Glacial Isostatic Adjustment

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Urbino University “Carlo Bo”

with:

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GLOSS/PSMSL-80 workshop, Liverpool 2013

Overview:

1). General ideas about Glacial Isostatic Adjustment (GIA),

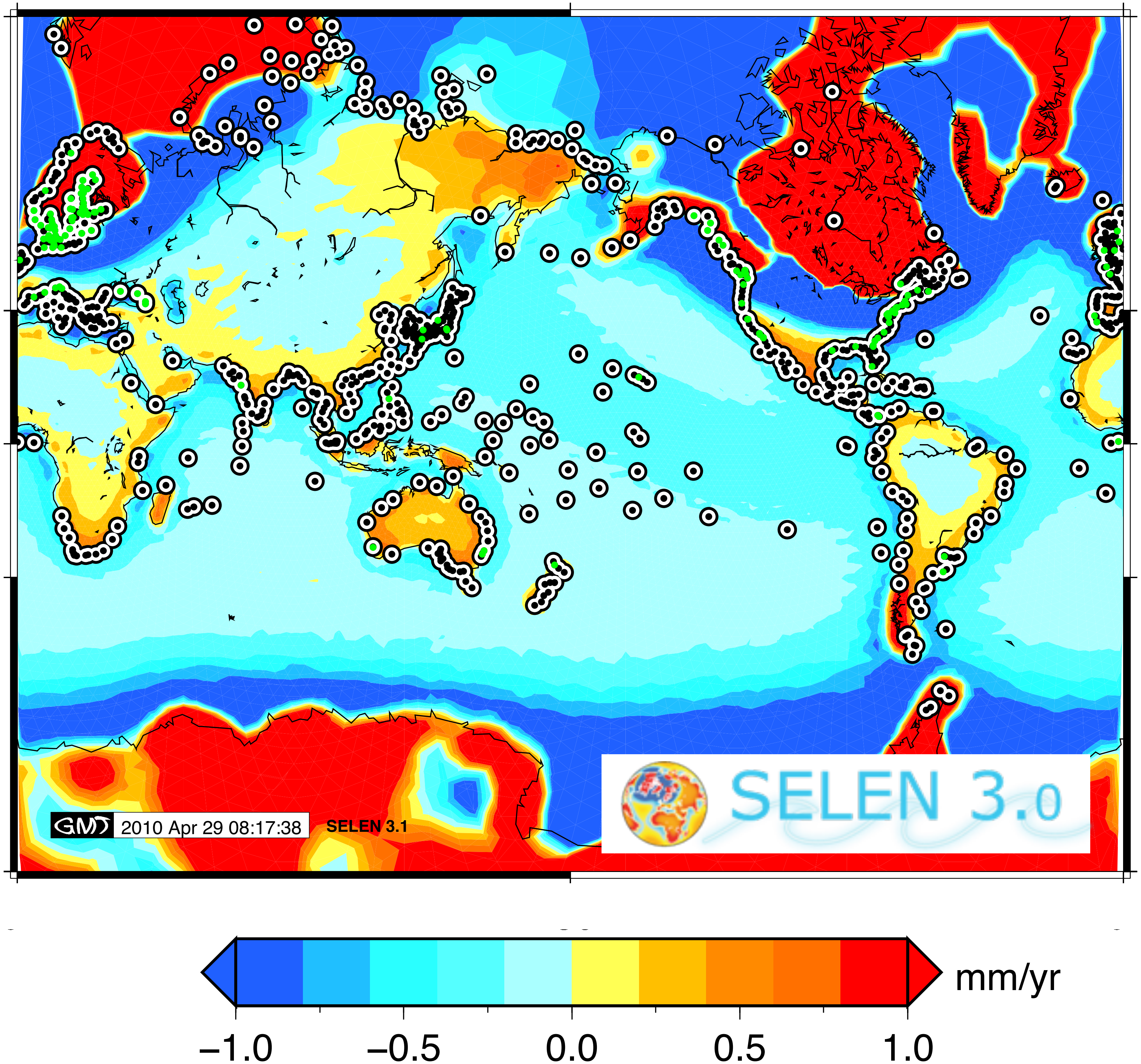
2). Physics of GIA and "gravitationally self-consistent" modeling of sea level changes,

3). GIA and secular sea level rise, using PSMSL data (1880 to present),

Questions / discussion

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)

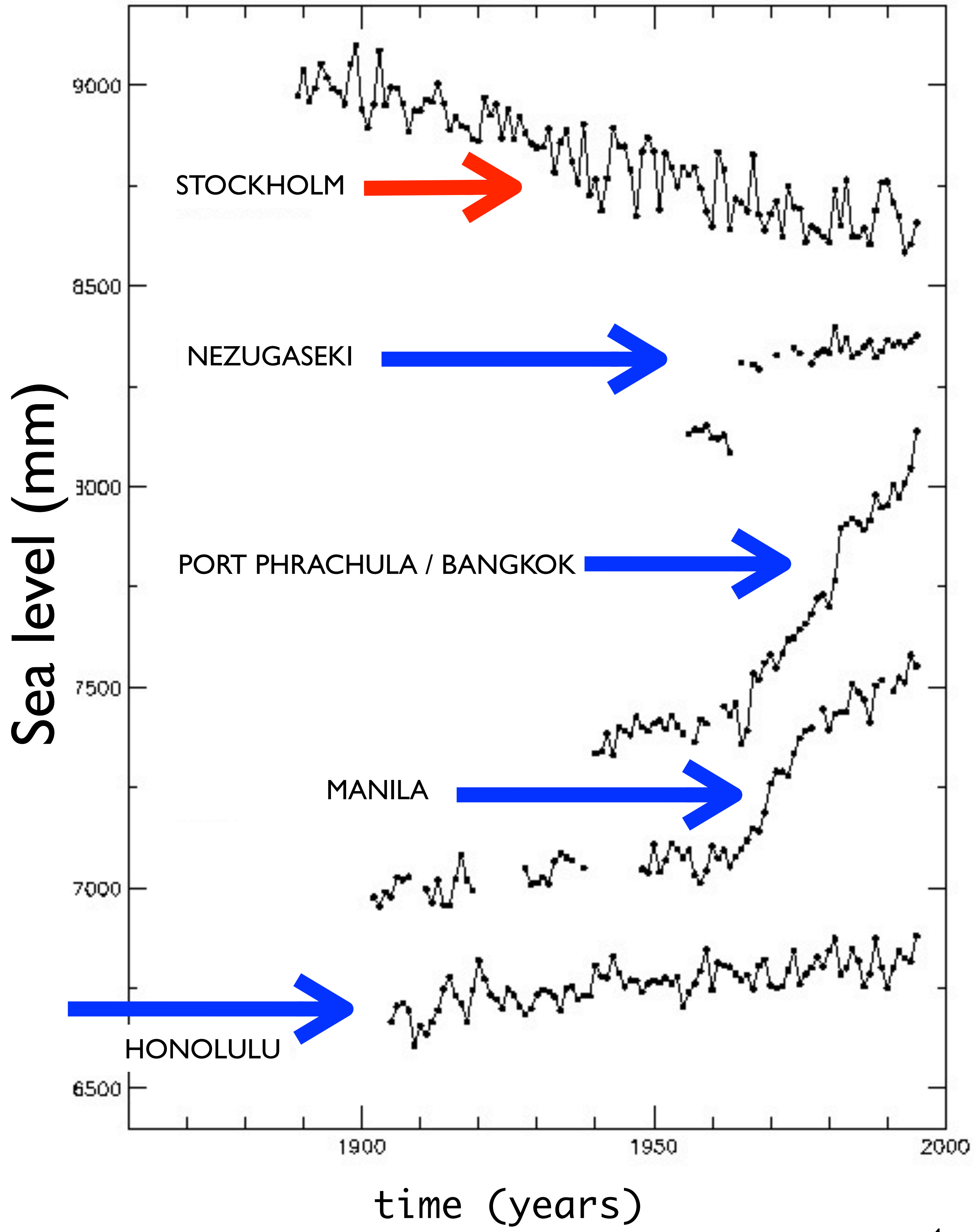
Most (all?) tide gauges are in regions of considerable GIA disequilibrium

(formerly) ICE COVERED areas

&

forebulge regions

“we do not believe any land to be completely stable”



This figure demonstrates signals from vertical land movements due to a number of different geological processes: **Stockholm**, **Sweden** as above (sea level fall due to Glacial Isostatic Adjustment), **Nezugaseki**, Japan (abrupt jump in sea level record following earthquake in 1964), Fort Phrachula **Bangkok**, Thailand (sea level rise due to increased groundwater extraction since about 1960), **Manila**, Philippines (recent deposit from river discharges and reclamation works) and Honolulu, **Hawaii** (a site in the PGR 'far field' without evident strong tectonic signals on timescales comparable to the length of the tide gauge record and with secular trend 1.5 mm/ year).

(The Honolulu record is shown above incidentally for some sort of comparison only. It should not be interpreted as suggesting the Hawaiian islands to be completely 'stable', as is obvious from their volcanic history. Similar comments would apply to other far field sites with long records but for different geological reasons depending on the location; in brief,

we do not believe any land to be completely 'stable',

which is the main motivation for interest in measuring vertical land movements.)

