Contributions from:
- *Marta Marcos*
- *Belén Martin Miguez*
- *Alvaro Santamaria-Gomez*

CeCile

Variations relatives et absolues du niveau marin

Guy Wöppelmann
guy.woppelmann@univ-lr.fr

Plan:
1. Les mesures du niveau marin
2. Une énigme stimulant la recherche depuis 2002
3. Variabilité spatiale et enjeux
4. Empreintes de la fonte des glaces continentales
5. Discussion & Concluding remarks

1. Les mesures du niveau de la mer

Echelle de marée

Marégraphe mécanique

Capteur pression

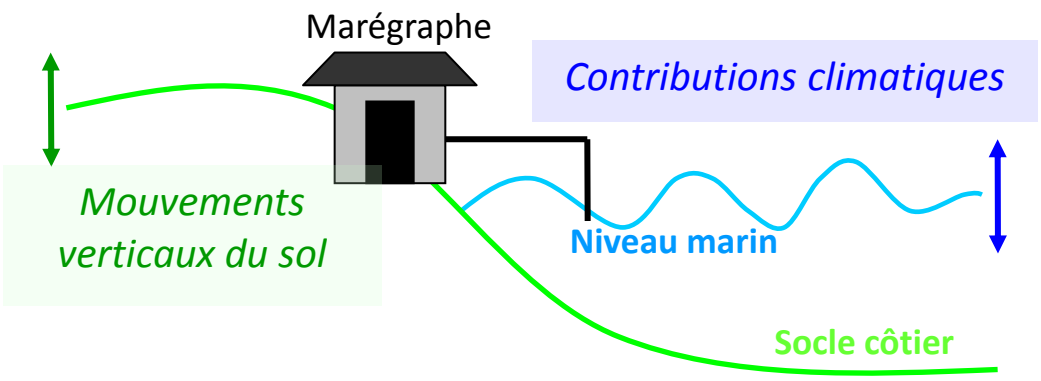
Acoustique & Radar

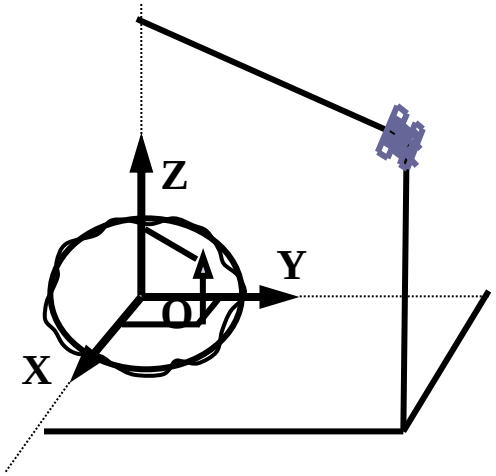
Altimétrie radar satellite

1679 — 1831 — 1960 — 1985 — **1992**

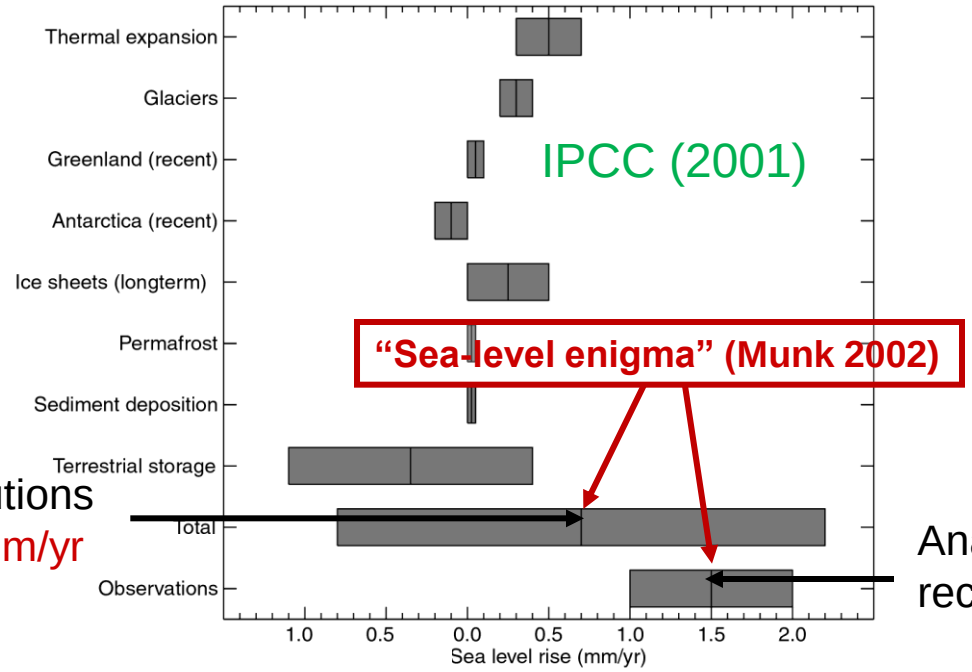
Niveau de la mer relatif

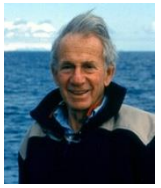
Niveau de la mer géocentrique





2. The "Sea level enigma"

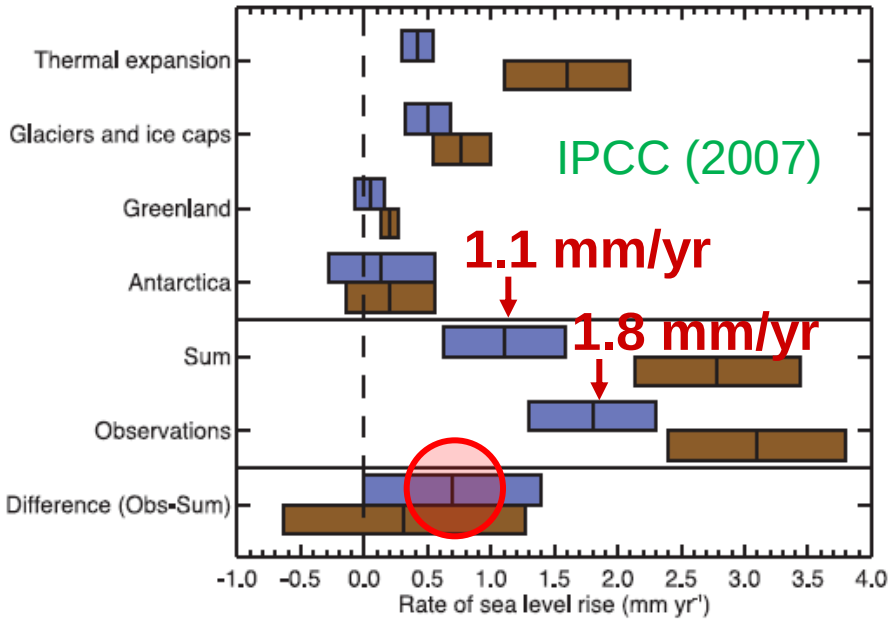




Scripps Institute, La Jolla, San Diego, California

Sum of climatic contributions to sea level rise: ~0.7mm/yr

Analyses of tide gauge records ~1.5mm/yr



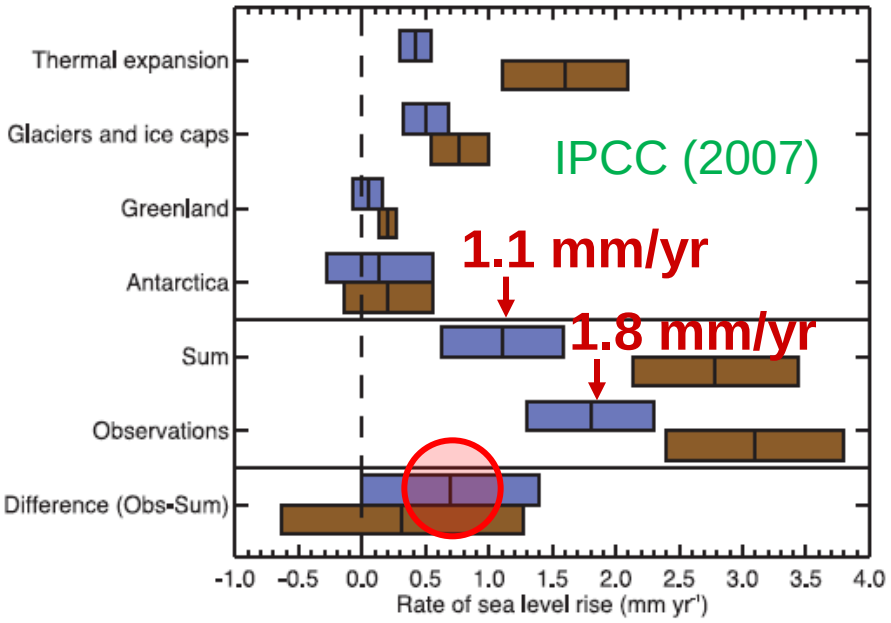
A stimulating enigma over the past decade

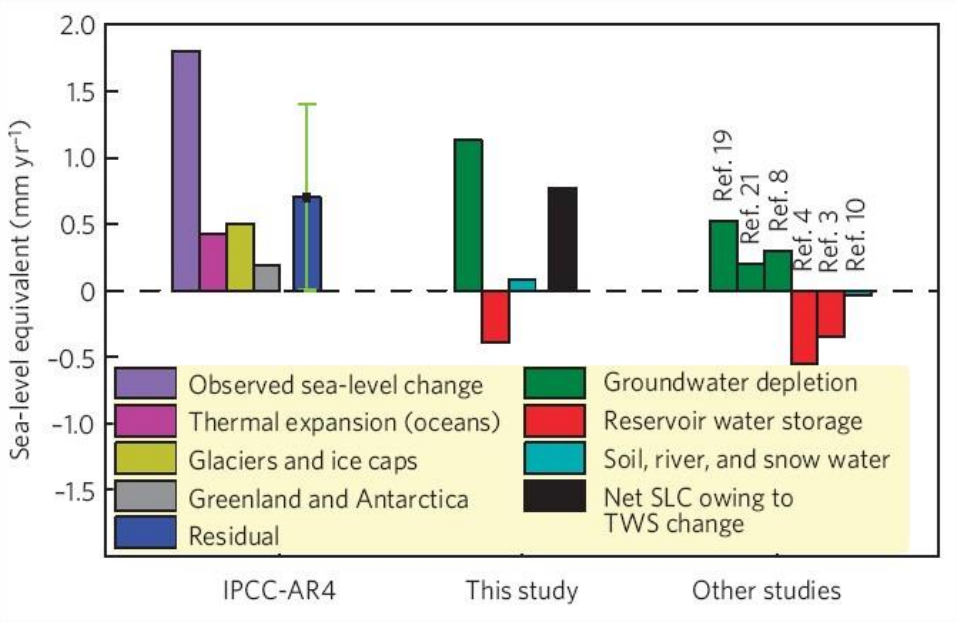
→ Where does the missing observed rise come from? (MWP 1a…?)

→ How to predict the future, if the recent past cannot be explained?

