Lecture course on

Sea level variations and global geodynamics

Charles University in Prague

November 7–11, 2011

Department of Geophysics

V Holešovičkách 2 (12th floor)

Prague 8

Giorgio Spada

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Urbino University "Carlo Bo"

Urbino, Italy

last revised november 7 2011

Lecture course on

Sea level variations and global geodynamics
November 7–11, 2011

1. Introductory notes about sea level and geodynamics
(November 7, start 12:20)

2. Loading problems and rheological models
(November 8, start 12:20)

3. The sea level equation, theory and applications
(November 9, start 13:10)

4. Secular sea level variations
(November 10, start 15:40)

5. Greenland uplift and regional sea level changes
(November 11, start 10:40)

Approximate length of a lecture: 2 hours

Lecture course on

Sea level variations and global geodynamics

Prague, November 7–11, 2011

General "philosophy" of these lectures:

classical topics (e.g., *the sea level equation*),
special topics (e.g., "*new*" *techniques of Laplace inversion*).
work in progress (e.g., *Greenland, etc.*), ...
...
a basic knowledge of SE geophysics and
math-phys is assumed
technical issues are minimized in the discussion
Questions and discussions are encouraged

Lecture course on

Sea level variations and global geodynamics

1. Introductory notes about sea level and geodynamics

(November 7, start 12:20)

Giorgio Spada

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Charles University in Prague, Department of Geophysics

November 7–11, 2011

Outline

Discussion of (and speculations on) sea level variations observed during the last 21,000 yrs (the LGM) and at present time

Stress on variability, extent, global character - but regional importance - of sea-level variations.

Is it possible to explain the spatio-temporal variability of sea level change by a simple law? (in spite of apparent complexity)
Does an "equation for sea level" exist?

Theory ("the equation") vs Holocene RSL observations: are they compatible?

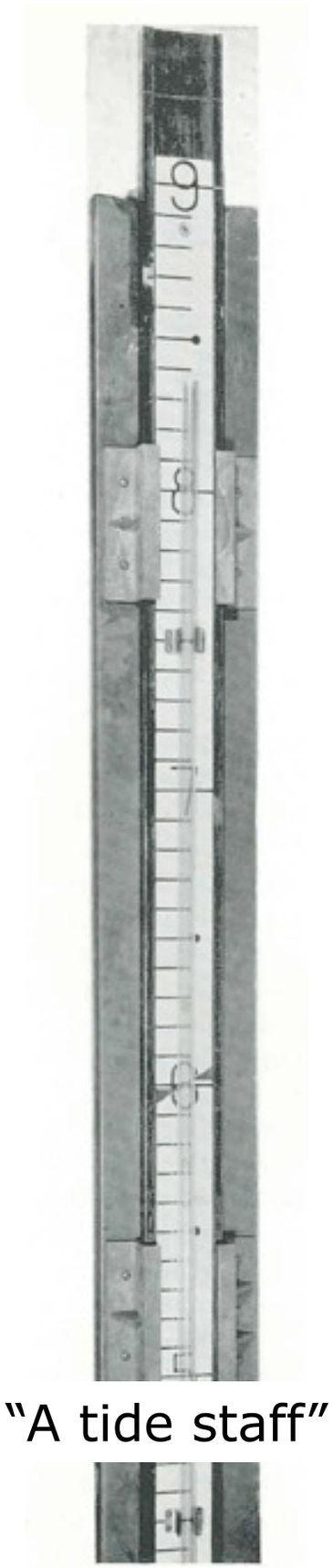
Sea level change during the era of "global warming" and a look into the future

is sea level *rising* or *falling* currently?

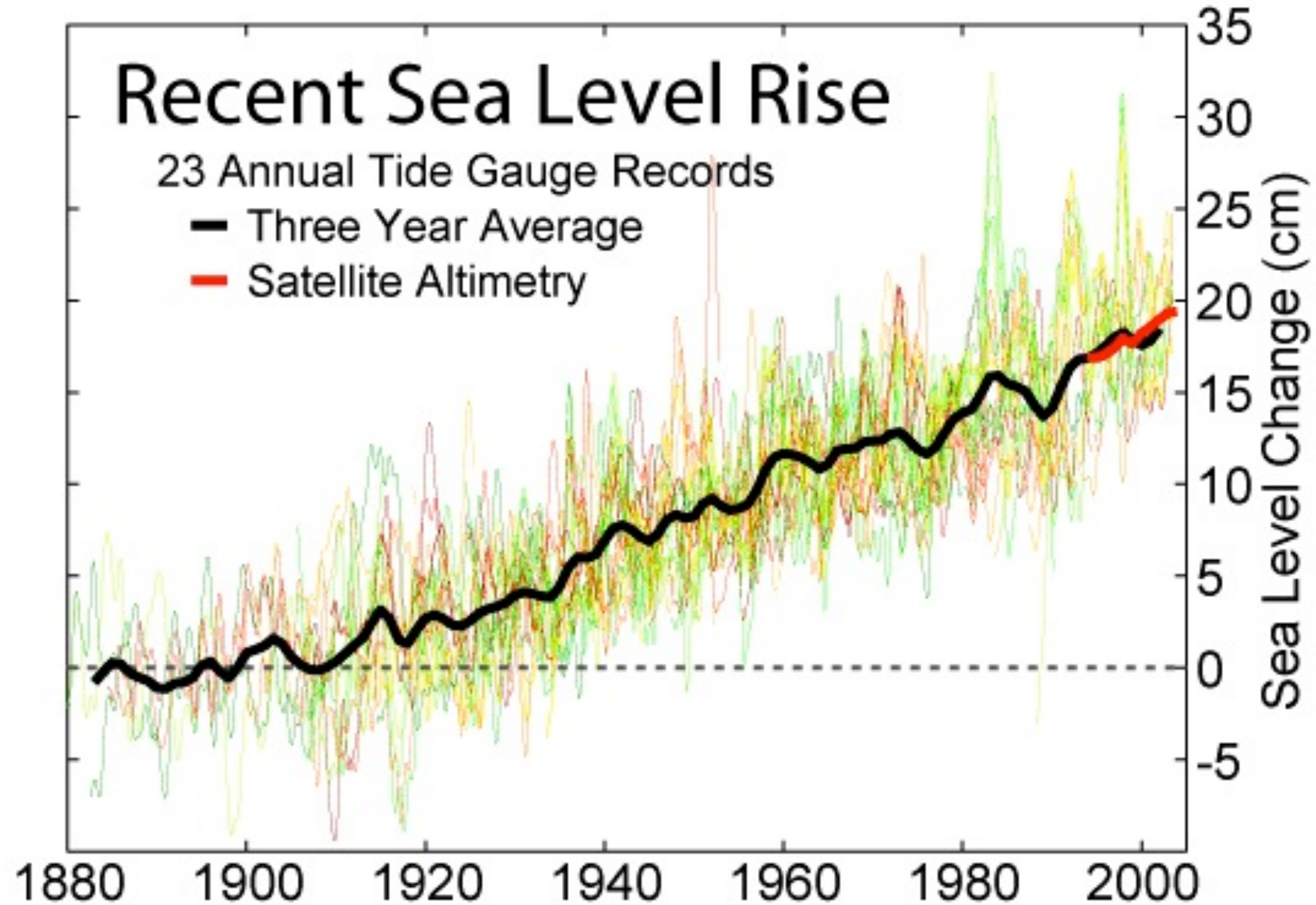
(a major environmental problem indeed)

Sea level rise from tide gauges

"viewpoint of the solid Earth"



"A tide staff"

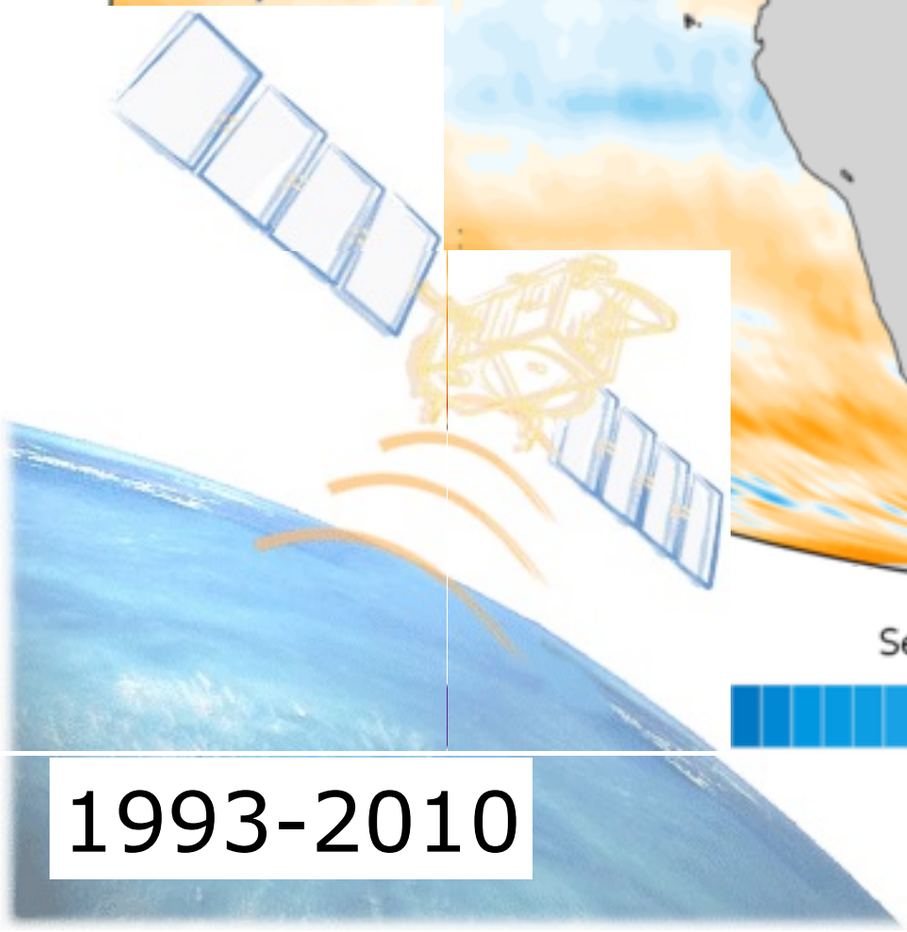


Rate is ~ 20 cm/century

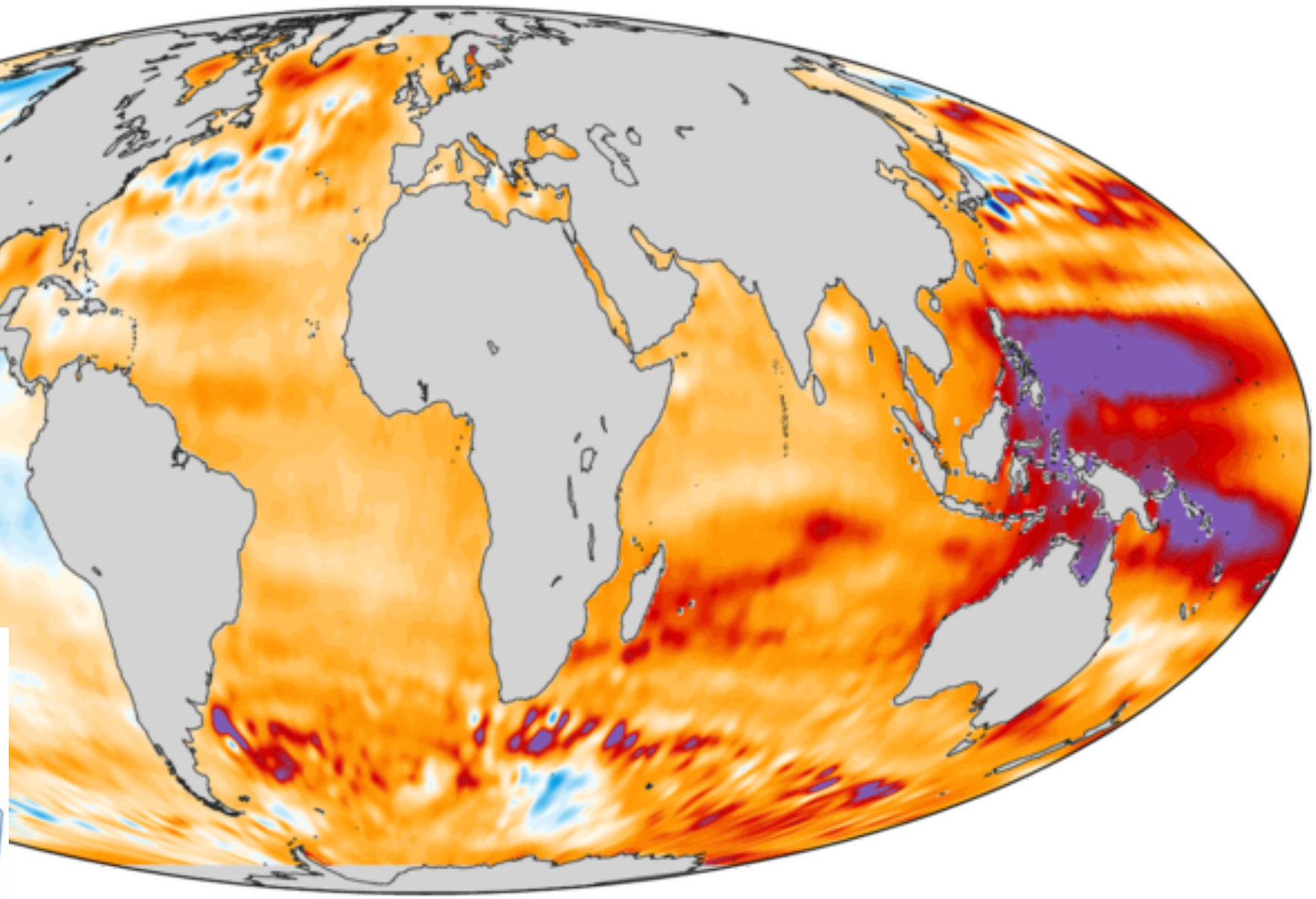
Sea Level rise between 1993 and 2010 by satellite ALTIMETRY

Sea level is rising (by altimetry)

"viewpoint of space"



1993-2010



<ipedia.org/wiki/File:NOAA_sea_level_trend_1993_2010.png

Sea level will be rising (IPCC scenarios)

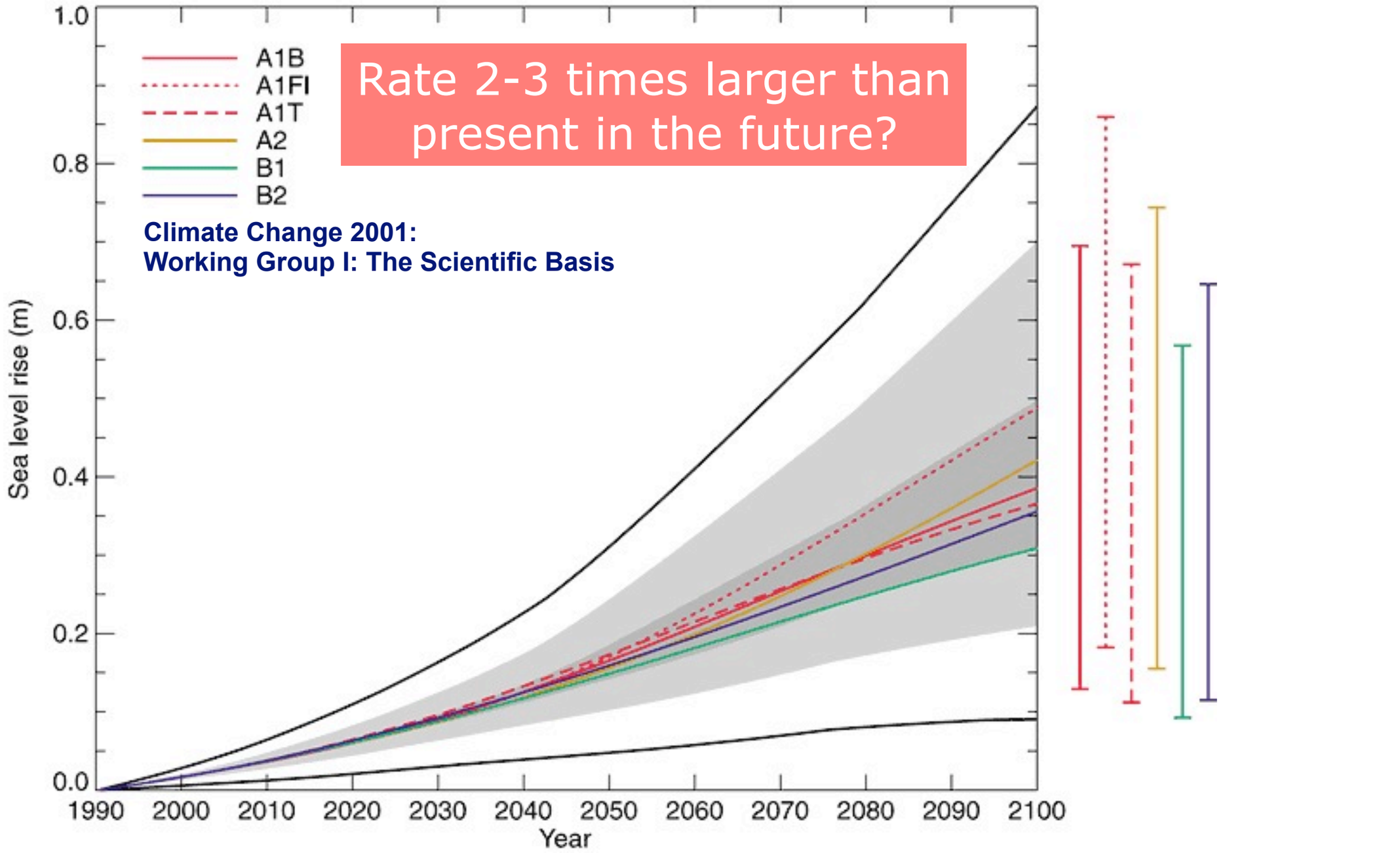


Figure 11.12: *Global average sea level rise 1990 to 2100 for the SRES scenarios. Thermal expansion and land ice changes were calculated using a simple climate model calibrated separately for each of seven AOGCMs, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate change were added. Each of the six lines appearing in the key is the average of AOGCMs for one of the six illustrative scenarios. The region in dark shading shows the range of the average of AOGCMs for all 35 SRES scenarios. The region in light shading shows the range of all AOGCMs for all 35 scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet. See 11.5.4.3 for a full discussion. The bars show the range in 2100 of all AOGCMs for the six illustrative scenarios*

Coastal zones and sea level rise

C. Day (2004)

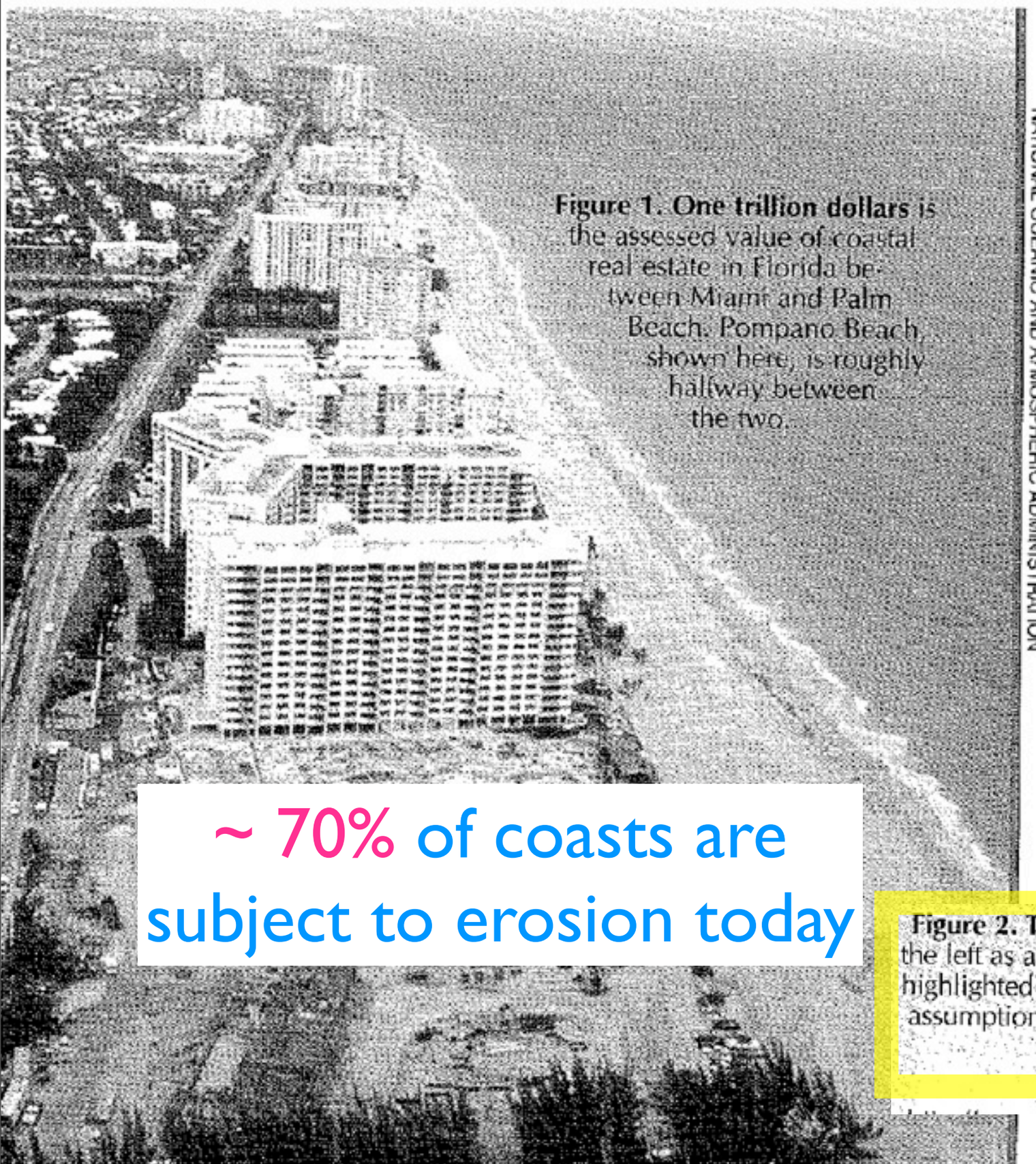


Figure 1. One trillion dollars is the assessed value of coastal real estate in Florida between Miami and Palm Beach. Pompano Beach, shown here, is roughly halfway between the two.

~ 70% of coasts are subject to erosion today

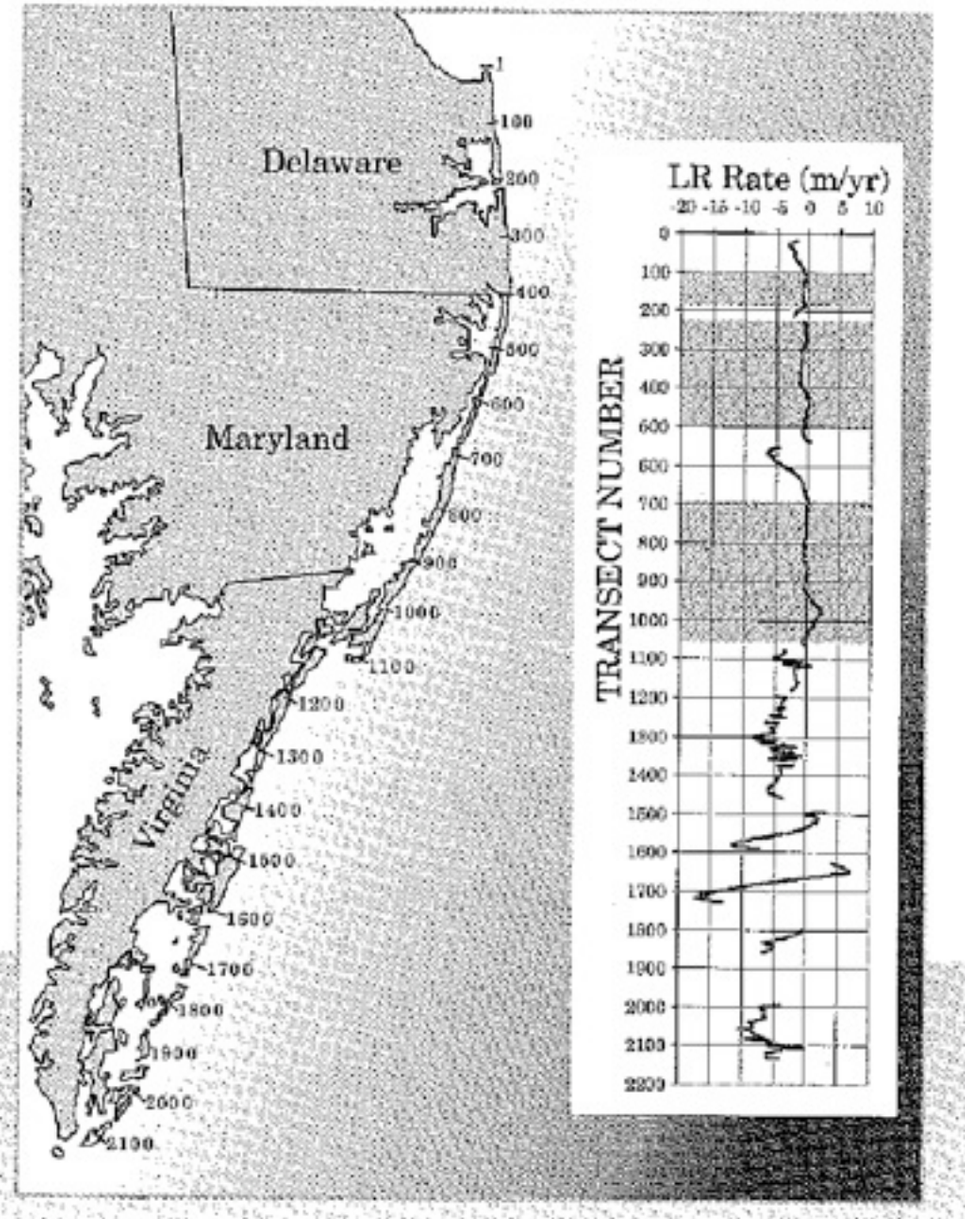
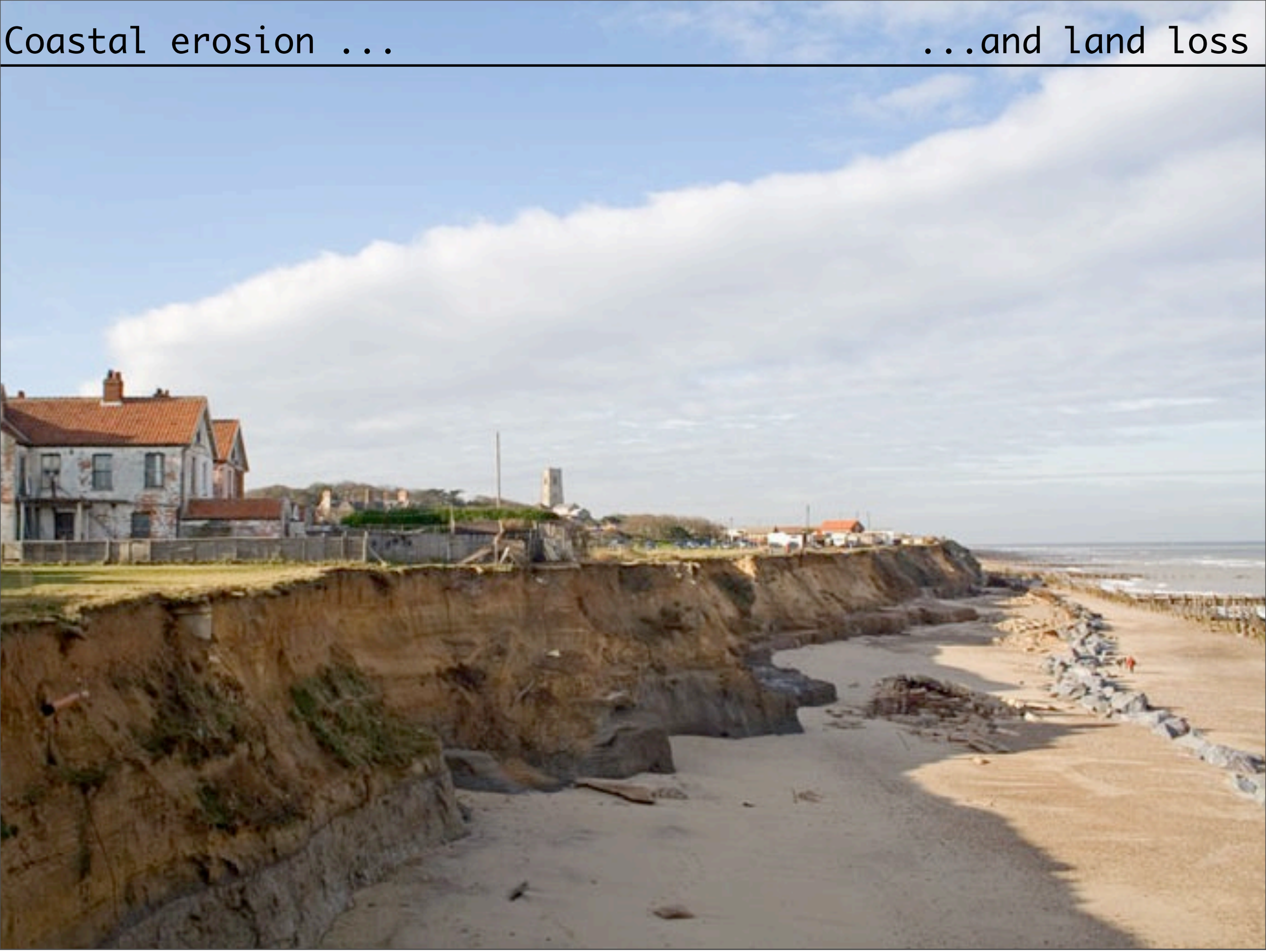


Figure 2. The local recession rate of the Delmarva coast is plotted on the left as a function of shoreline position (transect number). The areas highlighted in yellow correspond to those sections of beach where the assumptions of Brüun's model apply. There, the average rate of shoreline retreat was 0.2 meters per year. (Adapted from ref. 1.)

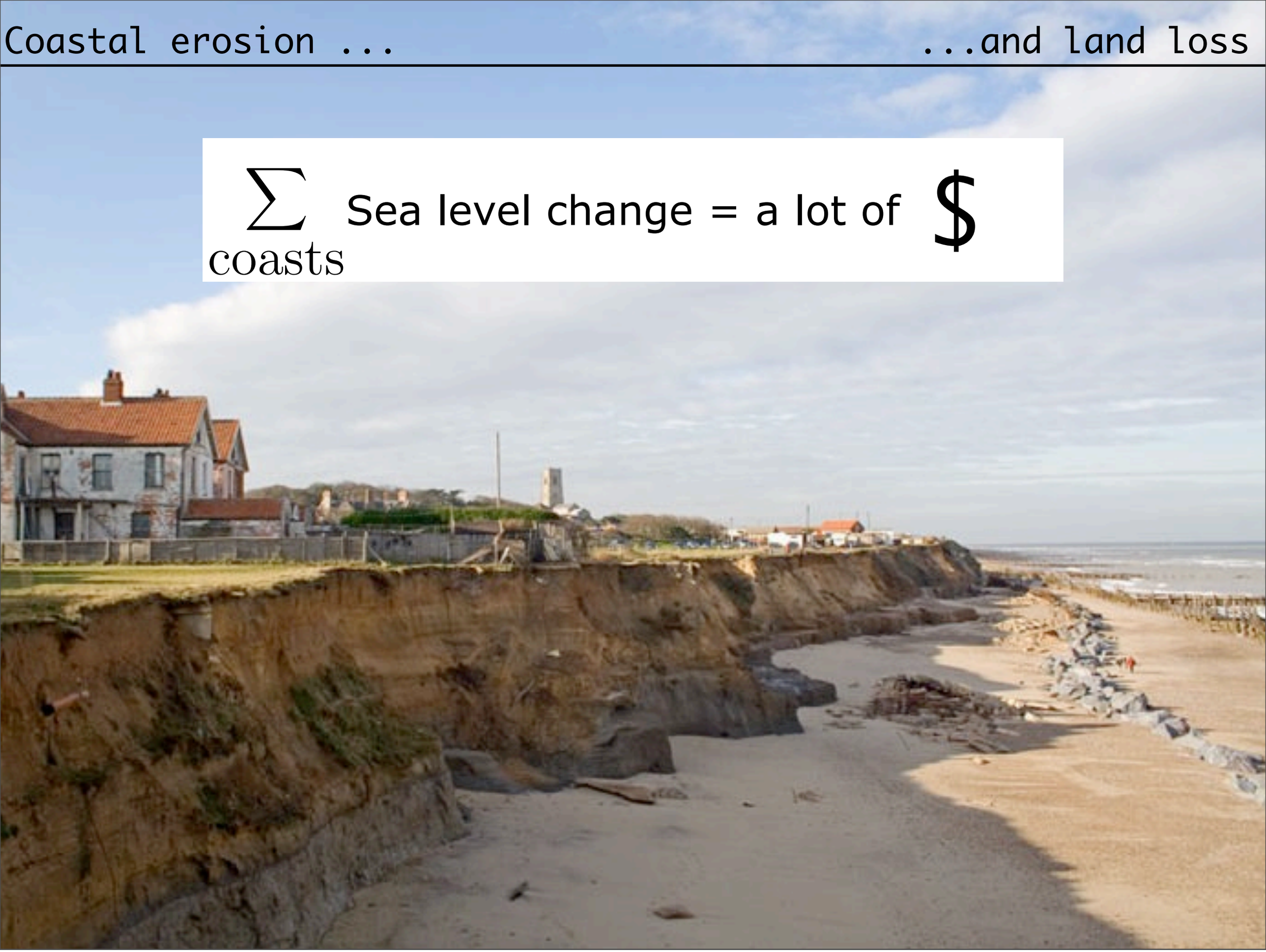
Day, C. (2004). Sea-Level rise exacerbates coastal erosion. Physics Today 57 (2): 24–26.

Coastal erosion ... ...and land loss



Coastal erosion ... ...and land loss

$$\sum_{\text{coasts}} \text{Sea level change} = \text{a lot of } \$$$



Stephen P. Leatherman - "Social and economic costs of sea level rise"

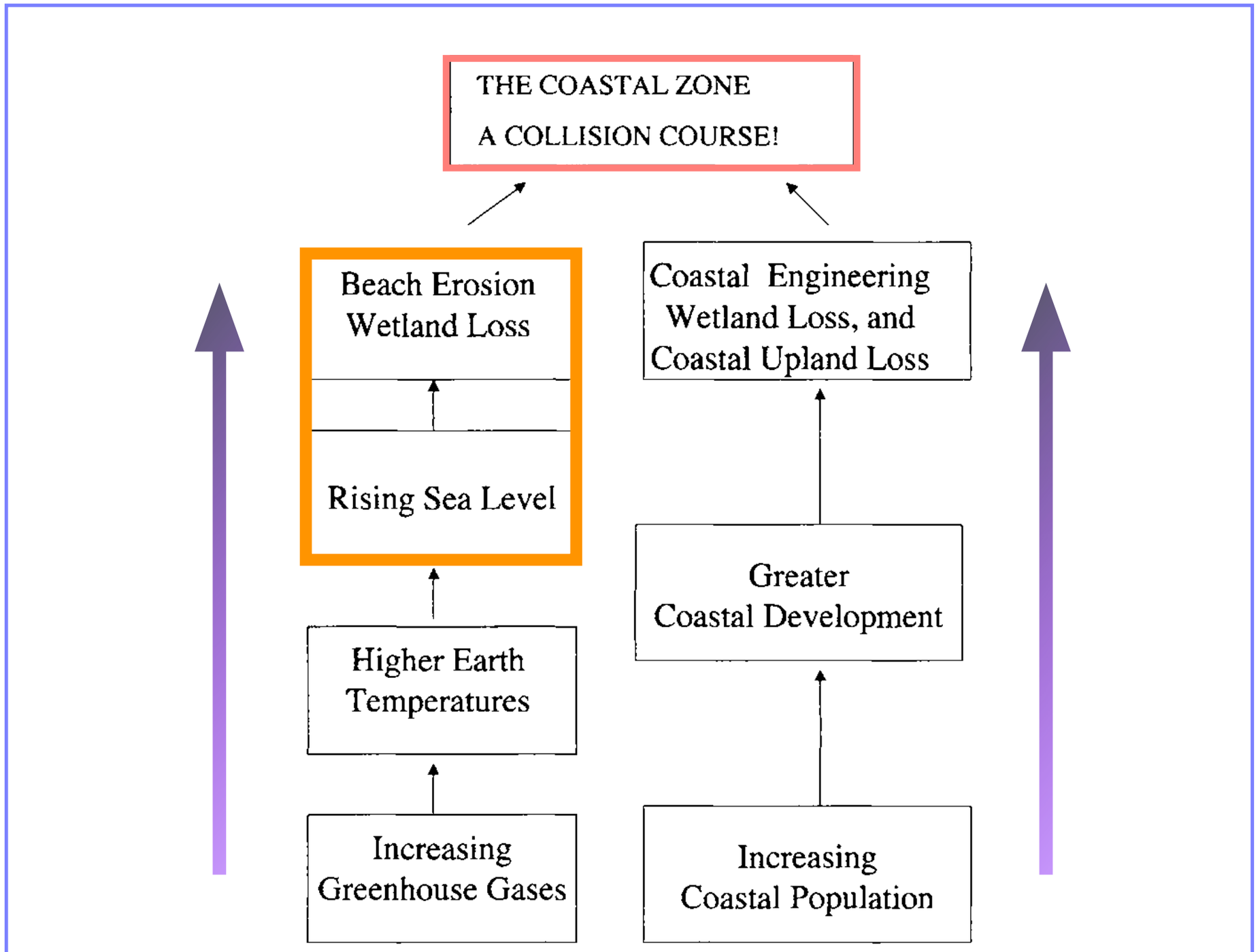
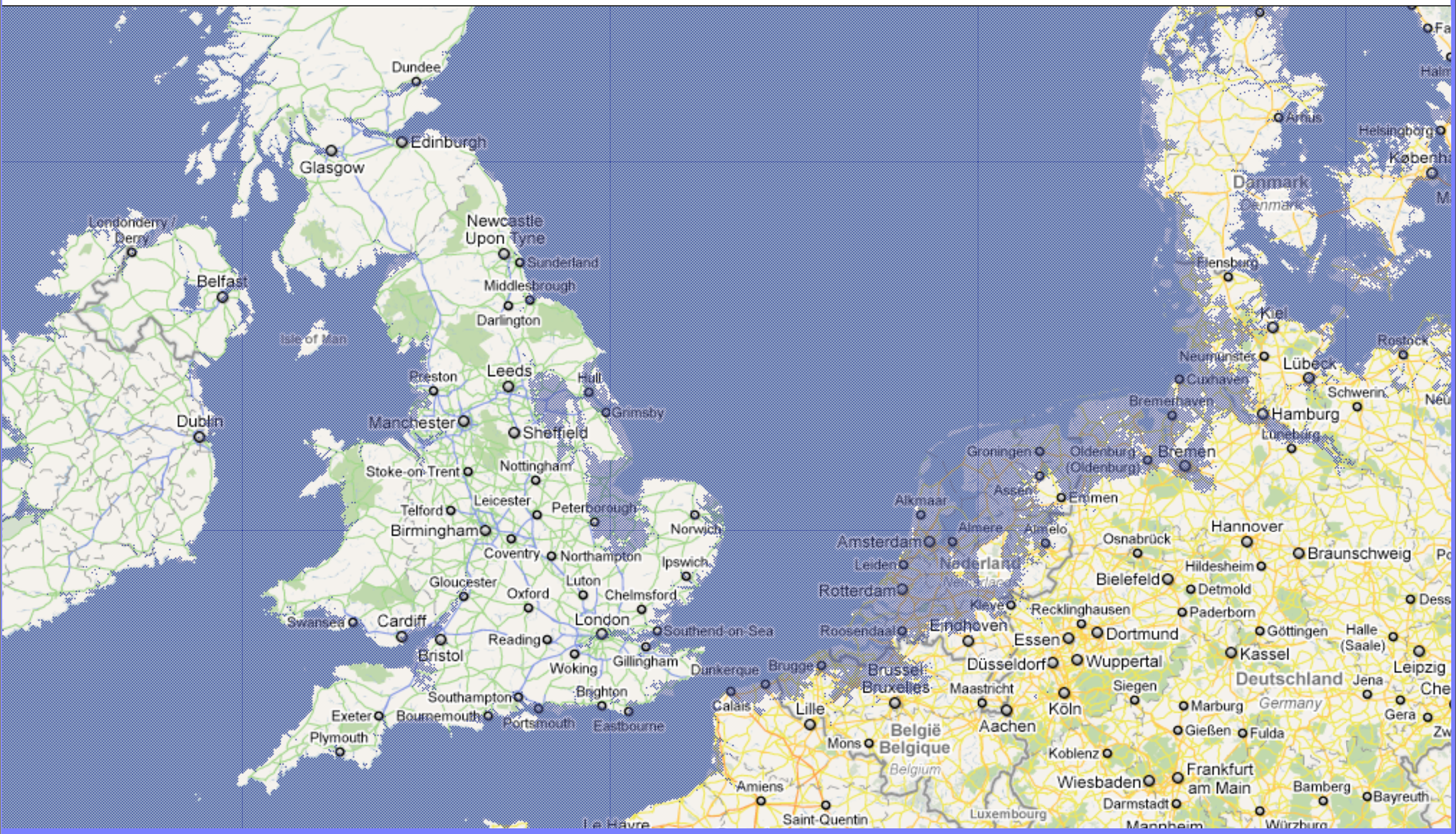


Figure 8.1 The coastal zone is increasingly becoming a collision course.

Sea level rise: history and consequences Di Bruce C. Douglas,Michael S. Kearney,Stephen P. Leatherman

Sea level rise: +12 m

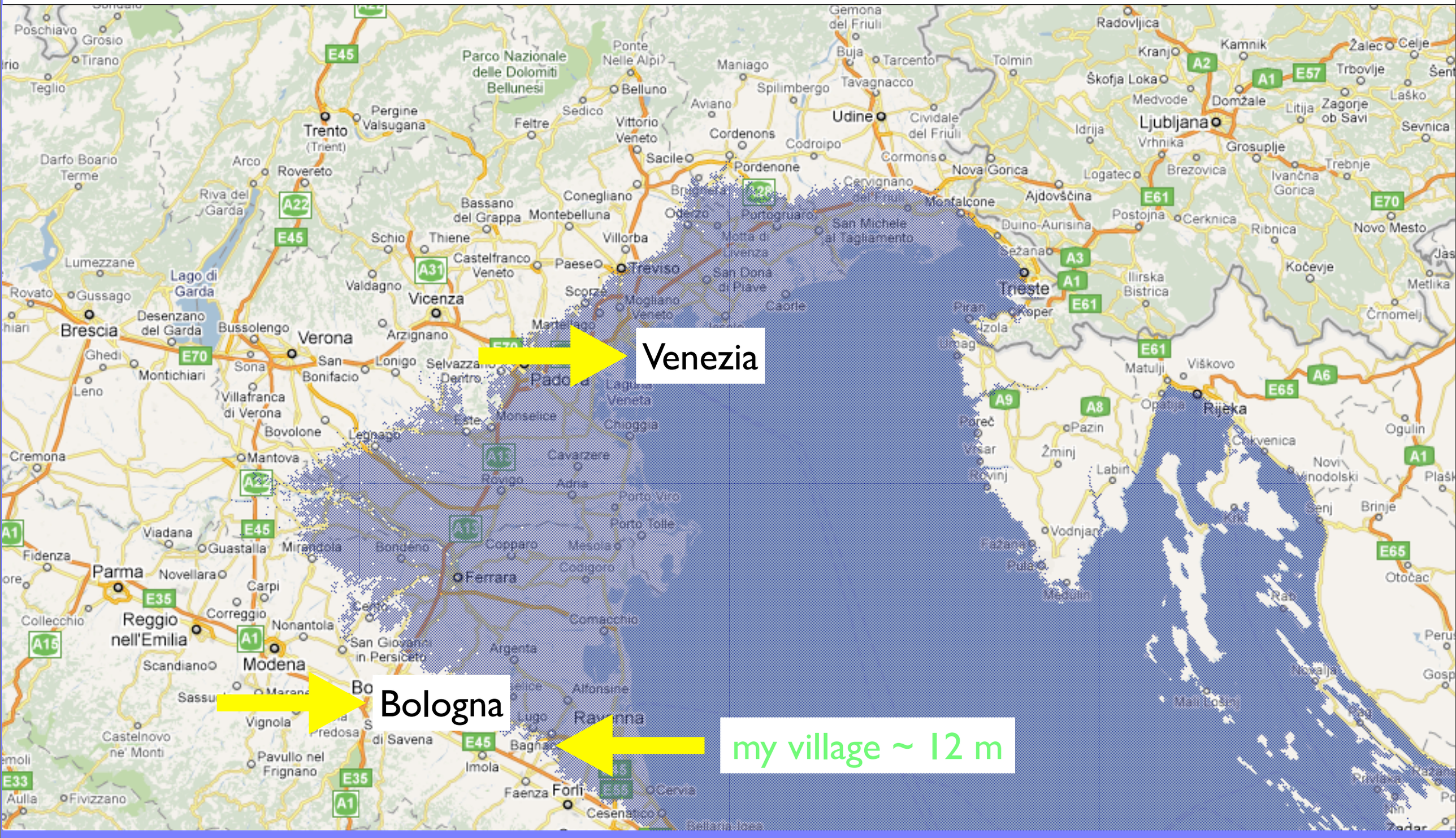
Europe N. America S. America Africa SE. Asia China & Japan Australia



http://flood.firetree.net/?ll=48.3416,14.6777&z=13&m=7

sea level + 12 m

Sea level rise: +12 m



sea level + 12 m


"How did we get here?"

