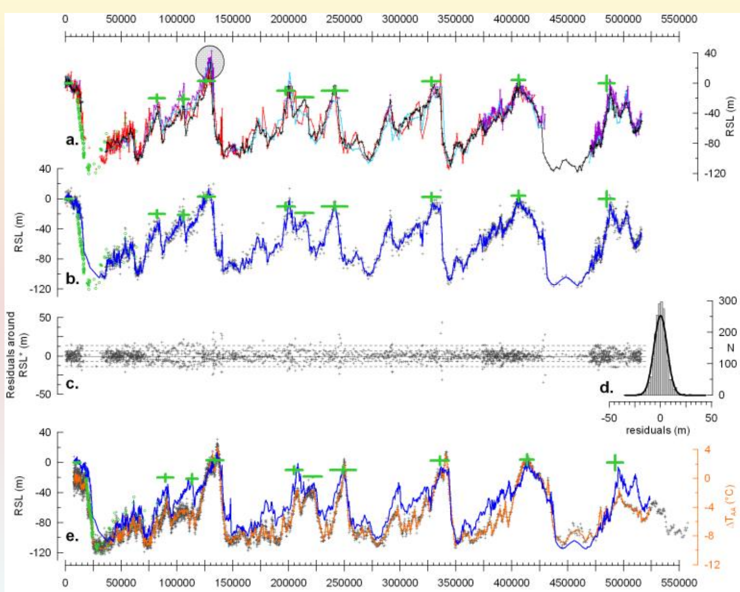
Latest continuous sea-level records over last half million years (Red Sea)

Good agreement with fossil corals (green)

Clear match with Antarctic Temperature anomaly record (orange)



Rohling et al., *Nature Geoscience 2*, 2009
Data at: http://www.highstand.org/erohling/ejrhome.htm

Average time resolution 200-250 y

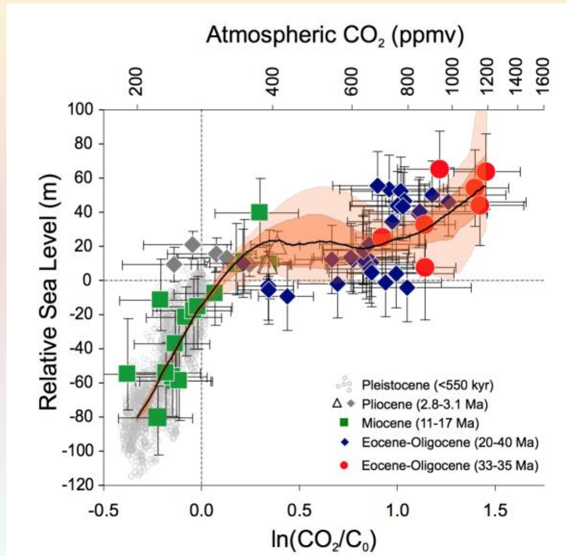
Adding data for past 40 Myr: Estimating the modern long-term disequilibrium

Evidence for equilibrium sea-level relative to CO_2 from data of the past 40 million years (Foster et al., 2013 *PNAS*).

At [CO2] = 390-400 ppmv, SL at 24 -15/+7 m (68%).

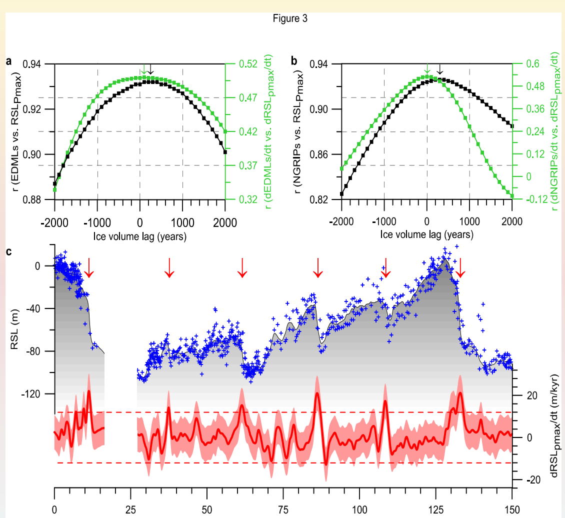
In other words, likely range at 9 or more m above the present.

