The present rate of sea level rise is far exceeding anything seen in the past 2000 years

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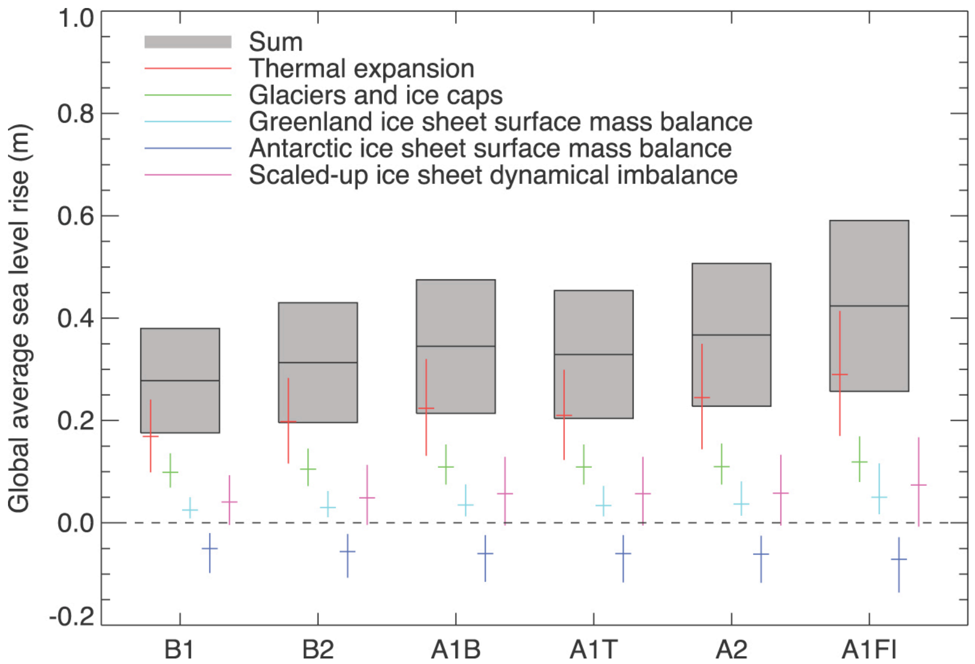
Outline

- Motivation
- Objectives
- Data and model
- Results (reconstruction since 200 AD, projections)
- Conclusion

Motivation

- What is the future sea level rise?

