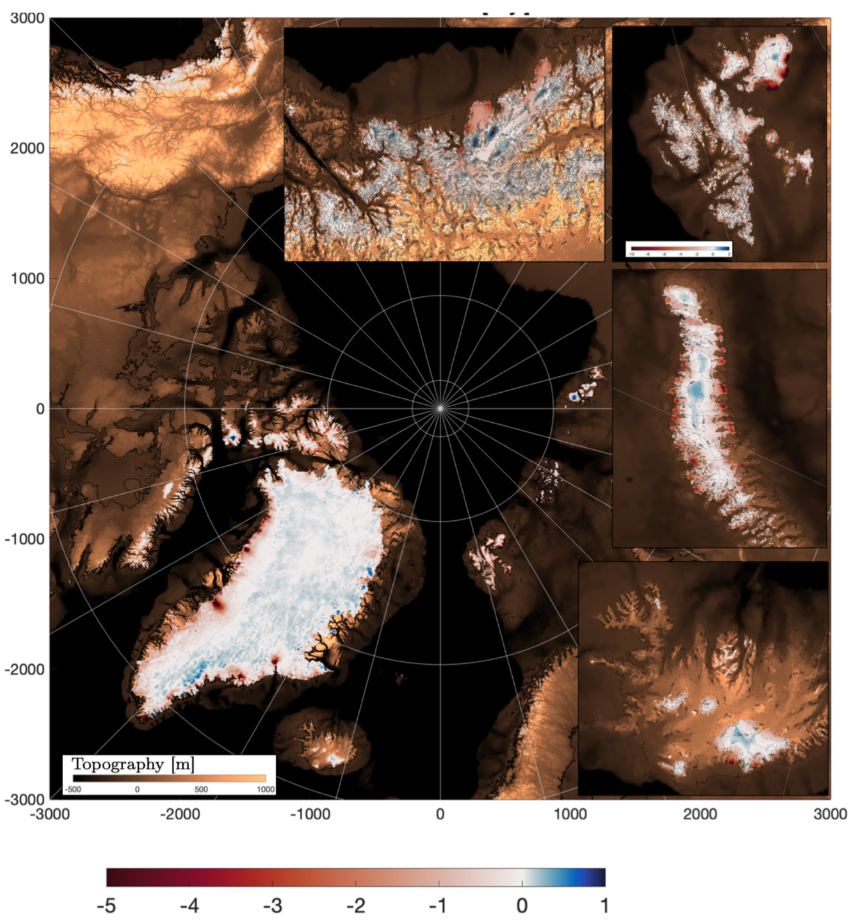


Figure S1.1. Ice elevation change from 2003 to 2015 in m yr^{-1} (red-blue scale) resulting from the redistribution explained above. The most interesting regions (Alaskian Coast, Svalbard (on a wider colorscale), Novaya Zemlja and Iceland) are enlarged. There is no significant ice loss in mainland Siberia.

Present-day ice changes

- Contemporary ice loss due to climate change changes the spatial distribution of sea level change.
- Also effects the far field: Ice loss on Greenland results in subsidience in the southern hemisphere and vice versa.

eVLM = elastic Vertical Land Motion (= U)

