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

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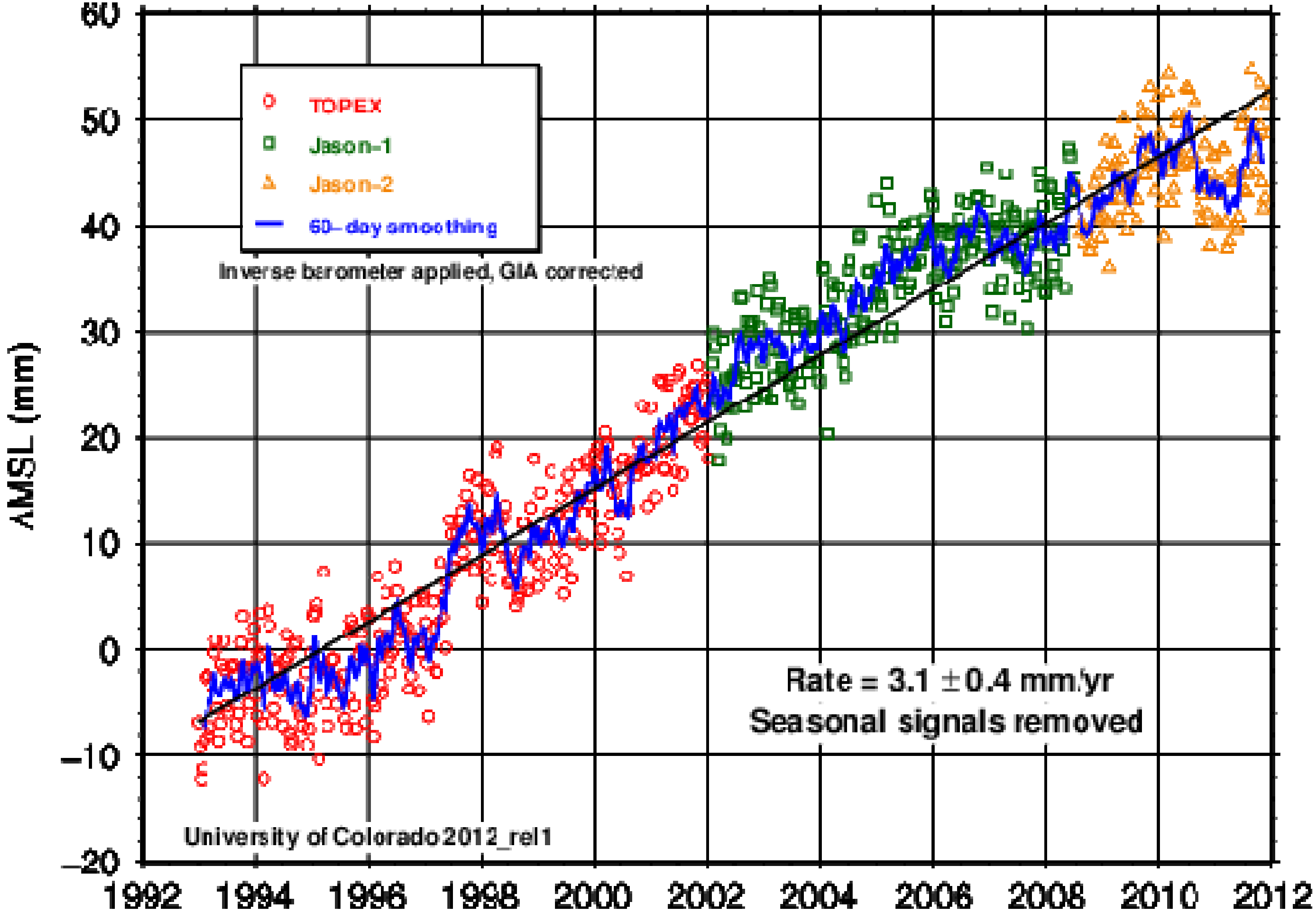
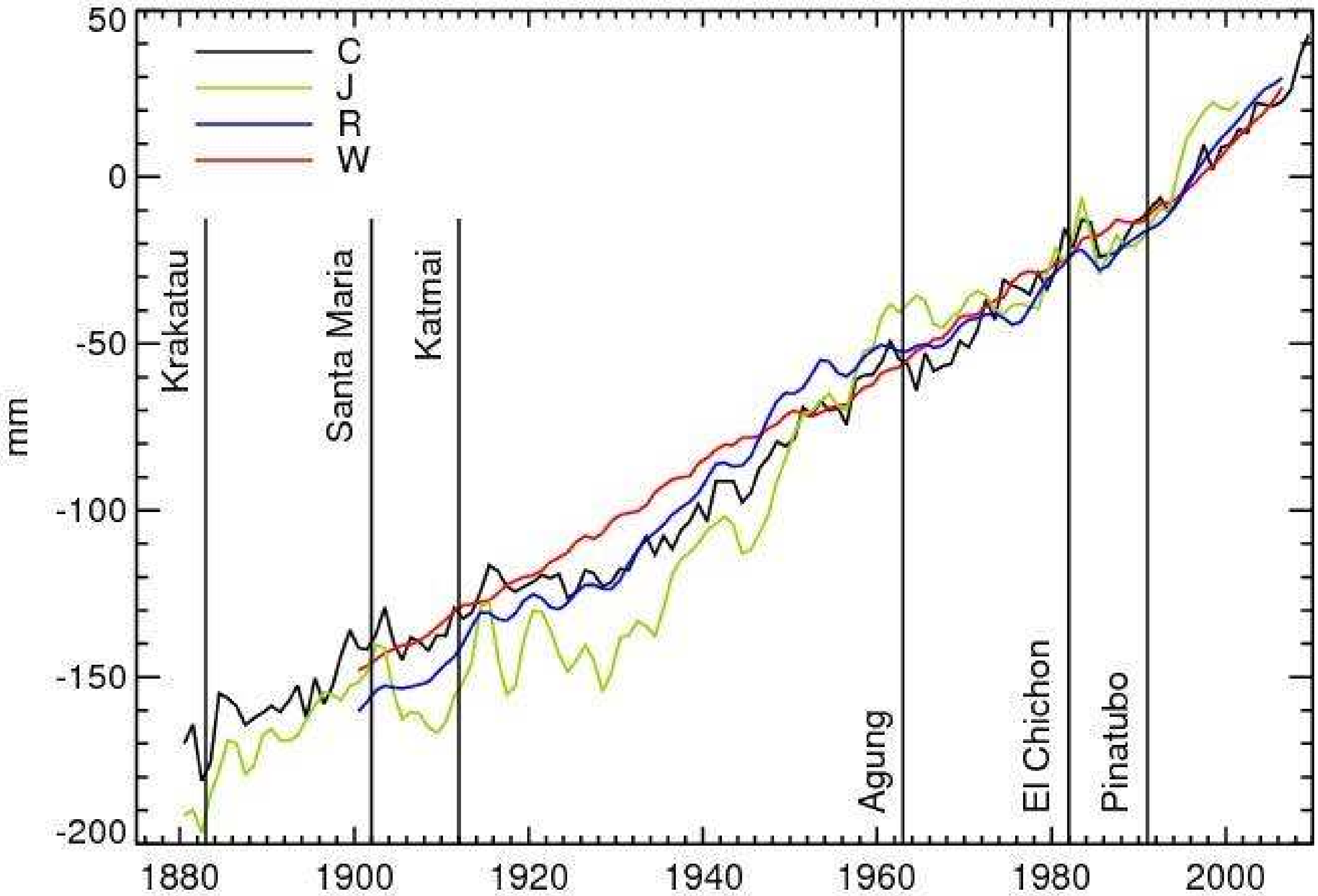
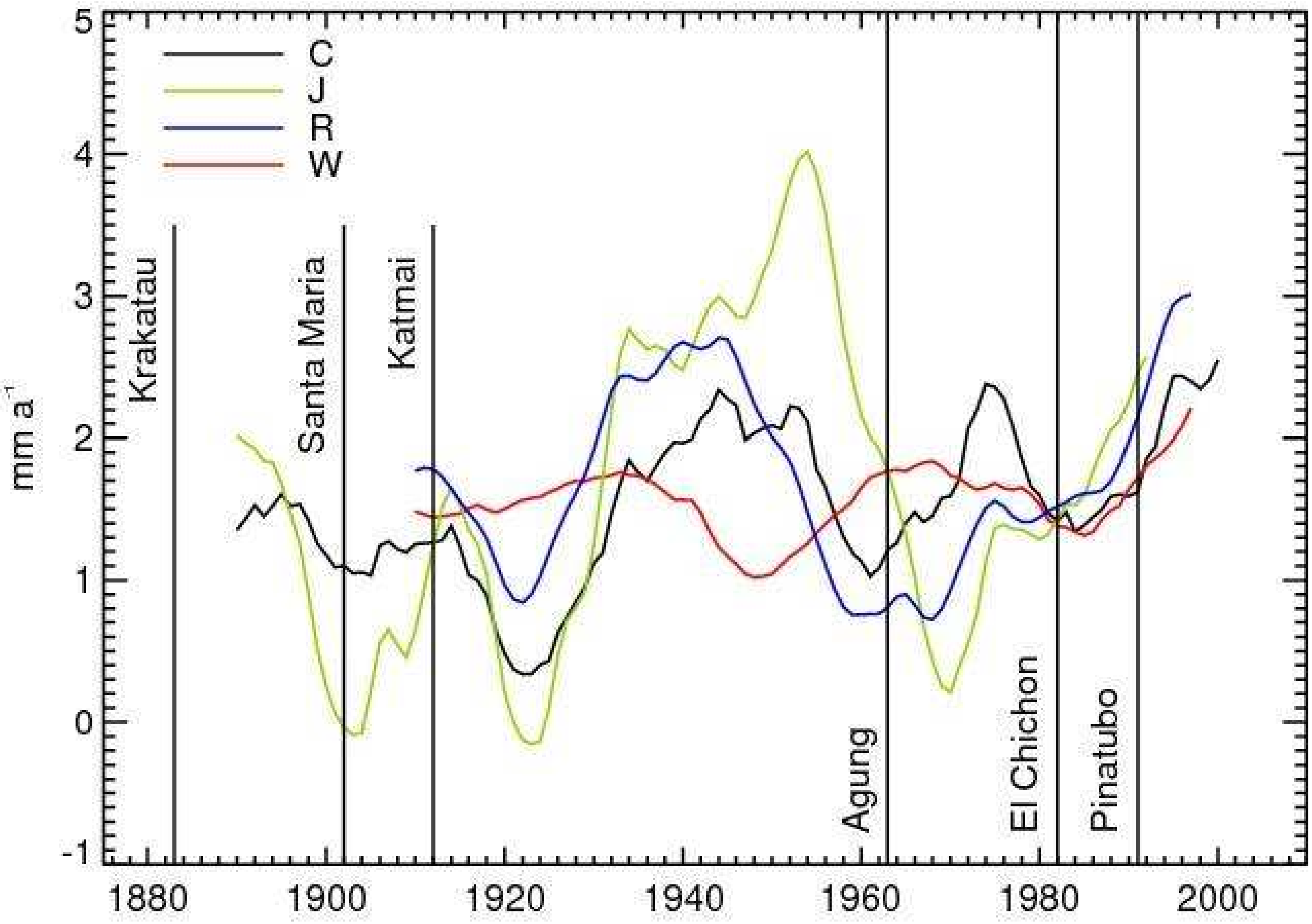
Global-mean sea-level rise (GMSLR) from altimetry



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.”

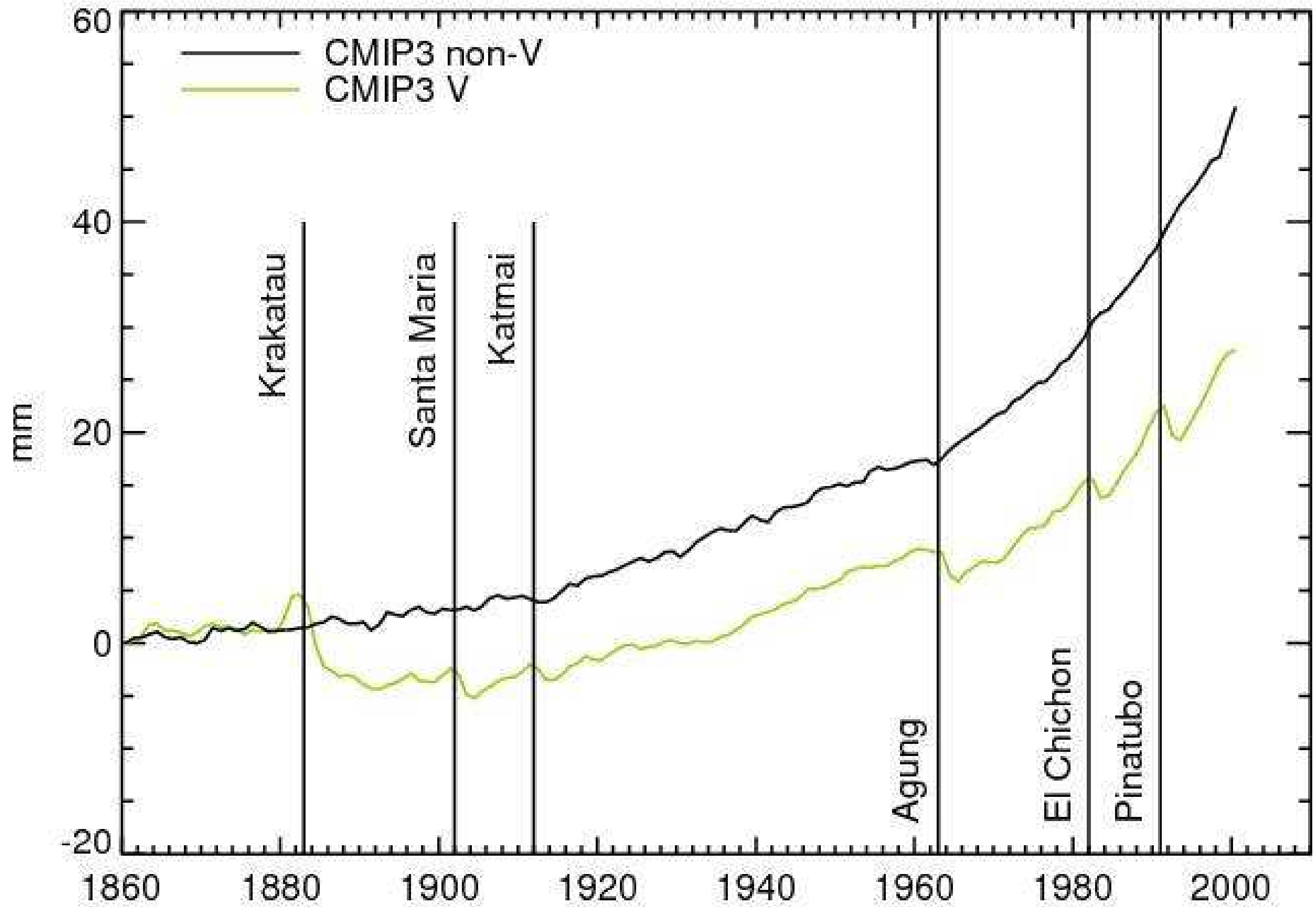
Can we account for twentieth-century GMSLR?