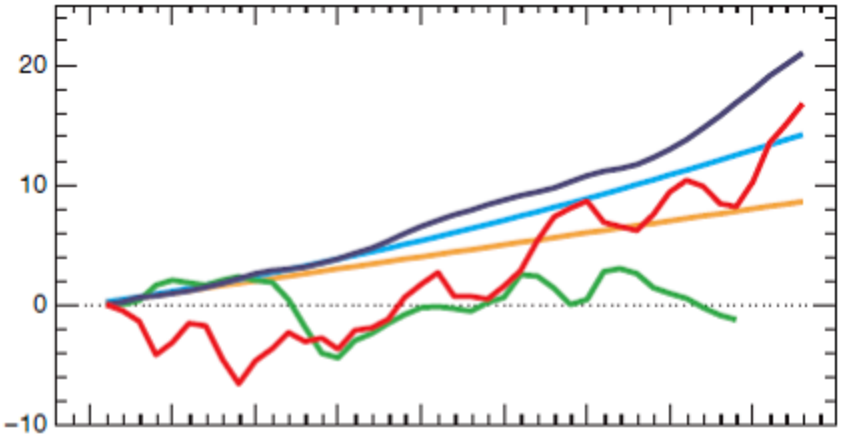
...

2. The "Sea level enigma": Updated contributions





➢ Thermosteric contribution (Domingues *et al.* 2008)



- ♦ Antarctic (0.2±0.4 mm/yr) & Greenland ice sheets (0.1±0.1 mm/yr)
- ♦ Glaciers & small Ice Caps (0.5±0.2 mm/yr)
- ♦ 0-700 m Thermosteric sea-level (0.5±0.1 mm/yr)
- ♦ Deep Thermosteric sea-level (0.2±0.1 mm/yr)
- ♦ Terrestrial storage (...)

→ Sum of contributions: **1.5 ± 0.4 mm/yr**

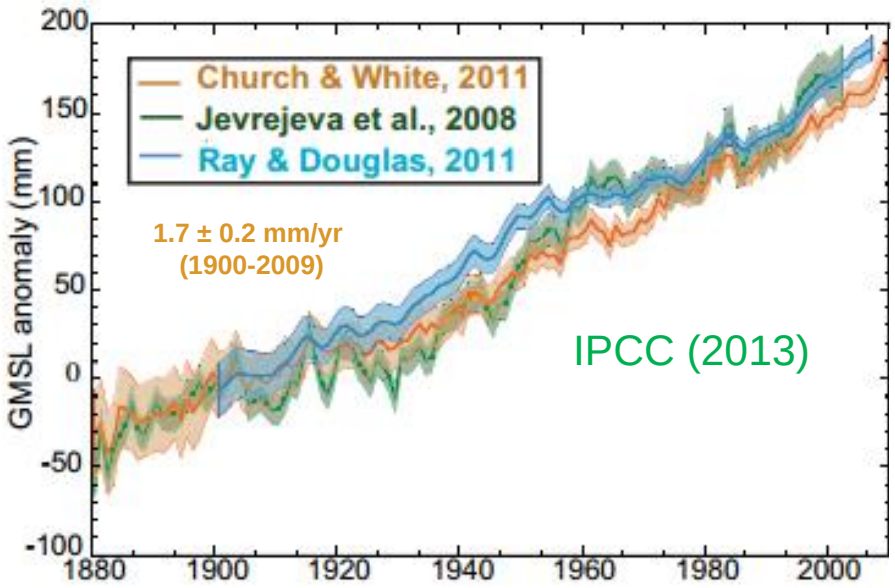
➢ Terrestrial water storage (Pokhrel *et al*. 2012)

- ♦ contributed a sea level rise of about 0.77 mm/yr

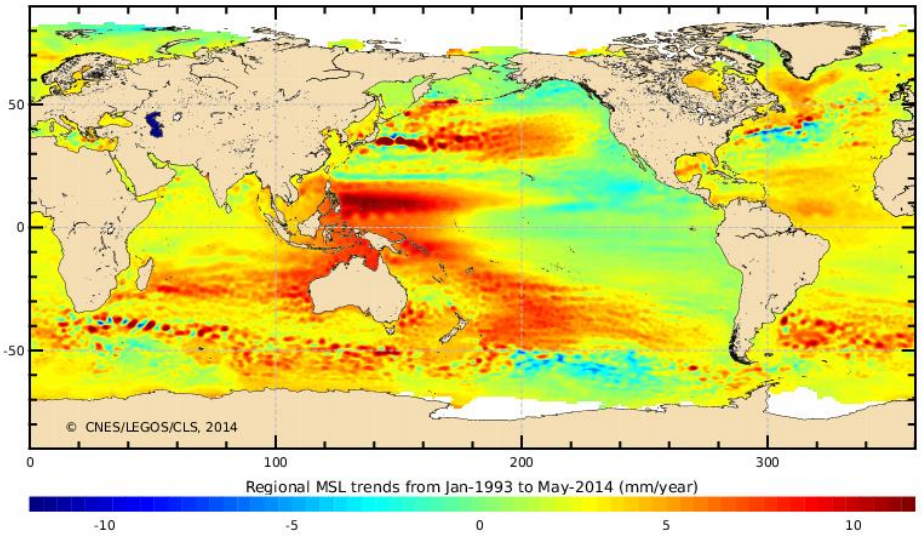
→ Sum of contributions: **~1.9 mm/yr**

(1.5+0.77) **~2.3 mm/yr**

3. Spatial variability in sea level trends



IPCC (2013)



Evidence for spatial variability in the rates of sea level change from satellite altimetry

The evidence for sea level change over multi-decadal to century timescales comes from tide gauge records

Tide Pole

Mechanical Gauge

Pressure Gauge

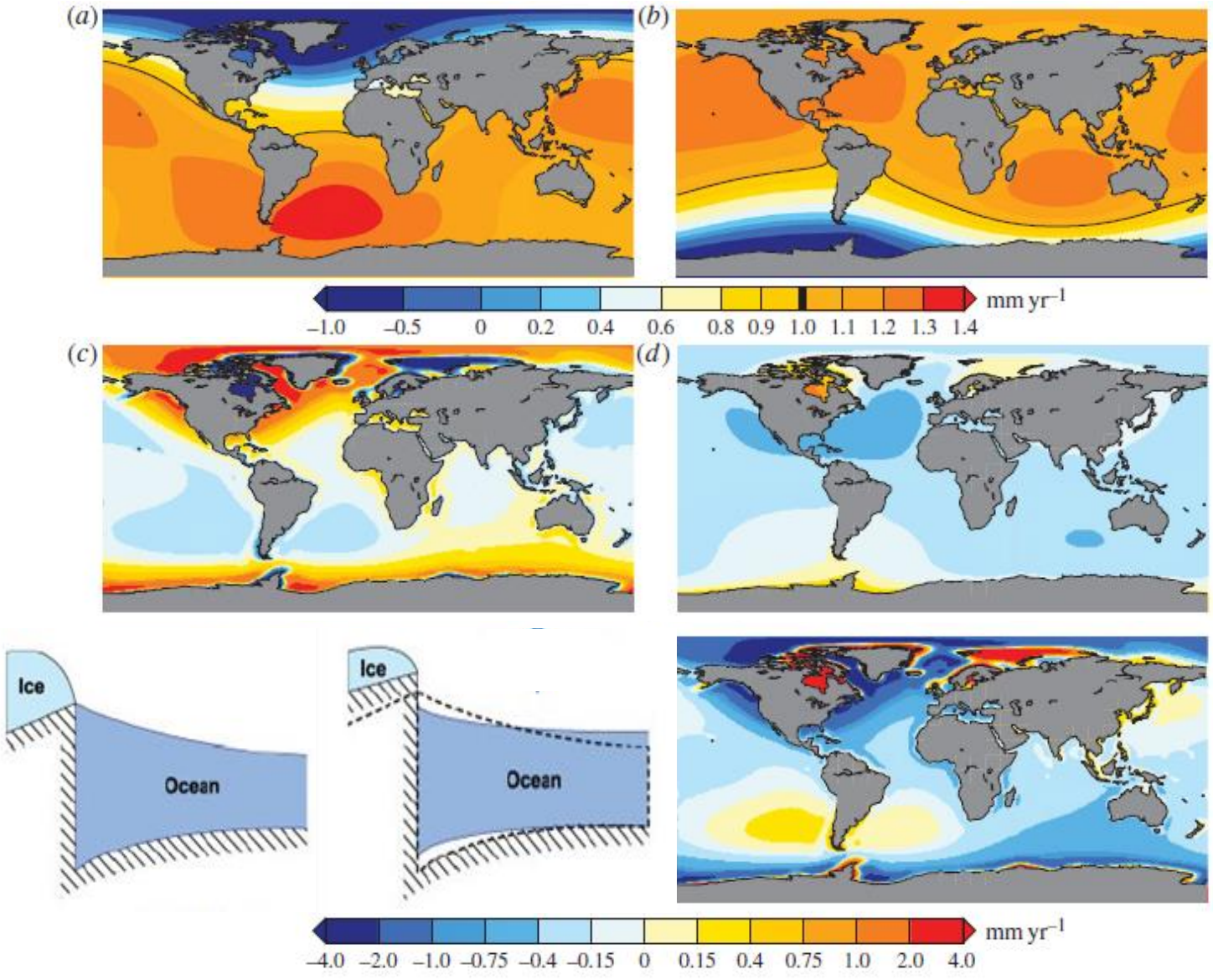
Acoustic & radar

1679 — 1831 — 1960 — 1985 — 1992

Relative Sea Level

Geocentric sea level

3. Evidence for fingerprints of land-ice melting ?



Tamisiea *et al.* (2014)

4. Searching for fingerprints…

- Station selection criteria:
  - → Tide gauge records > 50yr from 1900
    - → 70% of valid data
  - → Regional grouping based on correlation coefficients

Main repository of TG data:

PSMSL 1933 2013

www.psmsl.org

4. Searching for fingerprints…

- Station selection criteria:
  - → Tide gauge records > 50yr from 1900
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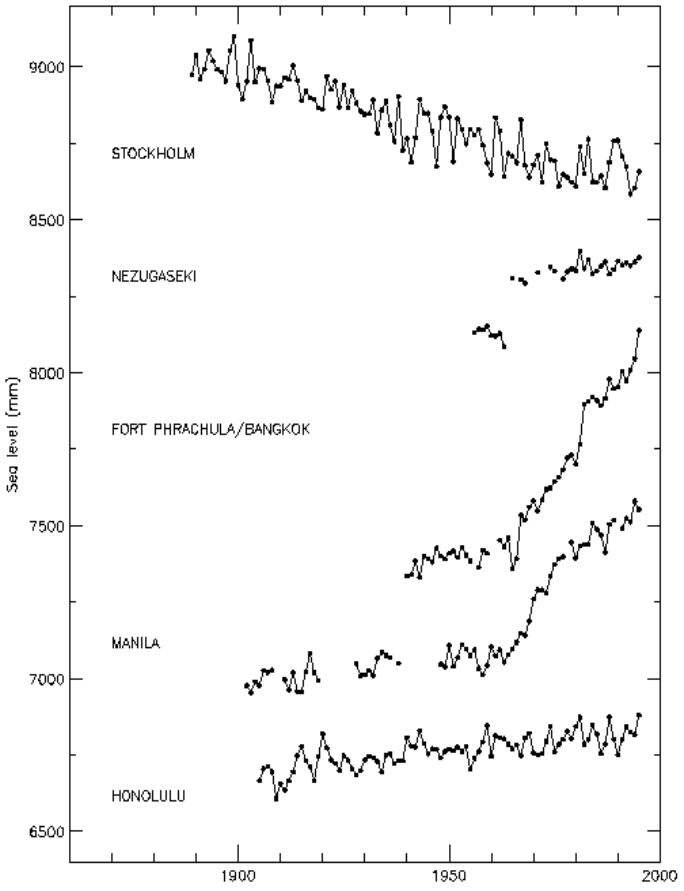
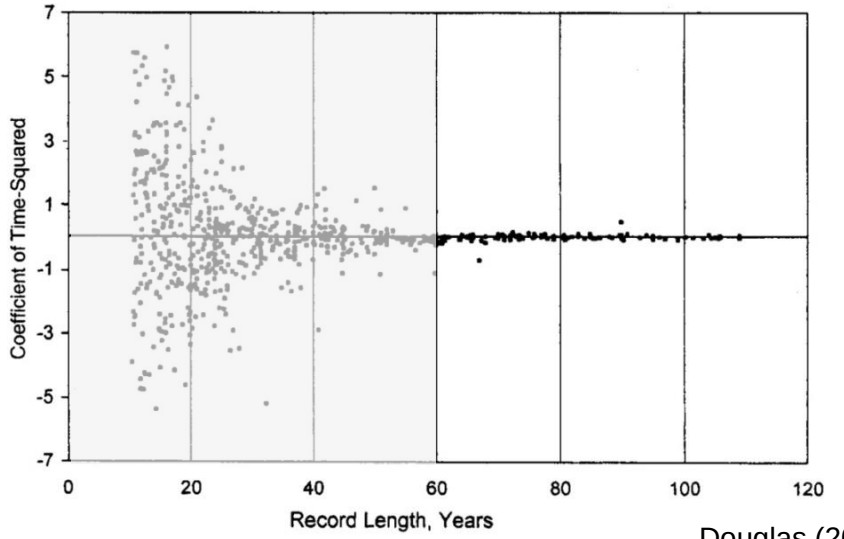
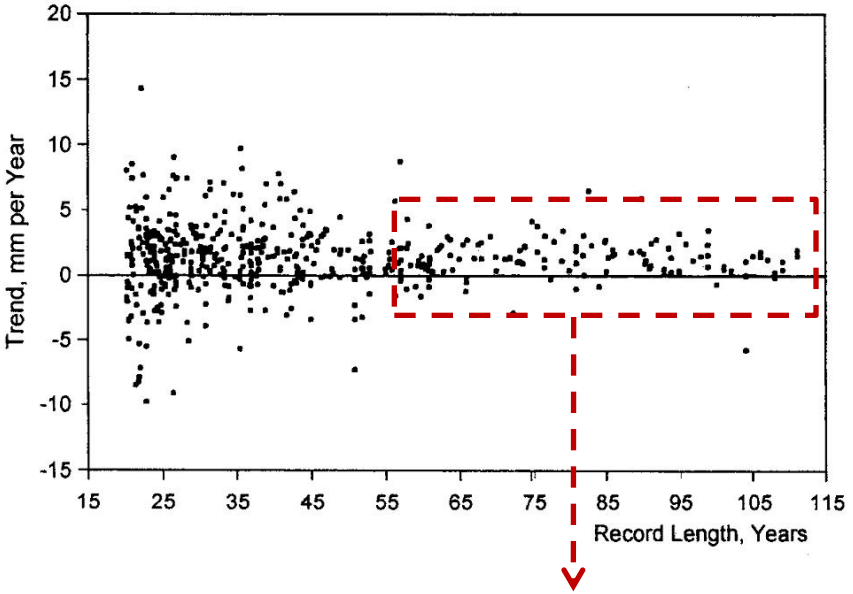


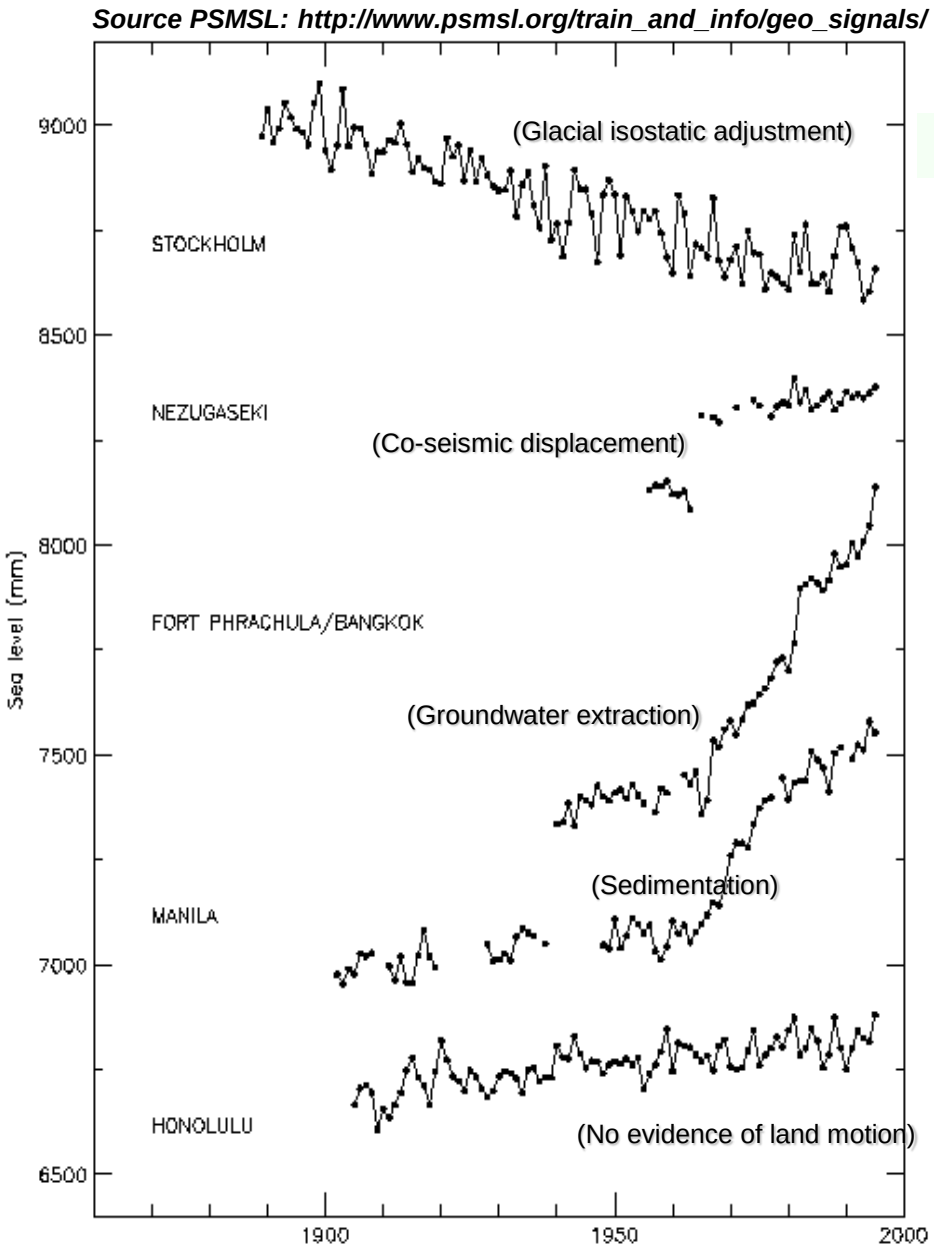


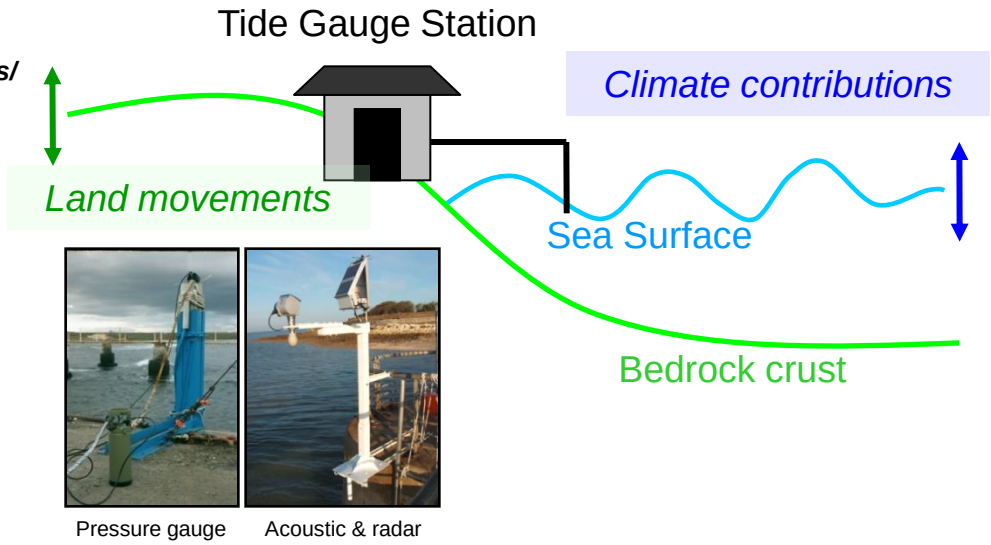
Douglas (2001)



Local land motion are the most likely source of this spatial variability

4. Vertical land motion





- **Determination**
  - → Modeling: Only Glacial Isostatic Adjustment
    - ↳ Uncertainties (viscosity profiles, lithosphere thickness, ice retreat)
    - ↳ Other processes?
  - → Monitoring: Space Geodesy
- **Challenges**
  - → Rates of sea-level change: **~2 mm/yr**
  - → Standard errors: one order of magnitude less to be useful in long term sea level studies!

