GLACIAL ISOSTATIC ADJUSTMENT AND RELATIVE SEA LEVEL (RISE) IN NORTHERN EUROPE

HOLGER STEFFEN

WITH ACKNOWLEDGMENTS TO MANY, MANY COLLEAGUES

LANTMÄTERIET

CONTENT

- Historical overview until the definition of GIA
- Two slides about GIA modelling
- GIA observations
  - Relative sea level (rise) in northern Europe (Baltic Sea)

In case of questions, ask!

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OTHER SOURCES

- GIA Training School videos:
  - https://polenet.org/2019-gia-training-school/
  - https://polenet.org/2023-gia-training-school/

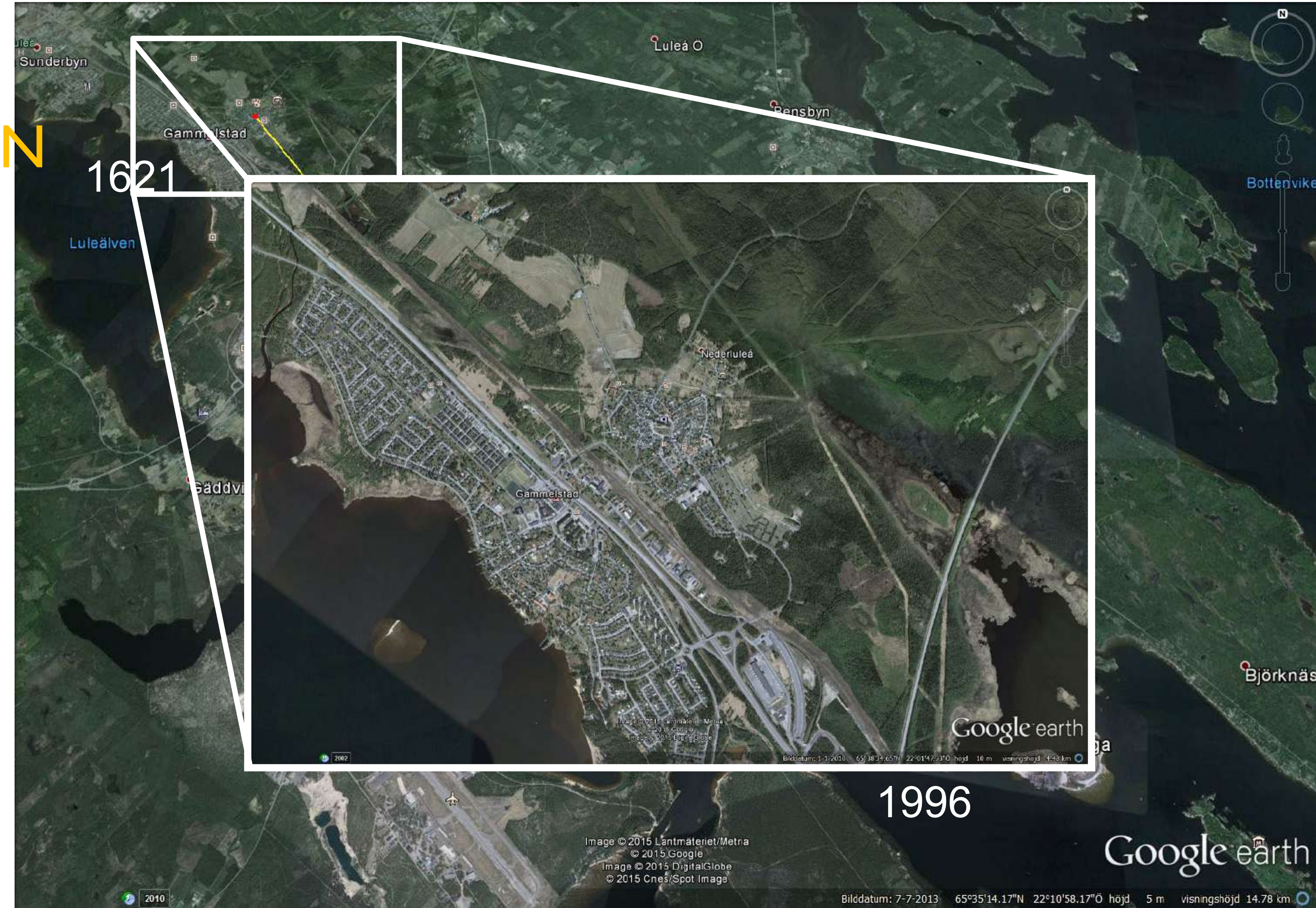
THE DISCOVERY OF THE ICE AGE THROUGH ITS CONSEQUENCES

LET'S GO BACK IN TIME

Northern Europe ca. 1635

(Source: https://upload.wikimedia.org/wikipedia/commons/7/73/Svecia%2C_Dania_et_Norvegia%2C_Regna_Europ%C3%A6_Septentrionalia.jpg)

LULEÅ'S RELOCATION



(Source: https://upload.wikimedia.org/wikipedia/commons/7/73/Svecia%2C_Dania_et_Norvegia%2C_Regna_Europ%C3%A6_Septentrionalia.jpg)

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(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

ATHANASIUS KIRCHER, MUNDUS SUBTERRANEUS (1665)

(Source: Cornell University Library)

ANDERS CELCIUS AND JOHANNES RUDMAN

Anders Celsius
(1701-1744)

?

Johannes Augustini Rudman
(1699-1760)

(Source:https://sv.wikipedia.org/wiki/Anders_Celsius#/media/File:Anders-Celsius-Head.jpg)

SEALS REST CLOSE TO THE WATER SURFACE


(Source:http://www.sll.fi/mita-me-teemme/lajit/saimaannorppa/ringed-seal/leadImage)

Saimaa ringed seal

Seal hunting (Carta Marina)

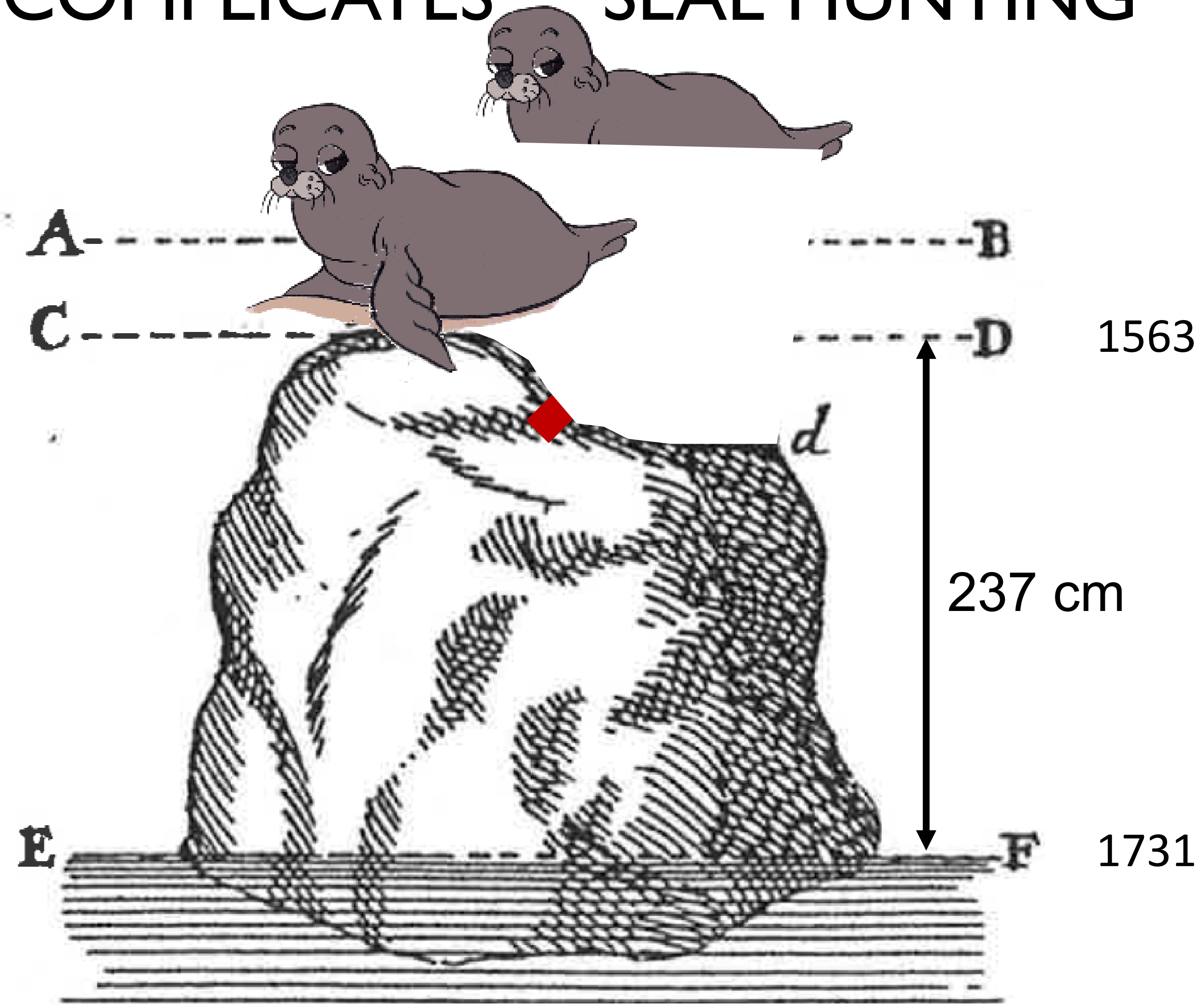
(Source: http://sydaby.eget.net/ody/opics/maps/saelfangst.jpg)

LANTMÄTERIET

View to Iggön

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

SEA RETREAT COMPLICATES SEAL HUNTING



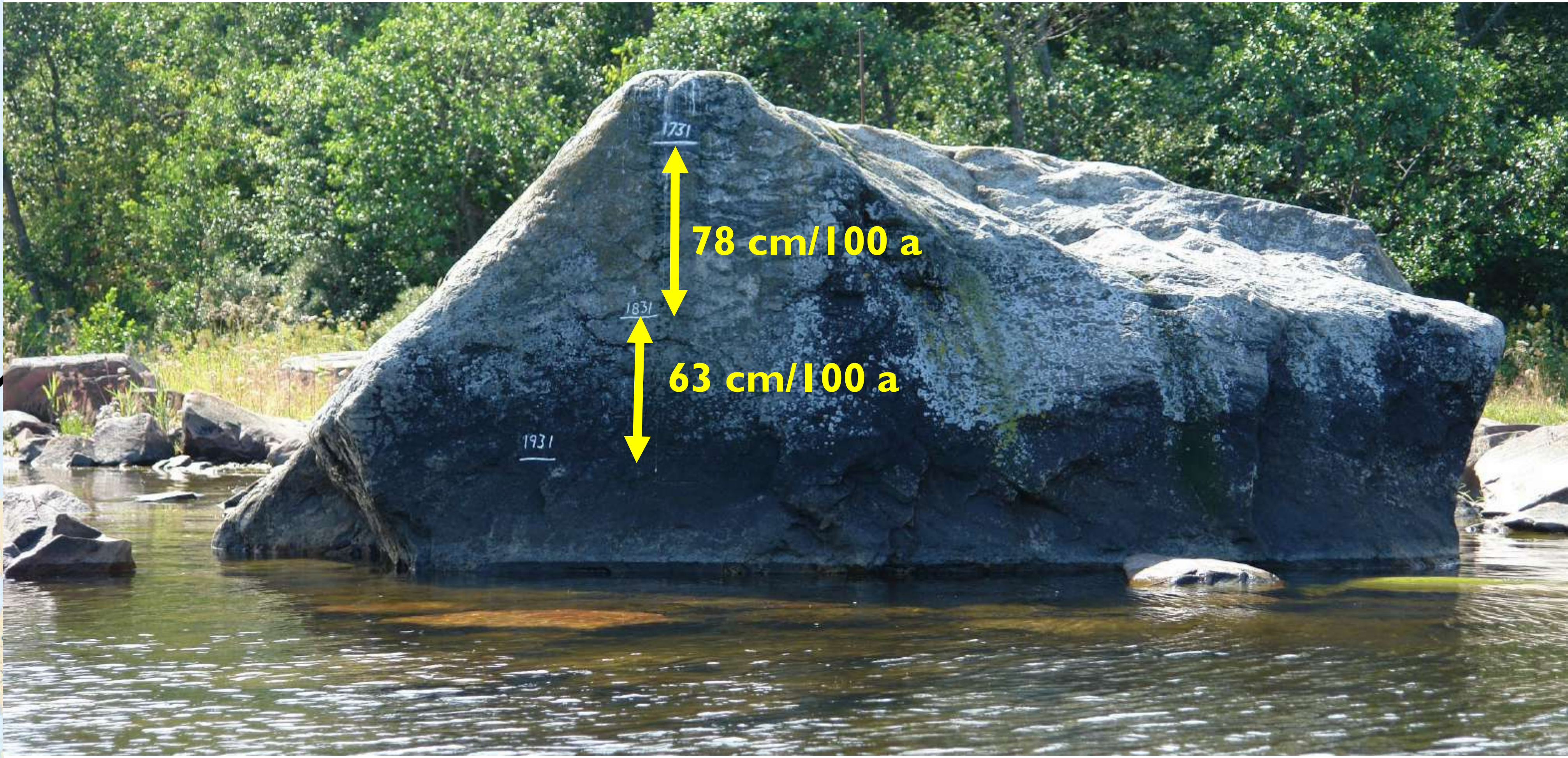
(Celsius 1743)

IGGÖN

Lövgrund

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

CELSIUS ROCK ON LÖVGRUND (08/2015)



(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

CELSIUS ROCK (AUGUST 2015)

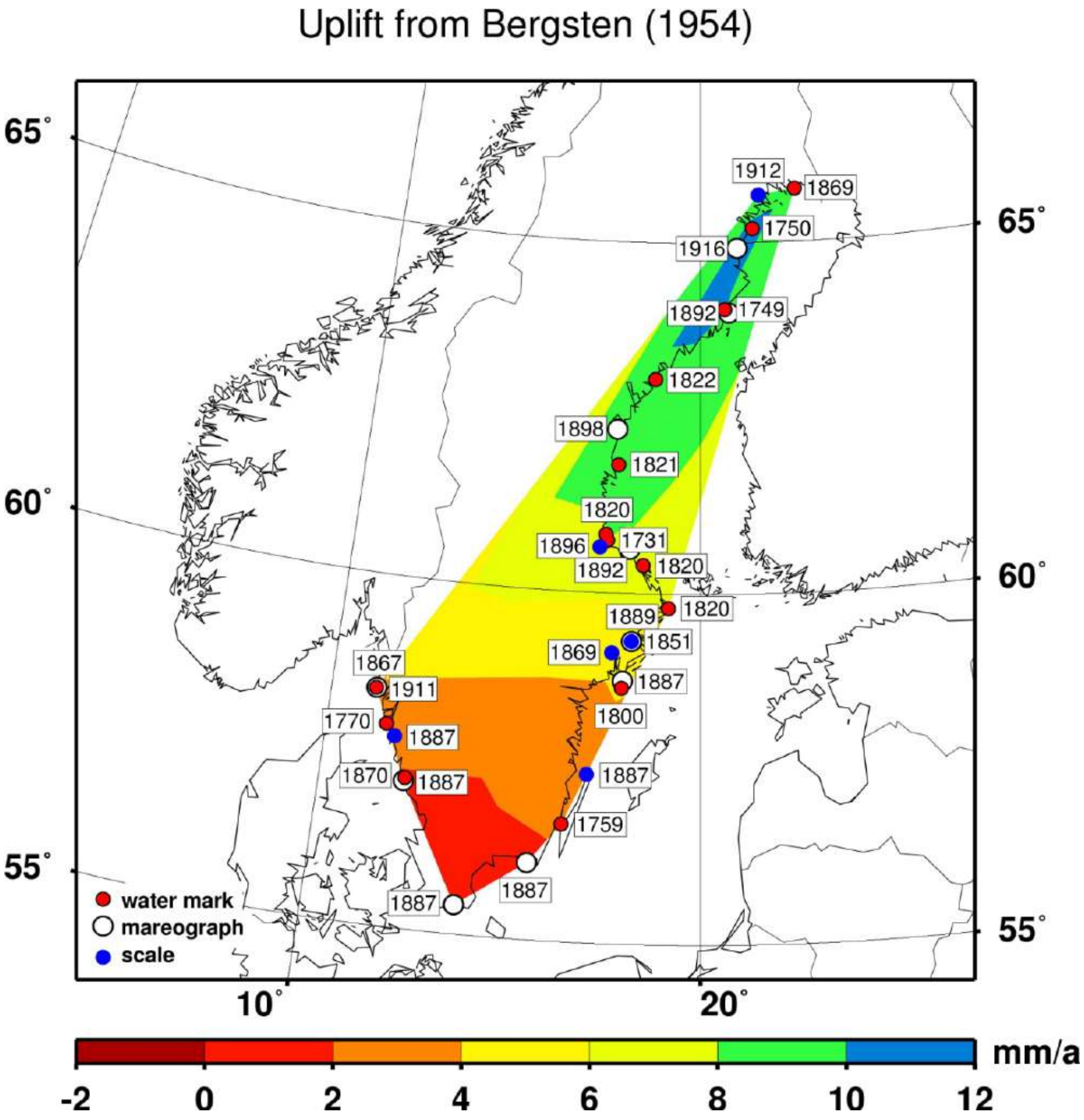
CELSIUS ROCK (JUNE 2016)

MORE WATER MARKS EXAMPLES: LEDSKÄR/RATAN

UPLIFT RATE FROM WATER MARKS IN FENNOSCANDIA

Uplift! Not sea-level fall!

We need another explanation…



(Steffen and Wu 2011)

A STEP FORWARD: EXPLAIN THESE STRUCTURES!

Kettles/Potholes

Striations in bedrock

STRUCTURES ARE RELATED TO GLACIERS/GLACIATIONS!

- Alp valley inhabitants in the 18th century linked erratics to glaciers
- People knew that glaciers extended much farther before
- Similar knowledge in South America
- Many reported about that, e.g. Pierre Martel (1706–1767) in 1744, James Hutton (1726–1797) in 1795, Jean-Pierre Perraudin (1767–1858) in 1815
- Göran Wahlenberg (1780–1851) published in 1818 theory of a glaciation of the Scandinavian Peninsula, but interpreted as regional phenomenon

JENS ESMARK (1763-1839)

https://upload.wikimedia.org/wikipedia/commons/3/37/Jens_Esmark.png

- Investigated glaciers and their traces
- Link between erratic boulders and moraines, and glacial transportation and deposition
- Fjords were carved by glaciers
- Introduced 1824 concept that glaciers once covered larger areas, they can advance and retreat (worldwide)

IGNAZ VENETZ (1788-1859)

https://upload.wikimedia.org/wikipedia/commons/e/e4/Ignaz_Venetz_1826_-_Wood_2014_p158.jpg

- Investigated glaciers in the Alps
- Suggested in 1821 (but presented in 1829 and published in 1833) that much of Europe had at one point in the past been covered by glaciers

KARL FRIEDRICH SCHIMPER (1803-1867)

https://upload.wikimedia.org/wikipedia/commons/f/fe/Schimper_Karl_Friedrich_1866.jpg

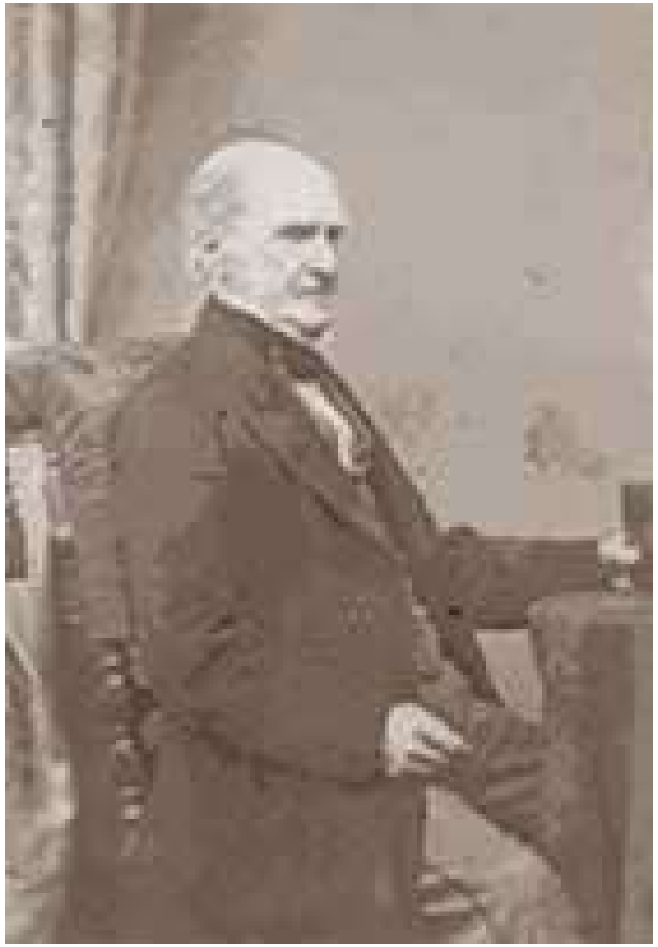
- Ice sheets once covered much of Europe, Asia, and North America
- Talked in 1835/36 about “world winter” and “world summer” – climate changes
- Did not publish much, preferred to give talks
- So his findings were later popularized by…

LOUIS AGASSIZ (1807-1873)

https://upload.wikimedia.org/wikipedia/commons/d/df/Louis_Agassiz-2.jpg

- Investigated glaciers and their traces
- Presented 1837 the theory of a past glaciation (”Eiszeit” – ice age) of large parts of Europe in a talk to Swiss scientists
- However, he was not the first (as shown on previous slides), but his numerous subsequent publications advertized this theory, triggered further investigations and eventually lead to acceptence of the ice age theory
- Theory expands in the British Empire & North America

CHARLES MACLAREN (1782-1866)



- Realized in 1841/2 that sea level must drop when the huge ice sheets formed during the Ice Age
- Estimated to be 800 ft lower (than in 1841)

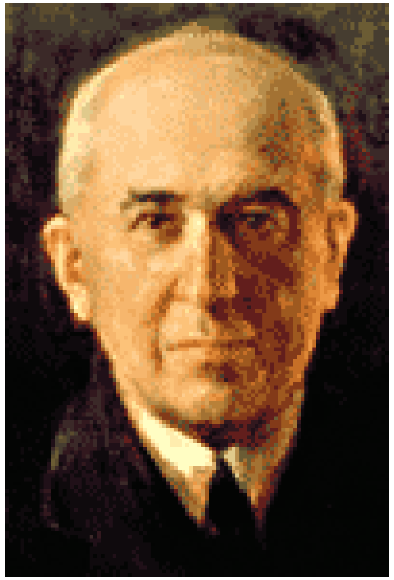
http://www.edinburghgeolsoc.org/images/z_40_02c.jpg

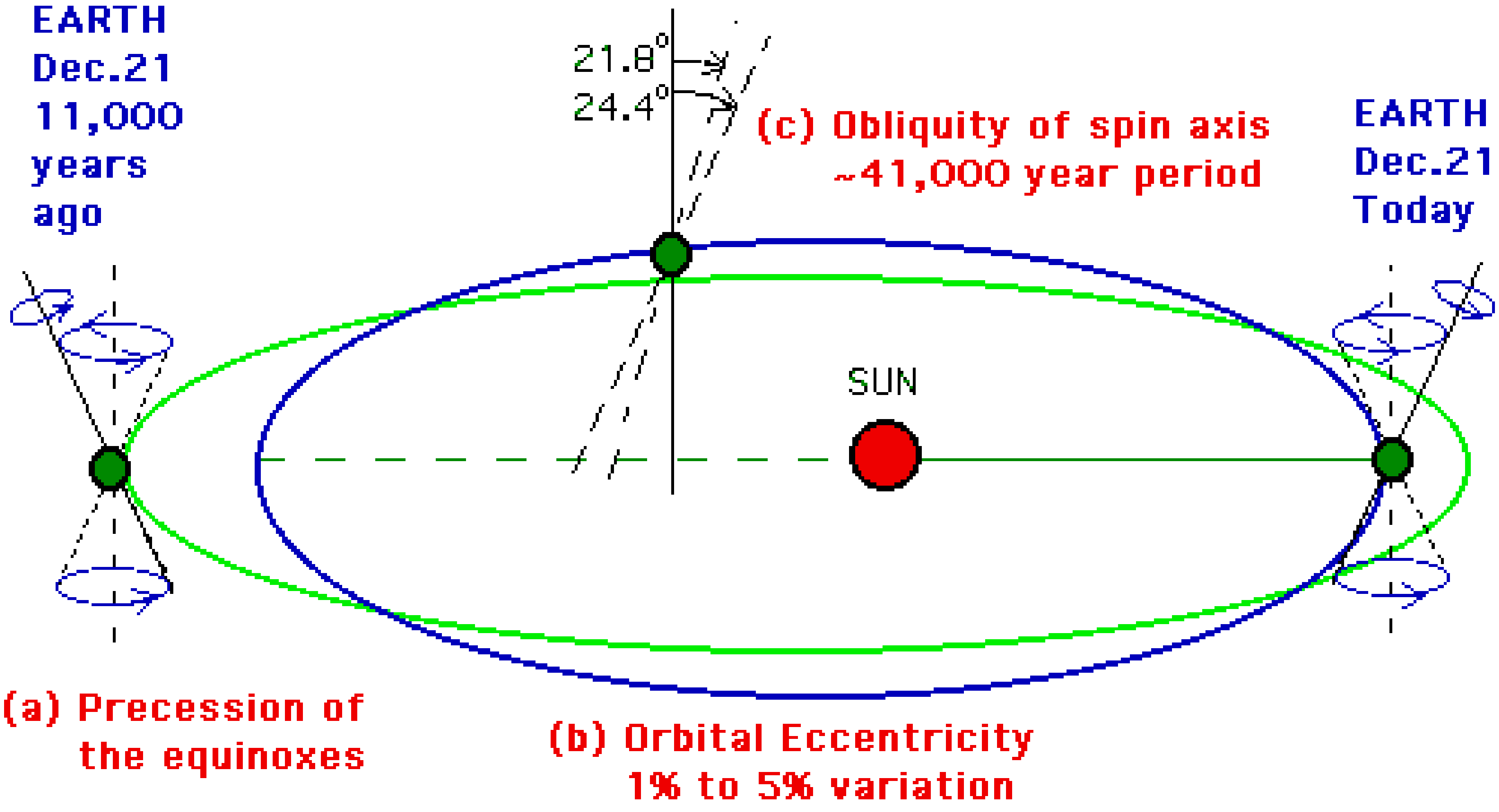
JOSEPH ADHÉMAR (1797–1862)

- Proposed in 1842 that ice ages were controlled by astronomical forces (much was wrong but at least!)
- Predicted the Antarctic Ice Sheet (and estimated its thickness to be 90 km… only)
- Astronomical theory was further developed by James Croll and by Milutin Milanković.

No picture

MILANKOVIC'S ORBITAL THEORY





Eccentricity splitting of the precessional singlet
gives 19,000 21,000 and 23,000 year periods

NOW WE HAVE TWO THINGS…

1. Sea-level fall/land uplift in northern Europe
2. Ice age theory

Where is the link (or better, who makes it)?

THOMAS JAMIESON (1829-1913)

2. *On the* History *of the* Last Geological Changes *in* Scotland. By Thomas F. Jamieson, Esq., F.G.S., Fordyce Lecturer in the University of Aberdeen.

