Sea level rise and acceleration

(from secular observations)

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Gaia Galassi, Marco Olivieri, and many others

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IPGS - Strasbourg
Tuesday March 17, 2015, h13:45

Sea level rise and acceleration
(from secular observations)

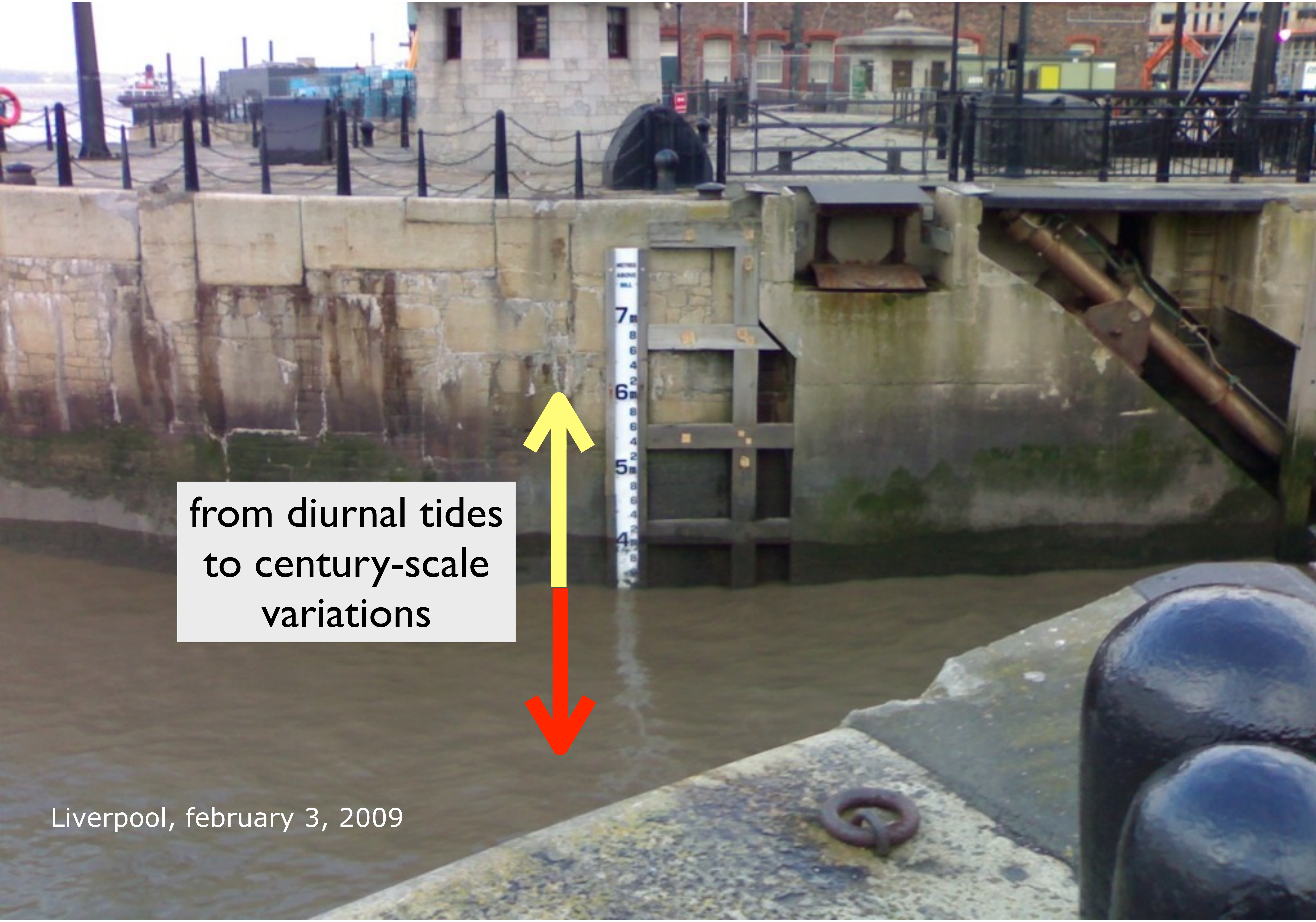
- My focus will be on sea level observations, not so much on the *causes* of secular sea-level rise. Major questions:

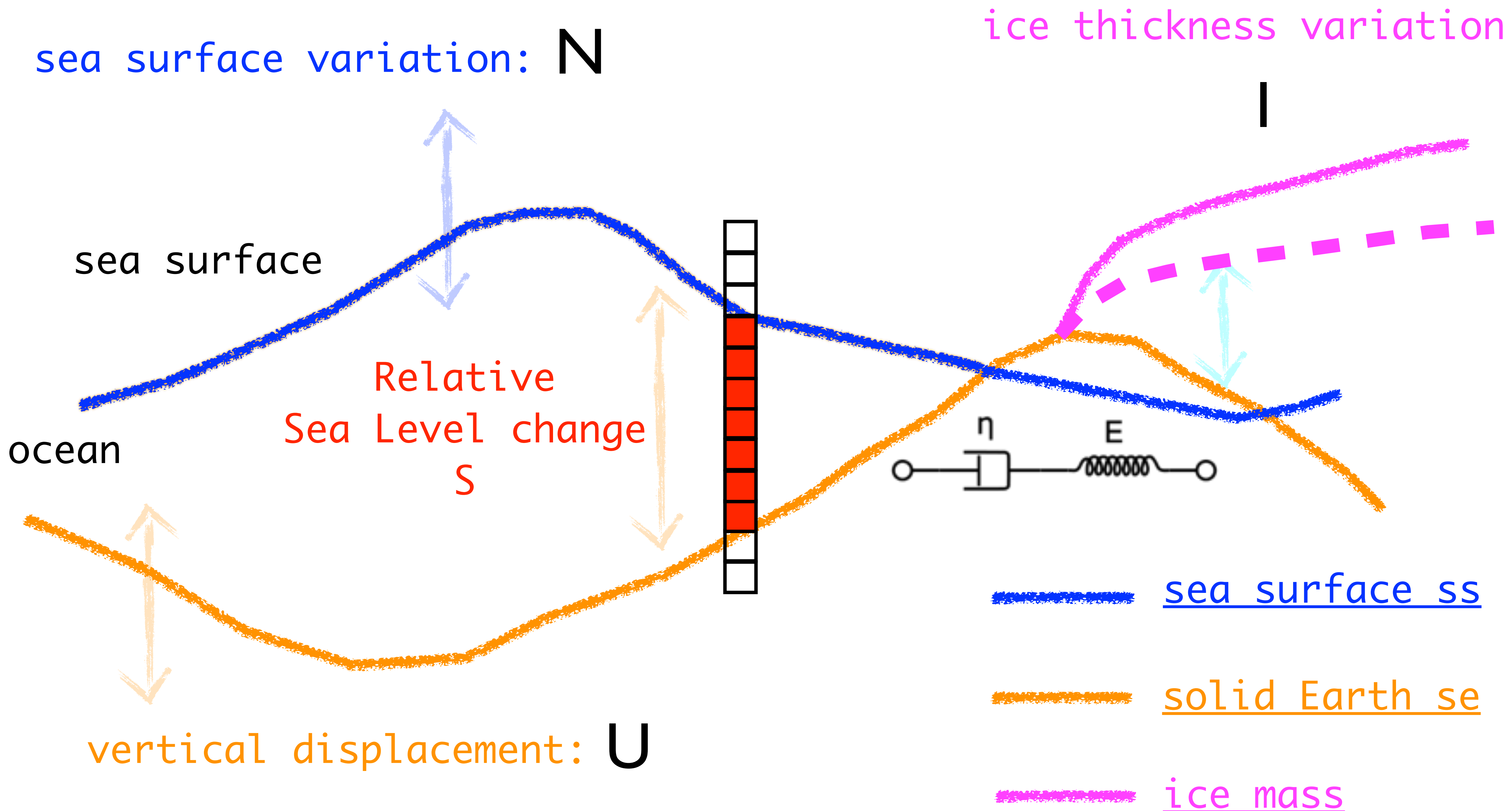
1) How do we know that sea-level has been rising (or falling?), and possibly accelerating, during the last century or so?

2) Is "global" secular sea-level rise/acceleration a meaningful and useful concept? Certainly it has been for a while.

Case studies involving individual tide gauge records pose a *lot of nice geophysical questions*. Collections of tide gauge observations are *useful to obtain a 'global value' of sea-level rise*.

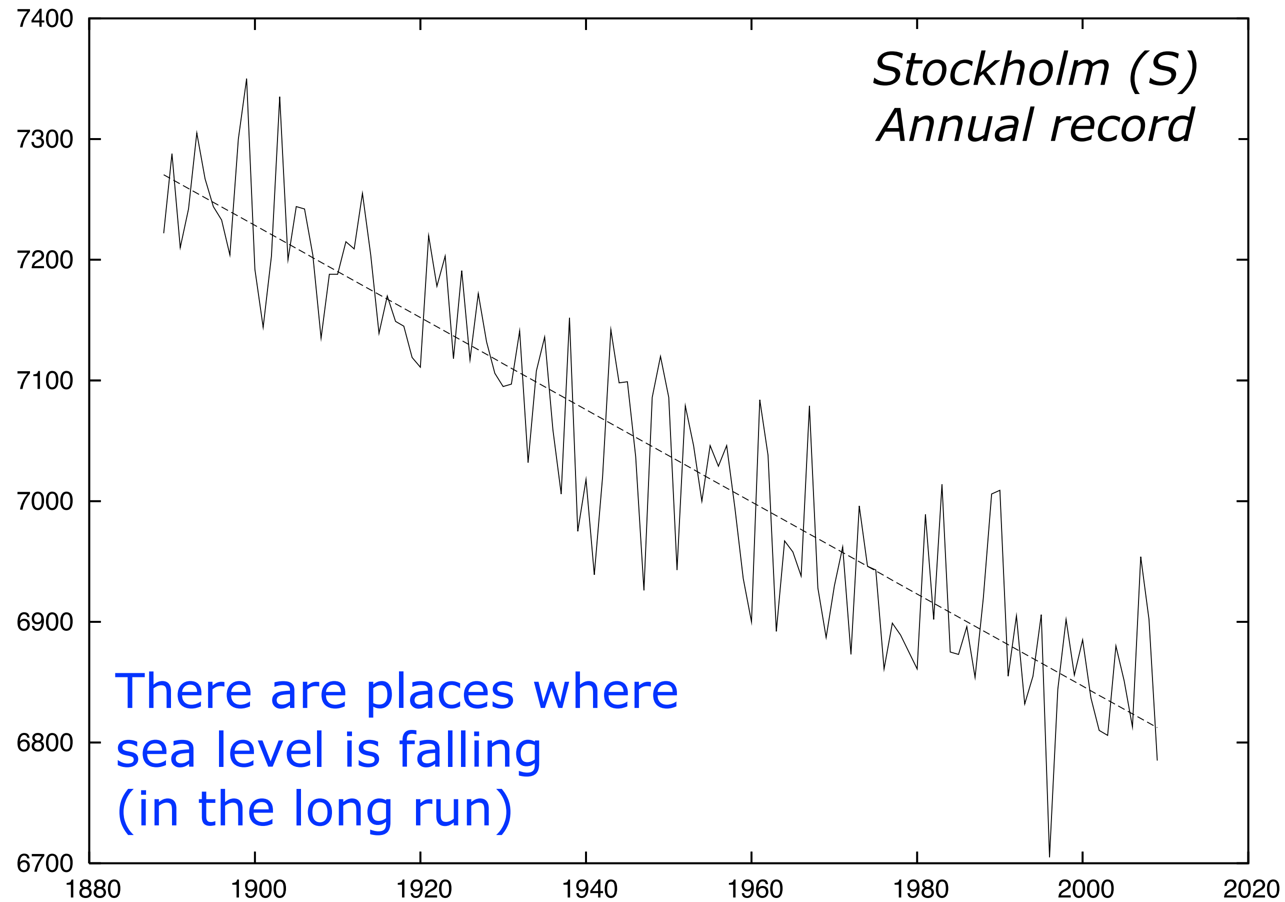
A simple instrument: the TIDE GAUGE (a pole tide)

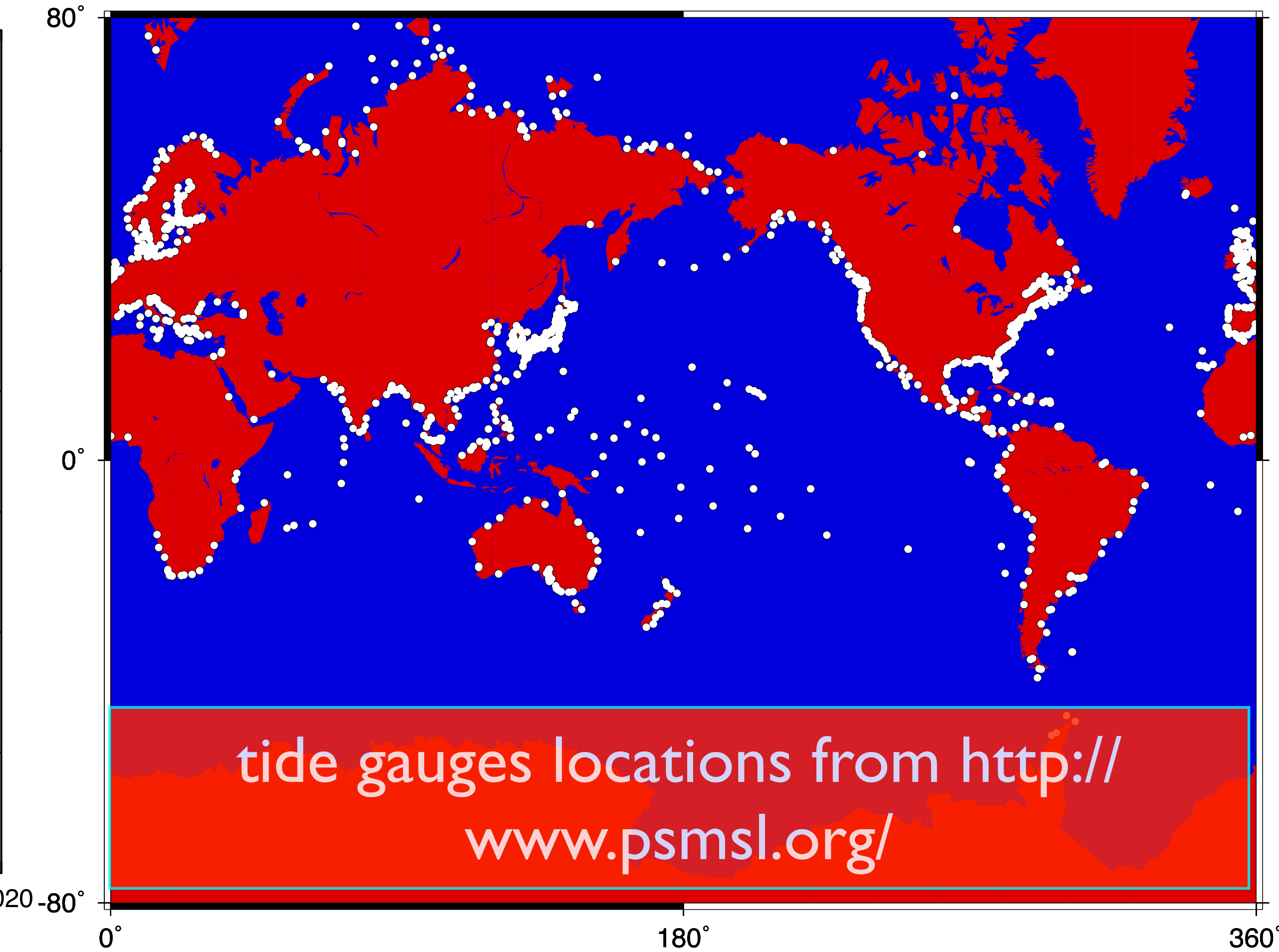


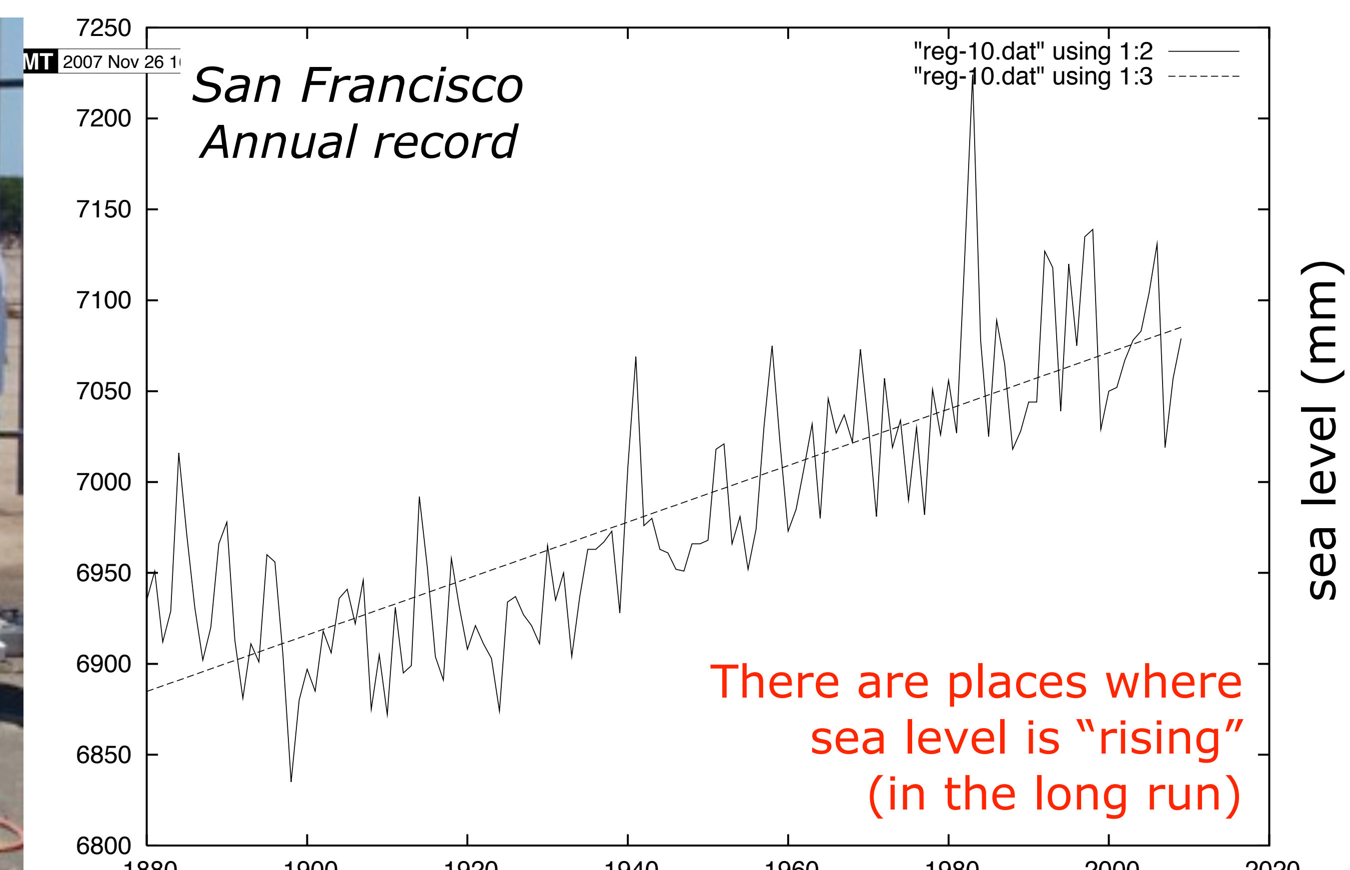


$$S(\omega, t) = N - U$$

TGs observe
RELATIVE SEA LEVEL


Stockholm (S)
Annual record
There are places where
sea level is falling
(in the long run)
7400
7300
7200
7100
7000
6900
6800
6700
1880
1900
1920
1940
1960
1980
2000
2020


tide gauges locations from http://
www.psmsl.org/
80˚
0˚
-80˚
0˚
180˚
360˚


San Francisco
Annual record
"reg-10.dat" using 1:2
"reg-10.dat" using 1:3
There are places where
sea level is "rising"
(in the long run)
sea level (mm)
7250
7200
7150
7100
7050
7000
6950
6900
6850
6800
1880
1900
1920
1940
1960
1980
2000
2020