4. Measure (if one can): The GPS solution

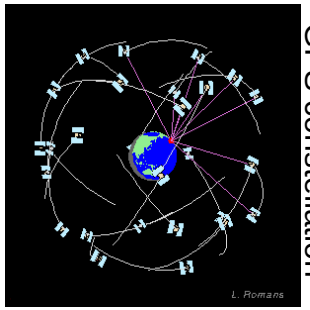
Satellite Laser Ranging (SLR)

VLBI

DORIS

Absolute Gravimetry

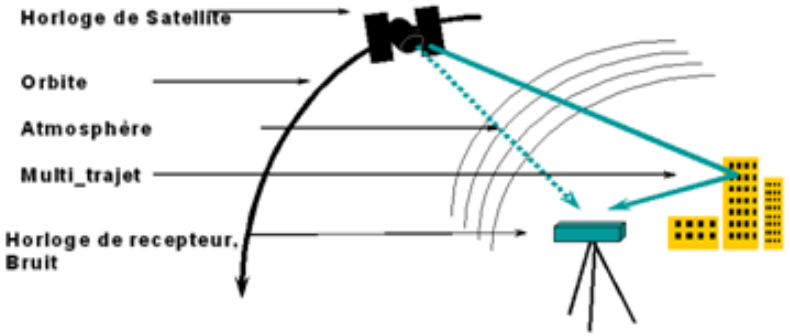
- Review of Geodetic Techniques Carter *et al.* (1989; 1993)
- Campaign *versus* Continuous GPS
- Regional *versus* Global GPS Processing
- International infrastructure (IGS)
- Cumulative GPS processing *versus* Homogenous GPS reprocessing



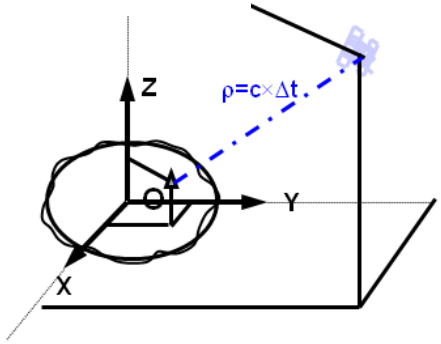
GPS constellation

Campaign mode

Continuous mode



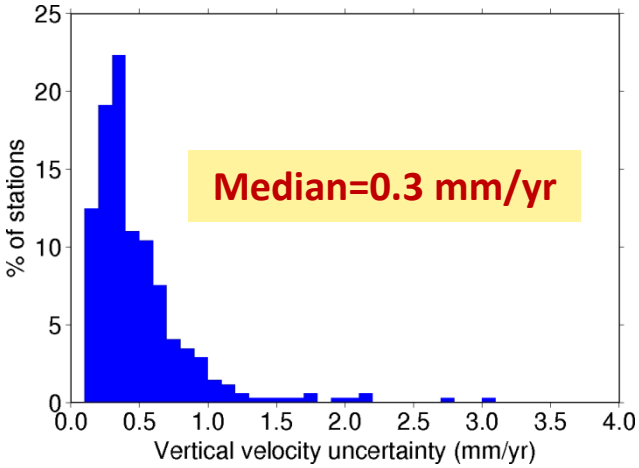
Time computation reduced from 1 year processing 10 years of data (300 stations) to 3 weeks

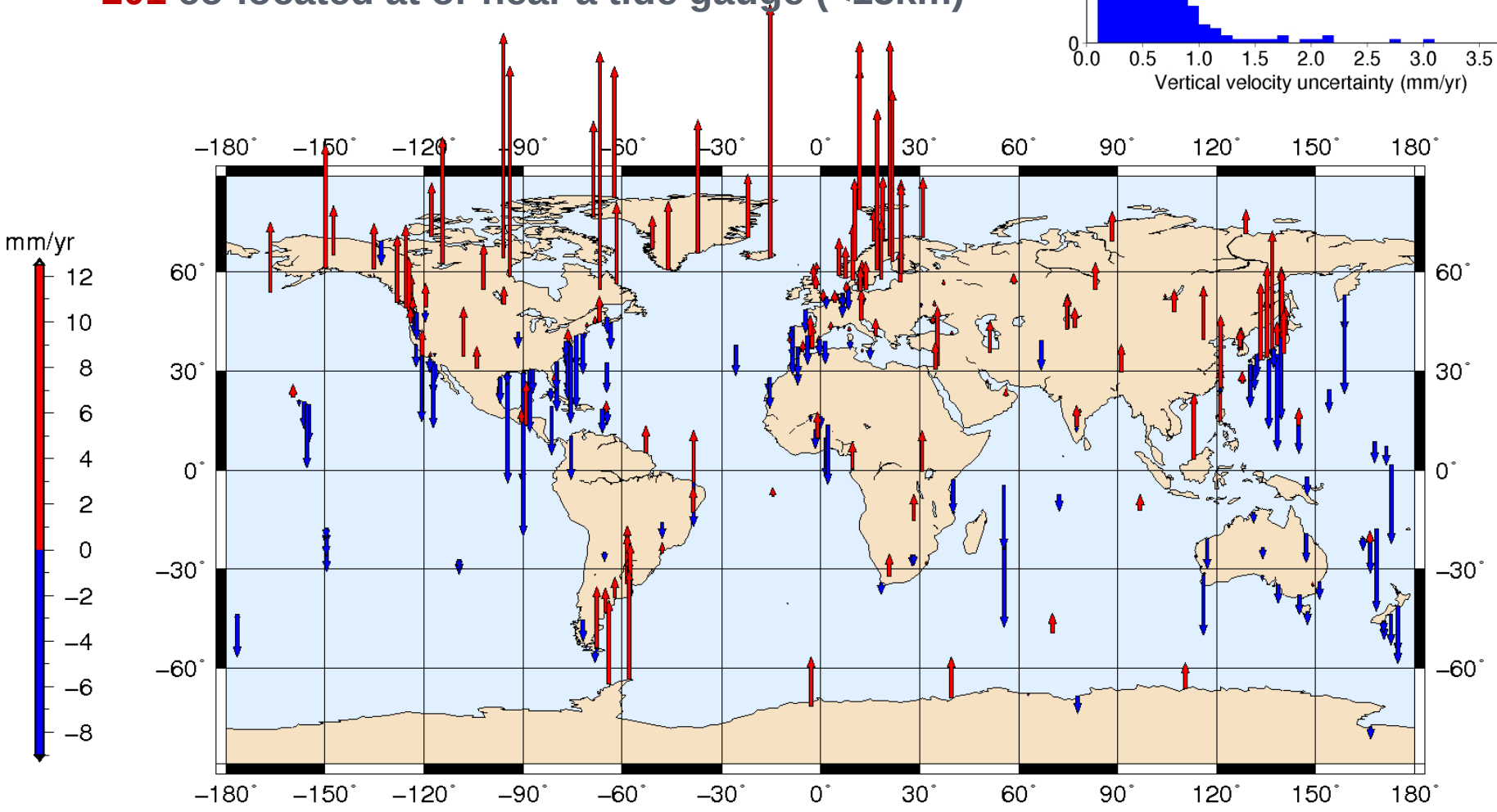


4. GPS vertical velocities from the ULR consortium

Solution available at www.sonel.org

- Calculation of uncertainties on velocities taking into account time-correlated noise
- **326 GPS velocities in the ITRF2008, from which 201 co-located at or near a tide gauge (<15km)**



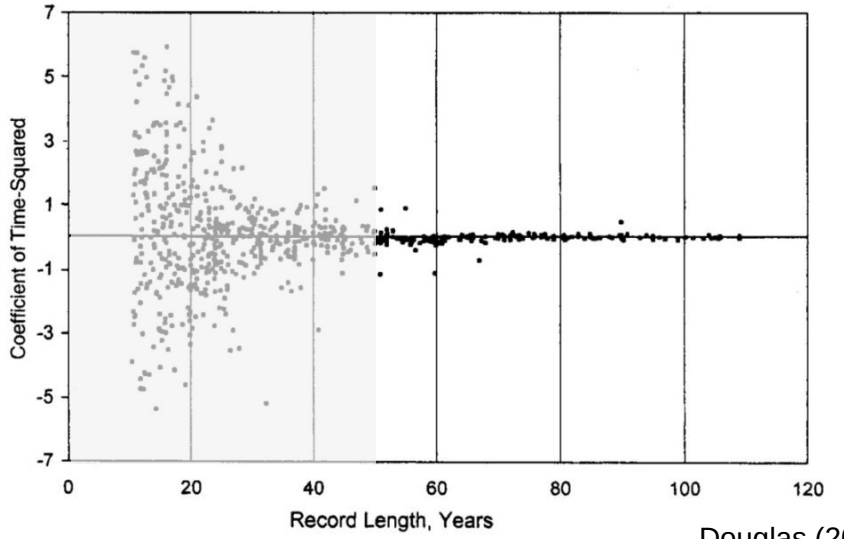


4. Searching for fingerprints - Data and methods

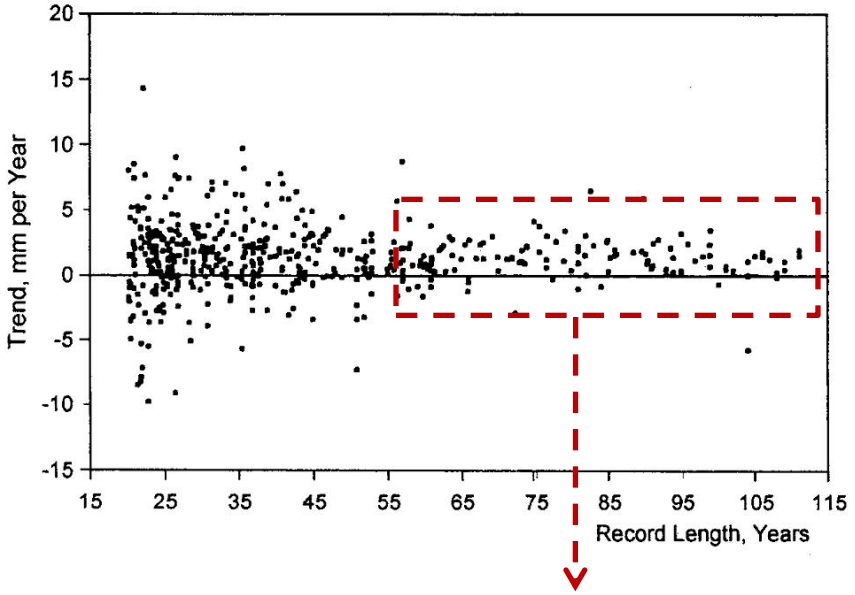
- Station selection criteria:
  - → Tide gauge records > 50yr from 1900
    - → 70% of valid data
  - → Regional grouping based on correlation coefficients
  - → Nearest robust GPS velocity estimate
    - → Same land (Islands)
    - → GIA gradient of TG-GPS stations < 0.4 mm/yr
    - → Active tectonic areas : co-location or redundant GPS data

76 records

grouped into 17 regions
following Jevrejeva *el al.* (2006)
for regional reconstructions