geoid (G) = N - C_{SL}

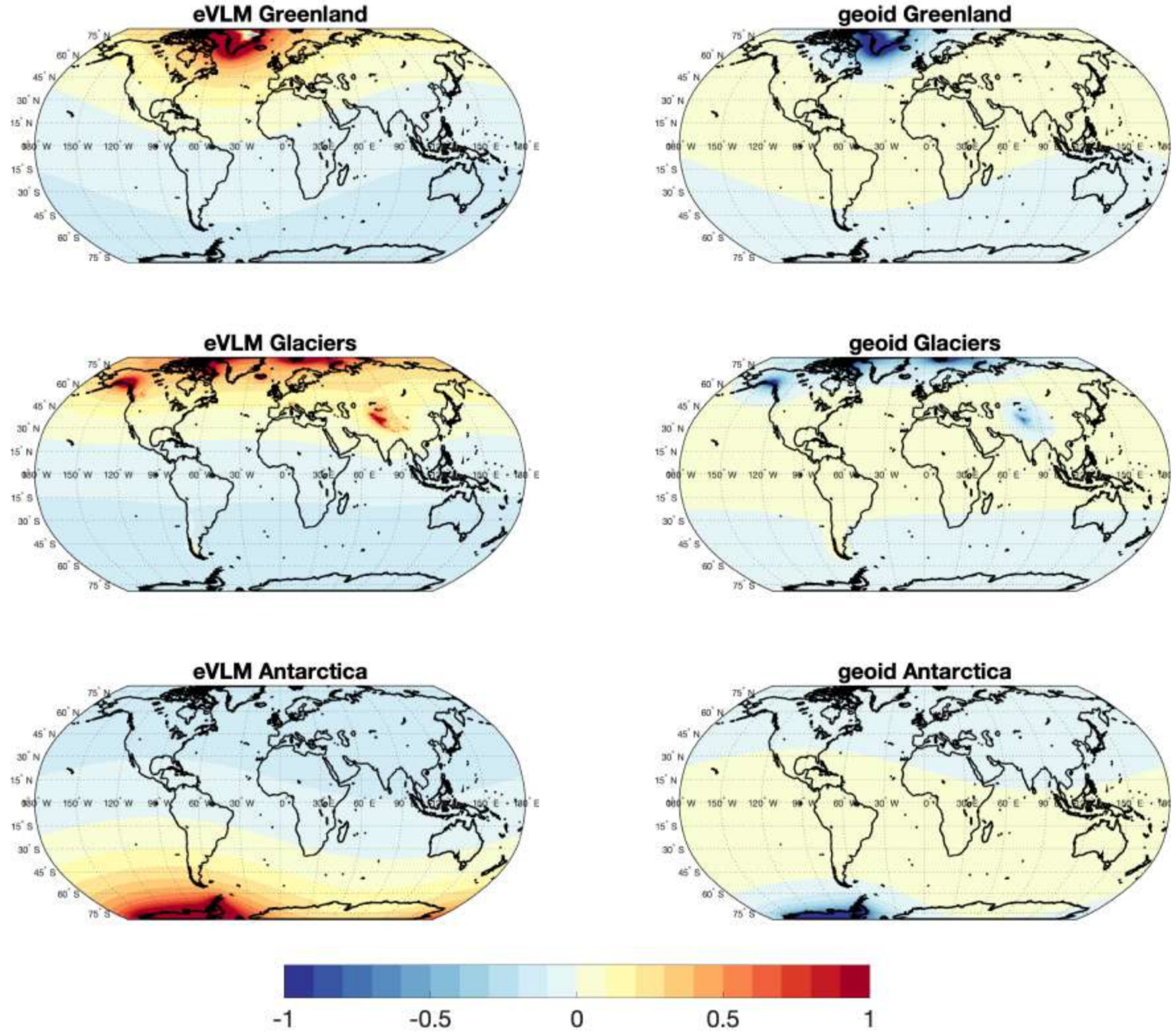


Figure 3.11: Left panel shows the VLM at global scale from each source [mm y^{-1}]. Right panel shows the geoid change ($\dot{G}$) associated with the melting of each source [mm y^{-1}].

VLM from present-day ice changes

- In the Northern region, vertical land motion (VLM) caused from elastic changes from present-day ice loss exceeds the VLM from GIA in many locations.
- Not enough to correct tide gauges with GIA. Present-day ice loss should be accounted for as well.