The last few millennia

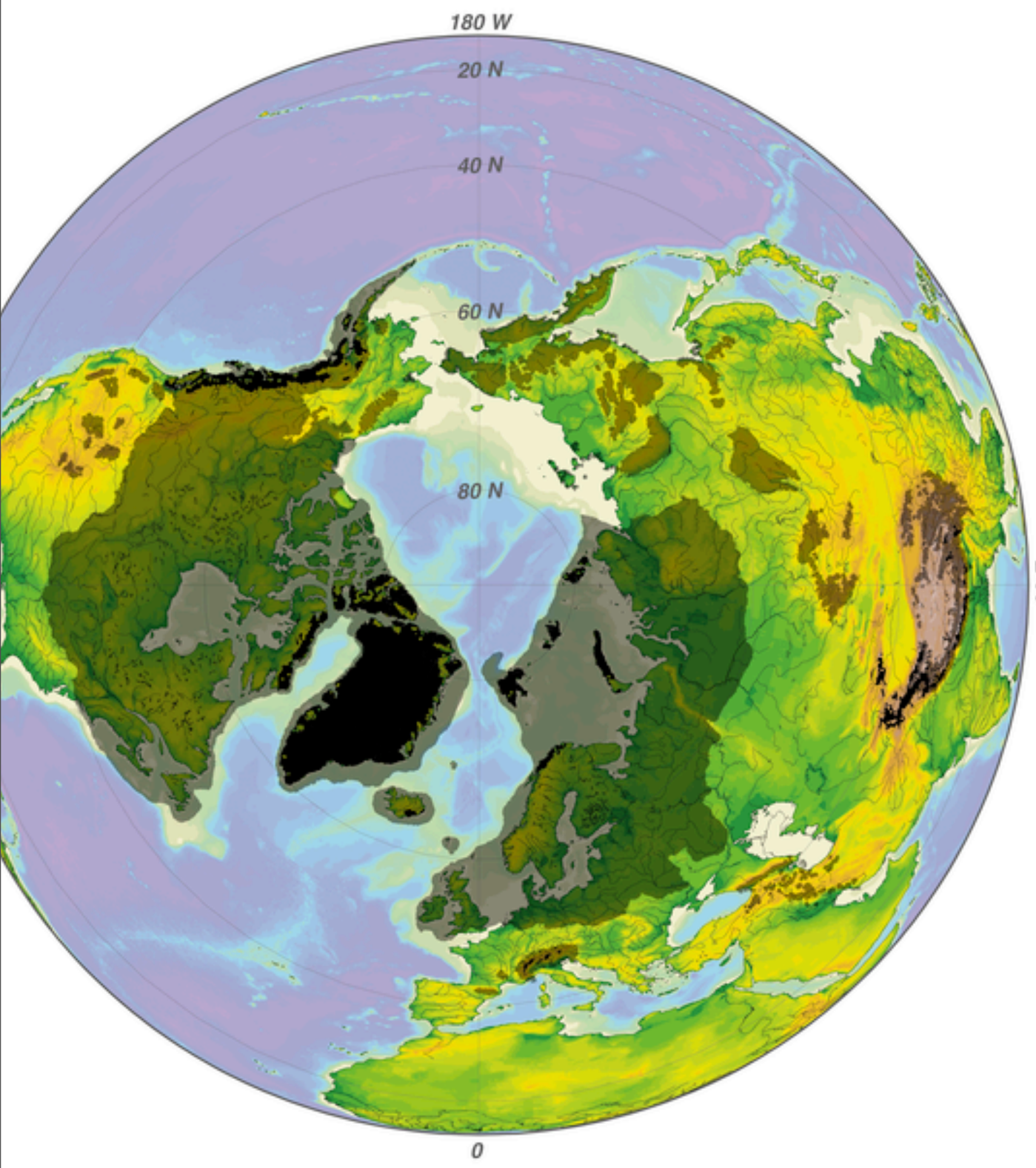
Last Glacial maximum (~ 21 kyrs BP)

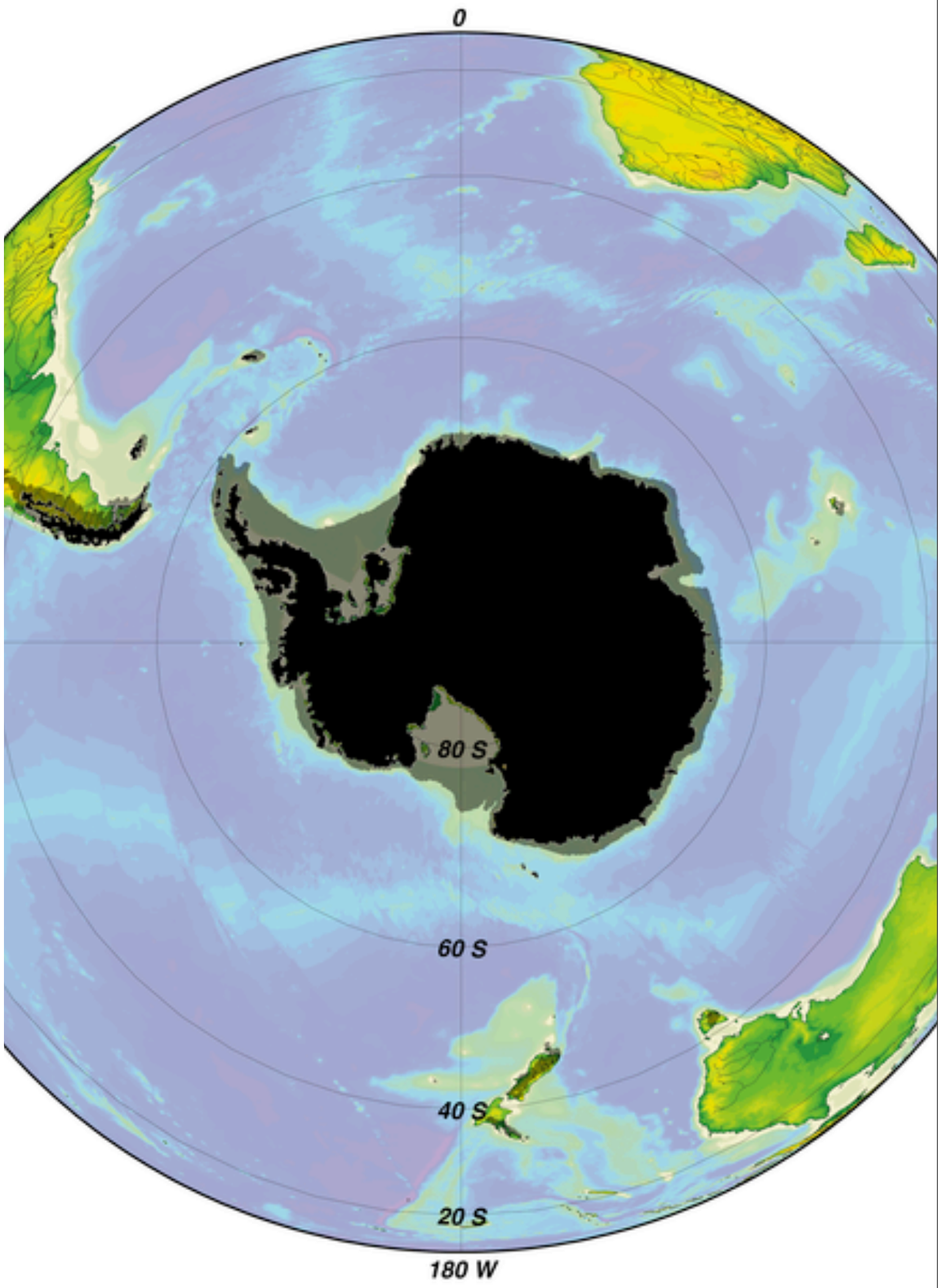
Northern hemisphere glaciation during the last ice ages. The set up of 3 to 4 km thick ice sheets caused a sea level lowering of about 120 m.

Alps
B
St
M
Himalaya
Ural
C
Greenland
North
Pole
W
Gobi
P
NORTH
AMERICA
H~4000 m
Rocky Mountains
A
Summer
sea ice
LA
T
Winter sea ice

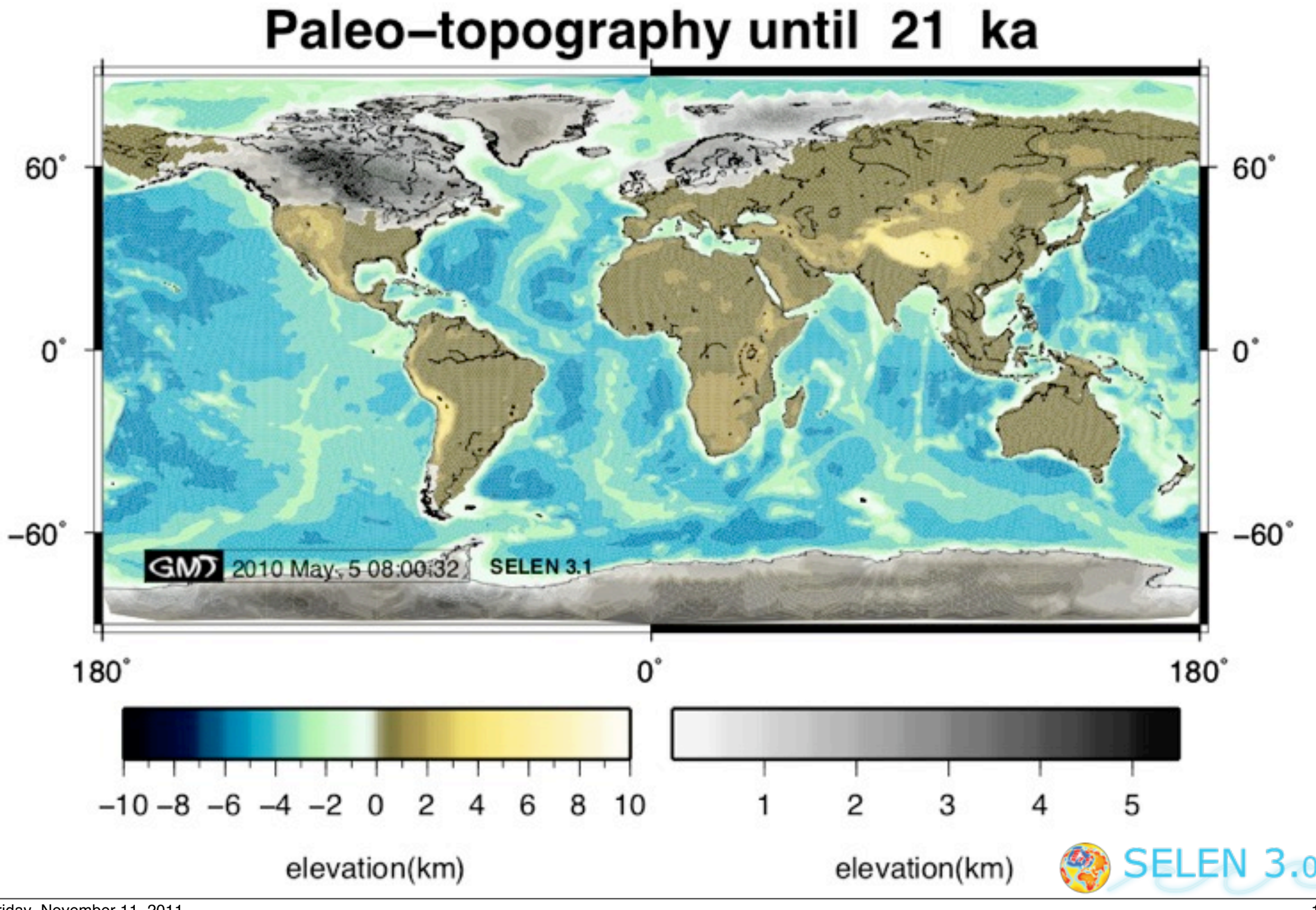
Paleogeography northern hemisphere LGM

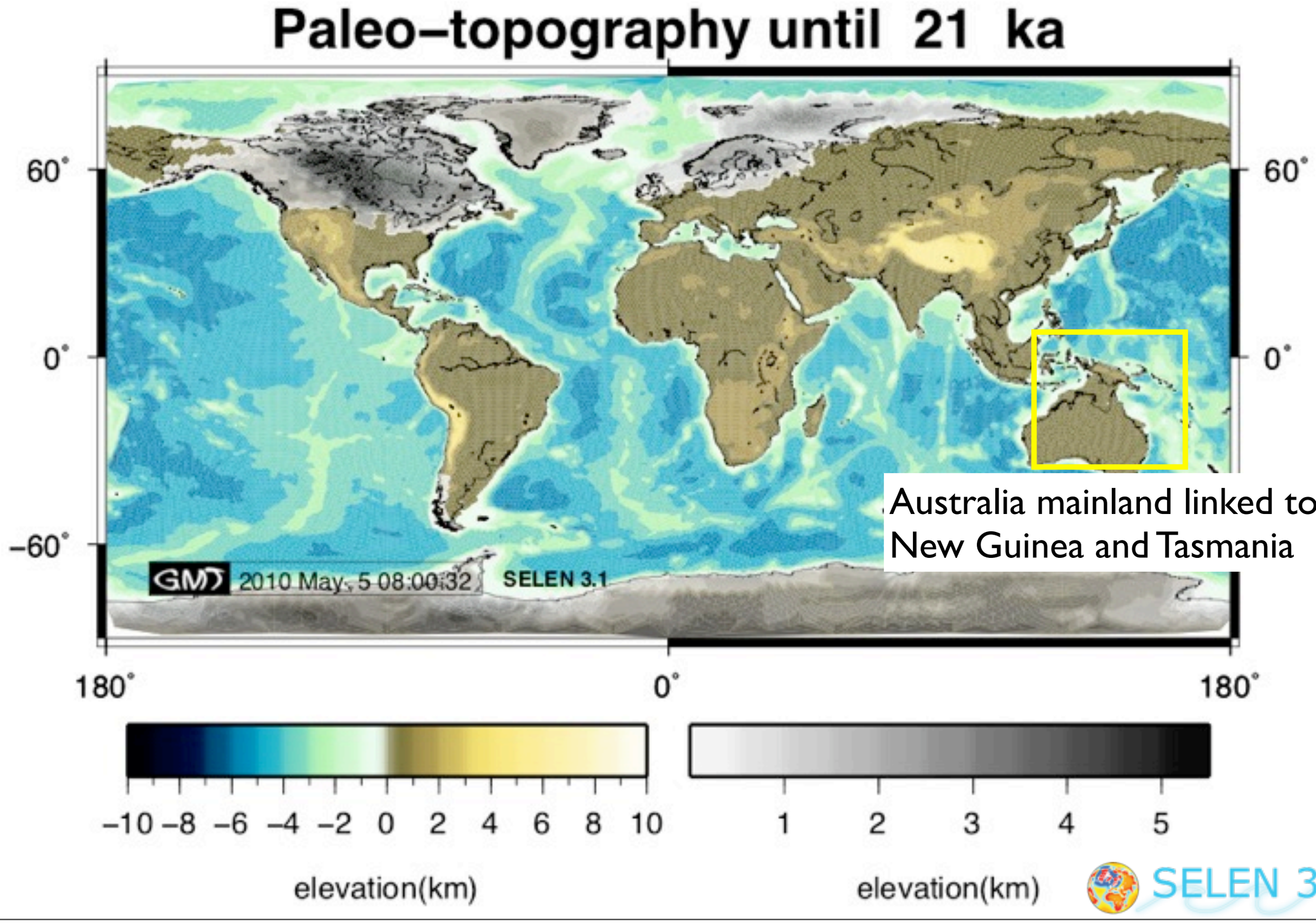
Minimum (interglacial, black) and maximum (glacial, grey) glaciation



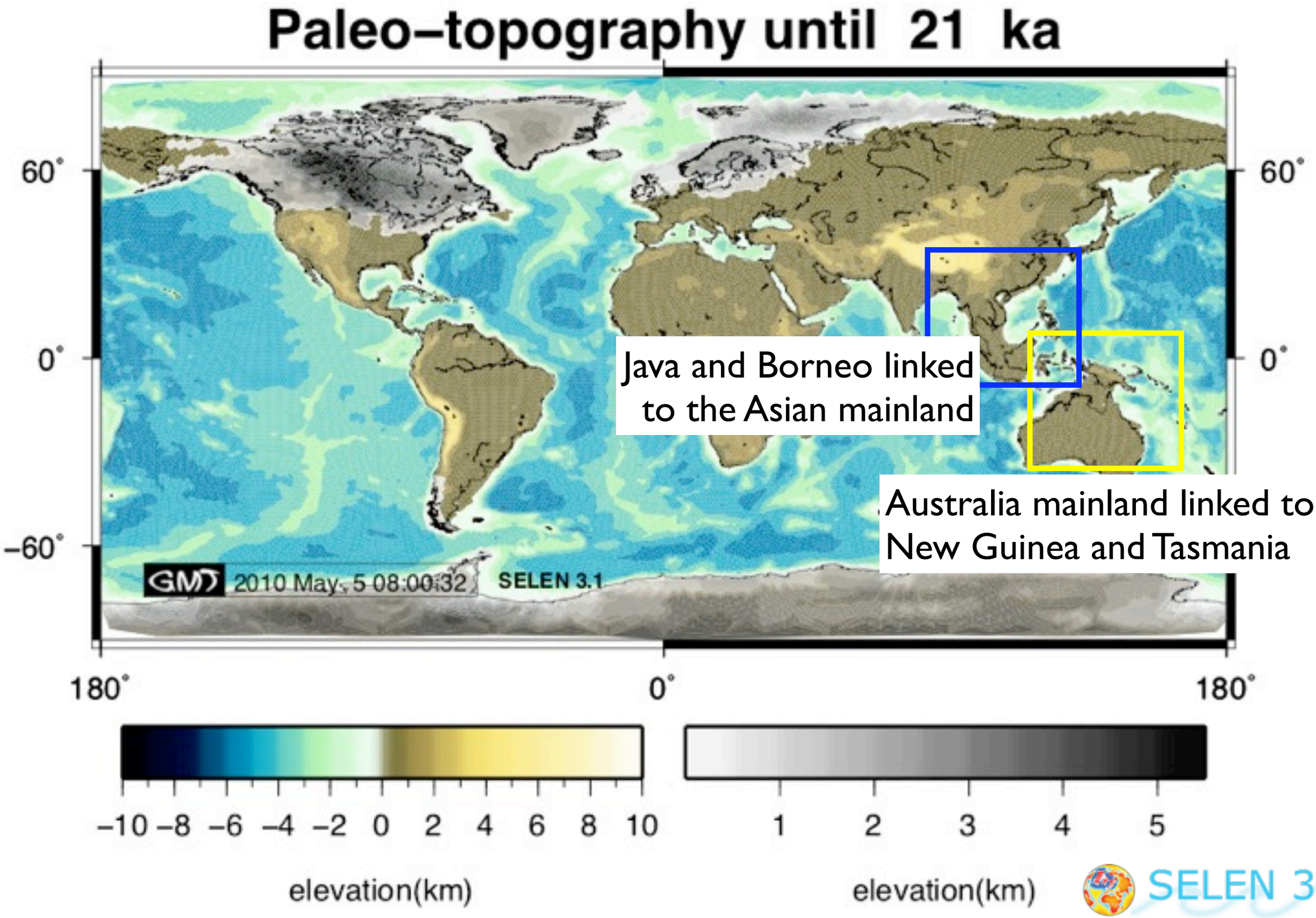


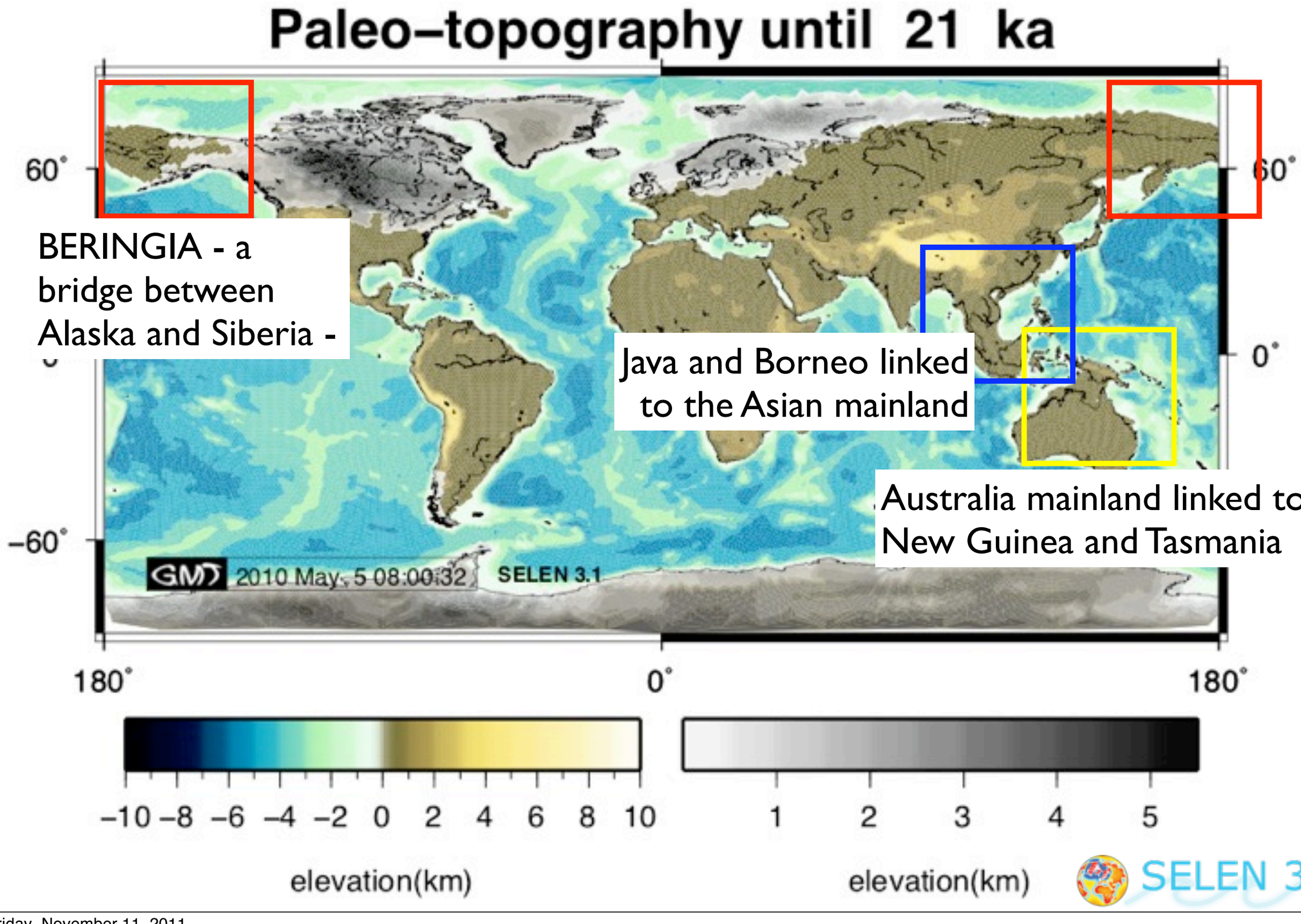
http://en.wikipedia.org/wiki/Ice_age


Paleo–topography until 21 ka
60°
0°
–60°
180°
0°
180°
GMT 2010 May, 5 08:00:32
SELEN 3.1
–10 –8 –6 –4 –2 0 2 4 6 8 10
elevation(km)
1 2 3 4 5
elevation(km)
SELEN 3.0



Australia mainland linked to New Guinea and Tasmania


Paleo–topography until 21 ka
60°
0°
−60°
180°
0°
180°
GMT 2010 May, 5 08:00:32
SELEN 3.1
Java and Borneo linked to the Asian mainland
Australia mainland linked to New Guinea and Tasmania
−10 −8 −6 −4 −2 0 2 4 6 8 10
elevation(km)
1 2 3 4 5
elevation(km)
SELEN 3.0

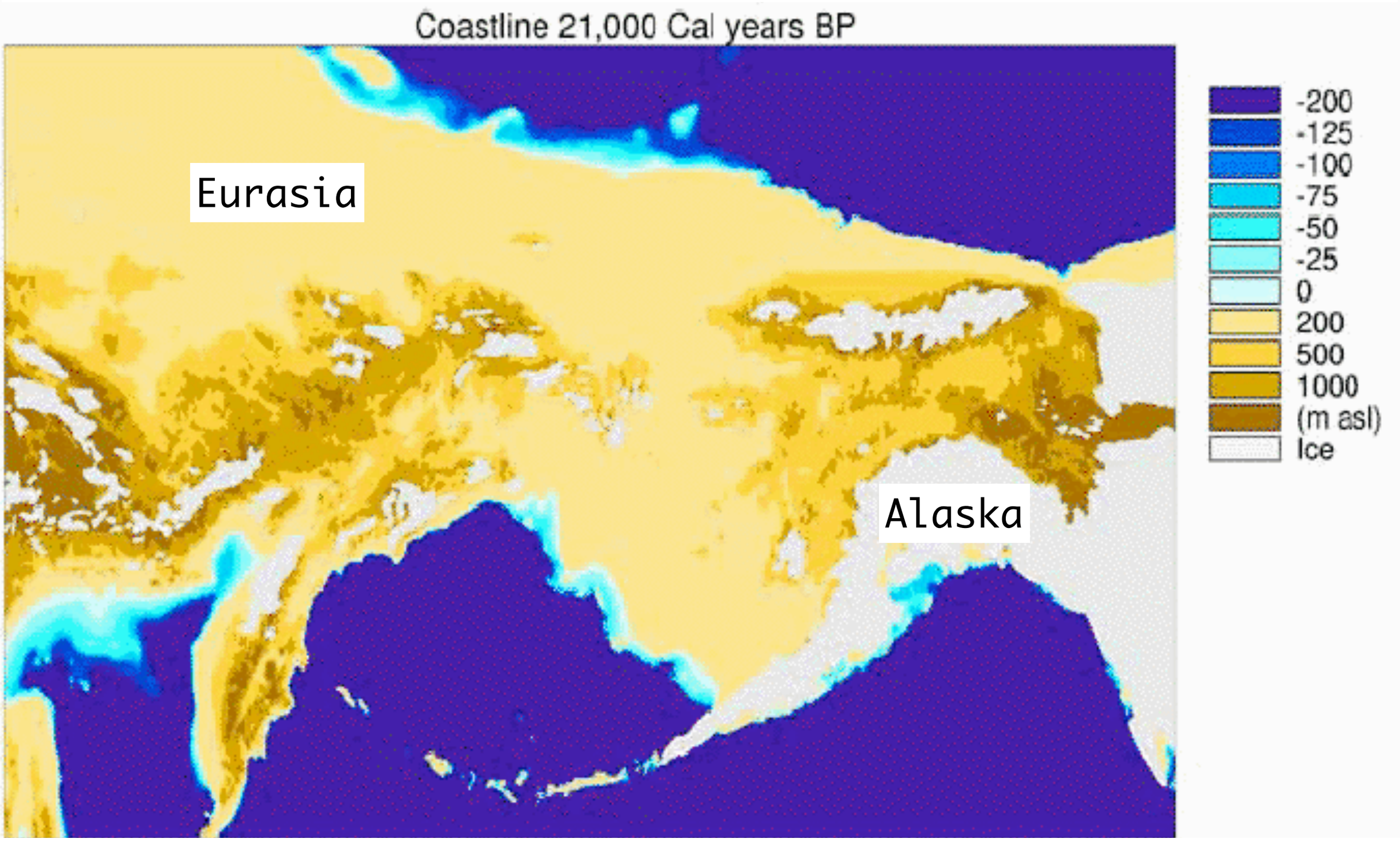


BERINGIA - a bridge between Alaska and Siberia -

Java and Borneo linked to the Asian mainland

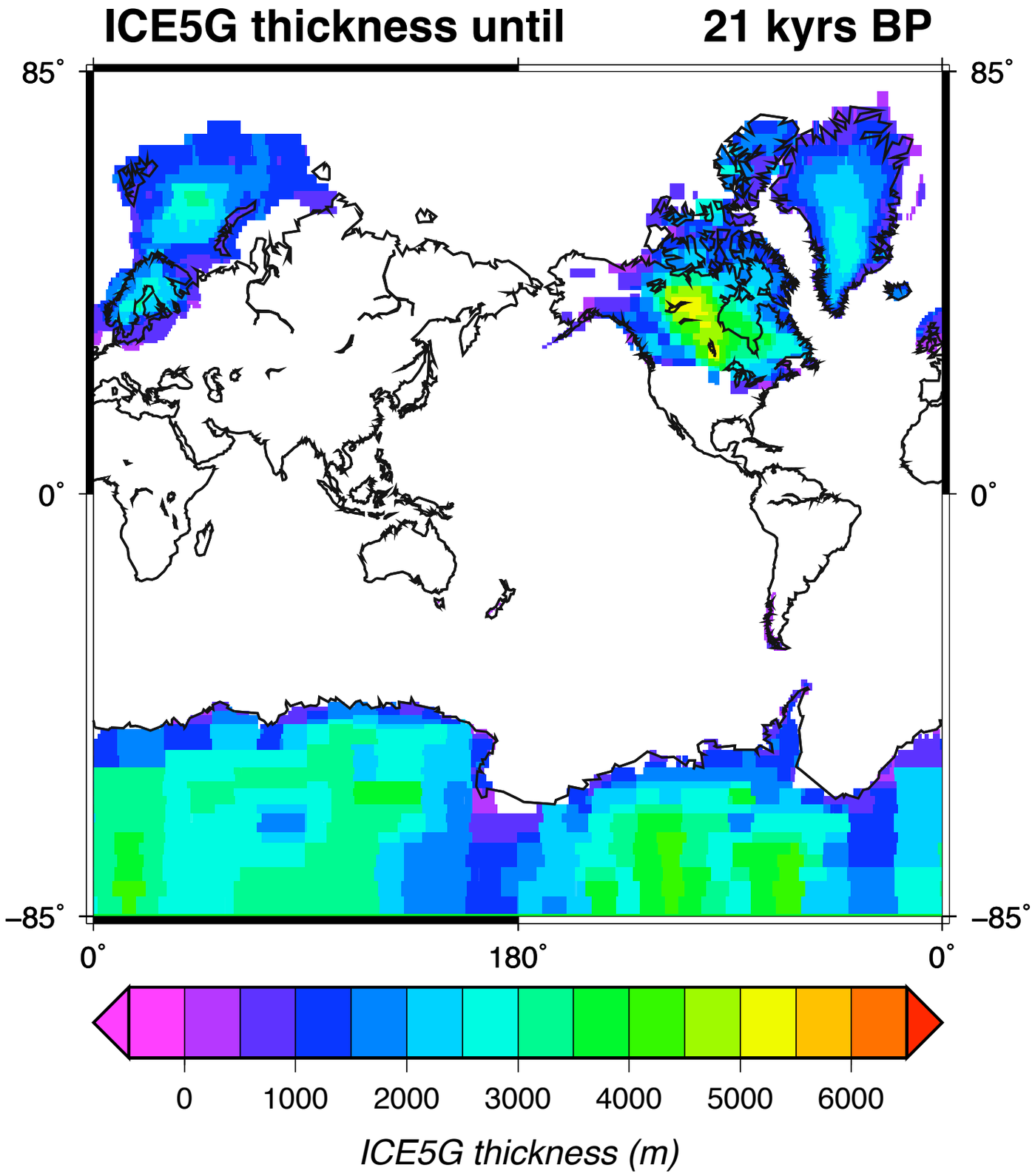
Australia mainland linked to New Guinea and Tasmania

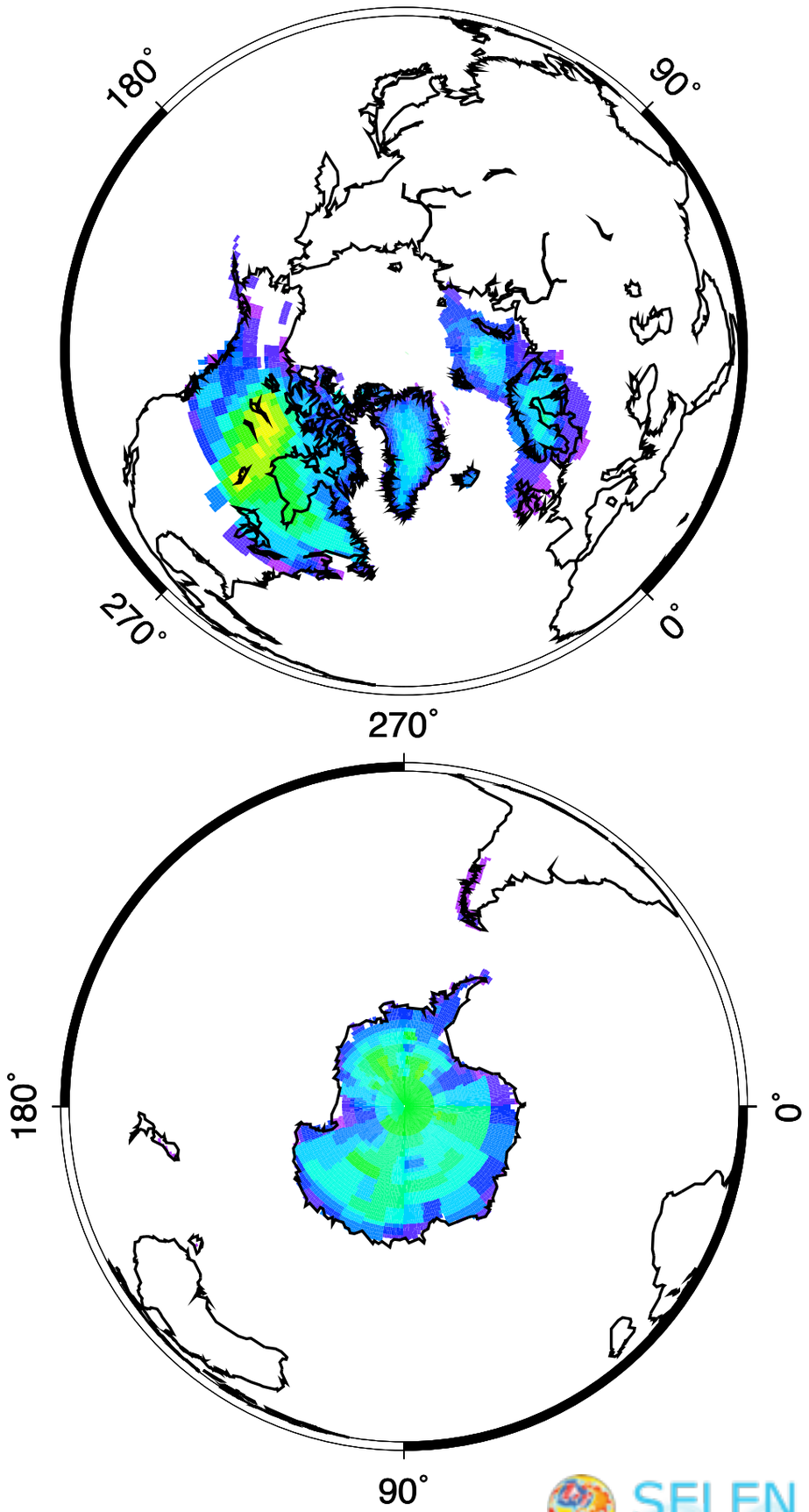
Paleo-environmental Atlas of Beringia

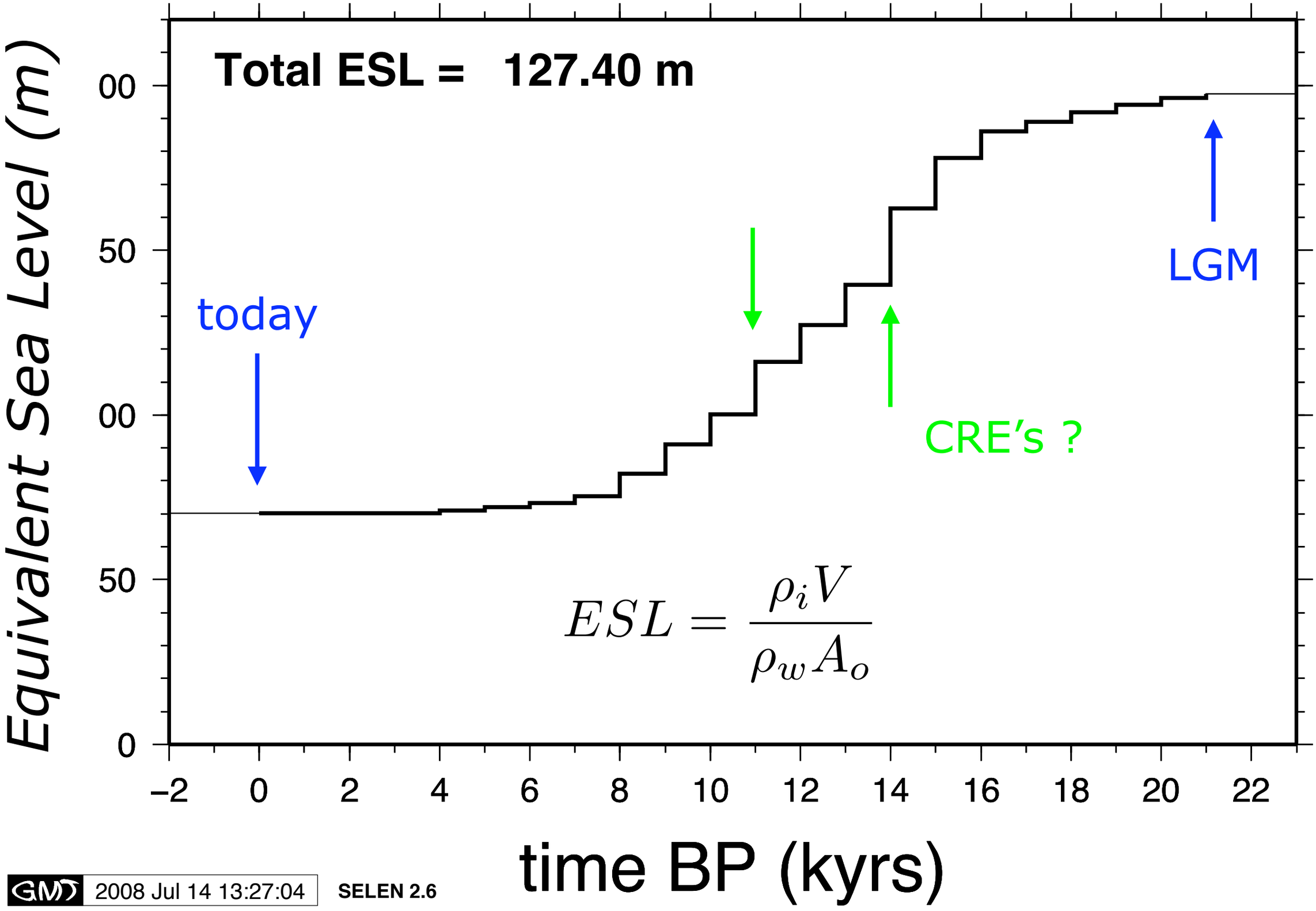


http://www.ncdc.noaa.gov/paleo/parcs/atlas/beringia/index.html

ICE-5G Peltier (2004)






Total ESL = 127.40 m
today
LGM
CRE's ?
$ESL = \frac{\rho_i V}{\rho_w A_o}$
Equivalent Sea Level (m)
00
50
00
50
0
–2
0
2
4
6
8
10
12
14
16
18
20
22
time BP (kyrs)
GMT 2008 Jul 14 13:27:04
SELEN 2.6

Consequences of melting?

Reasonable assumptions:

1. The Earth is a strong(*) body and ice has a low density (~ that of water). *Ice load has negligible effects*.

2. The amount of water filling the basins was huge: ~130 m of sea level equivalent. *Details of water load and its loading effects are not so important*.

3. *Gravity is a weak force* (Newton constant is small 10^-11 SI units). Small influence [?] upon the *changes of* shape of the Earth and of the oceans...

Hence, we expect - to a first approximation - a uniform sea level variation. In the views of Suess...

(*) See George Darwin argument about the rigidity of the Earth, in comparison to steel.

Reasonable assumptions:

1) Rigid Earth: "Love numbers" are zero,

2) no gravitational interactions: Newton constant is zero.

Sea level variations are "EUSTATIC", from "eustatism" a word coined by the English geologist Eduard Suess (1903):

$$S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}$$

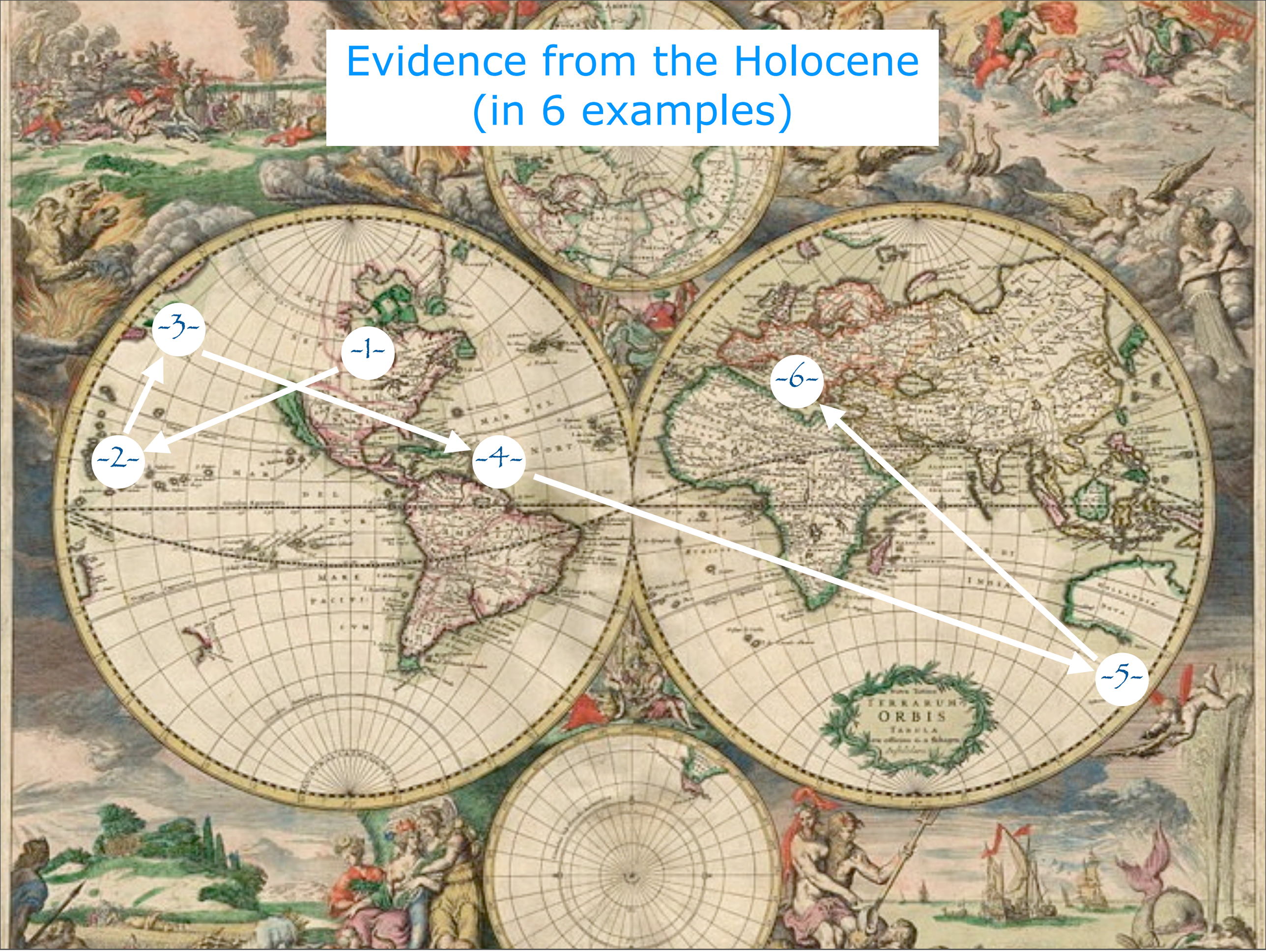


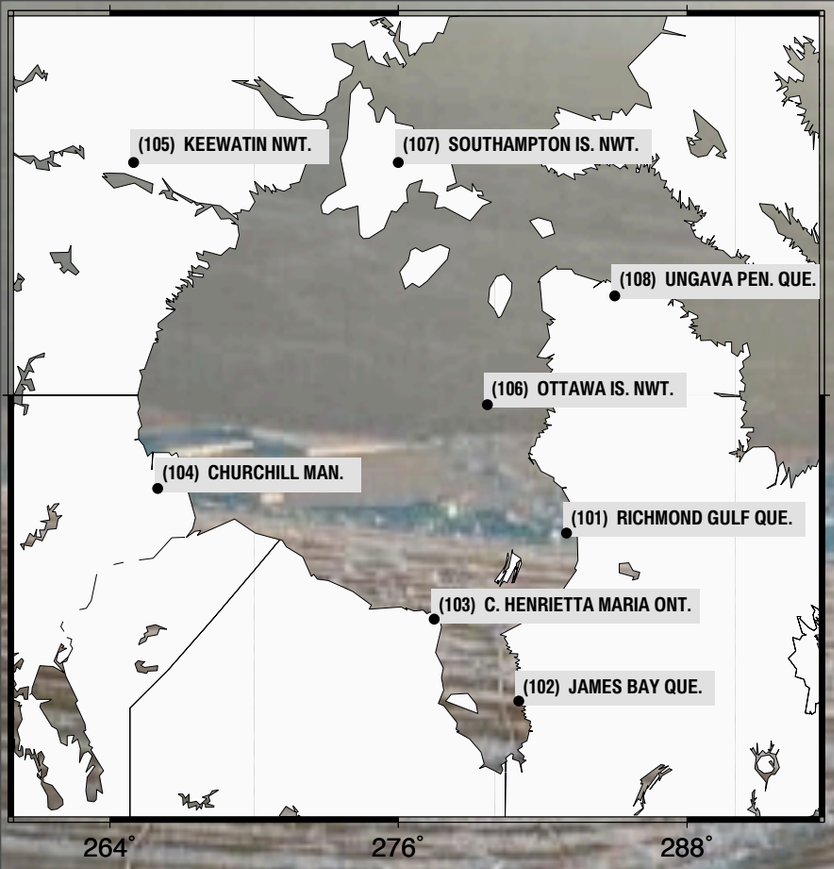
Eduard Suess

(20. August 1831 in London - † 26. April 1914 in Wien)*

war ein österreichischer Geologe und Politiker des 19. Jahrhunderts und wurde bekannt als Experte für den tektonischen Bau der Alpen. Auf ihn sind zwei wesentliche paläo-geographische Entdeckungen zurückzuführen: der ehemalige Superkontinent Gondwana und das Tethysmeer.