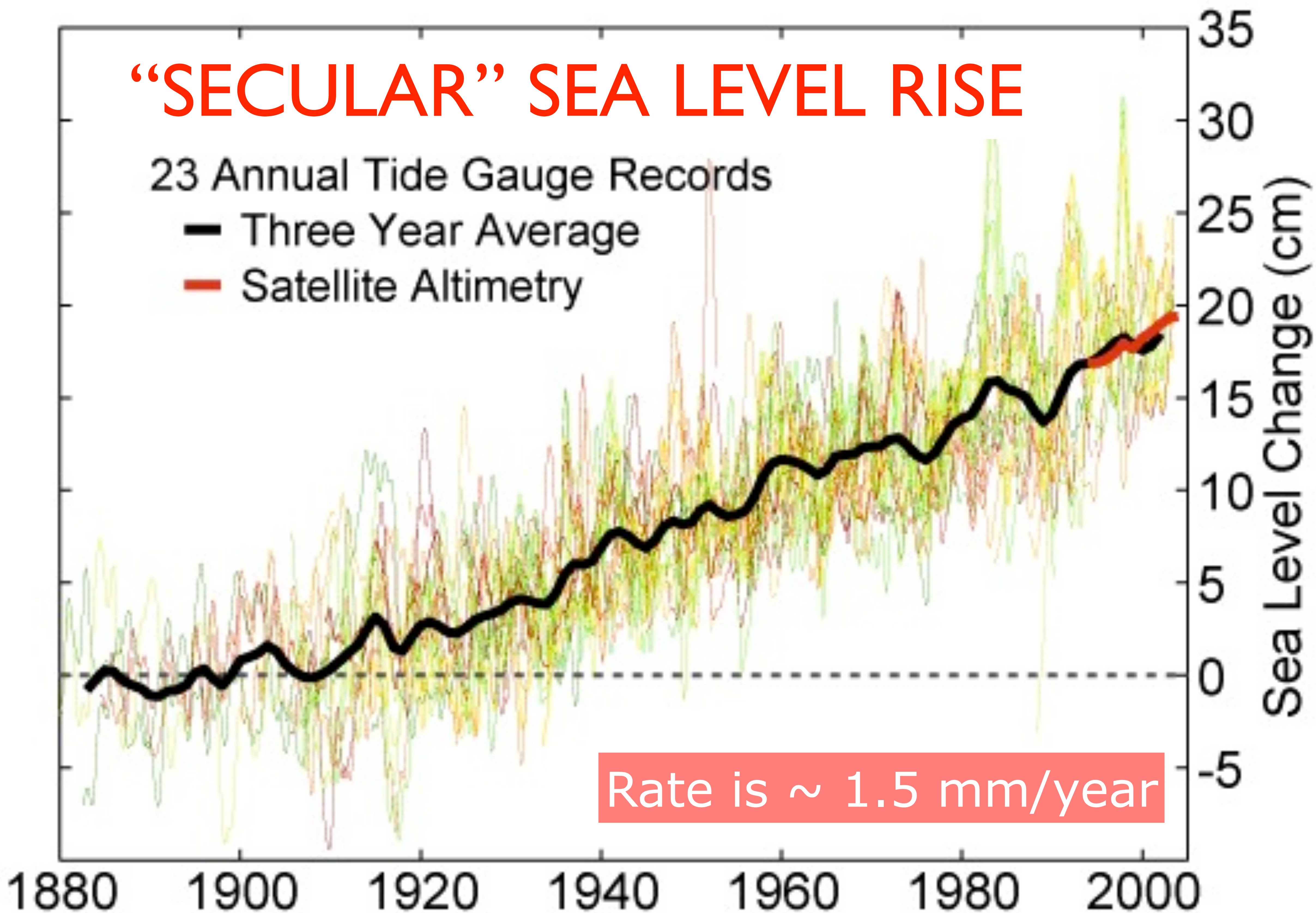
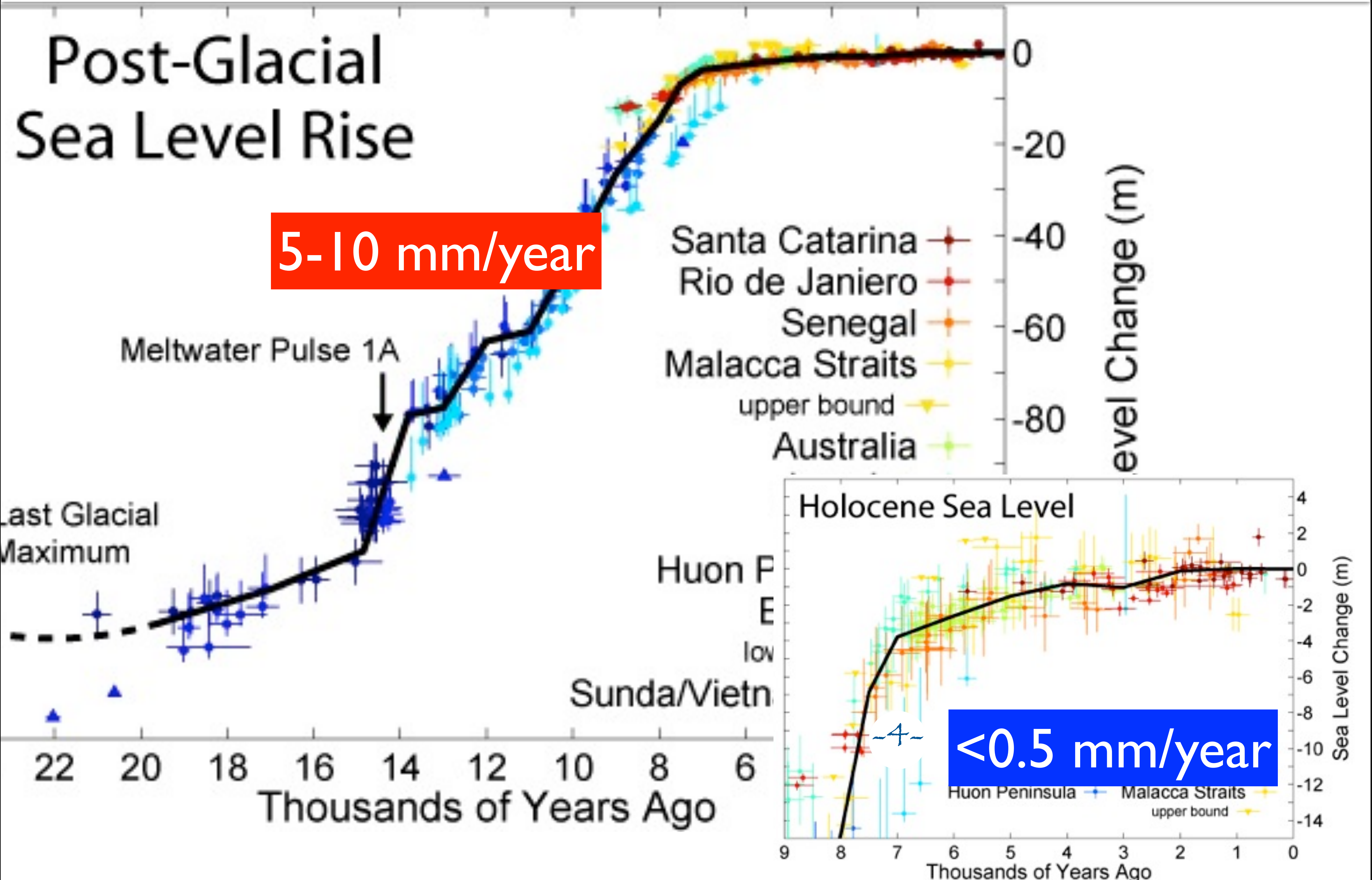


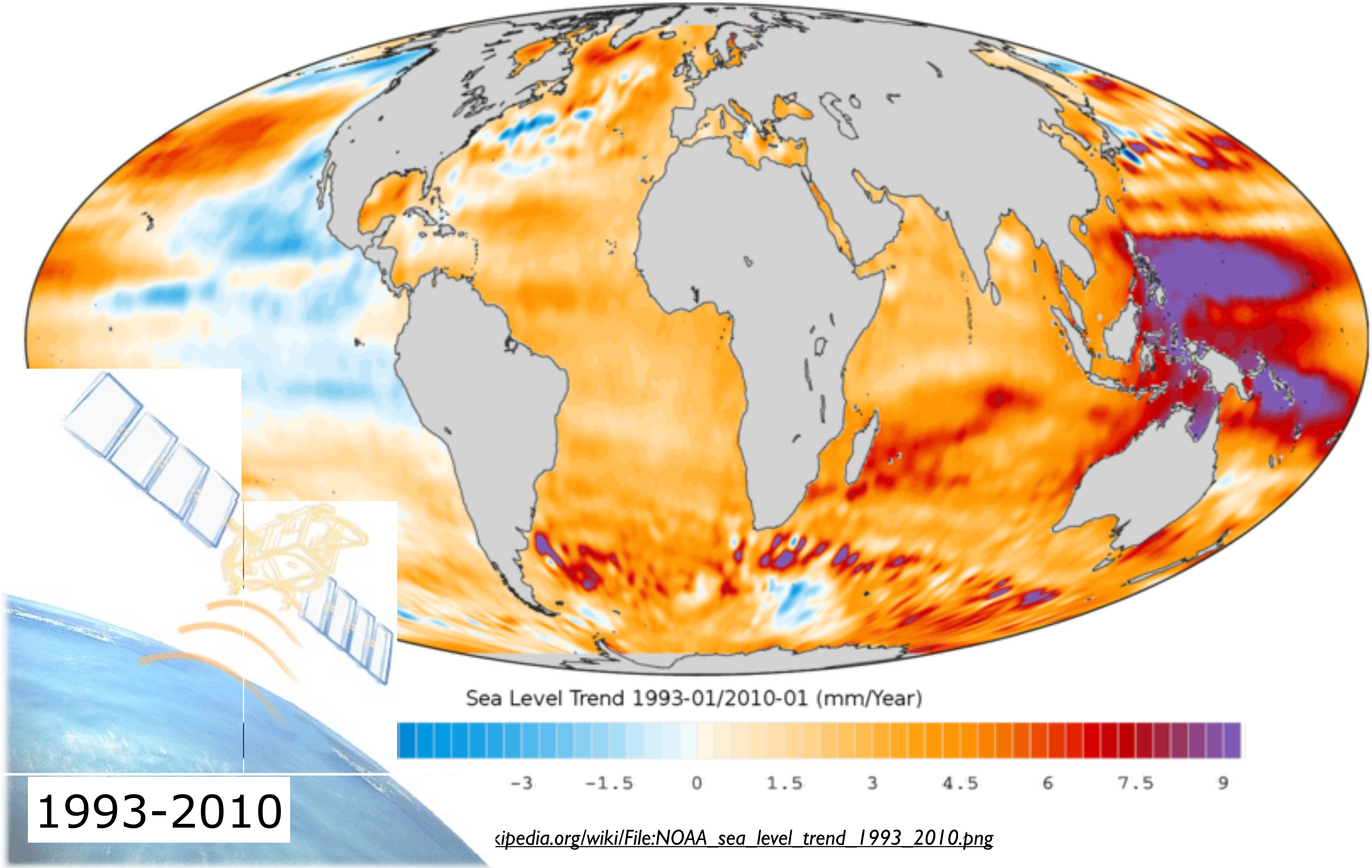
Image from Global Warming art project. Wikimedia Commons

Evidence from “remote sites” e.g. Barbados



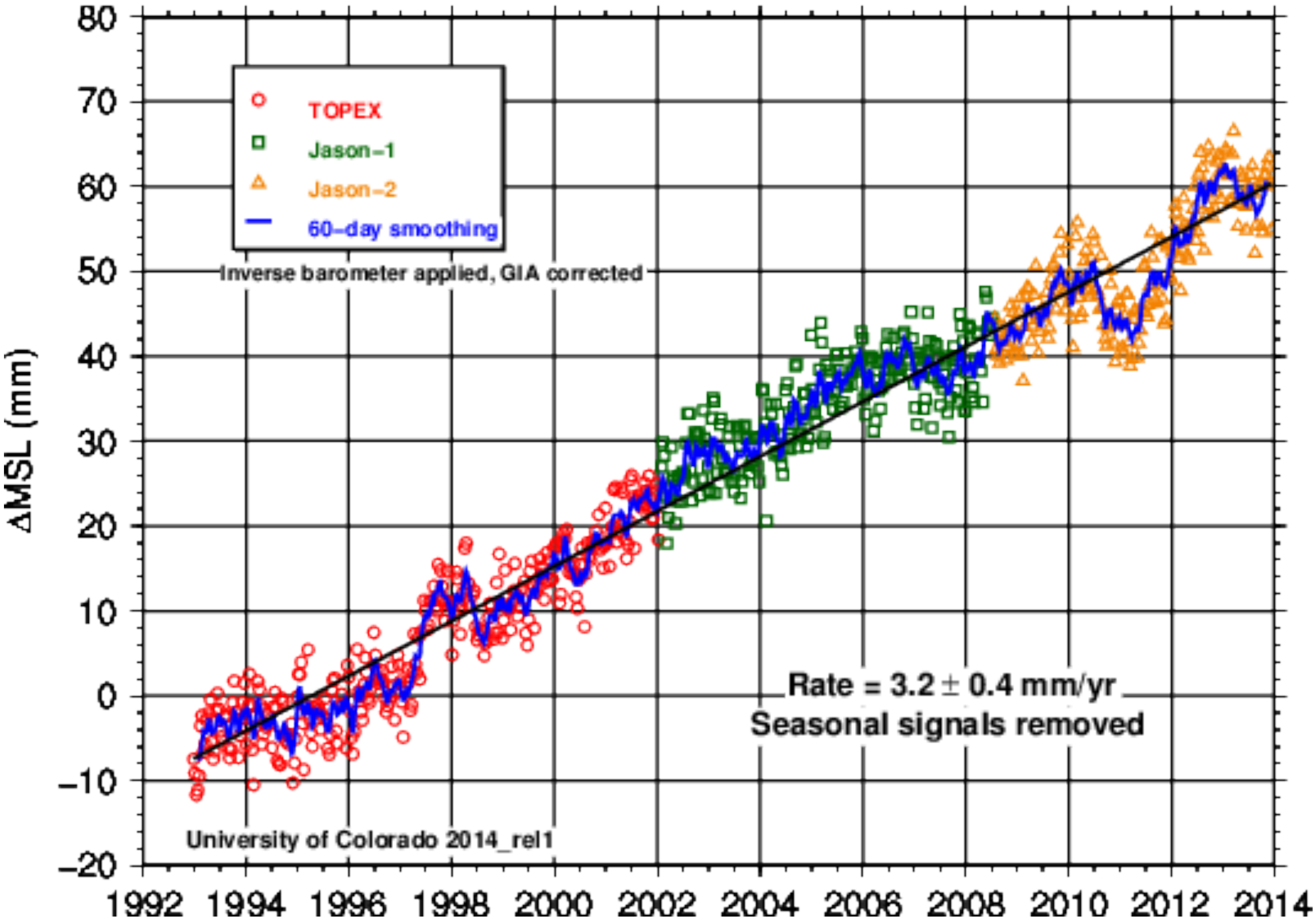
Sea Level rise between 1993 and 2010 by satellite ALTIMETRY

"viewpoint of space"



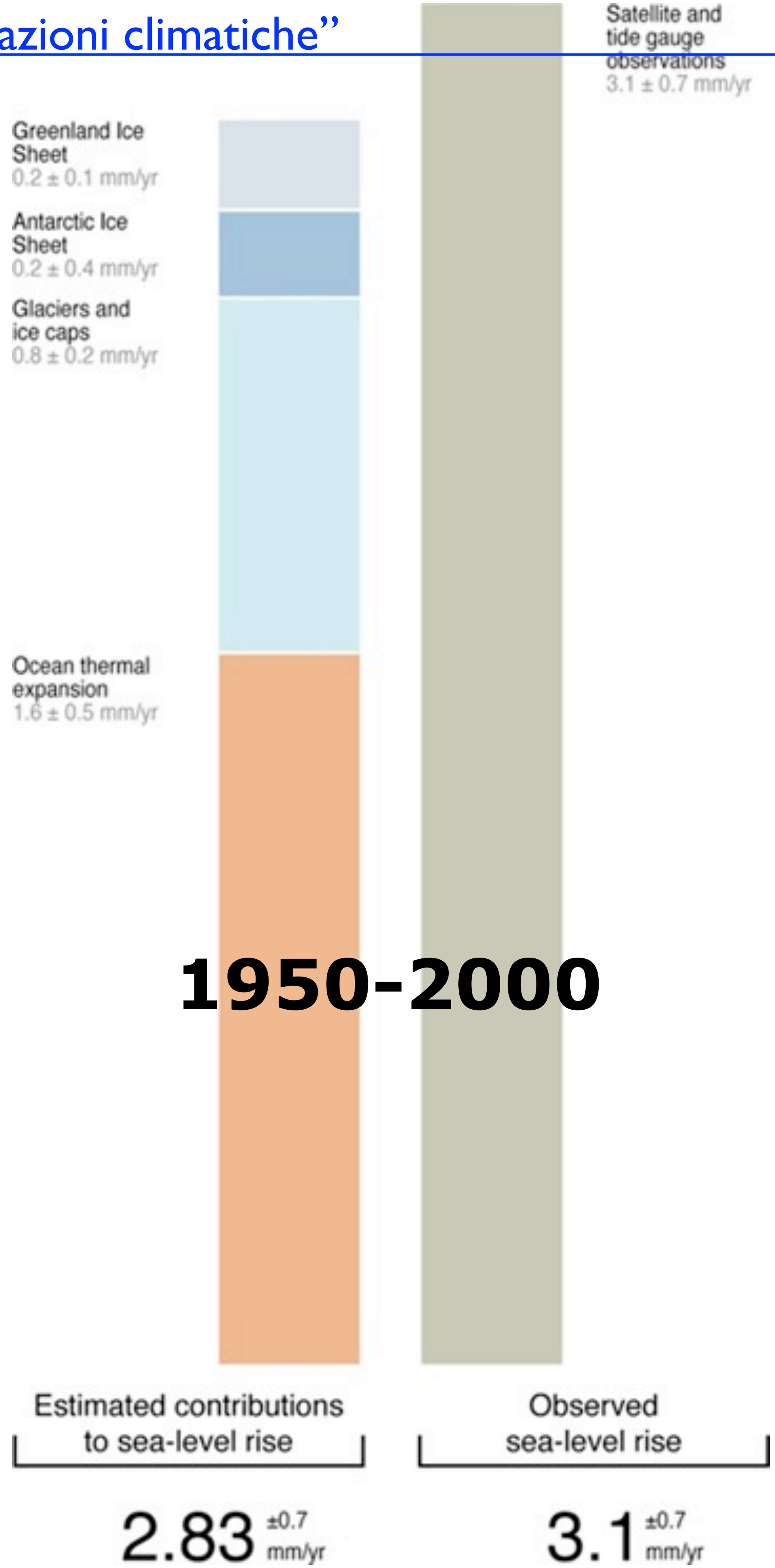
‹ipedia.org/wiki/File:NOAA_sea_level_trend_1993_2010.png

Sea Level rise between 1993 and 2010 by satellite ALTIMETRY



CU: 3.2 ± 0.4 mm/yr
AVISO: 3.2 ± 0.6 mm/yr
CSIRO: 3.2 ± 0.4 mm/yr
NASA GSFC: 3.2 ± 0.4 mm/yr
NOAA: 3.2 ± 0.4 mm/yr (w/ GIA)