http://www.pol.ac.uk/psmsl/landmove.html

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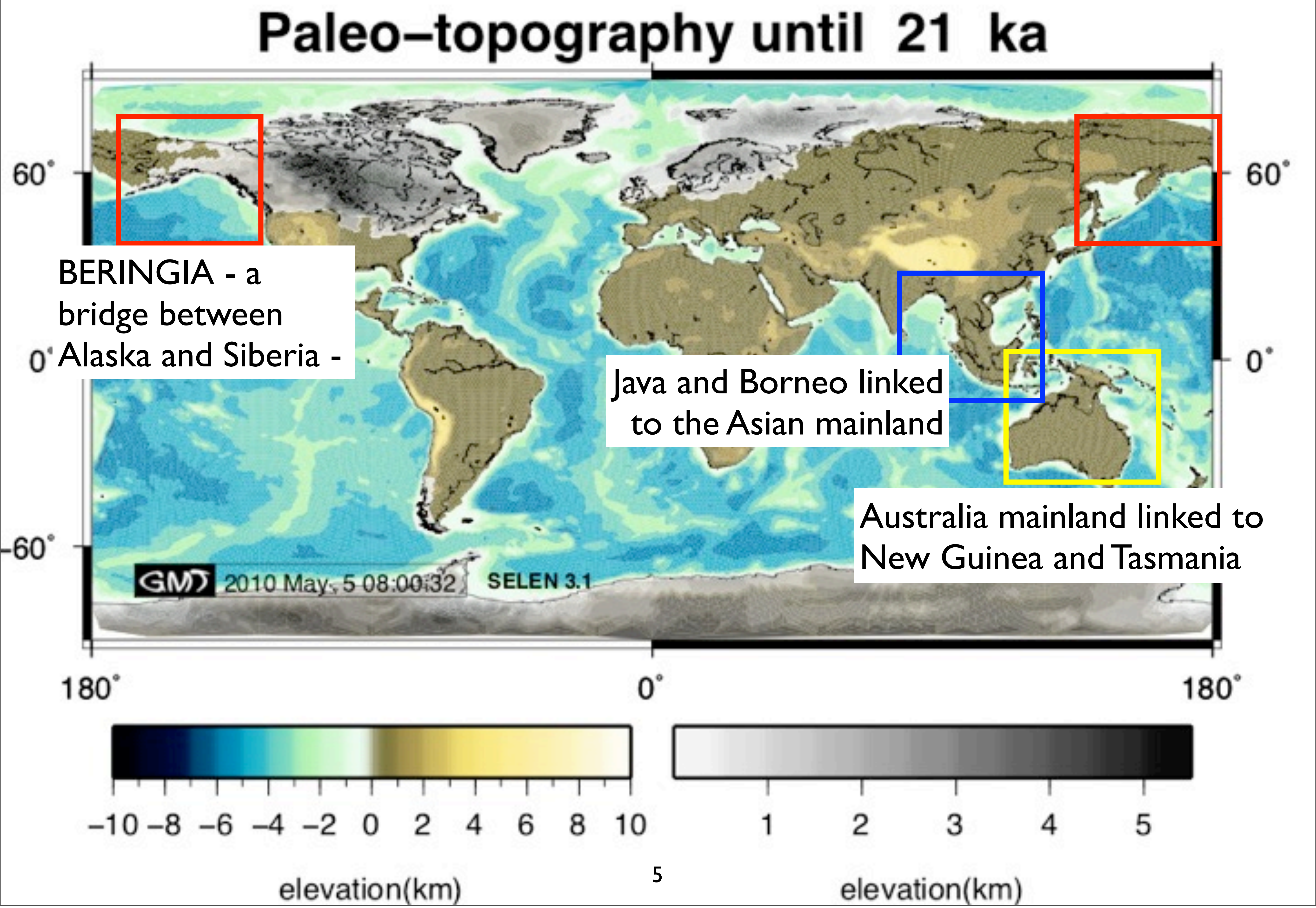
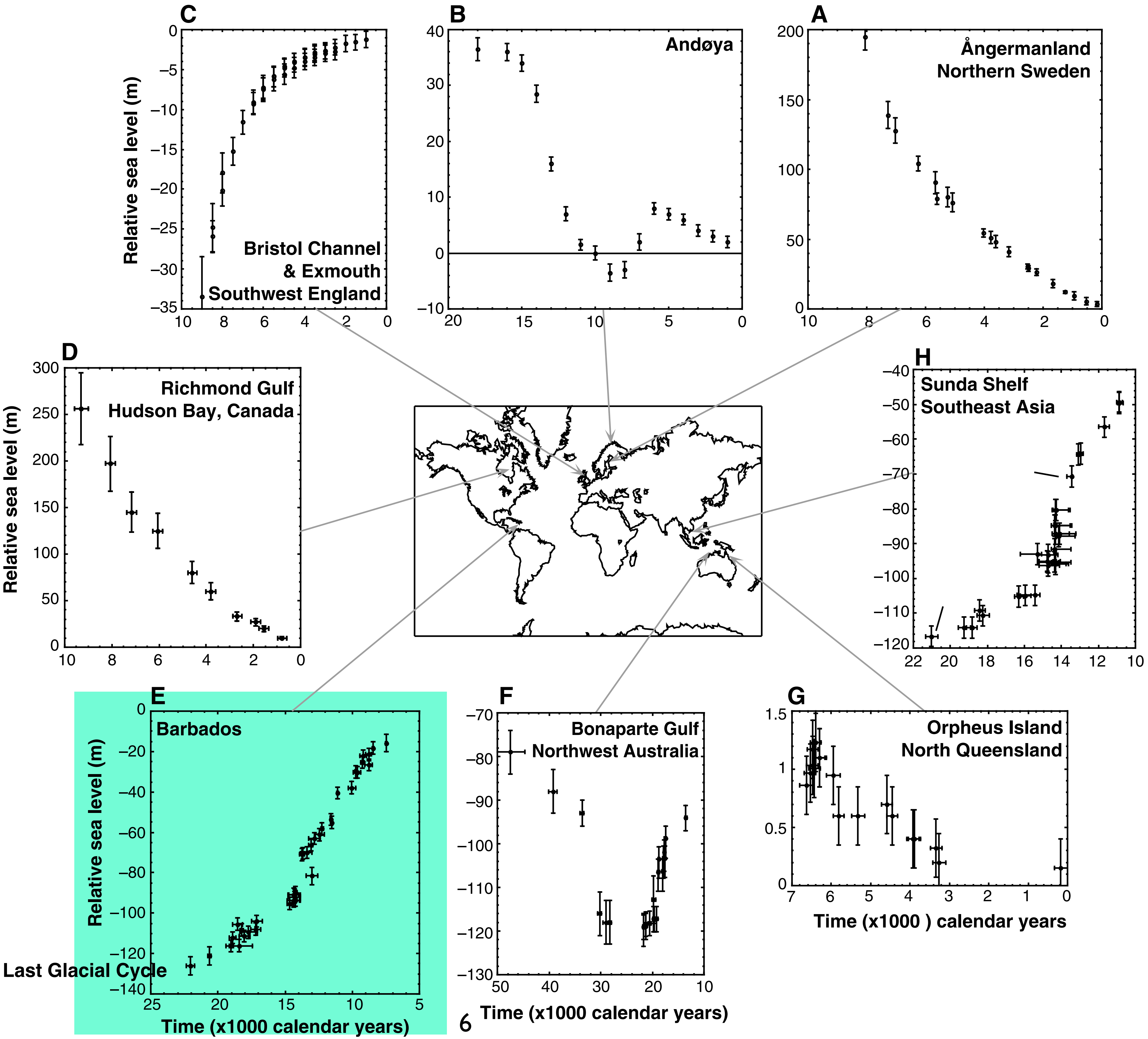

Paleo–topography until 21 ka
60°
0°
-60°
180°
0°
180°
GMT 2010 May, 5 08:00:32
SELEN 3.1
BERINGIA - a bridge between Alaska and Siberia -
Java and Borneo linked to the Asian mainland
Australia mainland linked to New Guinea and Tasmania
–10 –8 –6 –4 –2 0 2 4 6 8 10
elevation(km)
1 2 3 4 5
elevation(km)

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.



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

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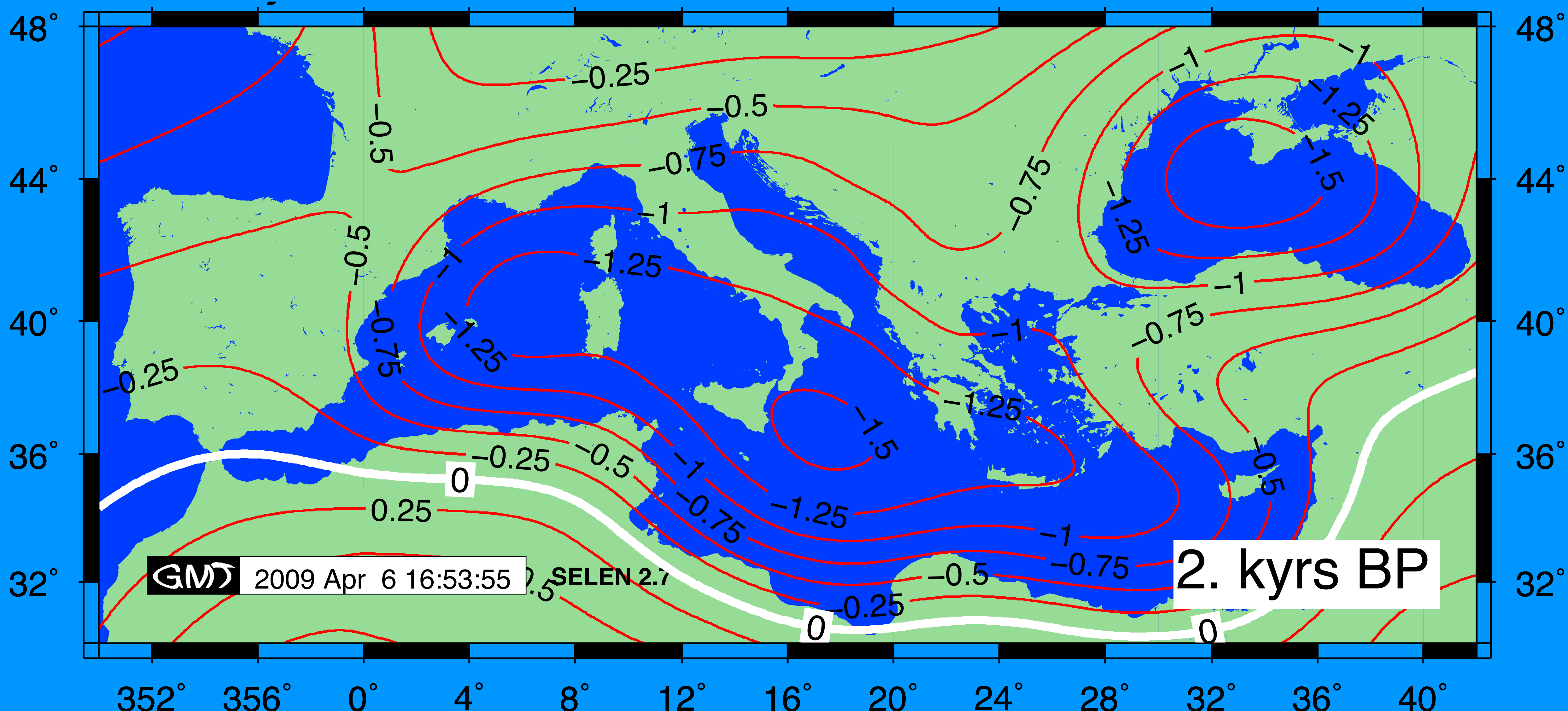
Sea-level in the Mediterranean 2,000 yrs BP

(relative to present sea level)



San Vito Lo Capo, Sicily (I)

Haifa (Is)

Mallorca (ES) caves

Roman fish tanks - Rome (I)

