Uncertainties and risks of regional sea-level change: Past, present and future

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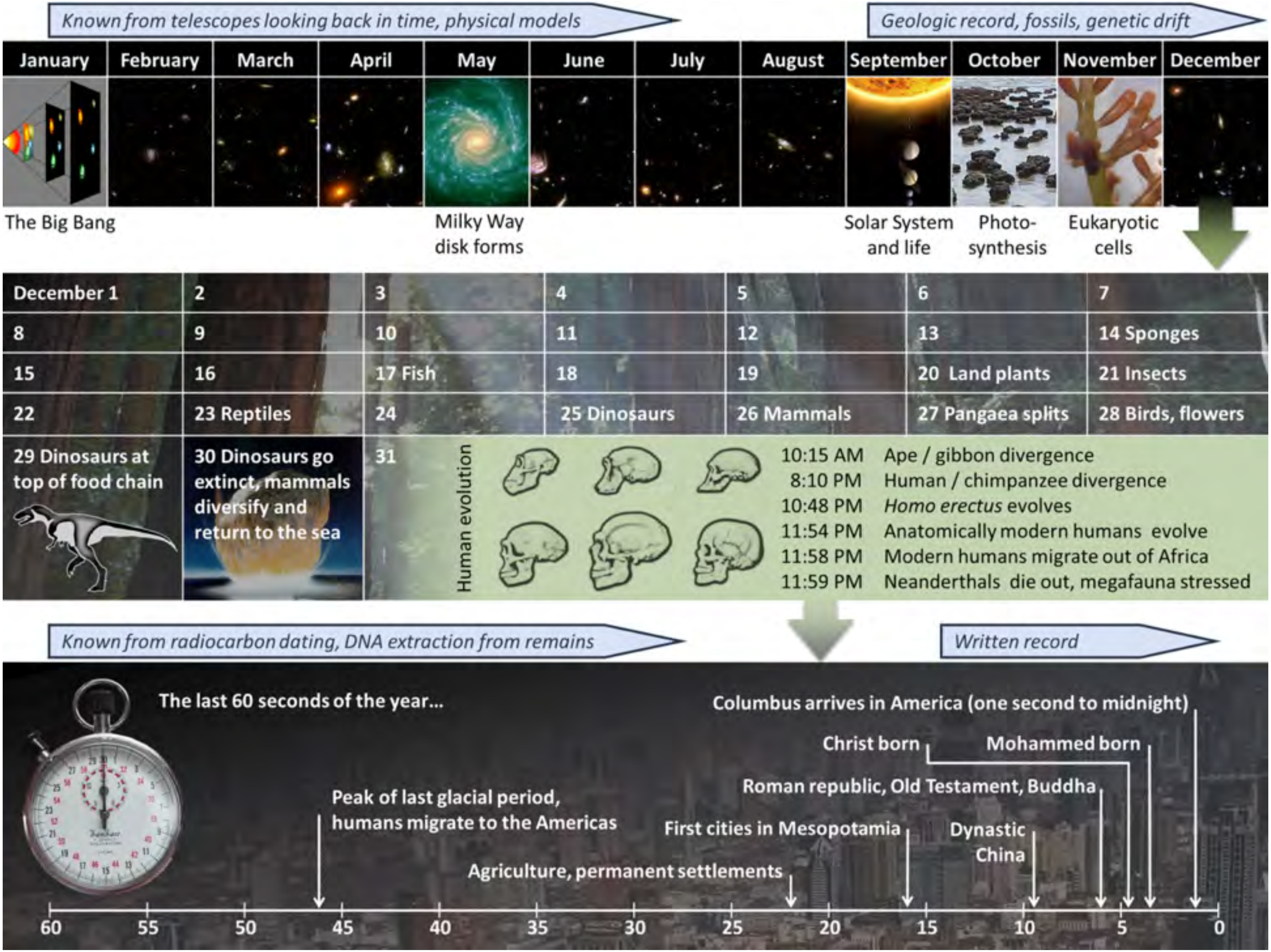
Pardee Center for the Longer-Range Future, Boston University
10 February 2014



Known from telescopes looking back in time, physical models
Geologic record, fossils, genetic drift
January
February
March
April
May
June
July
August
September
October
November
December
The Big Bang
Milky Way disk forms
Solar System and life
Photo-synthesis
Eukaryotic cells
December 1
2
3
4
5
6
7
8
9
10
11
12
13
14 Sponges
15
16
17 Fish
18
19
20 Land plants
21 Insects
22
23 Reptiles
24
25 Dinosaurs
26 Mammals
27 Pangaea splits
28 Birds, flowers
29 Dinosaurs at top of food chain
30 Dinosaurs go extinct, mammals diversify and return to the sea
31
Human evolution
10:15 AM Ape / gibbon divergence
8:10 PM Human / chimpanzee divergence
10:48 PM Homo erectus evolves
11:54 PM Anatomically modern humans evolve
11:58 PM Modern humans migrate out of Africa
11:59 PM Neanderthals die out, megafauna stressed
Known from radiocarbon dating, DNA extraction from remains
Written record
The last 60 seconds of the year...
Columbus arrives in America (one second to midnight)
Christ born
Mohammed born
Roman republic, Old Testament, Buddha
Peak of last glacial period, humans migrate to the Americas
First cities in Mesopotamia
Dynastic China
Agriculture, permanent settlements
60
55
50
45
40
35
30
25
20
15
10
5
0

Wikipedia

Ship Bottom, NJ

→ N

2008

(Courtesy Prof. Ken Miller)

The Philadelphia Inquirer

philly.com

Wednesday, Oct. 31, 2012 ★ 2012 Pulitzer Prize Winner ★ $1

Death Toll Hurricane claims 50 on East Coast.

New York City Devastating blow cripples Big Apple.

Powerless Fallen trees leave millions in dark.

Swath of Destruction

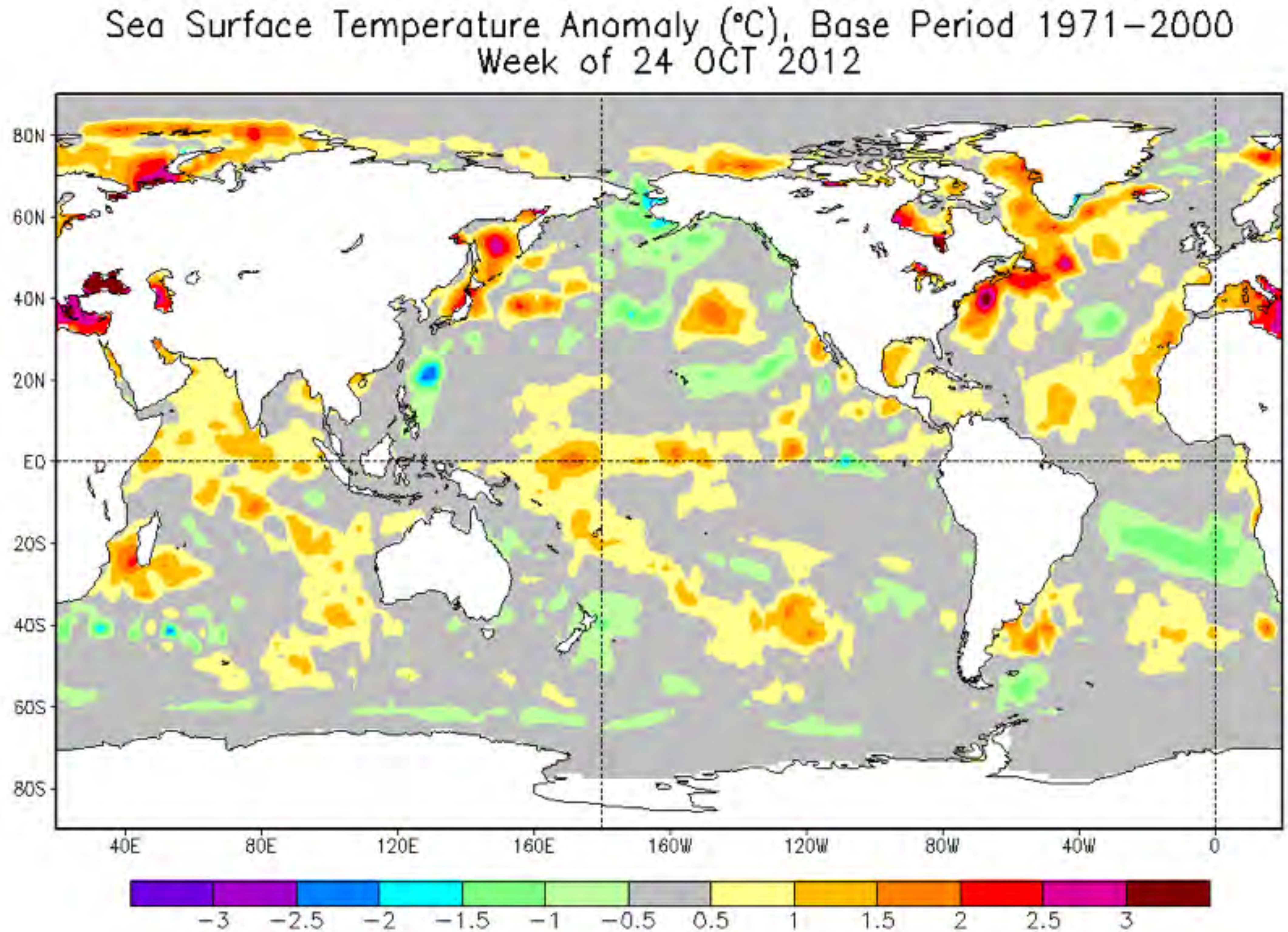
Deluged Shore towns face daunting cleanup

N ←

October 31, 2012

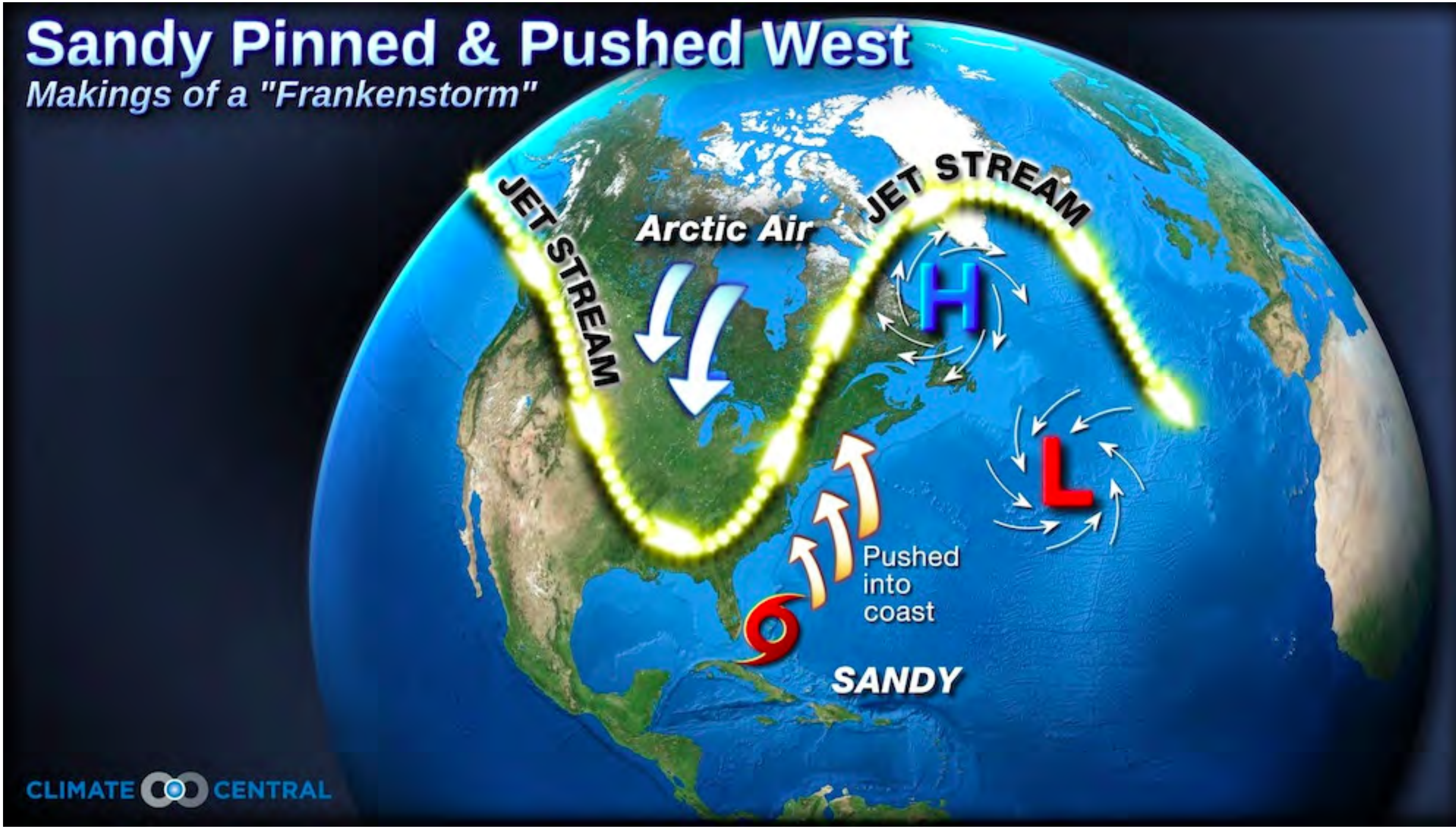
Above average sea surface temperatures provided fuel for Sandy