Global mean sea level change is caused by

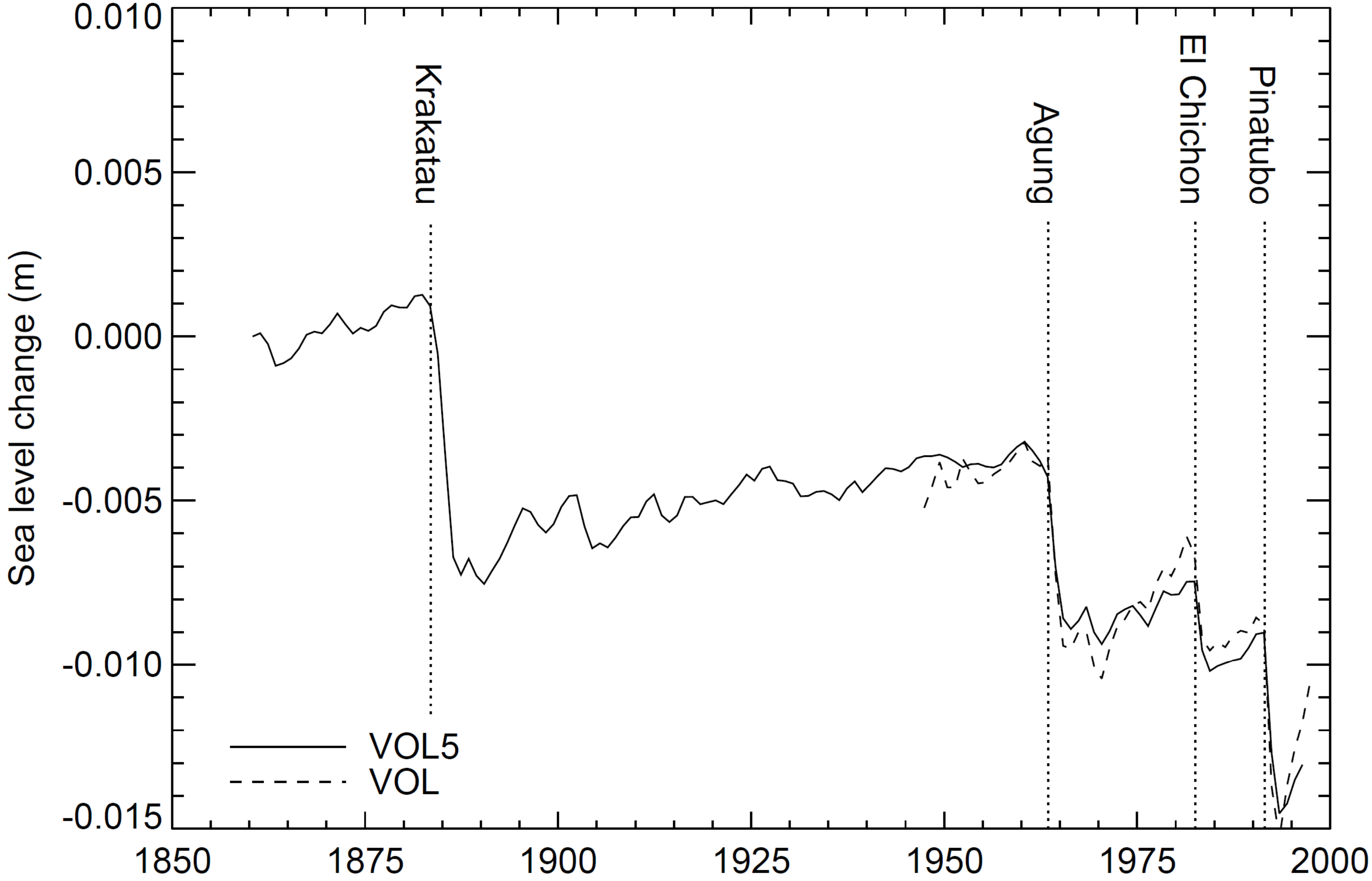
- change in the volume of the ocean basin (on geological timescales)
- change in the volume of the ocean water, which is caused by
  - change in the density of the ocean water (steric), which is
    - nearly entirely thermal expansion (thermosteric), because
    - the effect of salinity change (halosteric) 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

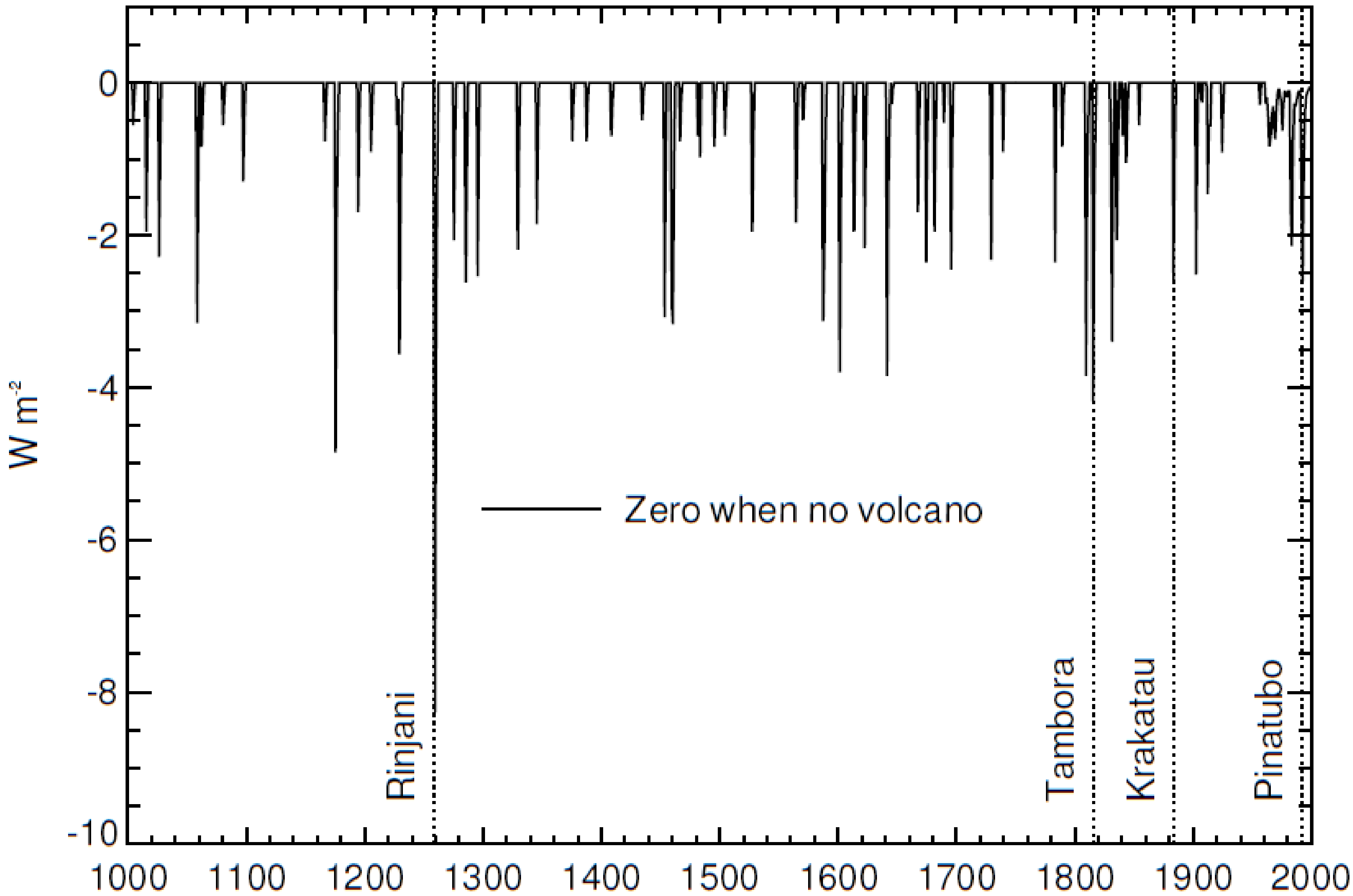


Thermal expansion from HadCM3 with volcanic forcing only



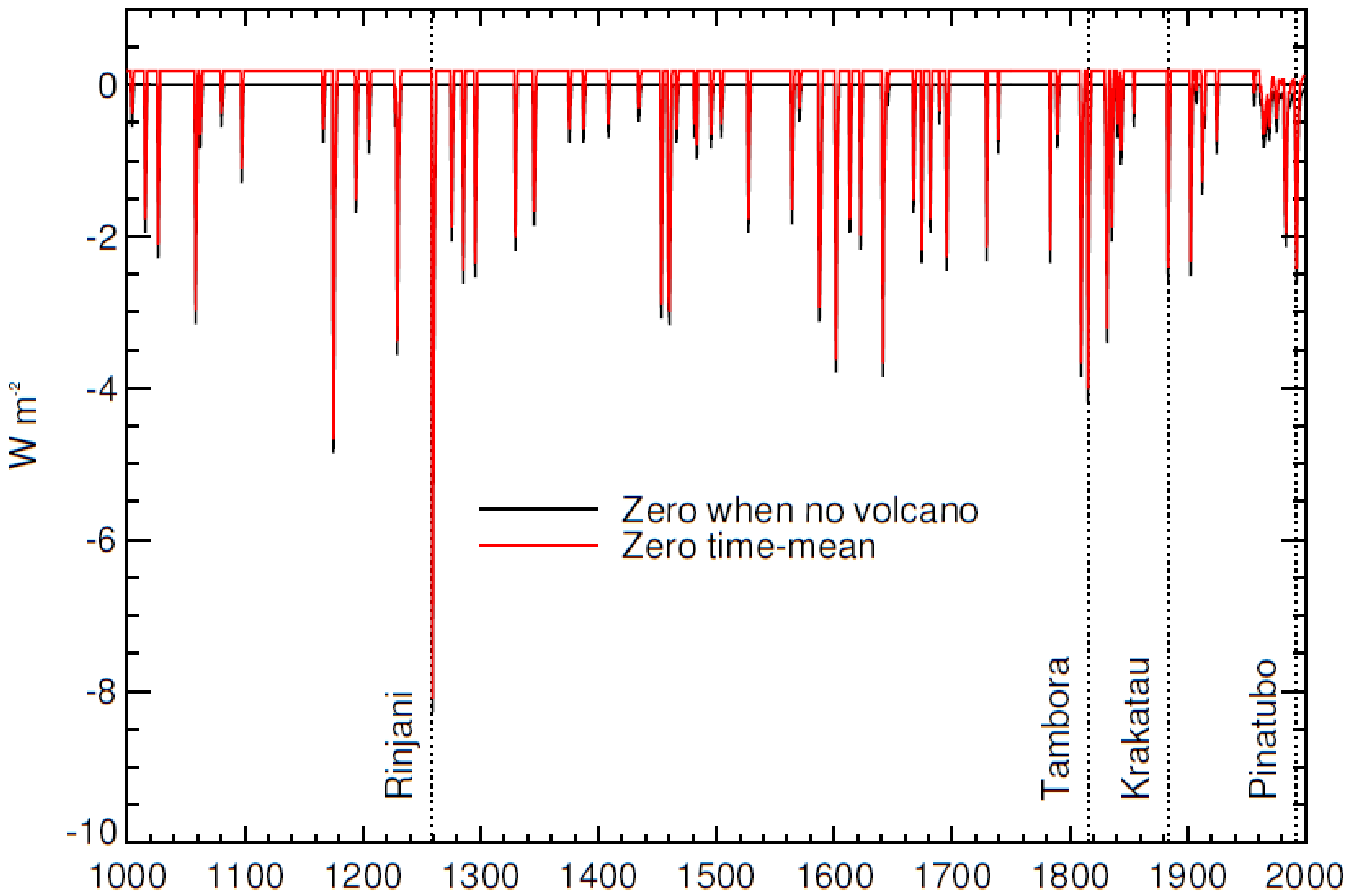
Gregory et al. (2006)

What is the reference level for volcanic forcing?

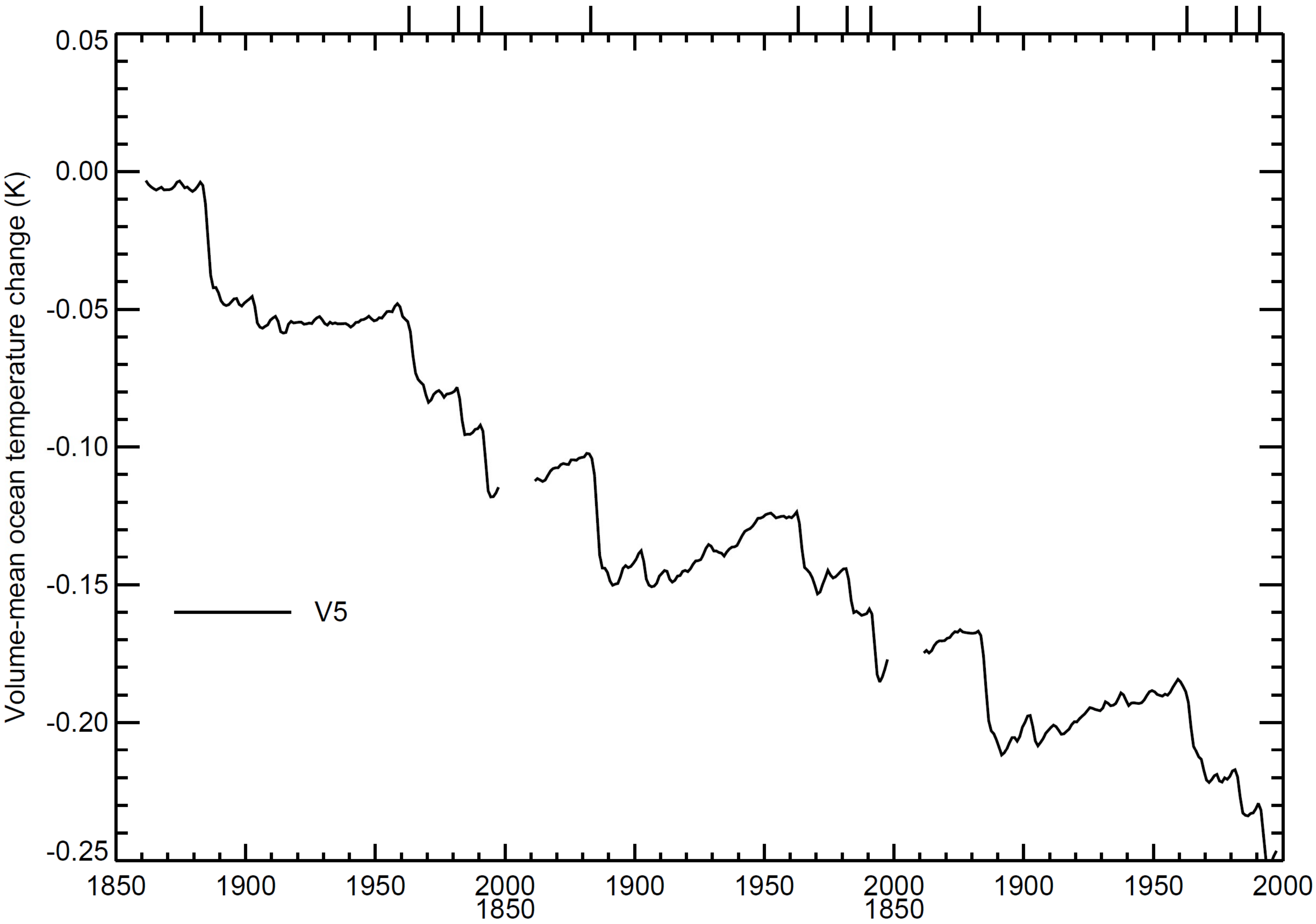


Crowley (2000)

What is the reference level for volcanic forcing?

