Interpreting the noisy historical and geological records of ancient sea level changes: What can the past tell us about the future?

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Carnegie Mellon University CEDM Seminar
14 January 2013

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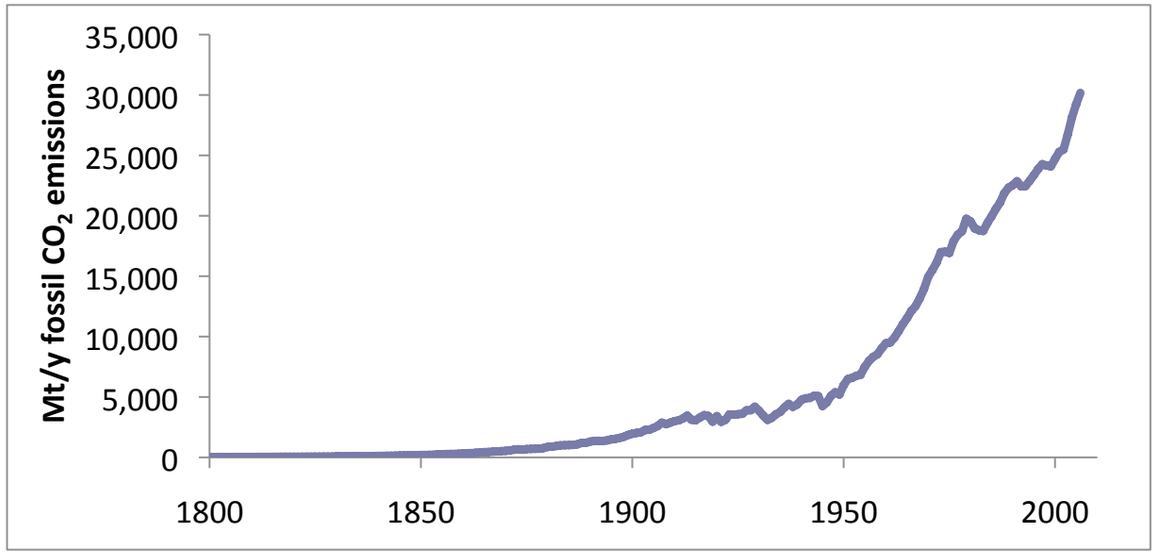
Road Map

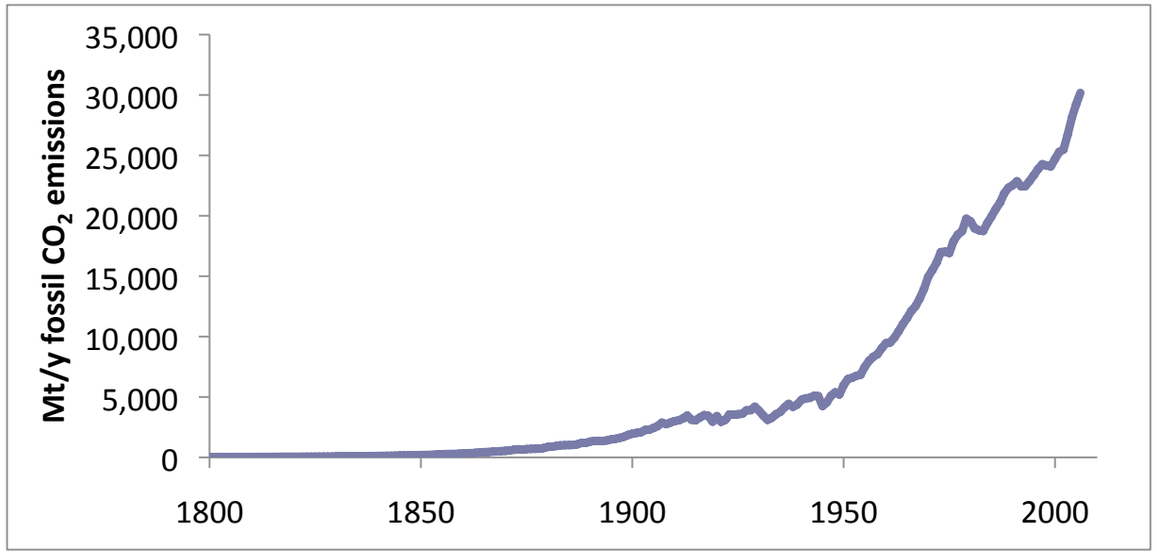
- Humans are shifting the Earth's climate into a state novel for our species, though familiar to the planet.
- The potential sea level hazard from melting grounded ice is large but geographically variable.
- The sea level risk for ice sheets is difficult to model; geological and historical records provide a complementary approach.
- But to leverage these records, we must see through a host of uncertainties.

Humans are shifting the Earth's climate into a state novel for our species, though familiar to the planet.



About 1.2 billion metric tons of fossil carbon dioxide have been released by human activities since 1800.

Dats Sources: CDIAC, Etheridge et al. (1996), GISS



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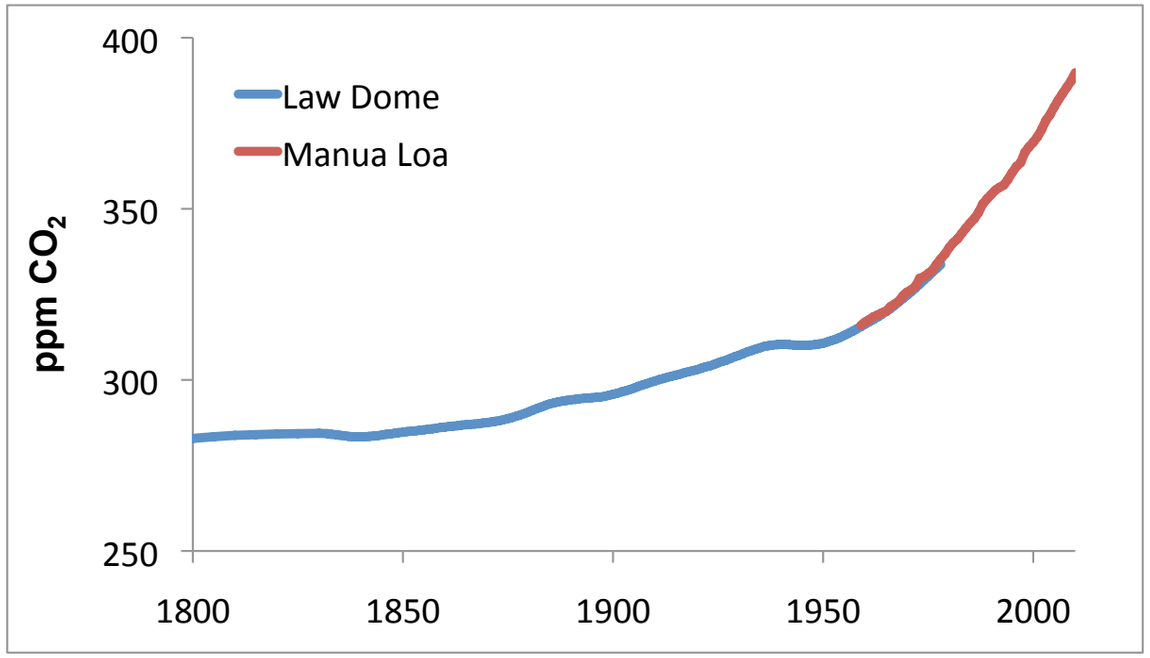

As a consequence, CO_2 concentrations have risen by about 40% over the last two centuries.

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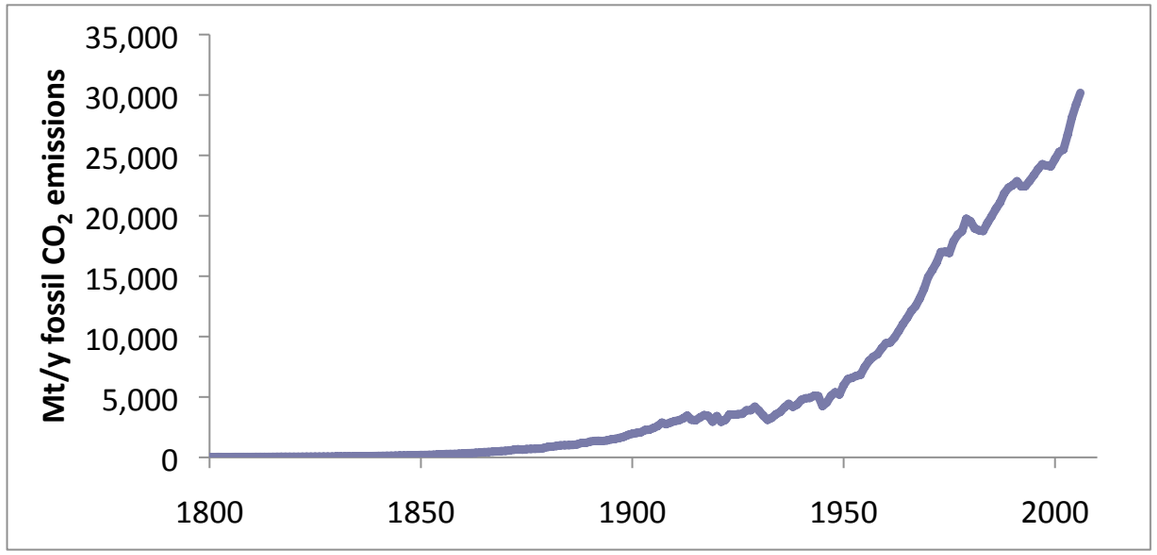

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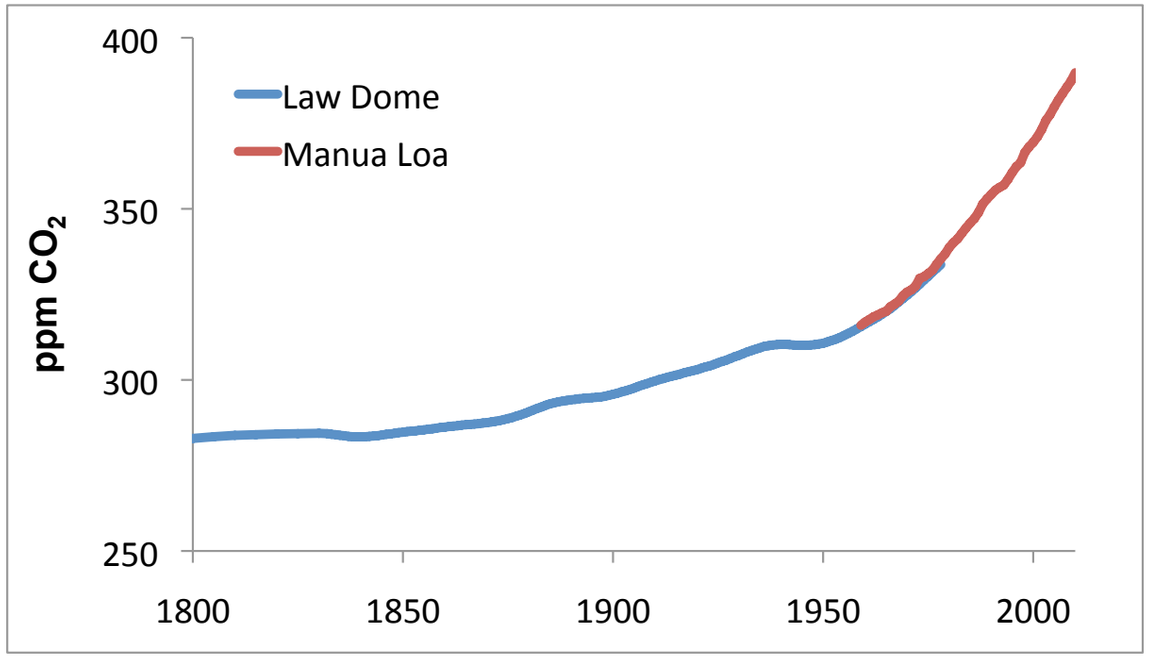

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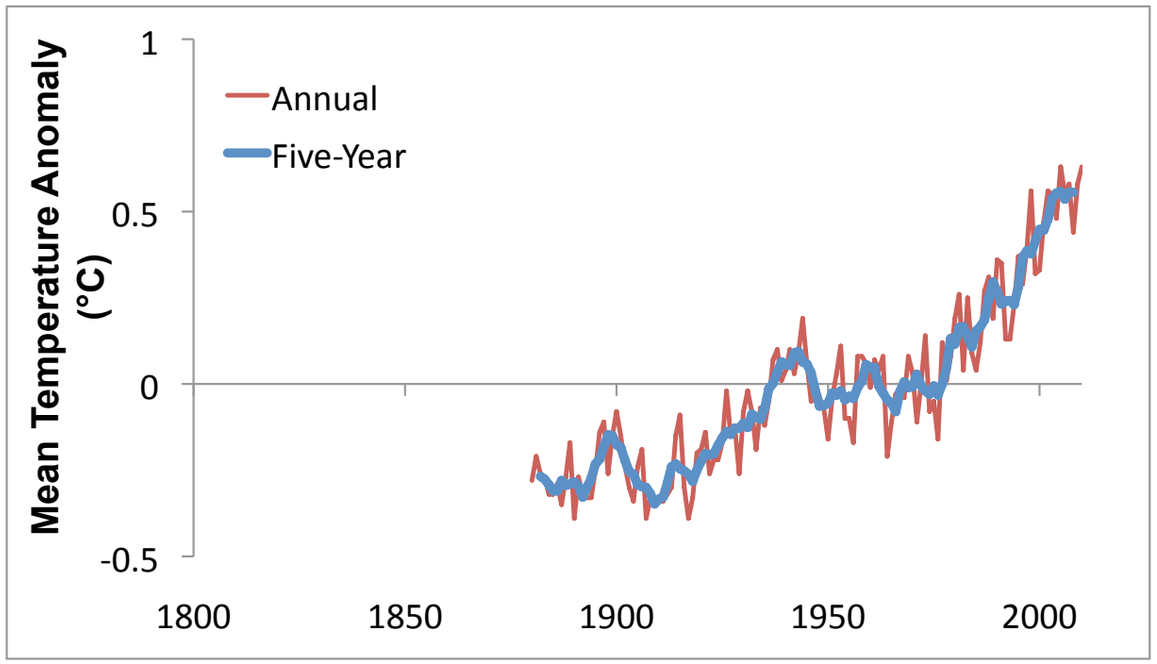
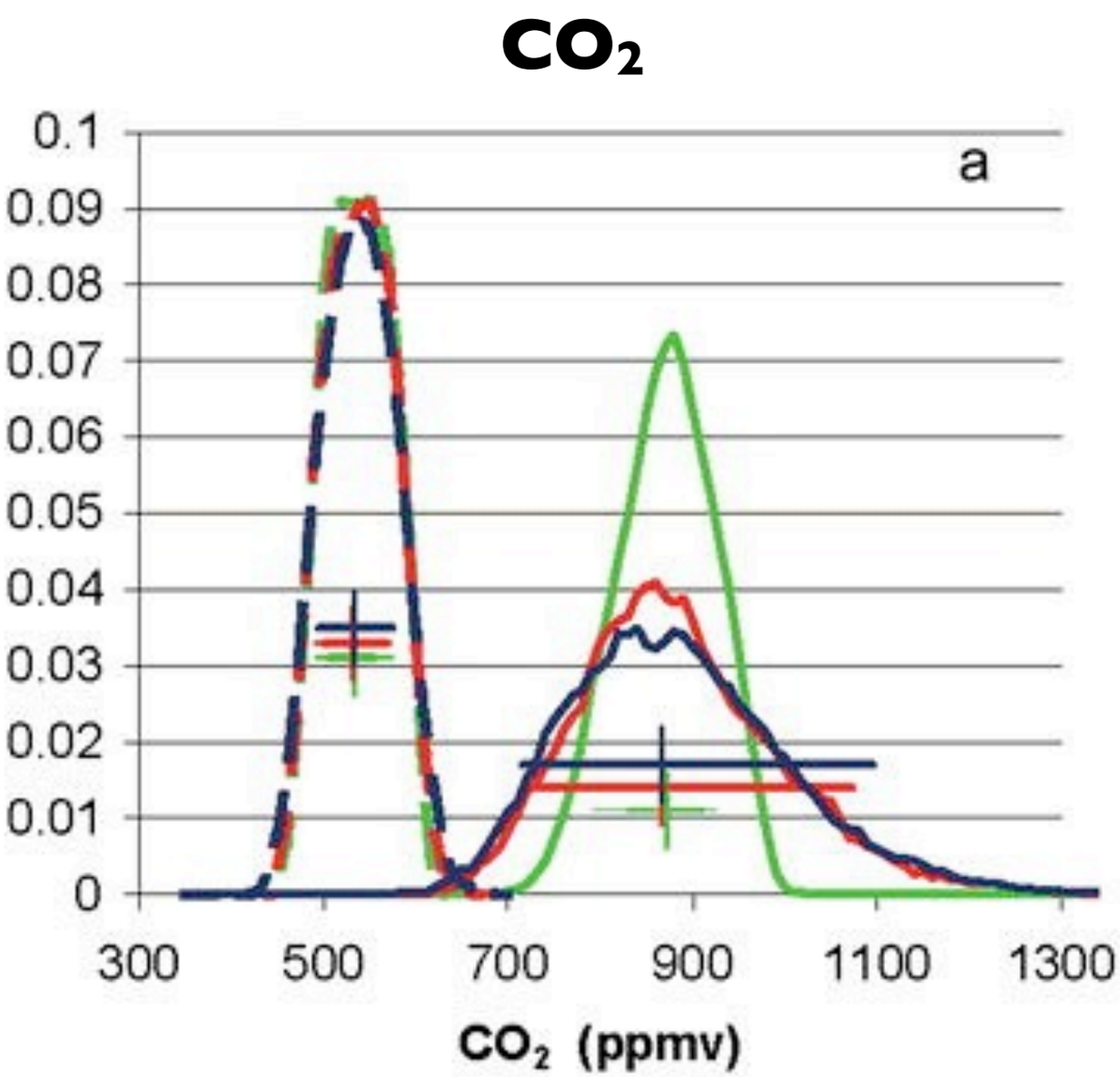


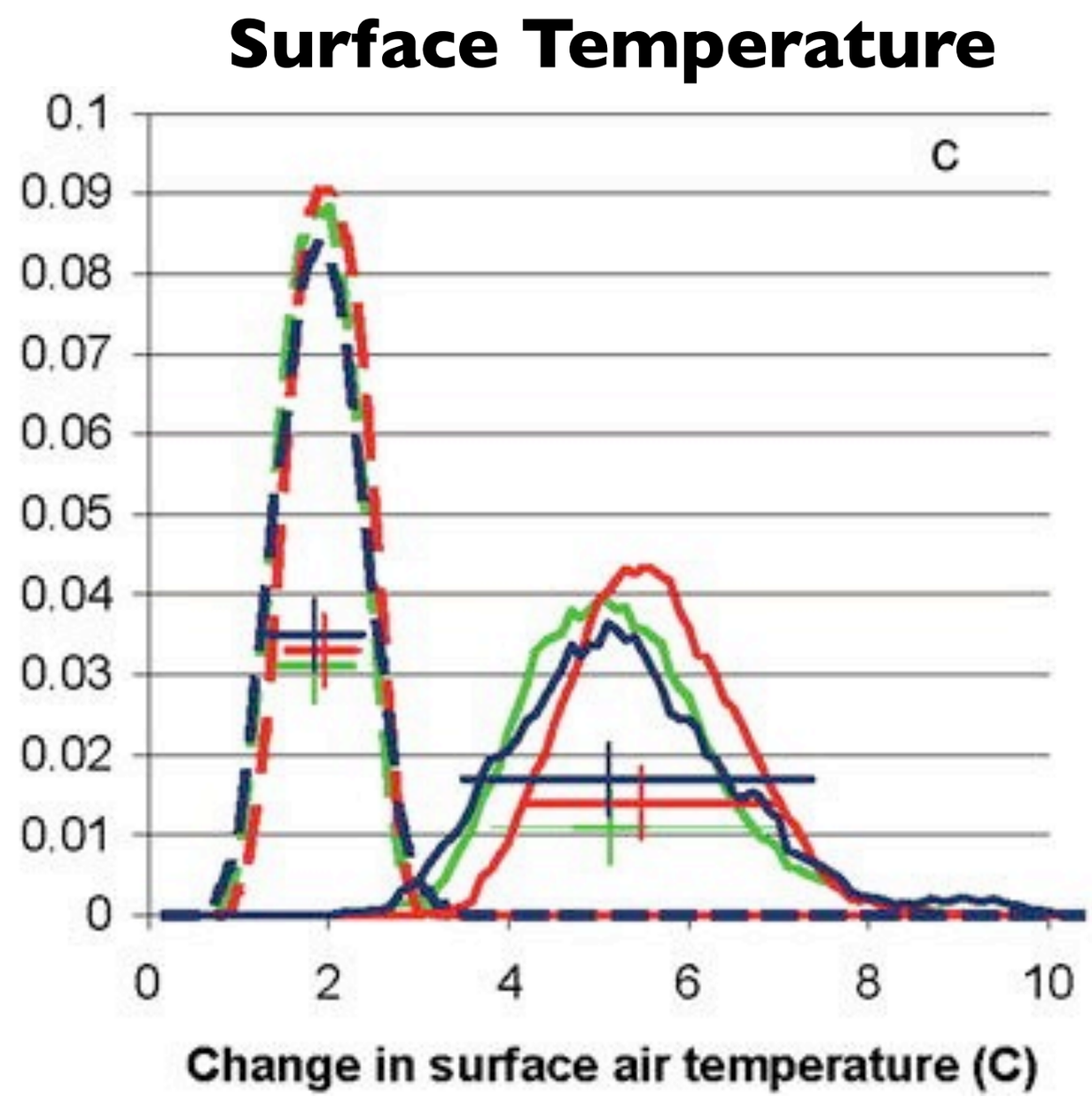
Global temperatures today are ~0.8°C warmer than in 1880-1900.

Dats Sources: CDIAC, Etheridge et al. (1996), GISS

MIT IGSM projections for 2041-2050 and 2091-2100

("Business-as-usual" no policy case)





Red: Emissions Uncertainty

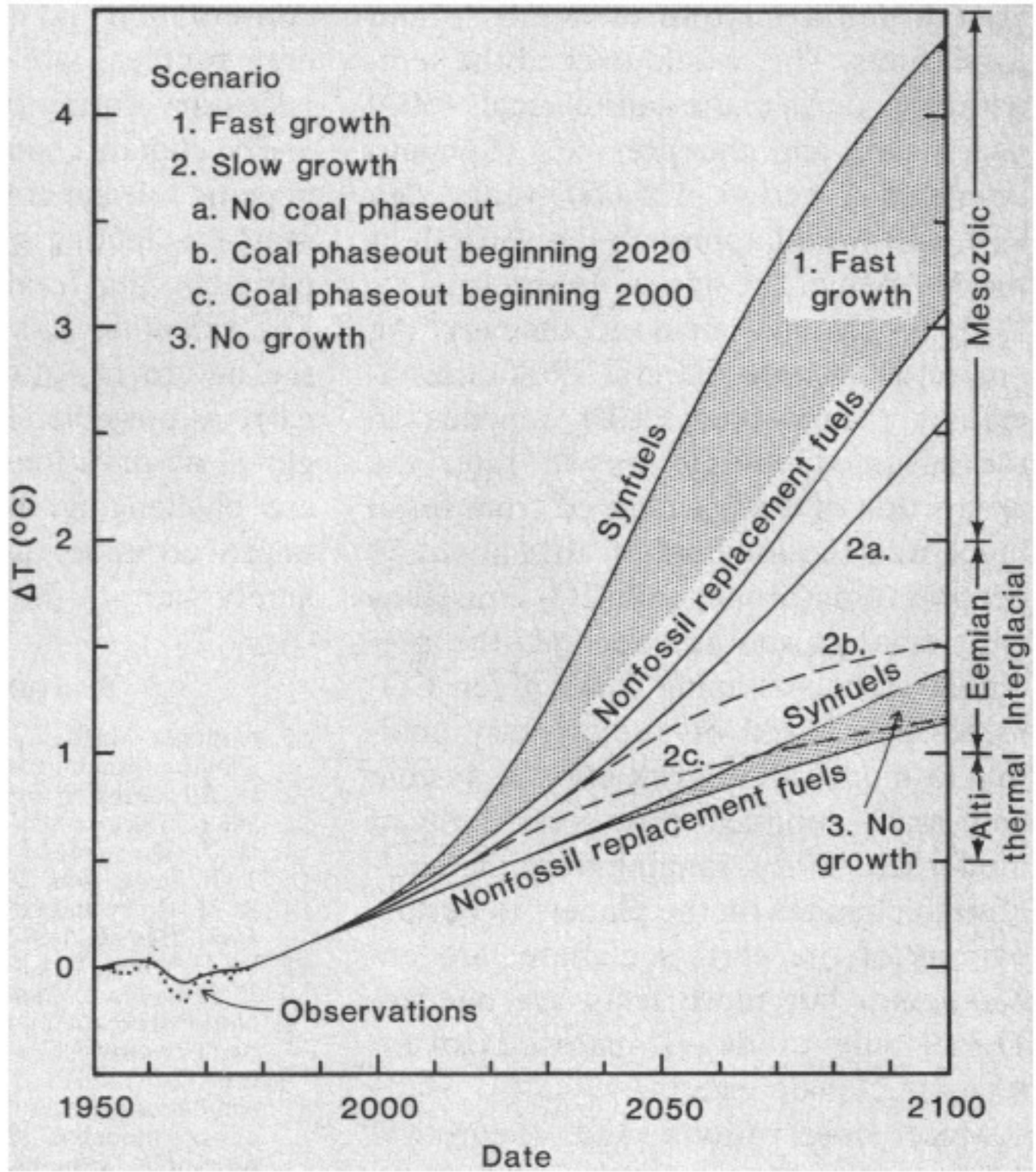
Green: Climate and Carbon Cycle Uncertainty

Blue: Combined Uncertainty

Sokolov et al. (2009)

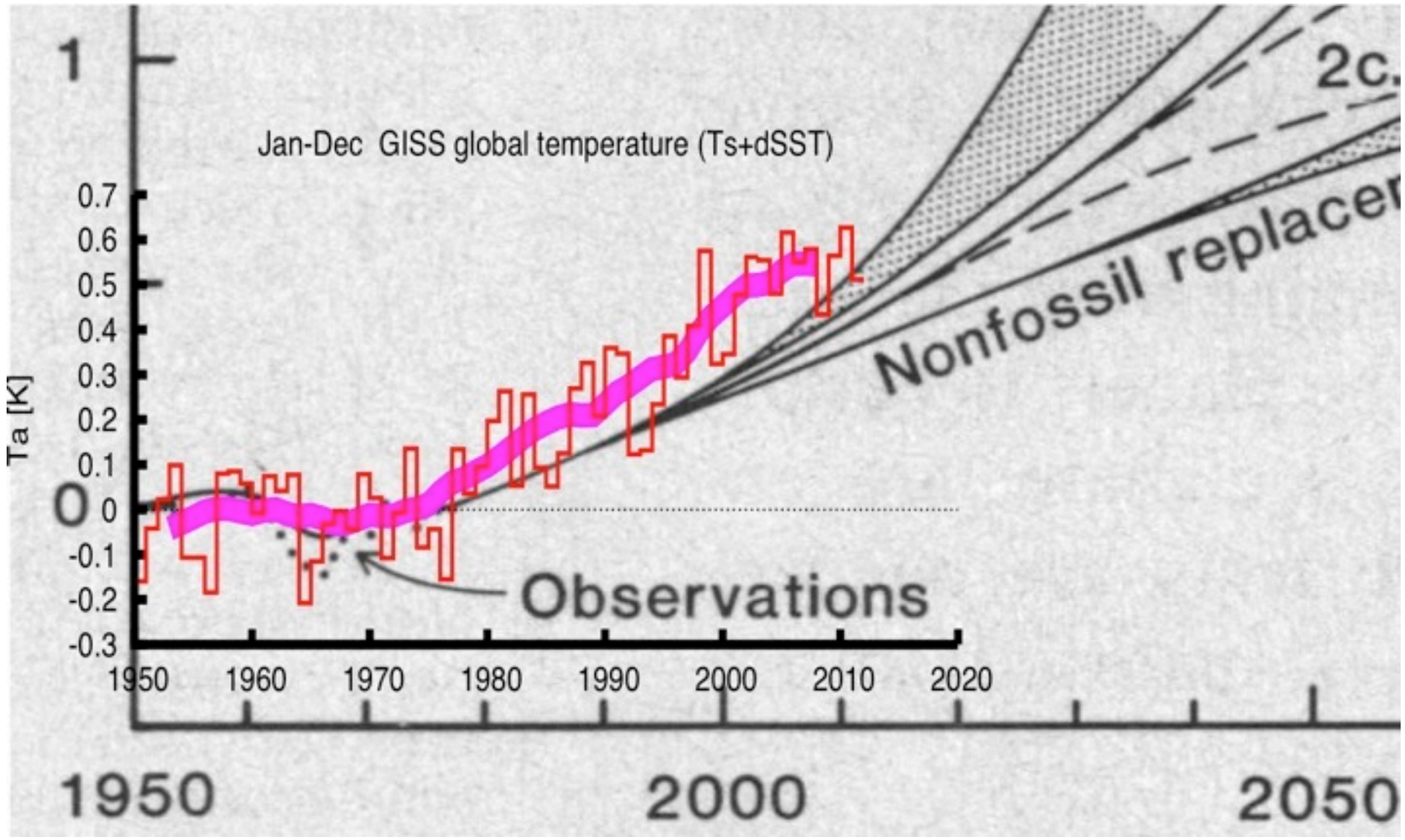
The basic outlines have been known for quite some time

Fig. 6. Projections of global temperature. The diffusion coefficient beneath the ocean mixed layer is 1.2 cm^2 sec^{-1}, as required for best fit of the model and observations for the period 1880 to 1978. Estimated global mean warming in earlier warm periods is indicated on the right.