(Oct. 21, 2012, difference from Oct. average of 1971-2000)

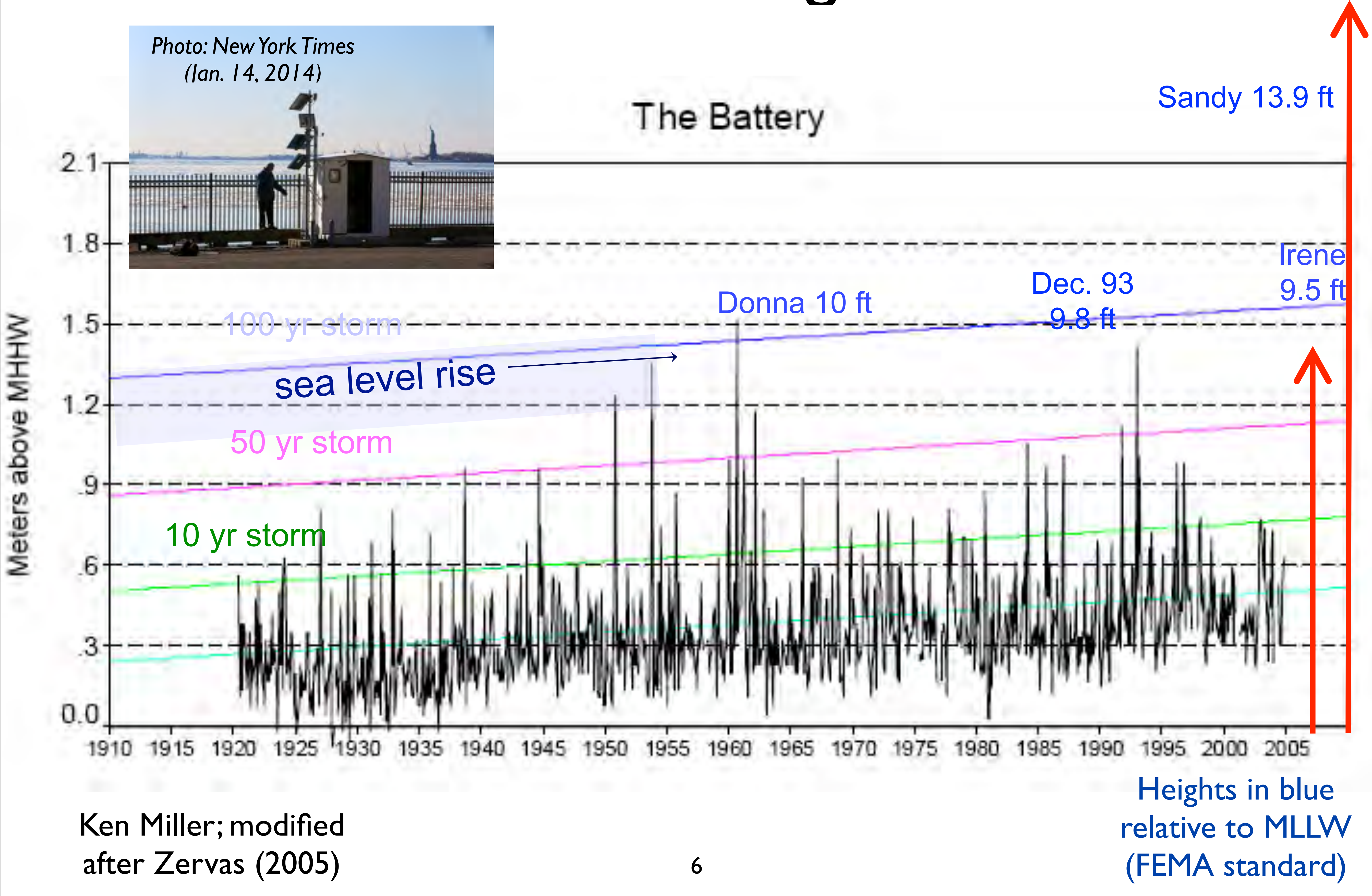


Source: NOAA NCDC

Low Arctic summer sea ice possibly tied to "blocking high" over Greenland

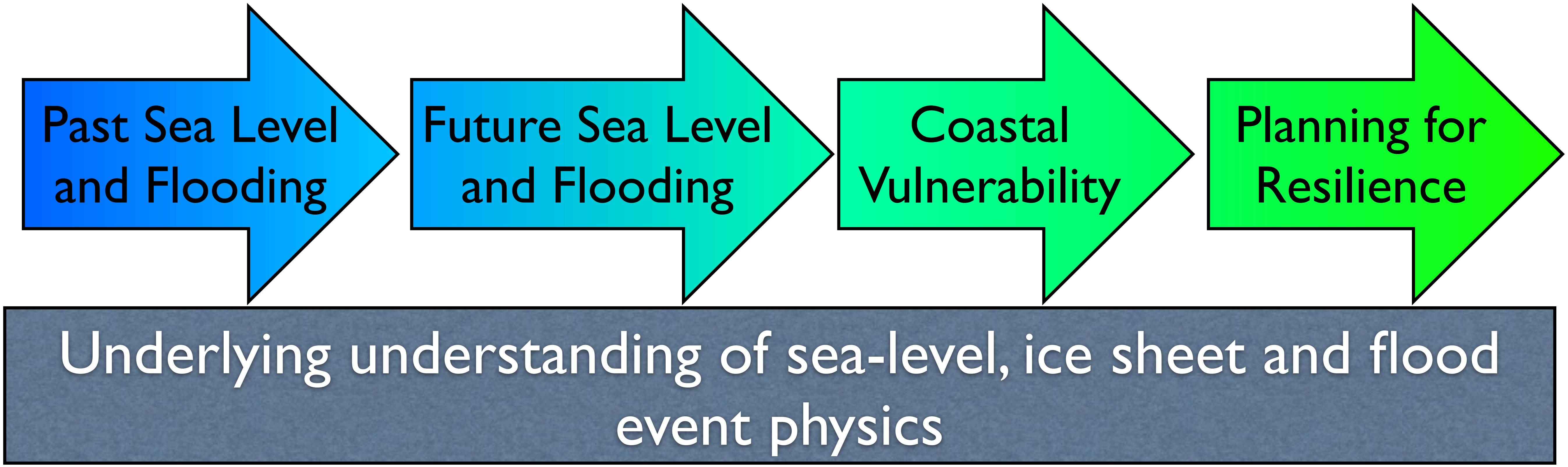


Storm surges take place in a context of sea-level change



Ken Miller; modified after Zervas (2005)

The coastal impacts, vulnerability and adaptation knowledge chain

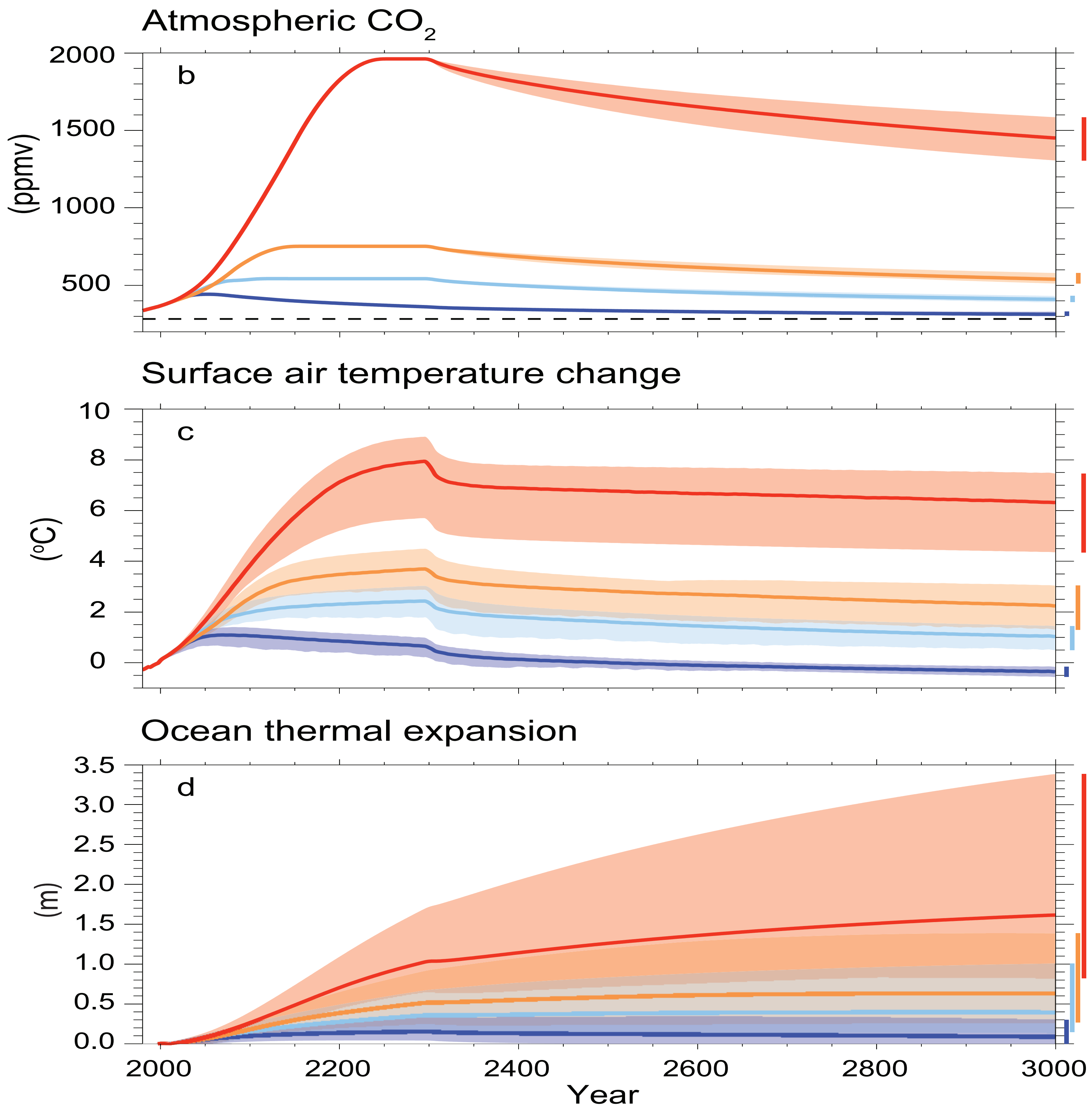


Roadmap

- What controls global and local sea-level change?
- How can we use our understanding of sea-level physics to interpret records of past and present changes, and what do they tell us for the future?
- How can we synthesize multiple lines of knowledge to assess sea-level change risks?
- What are the implications of sea-level change risk for flood risk?
- How might we manage with it?