But: *How fast?*



Rates of rise:

Millennial events of last glacial cycle show typical rates of rise of order **1 m century^{-1}**

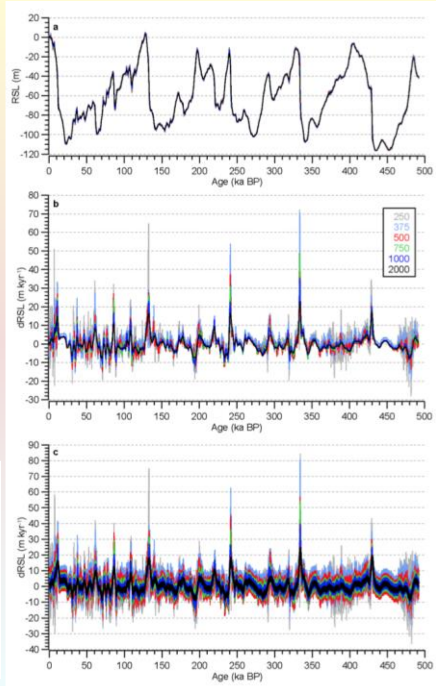


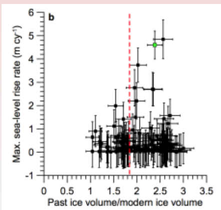
Grant et al. (*Nature* 2012): U-Th supported chronology.
Also note response-time lags of only several centuries.

Rates of rise:

Detailed chronology for Red Sea sea-level reconstruction now extended over past 520,000 years (**Grant et al. *Nature Comms.* mid-end Sept. 2014**)

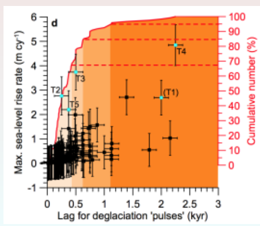
Gives detailed account of rates of rise over all rises of the past 520,000 years:





At modern ice volume, Rates typically up to ~1 m century^{-1}.

And of lag times
(99% less than 2000 y)
(85% less than 650y):



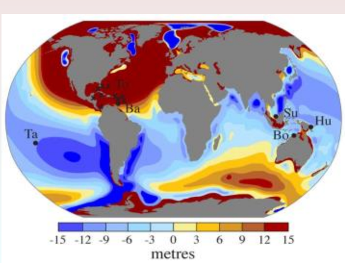
Statistical assessment of corals for the last deglaciation

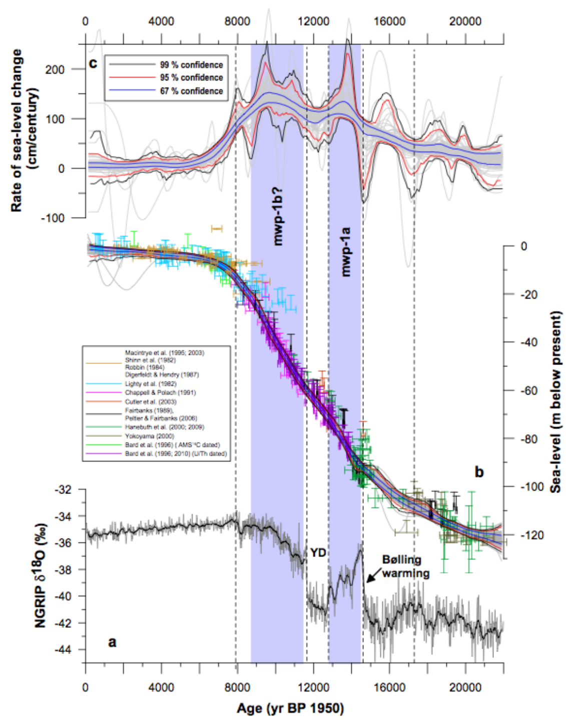
(Stanford et al., 2011 *GPC*)

Uses all quality far-field data, with all uncertainties in both age and sea-level directions.

It suggests robust values of up to **2.5 m per century** (95% confidence).