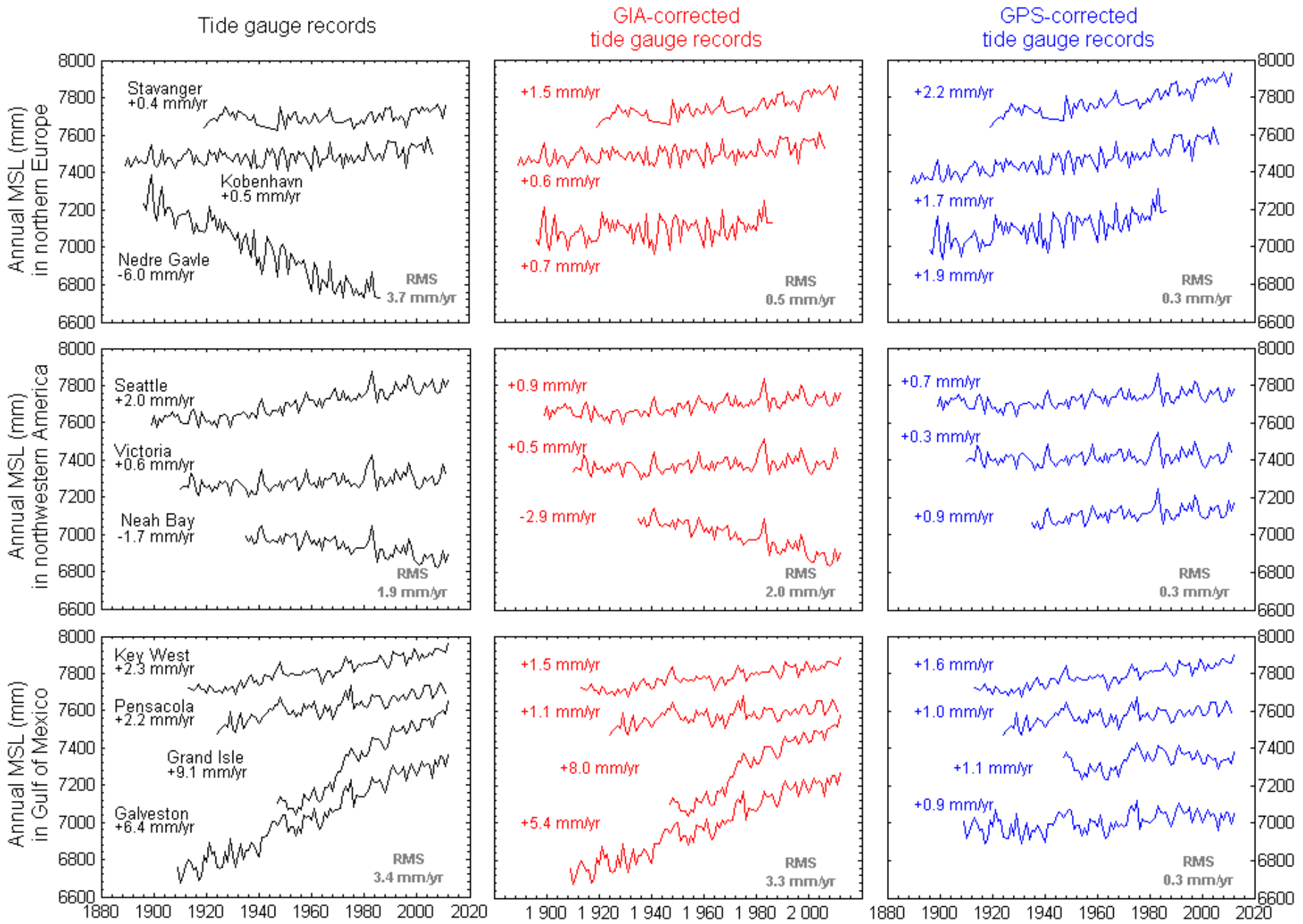


Douglas (2001)



Local land motion are the most
likely source of this spatial variability

4. GPS velocities at TG... How well do they work?



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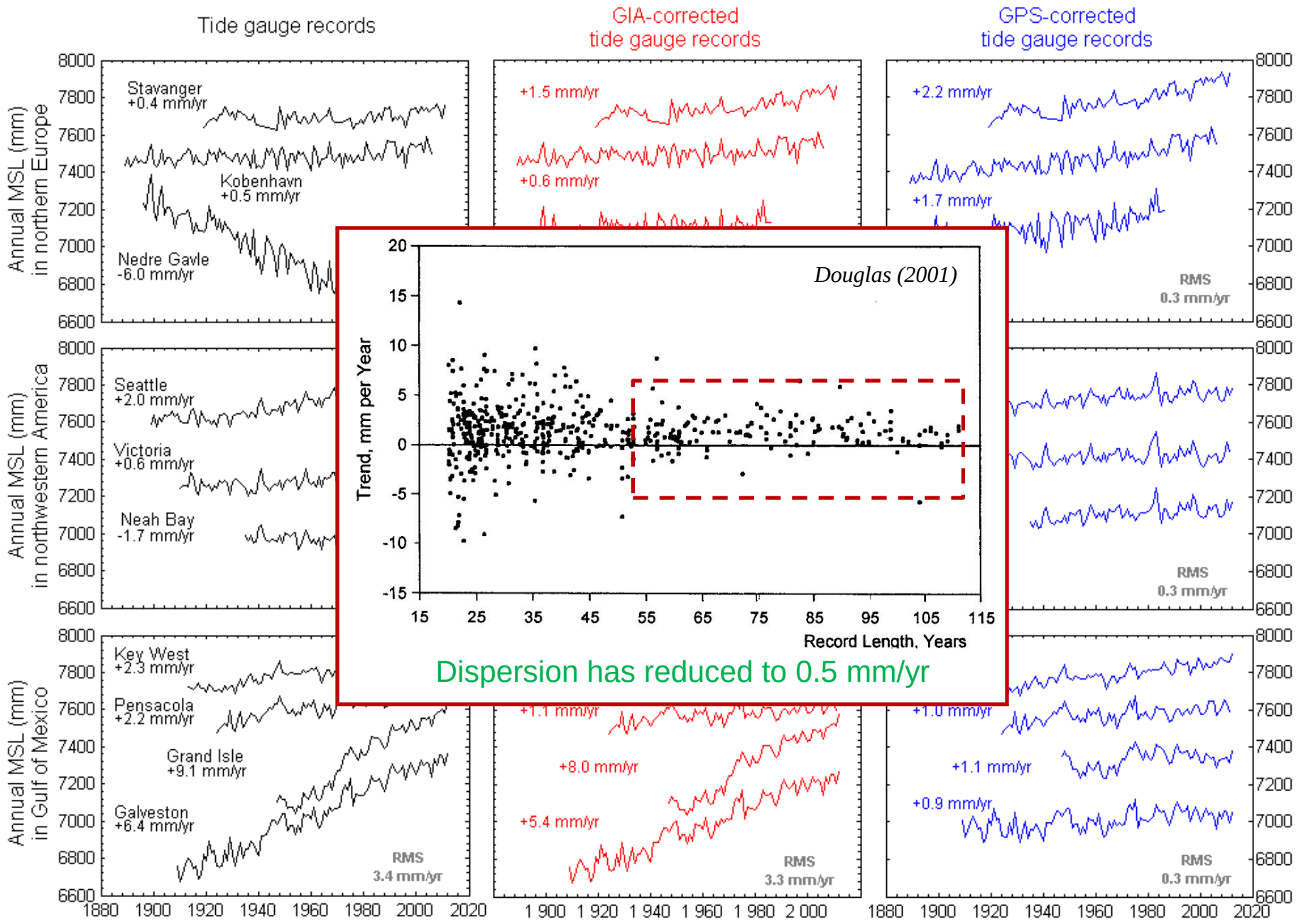
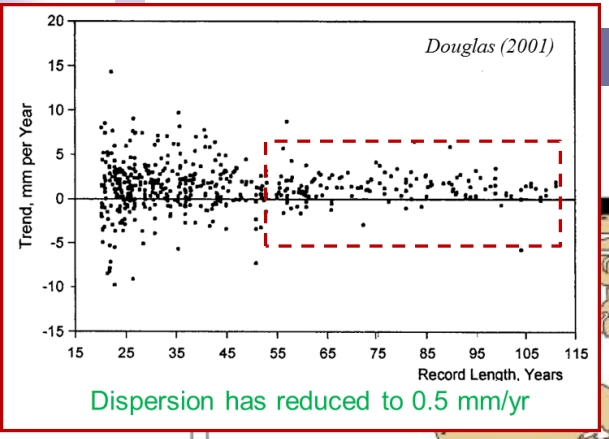
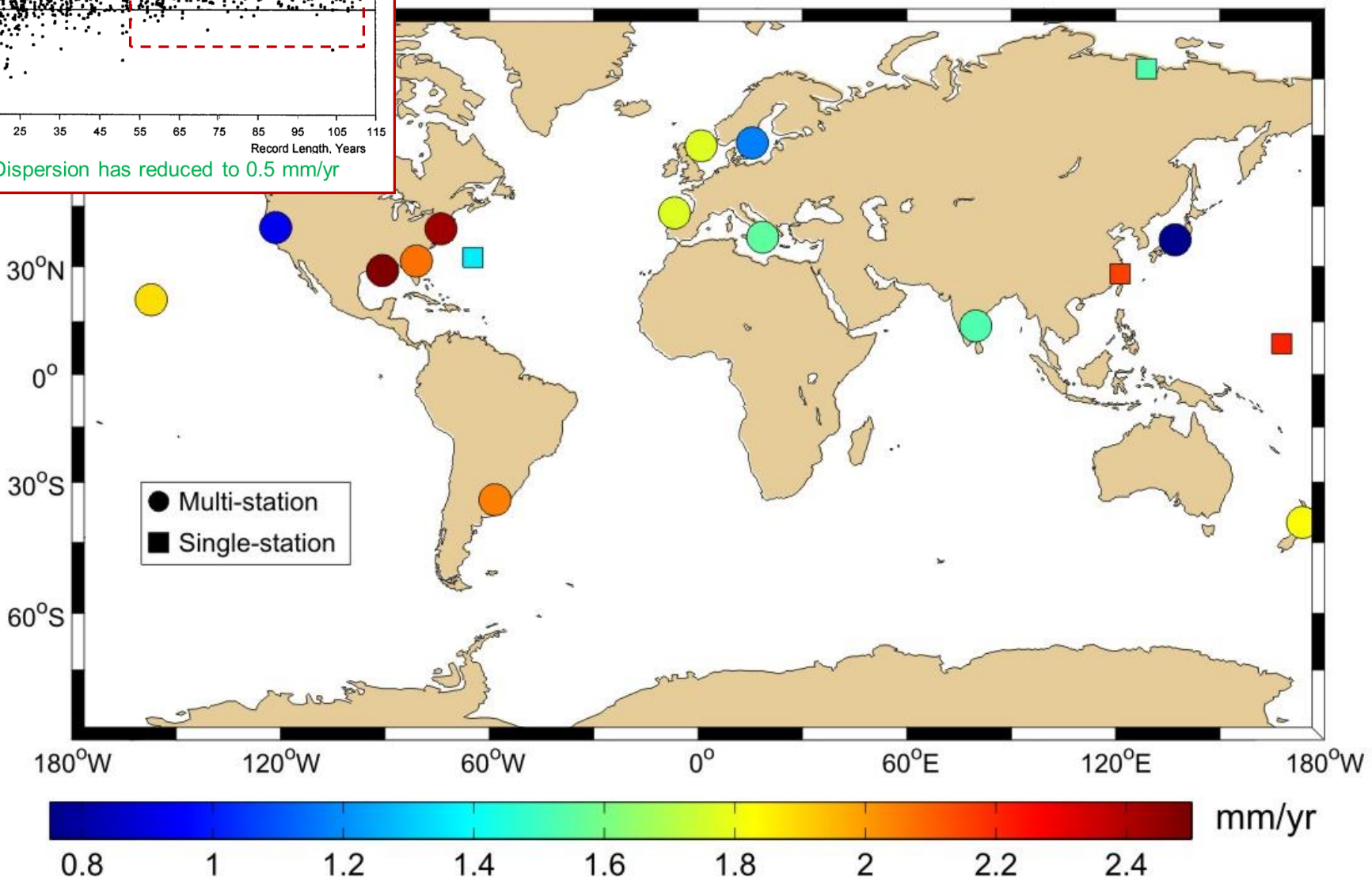