Factors controlling global and local sea-level change

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



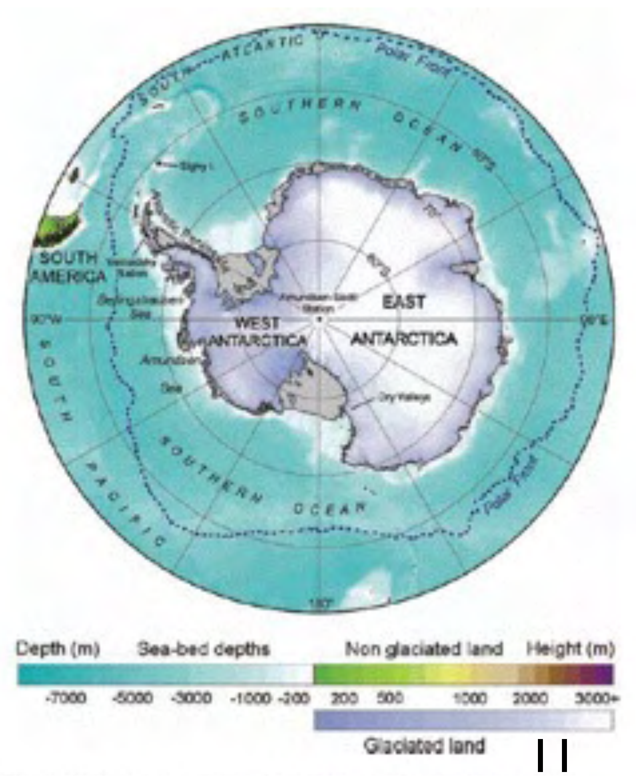
Compare observed thermal expansion of about 1.1 ± 0.3 mm/yr from 1993–2010

Collins et al. (2013)

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 & 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

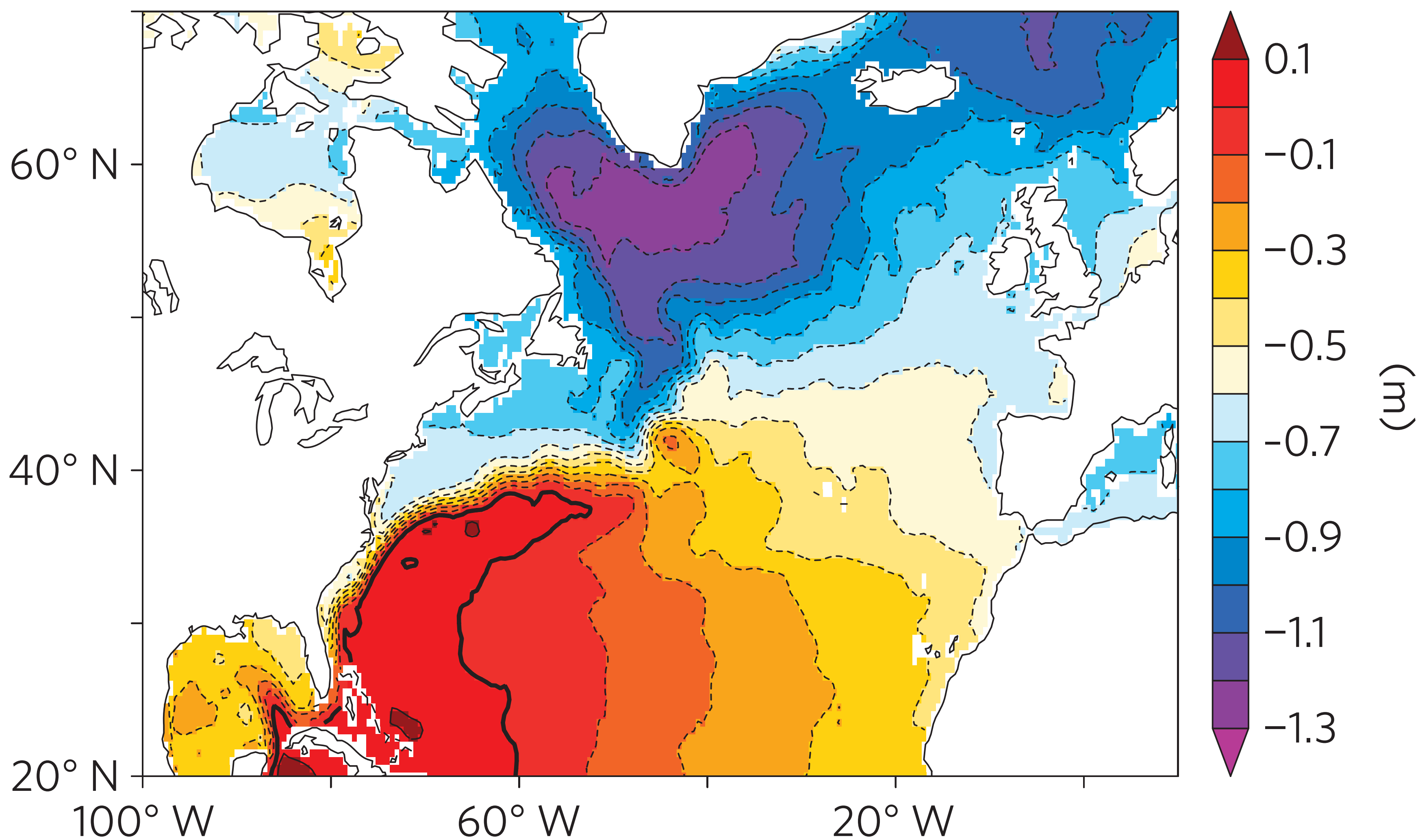


Maps by P. Fretwell (British Antarctic Survey)

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

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



SSH, 1992-2002

The sea is higher off Bermuda than off the northeastern U.S. by about 2 feet because of atmosphere and ocean dynamics that could weaken over the century.

Yin et al. (2009)

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

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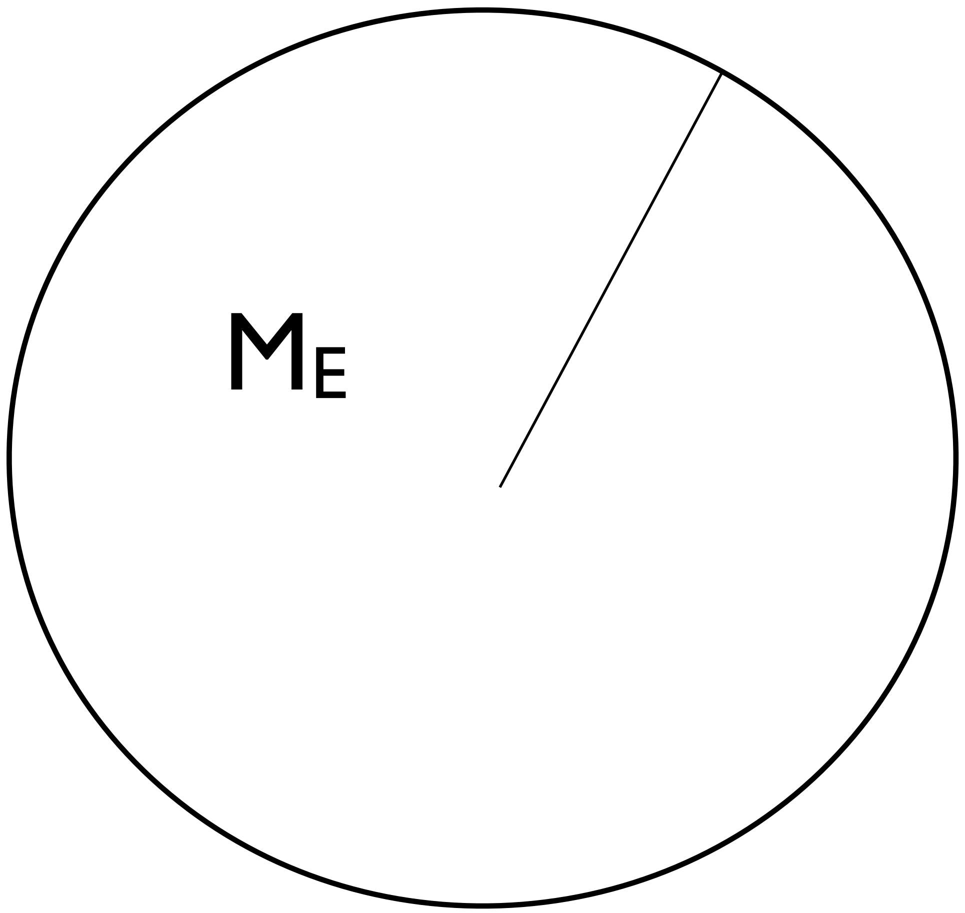

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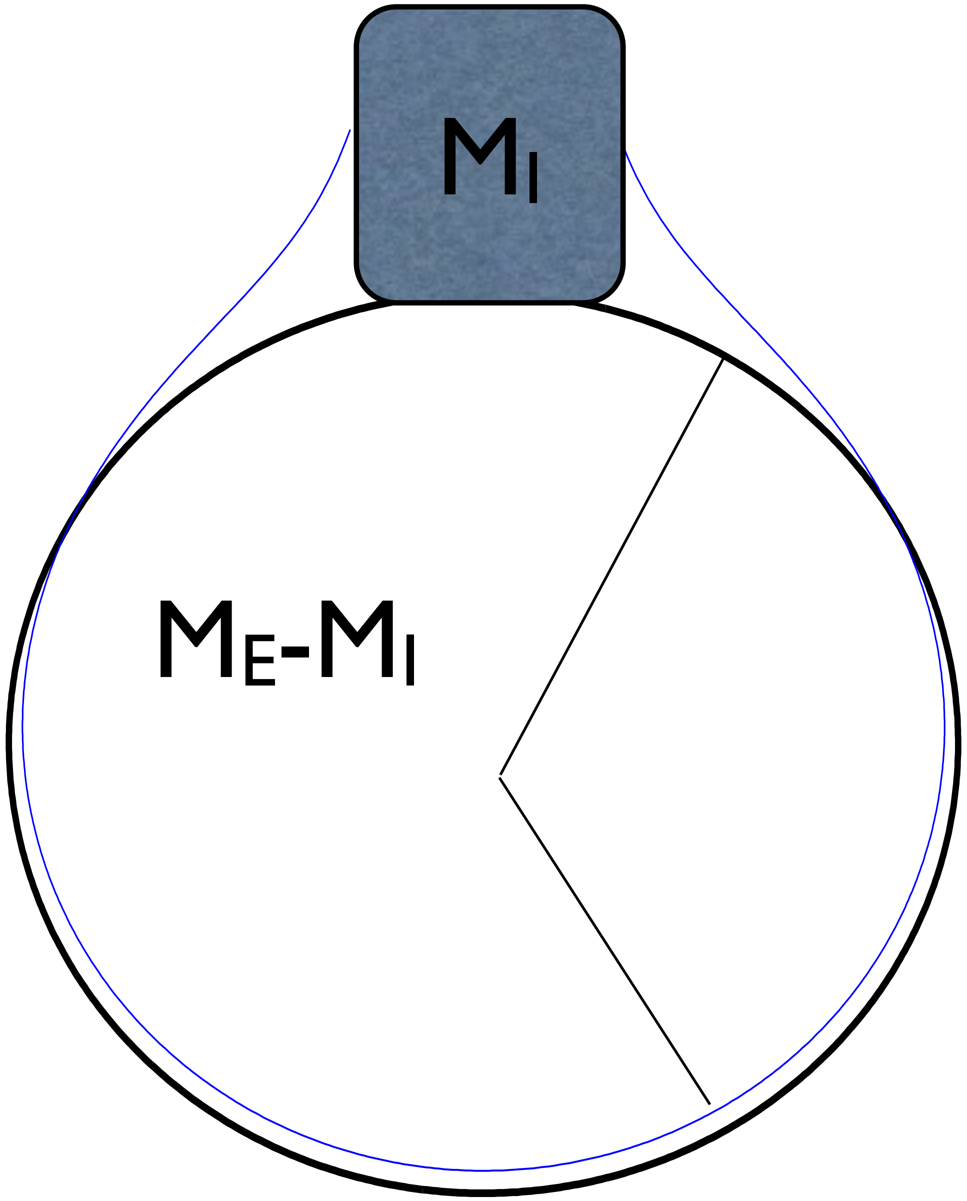

Not to scale!