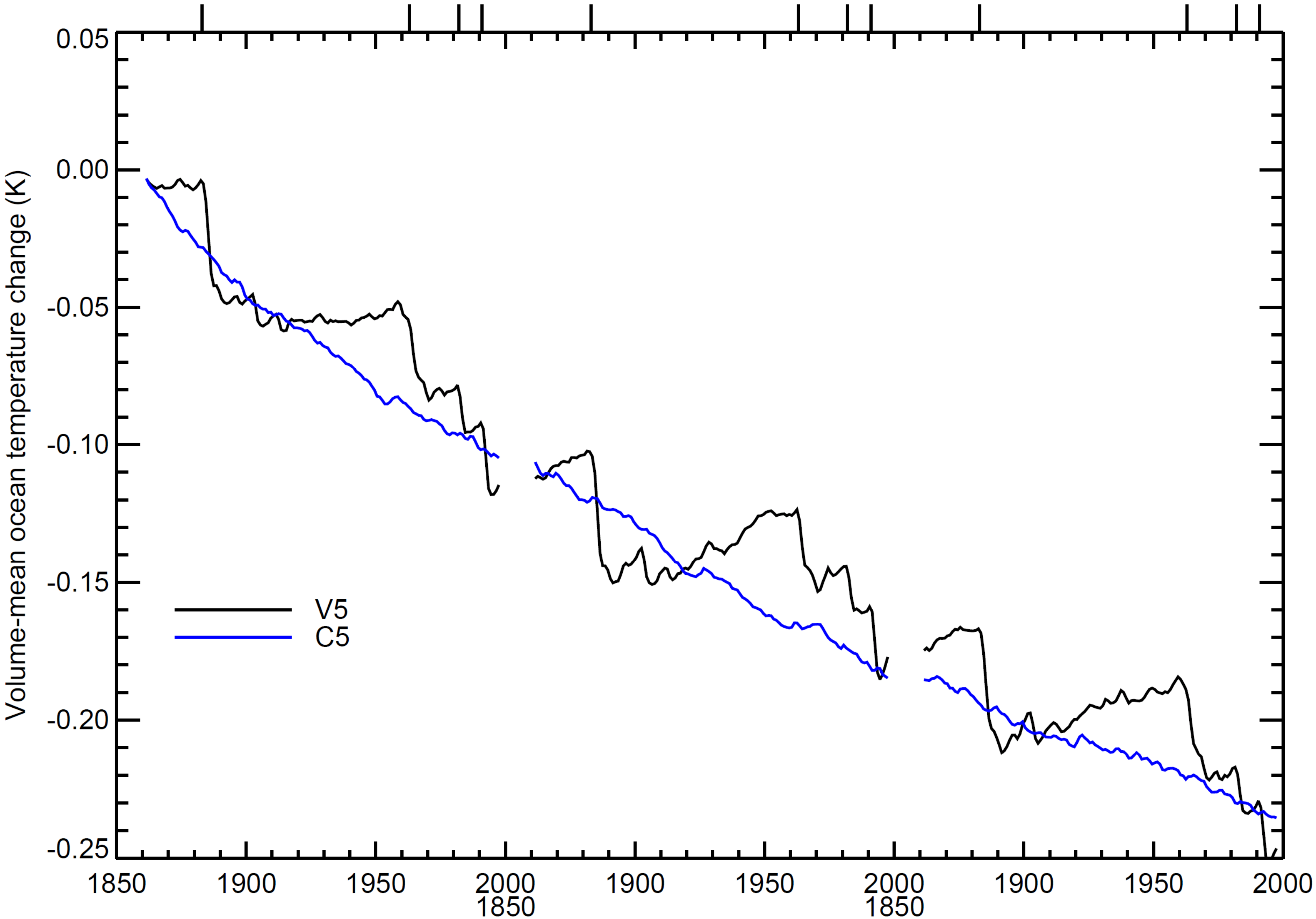


FAMOUS with repeated pseudovolcanoes



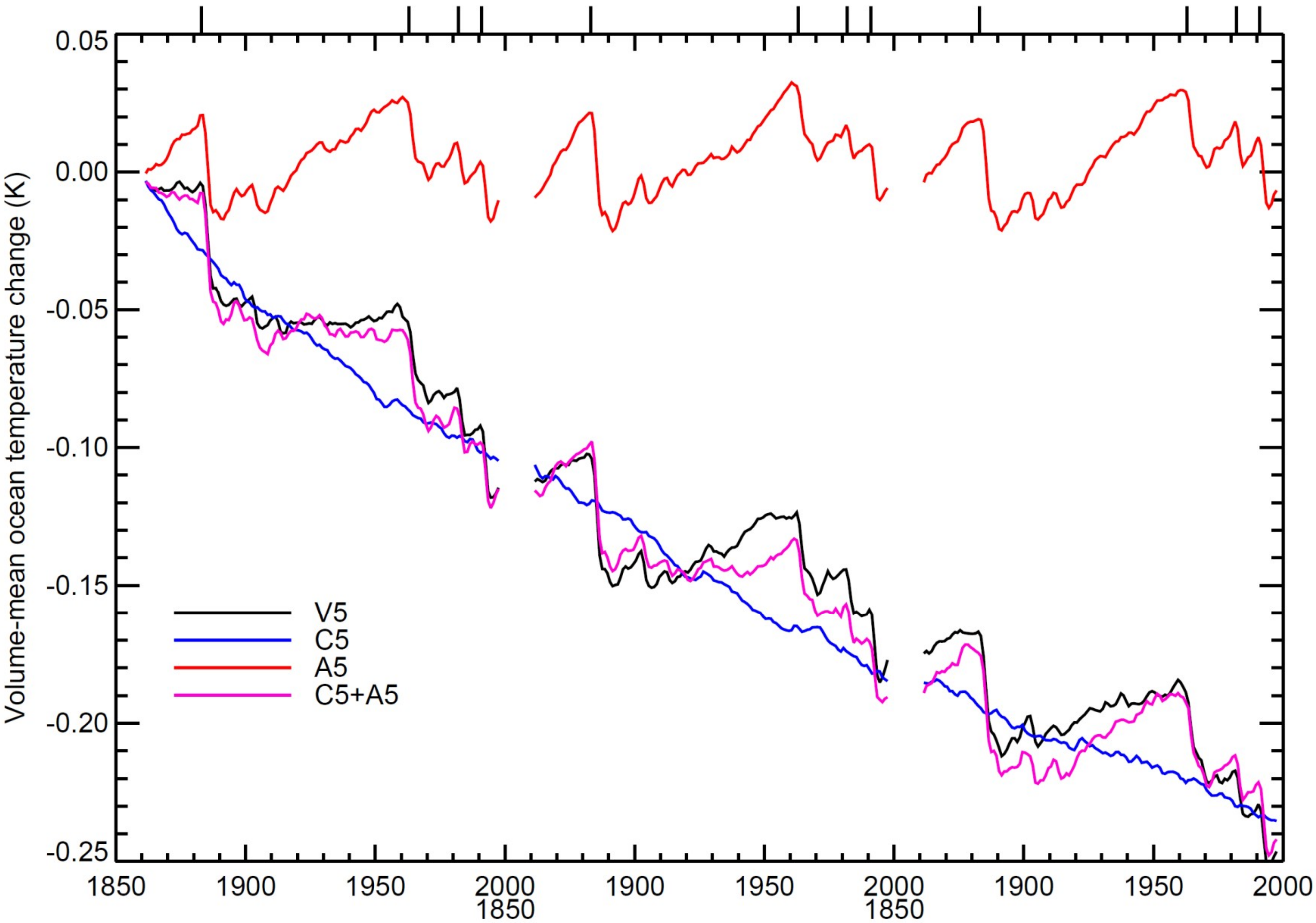
Gregory (2010)

FAMOUS with pseudovolcanoes and constant forcing



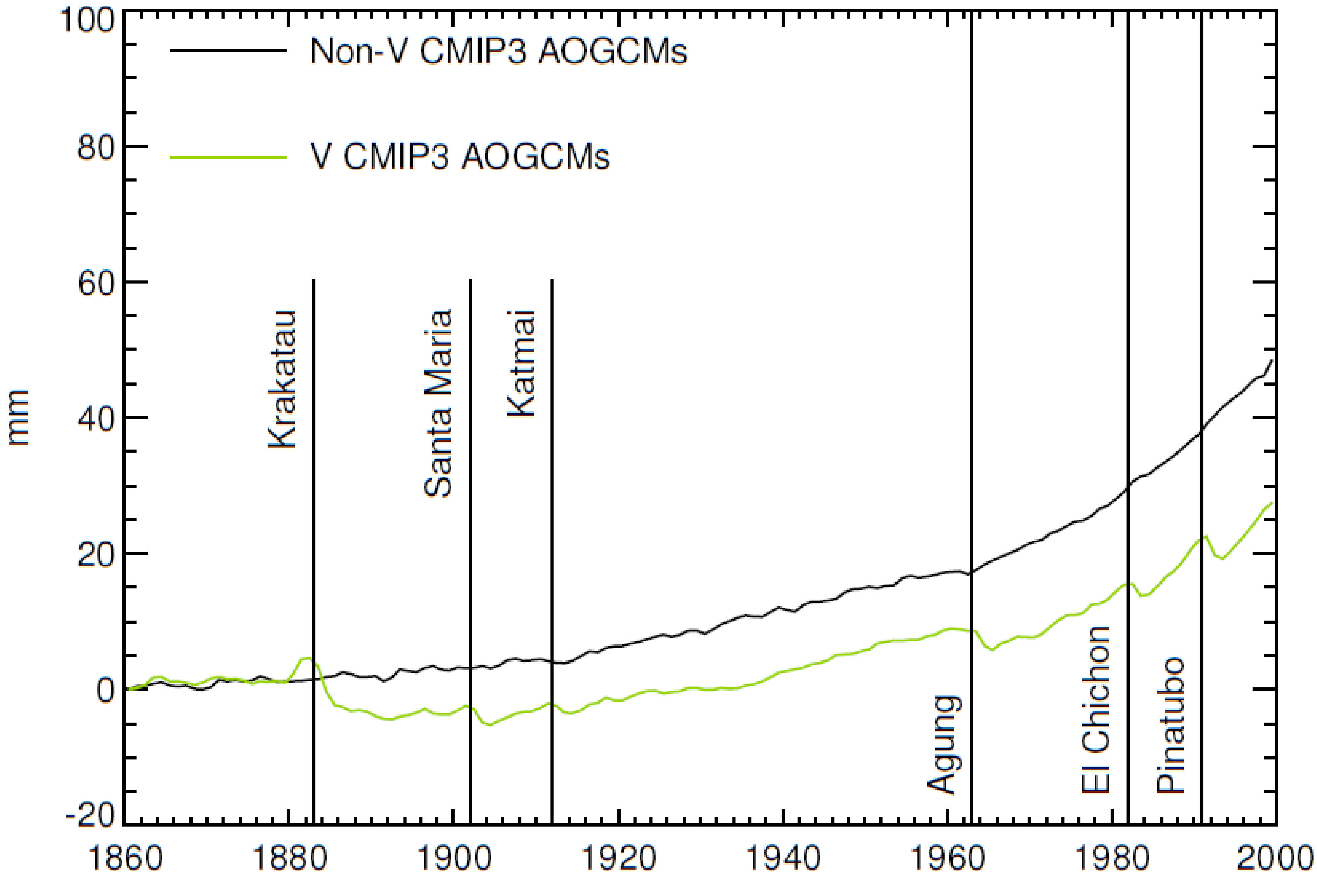
Gregory (2010)

Together they explain the downward-stepping behaviour

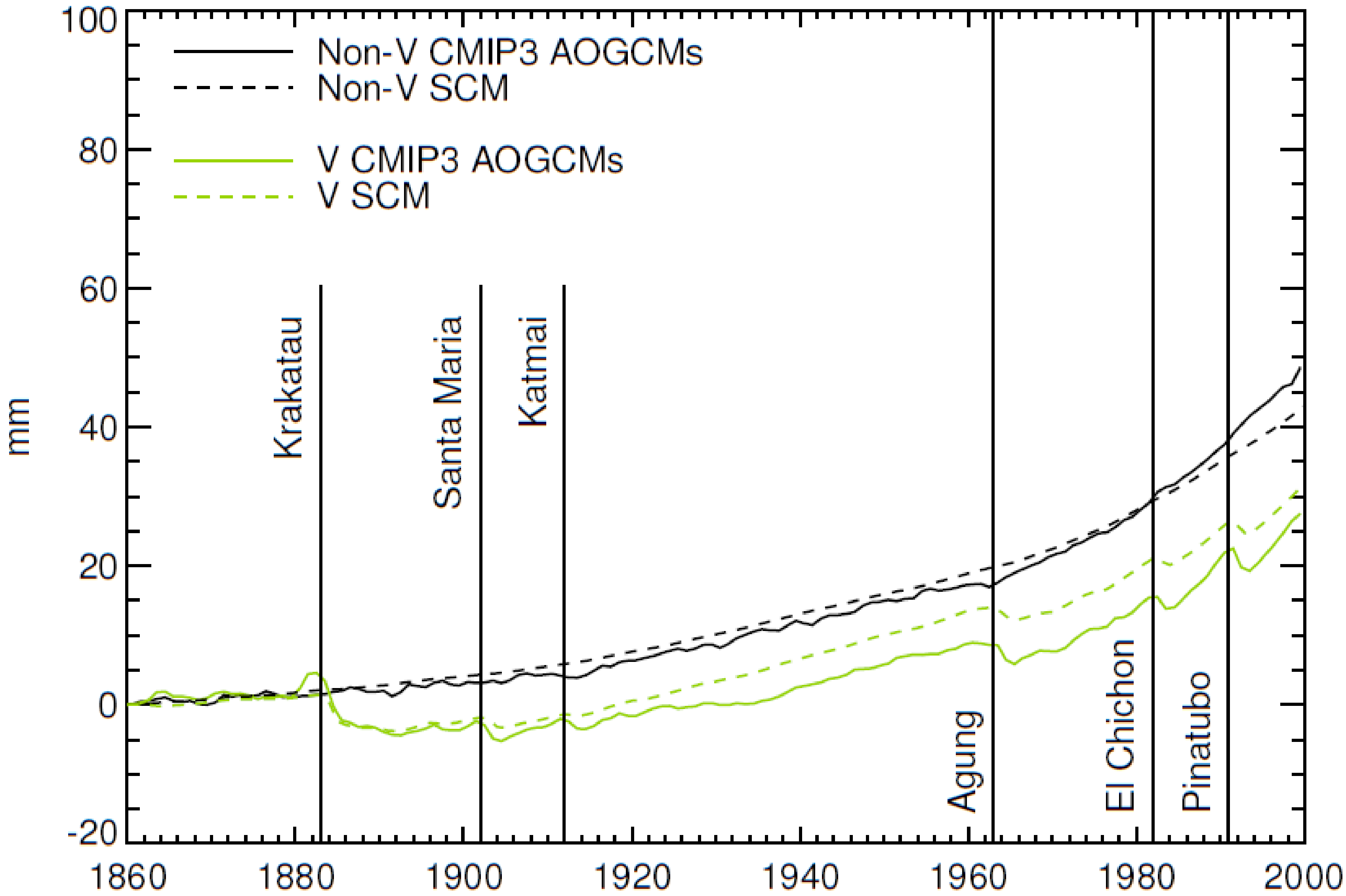


Gregory (2010)

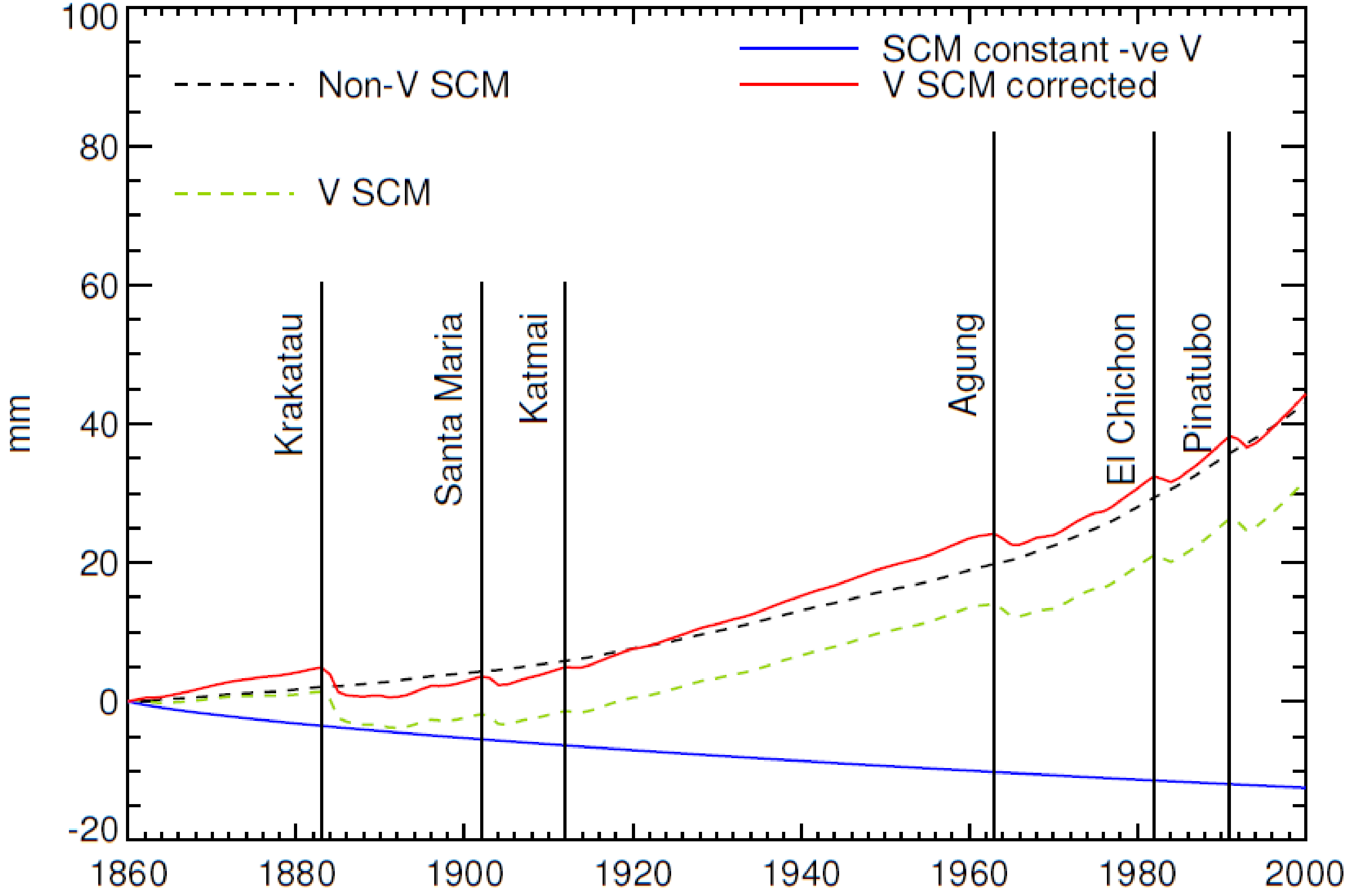
How can we correct this negative bias?