"Current" sea level rise 1993-2014



Causes of sea level rise

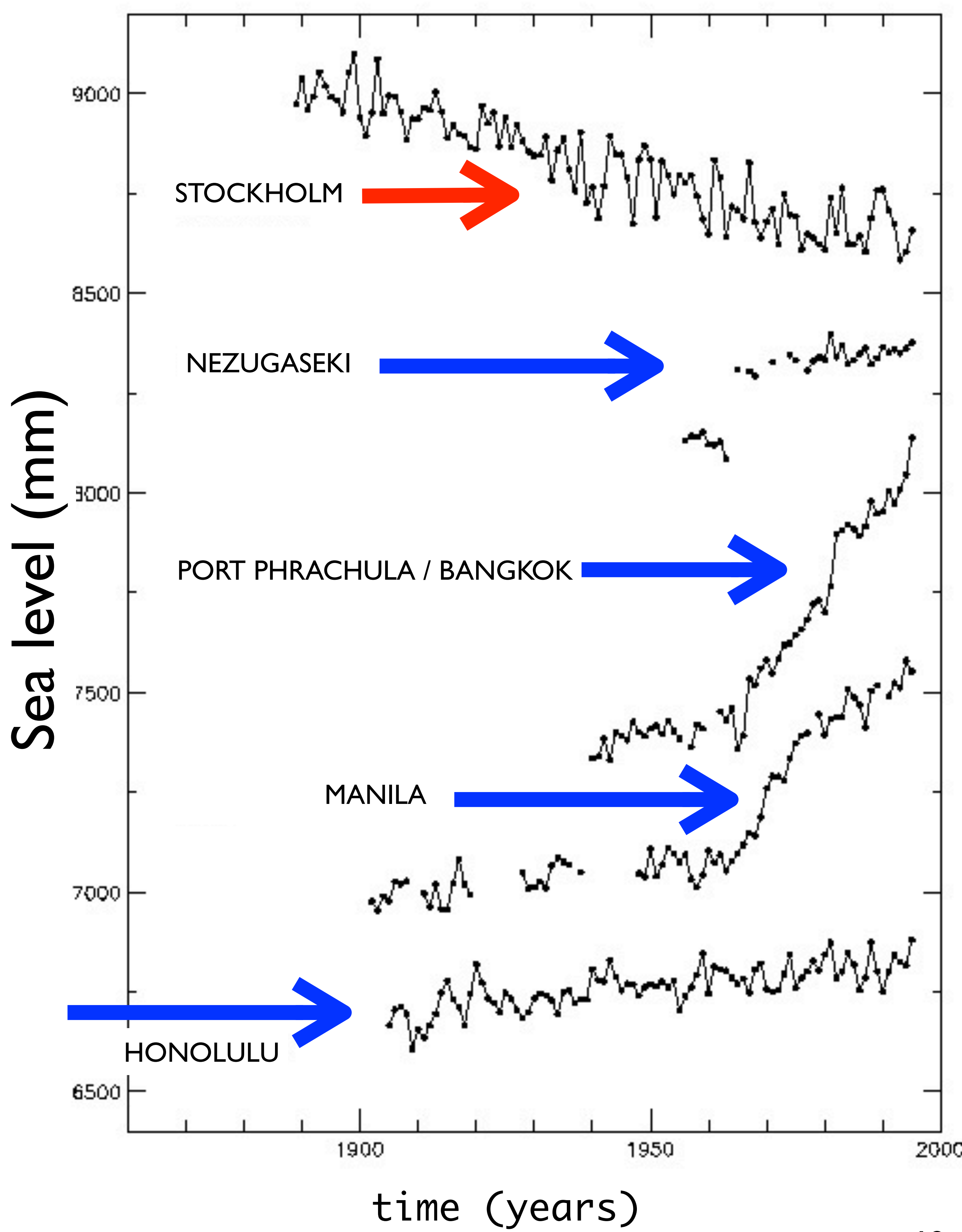
1. Thermal expansion of the oceans in response to global warming

2. Melting of mountain glaciers and ice caps

3. Melting of large ice sheets (Greenland and Antarctica)

2.) Records from individual tide gauges

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



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The 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).

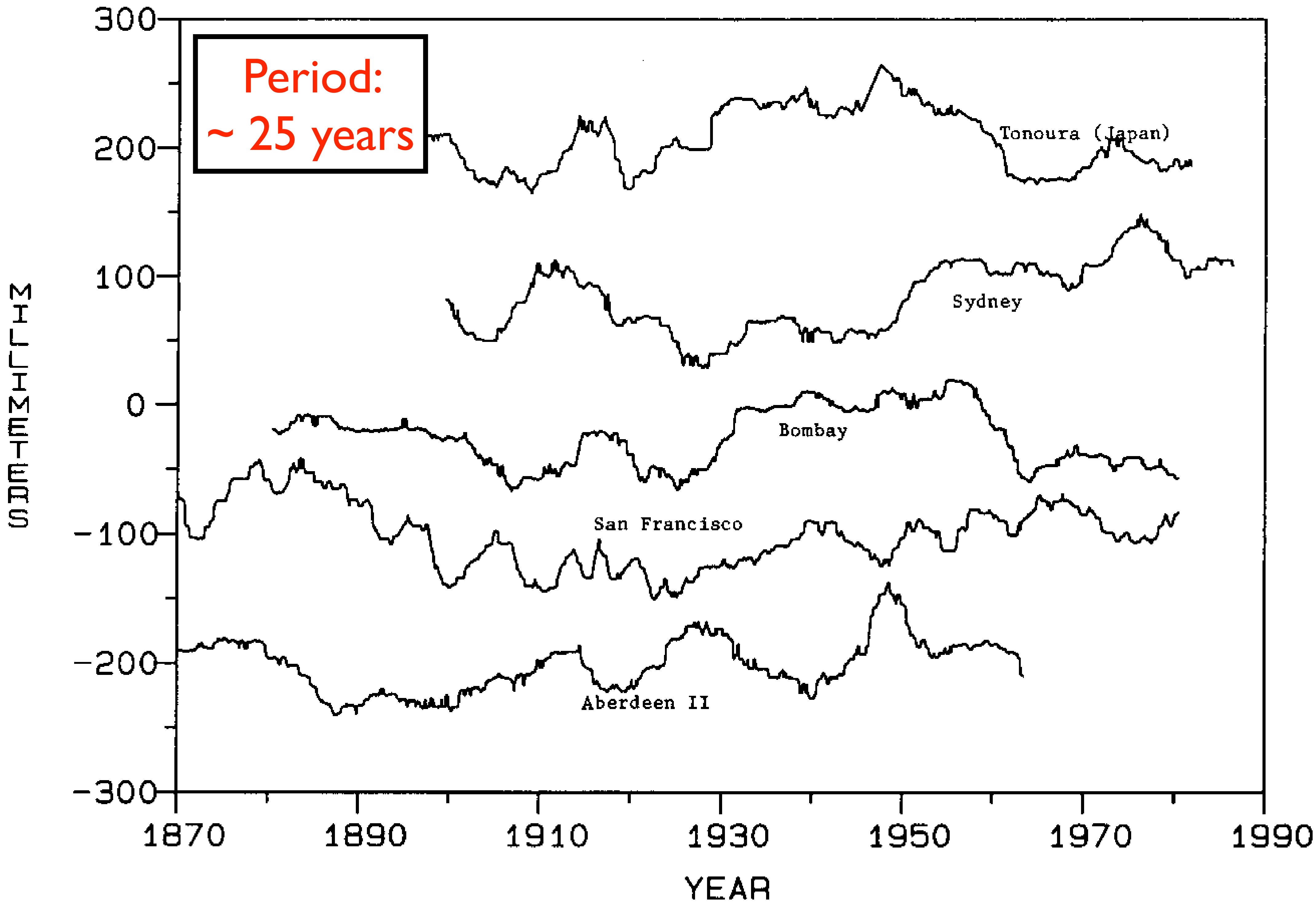
(The Honolulu record is shown above incidentally for some sort of comparison only. It should not be interpreted as suggesting the Hawaiian islands to be completely 'stable', as is obvious from their volcanic history. Similar comments would apply to other far field sites with long records but for different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

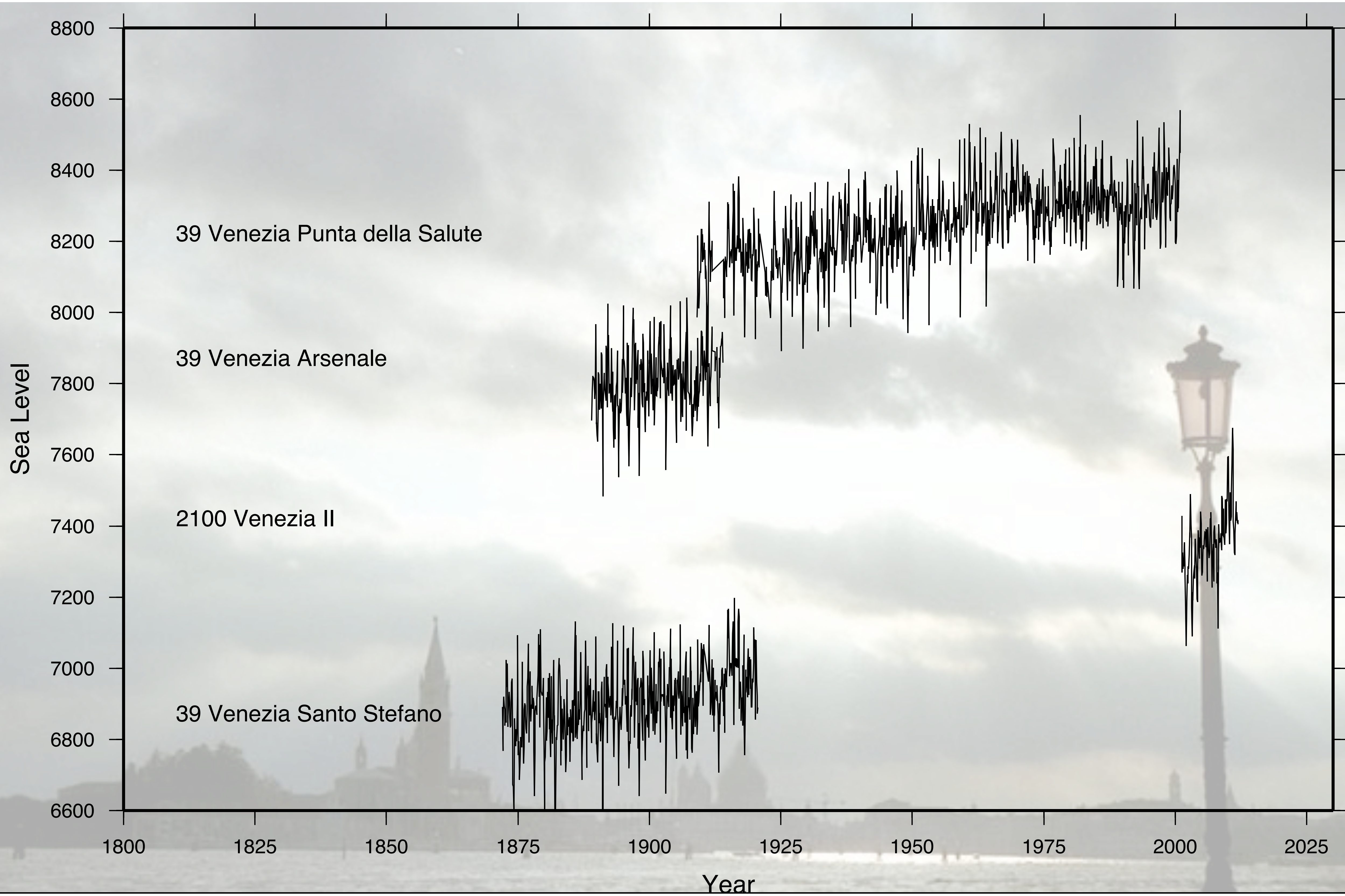
(High energy) decade oscillations in the TG series



3. Median filtered and detrended sea level records for five widely distributed tide gauge sites. Note the apparent correlations of the records at low frequenci

Douglas, 1991 JGR

As Sea Levels Rise, Venice Sinks

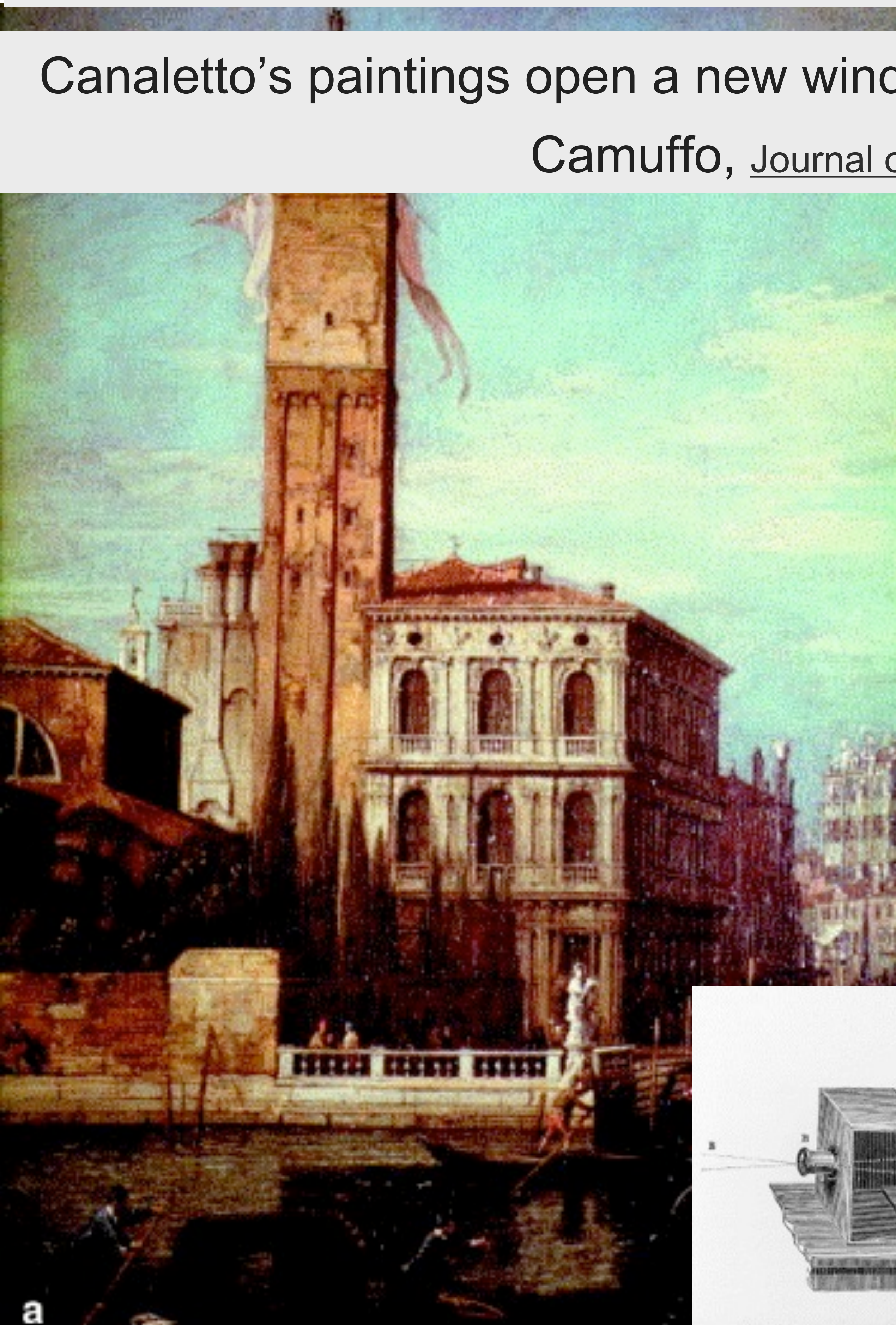


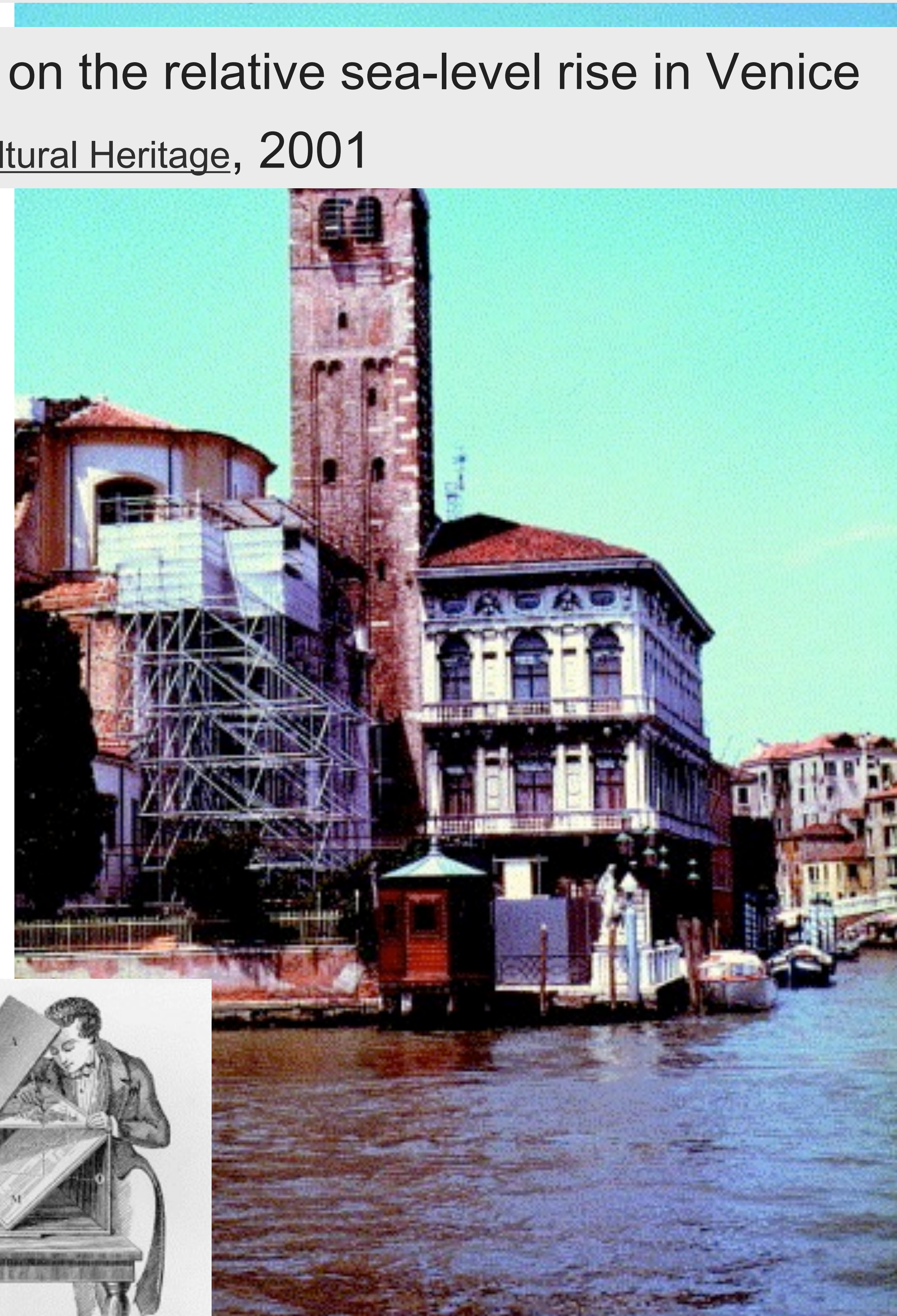
Major issue: can we EXTEND the "TG record" to the last centuries/millennia?
importance of archaeology and other proxies...

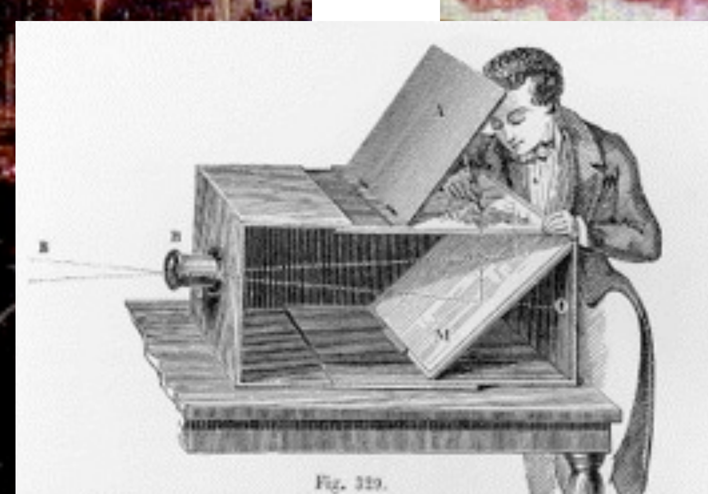
The paintings by Canaletto (1697–1768), made with the help of a camera obscura, are just like real photographs, documenting as they do the Venice of the XVIII century with an accurate reproduction of all the details.