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

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

- Ocean dynamic effects
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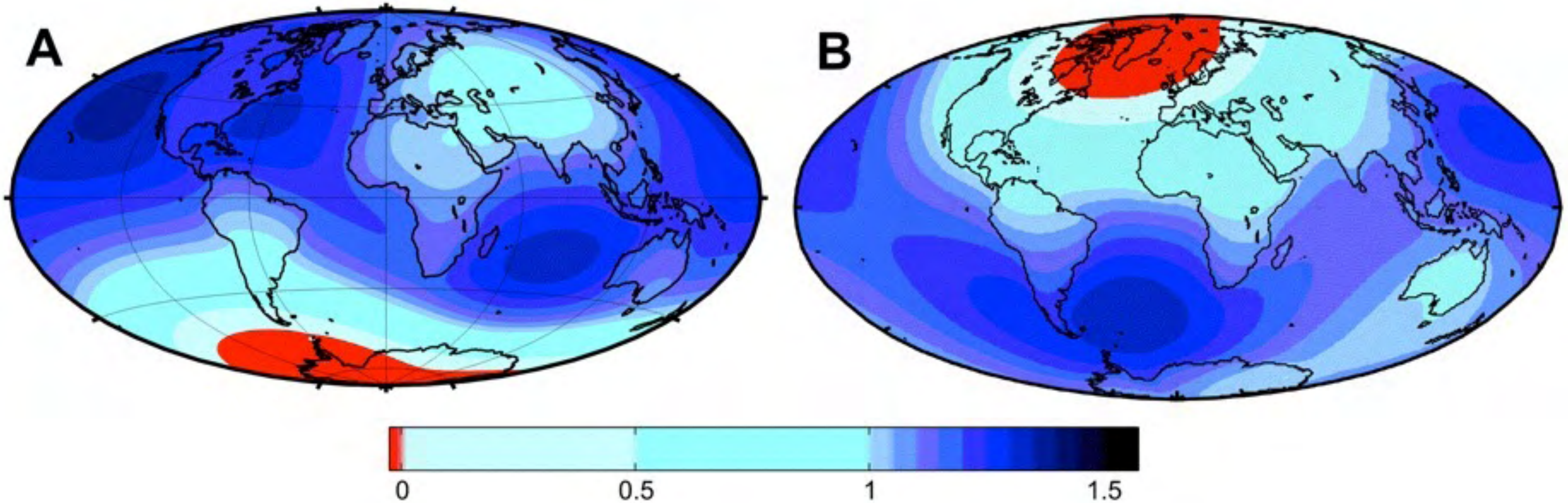
Static-Equilibrium Fingerprints of Greenland and WAIS melting, per meter GSL rise

West Antarctica *Greenland*



Mitrovica et al. (2011)

Global Sea Level change
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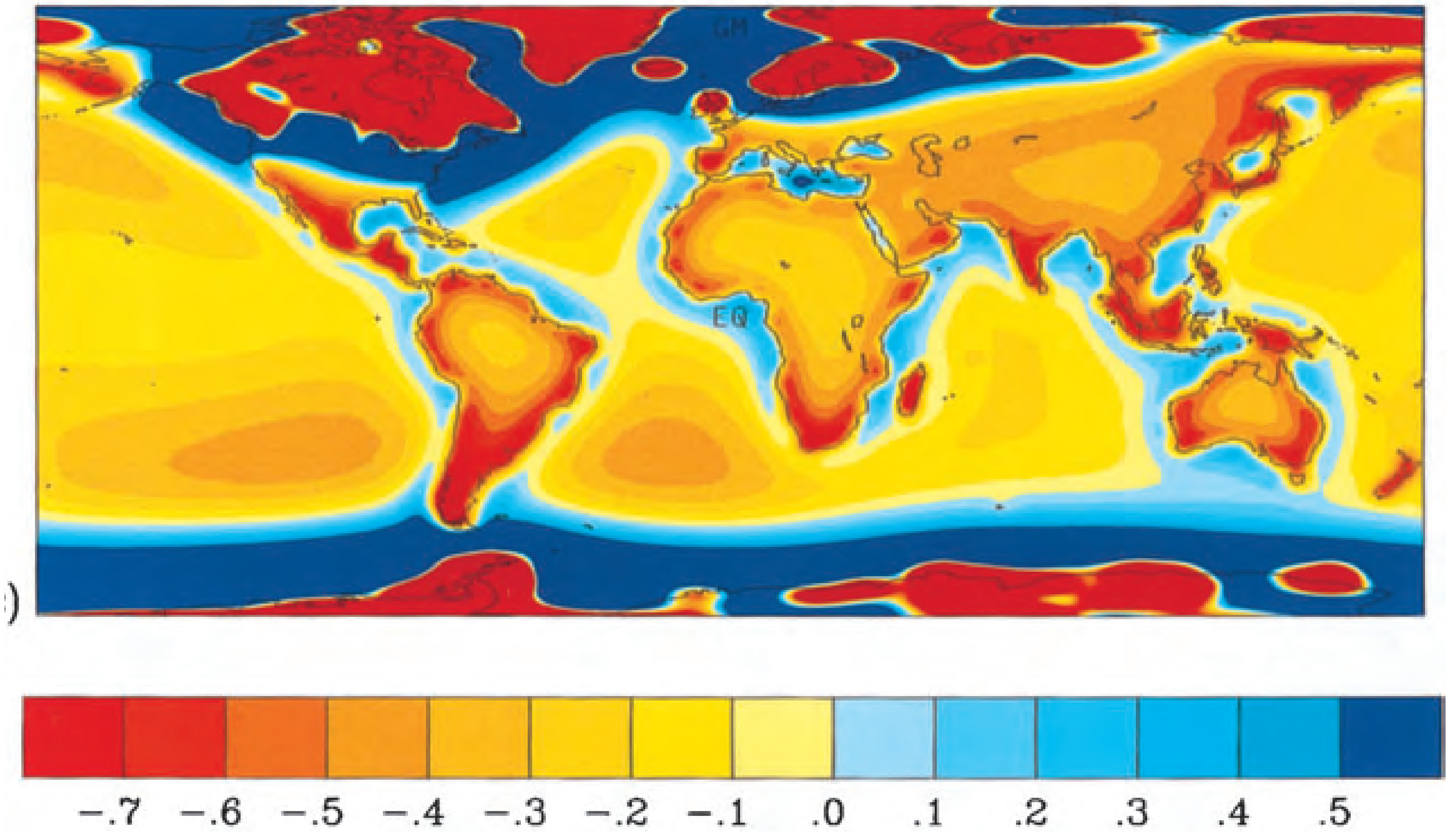
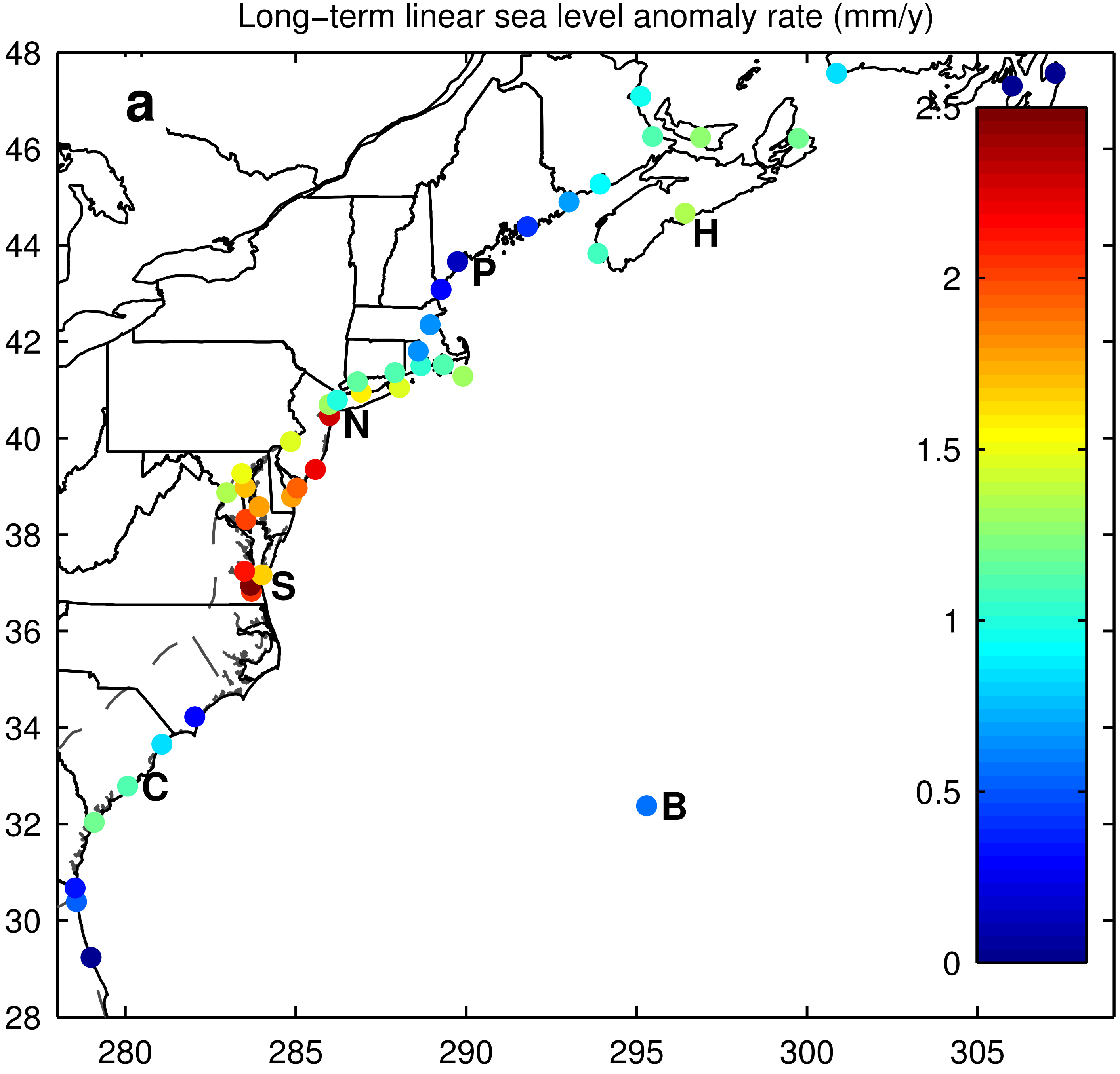


Sea-level rise due to GIA (mm/y)

Mitrovica et al., 2001

Effects of GIA and compaction in eastern North America



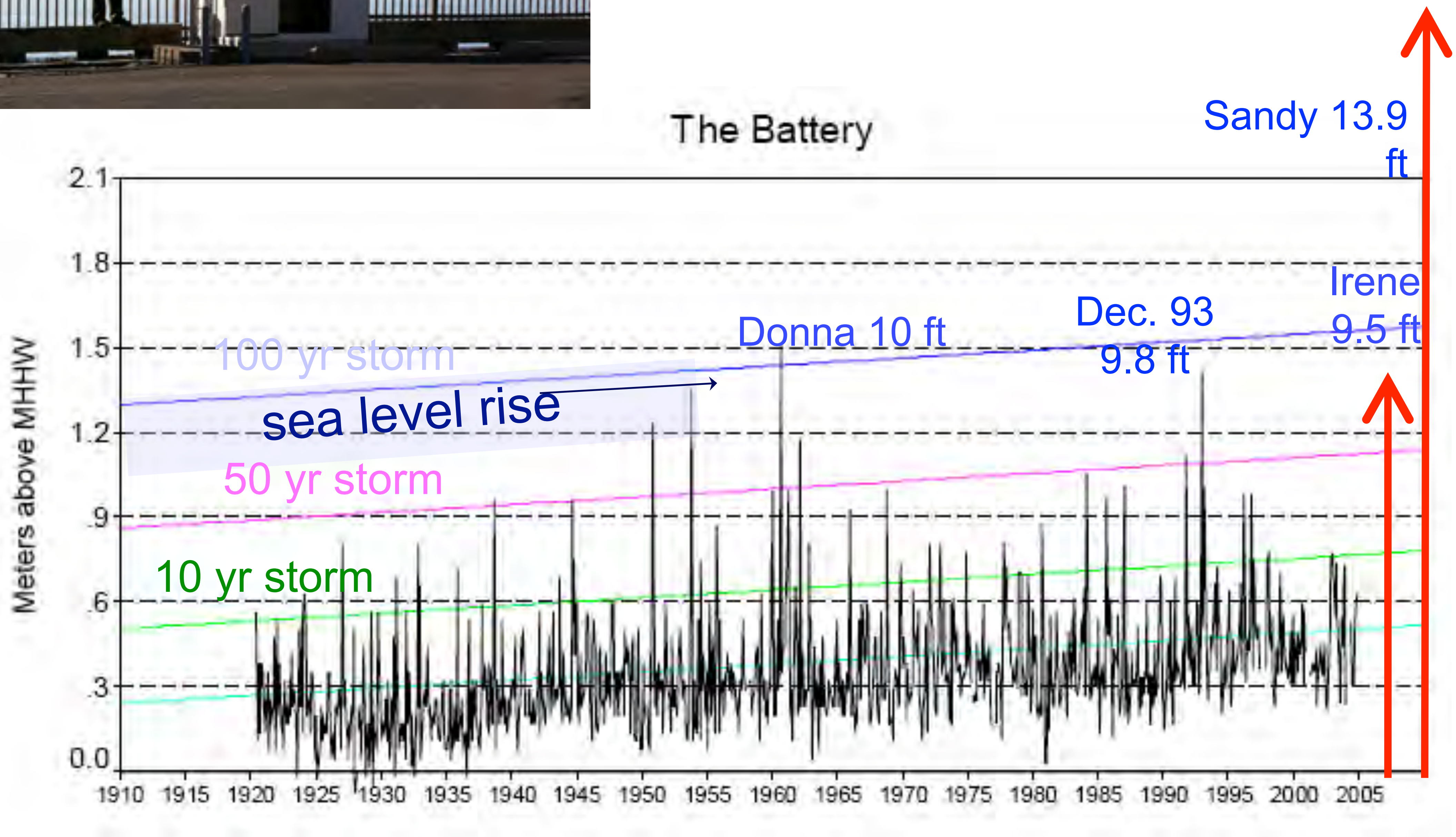
Compare to 20th century GSL rise of ~1.7 mm/y (~7"/century)

