

Semi-empirical modelling of the sea level – temperature relationship

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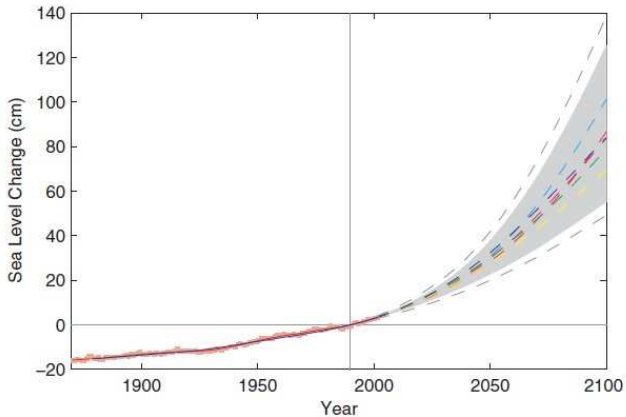
Monday November 2nd, 2009

Data used

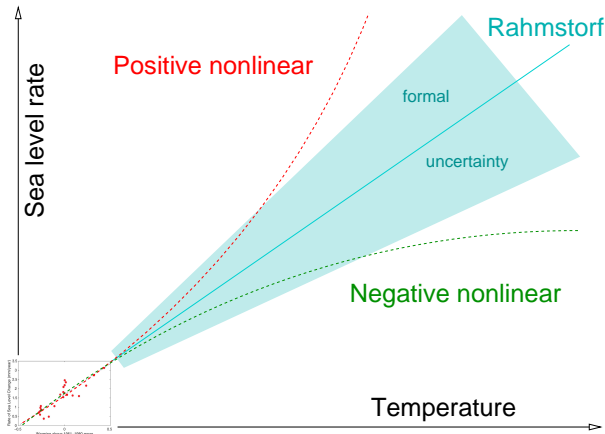
- ▶ Global sea level data from Church and White [CW06], derived by optimal combination of tide gauges and satellite radar altimetry, corrected for glacial isostatic adjustment (GIA), averaged to annual
- ▶ Global mean temperature anomaly data from GISTemp [HRS+01]
- ▶ Both data sets were smoothed using SSA [MGJ05] with an “embedding period” of 15 years, and binned into either 5-year or 15-year bins
- ▶ Regression of $\frac{dH}{dt}$ against T to obtain a and T_0 .

Projections to 2100 AD

based on IPCC Third Assessment Report [IPCC01] temperature scenarios.



Limitation: we are *extrapolating!*



Vermeer & Rahmstorf, in press with PNAS

- ▶ Rahmstorf (2007) model [Rah07]:

$$\frac{dH}{dt} = a(T - T_0),$$

with T_0 and a fit parameters. The a parameter describes the long-term response of both deep ocean and ice sheets to a temperature anomaly, cf. the "degree-day" rule of glaciology.

- ▶ New, **dual model** [VR09, in press]¹:

$$\frac{dH}{dt} = a(T - T_0) + b\frac{dT}{dt},$$

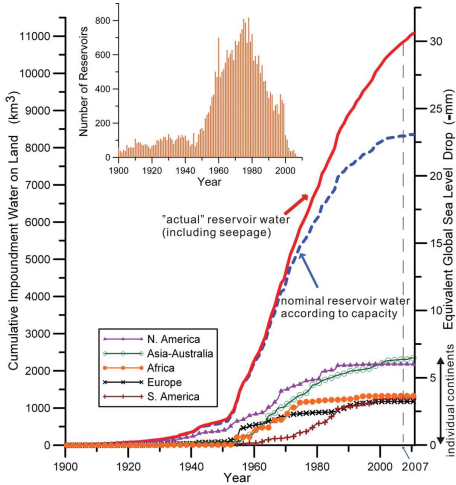
with a rapid response term and coefficient b added. Represents effects like the thermal expansion of ocean surface water, running to completion in a small number of years: $\frac{dH}{dt} \sim \frac{dT}{dt} \Rightarrow H \sim T$.

For fit to instrumental data, we obtain, surprisingly, a **negative** b .

Interpretation: **delay?**

¹Under embargo

Artificial reservoir effect

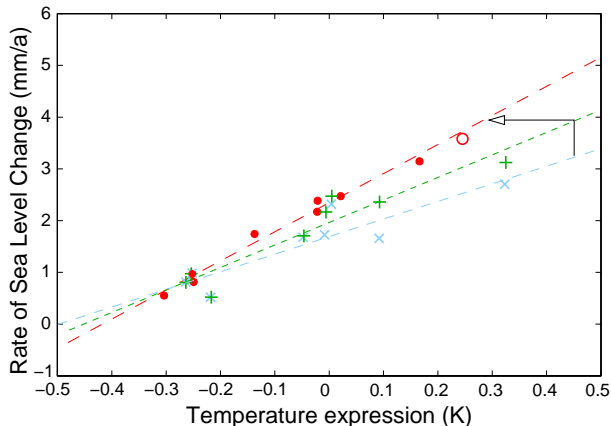


Chao *et al.* [CWL08] painstakingly tabulated the amount of water stored on land in artificial reservoirs. We use their curve, approximated by

$$\Delta H = 1.65 \text{ cm} + \frac{3.7 \text{ cm}}{\pi} \arctan \frac{t - 1978}{13},$$