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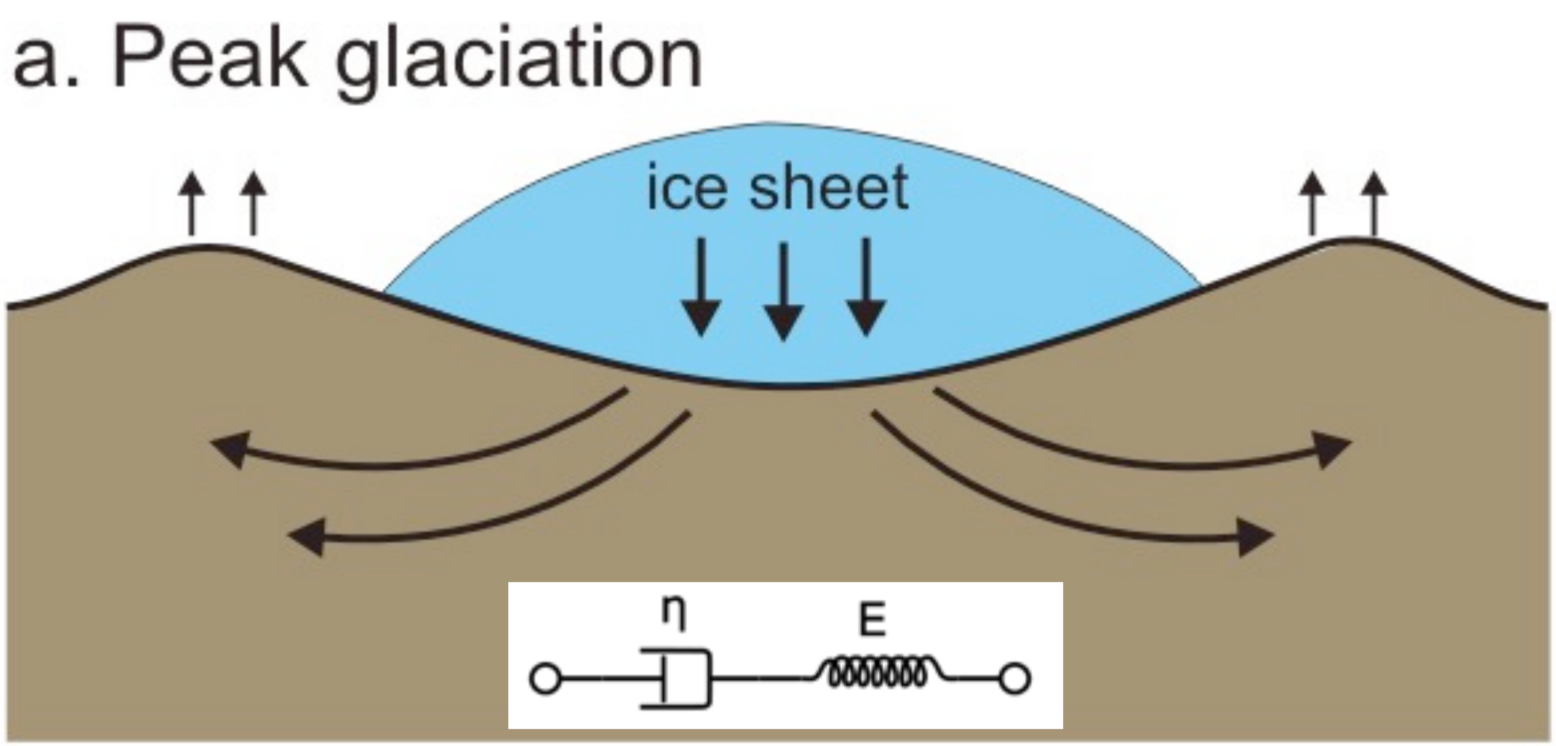
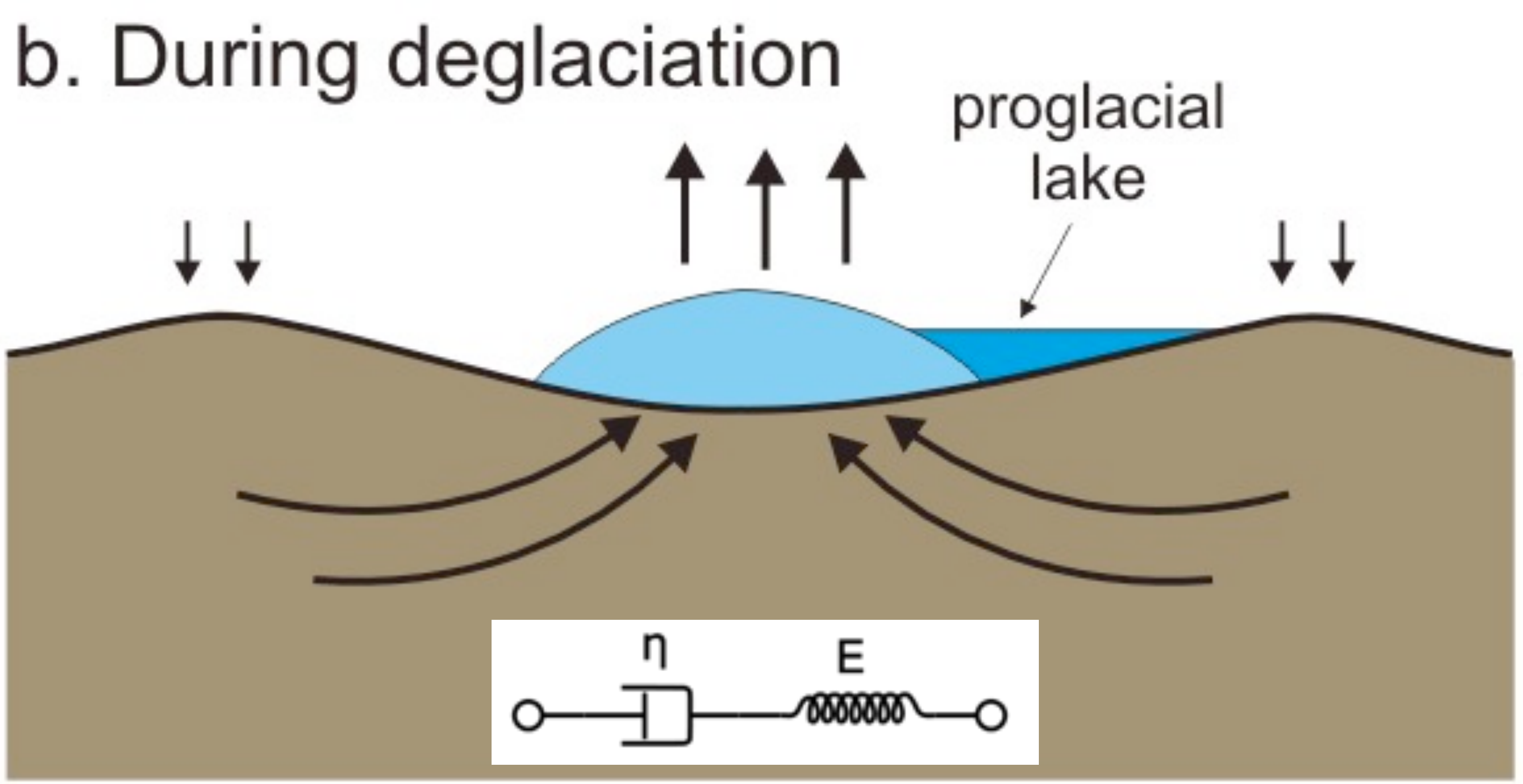




"POST GLACIAL REBOUND"

21 kyrs BP

(a) At peak glacial conditions the Earth's surface is depressed beneath the ice sheet and slightly elevated outside the ice sheet owing to mantle flow.

Later on...

(b) During deglaciation the depressed region rises and peripheral regions subside. Uplift of the Earth's surface is frequently observed as relative sea level fall in recently deglaciated areas.

Adapted from: *http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/geodynamics/earthquake-processes/9593*

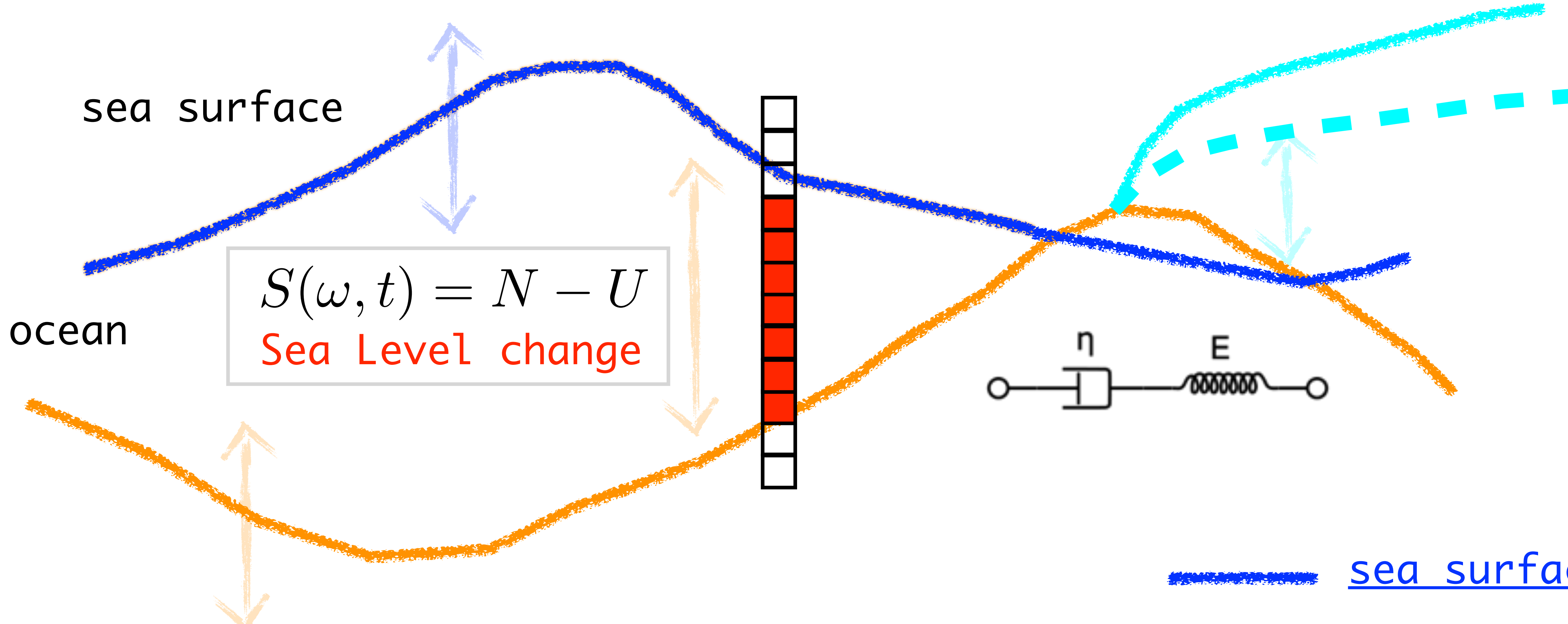
Causes of regional variability in TIM - induced sea level change (i)

sea surface variation:

$$N = R_{ss}(\omega, t) - R_{ss}(\omega, t_0)$$

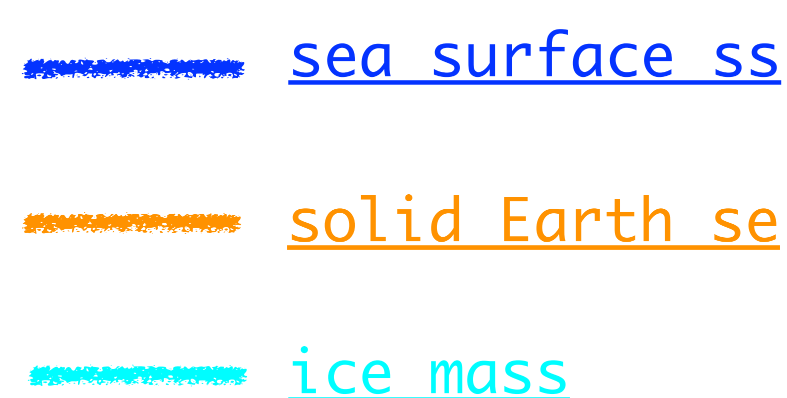
ice thickness variation

$$I(\omega, t) = T(\omega, t) - T(\omega, t_0)$$



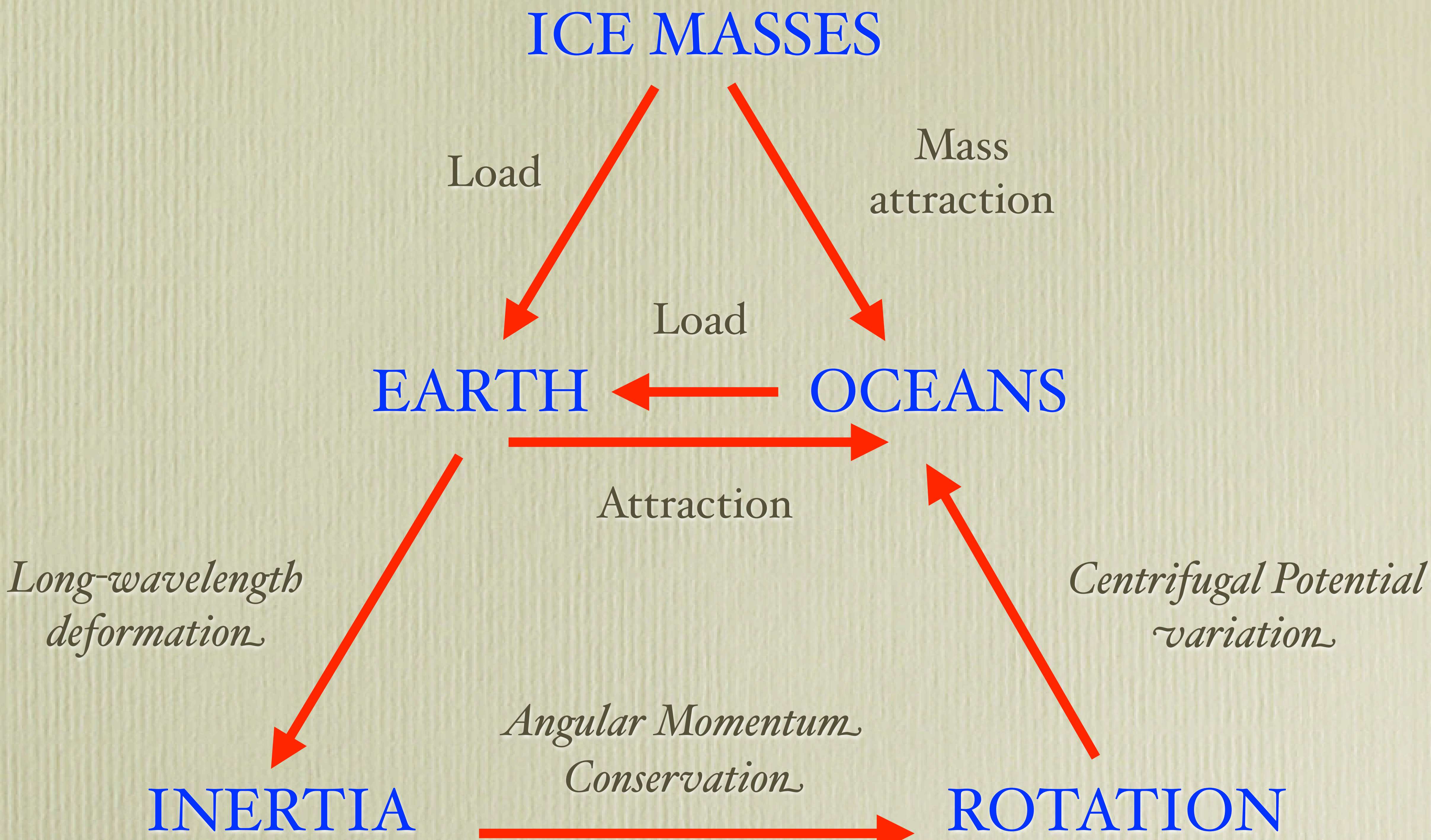
vertical displacement:

$$U = R_{se}(\omega, t) - R_{se}(\omega, t_0)$$



Causes of regional variability in TIM - induced sea level change (ii)

Adapted from Clark & Lingle, 1979



$$S \neq -\frac{\Delta m_{ice}}{\rho_w A_{oc}}$$

G. Spada ice2sea Forum
London, May 2013

the "Sea Level Equation"

Farrell & Clark (1976)

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

with:

$S =$ sea level change

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

$G_s =$ sea level Green function

$I =$ ice thickness variation

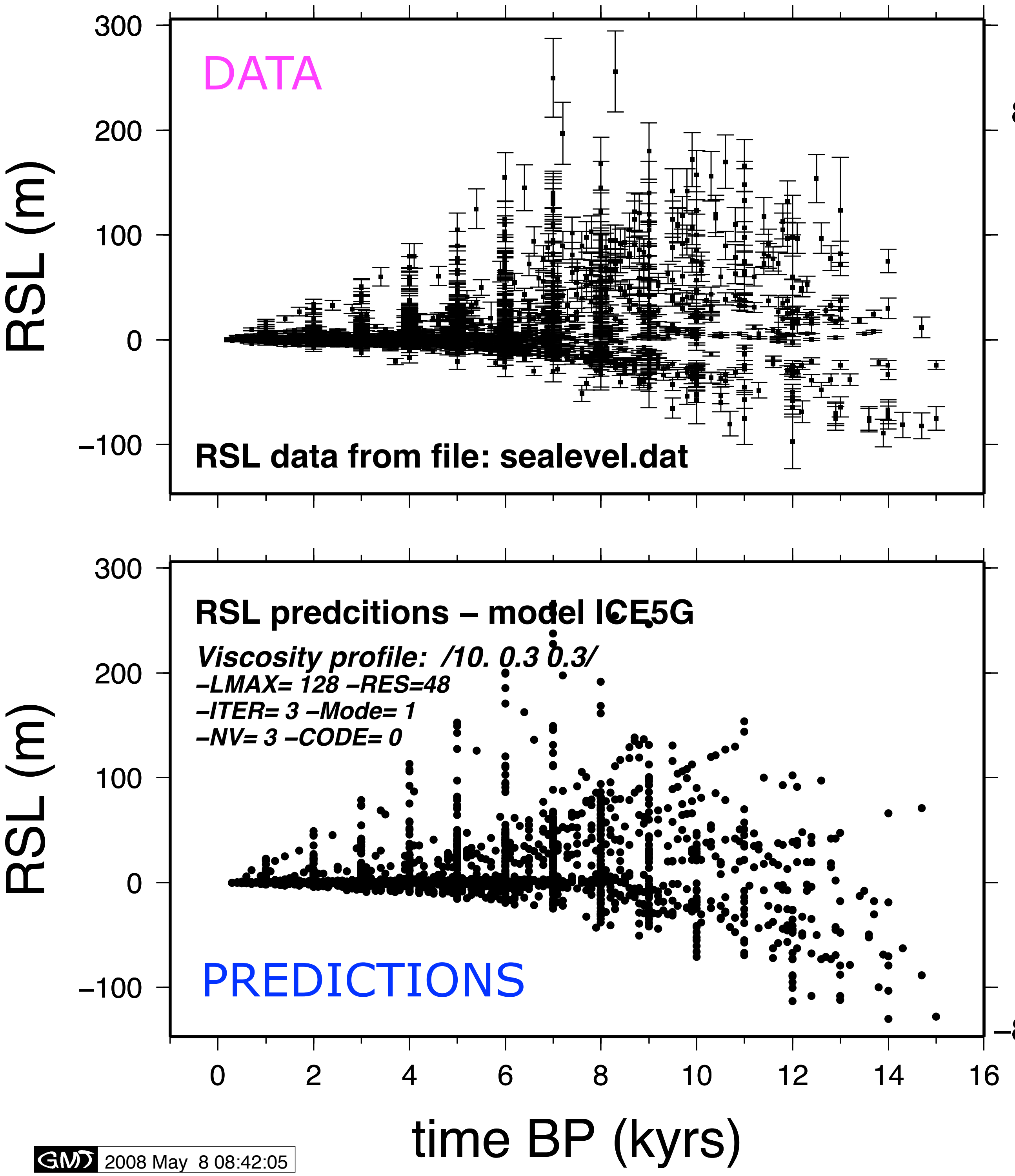
$m_i =$ ice mass variation

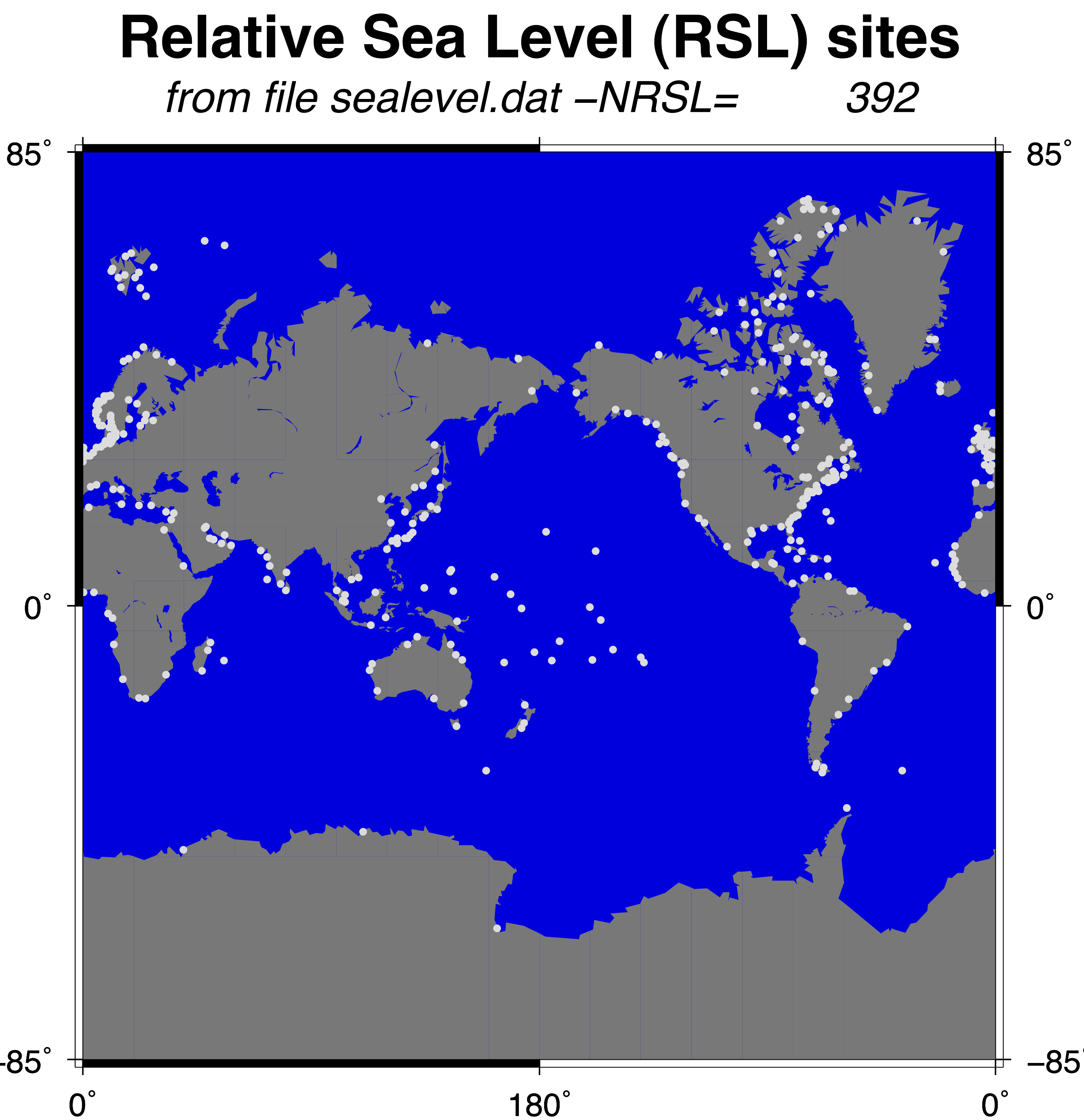
$A_o =$ area of the oceans

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

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

$$\left\{ \begin{array}{c} U_i \\ \Phi_i \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_i \rho_i I, \quad \text{and} \quad \left\{ \begin{array}{c} U_o \\ \Phi_o \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_o \rho_w S$$





SELEN 3.0

T/P database

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

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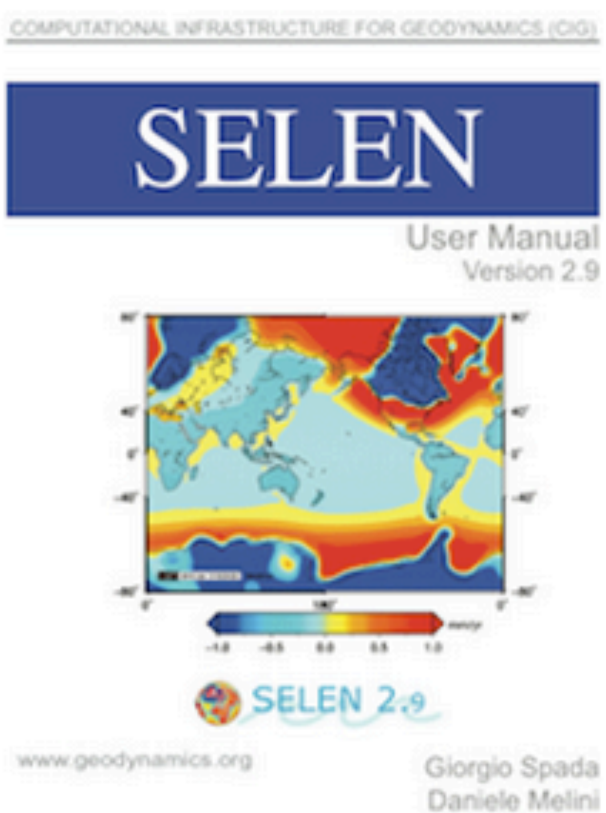
COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

SELEN

SELEN: a program for solving the "Sea Level Equation".