Boston	~2.5 mm/y (10"/century)
New York City	~3.0 mm/y (12"/century)
Atlantic City	~3.9 mm/y (15"/century)
Norfolk	~4.3 mm/y (17"/century)

Kopp (2013)

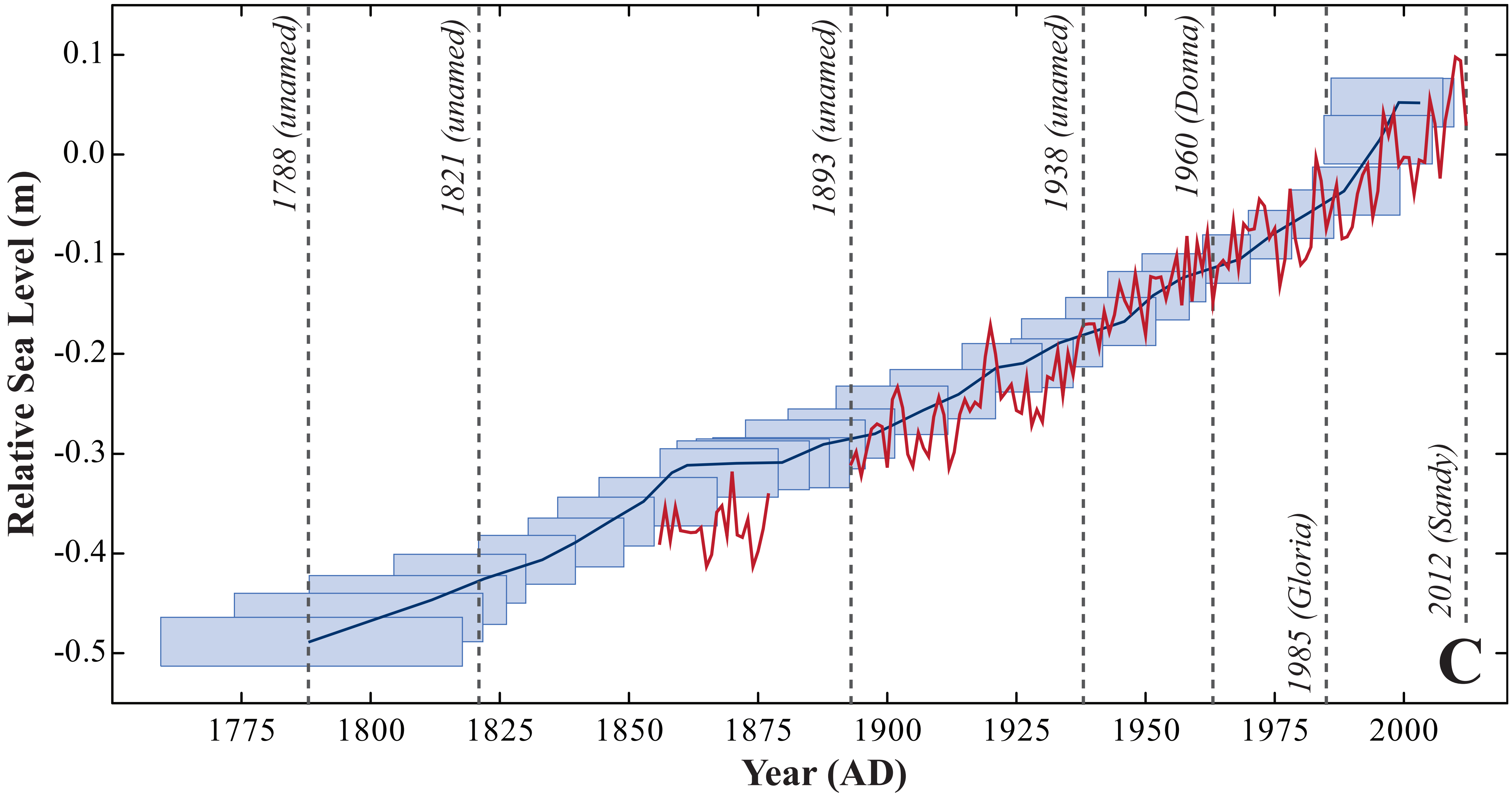
Records of past and present changes

Battery Tide Gauge, Battery Park, New York City



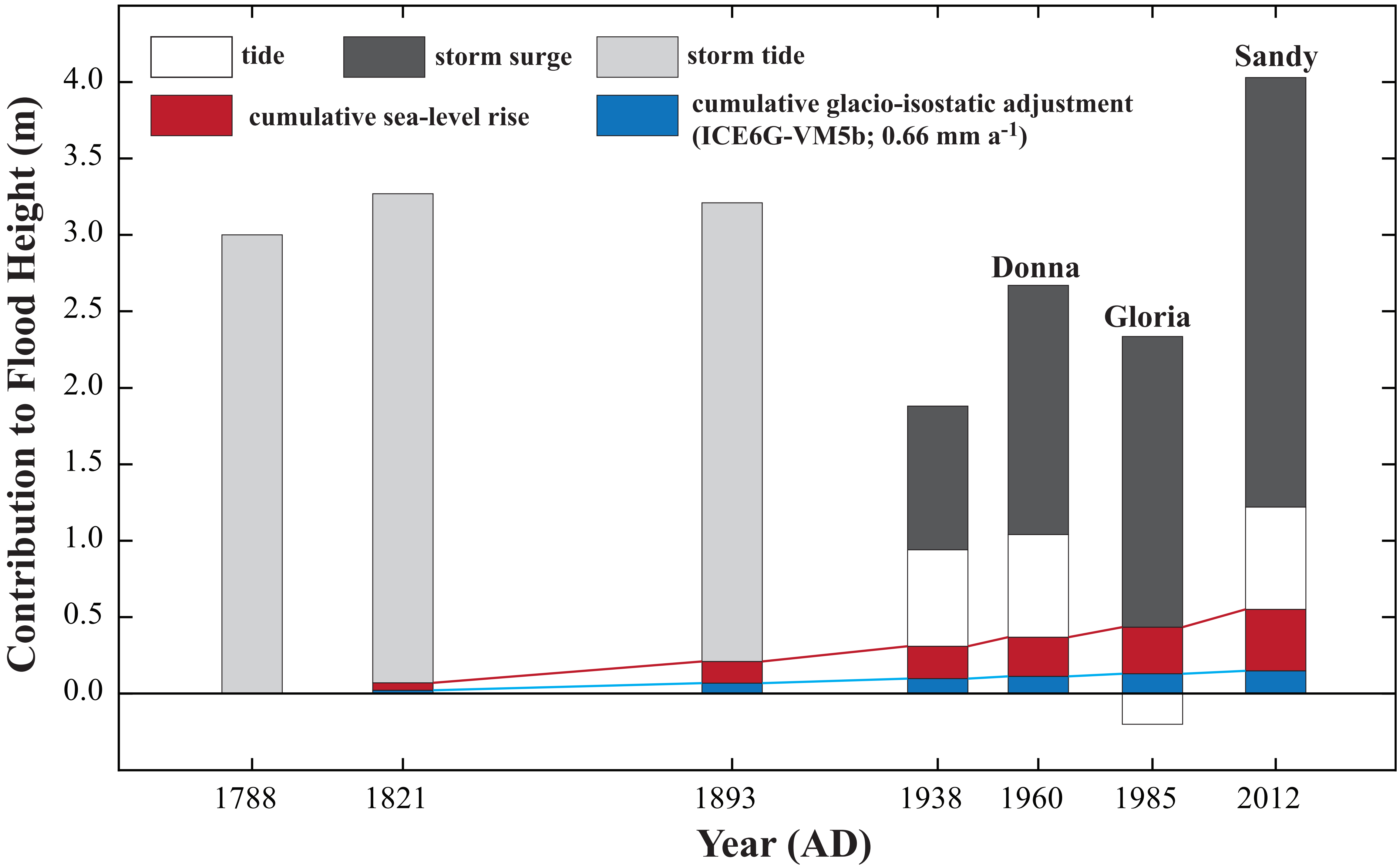
Sediment cores from New Jersey salt marshes

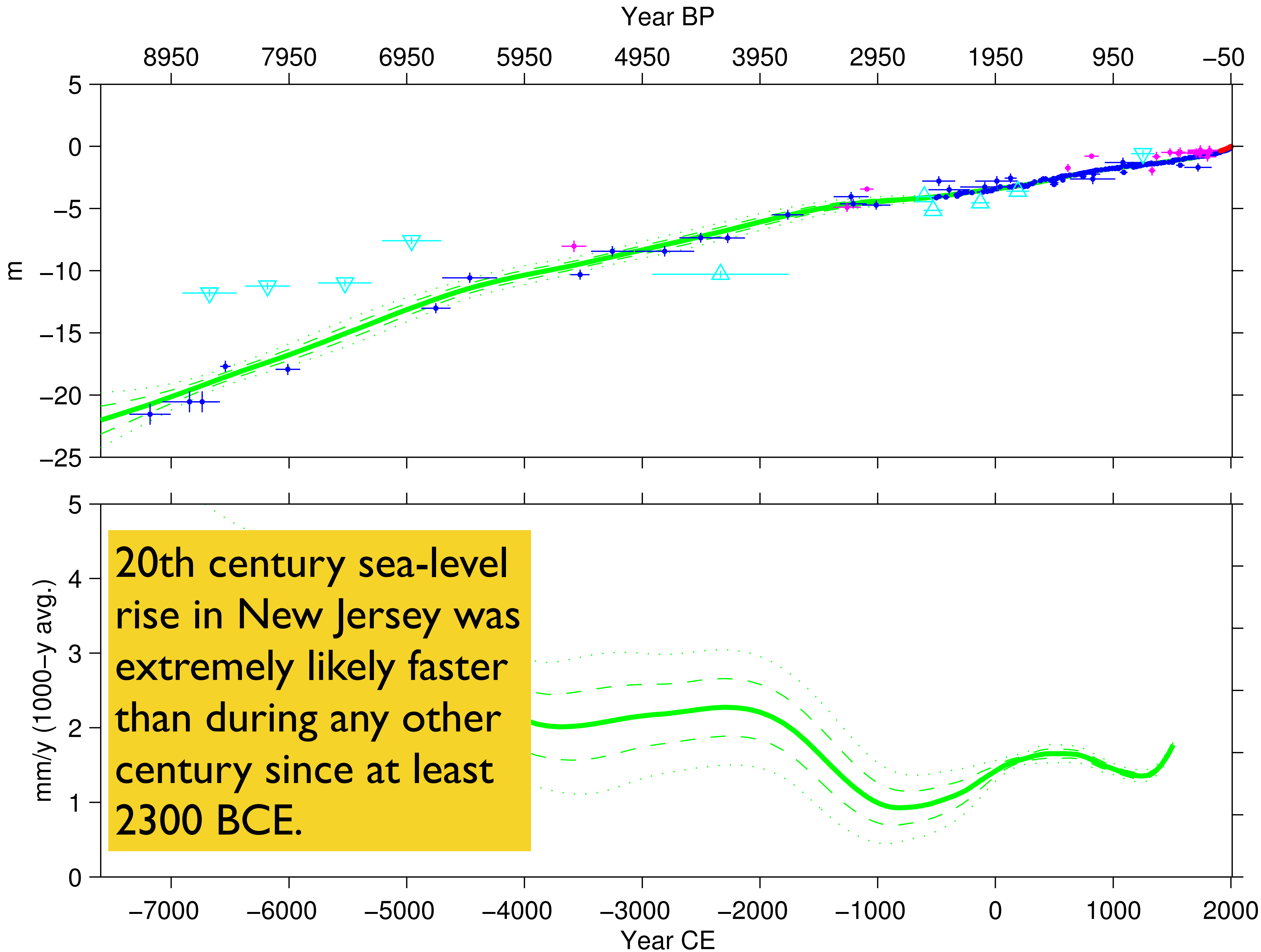
Photo courtesy B. Horton



Kemp & Horton (2013)