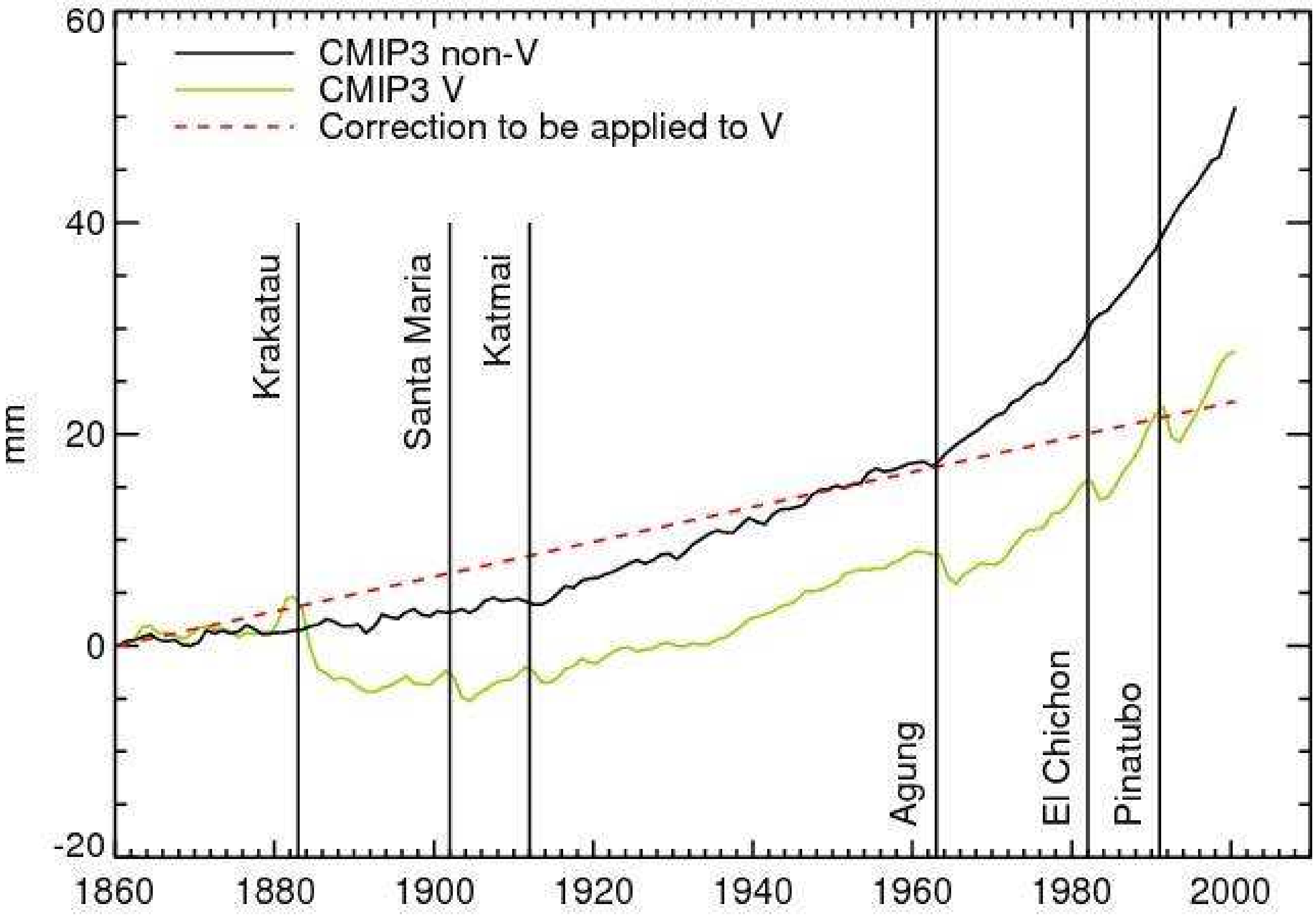
Testing a method to correct the negative bias



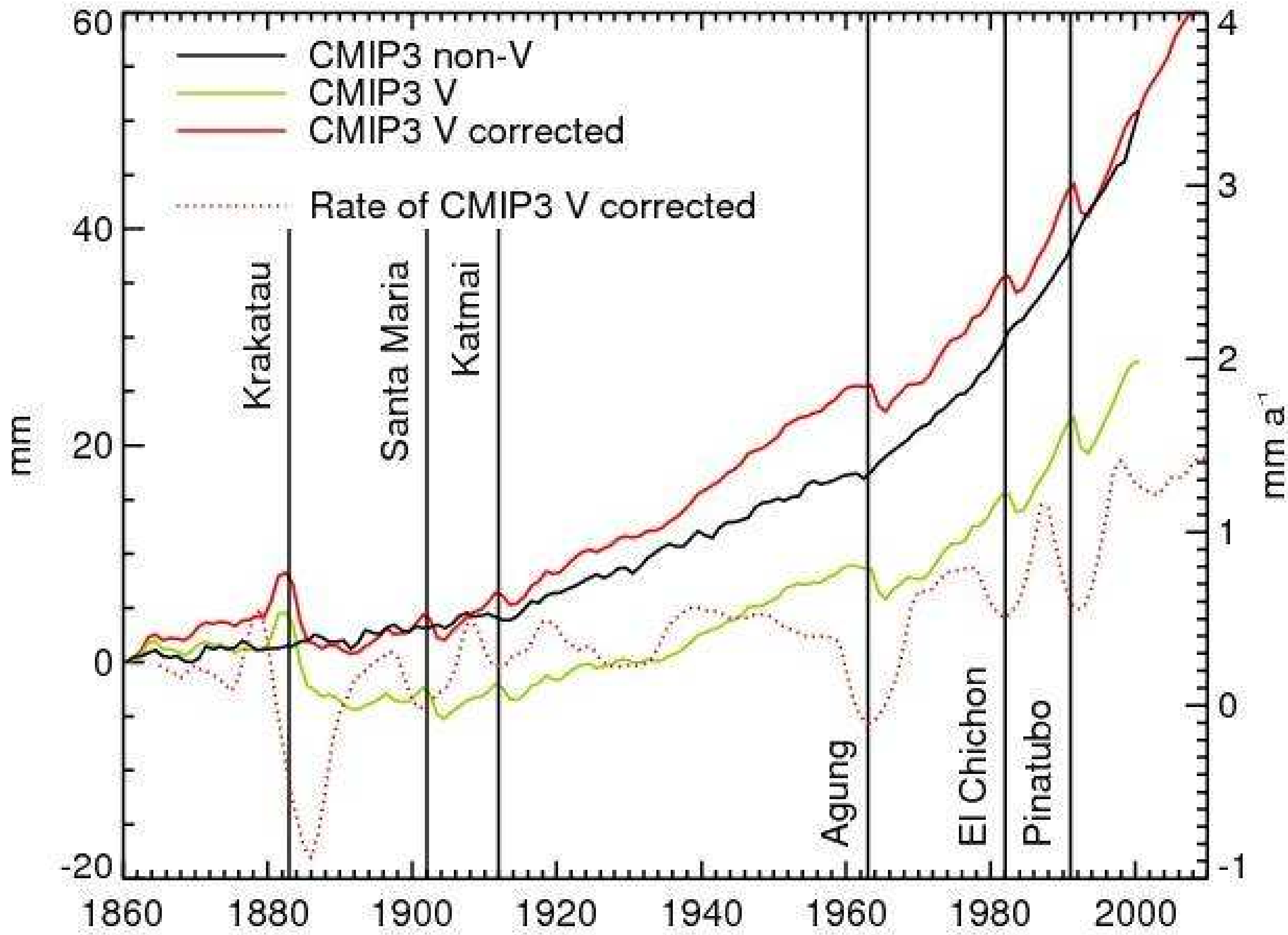
Testing a method to correct the negative bias



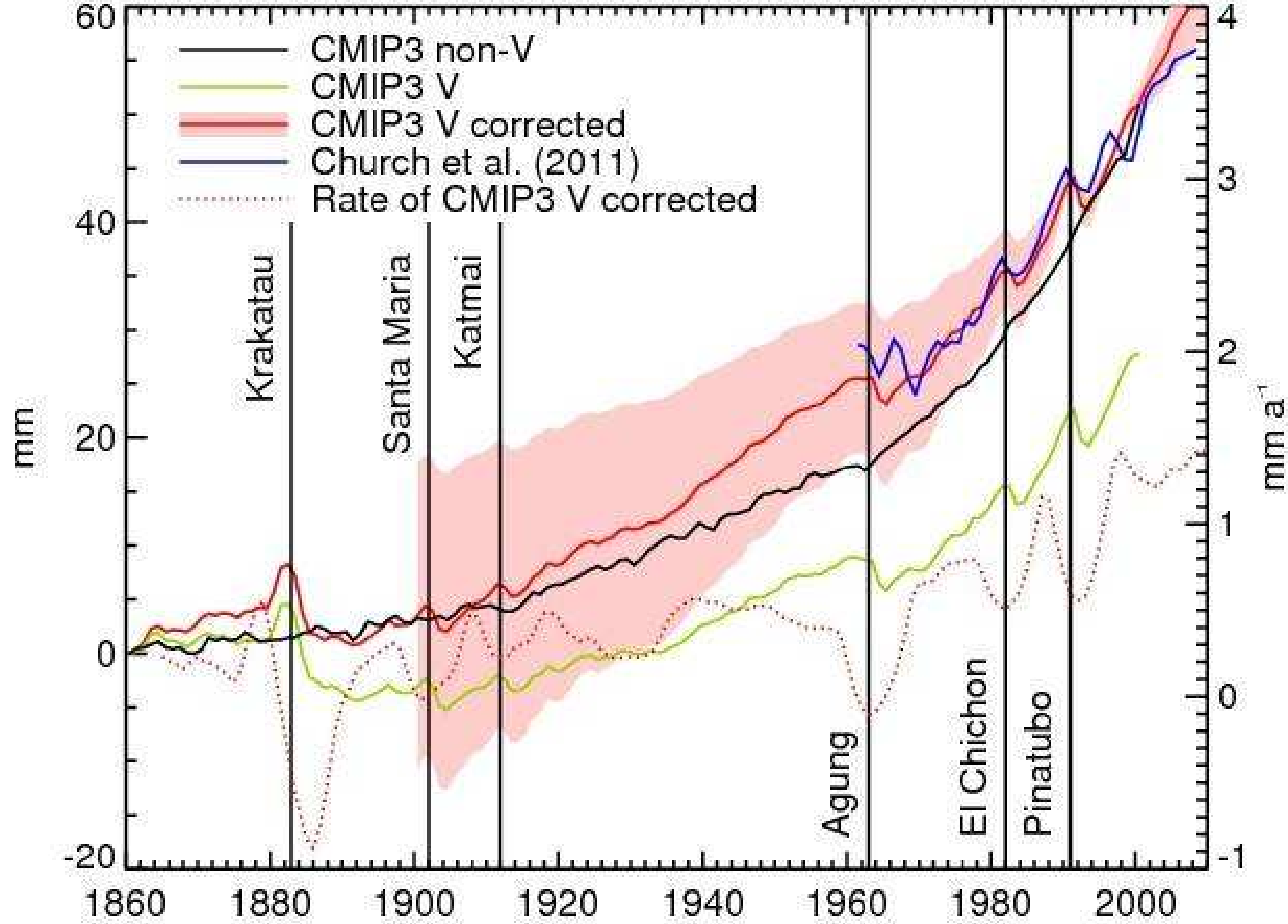
Correction for volcanic spin-up in CMIP3 V AOGCMs



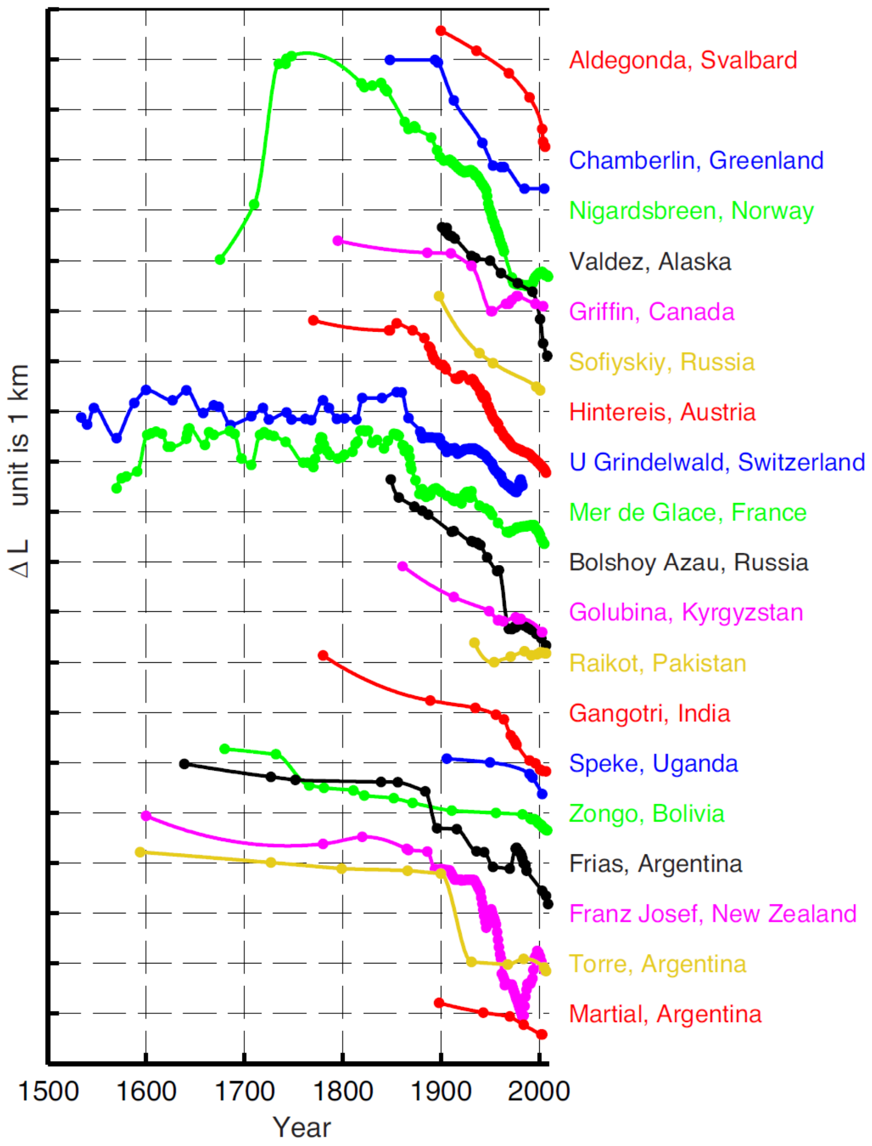
Corrected thermal expansion in CMIP3 V AOGCMs



