Lecture course on
Sea level variations and global geodynamics

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

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Charles University in Prague, Department of Geophysics
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Il livello marino sta cambiando?

Giorgio Spada e Gaia Galassi

*DiSBeF - Urbino University*

Seminari INGV BO - 19 Oct 2011 +
seminari Charles University PRAGA Nov. 2011
Contents:

1). Motivations, previous work, relevance

2). Data: RLR tide gauge (TG) observations since 1880

3). Obtaining sea level trends from TG time series

4). Corrections in general and GIA corrections

5). Some new estimates of the secular sea level rise

6). Outlook
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5). Some new estimates of the secular sea level rise

6). Outlook
Observations from submerged coral reefs
Average rate $\sim 100 \text{ m /10,000 yr} \sim 1 \text{ cm/yr}$

Observations from submerged coral reefs
(*) From geomorphology, geology, archaeology...
Average rate ~ 4 m / 7000yr ~ 0.5 mm/yr

(*) From geomorphology, geology, archaeology...
Average rate $\sim 4 \text{ m} / 7000\text{yr} \sim 0.5 \text{ mm/yr}$

(*) From geomorphology, geology, archaeology...
Recent Sea Level Rise

23 Annual Tide Gauge Records
- Three Year Average
- Satellite Altimetry

From direct observations: TIDE GAUGES
Average rate ~ 20 m/100 yr ~ 2 mm/yr

From direct observations: TIDE GAUGES
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.
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.
Identifying the causes of sea-level change
Glenn A. Milne, W. Roland Gehrels, Chris W. Hughes and Mark E. Tamisiea, NATURE GEOSCI 2009

Possible causes

1. Thermal expansion
   - Ocean ATMOSMOSPHERE interaction
   - Terrestrial water storage
   - Vertical land motion
   - Ocean circulation
   - Density changes

2. Current ice melting
   - Greenland
   - Antarctica

“steric contribution”

“mass contribution”
Causes of “secular” 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)
GIA: signals from the past - NOT related to current climate change
How and what do we observe?

* a few words about tide gauges
Tide gauge types

Radar gauges

High-frequency sampling of the ocean surface (relative to the solid Earth)

Courtesy of Philip L. Woodworth - PSMSL
OTT Kalesto Radar Gauge
High-frequency sampling of the ocean surface (relative to the solid Earth)
Liverpool, February 3, 2009

Tide gauge types

Sea level relative to land

Tide pole / Tide staff
Classical stilling well float gauge from the US east coast high tidal range area
The SRD Digital Tide Monitor is an acoustic above-water, temperature-corrected tide monitoring system, which is a 53 kHz 'in air' echo-sounder measuring the distance from the transducer to the water surface. Any temperature-dependent variation of the speed of sound is taken into account by the use of a reference target, providing auto-calibration.

**The system-displayed resolution is 10 mm. System accuracy is 1 per cent.**

Tidal variation of up to 10 m can be monitored.
Another means of measuring water level variations is a "bubbler" gauge (pneumatic tide gauge).

A flow of nitrogen or compressed air into a tube with one end in the water is adjusted continuously by a mechanism so that it releases bubbles at a constant rate.

*When the water level rises, the pressure must be increased to maintain the flow of bubbles.*

The pressure variations are thus a measure of water level. A small tank of gas can operate this system for many months.
Tide gauge types

Bubbler and Radar gauge

Courtesy of Philip L. Woodworth - PSMSL
Satellite altimetry

Radar altimeters on board the satellite permanently transmit signals at high frequency (over 1700 pulses per second) to Earth, and receive the echo from the sea surface. This is analyzed to derive a precise measurement of the round-trip time between the satellite and the sea surface. The time measurement, scaled by the speed of light yields a range measurement. By averaging the estimates over a second, this produces a very accurate measurement of the satellite-to-ocean range.

Sea Level rise between 1993 and 2010 by satellite ALTIMETRY

Sea level is rising (by altimetry)
“viewpoint of space”

Recent Sea Level Rise

23 Annual Tide Gauge Records
- Three Year Average
- Satellite Altimetry

"A tide staff"

Rate is ~ 20 cm/century
Previous work on sea level rise from tide gauges
### Previous estimates of global sea level rise

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<th>Year and Author(s)</th>
<th>( \mu^a ) (mm/yr)</th>
<th>Period(^b)</th>
<th>Method(s)(^c)</th>
<th>GIA correction (^d)</th>
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<td>1993–2009</td>
<td>EOF</td>
<td>-???-</td>
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</table>

\(^a\) When made explicit by the Authors, a star (*) denotes sdom, a dag (†) rms. 

\(^b\) Global data are used, unless otherwise stated (En=Europe, USE=United States East coast). 

\(^c\) RA=Regional Average, SA=Simple average from individual TGs, EOF=Empirical Orthogonal Function, SHA=Spherical Harmonics Analysis, APE=Average of Previous Estimates. 

\(^d\) If one is applied, the model is indicated. Geological corrections are based on Holocene RSL curves.

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**Seminario INGV - BO 19.10.2011** Livello Marino
Previous estimates of global sea level rise from TG observations

Seminario INGV - BO  19.10.2011                                                                    Livello marino

Friday, November 11, 2011
Previous estimates of global sea level rise
Contents:

1). Motivations, previous work, relevance

2). Data: RLR tide gauge (TG) observations since 1880

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Welcome to the Permanent Service for Mean Sea Level (PSMSL)

PSMSL is the global data bank for long term sea level change information from tide gauges and bottom pressure recorders.

About Us:
Learn about PSMSL, contact us, read news items and annual reports

Data:
Obtain and submit tide gauge and bottom pressure data

Products:
Browse the data set via GoogleEarth or obtain derived products, view regional commentaries and author archives

Training & Information:
A wide variety of FAQs, training and software documentation, information on non-oceanographic signals in tide gauge records (e.g., glacial isostatic adjustment, atmospheric pressure, etc.)

Links:
Links to other networks and programs, as well as international sea level contacts

http://www.psmsl.org/
✓ In order to construct time series of sea level measurements at each station, the monthly and annual means have to be *reduced to a common datum*.