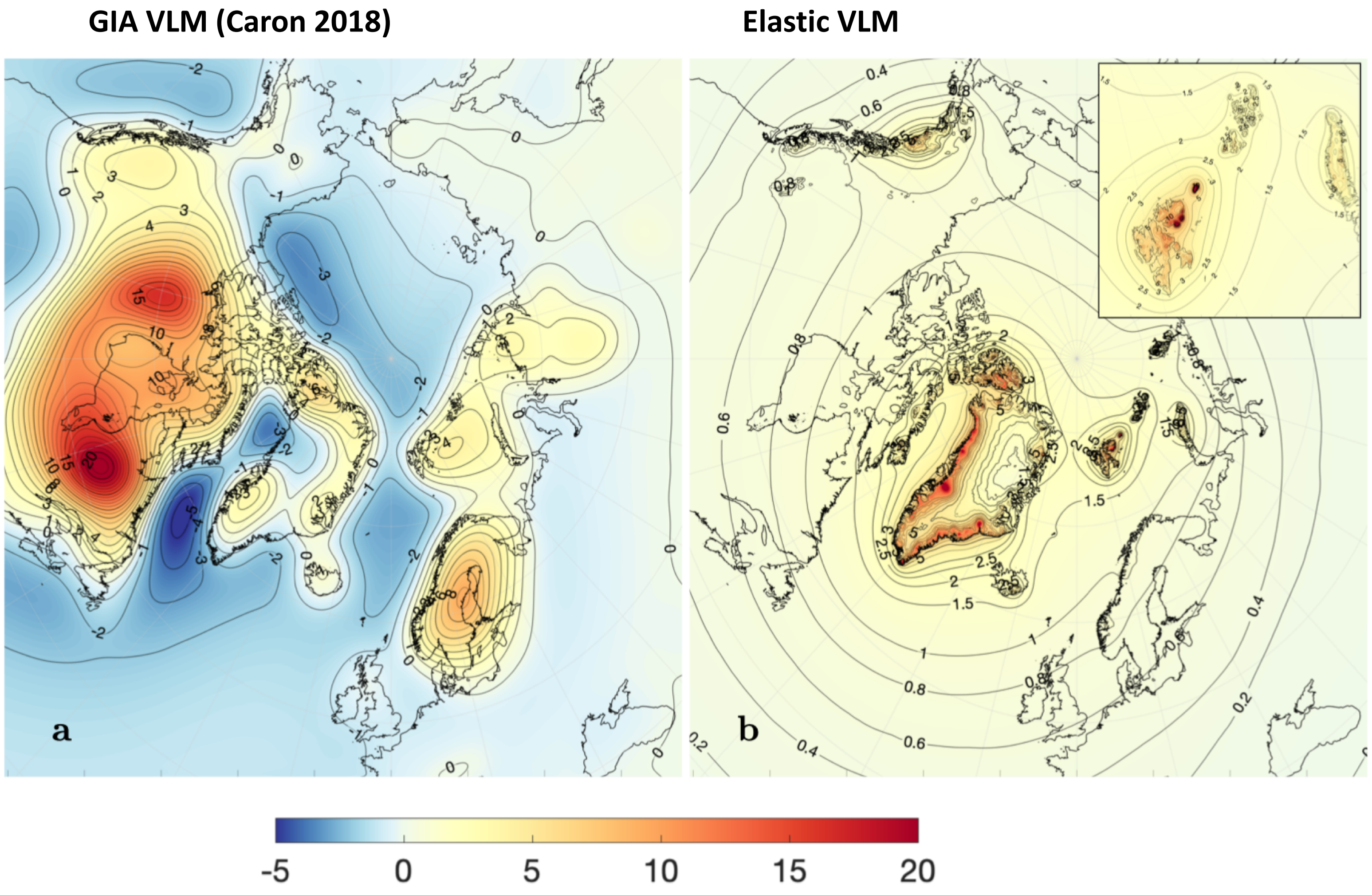


Figure 1. Average VLM rates (mm yr^{-1}) from 2003-2015 from Glacial Isostatic Adjustment (Caron et al., 2018) (**a**) and elastic rebound from contemporary land ice loss with enlargement of Svalbard (**b**).