4. Spatial Patterns of Sea Level Change



Dispersion has reduced to 0.5 mm/yr



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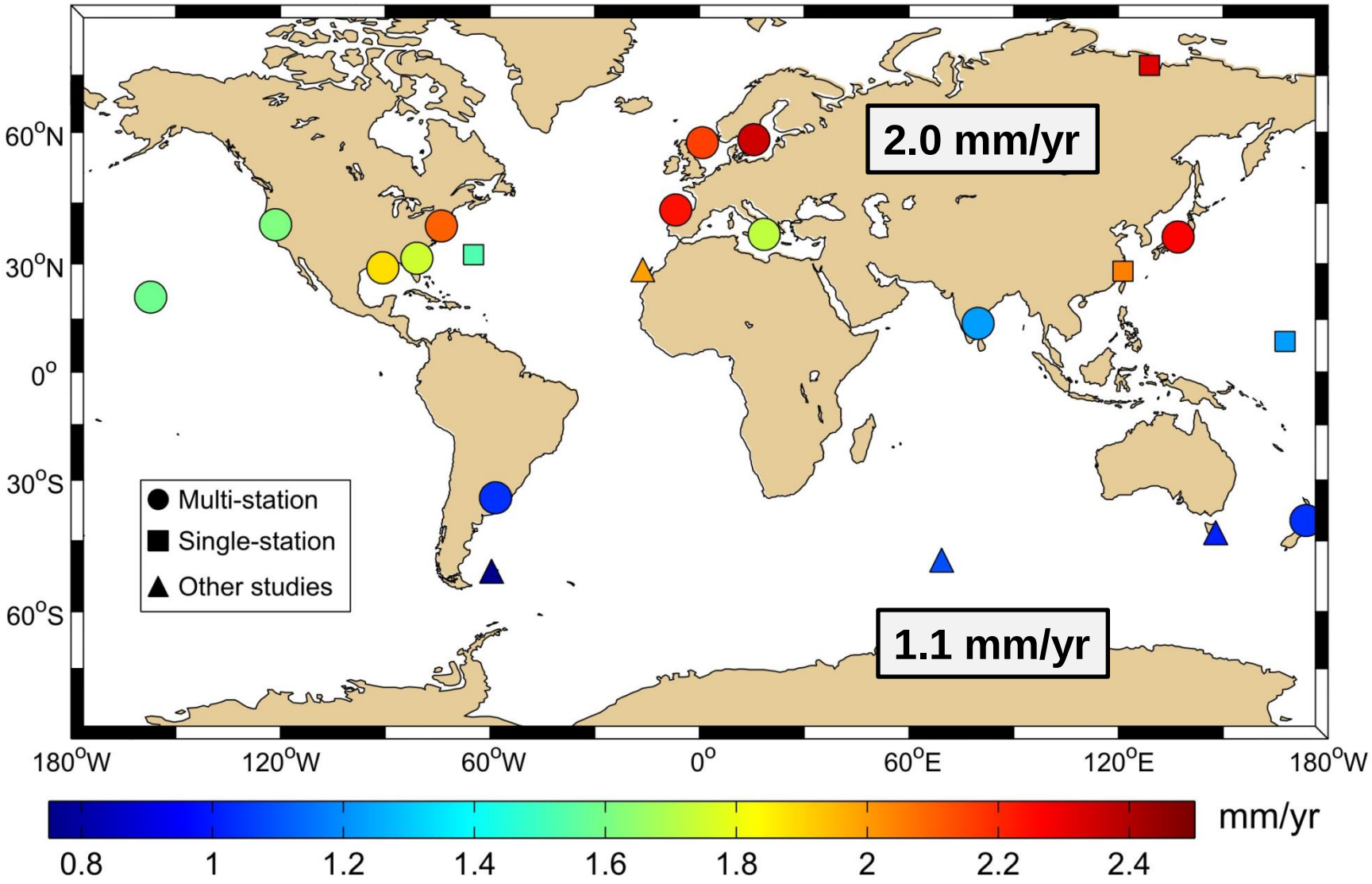
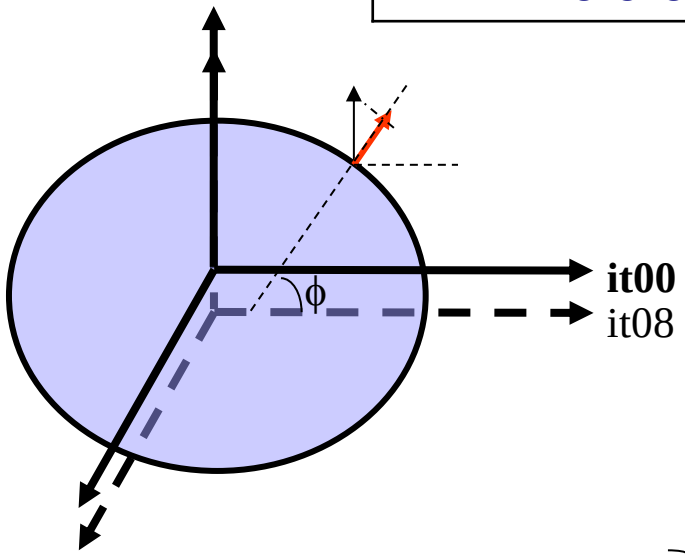


5. Causes?

Reference frame origin?	X



- Impact on the vertical velocities

$$\Delta v_{i,j}^{up}(\Delta\dot{d}, \Delta\dot{\mathbf{T}}) = \Delta\dot{d} + \mathbf{G}(\lambda_{ij}, \phi_{ij}) \cdot \Delta\dot{\mathbf{T}}$$

$$\mathbf{G}(\lambda_{ij}, \phi_{ij}) = [\cos(\phi_{ij})\cos(\lambda_{ij}) \quad \cos(\phi_{ij})\sin(\lambda_{ij}) \quad \sin(\phi_{ij})]$$

- Impact on the GSL change

$$\Delta\frac{\mathrm{d}S}{\mathrm{d}t}(\Delta\dot{\mathbf{T}}, \Delta\dot{d}) = \Delta\dot{d} + \left[\frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{n_i} p_{i,j}\mathbf{G}(\lambda_{ij}, \phi_{ij})\right] \cdot \Delta\dot{\mathbf{T}}$$

(Collilieux & Wöppelmann, 2011)

using: $\Delta Tz \cong 0.5$ mm/yr
$\Delta d \cong 0.3$ mm/yr
Collilieux *et al.* (2014)

ULR5 → **~ 0.5 mm/yr**

Tide gauge distribution?	X
Fingerprints of land ice melting?	X
Thermo-steric effect? (Ocean temperature)	X

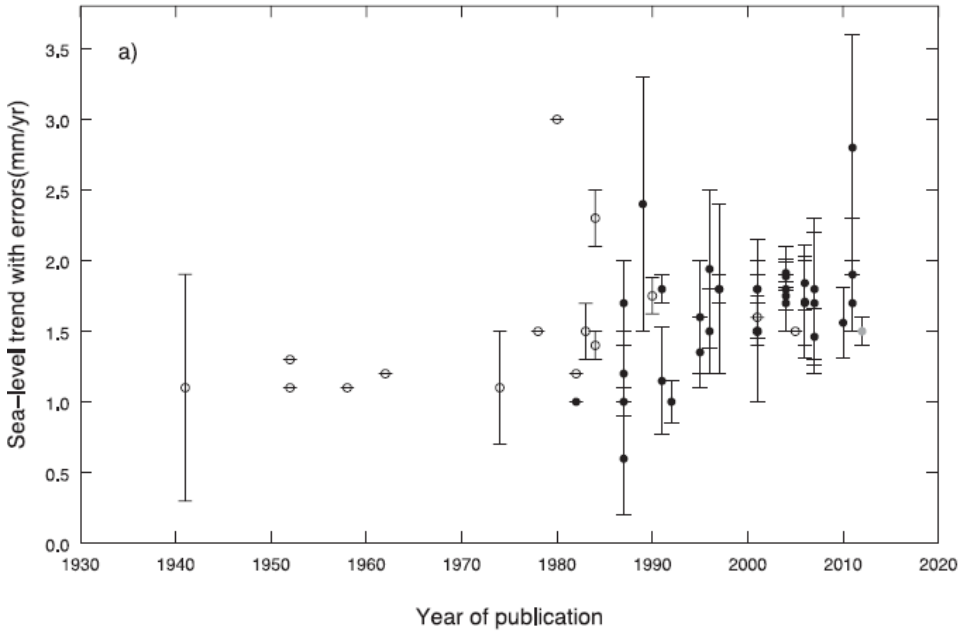
ANY OTHER IDEAS OR SUGGESTIONS?