✓ This reduction is performed by the PSMSL making use of the tide gauge datum history provided by the supplying authority.

✓ To date, approximately **two thirds of the stations** in the PSMSL database have had their data adjusted in this way, forming the 'REVISED LOCAL REFERENCE' (or 'RLR') dataset.

✓ In general, **only RLR data should be used for time series analysis**.

✓ Without the provision of full benchmark datum history information, records generally remain as 'Metric only' in the databank and not as 'RLR'. **In general, 'Metric' records should NEVER be used** for time series analysis or for the computation of secular trends.

http://www.psmsl.org/data/obtaining/rlr.php
Tide gauge signals  

http://www.pol.ac.uk/psml/psml_individual_stations.html

We now give a look into the PSMSL directories...

The individual stations file is:

http://www.pol.ac.uk/psml/psml_individual_stations.html

This is actually a link to ALL the information available for the PSMSL stations.

We now browse this archive to get basic information...
PSMSL Monthly and Annual Mean Sea Level Station Files

The following list of PSMSL stations is in PSMSL country/station code order, essentially west to east around the world coastline, starting in the N.E. Asia and Greenland, with the Antarctic following subsequently.

Column 1/2 = PSMSL Country/Station Code. Click on this to get a small map showing station location

Column 3 = Rm. Click on this to obtain RLR monthly data for this station (if an RLR station)
Column 4 = Pm. Click on this to obtain a plot of the RLR monthly data (if an RLR station)
Column 5 = Mm. Click on this to obtain Metric monthly data for this station
Column 6 = Ra. Click on this to obtain RLR annual data for this station (if an RLR station)
Column 7 = Pa. Click on this to obtain a plot of the RLR annual data (if an RLR station)

Column 8 = Docu. Click on this to obtain brief station documentation
Column 9 = GLOSS Code. Click to obtain GLOSS Handbook documentation for this station

Column 10 = Dg. Click on this for an RLR diagram chart (if available)
Column 11 = Authority Code (data supplier). Click on this for the authority's address

Column 12/13 = Latitude/Longitude
Column 14 = Station Name

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~ 1100 sites
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<td>280/056</td>
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<tr>
<td>Column 1/2</td>
<td>PSMSL Country/Station Code. Small map showing station location</td>
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<td></td>
</tr>
<tr>
<td>Column 3</td>
<td><strong>Rm.</strong> Click on this to obtain RLR monthly data for this station <em>(if an RLR station)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 4</td>
<td><strong>Pm.</strong> Click on this to obtain a plot of the RLR monthly data <em>(if an RLR station)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 5</td>
<td><strong>Mm.</strong> Click on this to obtain Metric monthly data for this station</td>
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<td></td>
</tr>
<tr>
<td>Column 6</td>
<td><strong>Ra.</strong> Click on this to obtain <strong>RLR annual data</strong> for this station <em>(if an RLR station)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 7</td>
<td><strong>Pa.</strong> Click on this to obtain a plot of the RLR annual data (if an RLR station)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 8</td>
<td><strong>Docu.</strong> Click on this to obtain brief station documentation</td>
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<td></td>
</tr>
<tr>
<td>Column 9</td>
<td><strong>GLOSS Code.</strong> Click to obtain GLOSS Handbook documentation for this station</td>
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<tr>
<td>Column 10</td>
<td><strong>Dg.</strong> Click on this for an RLR diagram chart (if available)</td>
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</tr>
<tr>
<td>Column 11</td>
<td><strong>Authority Code (data supplier).</strong> Click on this for the authority's address</td>
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</tr>
<tr>
<td>Column 12/13</td>
<td>Latitude/Longitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 14</td>
<td>Station Name</td>
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<td></td>
</tr>
</tbody>
</table>

**E.g., TRIESTE, ITA:**

```
270/061   Rm   Pm   Mm   Ra   Pa   Docu   Dg  23   45  39  N  13  45  E  TRIESTE
1/2       3    4    5    6    7    8    9    10   12/13   14
```
PSMSL country/station code = 270/061
GLOSS code (if a GLOSS station) =
Location = 45 39 N 13 45 E

Number of years of data = 97
Spanning 1905 to 2007

Station Comments:
DATA 1927-1936, VALUES BASED ON READINGS OF HIGH & LOW WATERS

Analysis of Trieste data indicates September 1958 larger than expected, compared to neighbouring stations; June-July 1961 smaller; December 1954 to February 1955 smaller; and May-June 1955 larger. These values have been checked to be correct as received from authority.

Trieste 270/061 RLR(1964) is 9.4m below BM

Some information on Trieste provided by Fabio Raicich (CNR, Trieste) in September 2000:

The tide gauge site has always been the same as today, except that before 1926 the station was 10-20 m away from present location, but still on the same pier, namely 'Molo Sartorio'. The present position is 45 deg 38' 50.5" N, 13 deg 45' 30.5" E.

Gauges used have included:
1859-1884: Schaub ; 1884-1911: Strudhoff ;
1911-June 1961 and January 1962-1984: Seibt-Fuess ;
June 1961-December 1961: Pagan (a local manufacturer) ;
1966-present: Buesum-Ott ; 1985-present: Pagan ;

but only float gauges have been used throughout since the very beginning.