Hansen et al. (1981)

The basic outlines have been known for quite some time

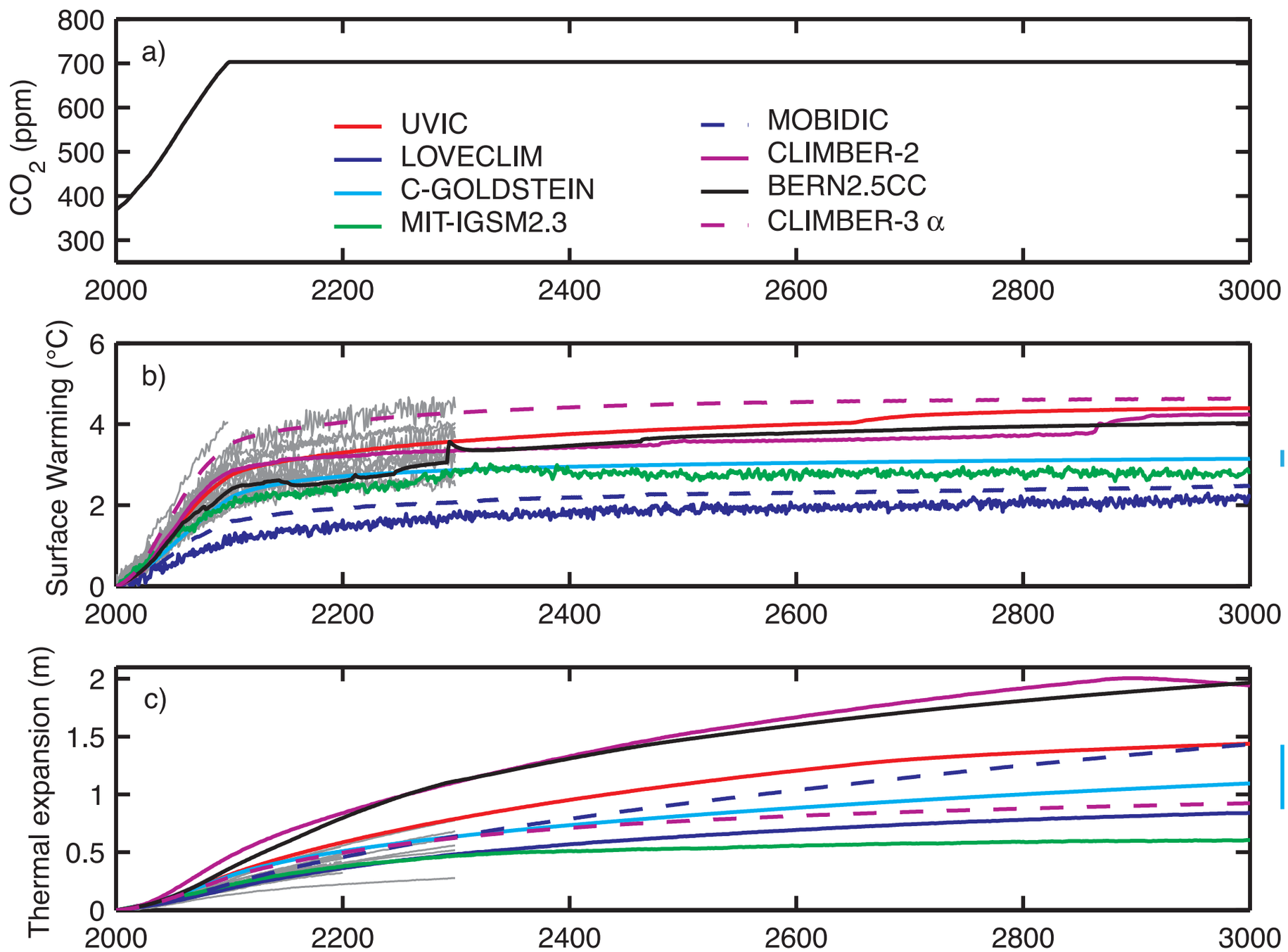


van Oldenborgh and Haarsma (realclimate.org, 2 April 2012)

Hansen et al. (1981)

The potential sea level hazard from melting grounded ice is large but geographically variable.

Dominant factors in global sea level rise: 1. Thermal Expansion



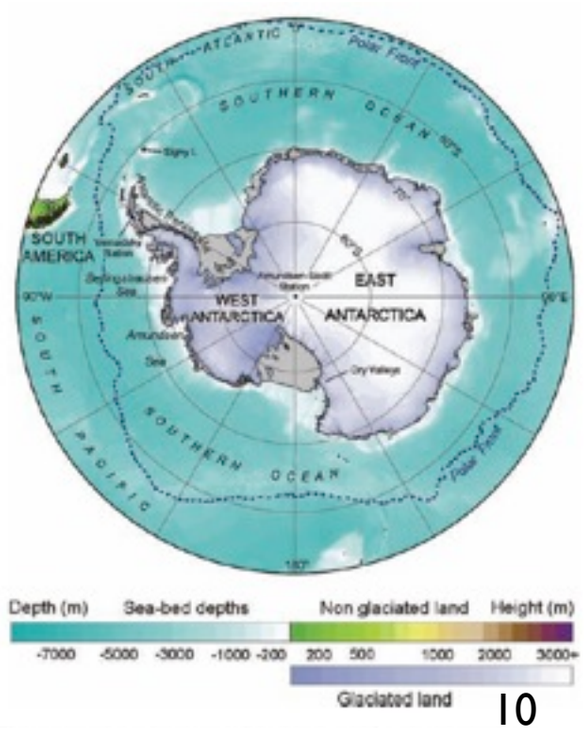
Compare observed thermal expansion of about 1.0 mm/yr from 1983-2003 (Domingues et al., 2008)

Meehl et al. (2007)

Dominant factors in global sea level rise: II. Glacier and ice sheet melt

Total Hazard

Non-polar glaciers and ice caps	0.26 ± 0.11 m
Greenland & W. Antarctic glaciers and ice caps	0.46 ± 0.17 m
Greenland Ice Sheet	7 m
West Antarctic Ice Sheet	5 m
East Antarctic Ice Sheet	52 m



Maps by P. Fretwell (British Antarctic Survey)

Lemke et al. (2007); Bamber et al. (2001); Lythe et al. (2001)

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

- Short-term: Dynamic effects
- Short to medium term: Gravitational, elastic and rotational effects
- Long term: Isostasy and tectonics

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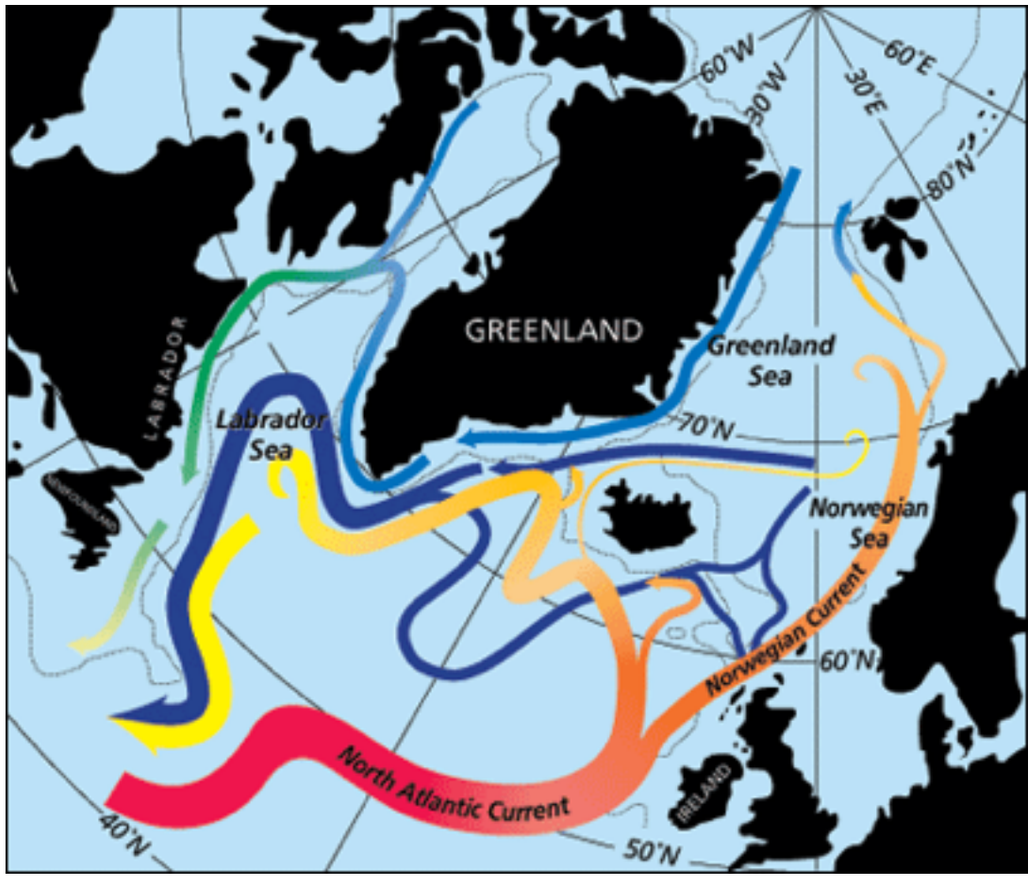

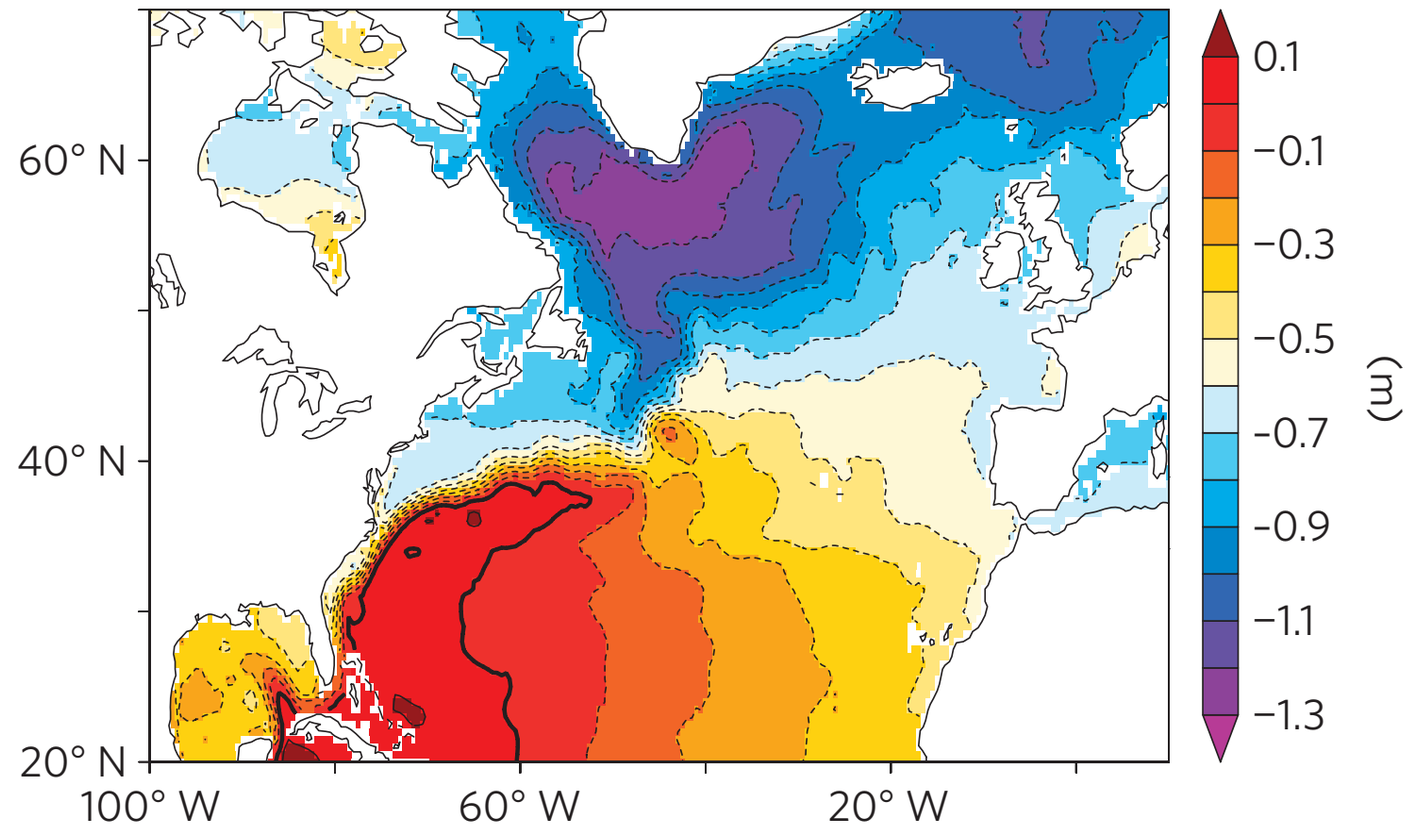

SSH, 1992-2002

NASA.gov
Yin et al. (2009)

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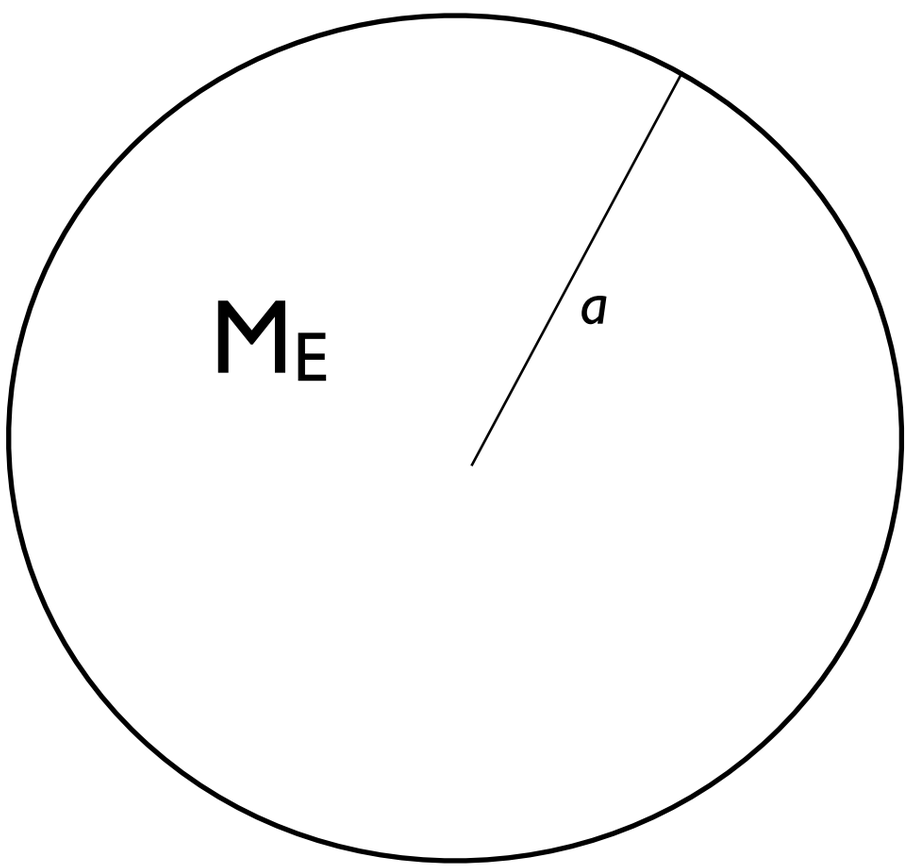

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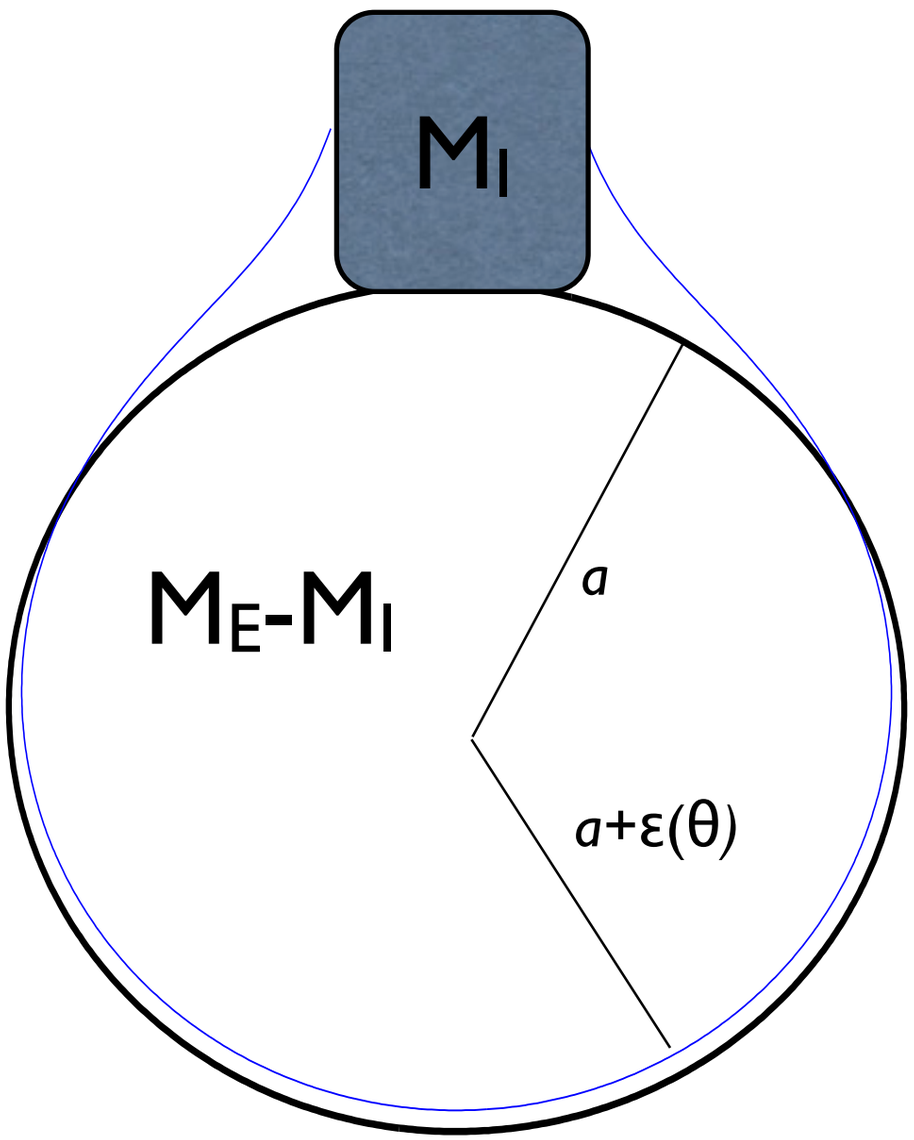

Not to scale!

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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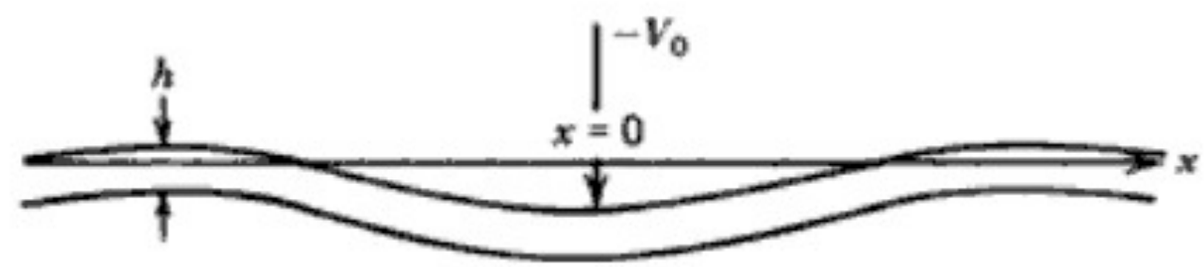

3–29 Deflection of the elastic lithosphere under a line load.

Turcotte and Schubert (2002)

and so wavelength $2\pi\alpha \sim 7000$ km

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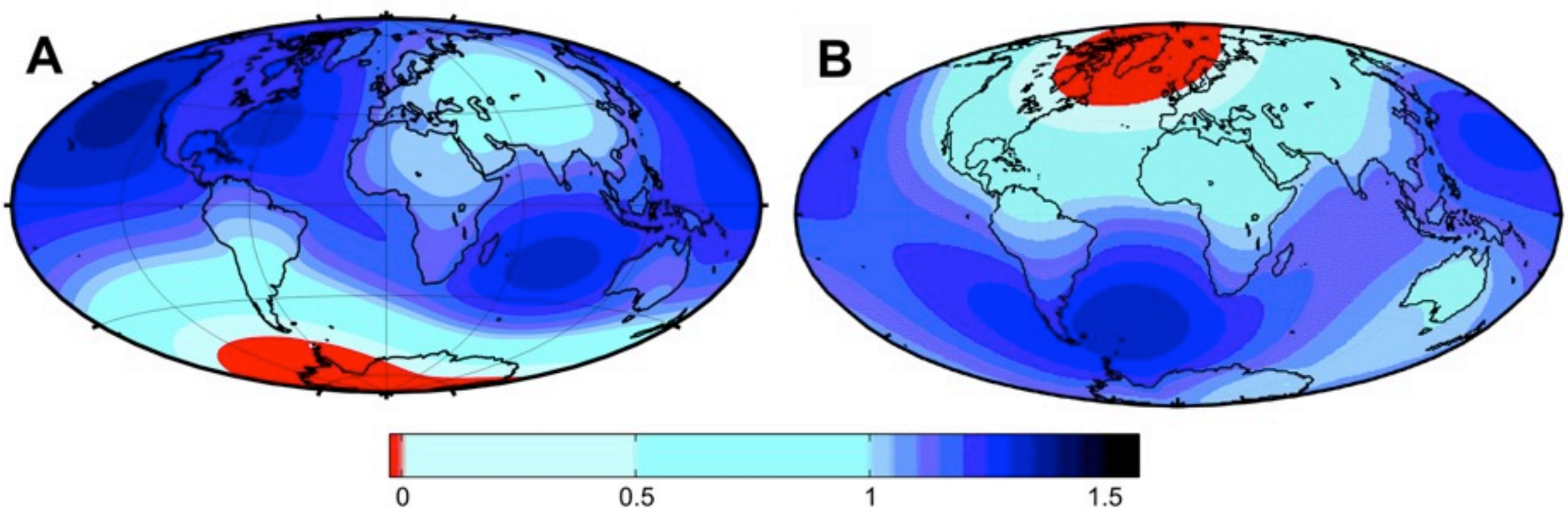
Gravitational-Elastic-Rotational Fingerprints of Greenland and WAIS melting, per meter GSL rise

West Antarctica *Greenland*



Mitrovica et al. (2011)

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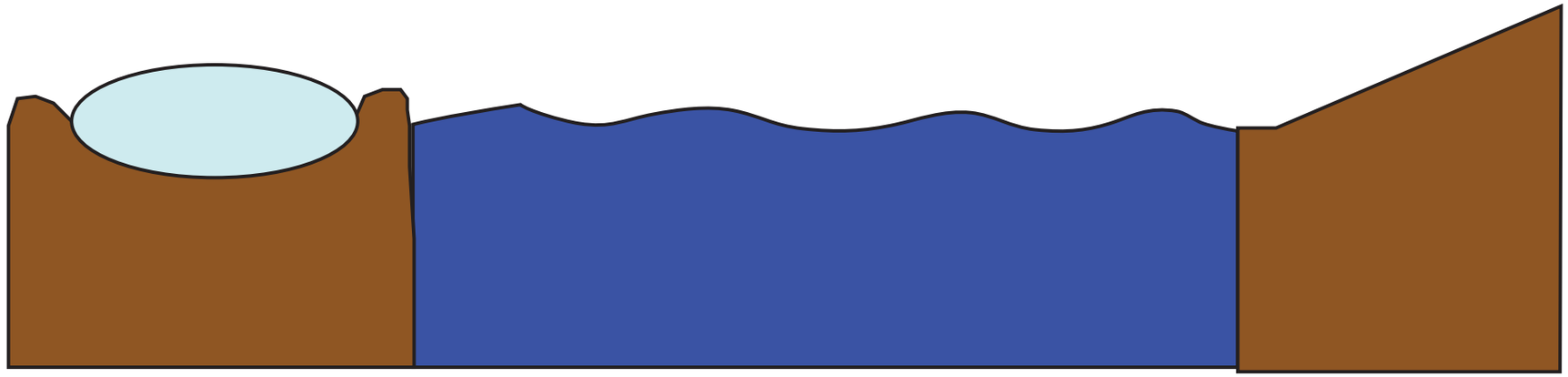

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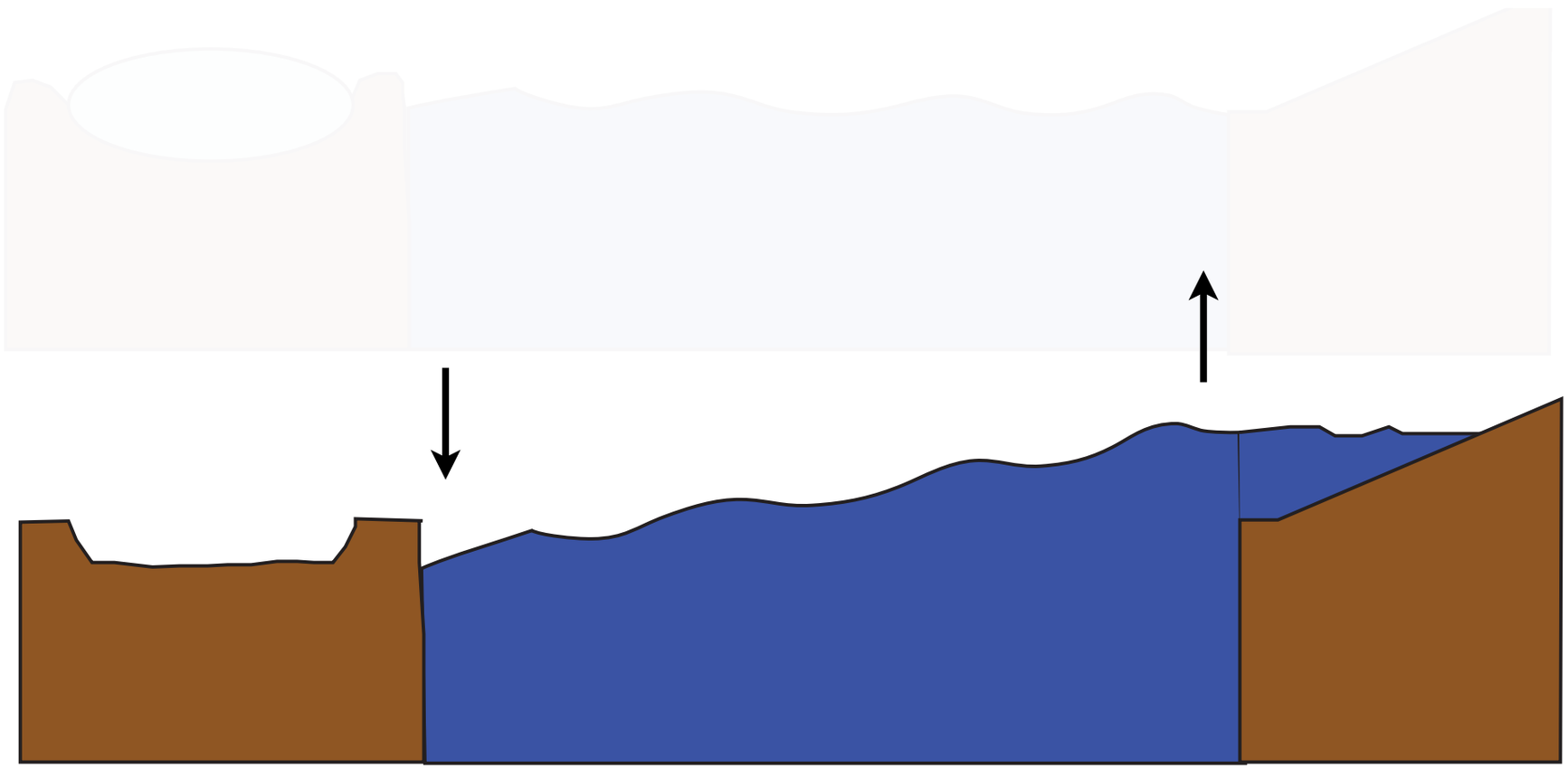

Gravitational and elastic response

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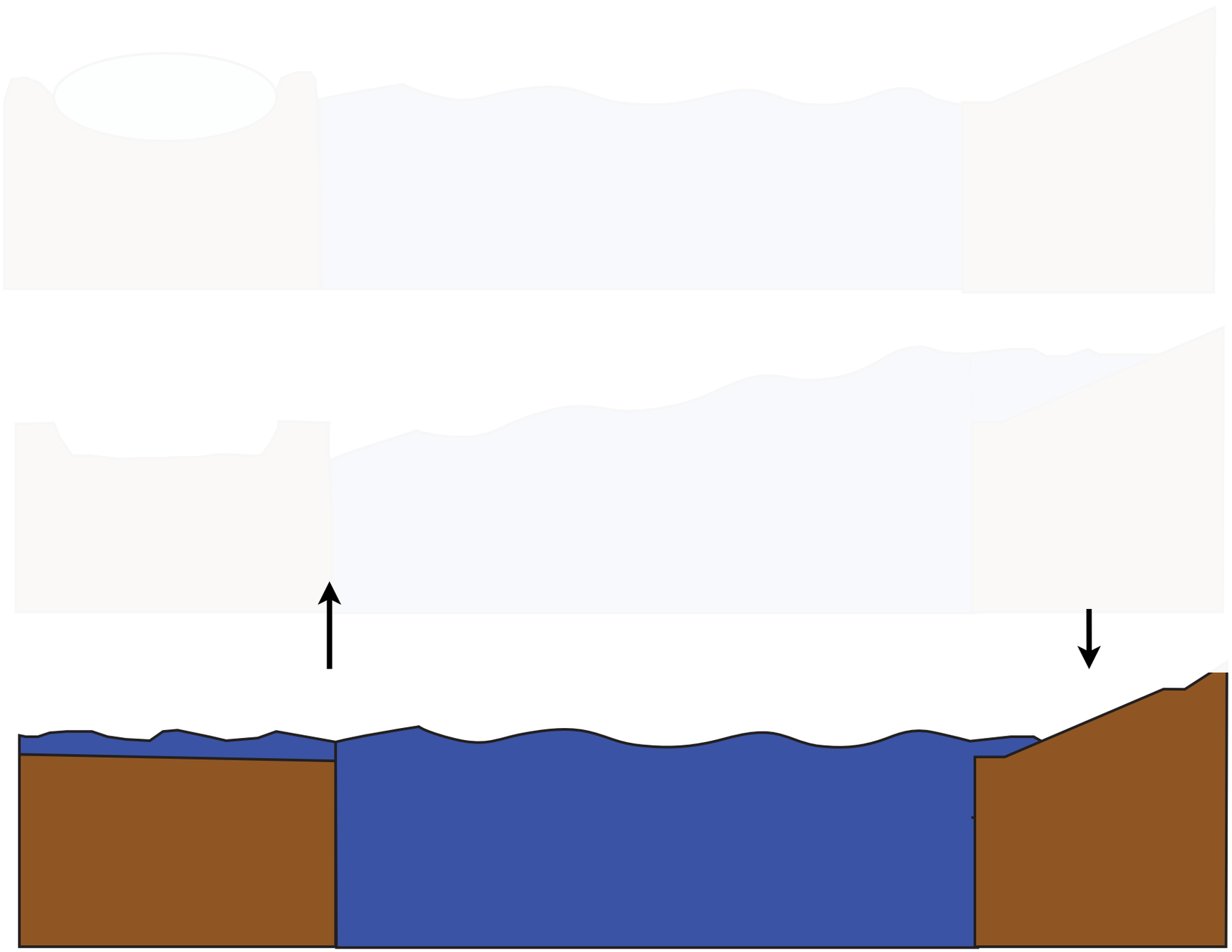


Isostatic response

The sea level risk for ice sheets is difficult to model; geological and historical records provide a complementary approach.