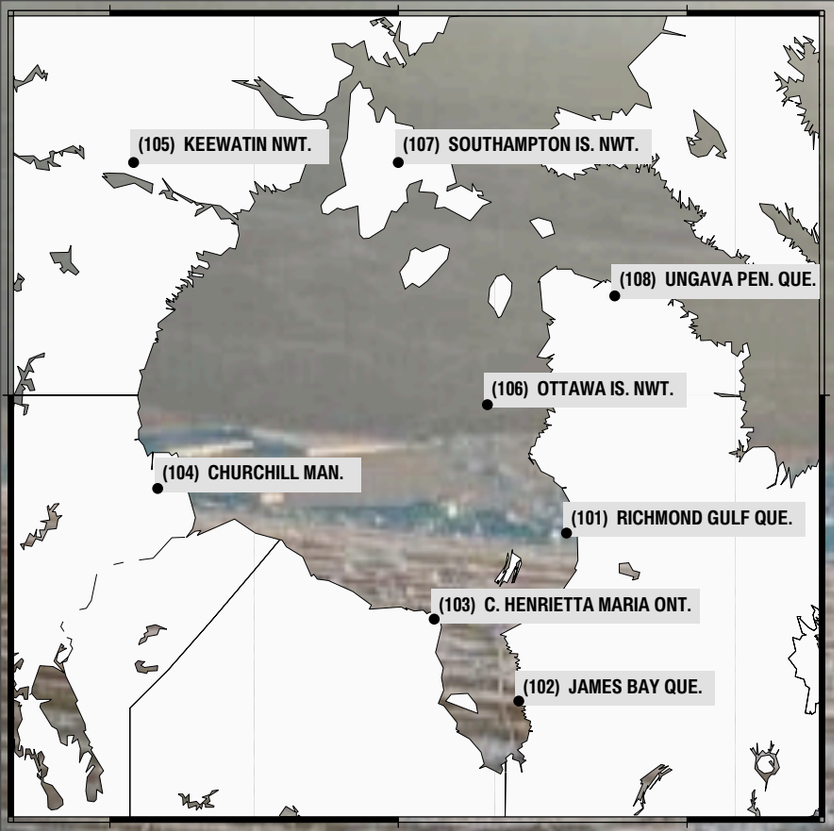
Evidence from the Holocene (in 6 examples)





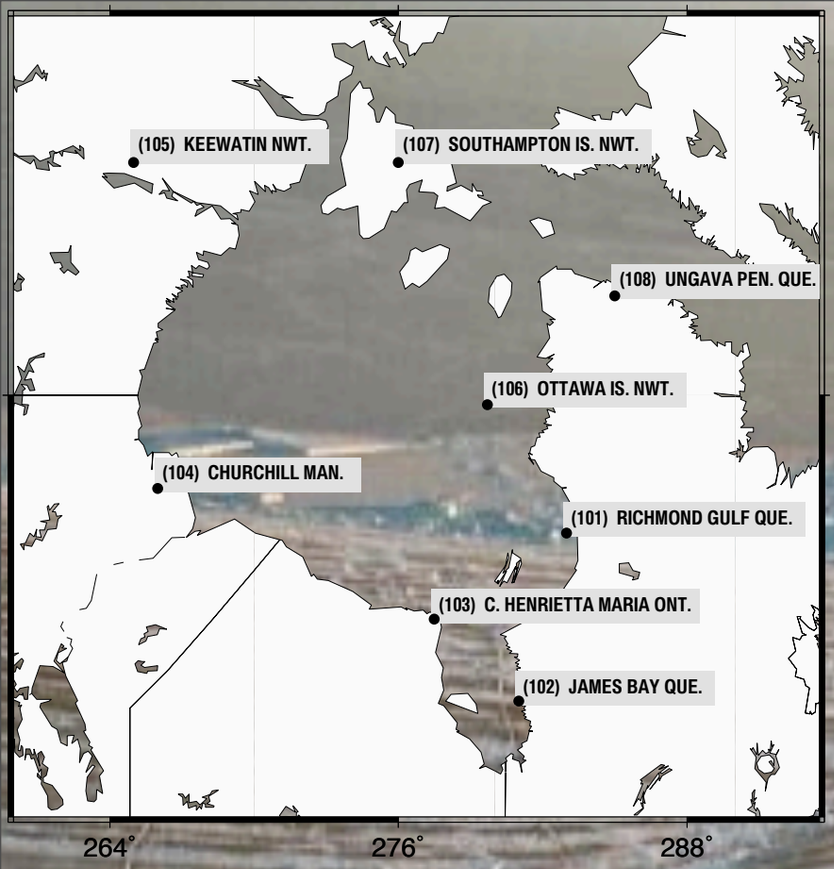
Raised beach

Evidence from the Hudson Bay



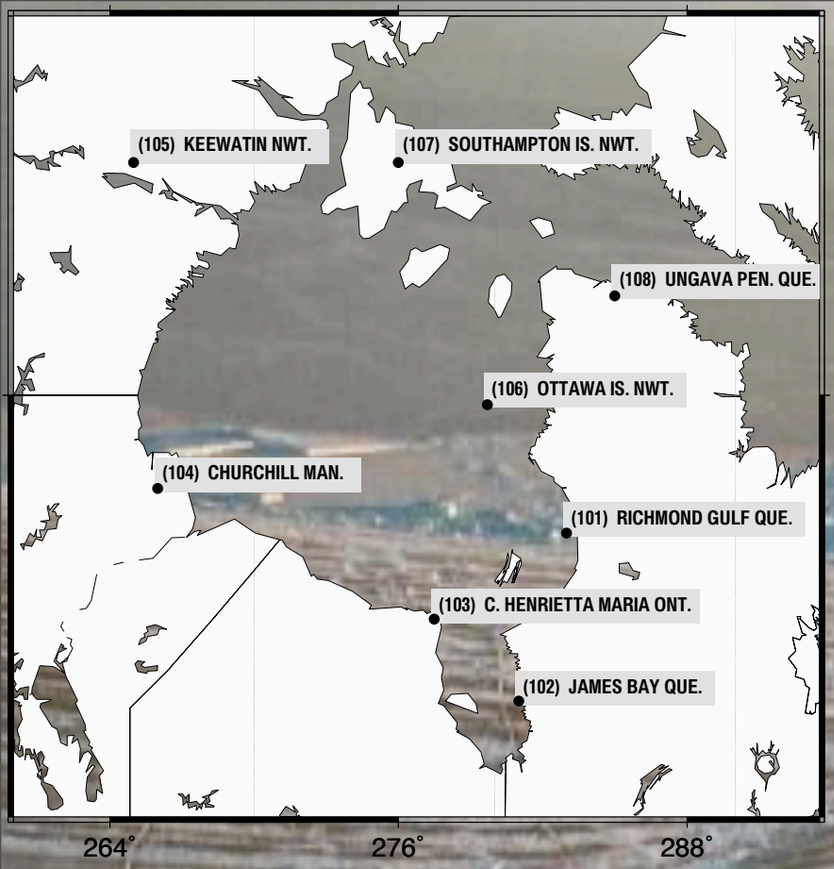
Raised beach

Evidence from the Hudson Bay



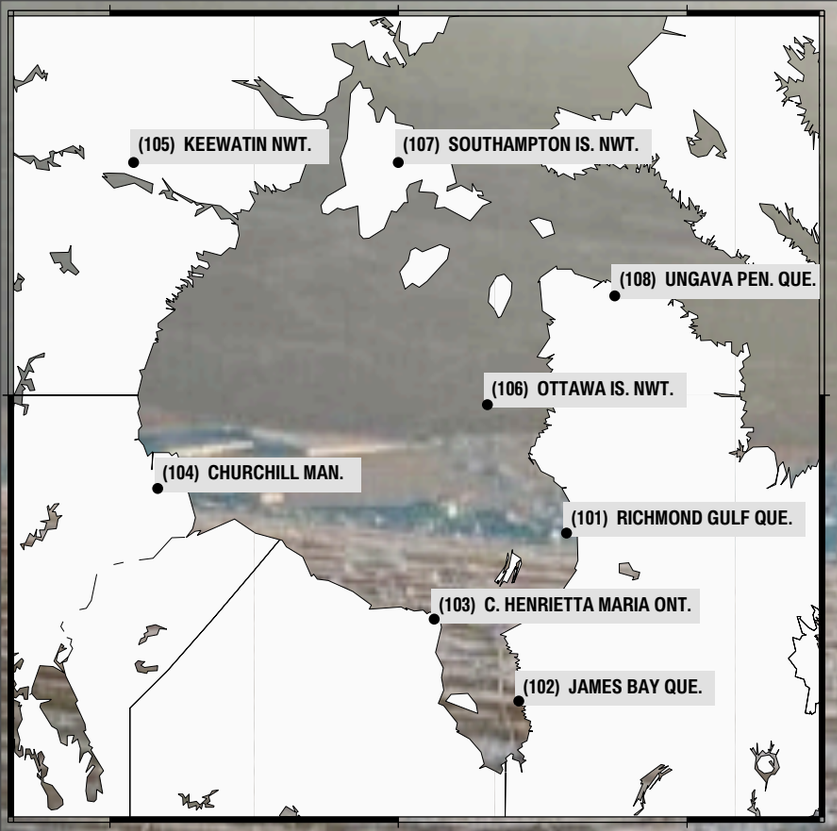
Raised beach

Evidence from the Hudson Bay



Raised beach

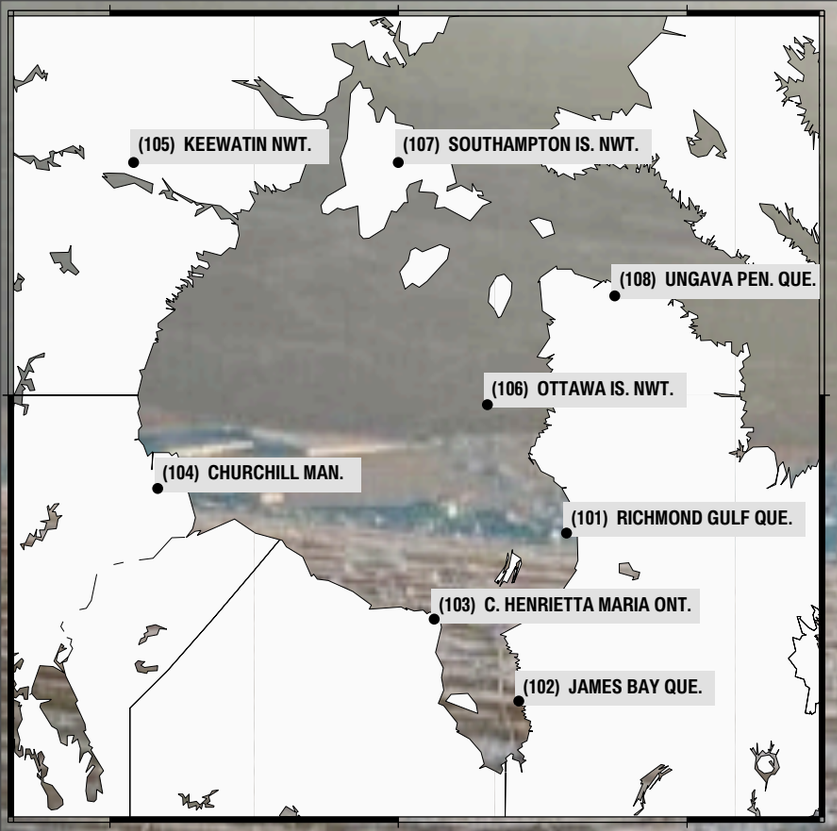
Evidence from the Hudson Bay



former sea level

Raised beach

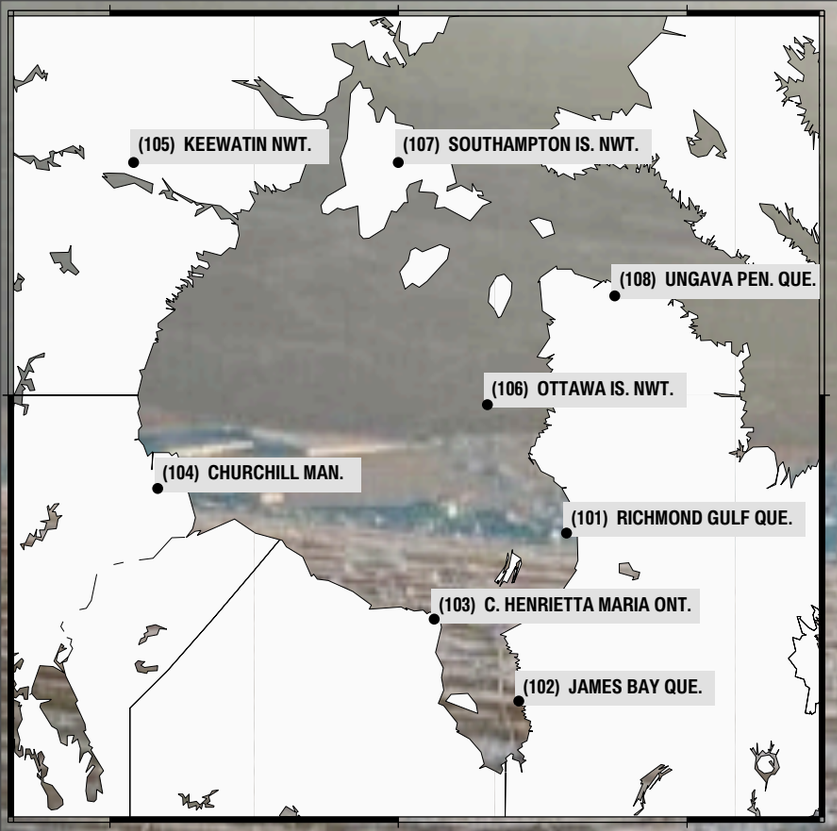
Evidence from the Hudson Bay



former sea level

Raised beach

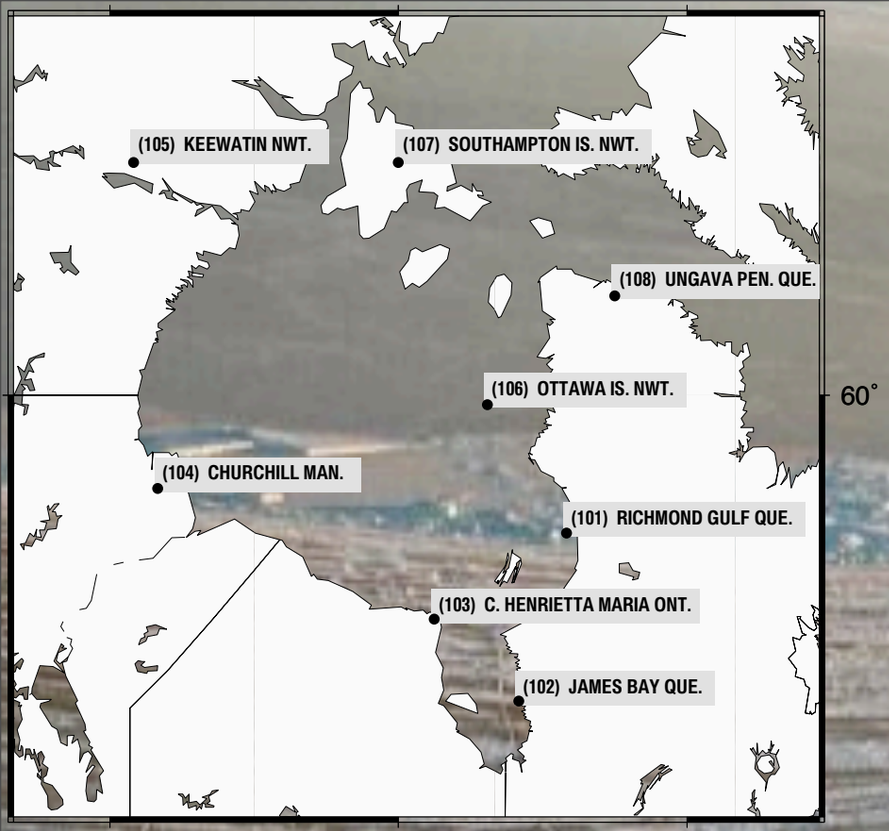
Evidence from the Hudson Bay



former sea level

Raised beach

Evidence from the Hudson Bay



modern shoreline

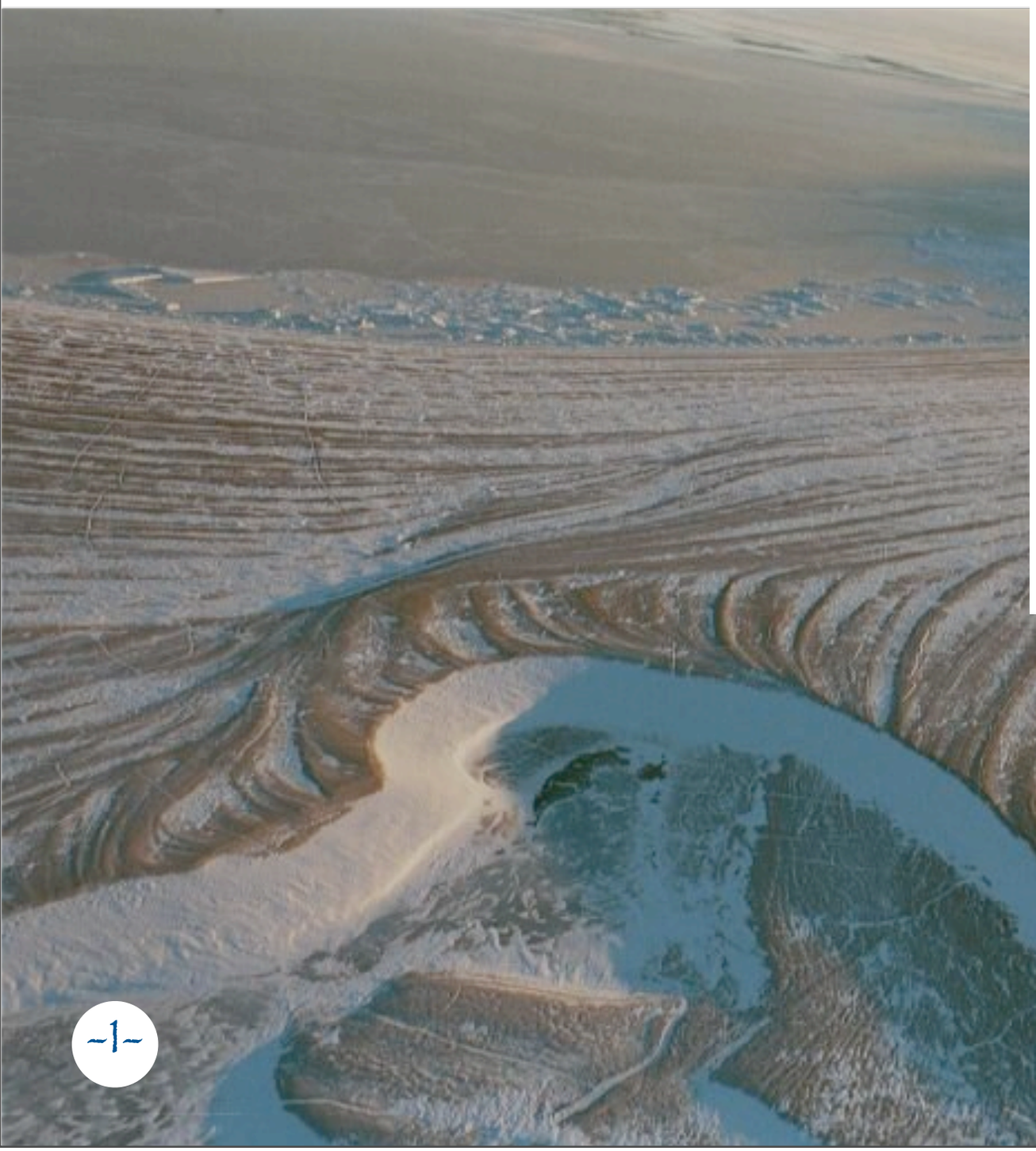
former sea level

Raised beach

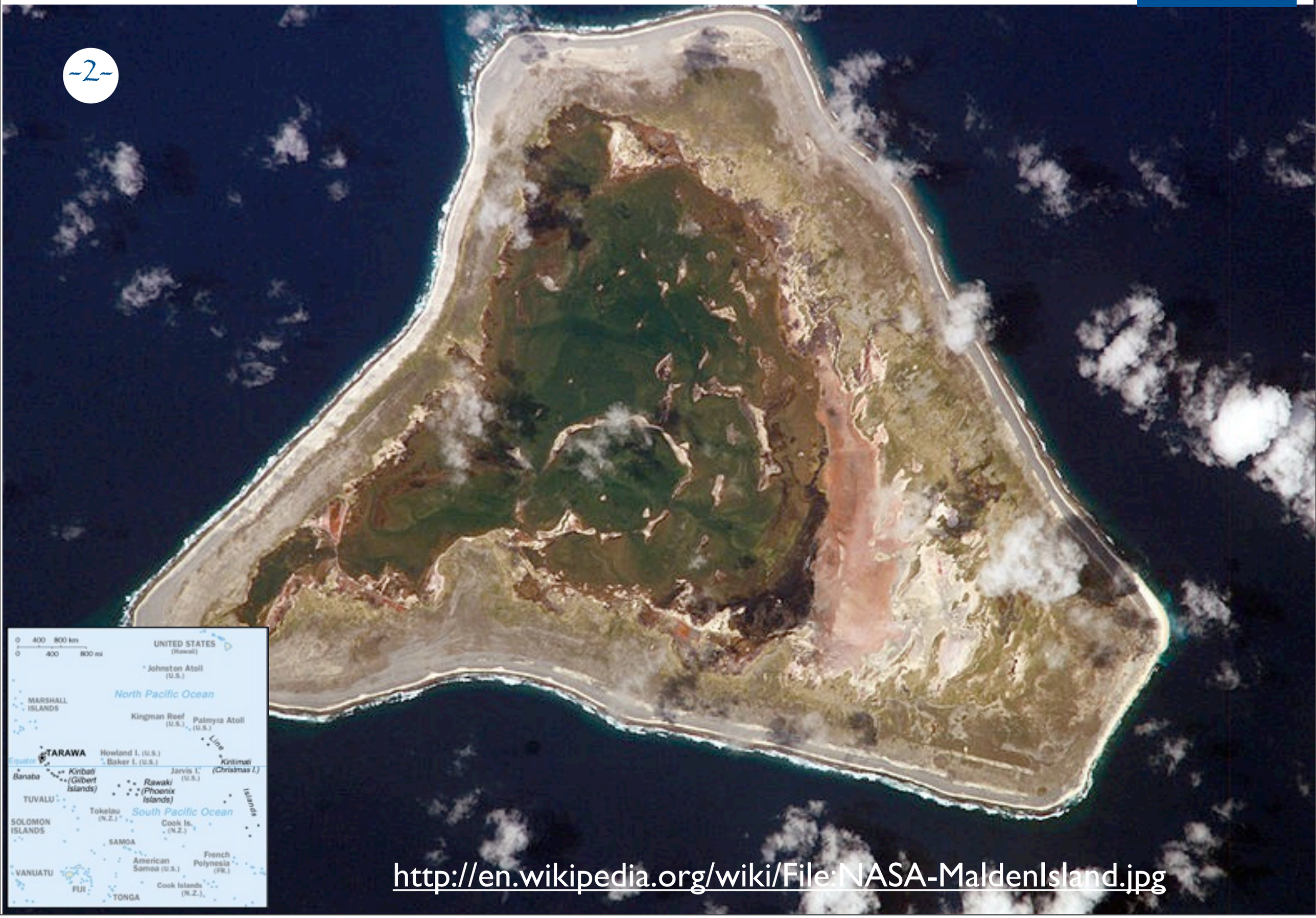
Evidence from the Hudson Bay

Evidence from the Hudson Bay

A *qualitative*
RELATIVE SEA LEVEL curve
for the Hudson bay
based on *raised shorelines*



Evidence from the Pacific (Malden Island) ...



Modern intertidal bench

leeward

N

20 m

Fossil beach

Emerged intertidal bench

P 3595 3618

E 3595

E 3135

P 2339

E 515

E modern

1 2 3 4

seaward sea level FALL

Trade winds

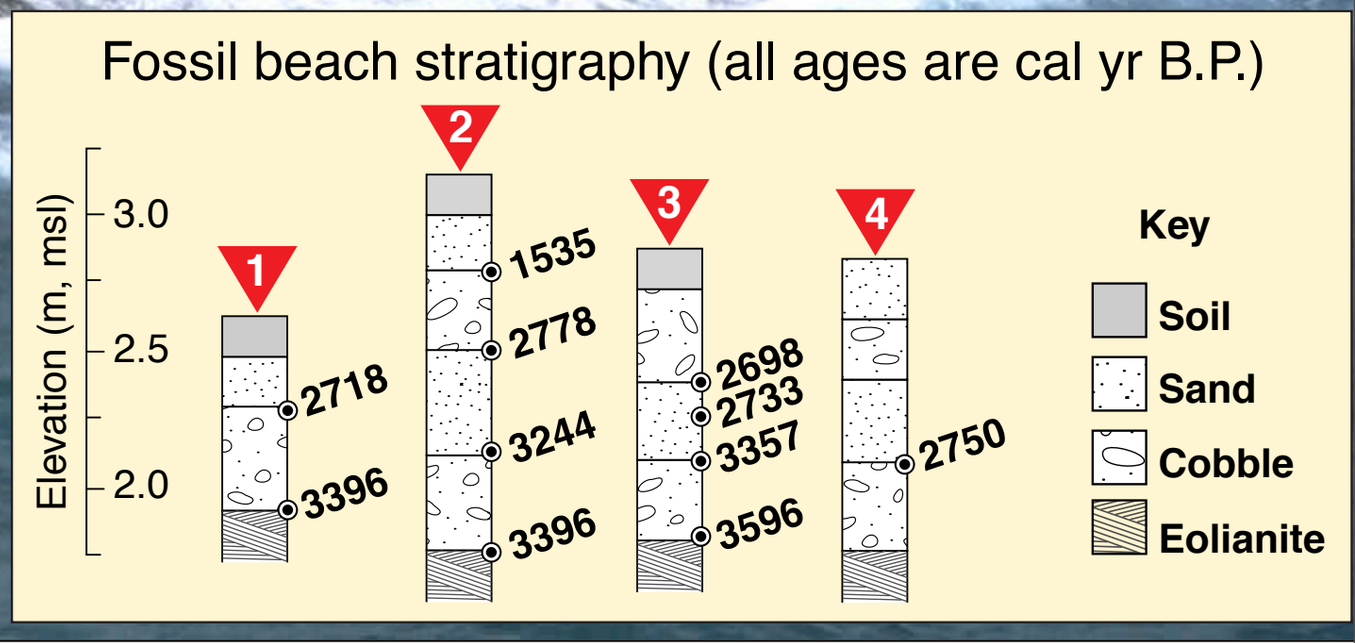
6 offshore samples seaward and leeward are modern

Excavation pits

erged bench samples

P Samples buried in solution pipes





-3-

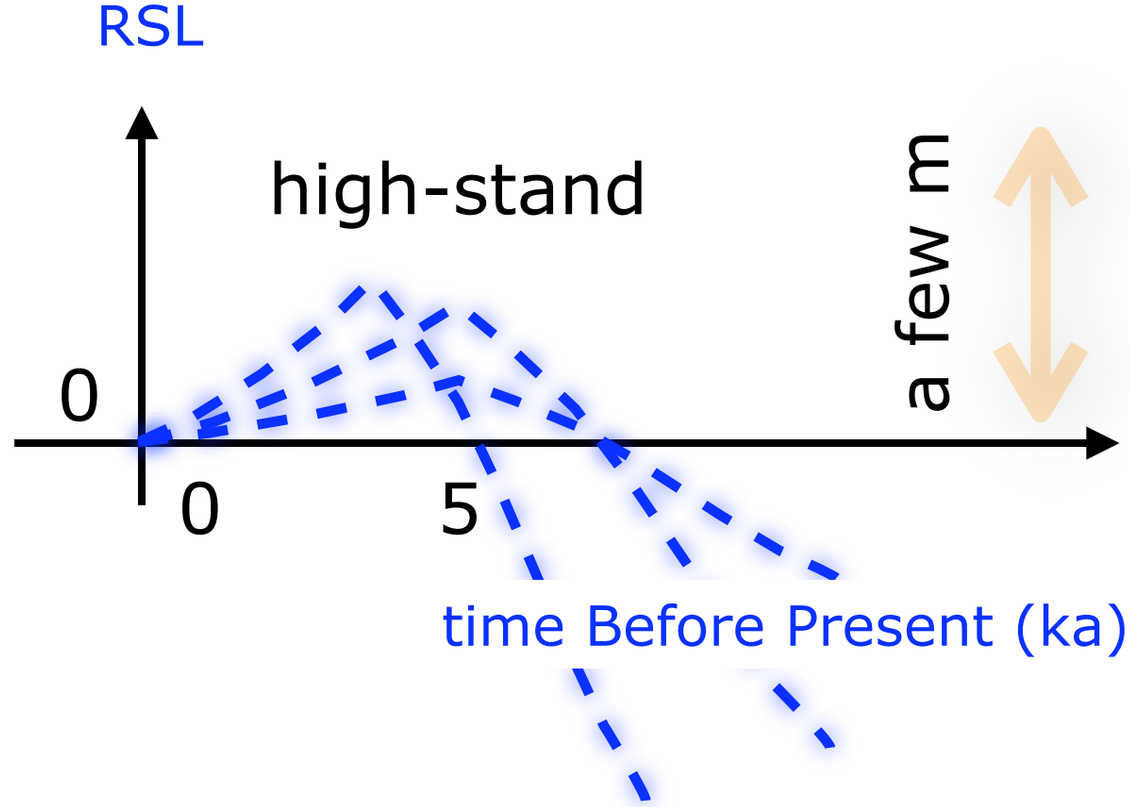
Kapapa Island (Ohau), Hawaiian Islands

Evidence from the Pacific

Kapapa & Malden Island

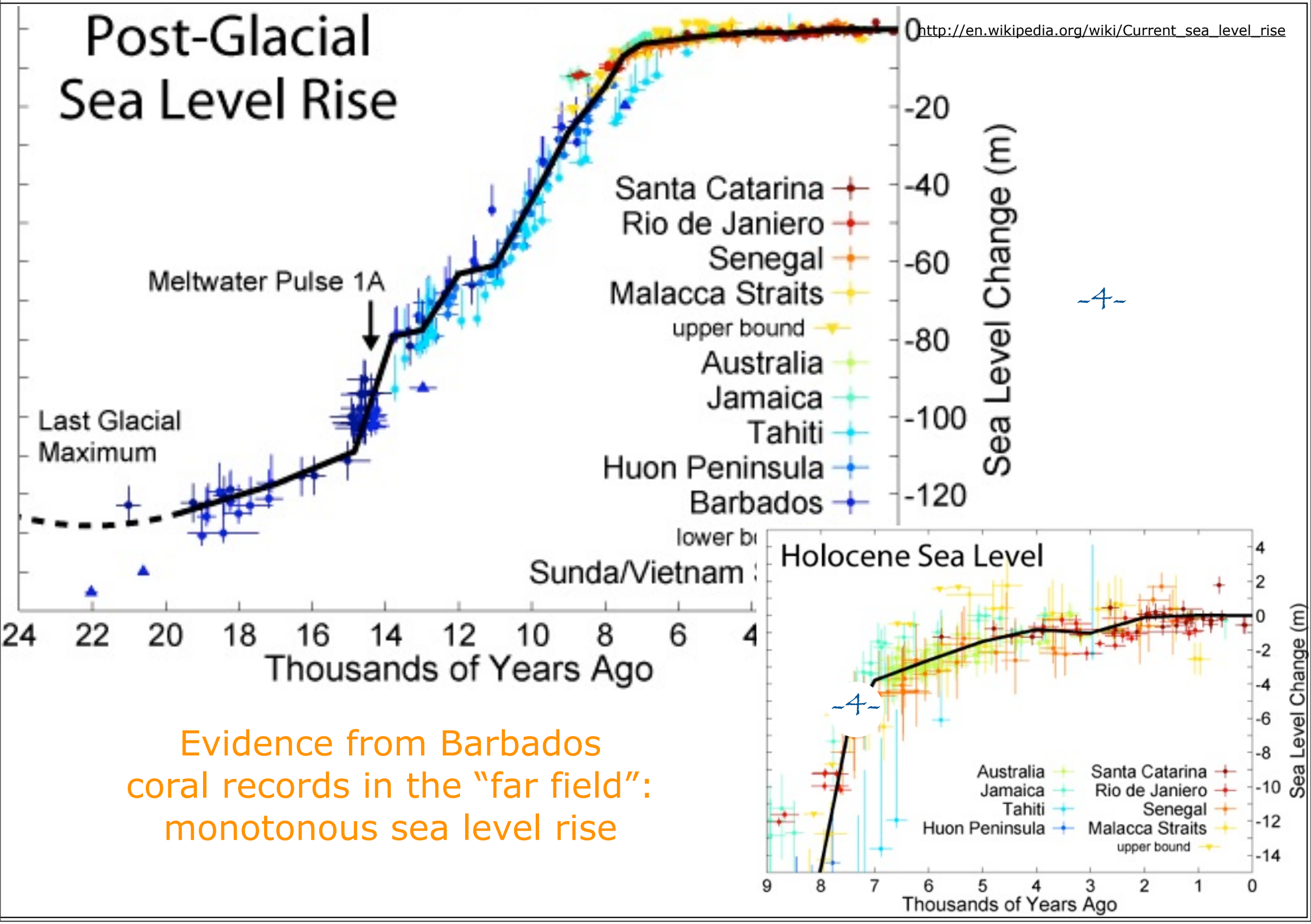


A *qualitative*
RELATIVE SEA LEVEL curve
for the Pacific Islands
based on *recently raised shorelines - Marine terraces*



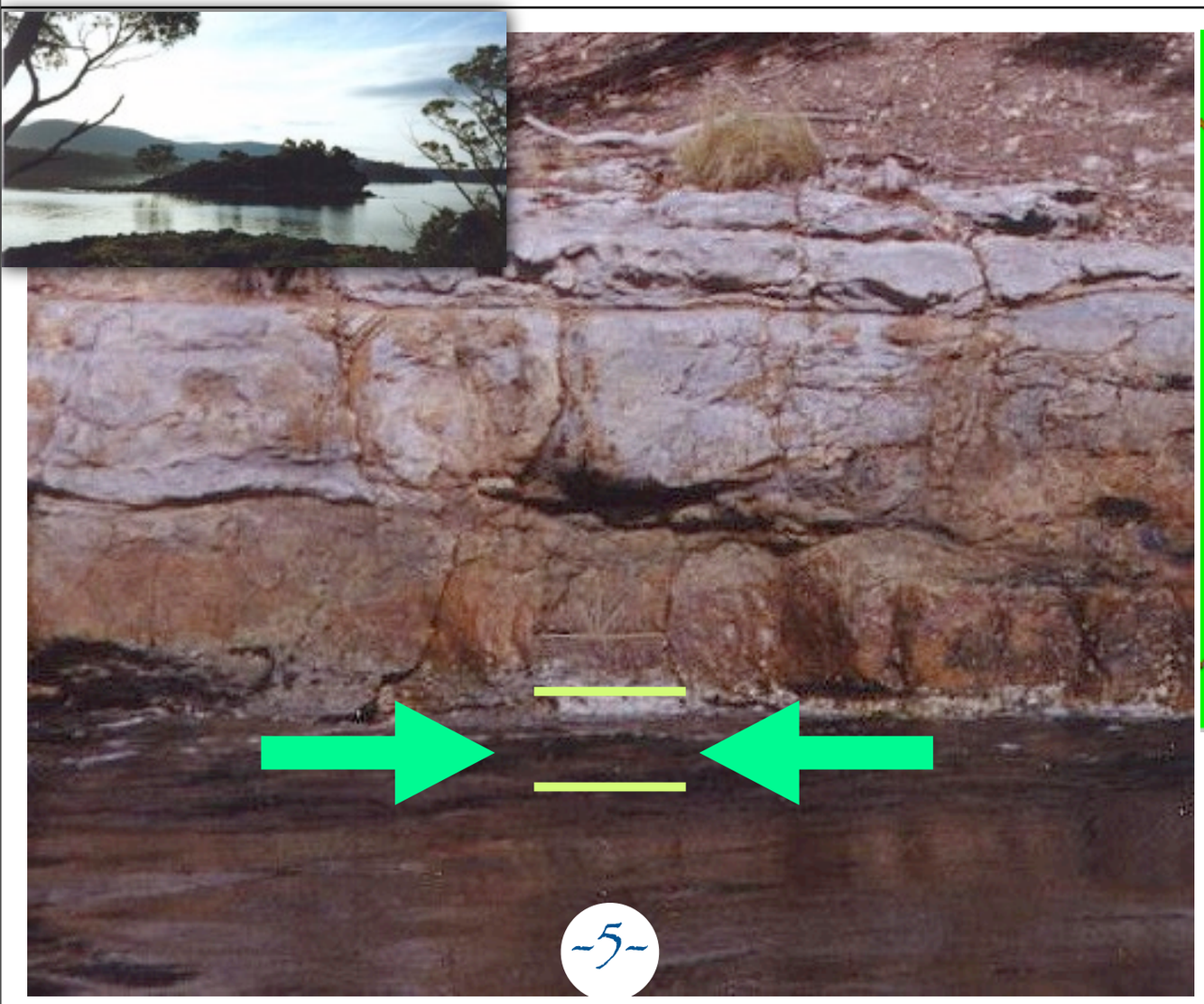
Evidence of a
Late-Holocene *high-stand*

Evidence from “remote sites” e.g. Barbados

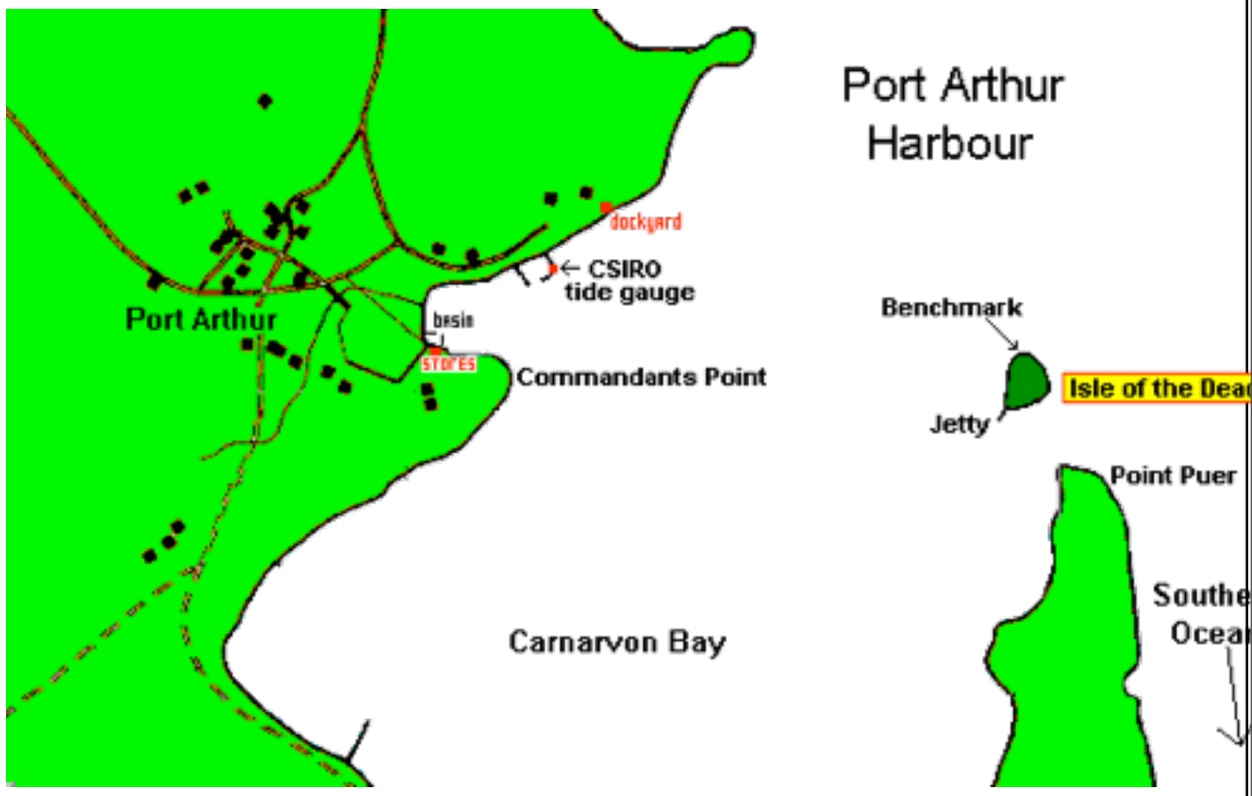


Evidence from Barbados
coral records in the “far field”:
monotonous sea level rise

Evidence from “remote sites”



Isle of the Dead



A proposal by **Baron Von Humboldt** to the **British Colonial Secretary**

… that mean sea level marks should be struck on newly discovered coasts and islands….

The Ross-Lempriere sea level **benchmark** on the `Isle of the Dead' , ca 1841

A stationary sea level in the last ~ 1.5 centuries?

What about the ~20 cm/century suggested by IPCC?