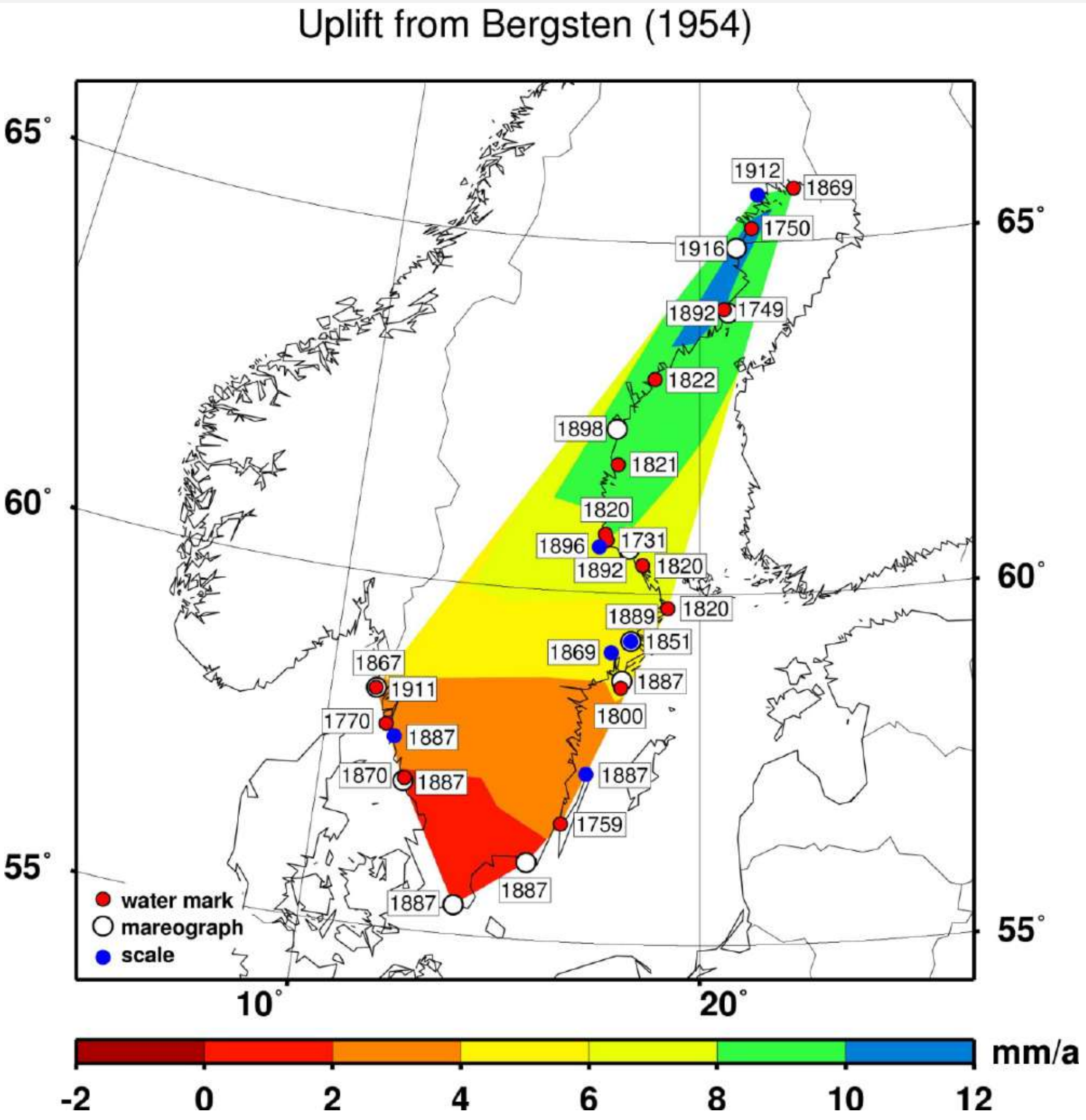
- Investigated sediments in Scotland and found a sequence of glacial, marine, terrestrial, marine, terrestrial sediments
- Concluded in 1865 that a glacier depressed the area, which was then flooded by the sea and later rose → link ice sheet – land uplift
- Did not use the word ”isostasy”
- Later (1882) found that depression relates to ice thickness

http://www.landforms.eu/ScottishSeaLevels/images/Thomas-Jamieson_small.gif

BACK TO THIS SLIDE…

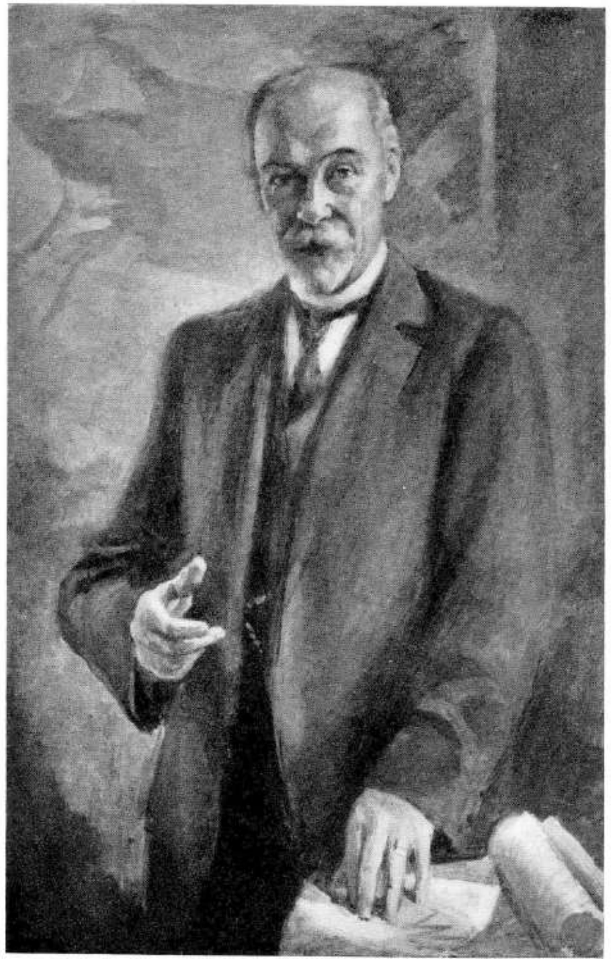
Questions:

- Did sea level fall or did land rise?
  Land uplift!
- What is the cause?
  Former glaciation!
- Where does land uplift occur and how much is it?
- When was the glaciation?
- What are the underlying physics?



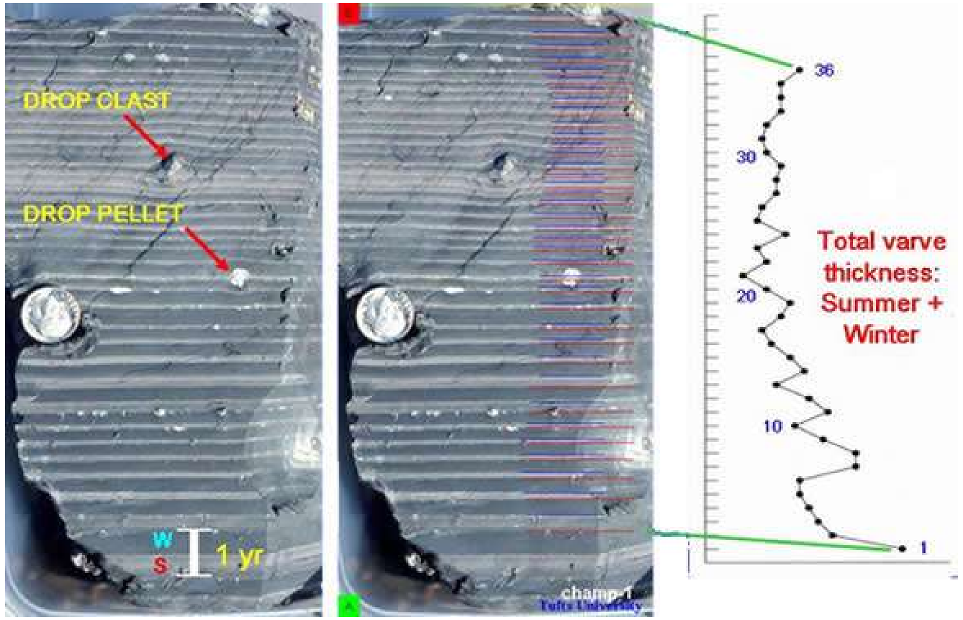
(Steffen and Wu 2011)

GERARD DE GEER (1858–1943)



http://sok.riksarkivet.se/sbl/bilder/
17350_7_010_00000553_0.jpg

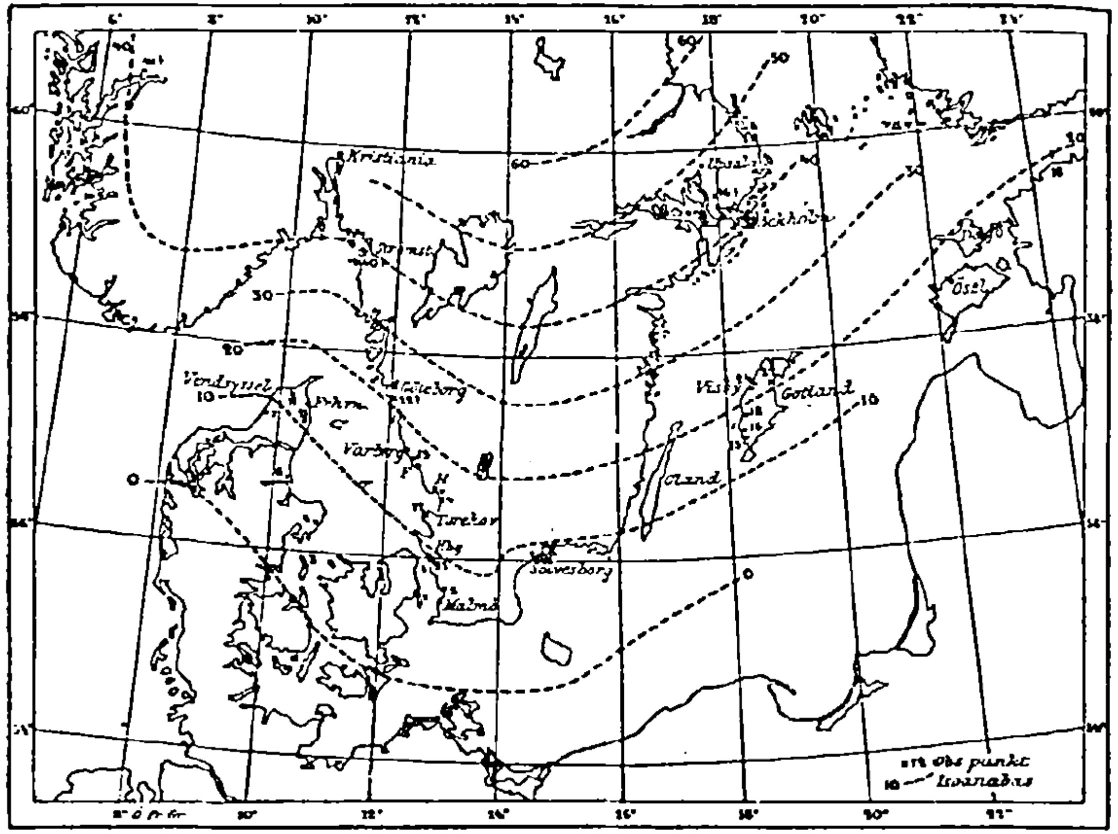
- Varve chronology, the Swedish time scale and glacial features (de Geer moraines)
- Land uplift map in 1888/90
- Last glaciation was not longer than ~9000 years ago



http://eos.tufts.edu/varves/images/varve_chron1.jpg

POSTGLACIAL LAND UPLIFT

Isoanabaser för den postglaciala höjningen.



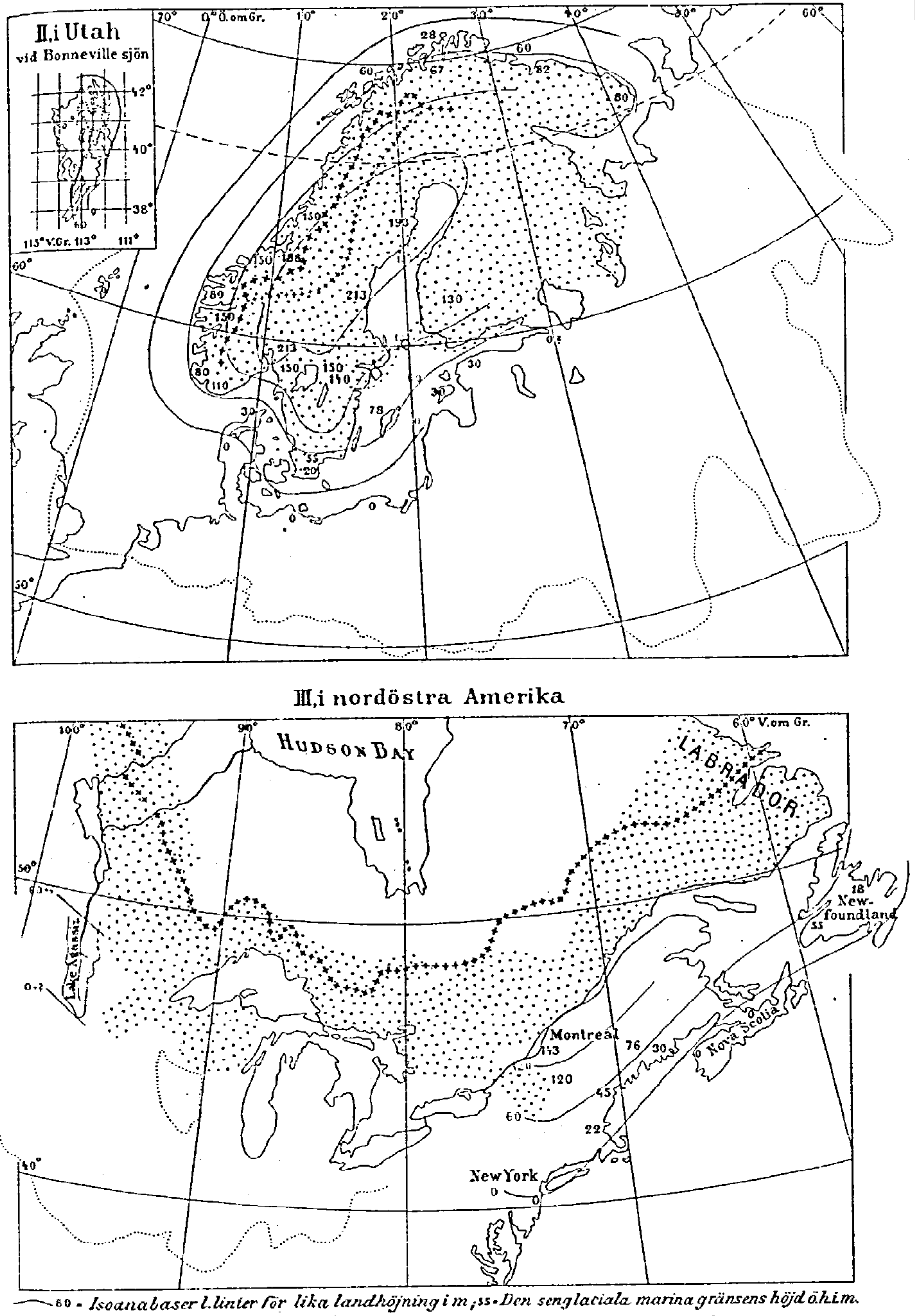
Måtten i meter.

Skala 1 : 11 750 000.

de Geer (1890)

Isoanabaser öfver landhöjningen efter Istiden

I, i Skandinavien



60 - Isoanabaser l. linier för lika landhöjning i m; 55 - Den senglaciala marina gränsens höjd ö.h.i.m. - Den första nedisningens gräns; - Den sista nedisn:s, och i Utah den sista öfversvämningens utbredning; ++++ - Isdelare; +++++ - Vattendelare; - Urbergsområden.

de Geer (1888)

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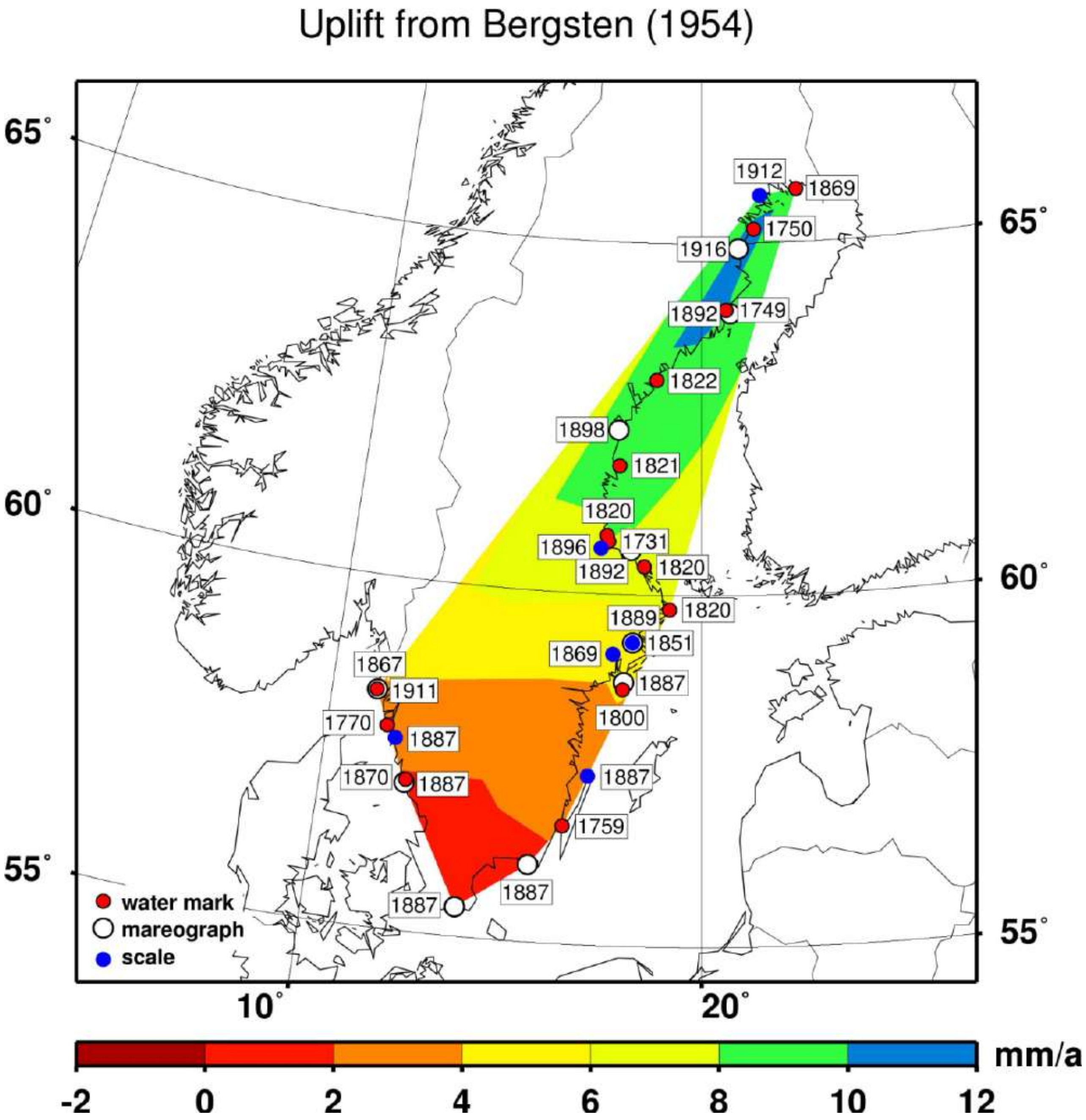
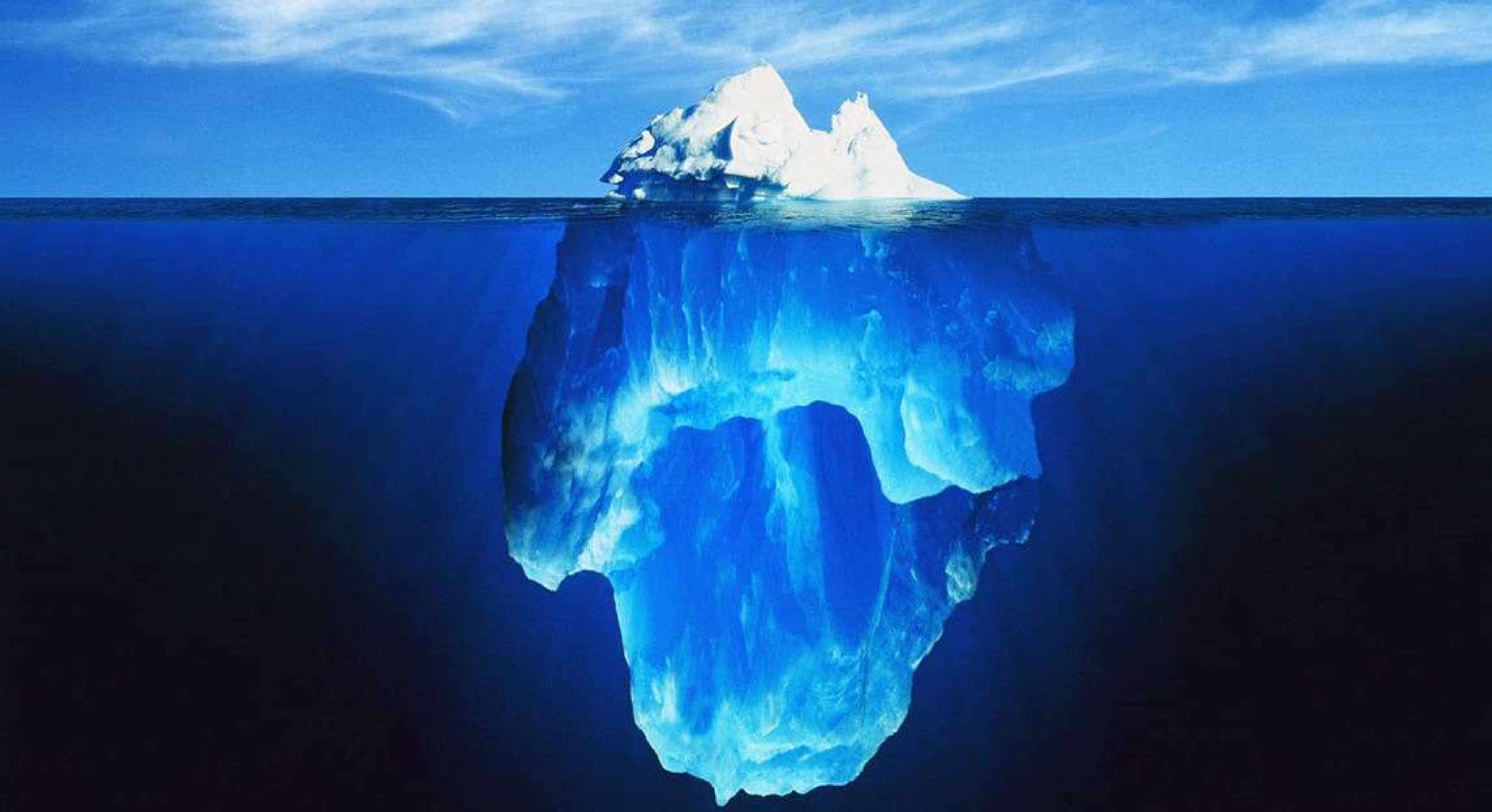
- What is the cause?
  - Former glaciation!
- Where does land uplift occur?
  - Identified in maps and gravity anomalies
- When was the glaciation?
  - Can be calculated from varves
- What are the underlying physics?

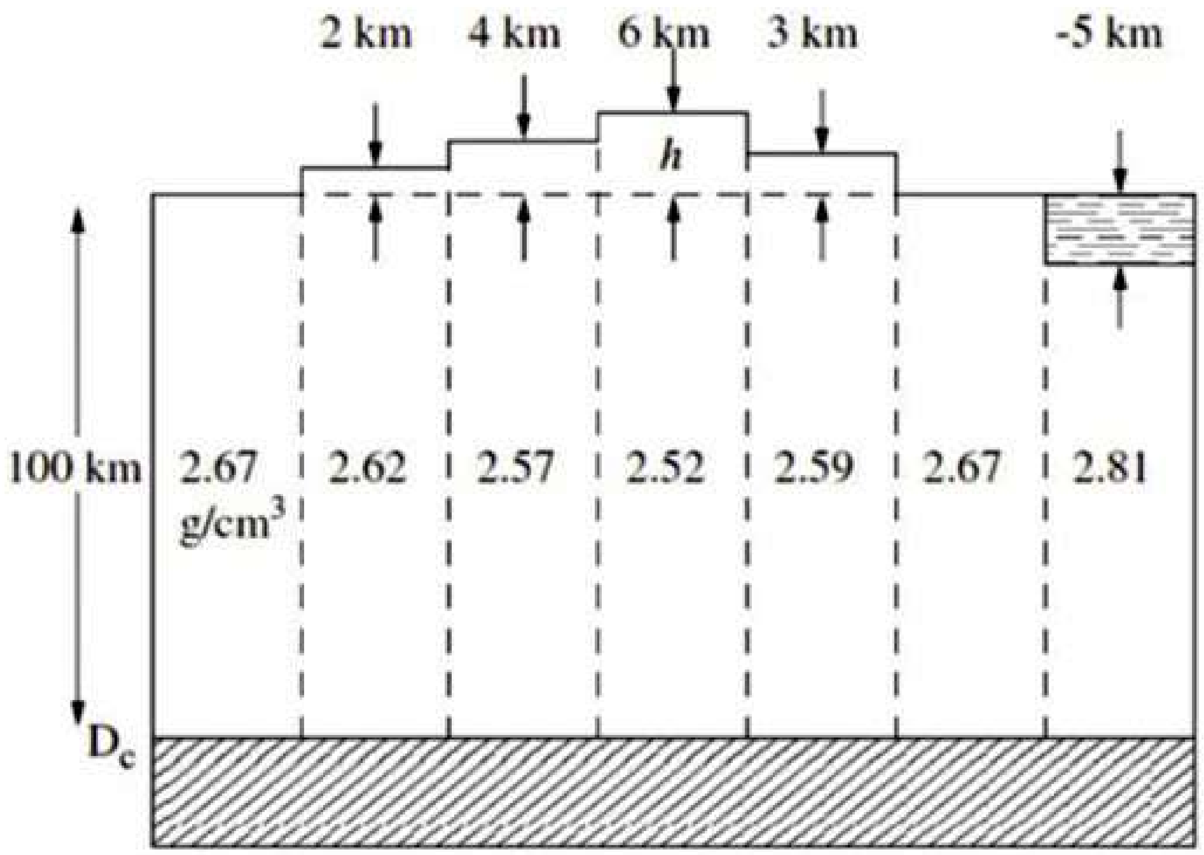


(Steffen and Wu 2011)

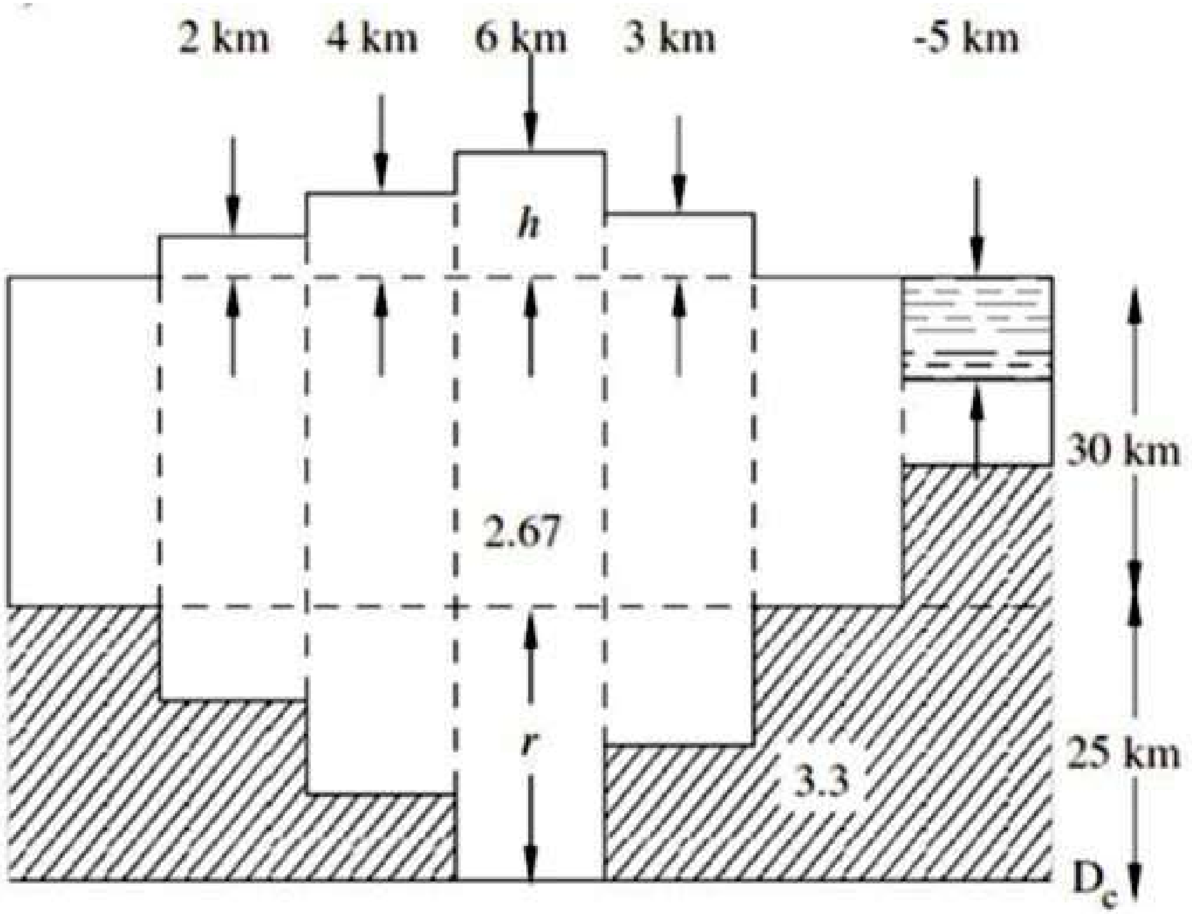


http://www.eisberg-tauchen.de

ISOSTATIC MODELS OF AIRY & PRATT



Airy-Heiskanen model

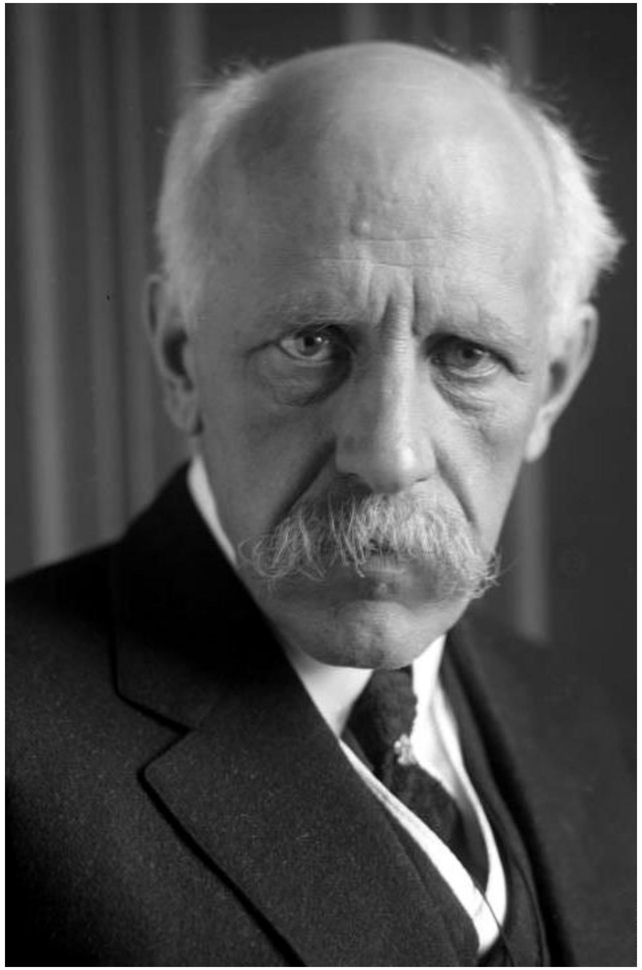


Pratt-Hayford model

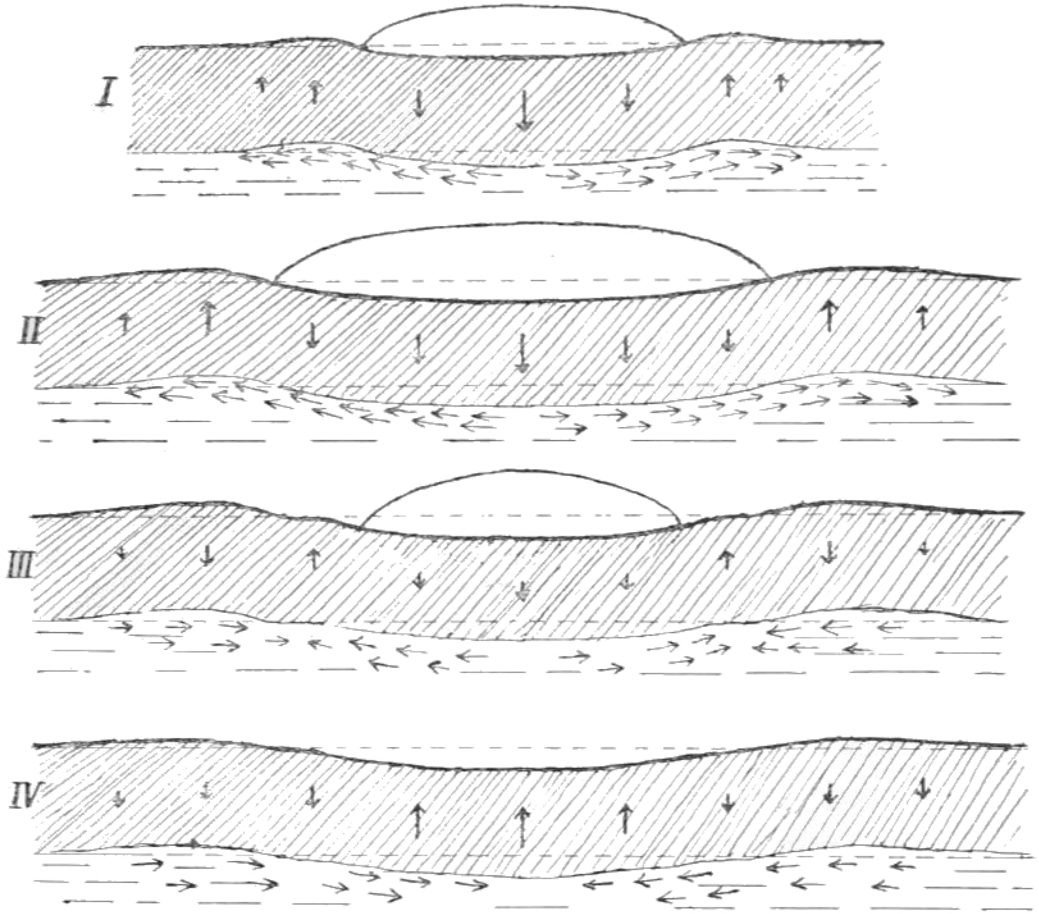
Introduced for mountains!