Data from Trieste from 1875-1904 which precede the data in the PSMSL data bank but which are probably of lower accuracy than later data can be found in the paper by Fabio Raicich, Journal of Coastal Research, 23, 1067-1073, 2007.
### RLR monthly

<table>
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<th>Year</th>
<th>Rm (mm)</th>
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</tr>
<tr>
<td>1905.125</td>
<td>6726</td>
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<td>1905.542</td>
<td>6922</td>
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<tr>
<td>1905.625</td>
<td>6986</td>
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...  
...  
...  
...  
2006.708 | 7126 |
2006.792 | 7163 |
2006.875 | 7081 |
2006.958 | 6939 |
2007.042 | 6994 |
2007.125 | 7061 |
2007.208 | 7061 |
2007.292 | 6965 |
2007.375 | 7109 |
2007.458 | 7124 |
2007.542 | 7068 |
2007.625 | 7056 |
2007.708 | 7042 |
2007.792 | 7055 |
2007.875 | 7057 |
2007.958 | 6956 |

### RLR annual

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<td>6923</td>
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<td>1907</td>
<td>6871</td>
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<td>1908</td>
<td>6893</td>
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<td>1909</td>
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<td>1910</td>
<td>7009</td>
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<td>1911</td>
<td>6908</td>
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<td>1912</td>
<td>6927</td>
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<td>1914</td>
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<tr>
<td>1919</td>
<td>6961</td>
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<tr>
<td>1920</td>
<td>6957</td>
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...  
...  
2006.708 | 7126 |
2006.792 | 7163 |
2006.875 | 7081 |
2006.958 | 6939 |
2007.042 | 6994 |
2007.125 | 7061 |
2007.208 | 7061 |
2007.292 | 6965 |
2007.375 | 7109 |
2007.458 | 7124 |
2007.542 | 7068 |
2007.625 | 7056 |
2007.708 | 7042 |
2007.792 | 7055 |
2007.875 | 7057 |
2007.958 | 6956 |
Distribution of PSMSL stations as of 22 Jan 07

- All PSMSL stations: N = 1123
- More than 30 years of data: N = 460
- More than 60 years of data: N = 139
- More than 90 years of data: N = 46
Contents:

1). Motivations, previous work, relevance

2). Data: RLR tide gauge (TG) observations since 1880

3). Obtaining sea level trends from TG time series

4). Corrections in general and GIA corrections

5). Some new estimates of the secular sea level rise

6). Outlook
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

Seminario INGV - BO 19.10.2011
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 to eliminate also records from sites in the area of the peripheral bulge immediately adjacent to formerly deeply ice covered regions.

(D91) Douglas (1991, JGR) “Global Sea Level rise”
(a) ALL sites, $N_{tg} = 1213$

(b) D97 sites, $N_{tg} = 23$

ALL (1123)

D97 (23)
The 23 D97 PSMSL time series

12. Honolulu
11. Wellington II
10. Dunedin II
9. Auckland II
8. Trieste
7. Genova
6. Marseille
5. Santa Cruz de Tenerife I
4. Lagos
3. Cascais
2. Brest
1. Newlyn

12. Wellington II
11. Dunedin II
10. Auckland II
9. Genova
8. Marseille
7. Santa Cruz de Tenerife I
6. Lagos
5. Cascais
4. Brest
3. Newlyn

23. Fernandina
22. Key West
21. Pensacola
20. Buenos Aires
19. Quenken
18. Cristobal
17. Balboa
16. San Diego (Quarantine St.)
15. La Jolla (Scripps Pier)
14. Santa Monica (Municipal Pier)
13. San Francisco
Stacking of global sea level rise time series

Thanks to Marco Olivieri for advice

(a) D97 sites, $N_{tg}=23$

(b) ALL sites, $N_{tg}=1213$

Sea level minus average (mm)

Number of operating TGs

Number of operating TGs /100

Sea level minus average (mm)

Number of operating TGs

Number of operating TGs /100

year

Friday, November 11, 2011
Nature of the (annual) TG record

San Francisco

sea level (mm)

year

"reg-10.dat" using 1:2
"reg-10.dat" using 1:3
Nature of the (annual) TG record

Stockholm

"reg-78.dat" using 1:2
"reg-78.dat" using 1:3

sea level (mm)

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

_Figure 1. Decade oscillations in the TG series._

_Douglas, 1991 JGR_
Nature of the (annual) TG record

Epoch (year)

1. Newlyn
2. Brest
3. Cascais
4. Lagos
5. Santa Cruz

sea level (mm)
Obtaining a trend from the TG record

A simple “pencil and ruler” approach (Sturges & Hong 2001)

“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)
- \( \sigma_k \) is the uncertainty on the trend (95% confidence), obtained using the Student t distribution

So, the tide gauge rate (with uncertainty) is:

\[ \rho_k = r_k \pm \sigma_k \]
Obtaining a trend from the TG record

Statistics of the RLR PSMSL TG trends

Number of TGs per bin

Computed best fit rate

Uncertainties on individual rates

Number of valid yearly records

Friday, November 11, 2011
### Comparing “our” computed trends with D97

<table>
<thead>
<tr>
<th>Region</th>
<th>Tide gauge site</th>
<th>Period span, year–year</th>
<th>span(_k) years</th>
<th>(N^v_k) years</th>
<th>(r^a_k) (D97) mm/yr</th>
<th>(\rho_k = r_k \pm \sigma_k) mm/yr</th>
<th>(r^{gia}_{k}) mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>English Channel</td>
<td>1. Newlyn*</td>
<td>1916–2009</td>
<td>94</td>
<td>93</td>
<td>1.7</td>
<td>1.8 ± 0.1</td>
<td>+0.2</td>
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<tr>
<td></td>
<td>2. Brest*</td>
<td>1880–2009</td>
<td>130</td>
<td>121</td>
<td>1.4</td>
<td>1.4 ± 0.1</td>
<td>+0.2</td>
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<tr>
<td>Atlantic</td>
<td>3. Cascais*</td>
<td>1882–1993</td>
<td>112</td>
<td>101</td>
<td>1.3</td>
<td>1.3 ± 0.1</td>
<td>−0.2</td>
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<tr>
<td></td>
<td>4. Lagos*</td>
<td>1909–1987</td>
<td>79</td>
<td>69</td>
<td>1.5</td>
<td>1.4 ± 0.2</td>
<td>−0.2</td>
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<td></td>
<td>5. S. C. Tenerife I*</td>
<td>1927–1989</td>
<td>63</td>
<td>56</td>
<td>1.5</td>
<td>1.6 ± 0.2</td>
<td>−0.0</td>
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<td>Mediterranean</td>
<td>6. Marseille*</td>
<td>1885–2009</td>
<td>125</td>
<td>119</td>
<td>1.2</td>
<td>1.2 ± 0.1</td>
<td>−0.1</td>
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<td>Sea</td>
<td>7. Genova*</td>
<td>1884–1996</td>
<td>113</td>
<td>85</td>
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<td>1.2 ± 0.1</td>
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<td>8. Trieste*</td>
<td>1905–2010</td>
<td>106</td>
<td>100</td>
<td>1.2</td>
<td>1.3 ± 0.1</td>
<td>−0.2</td>
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<tr>
<td>New Zealand</td>
<td>9. Auckland II*</td>
<td>1904–1998</td>
<td>95</td>
<td>92</td>
<td>1.3</td>
<td>1.3 ± 0.1</td>
<td>−0.4</td>
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<td>10. Dunedin II*</td>
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<td>110</td>
<td>64</td>
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<td>1.2 ± 0.1</td>
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<td>11. Wellington II*</td>
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<td>2.0 ± 0.3</td>
<td>−0.5</td>
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<tr>
<td>Pacific</td>
<td>12. Honolulu*</td>
<td>1905–2009</td>
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<td>105</td>
<td>1.5</td>
<td>1.5 ± 0.1</td>
<td>−0.2</td>
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<tr>
<td>North American</td>
<td>13. San Francisco</td>
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<td>130</td>
<td>1.5</td>
<td>1.6 ± 0.1</td>
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<tr>
<td>West Coast</td>
<td>14. Santa Monica(b)</td>
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<td>67</td>
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<td>1.4 ± 0.2</td>
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<td>15. La Jolla(c)</td>
<td>1925–2009</td>
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<td>78</td>
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<td>2.1 ± 0.1</td>
<td>−0.3</td>
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<td>16. San Diego(d)</td>
<td>1906–2009</td>
<td>104</td>
<td>101</td>
<td></td>
<td></td>
<td>−0.2</td>
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<td>Central America</td>
<td>17. Balboa*</td>
<td>1908–2003</td>
<td>96</td>
<td>95</td>
<td>1.0</td>
<td>1.4 ± 0.1</td>
<td>−0.2</td>
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<td>18. Cristobal*</td>
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<td>South America</td>
<td>19. Quequen*</td>
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<td>20. Buenos Aires*</td>
<td>1905–1987</td>
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<td>83</td>
<td>1.5</td>
<td>1.6 ± 0.2</td>
<td>−0.5</td>
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<td>South East</td>
<td>21. Pensacola</td>
<td>1924–2009</td>
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<td>84</td>
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<td>2.2 ± 0.2</td>
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<td>North America</td>
<td>22. Key West</td>
<td>1913–2009</td>
<td>97</td>
<td>96</td>
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<td>2.3 ± 0.1</td>
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<td>23. Fernandina</td>
<td>1898–2009</td>
<td>112</td>
<td>91</td>
<td>1.8</td>
<td>2.0 ± 0.1</td>
<td>−0.0</td>
</tr>
</tbody>
</table>

0.1–0.4 mm/yr
Obtaining a “global mean rate of sea level rise”

\[
m = \frac{\sum_k r_k}{N_{tg}}
\]

Arithmetic mean

“best estimate” of the GMSLR

\[
rm_{s} = \sqrt{\frac{\sum_k (r_k - m)^2}{N_{tg} - 1}}
\]

Root mean square

average uncertainty of individual trends

\[
s_{dom} = \frac{rm_{s}}{\sqrt{N_{tg}}}
\]

Standard deviation of the mean

uncertainty of the best estimate \( m \)

\[
w_{rms} = \sqrt{\frac{\sum_k (r_k - m)^2 w_k}{\sum_k w_k}}
\]

Weighted root mean square

uncertainty of the best estimate \( m \)

\[w_k = \frac{1}{\sigma_k^2}\]

Global mean sea level rise:

\[
\mu = m \pm s_{dom}
\]

\( (rsm = ..., wrms = ...) \)

see Taylor
\[ \mu = 1.4 \pm 0.2 \text{ mm/yr} \]
\[ \mu = 1.6 \pm 0.1 \text{ mm/yr} \]
\[ \text{rms} \approx 6 \text{ mm/yr} \]
\[ \text{rms} \approx 0.5 \text{ mm/yr} \]
Decimation of TGs according to the length criterion

The minimum number of valid years increases

The number of TGs decreases

The SDOM increases

The rms does NOT vary

### Results

- **Case (a)**: $N_{\min} = 30$, $N_g = 535$
  - Observed rate $r_k$ (mm/yr)
  - $\mu = 1.0 \pm 0.1$ mm/yr
  - $\text{wrms} = 2.3$ mm/yr
  - $\text{rms} = 3.2$ mm/yr

- **Case (b)**: $N_{\min} = 60$, $N_g = 155$
  - Observed rate $r_k$ (mm/yr)
  - $\mu = 0.4 \pm 0.3$ mm/yr
  - $\text{wrms} = 2.3$ mm/yr
  - $\text{rms} = 3.3$ mm/yr

- **Case (c)**: $N_{\min} = 90$, $N_g = 61$
  - Observed rate $r_k$ (mm/yr)
  - $\mu = 0.1 \pm 0.4$ mm/yr
  - $\text{wrms} = 2.1$ mm/yr
  - $\text{rms} = 3.0$ mm/yr

- **Case (d)**: $N_{\min} = 110$, $N_g = 23$
  - Observed rate $r_k$ (mm/yr)
  - $\mu = 0.2 \pm 0.7$ mm/yr
  - $\text{wrms} = 2.3$ mm/yr
  - $\text{rms} = 3.2$ mm/yr

---

Friday, November 11, 2011
Decimation of TGs according to the length criterion

![Graph showing the relationship between rate (mm/yr) and \( N_{tg} \) with error bars and various lines representing different measures: \( m \pm sdom \), rms, and wrms.](image-url)
Contents:

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(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,

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http://www.pol.ac.uk/psmsl/landmove.html
**Rate of vertical displacement today**

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

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
Northern hemisphere glaciation during the last ice ages. The setup of 3 to 4 km thick ice sheets caused a sea level lowering of about 120 m.
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). Not 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.
A GIA-independent sea-level correction?

