Uncertainties and risks of regional sea-level change: Present, past and future

Bob Kopp
Department of Earth & Planetary Sciences and Rutgers Energy Institute
Rutgers University

<u>Collaborators:</u> Ken Miller, Ben Horton, Jim Browning, Vladimir Pavlovic (Rutgers); Jerry Mitrovica (Harvard); Frederik Simons, Adam Maloof, Michael Oppenheimer (Princeton); Andrew Kemp (Tufts)

<u>Students and Postdocs:</u> Carling Hay, Eric Morrow (Harvard)

Climate Change Impacts/Integrated Assessment Workshop
Snowmass, CO / 30 July 2013

Road Map

- Why is regional sea-level rise different from global mean sea-level rise?
- What do we actually see in local sea-level projections? How can this inform localization of sea-level projections?
- What can paleo-sea level rise patterns tell us about ice-sheet stability?

Why is regional sea-level rise different from global mean sea-level rise?

Global Sea Level change is not the same as local sea level change

- Ocean dynamic effects
- Mass redistribution effects: Gravitational, elastic and rotational
- Natural and groundwater withdrawal-related sediment compaction
- Long term: Isostasy and tectonics

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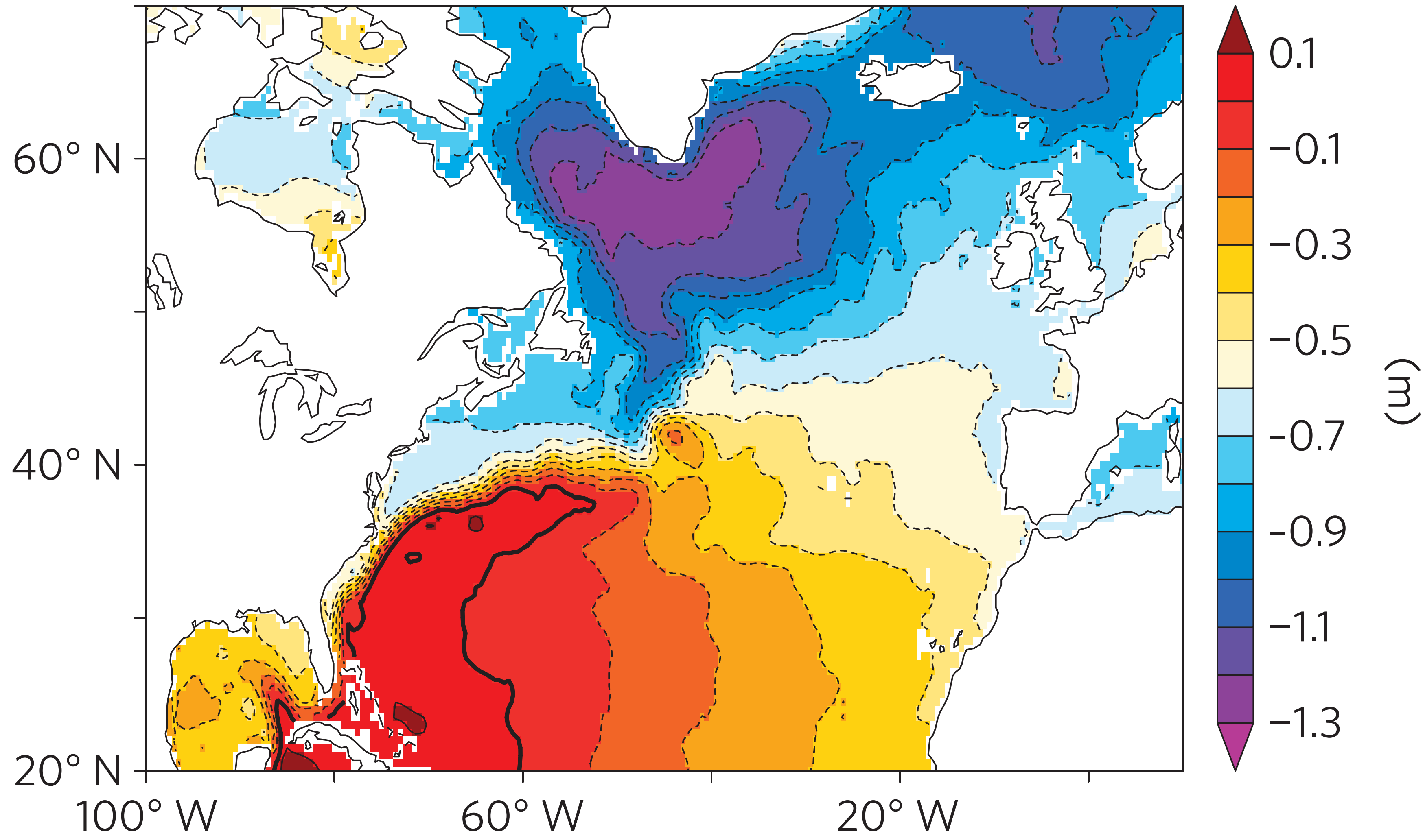

SSH, 1992-2002

Yin et al. (2009)

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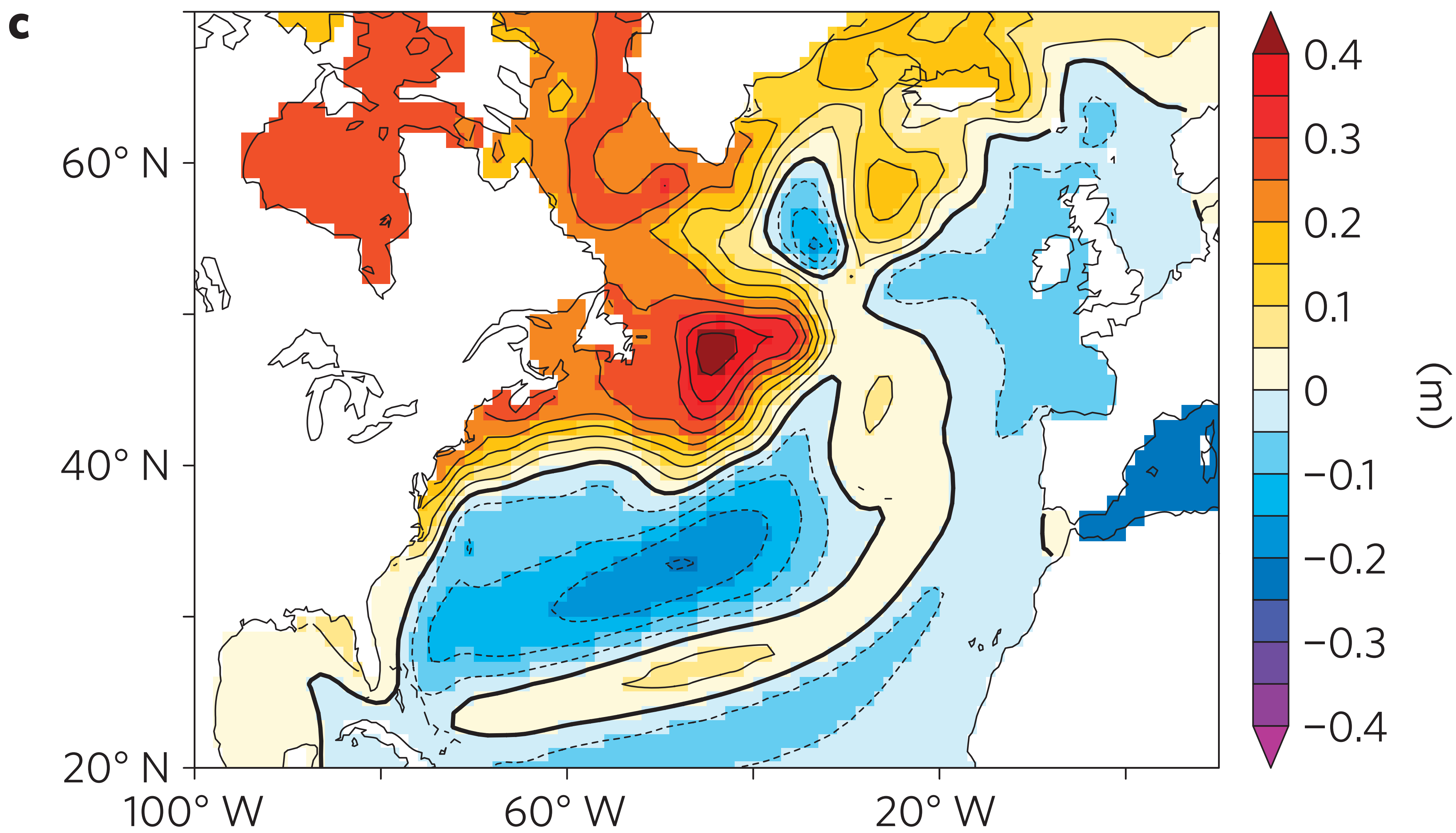

Projected dynamic sea level anomalies from changes in the Atlantic Meridional Overturning Circulation in A1B in 2091-2100, relative to 1981-2000

Yin et al. (2009)

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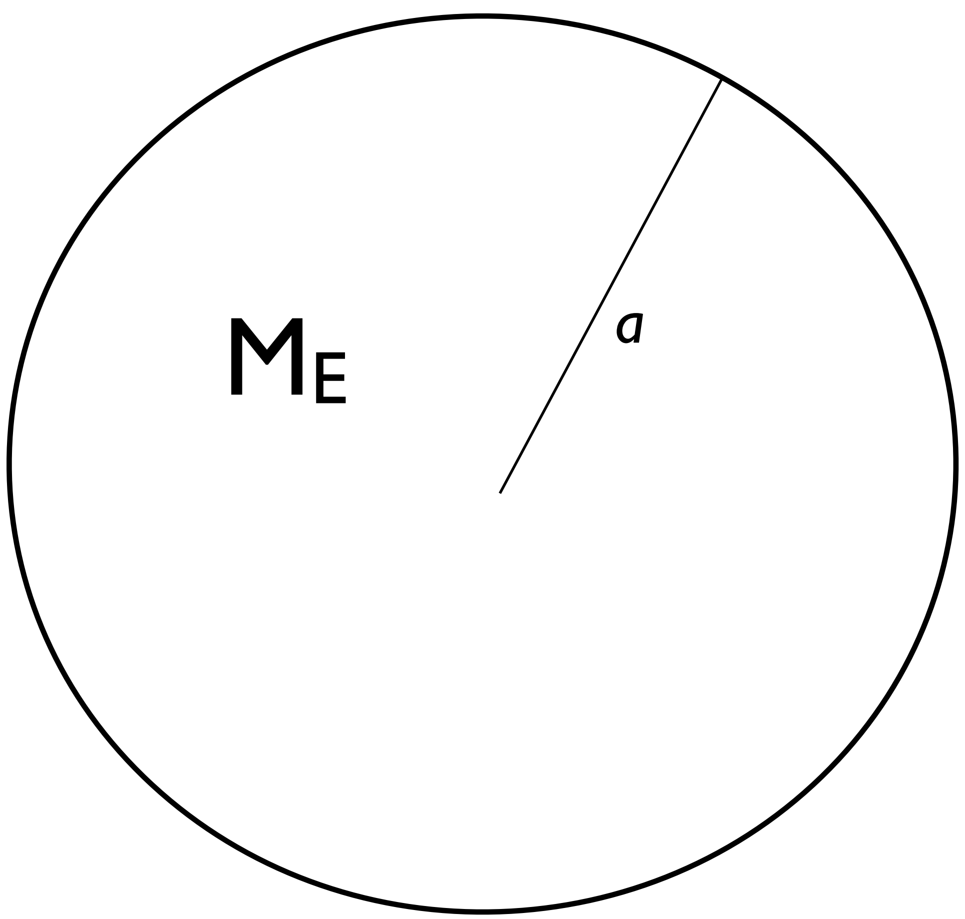

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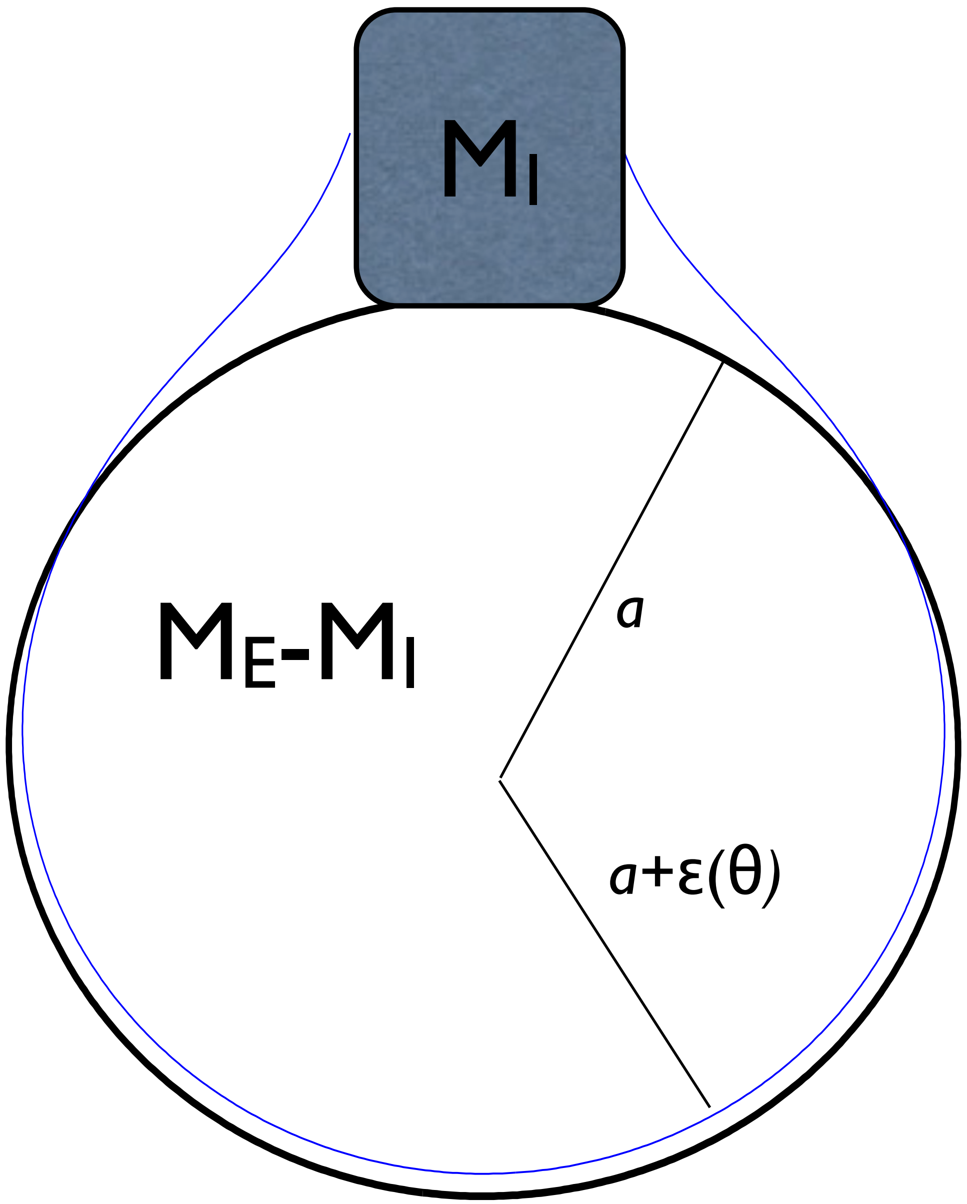

Not to scale!

n.b. $\varepsilon(\theta) = 0$ at $\theta \sim 2 \arcsin(.5\ (\rho_E+3\rho_w)/3\rho_w)$
$\sim 30°$

Farrell & Clark (1976), after Woodward (1888)

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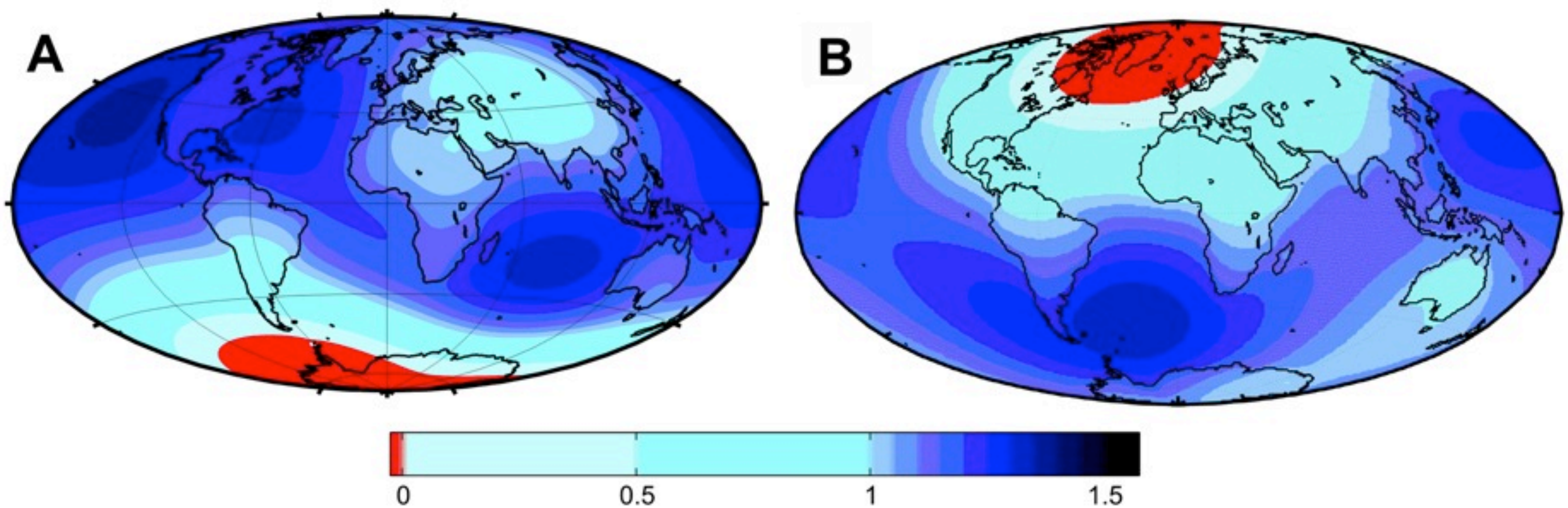
Gravitational-Elastic-Rotational Fingerprints of Greenland and WAIS melting, per meter GSL rise

West Antarctica *Greenland*



Mitrovica et al. (2011)