Uncertainty of thermal expansion in CMIP3 V AOGCMs



Glacier length change as a proxy for glacier mass change



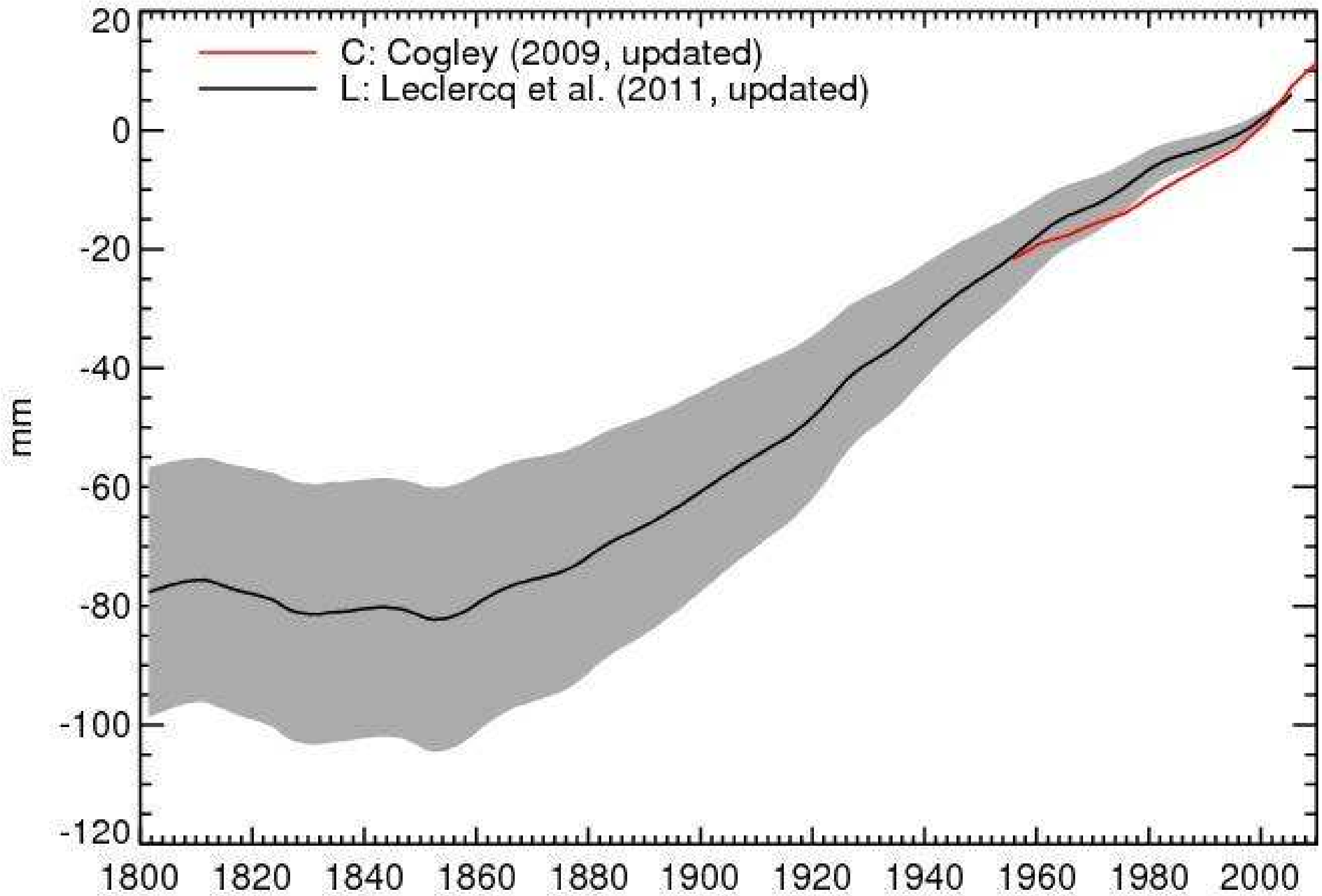
Convert to volume according to

$$V = L^{\eta}$$

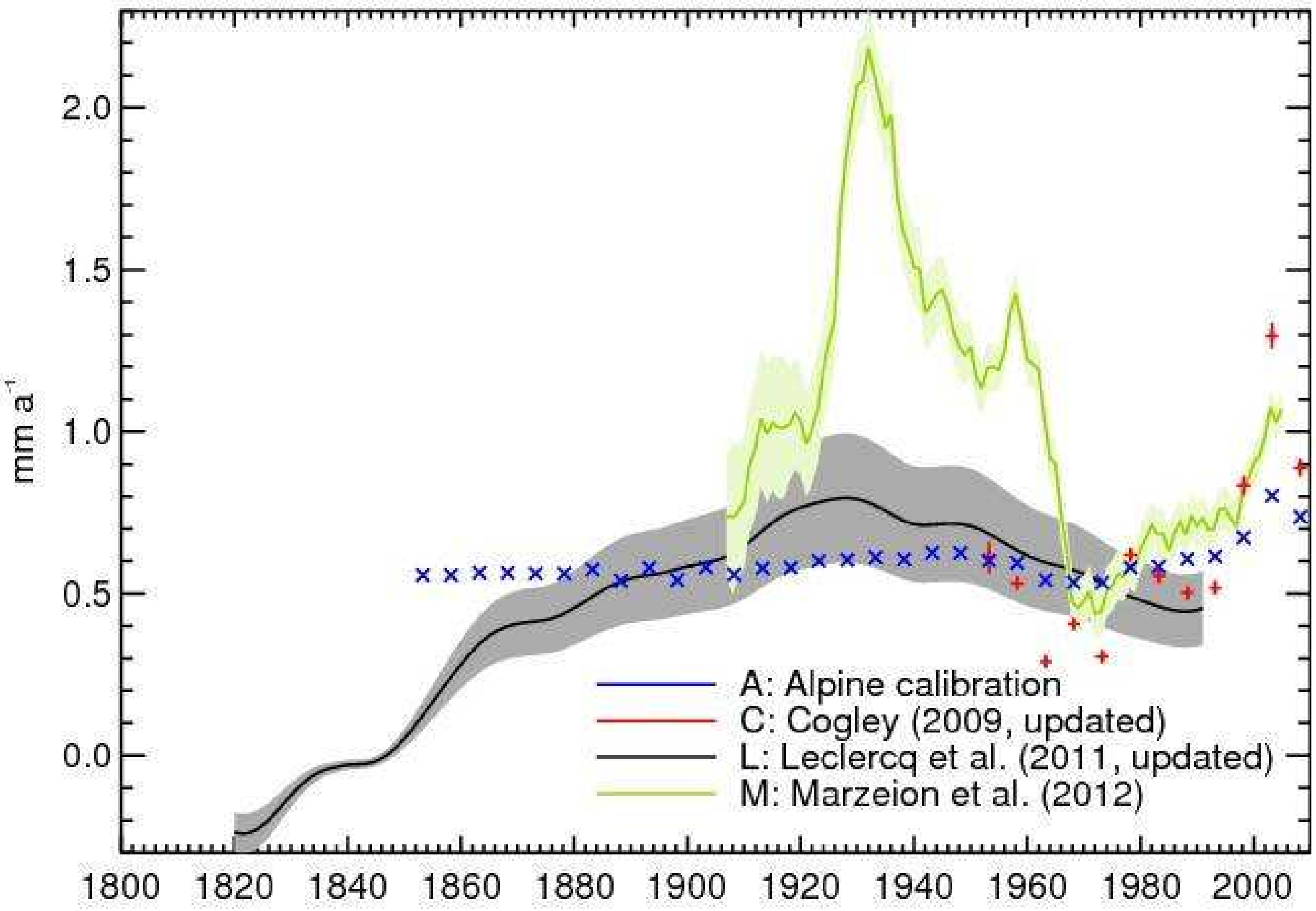
where $\eta \approx 2$.

Leclercq et al. (2011)

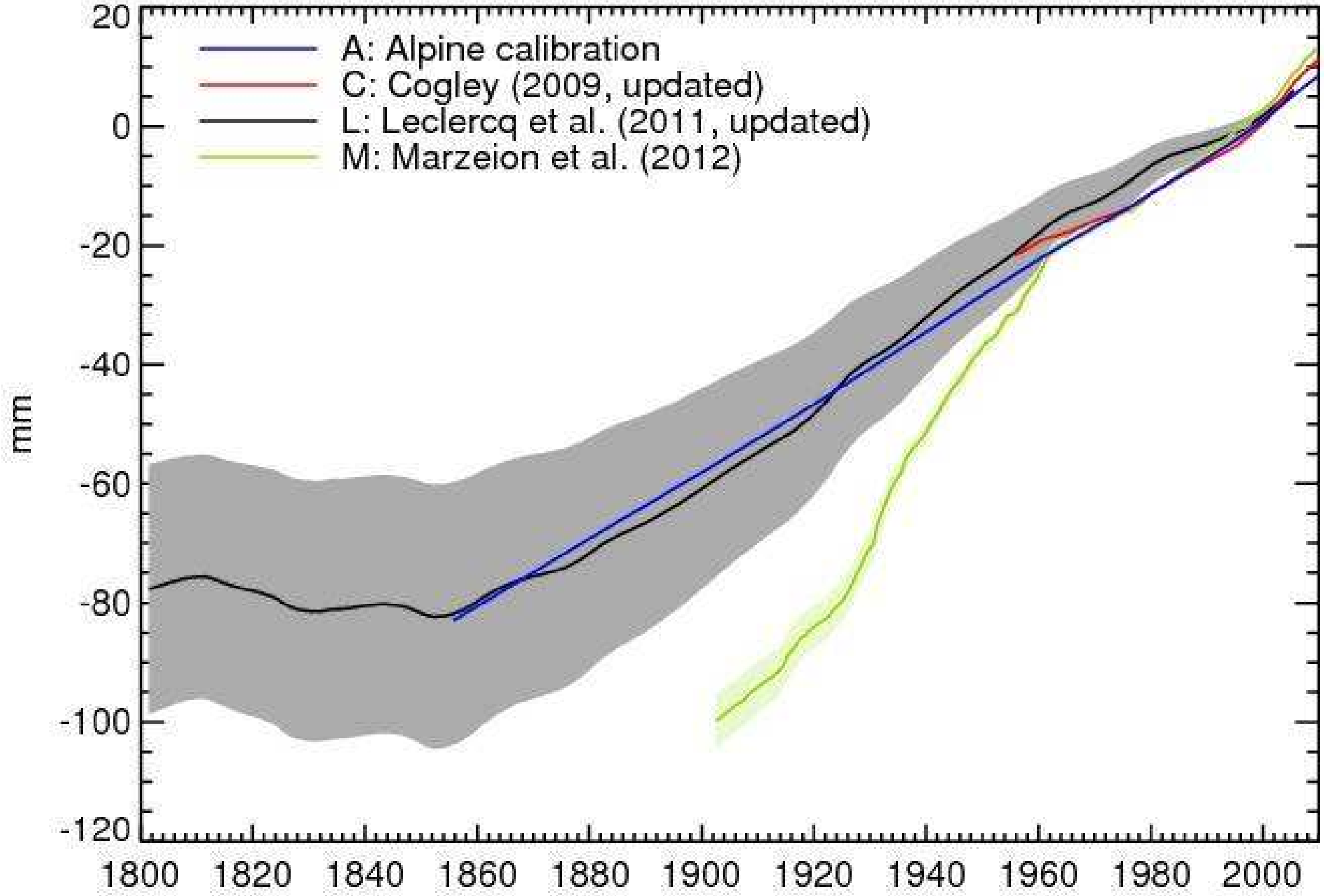
Glacier contribution to GMSLR



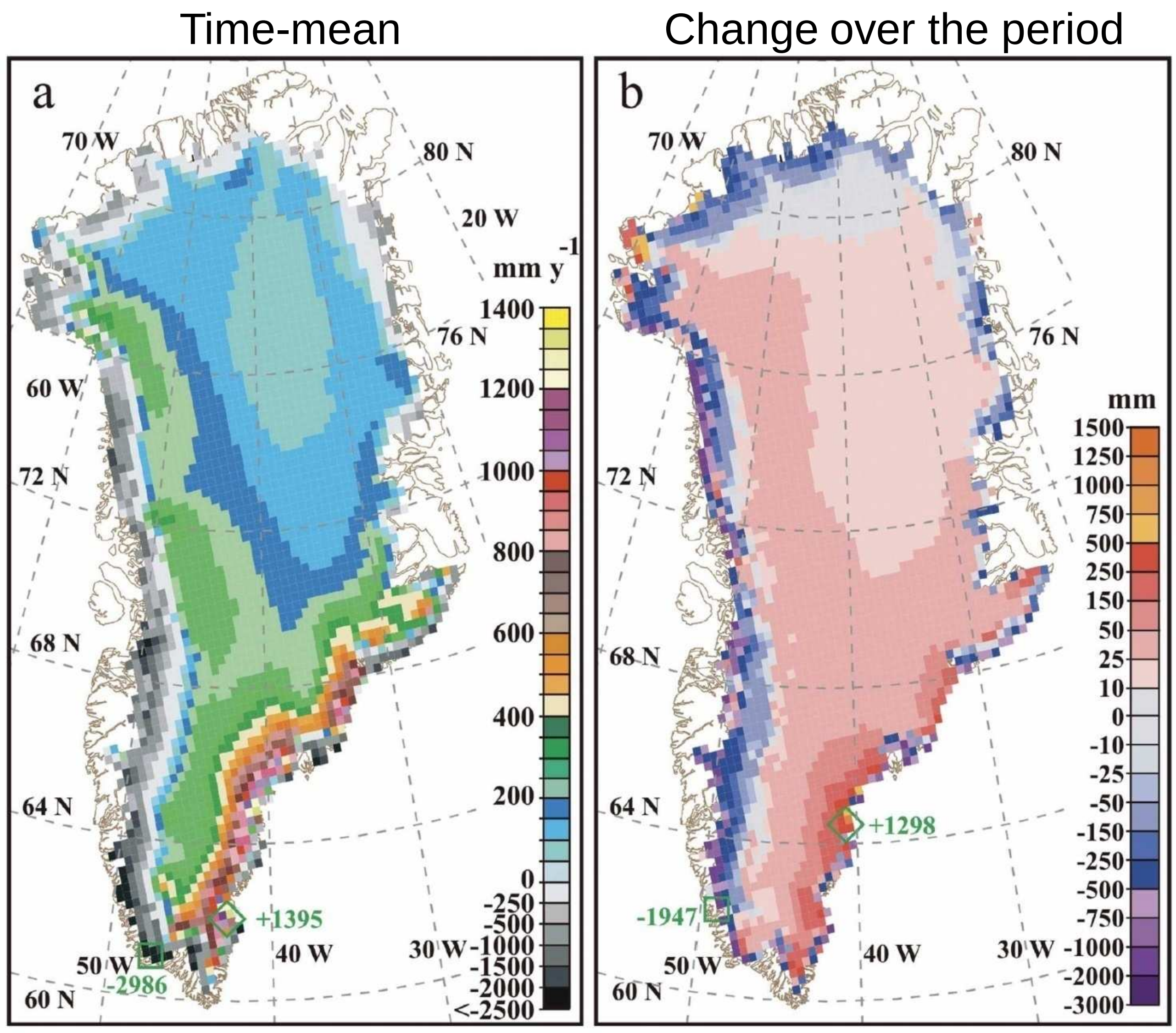
Glacier contribution to rate of GMSLR



Glacier contribution to GMSLR



Greenland ice-sheet surface mass balance (SMB, 1988-2004)



SMB

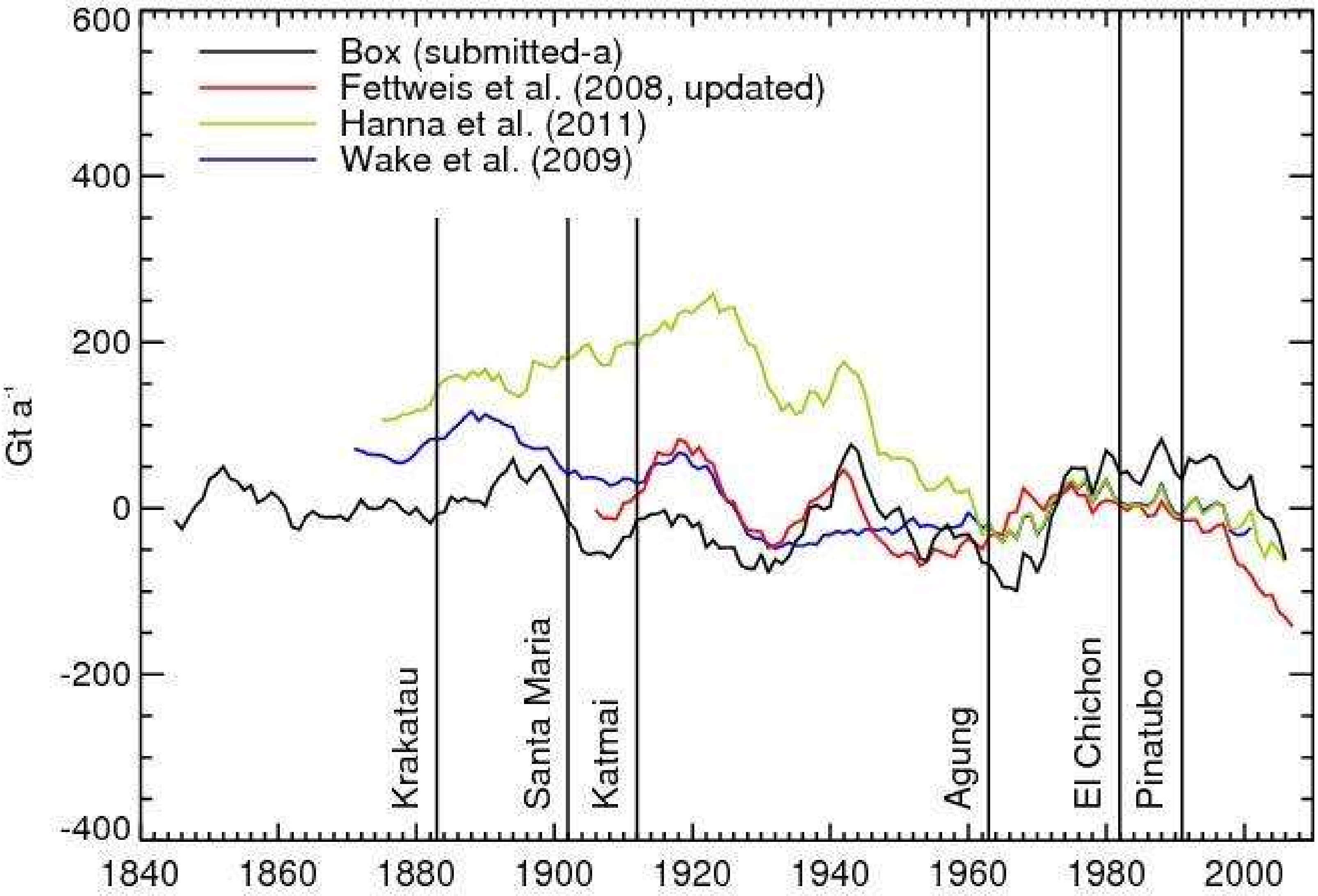
$S = P - R$

P Accum.

R Runoff

Box et al. (2006)

Greenland ice-sheet SMB anomaly wrt 1961-1990



Ice-sheet mass balance

NB: It may not be in balance!

$$dM_G/dt = S - D$$

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

Suppose that for some reference period $\langle dM_G/dt \rangle = 0 \Rightarrow \langle S \rangle - \langle D \rangle = 0$.

Define $\Delta X = X - \langle X \rangle$.