Close (2010)

FRIDTJOF NANSEN (1861–1930)



- Isostasy as explanation of readjustment
- But why does it take so much time for readjustment (we see it today!)?



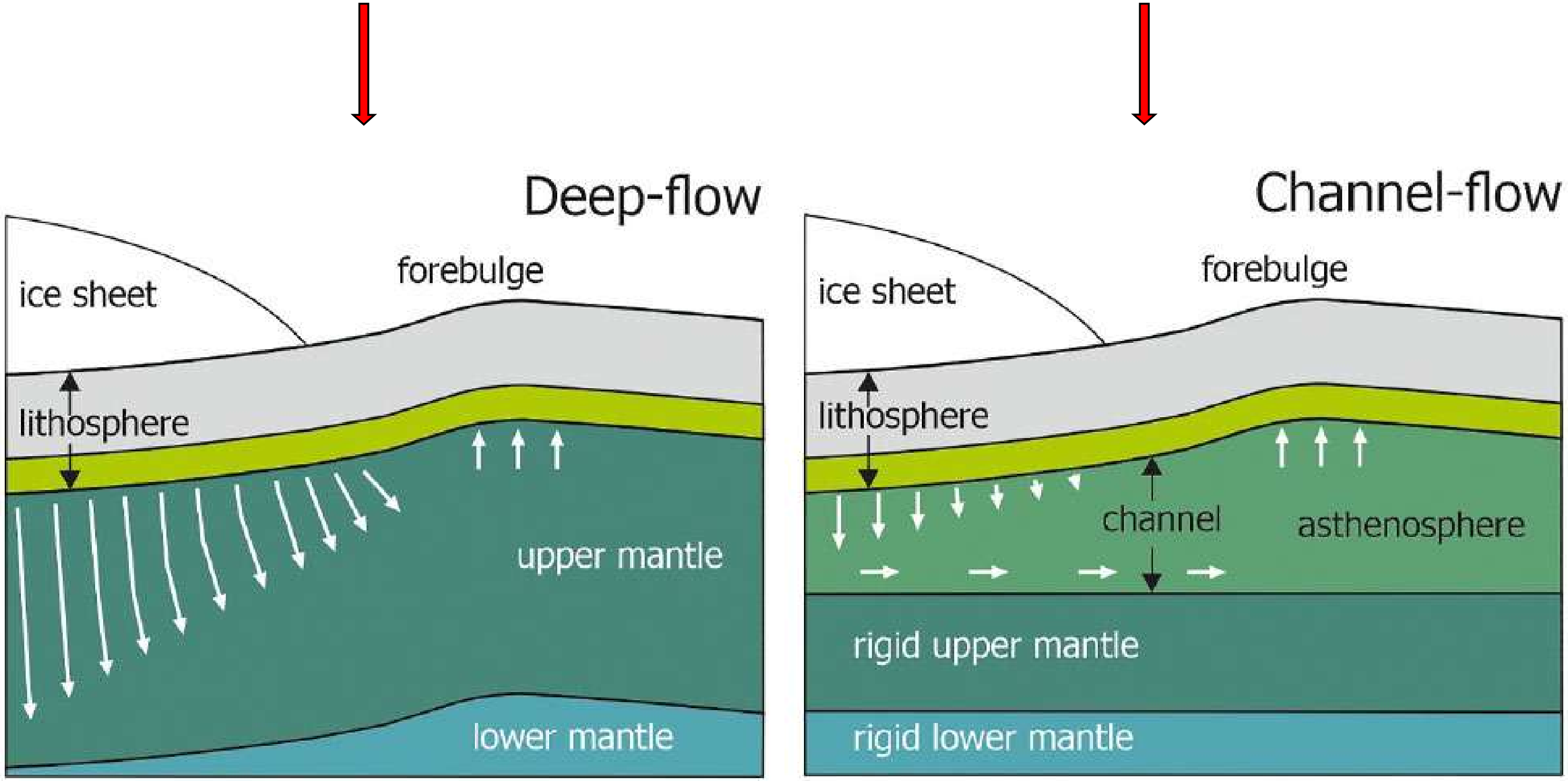
https://upload.wikimedia.org/wikipedia/en/c/c6/Bundesarchiv_Bild_102-09772%2C_Fridjof_Nansen_%28cropped%29.jpg

Nansen (1921)

REGINALD A. DALY (1871-1957)

https://upload.wikimedia.org/wikipedia/en/0/09/RA_Daly.jpg

- Two rheological earth models,
  "punching hypothesis" and "bulge hypothesis“



(Brandes et al. 2025)

REBOUND MODELING AND VISCOSITY ESTIMATES

Deep Flow (Punch)	**Channel Flow (Bulge)** **High Visc. Lower Mantle**
Daly (1934)	
Haskell (1935, 1936, 1937) ν ~0.95 x 10^{21} Pa s Predict uplift remaining ~ 20 m*	Van Bemmelen & Berlage (1935) 100 km channel, ν ~1.3 x 10^{20} Pa s Predict uplift remaining ~210 m*
Vening Meinesz (1937) ν ~3 x 10^{21} Pa s	Niskanen (1939) ν ~ 3.6 x 10^{21} Pa s Predict uplift remaining ~200 m*
Gutenberg (1941) ν ~2 x 10^{21} Pa s	Crittenden (1963), McConnell (1968)
Andrews (1968, 1970)	Lliboutry (1971), Artyushkov (1971)
Cathles (1971), Parsons (1972)	Post & Griggs (1973) nonlinear flow
Peltier (1974)	Walcott (1972)

*Fennoscandia!

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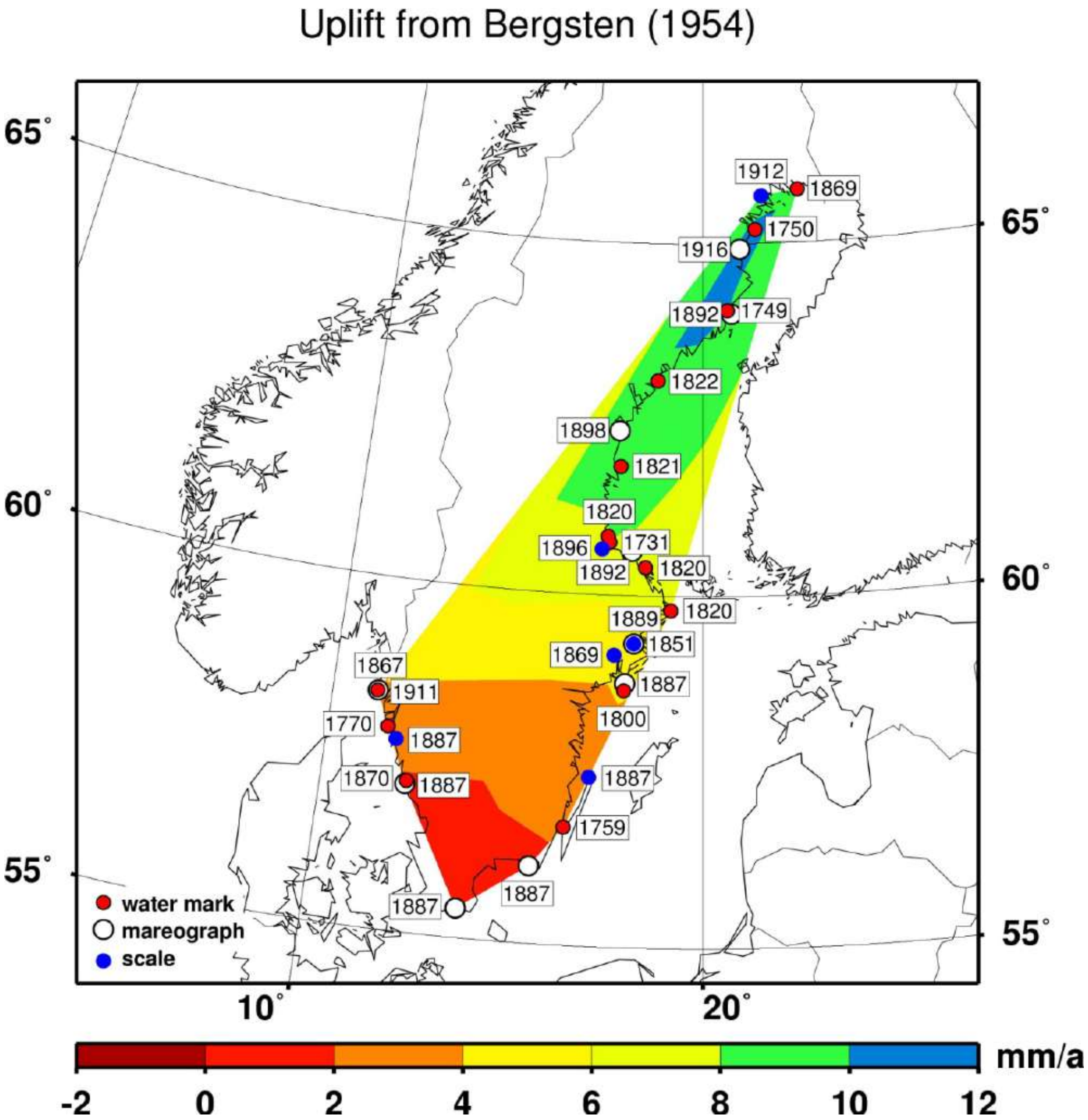
  - Identified in maps and gravity anomalies
- When was the glaciation?
  - Can be calculated from varves
- What are the underlying physics?
  - Postglacial rebound/Glacial isostasy



(Steffen and Wu 2011)

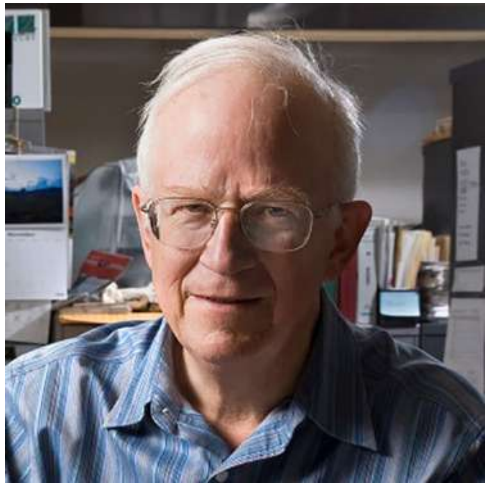
DEVELOPMENT SINCE THE 1950S

- Theory of physics → equations to describe processes
- Computers and increase in computational power
- Dating methods (for fossils, ice cores etc.) → knowledge of past glaciations and sea levels
- Mapping of the oceans → continental drift → convection
- Satellite missions → global gravity models

Kurt Lambeck

W. Richard Peltier

(http://www.news.utoronto.ca/sites/default/files/Peltier_12_02-27_0.jpg?1364827862)



Larry Cathles

(https://larrycathles.eas.cornell.edu/files/2020/11/Larry-Cathles.jpg)

A NEW THEORY AND A NEW TERM

EQUATIONS TO MODEL EARTH DEFORMATION

Newton's Law:

$$\vec{\nabla}\cdot\overline{\overline{\tau}}-\vec{\nabla}\left(\vec{u}\cdot\rho_o g_o\hat{r}\right)-\rho_1 g_o\hat{r}-\rho_o\vec{\nabla}\phi_1=0$$

Div of stress

Advection of Prestress

Internal buoyancy

Incremental gravity

Mass Conservation

$$\rho_1=-\rho_0\vec{\nabla}\cdot\vec{u}-\vec{u}\cdot\left(\partial_r\rho_0\right)\hat{r}$$

Perturbed density

Volume change

Density stratification

Self Gravitation

$$\nabla^2\phi_1=4\pi G\rho_1$$

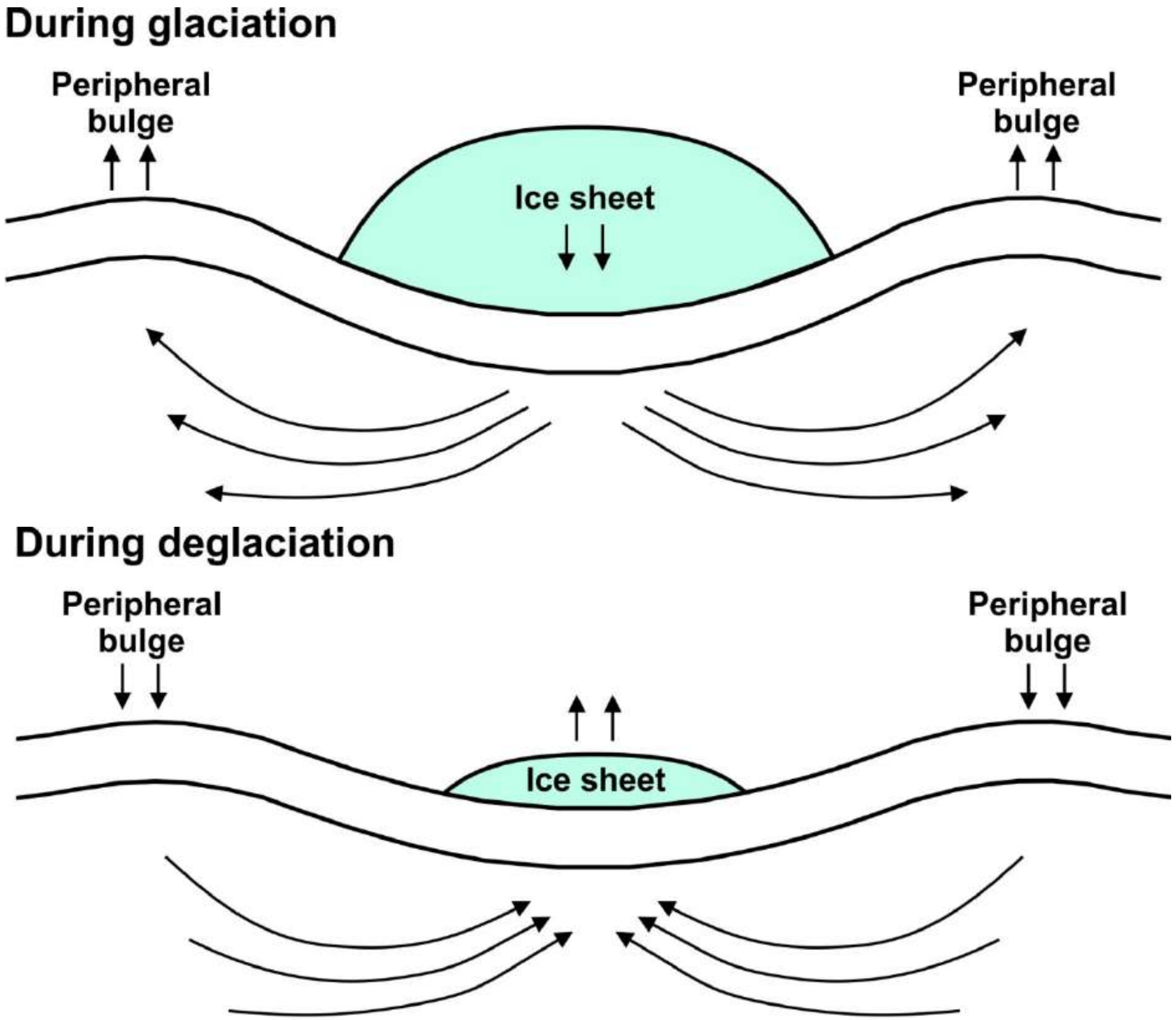
Perturbed Grav. Potential generated by perturbed density

Visco-elastic Maxwell

$$\partial_t\overline{\overline{\tau}}=\partial_t\overline{\overline{\tau}}^{0}-\frac{\mu}{\nu}\left(\overline{\overline{\tau}}-\Pi\overline{\overline{I}}\right)\qquad\overline{\overline{\tau}}^{0}=\lambda\theta\overline{\overline{I}}+2\mu\overline{\overline{\varepsilon}}$$

Elastic & Viscous contribution

GLACIAL ISOSTATIC ADJUSTMENT

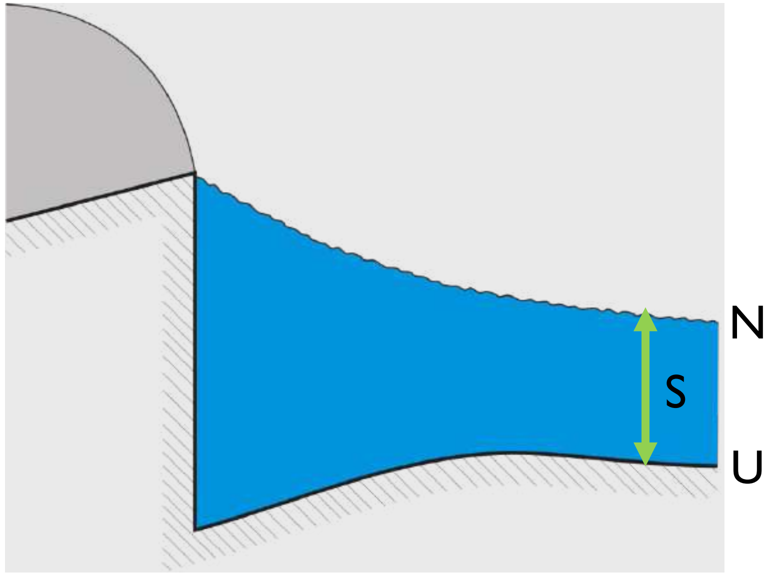


Solid earth, simplest form

(R. Steffen, 2013)

WHAT IS SEA LEVEL?

$$S = N - U$$

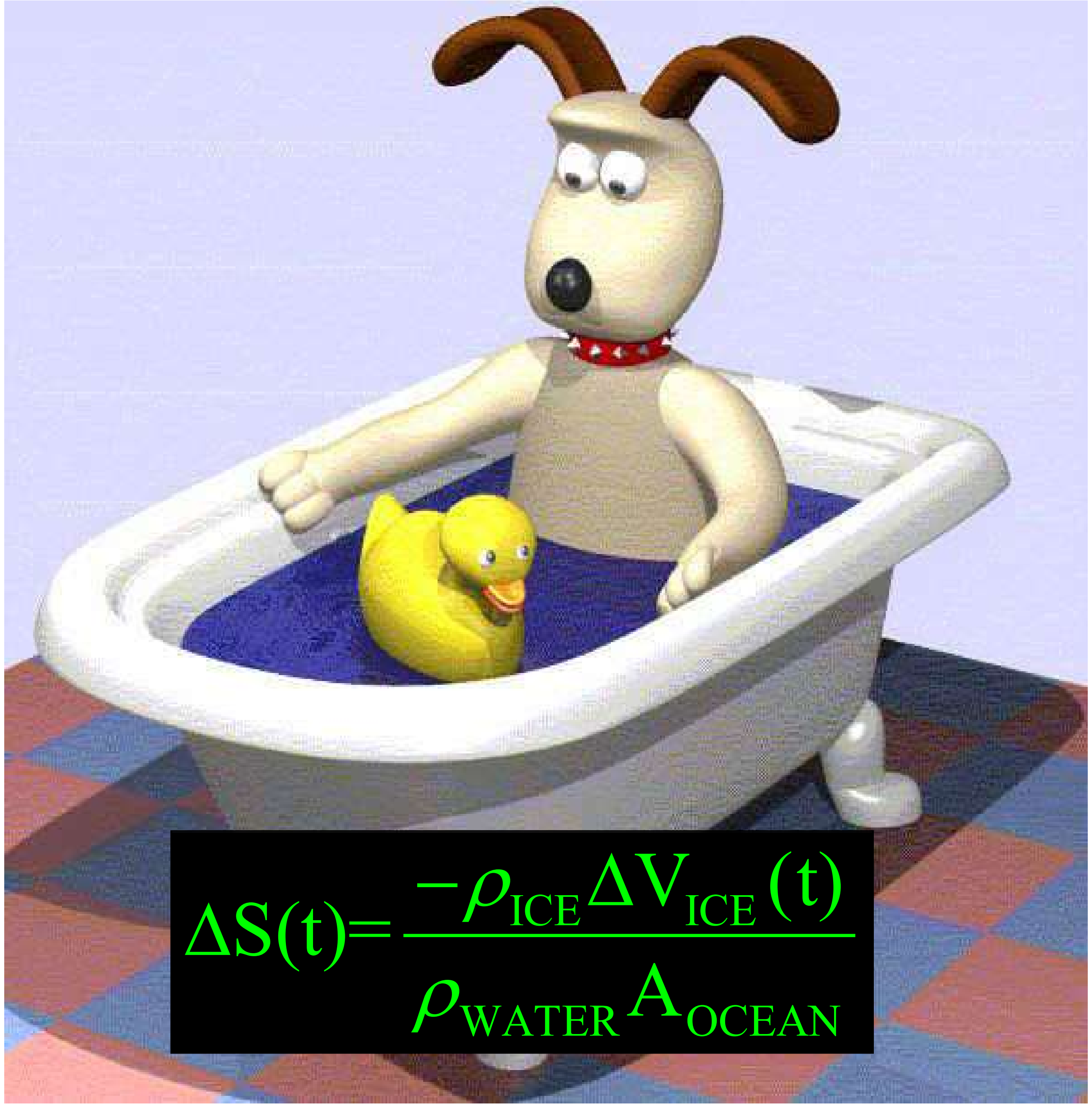


S relative sea level or water depth

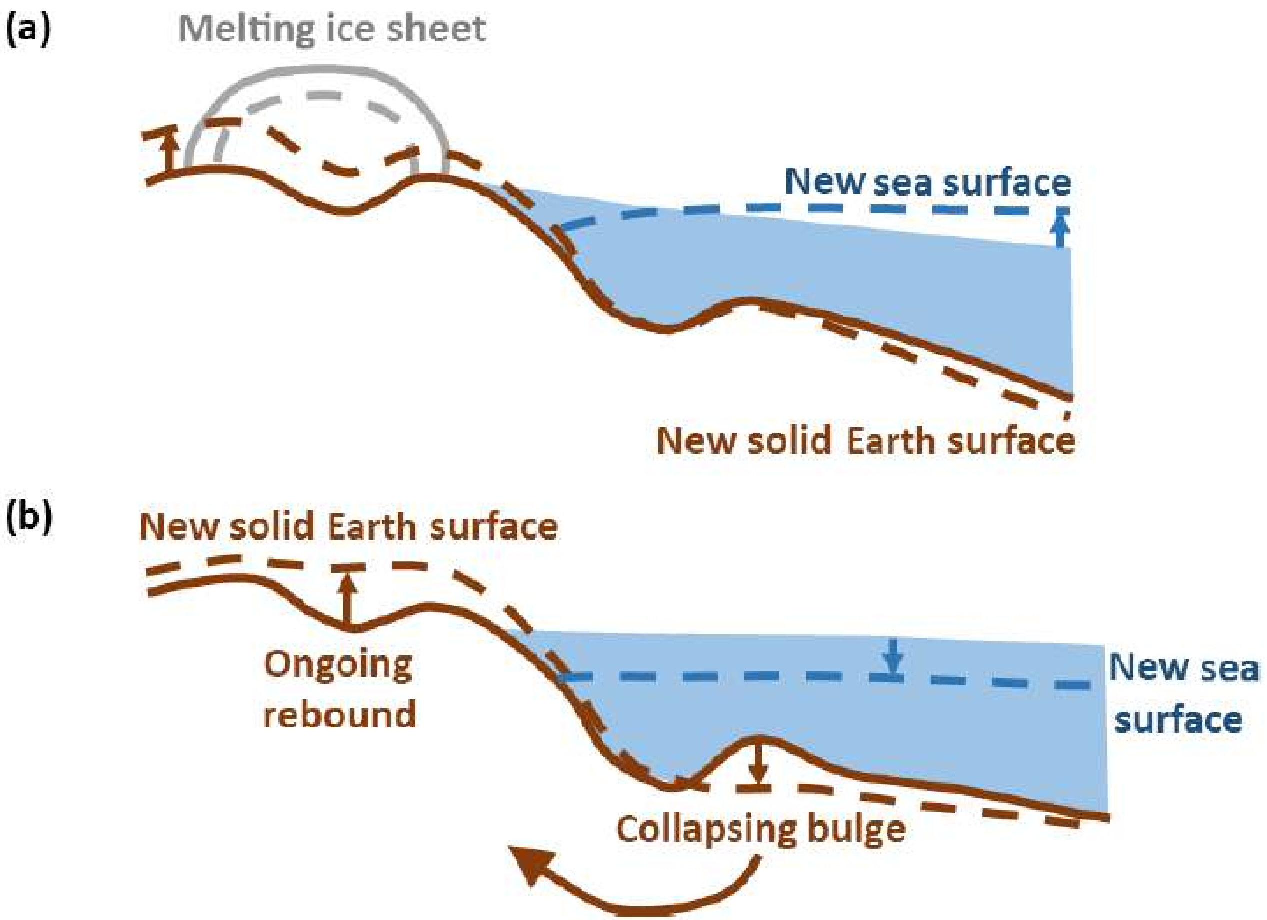
N absolute sea level, defined as the height of the sea surface above the centre of mass of the solid Earth

U height of the seafloor, defined relative to the centre of mass of the solid Earth