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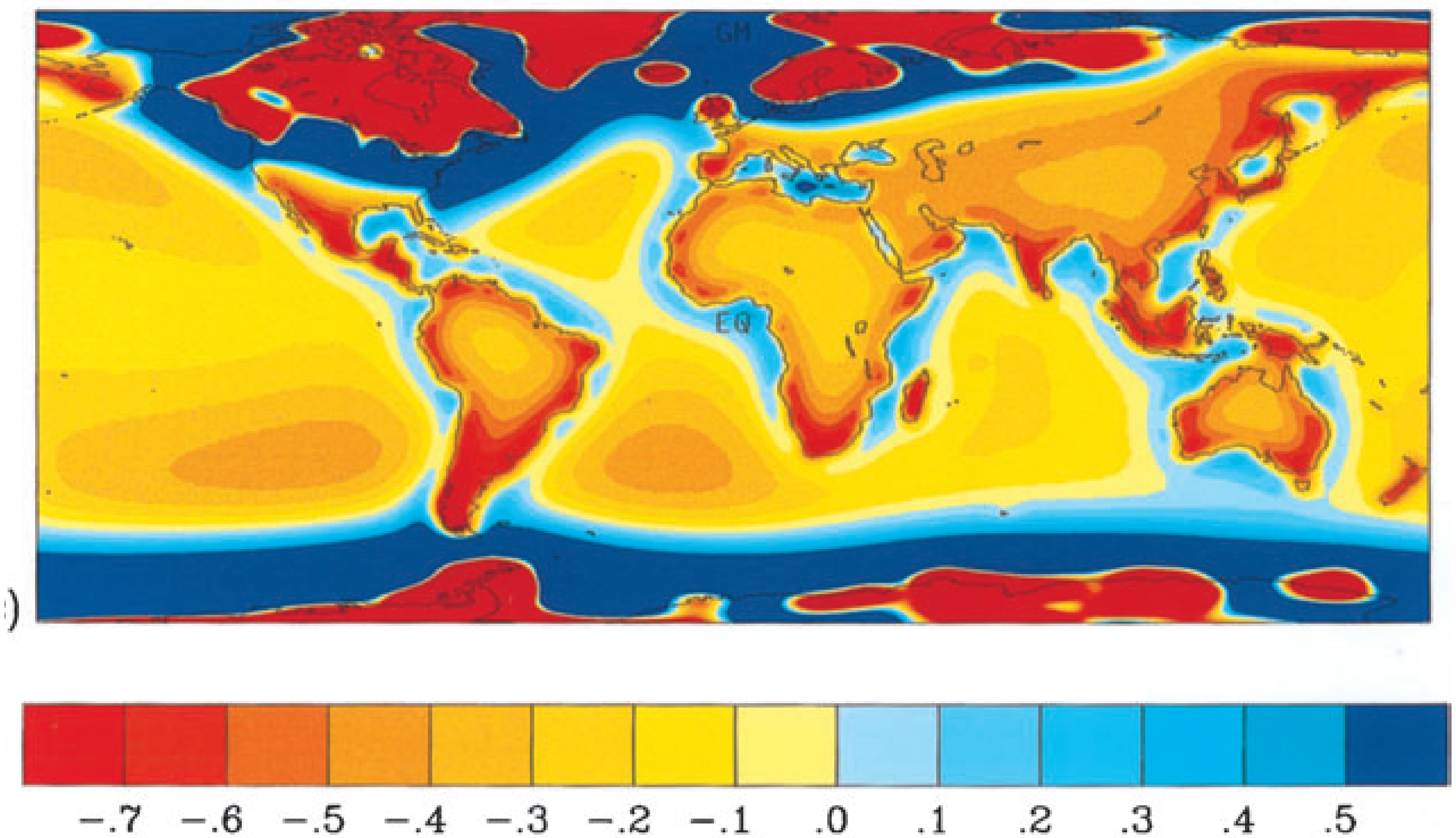
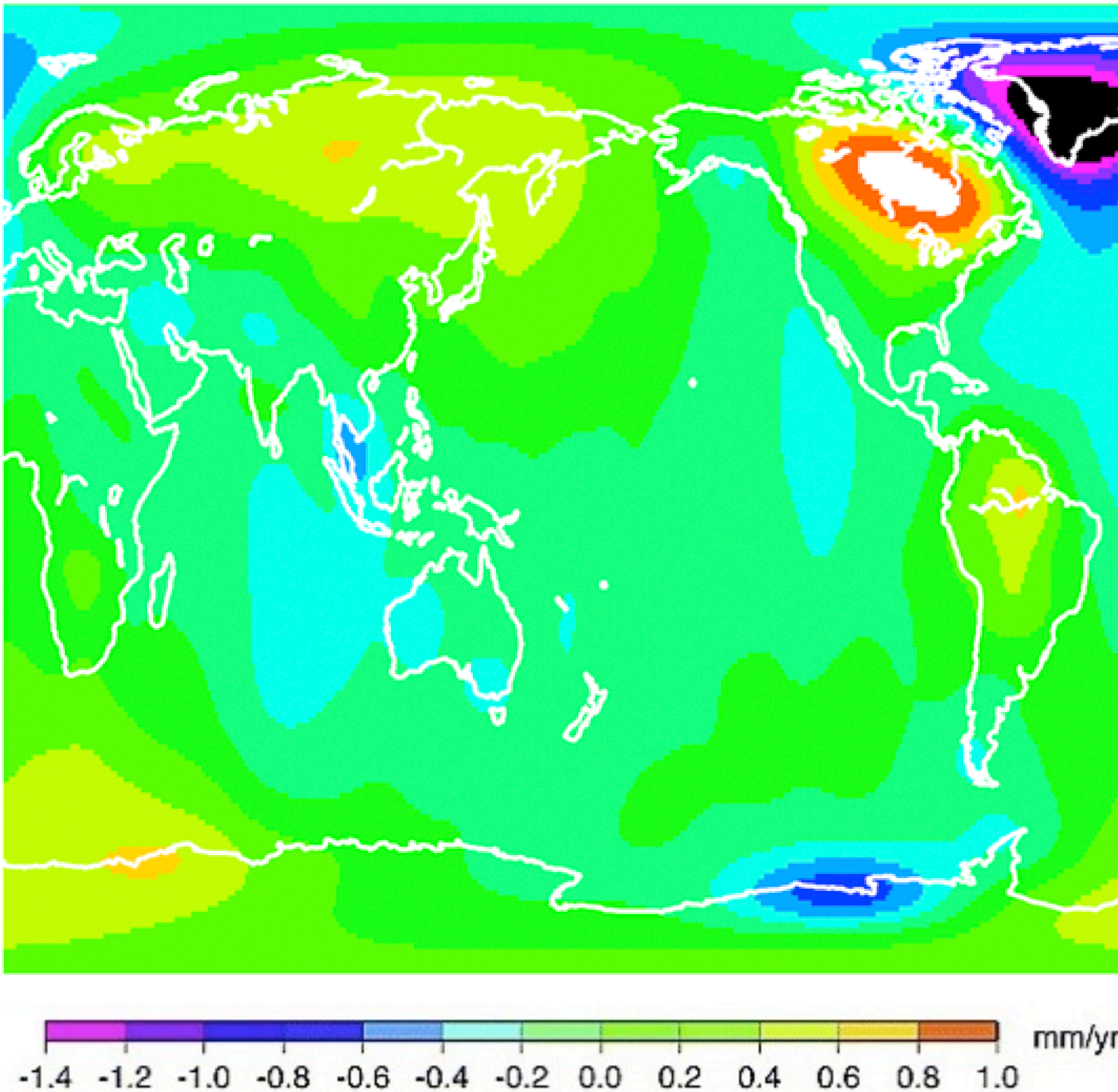


Sea-level rise due to GIA (mm/y)

Mitrovica et al., 2001

Geoid trends inferred from GRACE, 2002-2009

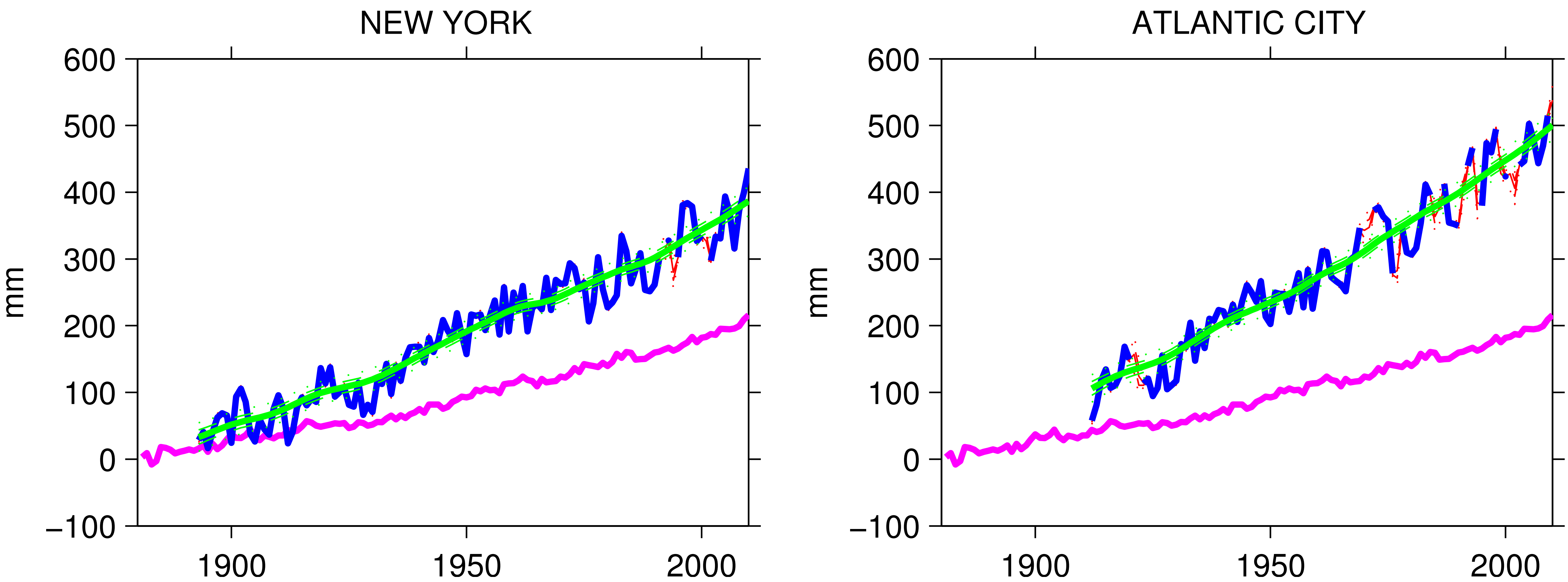


Chambers et al. (2010)

What do we actually see in local sea-level records?

How can this inform localization of sea-level projections?

What do we actually see?



Purple: Church & White (2011) GSL
Blue: Tide gauge data
Green: Long-term sea-level signal

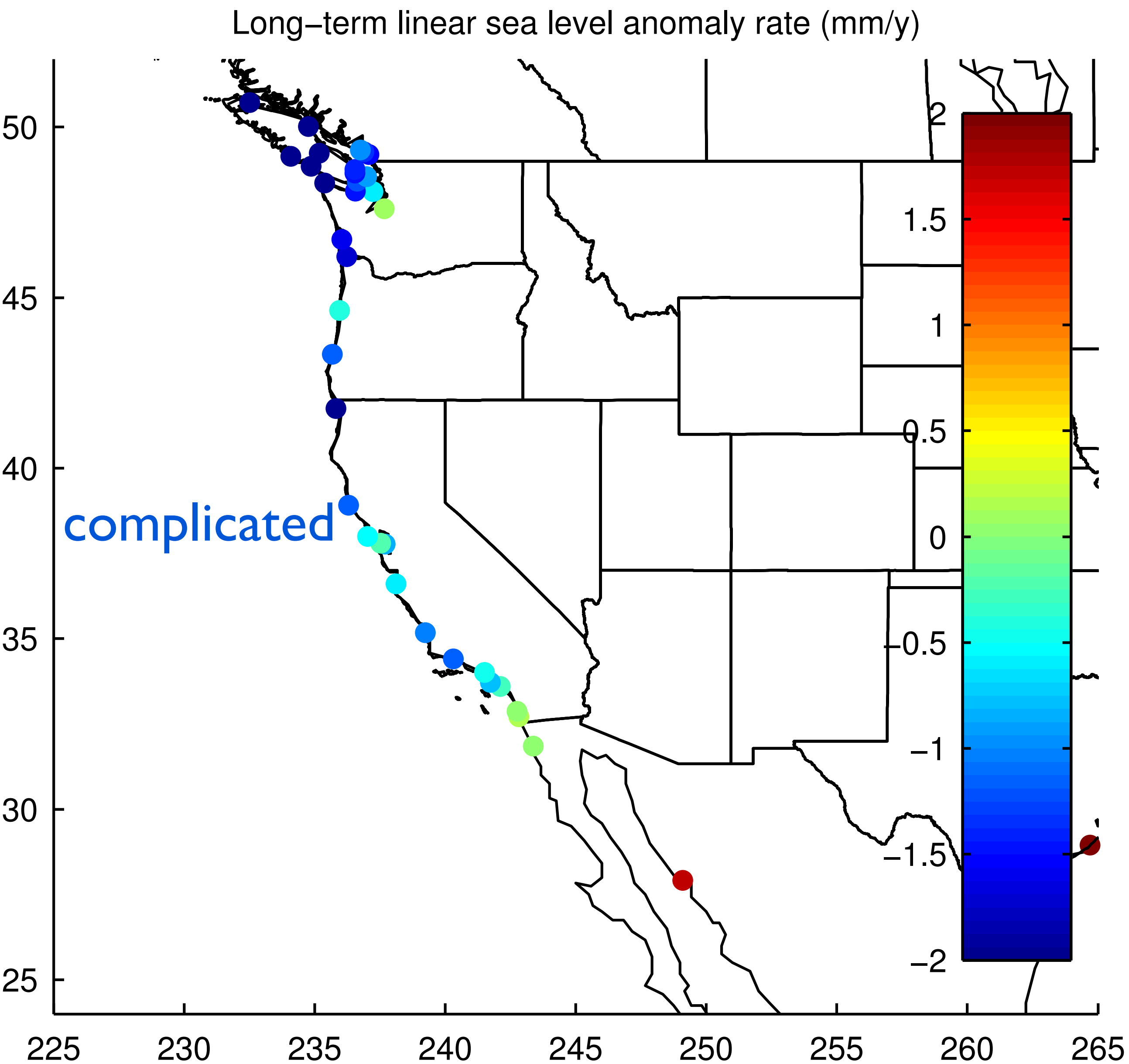
Gaussian process decomposition of tide gauge records

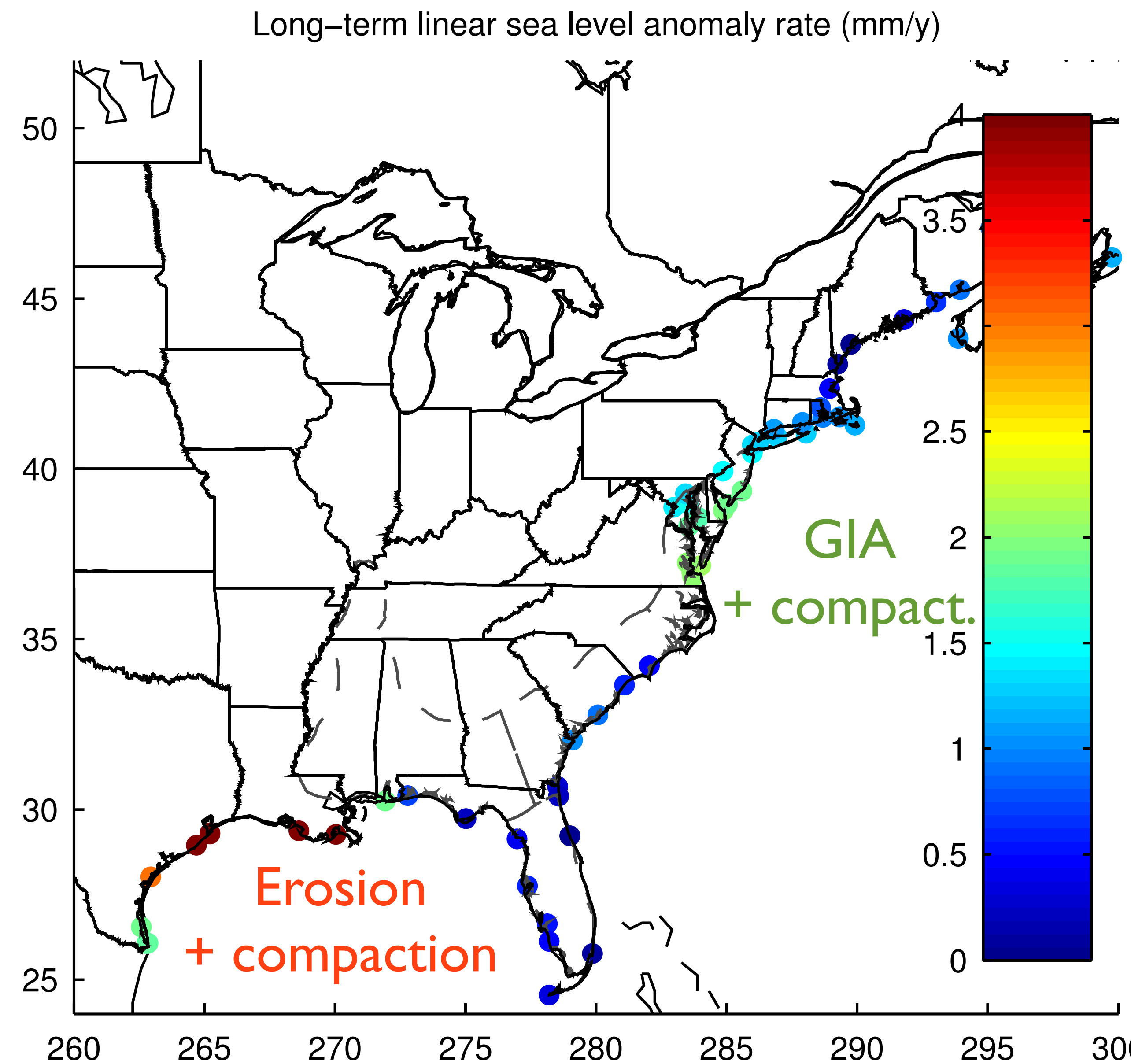
$$\mathbf{f} = (\mathbf{g}_l + \mathbf{g}_s + \mathbf{g}_n) + (\mathbf{r}_l + \mathbf{r}_s + \mathbf{r}_n) + (\mathbf{l}_l + \mathbf{l}_s + \mathbf{l}_n)$$

global	**regional**	**local**

linear	smooth non-linear (rational quadratic prior cov.)	red noise -like (Matérn 1/2 prior cov.)

Local long-term ~linear sea-level anomaly rate (mm/y)





$$\mathbf{f} = (\mathbf{g}_l + \mathbf{g}_s + \mathbf{g}_n) + (\mathbf{r}_l + \mathbf{r}_s + \mathbf{r}_n) + (\mathbf{l}_l + \mathbf{l}_s + \mathbf{l}_n)$$

after Kopp (in press)

nature climate change
LETTERS
PUBLISHED ONLINE: 24 JUNE 2012 | DOI: 10.1038/NCLIMATE1597

Hotspot of accelerated sea-level rise on the Atlantic coast of North America

Asbury H. Sallenger Jr*, Kara S. Doran and Peter A. Howd

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Hotspot of accelerated sea-level rise on the Atlantic coast of North America

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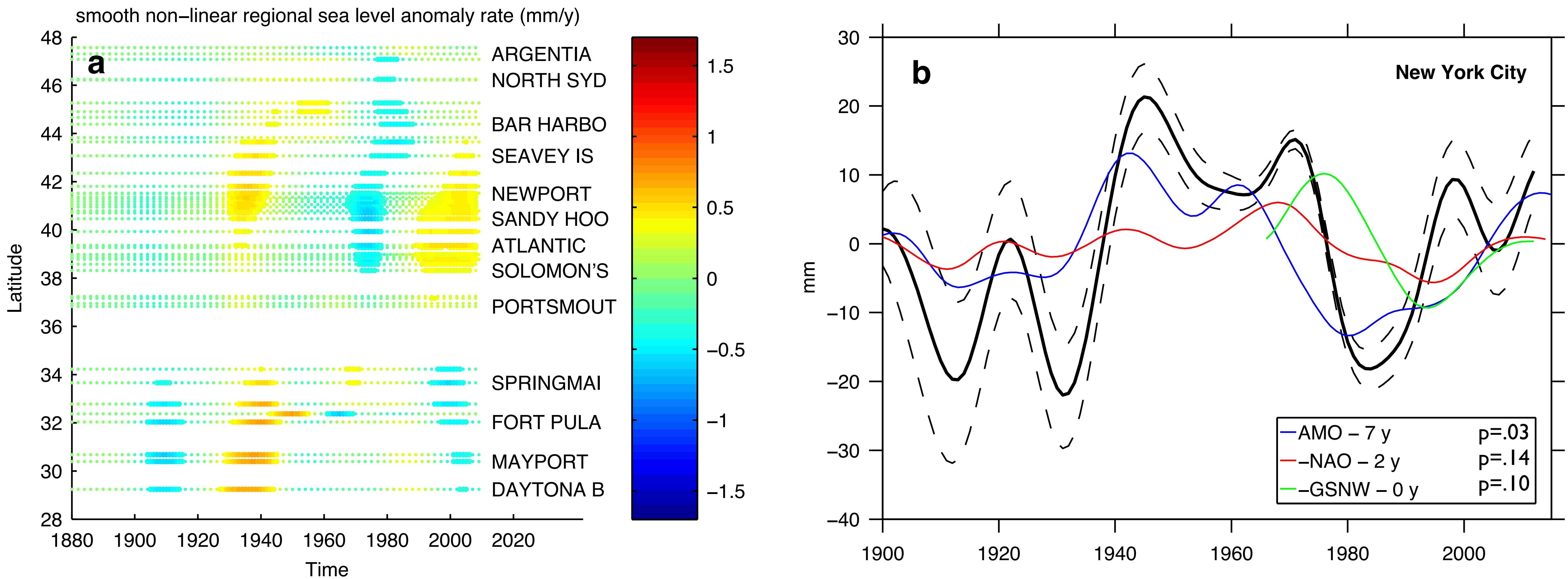
Really? Yes, but it's too early to tell if it goes beyond natural variability...

$$\mathbf{f} = (\mathbf{g}_l + \mathbf{g}_s + \mathbf{g}_n) + (\mathbf{r}_l + \mathbf{r}_s + \mathbf{r}_n) + (\mathbf{l}_l + \mathbf{l}_s + \mathbf{l}_n)$$



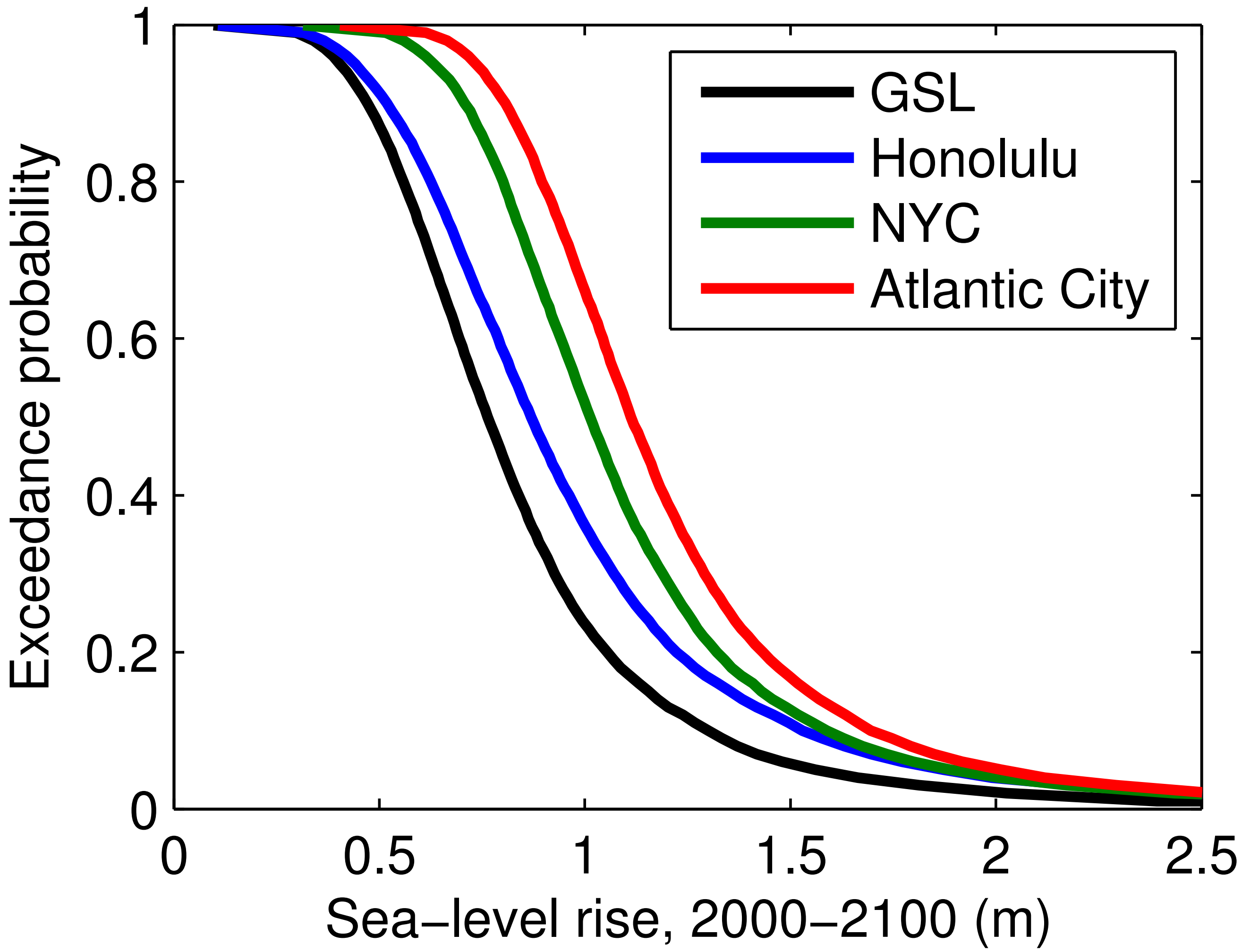
Kopp (in press)

Scenario-based localization example: SLR scenarios for NYC and New Jersey

	Global effects				Regional effects			Local eff.	Totals		
	Thermal cm	Glaciers cm	GIS cm	AIS cm	Ocean dynamics cm	Mass redist. cm	GIA cm	Coastal subsidence cm	Global cm	NYC cm	Shore cm
2030 best	**5**	**3**	**3**	**2**	**6**	**-1**	**4**	**3**	**13**	**22**	**25**
2030 low	2	3	1	1	2	-1	3	2	8	15	18
2030 high	11	4	4	6	8	-1	5	4	21	30	33
2030 higher	11	4	4	6	8	-1	5	4	24	36	40
2050 best	**10**	**6**	**8**	**2**	**10**	**-4**	**7**	**5**	**25**	**38**	**43**
2050 low	4	5	2	1	3	-1	5	4	16	27	32
2050 high	19	7	10	9	13	-3	9	6	39	52	57
2050 higher	19	7	10	9	13	-3	9	6	45	62	68
2100 best	**24**	**14**	**27**	**8**	**20**	**-13**	**13**	**10**	**73**	**93**	**103**
2100 low	10	13	4	2	5	-3	9	8	40	64	74
2100 high	46	19	35	33	25	-11	17	12	117	139	149
2100 higher	46	19	35	33	25	-11	17	12	133	164	176

after Miller et al. (in rev.)