Canaletto’s paintings open a new window on the relative sea-level rise in Venice

Camuffo, Journal of Cultural Heritage, 2001







Climate related sea-level variations over the past two millennia

Andrew C. Kemp[a,b], Benjamin P. Horton[a,1], Jeffrey P. Donnelly[c], Michael E. Mann[d], Martin Vermeer[e], and Stefan Rahmstorf[f]

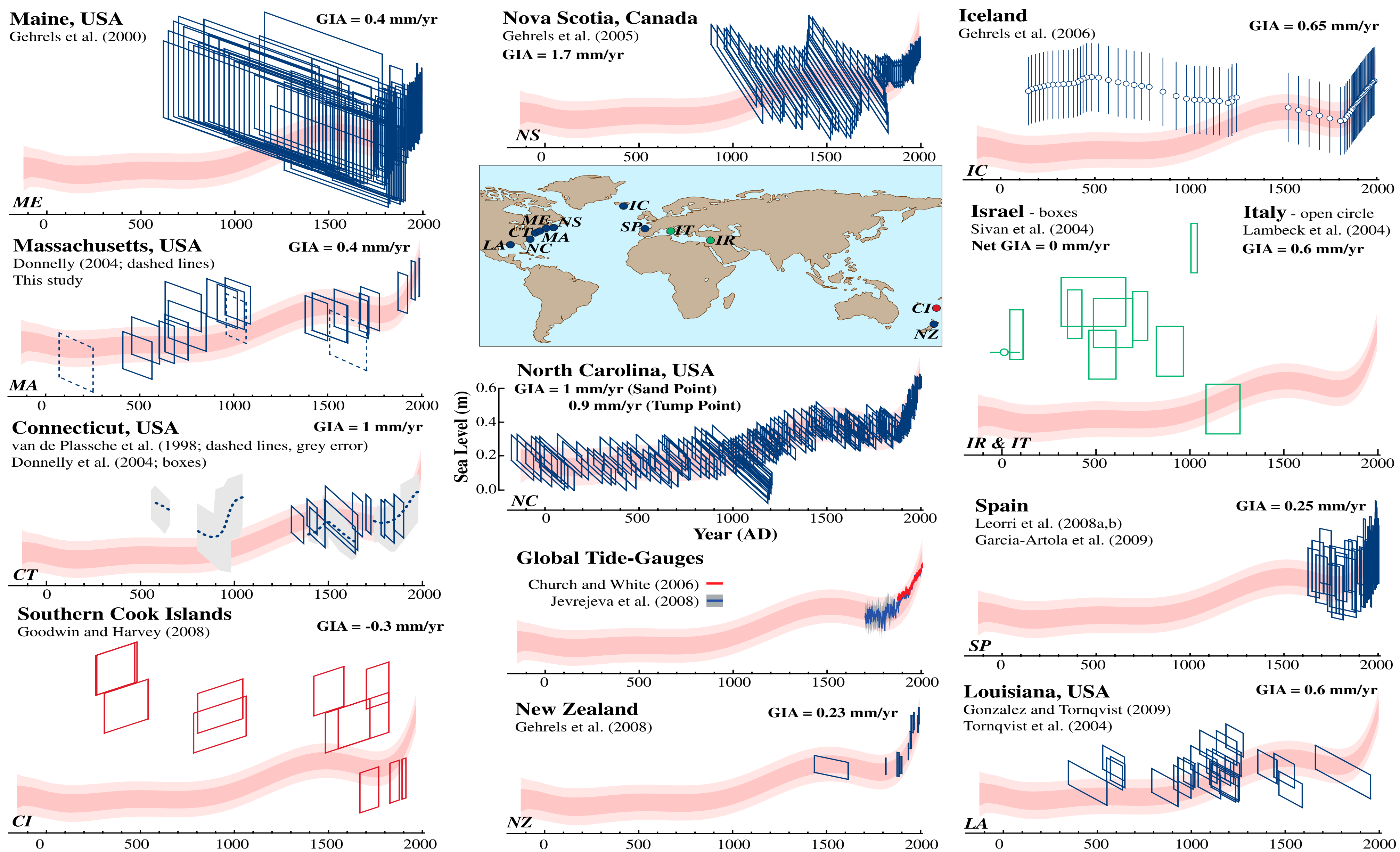


Fig. 3. Late Holocene sea-level reconstructions after correction for GIA. Rate applied (listed) was taken from the original publication when possible. In Israel, land and ocean basin subsidence had a net effect of zero (26). Reconstructions from salt marshes are shown in blue; archaeological data in green; and coral microatolls in red. Tide-gauge data expressed relative to AD 1950–2000 average, error from (32) in gray. Vertical and horizontal scales for all datasets are the same, and are shown for North Carolina. Datasets were vertically aligned for comparison with the summarized North Carolina reconstruction (pink).

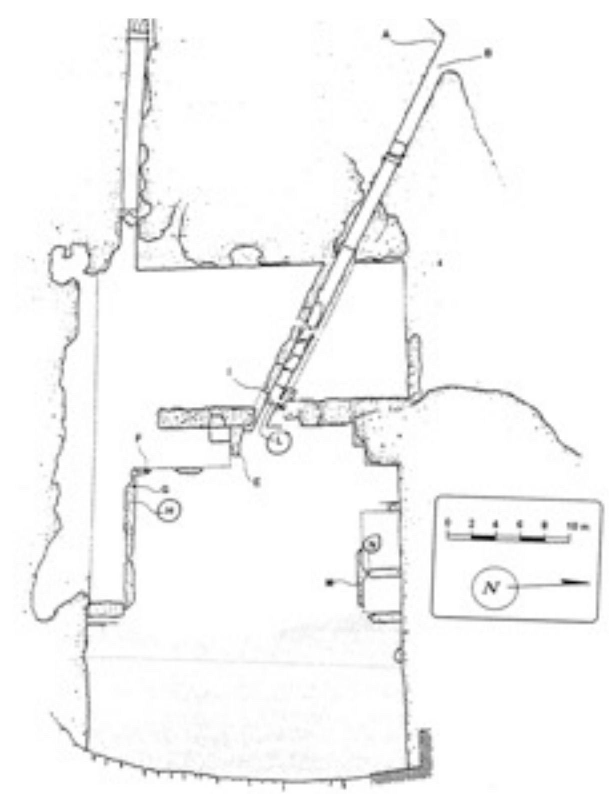
Major issue: can we EXTEND the "TG record" to the last centuries/millennia?
importance of archaeology and geological proxies...

Evidence from the Mediterranean — The Tyrrhenian coast

A non-traditional "tide gauge": Roman fish tanks in the ROME area

Fig. 2: Part of La Mattonara fish tank.

Roman fish tanks, Lazio: sea level rise of ~60 cm since 2000 BP



Evidence from the Mediterranean — The Tyrrhenian coast

Roman fish tanks, Lazio:
sea level rise of ~60 cm
since 2000 BP

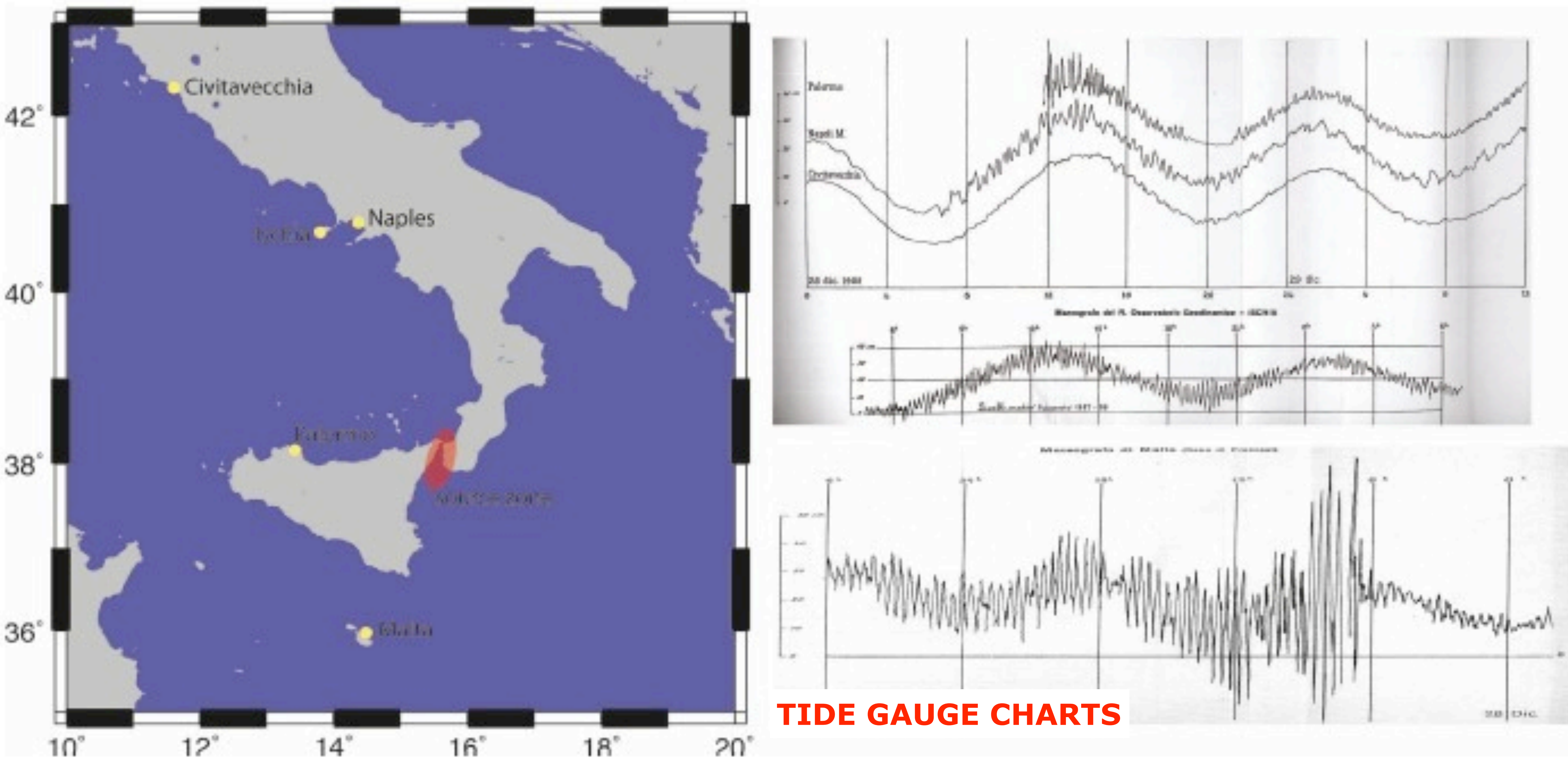
The MESSINA (Sicily) earthquake of dec 28, 1908
~ 70,000 casualties (M=7.1)

March/April 2009

The 28 December 1908 Messina Straits Earthquake (M_w 7.1): A Great Earthquake throughout a Century of Seismology

Nicola Alessandro Pino, Alessio Piatanesi, Gianluca Valensise, and Enzo Boschi
Istituto Nazionale di Geofisica e Vulcanologia, Italy

HISTORICAL SEISMOLOGIST



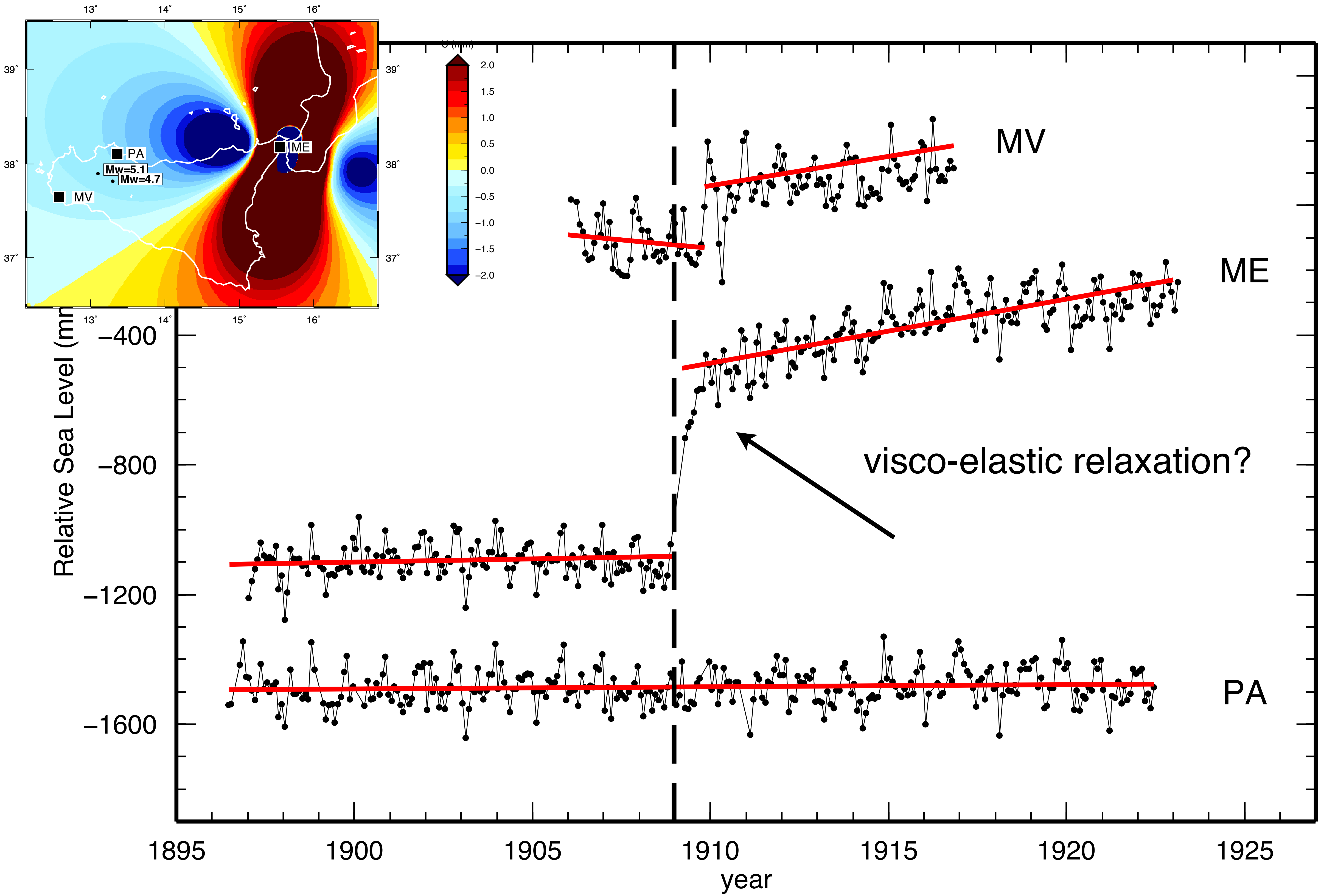
▲ **Figure 3. (A) Location of tide-gauge stations that recorded the tsunami (yellow dots). The red transparent ellipse indicates the source area of the earthquake. (B) Original tide-gauge records of the tsunami, as reported in Platania (1909). From top to bottom: Palermo, Naples, Civitavecchia, Ischia, and Malta. Note that time runs from right to left in the record of Malta.**

Recorded TSUNAMI (Platania, 1909)

Mazara del Vallo Tide Gauge Observations (1906–16): Land Subsidence or Sea Level Rise?

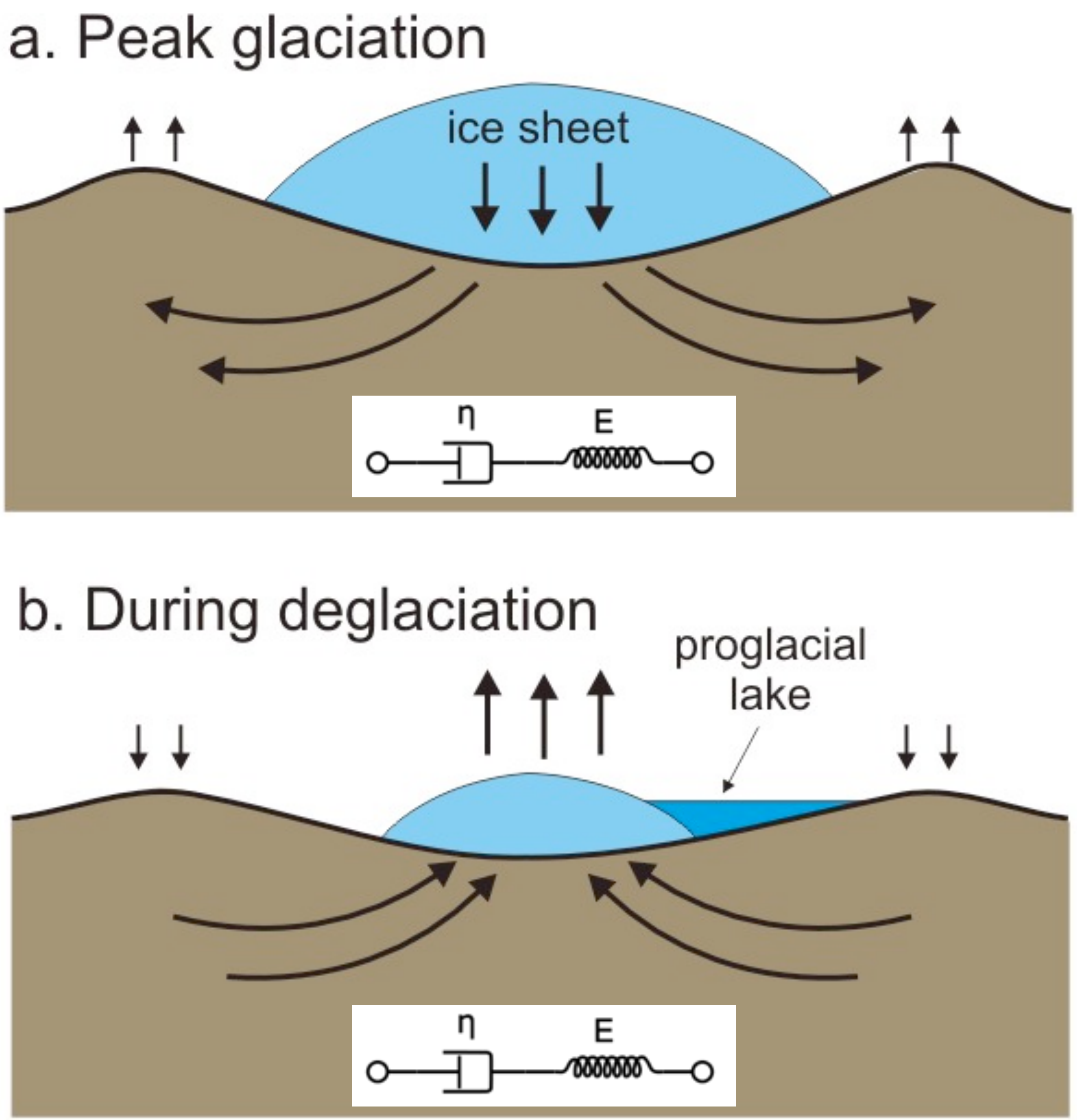
Marco Olivieri ‡, Giorgio Spada ‡, Andrea Antonioli § Gaia Galassi ‡

Journal of Coastal Research - 2015.



Tide gauge observations in Sicily

2.) Tide gauge sets



"Problem I":

"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.