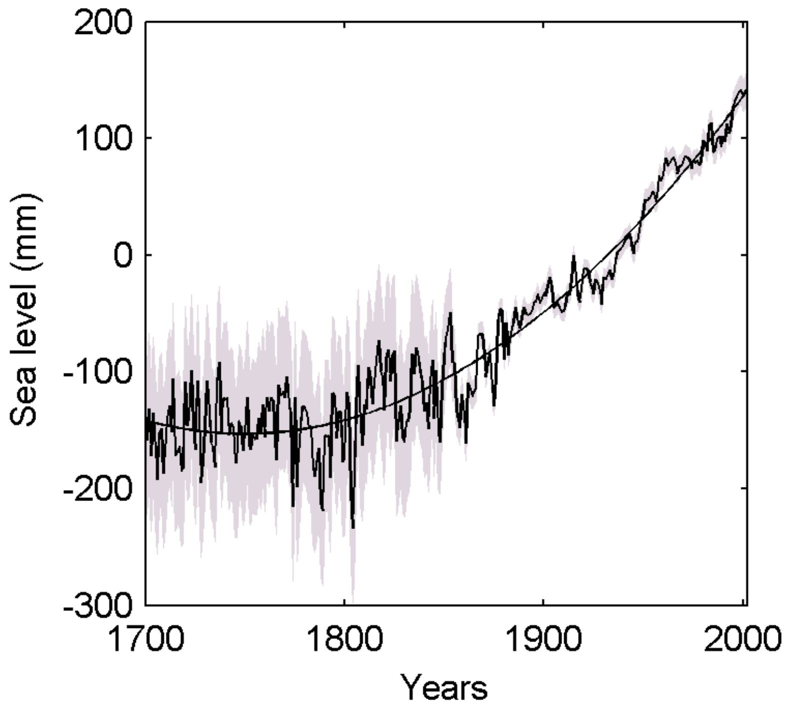


1.8°C 2.4°C 2.4°C 2.8°C 3.4°C 4.0°C

IPCC, 2007

Motivation

Global sea level (tide gauge based) reconstruction since 1700



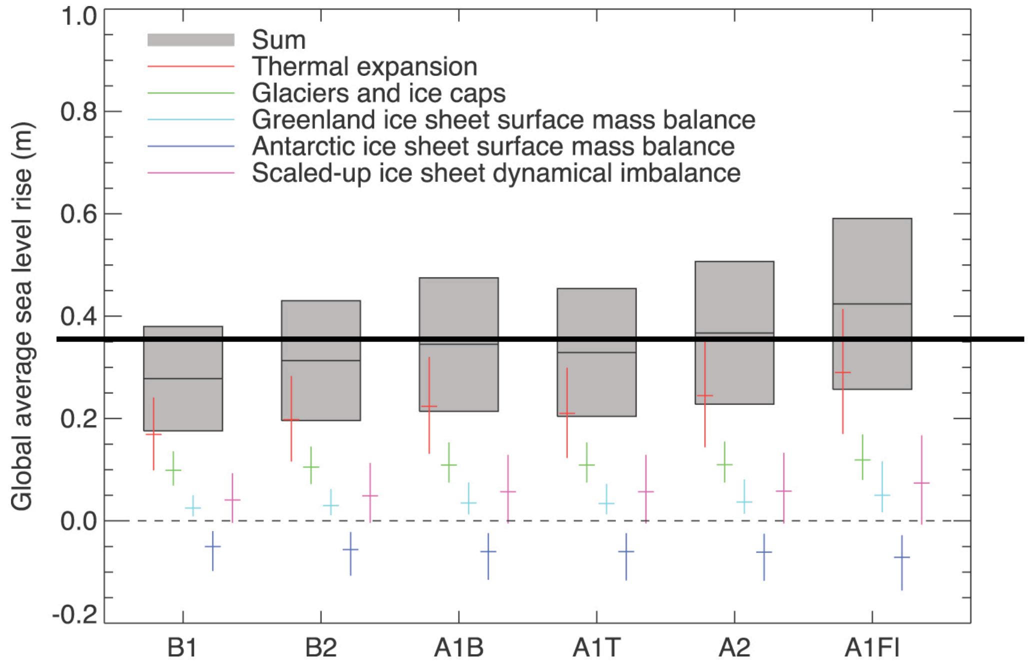
Sea level rise

1700-1800 **2** cm
1800-1900 **6** cm
1900-2000 **19** cm

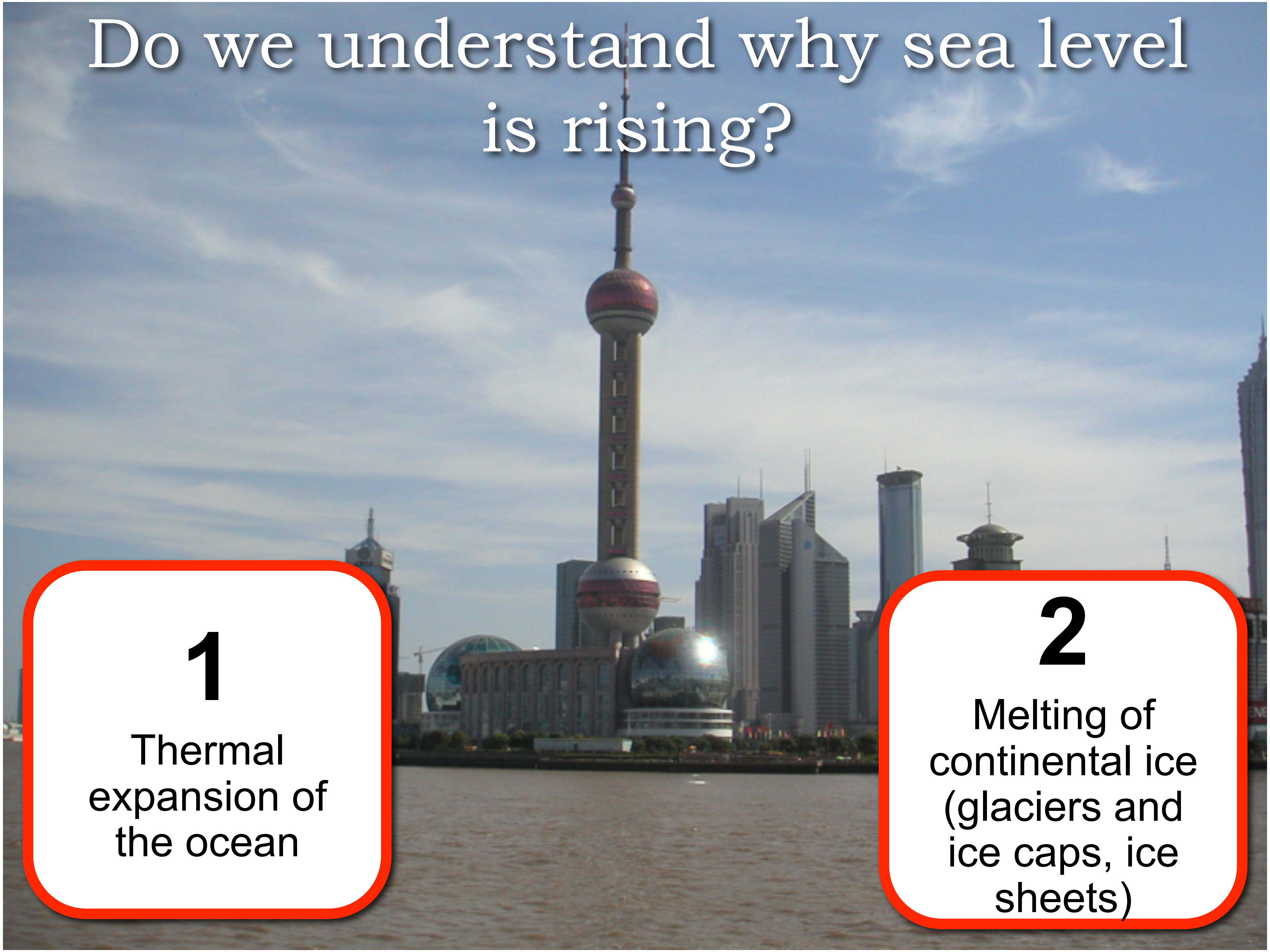
2000-2090 34cm

Jevrejeva et al., 2008, GRL

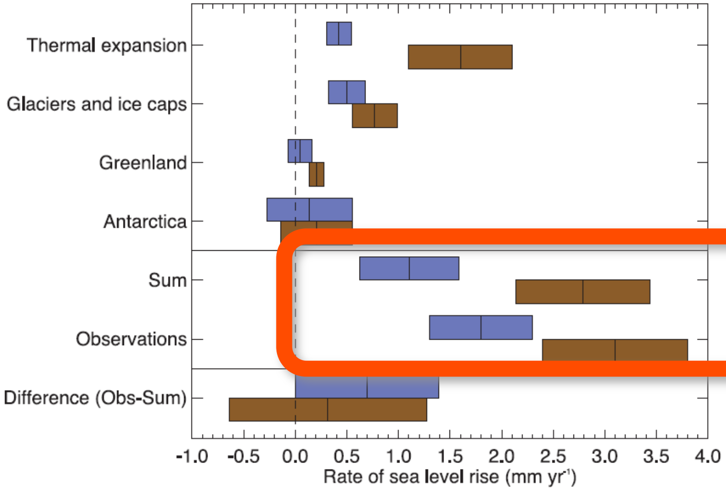
Motivation



1.8°C 2.4°C 2.4°C 2.8°C 3.4°C 4.0°C.


Do we understand why sea level is rising?
1
Thermal expansion of the ocean
2
Melting of continental ice (glaciers and ice caps, ice sheets)

Main components of sea level balance

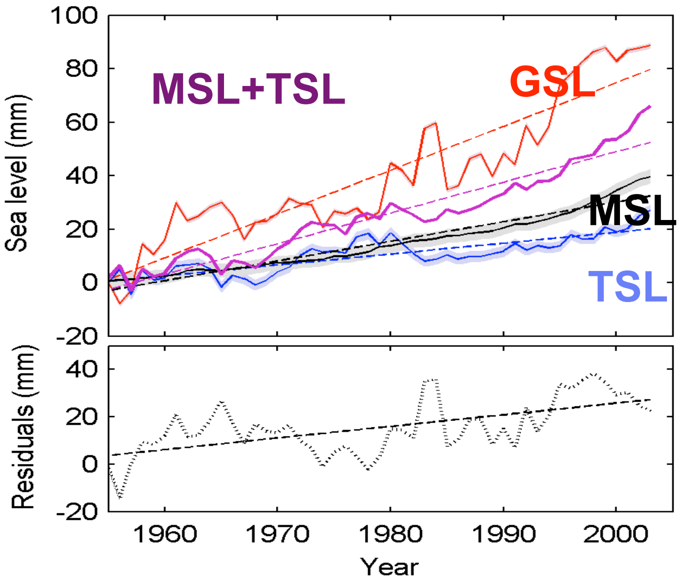


1961-2003

1993-2003

We still have quite a lot to explain….

IPCC 4AR



Observed Sea Level (**GSL**)

Melting of Greenland, Antarctica & glaciers (**MSL)**

Thermosteric hydrographic data (**TSL**)

Unexplained residuals (**GSL** - **TSL** - **MSL**) = 0.41 mm/yr (25%)

Jevrejeva et al., 2008, JGR

Objectives

Objectives

- To establish a semi-empirical model to relate 2000 years of global temperatures and sea level
- To produce a reconstruction, with confidence limits, of past sea level over the past 2000 years
- Using our semi-empirical model and global temperature scenarios from IPCC to make predictions of sea level rise by the end of the 21st century

Model including a response time

It is reasonable to assume that there exists an equilibrium sea level (*Seq*) for a given temperature. The relationship between *Seq* and *T* must be non-linear for large changes in sea level and temperature, such as those that occur on glacial-interglacial timescales, and there may be multiple equilibria depending on the initial conditions. However, for the late Holocene-Anthropocene climate, where changes in sea level are much smaller, we can linearize as

$$S_{eq} = aT + b, \quad \text{(eq.1)}$$

where a is the coefficient of sea level to a temperature change and b is a constant.