But note, this procedure includes an amount of smoothing, so values found are *minima*



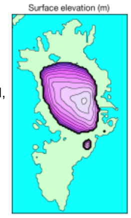


Rates of Rise – times when sea-level rose *ABOVE* the present:

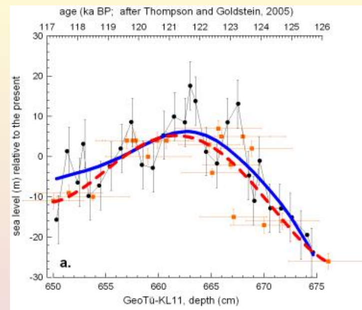
Rohling et al. *Nature Geoscience*, 2008

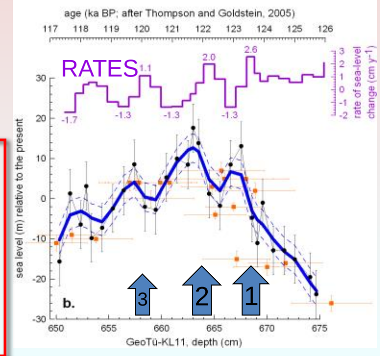
- Last interglacial: world avg. up to (likely less than) 2 ° C warmer than today. Greenland 3-5 ° C warmer
- *Mean* sea-level highstand 4-6 m above present (peaks considerably higher, up to ~9 m)
- Less than half of the high-stand due to Greenland melt (but not all ➔ **Antarctica involved** !)

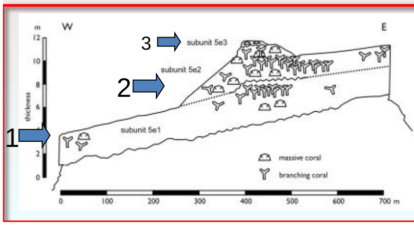
A modelled "best estimate" Eemian Greenland ice sheet (Cuffey and Marshall, 2000)



- Rate of rise above 0m: **1.6 ± 1.0 m century^{-1}**
- i.e., 2-3 times max IPCC rate



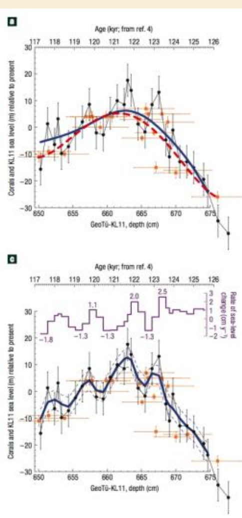


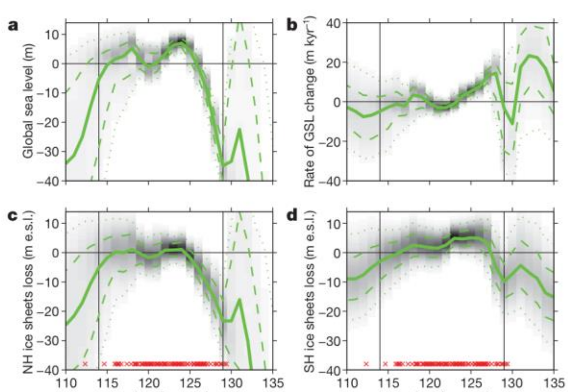


Structure of two main & one minor peak, separated by lowstands, corroborated by stratigraphic reef sequences (Bruggemann et al., 2004)

Probabilistic global summary for last interglacial concludes 1000-y mean value for Last Interglacial sea-level 'jumps' of order **0.6 to 0.9 m century^{-1}** (SL reached up to 8±1 m *above* the present!) (Kopp et al., 2009 *Nature*).

New chronology for Red Sea sea-level record (Grant et al., 2012 *Nature*) established that 1000-y mean value for the rise between -5 and +5 m of **0.7 ± 0.4 m century^{-1}**.





Global perspective strongly suggests that the ice loss responsible took place on Southern Hemisphere

Rohling et al., *Nature Geoscience 1*, 2008

Kopp et al., *Nature 462*, 2009

Summary of past observations:

Rates of sea-level rise during times of sustained climatic warming typically reached **mean values of ~1 m century^{-1}**, even when ice volume was similar to present

Maximum rates during deglaciations (*starting at 2-3x modern ice volume):

- Statistically **robust** (95% confidence) **values up to 2.5 m century^{-1}**
- Single-site interpolations suggest **peaks up to 6 m century^{-1}**

Final bit of the last deglaciation still at rates of **1 ±0.3 m century^{-1}** (Carlson et al., *Nature Geoscience* 2008 – not shown here)

Rises to 8±1 m *above* present-day sea-level at rates of order 1 m century^{-1} (Rohling et al., *Nature Geoscience* 2008; Kopp et al., *Nature* 2009; Grant et al., 2012 *Nature*).