IPCC AR4 projections for the 21st century

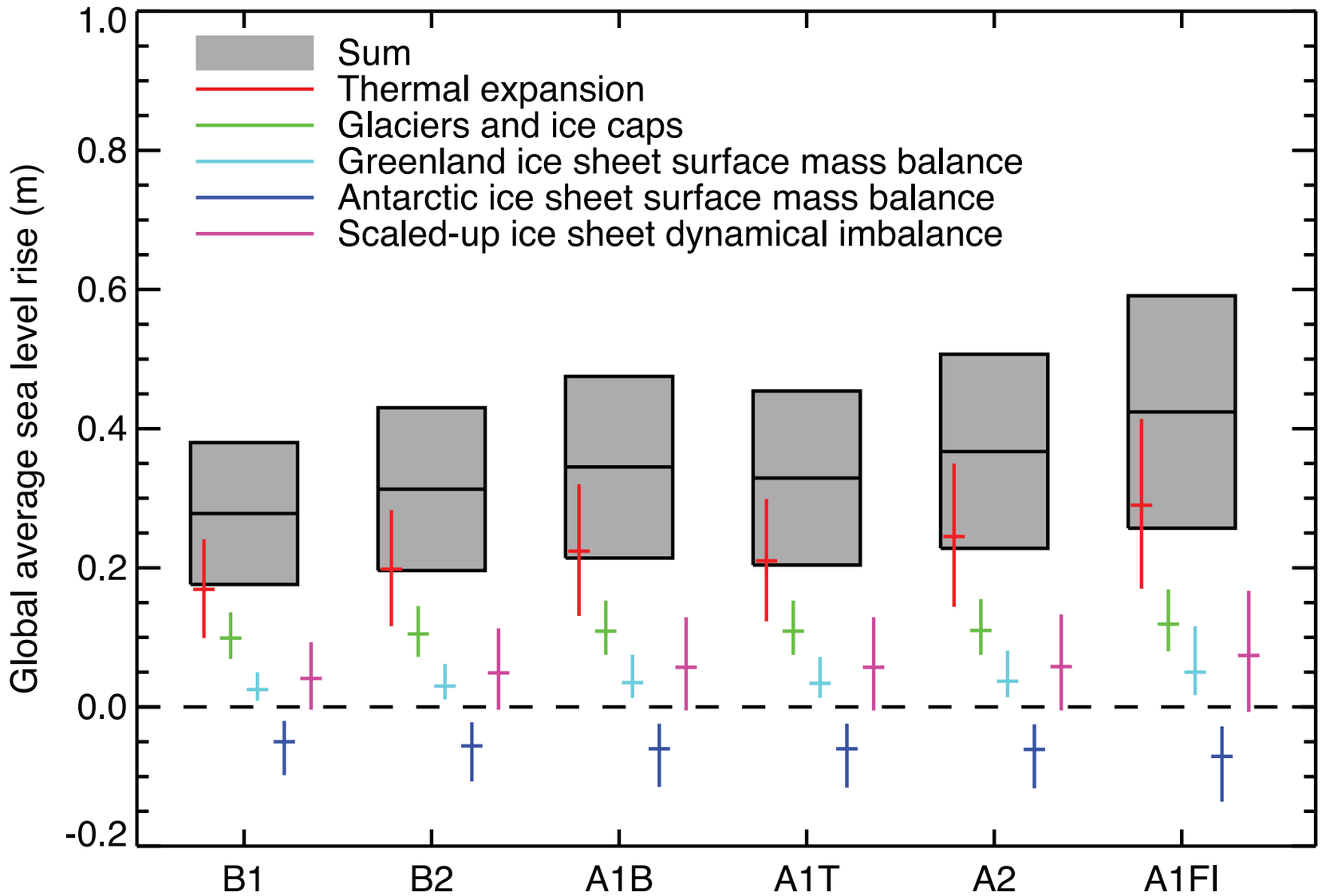
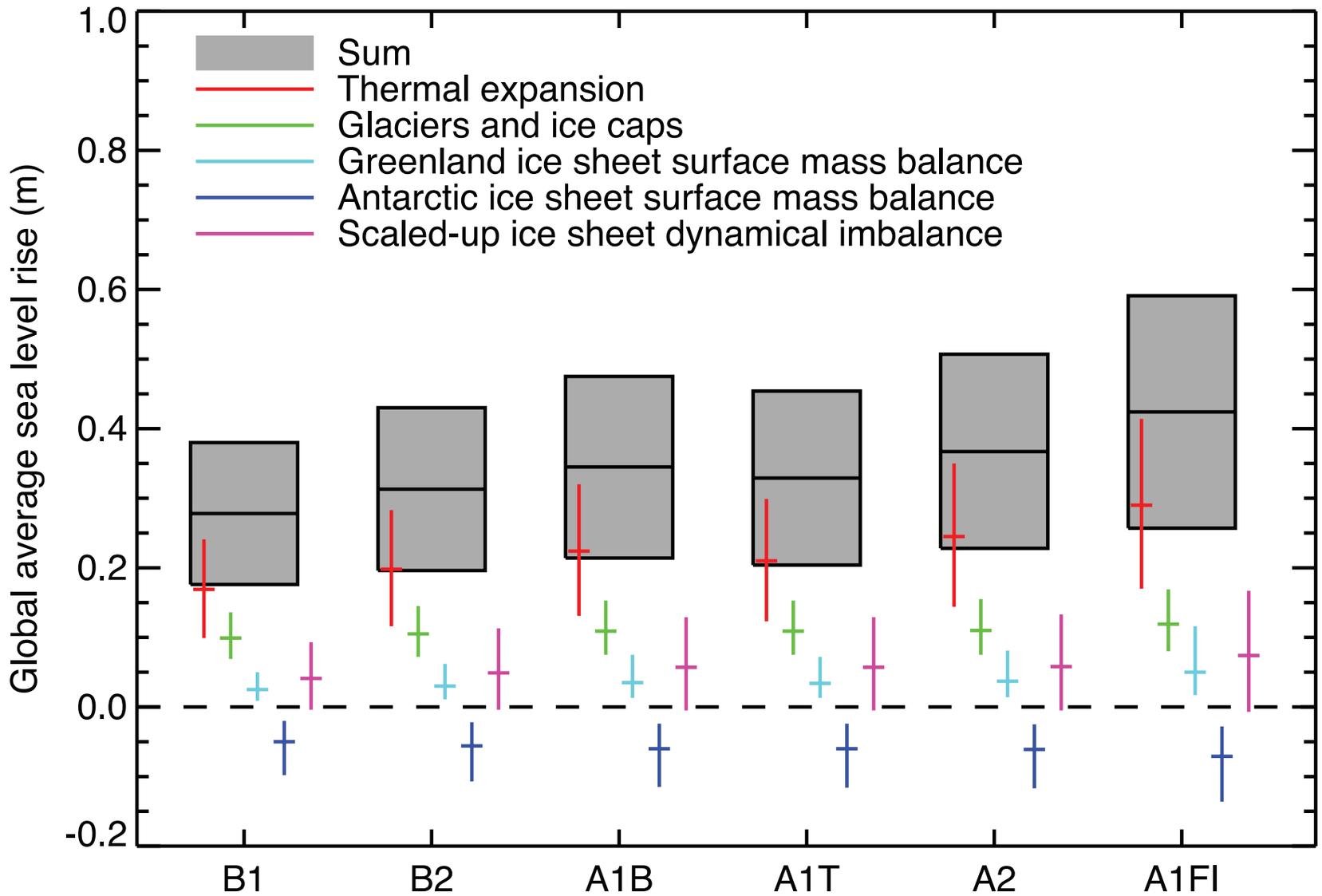


Figure 10.33. *Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m. It must be emphasized that we cannot assess the likelihood of any of these three alternatives, which are presented as illustrative. The state of understanding prevents a best estimate from being made.*

IPCC estimates likely fall at the low end of the probability distribution



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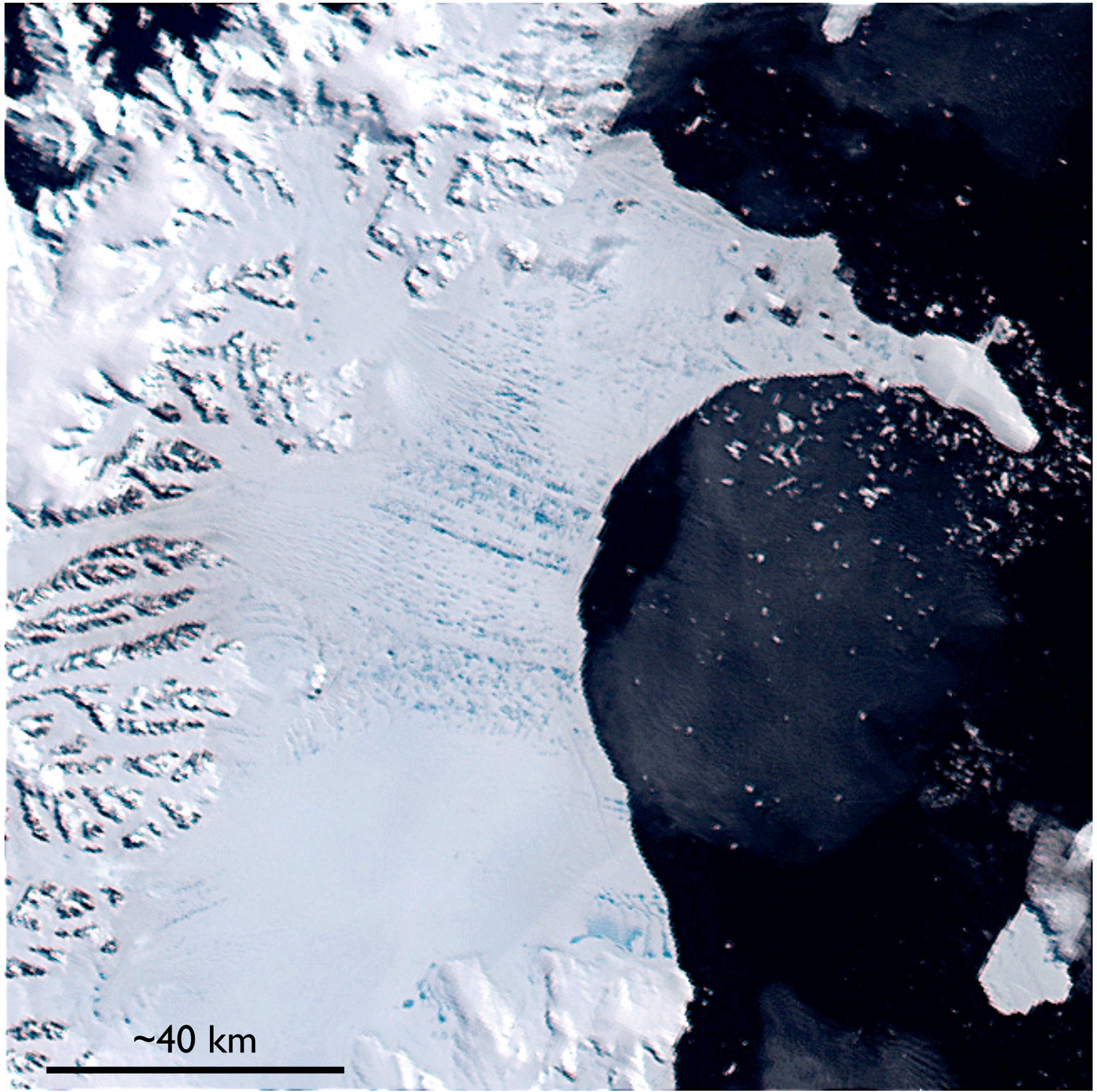
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

31 Jan. 2002

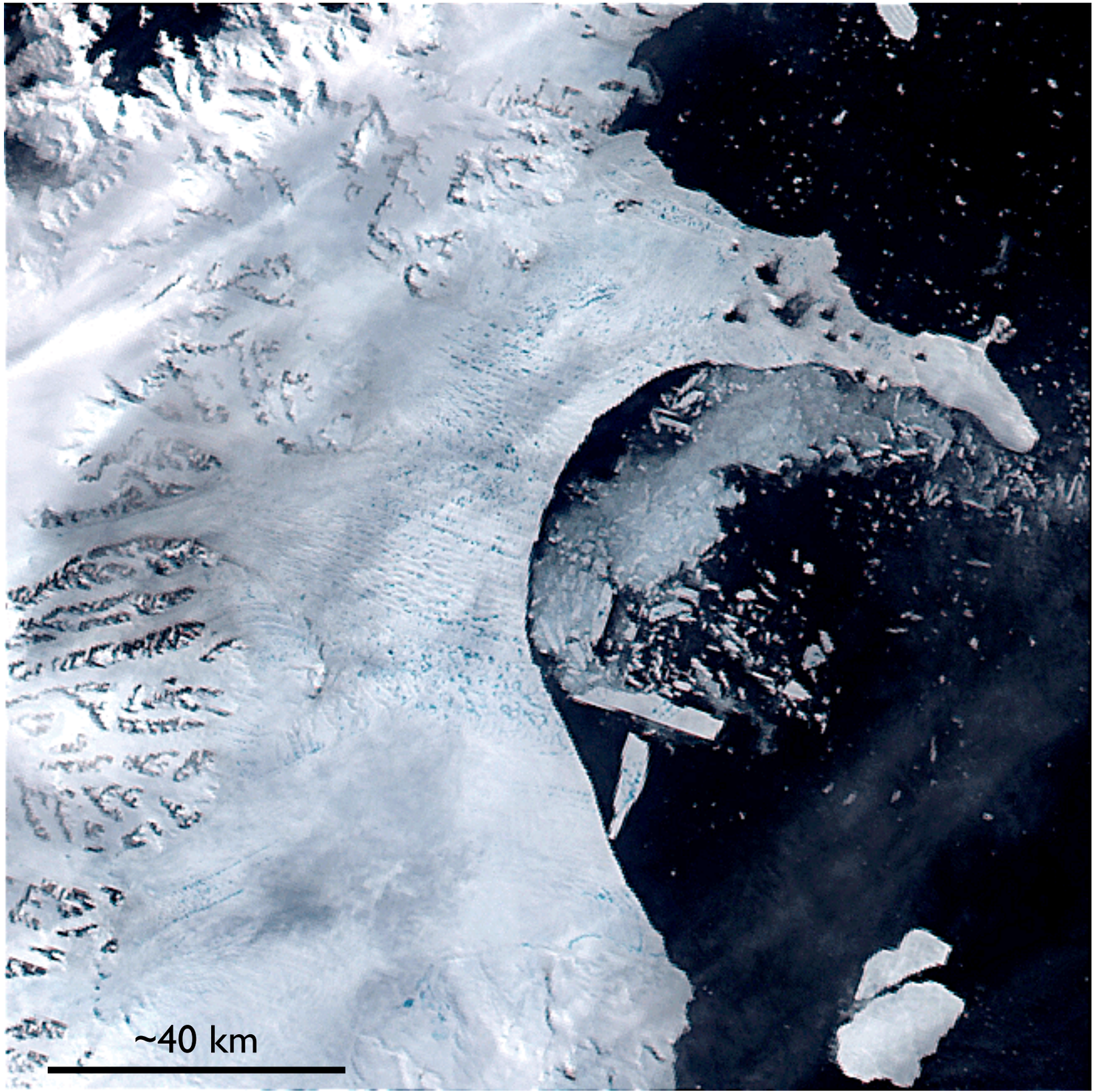


http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

17 Feb. 2002



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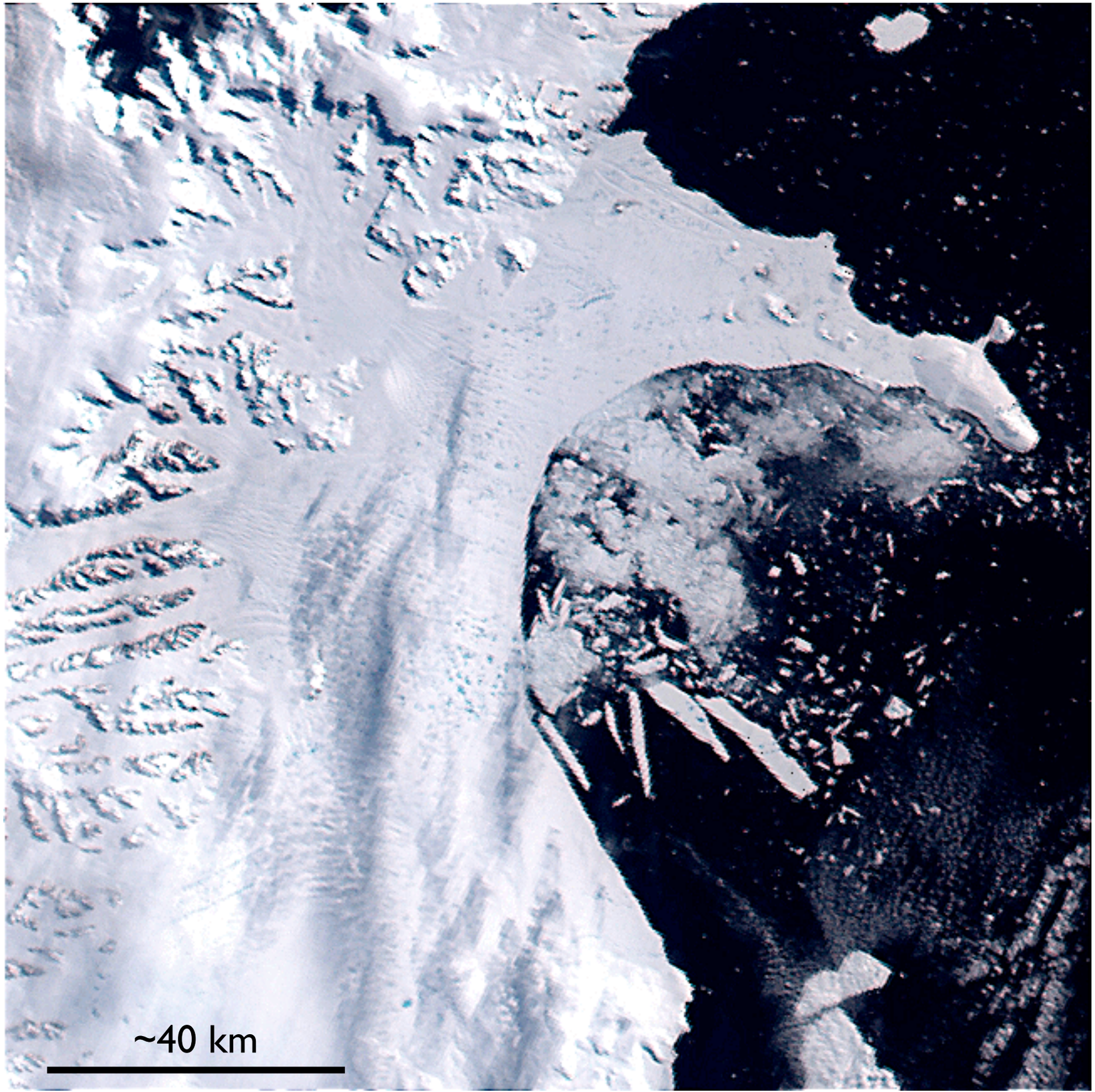
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

23 Feb. 2002



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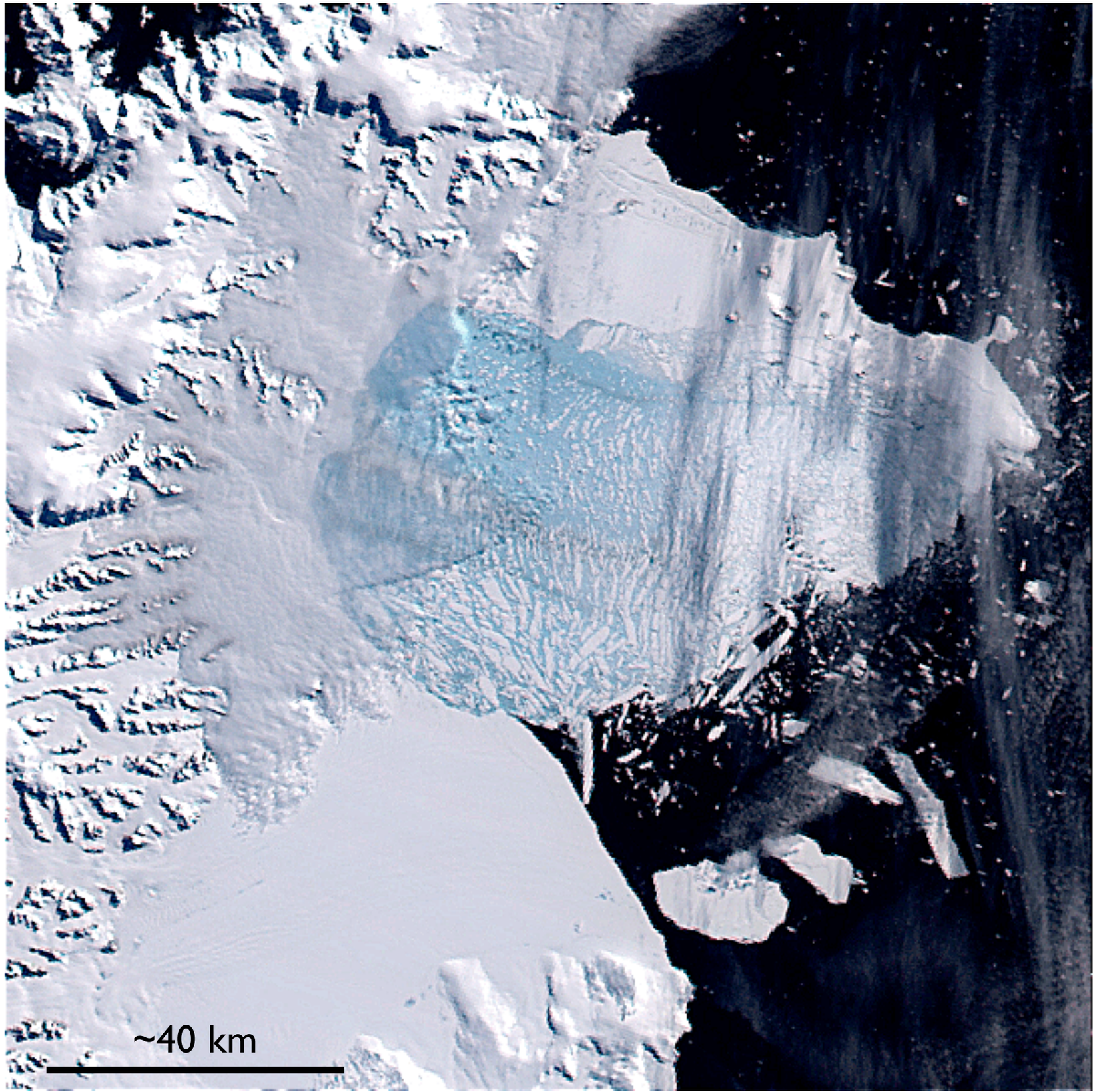
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

5 Mar. 2002



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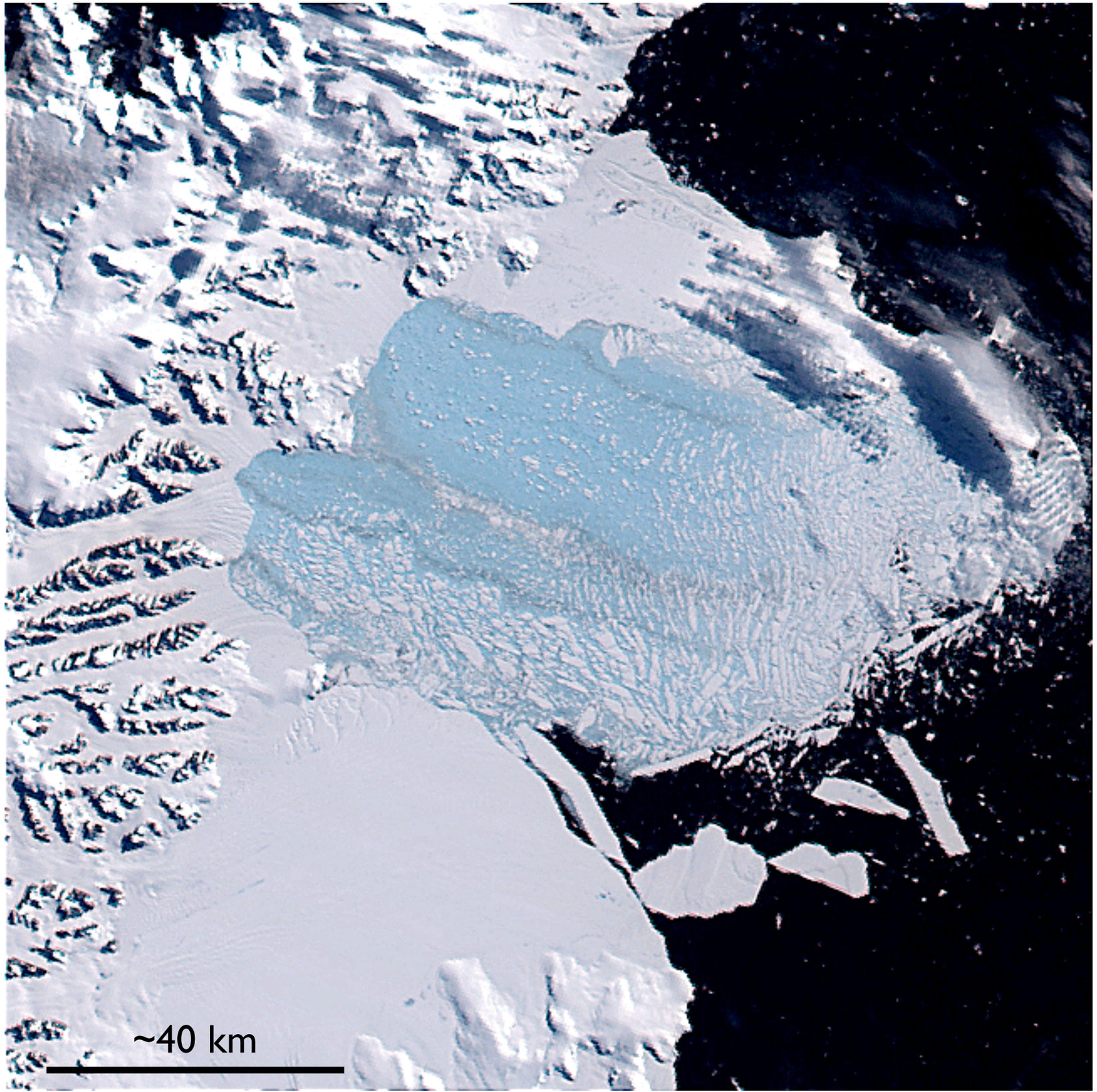
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