Probabilistic localization example



cm	**95%**	**50%**	**33%**	**5%**	**1%**
GSL	47	77	89	151	233
Honolulu	50	87	102	181	288
NYC	67	101	115	186	286
Atlantic City	77	112	125	196	298

using Bamber & Aspinall (2013) for ice sheets: 30 cm (10-103 cm, 90% range)
Glaciers from Radic et al. (2013): 20 cm (10-30 cm)
Thermal expansion from NRC (2012): 24 cm (10-46 cm)
Dynamic sea level from Yin et al. (2009)
GIA and subsidence from Kopp (2013)
Fingerprints from Mitrovica

What can paleo-sea level rise patterns tell us about ice-sheet stability?

How can historical records help?

Possible forcing parameters

- Temperature
  - Global mean
  - Polar air
  - Circumpolar marine
- Insolation (intensity, duration)
  - Northern Hemisphere
  - Southern Hemisphere
- Ice sheet configuration

→

Model parameters
(including stochasticity)

↗

Model Structures

Complexity →

Temporal resolution ↓

	Global semi-empirical	Process semi-empirical	3-D
"Equilibrium"			
Transient			

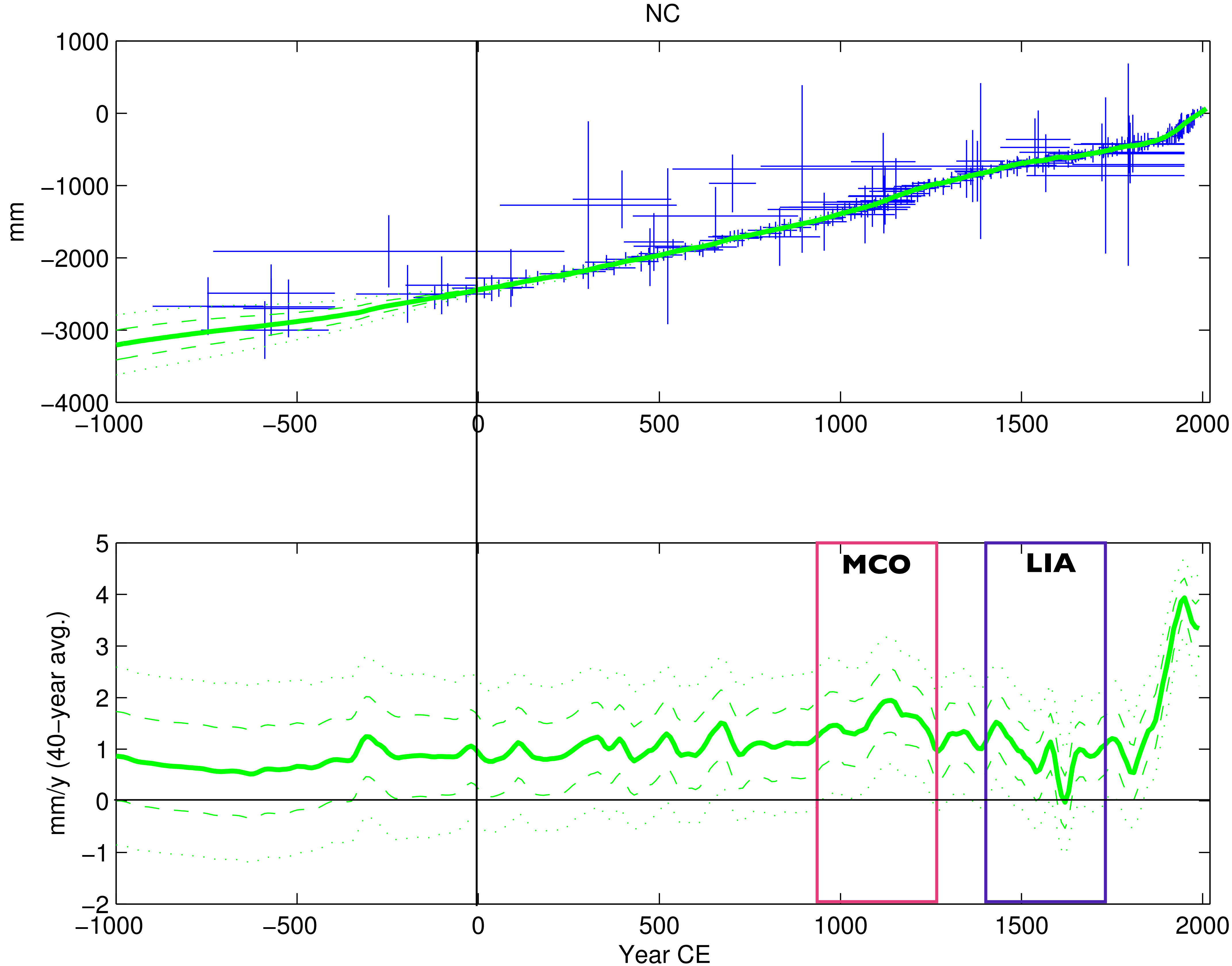
↓

Hindcast

↓

Proxy data/Observations → **Model likelihood**

Sea-level change in Common Era North Carolina



Data from Kemp et al., 2011, Engelhart & Horton (2011), Horton et al. (2013), Kemp et al. (in rev.) and PSMSL

SLR projections calibrated against NC record

Sea level rise rate | Sea level

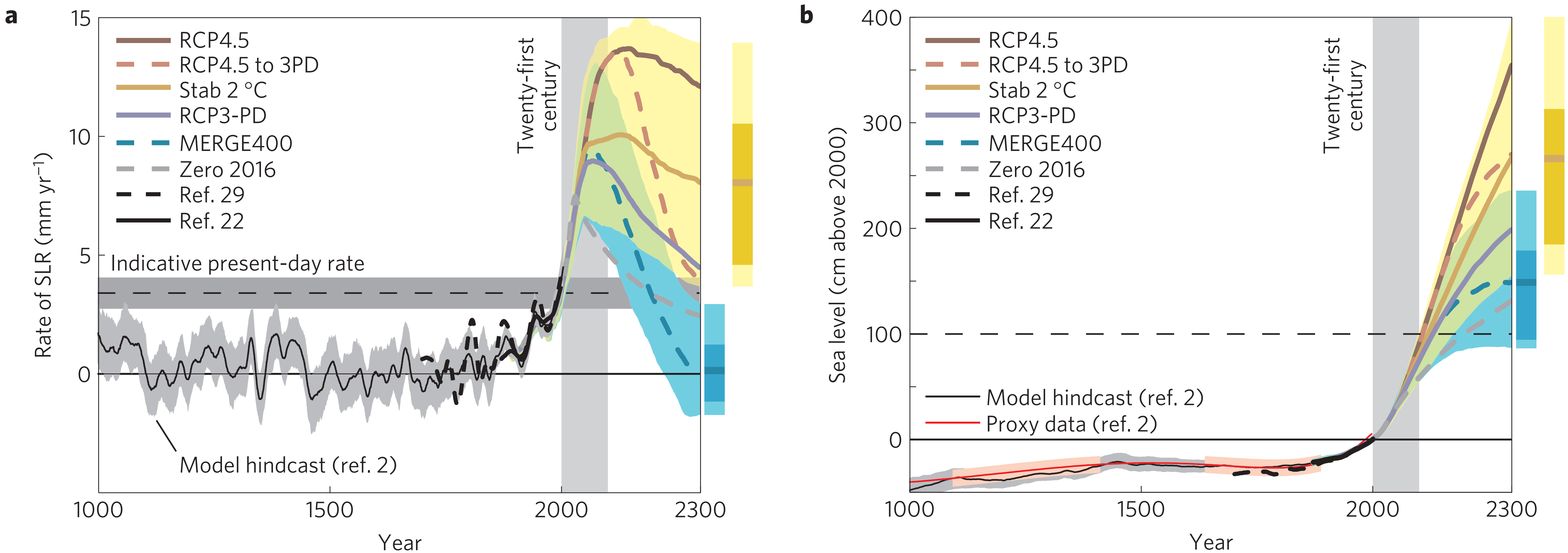


Figure 3 | Long-term SLR. a, Rate of SLR and **b**, SLR calculated from temperature reconstructions[28] for 1000–2006 and from climate-model projections 1860–2300. For comparison, observed and proxy reconstructions for SLR are given as well from refs 2,22,29. 90% uncertainty ranges are shown for only two scenarios for reasons of readability, focusing on the lowest and highest temperature-goal scenarios. Error bars on the right-hand side as in Fig. 2.

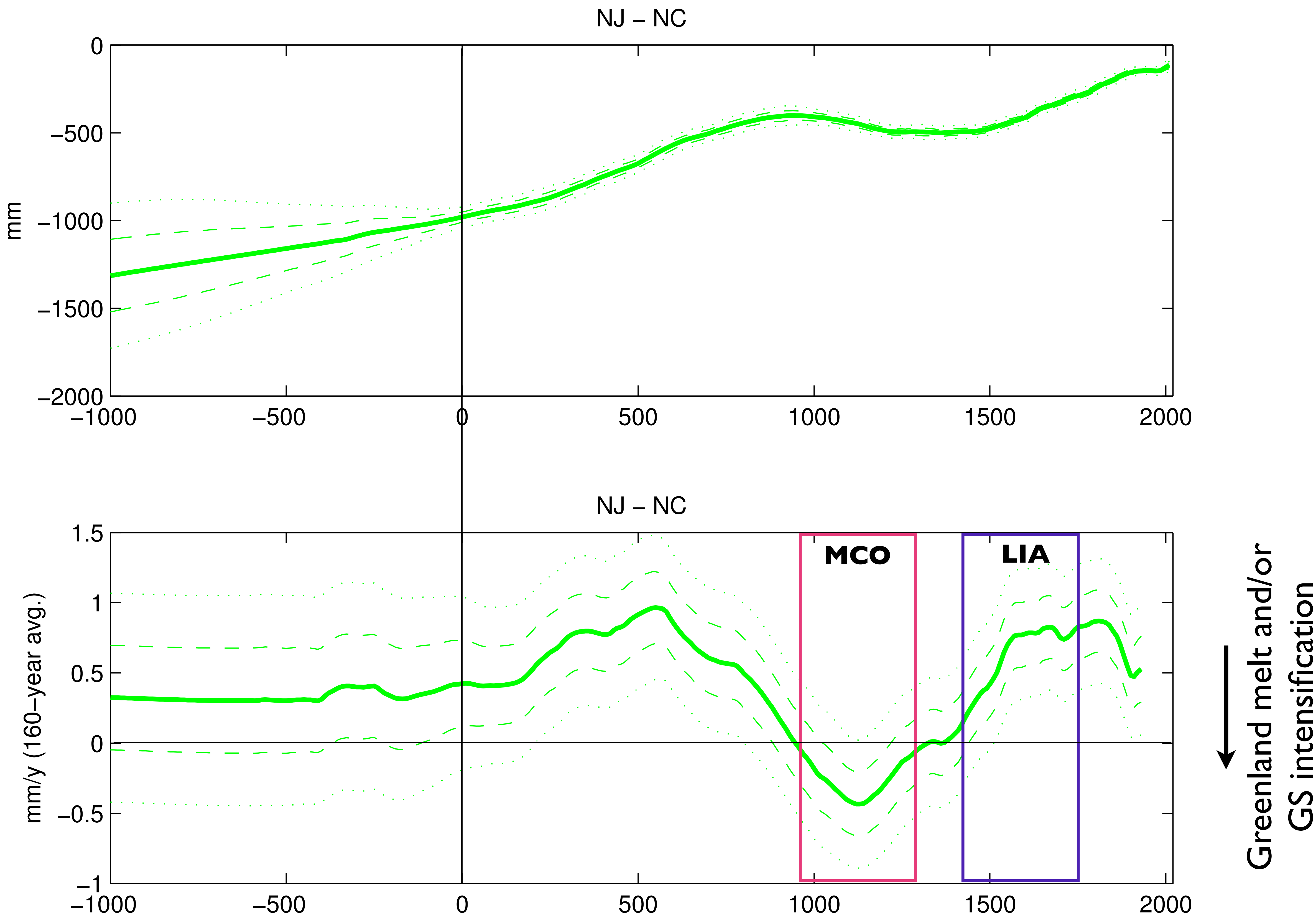
$$dH/dt = a_1[T(t) - T_{0,0}] + a_2[T(t) - T_0(t)] + b\,dT/dt$$

$$\text{with} \quad dT_0/dt = \tau^{-1}[T(t) - T_0(t)]$$

Global semi-empirical, transient estimate (1000-2300 CE)
Global mean temperature as only forcing parameter
Reference projection: 70-140 cm in 2100

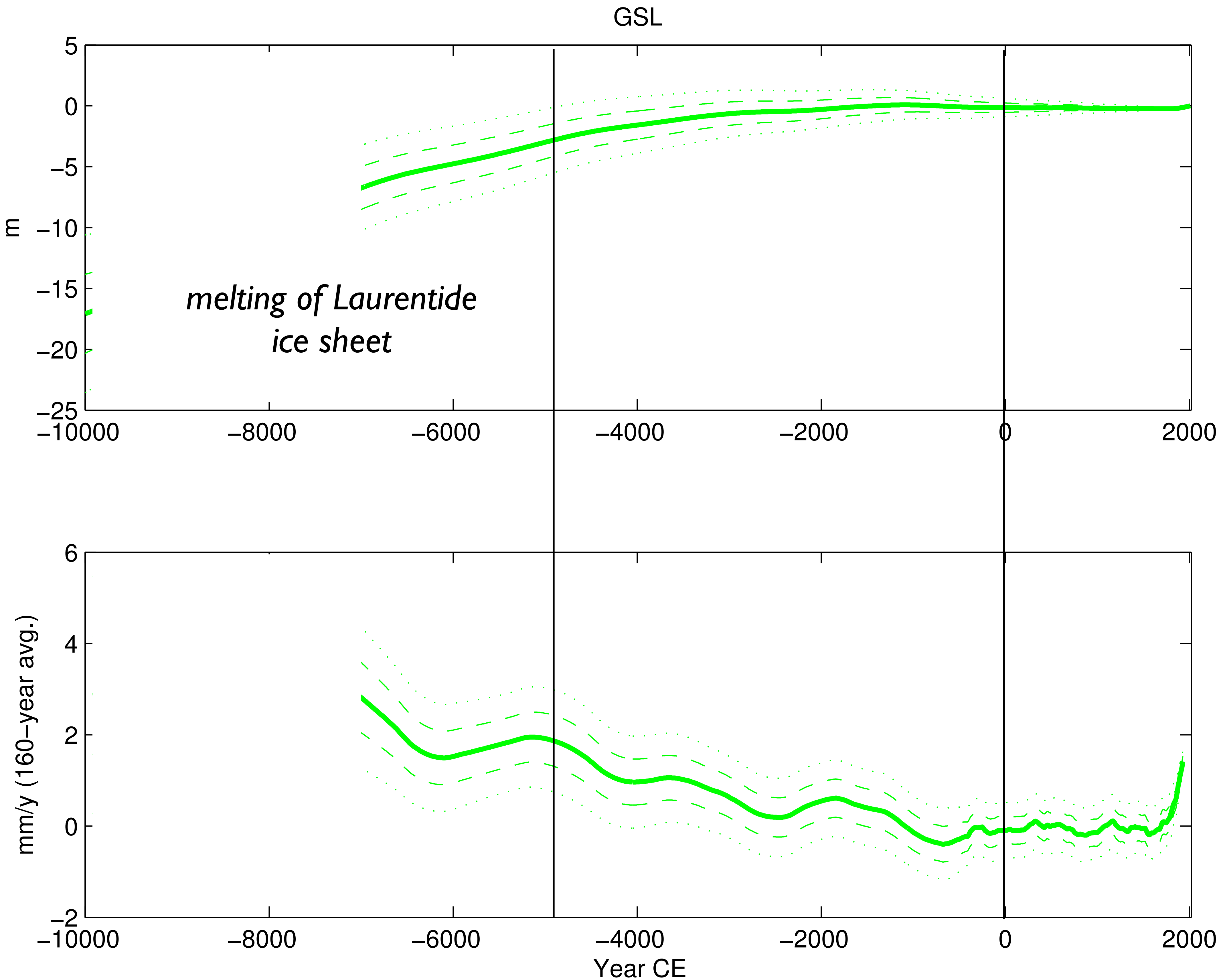
Schaeffer et al. (2012)

Toward a multi-site reconstruction: the Common Era mid-Atlantic "hot spot" record



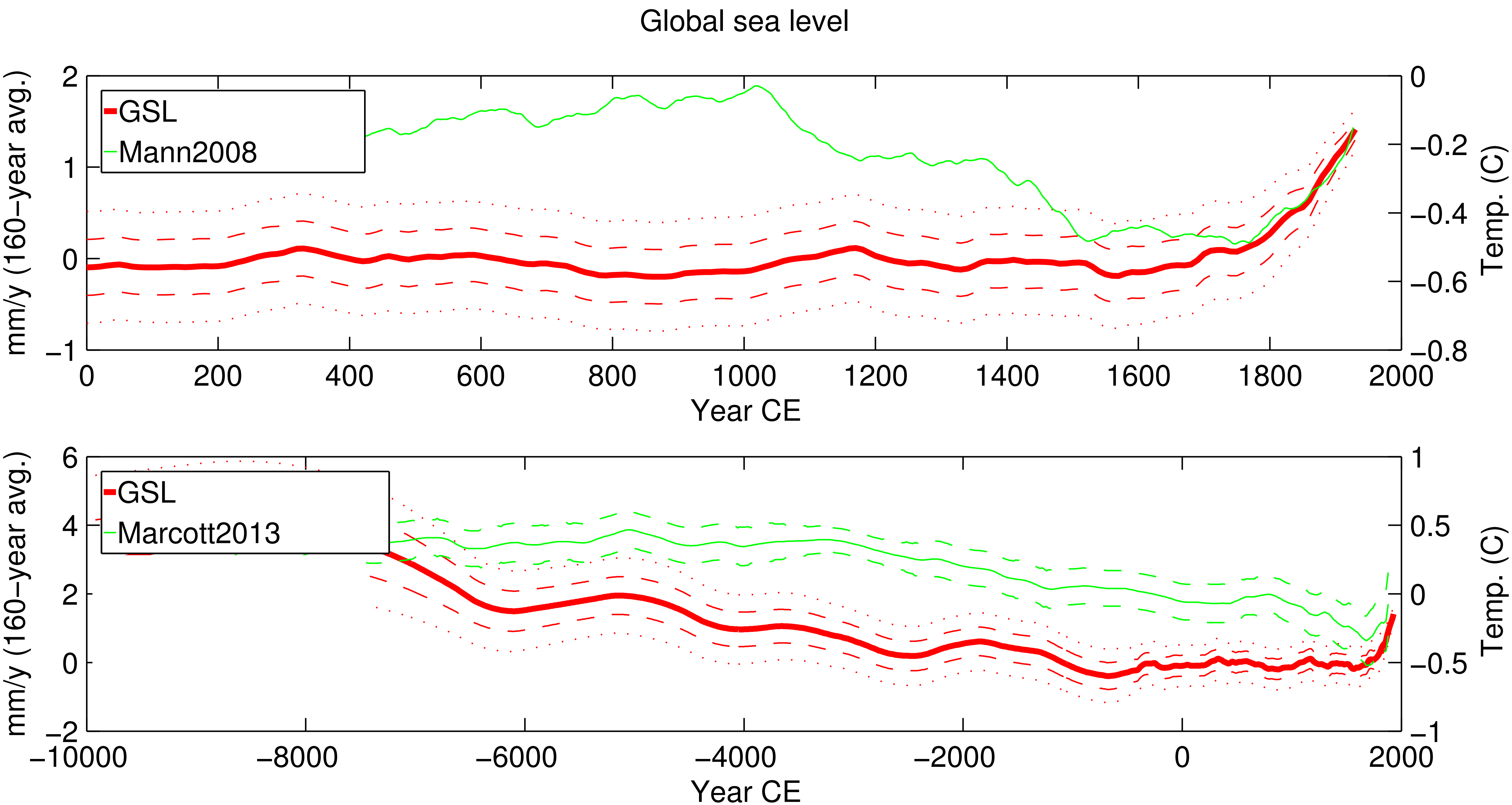
Rates are 160-y avg.