-6-

European collaboration
COST ES0701

4. Tyrrhenian

-4-

2. SE Tunisia

Liverpool University UK
MIUR project

-3-

-1-

1. Mallorca

University of South Florida USA

-2-

3. Cyclades

Remote Sensing Laboratory University of Athens
Delft University of Technology, Delft, NL

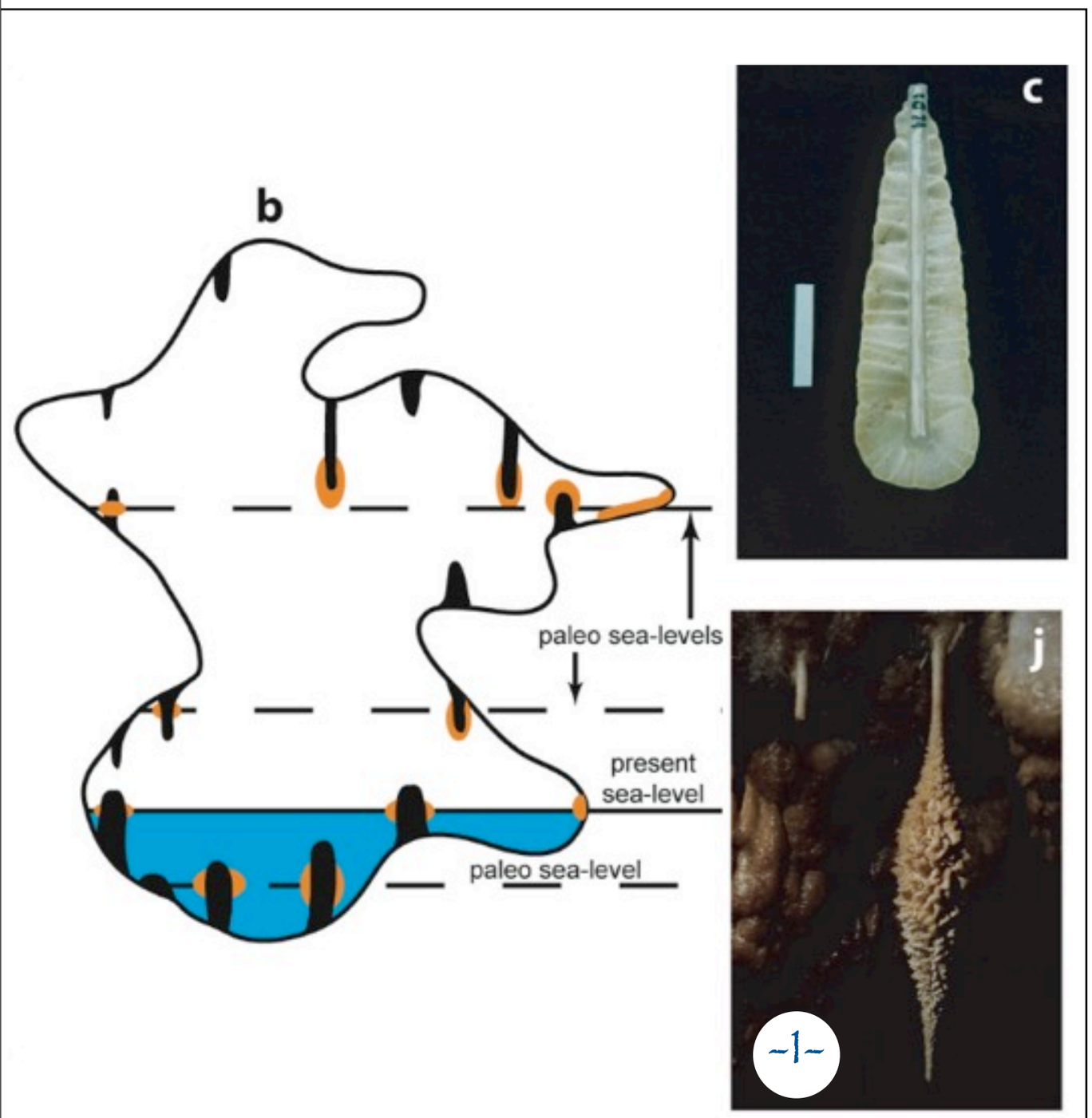
Avrupa Haritası, Piri Reis, Kitab-ı Bahriye
(16. yy. Sonuna Ait Bir Kopya) İstanbul Üniversitesi Kütüphanesi. No:6605
Map of Europe, Piri Reis, Kitab-ı Bahriye
(Copy Belonging to the end of 16. Century) Library of Istanbul University . No:6605

Courtesy of Bogdan Onac
Department of Geology
University of South Florida

Evidence from encrusted stalagmites Mallorca

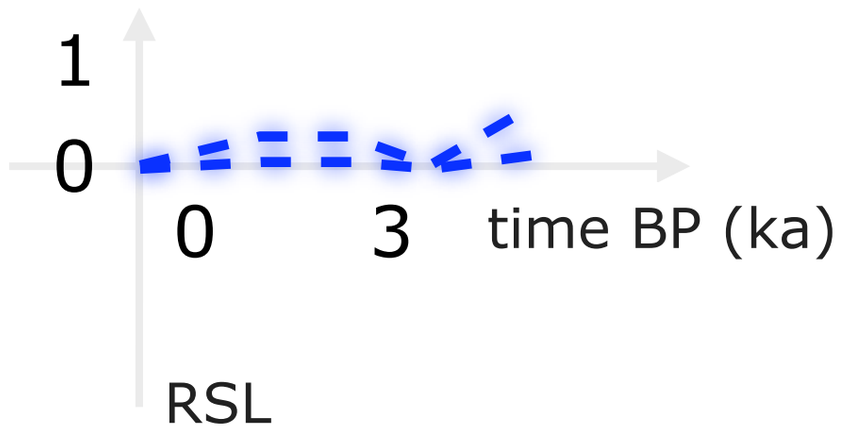
Evidence from encrusted stalagmites

Mallorca

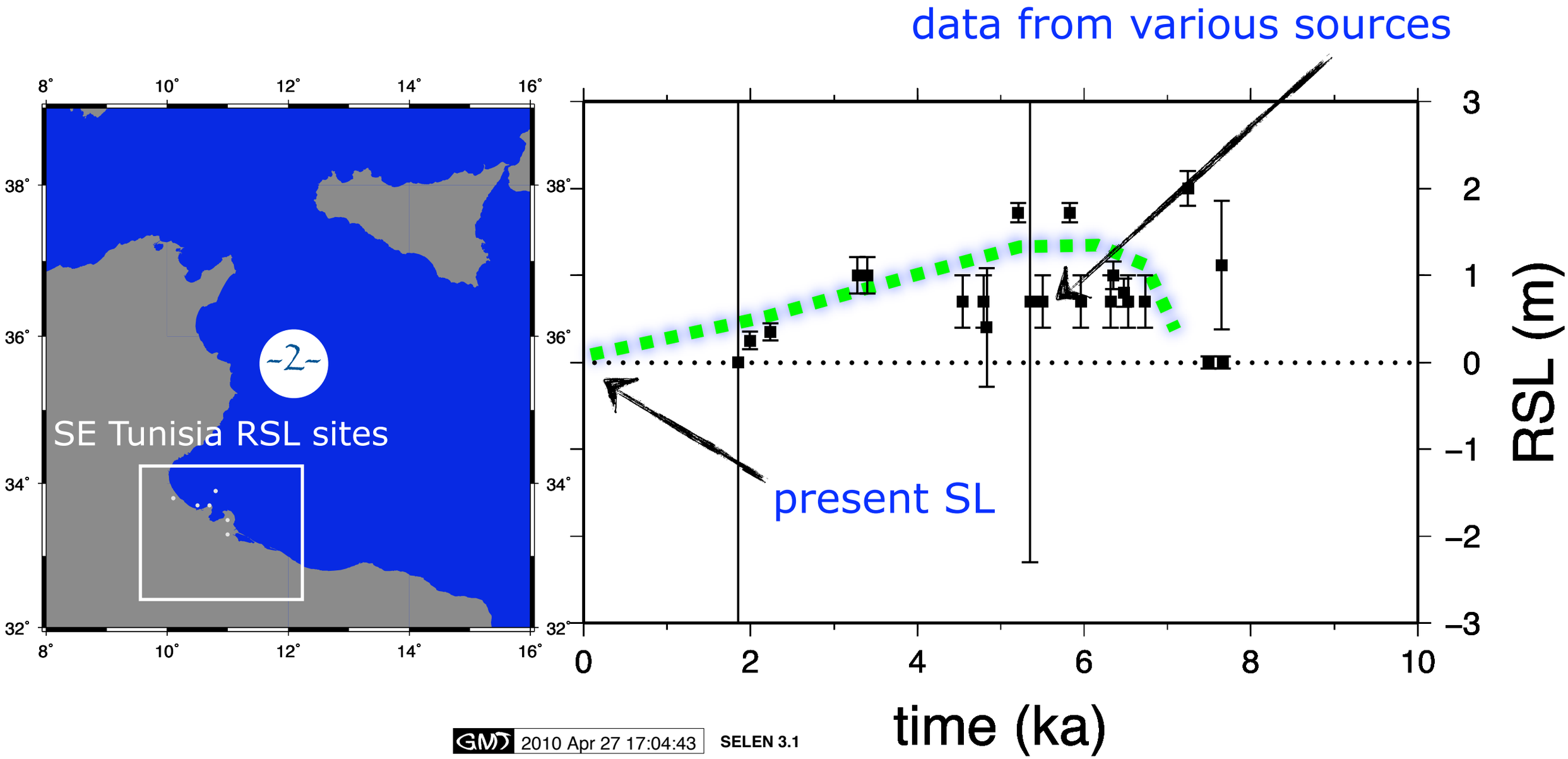


Evidence from stalagmites

"**Encrusted stalagmites**" are nowadays growing at present sea level (see image). The age of these bulbous calcite is 2800 years in the inner part and 0 at surface (forming now). The mean sea level corresponds to the thickest section of the stalagmite. These samples (dated by U/Th method) are 2800 years old or younger, which means the **sea level basically remained stable around Mallorca over the last ~3000 years** (+/- the tide effect).



~ stable sea level (since 3 ka)



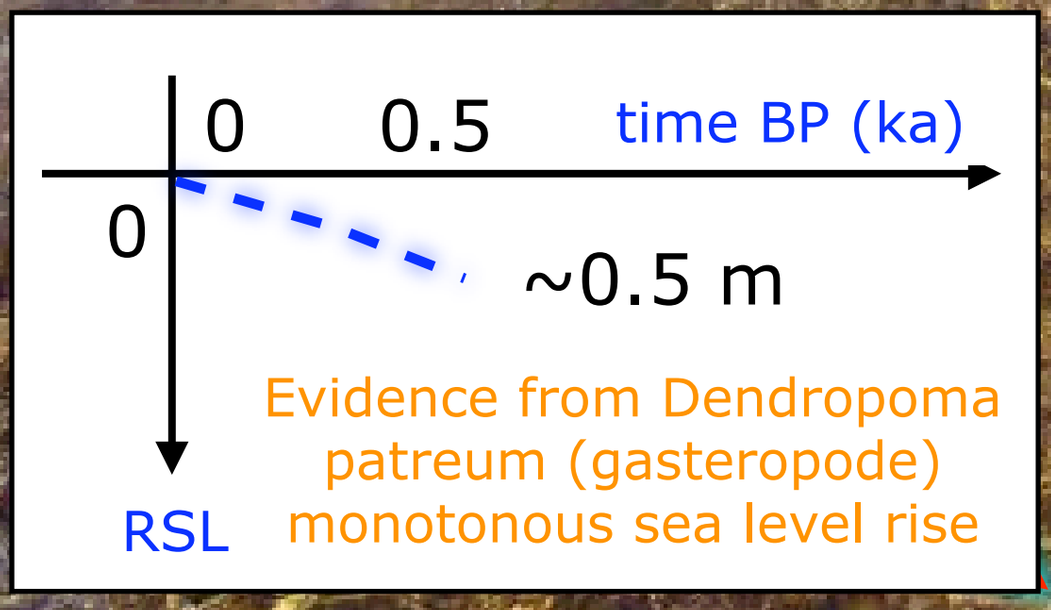
A late-Holocene high-stand in SE Tunisia?

possibly unique in the northern hemisphere

(also confirmed by recent beach rock field evidence, possibly unique in the Mediterranean).

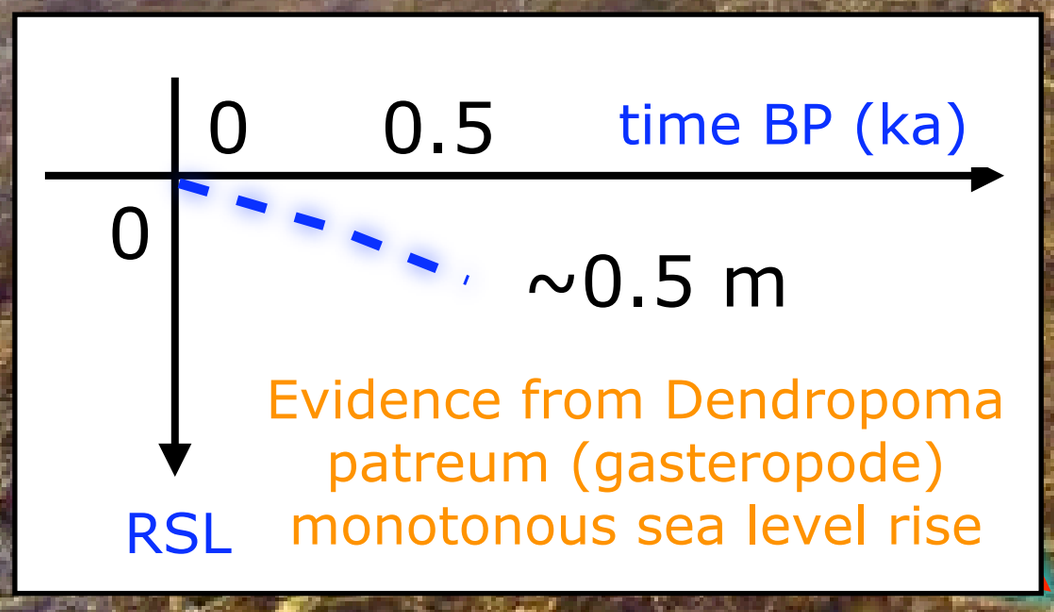
recent sea level RISE

San Vito lo Capo, NW Sicily



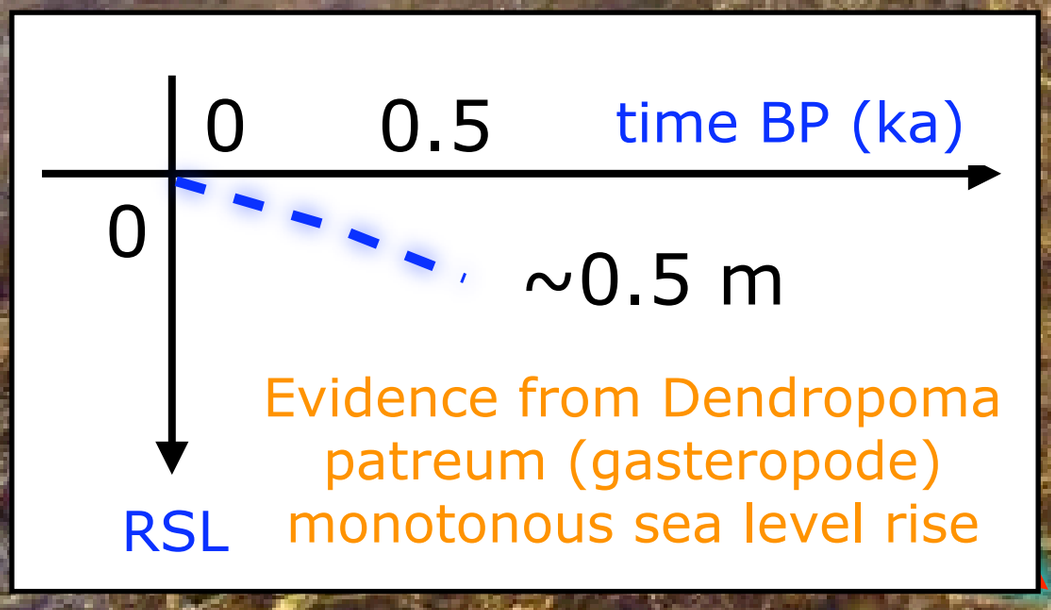
recent sea level RISE

San Vito lo Capo, NW Sicily



recent sea level RISE

San Vito lo Capo, NW Sicily



A case study the Mediterranean Sea



RSL observations

"RSL zones"

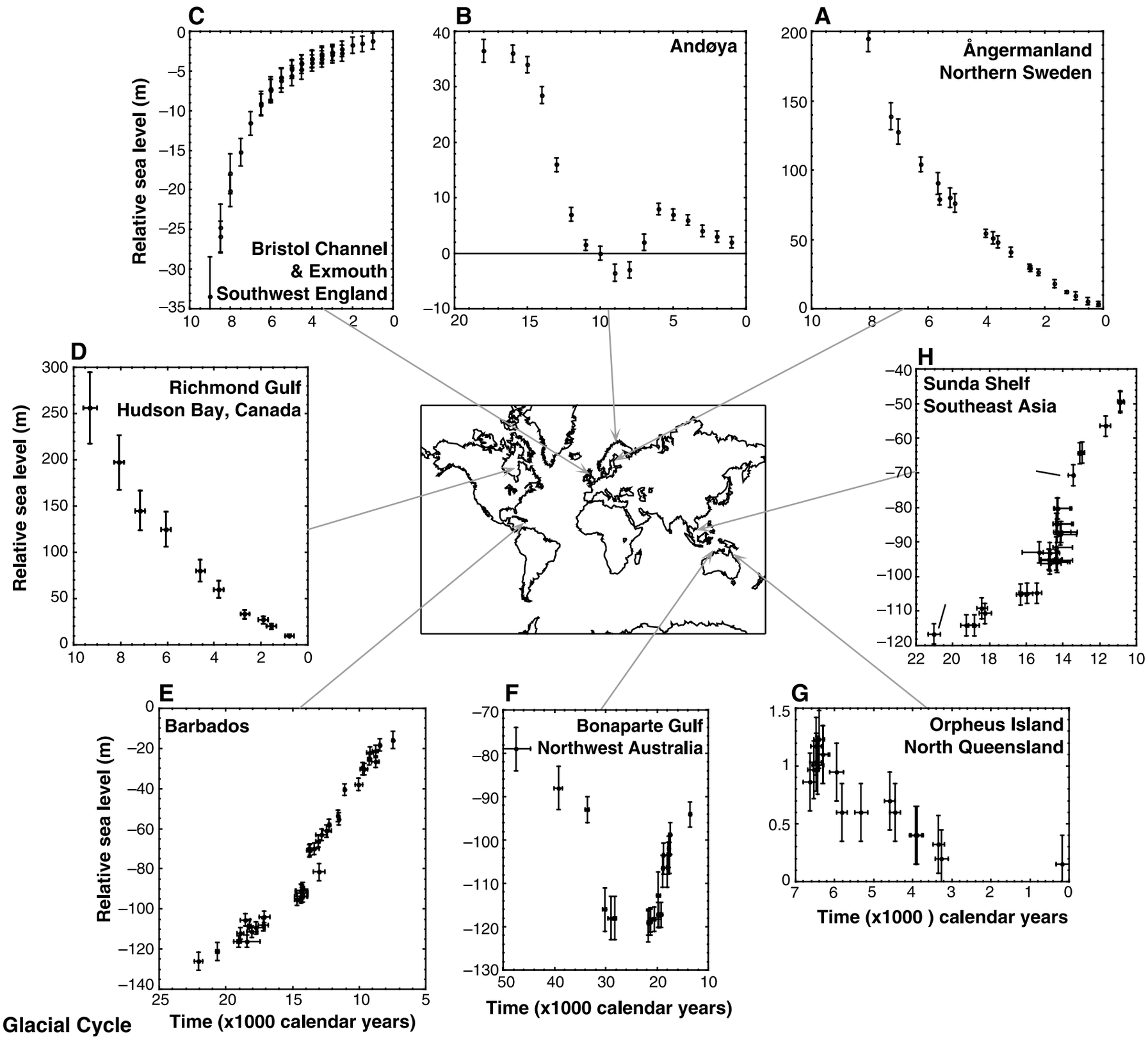


Fig. 2. Observed spatial variability of sea level change since the time of the LGM from tectonically stable areas or areas where the tectonic rate is known and has been removed from the observed signal. (**A**) Ångerman, Gulf of Bothnia, Sweden (*13*). (**B**) Andøya, Nordland, Norway (*12*). (**C**) South of England (*14*). (**D**) Hudson Bay, Canada (*4*). (**E**) Barbados (*16*–*18*). (**F**) Bonaparte Gulf, northwest Australia (*27*). (**G**) Orpheus Island, North Queensland, Australia [(*23*) and unpublished Australian National University data]. (**H**) Sunda Shelf, southeast Asia (*15*). Note the different time and amplitude scales. In the examples illustrated, all observed depths or elevations of the sea level indicators have been reduced to mean sea level. All time scales are in calendar years.

Downloaded from www.sciencemag.org

Sea Level Change Through the Last Glacial Cycle
Kurt Lambeck, *et al.*
Science **292**, 679 (2001);
DOI: 10.1126/science.1059549

Evidence from field data

To summarize, from these examples:

1. ... we observe sea level **rise**, sea level **fall**, **high-stands**, **rapid changes**, **stationary** sea levels... in different parts of the world, even in "tectonically stable" areas,

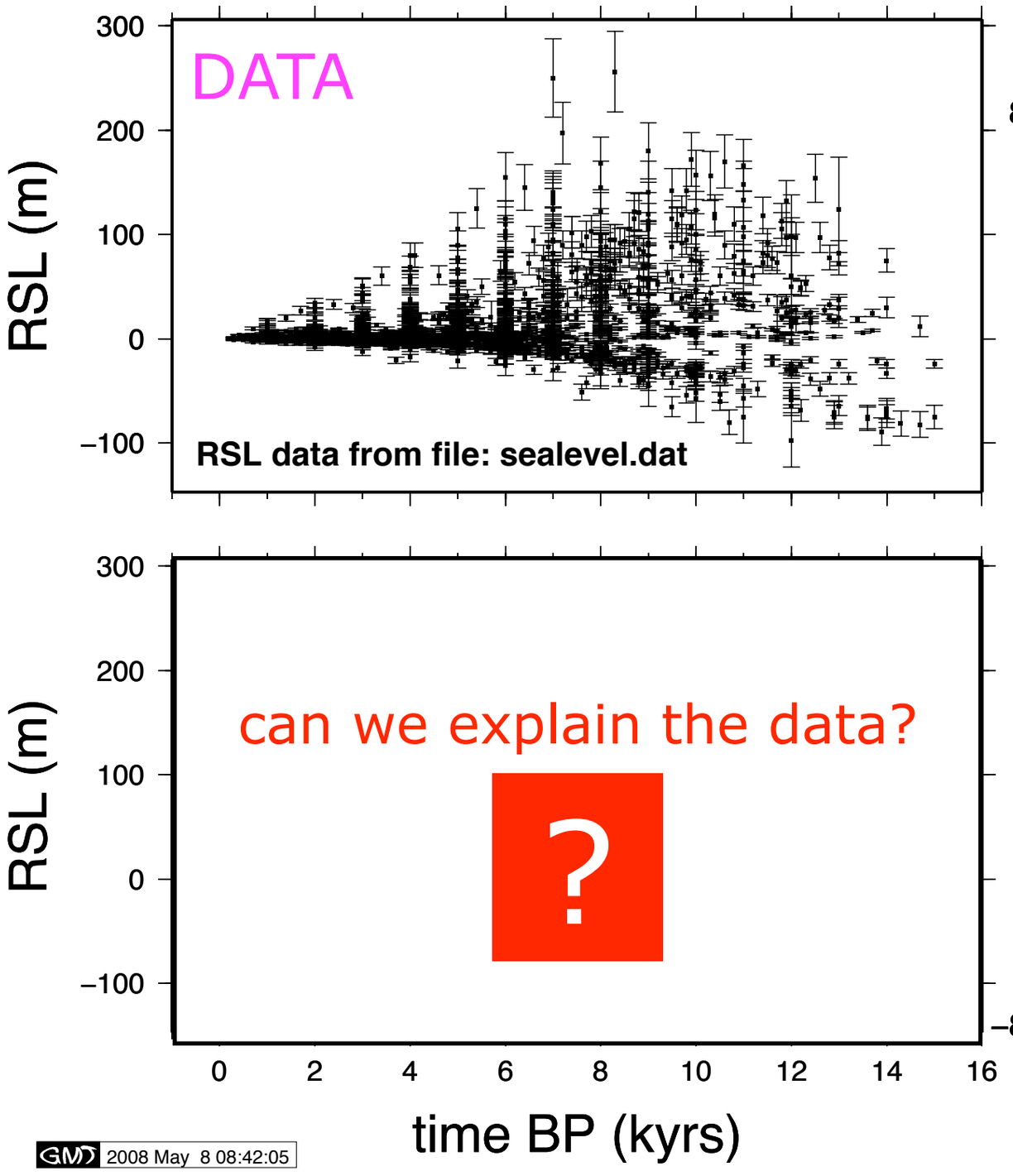
2. There is **no evidence of a globally uniform sea level rise** since the LGM. This contrasts with intuition that suggests a uniform filling of basins during melting,

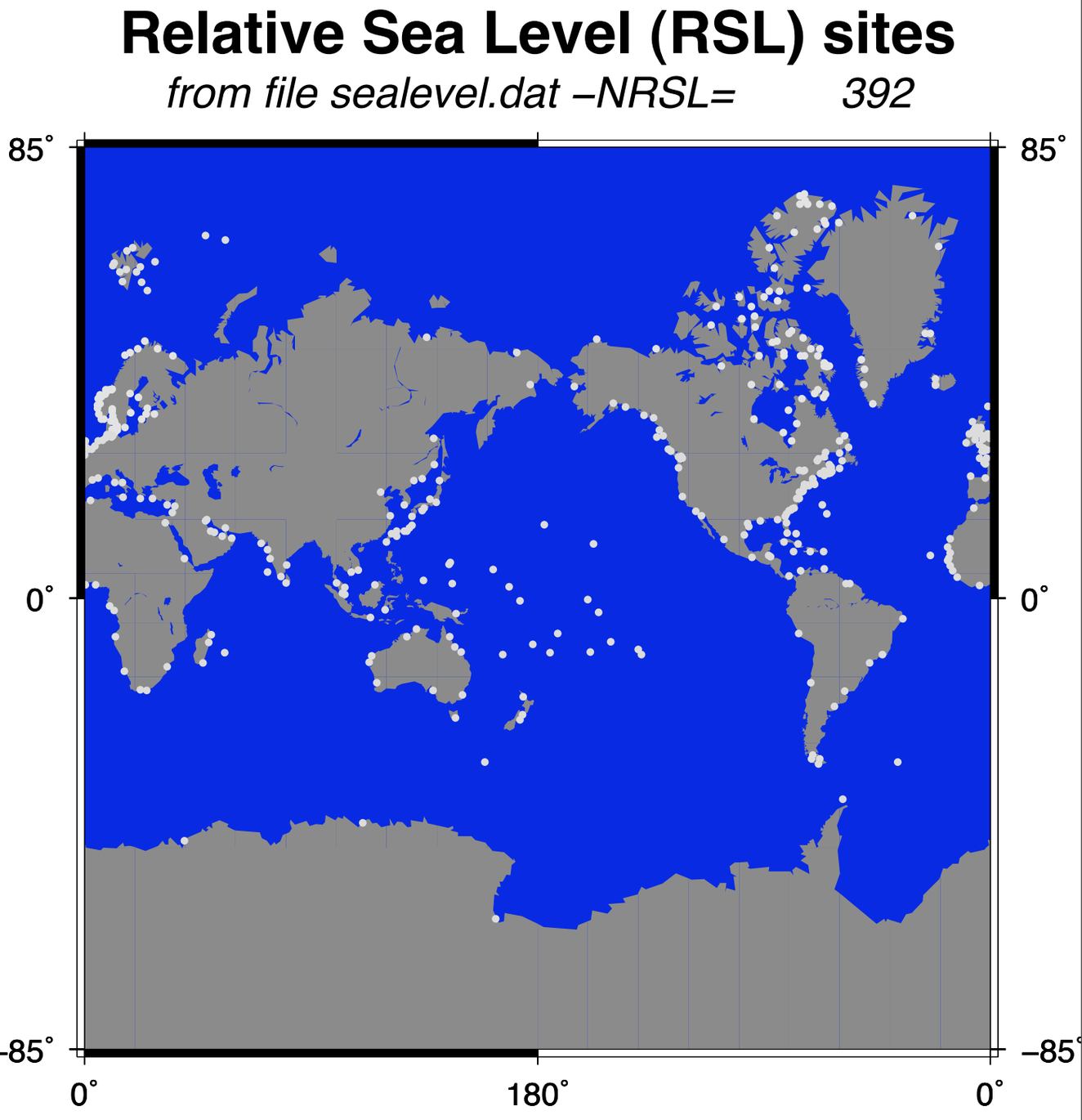
3. A **variety of sea level curves** is also observed across relatively narrow basins (e. g. the Mediterranean),

4. **Possible explanation (i):** errors in data, misinterpretation, ...

5. **Possible explanation (ii):** data are OK, but we need a valid "*theory of glacio-isostatic adjustment" (GIA).*

GLOBAL Relative Sea Level (RSL) observations



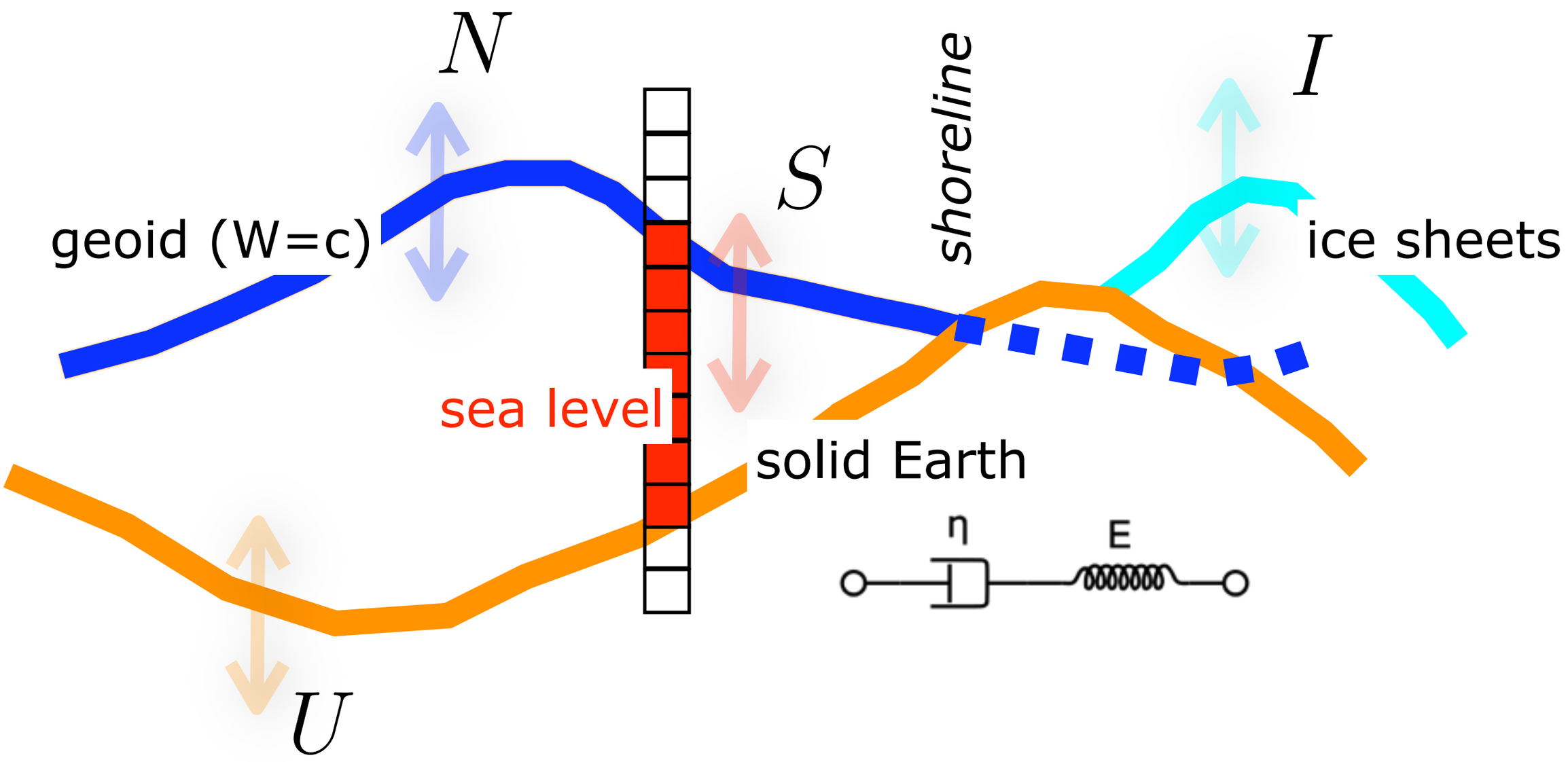


T/P database

http://gcmd.nasa.gov/records/GCMD_EARTH_LAND_NGDC_PALEO_SEALEVEL1.html

Is it possible to write a simple
“equation” for sea level
?

Geoid, ICE SHEETS, Solid Earth & SEA LEVEL



the "Sea Level Equation" is: $S = N - U$

A couple of difficulties:

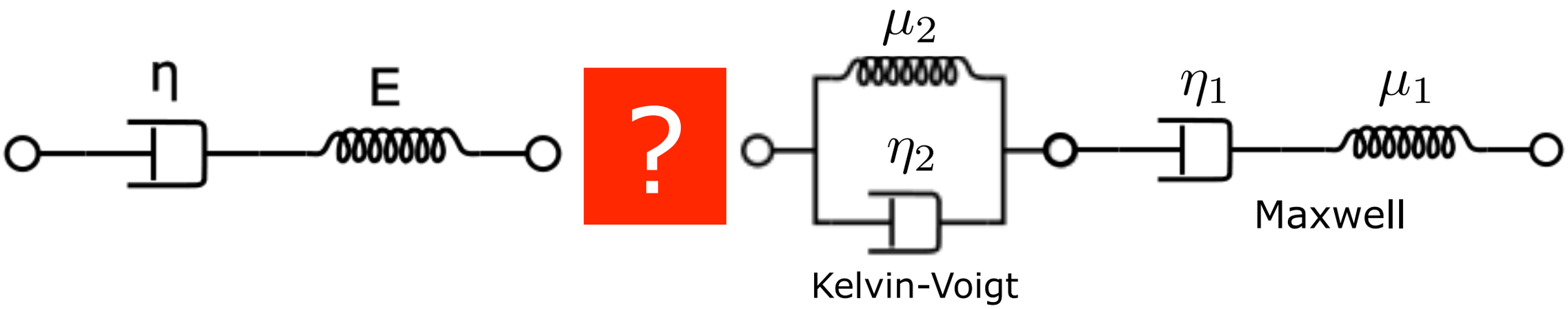
1. *N* and *U* both depend on *S* itself!

   In fact, *U* is determined by the ice load BUT also by the water load, whose amplitude is related with variations of the water column, e. g., from sea level change itself, S. Hence:

   U = U(S,I) and *N = N(S,I)*

   S = S(U,N,I) = Implicit function of S itself.

2. What about Earth rheology? What is the response to loads?



3. Which rheology for the Earth's mantle?

- Forward "Creep problem" (theoretical viscoelasticity)

Given the "LOAD" + *Rheology, then* compute the system response (e.g. strain)

- Inverse "Creep problem" (real world)

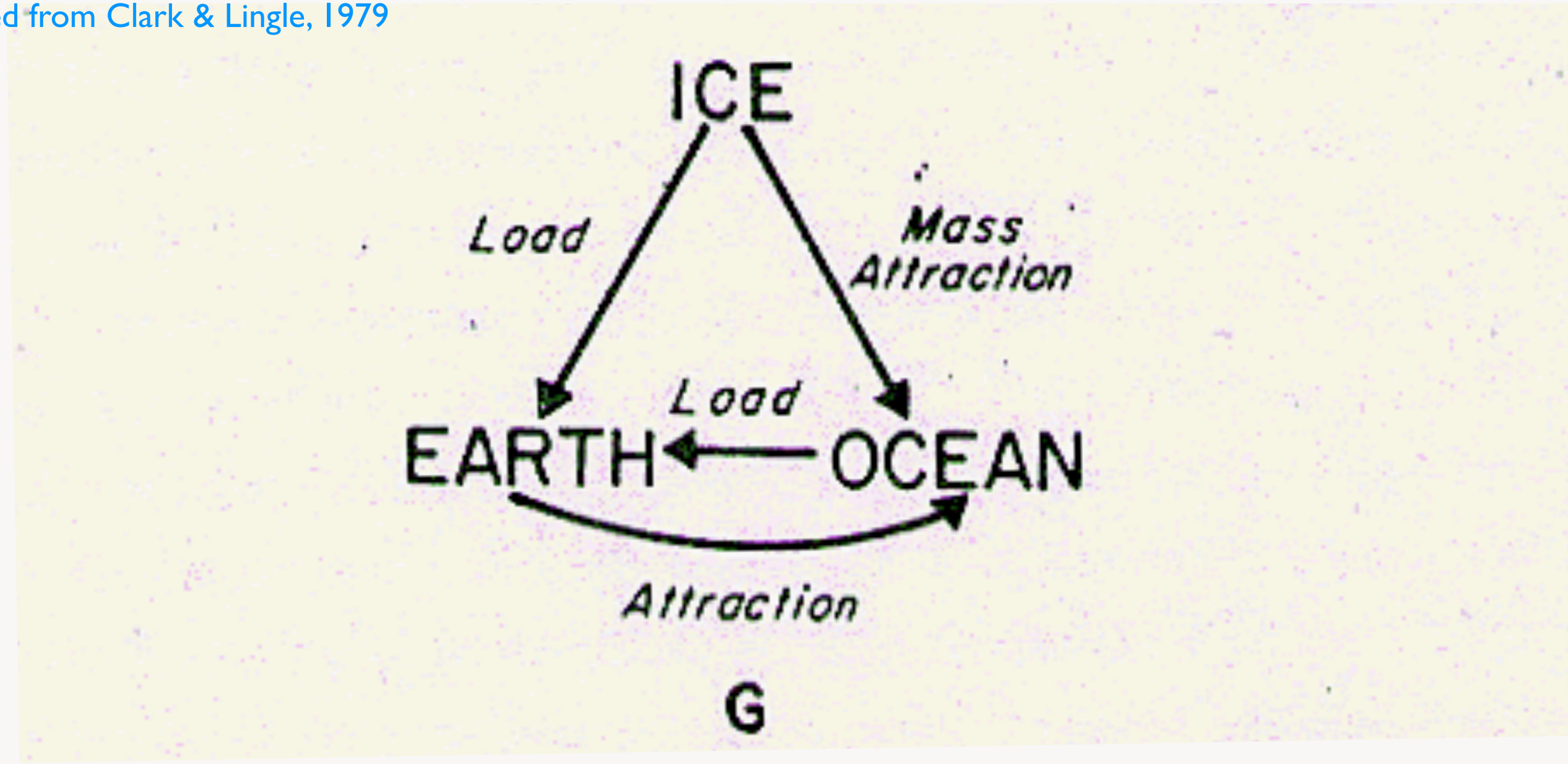
Given some (imperfect) knowledge about the "load" (ice sheets), obtained by glaciology, geology and geomorphology,

and given imperfect knowledge about the response (e.g. sea level change, from indirect evidence during the Holocene),

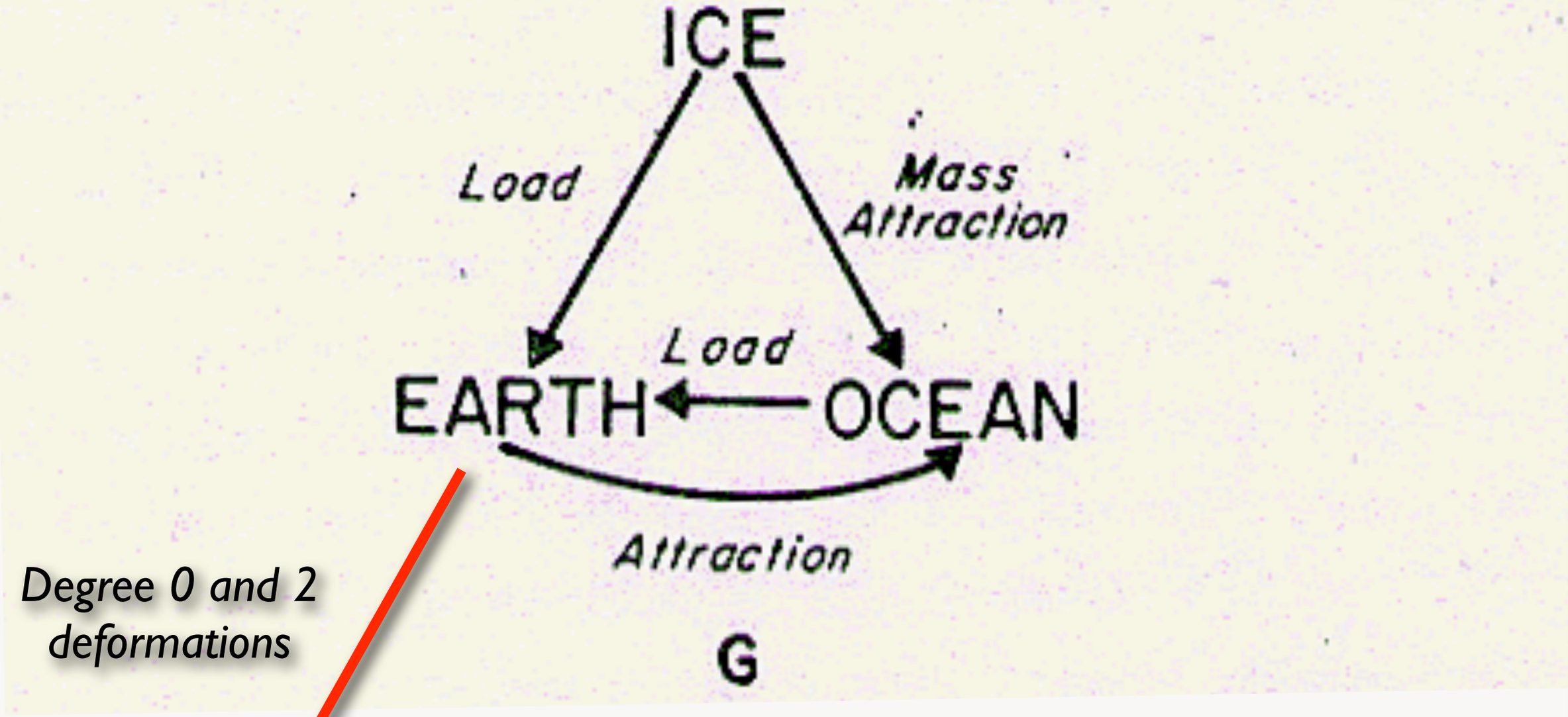
then, infer mantle rheology.

(*) In a "creep experiment", a load is applied instantaneously.