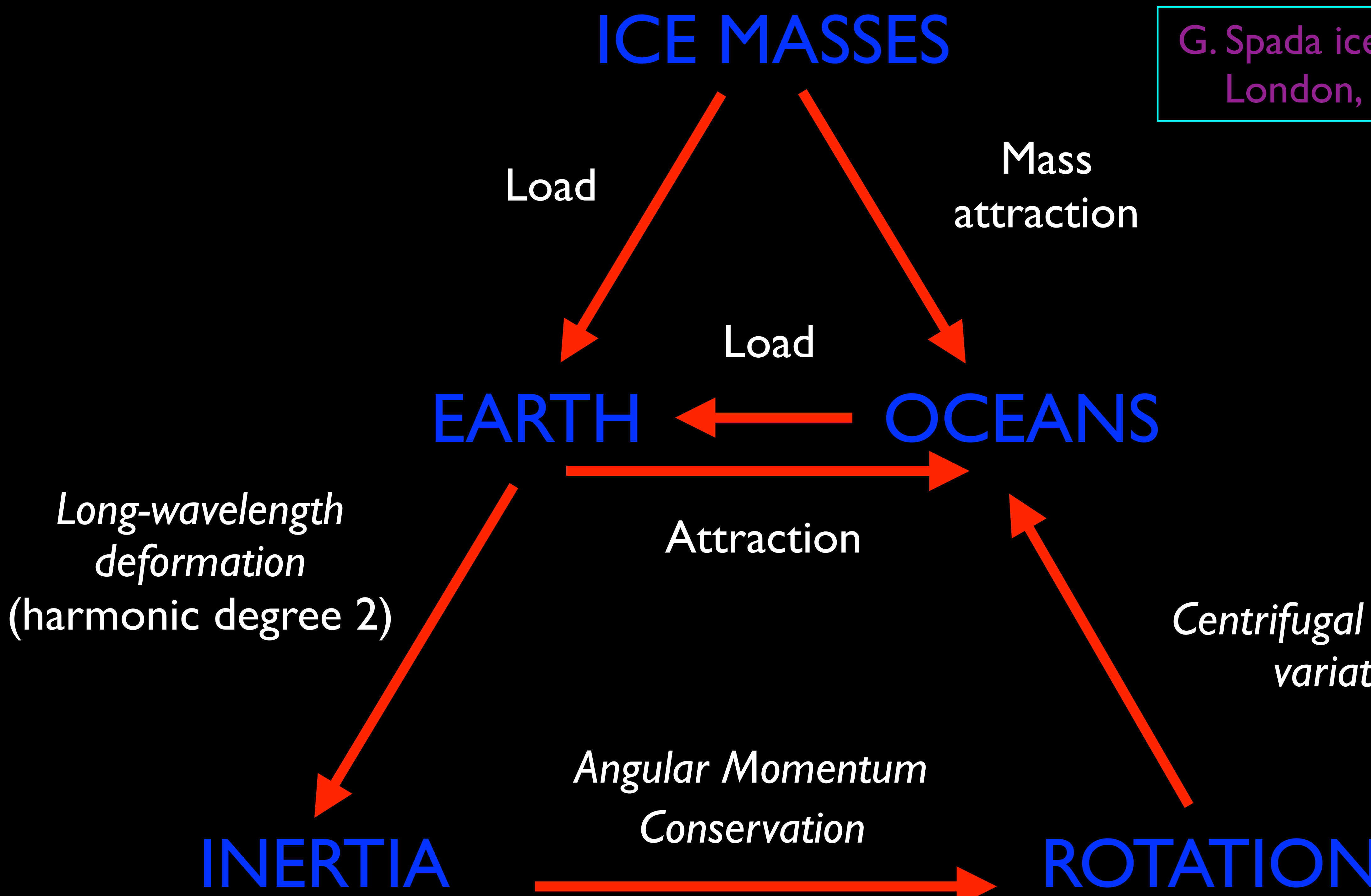
Later on...

(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*

Regional variability in GIA and glacial melting-induced SL change

G. Spada ice2sea Forum
London, May 2013



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

Adapted from Clark & Lingle, 1979

the “Sea Level Equation” (SLE, Farrell & Clark,1976)

$$S = N - U$$

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

$S =$ 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

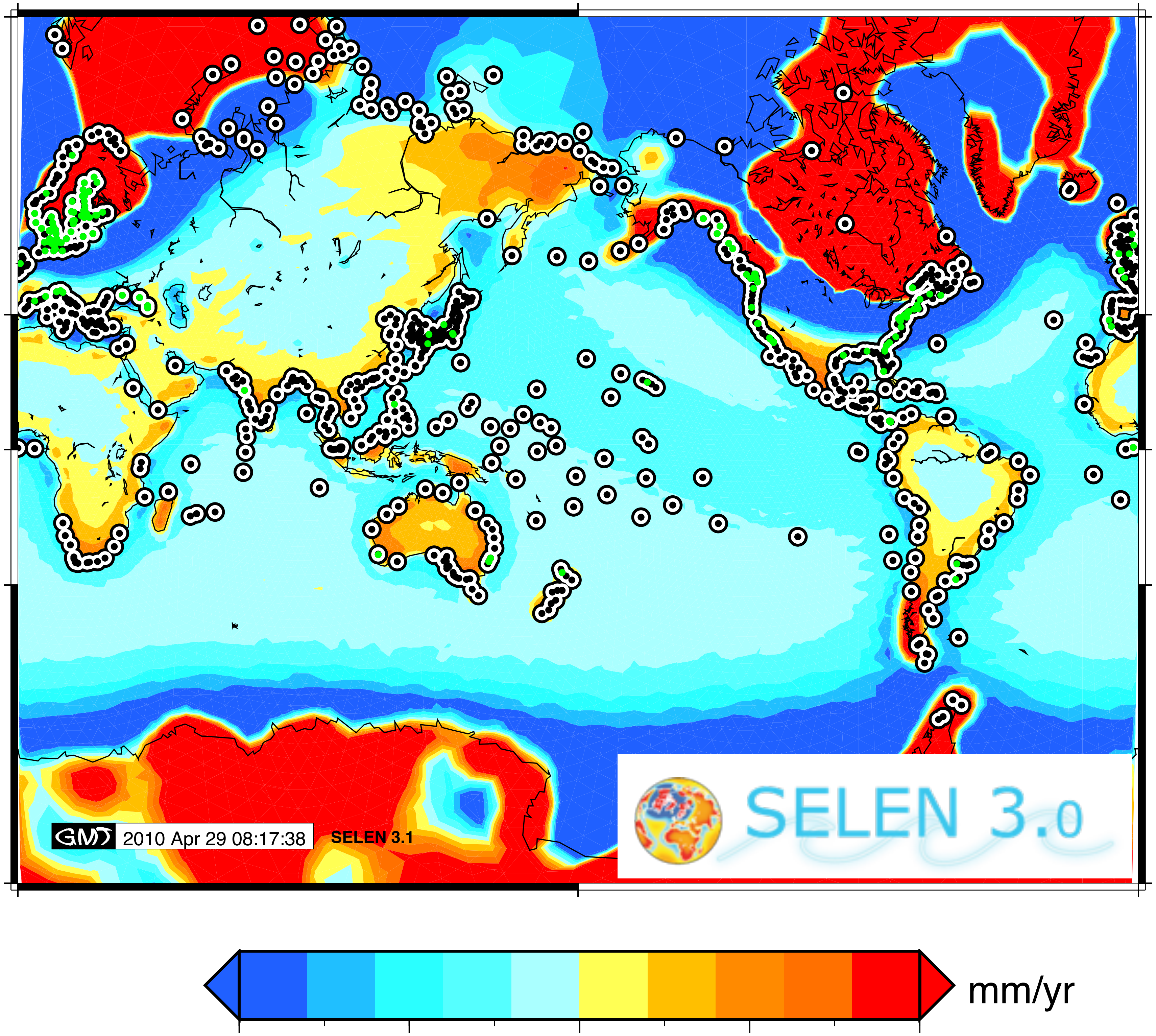
$\otimes_i, \otimes_o =$ 3(2+1)D convolutions

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

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

Rate of vertical displacement today

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

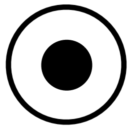


–LMAX=72 –RES=18 –NV=3 –MODE=1 –ITER=3

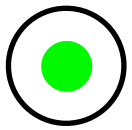
"Problem I":

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

All PSMSL tide gauges (~ 1200)



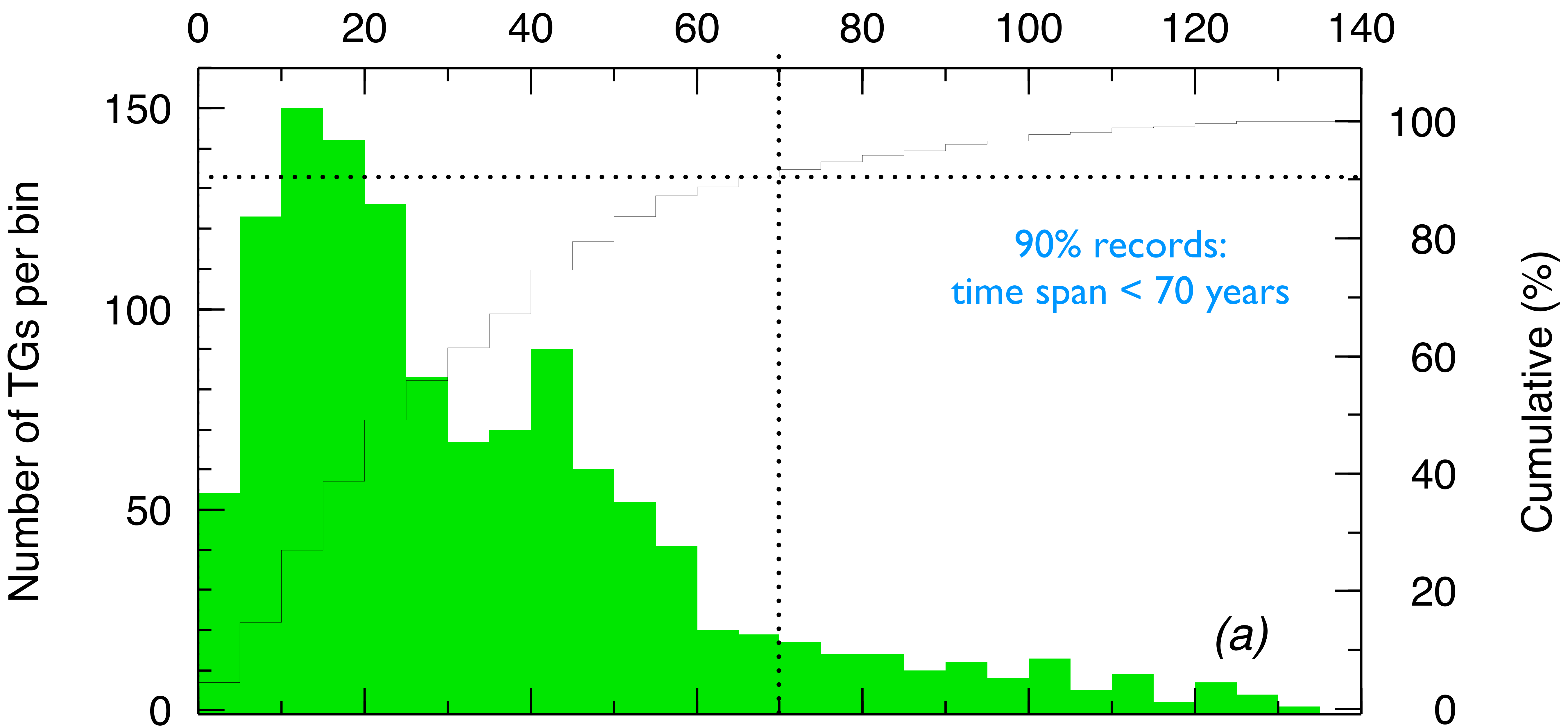
PSMSL tide gauges with T > 60 years (~ 140)



Statistics of the RLR PSMSL TG trends

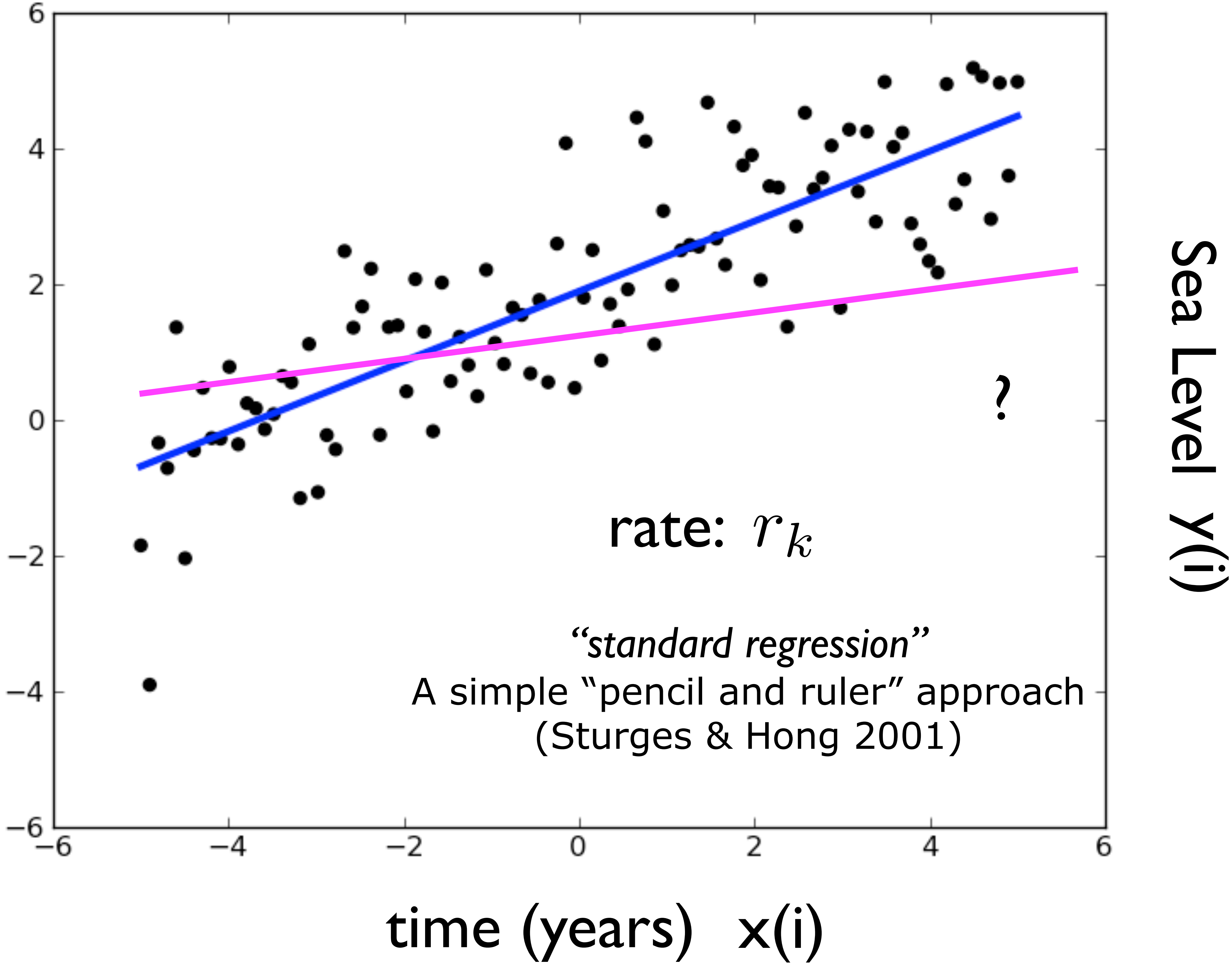
“Problem II”:

Issues in the space and time distribution of TG data



number of valid yearly records

Obtaining a trend from the TG records



Obtaining a trend from the TG records

"Best-fit rate:"

$$r_k = \frac{N_k^v \sum_j x_j y_j - \left(\sum_j x_j\right)\left(\sum_j y_j\right)}{N_k^v \left(\sum_j x_j^2 - \sum_j y_j^2\right)}, \quad k = 1, \ldots, N_{tg},$$

where:

y_j is sea level at time x_j $(j = 1, \ldots, N_k^v)$

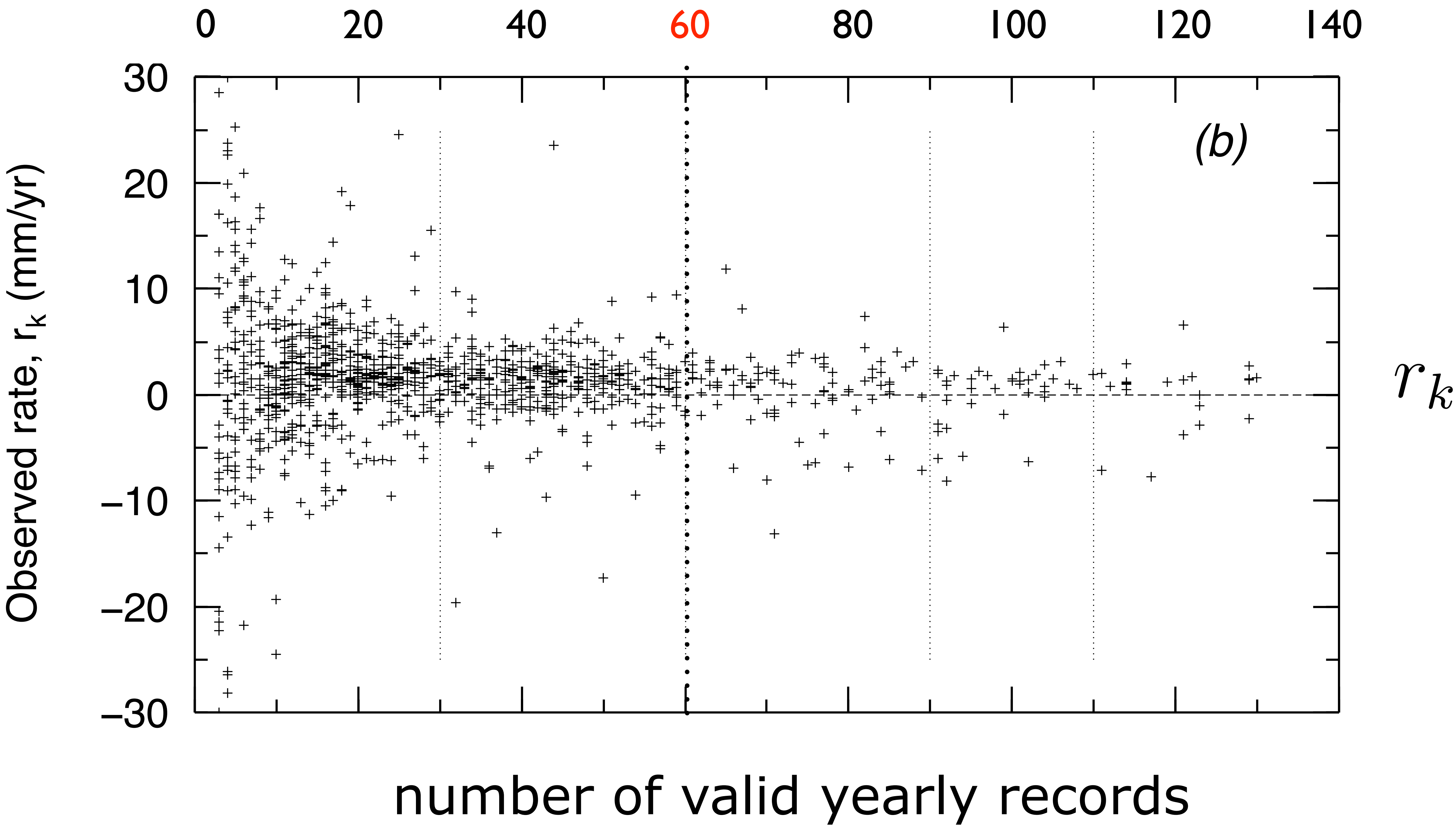
N_k^v is number of valid yearly data in the time series (twelve monthly observations available)

σ_k is the uncertainty on the trend (95% confidence), obtained using the Student t distribution