7 Mar. 2002



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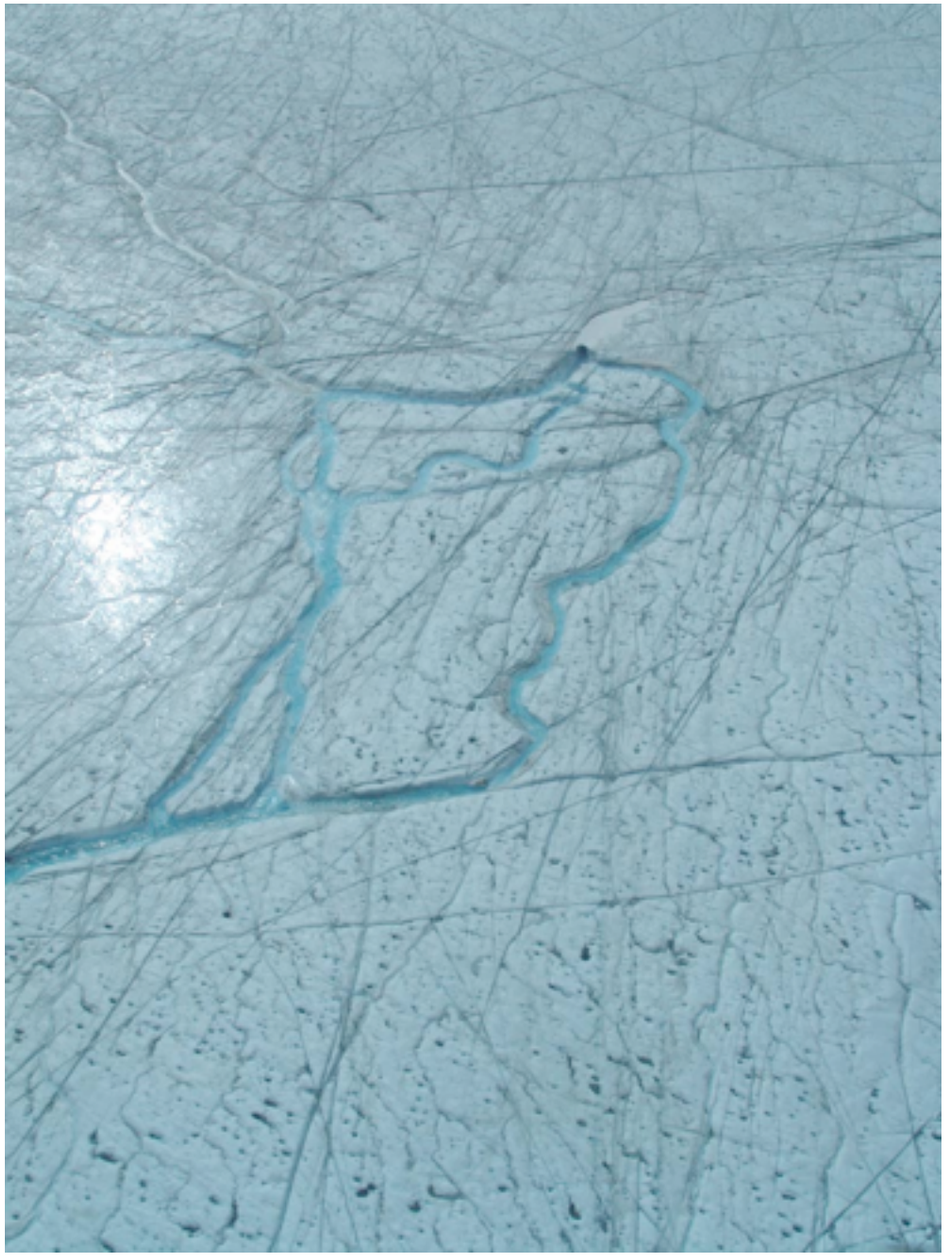
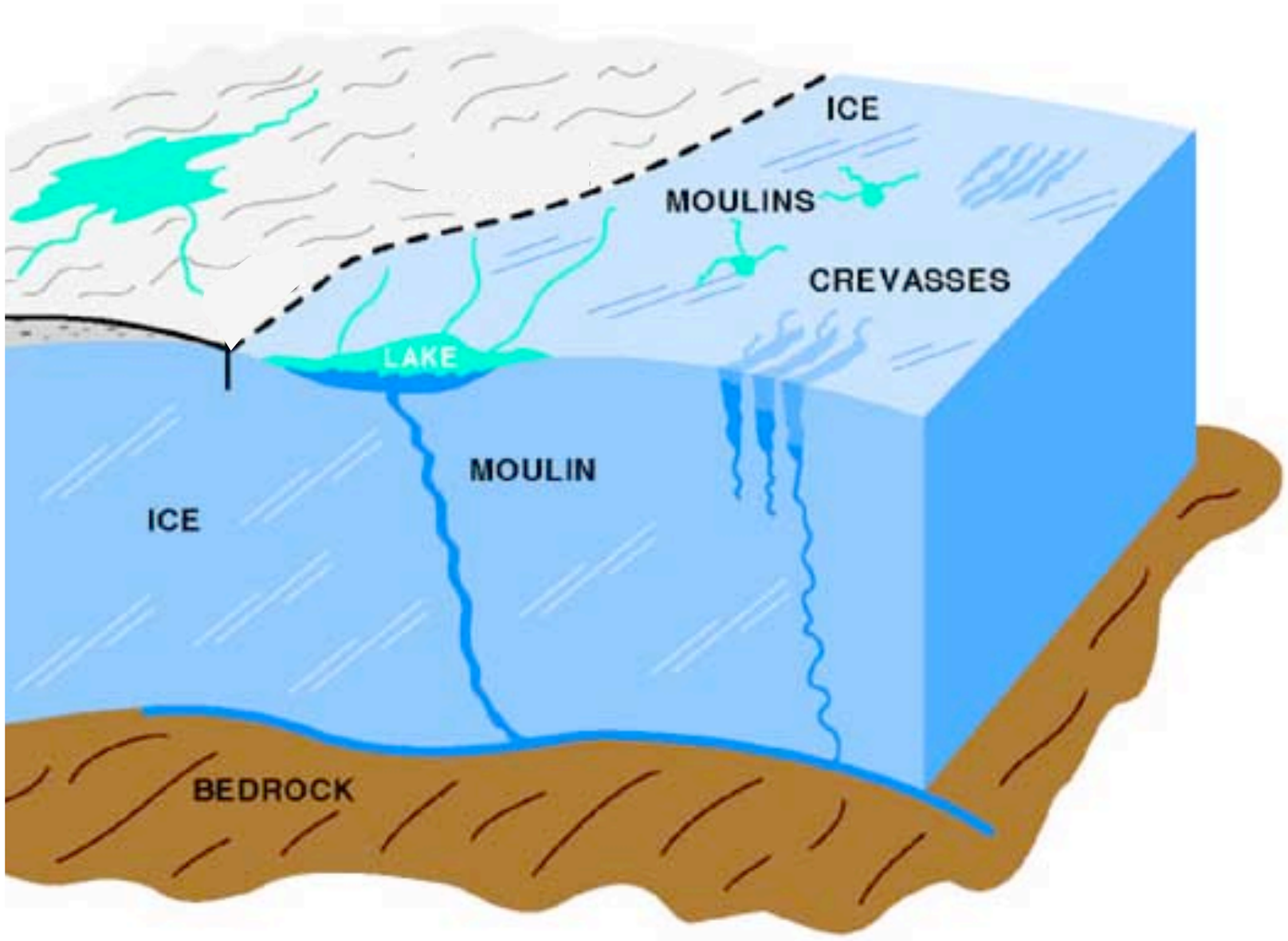
Poorly captured by models: hydrology and lubrication



http://www.nasa.gov/centers/jpl/news/moulin-20061211.html

Poorly captured by models: hydrology and lubrication



http://www.gsfc.nasa.gov/gsfc/earth/pictures/20020606greenland/figure1m.jpg

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 Structures

Complexity →

Temporal resolution ↓	Global semi-empirical	Process semi-empirical	1-D	3-D
"Equilibrium"				
Transient				

↗

Model parameters
(including stochasticity)

↓

Hindcast

↓

Proxy data/Observations → Model likelihood

How can historical records help?

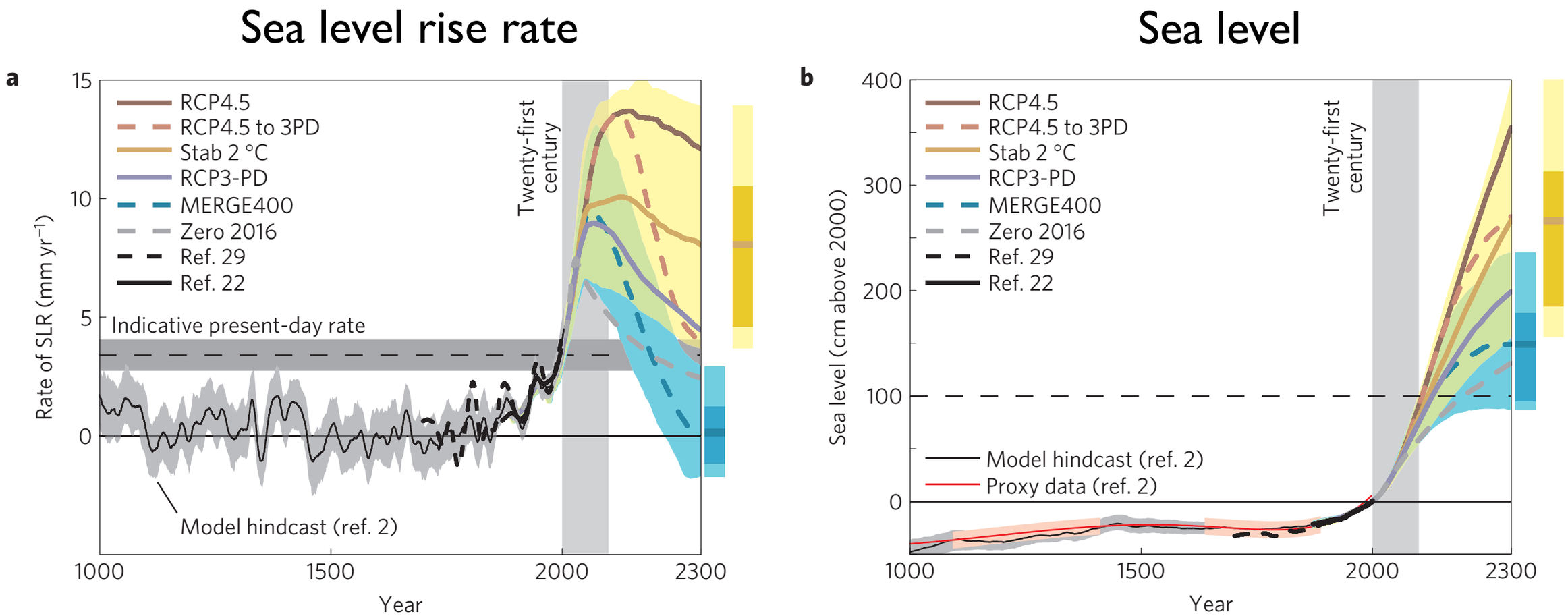


Figure 3 | Long-term SLR. a, Rate of SLR and **b**, SLR calculated from temperature reconstructions[28] for 1000–2006 and from climate-model projections 1860–2300. For comparison, observed and proxy reconstructions for SLR are given as well from refs 2,22,29. 90% uncertainty ranges are shown for only 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

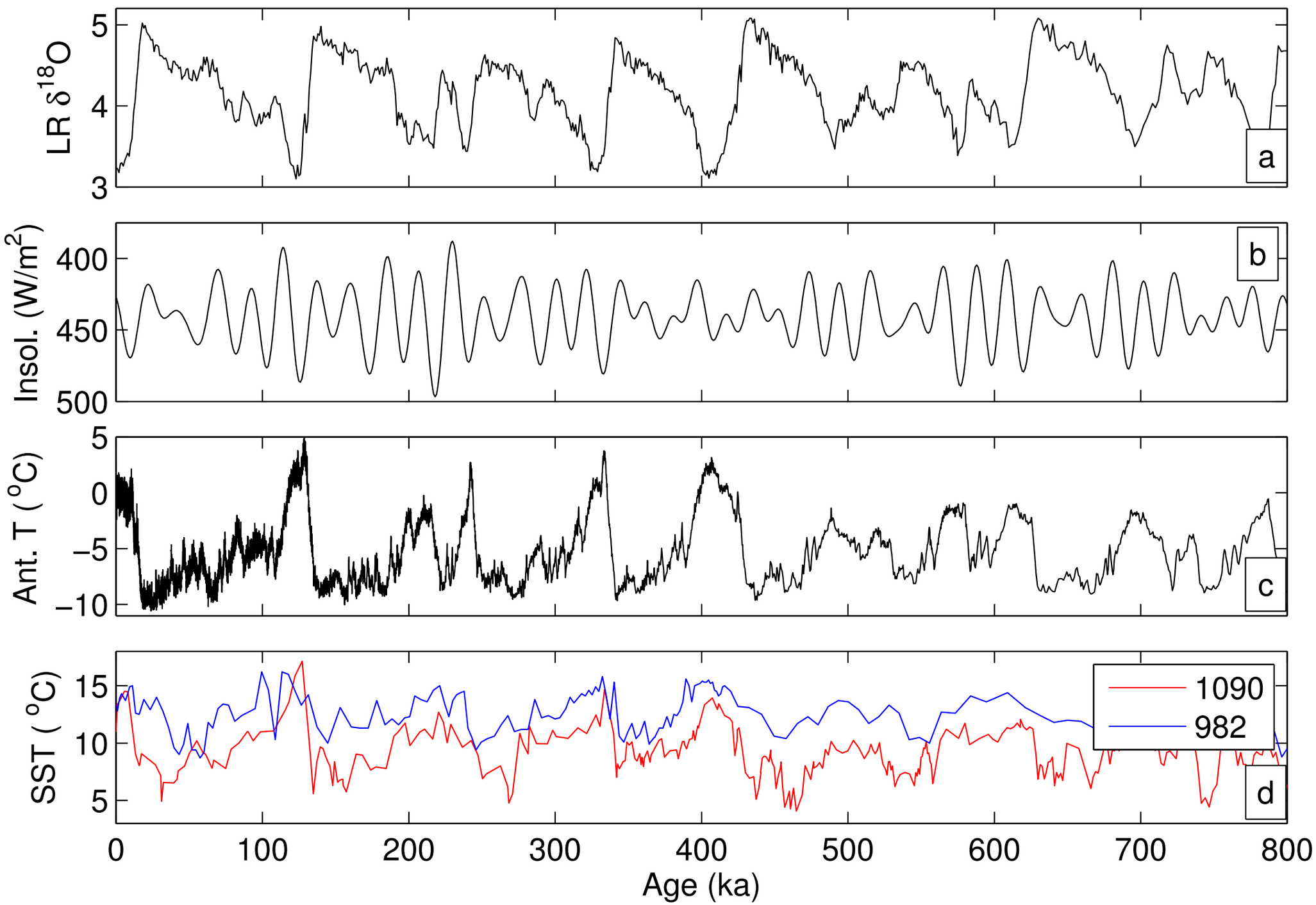
Schaeffer et al. (2012)

Complexity ⟶

Temporal resolution ↓

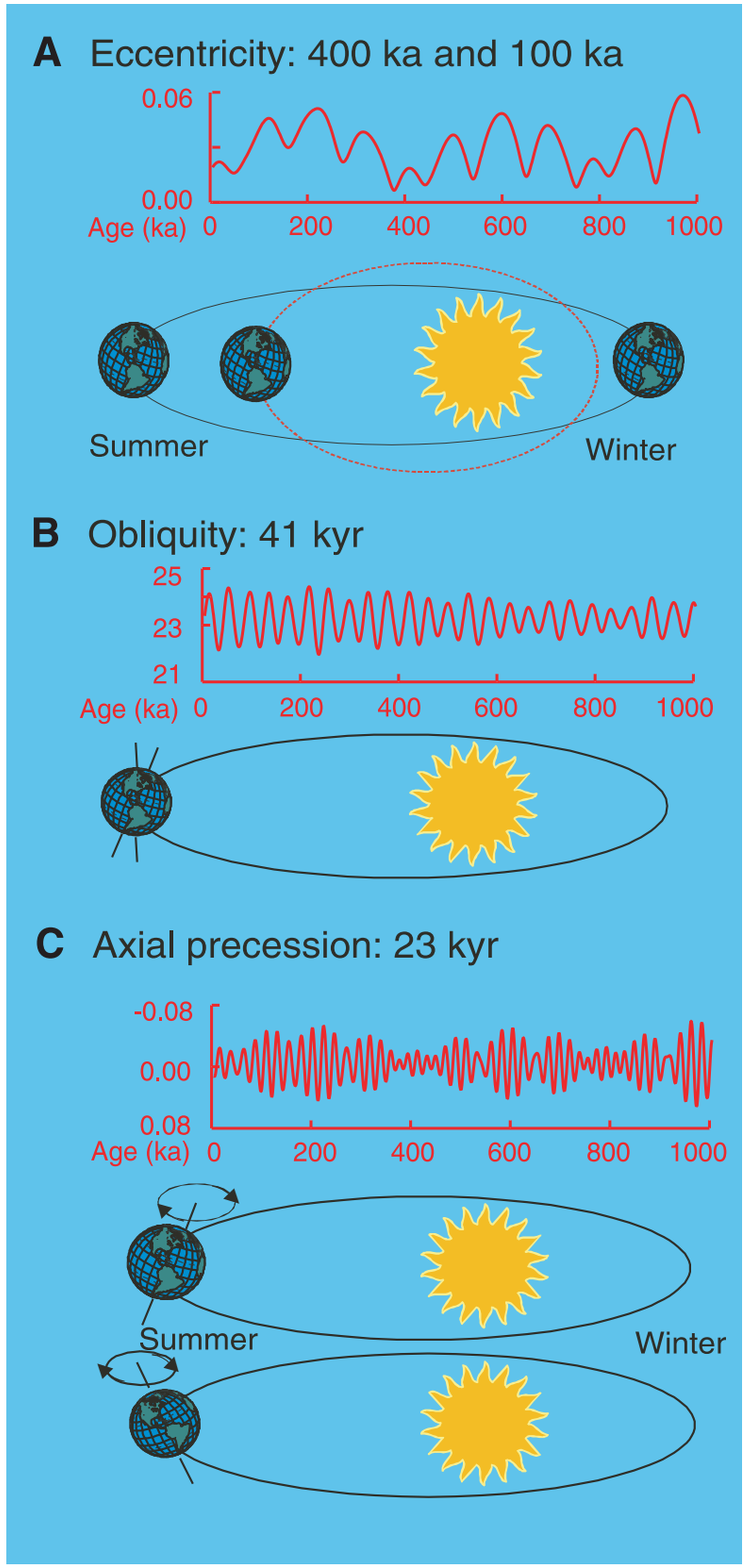
	Global semi-empirical	Process semi-empirical	1-D	3-D
"Equilib-rium"	e.g., *Gasson et al. (2012)*	this work, using the paleo record	e.g., *Applegate et al. (2012)*	e.g., *Pollard et al. (2009)*
Transient	e.g., *Schaeffer et al. (2012)*	this work, using the historical	e.g., *Applegate et al. (2012)*	e.g., *Goelzer et al. (2012)*

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



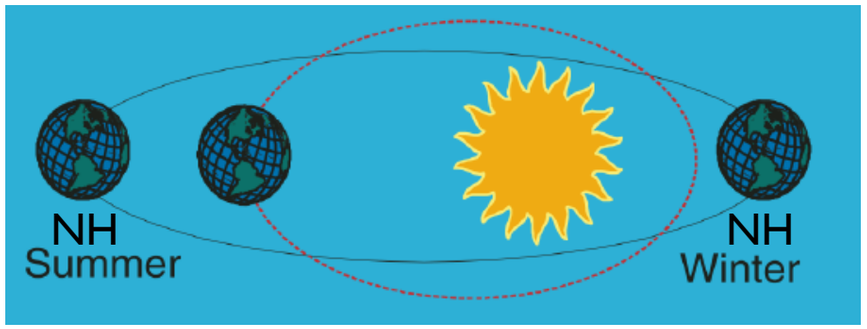
(a) The global benthic oxygen isotope stack of Lisiecki and Raymo (2005), which is a convolved record of global ice volume change and benthic temperature change, (b) summertime insolation at 65°N latitude (Berger and Loutre, 1991), and some paleoclimatic proxies that might be related to ice sheet changes – (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).

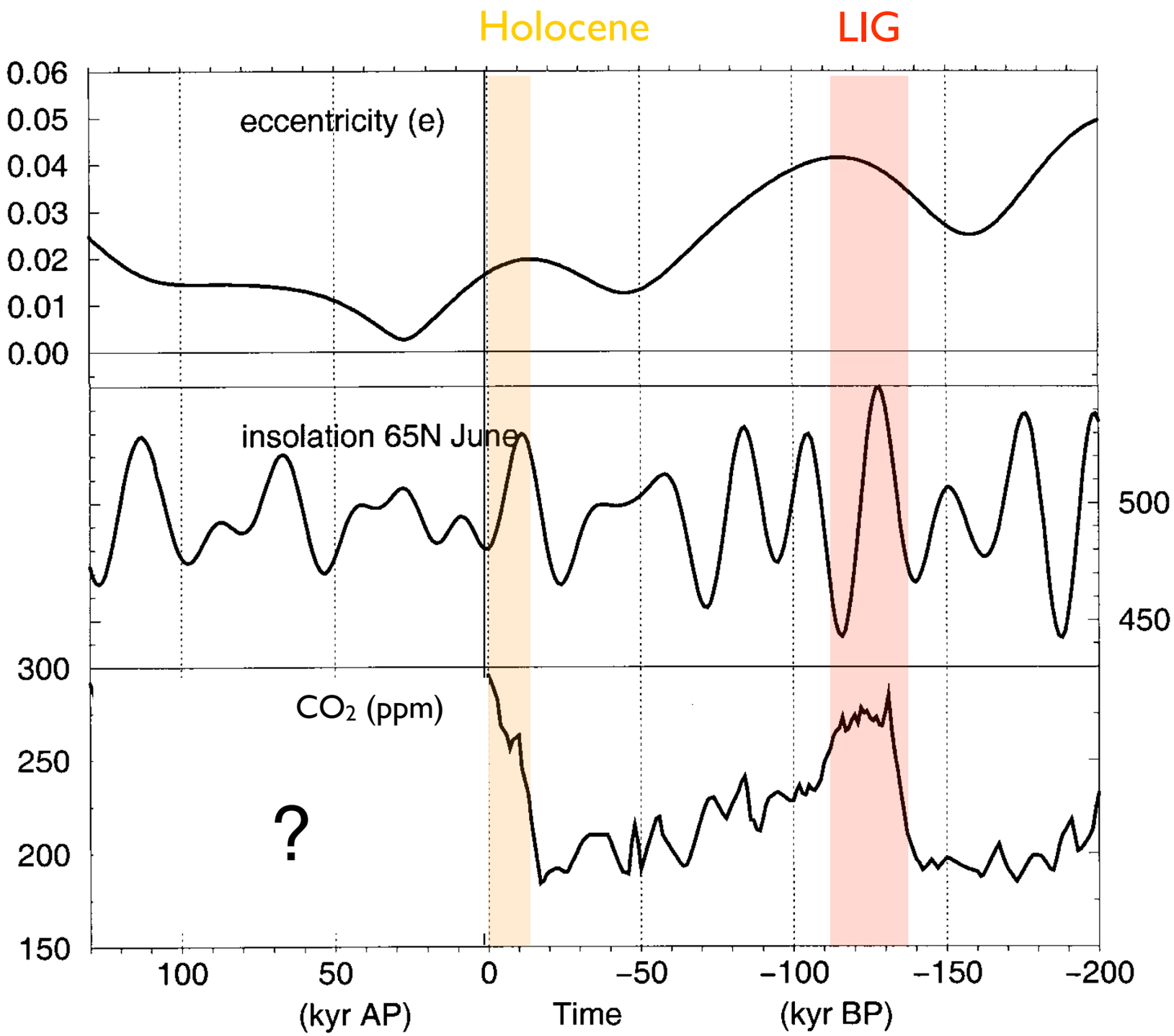
...with pacing sets by change's in Earth orbit



Zachos et al. (2003)

The Last Interglacial stage

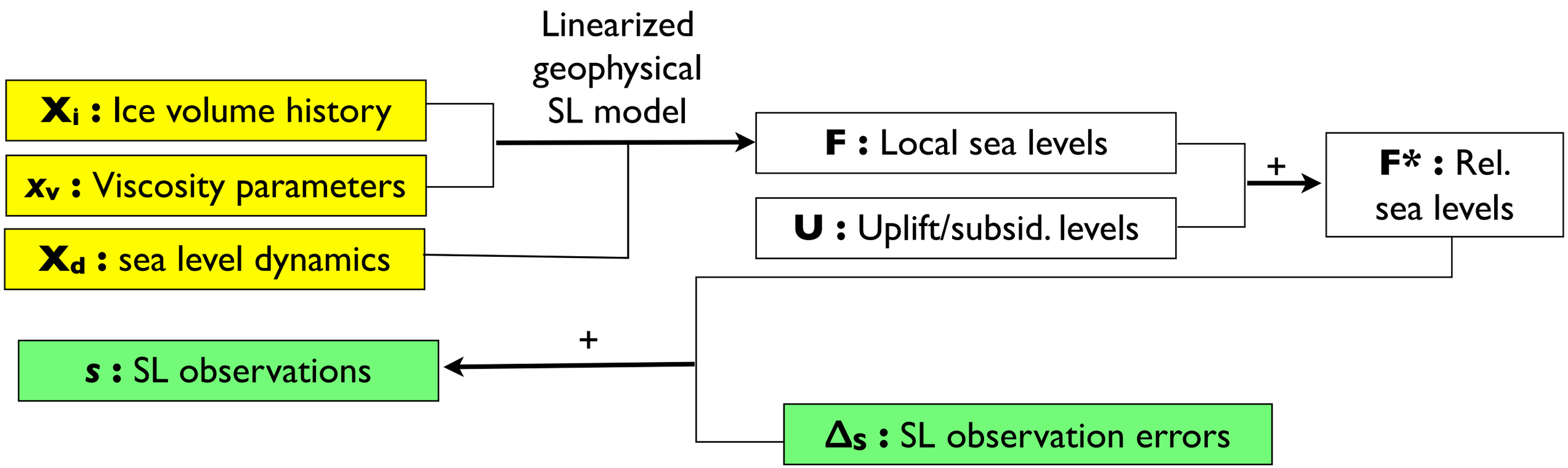




Berger et al. (2003)

But to leverage these records, we must see through a host of uncertainties.