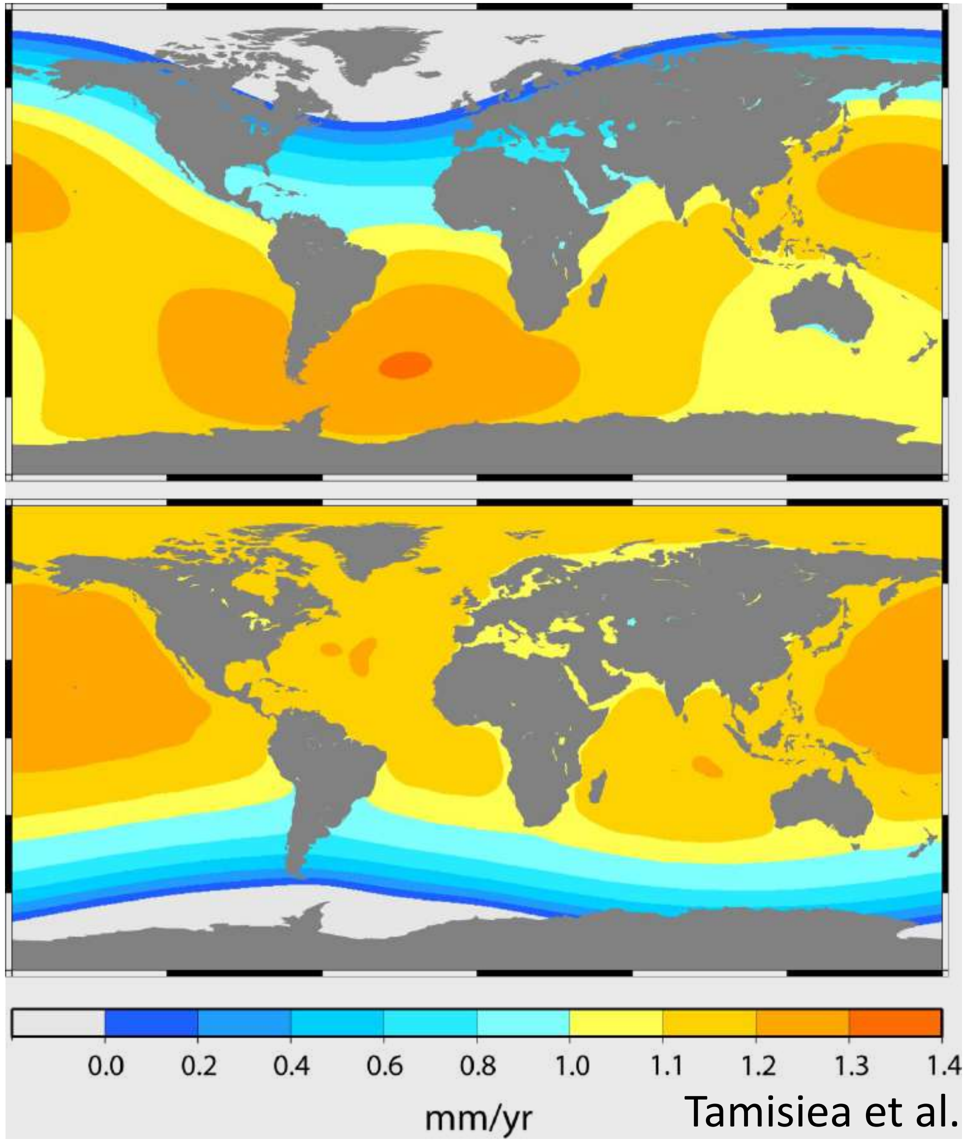
GLACIO-EUSTASY



PERTURBATIONS TO OCEAN FLOOR AND SURFACE

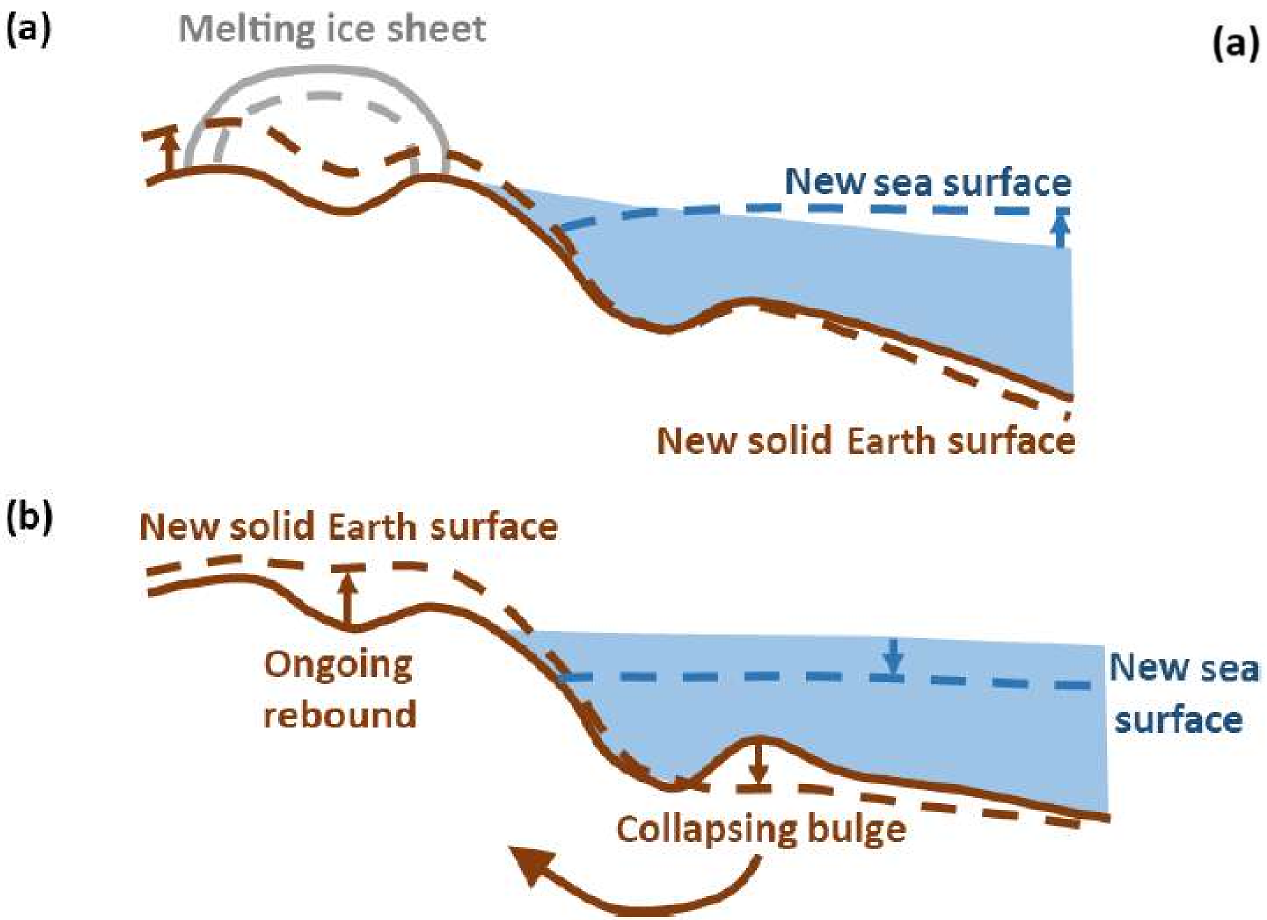


(Whitehouse, 2018)

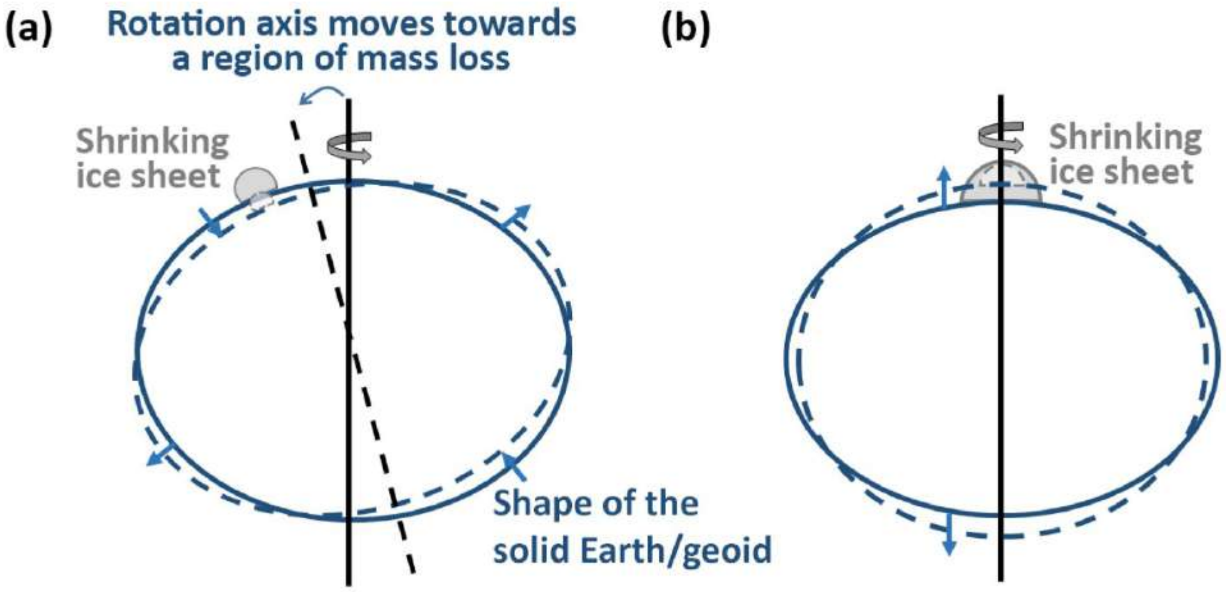


Tamisiea et al. (2003)

GIA AND EARTH ROTATION CHANGES

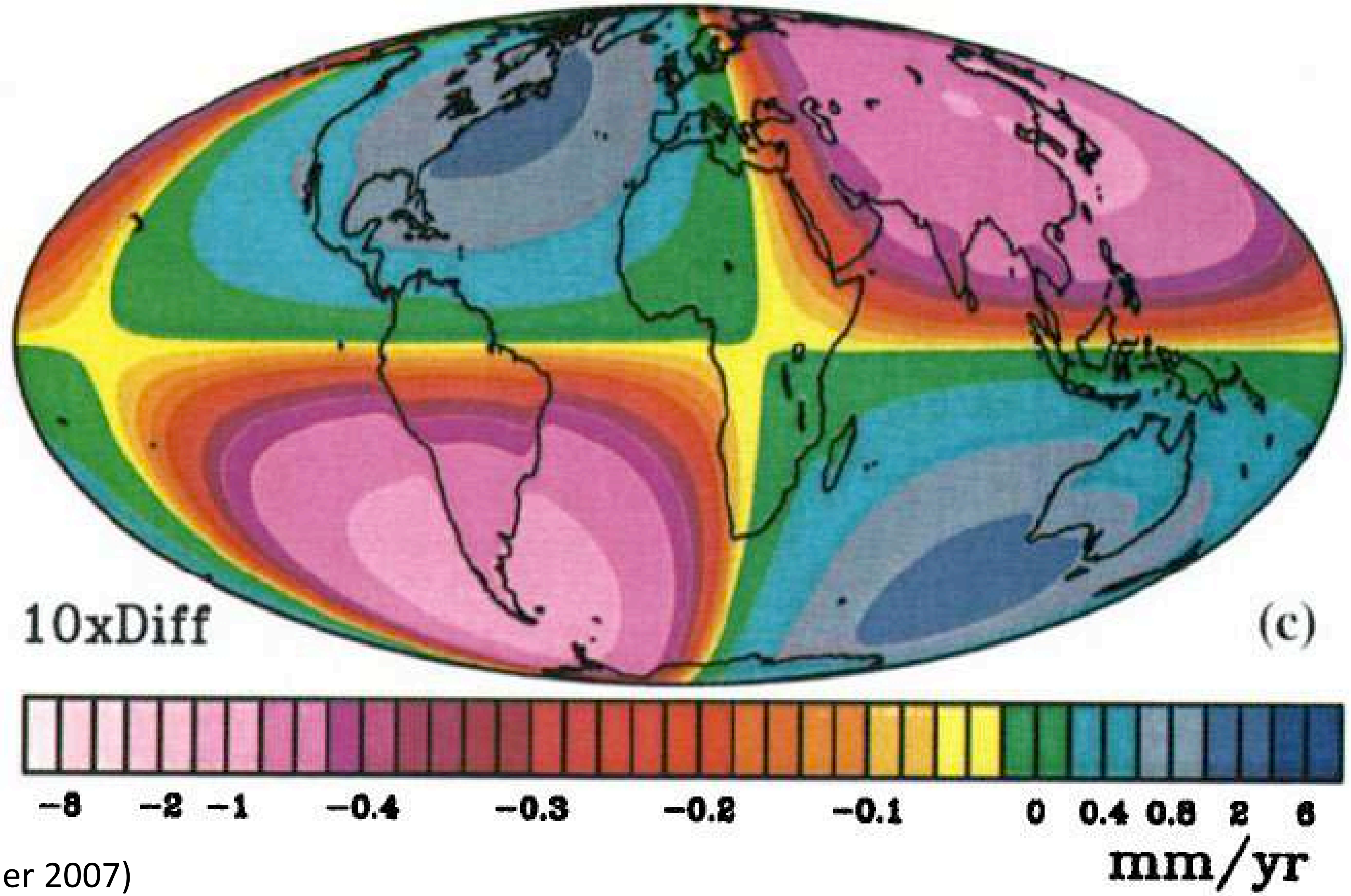


(Whitehouse, 2018)



(Whitehouse, 2018)

EFFECT OF ROTATION ON SEA-LEVEL RATE



(Peltier 2007)

SEA-LEVEL EQUATION WITH EVEN MORE EFFECTS

$$X_j = X(\theta, \varphi, t_j)$$

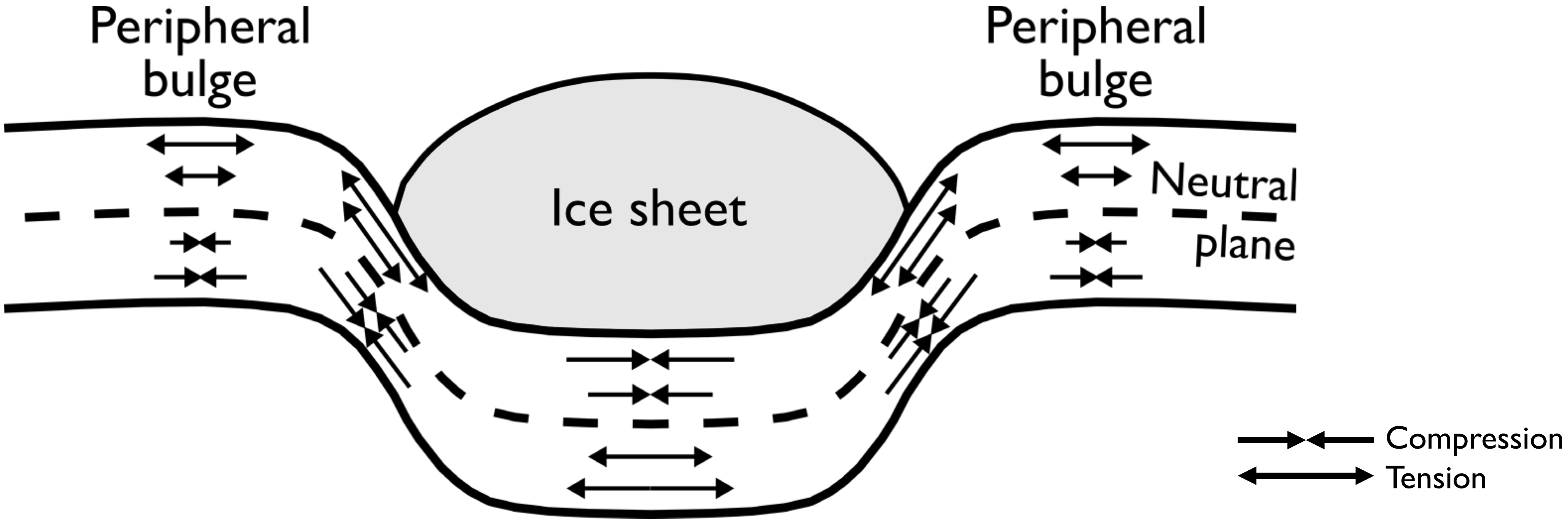
$$\Delta S_j = \Bigg[\Bigg(\left(N_j - U_j + RF_j\right) - \frac{1}{A_j} \cdot \frac{M_{ice,j}}{\rho_{water}} - \frac{1}{A_j} \iint\limits_{\Omega} \left(N_j - U_j + RF_j\right) \cdot O_j^* \, d\Omega$$

$$+ \frac{1}{A_j} \iint\limits_{\Omega} T_0 \left(O_j^* - O_0^*\right) d\Omega \Bigg) - \frac{\rho_{ice}}{\rho_{water}} h_{ice,j} \cdot \left(1 - O_j^*\right) \Bigg] \cdot O_j^* - T_0 \cdot \left(O_j^* - O_0^*\right)$$

$$M_{ice,j} = \rho_{ice} \iint_{\Omega} h_{ice,j} \left(1 - O_j^*\right) d\Omega; \qquad O_j^* = \begin{cases} 1 & h_{water,j} > 0 \; \& \; h_{water,j} \cdot \rho_{water} > h_{ice,j} \cdot \rho_{ice} \\ 0 & \text{otherwise} \end{cases}$$

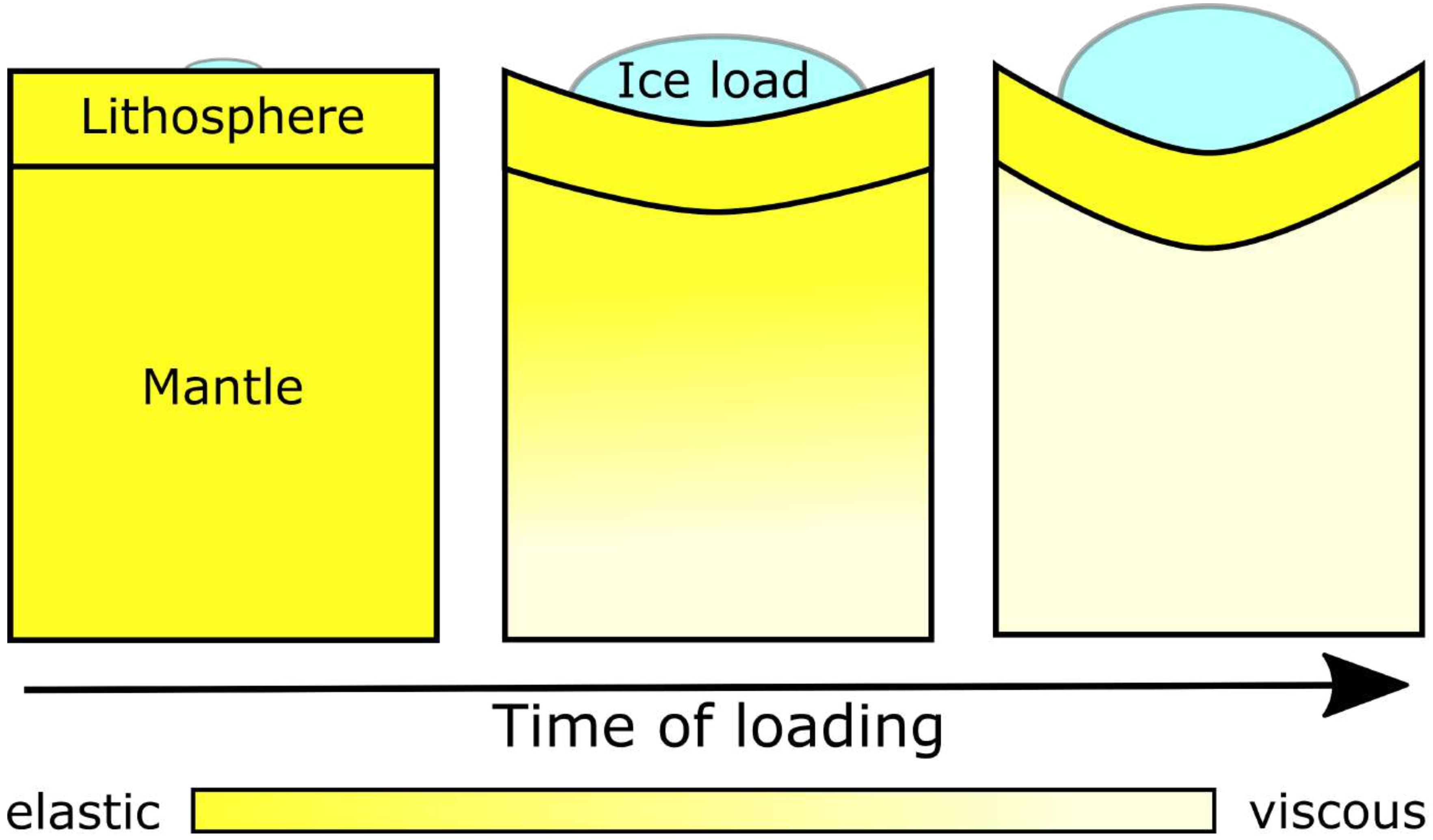
GLACIALLY INDUCED STRESSES

Steffen et al. (2021)



- Stresses are due to
- the **loading** itself (vertical stress, not shown here),
- the **flexure of the lithosphere** (horizontal stresses) and
- the **migration of stresses** from the mantle into the lithosphere (horizontal stresses, next slide)

GLACIALLY INDUCED STRESSES – STRESS MIGRATION

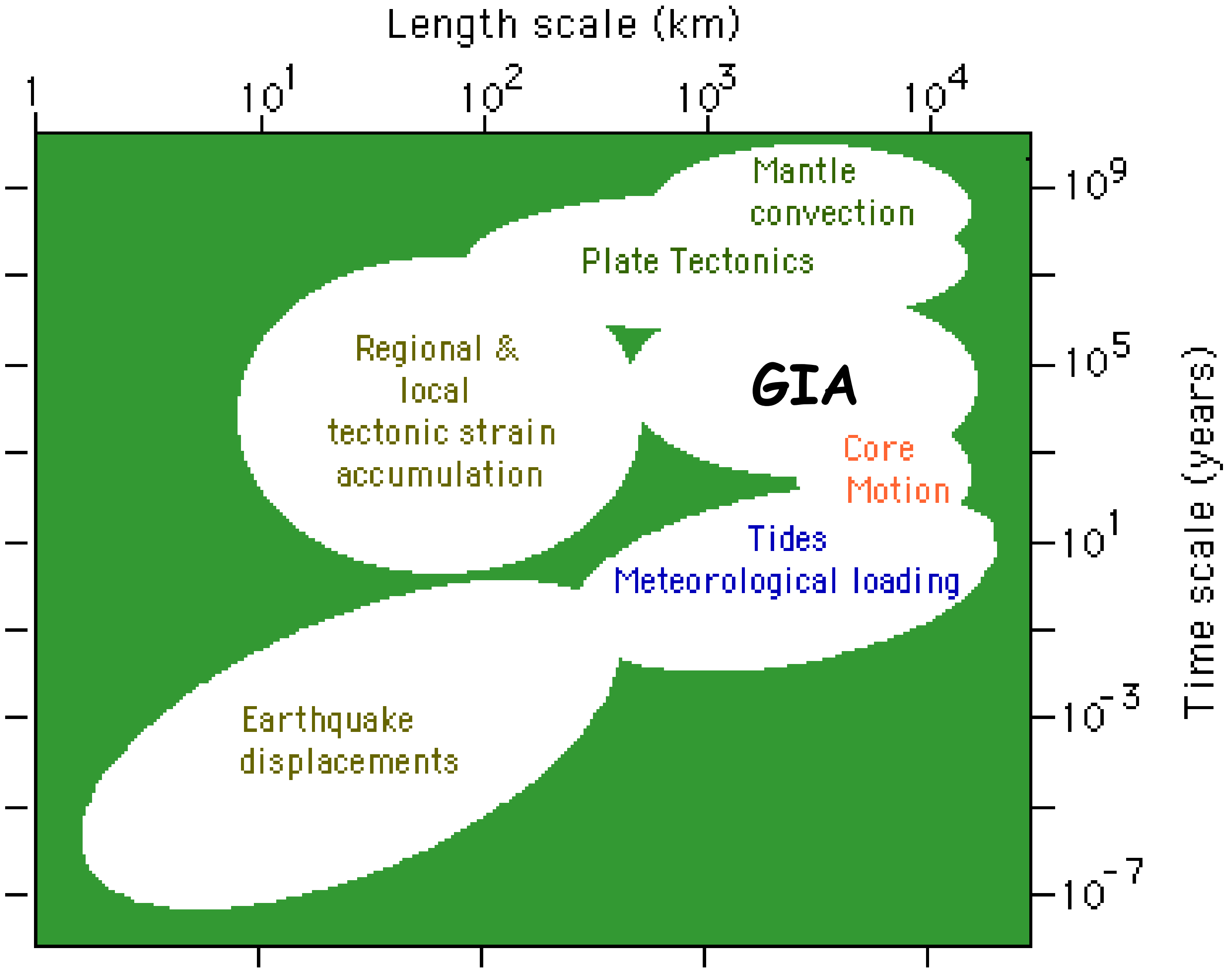


A NEW THEORY AND A NEW TERM

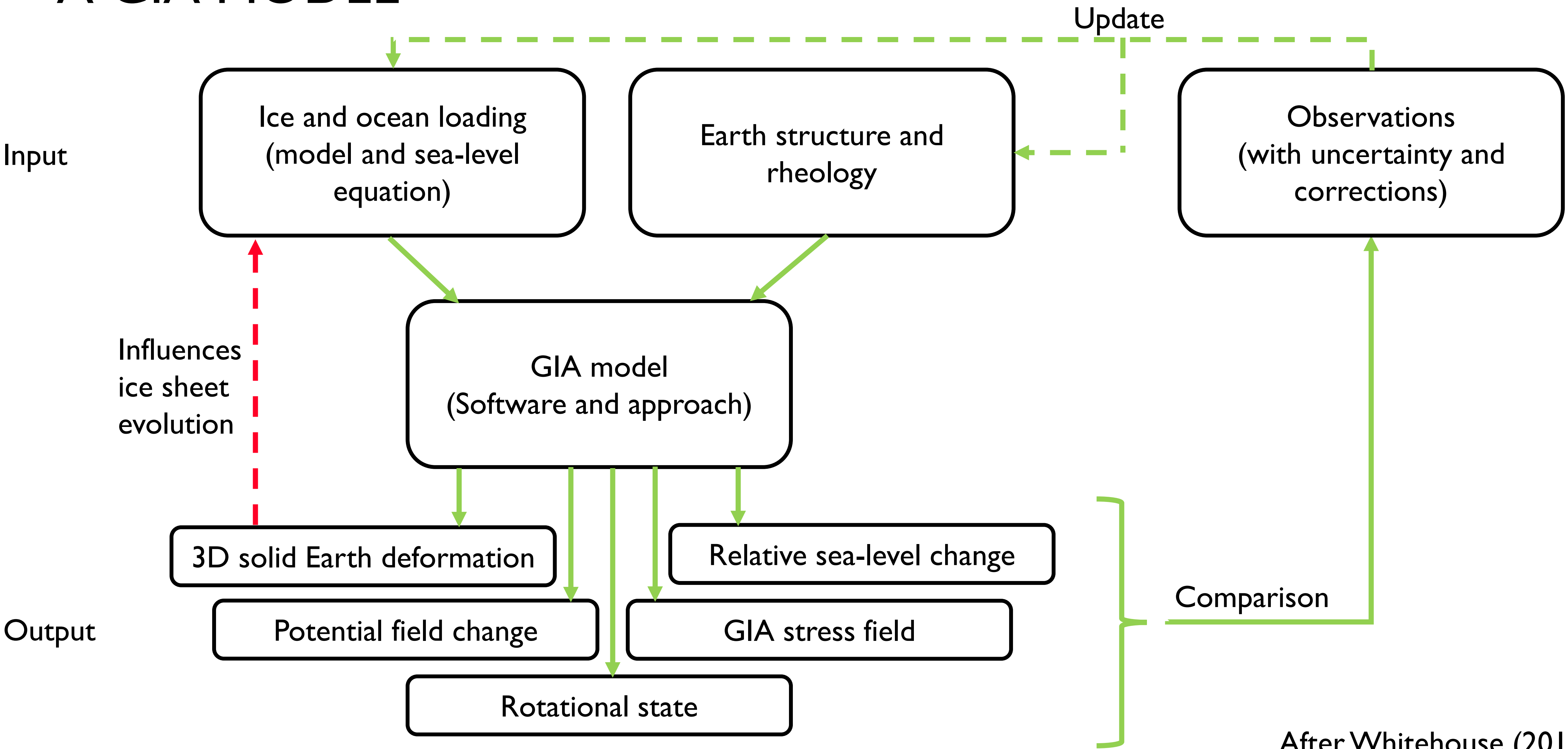
Glacial isostatic adjustment (GIA) is the adjustment of the Earth that leads to a new re-equilibration state due to the redistribution of surface ice and ocean masses and the flow of mantle rocks driven by the growth and decay of large ice sheets on the Earth's surface. The uplift of former glaciated areas is part of GIA and is commonly named postglacial rebound. But GIA is more than just postglacial uplift and sea-level change in previously glaciation areas—the adjustment process actually involves the whole Earth during the past, present and future. Next to radial and tangential motion, changes in sea levels, the Earth's gravity field and rotational motion, GIA also involves changes in lithospheric bending and the state of stress inside the Earth. Hence, it envelopes Earth's response to past glaciations as well as recent melting processes, for example, in Greenland and Antarctica.