So, the tide gauge rate (with uncertainty) is: $\rho_k = r_k \pm \sigma_k$

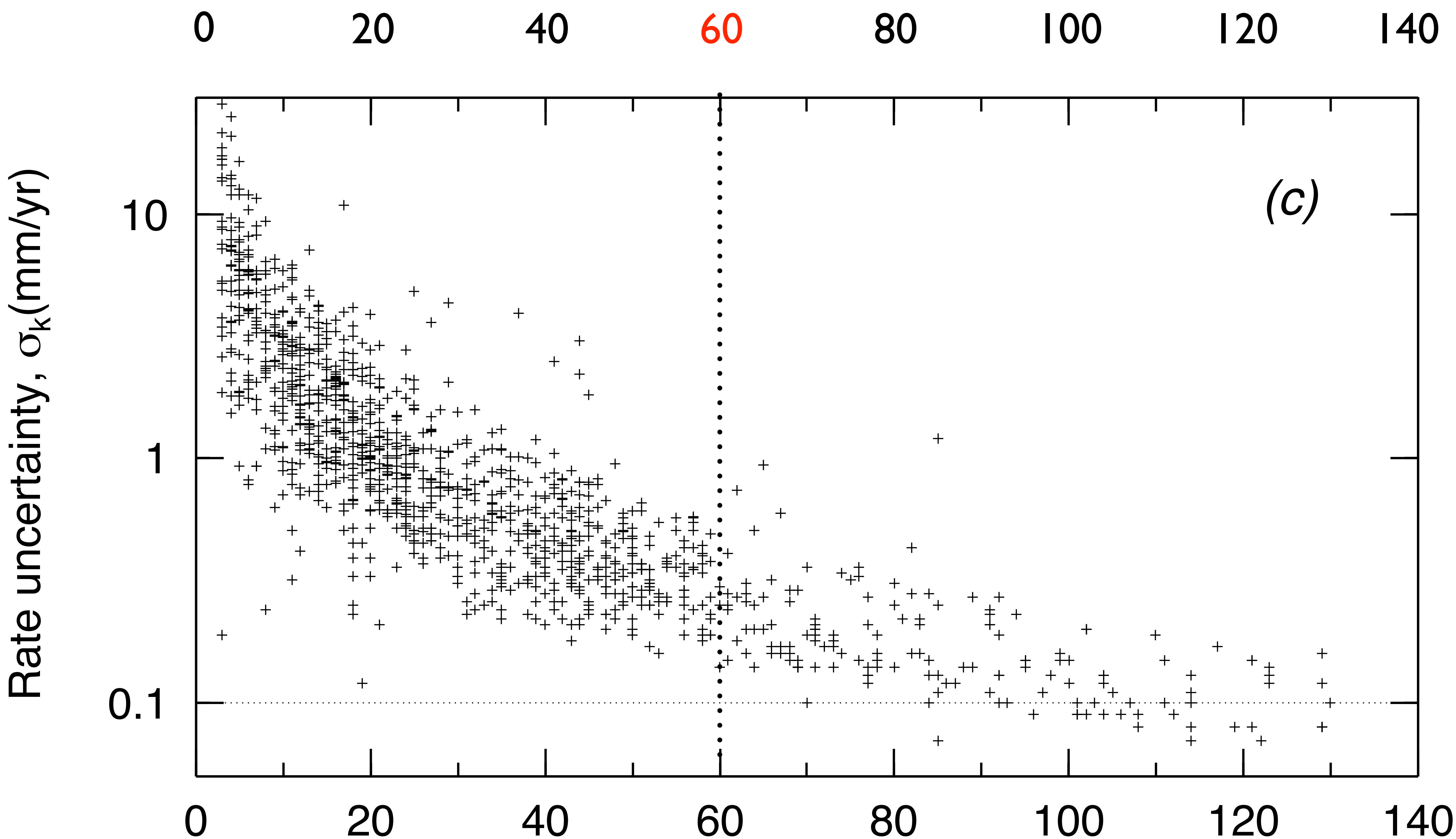
Statistics of the RLR PSMSL TG trends

Observed rate



Statistics of the RLR PSMSL TG trends

uncertainty on the rate



number of valid yearly records

IPGS Conference Strasbourg, March 2015

Obtaining a "global mean rate of sea level rise"

Preferred value

$$m = \frac{\sum_k r_k}{N_{tg}}$$

Arithmetic mean

"best estimate" of the GMSLR

Uncertainty estimates

$$rms = \sqrt{\frac{\sum_k (r_k - m)^2}{N_{tg} - 1}}$$

Root mean square

average uncertainty of individual trends

$$sdom = \frac{rms}{\sqrt{N_{tg}}}$$

Standard deviation of the mean

uncertainty of the best estimate m

"Global mean sea level rise:" $\mu = m \pm sdom$

$$(rsm = ..., wrms = ...)$$

Previous estimates of global sea level rise

1941

1980

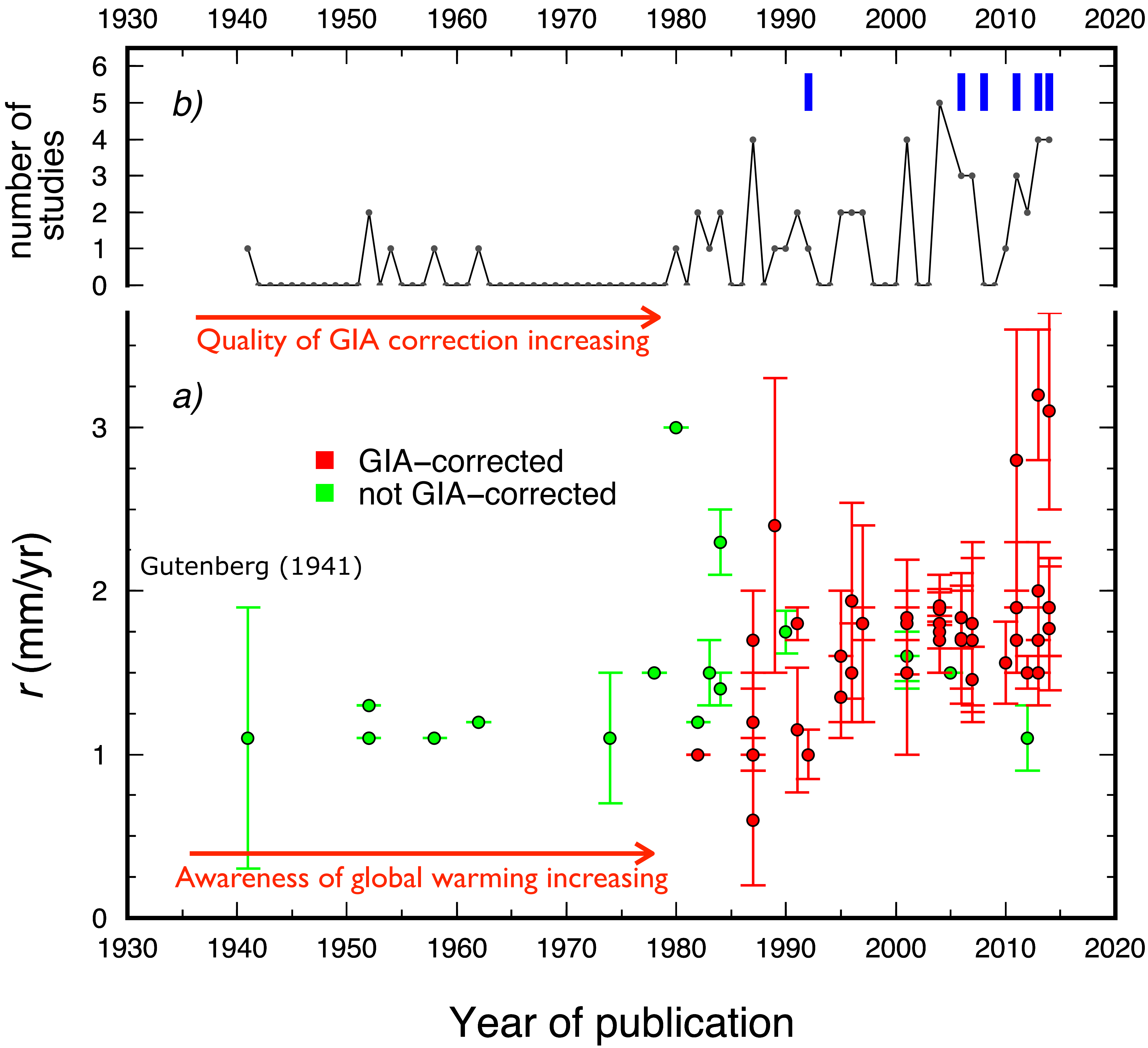
today

Year and Author(s)	μ (mm/yr)	Period	Method(s)	GIA correction
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	" "

from
Spada & Galassi
(*GJI*, 2012)

GIA corrections
since late 80s

Previous estimates of global sea level rise from TG observations



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a very influential paper: Douglas 1997 (D97)

SELECTION CRITERIA:

I) be at least 60 years in *length*

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

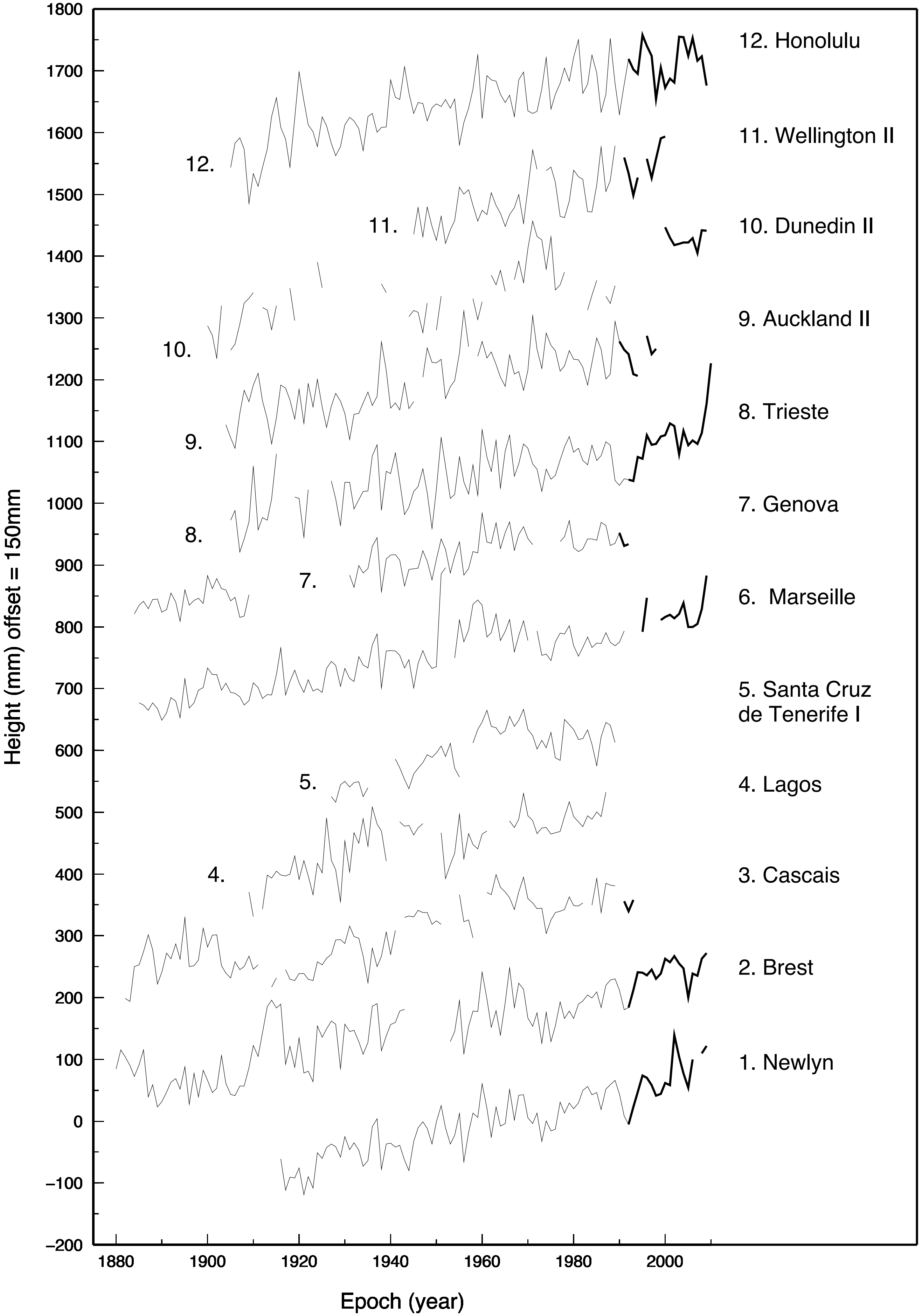
III) 80% *complete* or better (no big gaps)

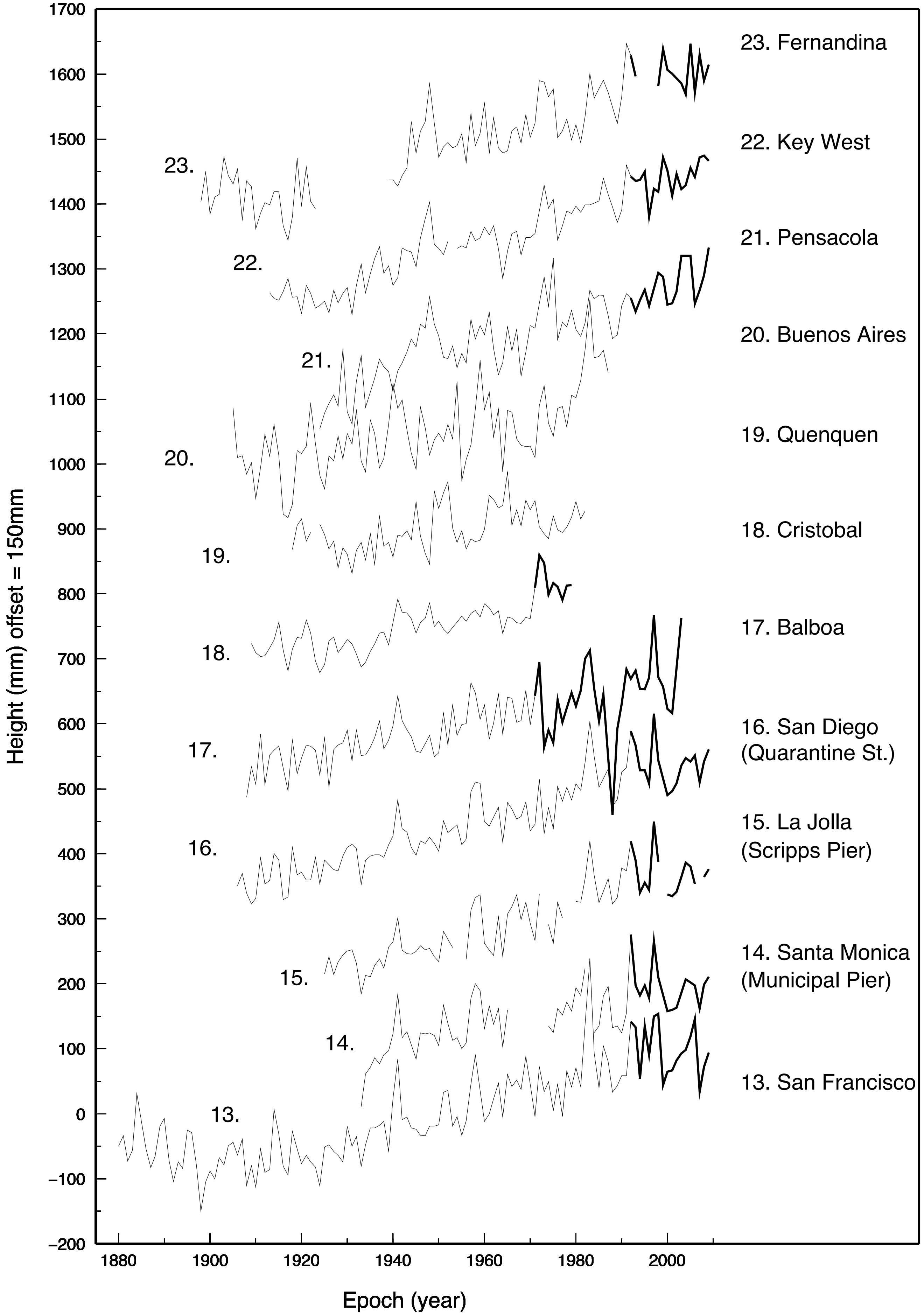
IV) in reasonable agreement (at low frequencies) with records from *nearby gauges* that sample the same water mass

V) not from areas *deeply covered by ice* during the last glacial maximum nor from their surroundings.

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

The 23 D97 PSMSL time series





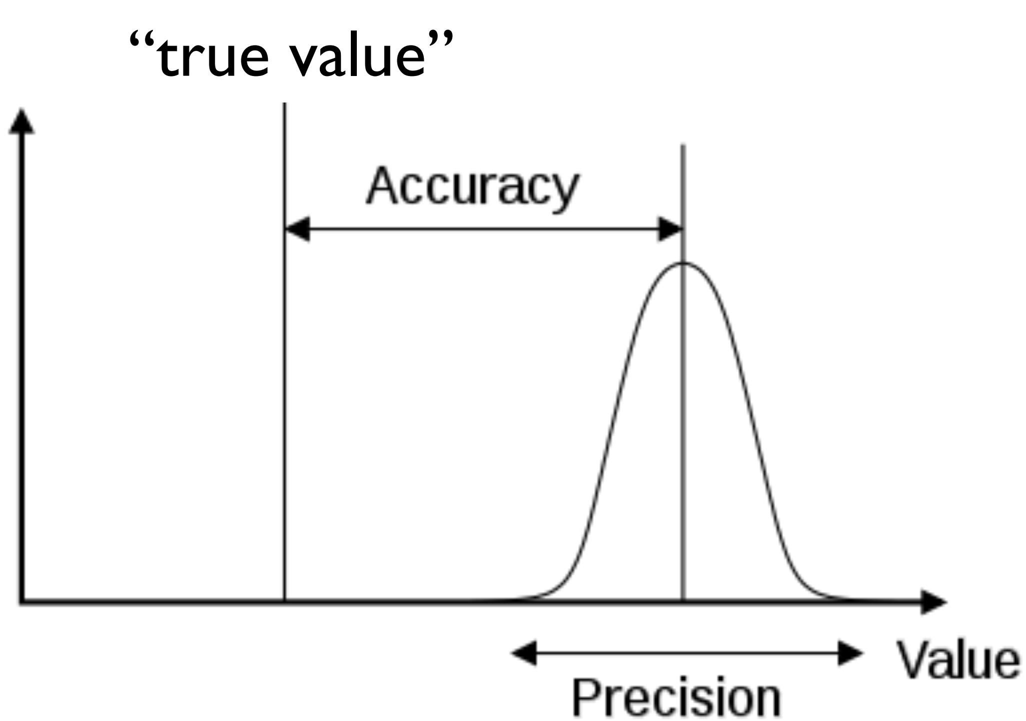
The 23 D97 PSMSL time series

The D97 criteria imply:
a huge reduction
of the population of TGs!