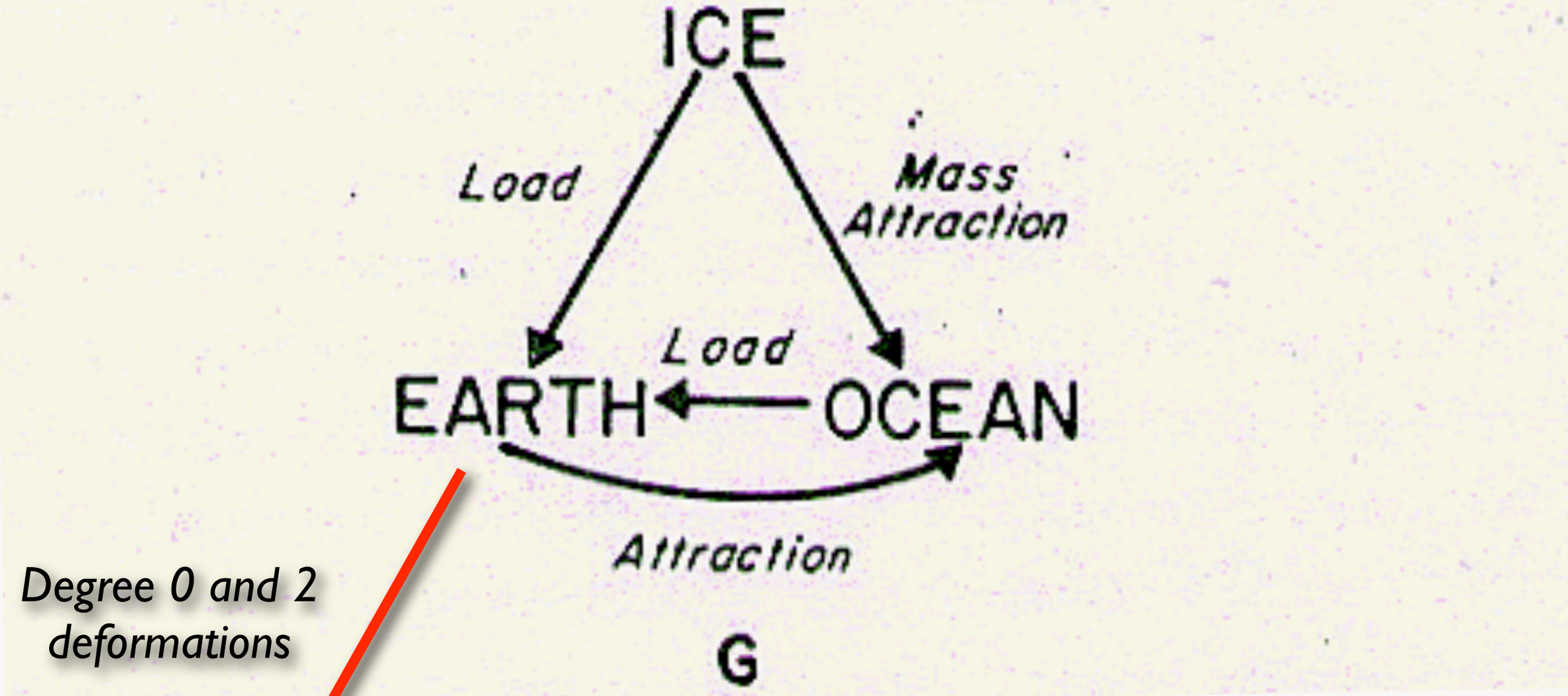
Adapted from Clark & Lingle, 1979



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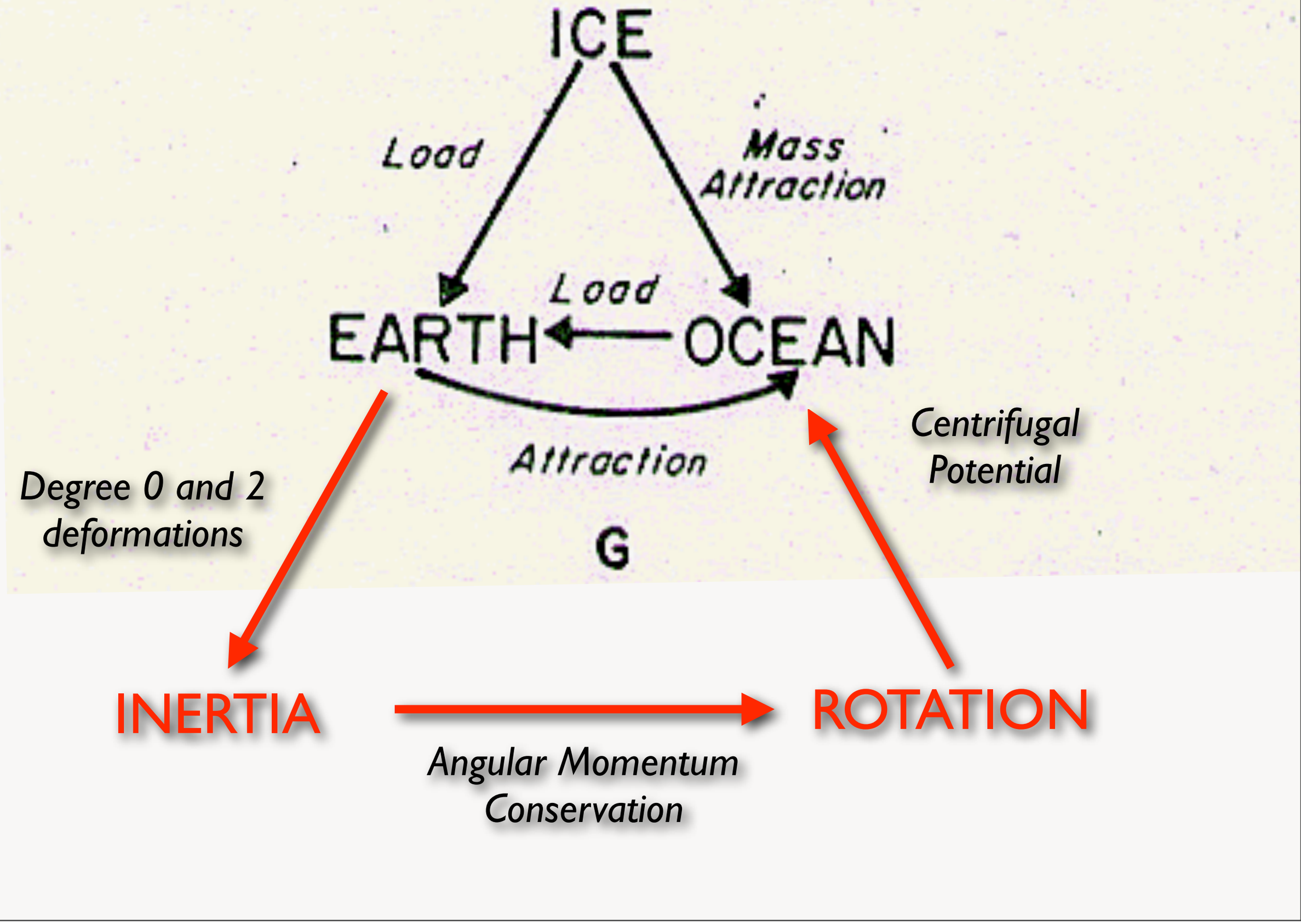


Degree 0 and 2 deformations

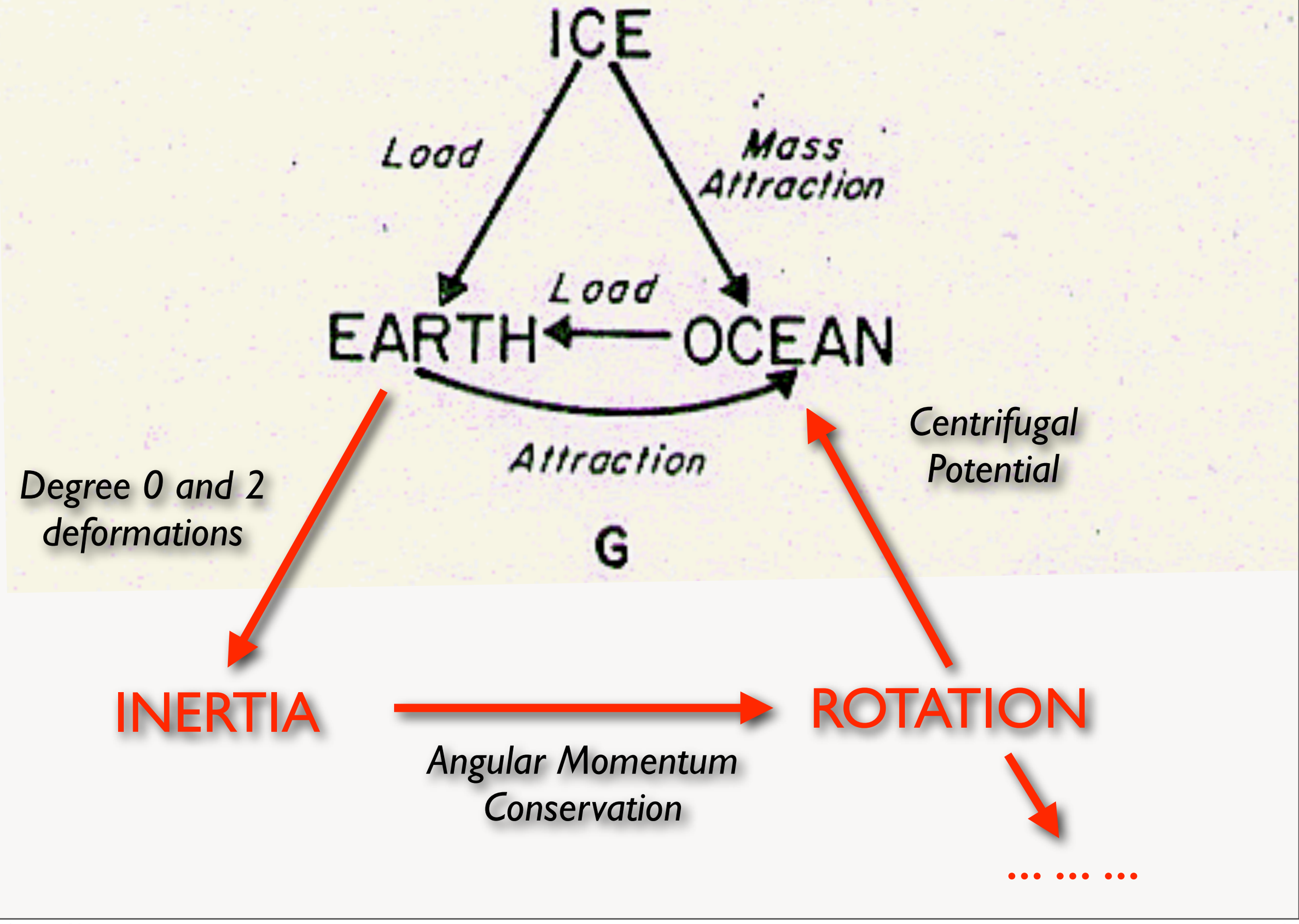
INERTIA → ROTATION

Angular Momentum Conservation

Adapted from Clark & Lingle, 1979



Adapted from Clark & Lingle, 1979



Farrell (1976) has shown that the "original" SLE:

$$S = N - U$$

can be transformed into:

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$

with:

$S =$ sea level change

$m_i =$ ice mass variation

$\rho_i, \rho_w =$ ice and water density

$A_o =$ area of the oceans

$G_s =$ sea level Green function

$\otimes_i, \otimes_o =$ 3(2+1)D convolutions

$I =$ ice thickness variation

$\overline{(\ldots)} =$ ocean average

About the SLE

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$

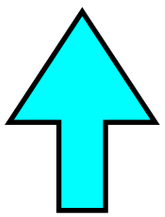
The SLE is a **linear**, **integral equation**, since the unknown S also appears within convolution integrals.

Sea level change at one point ω and time t depends on sea level change at any point ω' and at any time $t' \leq t$.

the problem of sea level change cannot be reduced to a regional scale

About the SLE

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$



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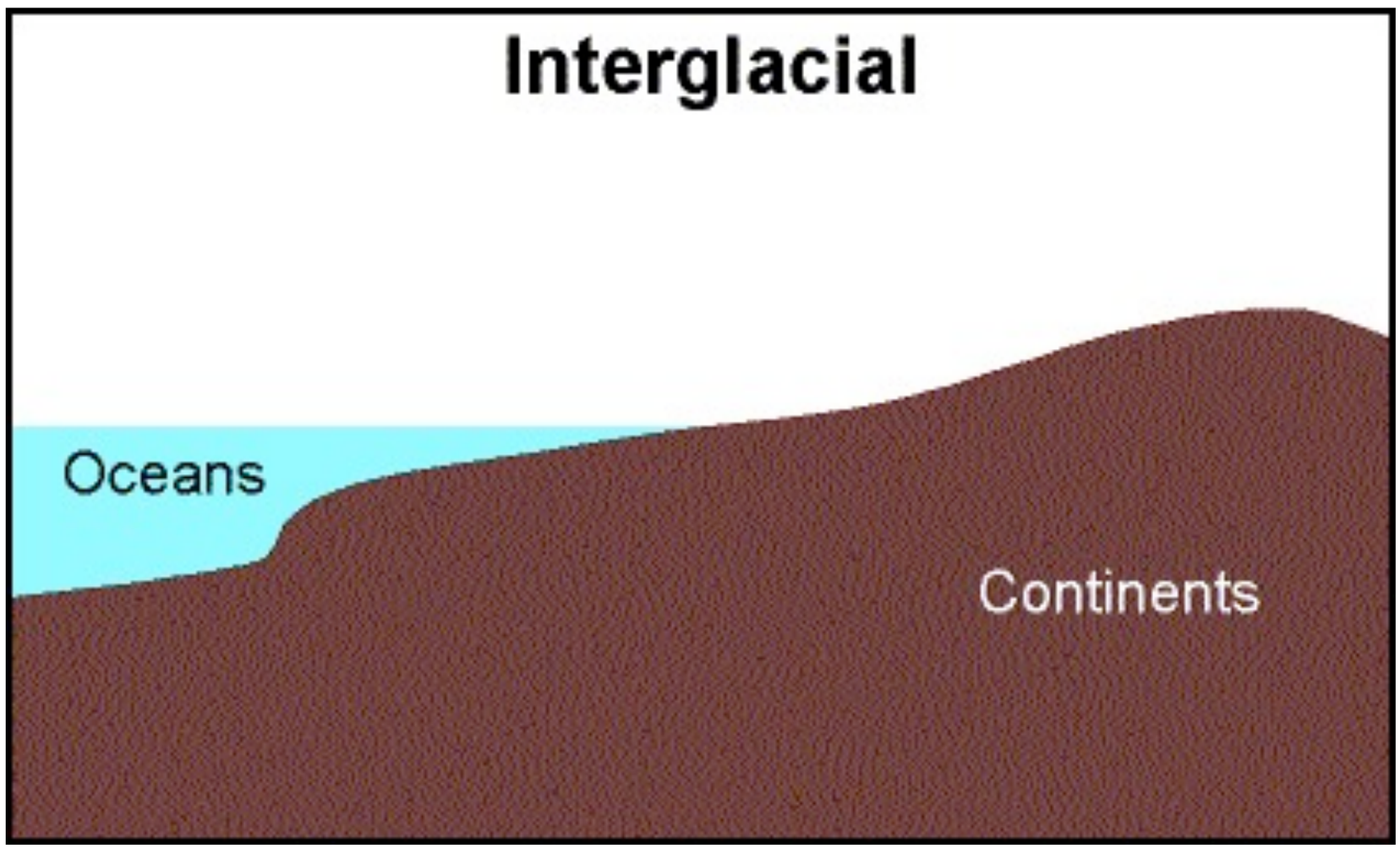
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the problem of sea level change cannot be reduced to a regional scale

Exercise #1: Dropping some terms in the SLE.

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$



Eustatic solution!

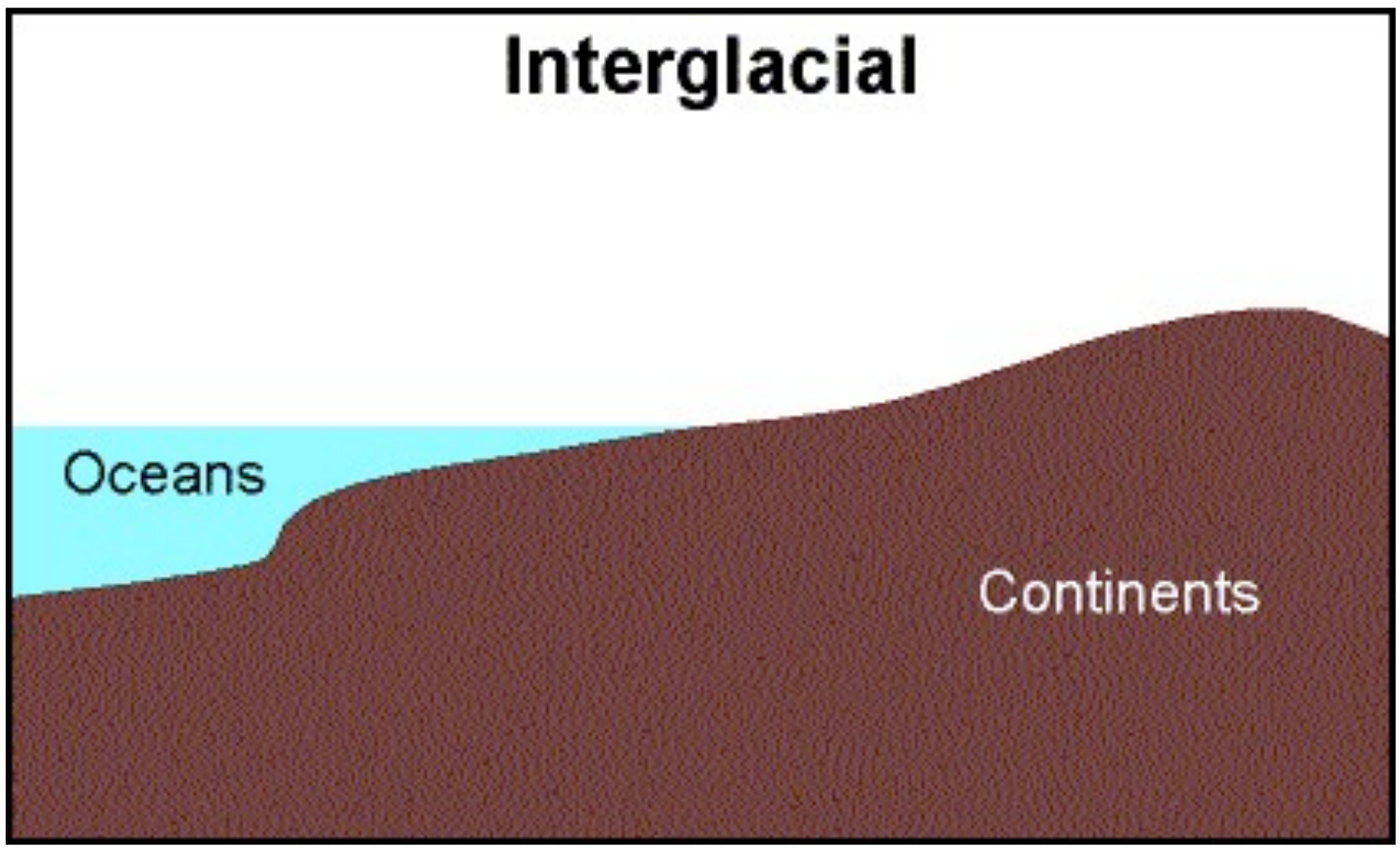
$$S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}$$

solves the SLE in the very special case:

the EARTH is RIGID
and
Newton constant is =0

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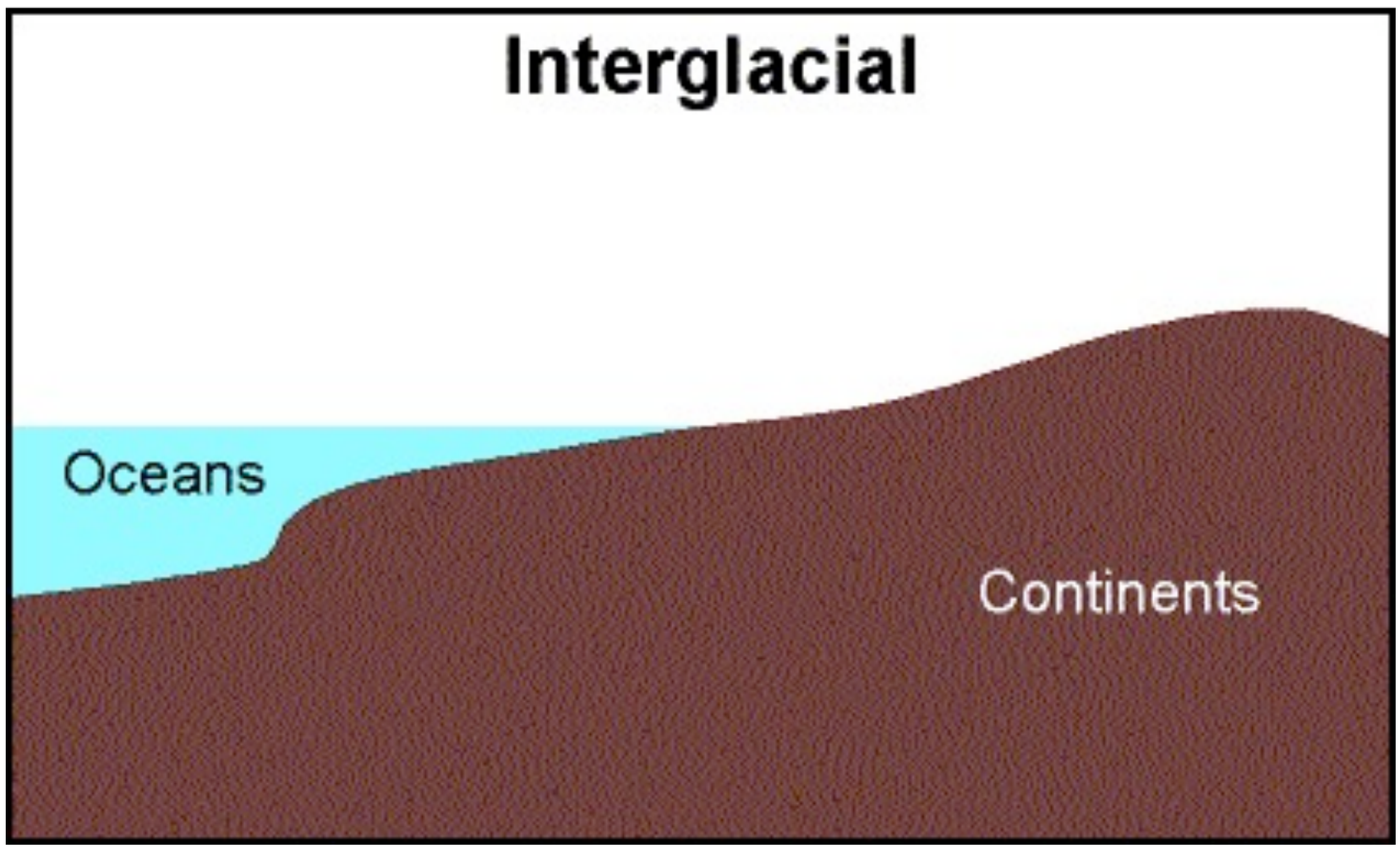
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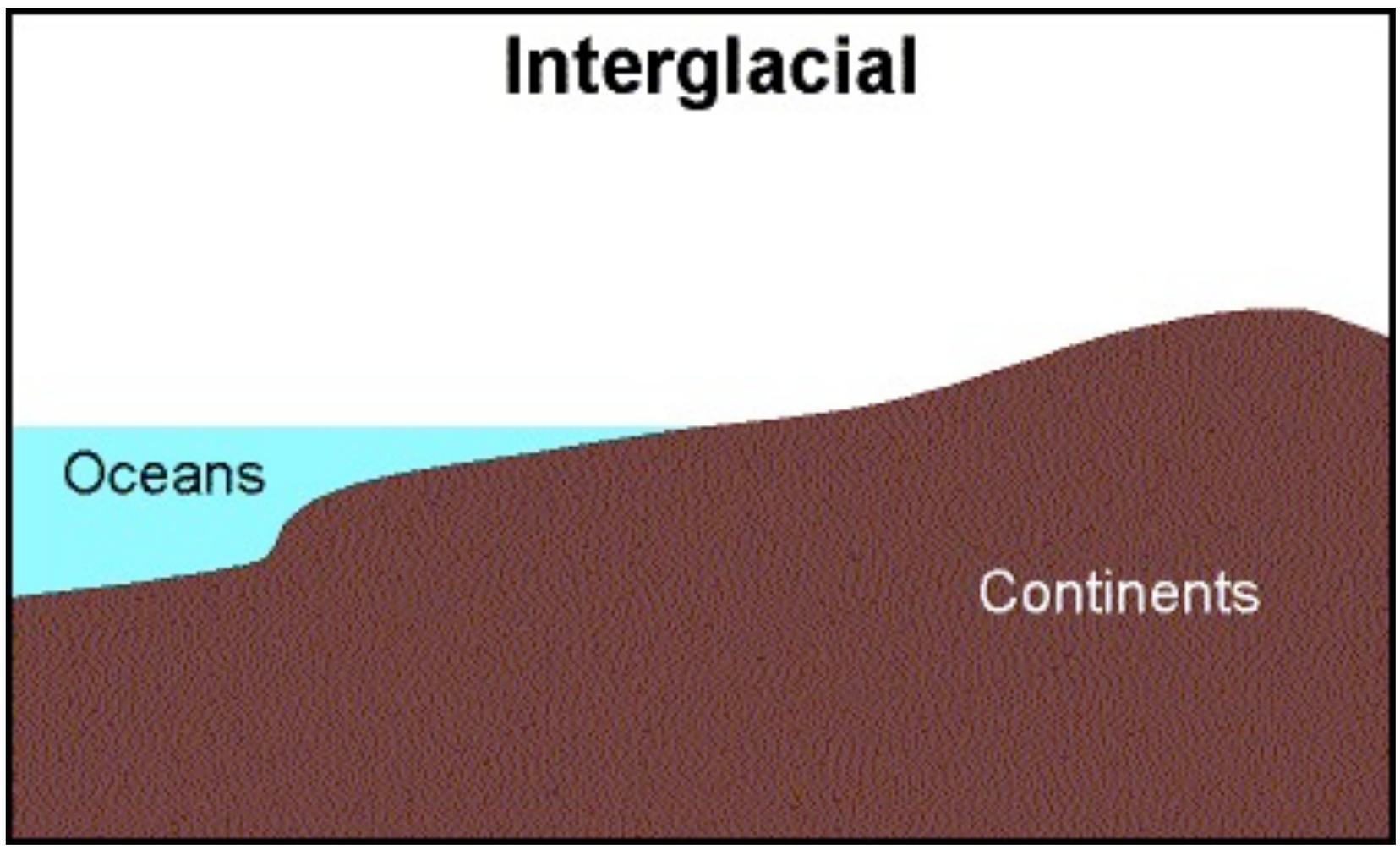
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Eustatic solution!

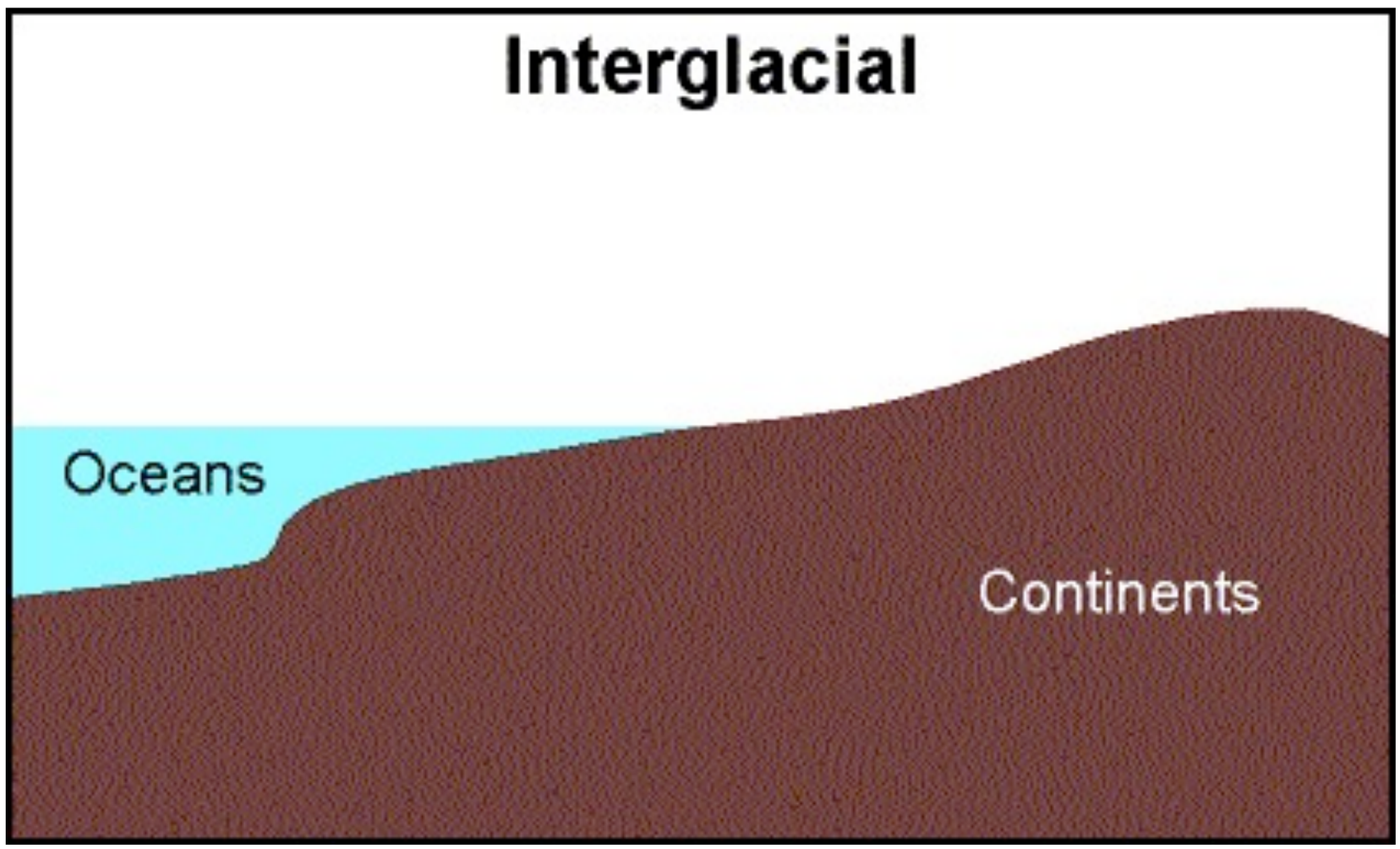
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Eustatic solution!

$$S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}$$

solves the SLE in the very special case:

the EARTH is RIGID
and
Newton constant is =0

Exercise #2: Taking the ocean-average of the SLE.

$$\overline{S} = \frac{\rho_i}{\gamma}\overline{G_s \otimes_i I} + \frac{\rho_w}{\gamma}\overline{G_s \otimes_o S} + \overline{S^E} - \frac{\rho_i}{\gamma}\overline{\overline{G_s \otimes_i I}} - \frac{\rho_w}{\gamma}\overline{\overline{G_s \otimes_o S}}$$

Hence:

$$\overline{S} = S^E$$

(regardless of rheology, actual shape of shorelines...).

"the ocean-averaged sea level change coincides with the sea level change we would observe in eustatic conditions".

A consequence:
If the ice masses do not vary, the ocean-averaged sea level change is ZERO *(and vice-versa)*.

HOW to solve the SLE ? A few ideas here ...

The SLE "looks like" a *"inhomogeneous integral Fredholm equation of the 2nd type"*, where the unknown occurs both inside and outside the integral, and the integration interval is fixed *(fixed shorelines, in our language)*, which in 1D sounds like:

$$\varphi(x) = f(x) + \lambda \int_a^b K(x, x')\varphi(x')dx',$$

The problem can be solved by "iteration" of a first-guess solution:

0. Assume $\varphi(x) = \varphi^{(0)}$

1. This gives $\varphi^{(1)}(x) = f(x) + \lambda \int_a^b K(x, x')\varphi^{(0)}dx'$

... ...

n. At step "n": $\varphi^{(n)}(x) = f(x) + \lambda \int_a^b K(x, x')\varphi^{(n-1)}(x')dx'$

... ...

and continue until some convergence criterion is met...



SELEN 3.0

A source free, pesudo-spectral Sea Level equation solver

Spada, G., Stocchi, P., 2007. Comput. & Geosci. doi: 10.1016/j.cageo.2006.08.006.

* NEW features under development * (helped by Florence Colleoni CMCC BO) *

TABOO (~ 1997)

A source-free Post-glacial rebound solver

Spada et al. Manuals & theory notes on the Samizdat page, http://samizdat.mines.edu.

ALMA (2008)

A Love number (Green function) calculator

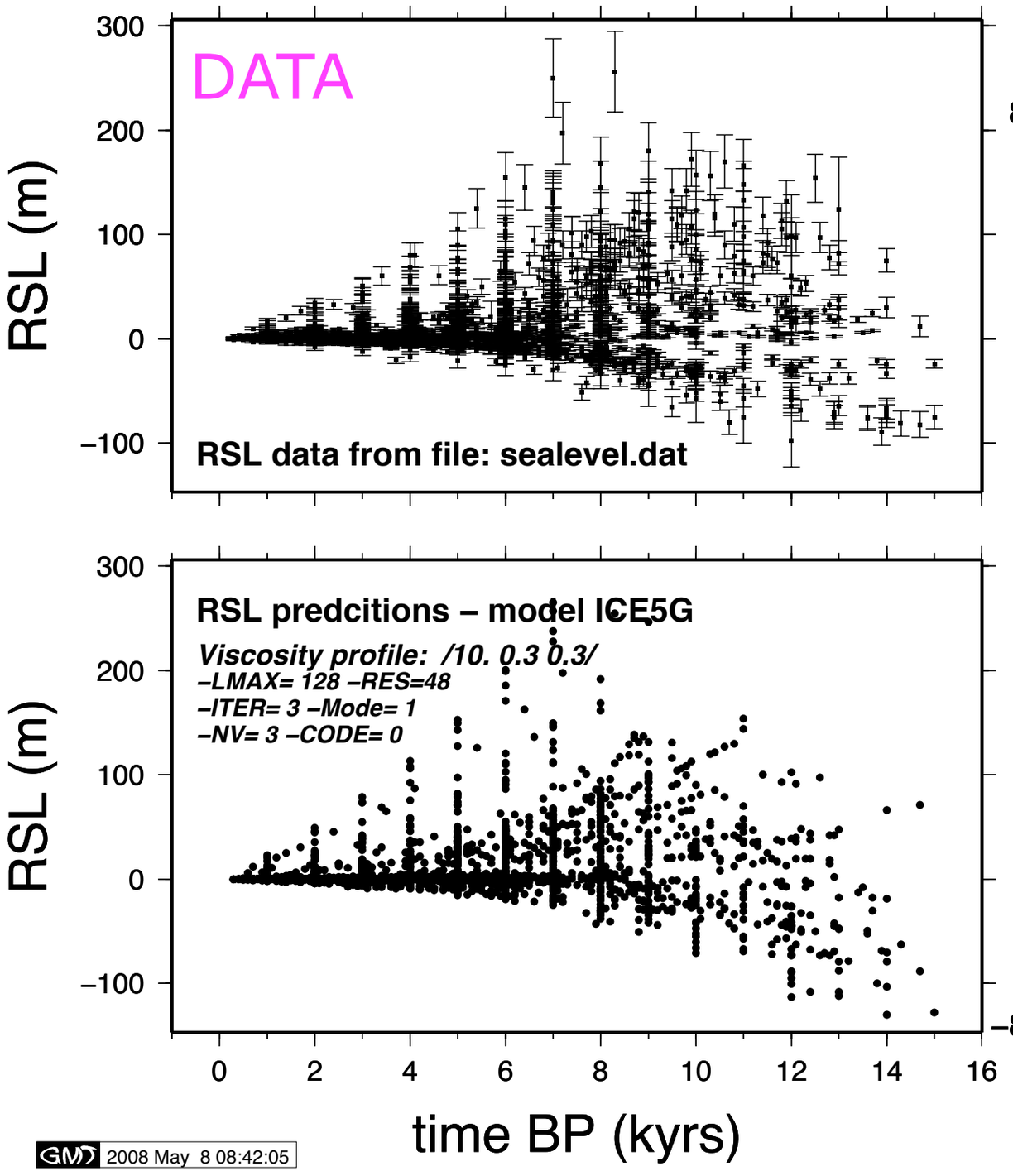
Spada, G., Boschi, L. 2006., Geophys. J. Int., doi: 10.1111/j.1365- 246X.2006.02995.x.

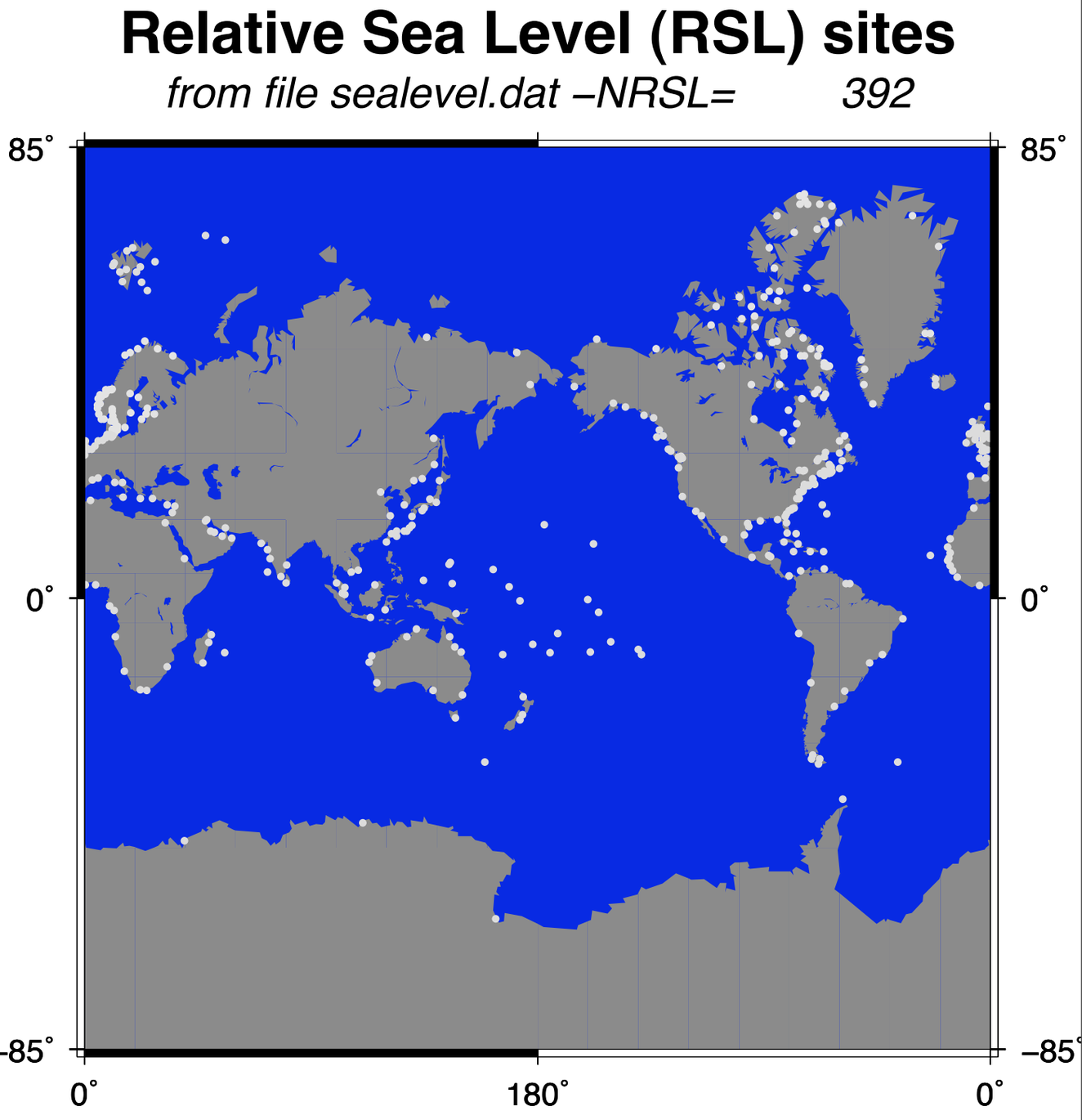
Spada, G., 2008. , Comput. & Geosci., doi: 0.1016/j.cageo.2007.12.001.