Changes in sea level are caused primarily by changes in global ice volume and glol
heat content (Bindoff et al., 2007), both of which will have a response time to warmi
ice melt and ocean warming will occur faster the further the system is from equilibri
therefore assume that sea level will approach *Seq* with a characteristic response tir
follows

$$\frac{\partial S}{\partial t} = (S_{eq} - S)/\tau, \quad \text{(eq.2)}$$

S=f(T)

Parameters:

(τ, a, b, S_0)

Inverse problem

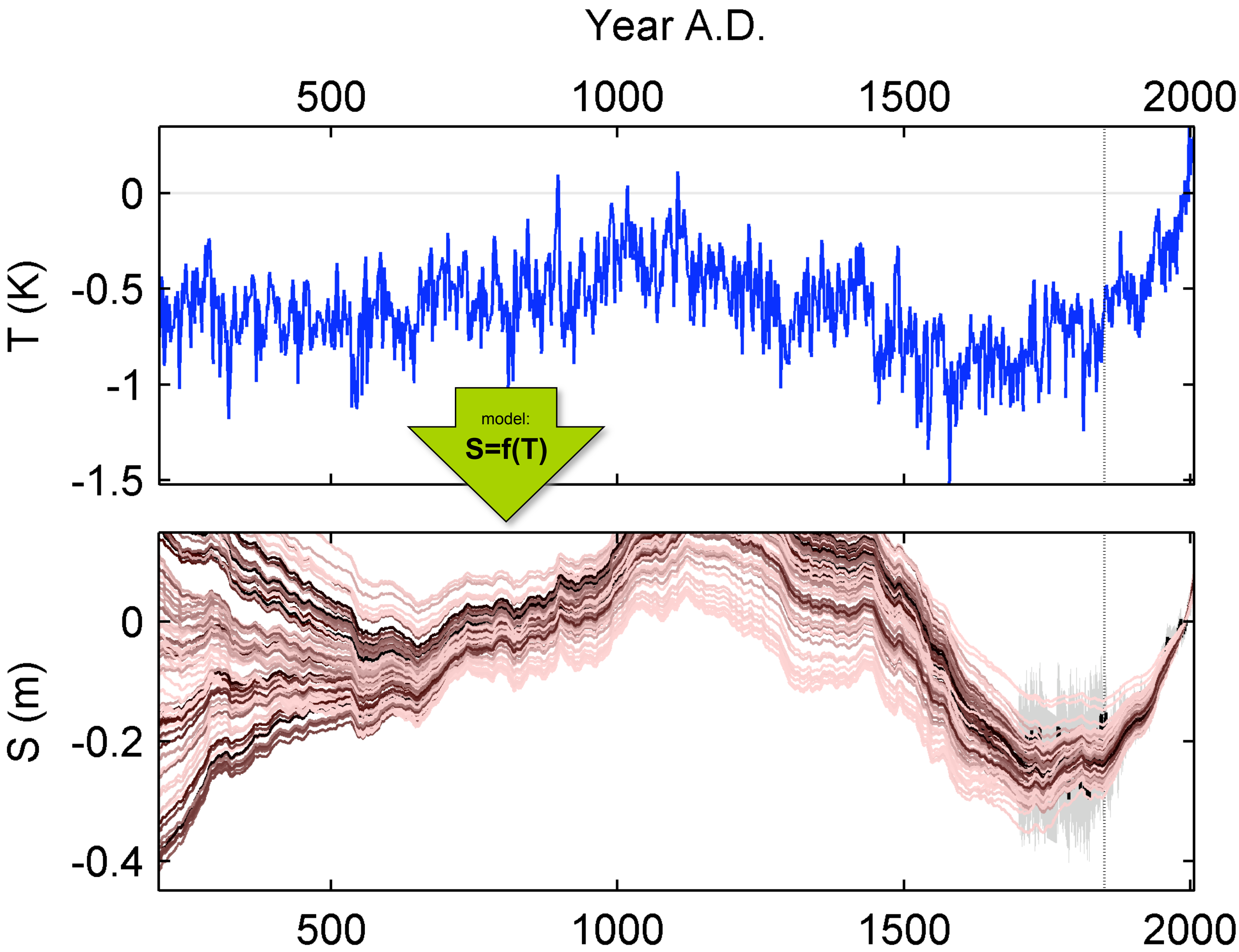
- We know T
  (for example, HadCRUT3v)
- We know S
  (for example, tide gauge records)
- We do not know the model parameters that allow us to calculate S from T:

  a, b, τ, S_0

- We use inverse Monte Carlo to find the best fitting parameters

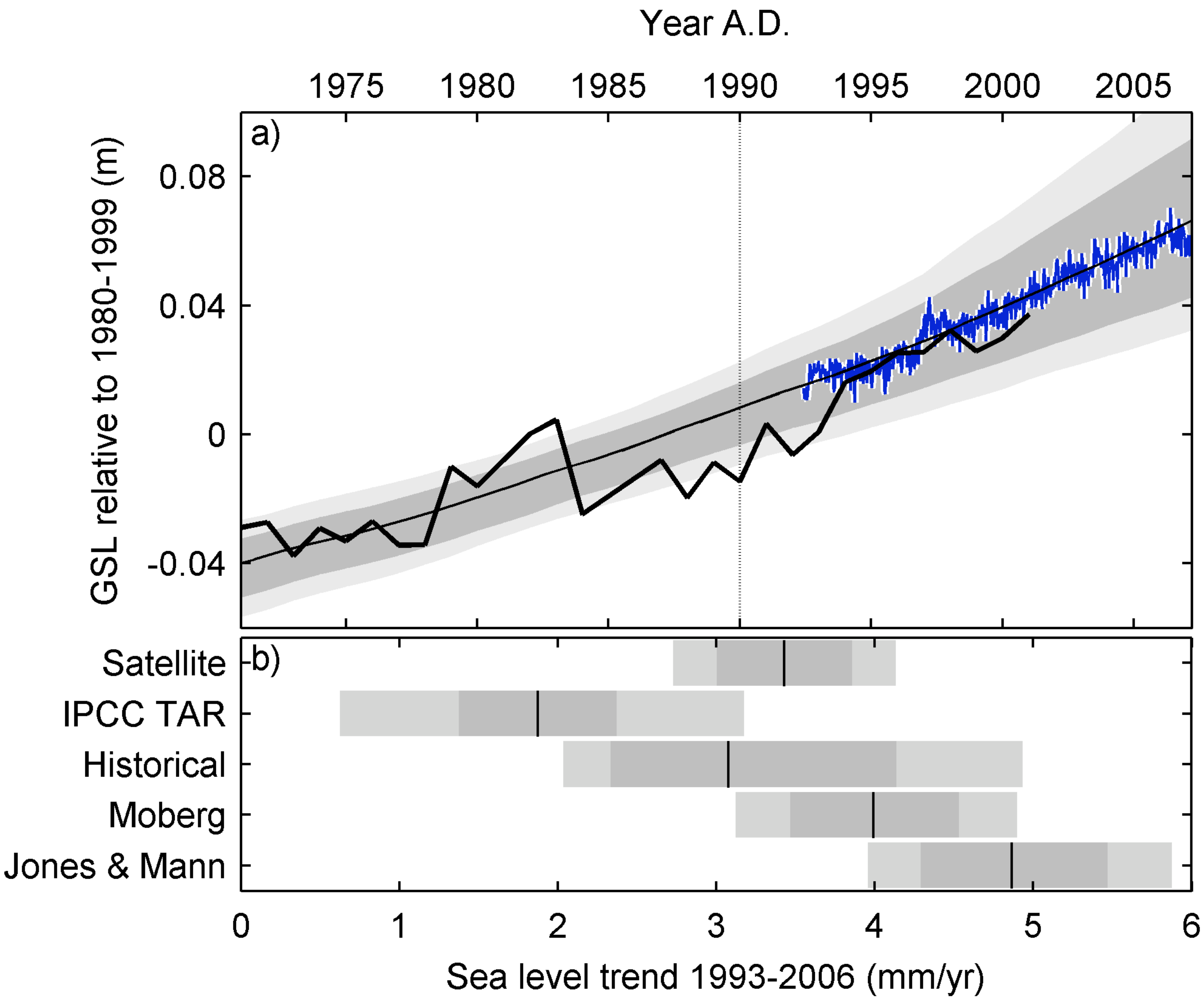
3 experiments

- **Historical:** Calibrate using historical temperatures only (HadCRUTv3 since 1850)
- **Moberg:** Add Moberg et al. 2005 reconstruction
- **Jones & Mann:** Add Jones & Mann 2004 reconstruction



Year A.D.
500
1000
1500
2000
T (K)
0
-0.5
-1
-1.5
model:
S=f(T)
S (m)
0
-0.2
-0.4
500
1000
1500
2000