Three-site (NJ, NC, FL) estimate of GSL



Result seems problematic for current semi-empirical models

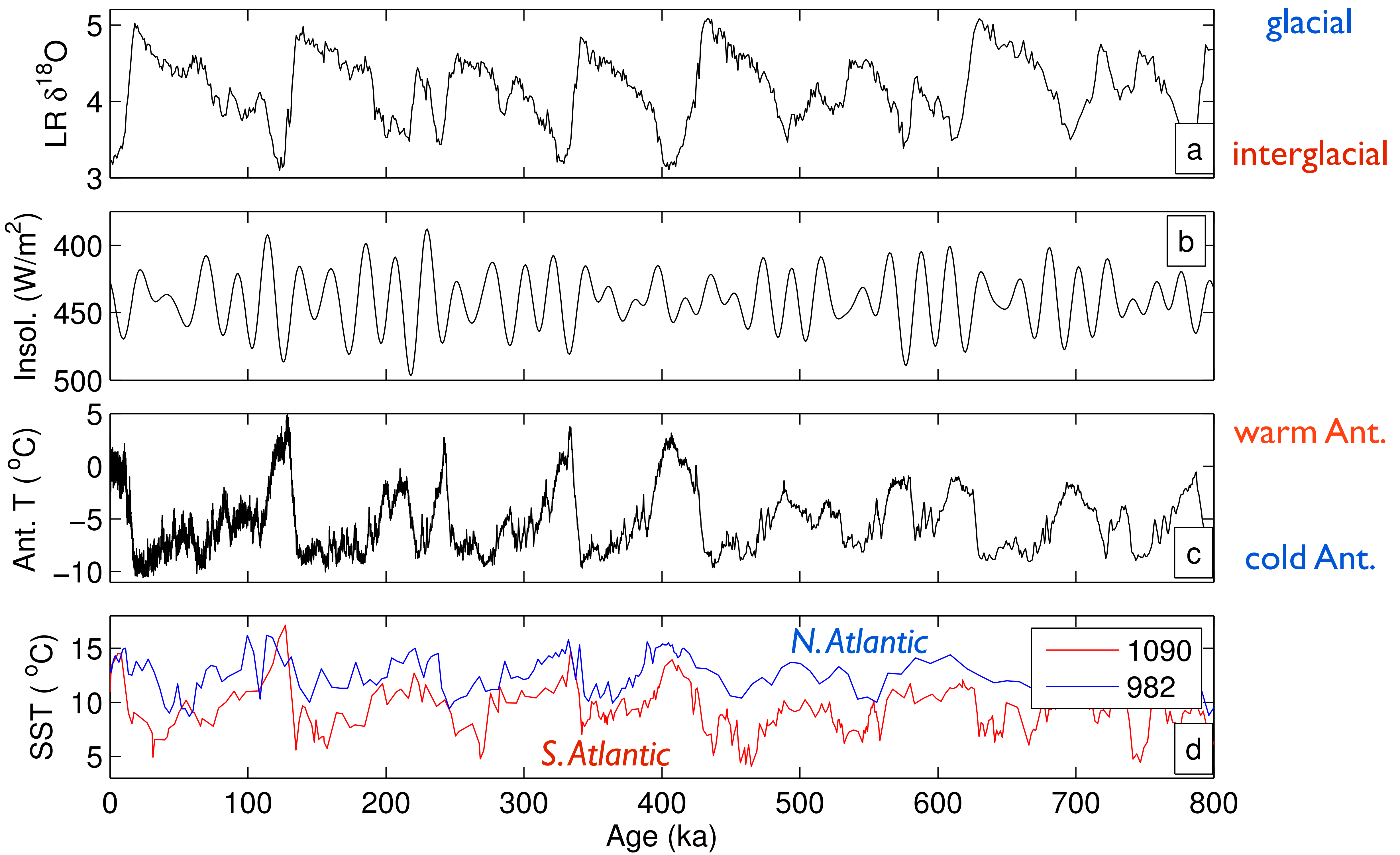
Do we need a frequency-dependent approach?



(note that Earth's orbital configuration is also changing over the course of the Holocene)

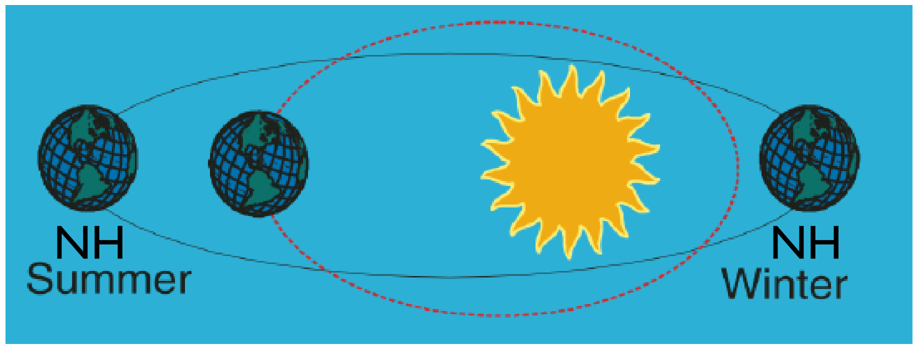
Can deeper time help with the out-of-sample issue?

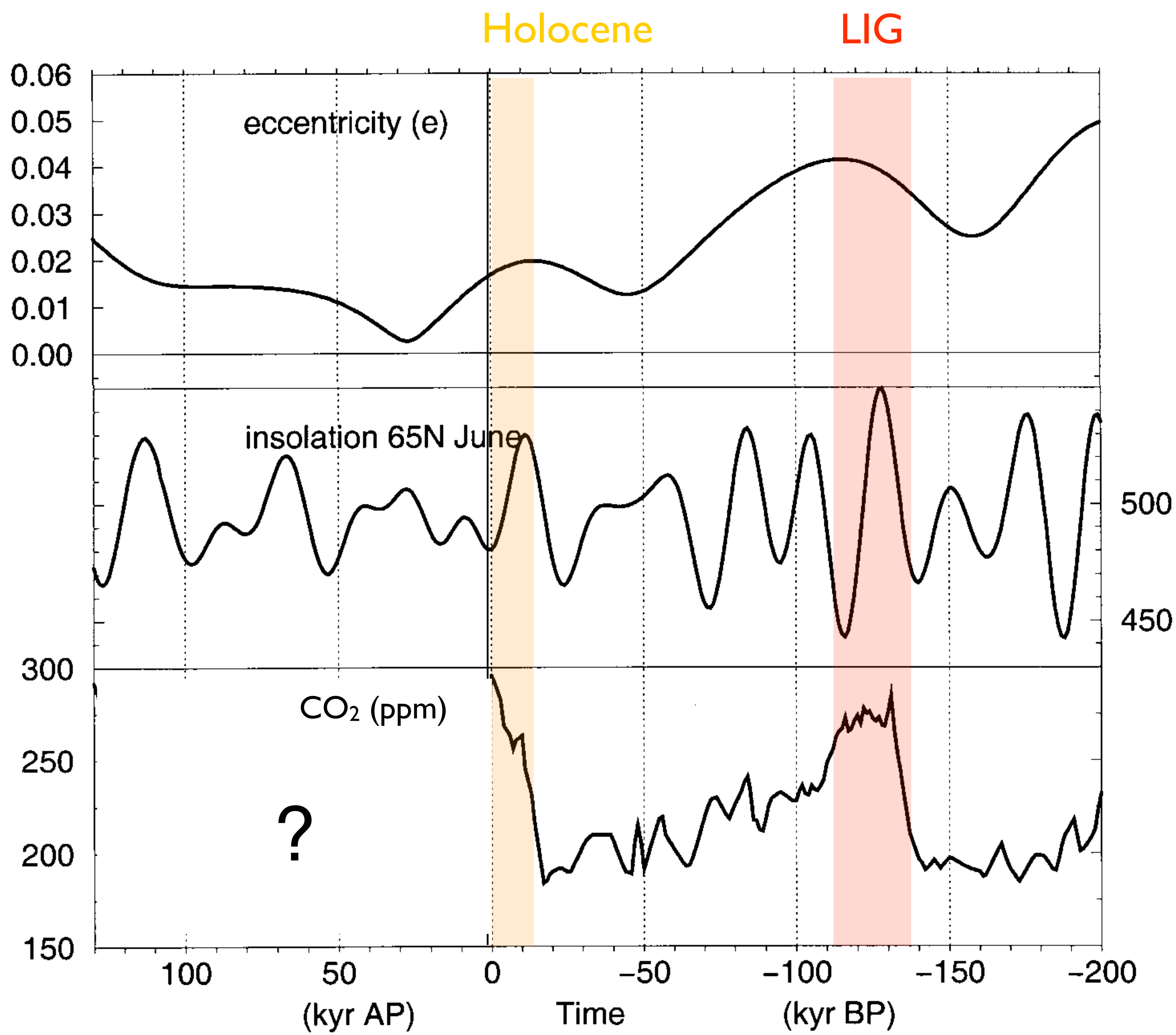
For the last 2 My, the Earth has oscillated between glacials and interglacials



(a) The global benthic oxygen isotope stack of Lisiecki and Raymo (2005), which is a convolved record of global ice volume change and benthic temperature change, (b) summertime insolation at 65°N latitude (Berger and Loutre, 1991), and some paleoclimatic proxies that might be related to ice sheet changes – (c) the deuterium-derived temperature record from Dome C in East Antarctica (Joulez et al, 2007), and (d) alkenone-derived sea surface temperature records from ODP 1090 from Agulhas Ridge in the South Atlantic (red: Marinez-Garcia et al., 2009) and ODP 982 from the Rockall Plateau in the North Atlantic (blue: Lawrence et al., 2009).

The Last Interglacial stage had Holocene-like pCO_2 but higher eccentricity





Berger et al. (2003)

The Last Interglacial was slightly warmer than today

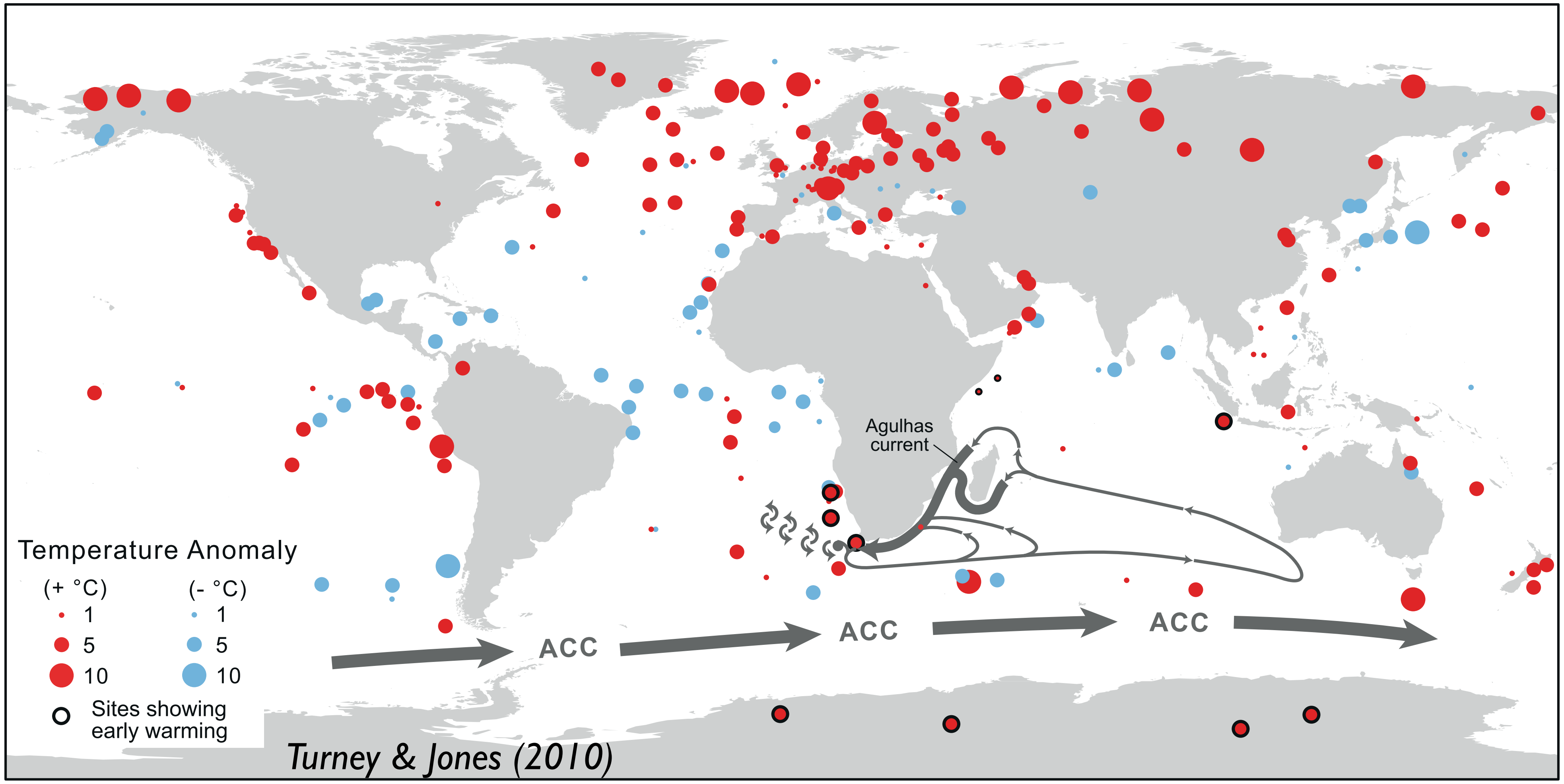


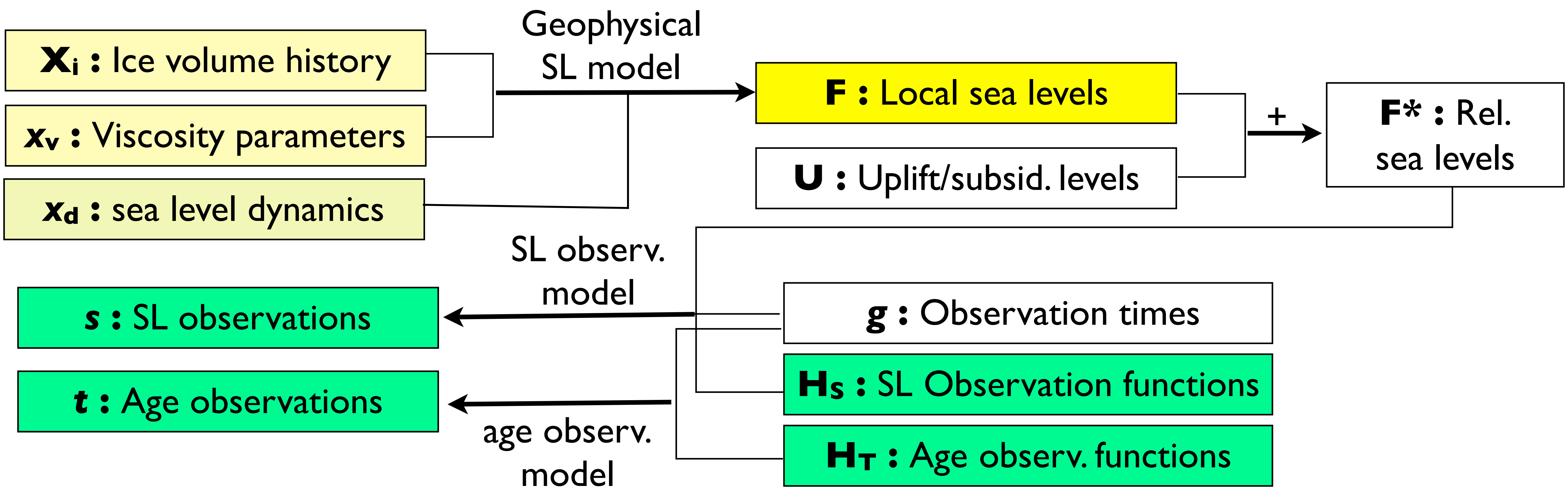
Figure 1 Temperature anomalies (relative to AD 1961–1990) in 263 Last Interglacial ice, marine and terrestrial sequences. The location of the Antarctic Circumpolar Current (ACC) and the Agulhas Current are shown. Sites suggesting local early warming are shown with bold circles. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

Turney & Jones (2010): global temperature ~1.9°C above pre-Industrial

McKay et al. (2011): SST 0.7 ± 0.6°C above pre-Industrial

- NH warming due to more intense summer insolation, amplified by ice sheet feedbacks (3-5°C in Arctic)
- SH warming perhaps due to ocean teleconnections and/or long SH summer

A forward model for geological sea level proxies

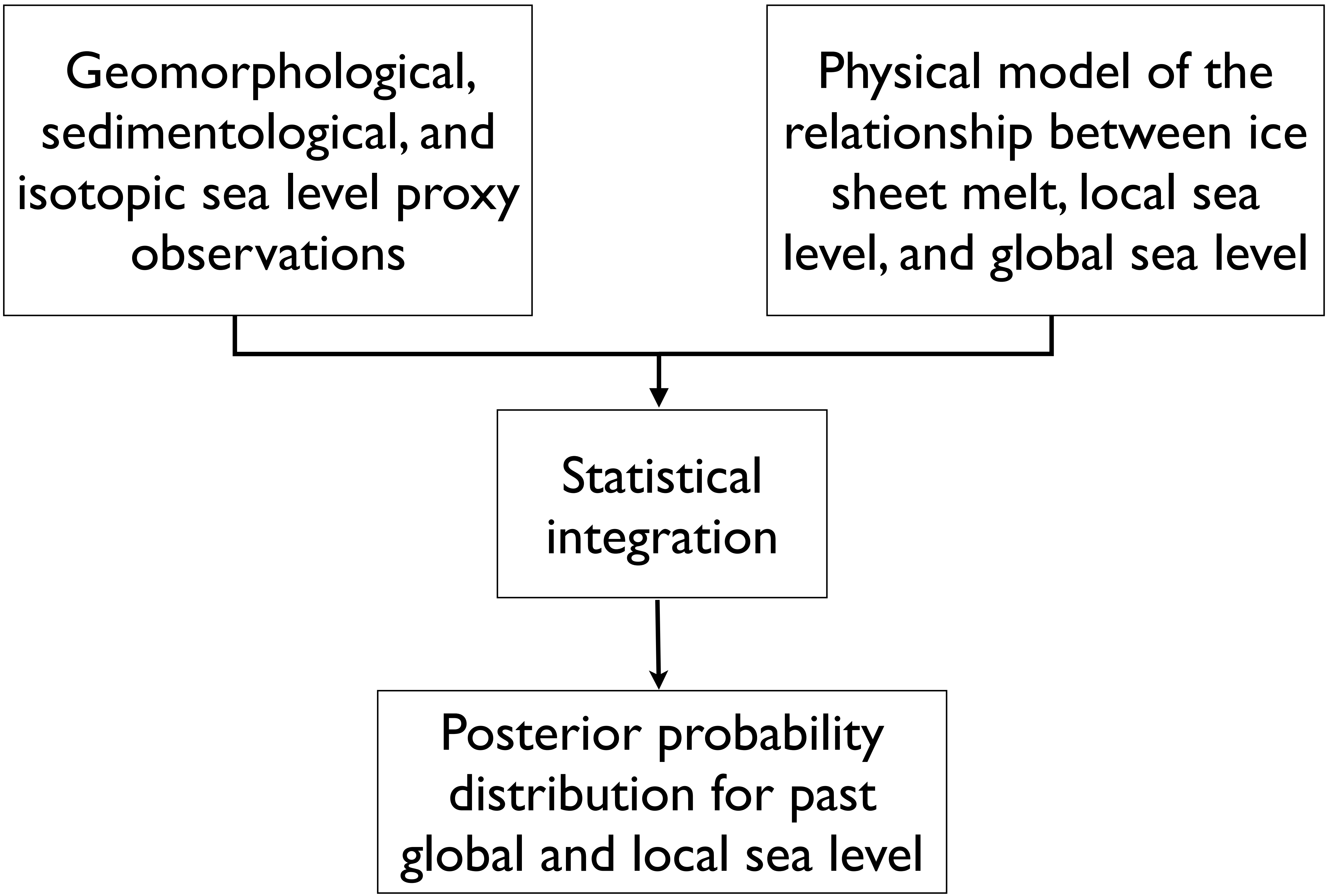


This gives us $P(\boldsymbol{s},\boldsymbol{t} \mid \mathbf{X}_i, \mathbf{x}_v, \mathbf{U}, \mathbf{g}, \mathbf{H}_S, \mathbf{H}_T)$.