ICE-3G

ICE-5G

ANU05

Laurentide ESL (m)

Antarctica ESL (m)

Time before present (ka)

ICE-3G

ICE-5G

ANU05

GIA-independent sea-level correction?
Farrell (1976) has shown that the “original” SLE:

\[ S = N - U \]

can be transformed into:

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

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
- \( (\ldots) = \) ocean average
Summary of relevant equations for GIA modeling

\[ S(\omega, t) = S^{gi} + S^e + S^{hi} \]

**Sea Level Equation**

- **Glacial Isostasy** \( S^{gi} \)
- **Hydro Isostasy** \( S^{hi} \)
- **Eustasy** \( S^e \)

functions of \((\theta, \lambda, t)\)

function of \(t\)
Summary of relevant equations for GIA modeling

\[ S(\omega, t) = S^{gi} + S^e + S^{hi} \]

**Sea Level Equation**

- **Glacial Isostasy** \( S^{gi} \)
- **Hydro Isostasy** \( S^{hi} \)
- **Eustasy** \( S^e \)

\[ S^e(t) = - \frac{m_i(t)}{\rho_w A_o} \]

**Eustatic term**

functions of \((\theta, \lambda, t)\)

function of \(t\)
Summary of relevant equations for GIA modeling

\[ S(\omega, t) = S^{gi} + S^e + S^{hi} \]

**Sea Level Equation**

- **Glacial Isostasy** \( S^{gi} \) functions of \( (\theta, \lambda, t) \)
- **Hydro Isostasy** \( S^{hi} \)
- **Eustasy** \( S^e \) function of \( t \)

\[ S^e(t) = -\frac{m_i(t)}{\rho_w A_o} \]

**Eustatic term**

\[ \overline{S} = S^e \]

**a remarkable property of the ocean averaged sea level**
Summary of relevant equations for GIA modeling

\[ S(\omega, t) = S^{gi} + S^e + S^{hi} \]

- **Sea Level Equation**
  - Glacial Isostasy \( S^{gi} \)
  - Hydro Isostasy \( S^{hi} \)
  - Eustasy \( S^e \)

- **Eustatic term**
  \[ S^e(t) = - \frac{m_i(t)}{\rho_w A_o} \]

- A remarkable property of the ocean averaged sea level
  \[ \overline{S} = S^e \]

- The GIA sea level change is zero on average if there is no mass exchange
  \[ \overline{S} = 0 \]
Present-day GIA rate of sea level change

ICE-3G
120/1/2

ICE-5G
90/0.5/2.7

ANU05
65/0.3/10

• D97 (23)

Rotational FB OFF

Rotational FB ON
Present-day GIA rate of sea level change

ICE-3G
120/1/2

ICE-5G
90/0.5/2.7

ANU05
65/0.3/10

• D97 (23)

Rotational FB OFF
Rotational FB ON
GIA corrections at tide-gauges

$$r'_k = r_k - r^{gia}_k$$

**Corrected trend**

$$r^{gia}_k = \frac{dS}{dt}(\theta_k, \lambda_k, t)$$

**GIA correction definition**

$$\rho'_k = r'_k \pm \sigma_k$$

**Corrected trend with uncertainty, assuming “exact” knowledge of GIA effects**

$$m' = m - \frac{1}{N_{tg}} \sum_{k=1}^{N_{tg}} r^{gia}_k$$

**Corrected GMSLR**

$$m' = m$$

**Ideal case of a uniformly spaced grid of TGs across the oceans**
Decimation of TGs according to the length criterion

GIA correction by ICE-3G

1. $\mu' = 1.7 \pm 0.1 \text{ mm/yr}$  
   D97 (23)

   vs

   $\mu' = 1.8 \pm 0.1 \text{ mm/yr}$  
   (original D97 data)

   a slight sea level deceleration?

2. $\mu' = 1.1 \pm 0.3 \text{ mm/yr}$

   from the 23 longest records (N Europe)

   ASSUMES GIA modeling is precise to the $\sim 0.5 \text{ mm/yr}$ level in de-glaciated areas
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6). Outlook
GIA models developed so far (ICE-3G, ICE-5G, ANU05) provide largely inconsistent predictions at the US coasts tide gauges:

**NA West coast (13-16)**
13. San Francisco
14. Santa Monica
15. La Jolla
16. San Diego

**SE North America (21-23)**
21. Pensacola
22. Key West
23. Fernandina
Table 2. Computed rates of sea–level change for the D97 set, compared with those determined by D97.

The average span of the time series is 95 years (in D97 it was 83 years), while the average number of valid yearly RLR records in each series is 88 years. Note that in D97, uncertainties on the individual trends were not provided. The average completeness of the time series for these TGs (i.e., the average of the ratio $N_v^k / \text{span}_k$) is XXX%. According to our computations, for this set of TGs the GMSLR is $\mu = 1.6 \pm 0.1 \text{ mm/yr}$ ($\text{rms} = \text{wrms} = 0.4 \text{ mm/yr}$). For reference, GIA corrections corresponding to model ICE–3G are shown in the last column. The sixteen TG sites marked by a star also belong to the D97R set (see Section 7).