Theory vs Holocene RSL observations

Model vs RSL observations

the global scale

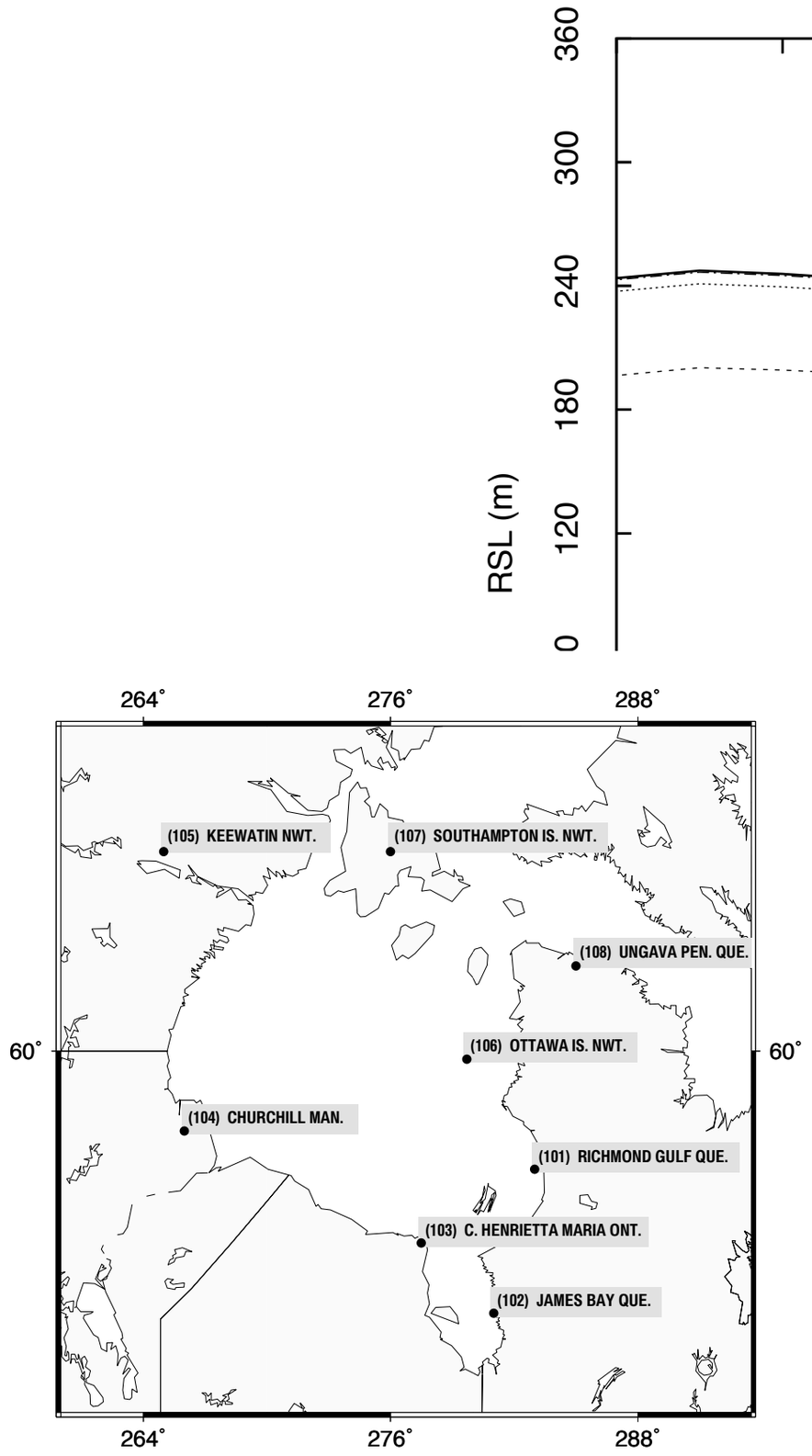


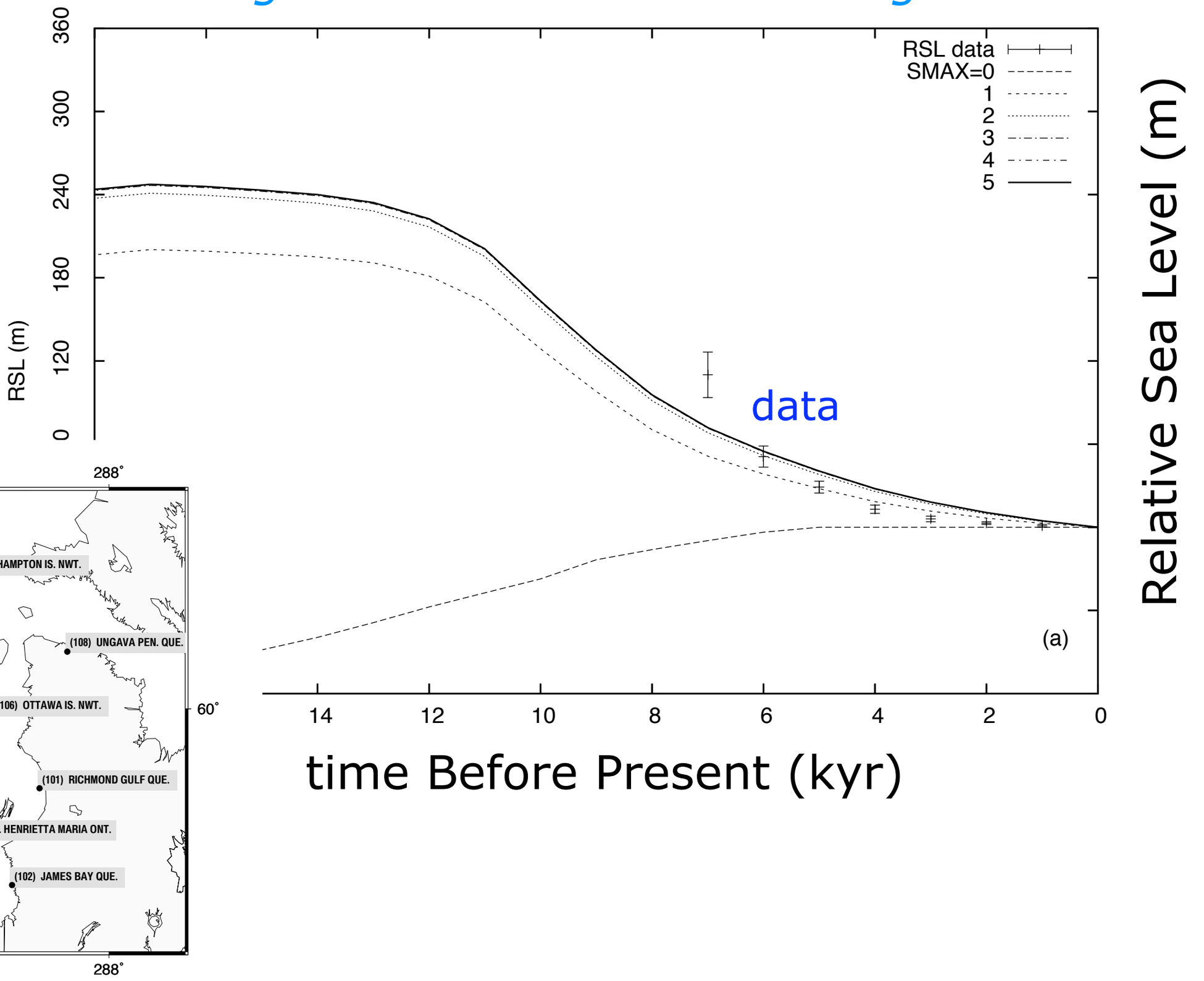


T/P database

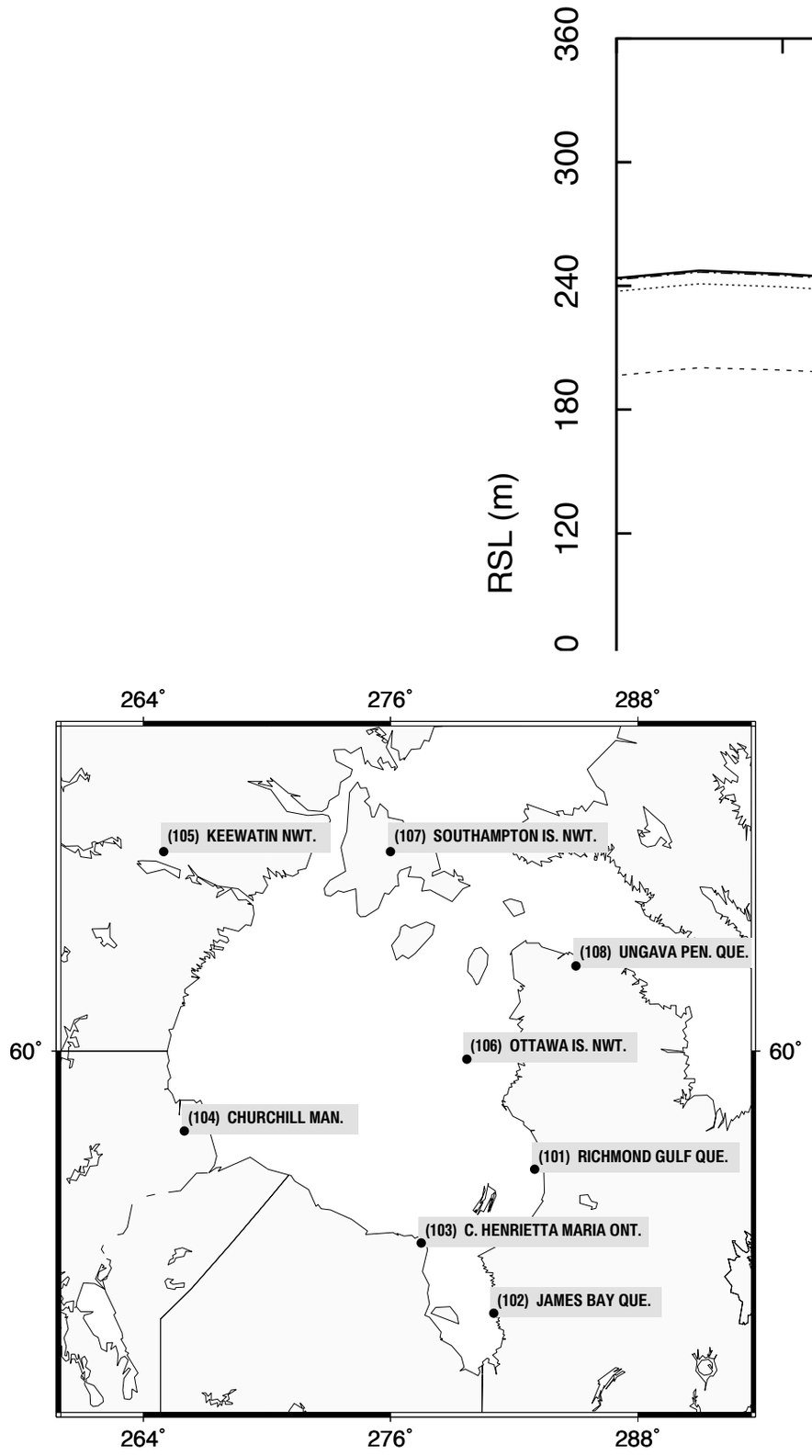
http://gcmd.nasa.gov/records/GCMD_EARTH_LAND_NGDC_PALEO_SEALEVEL1.html

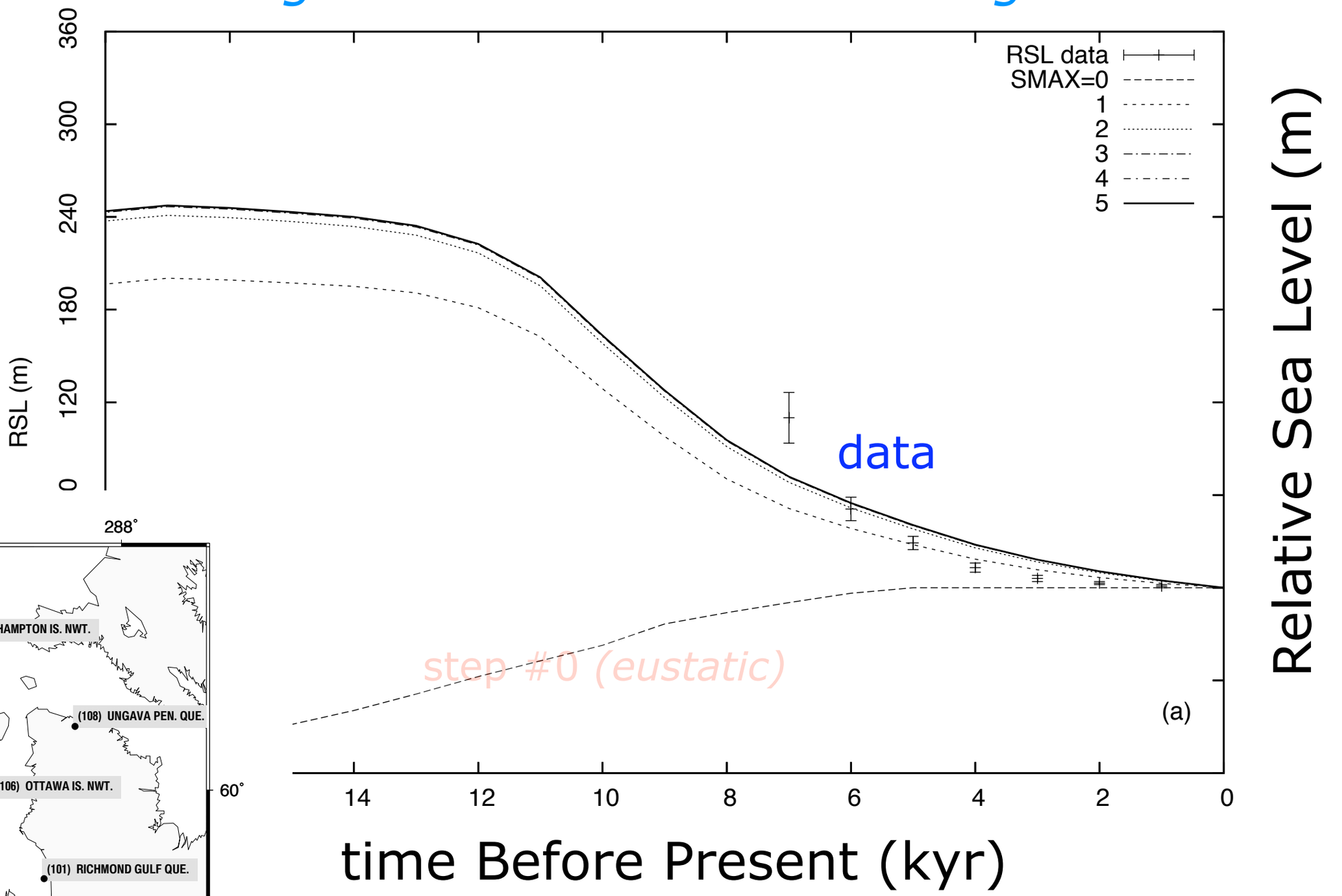
Convergence test for the SLE - Ungava Pen.



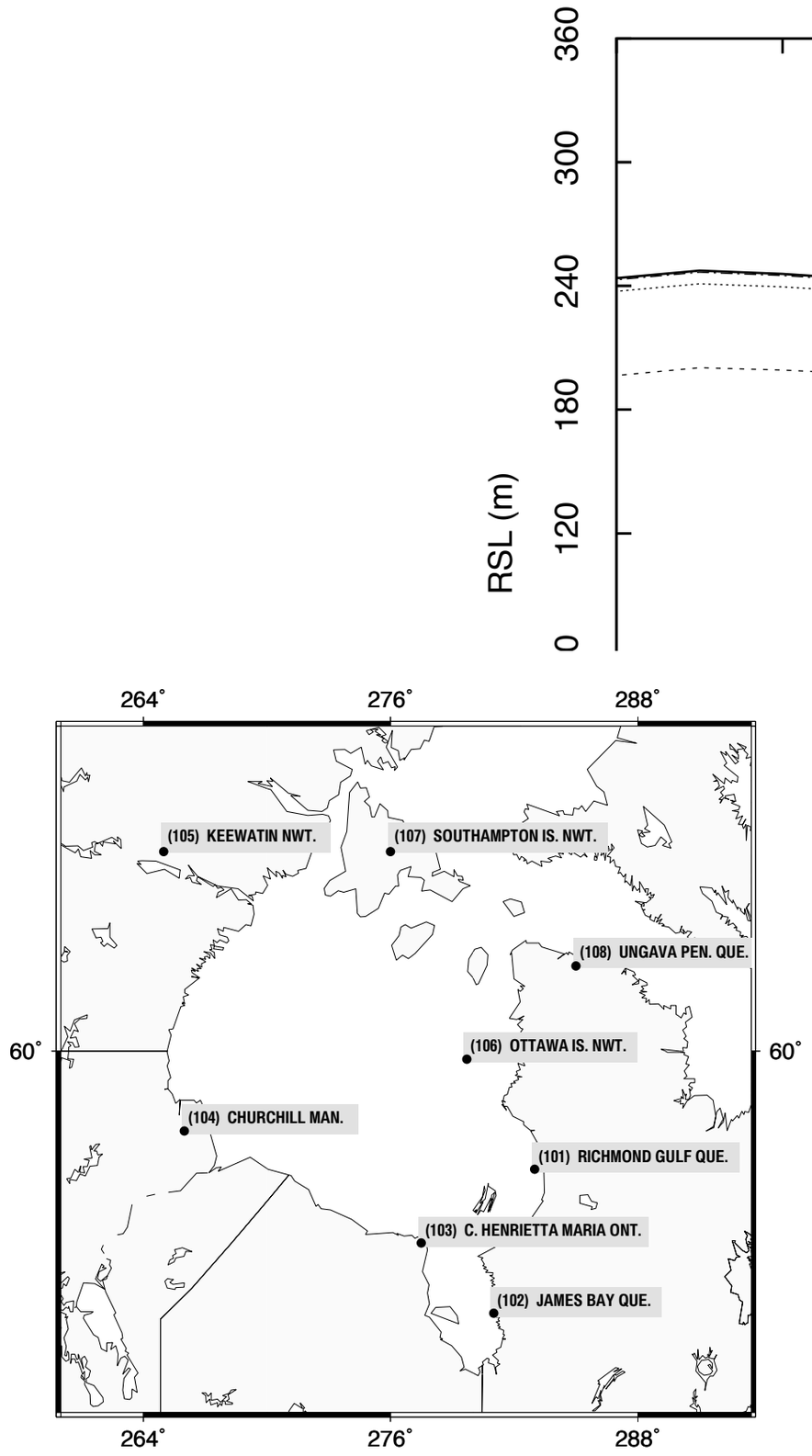


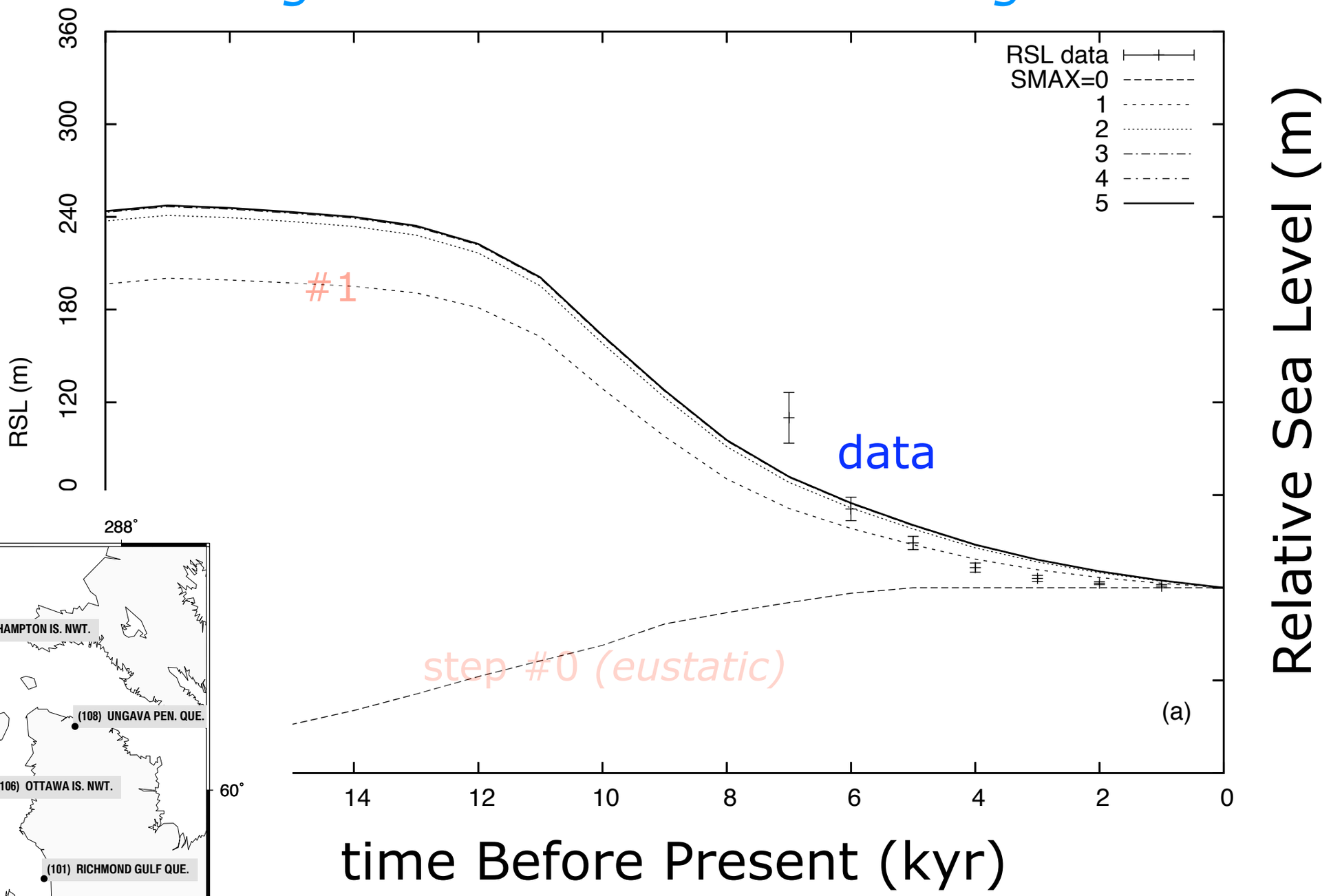
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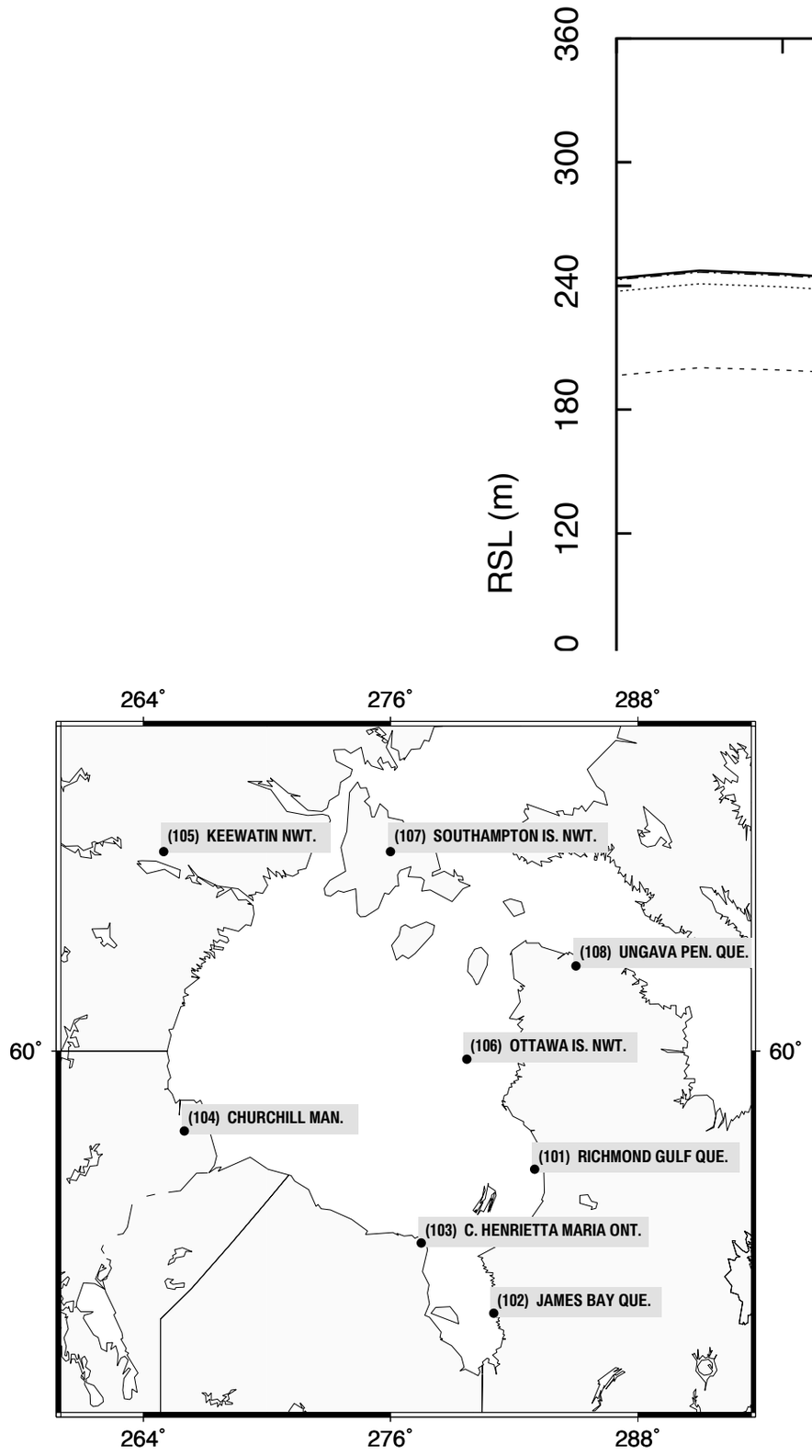


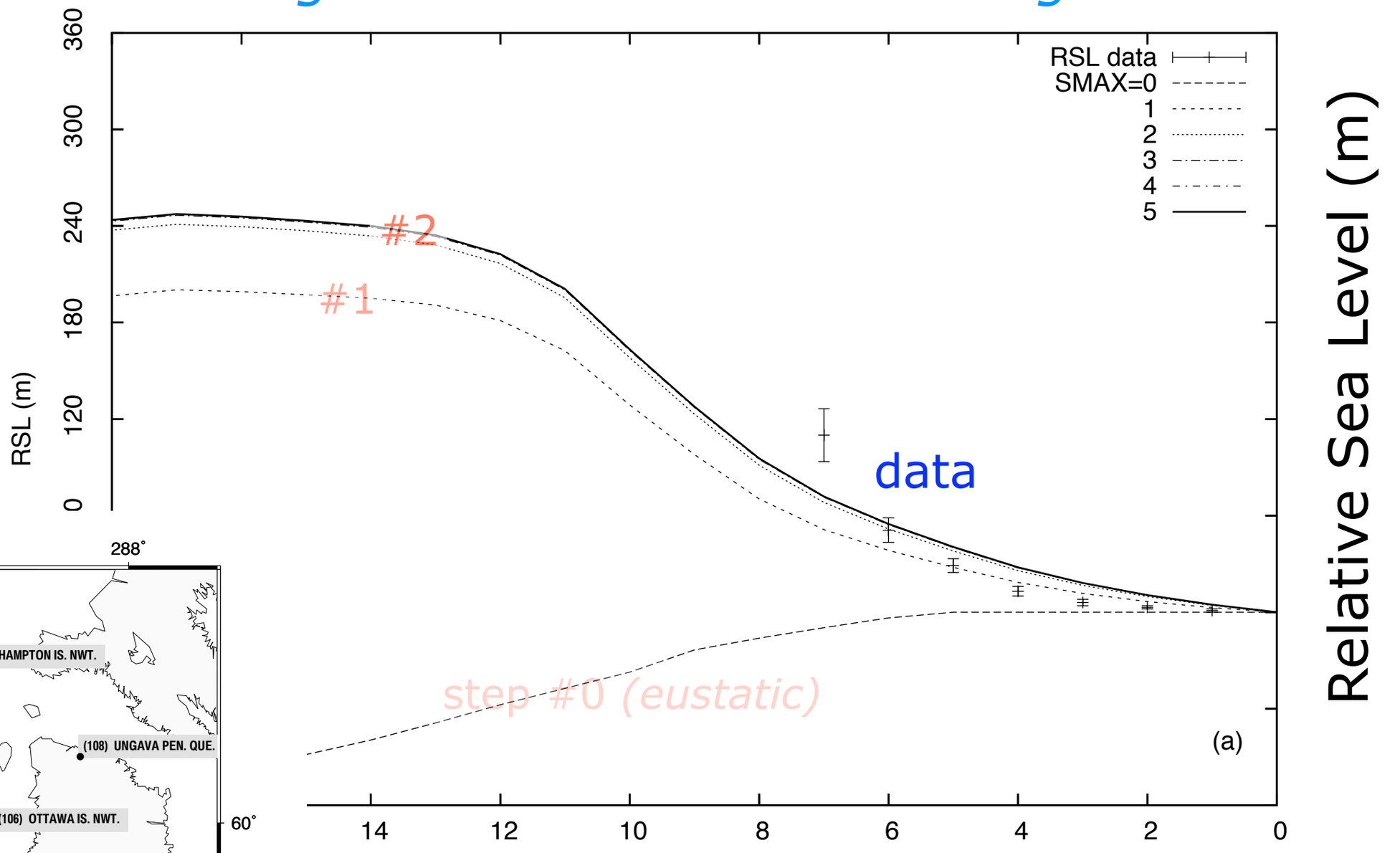
Convergence test for the SLE - Ungava Pen.

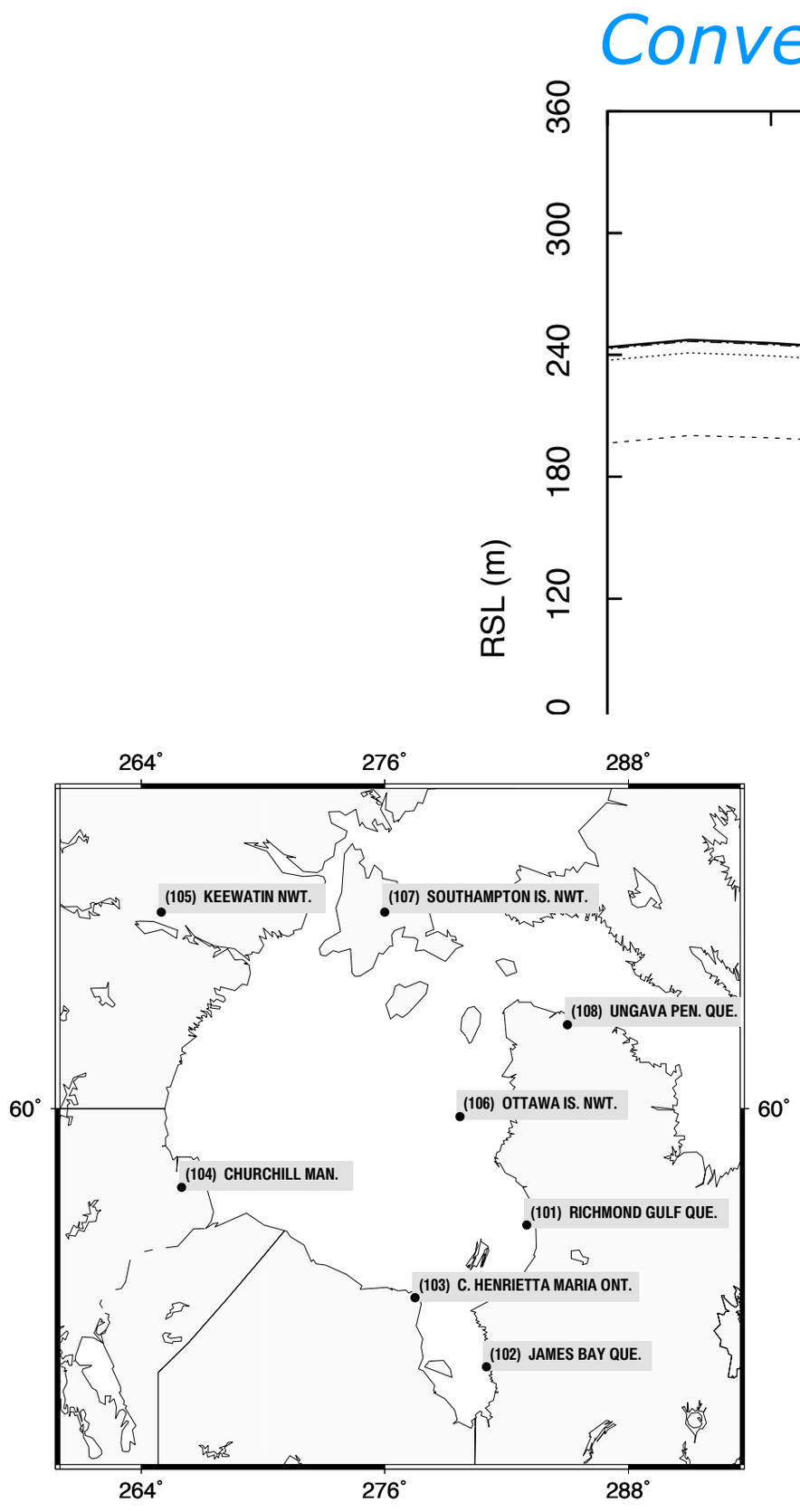




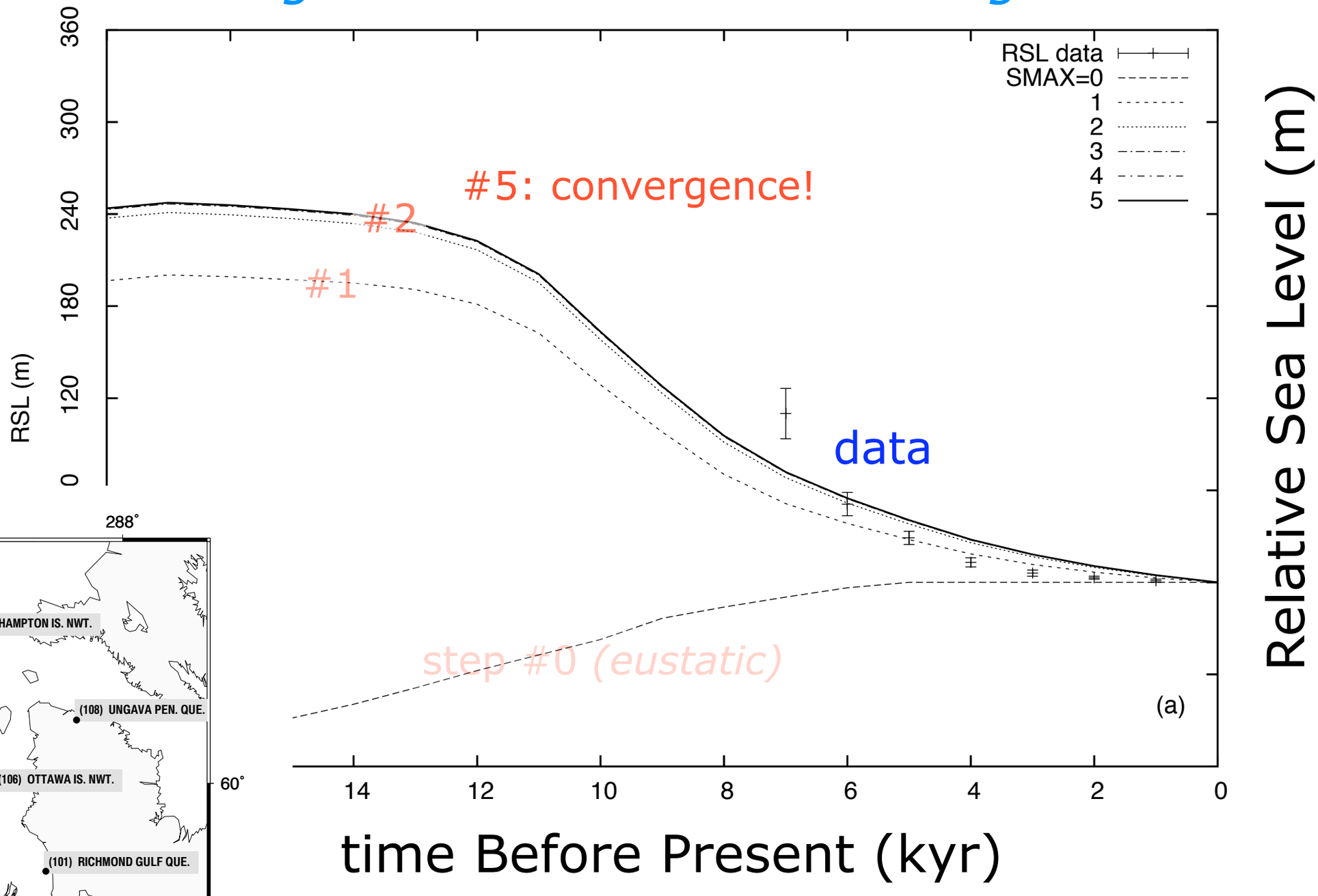
Convergence test for the SLE - Ungava Pen.





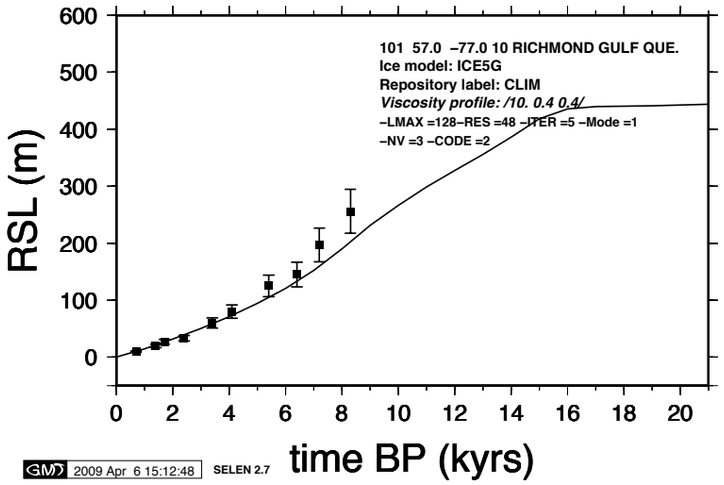


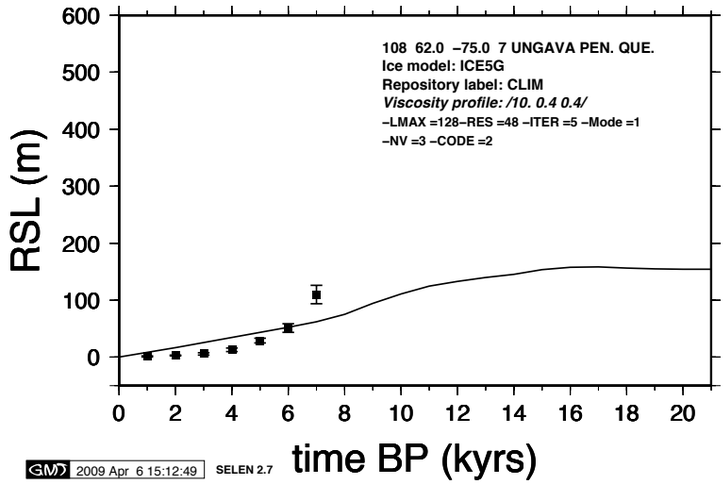
Convergence test for the SLE - Ungava Pen.

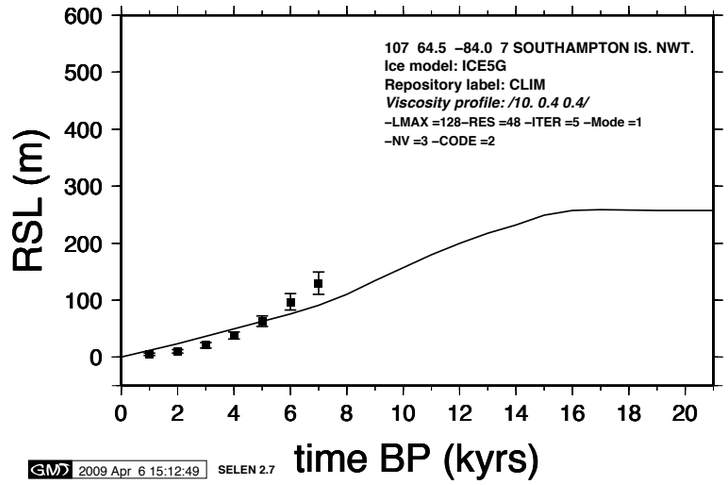


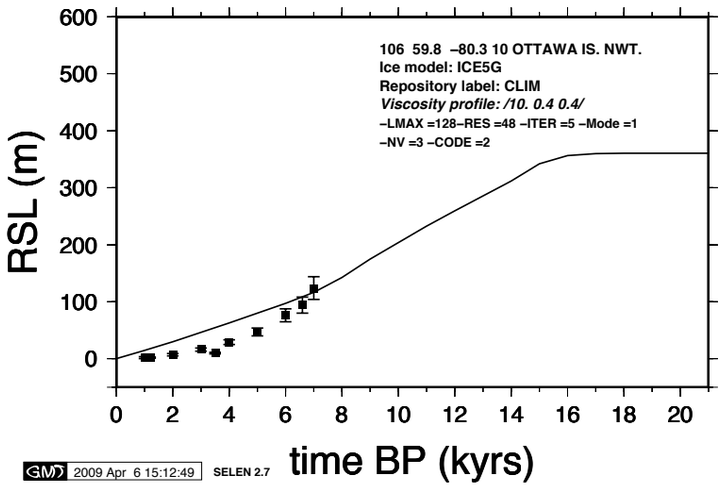
Model vs RSL observations

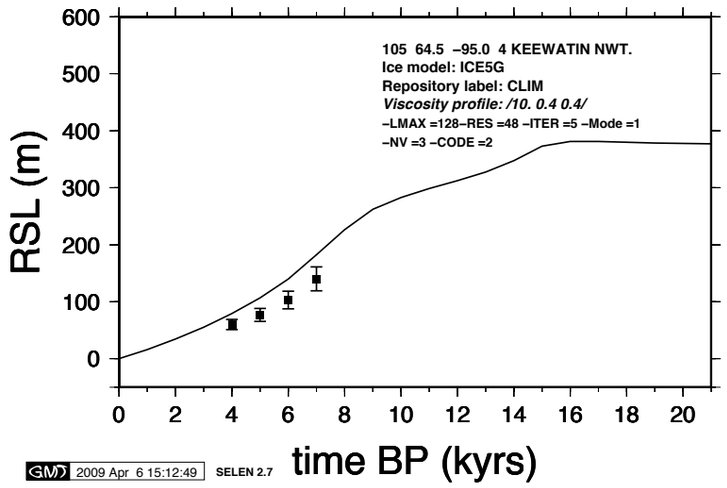
Hudson bay

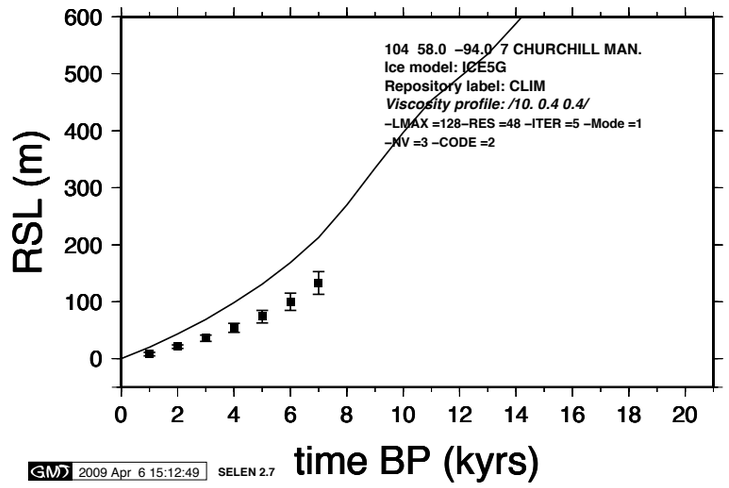


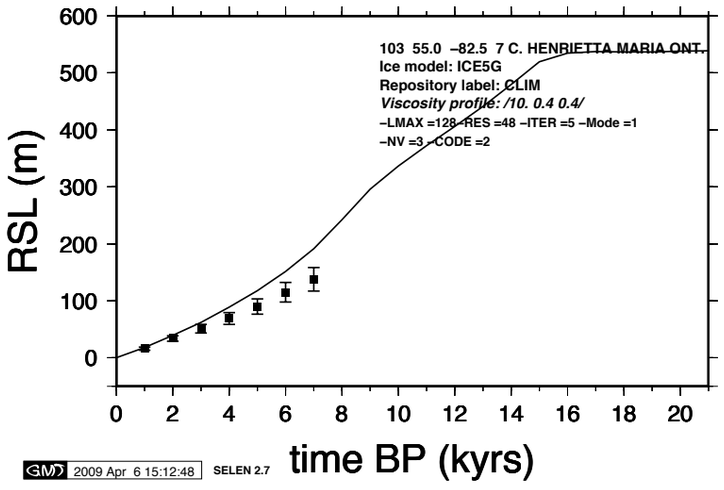


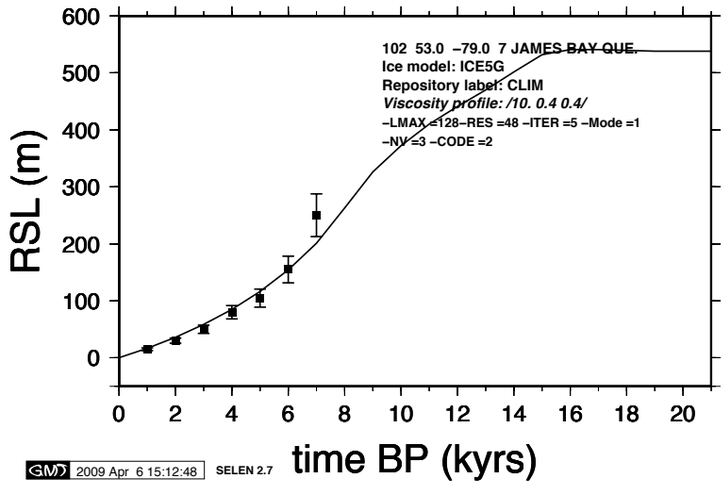


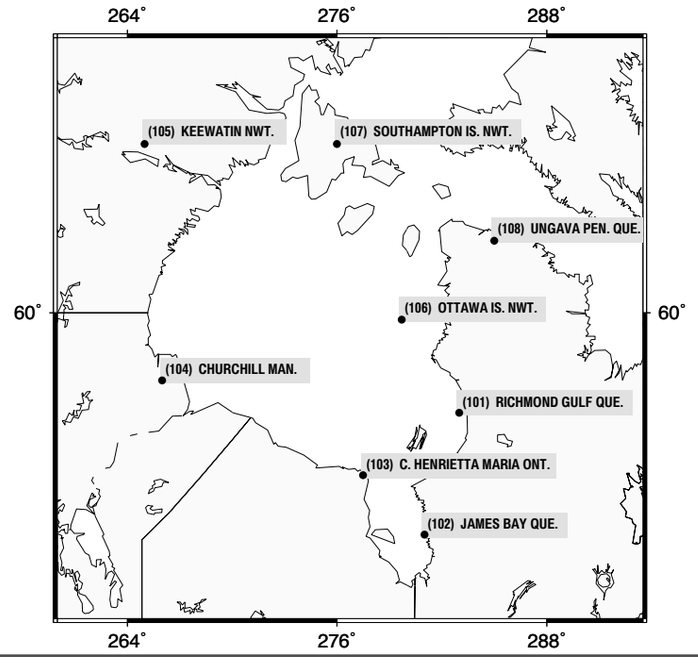




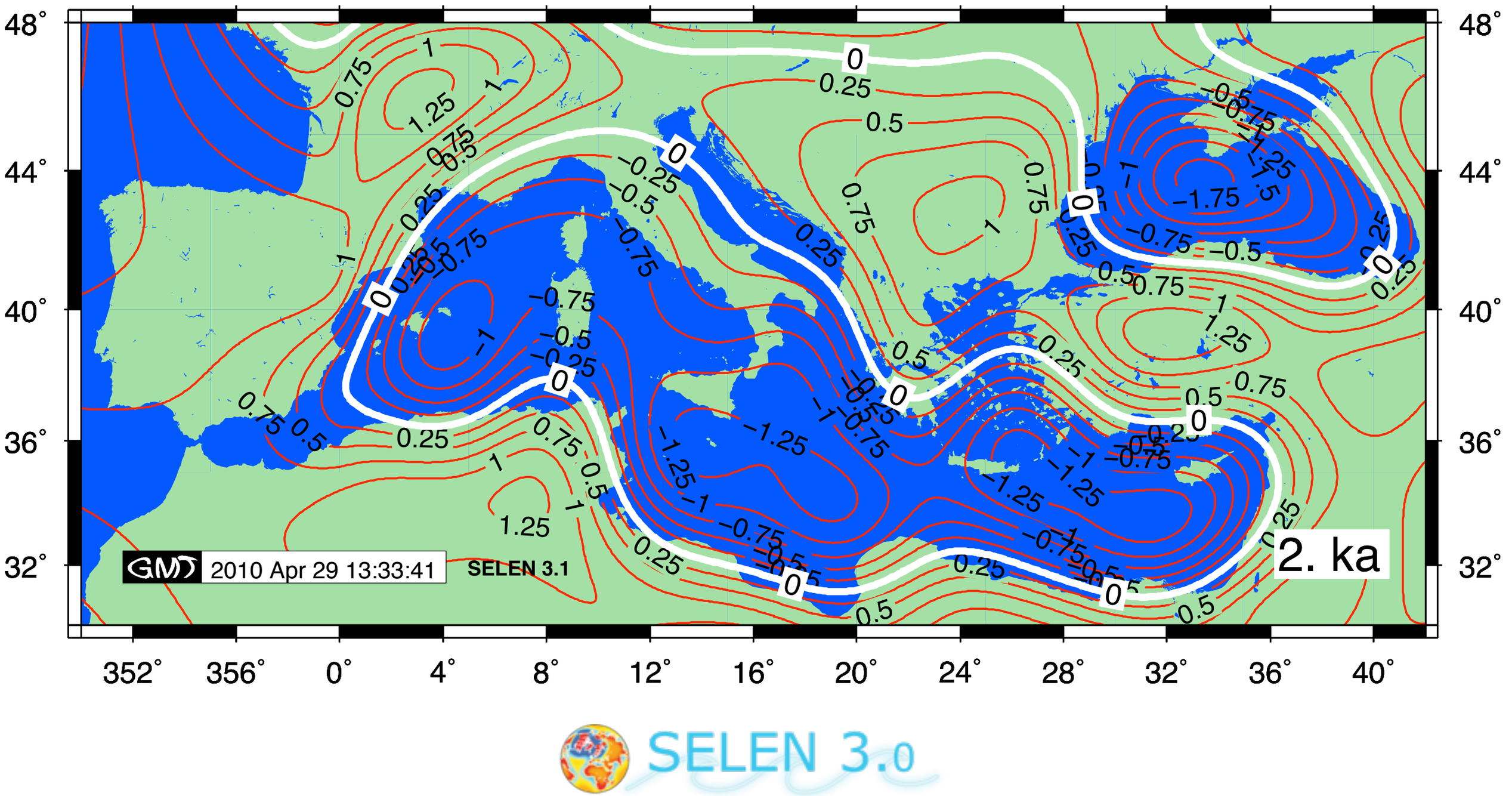


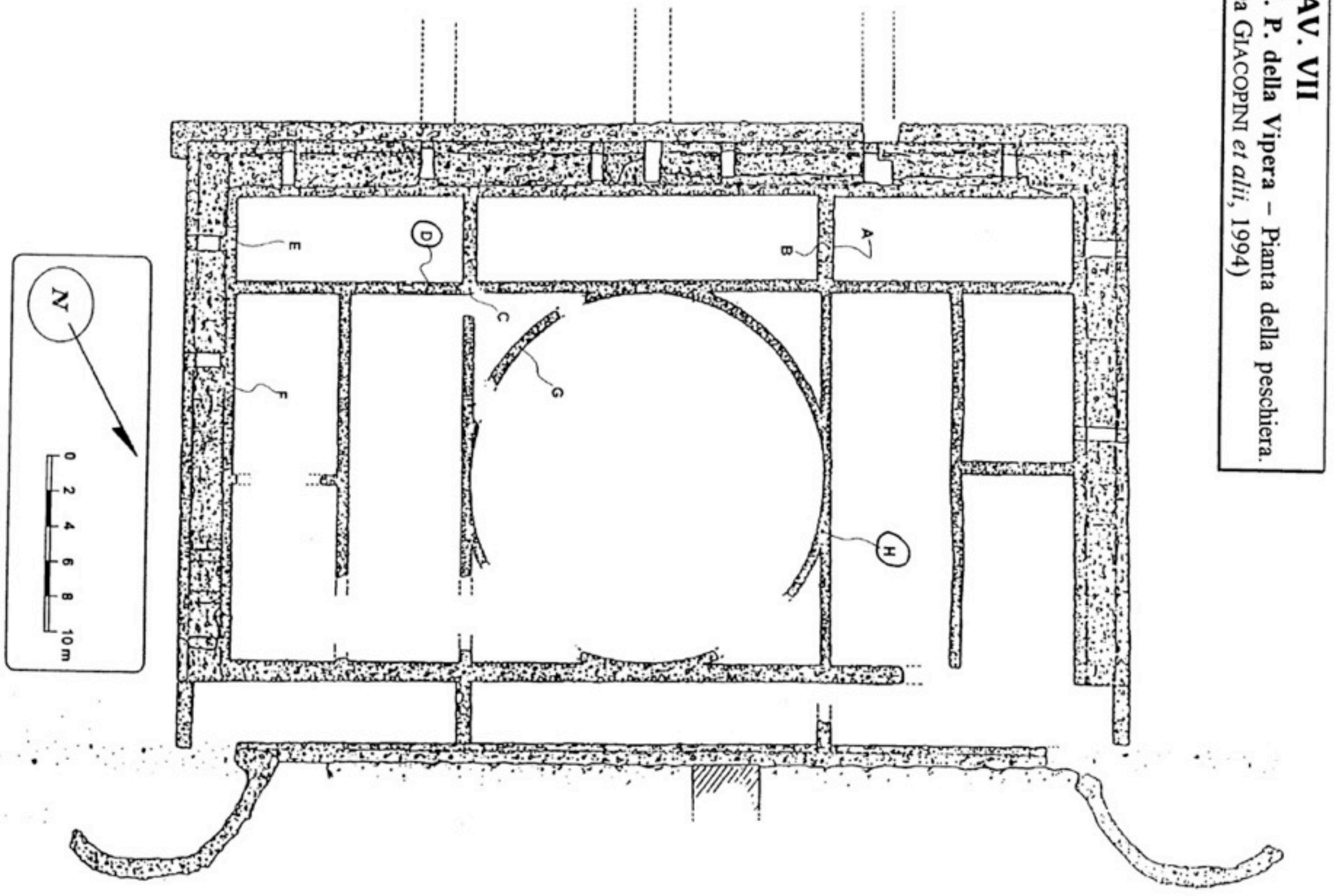






Sea level 2 kyrs BP (relative to present day datum)