(Brandes et al. 2025)

TIME & LENGTH SCALE OF SOME GEODYNAMIC PROCESSES



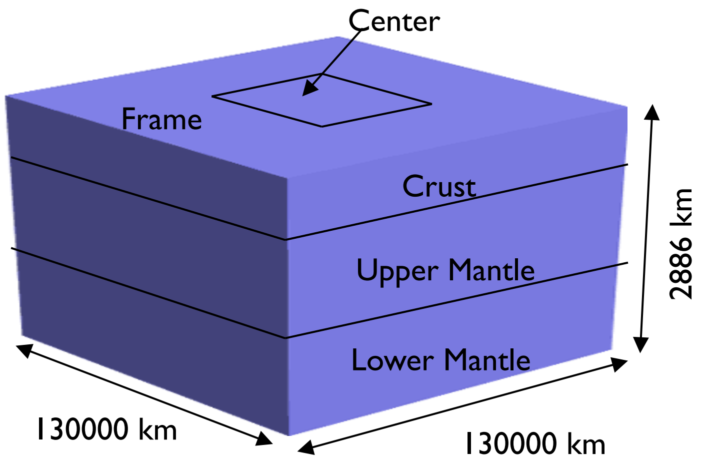
A GIA MODEL

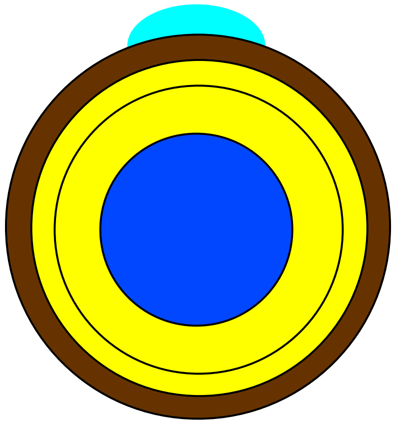


After Whitehouse (2018)

MODELLING APPROACHES

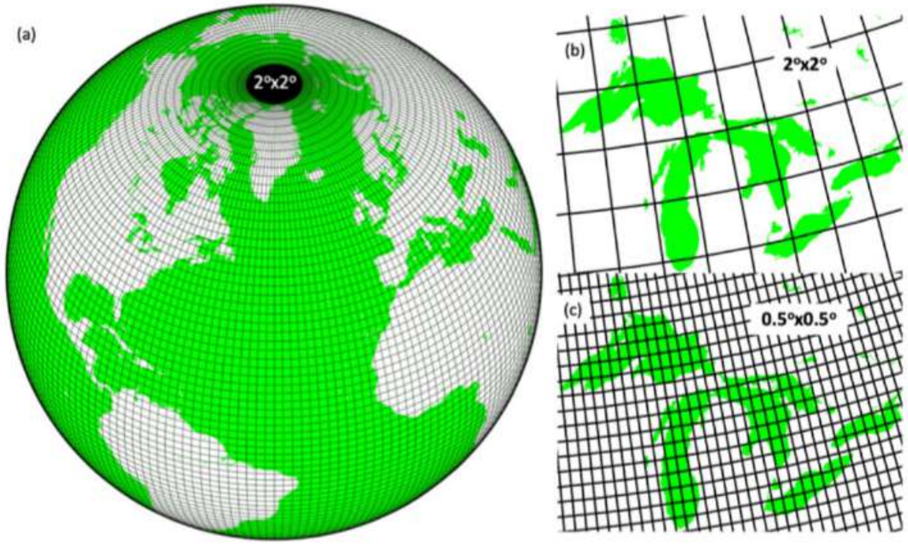
3D flat model
(Wu 2004)



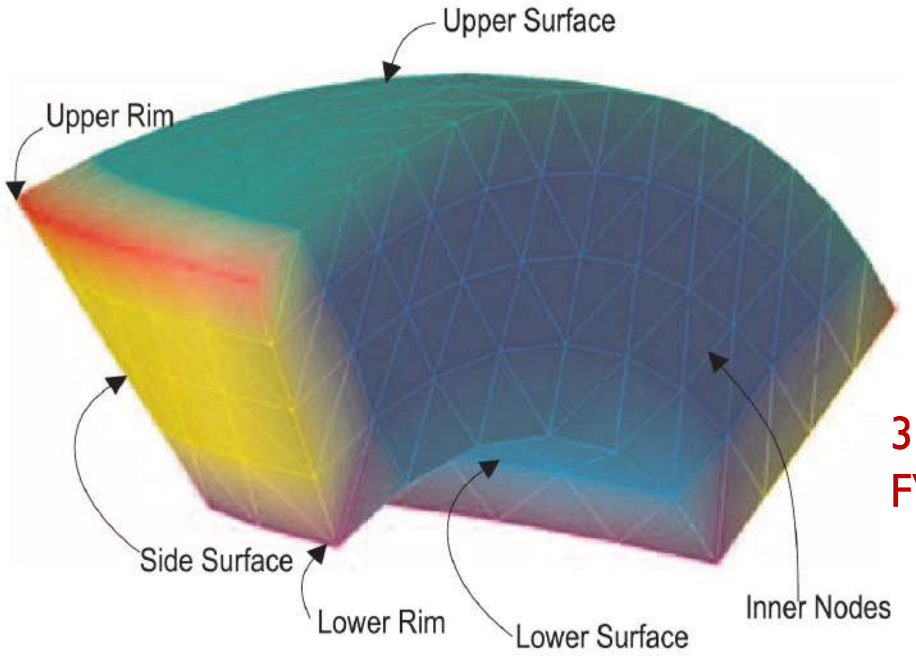


1D model
(Munk & MacDonald 1960;
Farrell and Clark 1976;
Mitrovica et al. 1994;
Mitrovica and Milne 1998;
Kaufmann et al. 2002;
Spada et al. 2007)

3D spherical FE model (Wu 2004; Wong & Wu 2018; Zhong et al. 2022; Huang et al. 2023)



(Peltier et al. 2022)



(Latychev et al. 2005)

3D spherical FV model

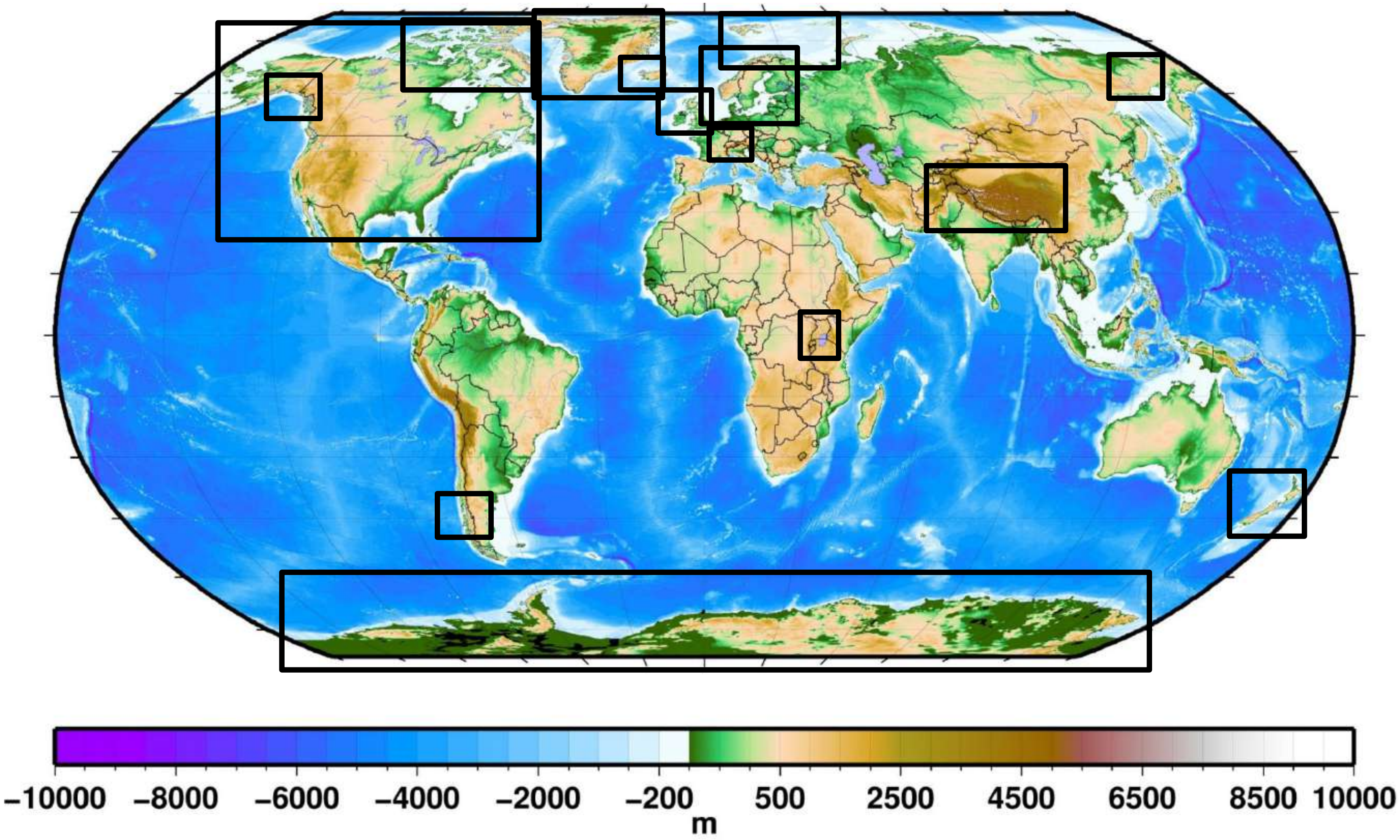
GIA OBSERVATIONS

GIA equation of motion
Sea-level equation
Liouville's equation

↔

- Vertical motion
  - Relative sea levels (geologic, palaeontological and archaeological evidence)
  - Present-day rate of uplift – Levelling, GNSS, tide gauges, altimetry, interferometry
- Horizontal motion - GNSS, VLBI, DORIS
- Gravity change due to redistribution of mass – terrestrial (gravimeter) and space-geodetic techniques (GRACE, GRACE-FO, GOCE, hlSST)
- Change in Moments of Inertia
  - Polar wander
  - Non-tidal acceleration (Length Of Day)
- Changes in the state of stress (earthquakes, faults)

GIA AROUND THE WORLD

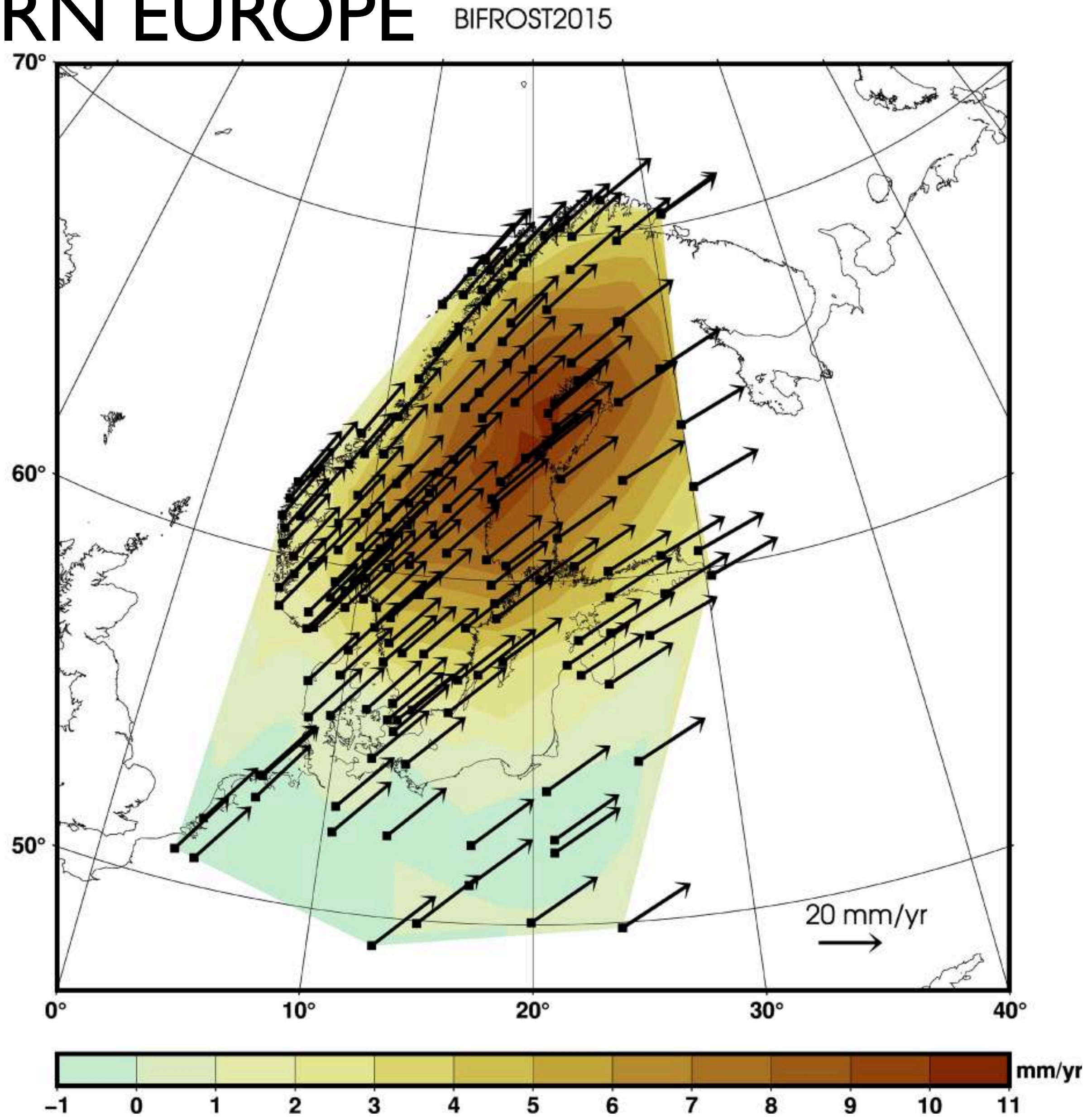


BIFROST

- Purpose: Determination of **horizontal rates** and **absolute land uplift** values
- Network: Public GNSS sites from IGS and EPN (EUREF Permanent Network) and sites not in the public domain
- Development:
    - 2002: 33 sites
    - 2007: 54
    - 2010: 83
    - Since 2013: >200 possible
    - (2025: at least 734)
- Reported and used in several publications in the last ~25 years

GEODYNAMICS IN NORTHERN EUROPE

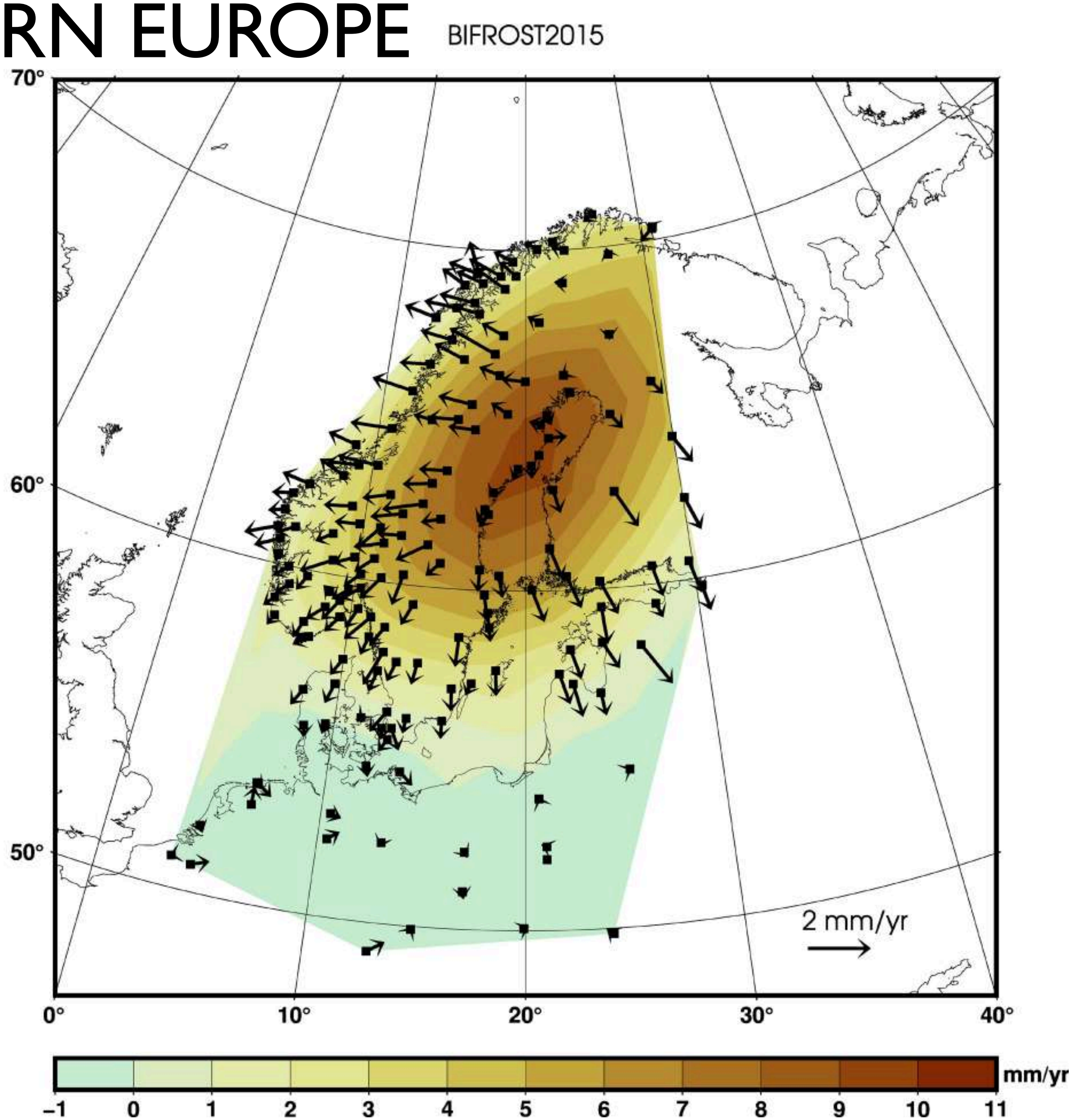
- Horizontal velocities show plate motion
- Uplift >1cm/a in the centre (somewhere between the cities of Umeå and Skellefteå), forebulge with 1-2 mm/a subsidence in northern Germany and Poland



(Kierulf et al. 2021)

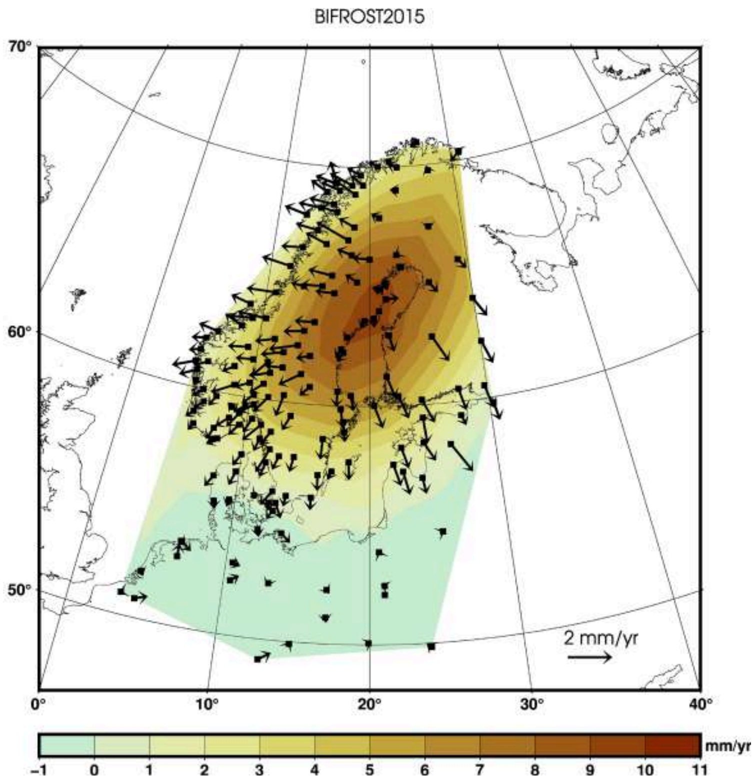
GEODYNAMICS IN NORTHERN EUROPE

- Horizontal velocities show motion away from the uplift centre
- Uplift >1cm/a in the centre (somewhere between the cities of Umeå and Skellefteå), forebulge with 1-2 mm/a subsidence in northern Germany and Poland



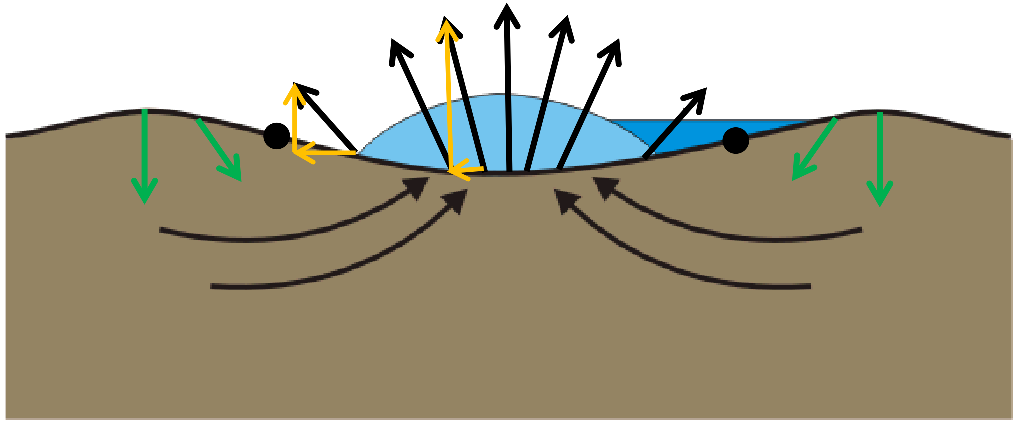
(Kierulf et al. 2021)

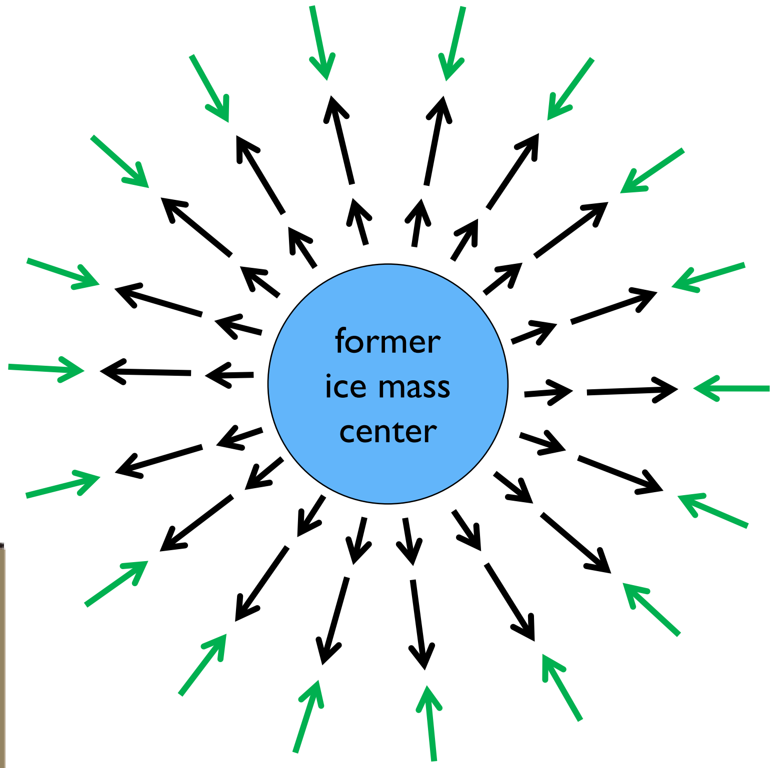
HORIZONTAL DEFORMATION DUE TO GIA



(Kierulf et al., 2021)

During deglaciation, crustal horizontal motions are radially away from the former ice mass center, and increase in magnitude away from the load.
In the forebulge region, motions are towards the former ice mass center.



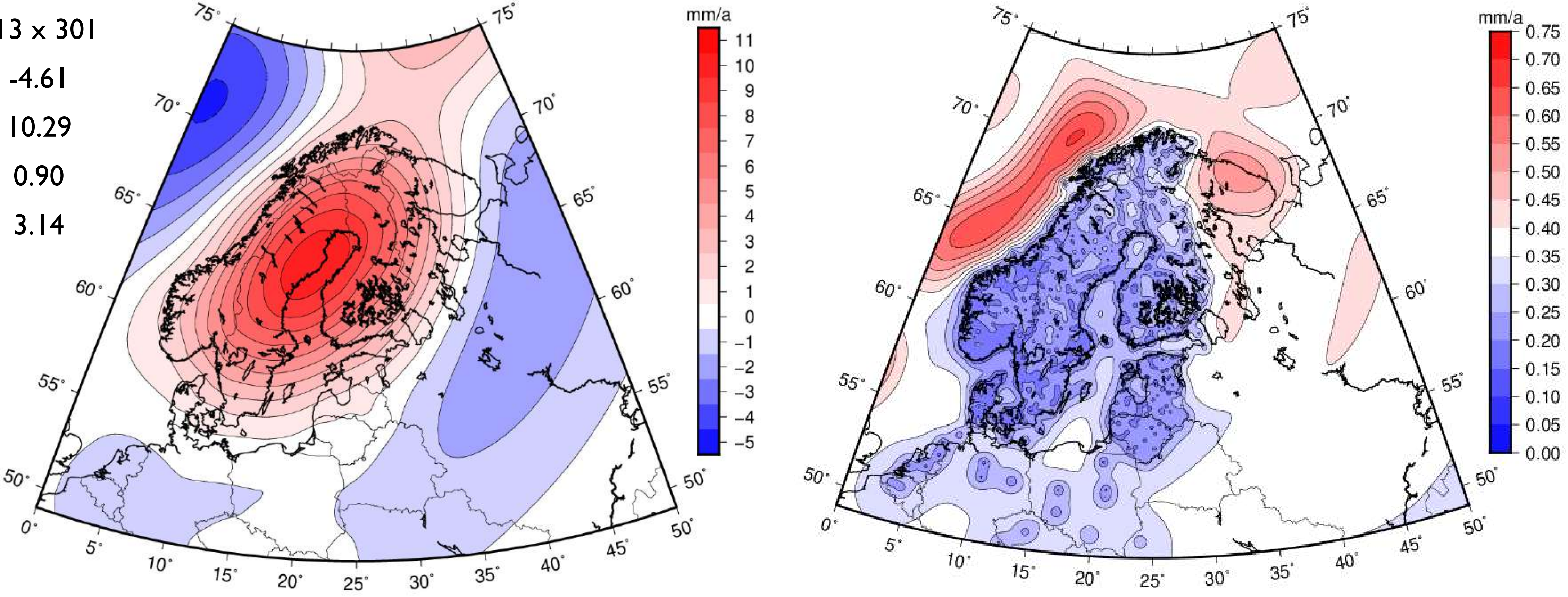


Valid for typically determined lithospheric thicknesses and mantle viscosities (Hermans et al., 2018)!

(Slide courtesy of Pippa Whitehouse and Stephanie Konfal)

NKG2016LU_ABS AND ITS UNCERTAINTY

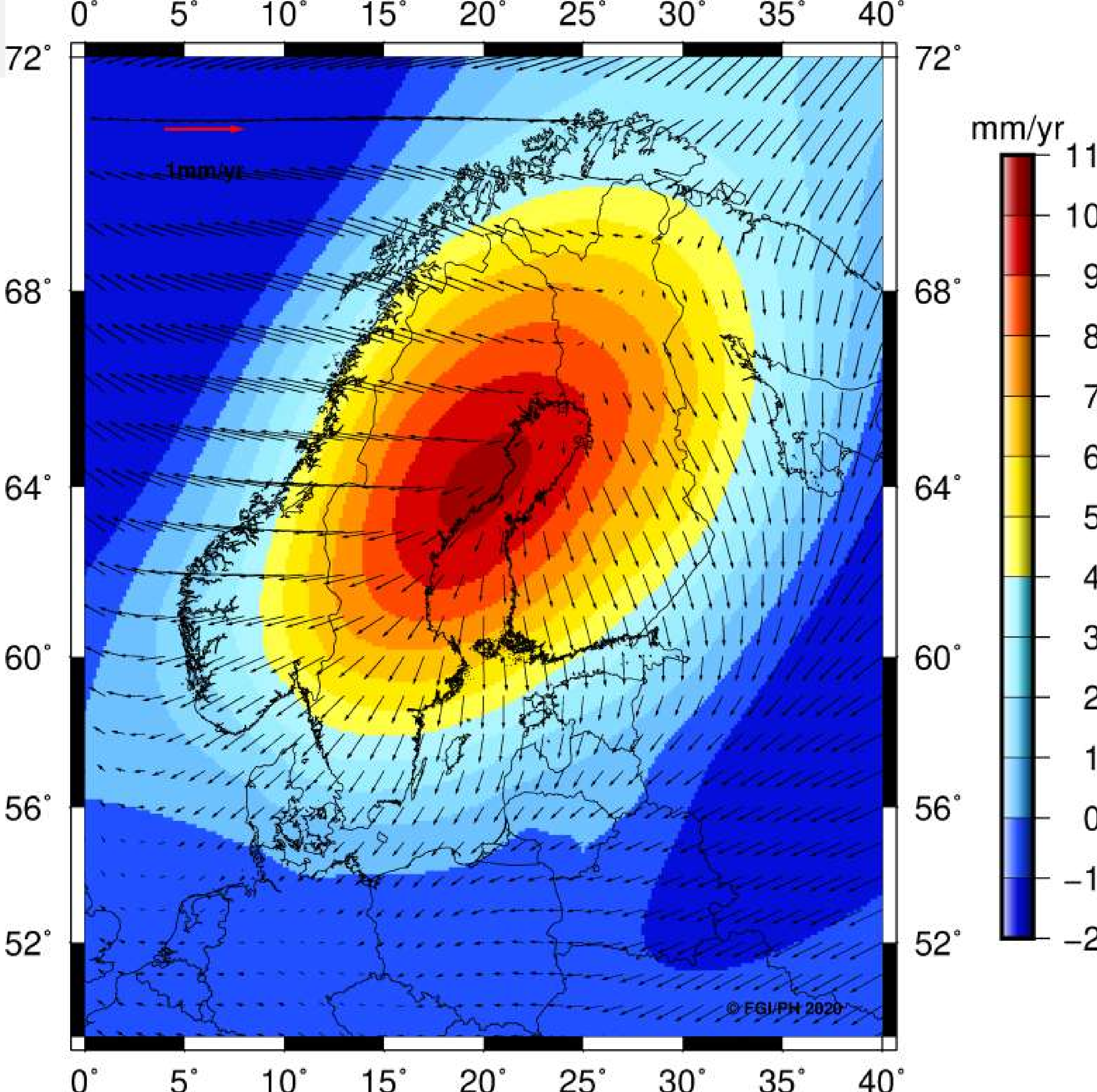
#	313 x 301
Min	-4.61
Max	10.29
Mean	0.90
StdDev	3.14



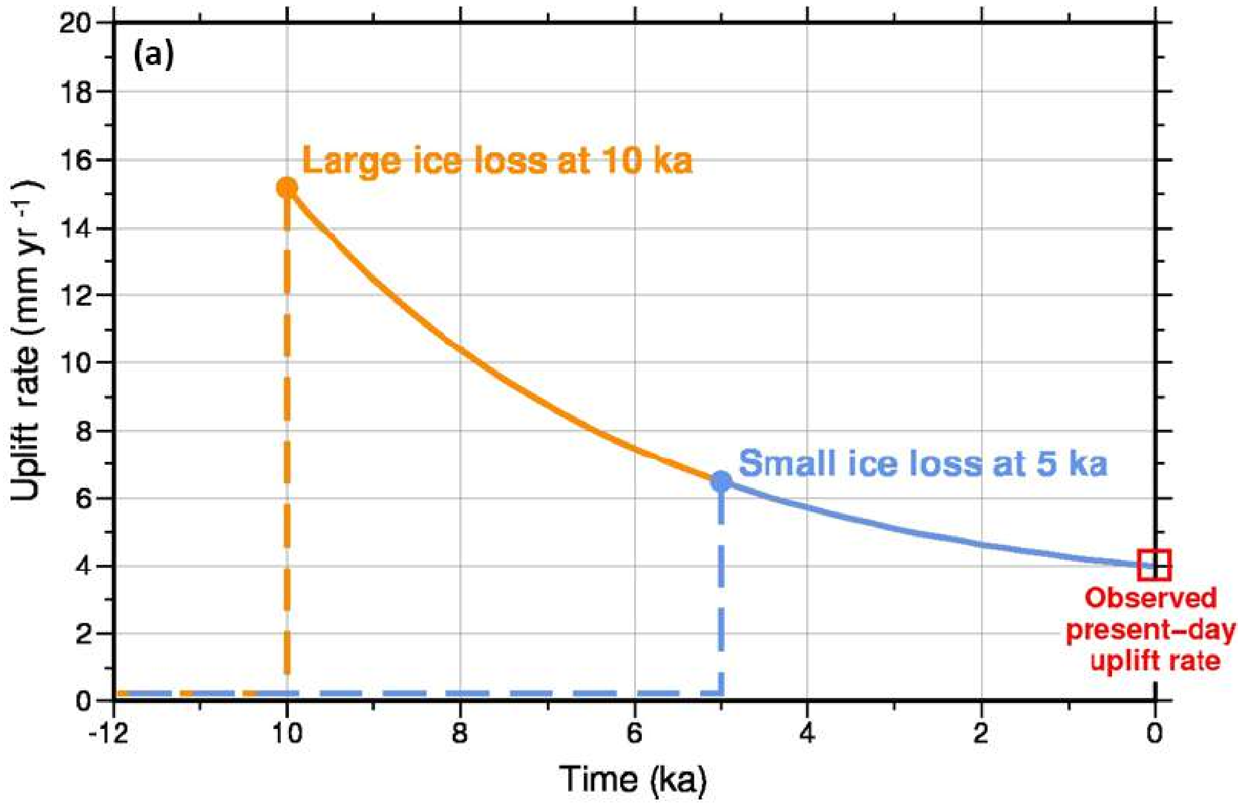
(Vestøl et al. 2019)