Then at any time

$$dM_G/dt = S - D = \Delta S - \Delta D + \langle S \rangle - \langle D \rangle = \Delta S - \Delta D.$$

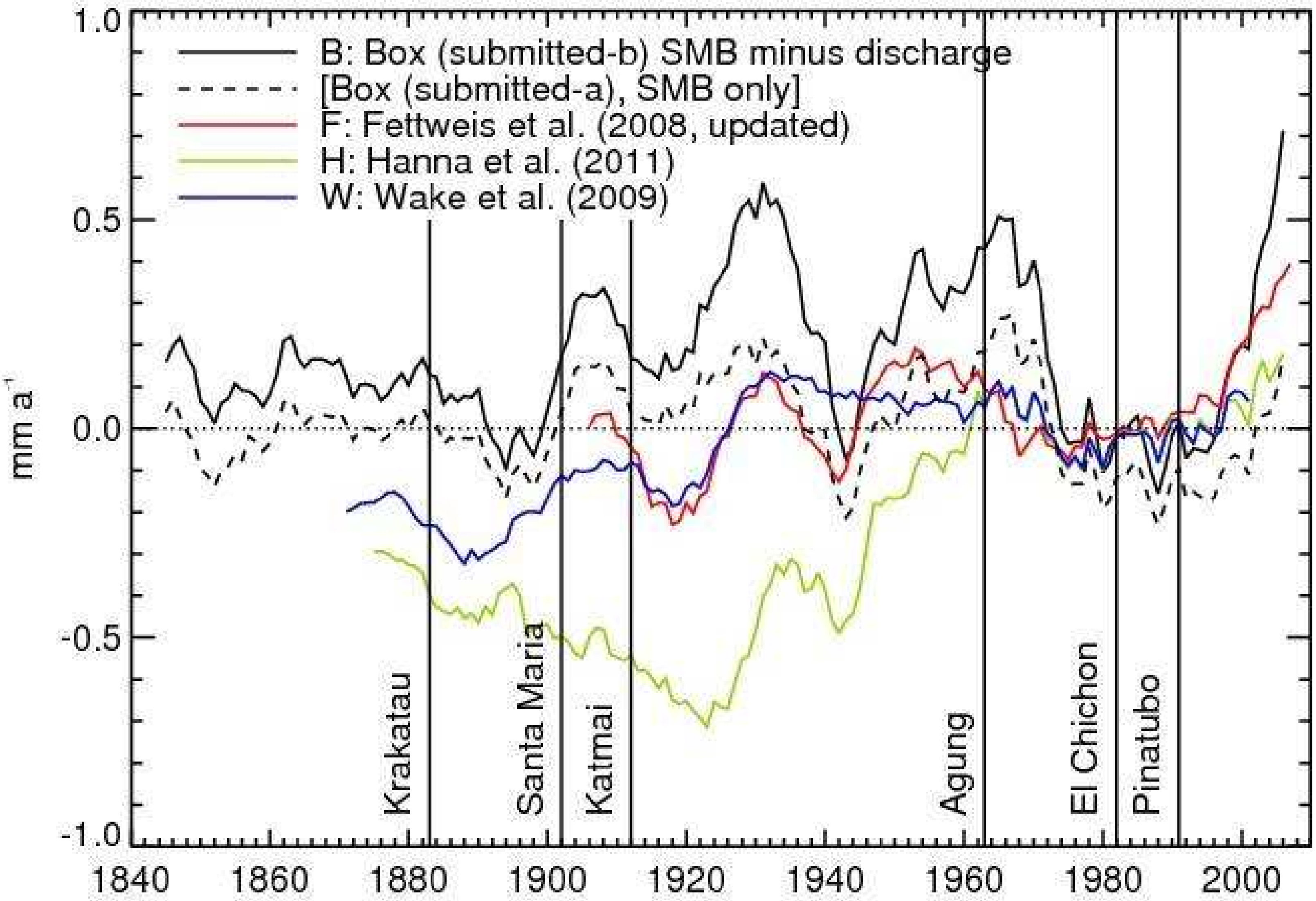
If we further assume that D does not change $\Rightarrow \Delta D = 0$, then

$$dM_G/dt = \Delta S$$

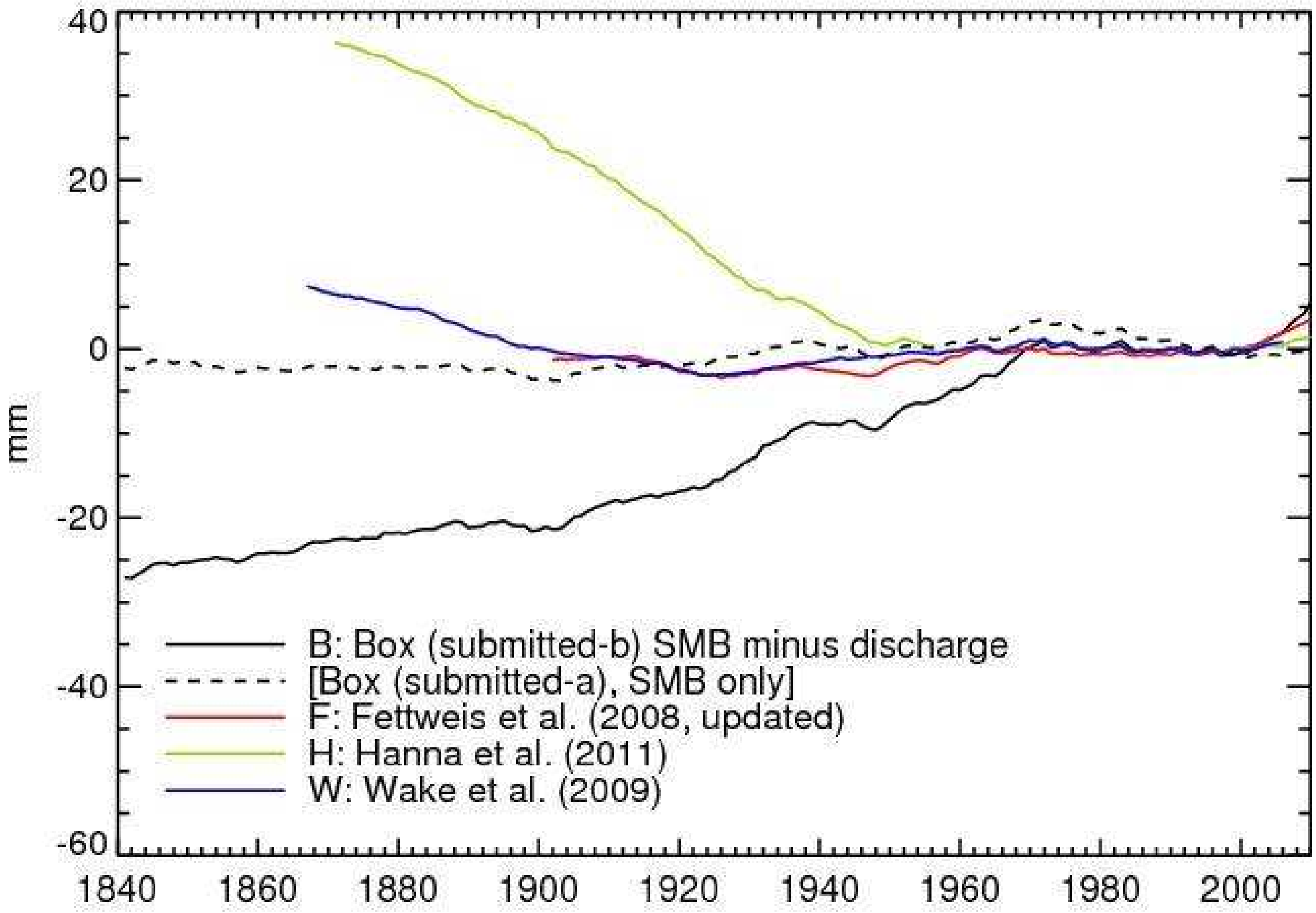
at any time (using only anomalies ΔS, not $\langle S \rangle$).

Alternatively, we need to estimate D.

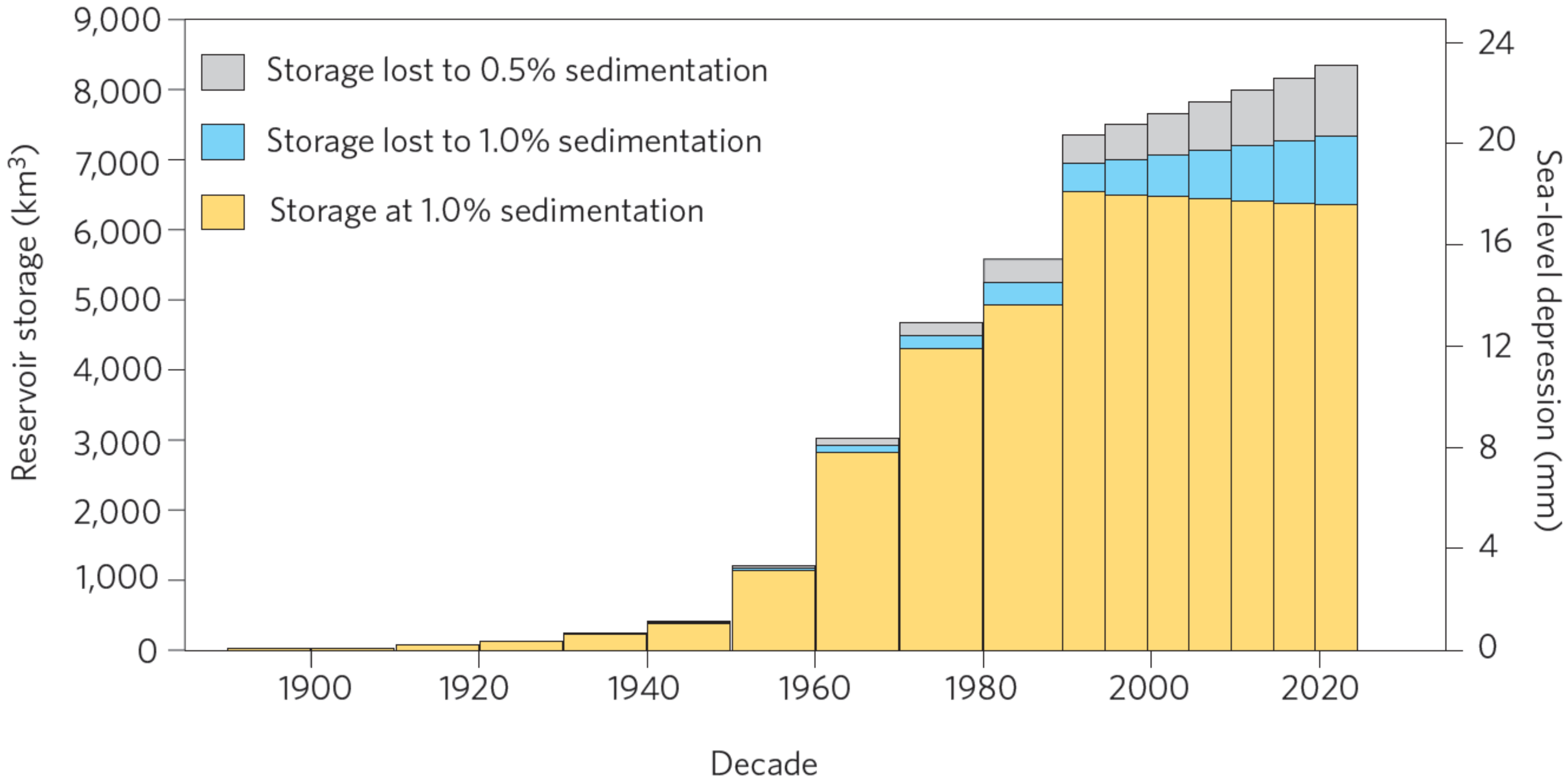
Greenland ice-sheet contribution to the rate of GMSLR



Greenland ice-sheet contribution to GMSLR

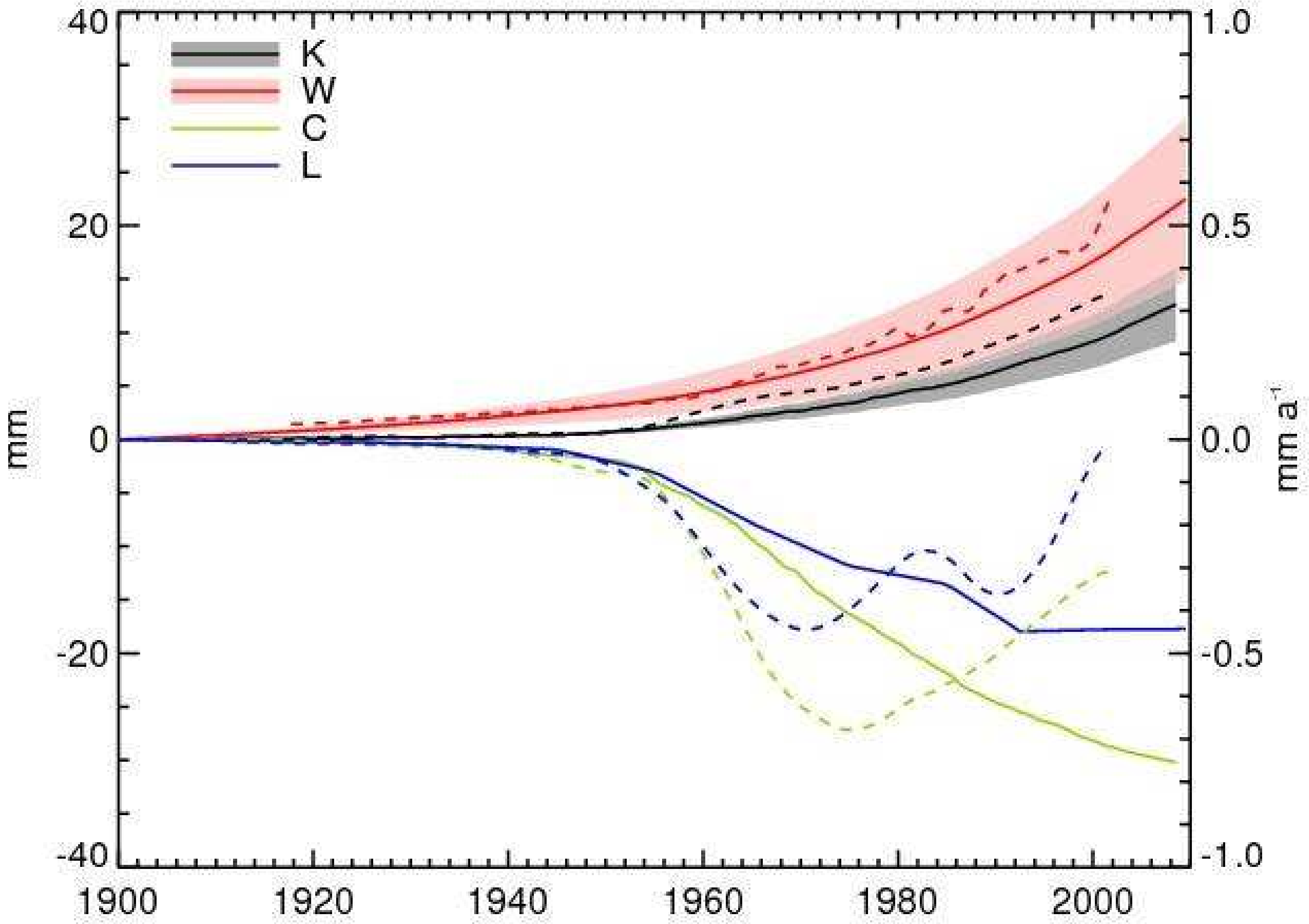


Anthropogenic GMSLR from reservoir impoundment



Lettenmaier and Milly (2009)