SELEN 2.9

The open source program SELEN solves numerically the so-called "Sea Level Equation" (SLE) for a spherical, layered, non-rotating Earth with Maxwell viscoelastic rheology. The SLE is an integral equation that was introduced in the 70s to model the sea level variations in response to the melting of late Pleistocene ice sheets, but it can also be employed for predictions of geodetic quantities in response to present-day melting of continental ice-sheets. SELEN can compute vertical and horizontal surface displacements, gravity variations and sea level changes on a global and regional scale. SELEN (acronym of SEa Level EquatioN solver) is particularly oriented to scientists at their first approach to the glacial isostatic adjustment (GIA) problem and, according to our experience, it can be successfully used in teaching. The current release (2.9) considerably improves the previous version of the code in terms of computational efficiency, portability and versatility.



Status	Accepting bug reports.
Contact	cig-short@geodynamics.org
Bug reports	RoundUp
License	GNU Public License

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Questions / discussion

Previous estimates of global sea level rise

1941

1980

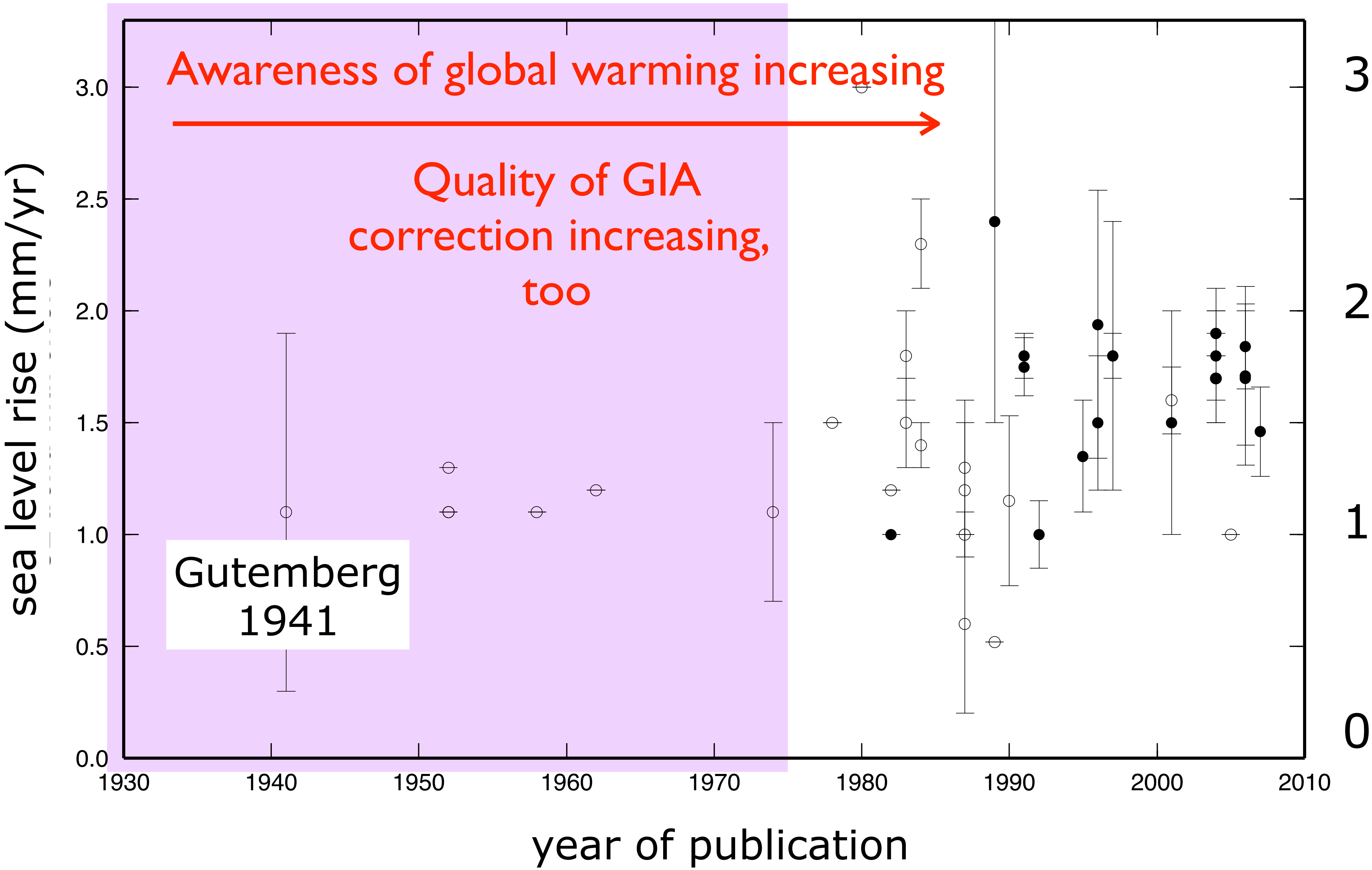
today

Year and Author(s)	μ^a (mm/yr)	Period^b	Method(s)^c	GIA correction ^{d}
1941 Gutenberg	1.1 ± 0.8	1807–1937	RA	no
1952 Polli	1.1	1871–1940	**-???-**	no
1952 Cailleux	1.3	1885–1951	SA	no
1952 Valentin	1.1	1807–1947	**-???-**	no
1958 Lisitzin	1.1	1807–1943	**-???-**	no
1962 Fairbridge & Krebs	1.2	1900–1950	SA	no
1974 Lisitzin	1.1 ± 0.4	**-???-**	SA	no
1978 Kalinin & Klige	1.5	1860–1960	**-???-**	no
1980 Emery	3	1850–1958	SA	no
1982 Gornitz *et al.*[1]	1.2	1880–1980	RA	no
" "	1.0	1880–1980	RA	Geological
1983a Barnett	1.5 ± 0.2	1903–1969	EOF	no
1983b Barnett	1.8 ± 0.2	**-???-**	EOF	**-???-**
1984 Barnett[a]	1.4 ± 0.1	1881–1980	EOF, RA	no
" "	2.3 ± 0.2	1930–1980	EOF, RA	no
1987 Gornitz & Lebedeff	0.6 ± 0.4	1880–1982	SA	Geological
" "	1.7 ± 0.3	1880–1982	SA	Geological
" "	1.2 ± 0.3	1880–1982	SA	Geological
" "	1.0 ± 0.1	1880–1982	RA	Geological
1989 Peltier & Tushingham	2.4 ± 0.9	1920–1970	EOF	presumably ICE–3G
1986 Pirazzoli	indeterminable	1807–1984	–	–
1989 Pirazzoli	$0.5 - 3.0$	1880–1980 Eu	**-???-**	**-???-**
1990a Trupin & Wahr	1.75 ± 0.13	1900–1979	SA	no
1991 Nakiboglu & Lambeck	1.15 ± 0.38	1820–1990	SHA, RA	ANU models
1991 Douglas	1.8 ± 0.1	1880–1980	SA	ICE–3G
1991 Emery & Aubrey	indeterminable	1807–1996	–	–
1992 Shennan & Woodworth	1.0 ± 0.15	1901–1988 Eu	SA	Geological
1993 Gröger & Plag	indeterminable	1807–1992	–	–
1995 Mitrovica & Davis	1.1–1.6	1880–1990	SA	ICE–3G
1996 Davis & Mitrovica	1.5 ± 0.3	1856–1995 USE	SA	ICE–3G
1996 Peltier	1.94 ± 0.56	1920–1970 USE	EOF	ICE–4G
1997 Peltier & Jiang	1.8 ± 0.6	1856–1995 USE	SA	ICE–4G
1997 Douglas	1.8 ± 0.1	1880–1980	SA	ICE–3G
2001 Cabanes *et al.*	1.6 ± 0.15	1955–1996	SA	no
2001 Church *et al.*	1.5 ± 0.50	1900–2000	APE	Various models
2001 Mitrovica *et al.*	1.5 ± 0.1	1880–2000	SA	no
" "	1.8 ± 0.1	1880–2000	SA	ICE–3G
2004 Church *et al.*	1.8 ± 0.3	1950–2000	EOF	ICE–4G(VM2), L,M
" "	1.75 ± 0.10	1950–2000	EOF	ICE–4G(VM2)
" "	1.89 ± 0.10	1950–2000	EOF	L
" "	1.91 ± 0.10	1950–2000	EOF	M
2004 Holgate & Woodworth	1.7 ± 0.20	**1950–?**	RA	**-???-**
2005 Nakada & Inoue	1.5	20th century	SA	no
2006 Church & White	1.7 ± 0.30	20th century	EOF	ICE–4G(VM2), L, M
" "	1.71 ± 0.40	1870–1935	EOF	ICE–4G(VM2), L, M
" "	1.84 ± 0.19	1936–2001	EOF	ICE–4G(VM2), L, M
2007 Church *et al.*	**-???-**	**-???-**	APE	**-???-**
2007 Hagedoorn *et al.*	1.46 ± 0.20	20th century	RA	ICE–3G
2011 Church & White	1.7 ± 0.2	1900–2009	EOF	as in Church *et al.* (2004)
" "	1.9 ± 0.4	1961–2009	EOF	" "

Spada & Galassi (*GJI*, 2012)

GIA corrections since late 80s

Previous estimates of global sea level rise
from TG observations



GLOBAL SEA RISE: A REDETERMINATION

BRUCE C. DOUGLAS
Department of Geography, University of Maryland, College Park, MD 20742, USA

a very influential paper: Douglas 1997 (D97)