NKG_RF17VEL

3D velocity model (Häkli et al. 2019)



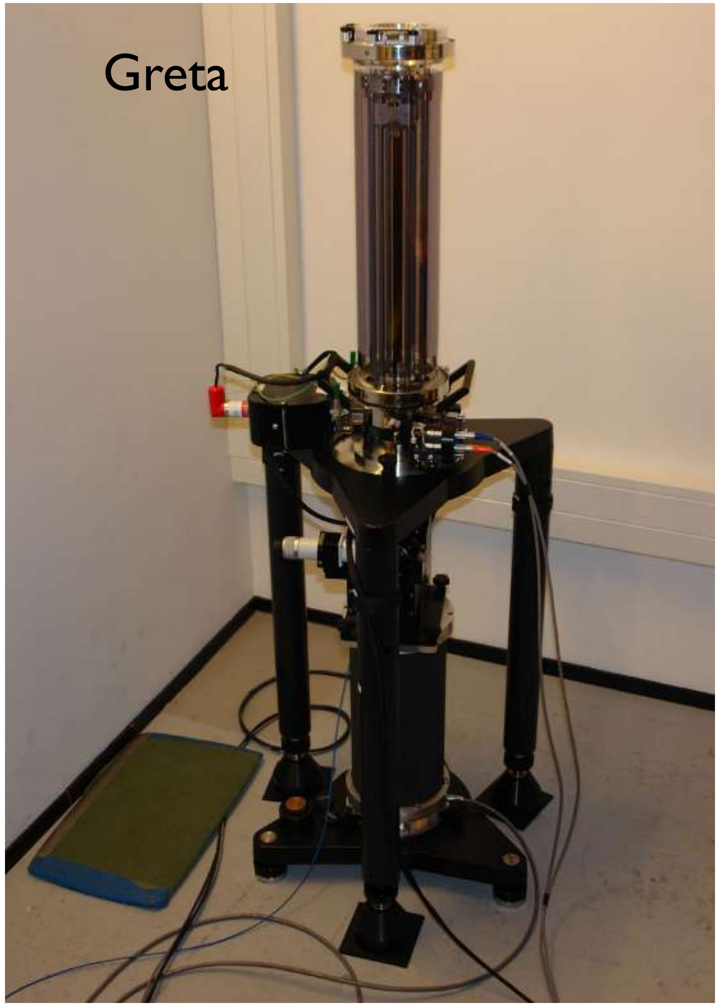
ONE RATE - DIFFERENT SOURCES

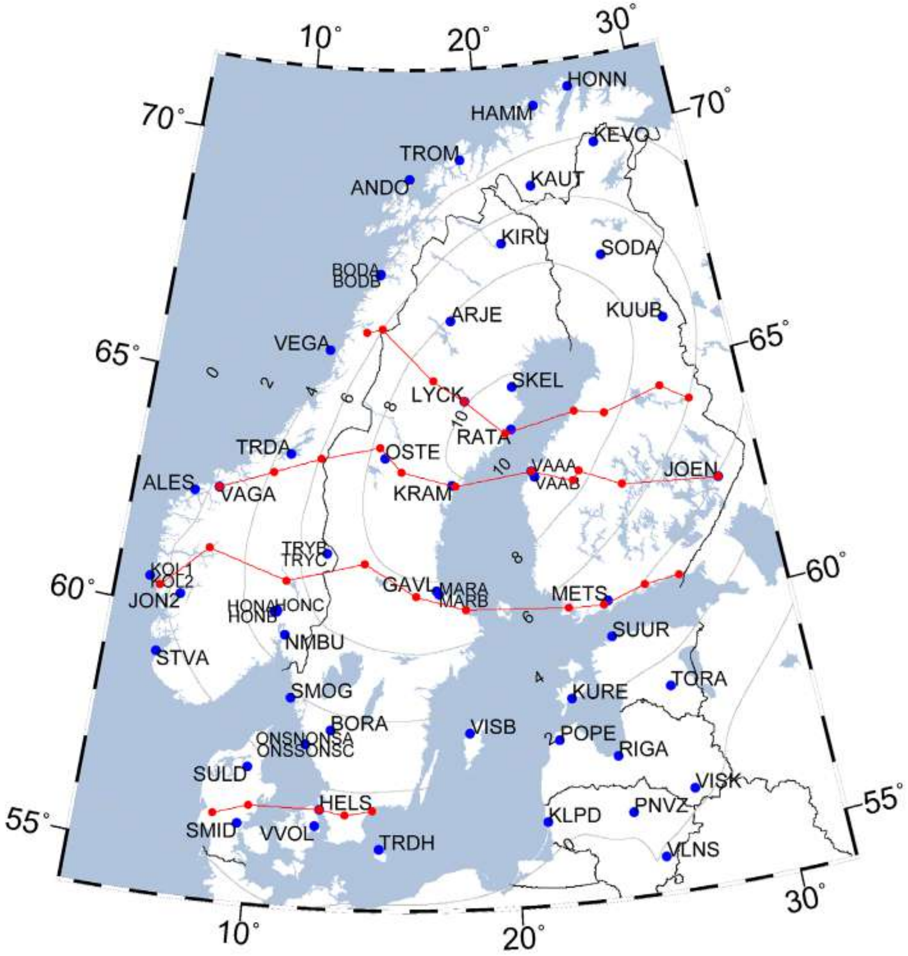


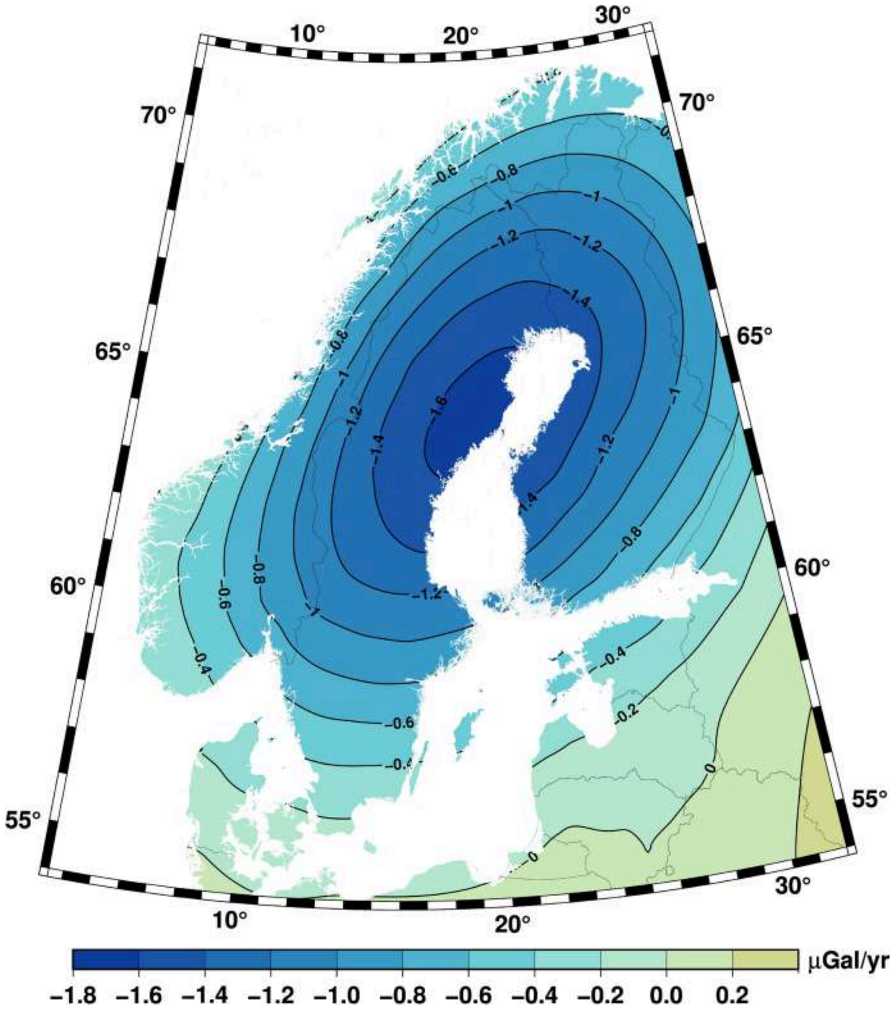
(Whitehouse, 2018)

ABSOLUTE GRAVITY OBSERVATIONS IN FENNOSCANDIA

FG5X-233 from Lantmäteriet



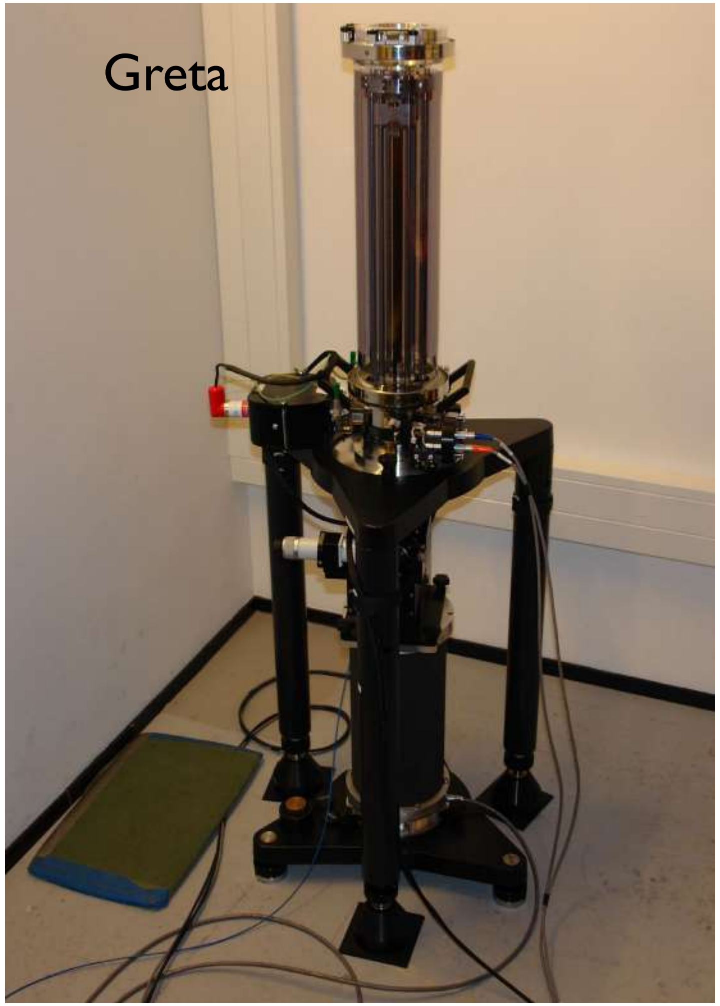


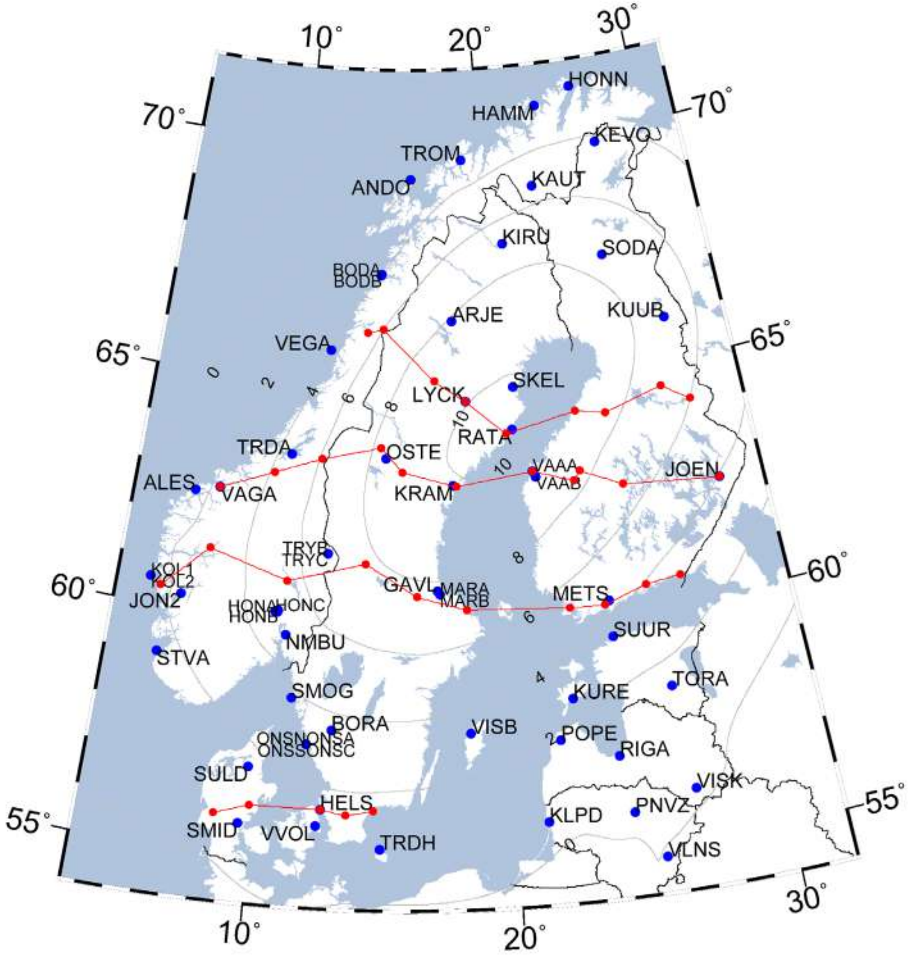


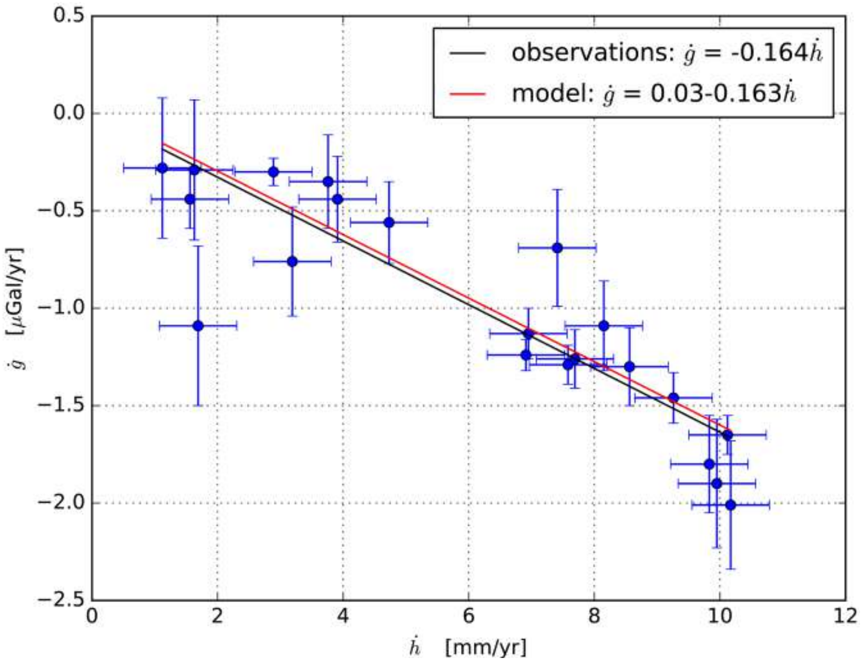
(Olsson et al. 2019)

ABSOLUTE GRAVITY OBSERVATIONS IN FENNOSCANDIA

FG5X-233 from Lantmäteriet

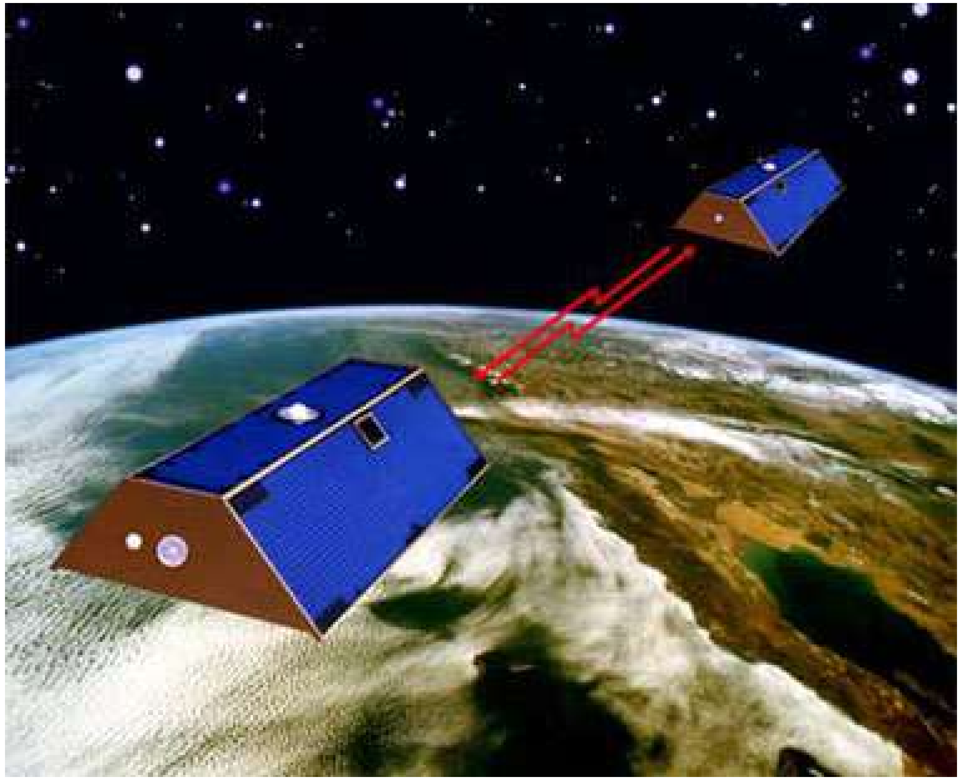


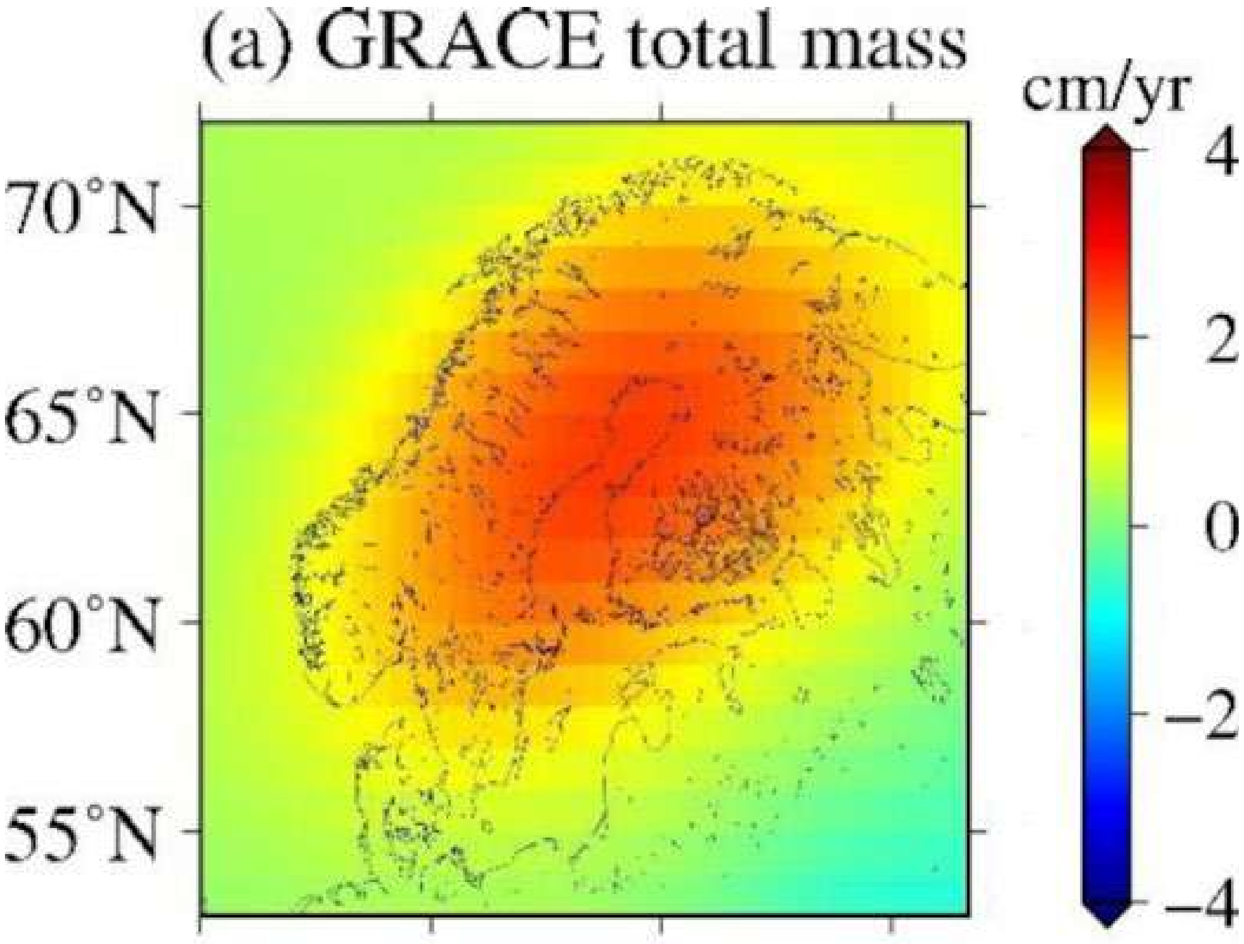




(Olsson et al. 2019)

GRACE RESULT



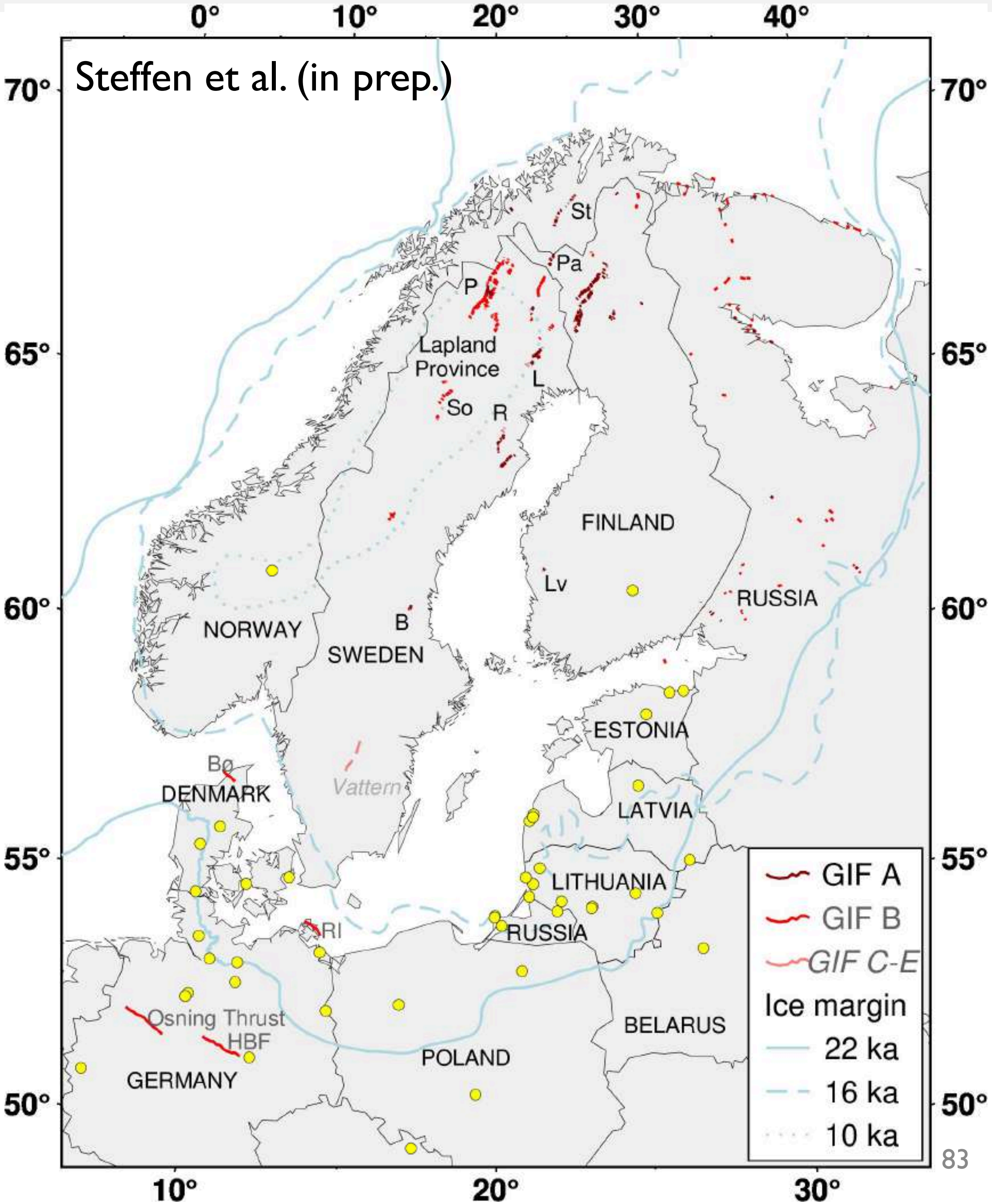


GFZ RL06, 300 km Fan filter, d/o 60, 01/2003-12/2016

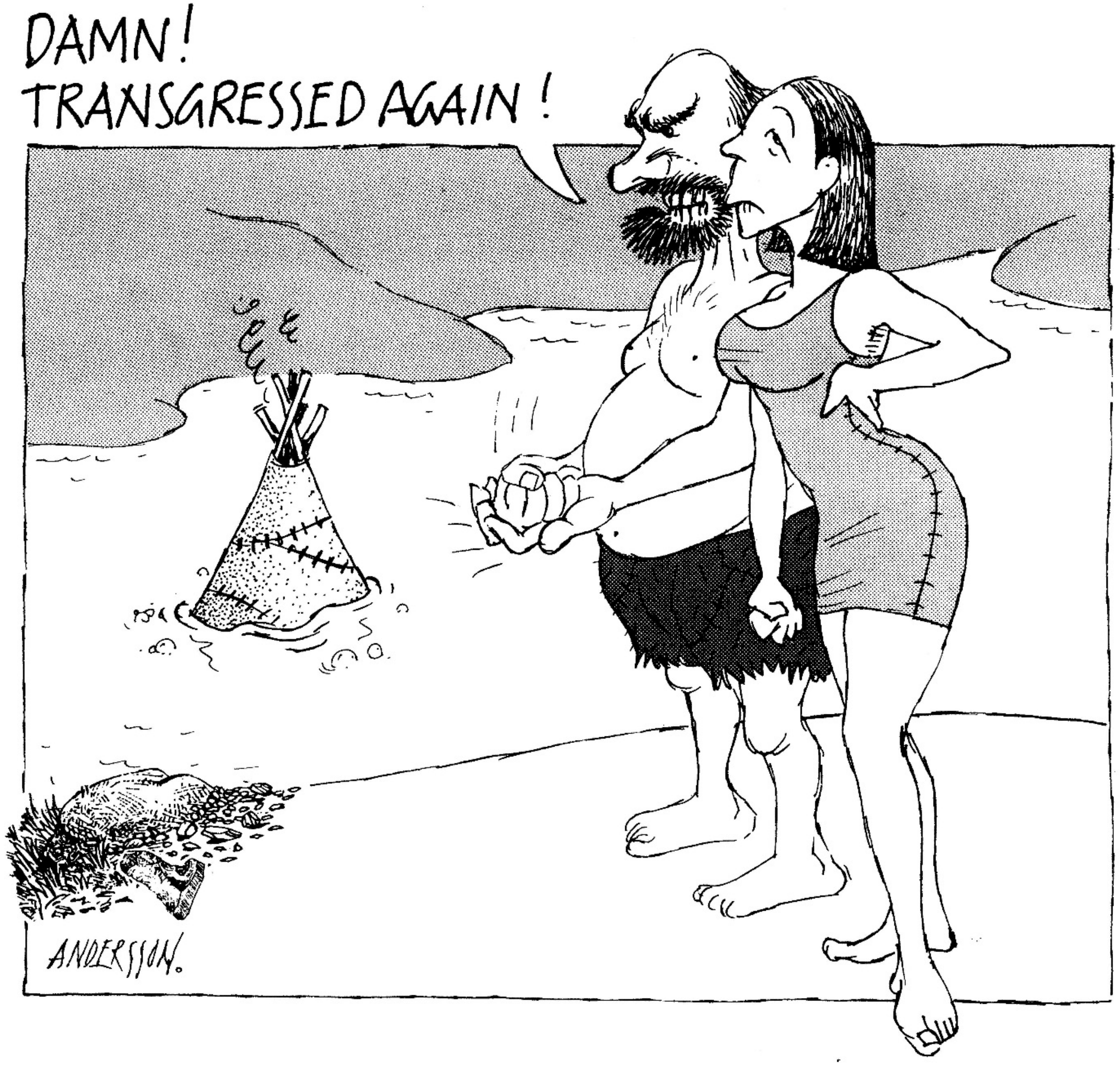
(Jiao et al. 2020)