VLM compared with GPS

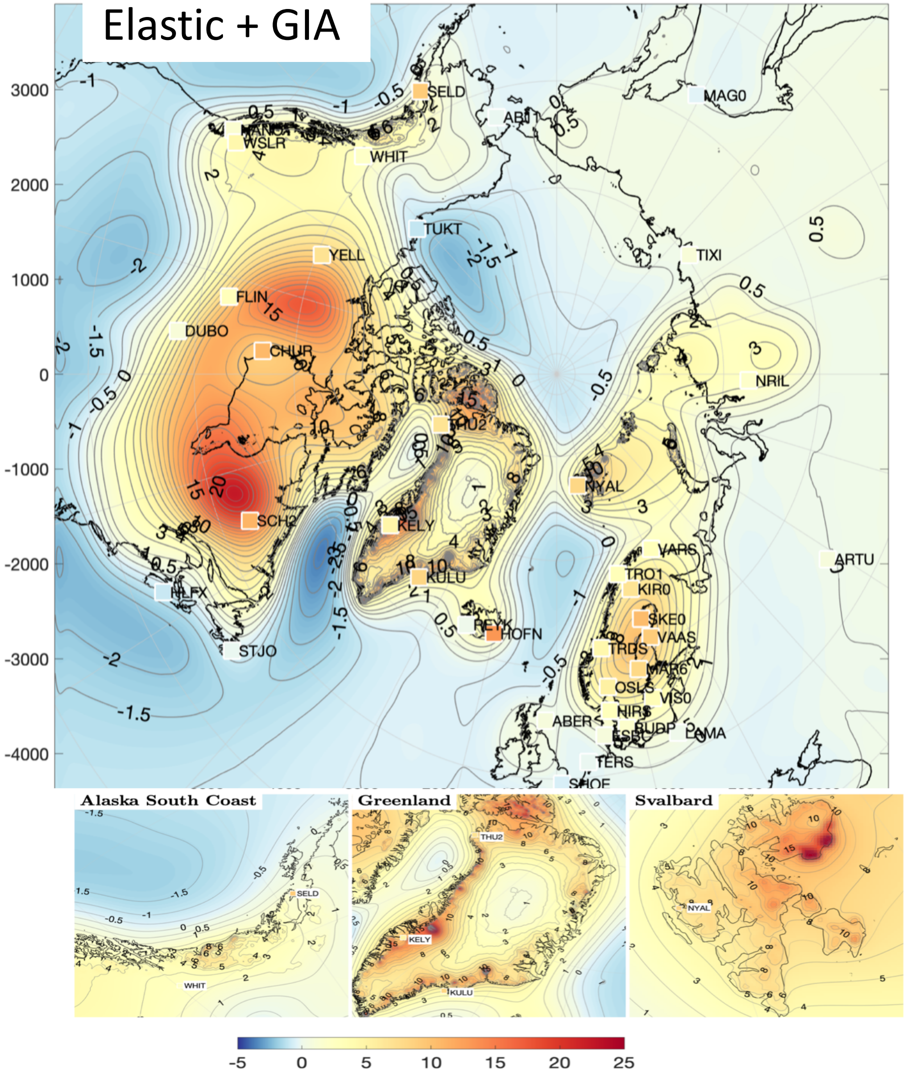


Figure 2. Average VLM-rates (mm yr^{-1}) from 2003-2015 from the VLM-model (Glacial Isostatic Adjustment + elastic VLM). The color of the squares represent the GNSS measured average VLM-rate for the same period. For clarification Alaska South Coast, Greenland and Svalbard are enlarged below.