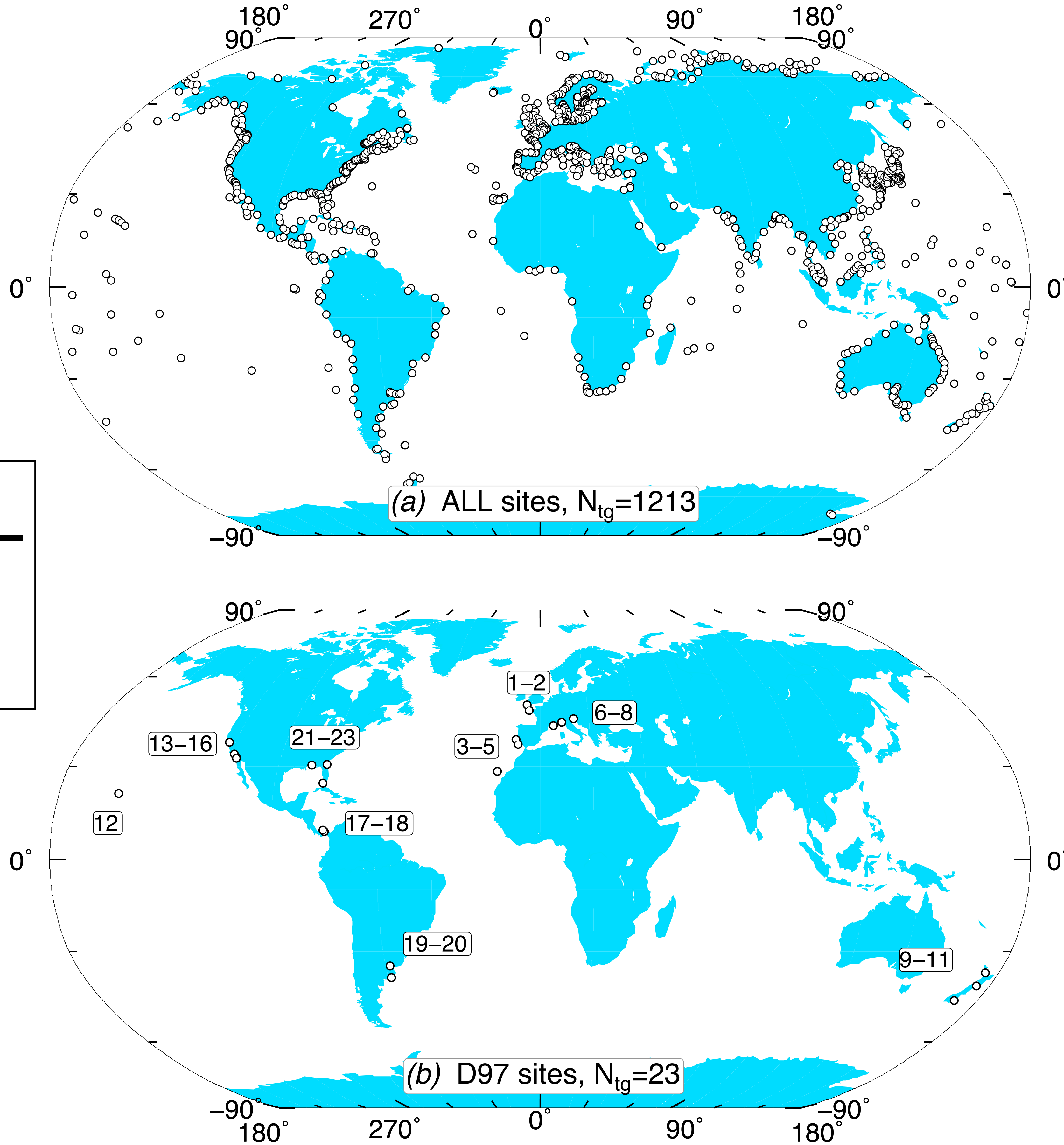
Abstract. It is well established that sea level trends obtained from tide gauge records shorter than about 50-60 years are corrupted by interdecadal sea level variation. However, only a fraction (<25%) of even the long records exhibit globally consistent trends, because of vertical crustal movements. The coherent trends are from tide gauges not at collisional plate boundaries, and not located in or near areas deeply ice-covered during the last glaciation. Douglas (1991), using ICE-3G values for the postglacial (PGR) rebound correction, found 21 usable records (minimum length 60 years, average 76) in 9 oceanographic groups that gave a mean trend for global sea level rise of 1.8 mm/yr ± 0.1 for the period 1880–1980. In that analysis, a significant inconsistency of PGR-corrected U.S. east coast trends was noted, but not resolved. Now, even after eliminating those trends, more (24) long records (minimum 60 years, average 83) are available, including series in the southern hemisphere

(ICE-3G GIA-corrected)

mean trend of global secular sea level rise:

1.8 +/- 0.1 mm/yr

PSMSL
RLR
records



ALL
(1123)

D97
(23)

The D97 requirements on PSMSL data

I) be at least 60 years in *length*

II) not be from sites at collisional *tectonic plate boundaries*

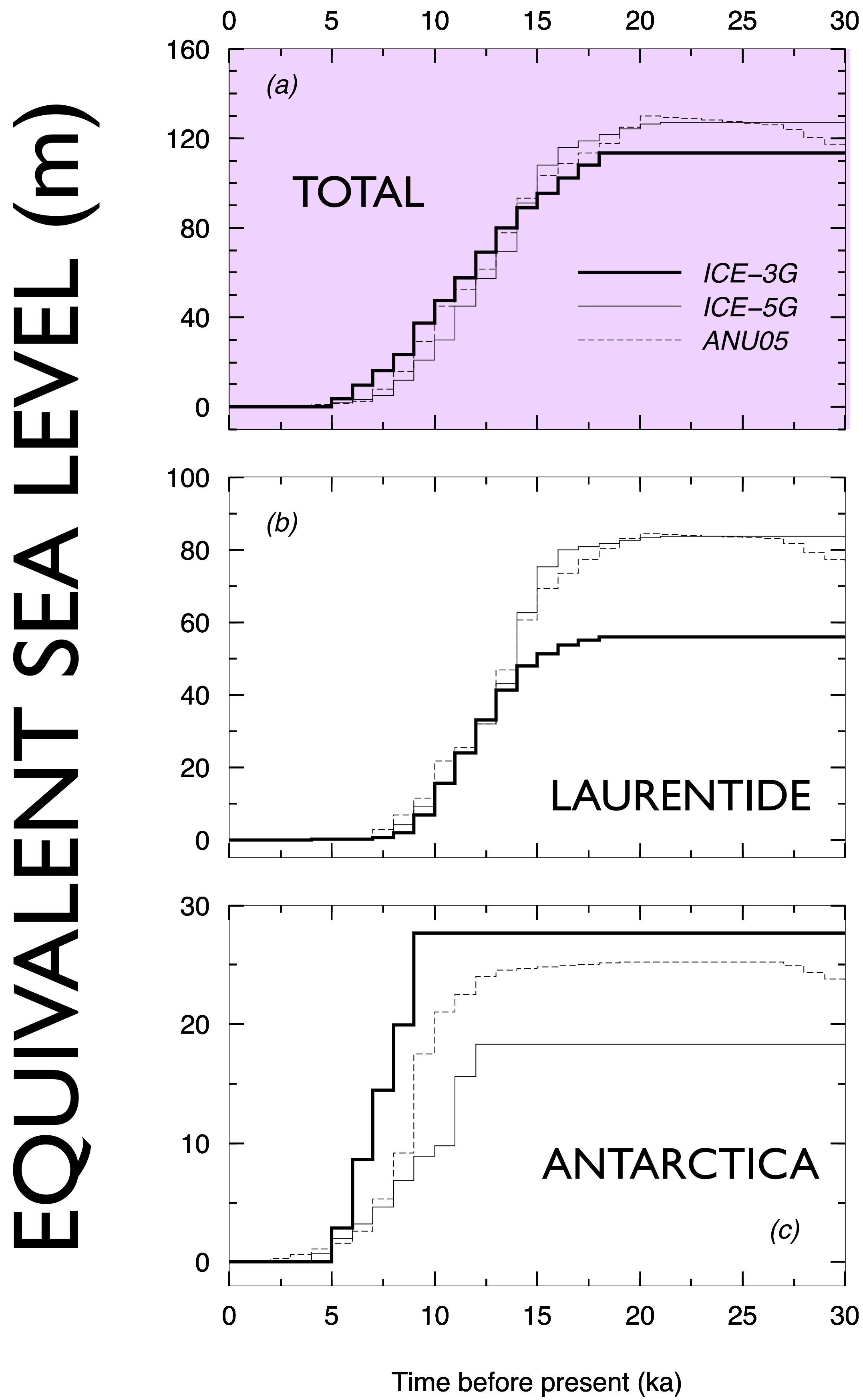
III) 80% *complete* or better

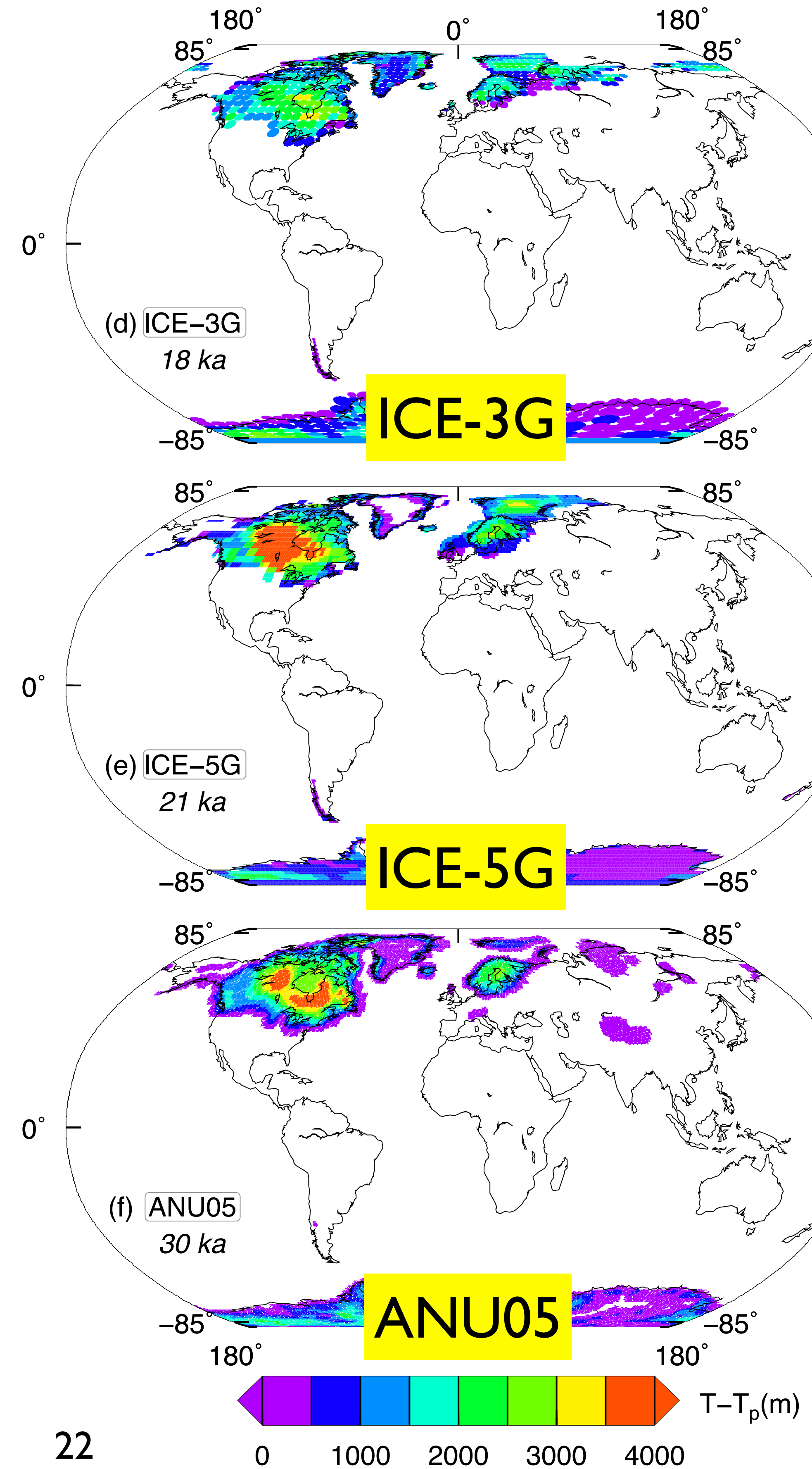
IV) in reasonable agreement (at low frequencies) with records from *nearby gauges* that sample the same water mass

V) not from areas *deeply covered by ice* during the last glacial maximum (D91).
Strengthened in D97 to eliminate also records from sites in the area of the immediately adjacent *peripheral bulge*.