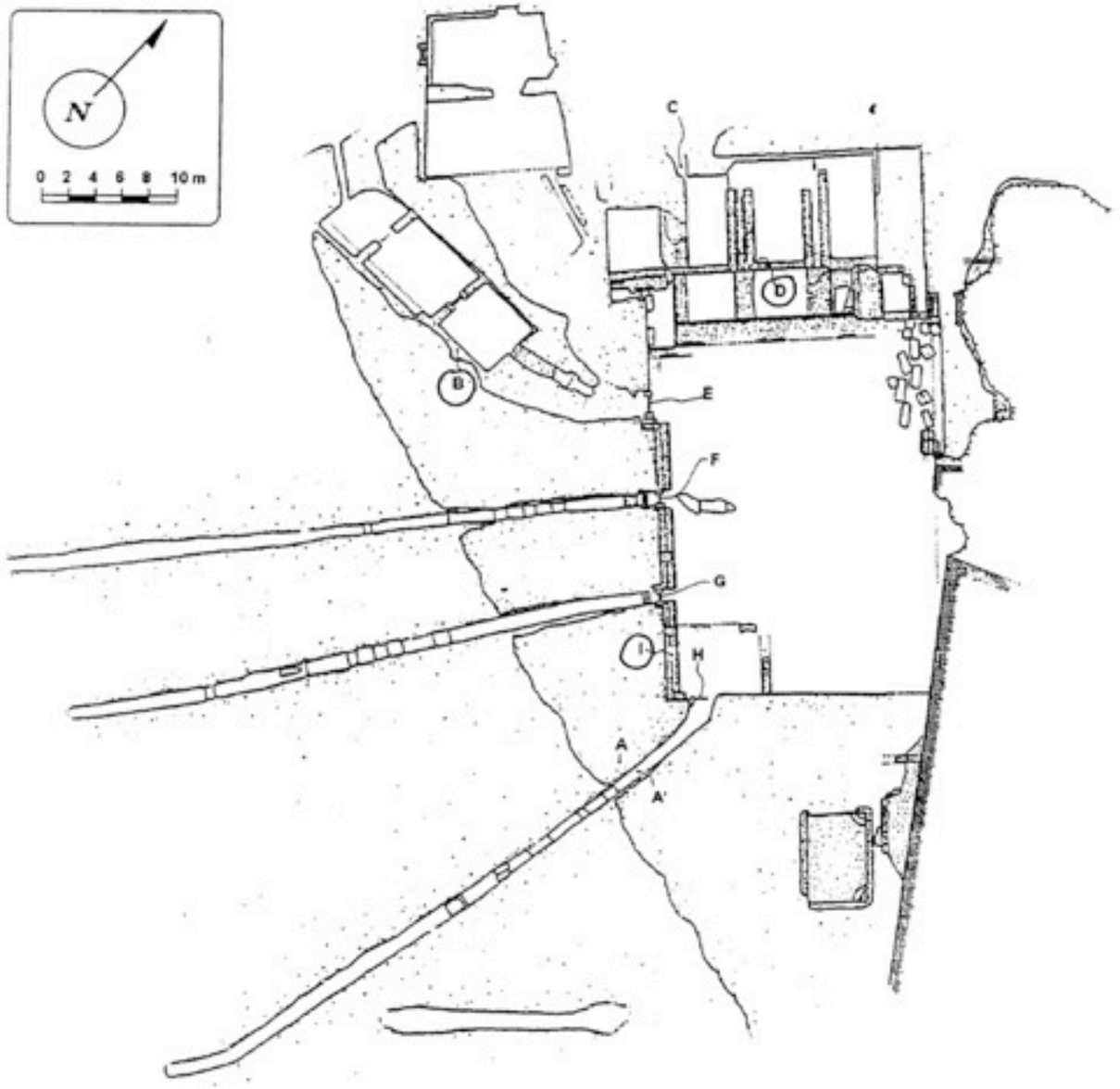


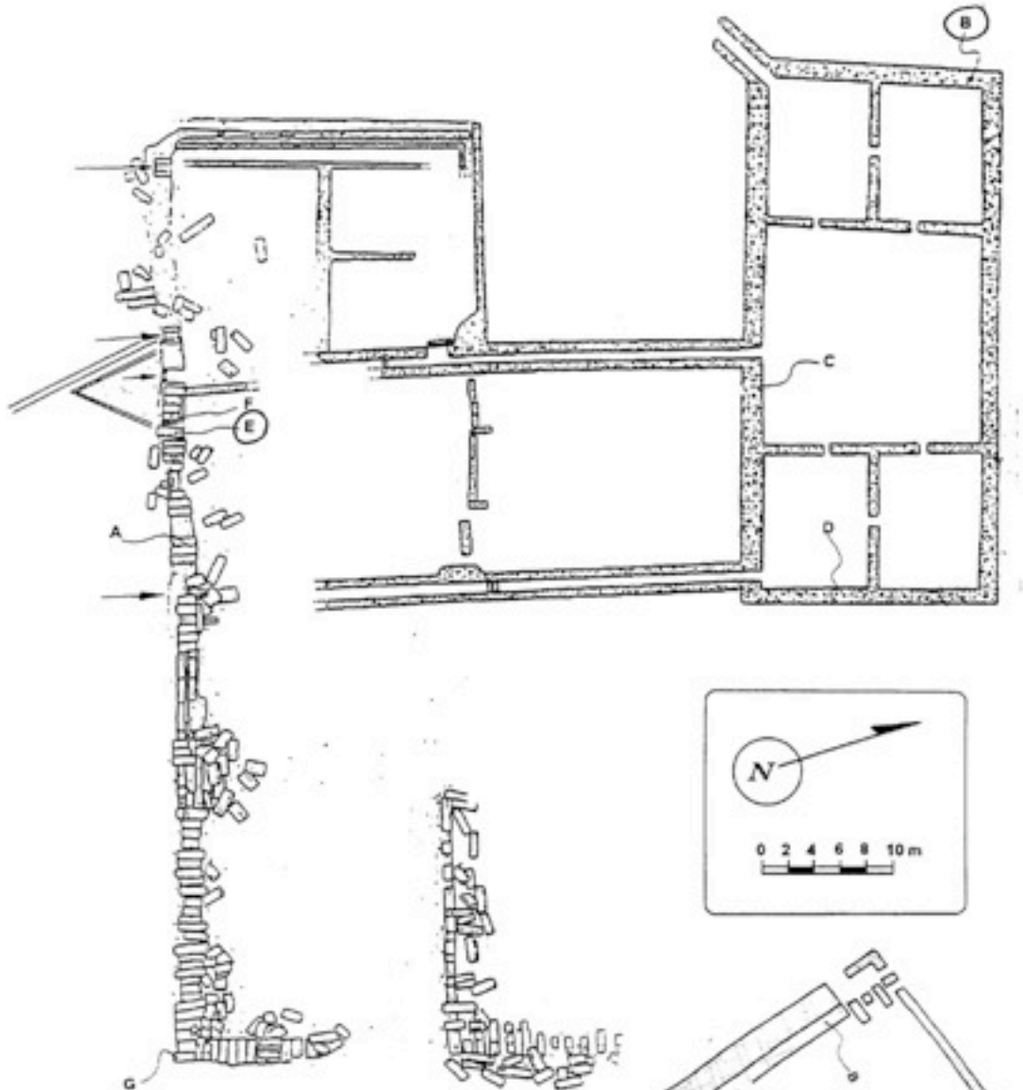


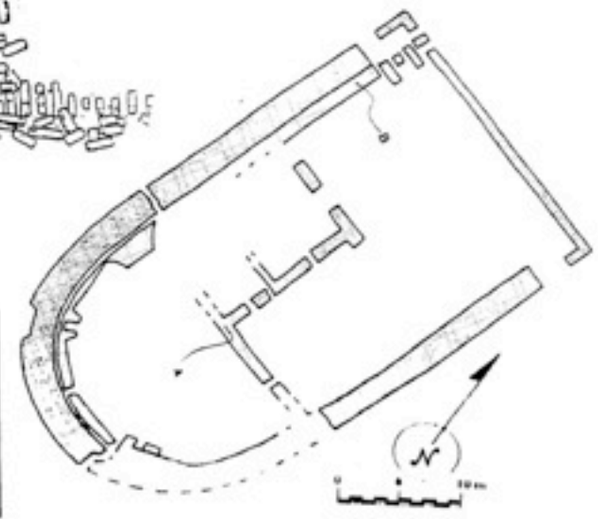
TAV. VII

16. P. della Vipera – Pianta della peschiera.
(Da GIACOPINI *et alii*, 1994)

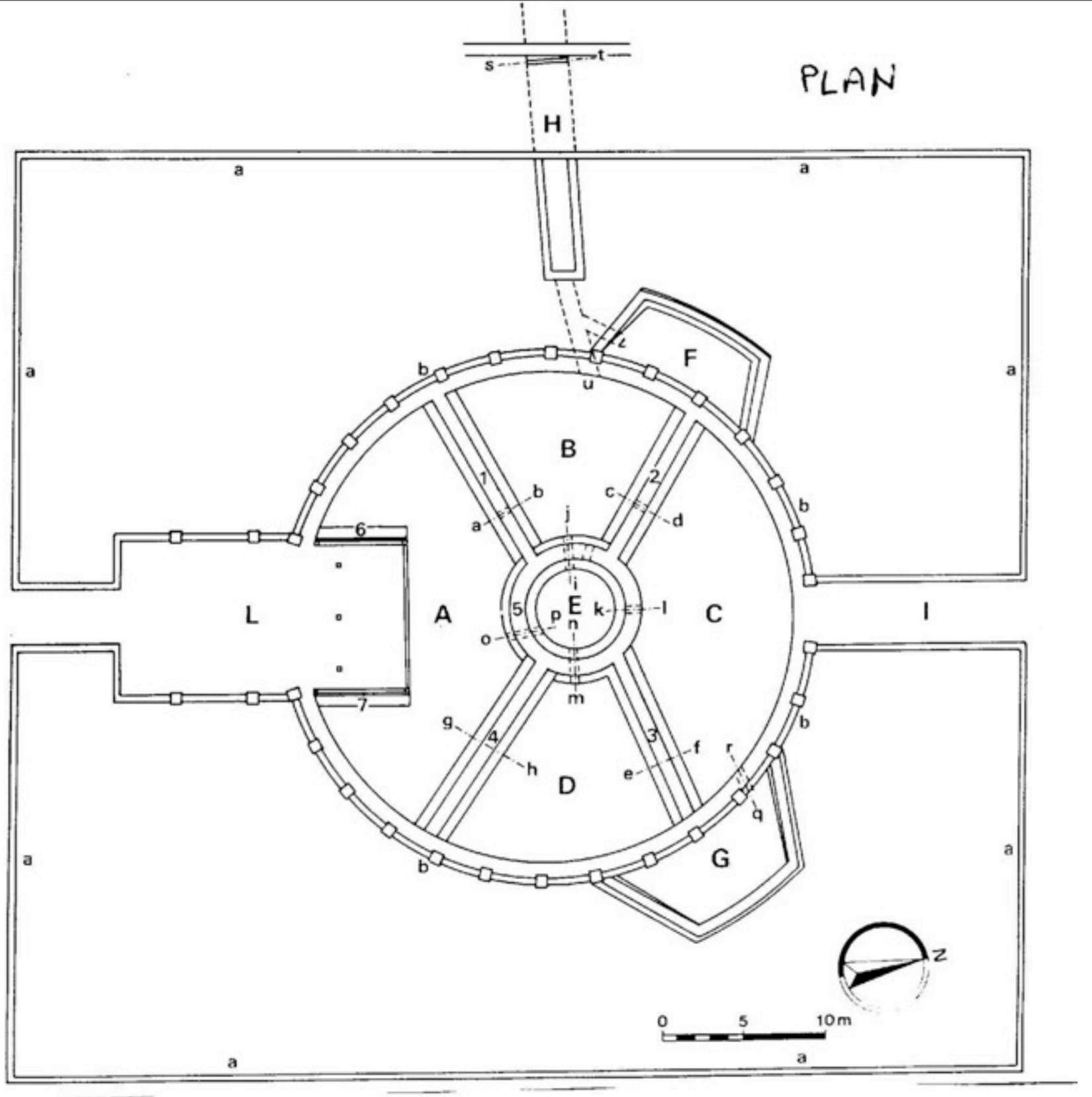
TAV. V
13. Valdaliga – Pianta della peschiera. (Da GIACOPINI *et alii*, 1994)

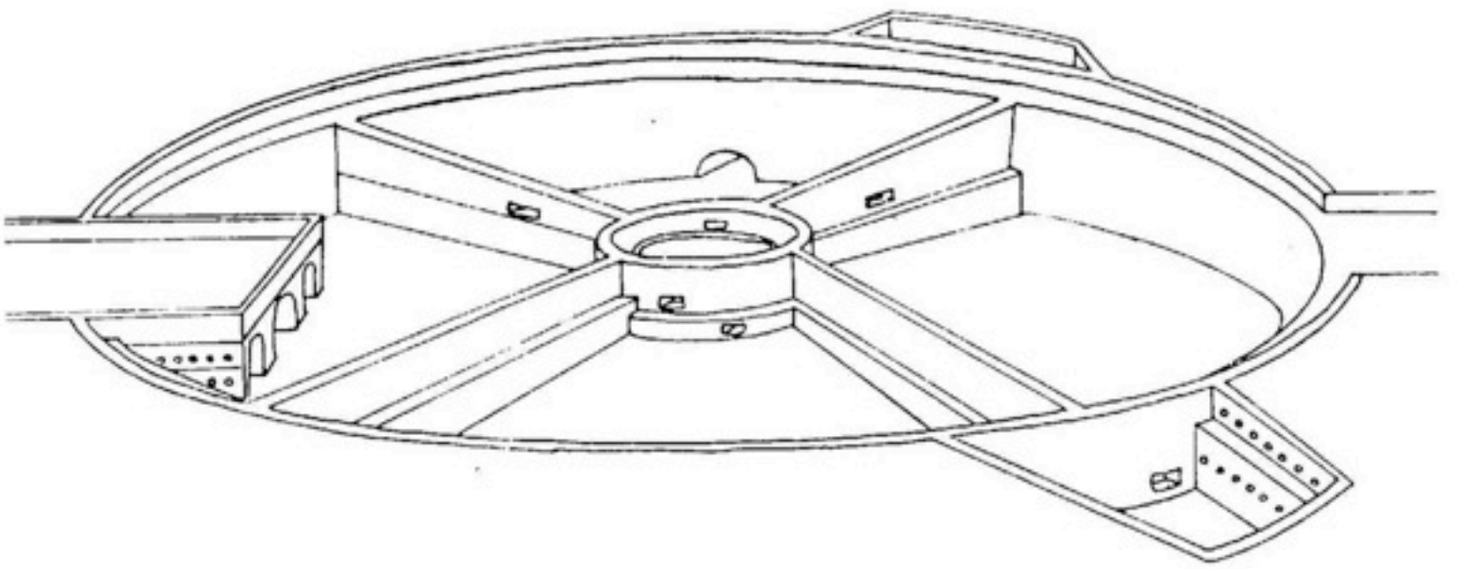






TAV. VIII
17. F.so Guardiole
Sopra: Pianta della peschiera principale e dei relativi moli esterni di protezione. (Da GIACOPINI *et alii*, 1994).
Sotto: pianta della peschiera minore alla foce del fosso.





135 - *Peschiera detta " Piscina di Lucullo "*. Veduta assonometrica da est (*da Chiappella*).

Evidence from the Mediterranean

The Tyrrhenian coast



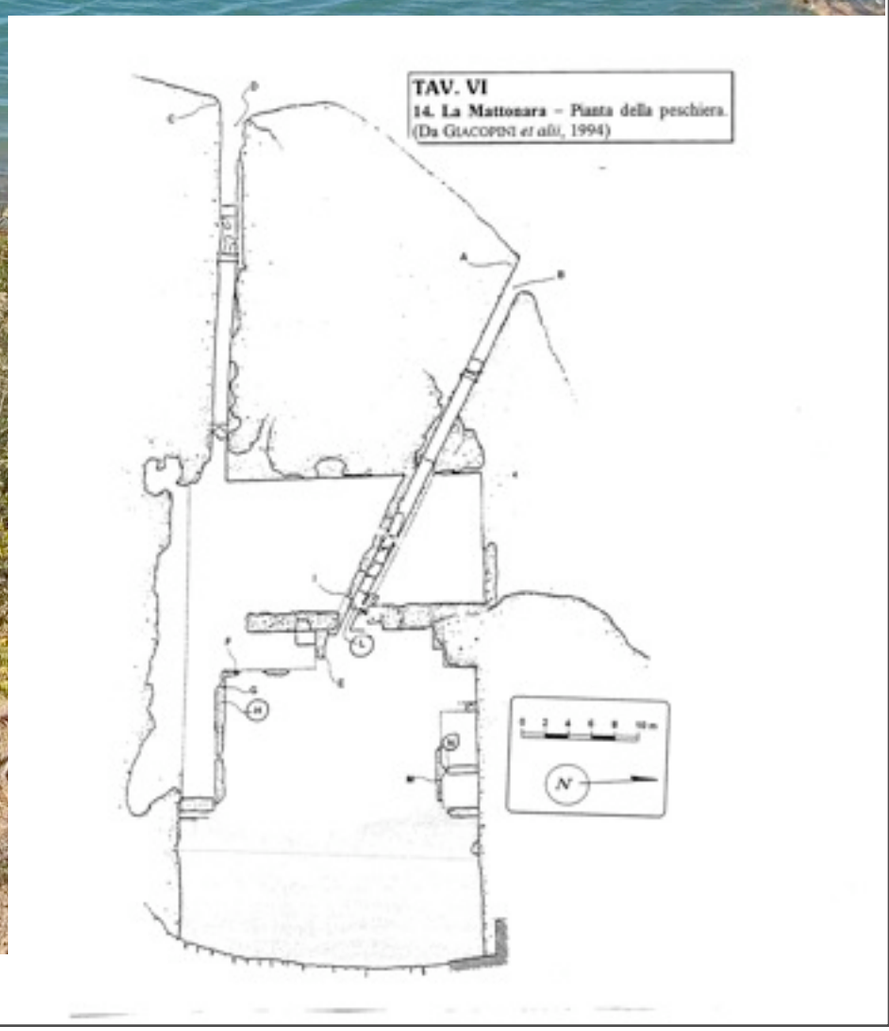


Fig. 2: Part of La Mattonara fish tank.

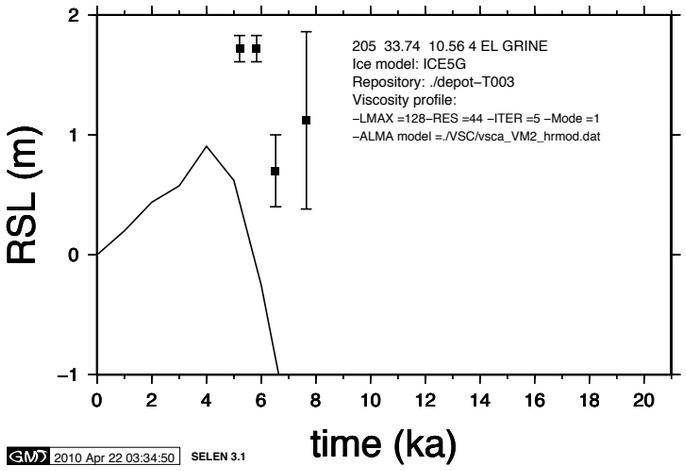


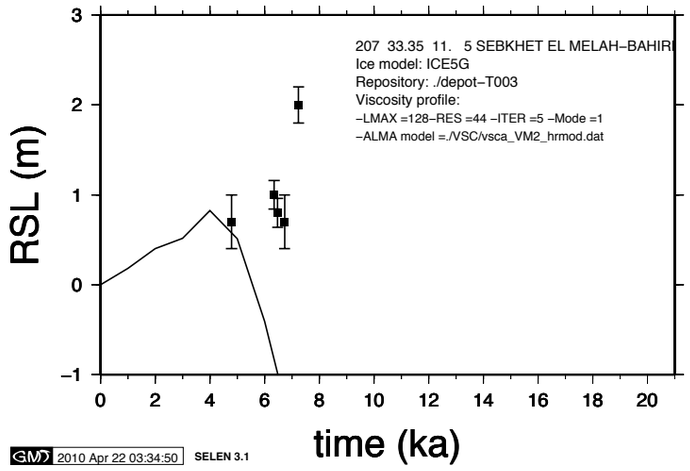


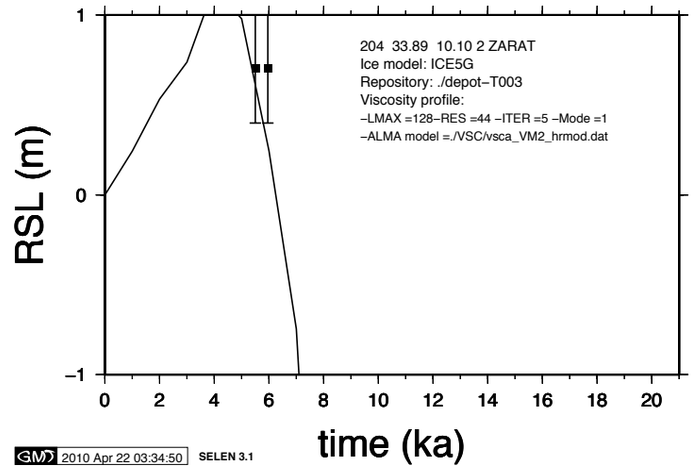


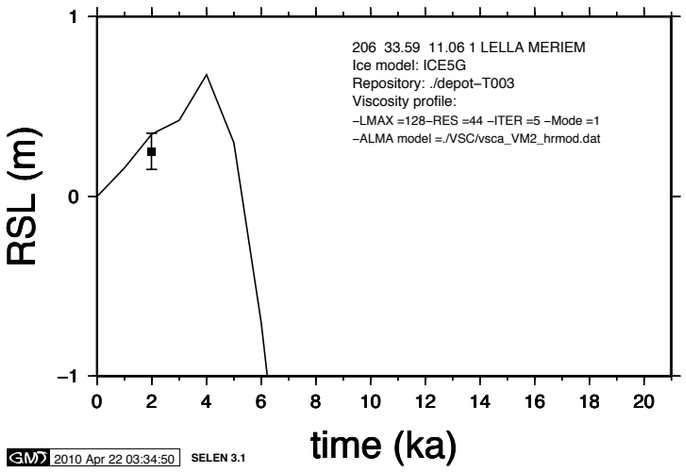
Model vs RSL observations

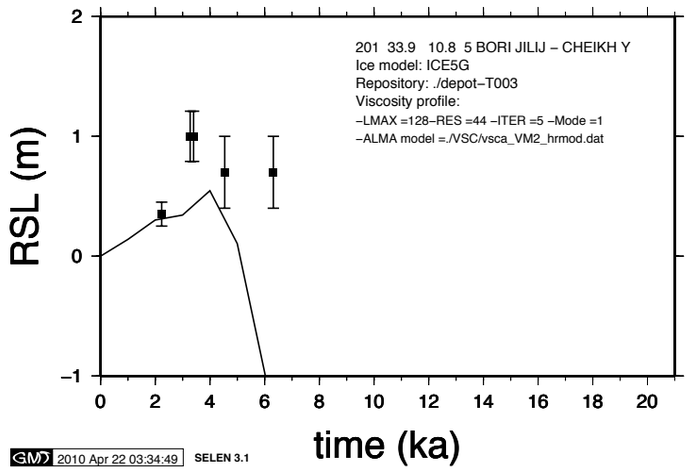
SE Tunisia

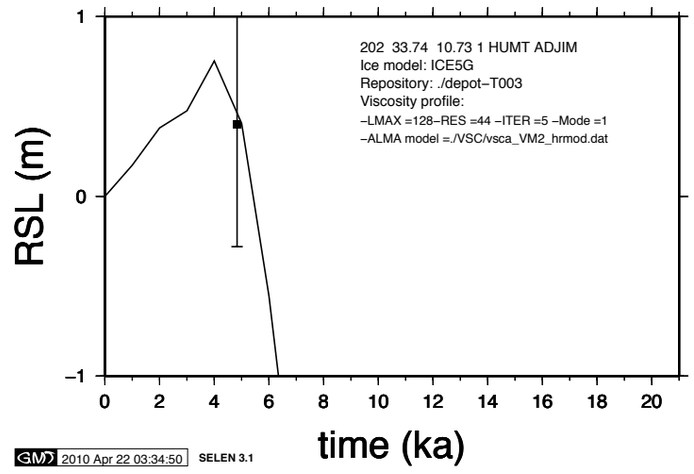


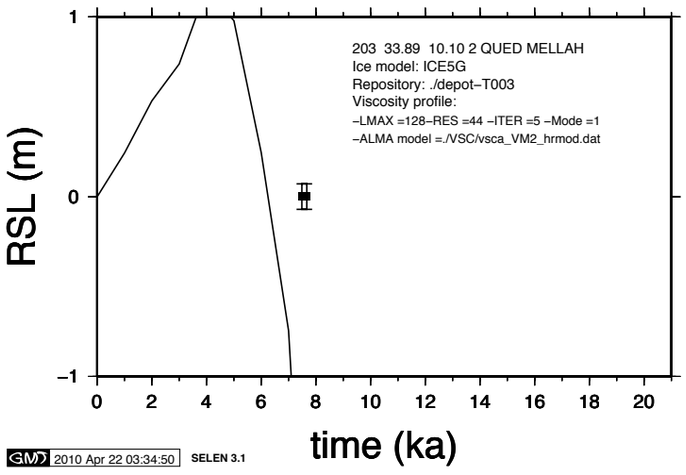


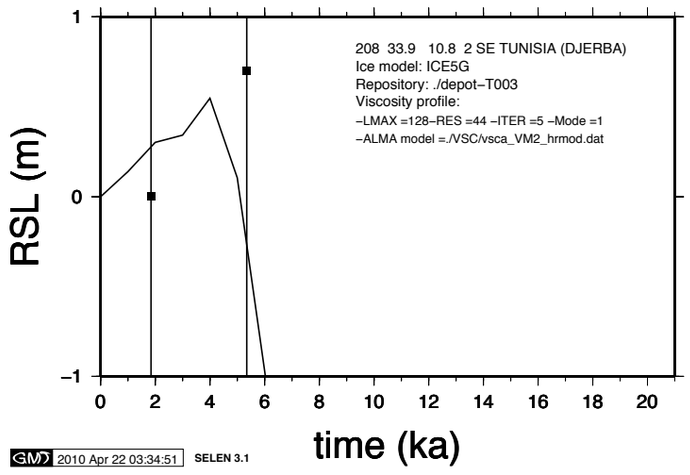


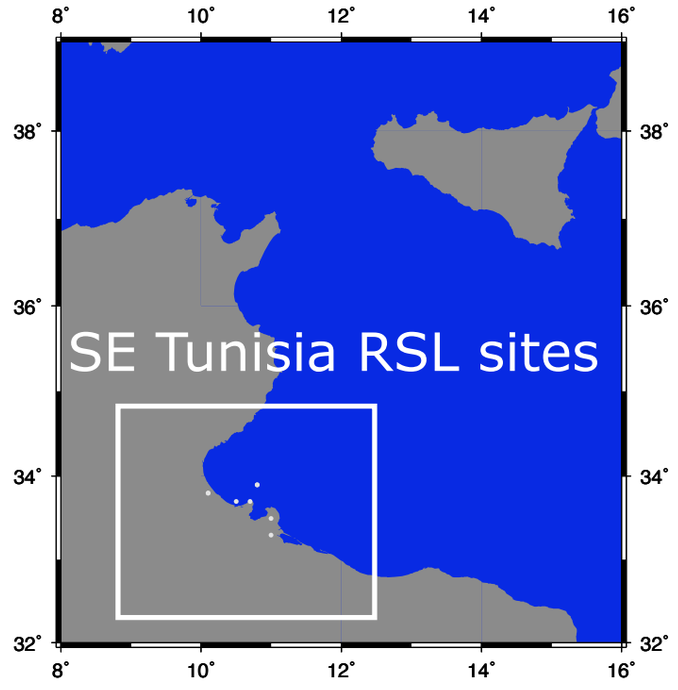












Evidence from the Mediterranean

SE Tunisia

Stocchi & Spada, 2007

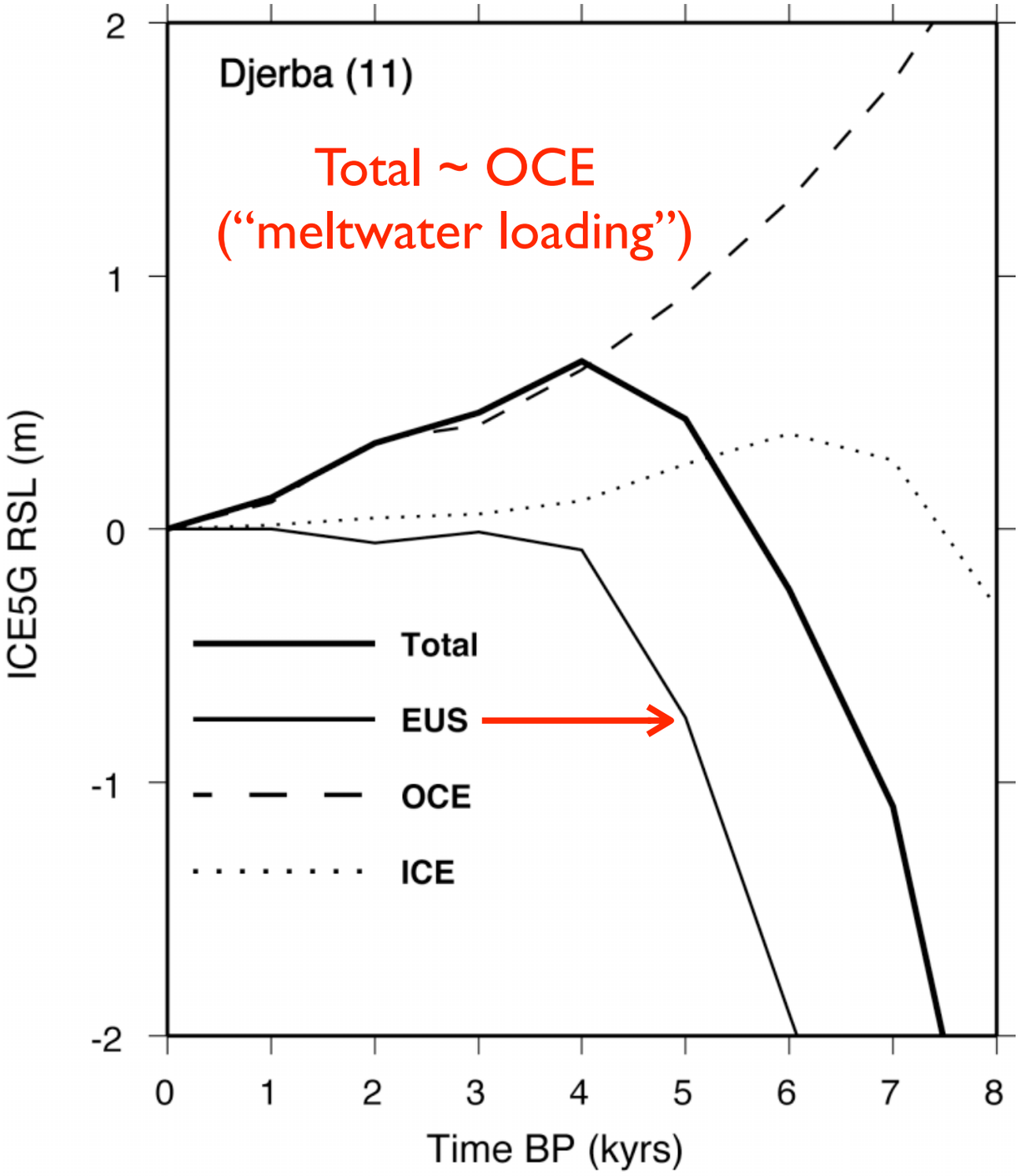
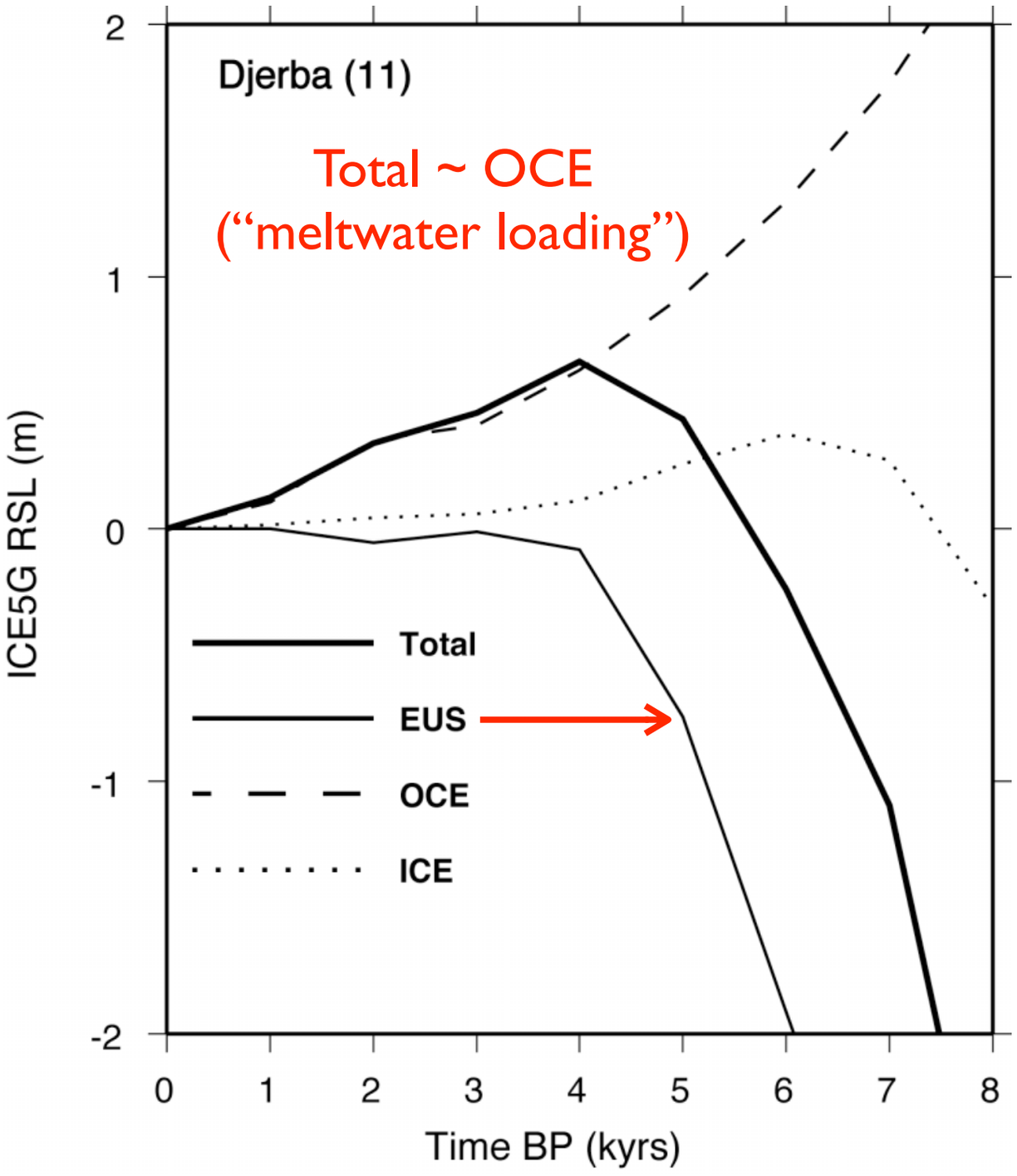


Fig. 6. Ice- and ocean-load induced components of RSL for the site of Djerba (see map of fig. 3a) obtained using model ICE5G (VM1).

Evidence from the Mediterranean — SE Tunisia

Stocchi & Spada, 2007



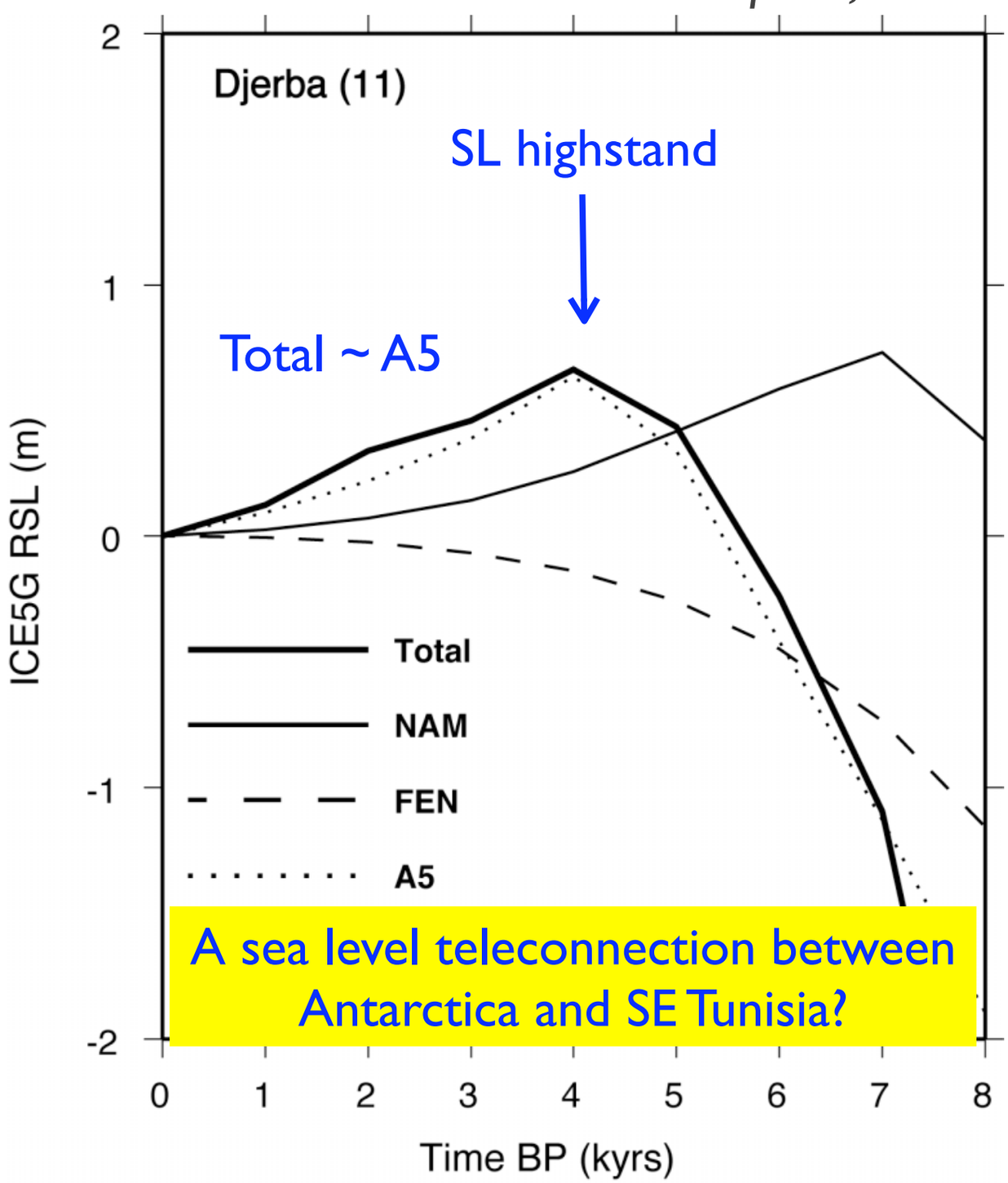


Fig. 6. Ice- and ocean-load induced components of RSL for the site of Djerba (see map of fig. 3a) obtained using model ICE5G (VM1).

Fig. 8. Contributions to RSL due to individual components of ICE5G (VM1) at the site of Djerba (see fig. 3a).