<table>
<thead>
<tr>
<th>Region</th>
<th>Tide gauge site</th>
<th>Period span</th>
<th>$N_v^k$</th>
<th>$r_k^{(D97a)}$</th>
<th>$\rho_k = r_k \pm \sigma_k$</th>
<th>$r_{gia}^{k}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>year–year</td>
<td>years</td>
<td>mm/yr</td>
<td>mm/yr</td>
<td>mm/yr</td>
</tr>
<tr>
<td>English Channel</td>
<td>1. Newlyn*</td>
<td>1916–2009</td>
<td>94</td>
<td>93</td>
<td>1.7</td>
<td>$1.8 \pm 0.1$ +0.2</td>
</tr>
<tr>
<td></td>
<td>2. Brest*</td>
<td>1880–2009</td>
<td>130</td>
<td>121</td>
<td>1.4</td>
<td>$1.4 \pm 0.1$ +0.2</td>
</tr>
<tr>
<td>Atlantic</td>
<td>3. Cascais*</td>
<td>1882–1993</td>
<td>112</td>
<td>101</td>
<td>1.3</td>
<td>$1.3 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td></td>
<td>4. Lagos*</td>
<td>1909–1987</td>
<td>79</td>
<td>69</td>
<td>1.5</td>
<td>$1.4 \pm 0.2$ −0.2</td>
</tr>
<tr>
<td></td>
<td>5. S. C. Tenerife I*</td>
<td>1927–1989</td>
<td>63</td>
<td>56</td>
<td>1.5</td>
<td>$1.6 \pm 0.2$ −0.0</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>6. Marseille*</td>
<td>1885–2009</td>
<td>125</td>
<td>119</td>
<td>1.2</td>
<td>$1.2 \pm 0.1$ −0.1</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>7. Genova*</td>
<td>1884–1996</td>
<td>113</td>
<td>85</td>
<td>1.2</td>
<td>$1.2 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>8. Trieste*</td>
<td>1905–2010</td>
<td>106</td>
<td>100</td>
<td>1.2</td>
<td>$1.3 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td>New Zealand</td>
<td>9. Auckland II*</td>
<td>1904–1998</td>
<td>95</td>
<td>92</td>
<td>1.3</td>
<td>$1.3 \pm 0.1$ −0.4</td>
</tr>
<tr>
<td></td>
<td>10. Dunedin II*</td>
<td>1900–2009</td>
<td>110</td>
<td>64</td>
<td>1.4</td>
<td>$1.2 \pm 0.1$ −0.4</td>
</tr>
<tr>
<td></td>
<td>11. Wellington II*</td>
<td>1945–2000</td>
<td>56</td>
<td>53</td>
<td>1.7</td>
<td>$2.0 \pm 0.3$ −0.5</td>
</tr>
<tr>
<td>Pacific</td>
<td>12. Honolulu*</td>
<td>1905–2009</td>
<td>105</td>
<td>105</td>
<td>1.5</td>
<td>$1.5 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td>North American</td>
<td>13. San Francisco</td>
<td>1880–2009</td>
<td>130</td>
<td>130</td>
<td>1.5</td>
<td>$1.6 \pm 0.1$ −0.1</td>
</tr>
<tr>
<td>West Coast</td>
<td>14. Santa Monica$^b$</td>
<td>1933–2009</td>
<td>77</td>
<td>67</td>
<td>1.4</td>
<td>$1.4 \pm 0.2$ −0.2</td>
</tr>
<tr>
<td></td>
<td>15. La Jolla$^c$</td>
<td>1925–2009</td>
<td>85</td>
<td>78</td>
<td>2.1</td>
<td>$2.1 \pm 0.1$ −0.3</td>
</tr>
<tr>
<td></td>
<td>16. San Diego$^d$</td>
<td>1906–2009</td>
<td>104</td>
<td>101</td>
<td>2.1</td>
<td>$2.1 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td>Central America</td>
<td>17. Balboa*</td>
<td>1908–2003</td>
<td>96</td>
<td>95</td>
<td>1.6</td>
<td>$1.5 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td></td>
<td>18. Cristobal*</td>
<td>1909–1979</td>
<td>71</td>
<td>71</td>
<td>1.0</td>
<td>$1.4 \pm 0.1$ −0.2</td>
</tr>
<tr>
<td>South America</td>
<td>19. Queuen*</td>
<td>1918–1982</td>
<td>65</td>
<td>64</td>
<td>0.8</td>
<td>$0.9 \pm 0.2$ −0.1</td>
</tr>
<tr>
<td></td>
<td>20. Buenos Aires*</td>
<td>1905–1987</td>
<td>83</td>
<td>83</td>
<td>1.5</td>
<td>$1.6 \pm 0.2$ −0.5</td>
</tr>
<tr>
<td>South East</td>
<td>21. Pensacola</td>
<td>1924–2009</td>
<td>86</td>
<td>84</td>
<td>2.2</td>
<td>$2.2 \pm 0.2$ −0.1</td>
</tr>
<tr>
<td>North America</td>
<td>22. Key West</td>
<td>1913–2009</td>
<td>97</td>
<td>96</td>
<td>2.2</td>
<td>$2.3 \pm 0.1$ −0.1</td>
</tr>
<tr>
<td></td>
<td>23. Fernandina</td>
<td>1898–2009</td>
<td>112</td>
<td>91</td>
<td>1.8</td>
<td>$2.0 \pm 0.1$ −0.0</td>
</tr>
</tbody>
</table>
## Our estimates so far...

<table>
<thead>
<tr>
<th>Estimate n.</th>
<th>TG set</th>
<th>$N_{tg}$</th>
<th>$\mu = m \pm sdom$ mm/yr</th>
<th>$rms (wrms)$ mm/yr</th>
<th>GIA correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>ALL</td>
<td>1123</td>
<td>1.4 ± 0.2</td>
<td>5.8 (2.3)</td>
<td>no</td>
</tr>
<tr>
<td>2.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.8 ± 0.2</td>
<td>5.6 (1.8)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>3.</td>
<td>D97</td>
<td>23</td>
<td>1.6 ± 0.1</td>
<td>0.4 (0.4)</td>
<td>no</td>
</tr>
<tr>
<td>4.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.7 ± 0.1</td>
<td>0.4 (0.4)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>5.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.5 ± 0.1</td>
<td>0.4 (0.3)</td>
<td>ICE–5G</td>
</tr>
<tr>
<td>6.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.3 ± 0.1</td>
<td>0.5 (0.4)</td>
<td>ANU05</td>
</tr>
<tr>
<td>7.</td>
<td>D97R</td>
<td>16</td>
<td>1.4 ± 0.1</td>
<td>0.3 (0.2)</td>
<td>no</td>
</tr>
<tr>
<td>8.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.6 ± 0.1</td>
<td>0.3 (0.2)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>9.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.5 ± 0.1</td>
<td>0.3 (0.3)</td>
<td>ICE–5G</td>
</tr>
<tr>
<td>10.</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.5 ± 0.1</td>
<td>0.3 (0.3)</td>
<td>ANU05</td>
</tr>
</tbody>
</table>

This suggests a new strategy that differs from D97:

<< valuable TG gauges (for the GMSLR) assessment are among those for which the GIA correction is *largely independent on modeling*...>>

... and are, of course, free from other accidents.
Searching for GIA-modeling-insensitive tide gauges

\[ |r_{M1}^{gia} - r_{M2}^{gia}| < 0.3 \text{ mm/yr} \]

SGX TGs are found in the “far field” of the LGM ice sheets, where...