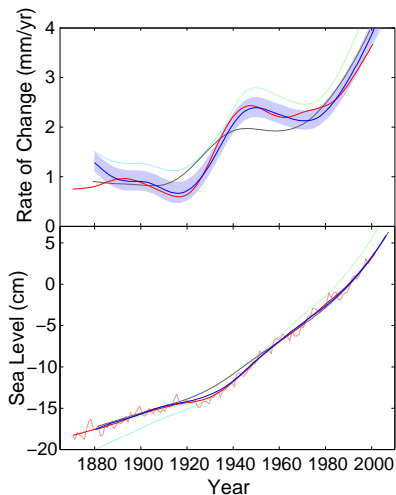
to correct our sea level time series from [CW06].

Dual model fit, stepwise improvement:



- Blue: original
Rahmstorf model
- Green: after applying
Chao *et al.*
- Red: after
introducing b
- Open circle:
satellite altimetry
(thx A. Cazenave)

... in the time domain:



Red: sea level data

Grey: original model fit

Blue: dual model fit

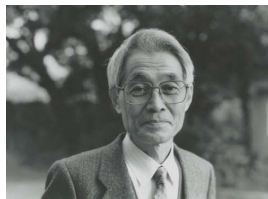
Light green, cyan: fits to
the first half and second
half of the data, respectively
(cross-validation)

Comparing the two models

Q. Is dual model fit significantly better?

A. Use Akaike Information Criterion (AIC_c, [Aka74, BA02])

	Original model (<i>a</i> only)	Dual model (<i>a</i> and <i>b</i>)
<i>K</i>	4	5
RSS (cm ²)	1.053	0.098
AIC _c	5.11	4.75
Parameters	<i>a</i> , <i>T</i> ₀ , <i>H</i> (<i>t</i> ₀), <i>σ</i> ²	<i>a</i> , <i>b</i> , <i>T</i> ₀ , <i>H</i> (<i>t</i> ₀), <i>σ</i> ²



Hirotugu Akaike 1927-2009

$$AIC_c = 2K + n \ln \frac{RSS}{n} + \frac{2K(K+1)}{n-K-1},$$

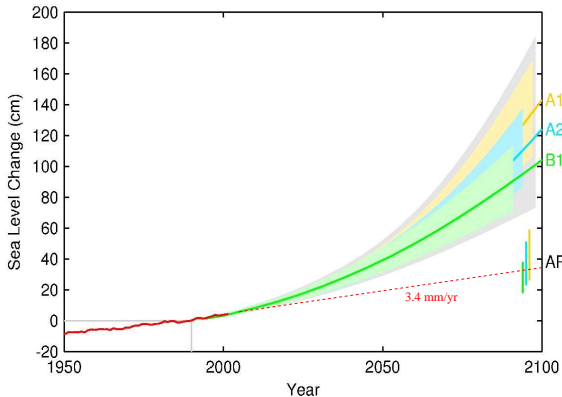
n number of data points (8)

K number of fit parameters including error variance *σ*²

H(*t*₀) sea level integration constant.

Dual model is "better", even considering extra parameter and fewer DoF.

Dual model for 2100, and lessons



- ▶ Based on IPCC Fourth Assessment Report [IPC07]
- ▶ Higher still (but **extrapolation** problem hasn't gone away!)
- ▶ Greatest inference uncertainty: emissions \Rightarrow temperatures, not temperatures \Rightarrow sea level
- ▶ Cuts needed to bring 2100AD sea level down must come **early**.

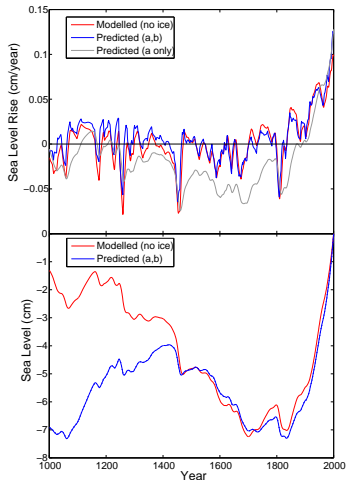
The millennium run (1)

120 years, or eight 15-year bins, of instrumental data is very little. We don't have a thousand years of precise instrumental data, but we can *simulate* it – for **both** sea level and global mean temperature – using a **general circulation model** (GCM). We did so using the model CLIMBER-3 α [MGL⁺05].

- ▶ Does not model **land ice processes**
- ▶ However, in many ways physically realistic, containing the effects of Solar variability, volcanic eruptions, greenhouse gases and tropospheric aerosols
- ▶ Also two other models were tested: ECHO-G [vSZGR08] and ECBilt-CLIO [GRTB05].
- ▶ Variance explained 65-80%; better if (unrealistically) volcanic forcing "lumped" over latitude zones.