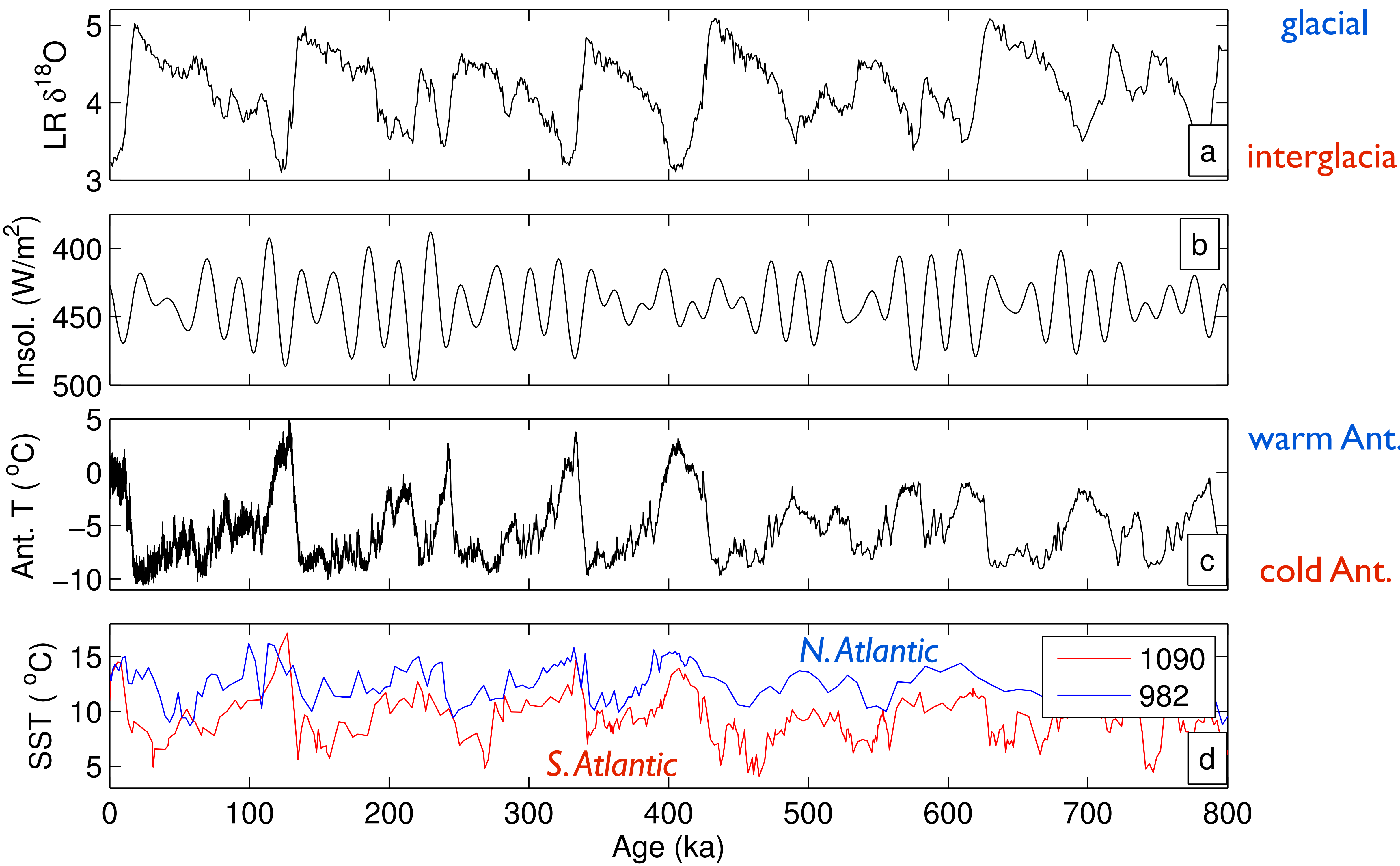
Kemp & Horton (2013) estimates of the contribution of historical sea-level rise to flooding at the Battery





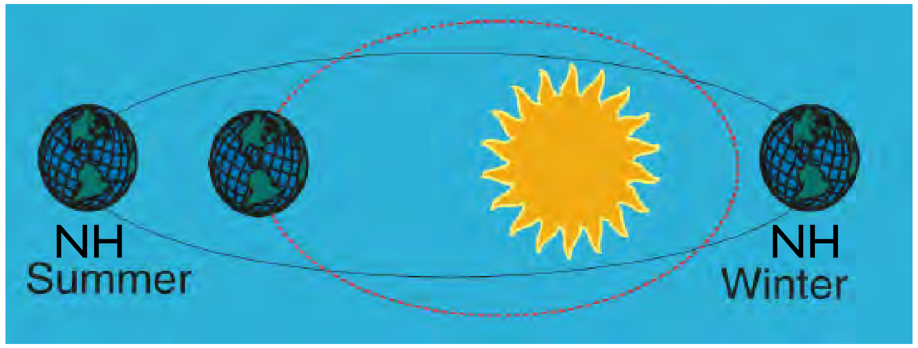
Miller et al. (2013)

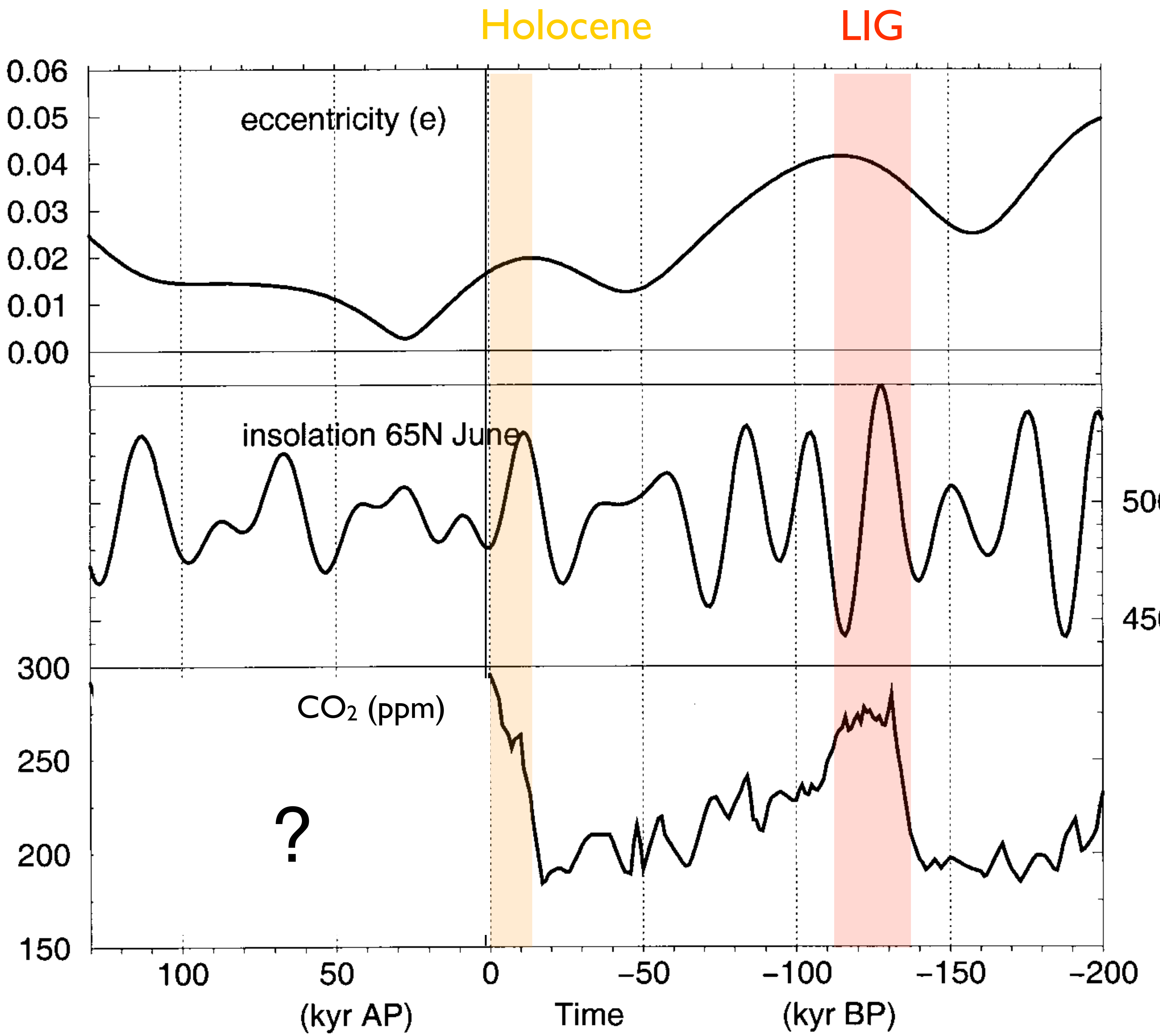
For the last 2 My, the Earth has oscillated between glacials and interglacials



(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).

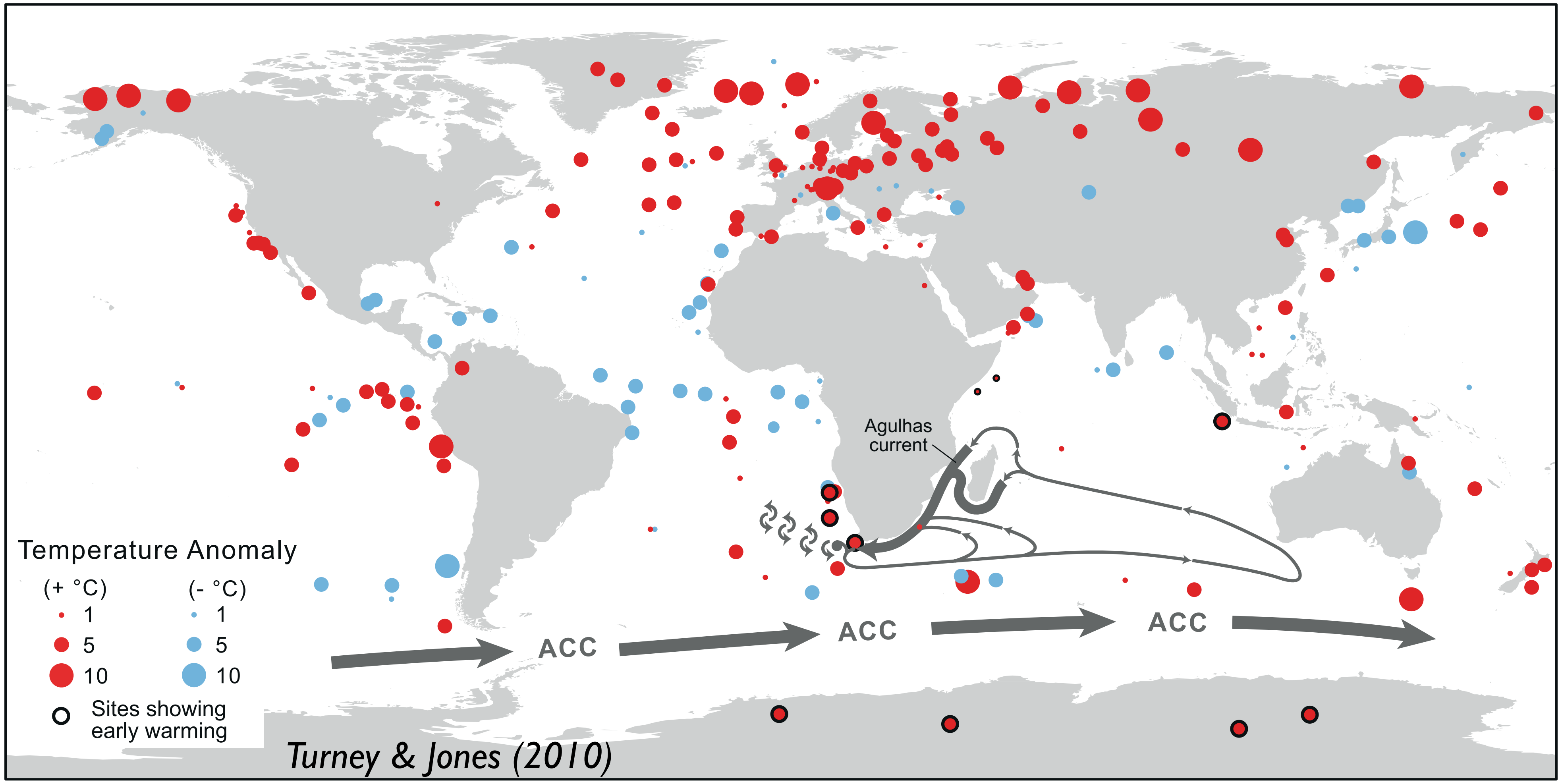
The Last Interglacial stage had Holocene-like pCO_2 but higher eccentricity