Typical rates when ice-volume ~same as today are up to **1 m century^{-1}.**

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Typical rates when ice-volume ~same as today are up to **1 m century^{-1}.**

Likelihood of such values of sea-level rise w.r.t. modern ice dynamics:

Current global understanding of ice dynamics allows modern rates of **0.8 to 2.0 m century^{-1}** (Pfeffer et al, *Science* 2008)

Antarctica alone may account for modern rates of up to **1.5 m century^{-1}** (*SCAR report*, 2009)

Also: Grant et al. (2012 *Nature;* 2014 in press *Nature Comms.*) find sea-level response-time lags relative to temperature of order of several centuries

(85% within 650 years; 99% within 2000 years)

Key points for future: Timescale, and ultimate rates and magnitude of response?

- Ice-sheet response to warming: generally slow (centennial), but not as slow as in some models (millennial) -- do we need a better understanding of grounding-line physics?
- Ice-shelf disintegrations and ice-stream accelerations may signal that ice-sheet response is slowly becoming significant, after ~150 years of warming
- Expect a gradual but almost irreversible 'ramping up' of the rates of rise (like a freight train, slow to get going, hard to stop once moving)
- Maximum rates of rise (in natural state) seem related to extent of global ice volume

Let's make some simple scenarios of past (observed) change, as 'natural context' to current changes. We use a simple logistic function for rate of rise changes:

Allow rates of SLR to gradually build as ice-loss processes build up, and then accelerate toward maximum rate for the mechanisms involved (α, in m y^{-1}).

Allow a timescale for adjustment in the rate of rise to take place (γ) (in y).

Define a factor β so that AD2000 rate of sea-level rise is 3 mm y^{-1}.

$$\frac{d\Delta_s}{dt} = \frac{\alpha}{1+\beta e^{-\frac{t}{\gamma}C}}$$

$$\beta = \frac{\alpha}{0.003} - 1$$

Sea level relative to pre-industrial then is:

$$\Delta_s = \int_0^t \left[\frac{\alpha}{1+\beta e^{-\frac{t}{\gamma}C}}\right] dt$$

Rohling et al., *Scientific Reports* 2013

Geologically informed PDFs of input variables

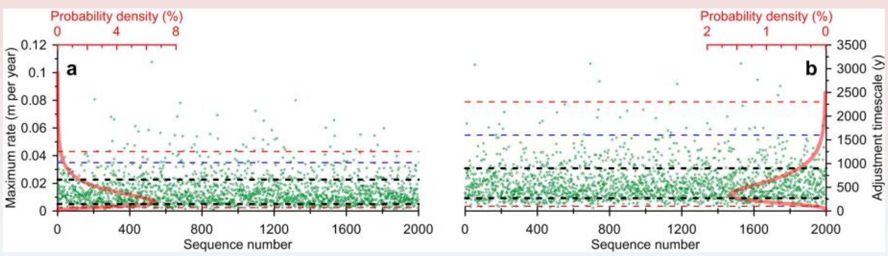
α, the rate of rise, must be >0 m cy^{-1} for sea-level rise to occur.

Probability peak at ~rate of LIg SLR above present sea level: 0.7±0.4 m cy^{-1} (i.e., <1.1 m cy^{-1}). But: these 500 to 1000-y avg. estimates may mask shorter episodes with higher values

Meltwater pulses (rates up to ~6 m cy^{-1}) give real-world examples of natural extremes.

➔lognormal distribution, so that $\alpha > 0$ m cy^{-1}, with 50% of possibilities for $\alpha \leq 1.1$ m cy^{-1}, and with 99% of $\alpha \leq 5.0$ m cy^{-1}.

Similarly for γ, the adjustment timescale, set a lognormal distribution so that $\gamma > 0$ y, with 50% of possibilities for $\gamma \leq 500$ y, and 99% of $\gamma \leq 2000$ y.