Sea level in the last century

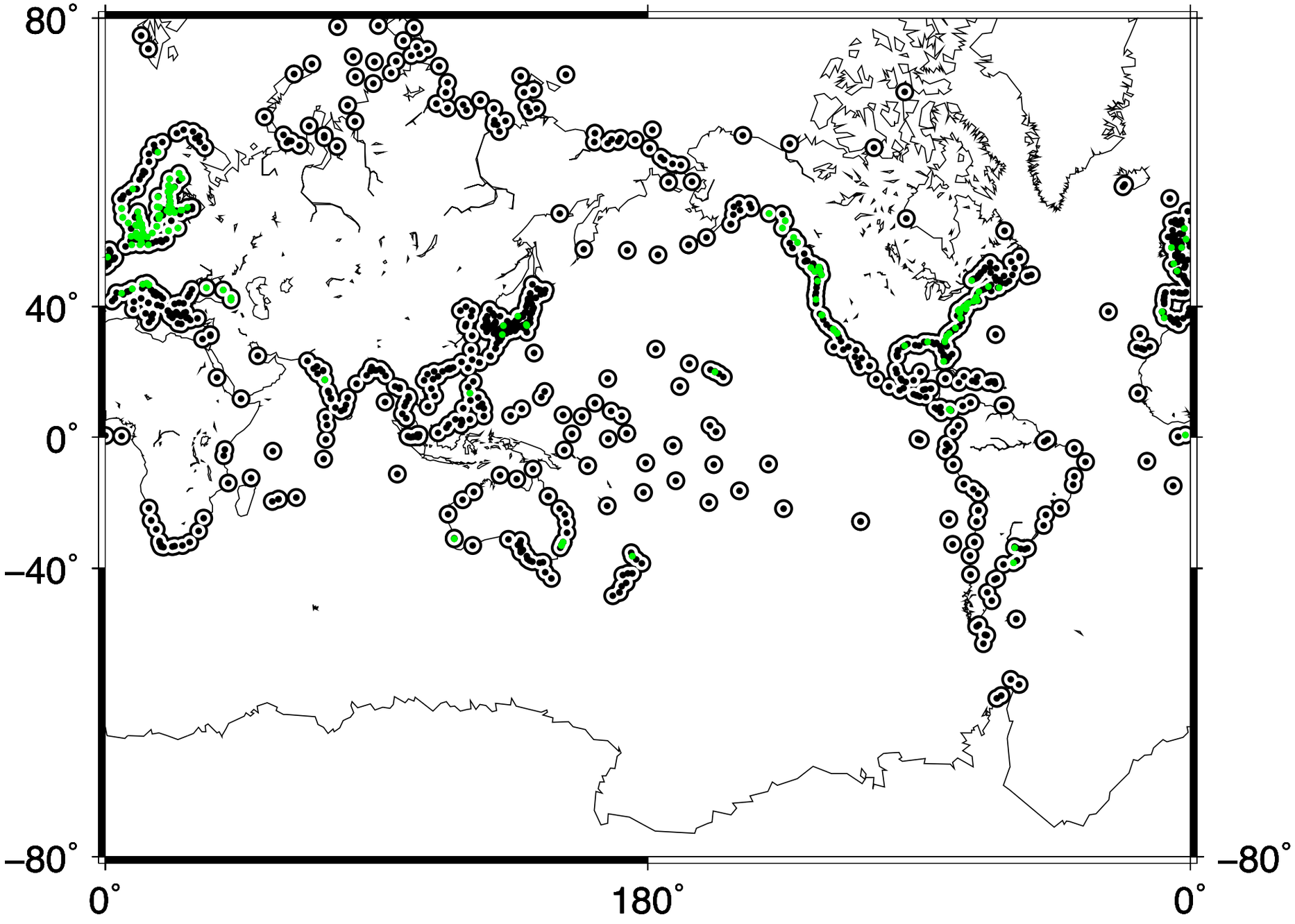
the era of tide gauges: DIRECT observation


Tide staff
Liverpool, february 3, 2009

SOUTH AFRICA



nature of tide gauge observations

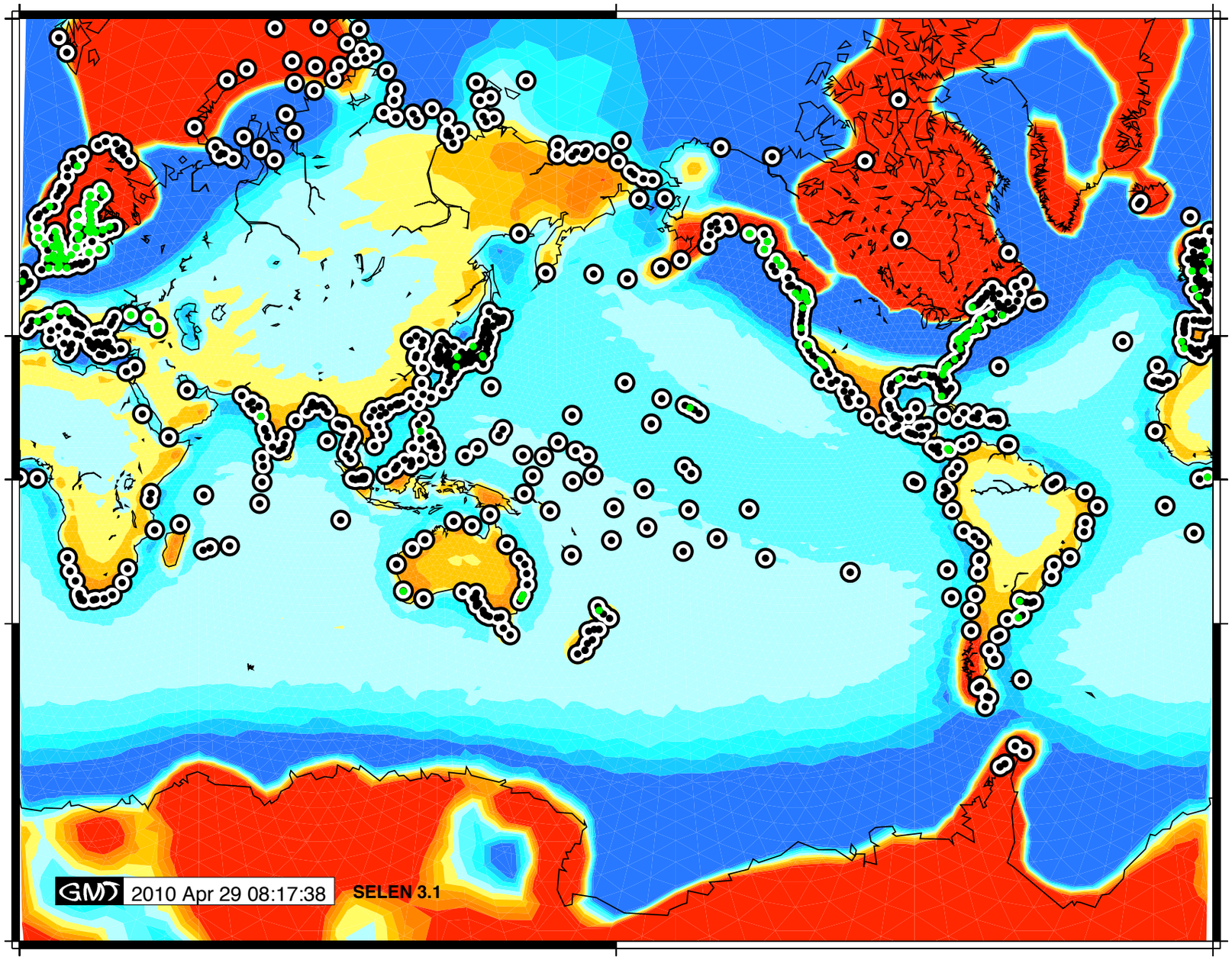


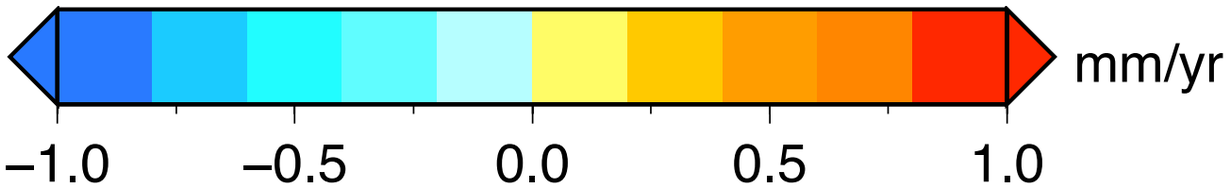
All PSMSL tide gauges
(~ 1200)

All PSMSL tide gauges
with T > 60 years
(~ 140)

Rate of vertical displacement today

–Ice model: ICE5G –ALMA rheology: ./VSC/vsca_BENCH.dat





–LMAX=72 –RES=18 –NV=3 –MODE=1 –ITER=3

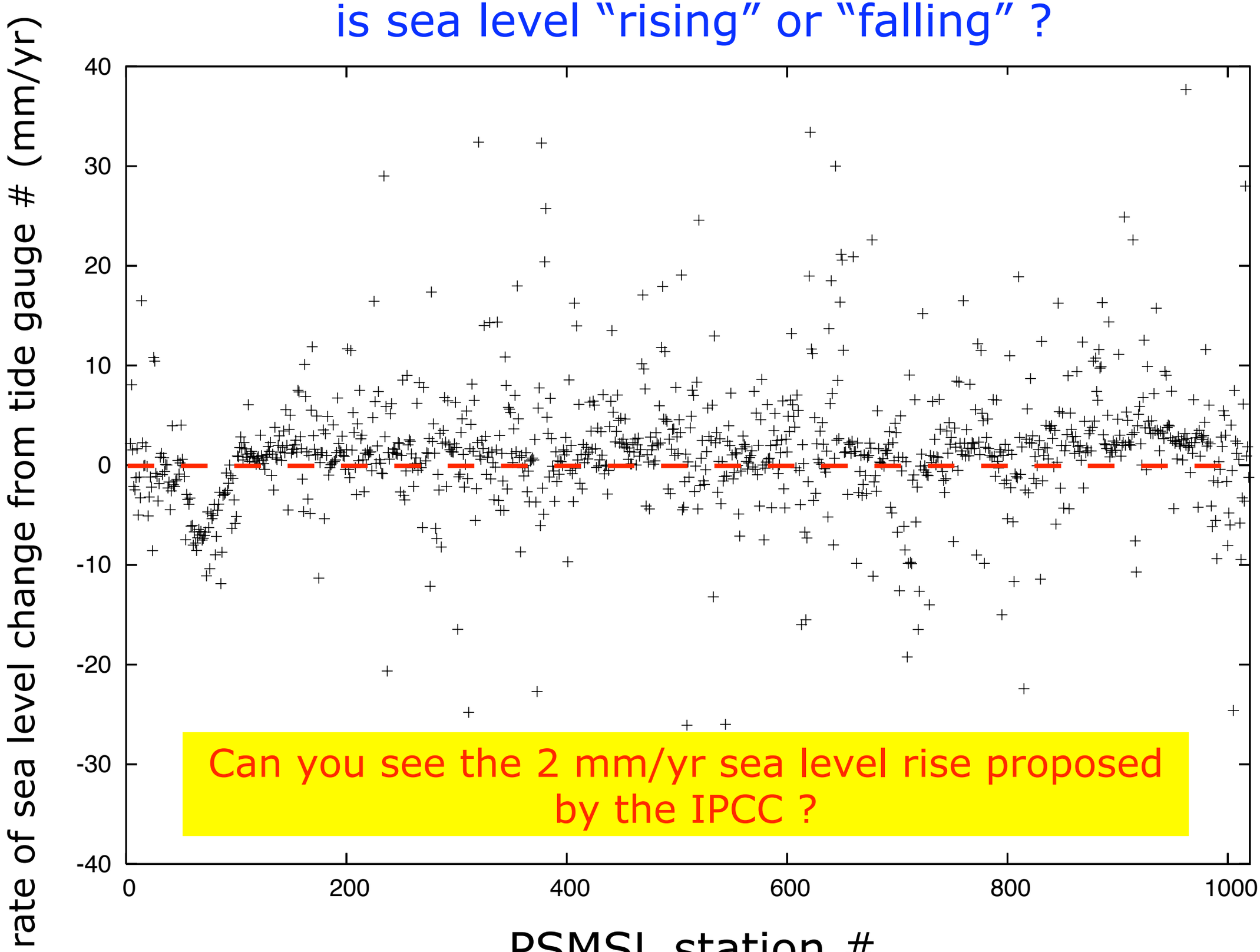
All PSMSL tide gauges
(~ 1200)

All PSMSL tide gauges
with T > 60 years
(~ 140)

Most (all?) tide gauges
are in regions of
considerable
GIA disequilibrium

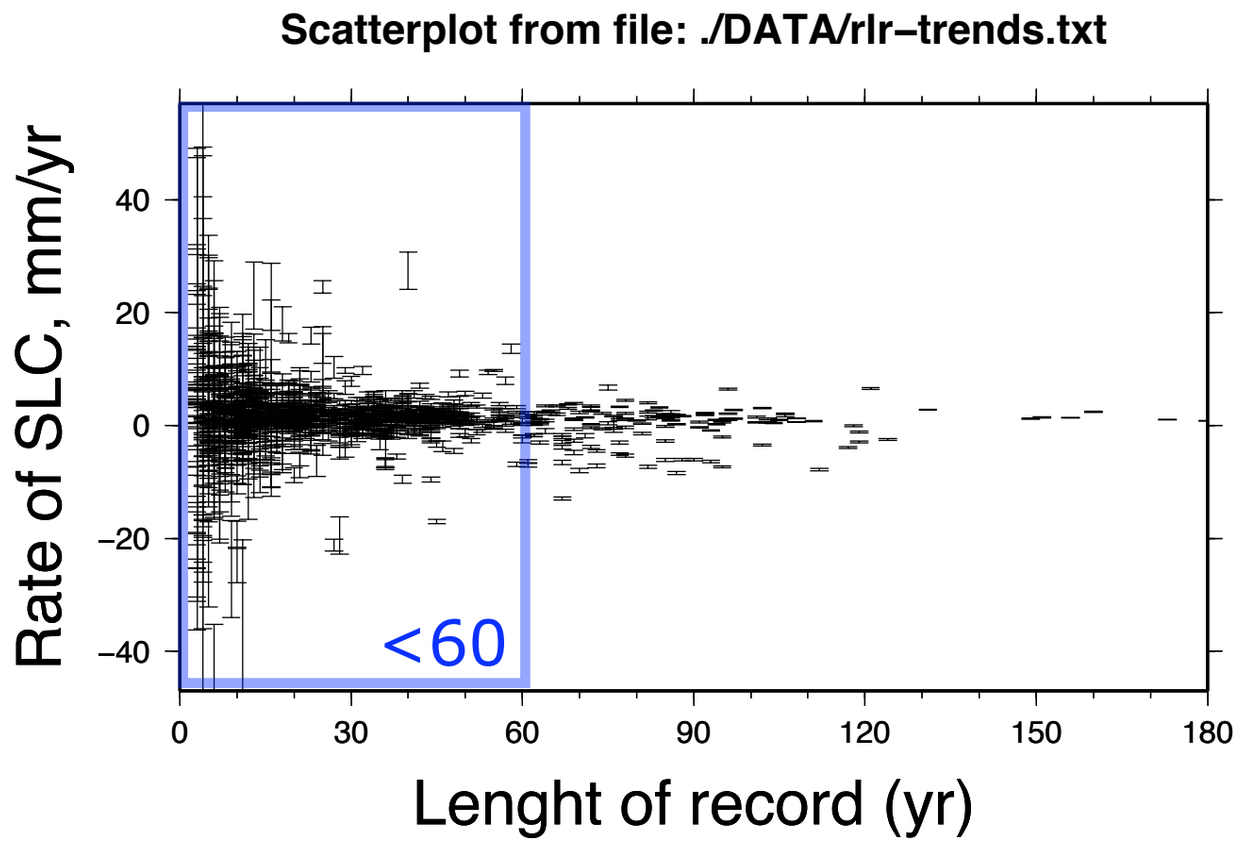
SELEN 3.0

is sea level “rising” or “falling” ?



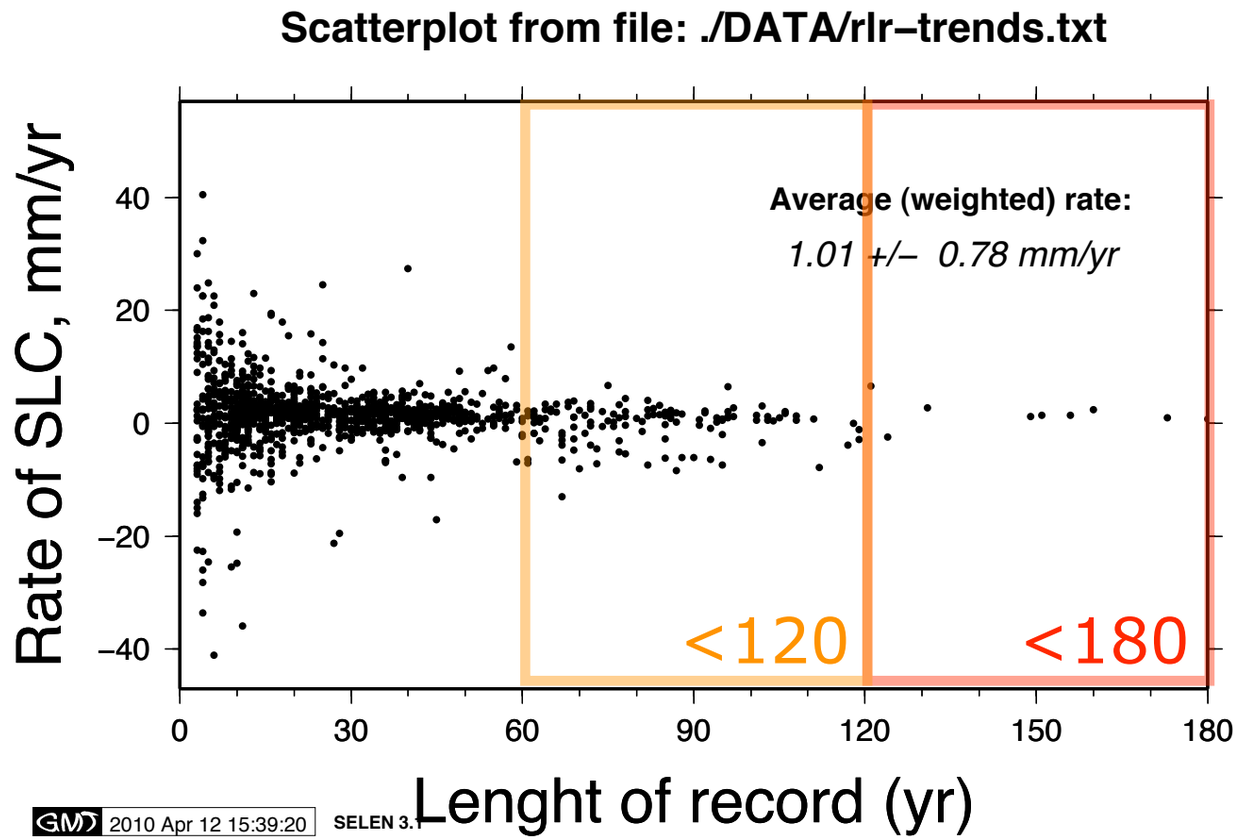
?

Can you see the 2 mm/yr sea level rise proposed by the IPCC ?



Short period:

Many noisy data



Long period:

A few, inconsistent, data.

The GLOBALLY AVERAGED RATE of SEA LEVEL RISE

is estimated using long series of T/G data

after GIA correction!

Table 3.1

Recent Determinations of Global Sea Level Rise from Tide Gauge Data

Author	Estimate (mm/yr)	Comments
Peltier and Tushingham (1989, 1991)	2.4 ± 0.9[a]	Global data
Barnett (1990)	1–2	Global data
Nakiboglu and Lambeck (1990)	1.15 ± 0.38	Global data
Trupin and Wahr (1990)	1.75 ± 0.13	Global data
Douglas (1991)	1.8 ± 0.1	Global data
Shennan and Woodworth (1992)	1.0 ± 0.15	U.K. and Europe
Mitrovica and Davis (1995)	1.1–1.6	Global data
Davis and Mitrovica (1996)	1.5 ± 0.3	U.S. east coast
Peltier (1996)	1.94 ± 0.6[a]	U.S. east coast
Peltier and Jiang (1997)	1.8 ± 0.6[a]	U.S. east coast
Douglas (1997)	1.8 ± 0.1	Global data

[a] Standard deviation of trends about their mean. The formal SE is a few tenths.

What is the color of sea level change?

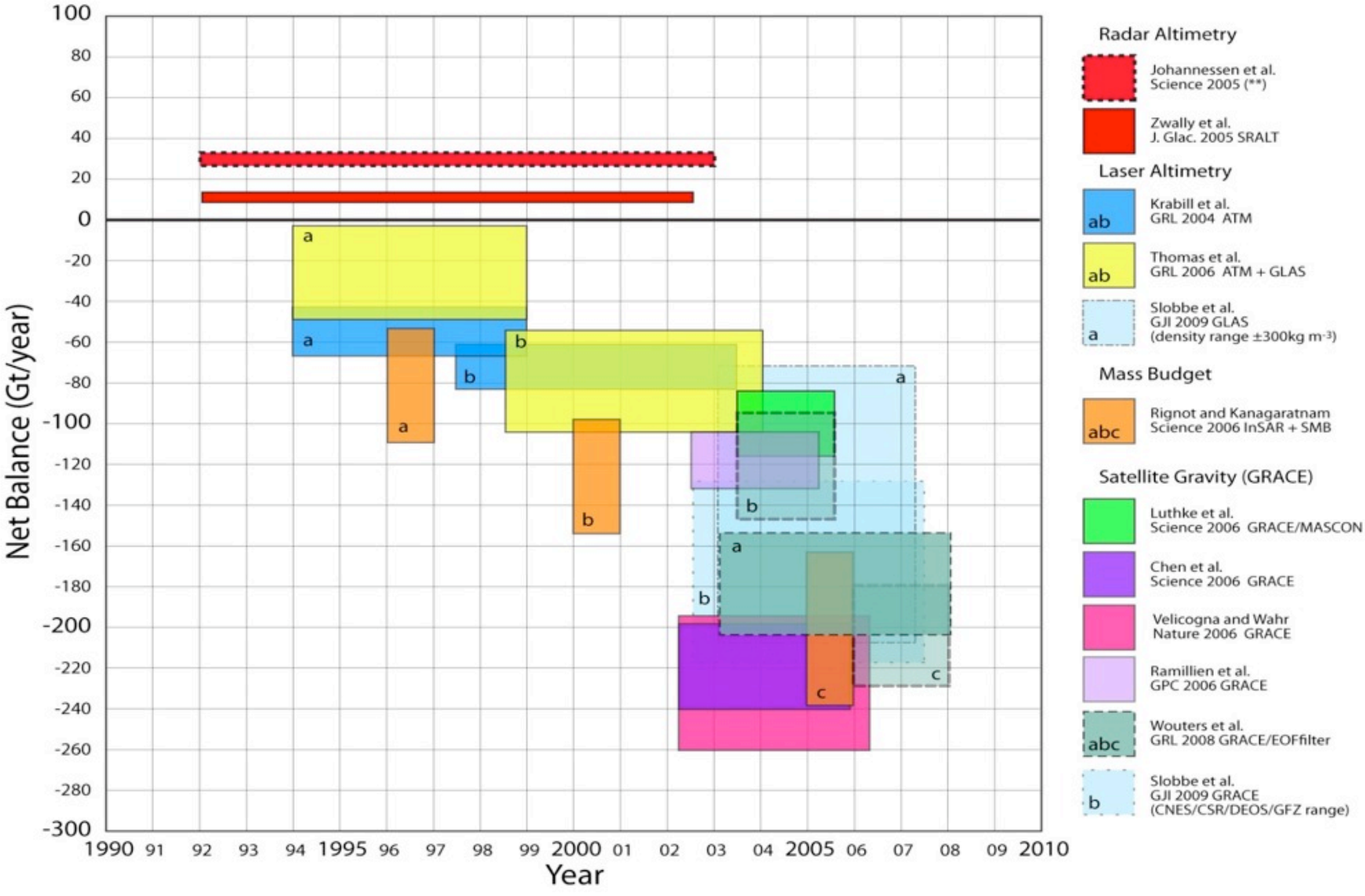
and regional (future) signals

http://www.ice2sea.eu/

Ice2sea is a science programme that is funded by the European Union Framework-7 scheme. Ice2sea will improve projections of the contribution of ice to future sea-level rise.

The mass balance of Greenland since 1990 from various sources

Courtesy of Jonathan Bamber, University of Bristol UK



Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets

Andrew Shepherd[1] and Duncan Wingham[2]*

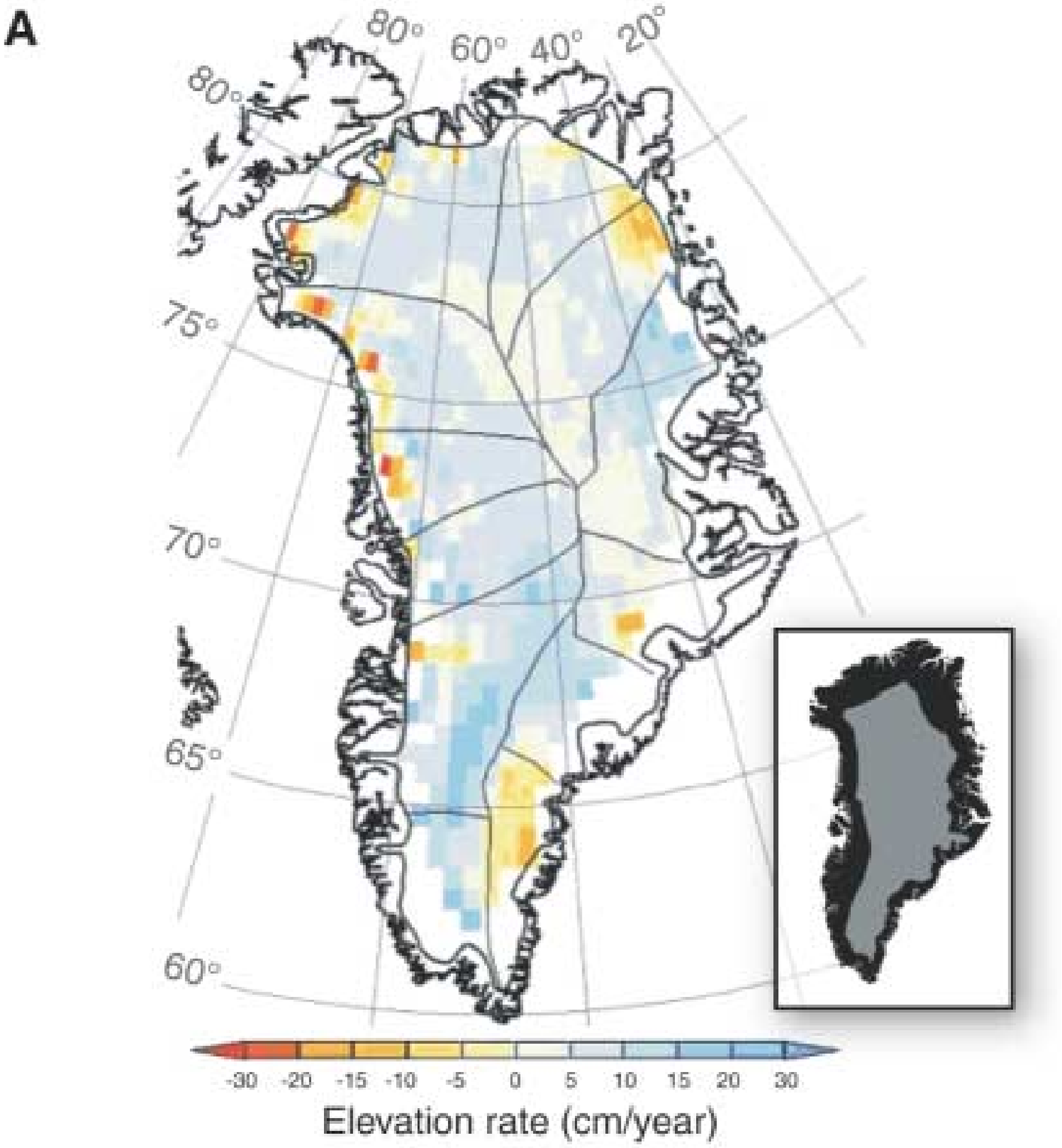
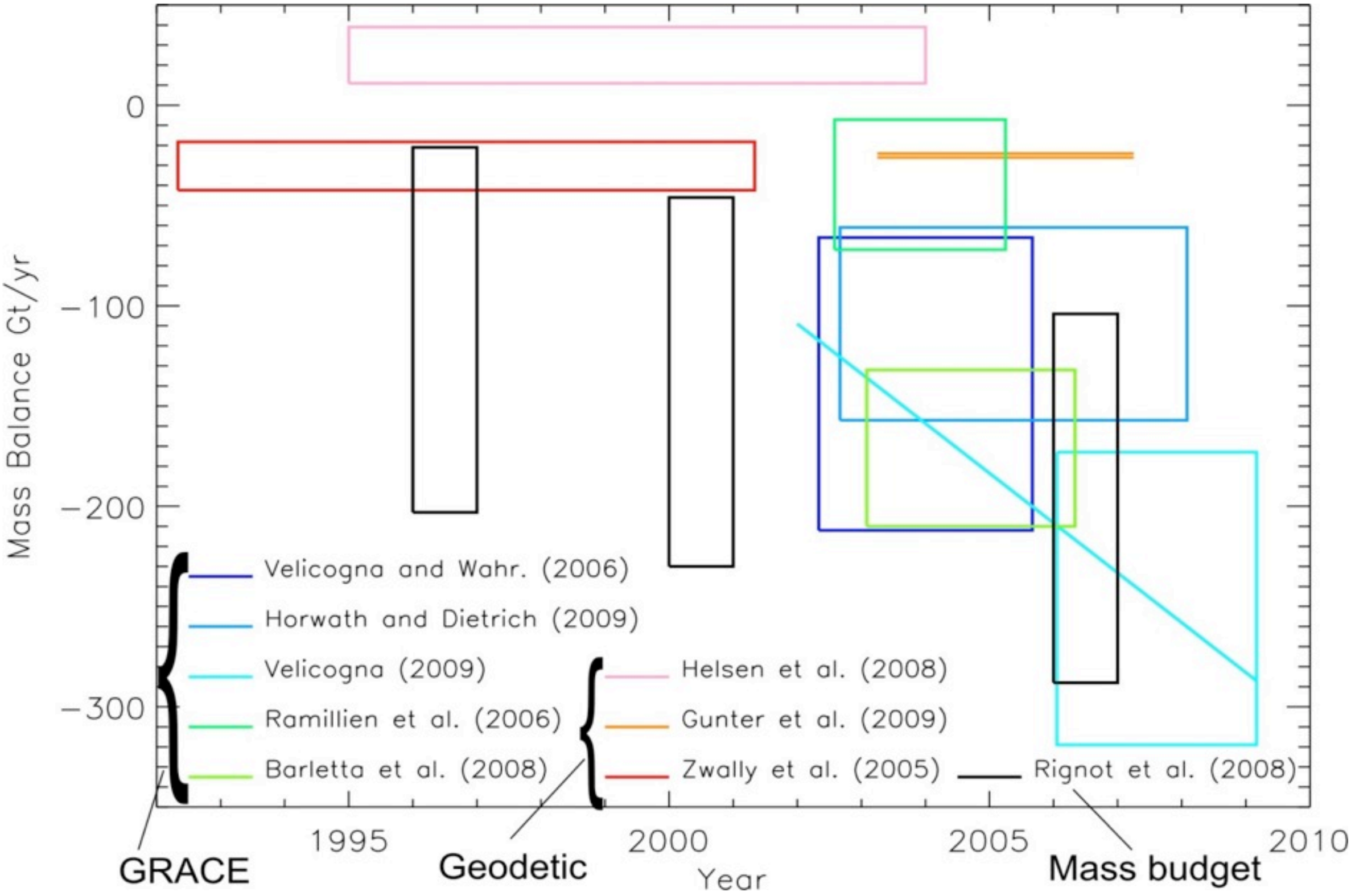


Fig. 3. (**A**) Rate of elevation change of the Greenland Ice Sheet, 1992 to 2003, determined from satellite radar altimetry [from (*22*)], and (**B**) time series of elevation change of individual sectors, 2003 to 2005, determined from satellite gravimetry [from (*16*)]. Also shown (inset) is the ice surface geometry, highlighting areas above (gray) and below (black) 2000 m elevation. Both instruments concur that high elevation areas are growing and low elevation areas are losing mass. According to gravimetry (*16*) and repeat InSAR measurements of ice discharge (*12*), the rate of mass loss at low elevations has increased over the past decade (see Table 1).

The mass balance of Antarctica since 1990 from various sources

Courtesy of Jonathan Bamber, University of Bristol UK

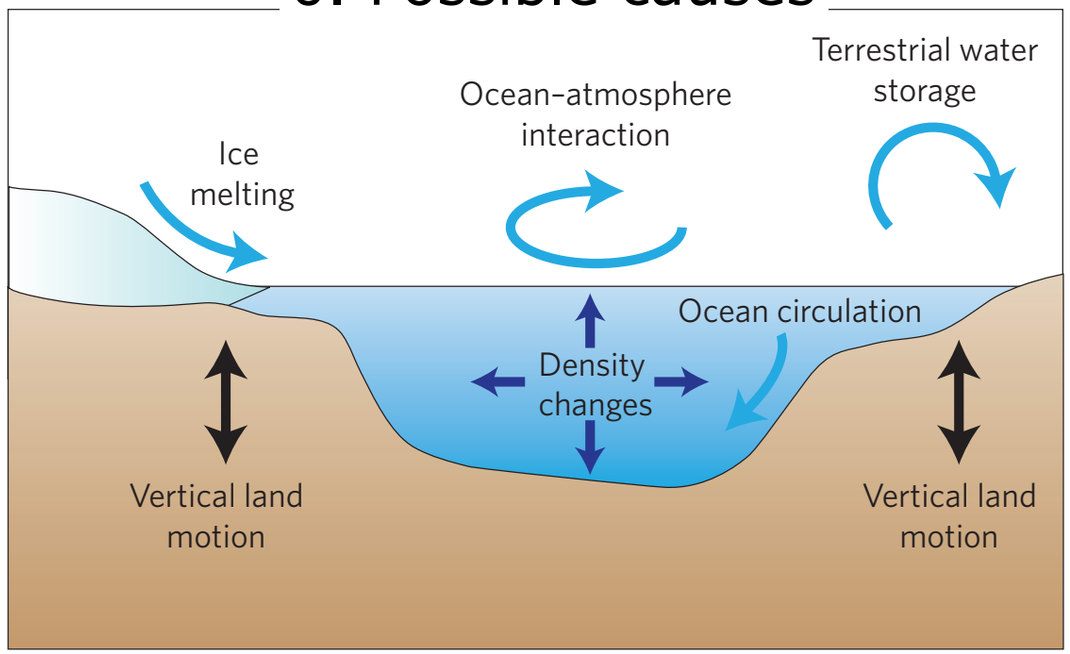


Identifying the causes of sea-level change

Glenn A. Milne, W. Roland Gehrels, Chris W. Hughes and Mark E. Tamisiea, NATURE GEOSCI 2009

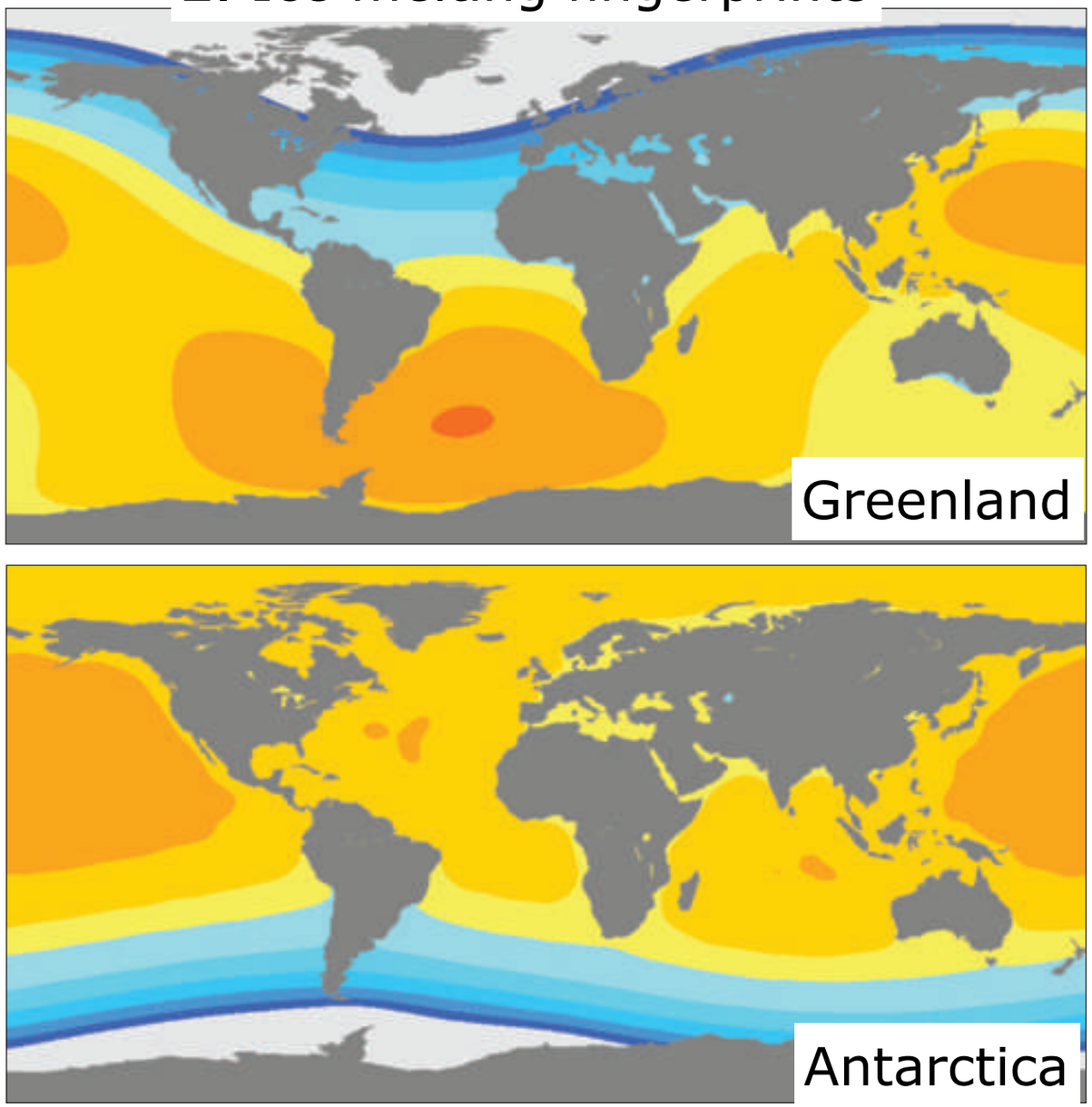
0. Possible causes

a



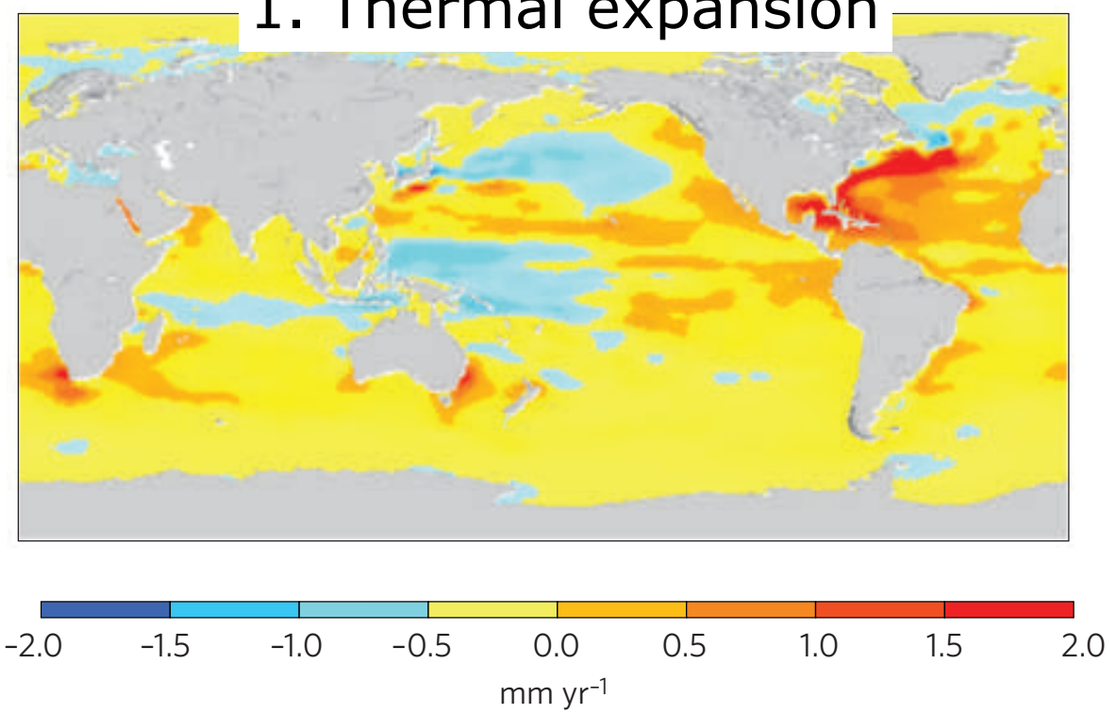
2. Ice melting fingerprints

b

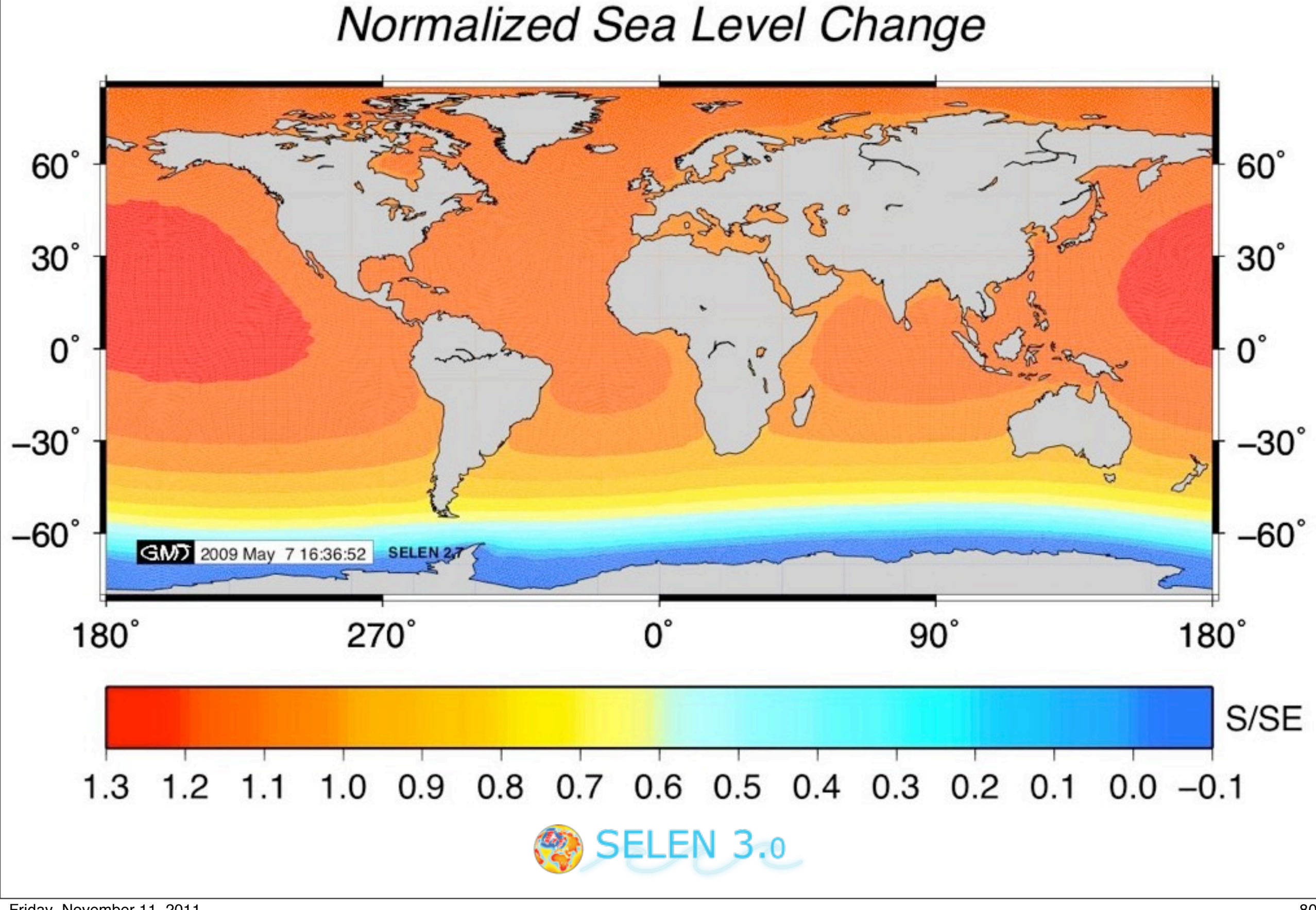


1. Thermal expansion

c



Sea level "*fingerprint*" from the (uniform) melting of Antarctica



Concluding remarks

1. Physical models of giacio-isostatic adjustment are simple to be stated but account for an extremely complex phenomenology - *in spite of their linearity* - Agreement among scientists difficult to reach (but reachable after some work, see benchmarks...)

2. There are LARGE uncertainties in GIA models, and large error bars in the mass balance models for e.g., Antarctica, Greenland and the small glaciers.
Sophisticated GIA theories are useful but probably we need data more than theories.

3. Future sea level rise/fall on a regional scale will be influenced by secular melting of glaciers, but they will be - reminiscent of GIA. So, understanding the effect of ongoing climate change is difficult without information on the solid Earth.