We want to find $P(\mathbf{F}, \mathbf{g} \mid \boldsymbol{s}, \boldsymbol{t}, \mathbf{U}, \mathbf{H}_S, \mathbf{H}_T)$

[and ideally $P(\mathbf{X}_i, \mathbf{x}_v, \mathbf{X}_d \mid \boldsymbol{s}, \boldsymbol{t}, \mathbf{U}, \mathbf{H}_S, \mathbf{H}_T)$]

Goal: Given database, assess the probability distribution of sea level through space and time



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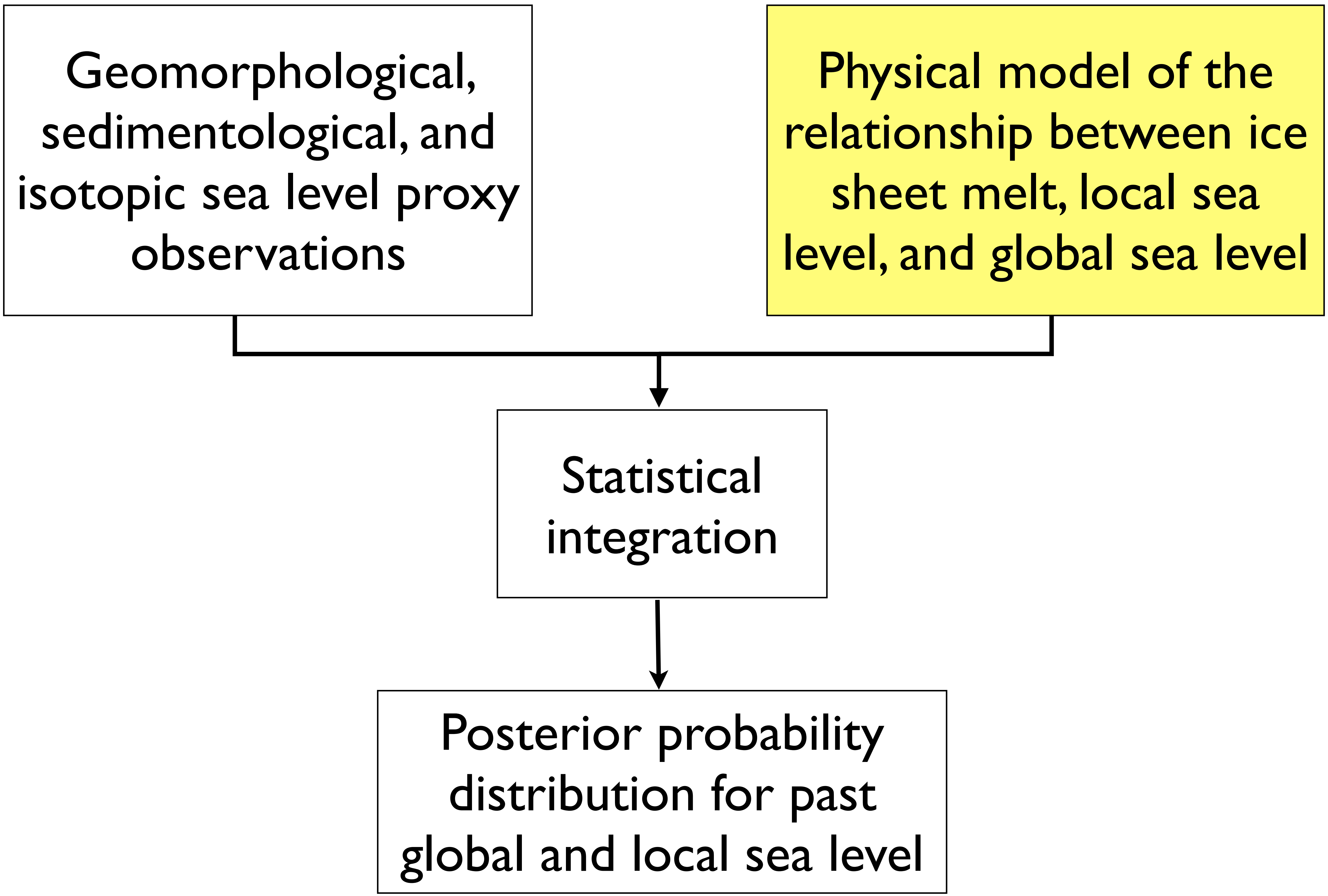
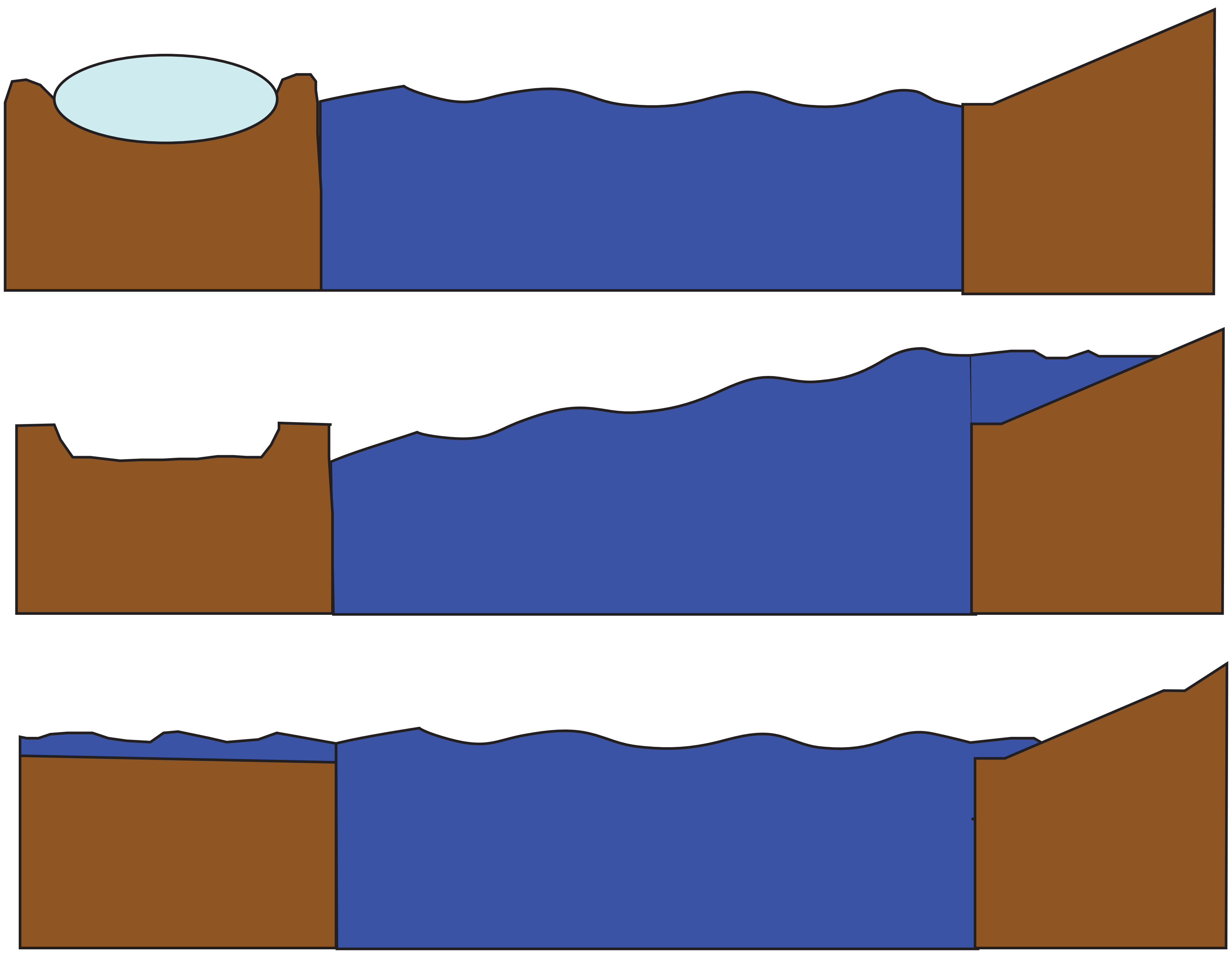


Samples from the ice volume prior are divided up among sources and run through the geophysical model...

Effects included:

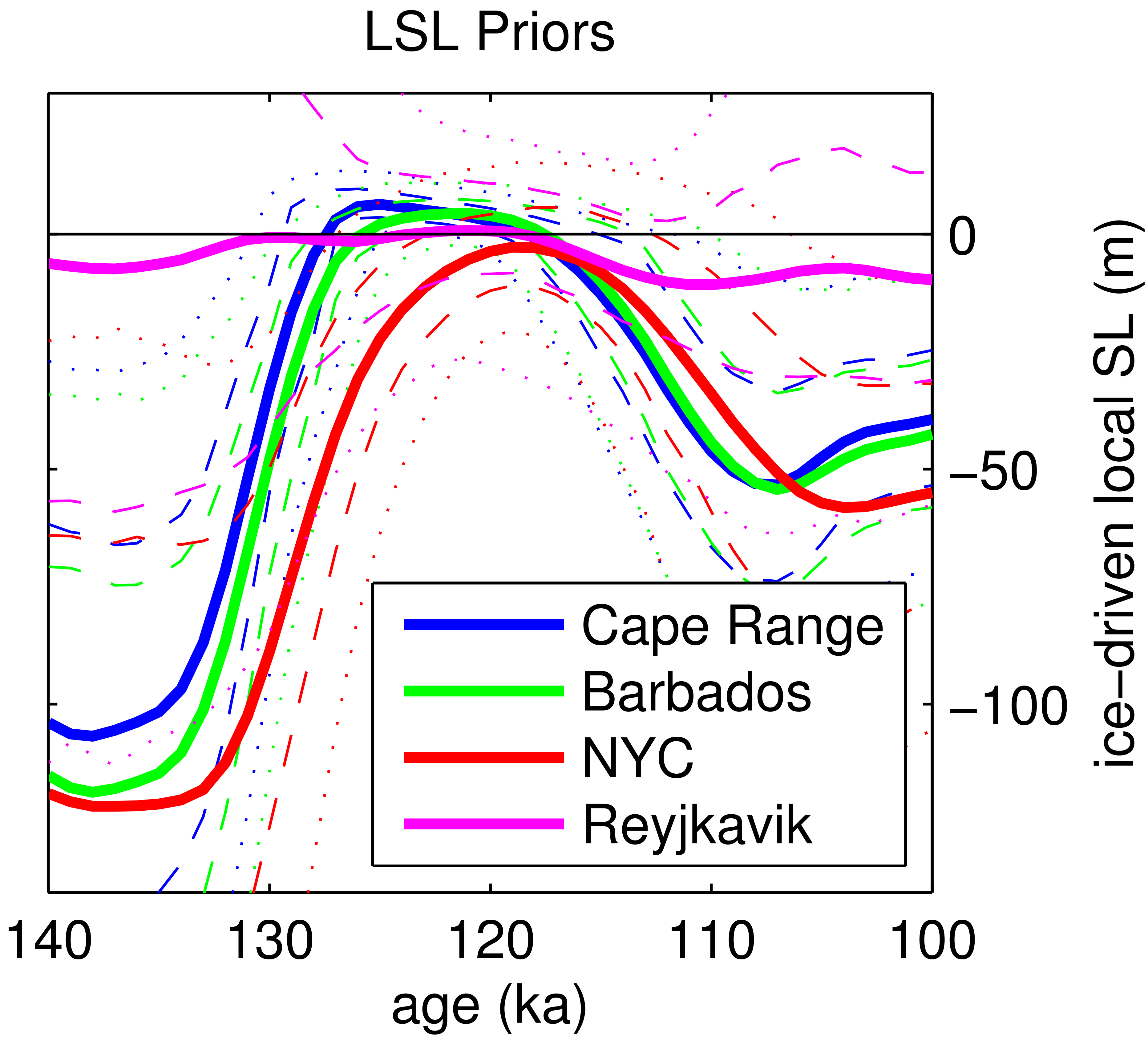
Gravitational, elastic, rotational, isostatic, shoreline migrations