5. Reconcile past estimates (a recent review)

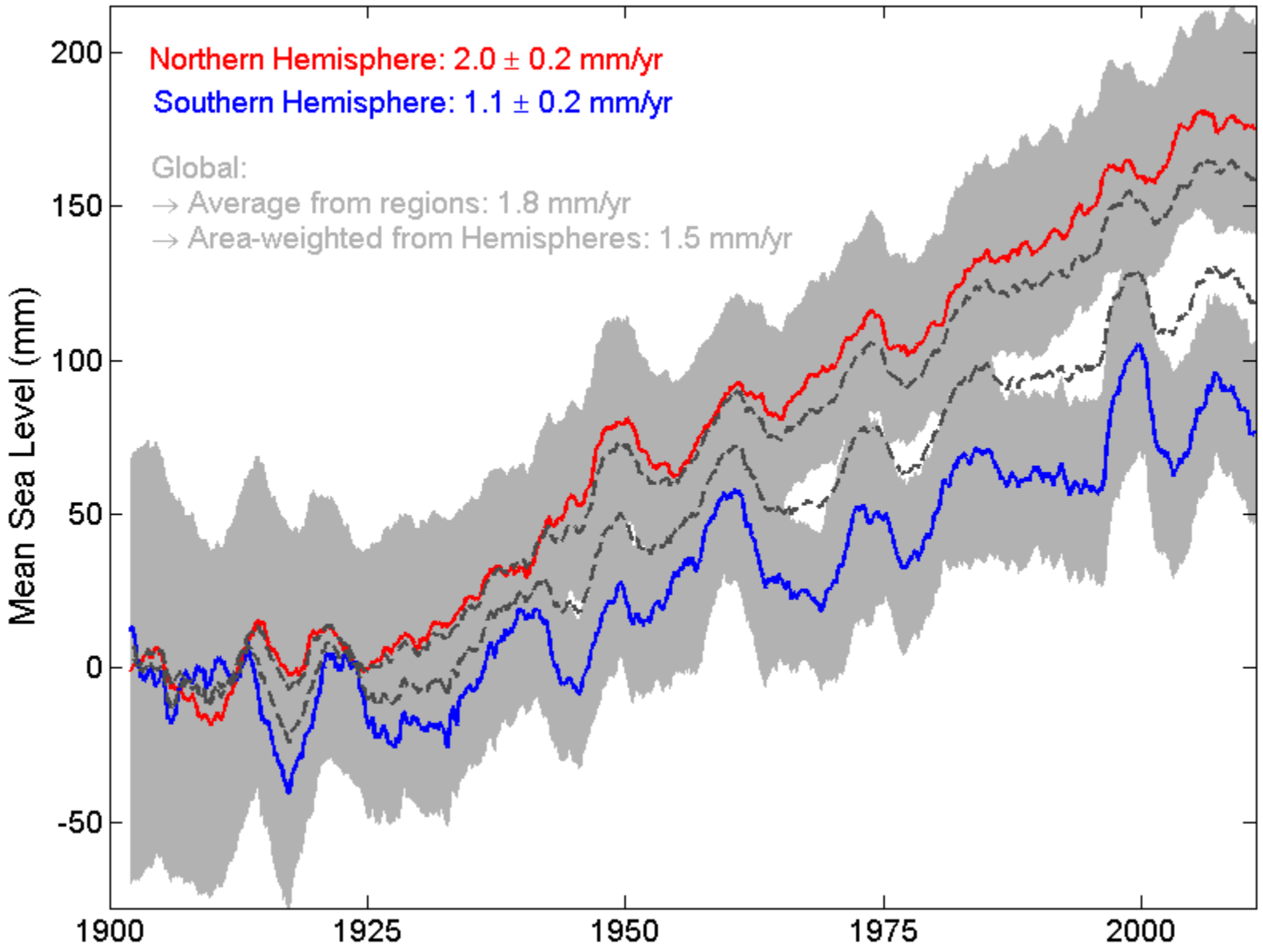
Spada & Galassi (2012)

Table 1. Previous GMSLR estimates (data are displayed in Fig. 1). See Pirazzoli (1993), Gröger & Plag (1993), Gornitz (1995) and Douglas (2001) for similar summary tables.

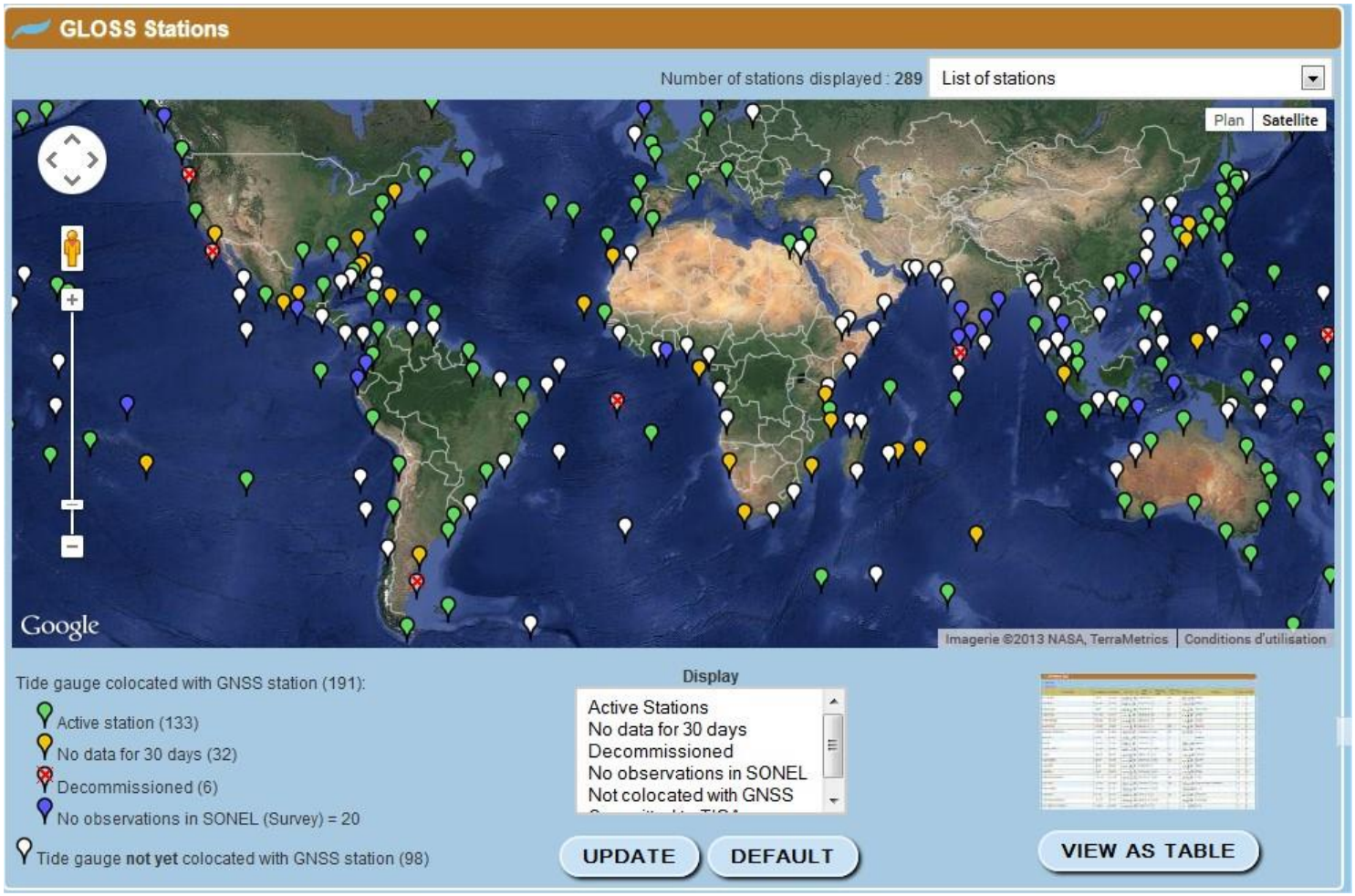
Year and author(s)	μ^a (mm yr^{-1})	Period[b]	Method(s)[c]	GIA correction[d]
1941 Gutenberg	1.1 ± 0.8	1807–1937	RA	No
1952 Polli	1.1	1871–1940	RA	No
1952 Cailleux	1.3	1885–1951	SA	No
1954 Valentin	1.1	1807–1947	—	No
1958 Lisitzin	1.1	1807–1943	—	No
1962 Fairbridge & Krebs	1.2	1900–1950	SA	No
1974 Lisitzin	1.1 ± 0.4	20th century	SA	No
1978 Kalinin & Klige	1.5	1860–1960	SA	No
1980 Emery	3	1850–1978	SA	No
1982 Gornitz *et al.*	1.2	1880–1980	RA	No
" "	1.0	1880–1980	RA	Geological
1983 Barnett	1.5 ± 0.2*	1903–1969	EOF	No
1984 Barnett[a]	1.4 ± 0.1†	1881–1980	EOF, RA	No
" "	2.3 ± 0.2†	1930–1980	EOF, RA	No
1987 Gornitz & Lebedeff[1]	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 Stewart	Indeterminable	20th century	—	—
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
1995 Unal & Ghil	1.6 ± 0.4*	1807–1990	RA	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.*	1.0 – 2.0	20th century	APE	Various models
2001 Peltier	1.84 ± 0.35†	1880–1980	RA	ICE–4G(VM2)
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	1948–2002	RA	ICE–4G
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 Bindoff *et al.*	1.8 ± 0.5	1961–2003	APE	Various models
" "	1.7 ± 0.5	20th century	APE	Various models
2007 Hagedoorn *et al.*	1.46 ± 0.20†	20th century	RA	ICE–3G
2010 Wenzel & Schröter	1.56 ± 0.25	1900–2006	NN	ICE–5G(VM4)
2011 Church & White	1.7 ± 0.2	1900–2009	EOF	As in Church *et al.* (2004)
" "	1.9 ± 0.4	1961–2009	EOF	" "

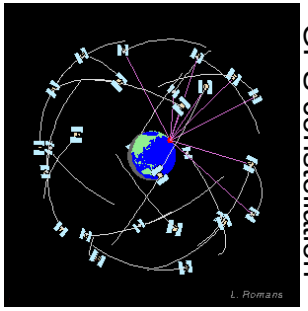


5. Hemispheric Sea Level Change

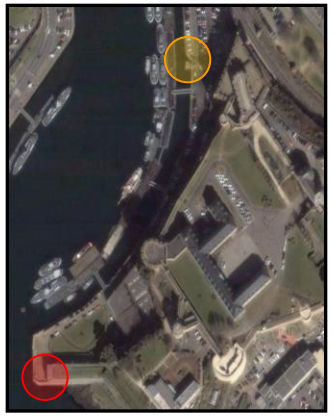


5. GPS Limitations: Data access & Assumptions





GPS constellation



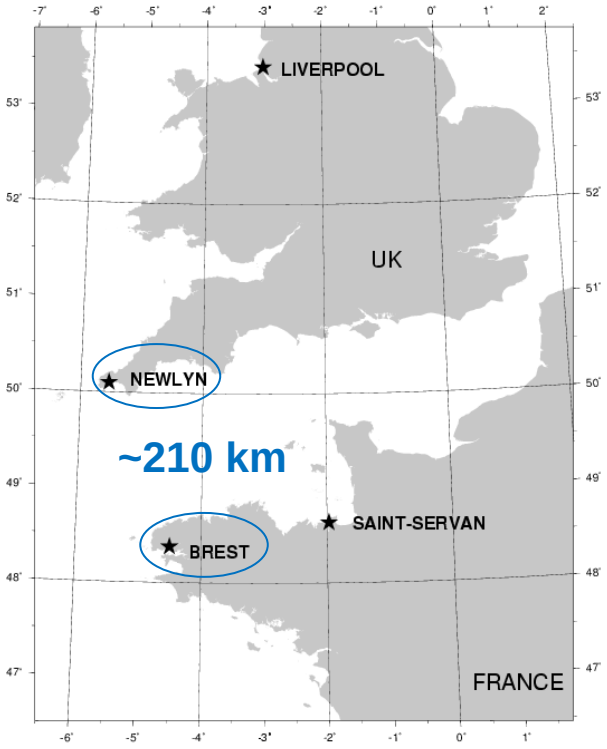
GLOSS dedicated GPS@TG Data Assembly Centre (www.sonel.org)