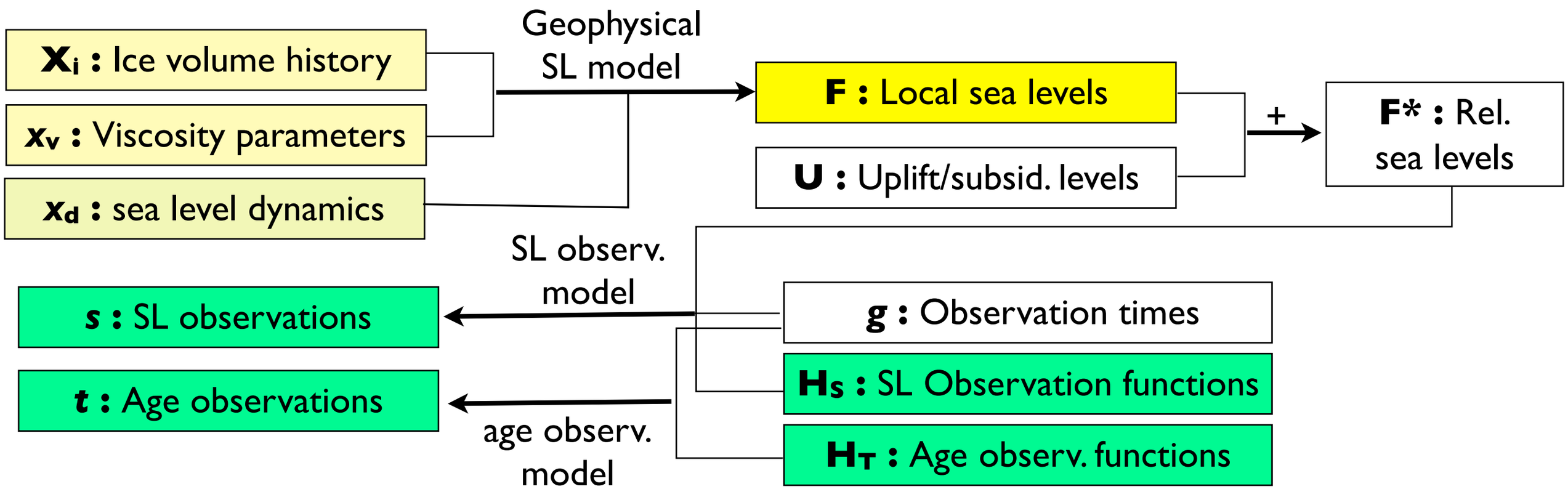
A forward model for historical SL observations



This gives us $P(s \mid \mathbf{X_i}, x_v, \mathbf{X_d}, \mathbf{U}, \Delta_s)$.

We want to find $P(\mathbf{X_i}, x_v, \mathbf{X_d} \mid s, \mathbf{U}, \Delta_s)$.

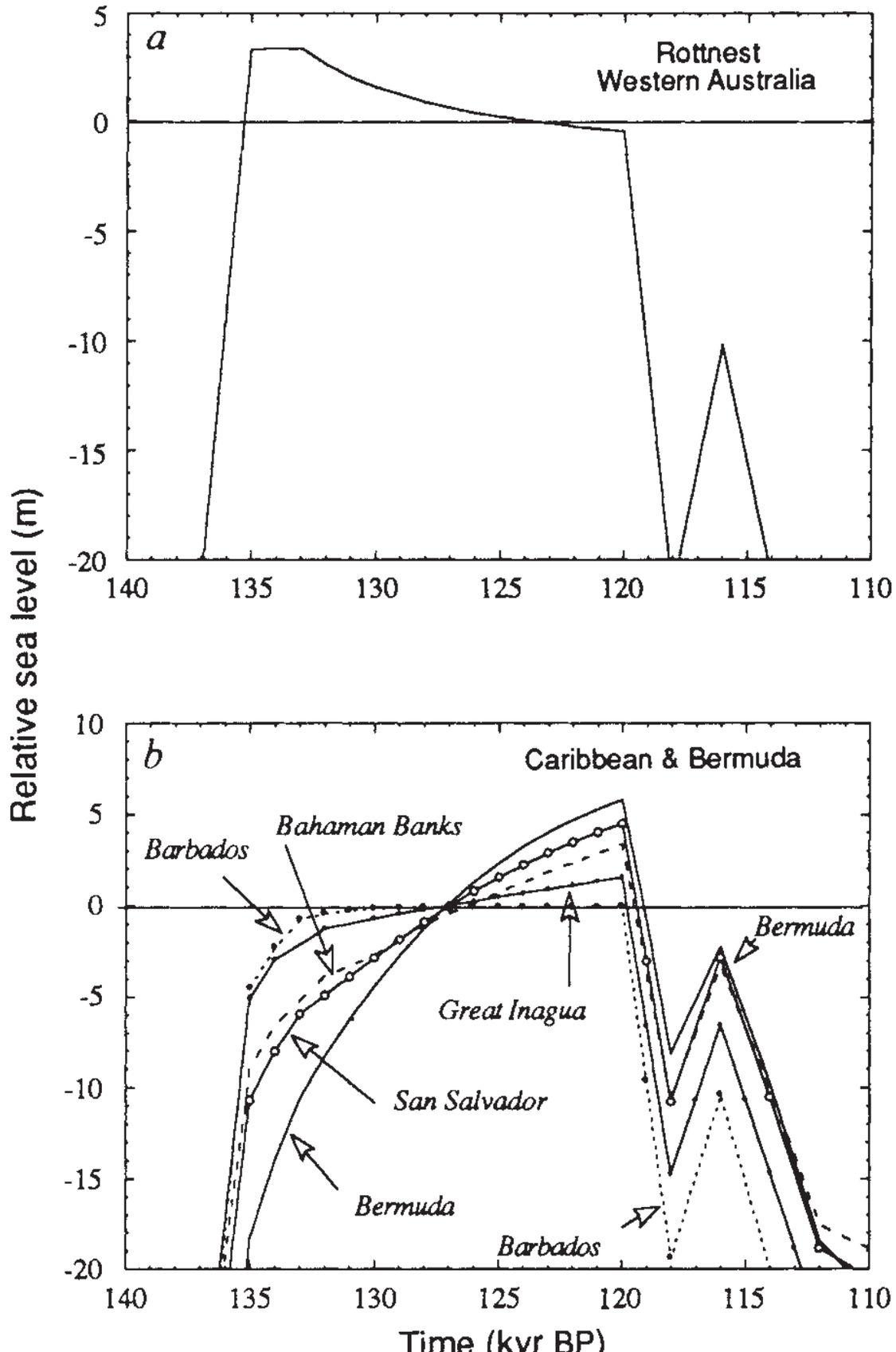
A forward model for geological sea level proxies



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 $P(\mathbf{X_i}, \mathbf{x_v}, \mathbf{X_d} \mid \boldsymbol{s}, \boldsymbol{t}, \mathbf{U}, \mathbf{H_S}, \mathbf{H_T})$]

It's possible to generate high LSL without high GSL



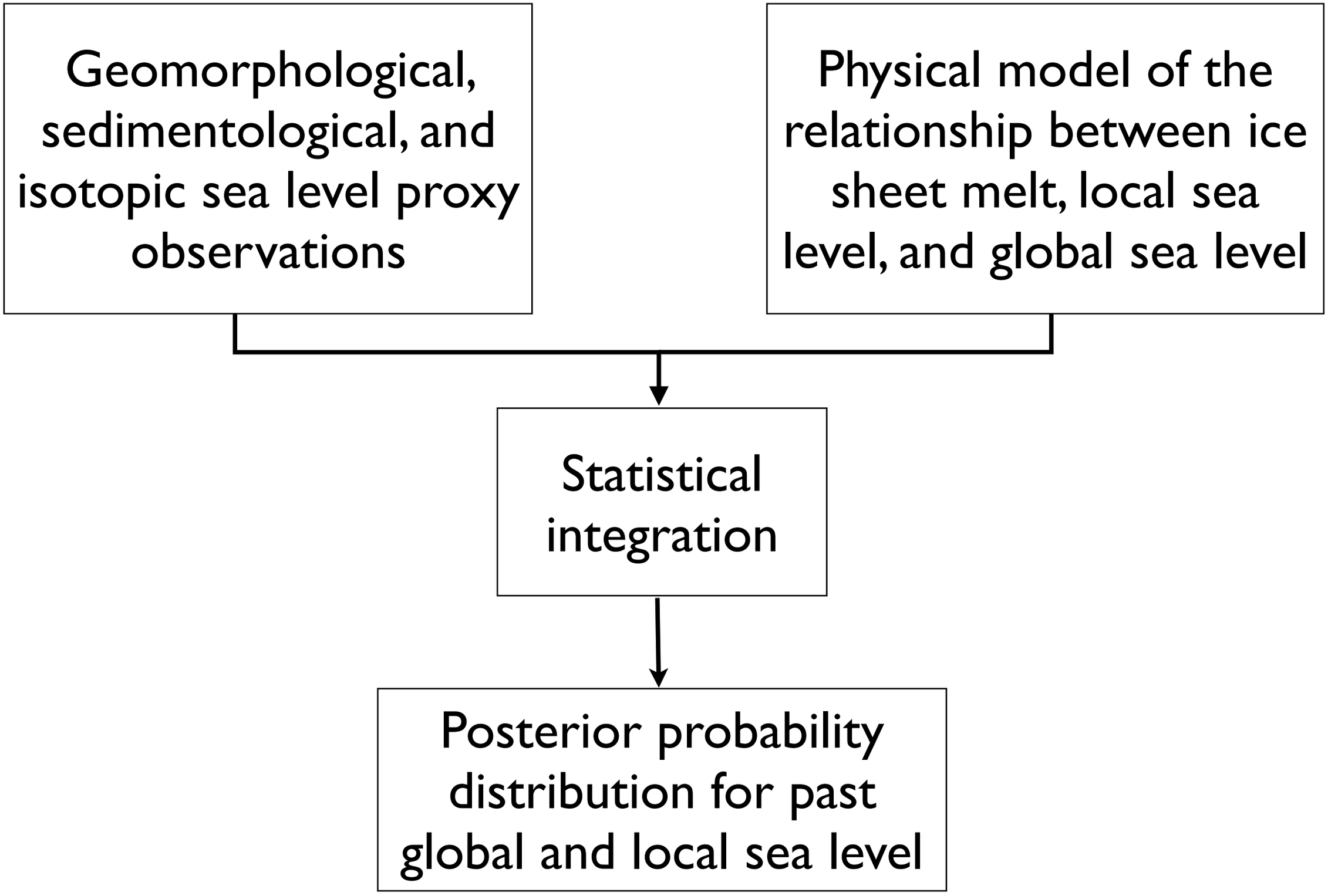
Far from Laurentide Ice Sheet

In this model, GSL from 135 to 120 ka is the same as today!

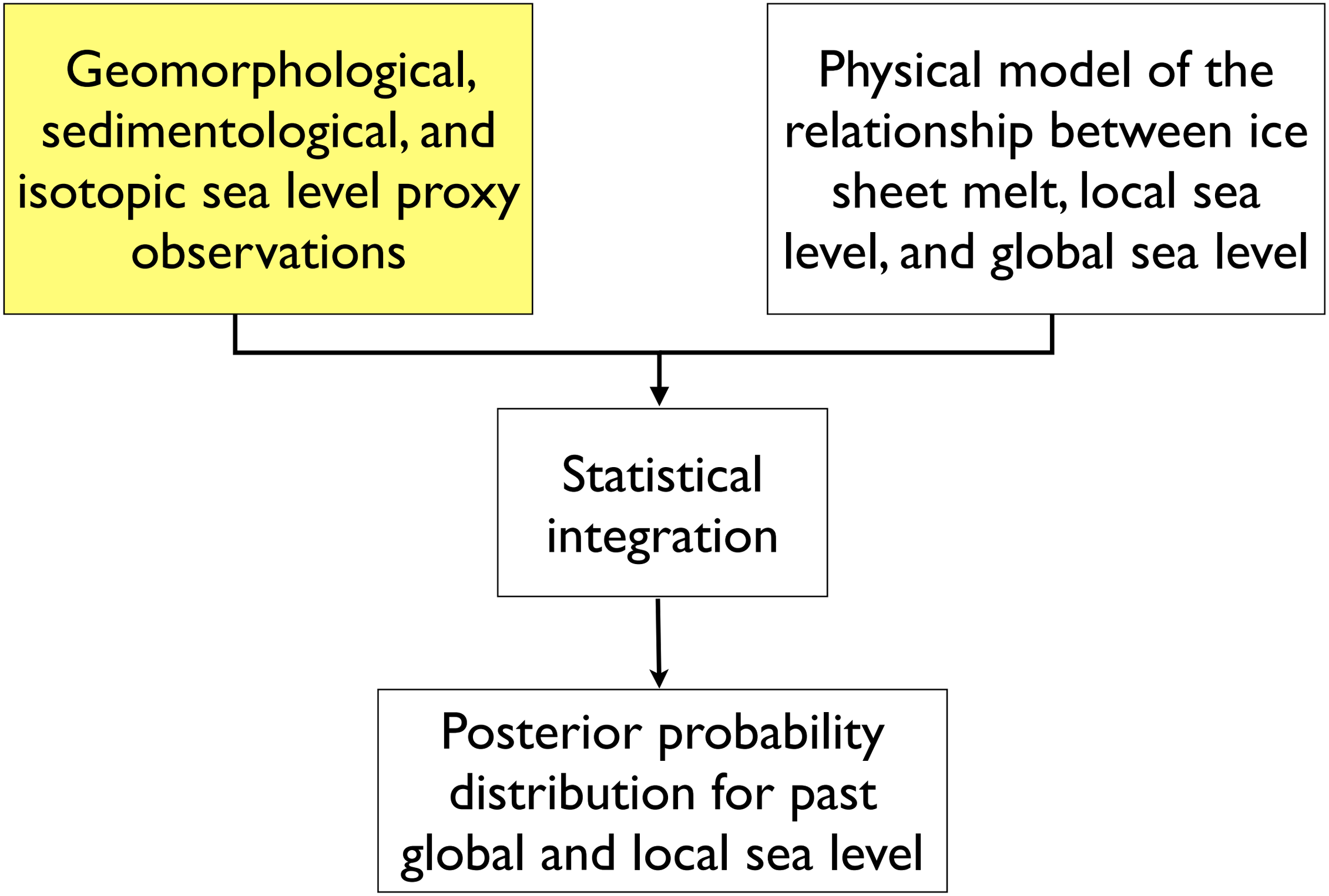
Closer to Laurentide Ice Sheet

Lambeck & Nakada (1992)

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

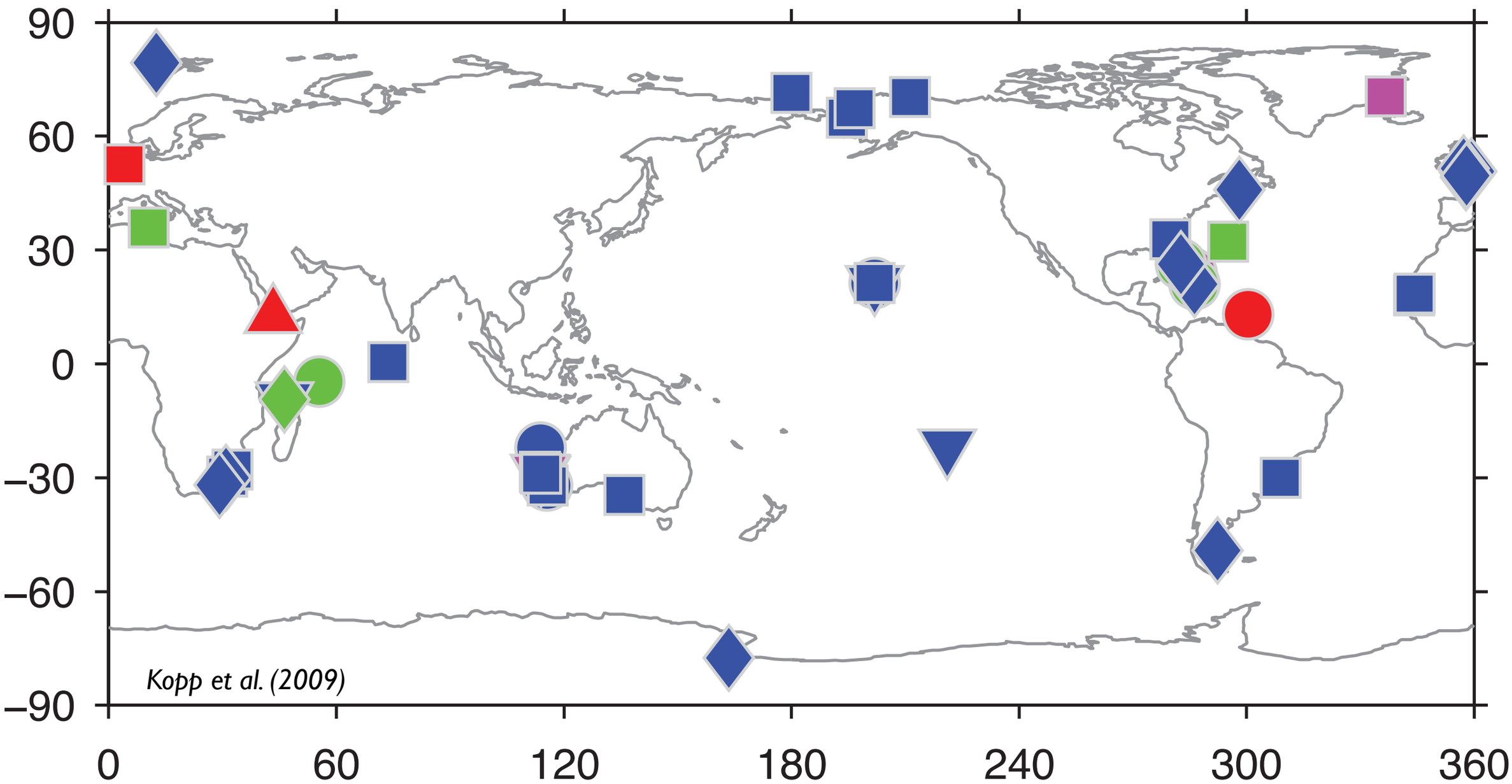


Goal: Given database, assess the probability distribution of sea level through space and time



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)

Key Characteristics of Observations

Sea Level (s) →

- Heteroscedastic, some non-Gaussian
- Some are platykurtic
- Some are censored

Ages (t) →

- Heteroscedastic
- Some have strong ordering constraints
- Some have relative ages better known than absolute ages

Sea Level Database

Example 1: Cockburn Town Reef, San Salvador, Bahamas

Chen et al. (1991)

Sea Level Database

Example 1: Cockburn Town Reef, San Salvador, Bahamas

Reef terrace dominated by *Acropora palmata*

Altitude of 1.5 ± 1.0 m

Composite U/Th age of 128.4 ± 8.0 ka

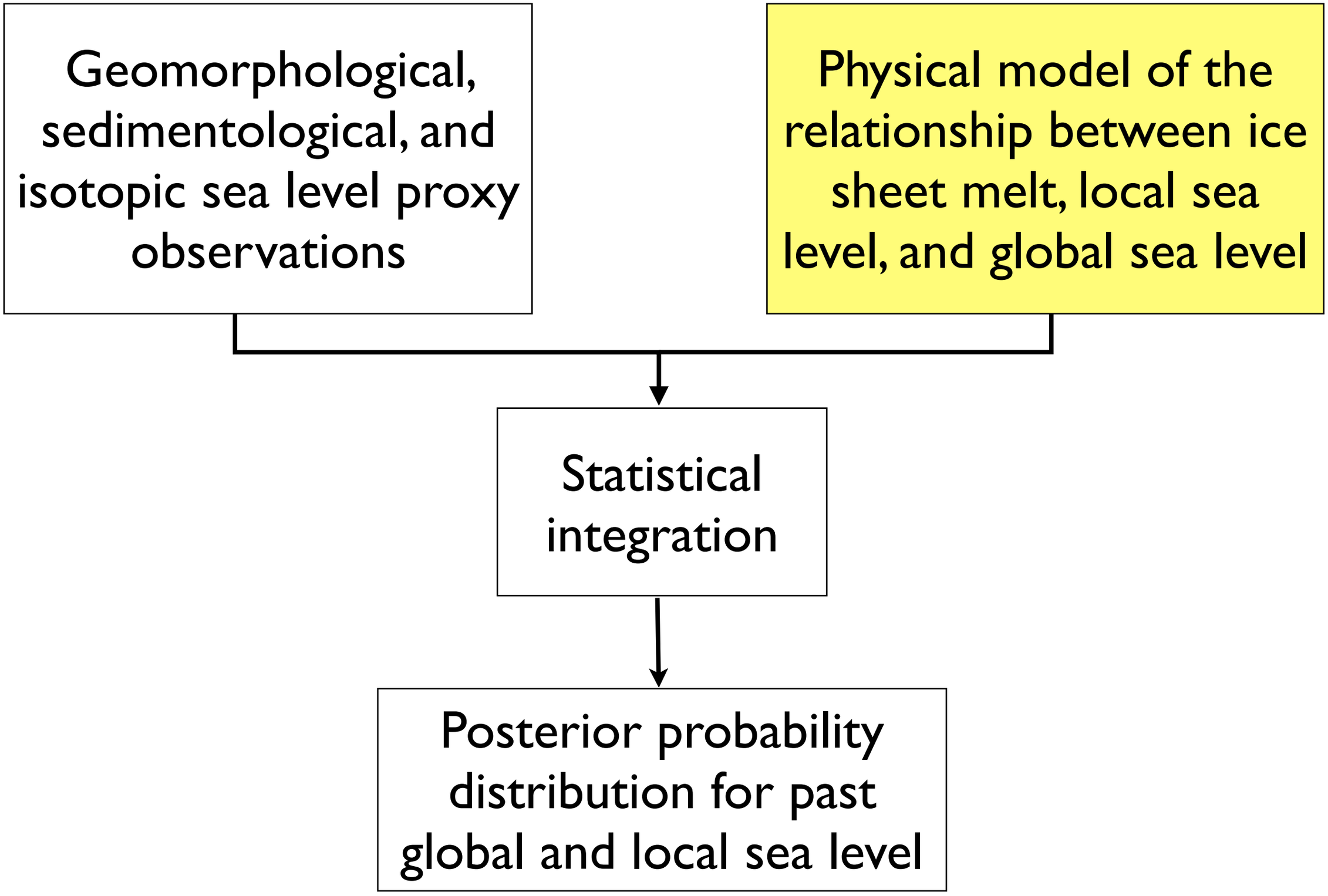
Depositional range based on assemblages: 0-5 m below MLTL

Subsidence rate estimate: 1-2 cm/ky

http://www.mnstate.edu/leonard/G390BPHOTOS.html

Chen et al. (1991)

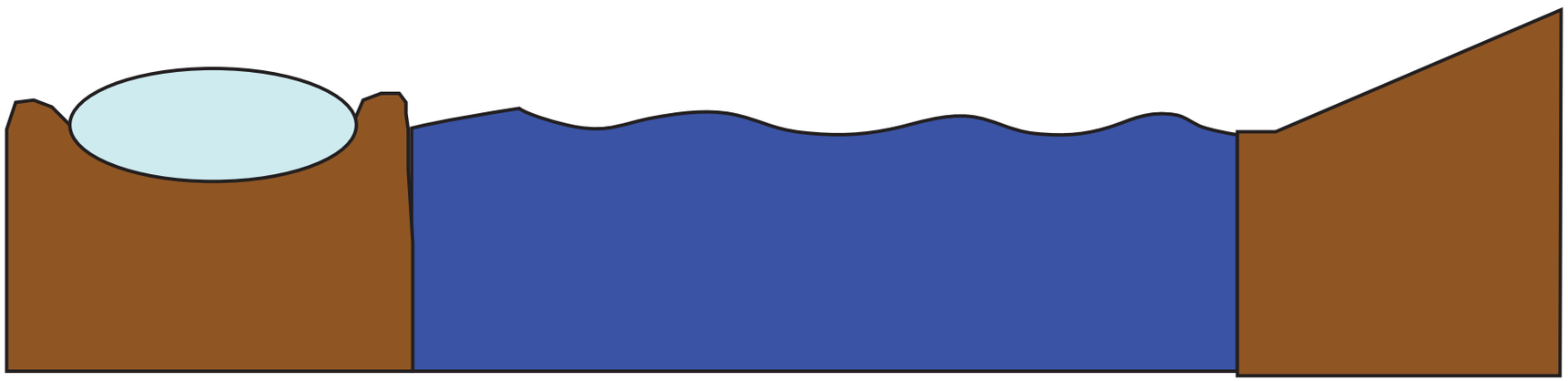
Goal: Given database, assess the probability distribution of sea level through space and time

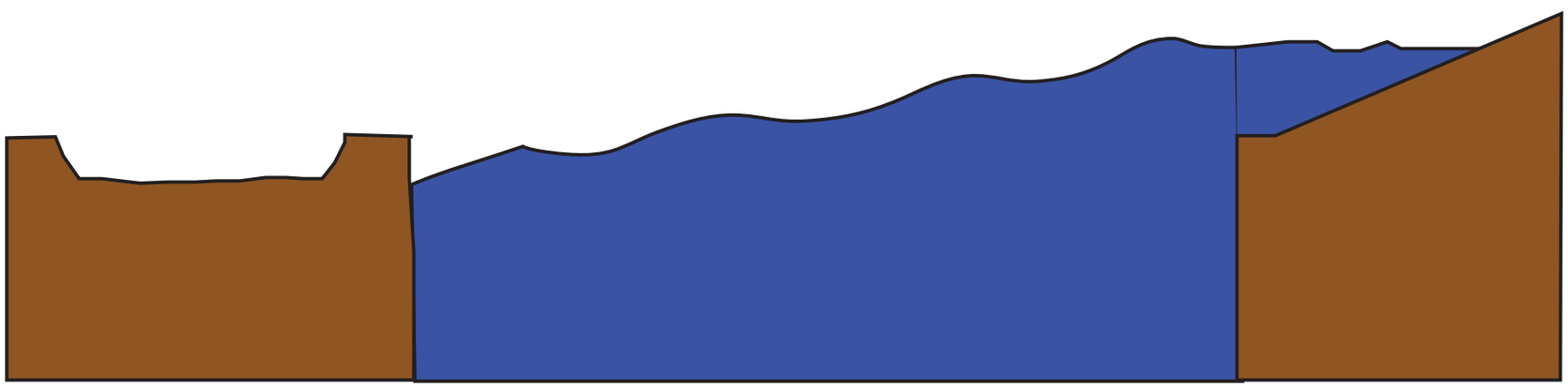


Prior covariance within F calculated from SL model

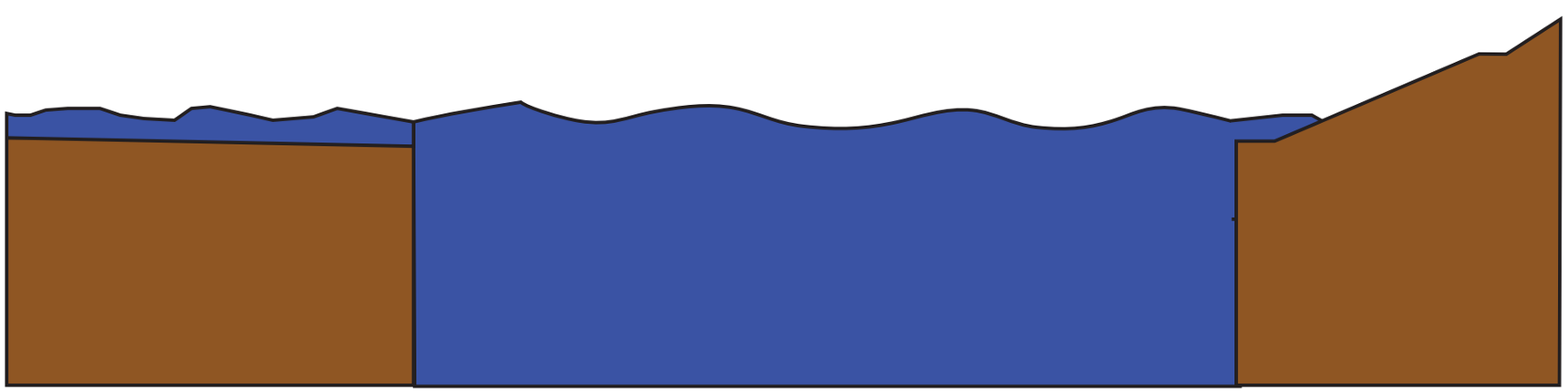
Effects included:

Gravitational, elastic, rotational, isostatic, shoreline migrations



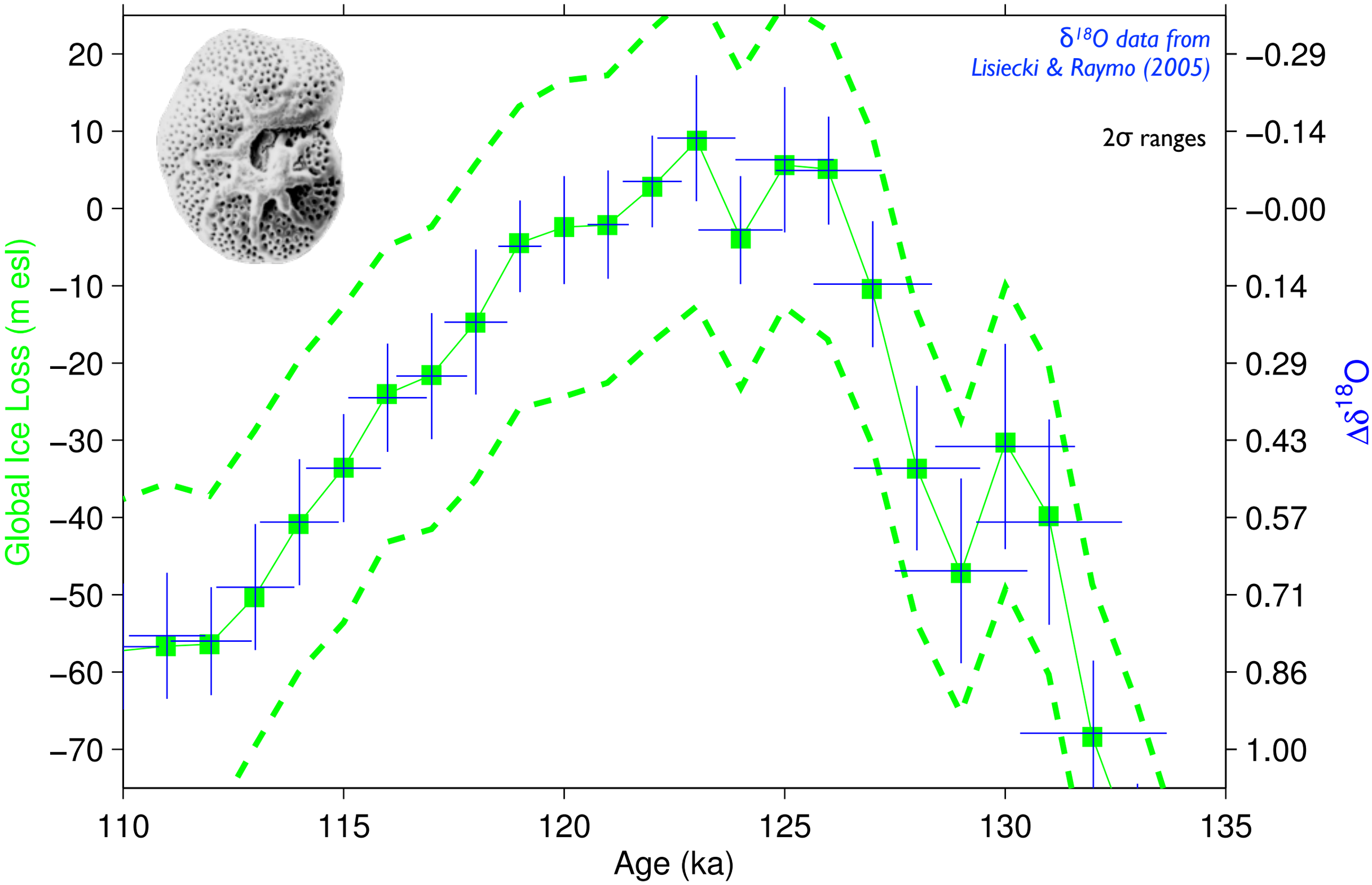


Gravitational and elastic response



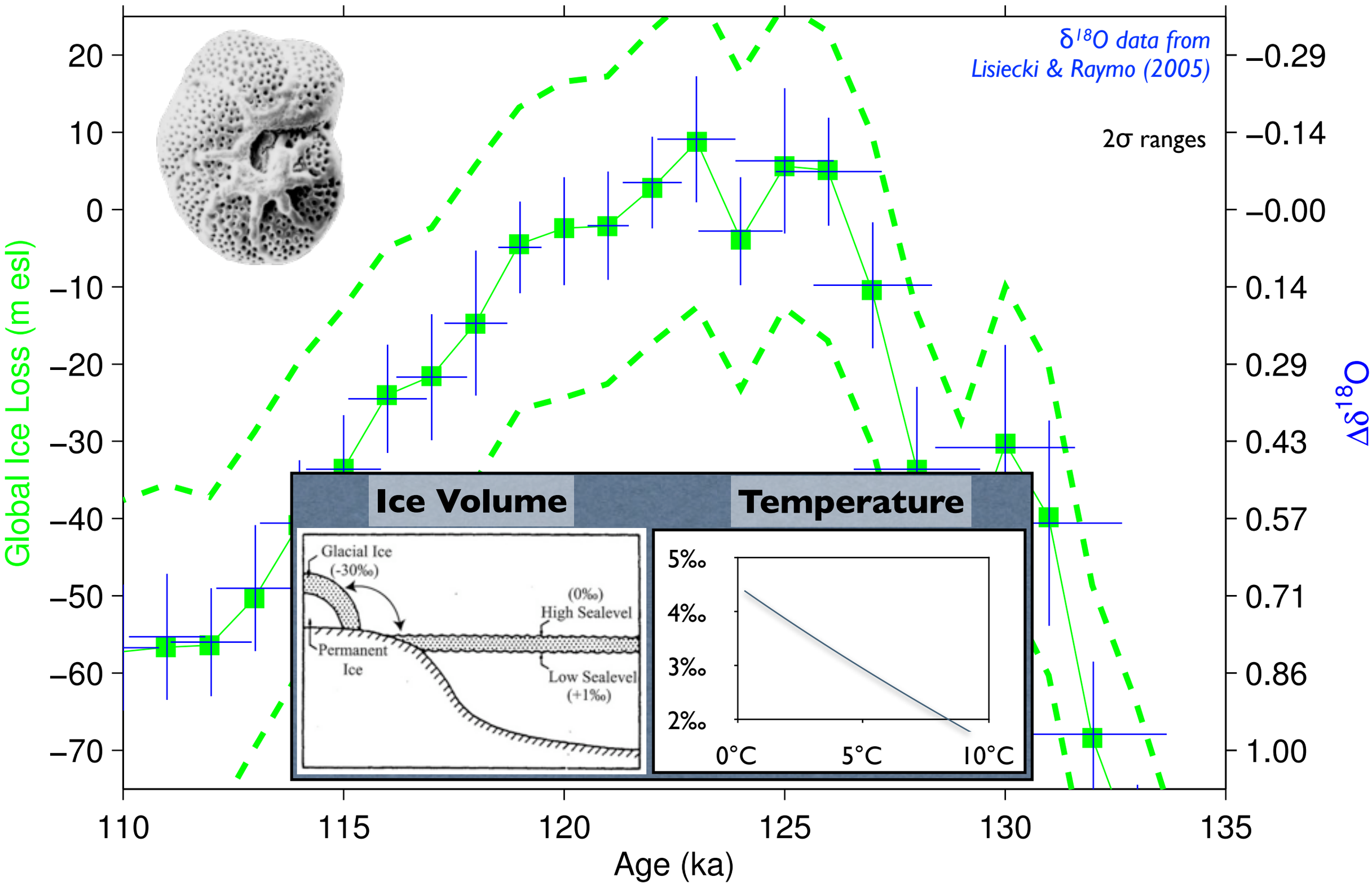
Isostatic response

With prior for total ice volume from $\delta^{18}O$ record



Cartoon from: http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml

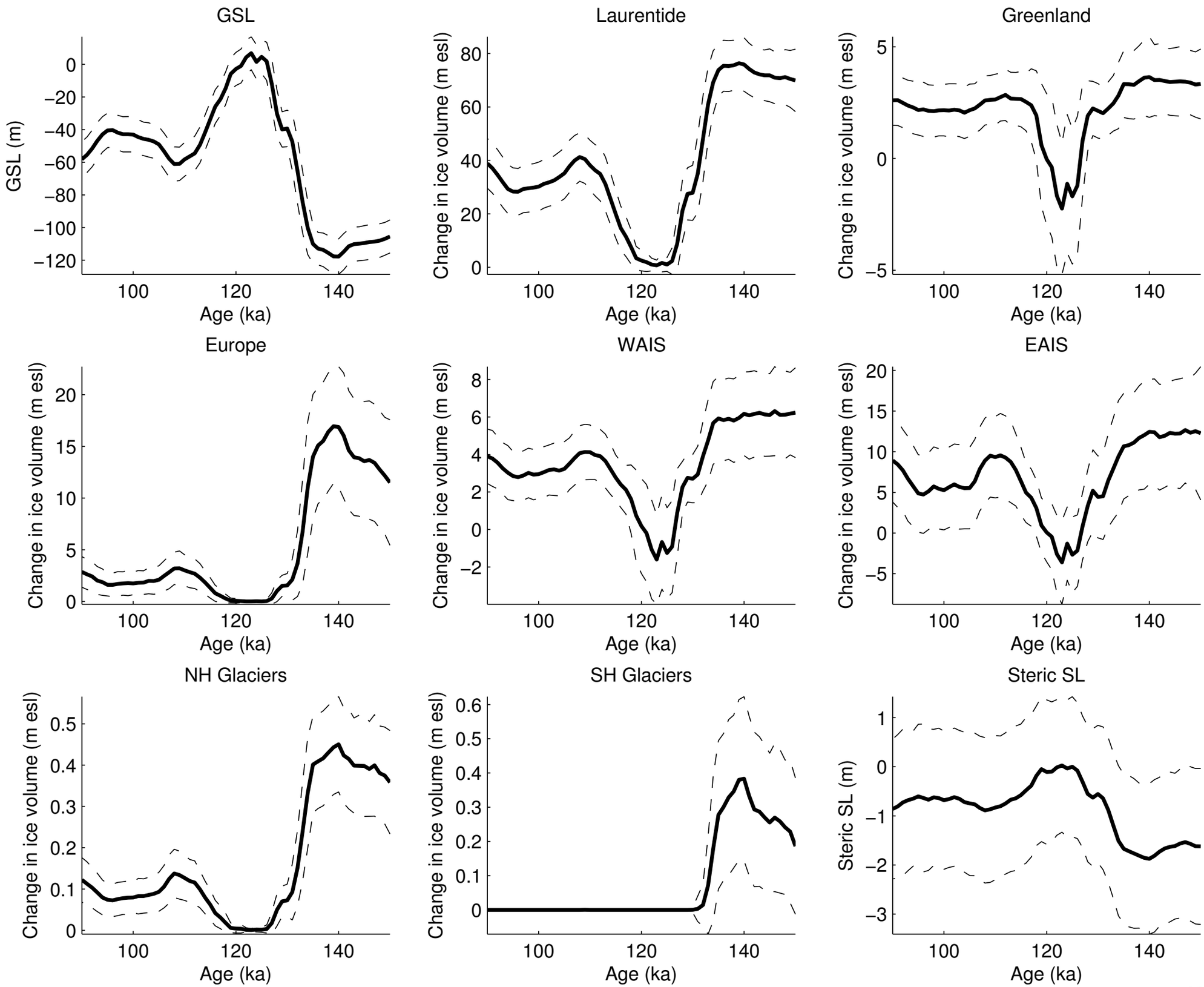
With prior for total ice volume from $\delta^{18}O$ record



Cartoon from: http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml

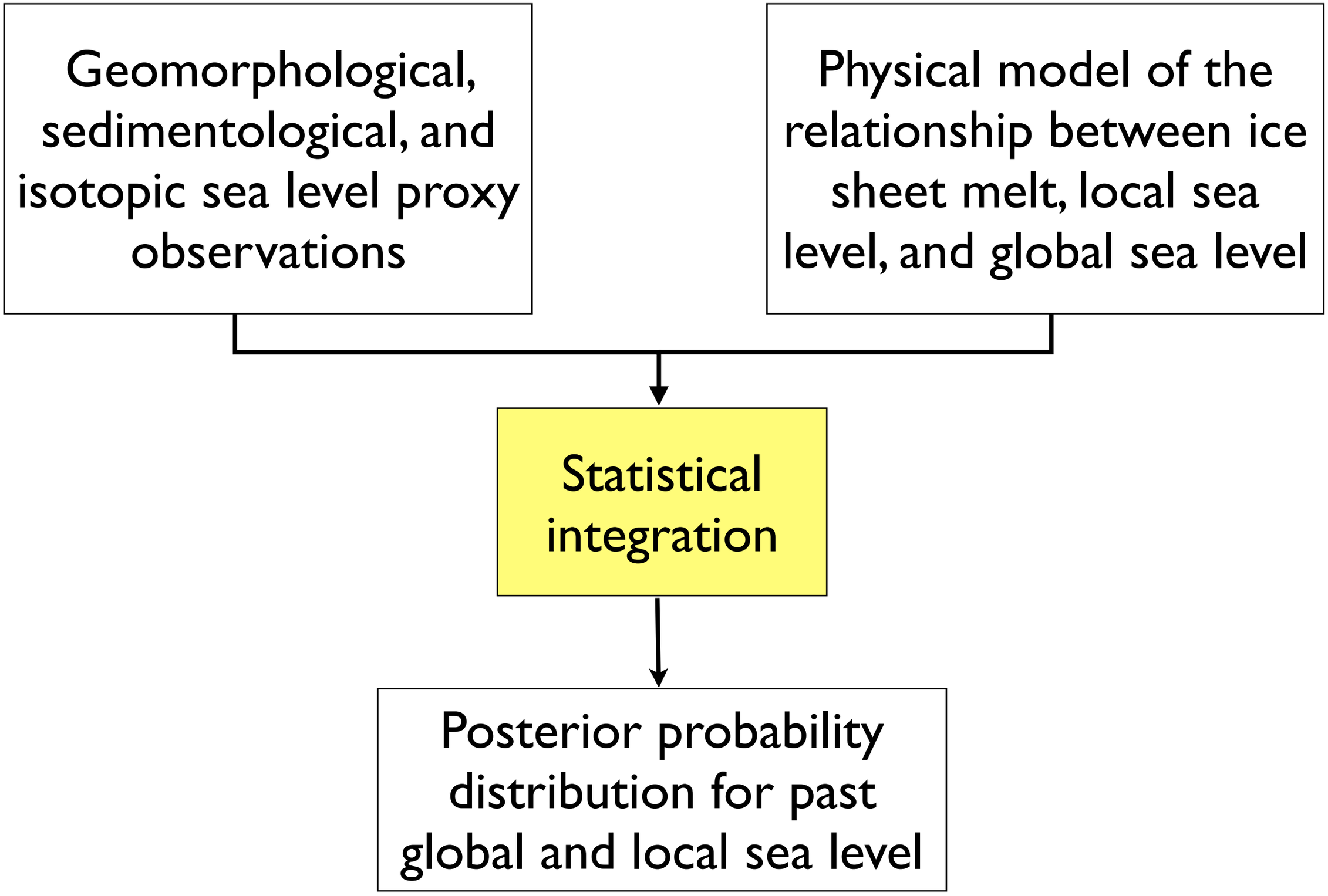
Prior probability distributions for GSL and ice sheets over time

(inferred from global benthic foram $\delta^{18}O$ stack)

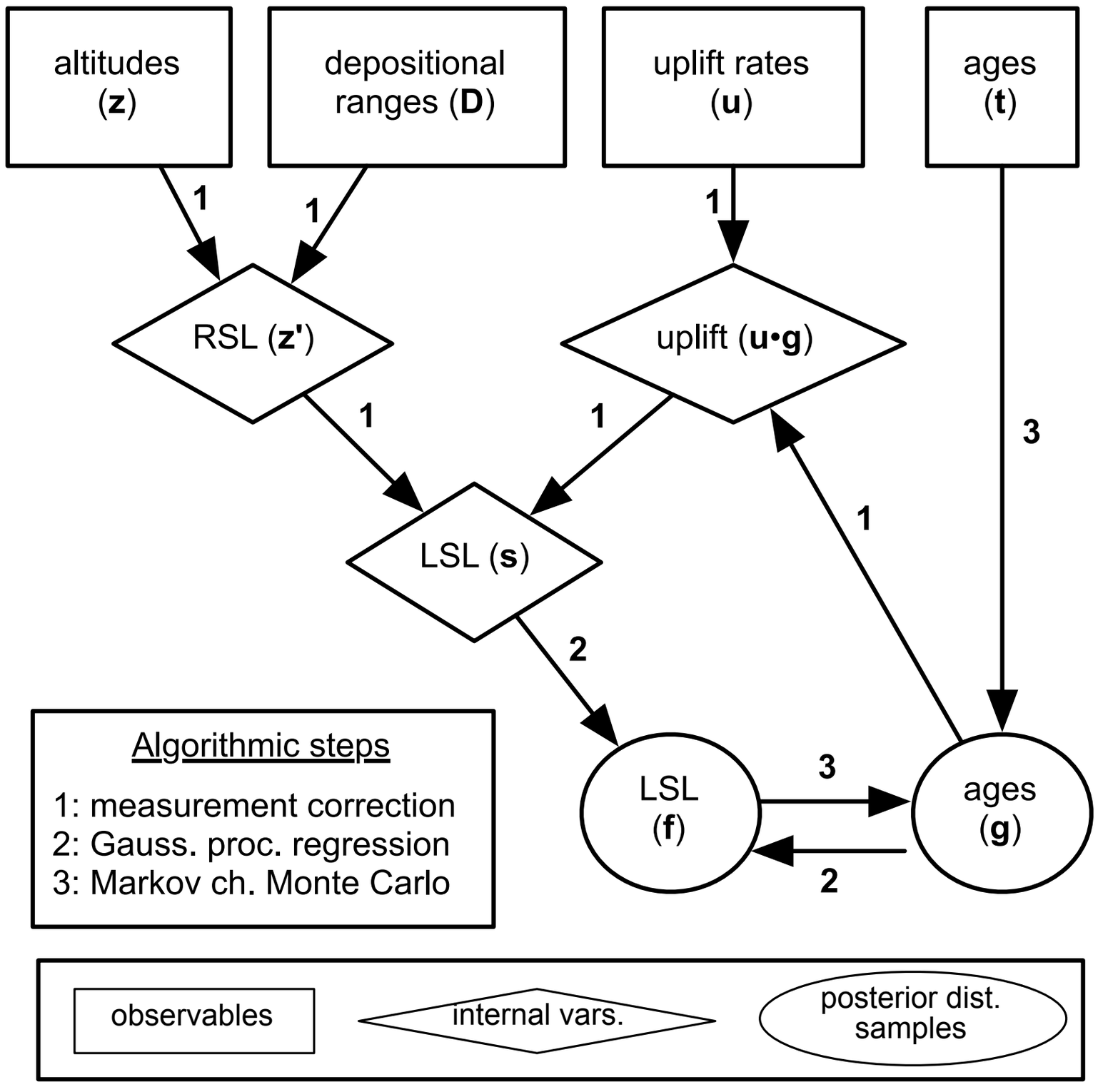


Kopp et al. (2009)

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



Statistical Integration Algorithm

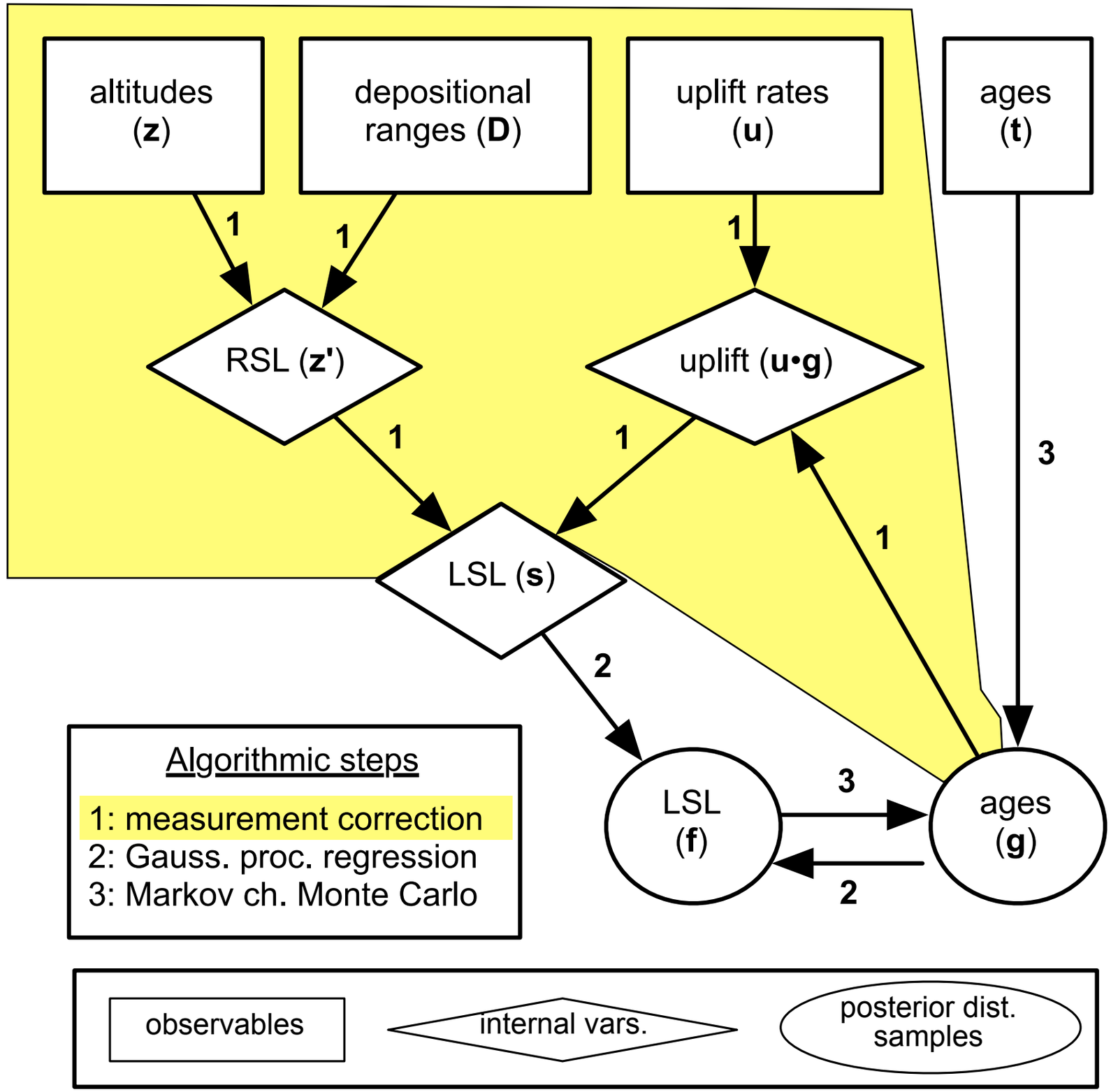


Kopp et al. (2009)

Statistical Integration Algorithm

Probability of **local sea level observations**, conditional on:

altitudes,
meanings,
uplift rates,
"true" ages

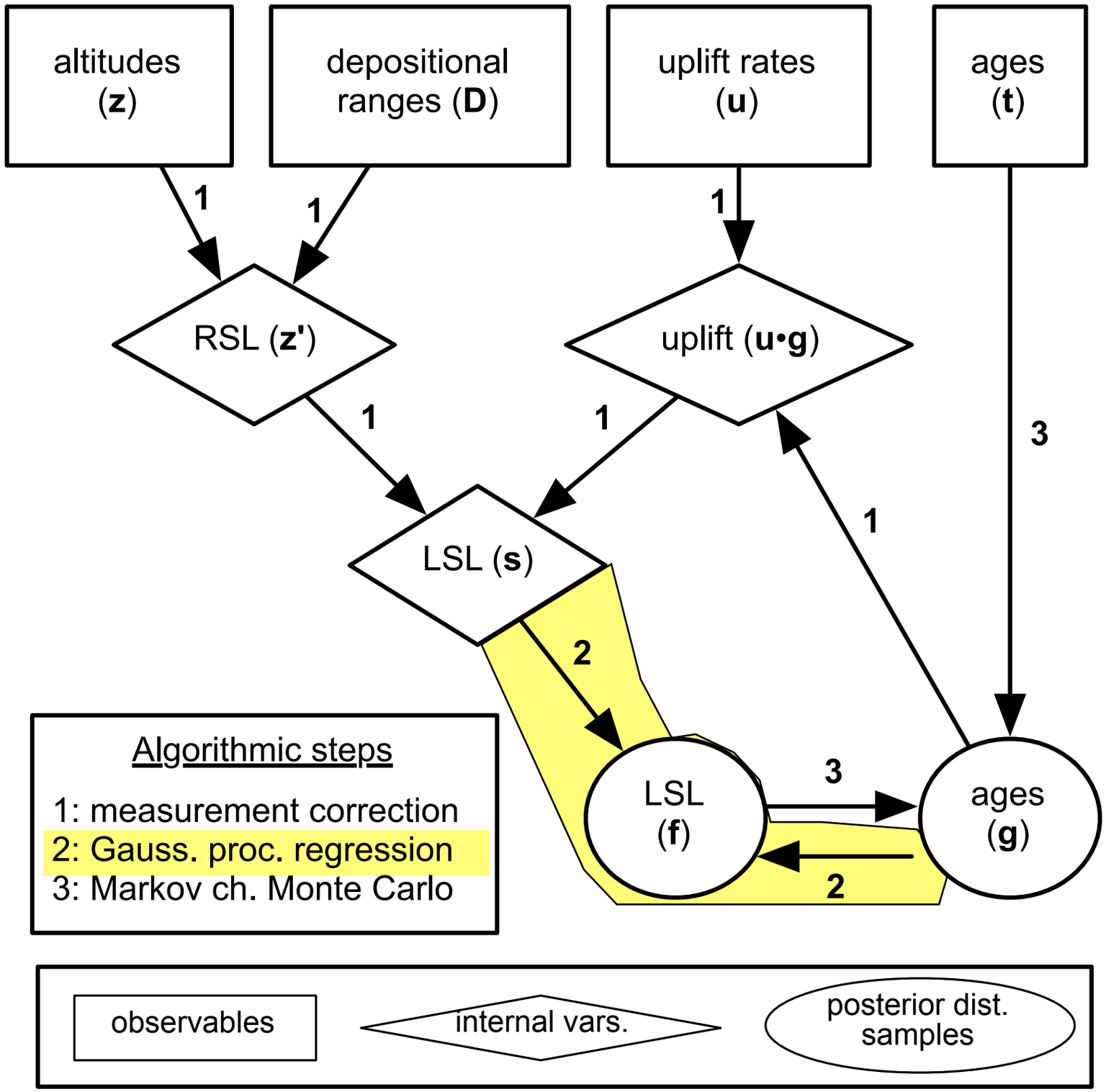


Statistical Integration Algorithm

Probability of **"true" local sea level**, conditional on:

local sea level observations,
"true" ages,

and the physical prior.