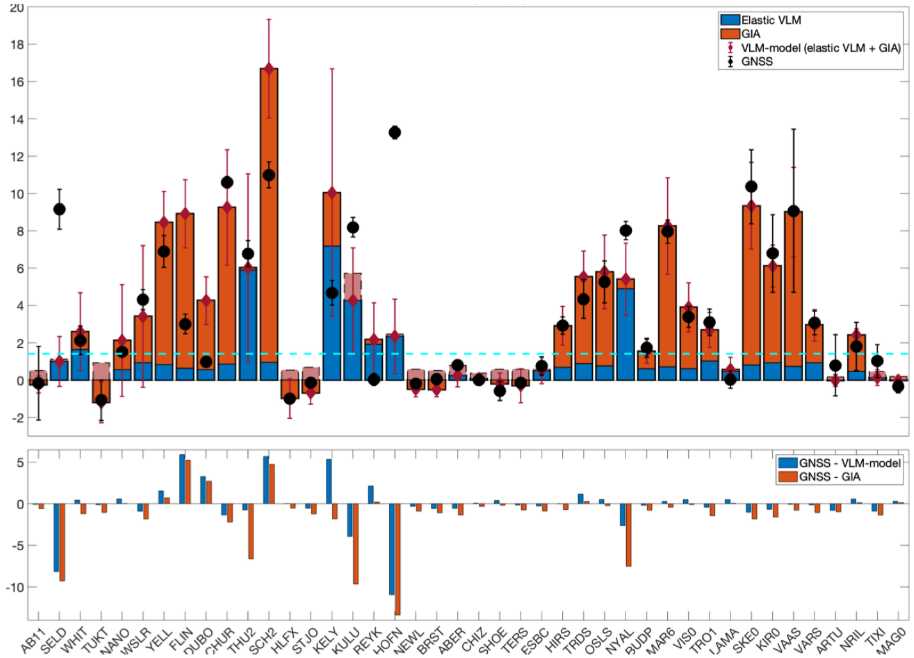
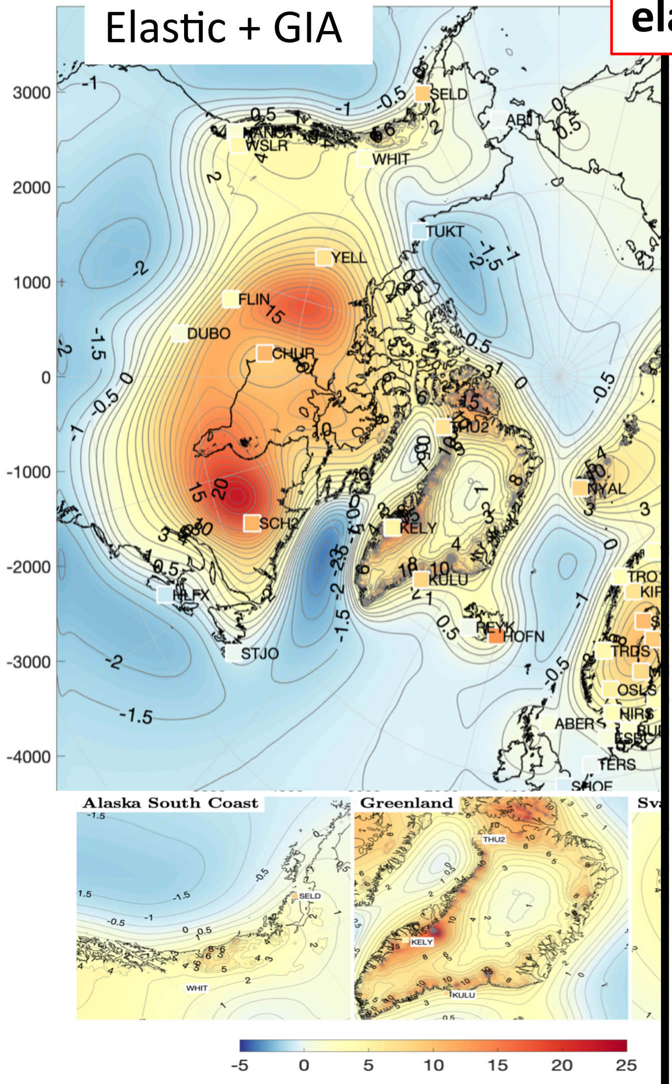


Figure 4. Top: 2003-2015 average VLM change [mm yr^{-1}] from the elastic VLM model (blue) and GIA (red) at 42 GNSS-sites shown in figure 2 and Supporting Information S2.1 ordered from most west (left) to most east (right). The dotted-cyan line indicates the average barysteric sea level rise ($\sim$ 1.4 mm yr^{-1}) from the ice loss included in this study. The total modeled VLM and the error is shown with red error bars and the GNSS measured VLM is shown with black error bars. The lighter red indicates where GIA is negative and hence overlaps the positive elastic VLM. Bottom: The residuals between GNSS-measured VLM and the VLM-model (blue) and GIA (red). The average of the absolute residuals (equivalent to Mean Absolute Error) is 1.54 mm yr^{-1} and 2.09 mm yr^{-1} respectively. All numbers for this figure are given in Supporting Information table S2.1.