... GIA effects are mostly dependent from the melt-water load, controlled by the history of ice volume
The final preferred set SG01 (22) is obtained from SGX after decimation of:

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

\(N_{tg}=44\) (SGX set)
### Table 5

Basic data and computed rates of sea–level change for the SG0 set of TGs, determined according to the discussion in Section 7. The average number of valid yearly RLR records for this set is 87 years. GIA corrections corresponding to models ICE–5G are also shown. According to Eq. (18), those pertaining to ICE–3G and ANU05 do not differ from those shown by more than 0.3 mm/yr.

The last column shows ICE–5G GIA corrections in which the effects of the rotational feedback on sea–level are taken into account.

<table>
<thead>
<tr>
<th>Region</th>
<th>Tide gauge site</th>
<th>Period year–year</th>
<th>Span years</th>
<th>(N_k^p) years</th>
<th>(\rho_k = r_k + \sigma_k) mm/yr</th>
<th>(r_{k,GIA}^{qia}) mm/yr</th>
<th>(r_{k,GIA}^{qia(b)}) mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siberia</td>
<td>1. Tiksi Bukhta</td>
<td>1949–2009</td>
<td>61</td>
<td>61</td>
<td>1.6 ± 0.4</td>
<td>-0.0</td>
<td>-0.2</td>
</tr>
<tr>
<td>Northern Europe</td>
<td>2. Heimsjo</td>
<td>1928–2009</td>
<td>82</td>
<td>71</td>
<td>-1.5 ± 0.2</td>
<td>-2.7</td>
<td>-2.7</td>
</tr>
<tr>
<td></td>
<td>3. Smogen</td>
<td>1911–2009</td>
<td>99</td>
<td>99</td>
<td>-1.9 ± 0.2</td>
<td>-2.8</td>
<td>-2.8</td>
</tr>
<tr>
<td>Scotland</td>
<td>4. Aberdeen II</td>
<td>1880–1965</td>
<td>86</td>
<td>85</td>
<td>1.0 ± 0.1</td>
<td>-0.4</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>5. North Shields</td>
<td>1896–2009</td>
<td>114</td>
<td>103</td>
<td>1.9 ± 0.1</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>English Channel</td>
<td>6. Newlyn(^a)</td>
<td>1916–2009</td>
<td>94</td>
<td>93</td>
<td>1.8 ± 0.1</td>
<td>+0.3</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>7. Brest(^a)</td>
<td>1880–2009</td>
<td>130</td>
<td>121</td>
<td>1.4 ± 0.1</td>
<td>+0.3</td>
<td>+0.3</td>
</tr>
<tr>
<td>Atlantic</td>
<td>8. Lagos(^a)</td>
<td>1909–1987</td>
<td>79</td>
<td>69</td>
<td>1.4 ± 0.2</td>
<td>+0.0</td>
<td>-0.0</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>9. Marseille(^a)</td>
<td>1885–2009</td>
<td>125</td>
<td>119</td>
<td>1.2 ± 0.1</td>
<td>+0.1</td>
<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>10. Genova(^a)</td>
<td>1884–1996</td>
<td>113</td>
<td>85</td>
<td>1.2 ± 0.1</td>
<td>+0.1</td>
<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>11. Trieste(^a)</td>
<td>1905–2010</td>
<td>106</td>
<td>100</td>
<td>1.3 ± 0.1</td>
<td>+0.0</td>
<td>+0.0</td>
</tr>
<tr>
<td></td>
<td>12. Bakar</td>
<td>1930–2008</td>
<td>79</td>
<td>66</td>
<td>0.9 ± 0.2</td>
<td>+0.0</td>
<td>+0.0</td>
</tr>
<tr>
<td>Black Sea</td>
<td>13. Sevastopol</td>
<td>1910–1994</td>
<td>85</td>
<td>82</td>
<td>1.3 ± 0.3</td>
<td>+0.4</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>14. Tuapse</td>
<td>1917–2009</td>
<td>93</td>
<td>91</td>
<td>2.3 ± 0.2</td>
<td>+0.2</td>
<td>+0.1</td>
</tr>
<tr>
<td>Australia</td>
<td>15. Fremantle</td>
<td>1897–2009</td>
<td>113</td>
<td>100</td>
<td>1.5 ± 0.2</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>New Zealand</td>
<td>16. Auckland II(^a)</td>
<td>1904–1998</td>
<td>95</td>
<td>92</td>
<td>1.3 ± 0.1</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>17. Dunedin II(^a)</td>
<td>1900–2009</td>
<td>110</td>
<td>64</td>
<td>1.2 ± 0.1</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>Central America</td>
<td>18. Balboa(^a)</td>
<td>1908–2003</td>
<td>96</td>
<td>95</td>
<td>1.5 ± 0.1</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>19. Cristobal(^a)</td>
<td>1909–1979</td>
<td>71</td>
<td>71</td>
<td>1.4 ± 0.1</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>South America</td>
<td>20. Quenquen(^a)</td>
<td>1918–1982</td>
<td>65</td>
<td>64</td>
<td>0.9 ± 0.2</td>
<td>-0.2</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>21. Buenos Aires(^a)</td>
<td>1905–1987</td>
<td>83</td>
<td>83</td>
<td>1.6 ± 0.2</td>
<td>-0.4</td>
<td>-0.5</td>
</tr>
<tr>
<td>Pacific</td>
<td>22. Honolulu(^a)</td>
<td>1905–2009</td>
<td>101</td>
<td>105</td>
<td>1.5 ± 0.1</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