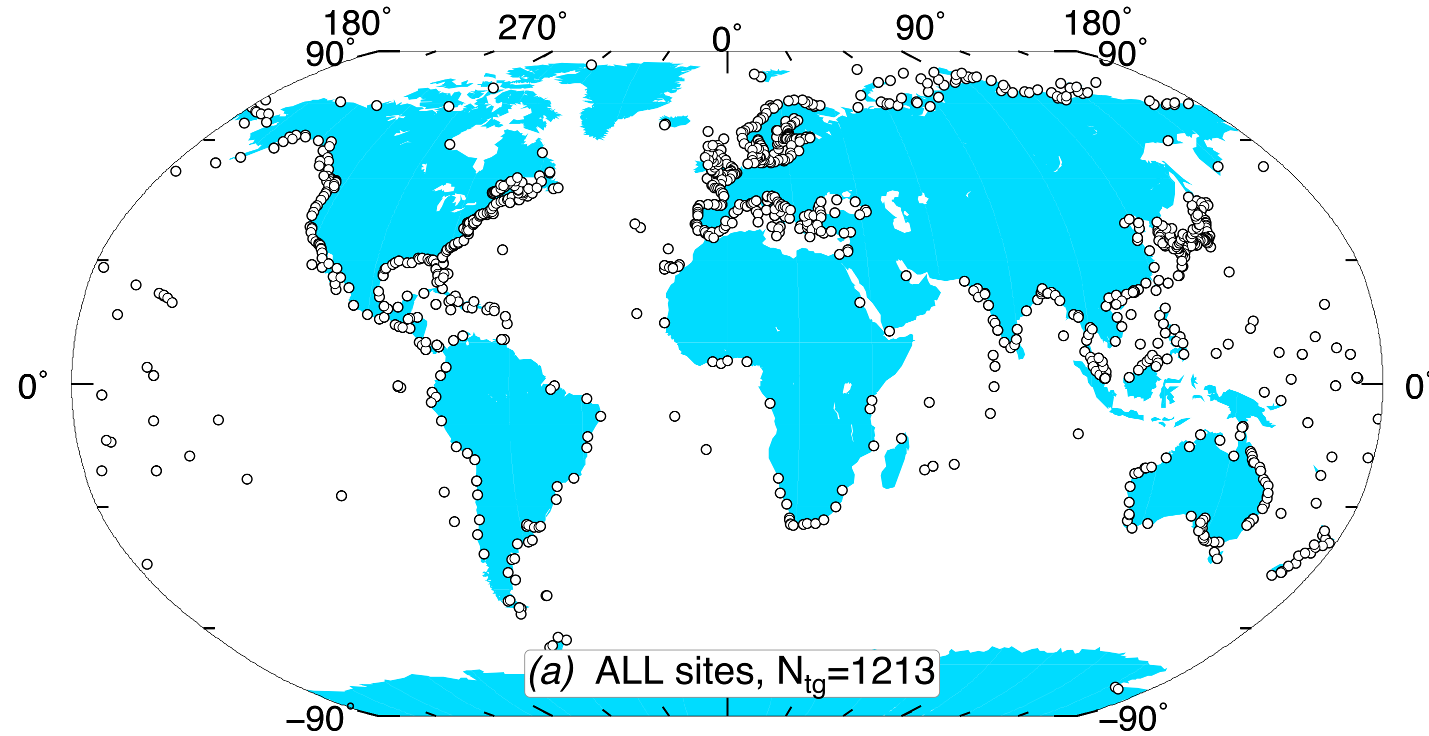
(by a factor ~50)

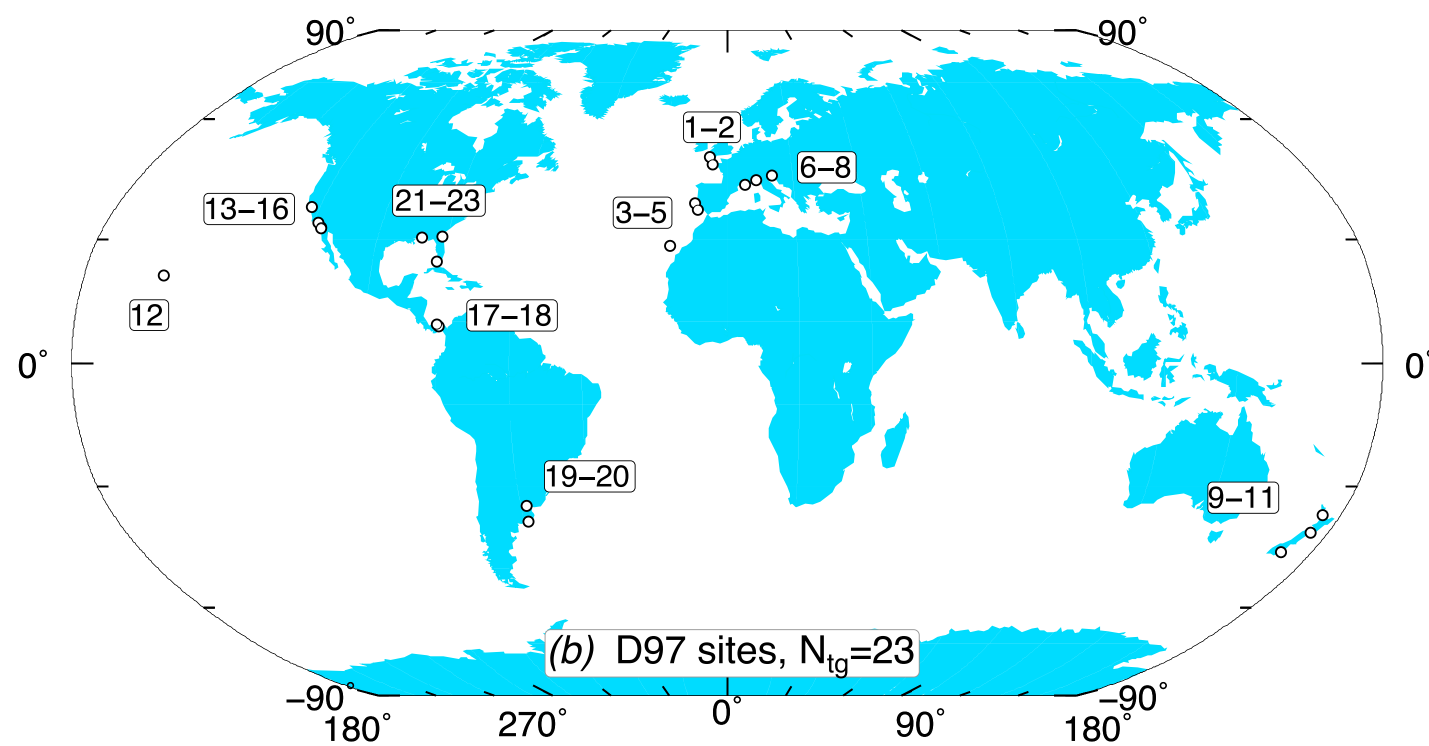
increased: coherency and
precision

but what about accuracy?

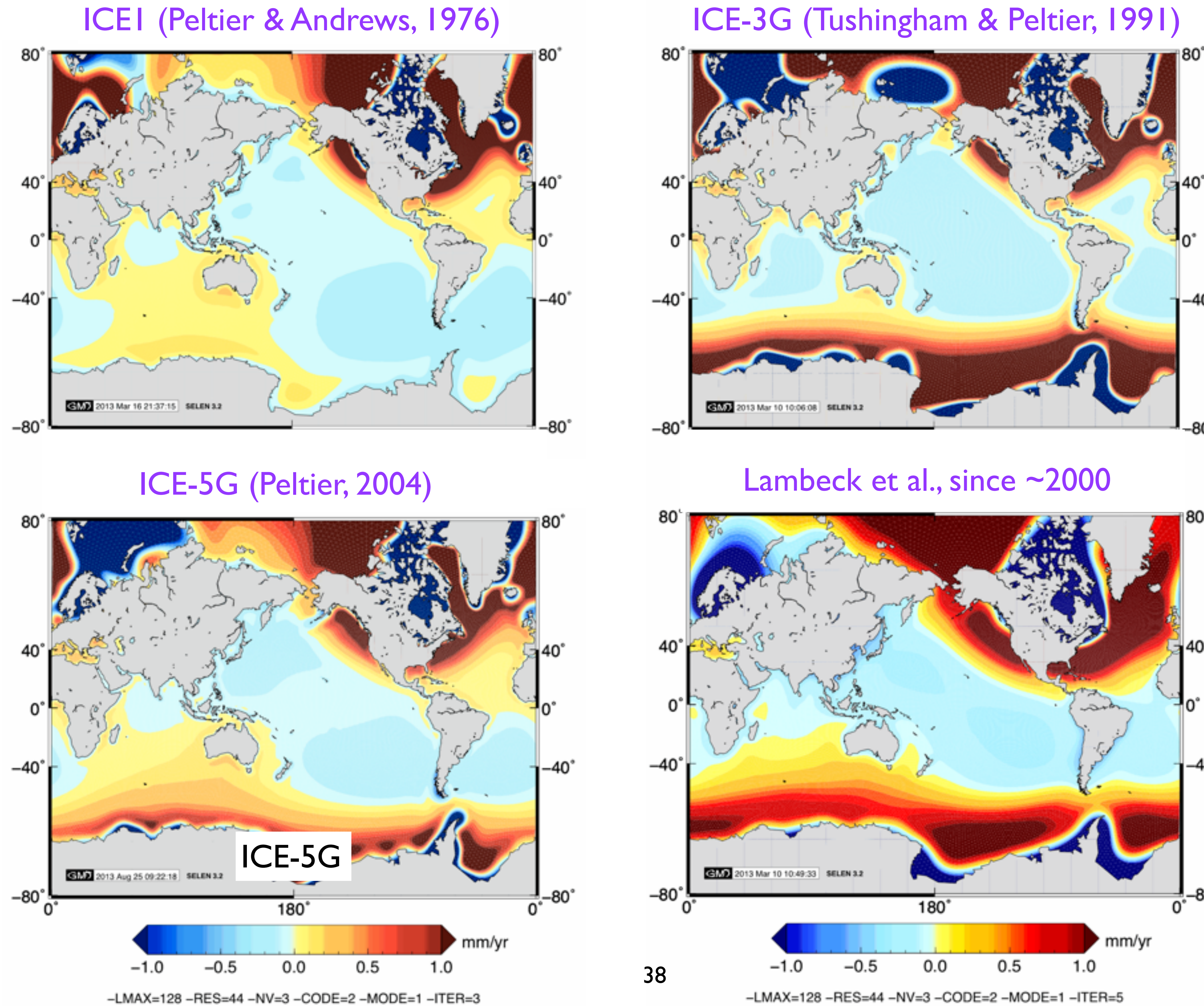


ALL set



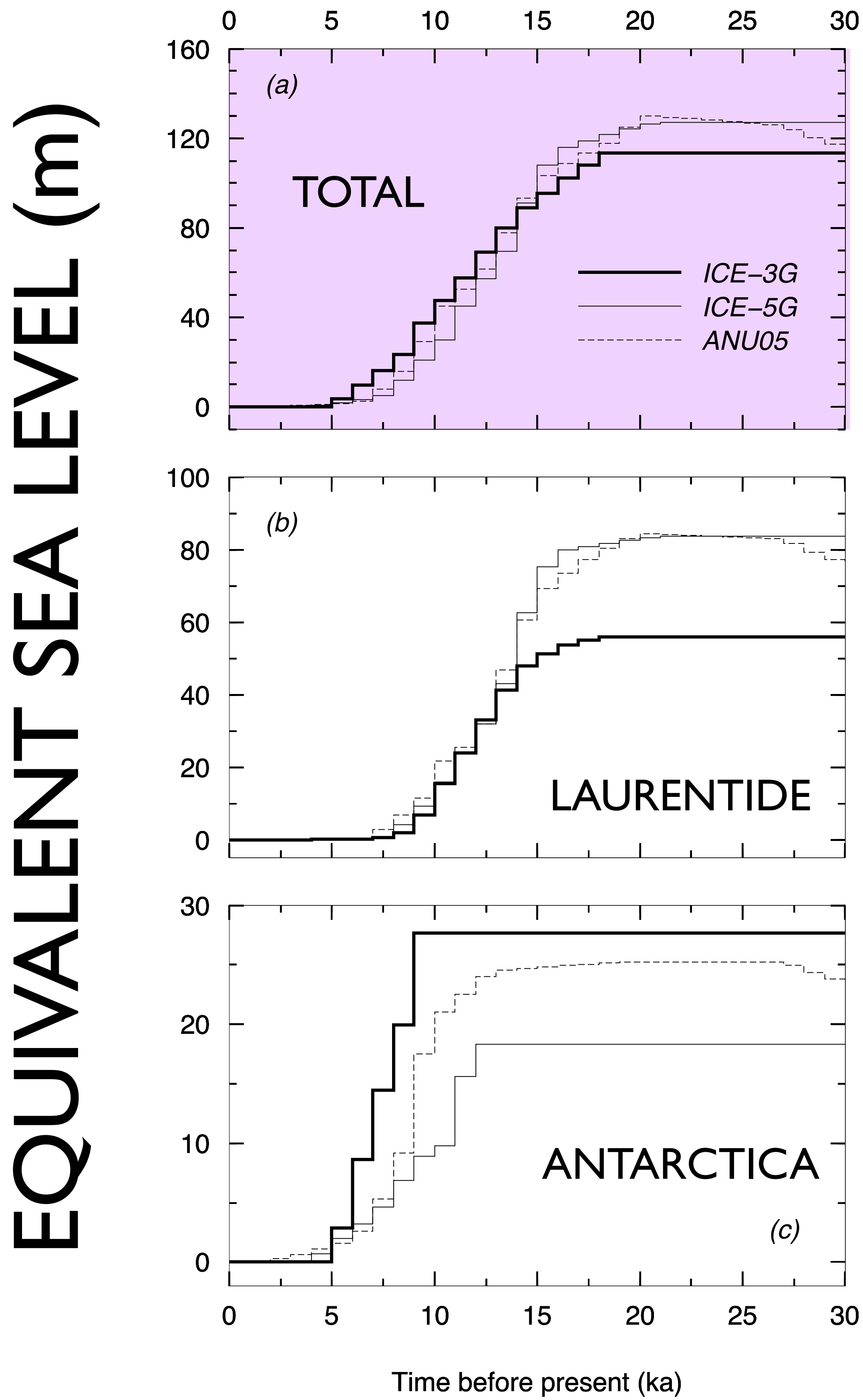


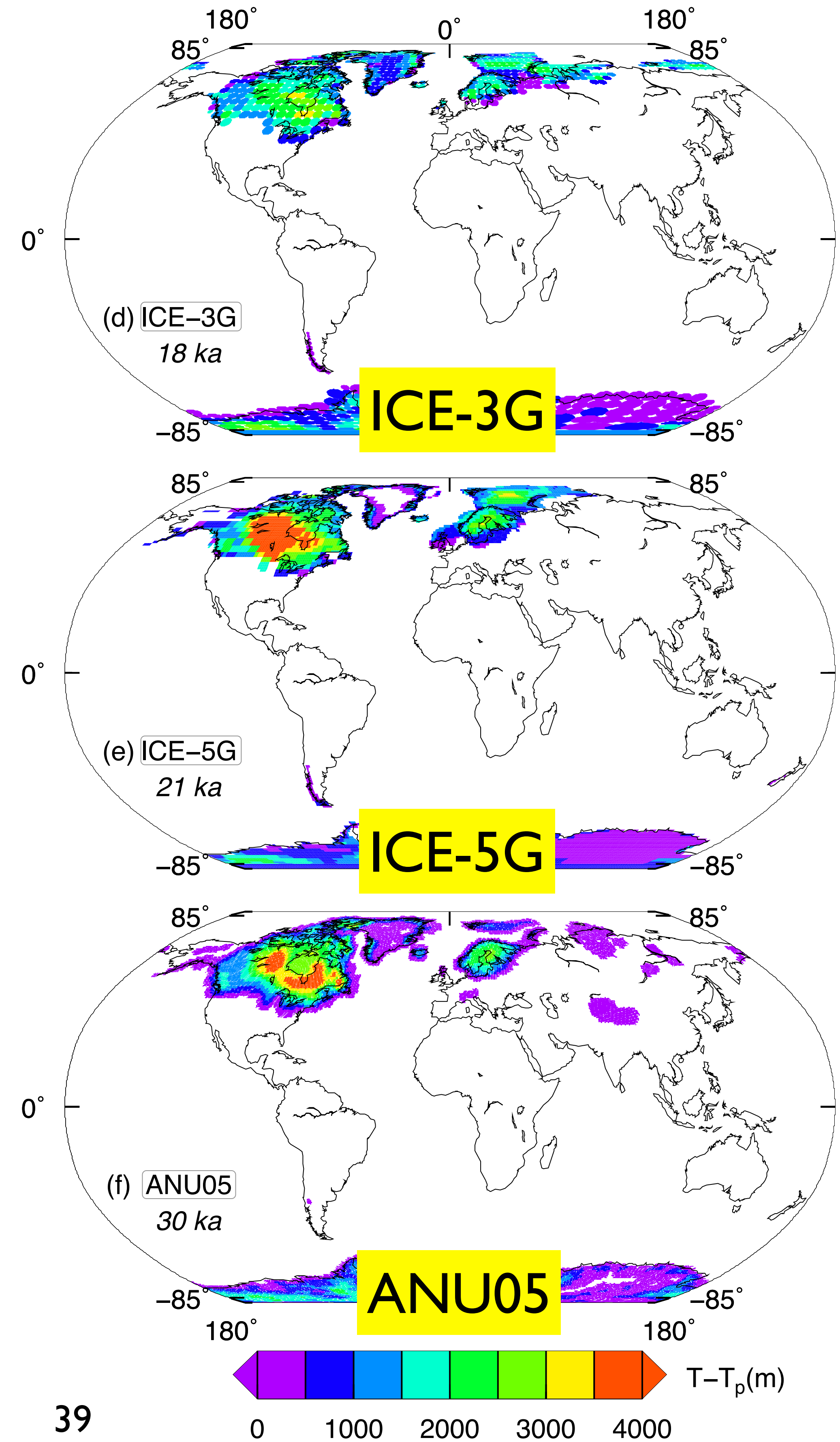
D97 set



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

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





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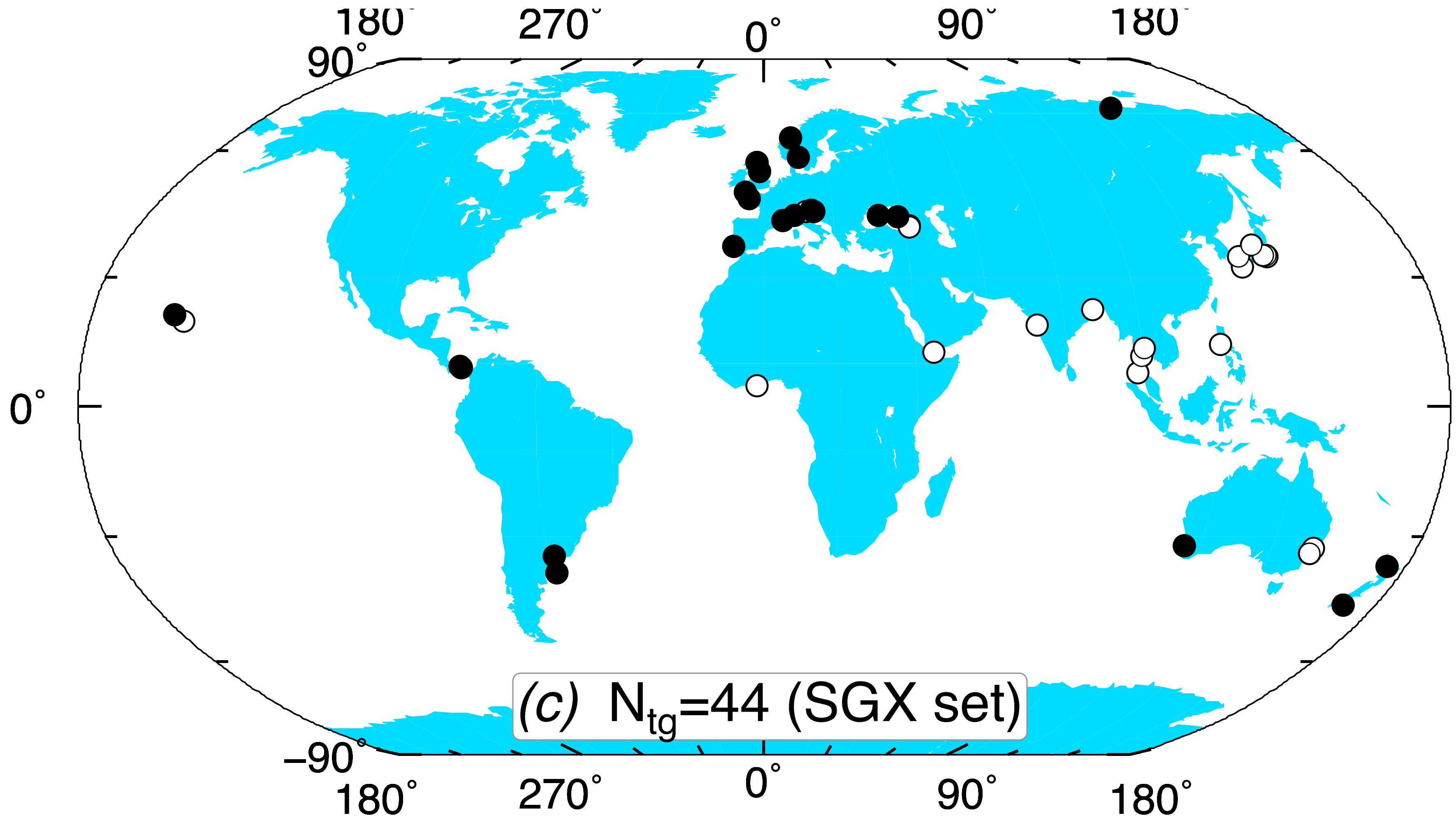
120/1/2
Peltier 92

90/0.5/2.7
Peltier 04

65/0.3/10
Lambeck 05

"from one another"

Searching for GIA-modeling-insensitive tide gauges



SGX ● + ○

~ same GIA correction for all the models available

SG01 ●

After application of the D97 criteria below

Set SG01 is obtained from SGX after removing:

1) too short records (N^v<60),
2) sites in "tectonically active" regions
3) sites showing "suspect accelerations..." (human activity?)
4) regionally inconsistent records ... other ...