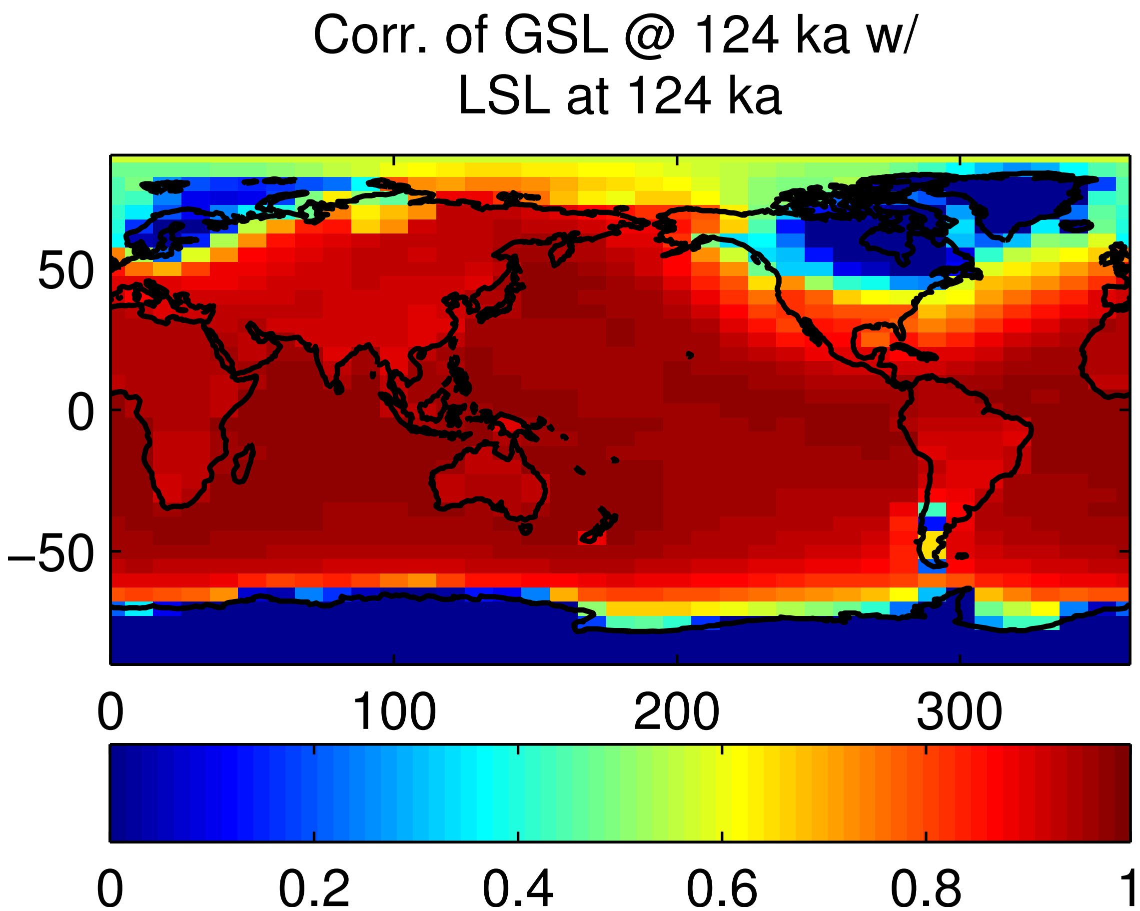
Gravitational and elastic response

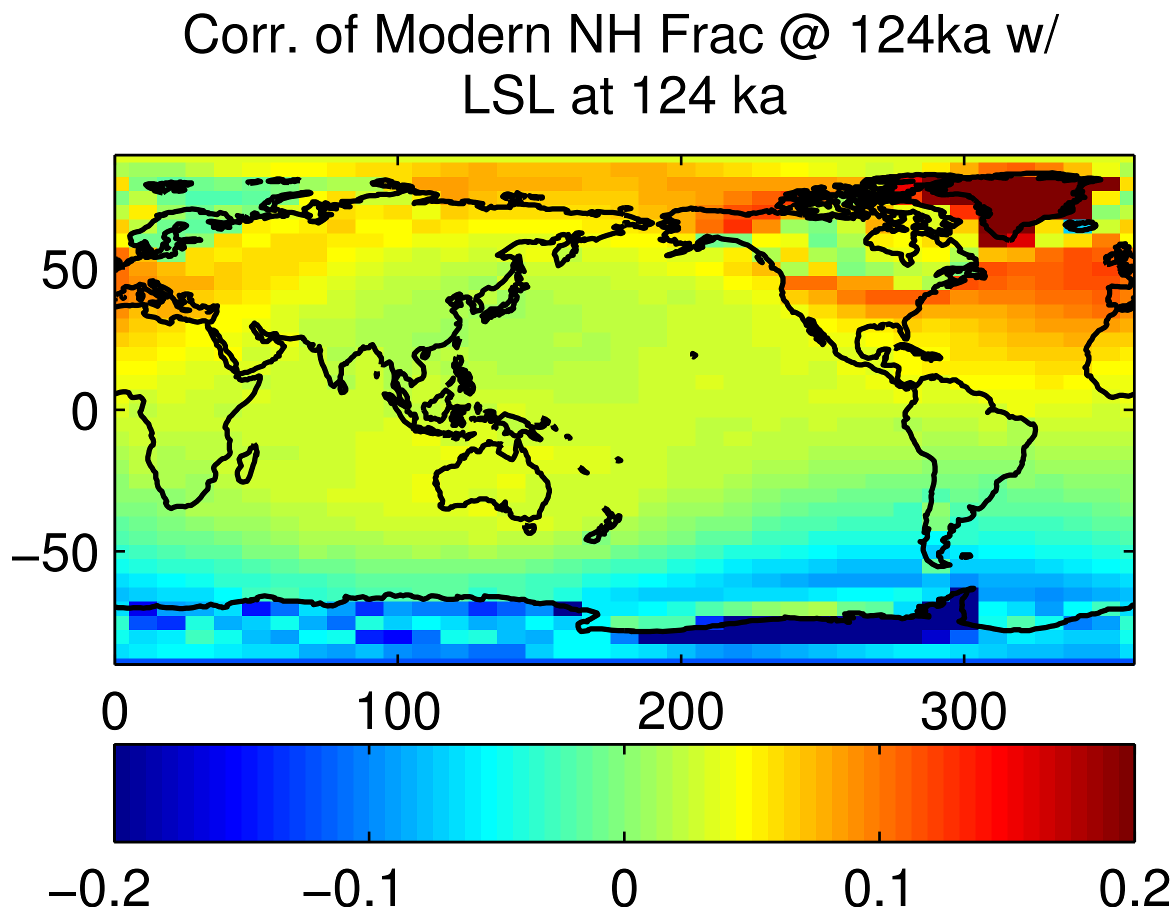
Isostatic response

...yielding priors for local sea levels over time



...which we use to approximate the sea level field as a Gaussian process





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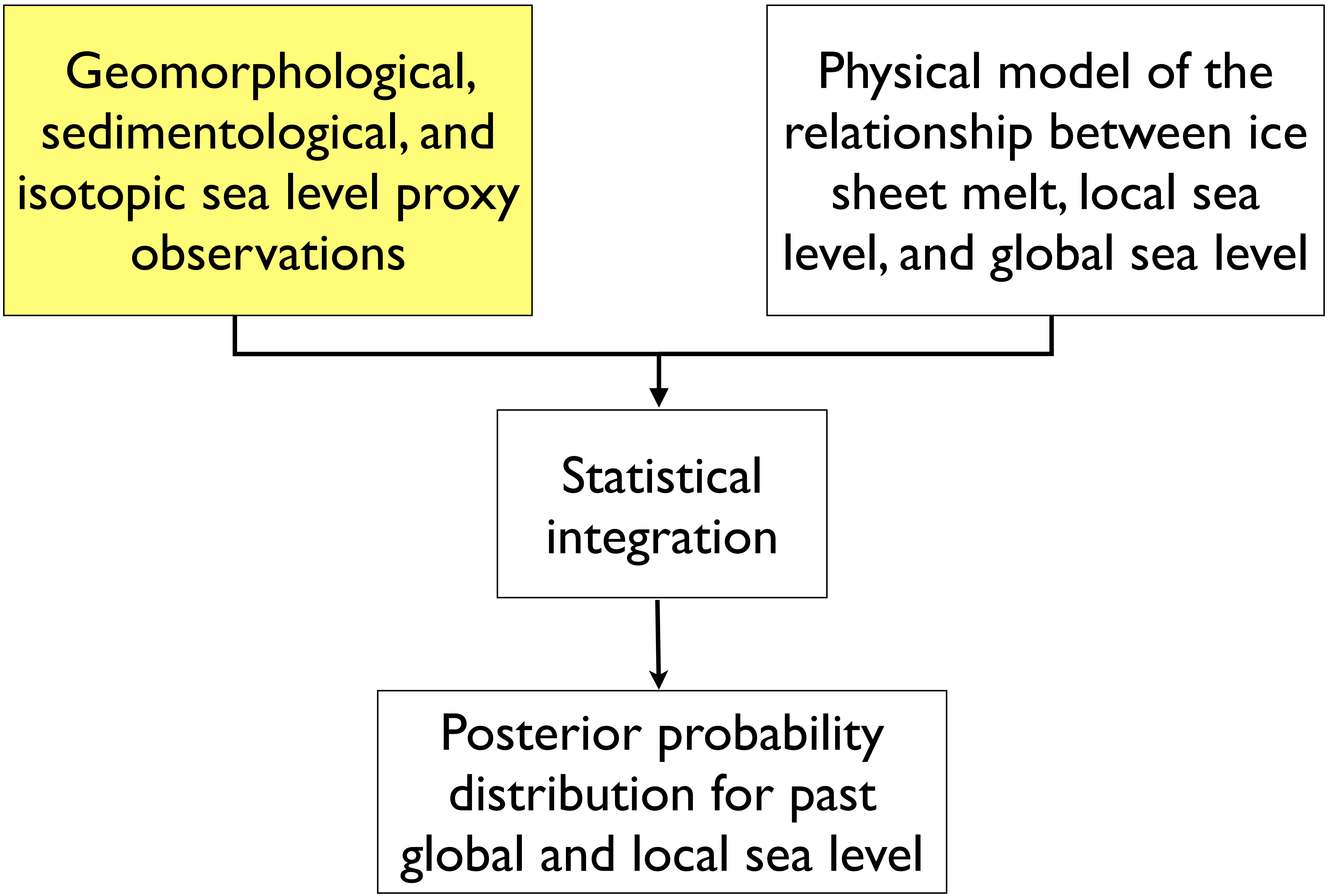
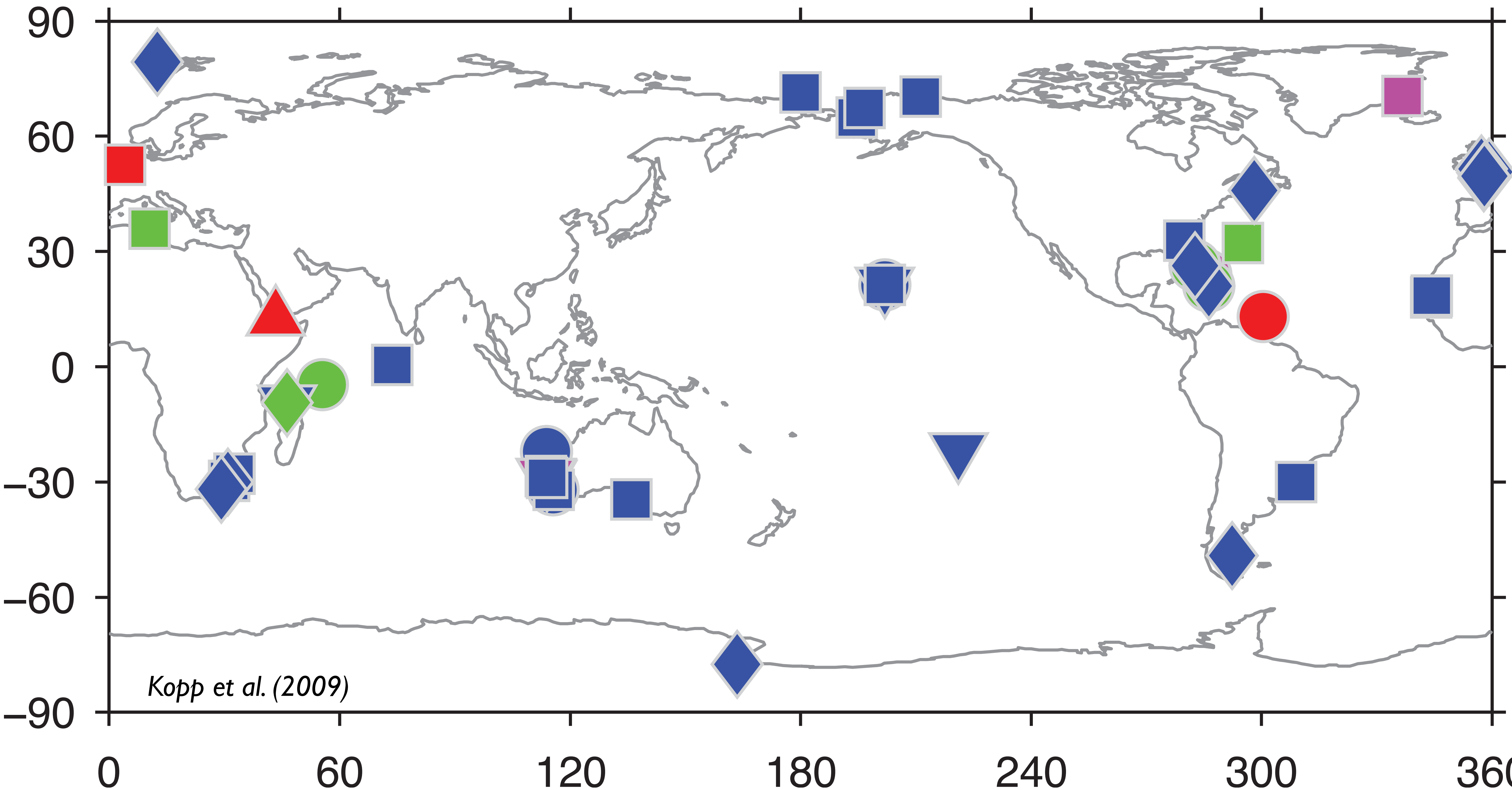


Database of sea level observations

Sites with at least one LIG Sea Level Indicator



Indicator Nature – Δ: isotopic; ○: reef terraces; ▽: coral biofacies; ▫: sedimentary facies and non-coral biofacies; ◇: erosional

Observations – 1, 2, 3, ≥4

Kopp et al. (2009)

Sea Level Database

Example 1: Cockburn Town Reef, San Salvador, Bahamas

Chen et al. (1991)

Sea Level Database

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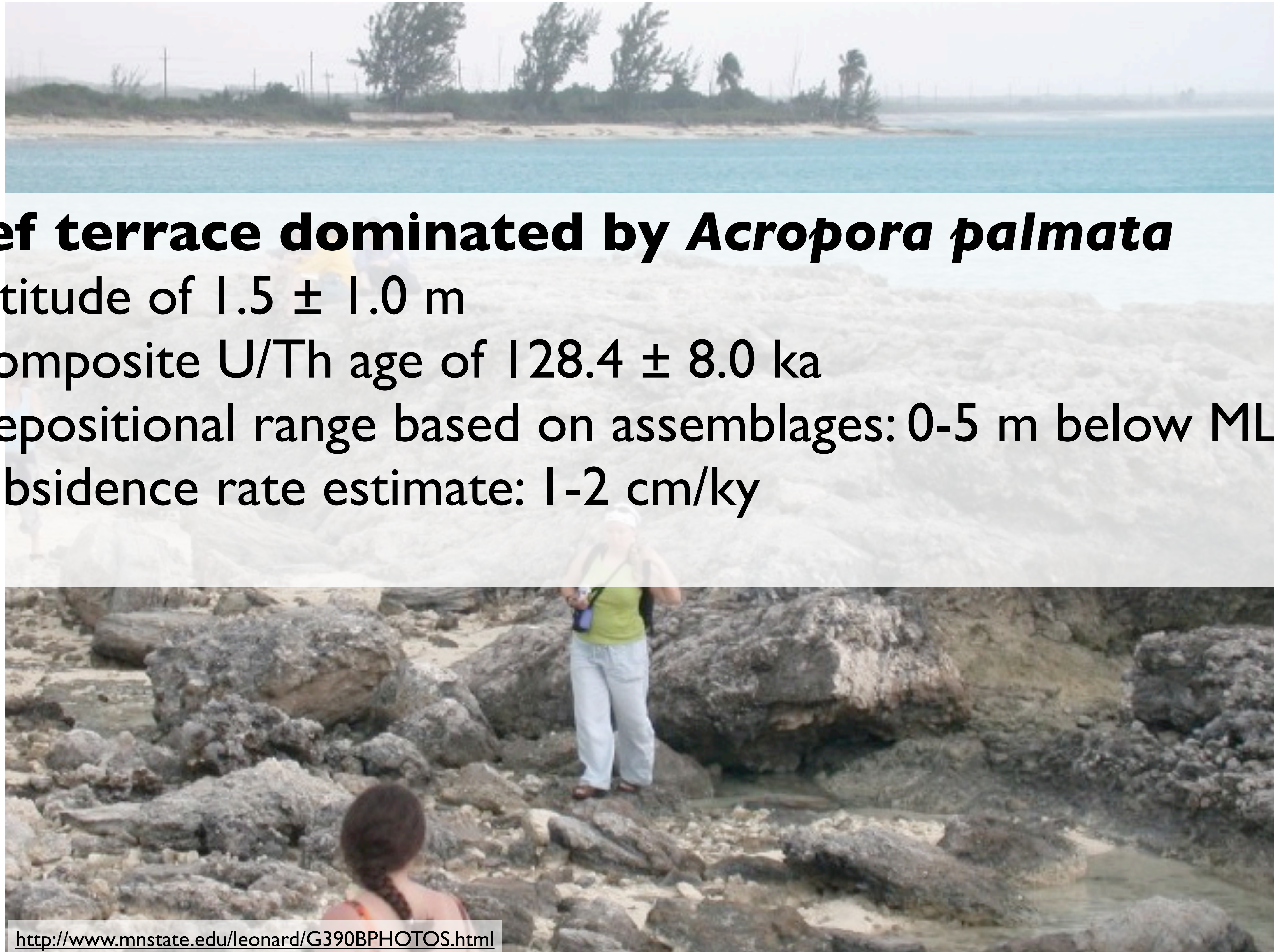


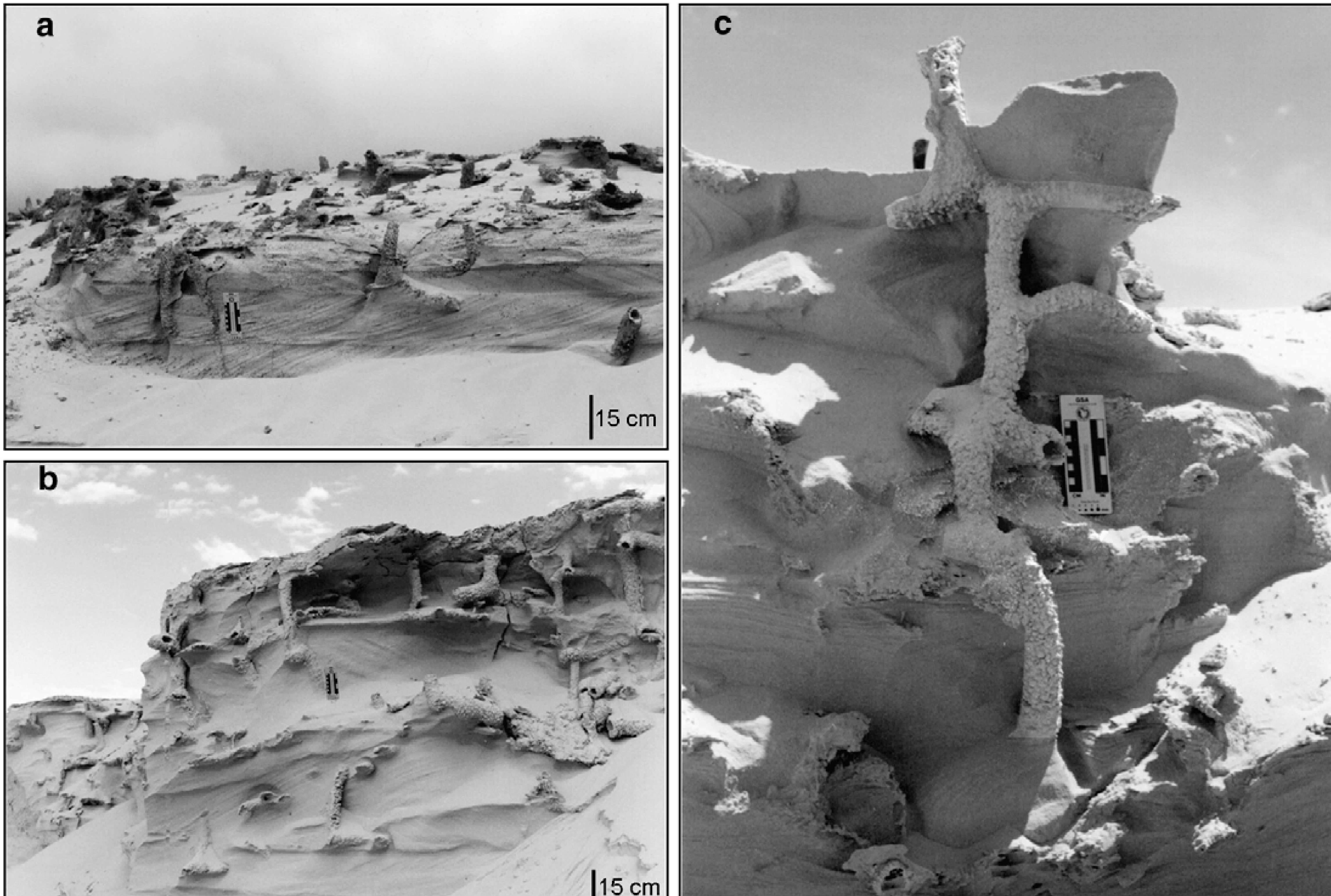
Reef terrace dominated by *Acropora palmata*

- Altitude of 1.5 ± 1.0 m
- Composite U/Th age of 128.4 ± 8.0 ka
- Depositional range based on assemblages: 0-5 m below MLTL
- Subsidence rate estimate: 1-2 cm/ky

Chen et al. (1991)

Sea Level Database

Example 2: Coastal barrier at Rio Grande do Sol Coastal Plain, Brazil



Tomazelli et al. (2007)

Sea Level Database

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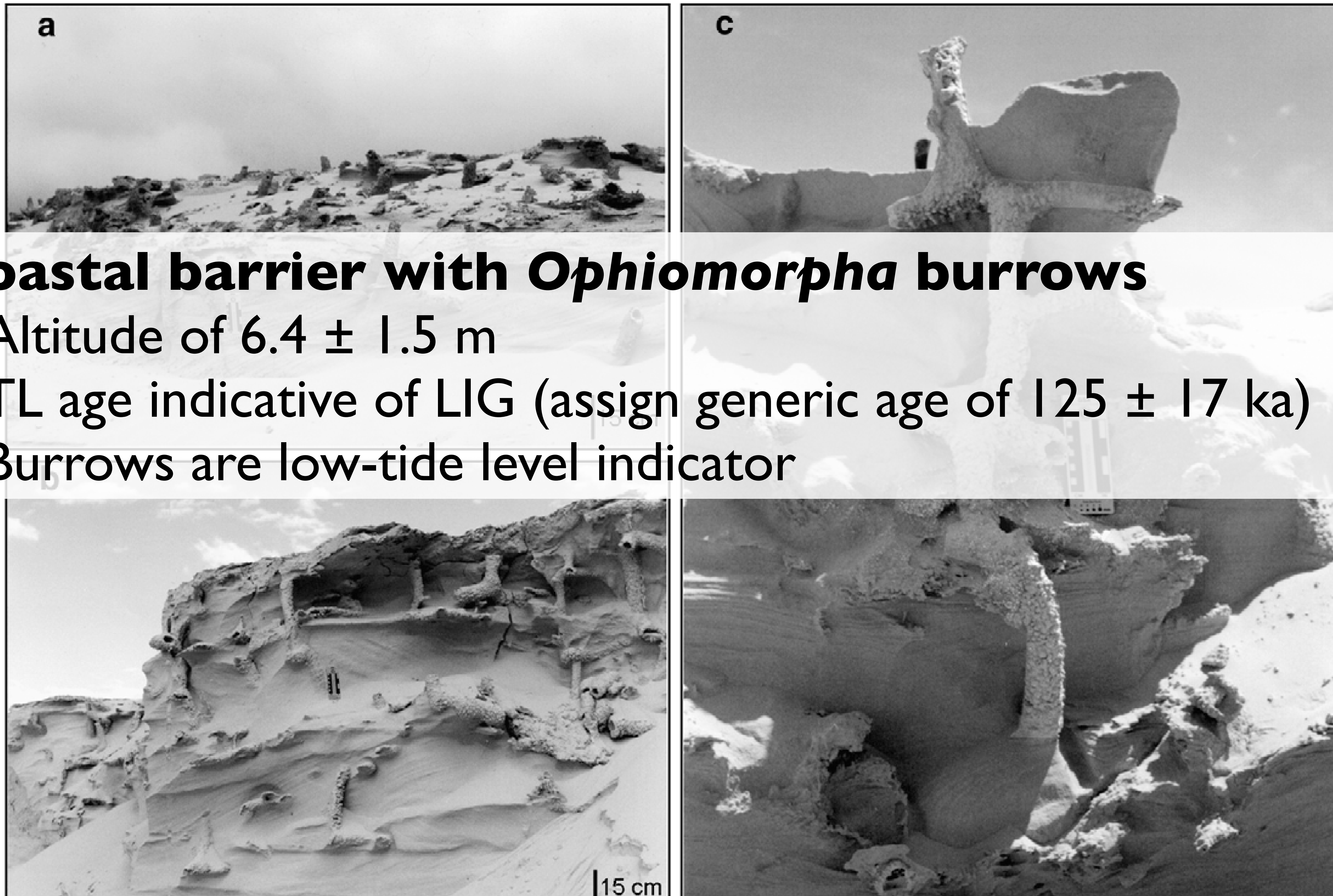


Coastal barrier with *Ophiomorpha* burrows

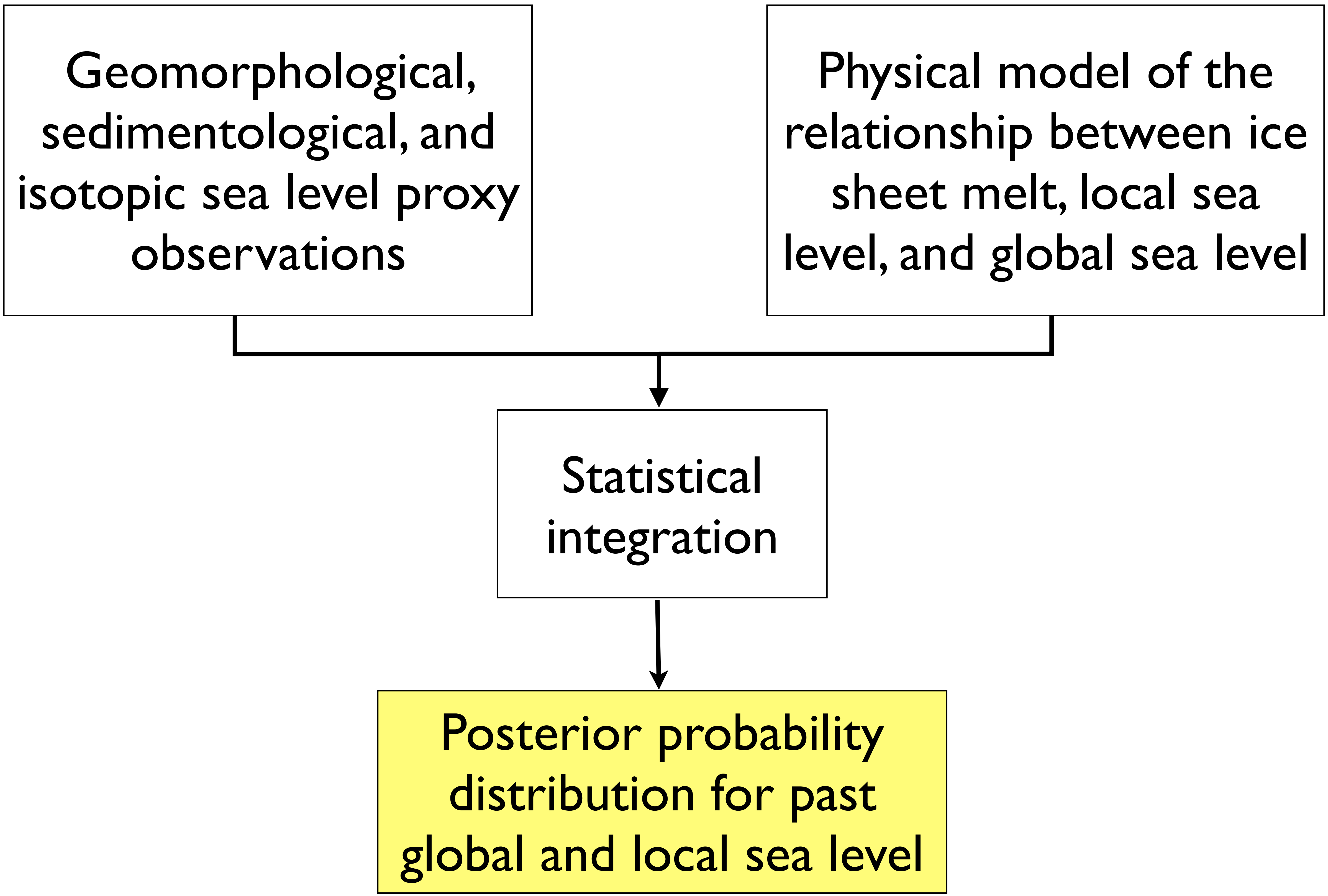
Altitude of 6.4 ± 1.5 m

TL age indicative of LIG (assign generic age of 125 ± 17 ka)