(D91) Douglas (1991, JGR) "Global Sea Level rise"

A GIA-*in*dependent sea-level correction?





120/1/2
Peltier 92

90/0.5/2.7
Peltier 04

65/0.3/10
Lambeck 05

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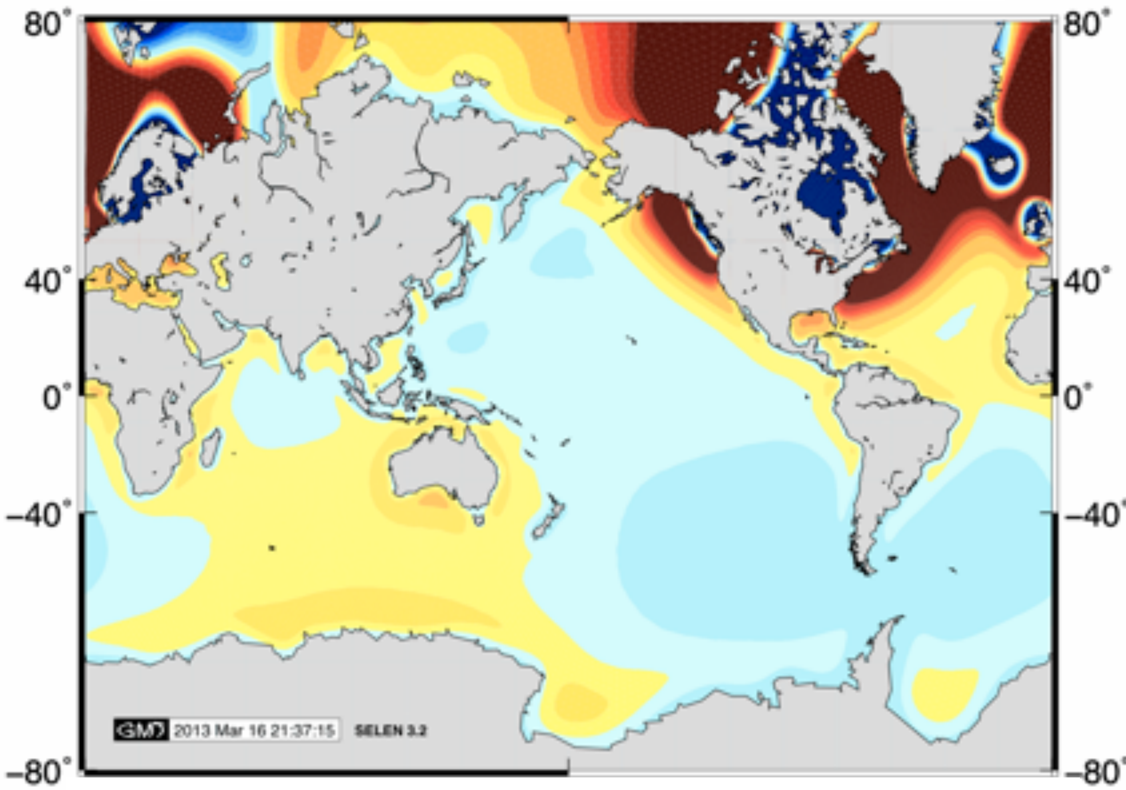
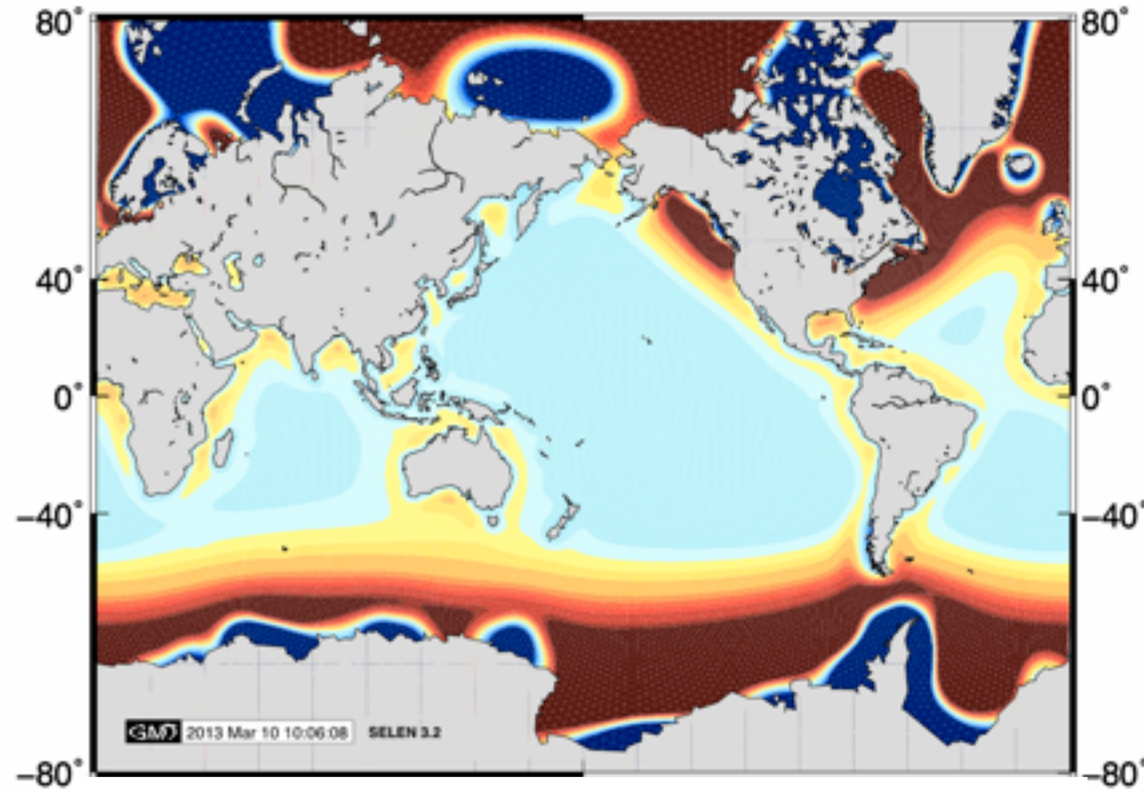
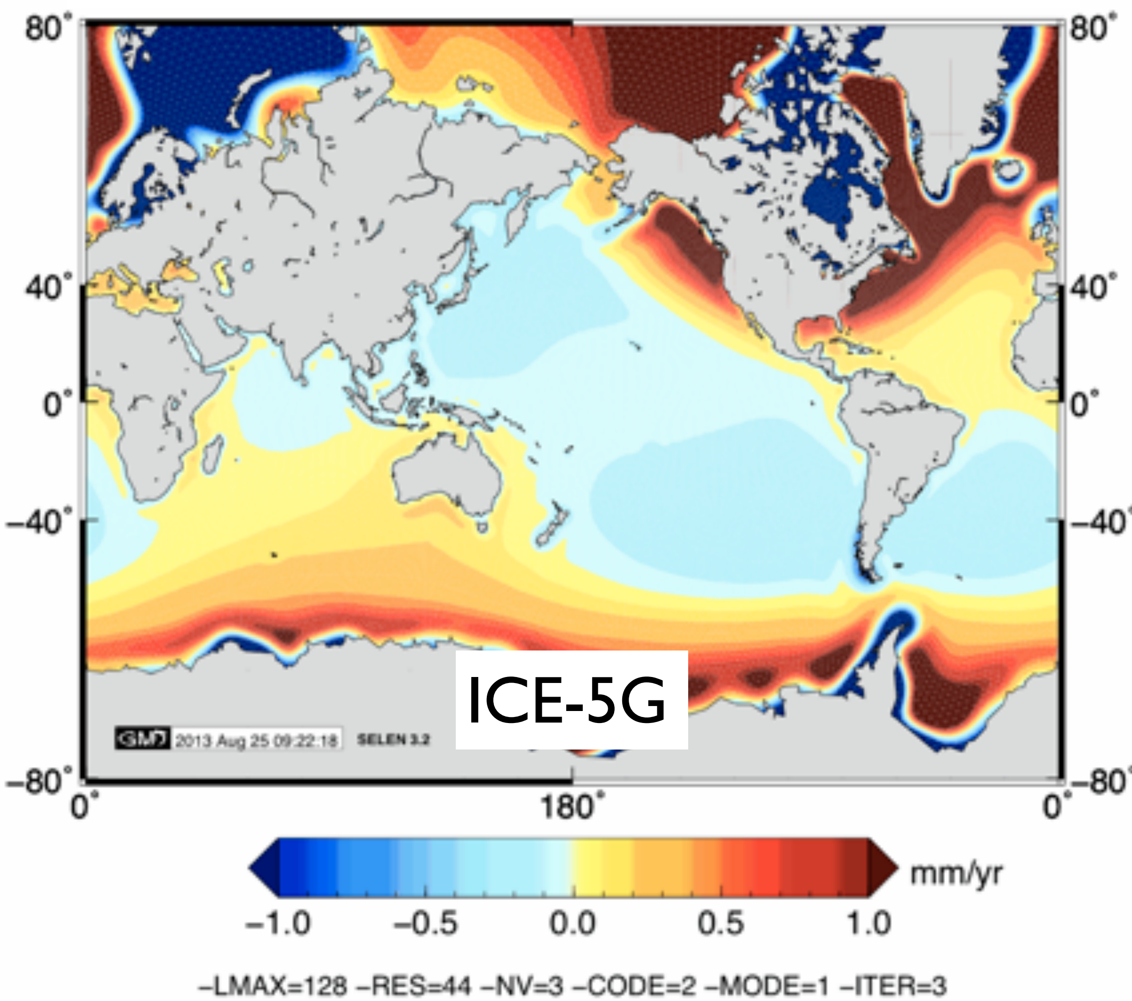
ICE1 (Peltier & Andrews, 1976)