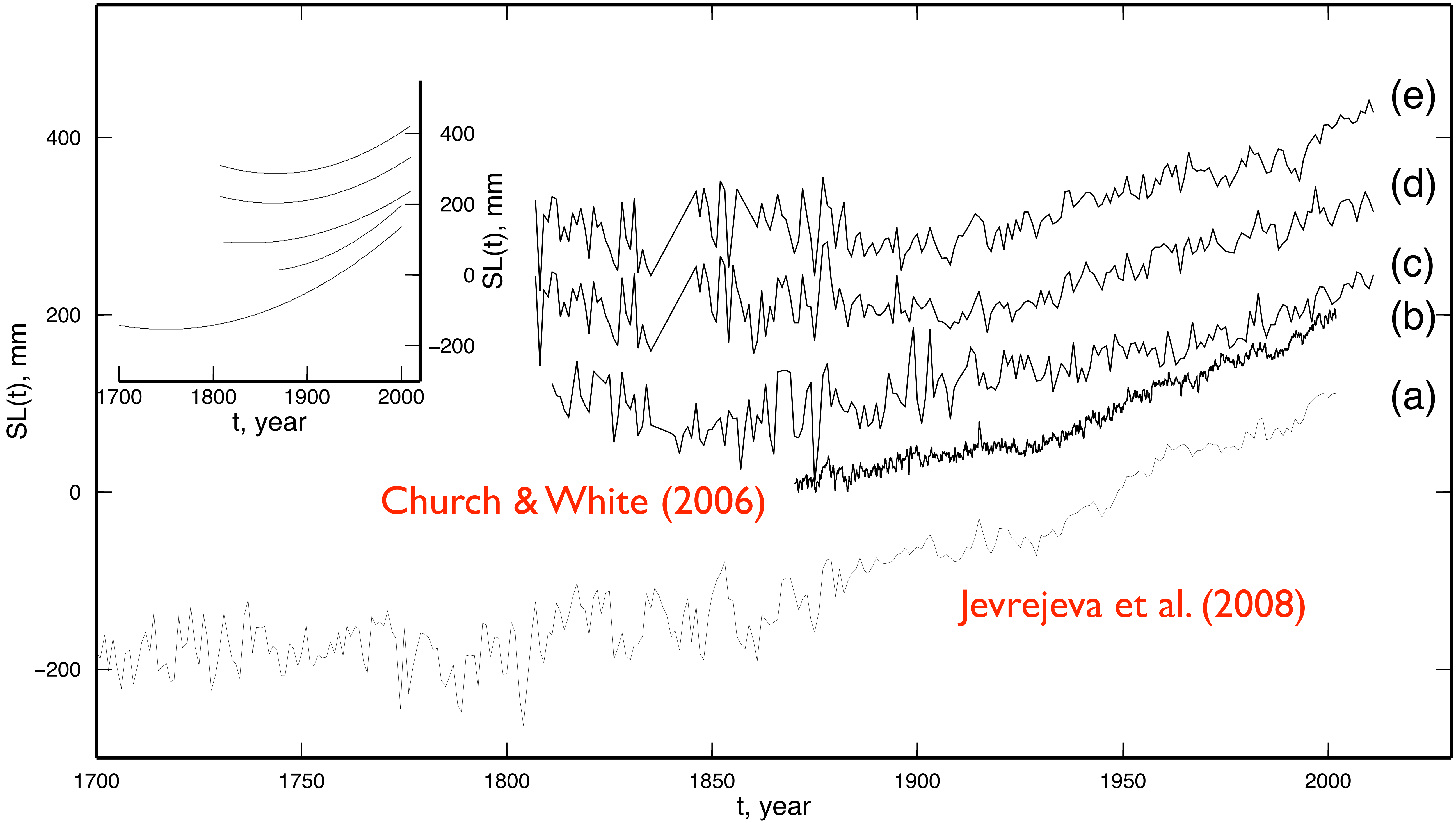
GIA-corrected and GIA-model-insensitive global mean rate of sea level rise (1880-2010)

$$\mu' = 1.5 \pm 0.1 \quad \text{mm/yr}$$

$$rms = 0.4 \text{ mm/yr}, wrms = 0.3 \text{ mm/yr},$$

Significantly LESS than Douglas' value of
1.8 +/- 0.1 mm/yr

secular sea-level acceleration ~ 1 mm/yr/century



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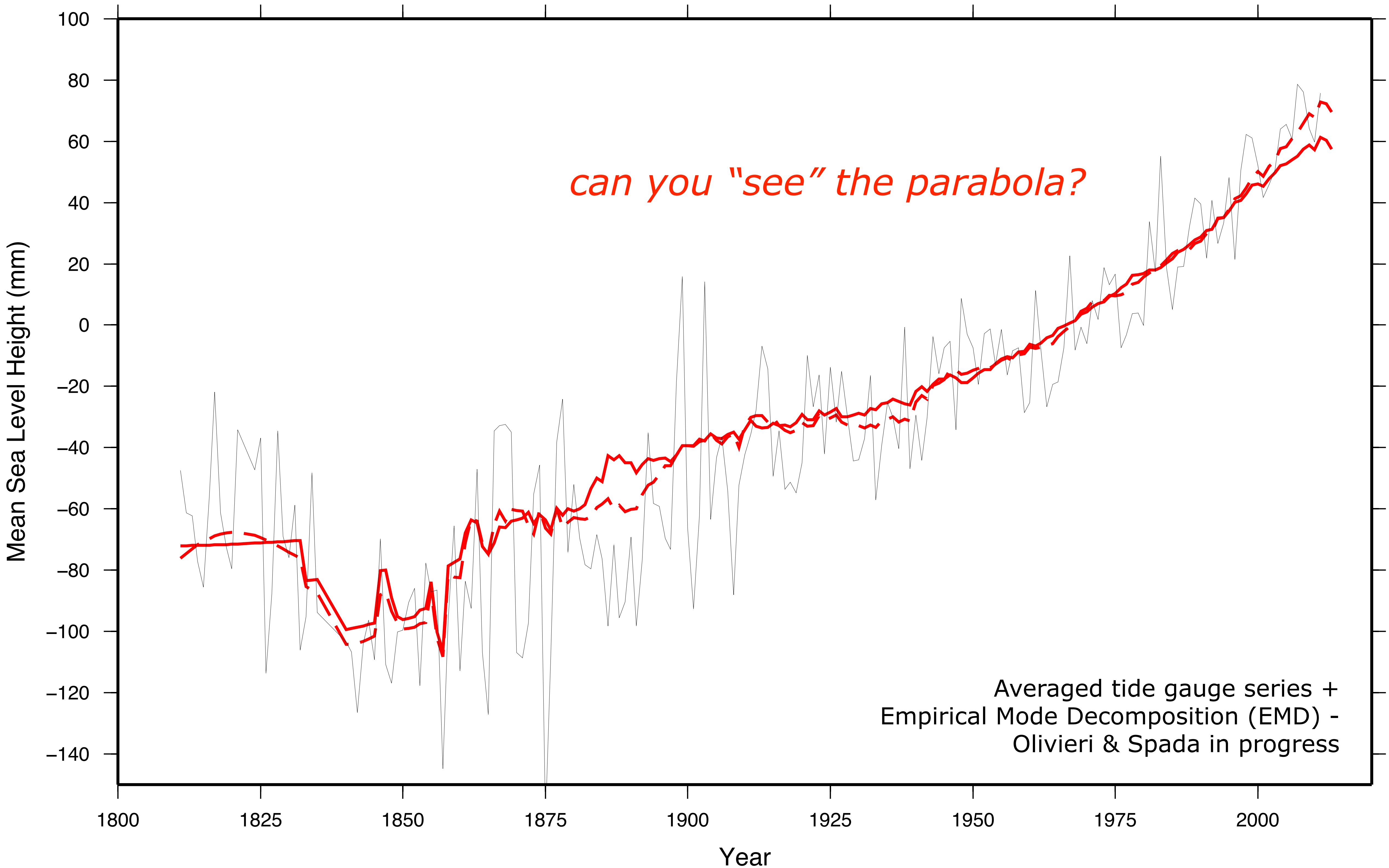
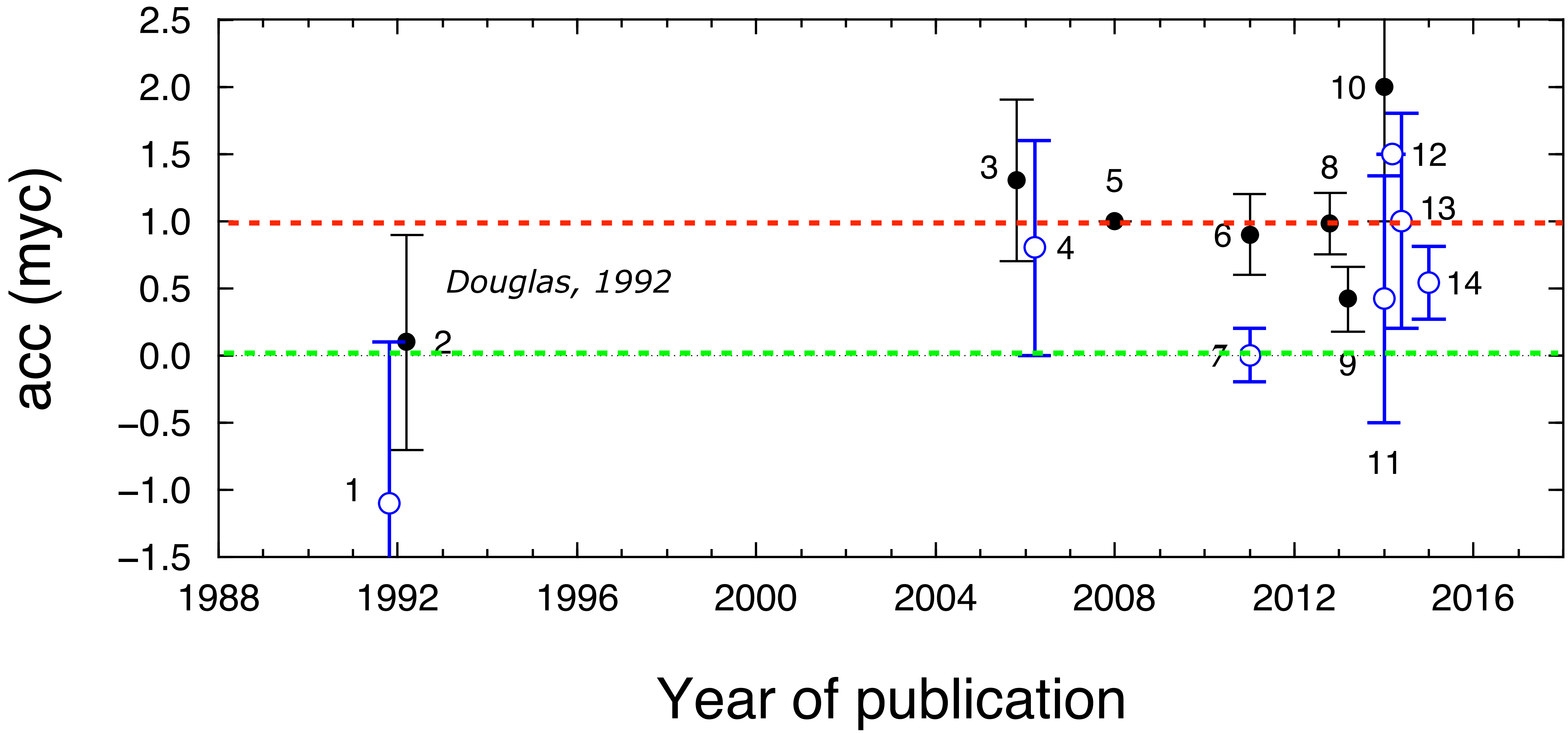
secular sea-level acceleration ~ 1 mm/yr/century



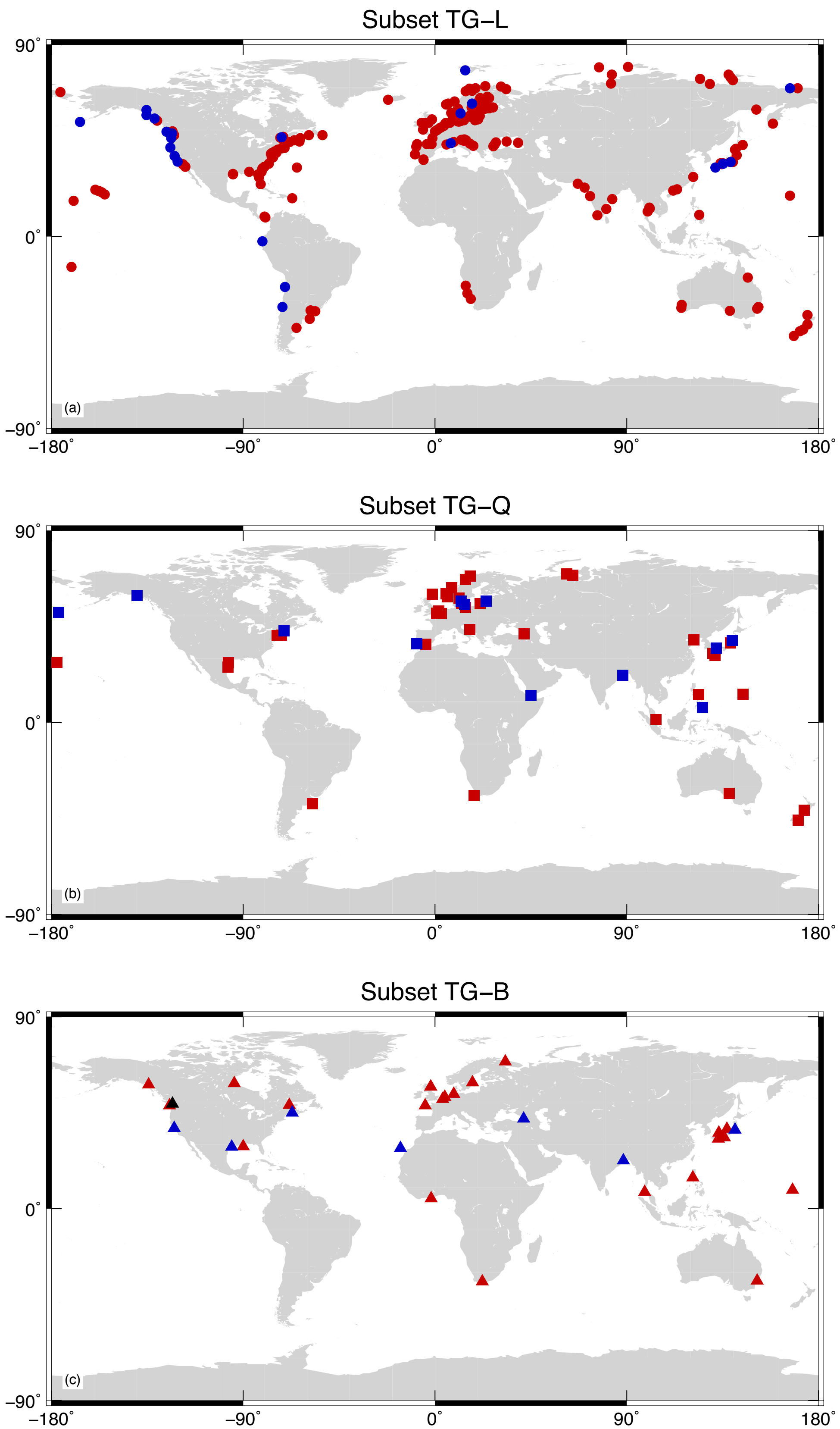
secular sea-level acceleration ~ 1 mm/yr/century

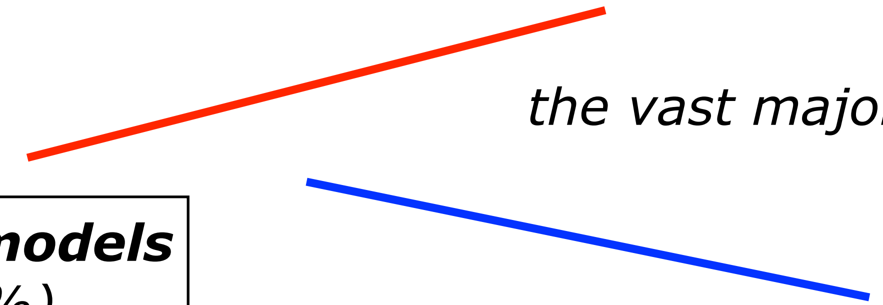
(with large uncertainties)



IPCC AR5: it is *likely* (probability > 66%) that a positive acceleration occurred between the 19th and 20th century

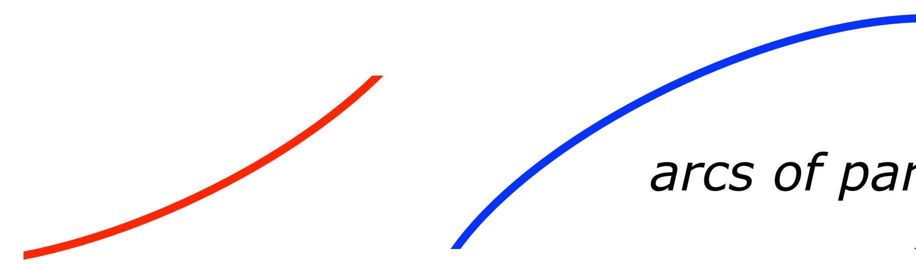
Is "sea-level acceleration" GLOBAL?





the vast majority

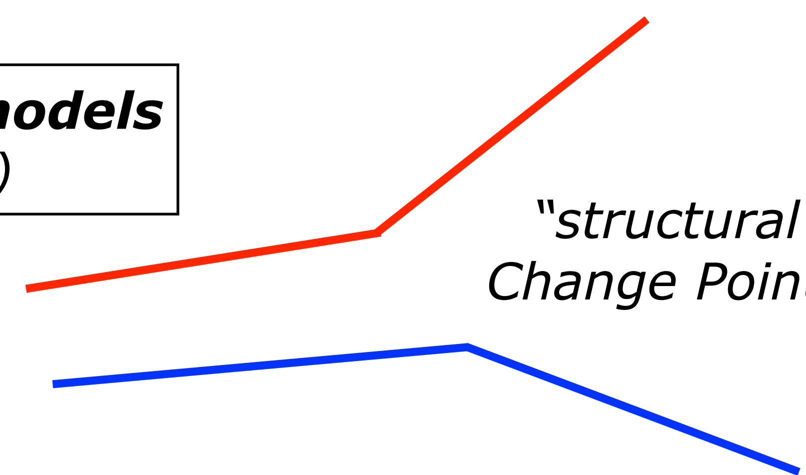
Linear models
(75%)



arcs of parabola

Quadratic models
(15%)

Bi-linear models
(10%)



"structural Change Point"

375 RLR PSMSL records with period > 50 years

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Olivieri and Spada, GPC (2013)

Sea level rise and acceleration
(from secular observations) - final remarks

- Tide gauges have a fundamental role in the assessment of secular sea-level rise, and contain an enormous amount of geophysical information,

- The concept of "global" secular sea-level rise is not perhaps so meaningful - now there is a big concern on the present (and future) patterns of regional sea level change,

- Sea-level acceleration is not constant nor smooth. Rather, it is intermittent and spatially variable. Still very difficult to constrain.