Contribution to GMSLR from anthropogenic intervention



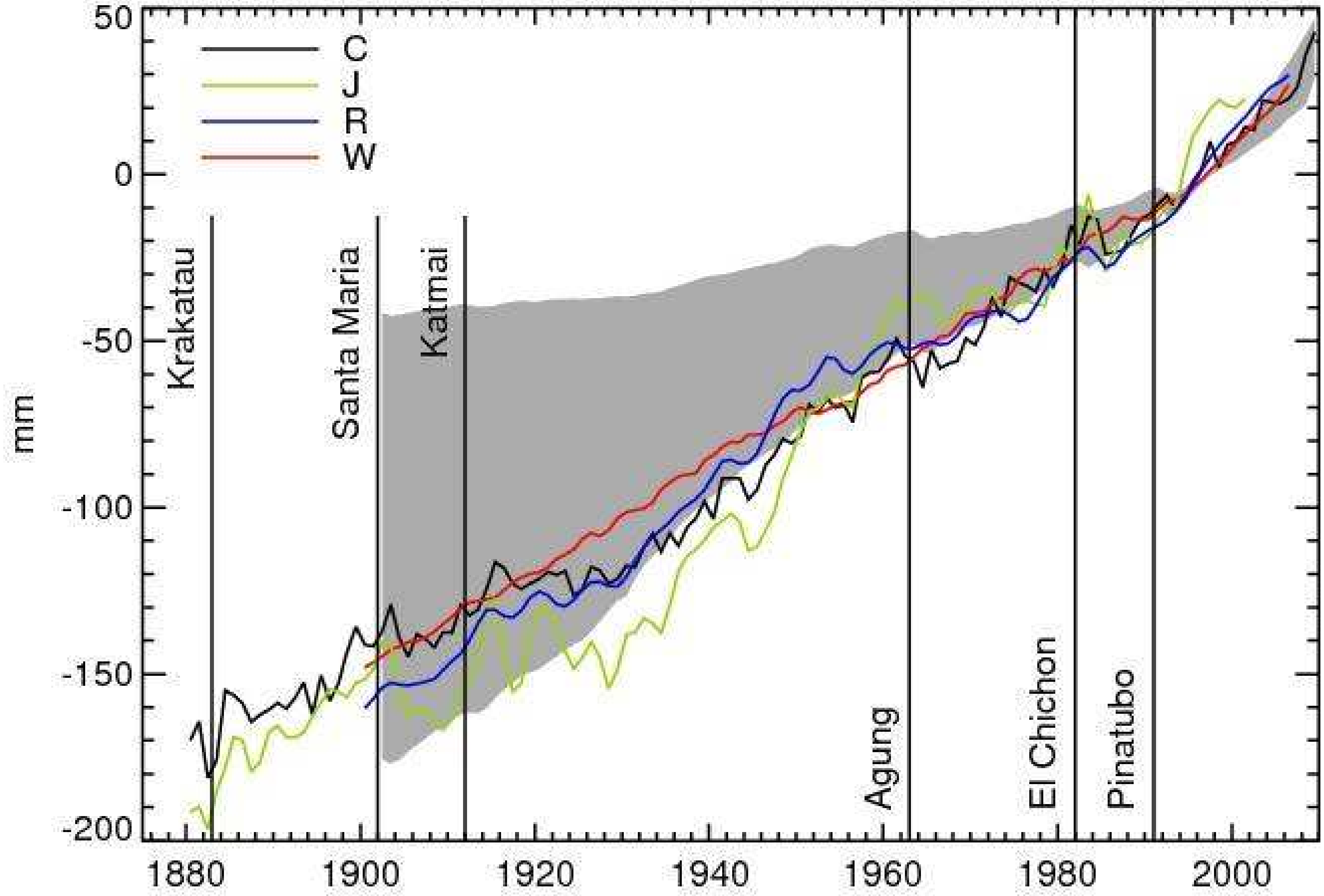
Synthetic timeseries of GMSLR

A synthetic timeseries is a sum of contributions

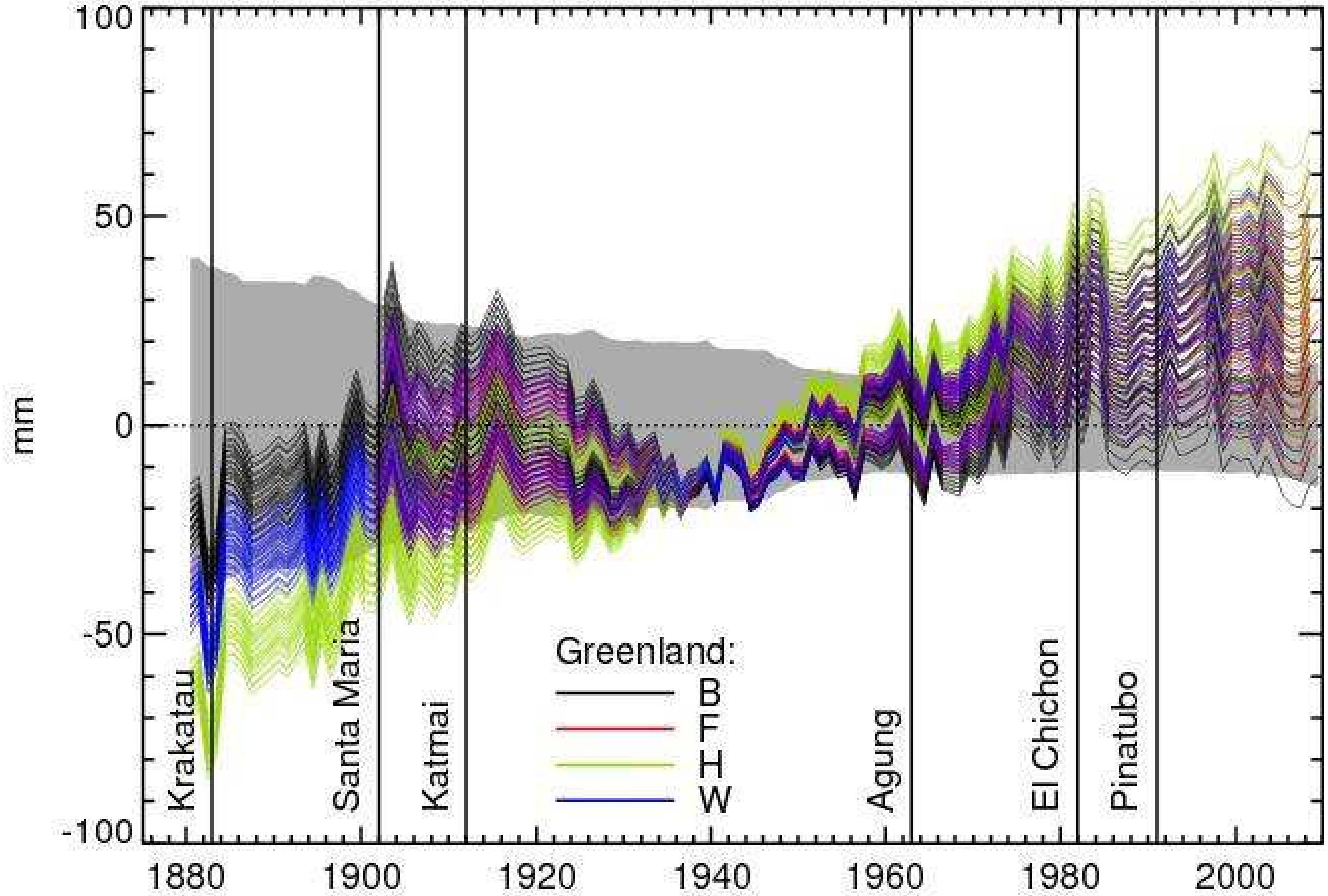
= Expansion (three choices)
+ Glacier (three)
+ Greenland ice-sheet (four)
+ Groundwater depletion (two)
+ Reservoir impoundment (two)

$3 \times 3 \times 4 \times 2 \times 2 = 144$ combinations

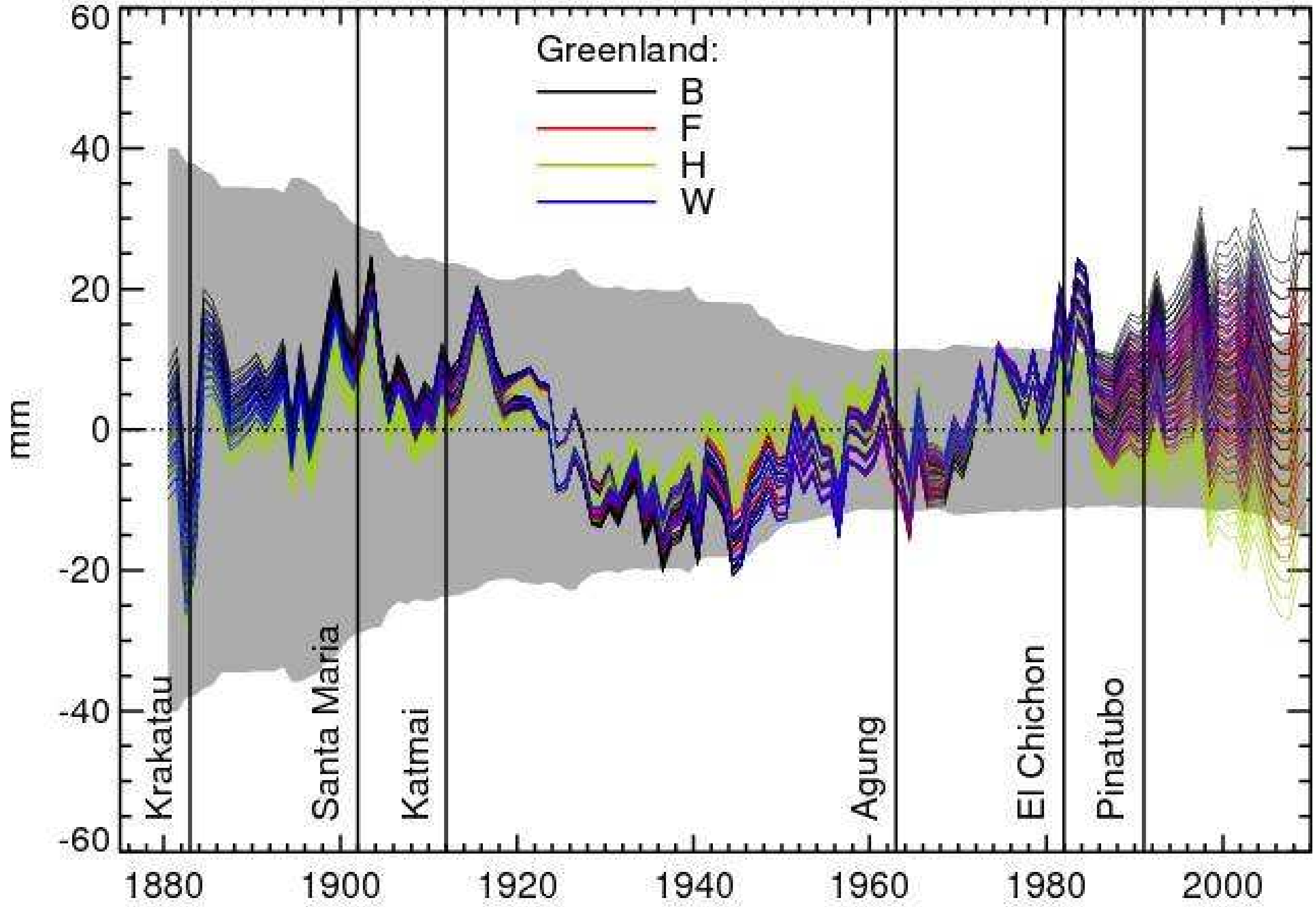
GMSLR from TGs compared with synthetic timeseries



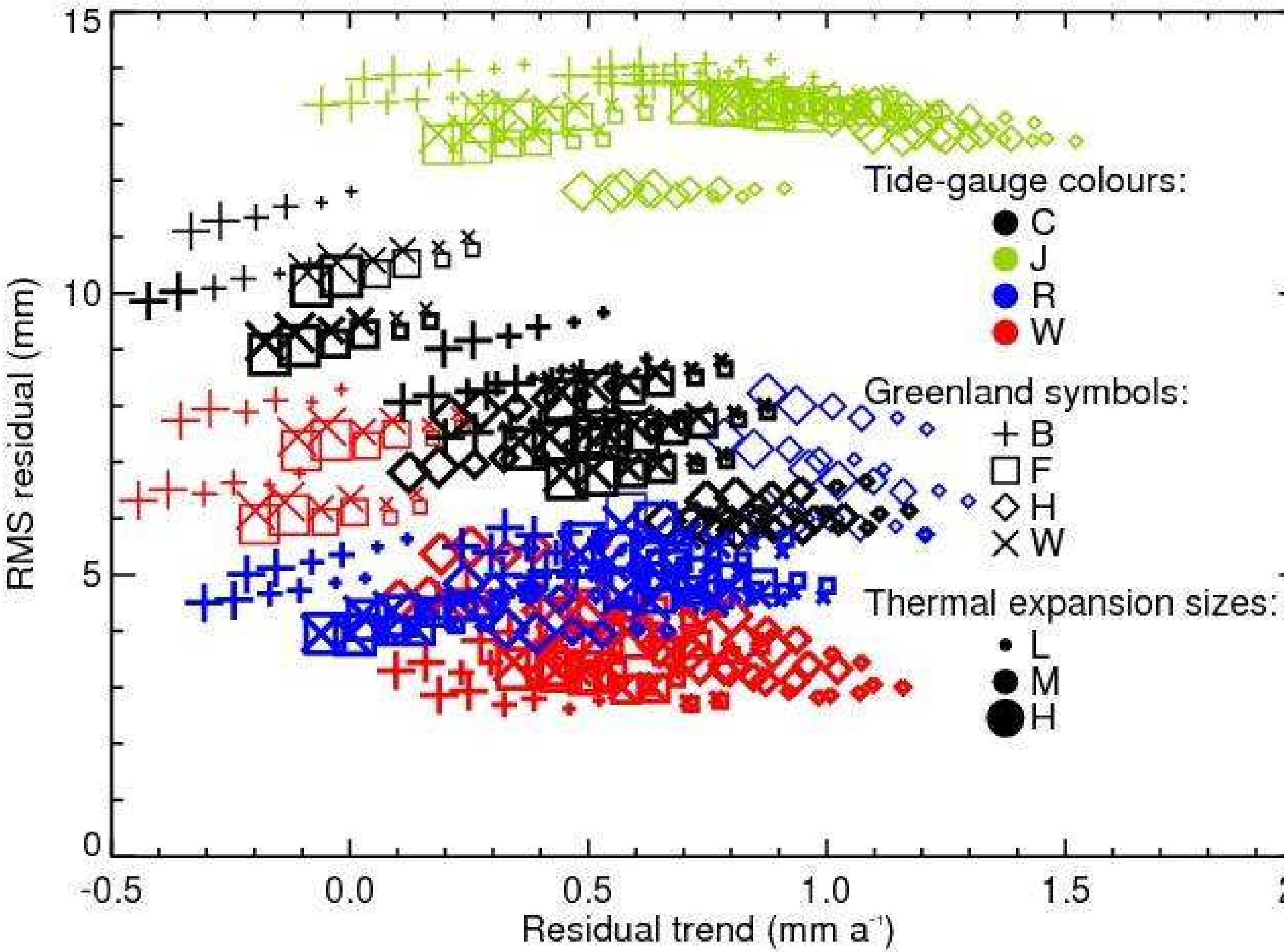
Observed GMSLR (TG-C) minus synthetic timeseries



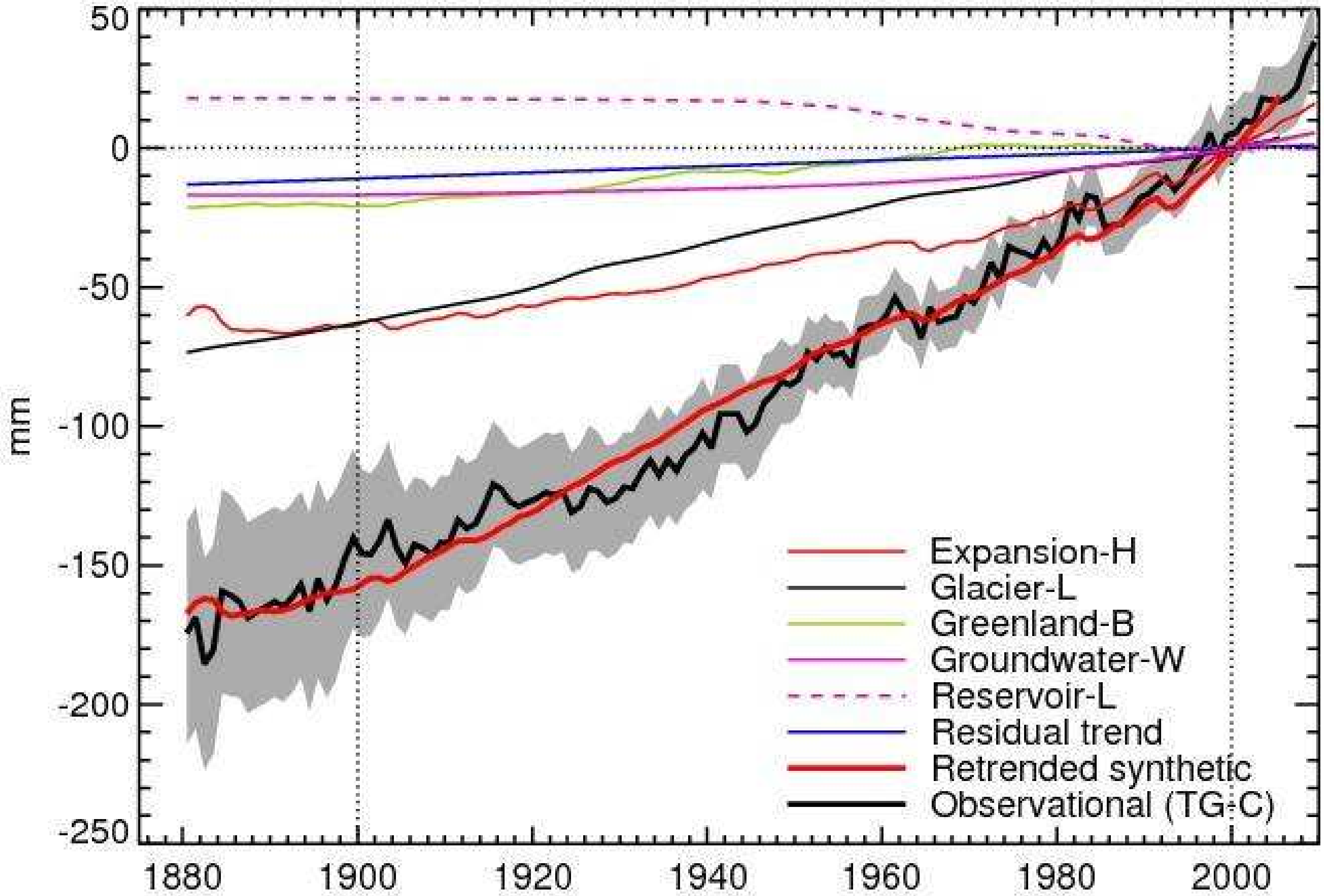
Observed GMSLR (TG-C) minus detrended synthetic timeseries



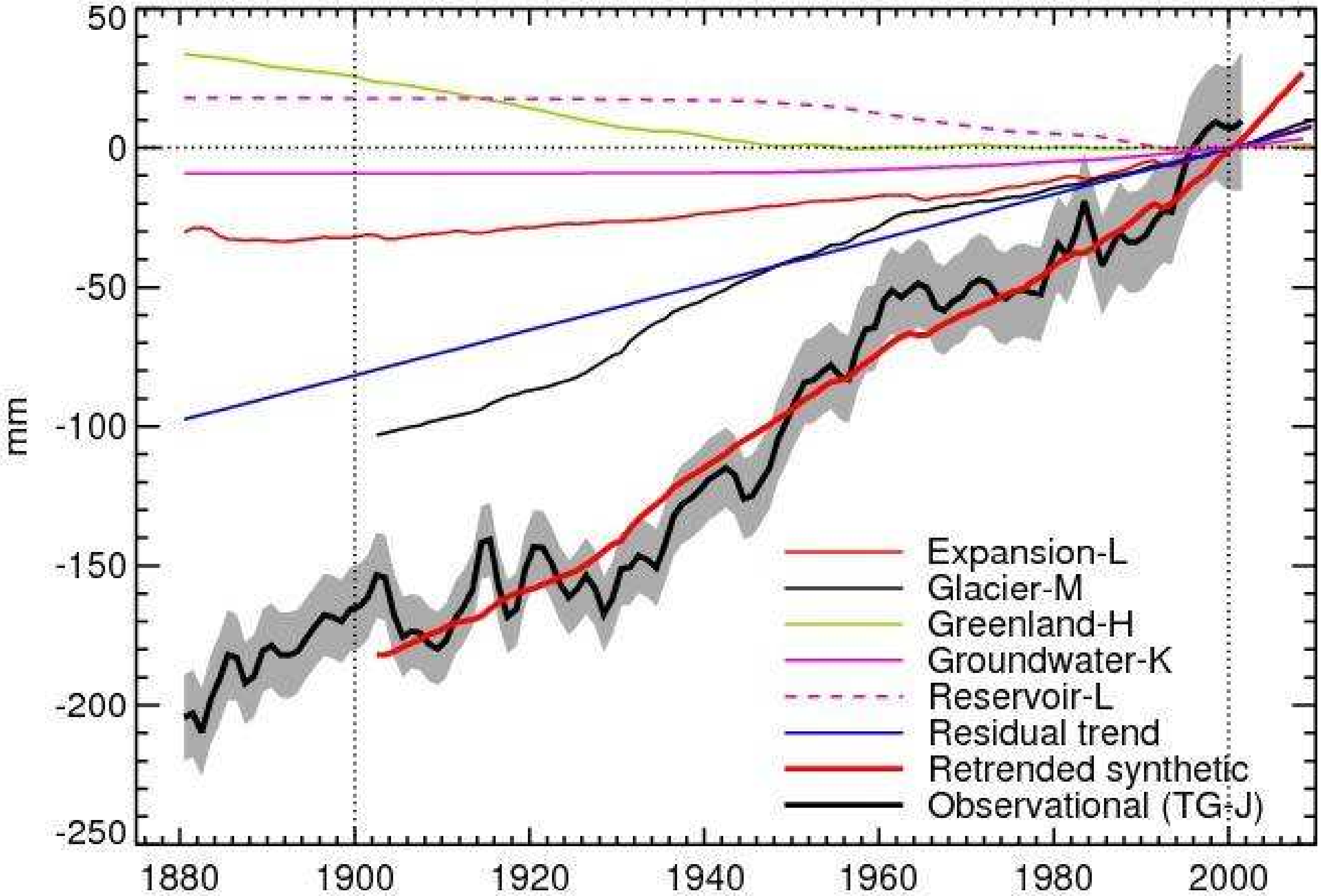
Residual trend and RMS



Observed and synthetic GMSLR (small residual)