Validation

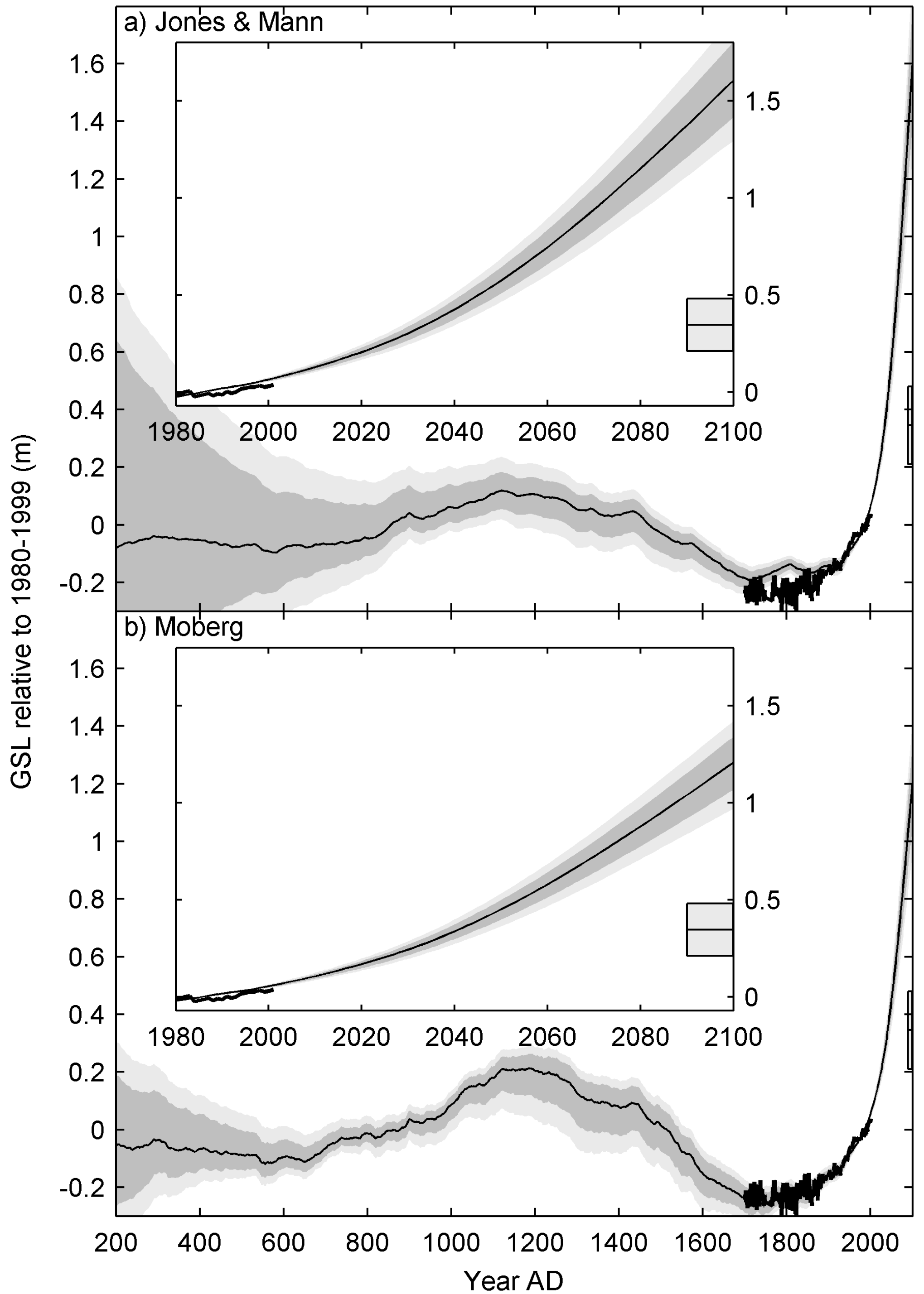


Calibrated using pre-1990 GSL (thick black line) compared to post-1990 satellite altimetry (blue line).

Main Results

(Using A1B temperatures, 2.4°C)

- The first well-constrained sea level reconstruction for the past 2000 years
- The rate of present sea level rise is far exceeding anything seen the last 2000 years
- IPCC much too conservative (although they do acknowledge that)
- Effective response time at present is a few centuries only



What is the 'missing link' in IPCC?

- NOT thermal expansion (it is well modeled)
- NOT glaciers and smaller ice caps (their total volume is too small; IPCC-AR4)
- The big ice sheets:
  - NOT Ice sheet surface mass balance (included in models)
  - Possibly ice sheet dynamics (explicitly excluded from IPCC estimates)

Short summary

Sea level has been within about 20 cm of present over the last 2000 years,

but will rise 0.8-1.35 m by 2100

Apriori constraints (1)

$$S_{eq} = aT + b, \quad \text{(eq.1)}$$
$$\frac{\partial S}{\partial t} = (S_{eq} - S)/\tau, \quad \text{(eq.2)}$$