GIF SITUATION IN NORTHERN EUROPE

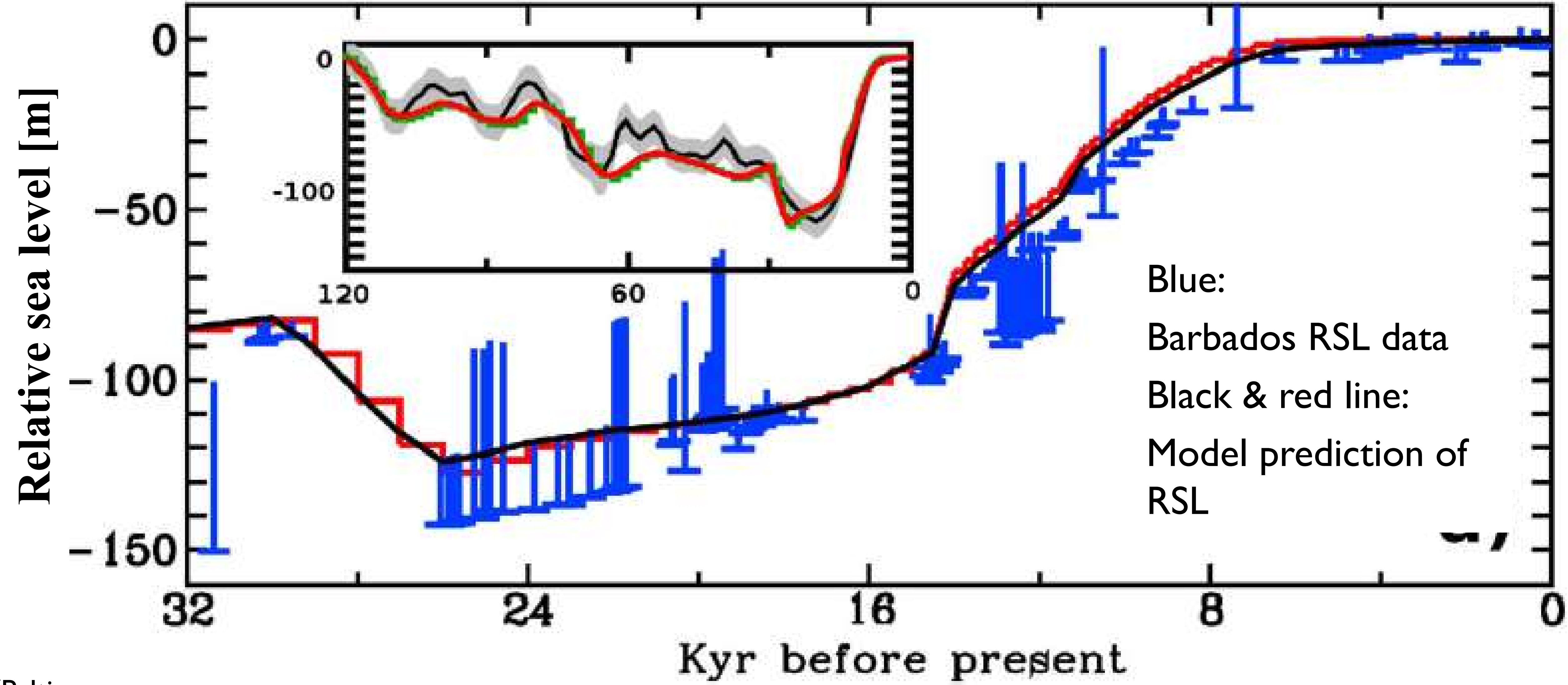
Photo credit: Tobias Bauer (LTU)



RELATIVE SEA LEVEL



SEA LEVEL IN THE LAST 32,000 YEARS – MANY CHANGES



Blue:

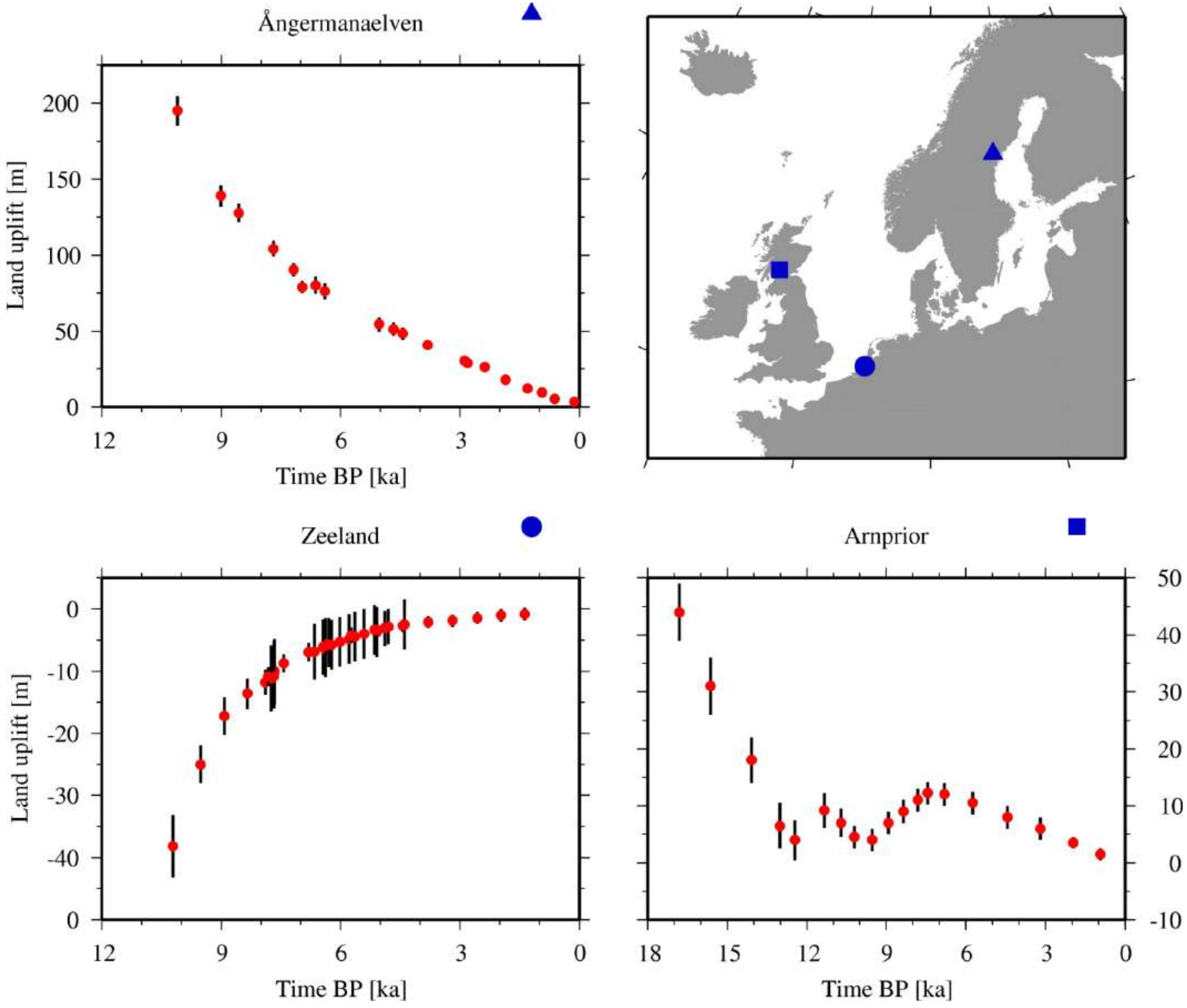
Barbados RSL data

Black & red line:

Model prediction of RSL

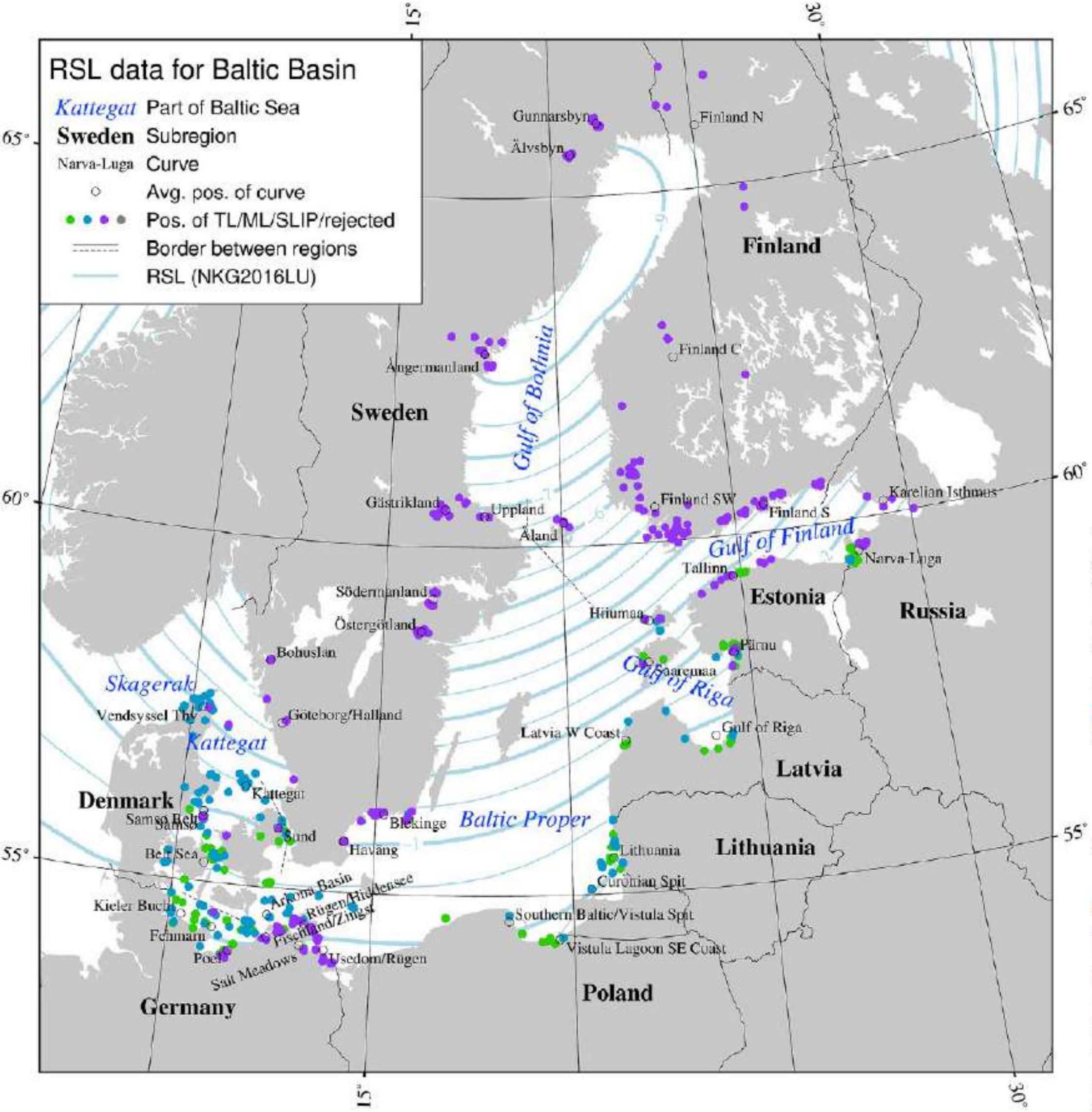
(Peltier et al., 2015)

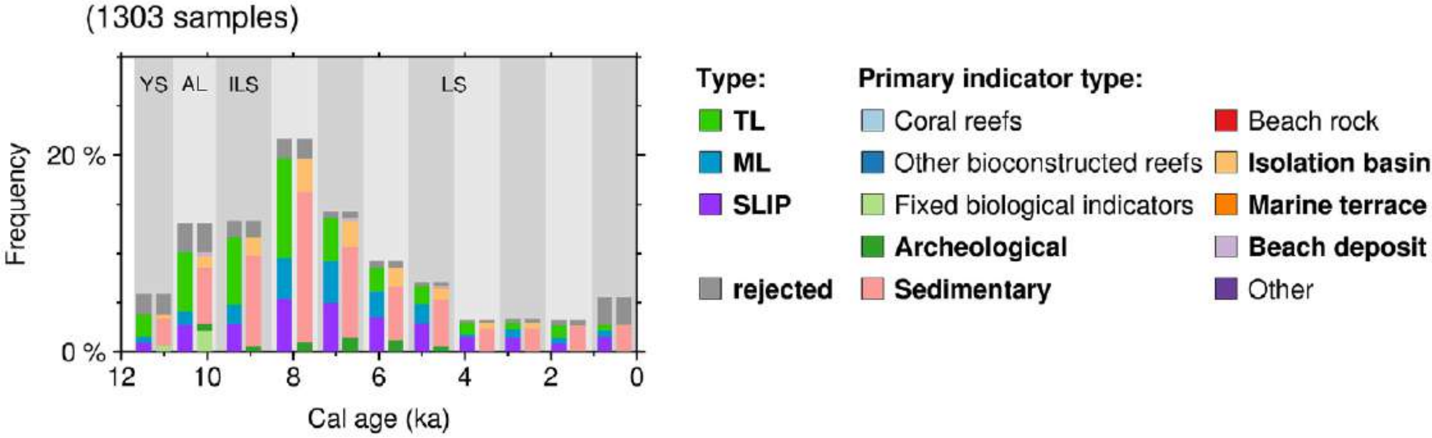
RELATIVE SEA-LEVEL DATA IN EUROPE



(Steffen & Wu 2011)

RSL DATABASE FOR THE BALTIC SEA





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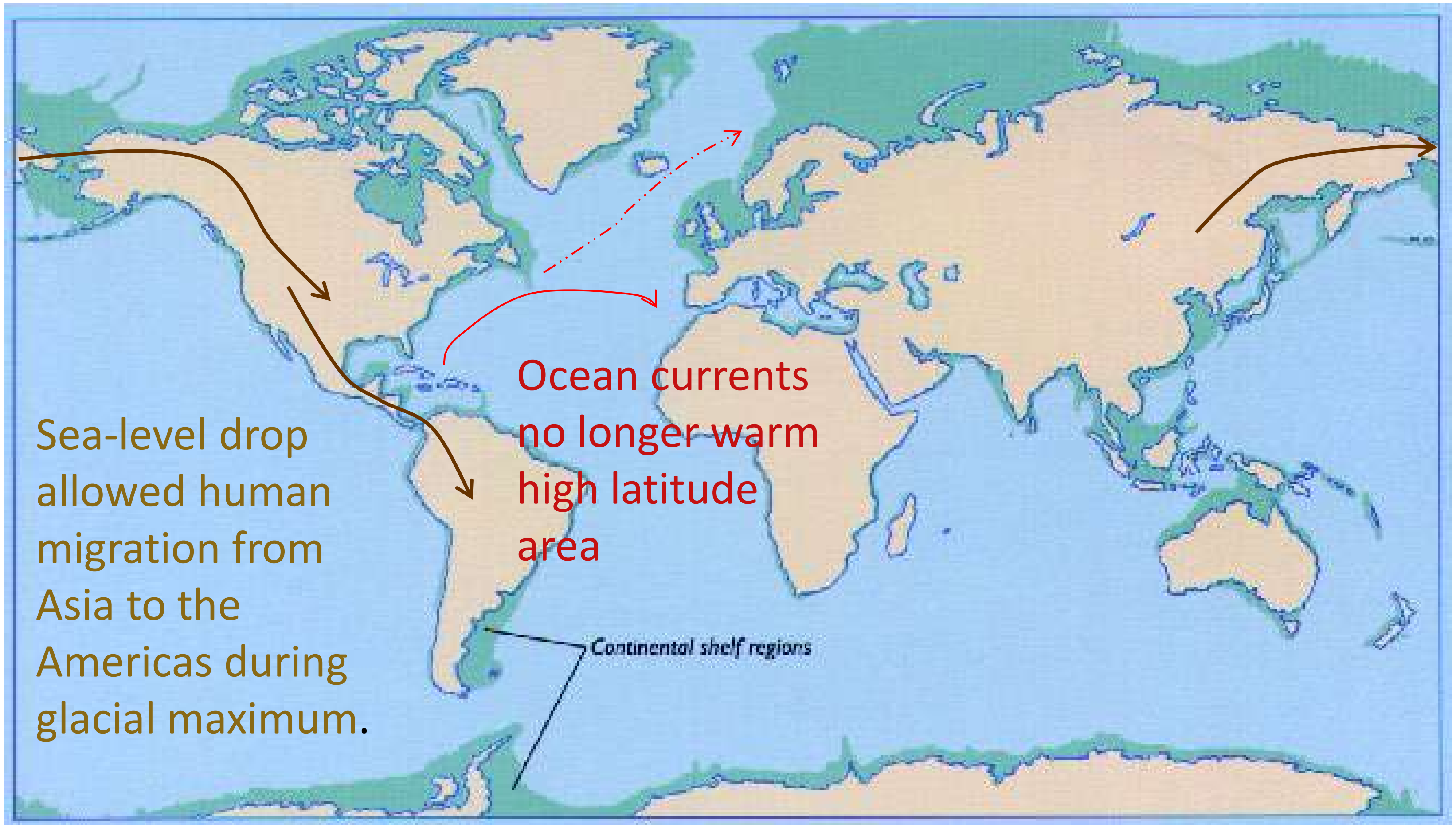
A Holocene relative sea-level database for the Baltic Sea

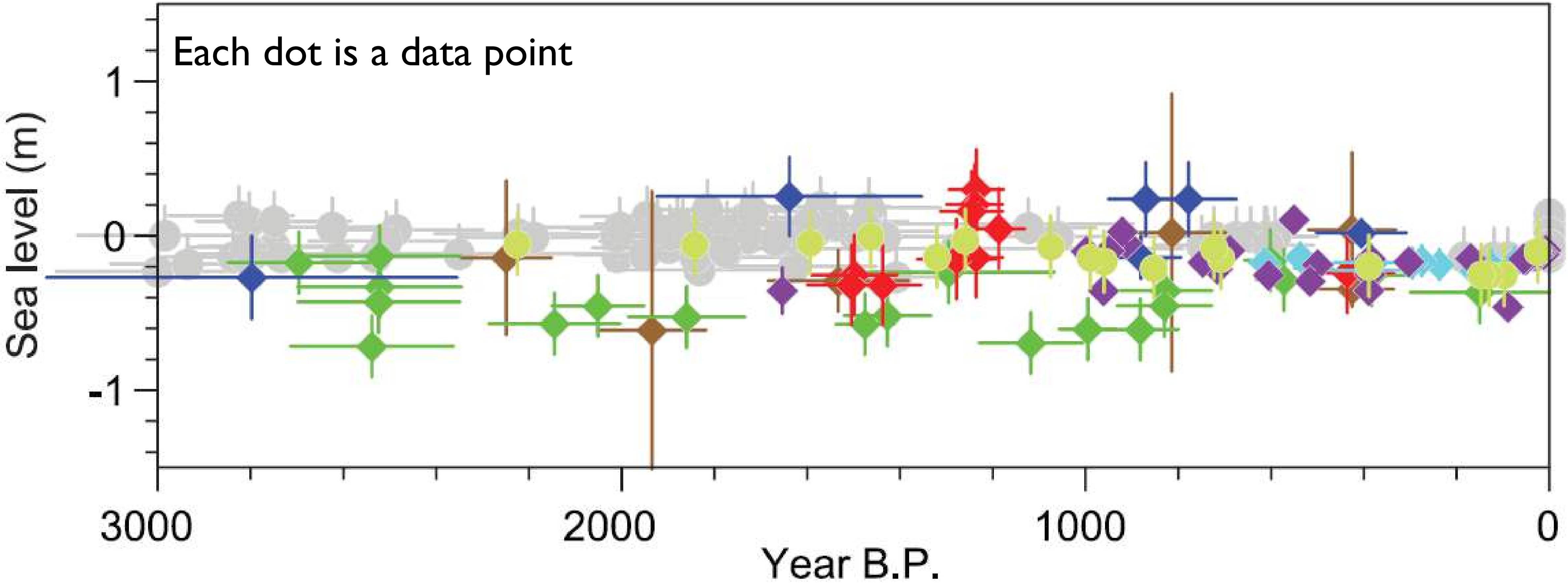
Alar Rosentau [a, *], Volker Klemann [b], Ole Bennike [c], Holger Steffen [d], Jasmin Wehr [e], Milena Latinović [b], Meike Bagge [b], Antti Ojala [f, g], Mikael Berglund [h], Gustaf Peterson Becher [i, j], Kristian Schoning [i], Anton Hansson [k], Lars Nielsen [l], Lars B. Clemmensen [l], Mikkel U. Hede [l, m], Aart Kroon [l], Morten Pejrup [l], Lasse Sander [l, n], Karl Stattegger [o], Klaus Schwarzer [o], Reinhard Lampe [p], Matthias Lampe [q], Szymon Uścinowicz [r], Albertas Bitinas [s], Ieva Grudzinska [t], Jüri Vassiljev [u], Triine Nirgi [a], Yuriy Kublitskiy [v], Dmitry Subetto [v, w, x]

SEA-LEVEL DROP ALLOWED HUMAN MIGRATION

During the last glacial maximum, global sea level dropped by ~120 m, exposing continental shelves & forming land bridges.

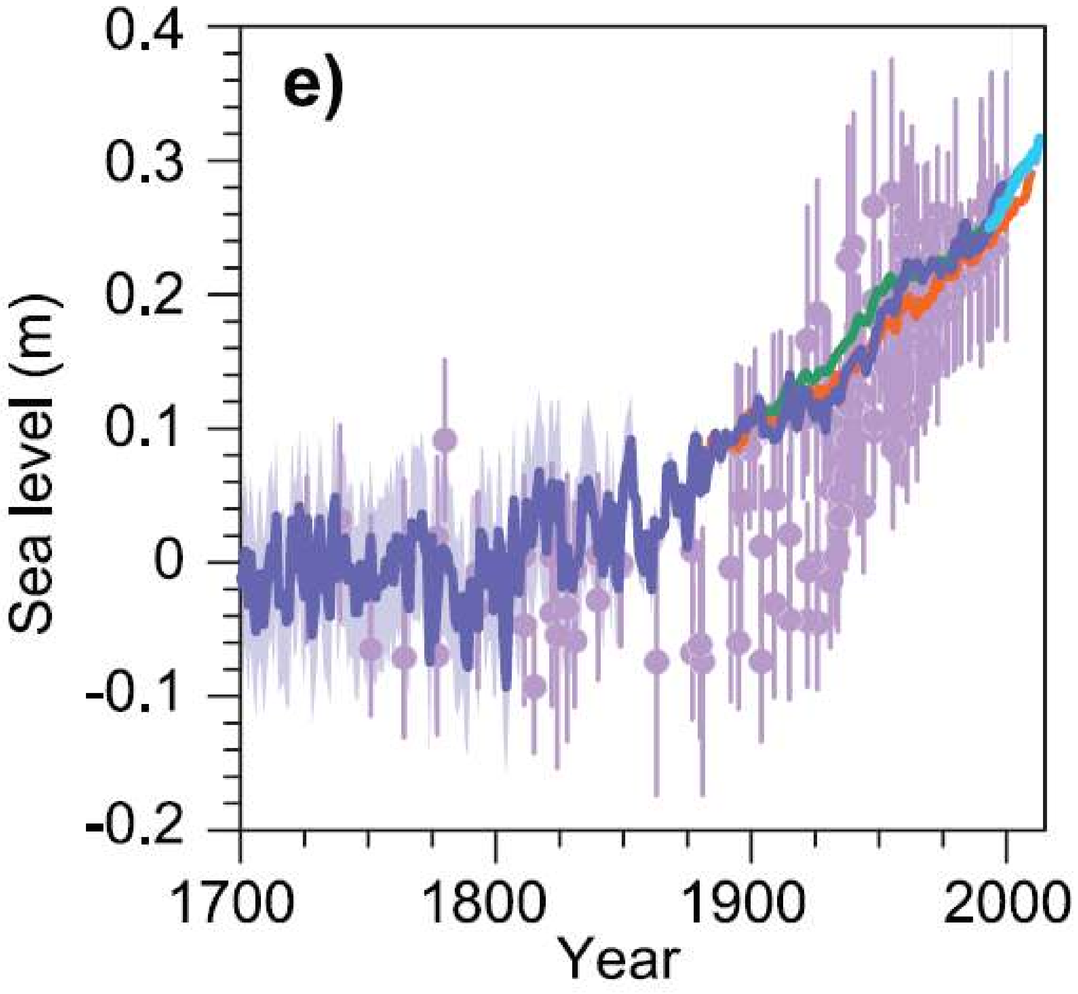


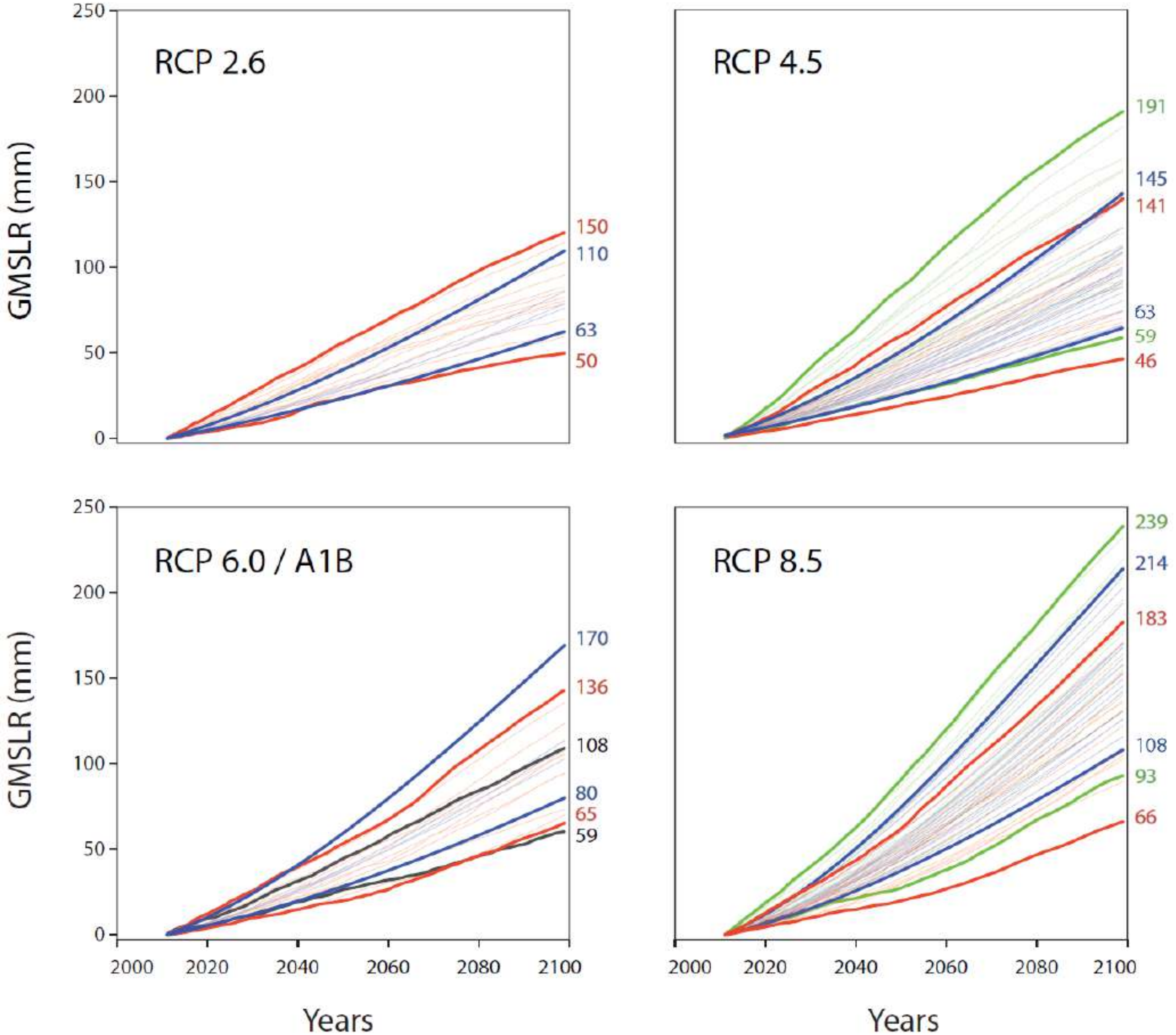
SEA LEVEL IN THE LAST 3000 YEARS – ALMOST NO CHANGE



(Church et al. 2013)

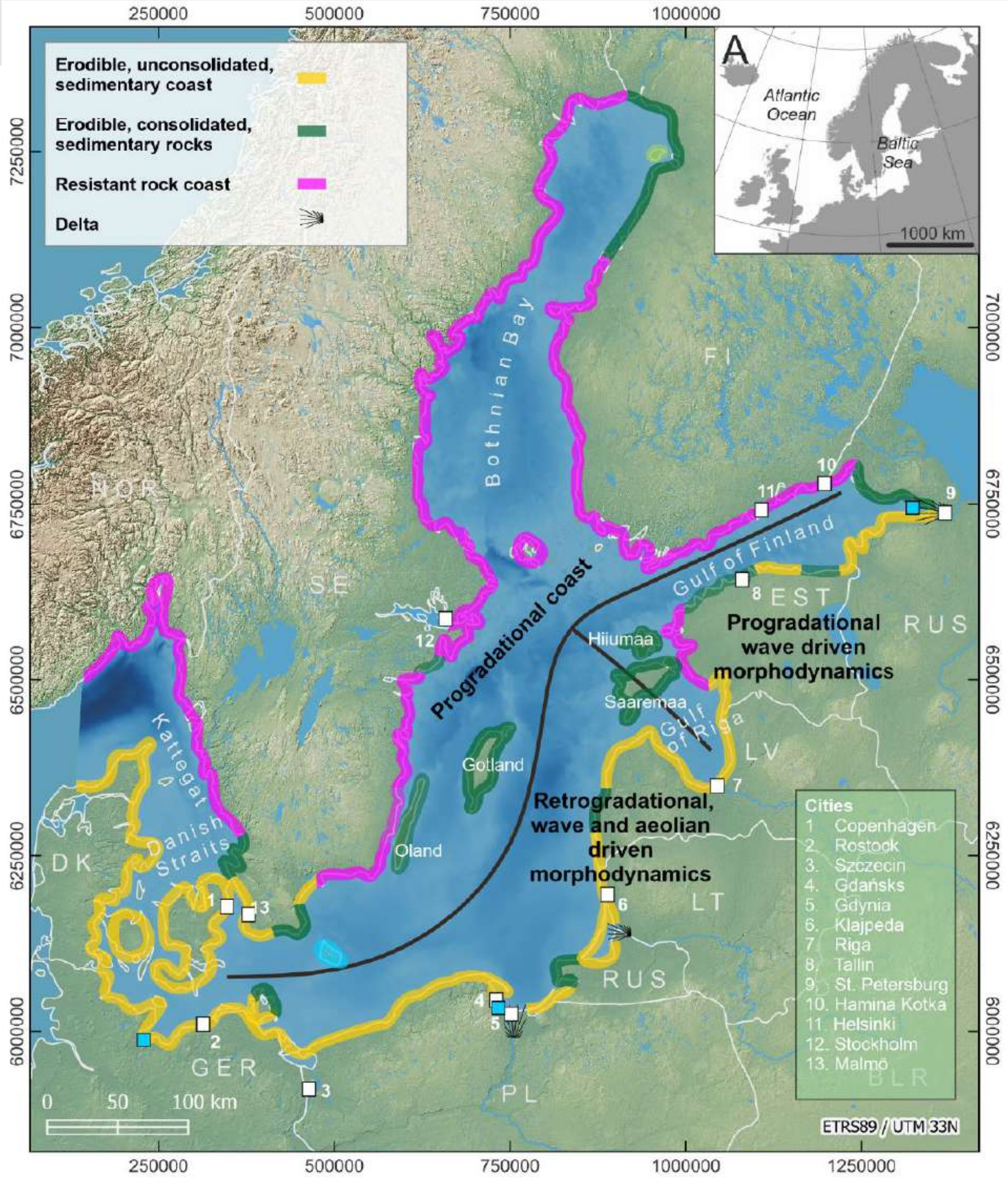
SEA LEVEL IN THE LAST 300 YEARS AND PREDICTION