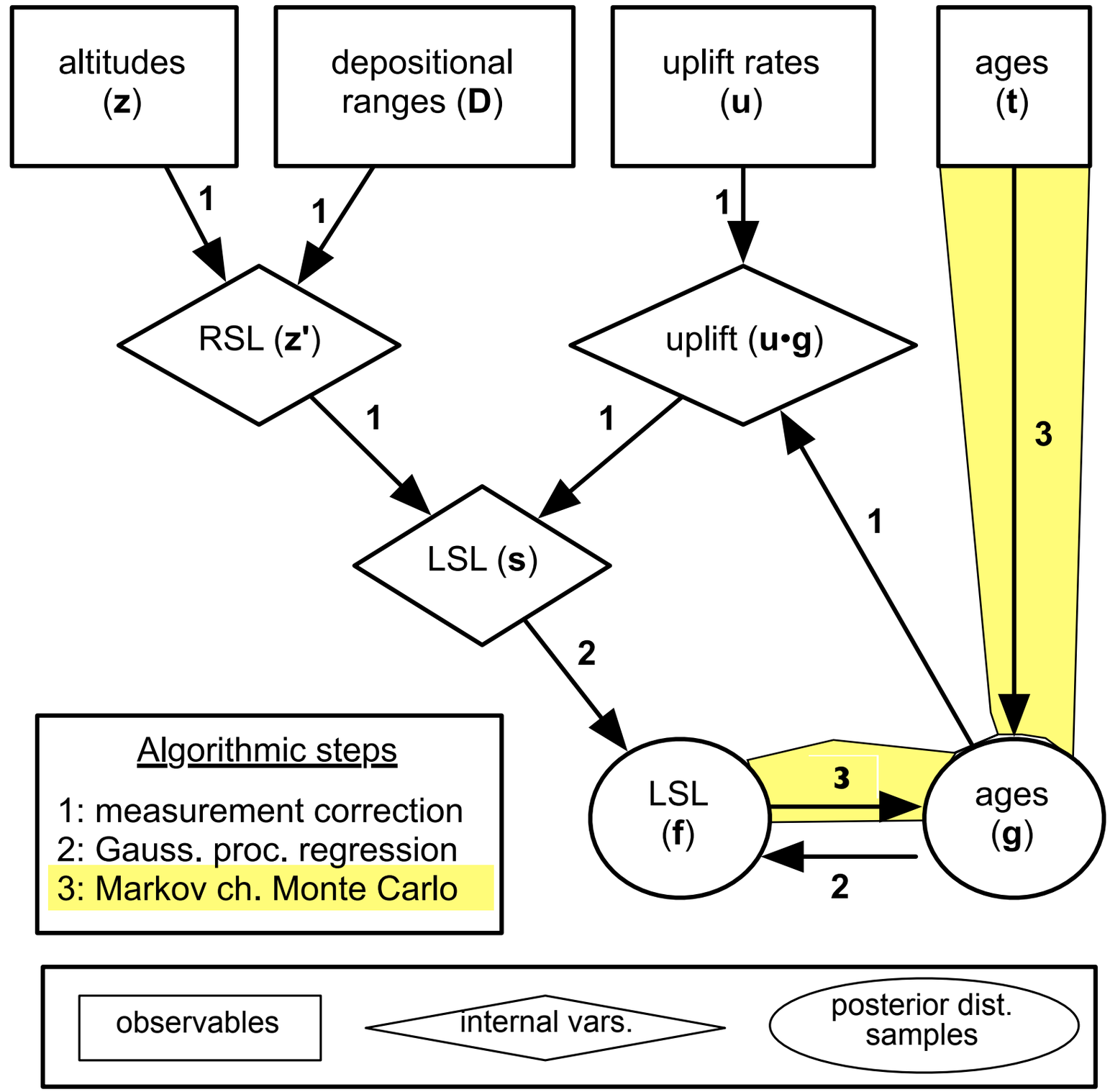


Statistical Integration Algorithm

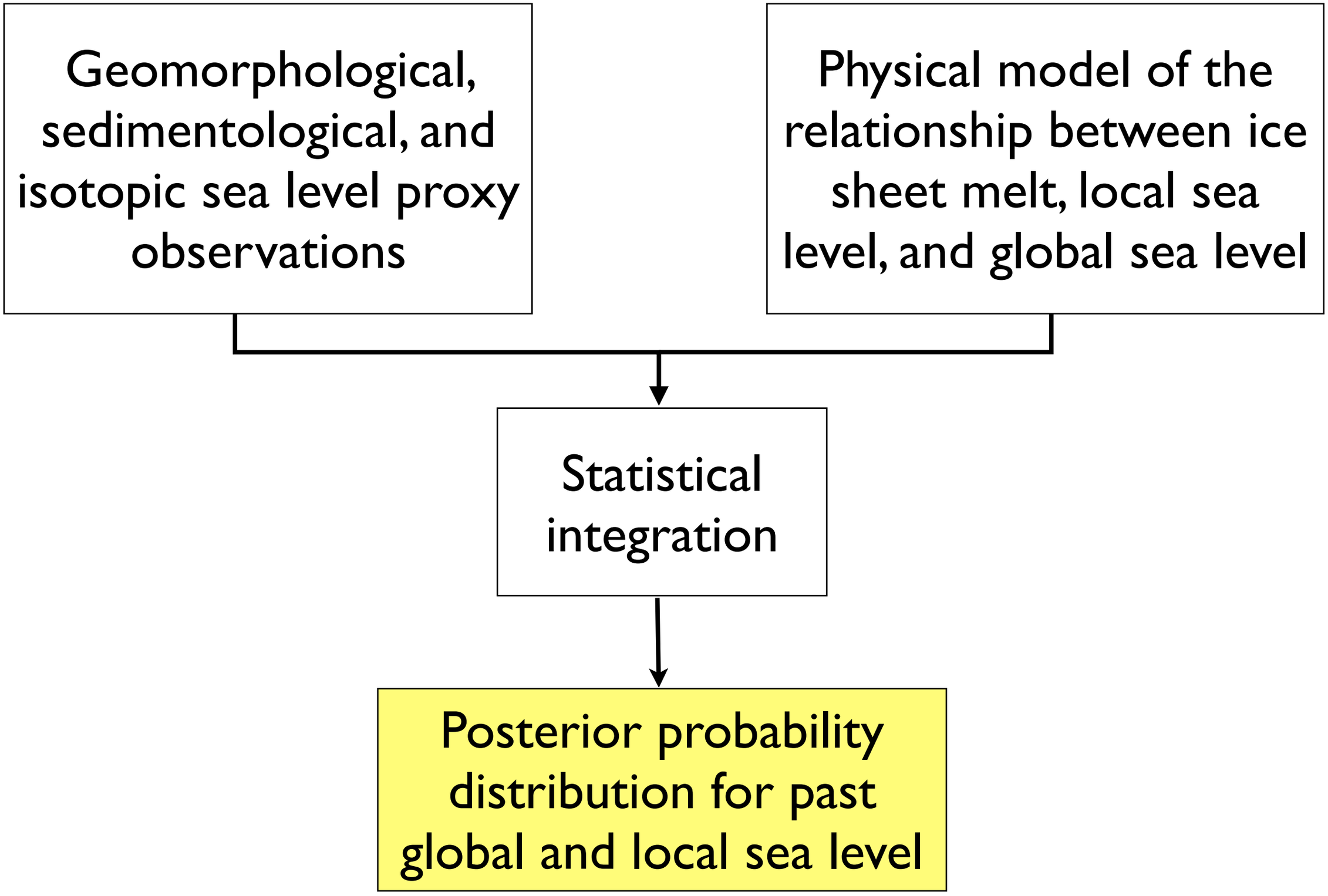
Probability of **"true" ages**, conditional on:

"true" local sea levels,
observed ages,

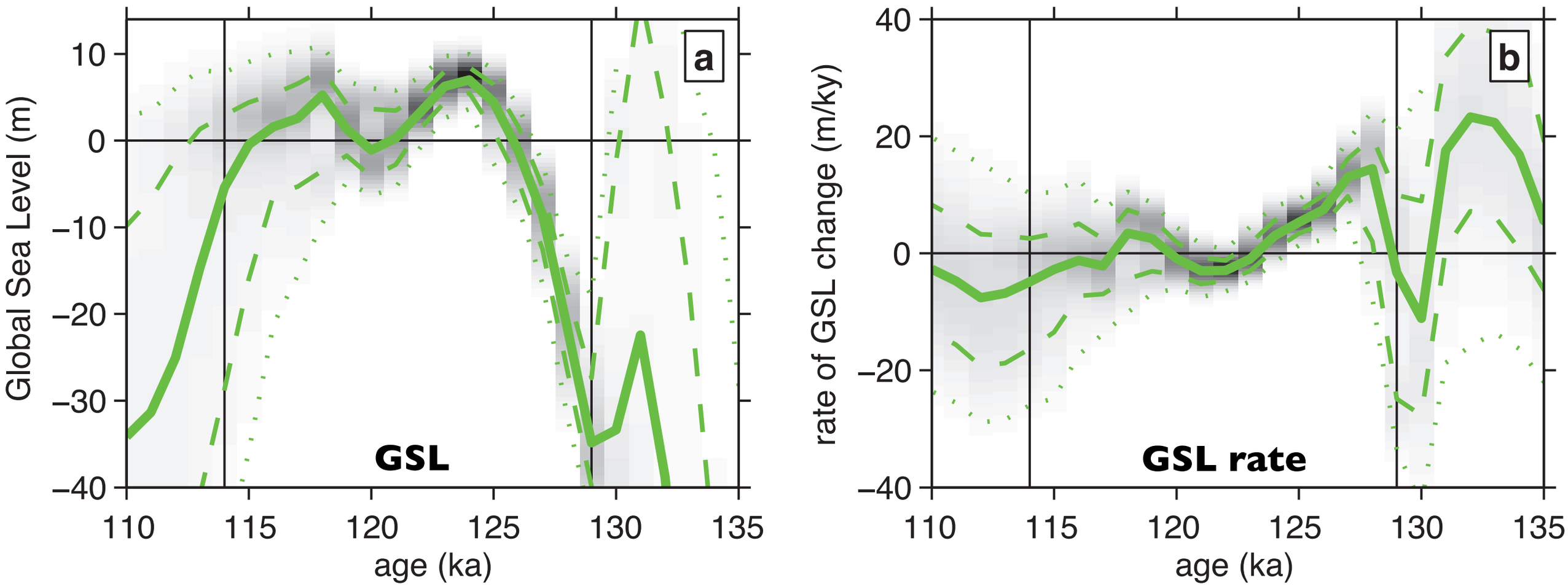
and the physical prior.



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

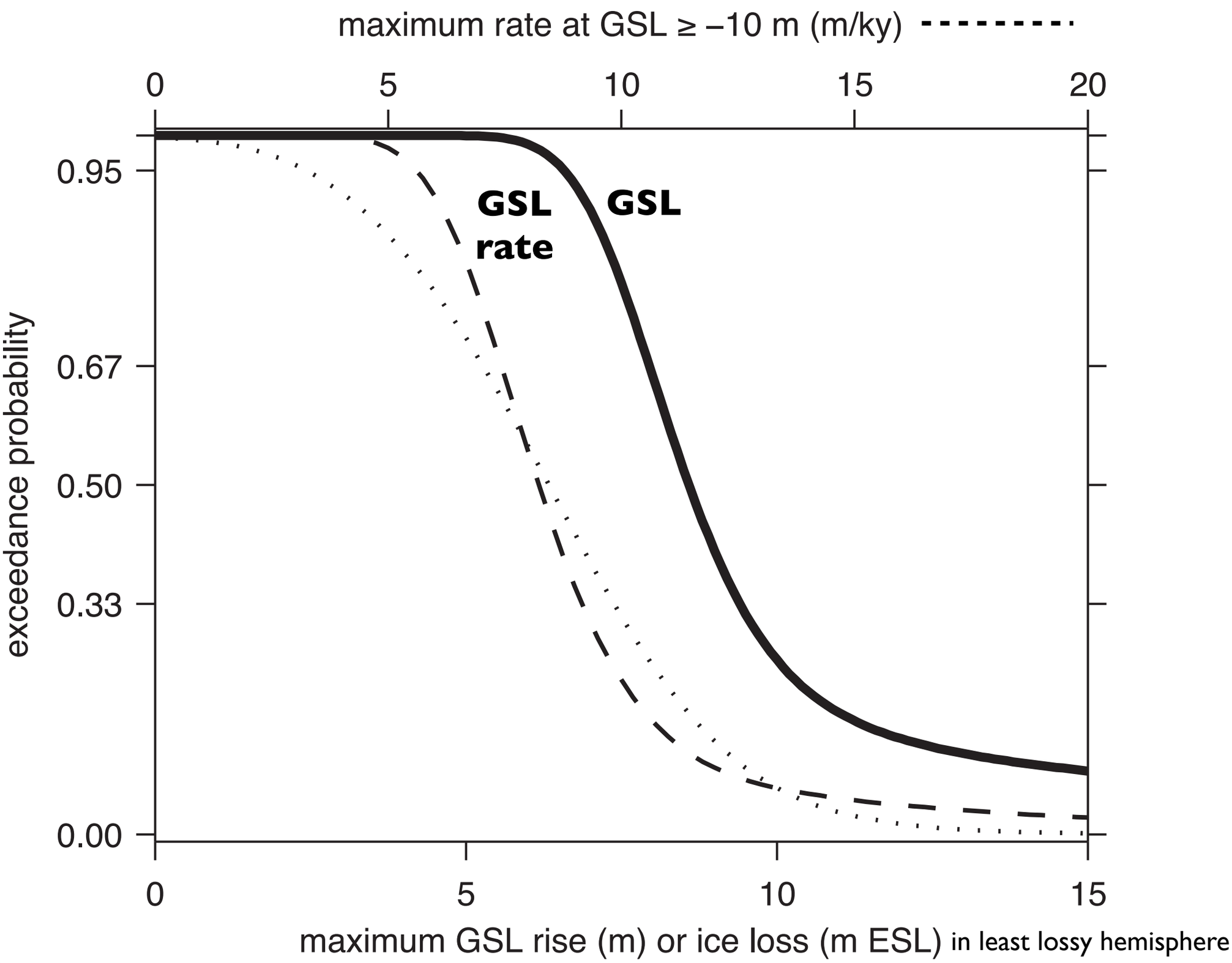


Posterior probability distributions



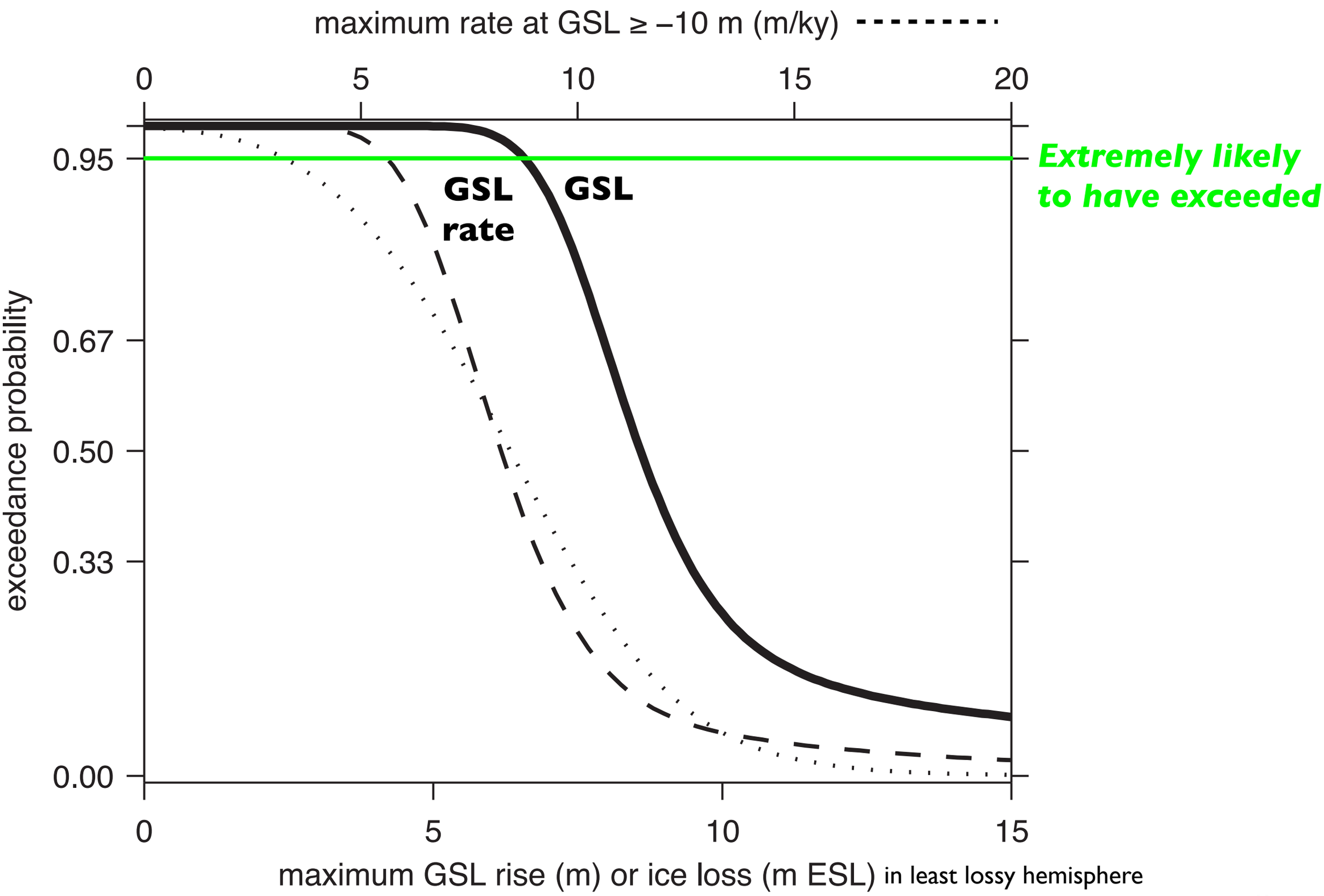
Kopp et al. (2009)

Posterior exceedance levels



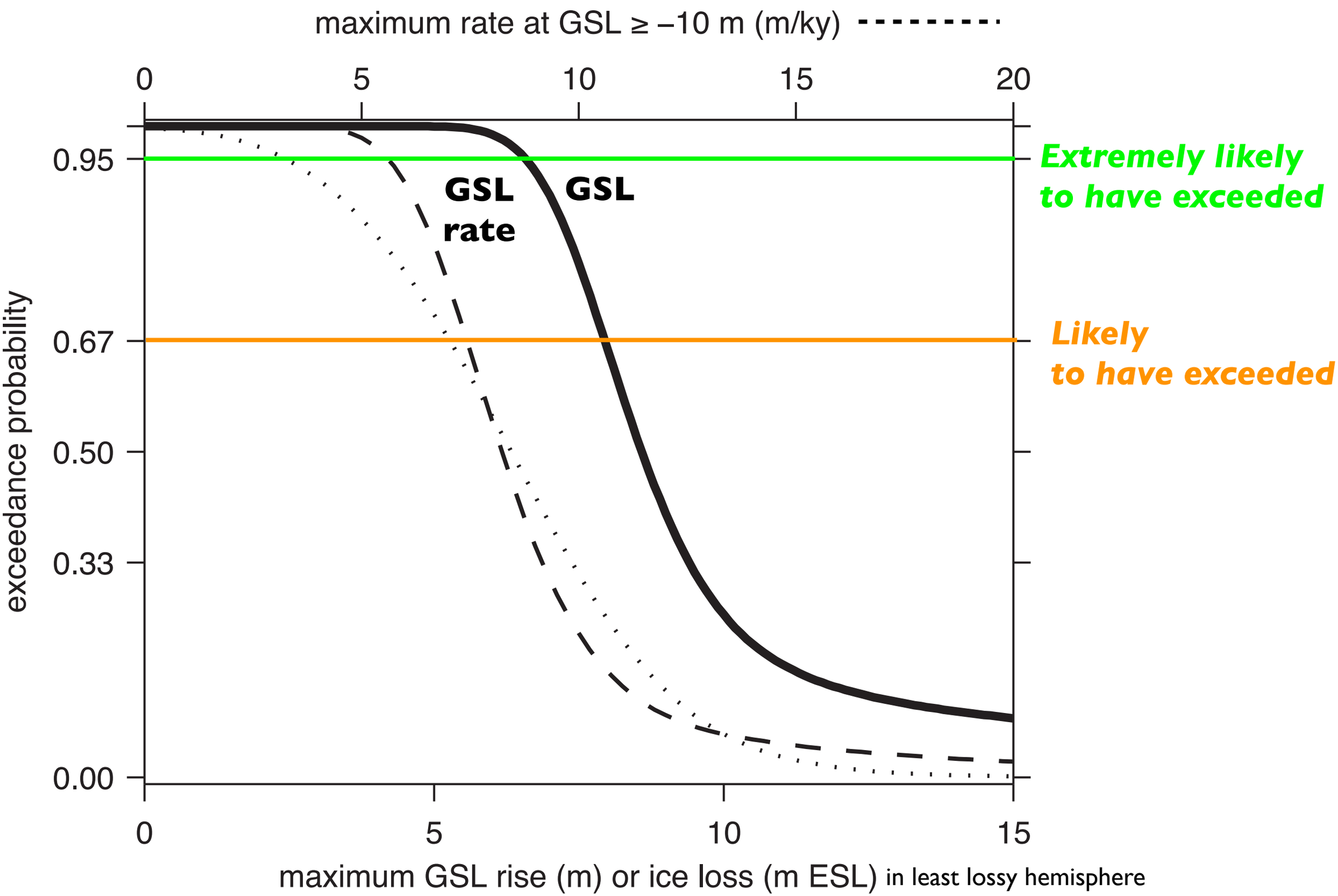
Kopp et al. (2009)

Posterior exceedance levels



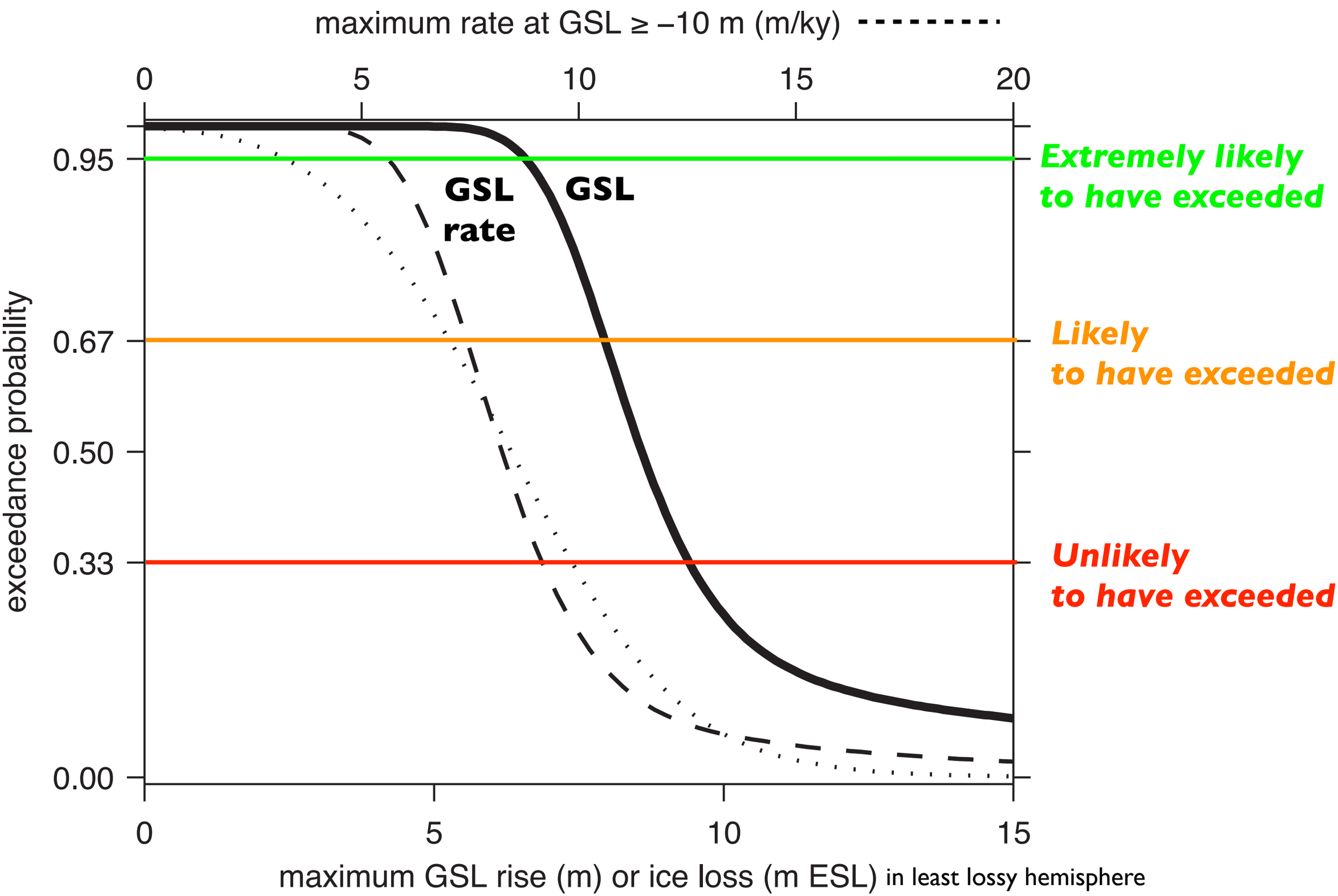
Kopp et al. (2009)

Posterior exceedance levels



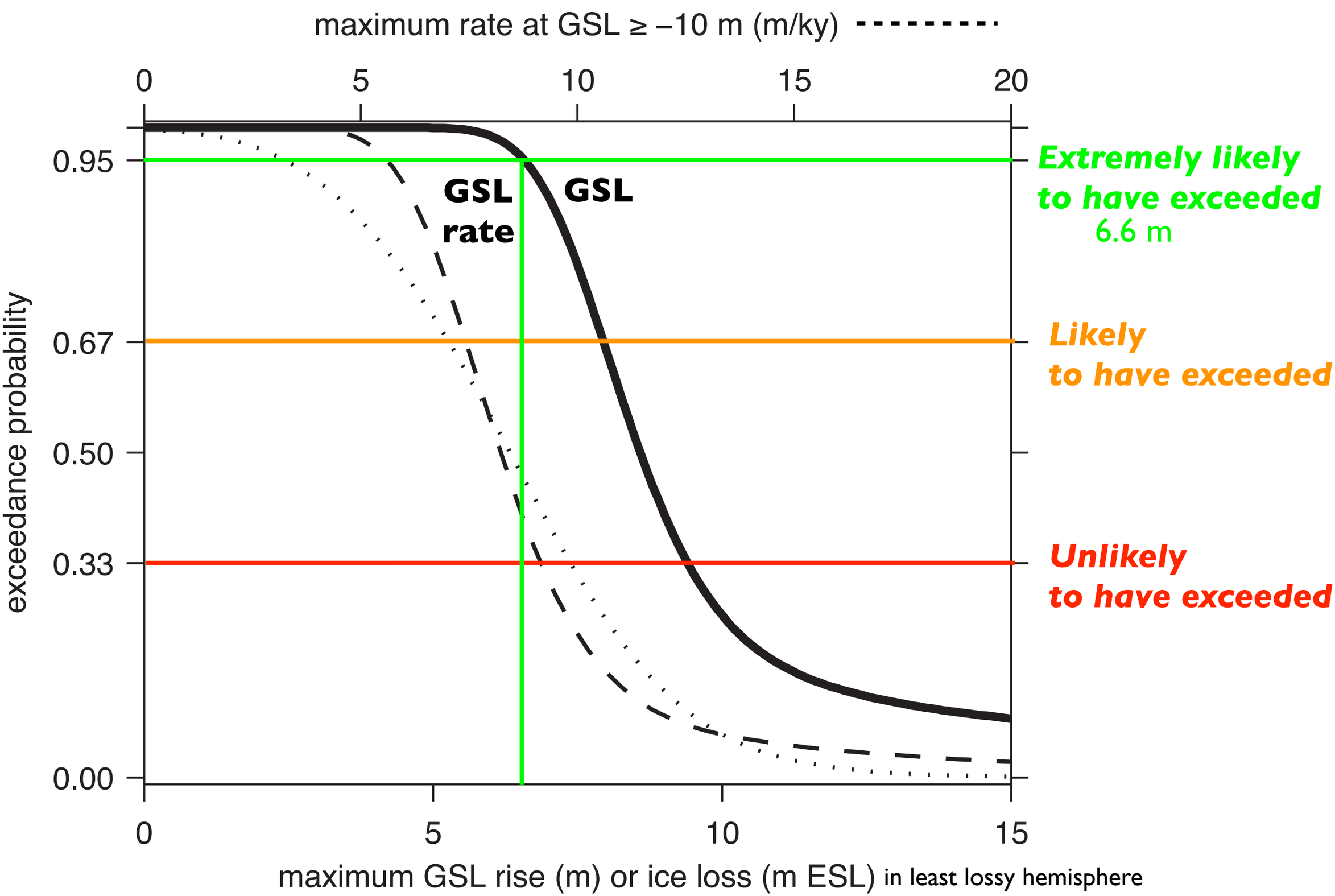
Kopp et al. (2009)

Posterior exceedance levels



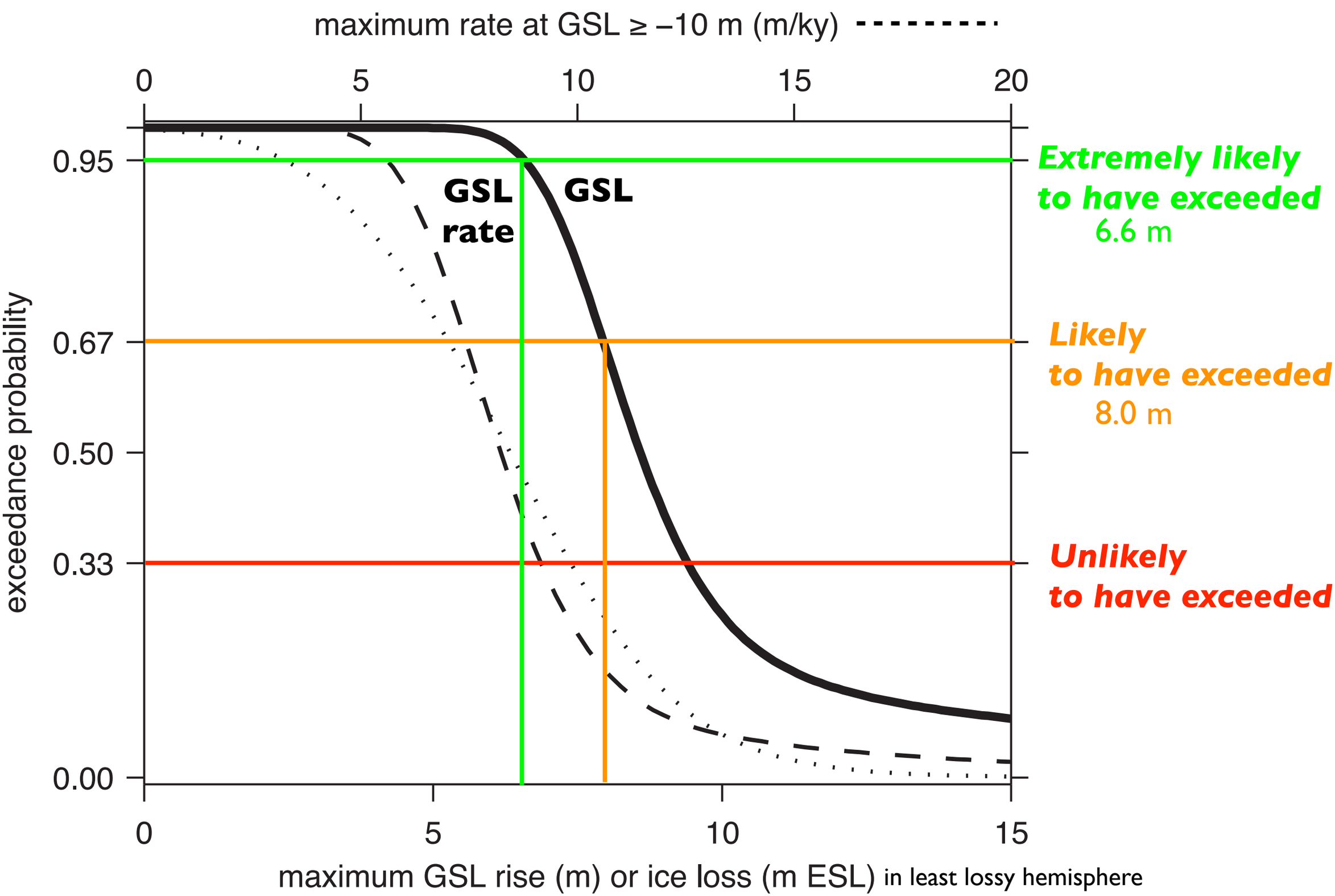
Kopp et al. (2009)