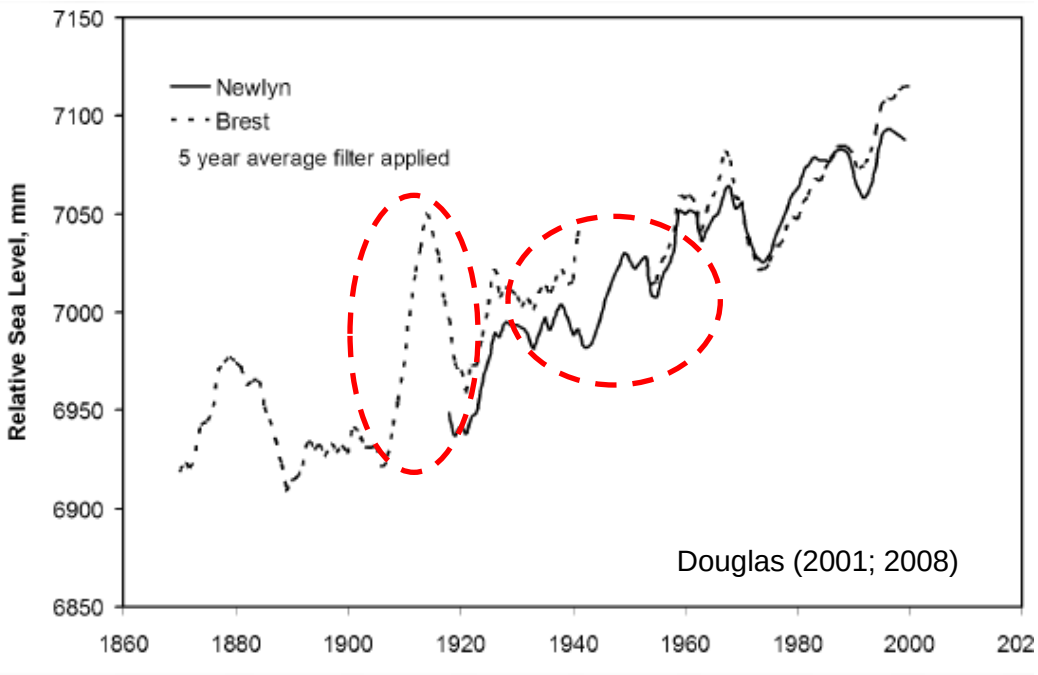
SONEL

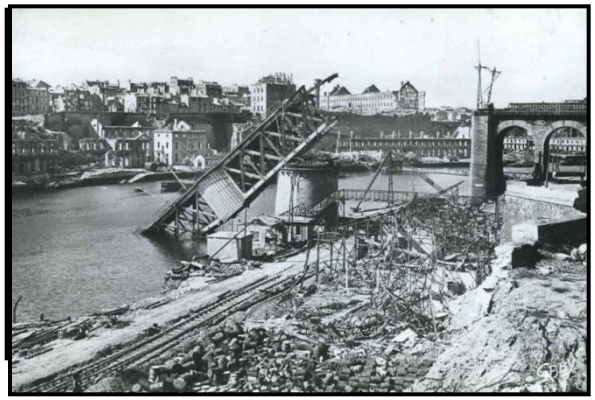
GLOSS

- Working hypotheses
  1. GPS antenna vertical movement ↔ Tide gauge land movement
  2. Land movements are linear over the tide gauge records length

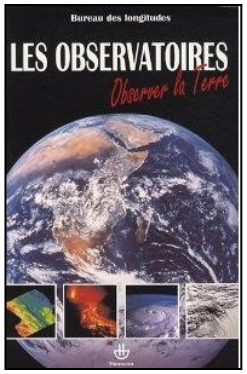
5. De l'importance d'observer…



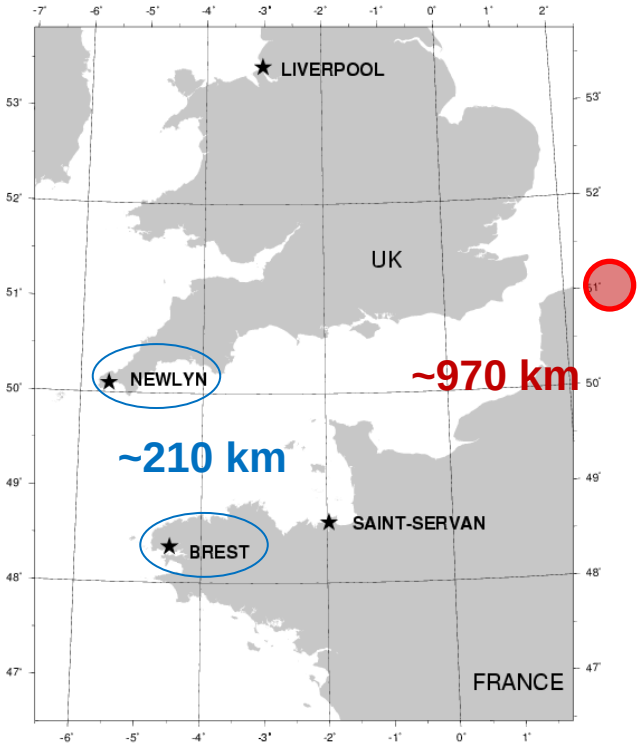


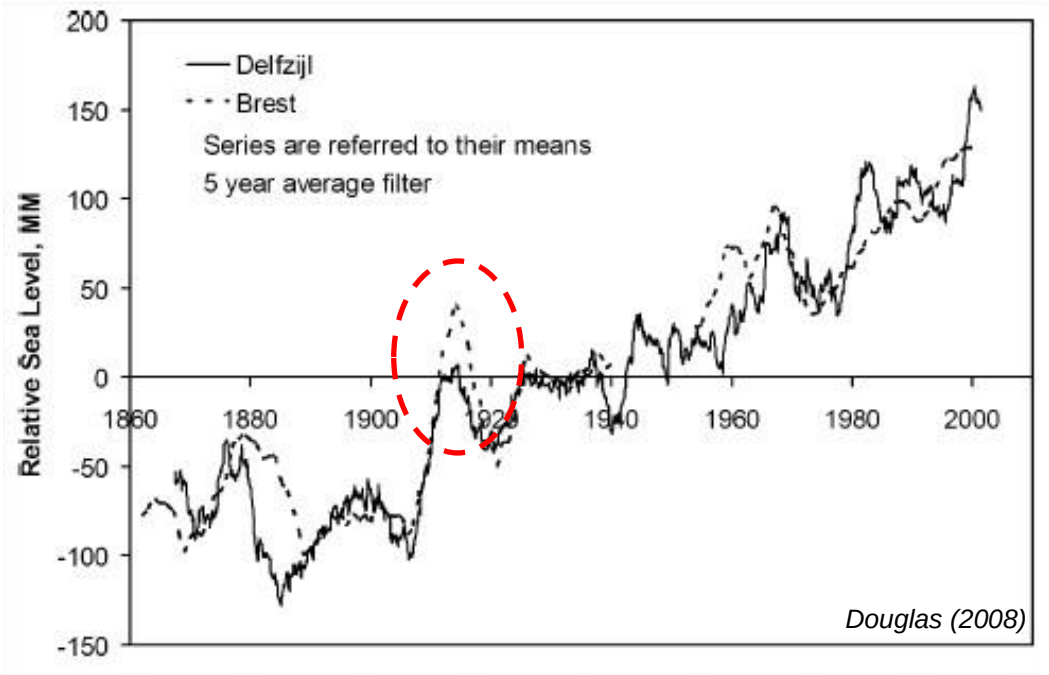


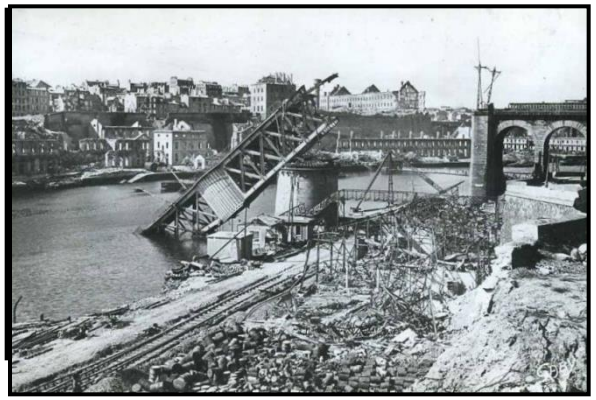
- ✓ Origine des écarts ? Processus physique ou question métrologique ?
- ✓ Erreur systématique ou anomalie ?
- ✓ Principaux attributs de l'observation :
  - ↳ Pérennité, Continuité, Accès, Qualité
    - ↳ des financements…



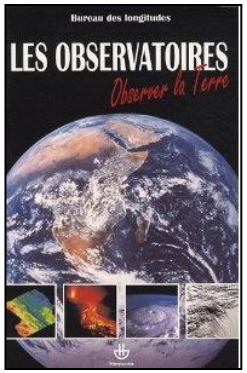
5. De l'importance d'observer…





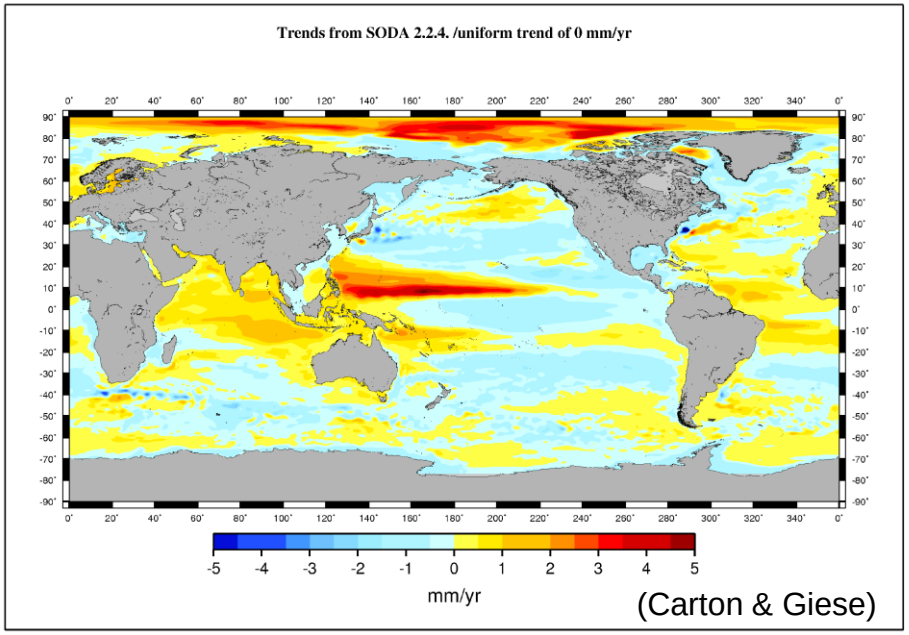


- ✓ Origine des écarts ? Processus physique ou question métrologique ?
- ✓ Erreur systématique ou anomalie ?
- ✓ Principaux attributs de l'observation :
  - ↳ Pérennité, Continuité, Accès, Qualité
    - ↳ des financements…



5. Other suspect: Tide gauge distribution

SODA ocean climate model (CMIP5)
1871-2008 Assimilation Run



(Carton & Giese)