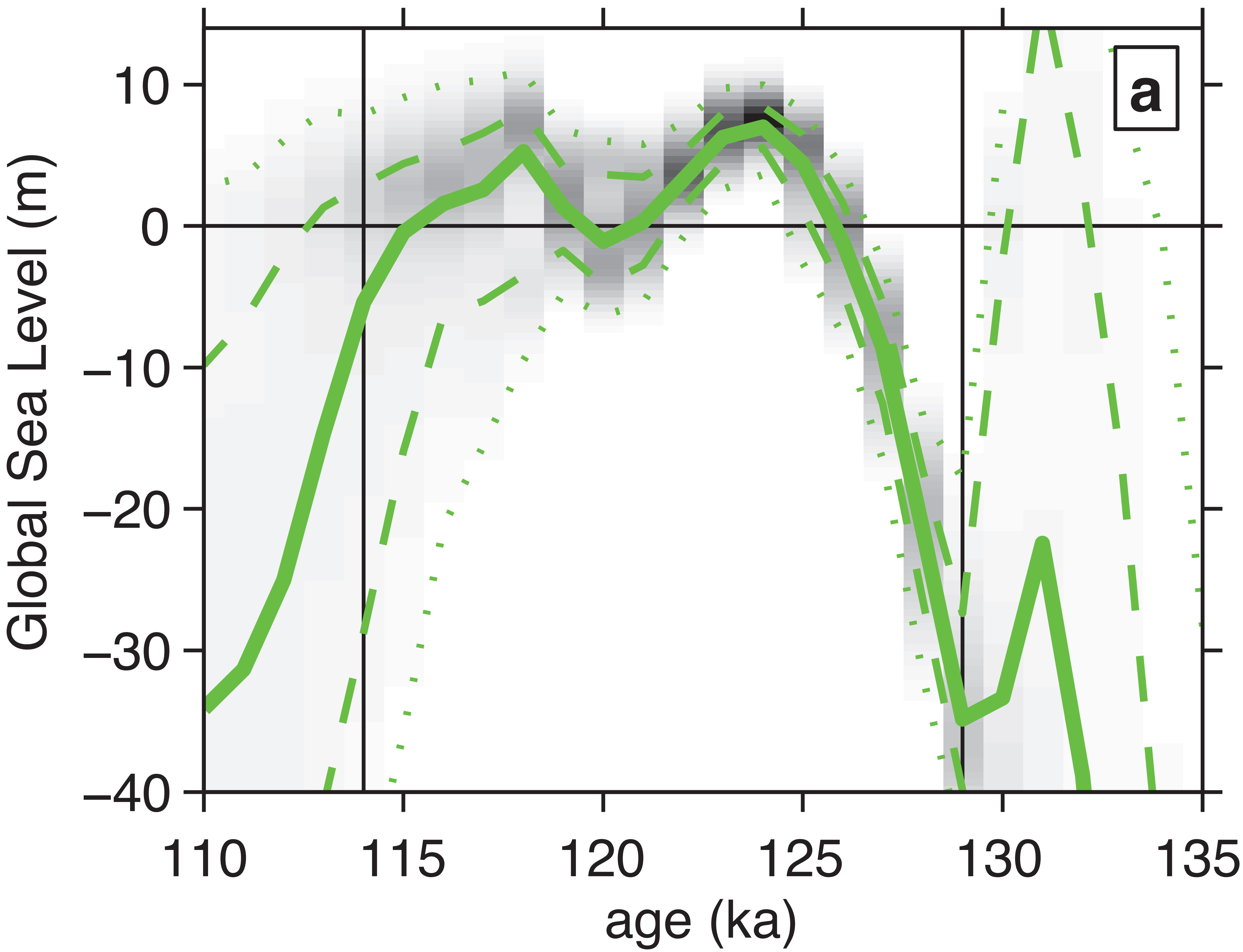
Burrows are low-tide level indicator

Tomazelli et al. (2007)

Goal: Given database, assess the probability distribution of sea level through space and time

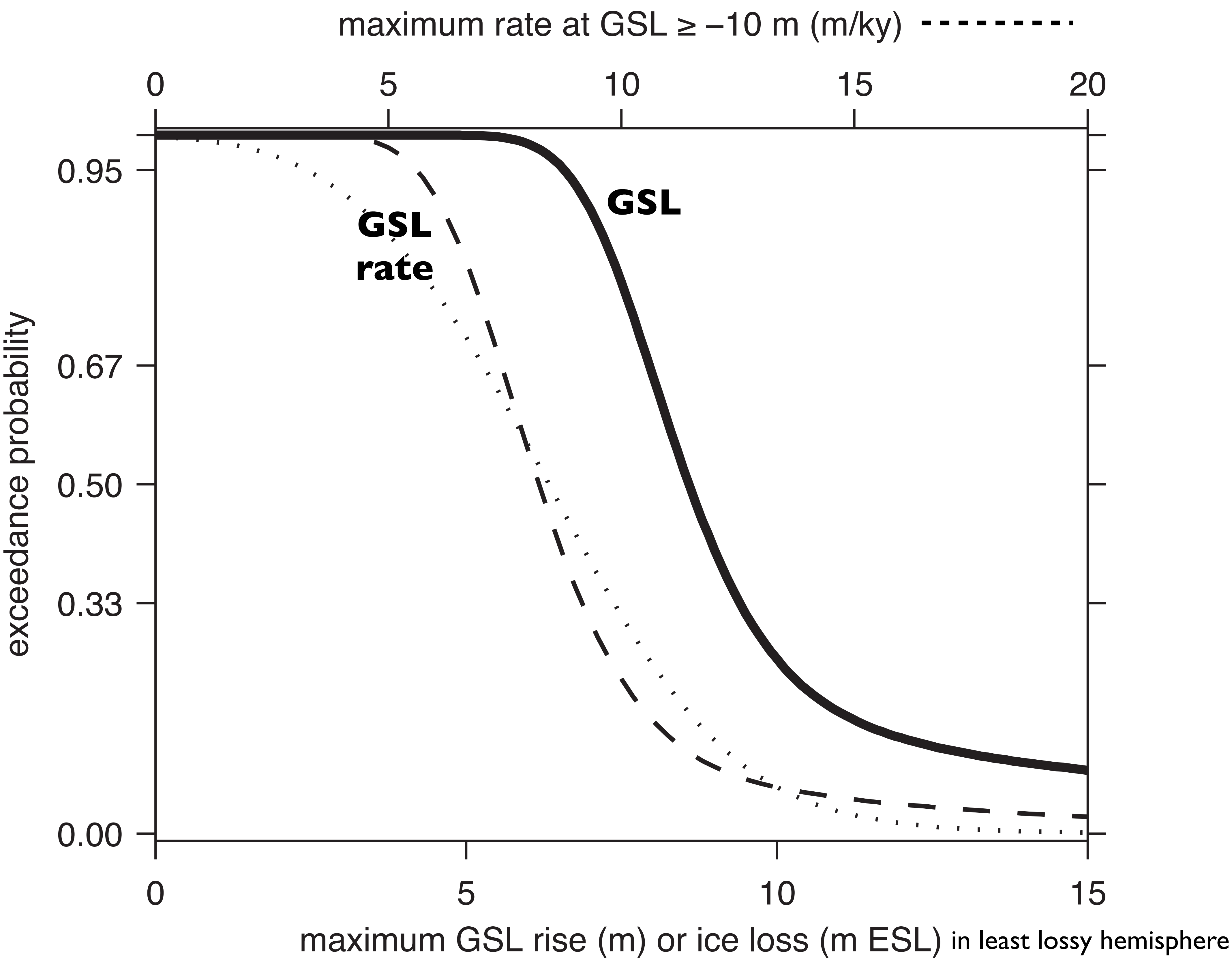


Posterior probability distribution for Last Interglacial GSL over time



Kopp et al. (2009)

Posterior exceedance levels



Kopp et al. (2009)

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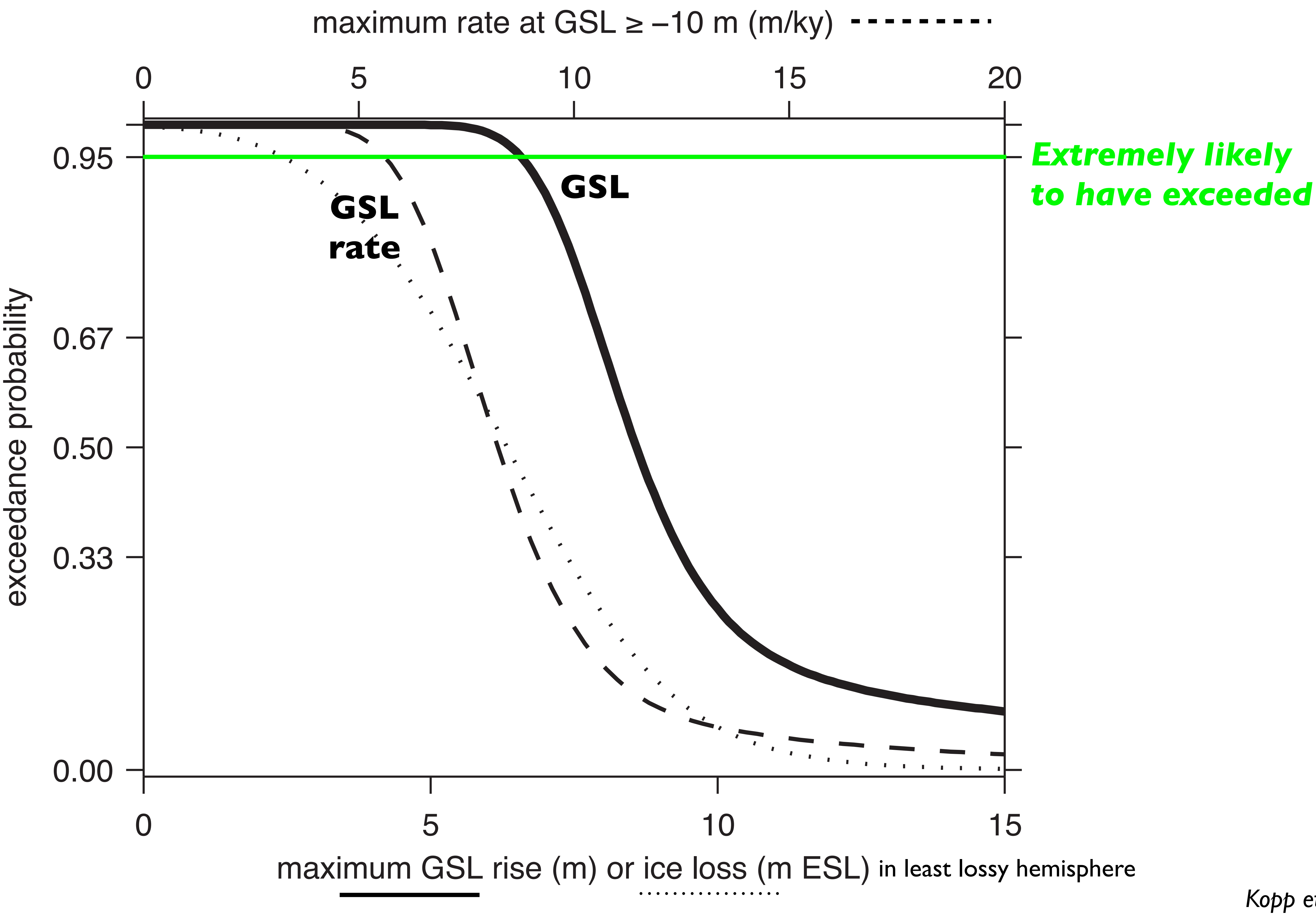

Kopp et al. (2009)

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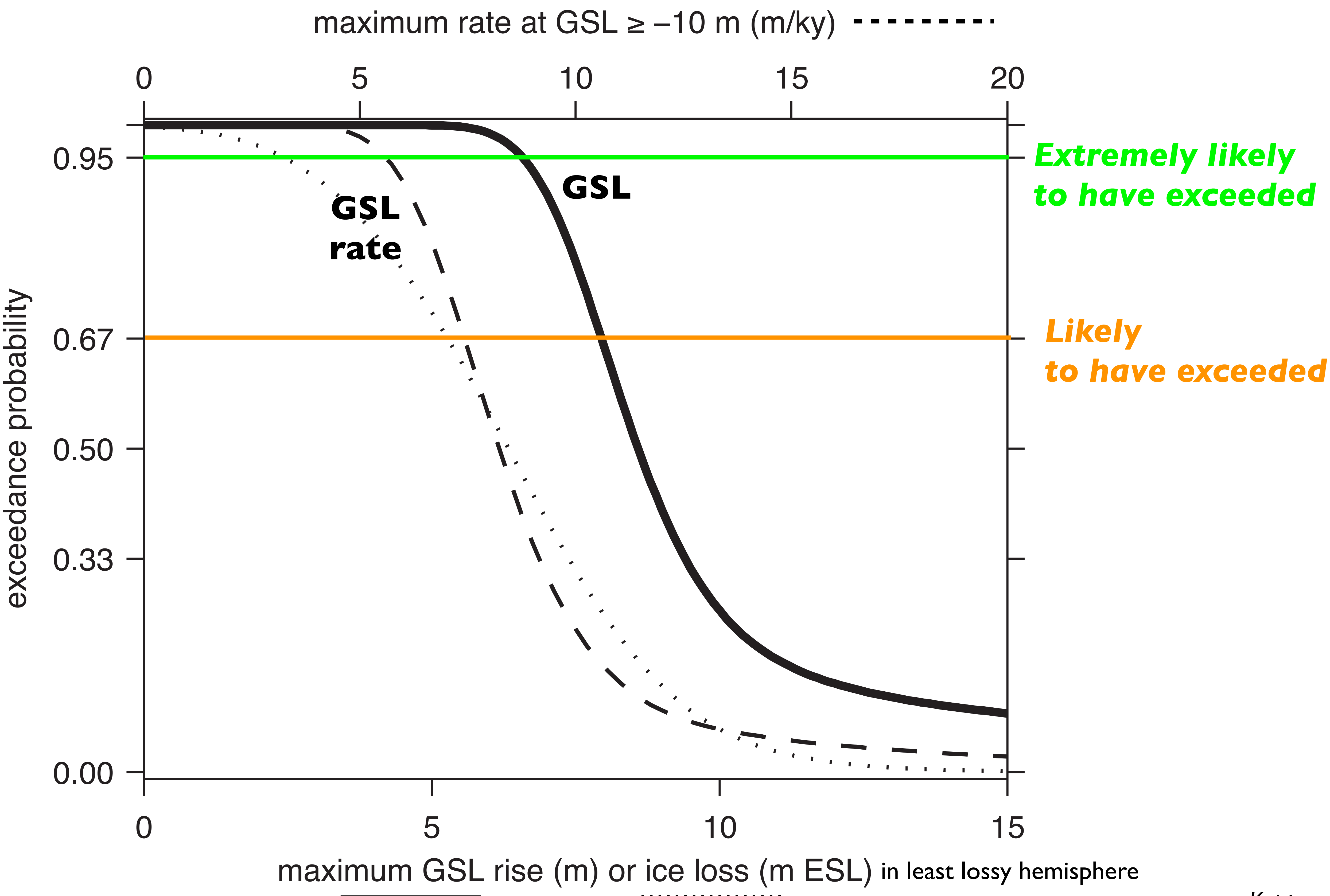

Kopp et al. (2009)

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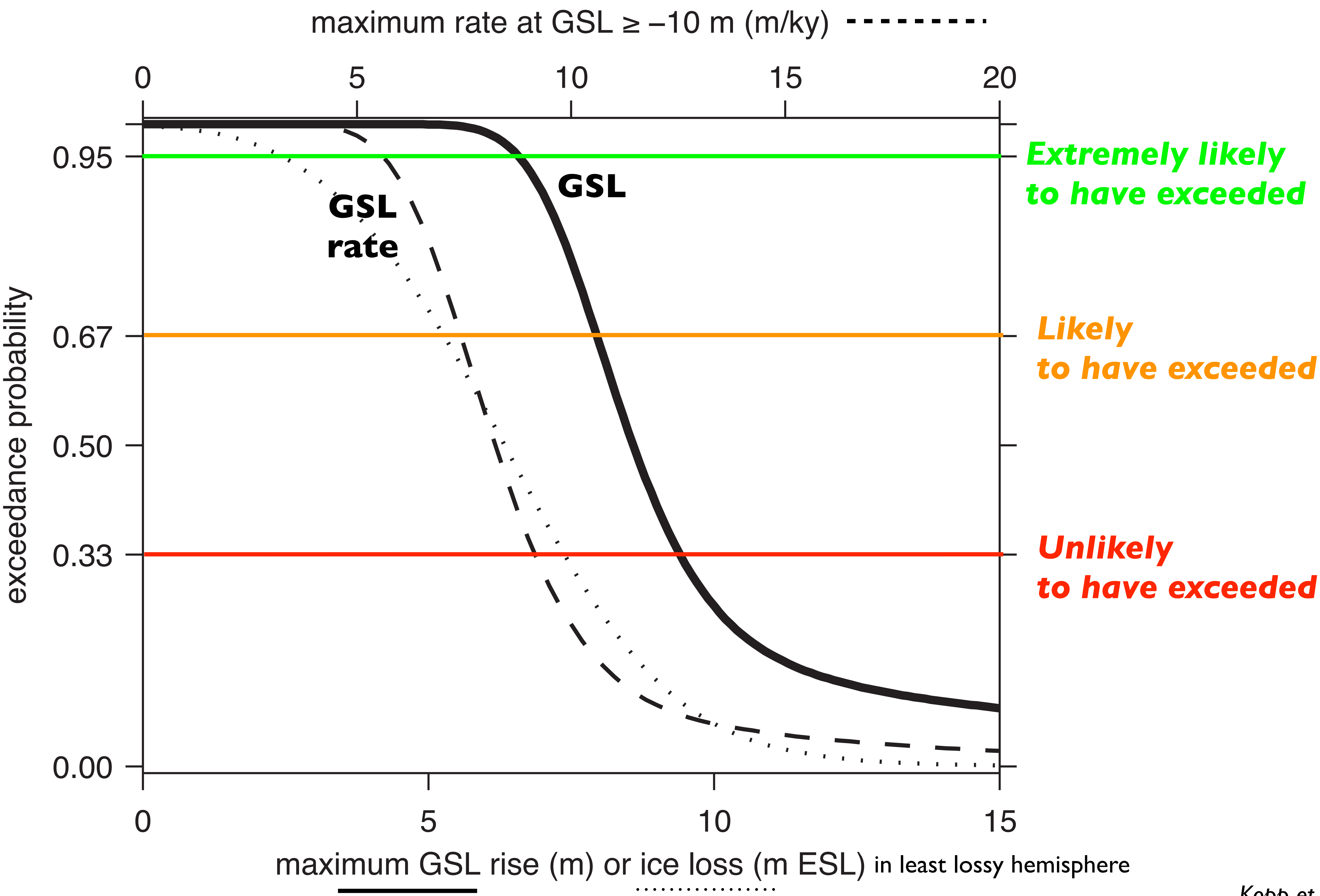