VLM compared with GPS

elastic VLM varies from year to year. GIA is nearly constant.



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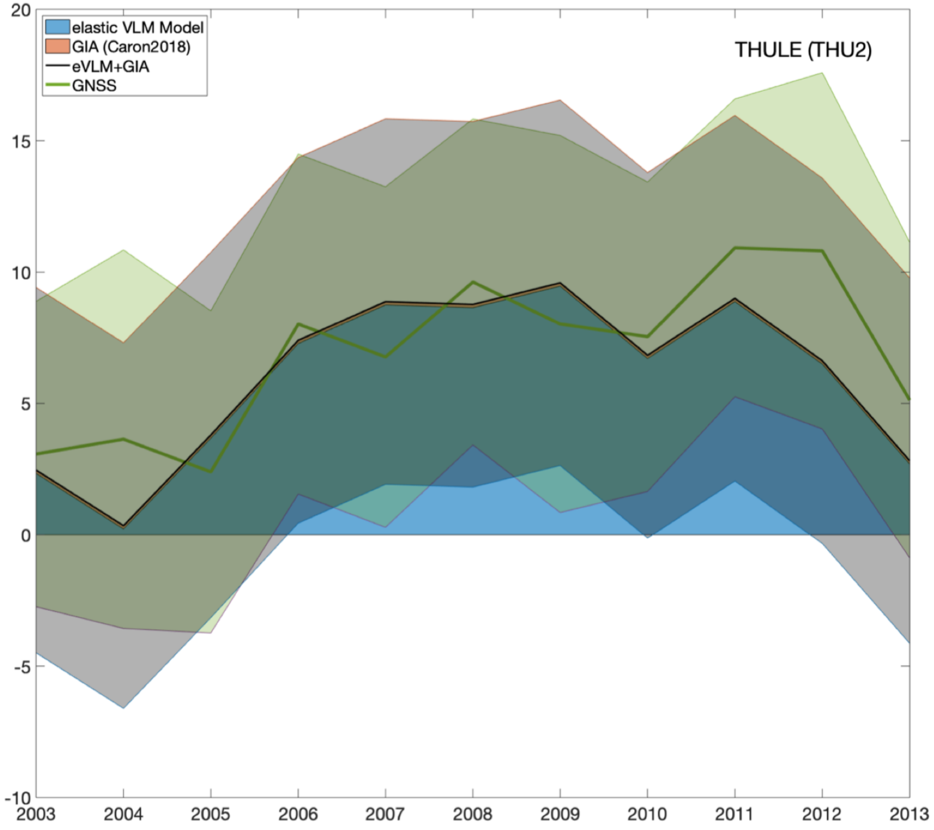
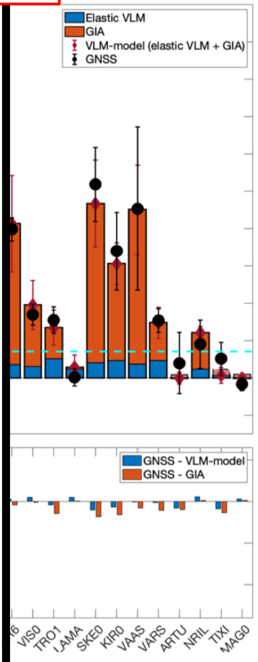


Figure 5. Yearly displacement (mm) for Thule (Northeast Greenland) from 2003 to 2013, measured by GNSS (green line - shaded green area is 1σ)) and from the VLM-model (black line - shaded grey area is 1σ). The elastic VLM is represented by the blue area and GIA by the orange area, which in this case is small.