(Church et al. 2013)

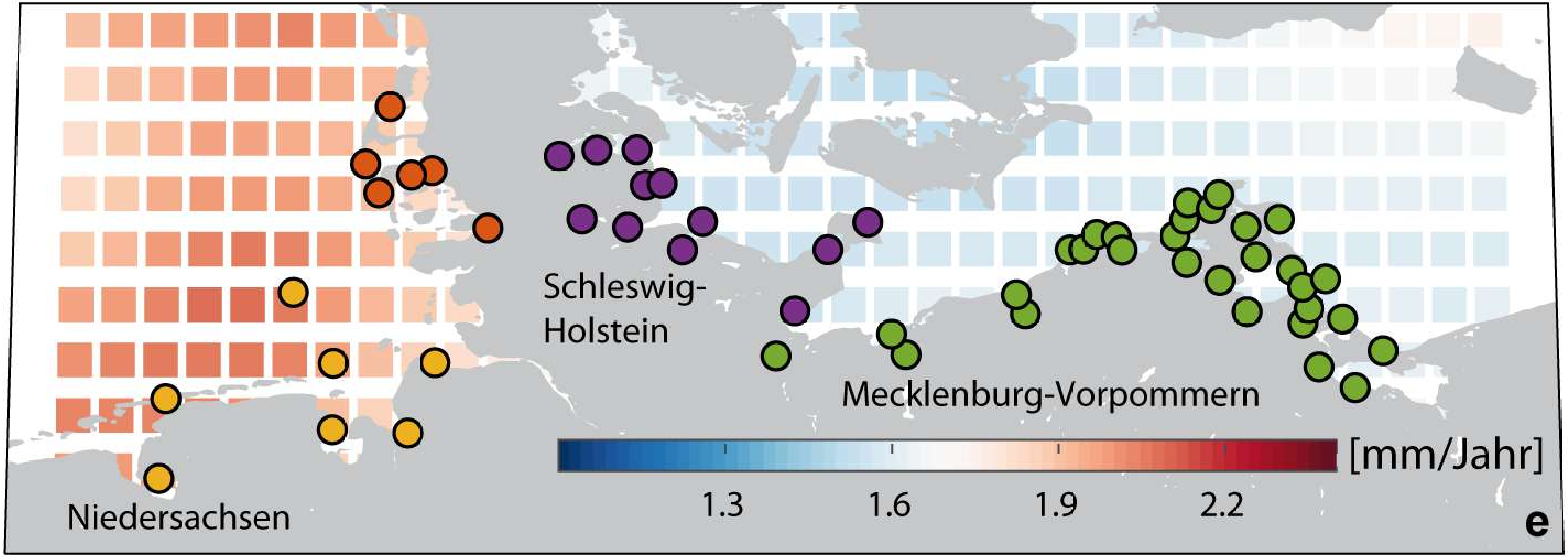
COASTAL TYPES AROUND THE BALTIC SEA



(Leszczynska et al. 2025)

AVERAGE SEA-LEVEL RISE IN RECENT YEARS

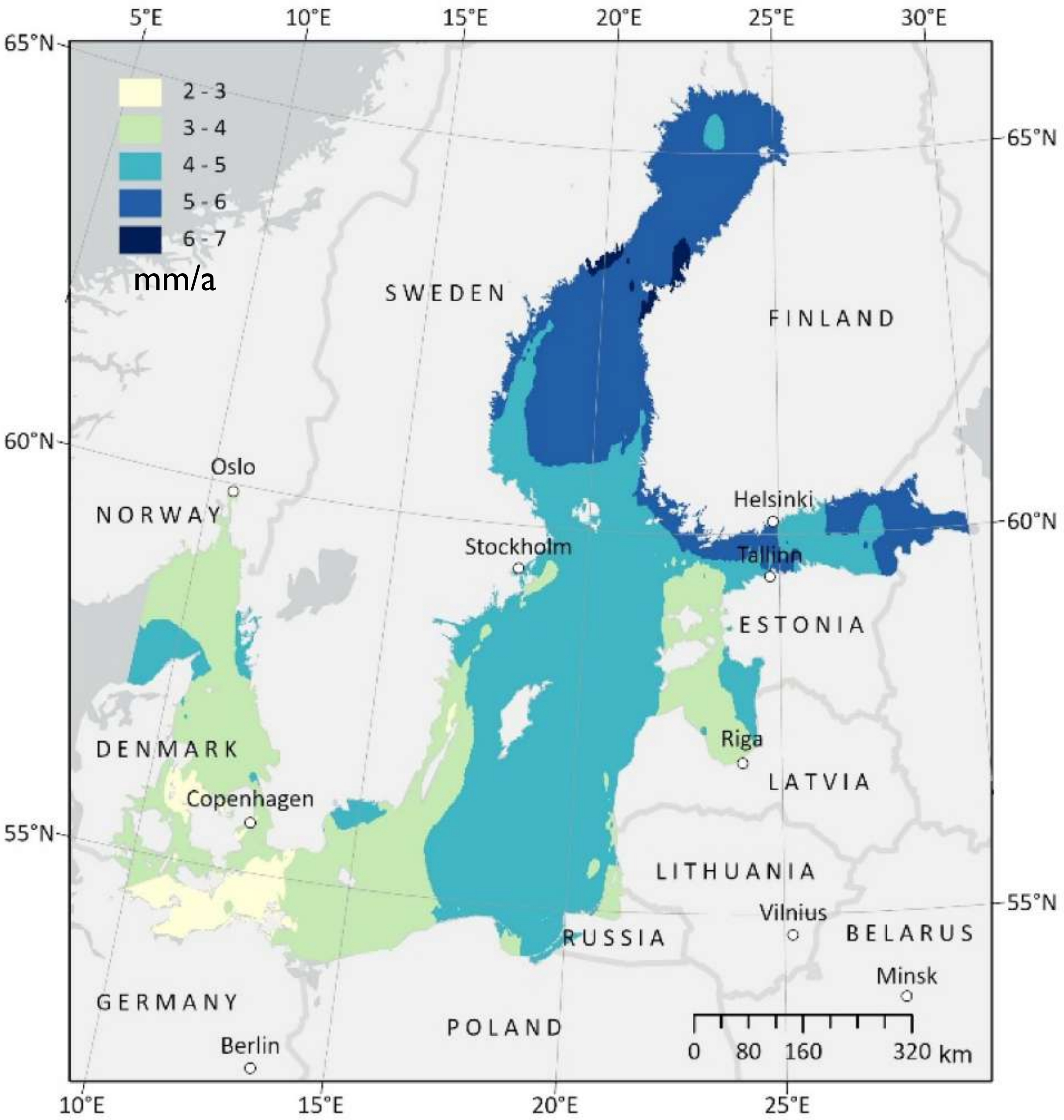
Average sea-level rise at the German coasts after correcting GIA effects with NKG2016LU



(Dangendorf et al., 2022)

ABSOLUTE SEA-LEVEL RISE

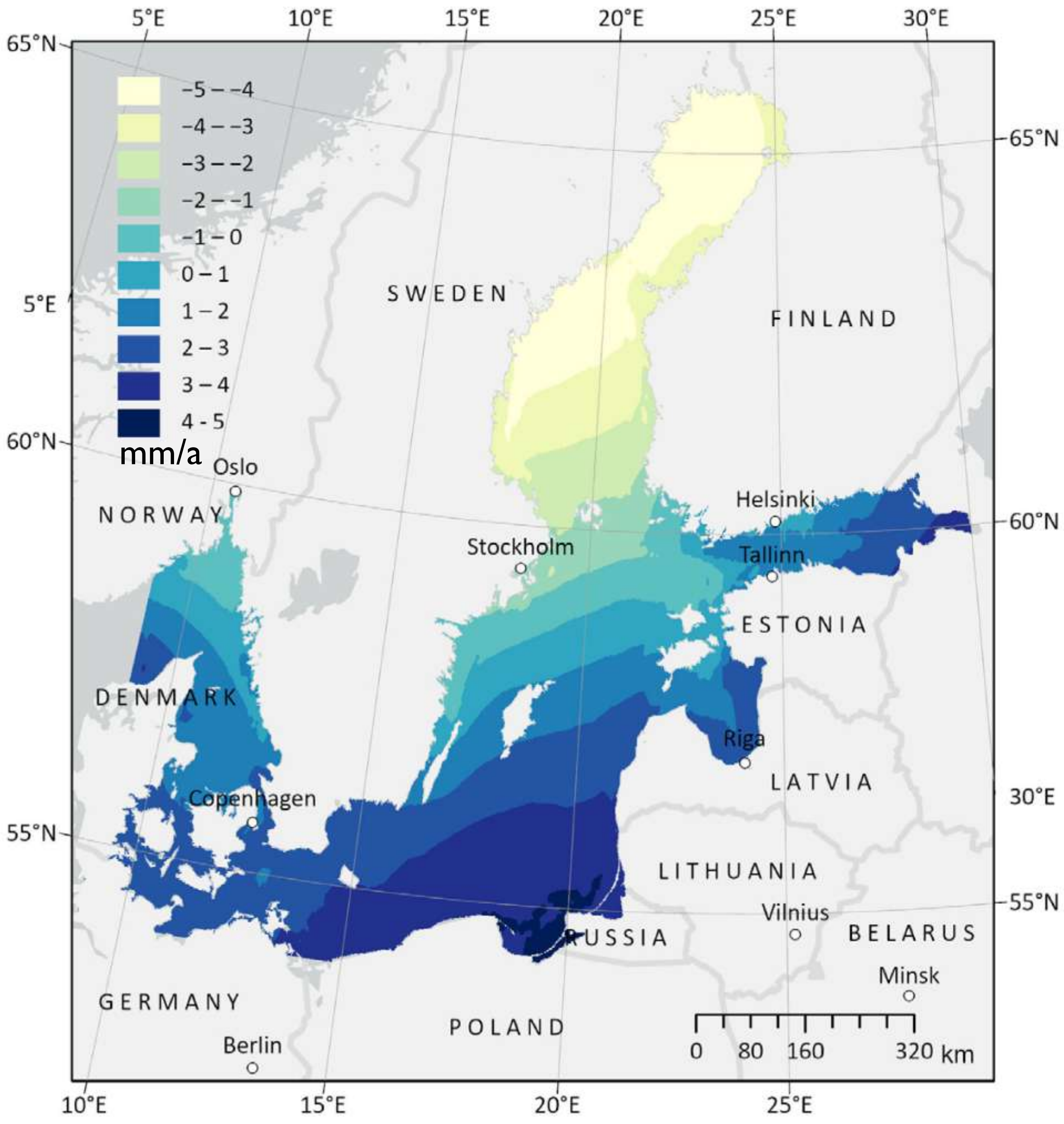
From 1995 to 2019 in the Baltic Sea according to ESA's BalticSEAL data



(Kapsi et al. 2023)

RELATIVE SEA-LEVEL RISE

From 1995 to 2019 in the Baltic Sea according to ESA's BalticSEAL data minus NKG2016LU



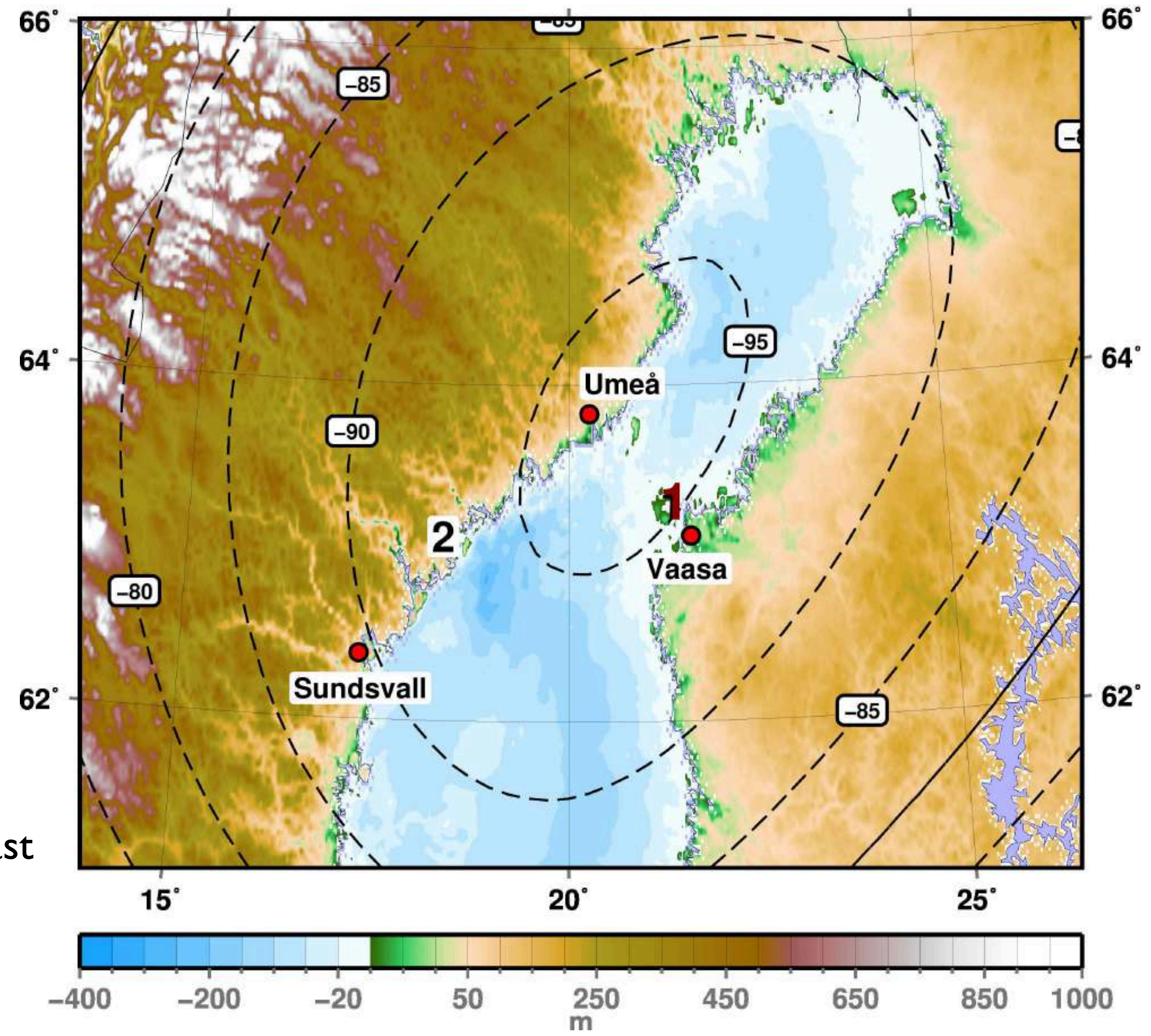
(Kapsi et al. 2023)

THE REMAINING UPLIFT

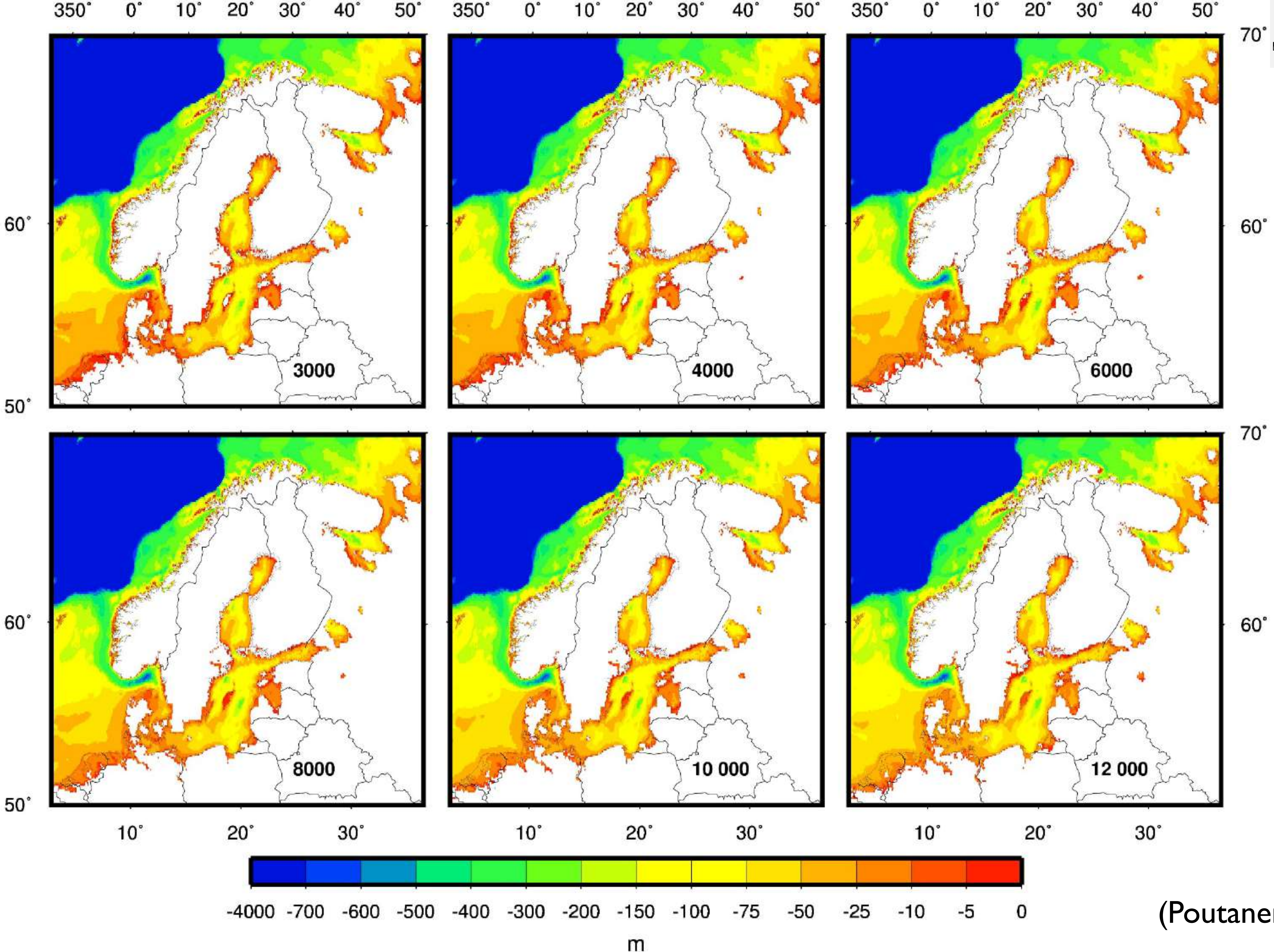
A maximum of **90-130 m** is predicted with the most reliable GIA models

Some geologists would like to have more than **200 m**!

(Poutanen & Steffen, 2014)



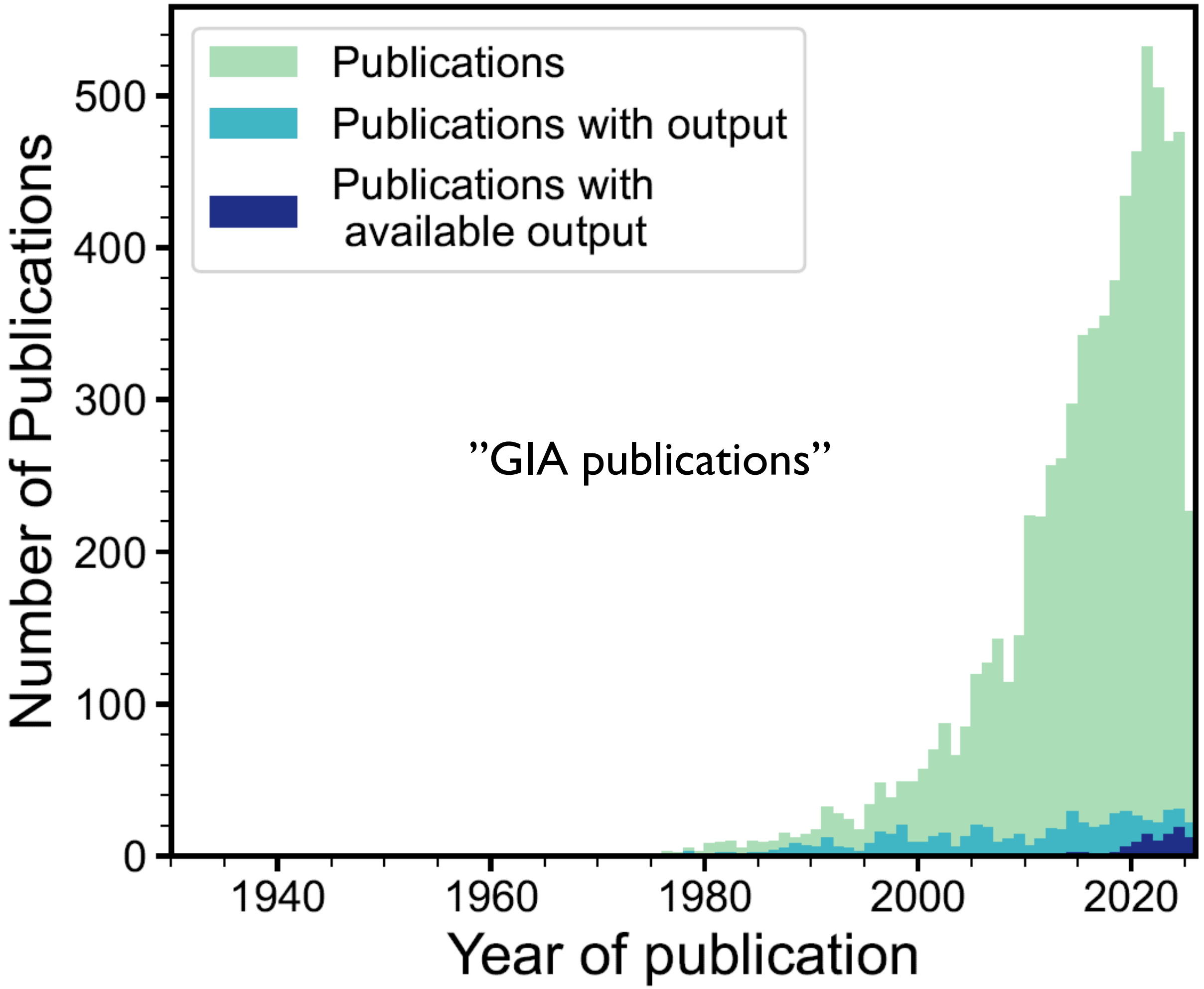
1 Kvarken
2 High Coast

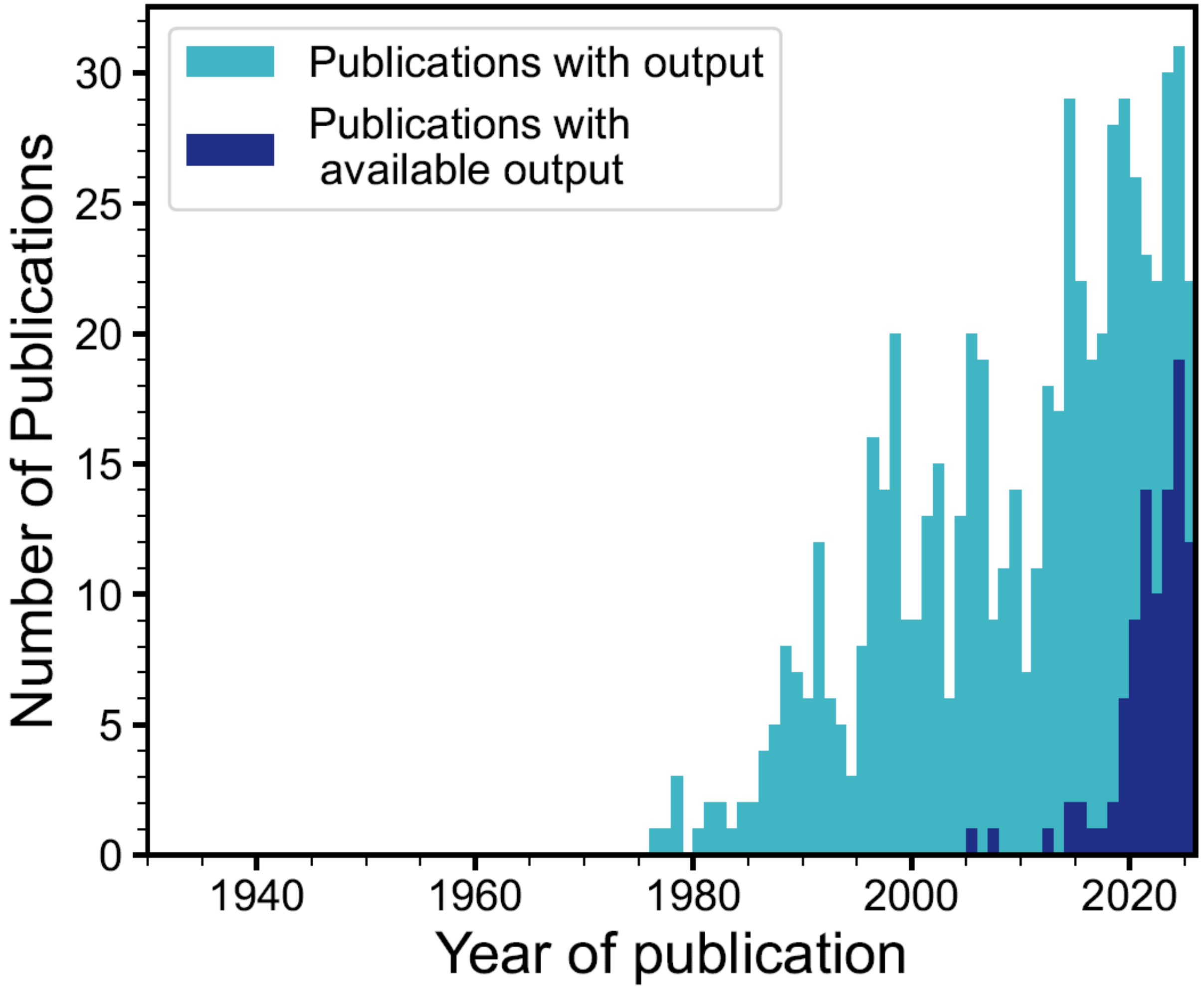


LANTMÄTERIET

(Poutanen & Steffen, 2014)

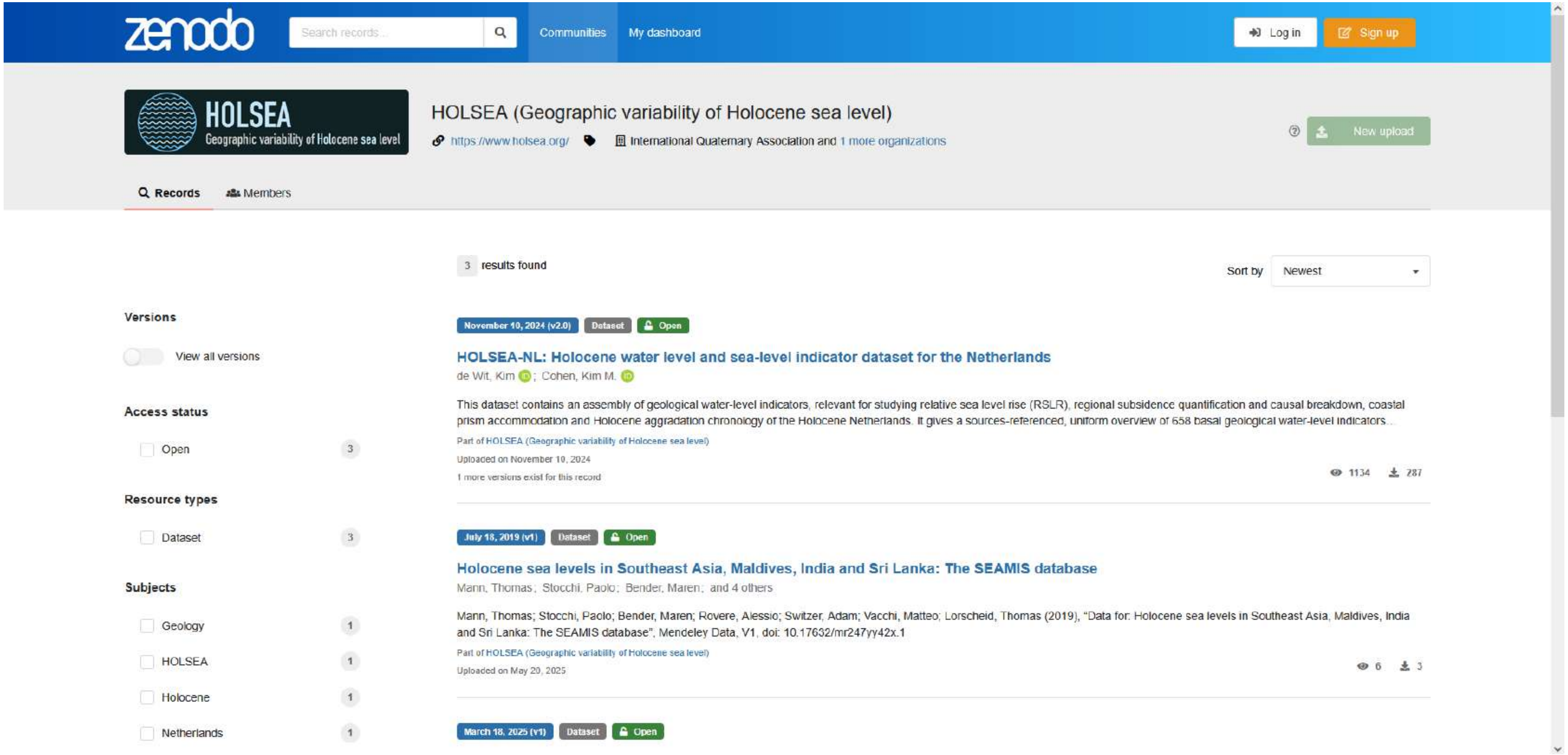
FORTHCOMING: GIAMACHINE





http://ghubgiamachine.uc.r.appspot.com/

FORTHCOMING: HOLSEA COMMUNITY ON ZENODO



https://zenodo.org/communities/holsea/records