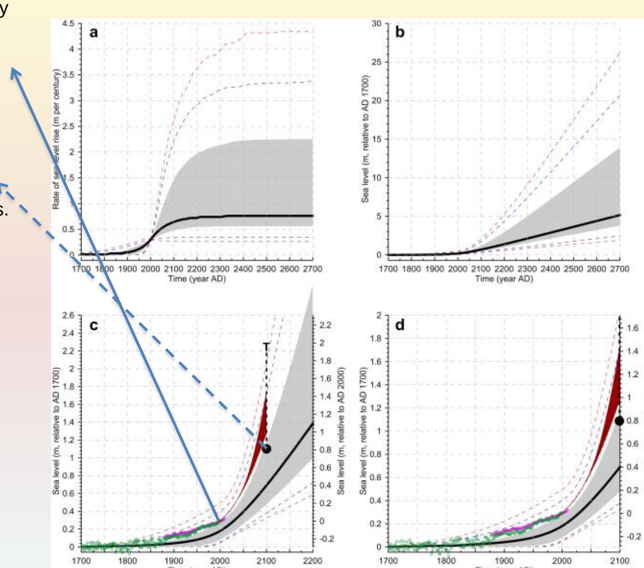


Rohling et al., *Scientific Reports* 2013

68% 90% 95%

Current sea-level rise strong by natural interglacial standards (latter lie in lower half of 68% interval).

Coincidence with Pfeffer et al. (2008 *Science*) 'best-estimate' for 2100 suggests that high current trajectory does not require unprecedented physics.



Rohling et al., *Scientific Reports* 2013

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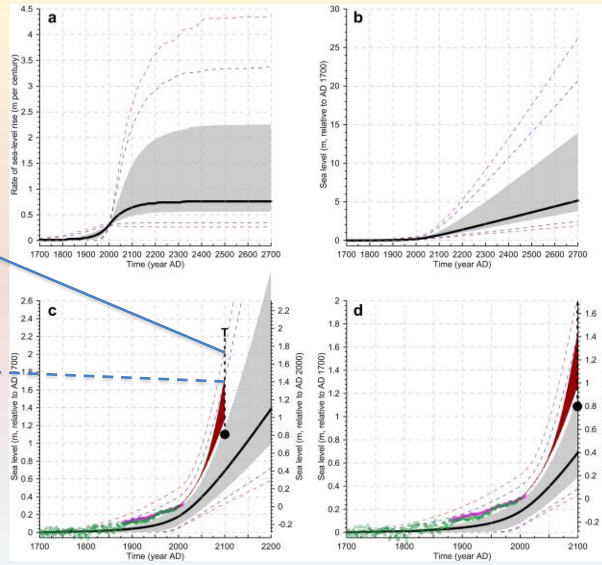
2m by 2100 requires pathway to eventual rates of ~4.3 m/cy^{-1} ➔ unlikely for existing volume of ice, if no unprecedented processes (e.g., collapse of WAIS).

Equally, 'special' conditions needed for semi-empirical projections for higher emissions scenarios.

2m by 2100 seems reasonable upper extreme for planning.
BUT: if reached, then we're on pathway to 6 m by 2200



Rohling et al., *Scientific Reports* 2013

Conclusions

- Past rates of rise offer natural context to future sea-level rise
- Our natural rates are *total* response rates (including thermosteric effects, etc.) for the global scale
- Natural rates of rise typically 1 to 2 m century^{-1} during variety of climate background states
- Reviews of modern ice dynamics support such rates as possible today
- Our scenarios based on these natural rates suggest 0.2 - 0.9 m of rise by 2100 and 0.7 – 2.6 m by 2200 (68% probability)
- For 390-400 ppmv CO_2, natural equilibrium would be of order 24 -15/+7 m (68%)
- Last Interglacial shows that fast rise continuing at least up to +8 or +9 m could happen without any dramatic change in circumstances

- Geological perspective suggests that:
  - current rise is on a high trajectory, but within the range of understood ice-dynamical processes; i.e., nothing truly exceptional (yet)
  - ~2 m by **2100** is a reasonable extreme for planning, and anticipated only if strong emissions continue
  - around **2200**, more than 2m rise is a reasonable expectation even if *no further* emissions took place from today (worst-case maximum around +6 m).


Thank you