e elastic VLM model (blue)
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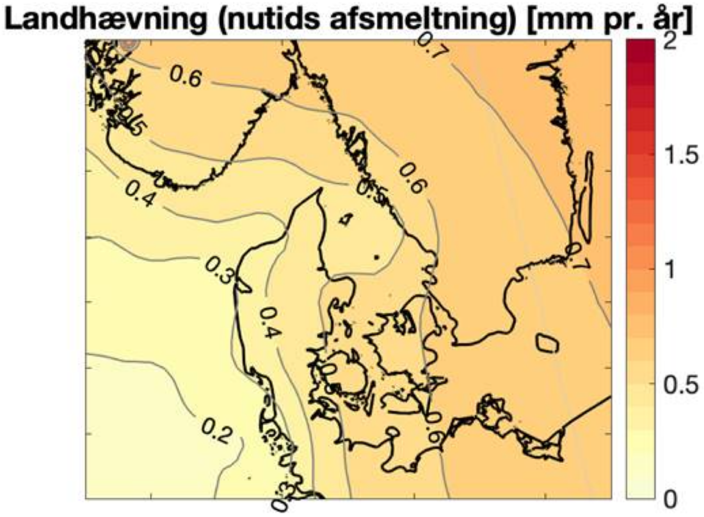
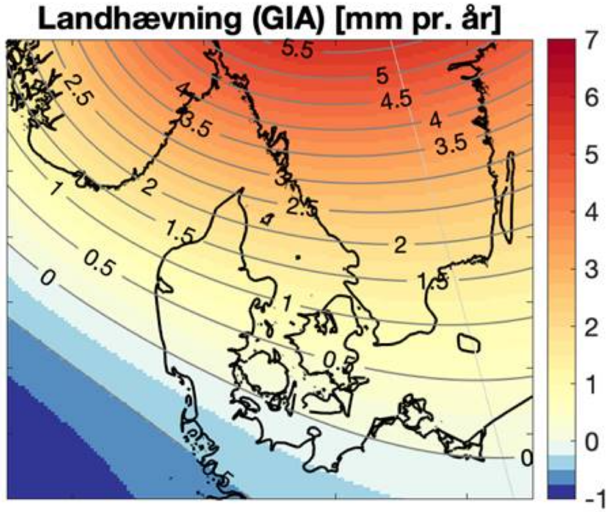
e average barysteric sea
e total modeled VLM and
s shown with black error
ps the positive elastic
VLM-model (blue) and
Absolute Error) is 1.54
re given in Supporting

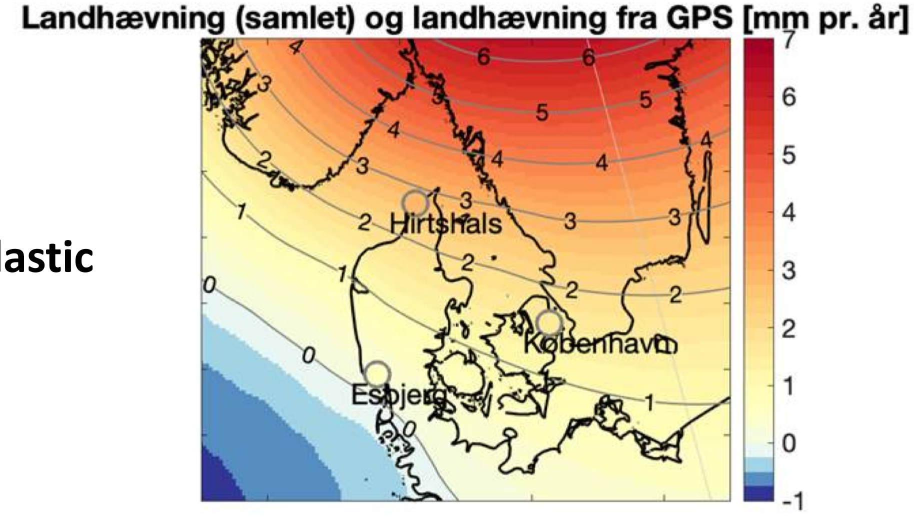
VLM compared with GPS (Denmark)

Elastic VLM





GIA + Elastic



Sources and further reading:

Glacial Isostatic Adjustment and Contemporary Sea Level Rise: An Overview, 2019, Giorgio Spada

The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth, 2019, Martin Ekman

Glacial isostatic adjustment modelling: historical perspectives, recent advances, and future directions, 2018, Pippa Whitehouse