The millennium run (2)

- ▶ Generated using the parameters fitted to a 1880-2000 simulation run.
- ▶ 15-year SSA smoothed
- ▶ **Red**: model output for sea level
- ▶ **Grey**: predicted using the a -only model
- ▶ **Blue**: predicted using the dual (a, b) model. Note better capture of volcanic features
- ▶ Top: $\frac{dH}{dt}$, bottom: H .
- ▶ Small offset to T_0 applied to eliminate drift 1500-1900; < 1400 needs different offset.



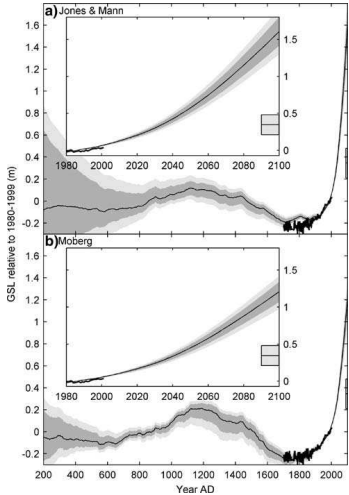
Grinsted et al. (2009)

Interesting study: Grinsted *et al.* (2009) [GMJ09], who found on millennial time scale a sea level response component to temperature with time scale of a few hundred (up to a thousand) years.

Grinsted *et al.* used in addition to the instrumental record, two proxy reconstructions, those of [MSH⁺05], and of [JM04]. Additionally, they used the very long sea level record of Amsterdam for calibration.

Several other loose constraints were imposed.

Results



The Grinsted *et al.* model is

$$H_{eq}(T) = aT(t) + b,$$

$$\tau \frac{dH(t)}{dt} = -(H(t) - H_{eq}(T)),$$

where H_{eq} is an "equilibrium sea level" at which ocean volume is assumed to remain constant. Real sea level H slowly tracks H_{eq} with a delay, or decay, time scale τ .

Upcoming paleo study

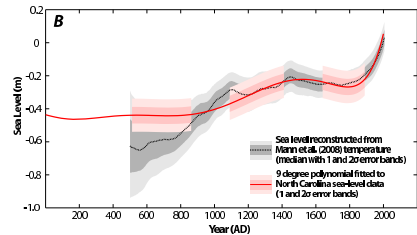
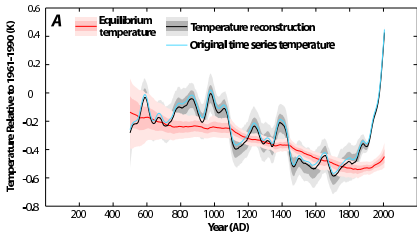
We have in preparation a study which replicates and improves on [GMJ09]. It uses as data:

- ▶ Mann *et al.* (2008) [MZH⁺08] for temperatures
- ▶ Superior quality sea level reconstructions by Kemp and Horton for the past two millennia from salt marsh proxies on the U.S. East Coast, e.g., [HPC⁺09].

The technique used by us was similar: Monte Carlo simulation of Bayesian inference. Temperature was inverted to a sea level prior using a variant of the Grinsted model, but with a non-zero “background” sea level rise. The posterior was obtained by fit to the sea level proxy data from salt marshes.

We use an equilibrium temperature $T_0(t)$ rather than equilibrium sea level $H_{eq}(T)$.

Results (1)



A: Temperature curve from [MZH⁺08] (blue). *A posteriori* temperature curve (black/grey). Equilibrium temperature $T_0(t)$ (red/pink).

B: *A posteriori* sea level curve (black/grey). Sea level proxy data represented by a polynomial fit, cutaway view (red/pink).

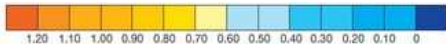
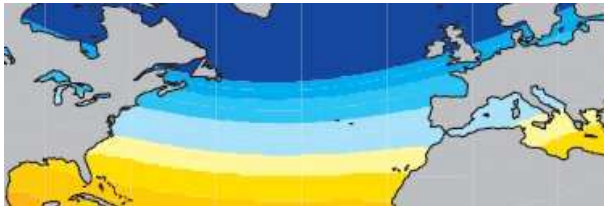
Uncertainty bands 1σ and 2σ .

Results (2)

- ▶ We find an optimal τ value of ~ 400 years but with rather much uncertainty: 200-1000 years. Our results are **not** compatible with $\tau = \infty$
- ▶ The background sea level rise rate ("infinite" time scale) is **non-zero** (though small)
- ▶ For the 20th and 21st Centuries, model reduces to earlier (dual) one – a design constraint
- ▶ Work done by: Andrew Kemp, Ben Horton, Jeff Donnelly, Stefan Rahmstorf, Michael E. Mann and yours truly.

Greenland fingerprint

Sea level rise is far from uniform!



When using proxy sea level data, one should consider, besides the correction for glacial isostatic adjustment after the last ice age, also the **fingerprint** of the various continental ice sheets.

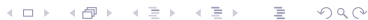
Left: Greenland, Mitrovica *et al.* 2001 [MTDM01].

Thank you!



Questions?

Photo: Liisa Vermeer





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