\(\rho_k = r_k + \sigma_k\) mm/yr

\(r_{k,GIA}^{qia}\) mm/yr

\(r_{k,GIA}^{qia(b)}\) mm/yr

---

**D97 TGs are marked in yellow**
### Table 6.

<table>
<thead>
<tr>
<th>Estimate n.</th>
<th>TG set</th>
<th>$N_{tg}$</th>
<th>$\mu = m \pm s_{dom}$ (mm/yr)</th>
<th>$rms (wrms)$ (mm/yr)</th>
<th>GIA correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>ALL</td>
<td>1123</td>
<td>1.4 (\pm) 0.2</td>
<td>5.8 (2.3)</td>
<td>no</td>
</tr>
<tr>
<td>2.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.8 (\pm) 0.2</td>
<td>5.6 (1.8)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>3.</td>
<td>D97</td>
<td>23</td>
<td>1.6 (\pm) 0.1</td>
<td>0.4 (0.4)</td>
<td>no</td>
</tr>
<tr>
<td>4.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.7 (\pm) 0.1</td>
<td>0.4 (0.4)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>5.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.5 (\pm) 0.1</td>
<td>0.4 (0.3)</td>
<td>ICE–5G</td>
</tr>
<tr>
<td>6.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.3 (\pm) 0.1</td>
<td>0.5 (0.4)</td>
<td>ANU05</td>
</tr>
<tr>
<td>7.</td>
<td>D97R</td>
<td>16</td>
<td>1.4 (\pm) 0.1</td>
<td>0.3 (0.2)</td>
<td>no</td>
</tr>
<tr>
<td>8.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.6 (\pm) 0.1</td>
<td>0.3 (0.2)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>9.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.5 (\pm) 0.1</td>
<td>0.3 (0.3)</td>
<td>ICE–5G</td>
</tr>
<tr>
<td>10.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.5 (\pm) 0.1</td>
<td>0.3 (0.3)</td>
<td>ANU05</td>
</tr>
<tr>
<td>11.</td>
<td>SG01</td>
<td>22</td>
<td>1.1 (\pm) 0.2</td>
<td>1.0 (0.7)</td>
<td>no</td>
</tr>
<tr>
<td>12.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.5 (\pm) 0.1</td>
<td>0.4 (0.3)</td>
<td>ICE–3G</td>
</tr>
<tr>
<td>13.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.4 (\pm) 0.1</td>
<td>0.4 (0.3)</td>
<td>ICE–5G</td>
</tr>
<tr>
<td>14.</td>
<td>” ”</td>
<td>” ”</td>
<td>1.5 (\pm) 0.1</td>
<td>0.4 (0.3)</td>
<td>ANU05</td>
</tr>
<tr>
<td>15.</td>
<td>SG01</td>
<td>22</td>
<td>1.5 (\pm) 0.1</td>
<td>0.4 (0.3)</td>
<td>Any of the three above$^a$</td>
</tr>
</tbody>
</table>

$^a$ Accounts for the effect of the rotational feedback on sea level change according to the theory outlined by Milne & Mitrovica (1998).
GIA-corrected, global mean rate of sea level rise (1880-2010)

\[ \mu' = 1.5 \pm 0.1 \text{ mm/yr} \]

\[ \text{rms} = 0.4 \text{ mm/yr}, \text{w rms} = 0.3 \text{ mm/yr}, \]

(first Italian estimate)
Contents:

1). Motivations, previous work, relevance
2). Data: RLR tide gauge (TG) observations since 1880
3). Obtaining sea level trends from TG time series
4). Corrections in general and GIA corrections
5). Some new estimates of the secular sea level rise
6). Outlook (a couple of points)
Figure 2. Contribution of global seismicity to the long-term relative sealevel variations considered by Douglas [1997].
Are EQs affecting the TG sea level trends?

Ocean - averaged effect is ZERO

but the EQs have a cumulatively NEGATIVE tendency at TGs

(\sim -0.2 \text{ mm/yr})

Melini et al. GRL 2004
GMSLC is the first term of a more general expression

\[ SLC(\theta, \lambda) = \mu + c_1 \mu_1(\theta, \lambda) + c_2 \mu_2(\theta, \lambda) + \ldots \]

\(\mu\) is Global Mean Sea Level Change includes steric effects and eustatic variations associated with glacial melting

\(\mu_i(\theta, \lambda)\) are the Sea Level Fingerprints - spatial dependent patterns - of major continental ice sheets and mountain glaciers (see next slide)

\(c_i\) are unknown constants

Simultaneous inversion of TG observations for:

1) the mass balances and 2) the GMSLC
GIA, Greenland, Antarctica, & Glaciers fingerprints

Sea level change

- Ice model: GREEN
- Elasticity: External
- LMAX=128
- RES=44
- CODE=2
- MODE=2
- ITER=3

2011 May 26 07:51:18
SELEN 3.2
0.5 0.0 0.5 mm/yr

Sea level change

- Ice model: ANTA
- Elasticity: External
- LMAX=128
- RES=44
- CODE=2
- MODE=2
- ITER=3

2011 May 26 07:43:53
SELEN 3.2
0.5 0.0 0.5 mm/yr

Sea level change

- Ice model: GLAC
- Elasticity: External
- LMAX=128
- RES=44
- CODE=2
- MODE=2
- ITER=3

2011 May 26 07:16:15
SELEN 3.2
0.5 0.0 0.5 mm/yr

Rate of sea level change today

- Ice model: ICE5G
- Viscosity profile: /4.0 0.4 0.4/
- LMAX=128
- RES=44
- NV=3
- CODE=2
- MODE=1
- ITER=3

2011 May 18 12:51:59
SELEN 3.2
1.0 0.5 0.0 0.5 1.0 mm/yr

GIA, Greenland, Antarctica, & Glaciers fingerprints

GIA + Greenland + Antarctica + glaciers & caps = 100 Gt/yr

Friday, November 11, 2011
Good news! At the current rate of global warming we should be able to just swim over there and eat him in under five years...!