- Constraining the model parameters to a physically sensible range.
- $\tau > 0$
- b > 0. Sea level in 1980-1999 was rising even though T=0 (by definition of the reference period).
- Sea level will max rise by 5 m, if global warming is stopped (i.e. b<5 m). In the Last Interglacial (LIG) temperatures inferred were 3-5 °C warmer than present and sea level was 4-6 m higher. It unlikely that if future temperature remains below the LIG level that sea level would rise as much as then.
- … continued …

Apriori constraints (2)

$$S_{eq} = aT + b, \quad \text{(eq.1)}$$

$$\frac{\partial S}{\partial t} = (S_{eq} - S)/\tau, \quad \text{(eq.2)}$$

- $a < 10$ m/°C

Using equation 1 and considering sea level in the LIG, the maximum sea level *Smax* (6 m) the minimum value of *bmin* (=0 from constraint 2) and minimum temperature difference *Tmin* =*3* °C we get
a < (*Smax*-*bmin*)/*Tmin* <2 m/°C.
An alternative value for this constraint comes from Bintanja et al. (2005) who used a combination of observations and models for the sea level over the past million years, to conclude that sea level during glacial stages, air temperatures were ~17 °C lower than present, with a ~120 m sea level equivalent of continental ice present. These numbers give a much higher limit for *a* of 7 m/°C.

- $a > 0.5$ m/°C (Thermal expansion alone gives that, IPCC)

- $|S_0| < 1$ m

Mediterranean archaeological data (Sivan et al., 2004), and salt-marsh records from New England (Gehrels et al., 2005) suggest variations in sea level have not exceeded ±0.25 m from 2,000 to 100 yr before present. Globally sea level has been more stable over the last 3000 years than during much of Holocene, with sea level 2000 BP probably slightly lower than at present, but within 1 m of present day levels (Lambeck et al. 2004).

A Semi-Empirical Approach to Projecting Future Sea-Level Rise

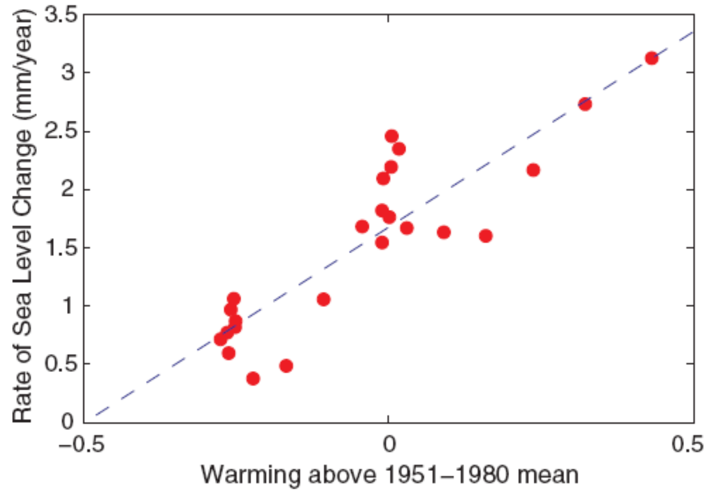
Stefan Rahmstorf

A semi-empirical relation is presented that connects global sea-level rise to global mean surface temperature. It is proposed that, for time scales relevant to anthropogenic warming, the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre–Industrial Age. This holds to good approximation for temperature and sea-level changes during the 20th century, with a proportionality constant of 3.4 millimeters/year per °C. W applied to future warming scenarios of the Intergovernmental Panel on Climate Chang relationship results in a projected sea-level rise in 2100 of 0.5 to 1.4 meters above the

$$dH/dt = a\,(T - T_0)$$

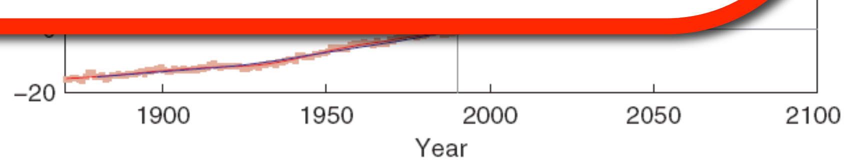
Criticized for poor statistics.

The (heavy) smoothing reduces the degrees of freedom and the regression is not significant. (Results also dependent on the degree of smoothing.)



Approach:

- Smooth GSL record
- Calculate dH/dt
- Linear regression against observ
- Use projected temperatures to project GSL



Potentially a long response time

- I.e. the sea level record may contain some memory of the Little Ice Age or The Medieval Warm Period.
- From temperature reconstructions we have some evidence of what the temperature is the last 2000 years.
- We include these data and start the integration ~2000 years ago.