Berger et al. (2003)

The Last Interglacial was slightly warmer than today



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

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

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

- 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

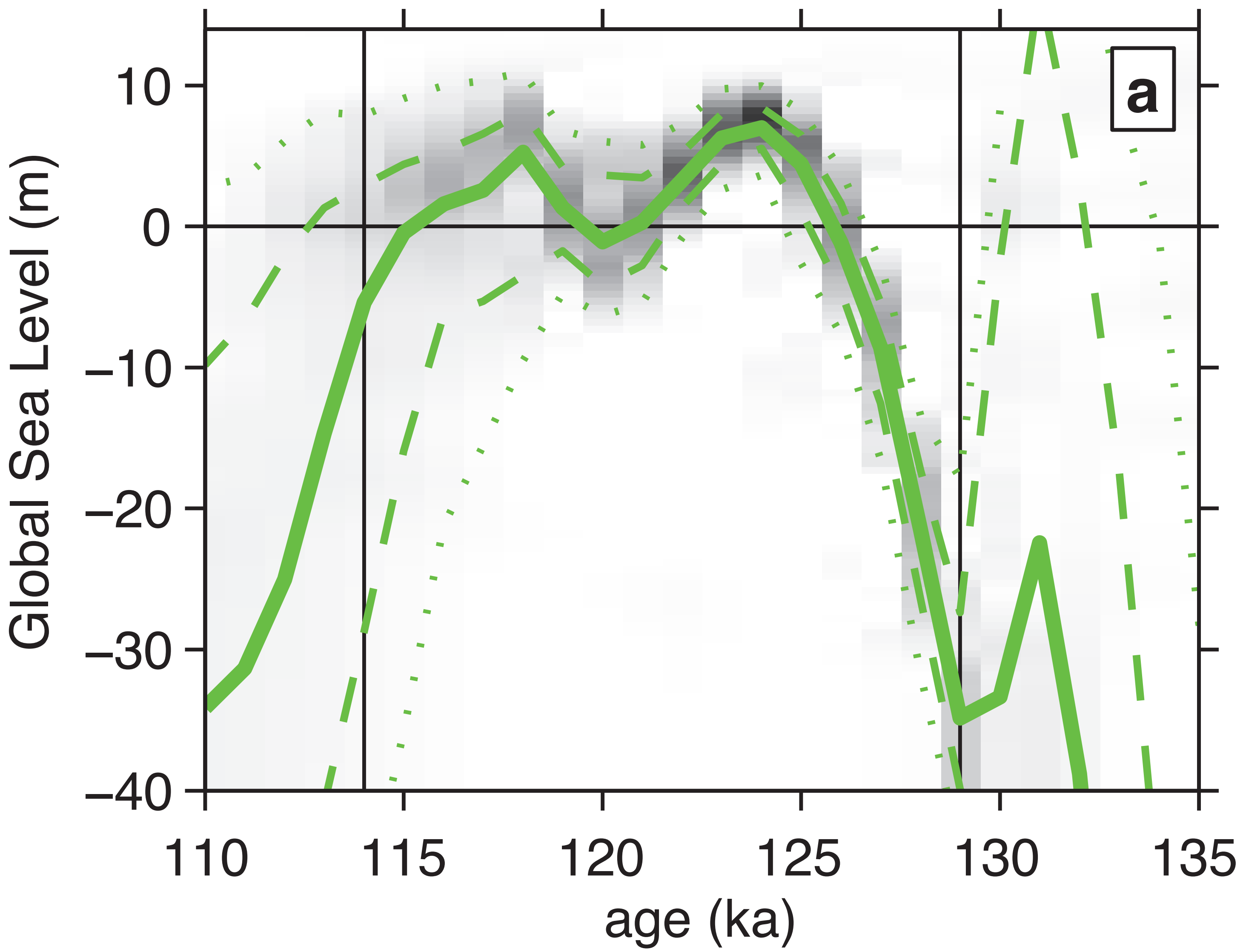
Fossil coral reefs from the Bahamas

Chen et al. (1991)

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

Raised beaches in southern England

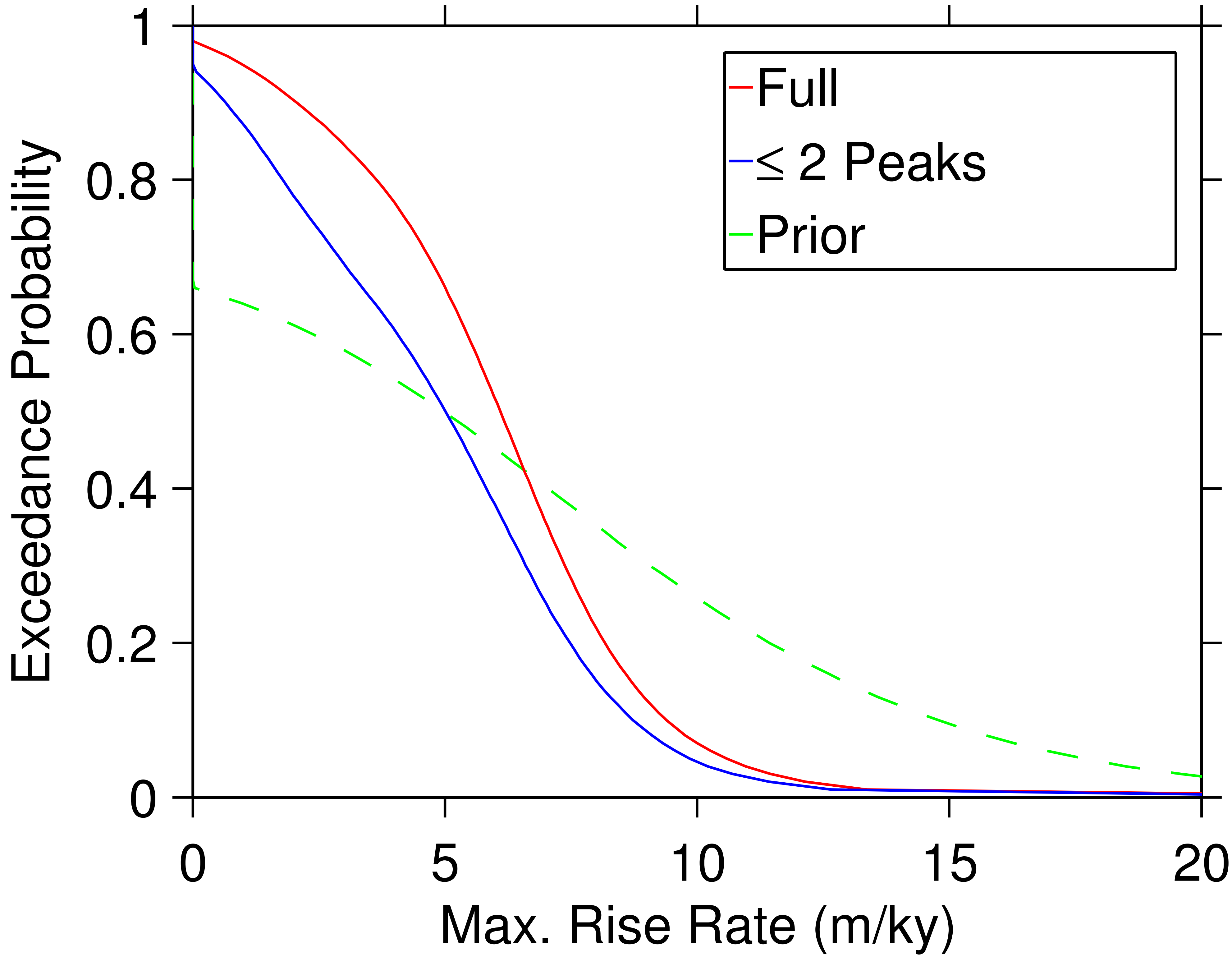
Mean global sea level reconstructed for the Last Interglacial



Extremely likely (95% probability) peaked at least 21 feet higher than today, unlikely (1-in-3 chance) to have been higher than 29 feet

Kopp et al. (2009)

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



Kopp et al. (2013)

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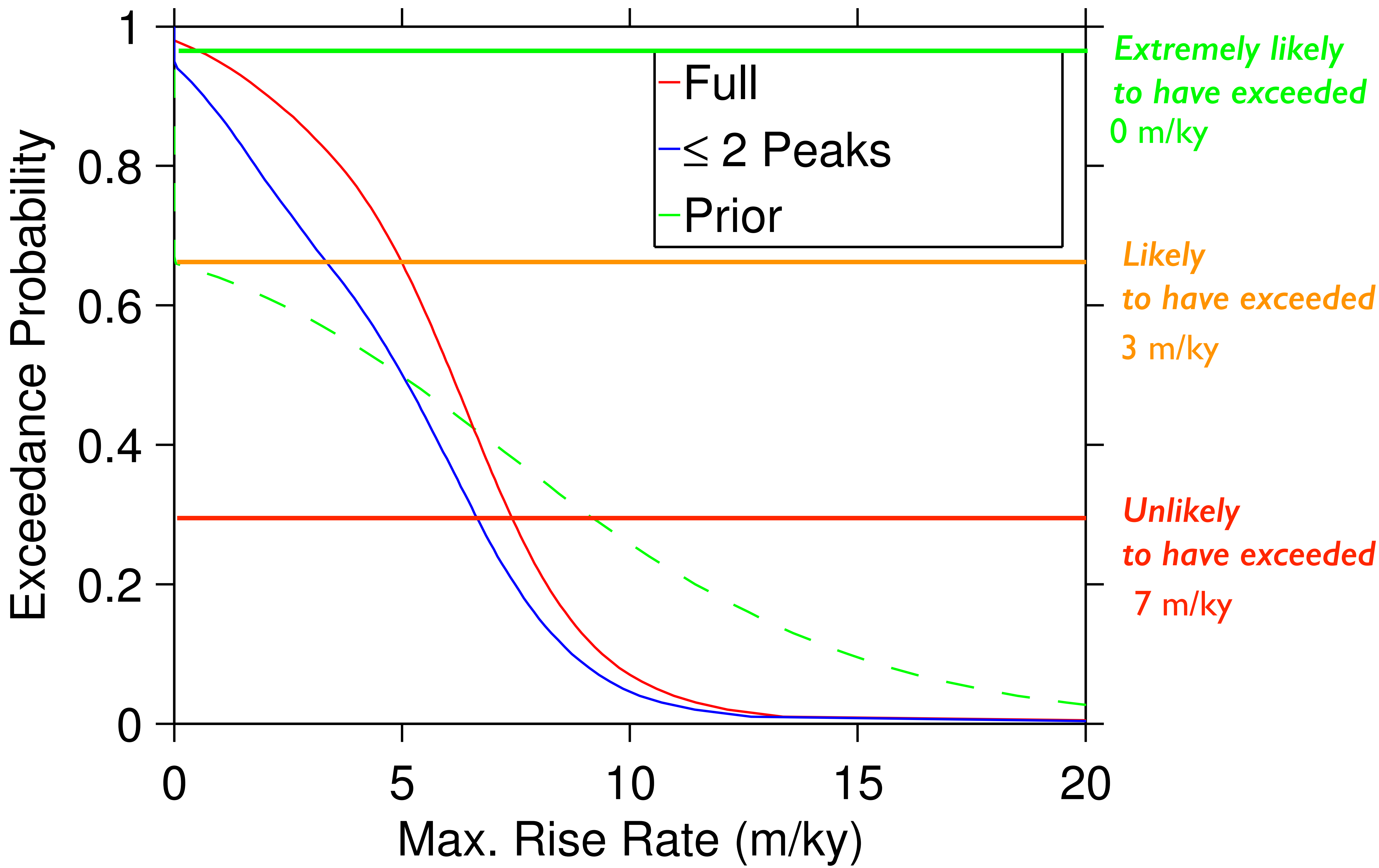