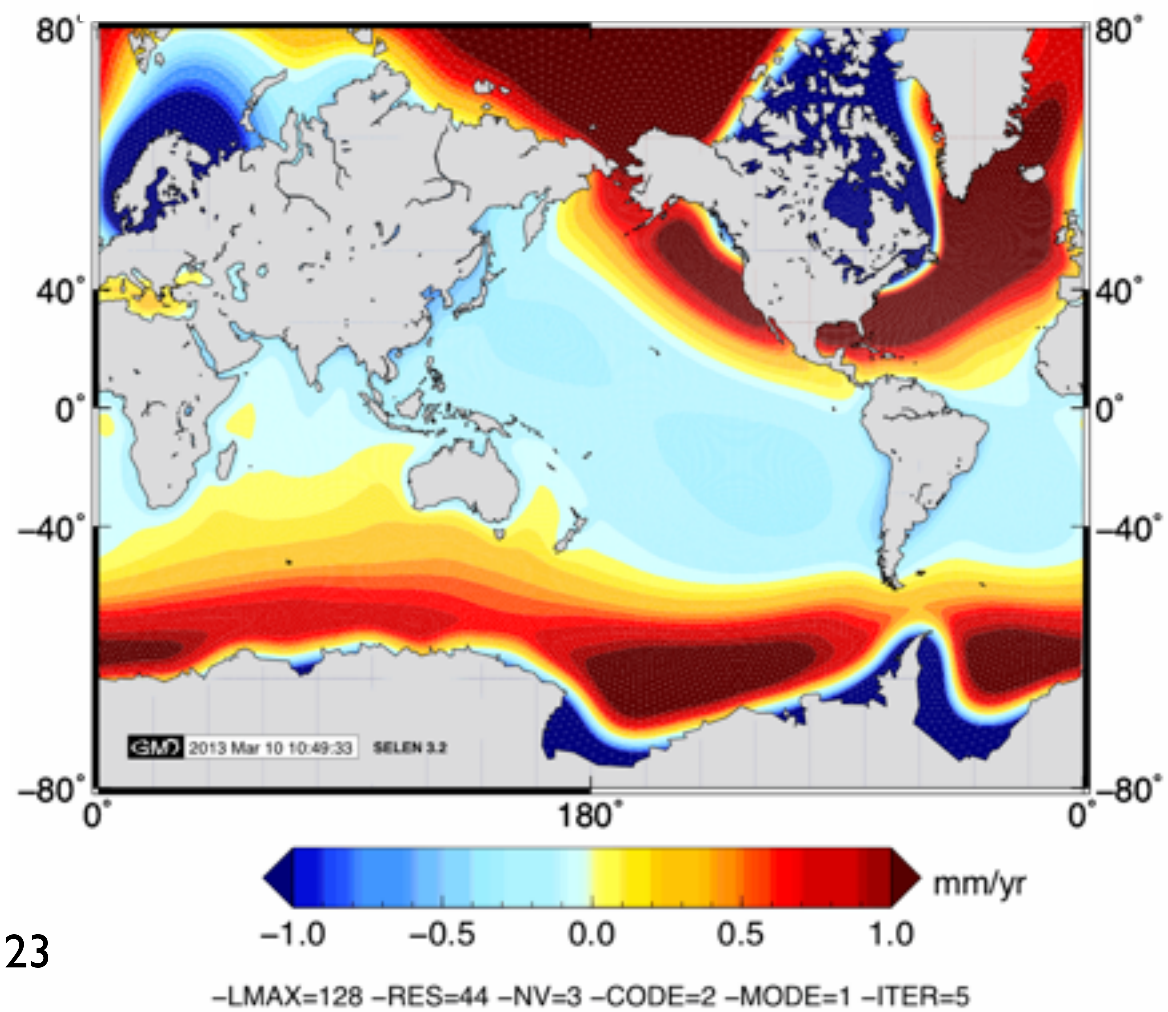
ICE-3G (Tushingham & Peltier, 1991)



ICE-5G (Peltier, 2004)



Lambeck et al., since ~2000



Jevrejeva *et al.* (2013) GPC in revision

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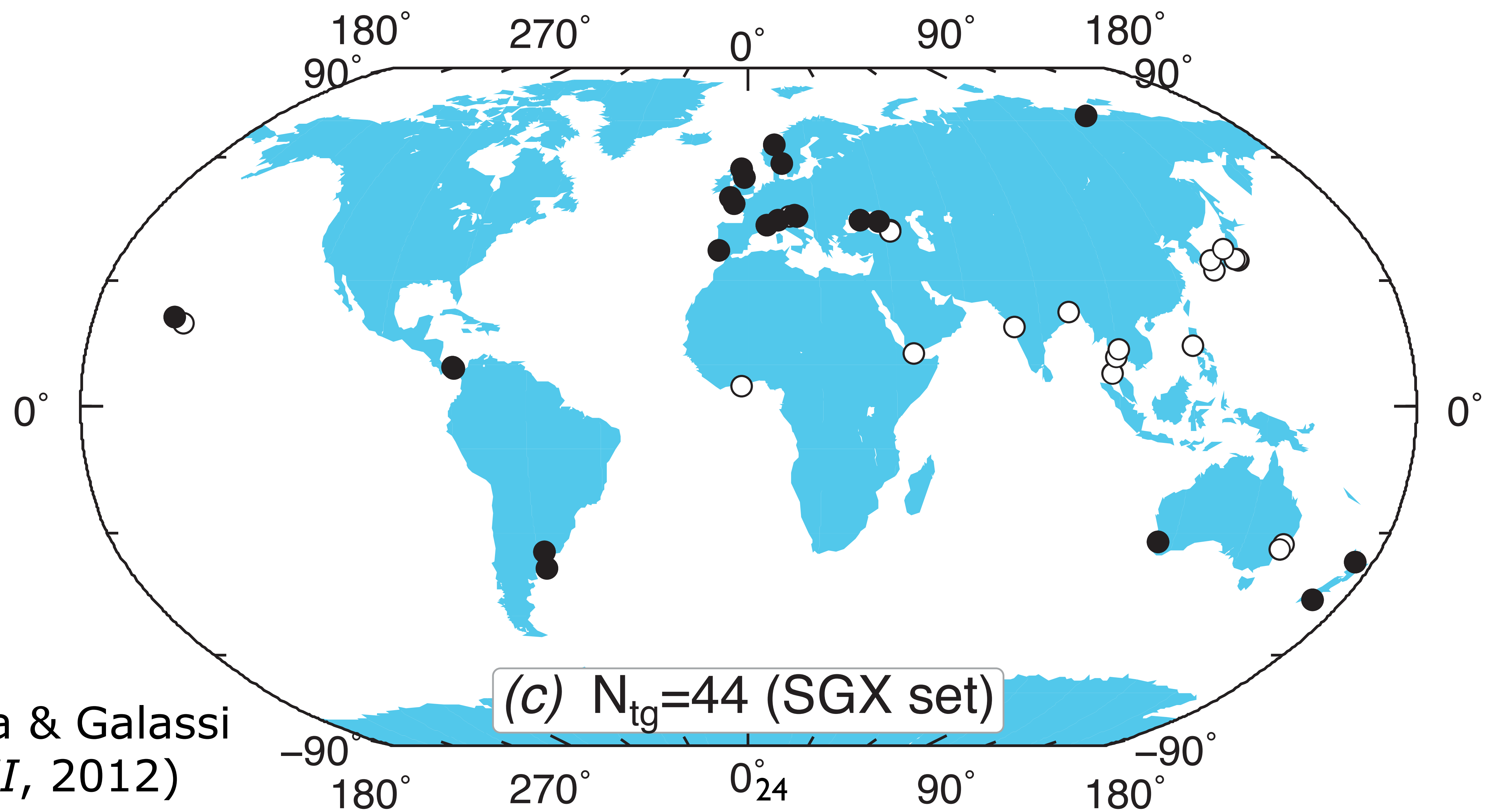
A GIA-*independent* sea-level correction?

1). GIA-model predictions are ~the same for all models:

-> "SGX set" (44 TGs) ● ○

2). Clean up the set using the D97 criteria I-IV

-> "SG01" set (22 TGs) ●



Spada & Galassi
(*GJI*, 2012)

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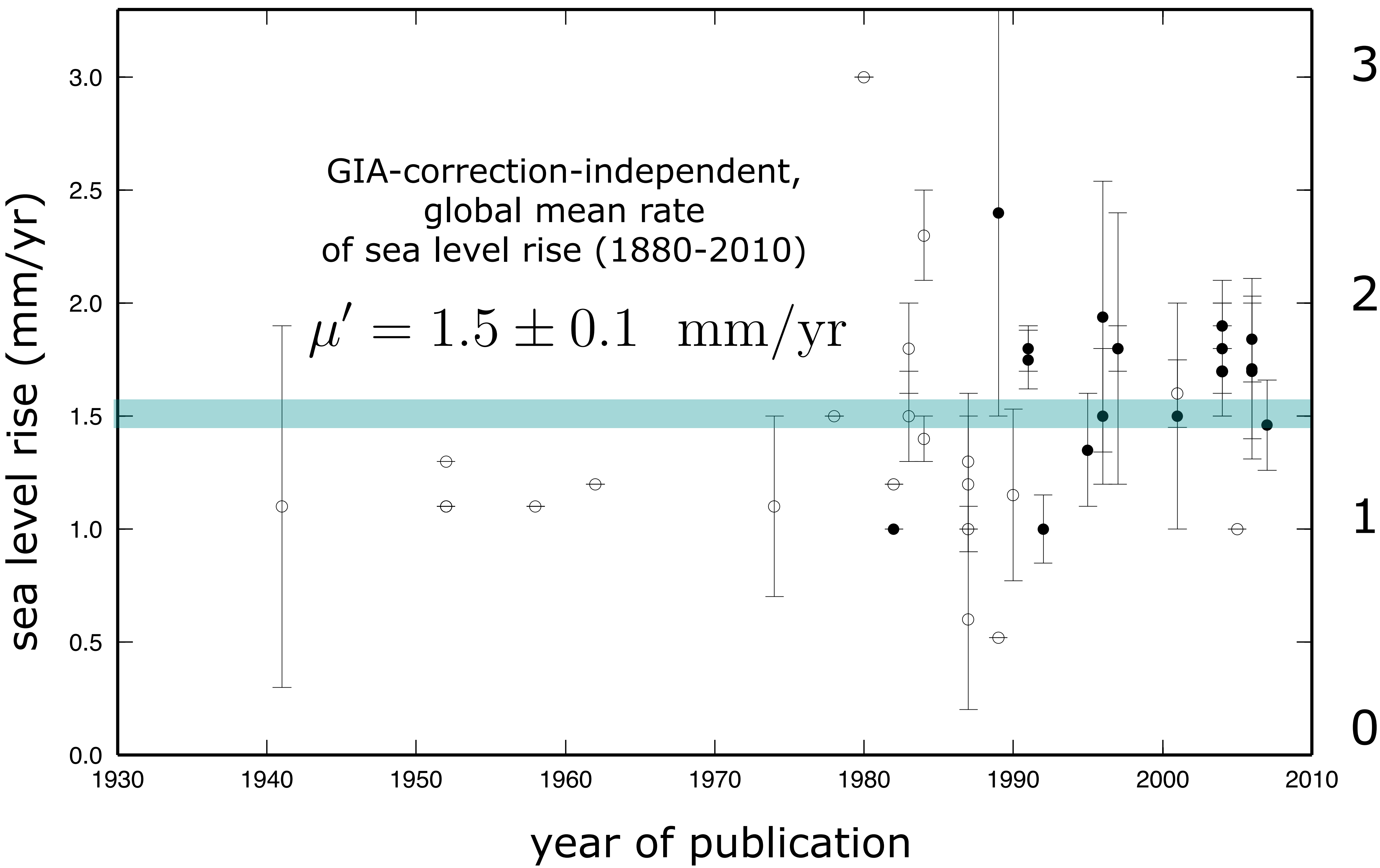

Thank you

and

happy 80th anniversary to GLOSS/PSMSL!

Glacial Isostatic Adjustment GLOSS/PSMSL-80 workshop, Liverpool Oct 2013