Observed and synthetic GMSLR (large residual)



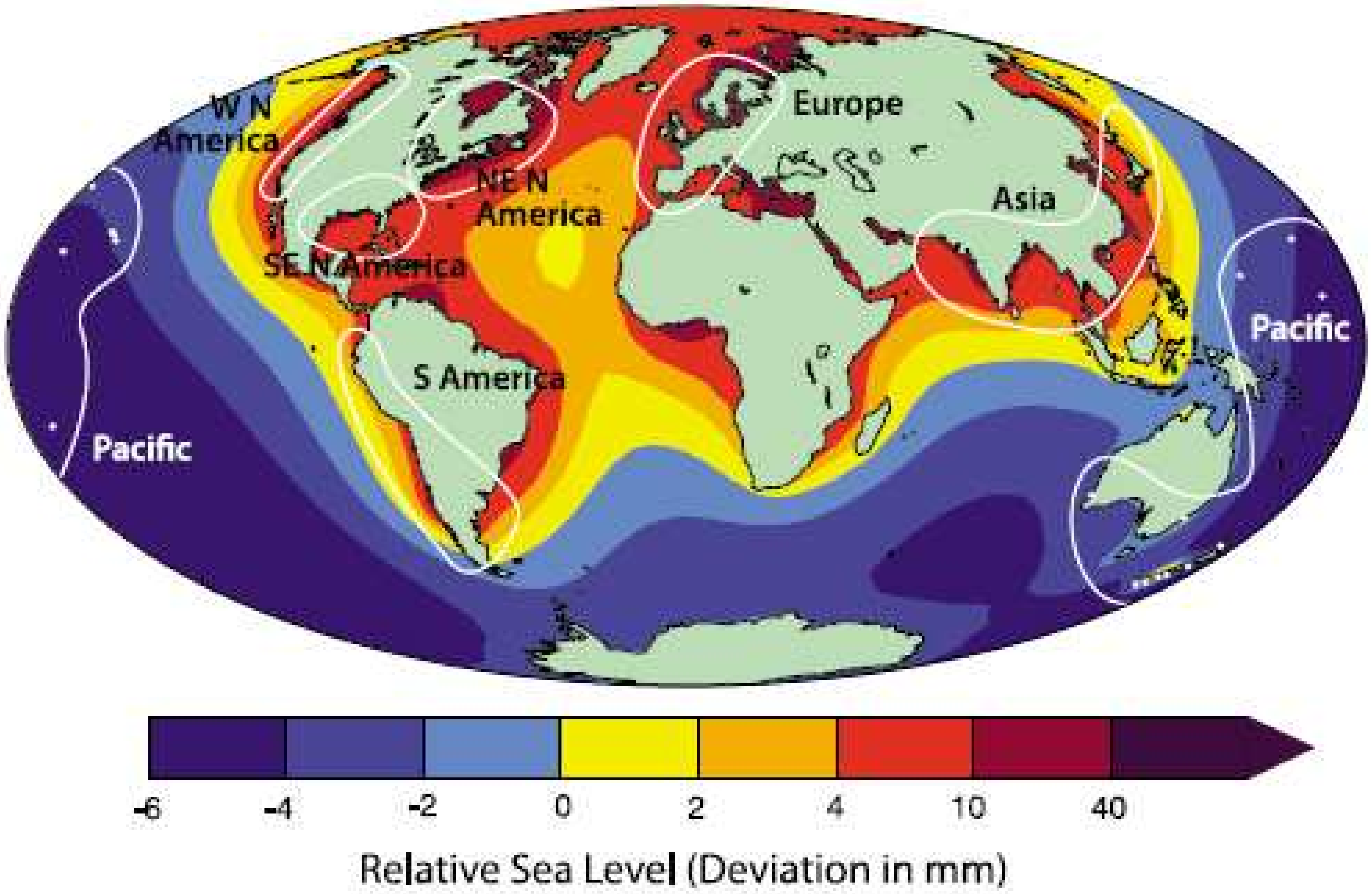
What is the cause of the residual trend?

Could it be a bias in the TG GMSLR estimates?

This could arise if

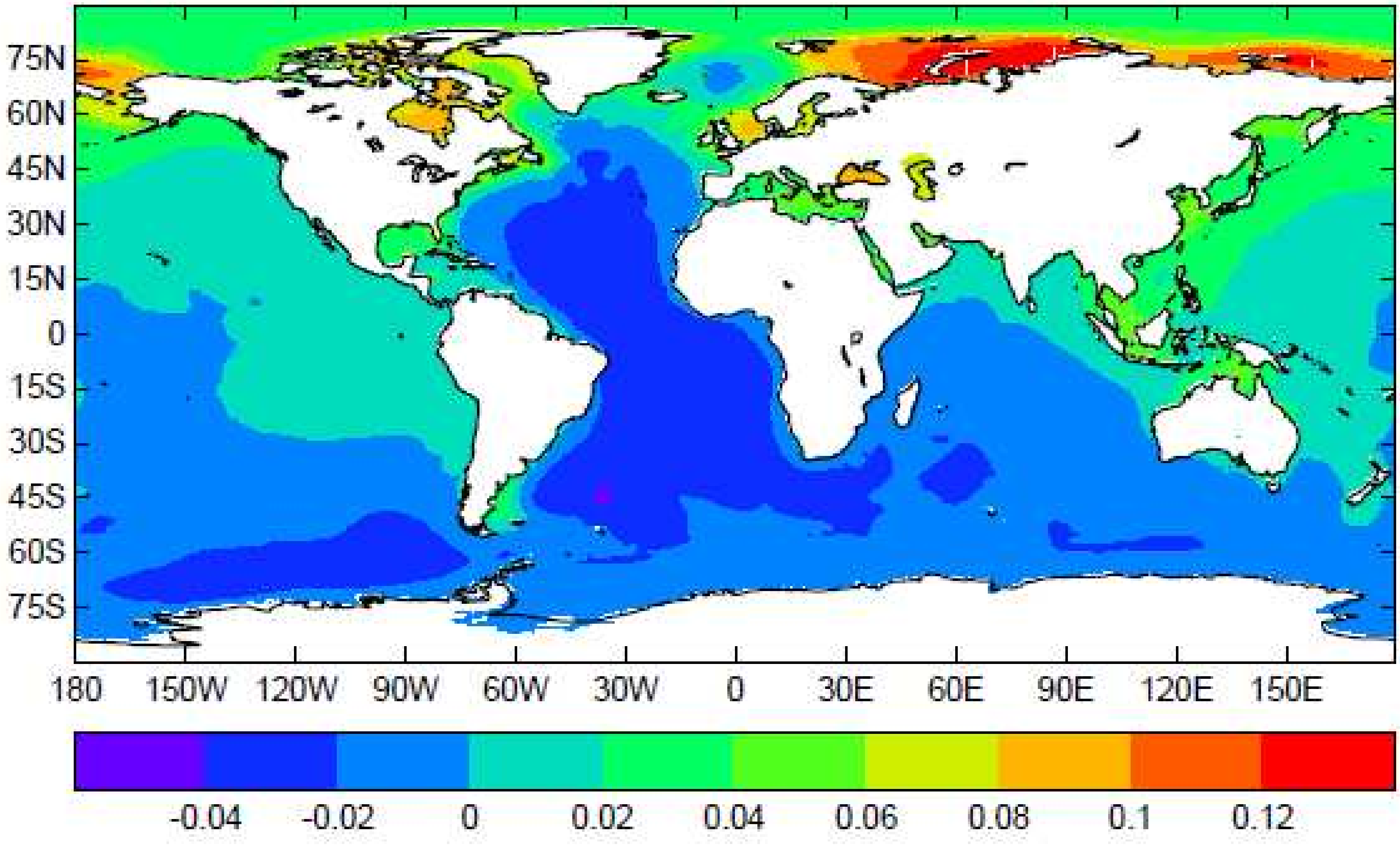
- Coastal sea level rise differs systematically from GMSLR for oceanographic reasons.
- Effects of contemporary changes in mass distribution (gravitational change, elastic flexure of the lithosphere, Earth rotational effects, *Gelirol*) cause a net bias in TG measurement of GMSLR.

Gelirol effects of impoundment in reservoirs



Fiedler and Conrad (2010)

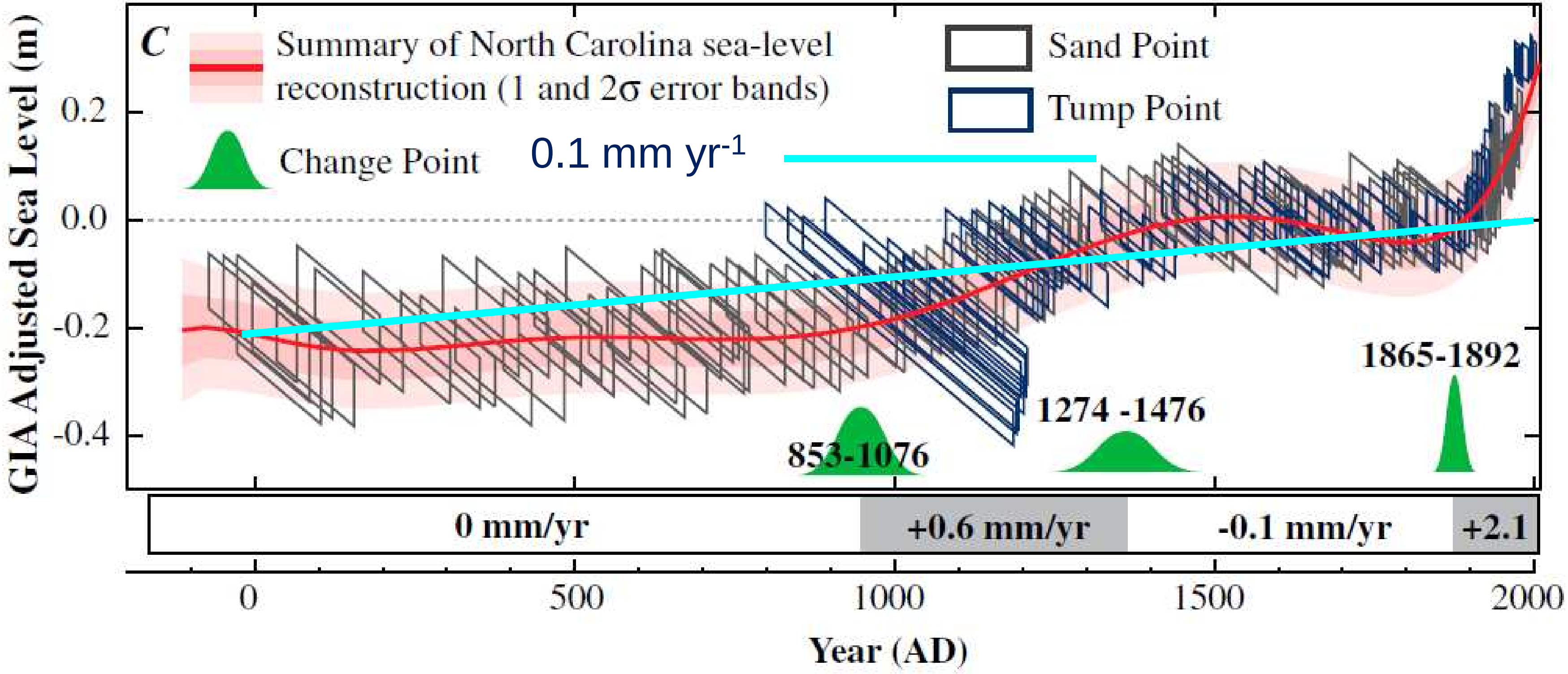
Gelirol effects of thermal expansion



Fraction of GMSLR due to thermal expansion

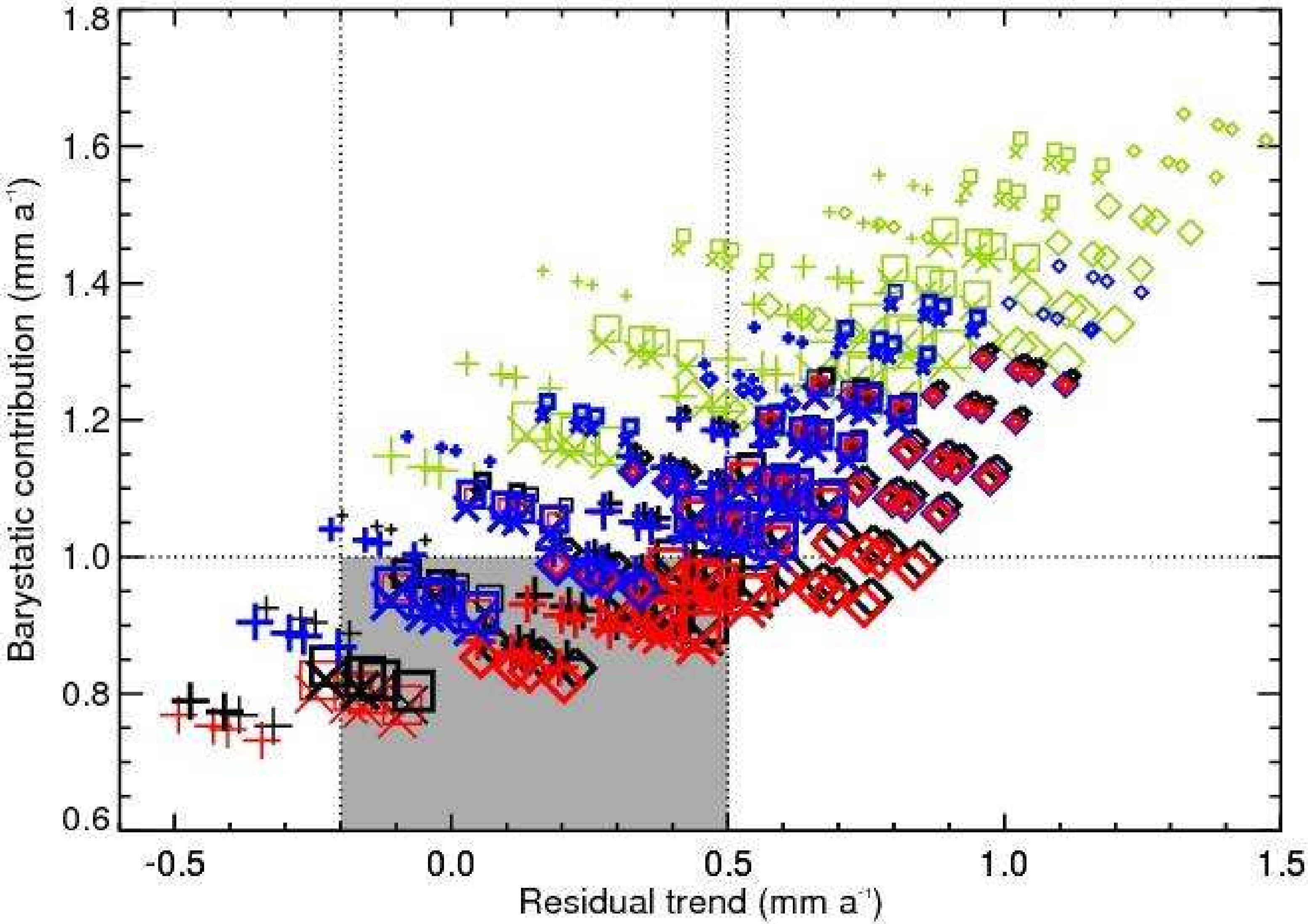
Could the residual be a long-term contribution to GMSLR?

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-laitutude 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 mm yr^{-1} $\Rightarrow$ barystatic contribution of 1.0 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 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.