Posterior exceedance levels



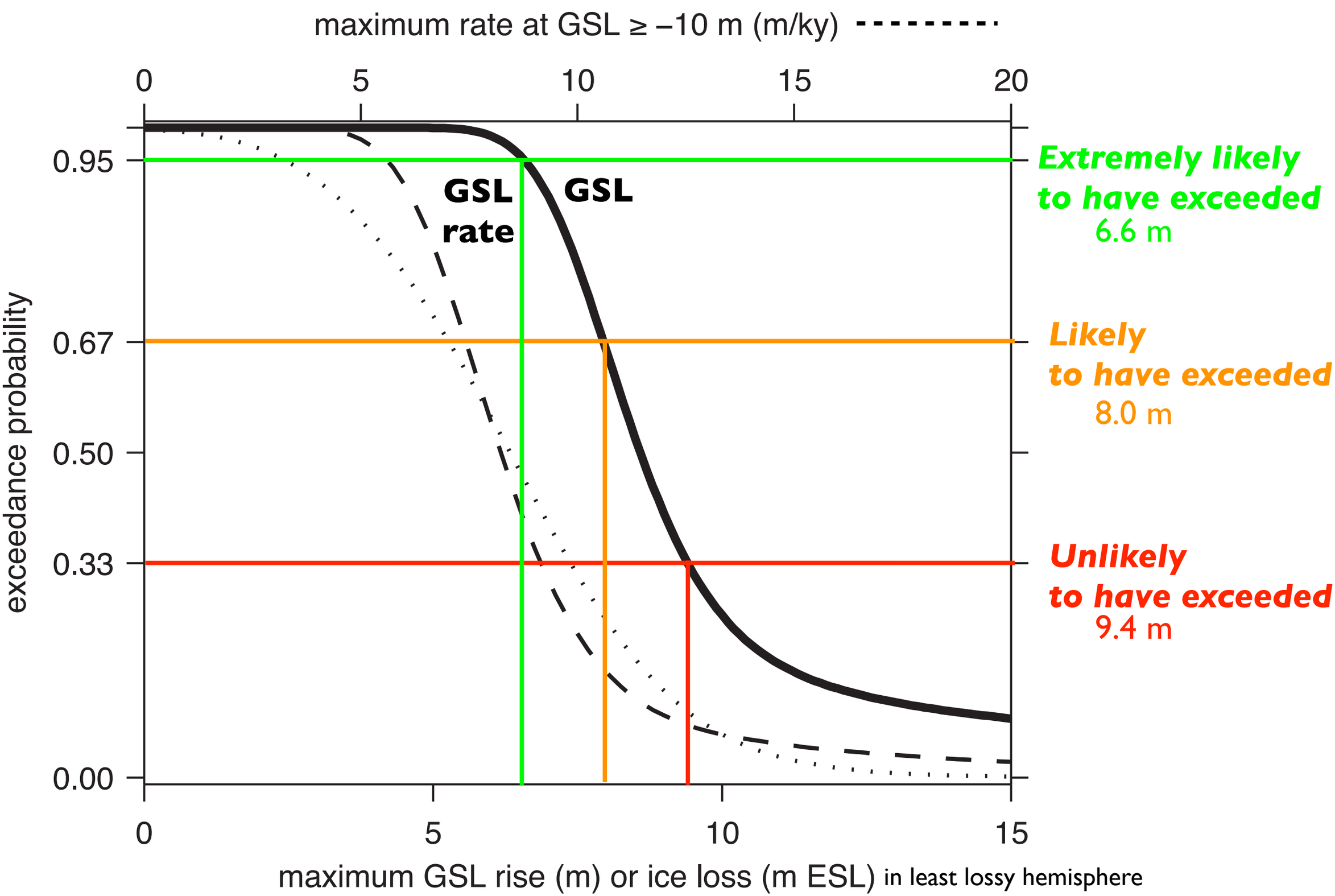
Kopp et al. (2009)

Posterior exceedance levels



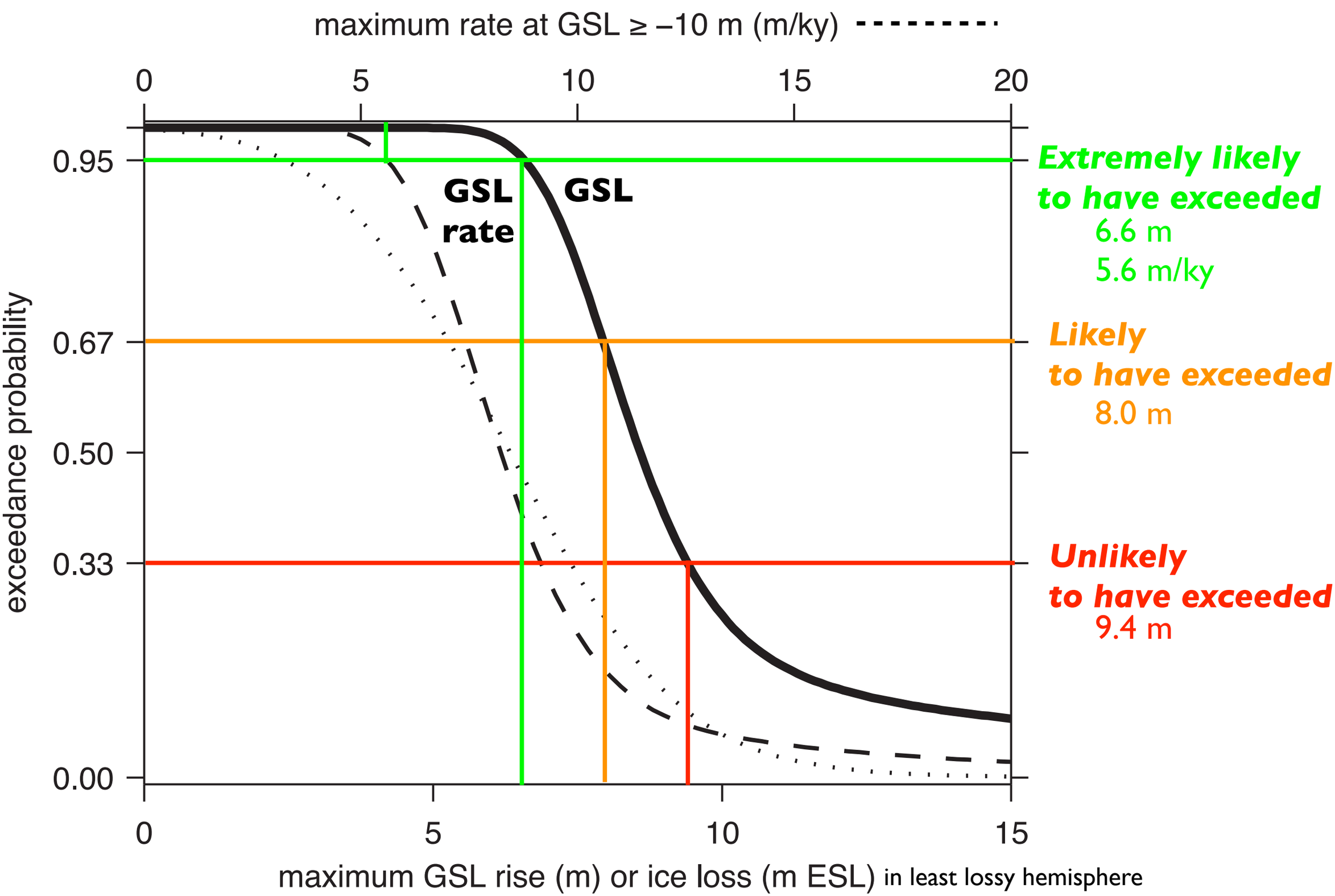
Kopp et al. (2009)

Posterior exceedance levels



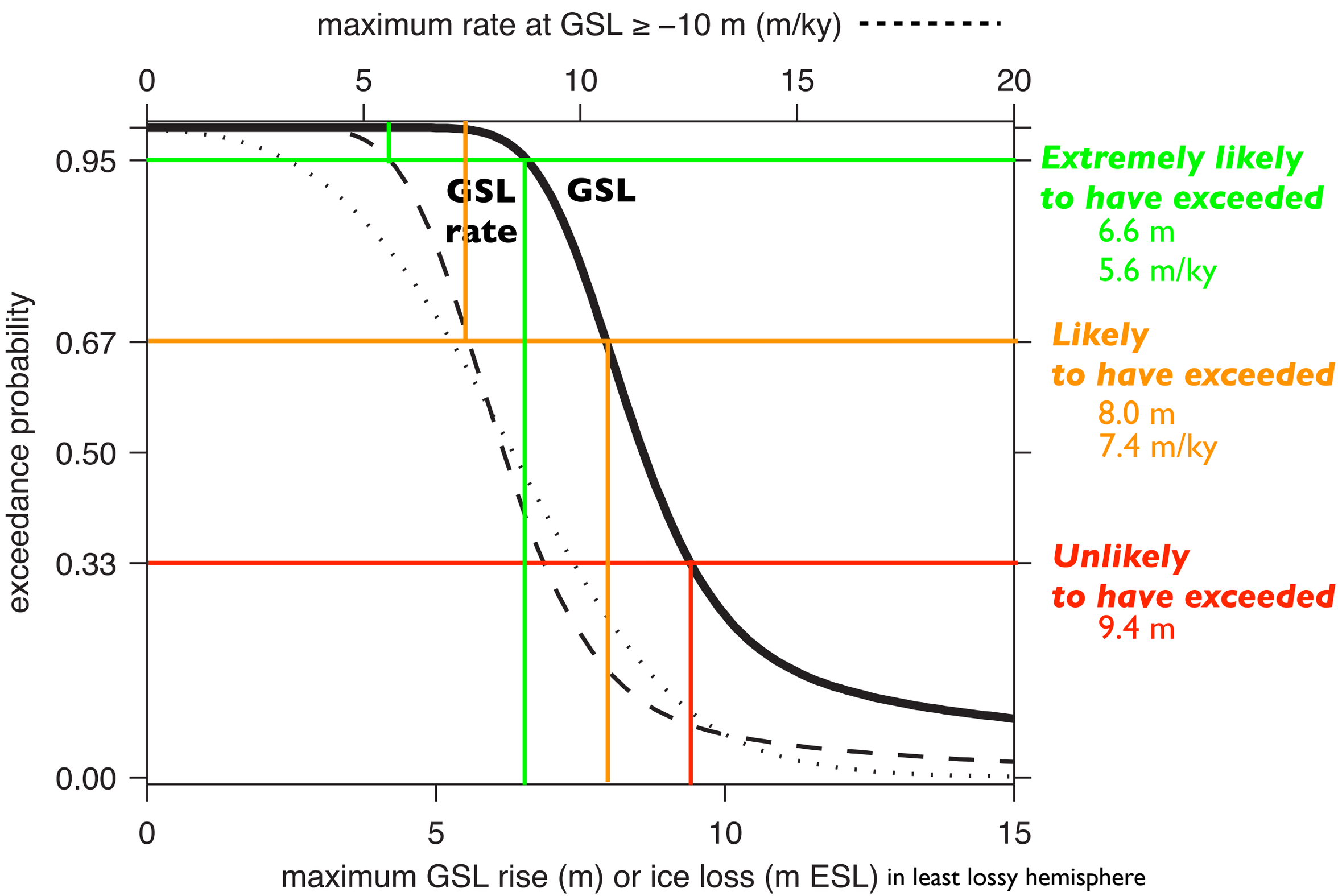
Kopp et al. (2009)

Posterior exceedance levels



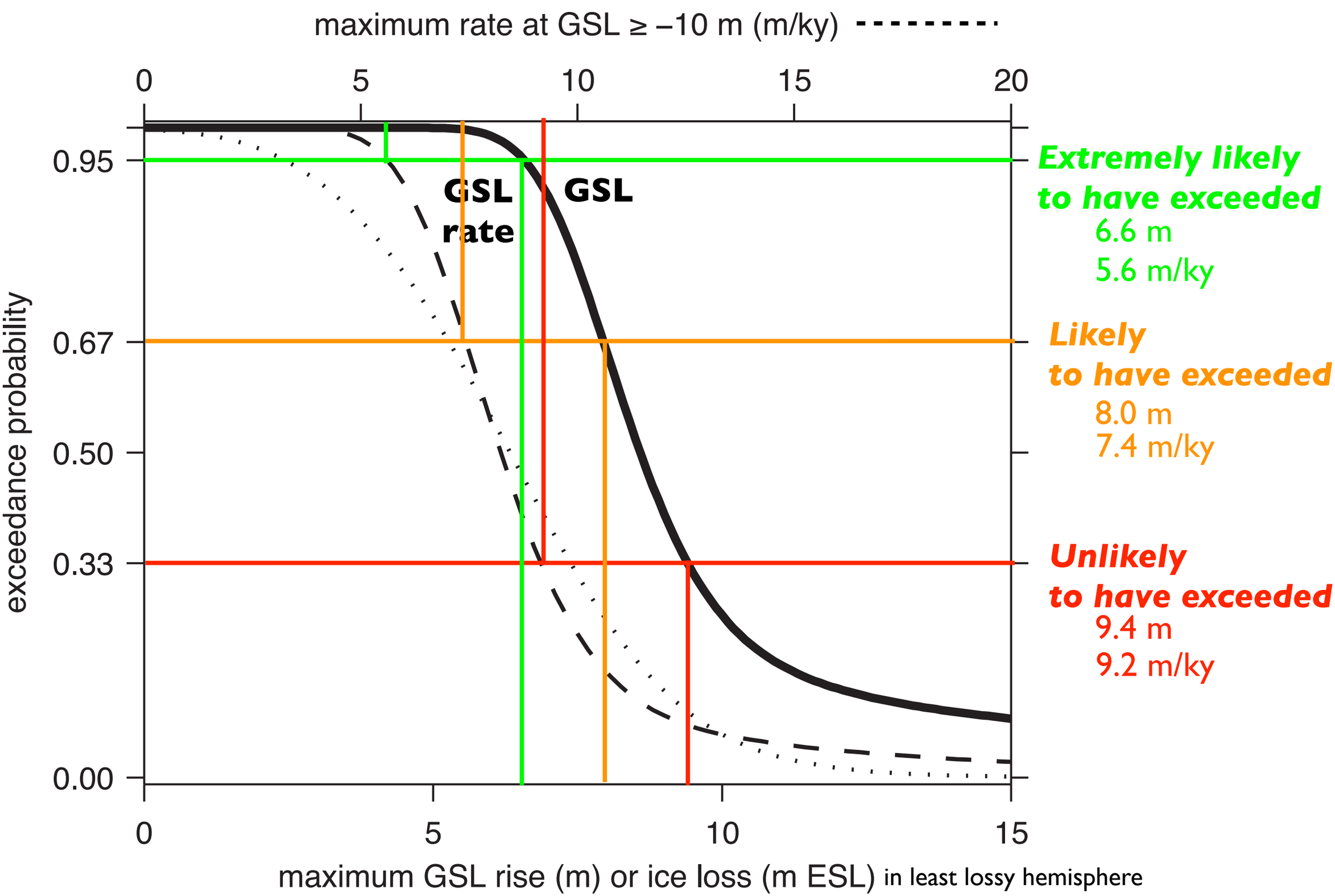
Kopp et al. (2009)

Posterior exceedance levels



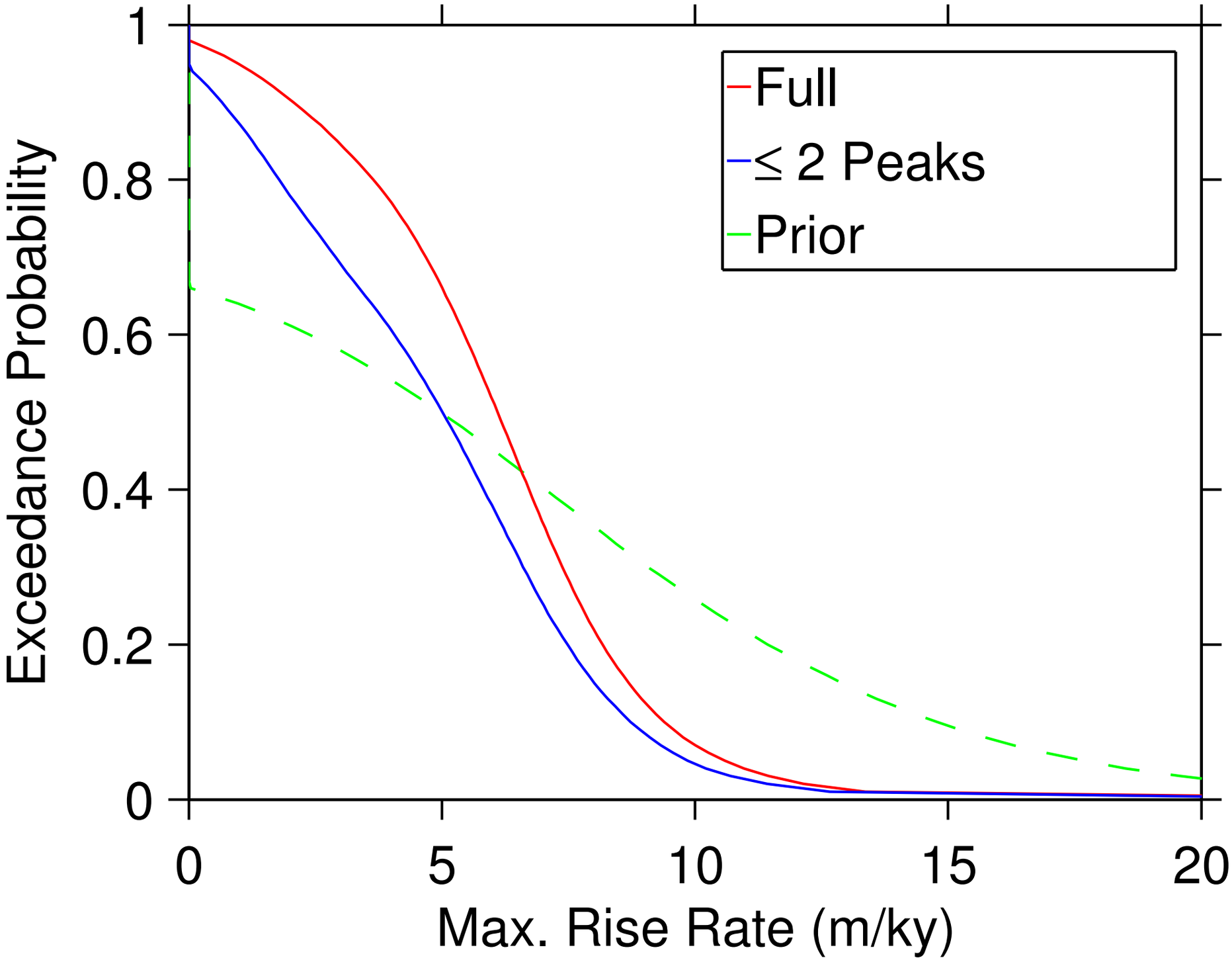
Kopp et al. (2009)

Posterior exceedance levels



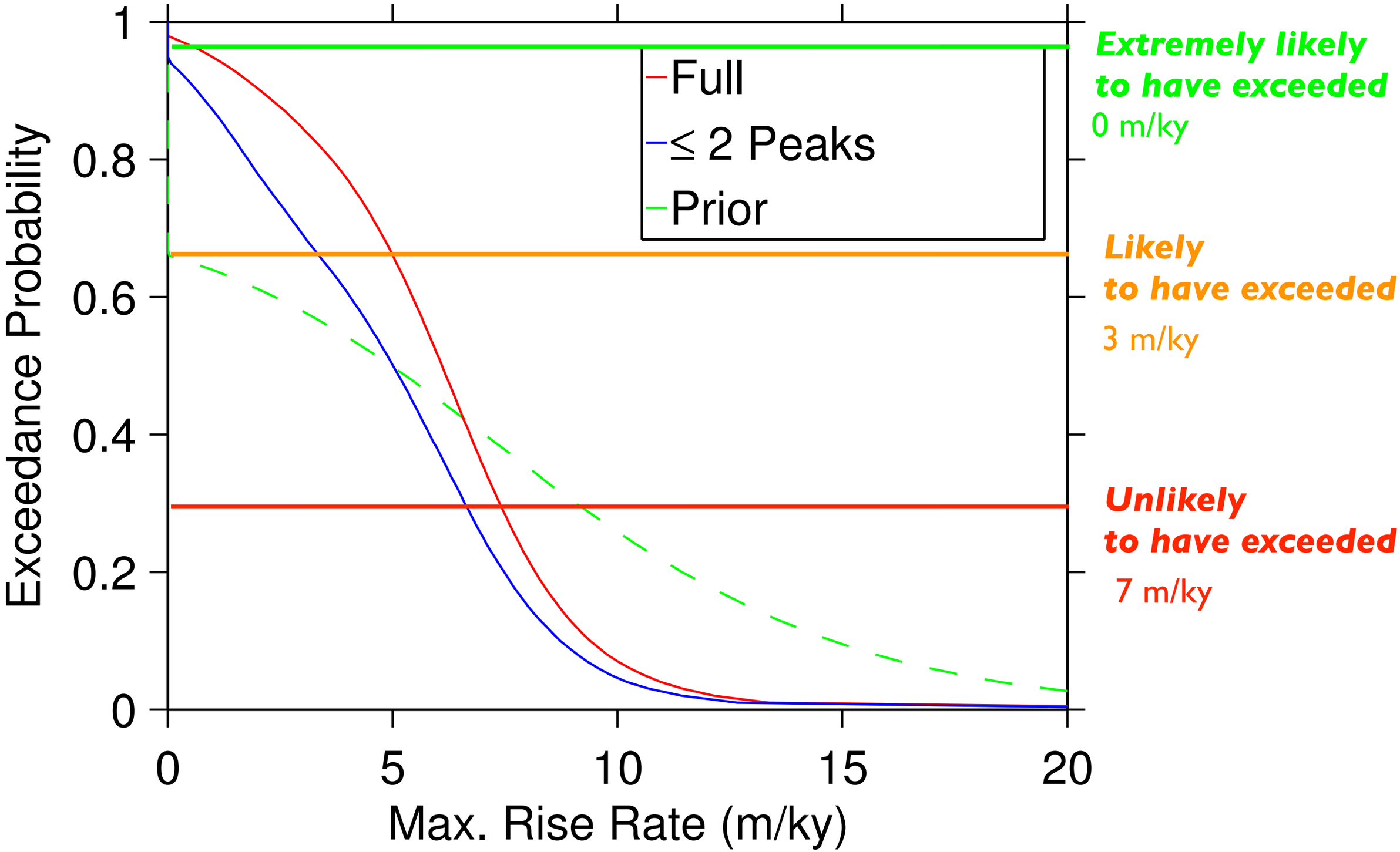
Kopp et al. (2009)

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



Kopp et al. (in sub.)

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

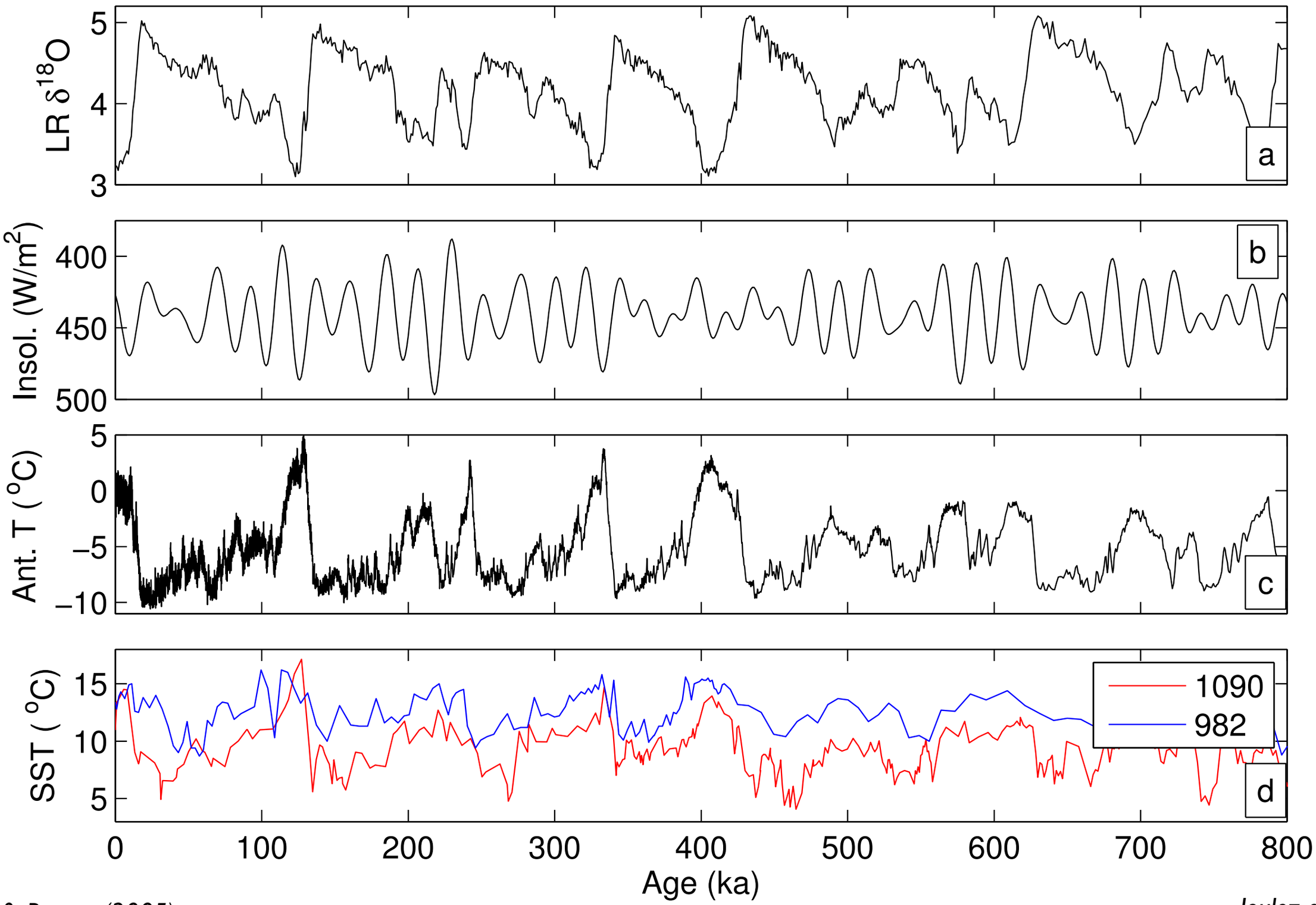


Kopp et al. (in sub.)

Conclusions: Last Interglacial Sea Level

- Despite a fairly modest warming with respect to the present (about 3-5°C in the Arctic, as expected with ~1.5-2.5°C globally), peak LIG global sea level was considerably higher than today (likely above 8.0 m).
- Long term (millennial) GSL rise rate was 2-3 times higher than current annual rates, while shorter term rates could have been faster.
- These high sea level were produced with contributions from both NH and SH ice sheet melt.
- *Within* the LIG, GSL likely rose at a rate between about 3-7 m/ky.
- These results suggest that the equilibrium sea level in a modestly warmer world is significantly higher than today.

One key question: Do internal dynamics vs. external forcing explain interglacial differences?



Lisiecki & Raymo (2005)
Berger & Loute (1991)

Joulez et al. (2007)
Martinez-Garcia et al. (2009)
Lawrence et al. (2009)

Summary

- Humans are shifting the Earth's climate into a state novel for our species, though familiar to the planet.
- The potential sea level hazard from melting grounded ice is large but geographically variable.
- The sea level risk for ice sheets is difficult to model; geological and historical records provide a complementary approach.
- But to leverage these records, we must see through a host of uncertainties.