Twentieth-century sea-level rise – is the whole greater than the sum of the parts?

Jonathan Gregory\textsuperscript{1,2}
1 NCAS-Climate, University of Reading
2 Met Office Hadley Centre, Exeter

N. White, J. Church, M. Bierkens, J. Box, M. van den Broeke,
G. Cogley, X. Fettweis, E. Hanna, P. Huybrechts, L. Konikow,
P. Leclercq, B. Marzeion, J. Oerlemans, M. Tamisiea,
Y. Wada, L. Wake, R. van de Wal,
A. Hu, M. Huber, R. Knutti, M. Meinshausen,
developers of ACCESS and CSIRO Mk3.6 AOGCMs
Global-mean sea-level rise (GMSLR) from altimetry

Inverse barometer applied, GIA corrected

Rate = 3.1 ± 0.4 mm/yr
Seasonal signals removed

University of Colorado 2012 rel1
GMSLR from tide gauges
Rate of GMSLR from tide gauges
Twentieth-century sea-level: an enigma

Walter Munk (PNAS, 2002)

“The historic rise started too early, has too linear a trend, and is too large.”
Can we account for twentieth-century GMSLR?

Global mean sea level change is caused by

- change in the volume of the ocean basin (on geological timescales)
- change in the volume of the ocean water, which is caused by
  - change in the density of the ocean water (steric), which is
    nearly entirely thermal expansion (thermosteric), because
    the effect of salinity change (halosteric) is negligible on the global mean
- change in the mass of the ocean (barystatic), due to change in mass of
  glaciers (including ice-caps)
  Greenland ice sheet
  Antarctic ice sheet
  groundwater
  reservoirs
  other negligible terms

The TAR, AR4 and AR5 recommend that the word eustatic should not be used.
Thermal expansion from CMIP3 AOGCMs
Thermal expansion from HadCM3 with volcanic forcing only

Gregory et al. (2006)
What is the reference level for volcanic forcing?

Crowley (2000)
What is the reference level for volcanic forcing?
FAMOUS with repeated pseudovolcanoes

Volume-mean ocean temperature change (K)


Gregory (2010)
FAMOUS with pseudovolcanoes and constant forcing
Together they explain the downward-stepping behaviour.
How can we correct this negative bias?
Testing a method to correct the negative bias
Testing a method to correct the negative bias
Correction for volcanic spin-up in CMIP3 V AOGCMs
Corrected thermal expansion in CMIP3 V AOGCMs
Uncertainty of thermal expansion in CMIP3 V AOGCMs
Glacier length change as a proxy for glacier mass change

Convert to volume according to

\[ V = L^\eta \]

where \( \eta \approx 2 \).

Leclercq et al. (2011)
Glacier contribution to rate of GMSLR
Glacier contribution to GMSLR

- A: Alpine calibration
- C: Cogley (2009, updated)
- L: Leclercq et al. (2011, updated)
- M: Marzeion et al. (2012)
Greenland ice-sheet surface mass balance (SMB, 1988-2004)

\[ S = P - R \]

- **S** for Accumulation
- **P** for Precipitation
- **R** for Runoff

Time-mean Change over the period

Box et al. (2006)
Greenland ice-sheet SMB anomaly wrt 1961-1990

- Box (submitted-a)
- Fettweis et al. (2008, updated)
- Hanna et al. (2011)
- Wake et al. (2009)

The graph shows the Greenland ice-sheet surface mass balance (SMB) anomaly with respect to the period 1961-1990. The y-axis represents the SMB in gigatons per year (Gt a⁻¹), and the x-axis represents time from 1840 to 2000.
Ice-sheet mass balance

NB: It may not be in balance!

\[ \frac{dM_G}{dt} = S - D \]

where \( S (= P - R) \) is SMB and \( D \) is ice discharge.

Suppose that for some reference period \( \langle \frac{dM_G}{dt} \rangle = 0 \Rightarrow \langle S \rangle - \langle D \rangle = 0 \).

Define \( \Delta X = X - \langle X \rangle \).

Then at any time

\[ \frac{dM_G}{dt} = S - D = \Delta S - \Delta D + \langle S \rangle - \langle D \rangle = \Delta S - \Delta D. \]

If we further assume that \( D \) does not change \( \Rightarrow \Delta D = 0 \), then

\[ \frac{dM_G}{dt} = \Delta S \]

at any time (using only anomalies \( \Delta S \), not \( \langle S \rangle \)).

Alternatively, we need to estimate \( D \).
Greenland ice-sheet contribution to the rate of GMSLR
Anthropogenic GMSLR from reservoir impoundment

Lettenmaier and Milly (2009)
Contribution to GMSLR from anthropogenic intervention
A synthetic timeseries is a sum of contributions

= Expansion (three choices)
+ Glacier (three)
+ Greenland ice-sheet (four)
+ Groundwater depletion (two)
+ Reservoir impoundment (two)

$3 \times 3 \times 4 \times 2 \times 2 = 144$ combinations
GMSLR from TGs compared with synthetic timeseries
Observed GMSLR (TG-C) minus synthetic timeseries
Observed GMSLR (TG-C) minus detrended synthetic timeseries
Residual trend and RMS

The diagram illustrates the relationship between residual trend and RMS. The chart features a scatter plot with different symbols and colors representing different categories:

- **Tide-gauge colours:**
  - C (black)
  - J (green)
  - R (blue)
  - W (red)

- **Greenland symbols:**
  - + (black)
  - □ (blue)
  - ♦ (red)
  - ✗ (green)

- **Thermal expansion sizes:**
  - L (black)
  - M (blue)
  - H (red)

The axes of the chart are labeled as follows:

- **RMS residual (mm)**
- **Residual trend (mm a⁻¹)**

The data points are distributed across the chart, showing the correlation between the residual trend and RMS values for different categories.
Observed and synthetic GMSLR (large residual)
What is the cause of the residual trend?

Could it be a bias in the TG GMSLR estimates?

This could arise if

● Coastal sea level rise differs systematically from GMSLR for oceanographic reasons.

● Effects of contemporary changes in mass distribution (gravitational change, elastic flexure of the lithosphere, Earth rotational effects, *Gelirol*) cause a net bias in TG measurement of GMSLR.
Gelirol effects of impoundment in reservoirs

Fiedler and Conrad (2010)
Gelirol effects of thermal expansion

Fraction of GMSLR due to thermal expansion
Could the residual be a long-term contribution to GMSLR?

North Carolina sea-level rise from proxy data

Kemp et al. (2011)
Constraints on the budget of GMSLR
Summary

20th-century GMSLR can be accounted for in terms of contributions from thermal expansion, glaciers, the Greenland ice-sheet, groundwater depletion, reservoir impoundment and a residual constant rate.

The glacier contribution is largest, and no greater in the second than the first half of the century, perhaps due to early-century high-latitude warming, and compensating tendencies caused by global warming and areal contraction.

Thermal expansion is second and a generally increasing rate, but reduced episodically by the climatic cooling due to volcanoes, and larger in the interim. Its time-mean is $0.5 \text{ mm yr}^{-1} \Rightarrow \text{barystatic contribution of } 1.0 \text{ mm yr}^{-1}$.

Greatest systematic uncertainty is for the Greenland ice-sheet.

If the Greenland ice-sheet contributed positively on average, the residual could be $0.0–0.2 \text{ mm yr}^{-1}$, consistent with a possible long-term Antarctic contribution.

GMSLR apparently began in the 19th century; this could be naturally forced.

The rate of GMSLR during the 20th century was fairly constant, and hence not proportional to global mean temperature.

Understanding the past better increases our confidence in projections.