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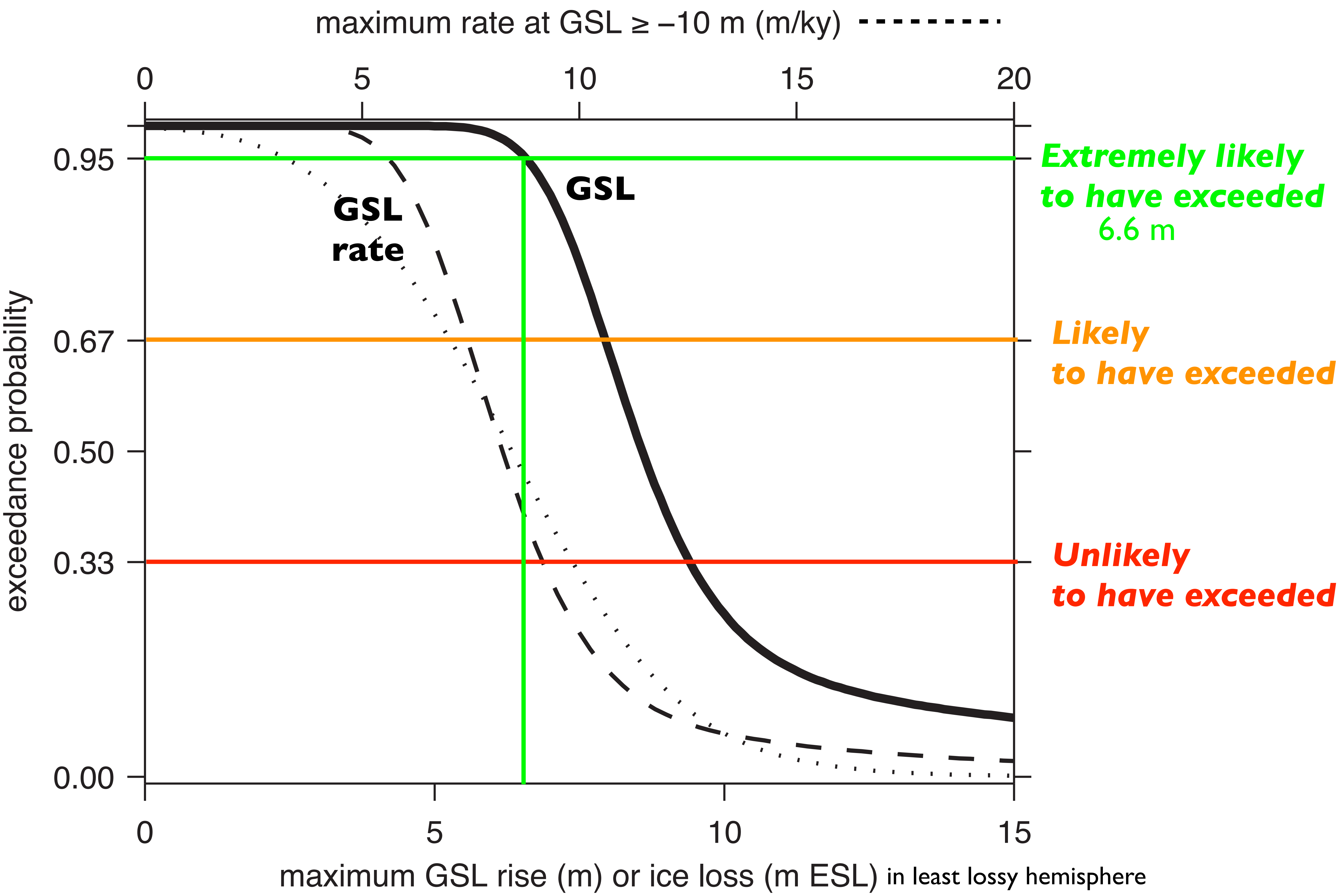
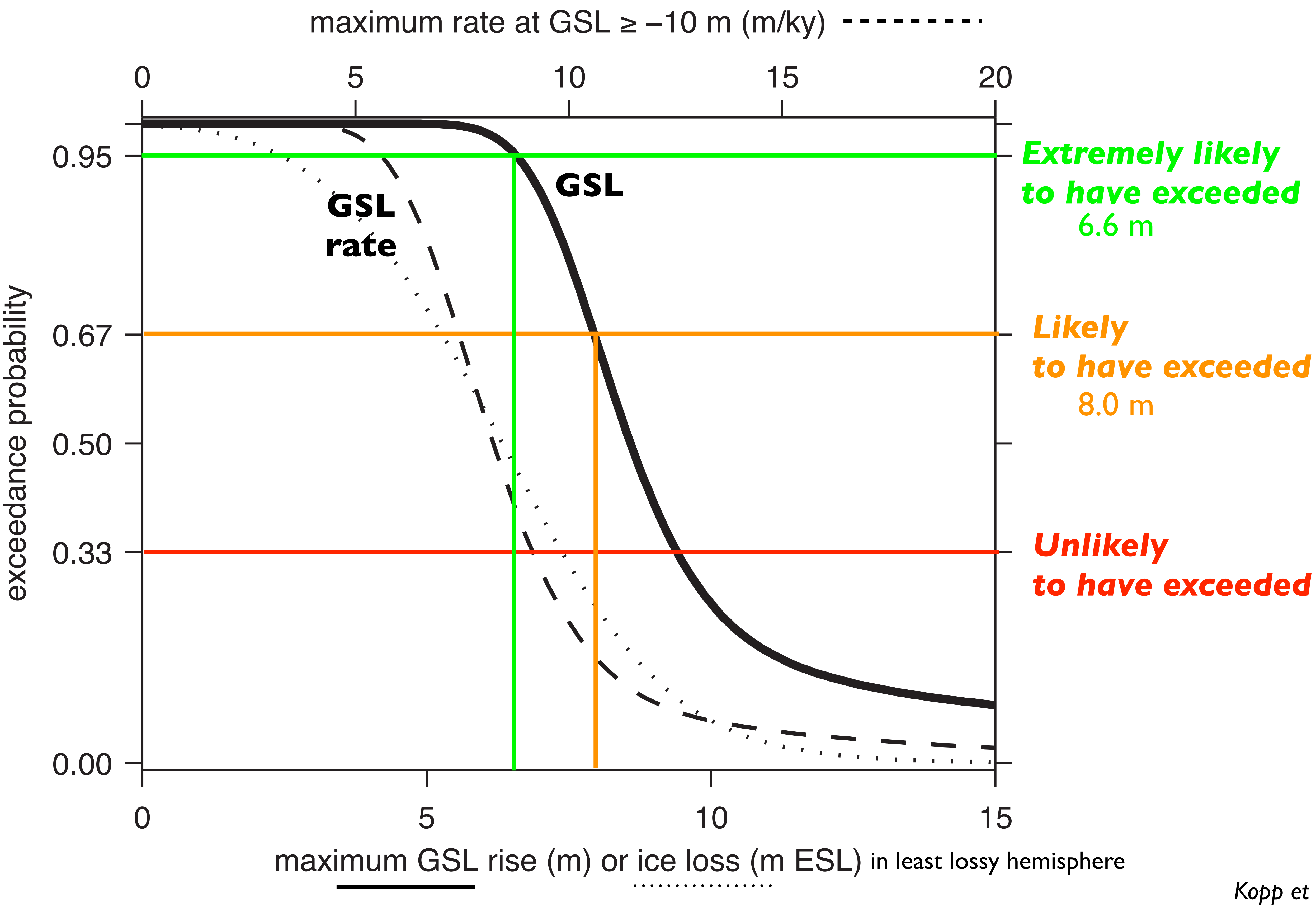


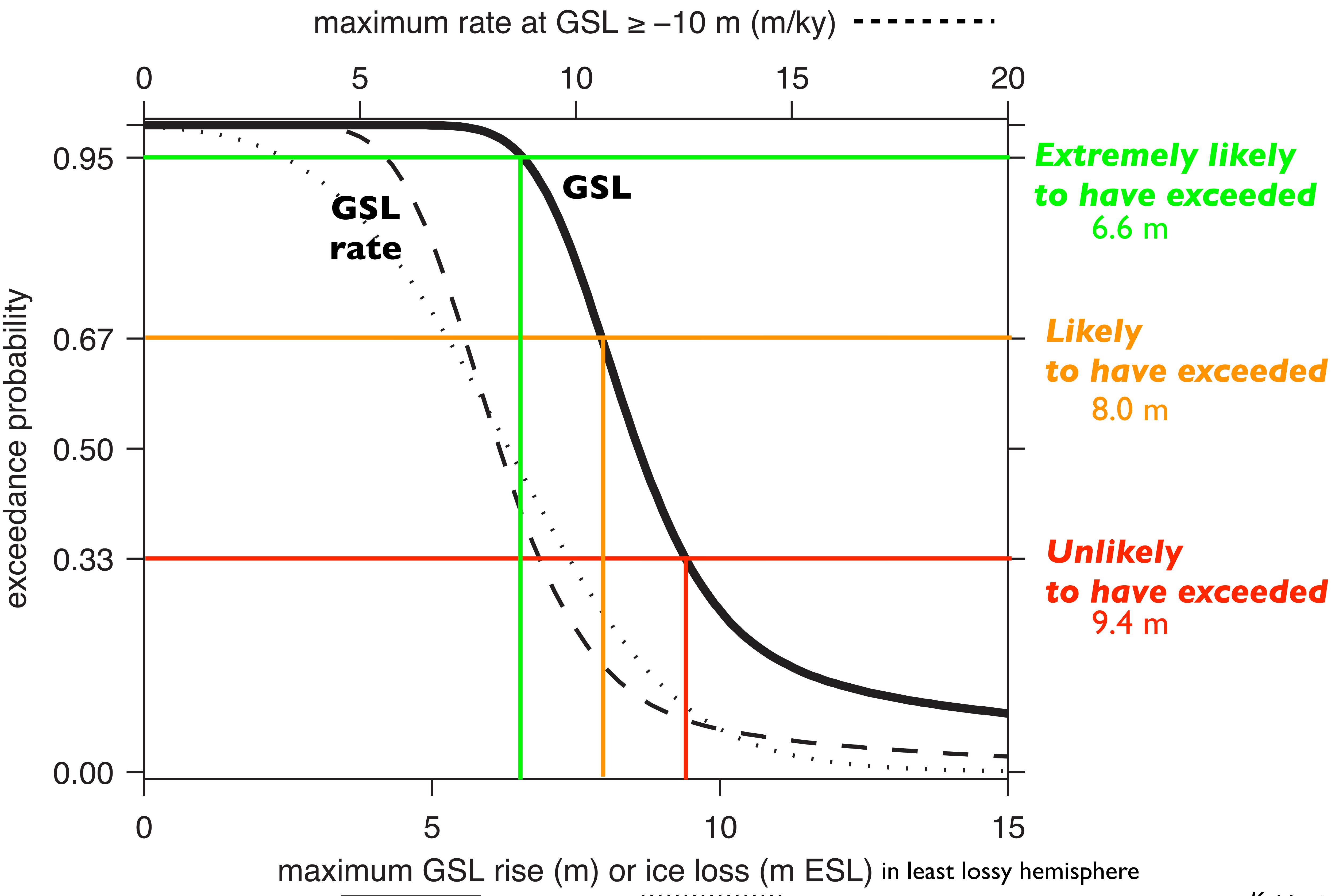
Kopp et al. (2009)

Posterior exceedance levels



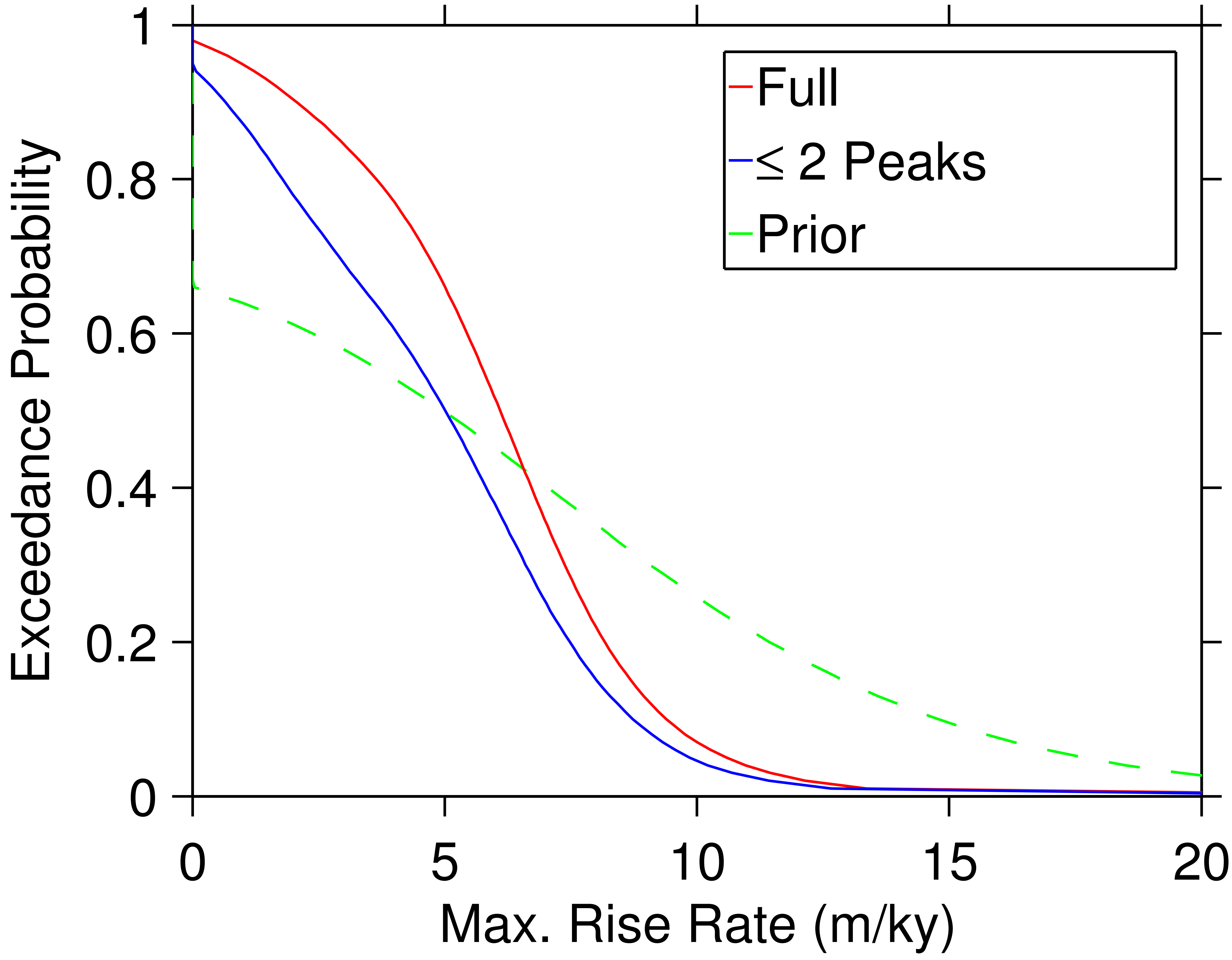
Kopp et al. (2009)

Posterior exceedance levels



Kopp et al. (2009)

How fast did sea level change *within* the LIG?



Kopp et al. (2013)

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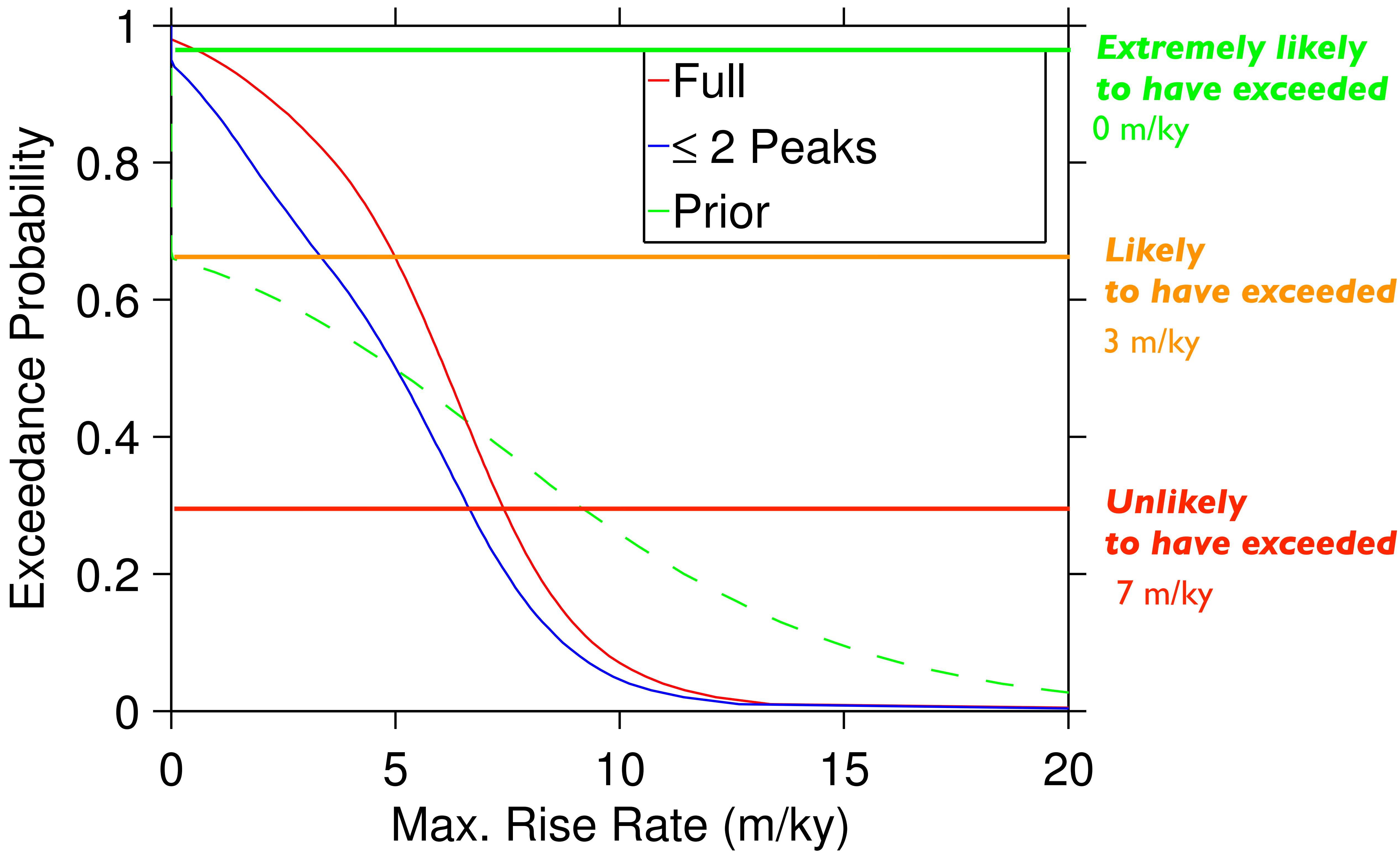


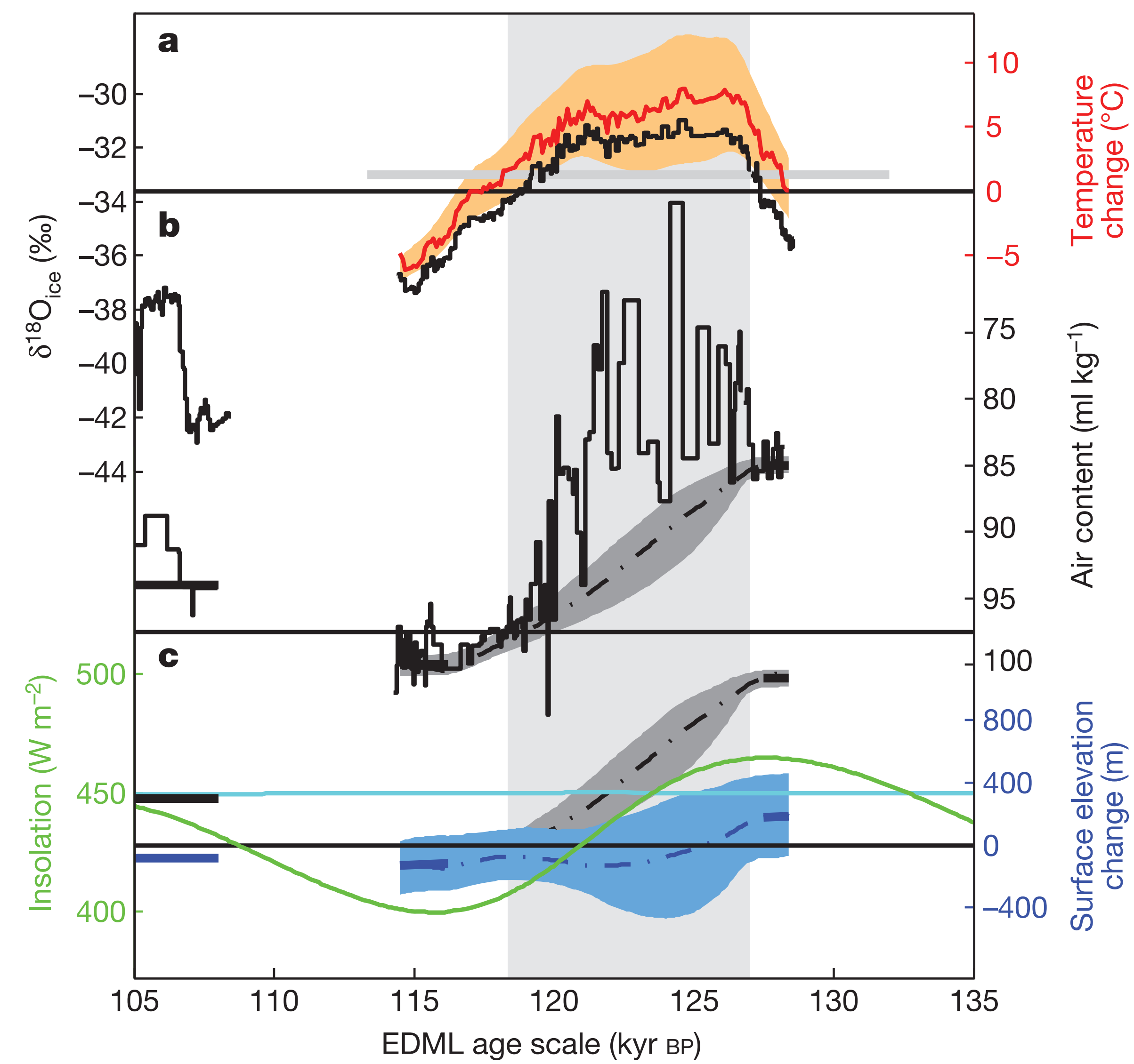
Kopp et al. (2013)

How do we divide up among sources?

Full Bayesian analysis in process, but for the moment:

"Although the documentation of ice thickness at one location on the Greenland ice sheet cannot constrain the overall ice-sheet changes during the last interglacial period, the NEEM data can only be reconciled with Greenland ice-sheet simulations that point to a modest contribution (2 m) to the observed 4–8m [*sic*] Eemian sea level high stand."

— NEEM community members (2013)



***If** correct, this would require very substantial loss of marine-based Antarctic ice to reach GSL of 7-9 m higher than today.*

Some tentative conclusions:

- Regional variations in sea-level rise can be important for planning purposes. Some regions are more vulnerable to ice sheet melt or ocean circulation changes than others.
- It's unclear whether trends due to ice-sheet melt or ocean circulation changes are visible in the twentieth-century tide gauge records, but we can look for them there, and also in the geological record.
- These records can be used to calibrate statistical sea-level rise models.
- Past warm periods suggests a large equilibrium ice sheet sensitivity to relatively small forcing changes.

Some future directions:

- How do the observed relationships between ocean dynamics and climate indices extend into the past? Can these relationships be used to extend projections into the future?
- What do spatial patterns in Holocene and tide gauge records reveal about ice sheet stability?
- What mechanism explains relatively dual peaks seen in the LIG highstand?
- What are the relative roles of temperature, insolation and stochasticity in explaining the differences among interglacials?
- Supposing a well-defined equilibrium sea level exists for a given temperature and insolation, what controls the rate at which it's approached?