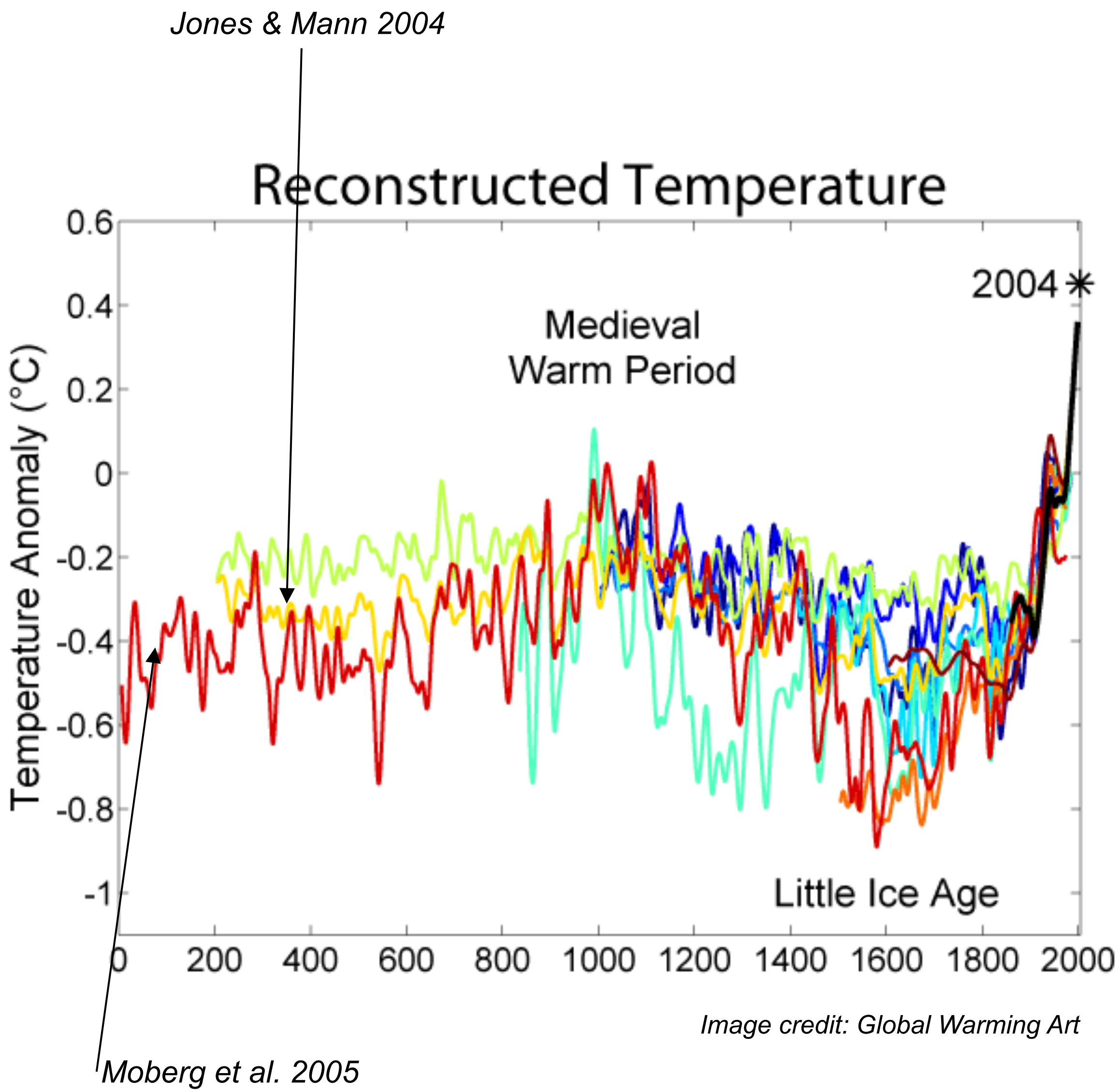


Image credit: Global Warming Art

IPCC projections are generally too low by roughly a factor 3

Table 2: Projected sea level rise 2090-2099 for the IPCC scenarios.

	A1B	A1FI	A1T	A2	B1	B2	T0*
Moberg	0.91-1.32	1.10-1.60	0.89-1.30	0.93-1.36	0.72-1.07	0.82-1.20	0.21-0.38
Jones & Mann	1.21-1.79	1.45-2.15	1.18-1.76	1.24-1.83	0.96-1.44	1.09-1.62	0.29-0.49
Historical only	0.32-1.34	0.34-1.59	0.32-1.32	0.32-1.37	0.30-1.10	0.31-1.22	0.22-0.44
Imm. / Inf.†	0.8 / 0.8	1.2 / 1.0	0.7 / 0.8	1.0 / 0.8	0.6 / 0.7	0.7 / 0.8	0.0 / 0.3
IPCC	0.21-0.48	0.26-0.59	0.20-0.45	0.23-0.51	0.18-0.38	0.20-0.43	

Range is 5-95 percentiles. * T0 is a scenario with no temperature rise. † Imm./Inf. refers to the projections assuming an immediate/infinite response time and with model parameters obtained from ordinary least squares (i.e. not using C).