Kopp et al. (2013)

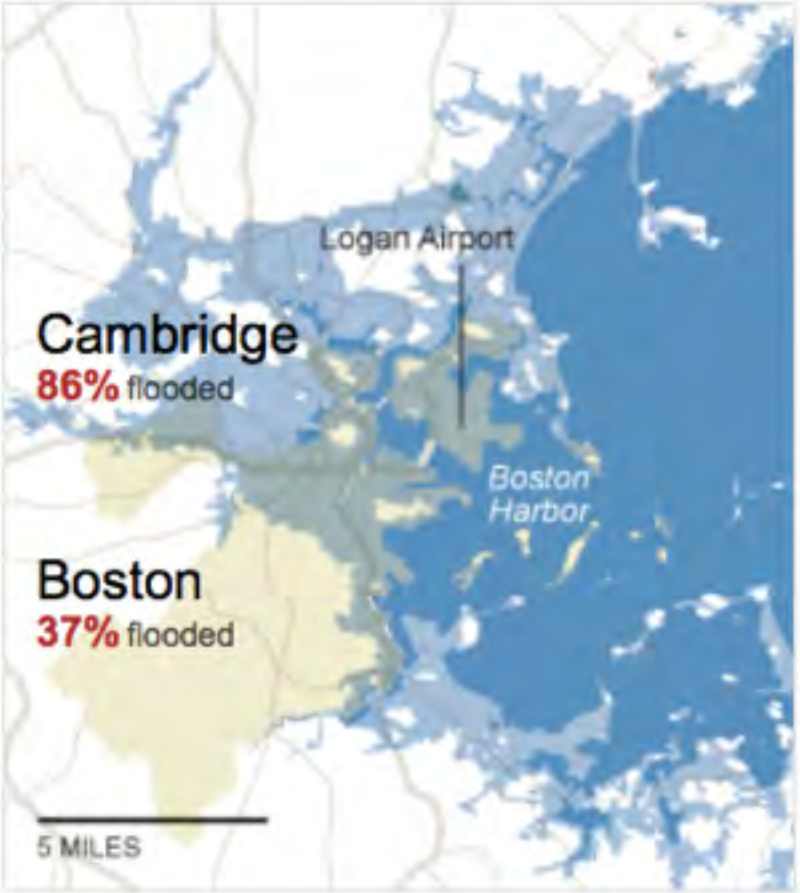
Pliocene global sea-level, three million years ago (last time CO_2 was comparable to today), peaked about 50-80 feet higher than today

Orangeburg Scarp, James River, Virginia

Photo: Harry Dowsett (USGS) via *Science*

With Last Interglacial sea levels (25 feet):

Boston



The downtown island shrinks to mostly Beacon Hill. Many shore communities are flooded.

New York City 39% flooded

Large portions of all five boroughs are gone, including much of Manhattan below 34th Street.

New Jersey

Downtown Newark, downtown Jersey City, Atlantic City, most of the state's coastal towns and the Cape May peninsula are all gone.

This won't happen over night – but could be the legacy we leave our descendants centuries hence.

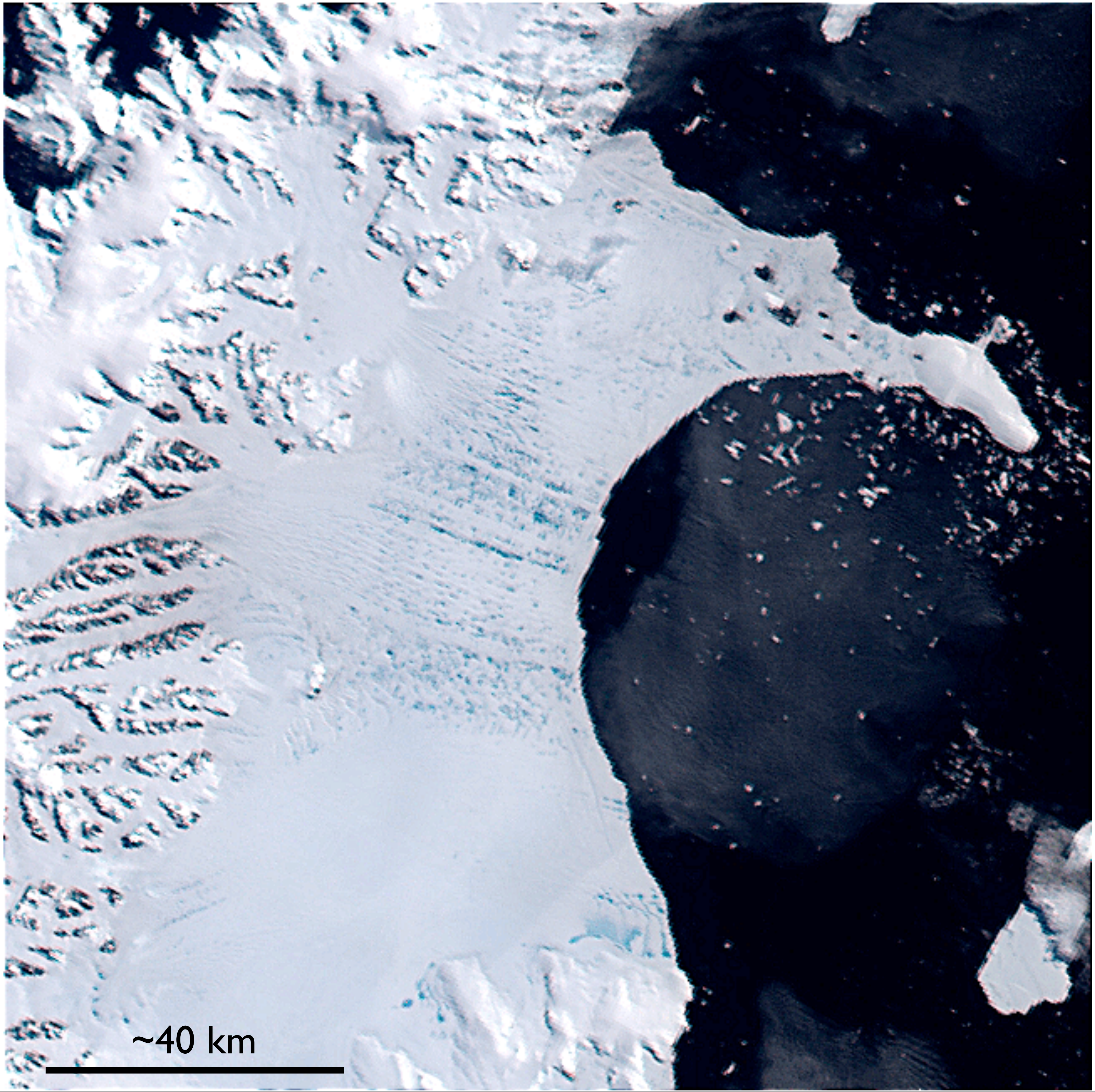
Source: New York Times (Nov. 24, 2012)

Future sea-level changes

It's still difficult for physical models to capture some key dynamics of ice sheet behavior.

Larsen B Ice Shelf

31 Jan. 2002

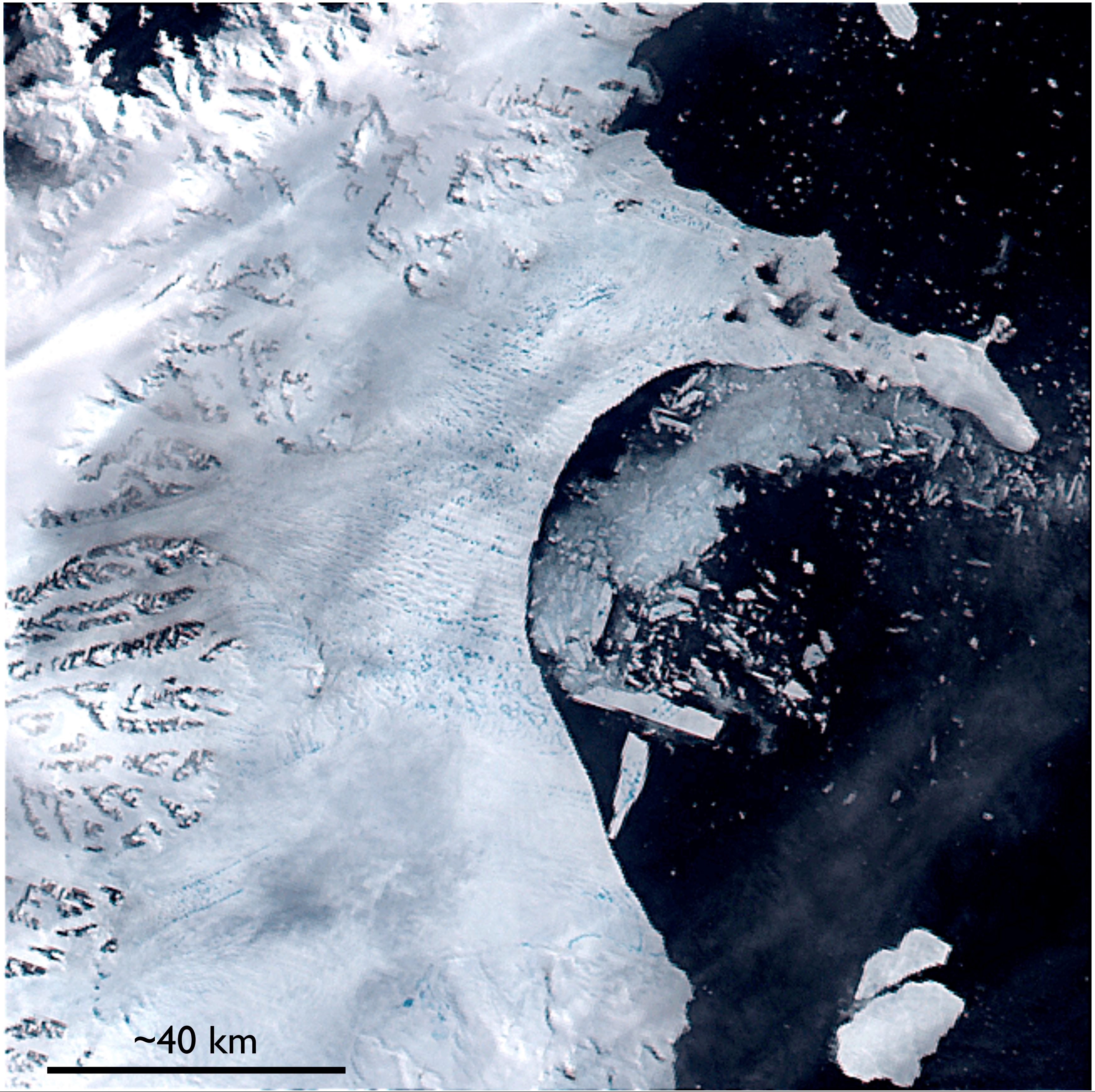


http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

It's still difficult for physical models to capture some key dynamics of ice sheet behavior.

Larsen B Ice Shelf

17 Feb. 2002

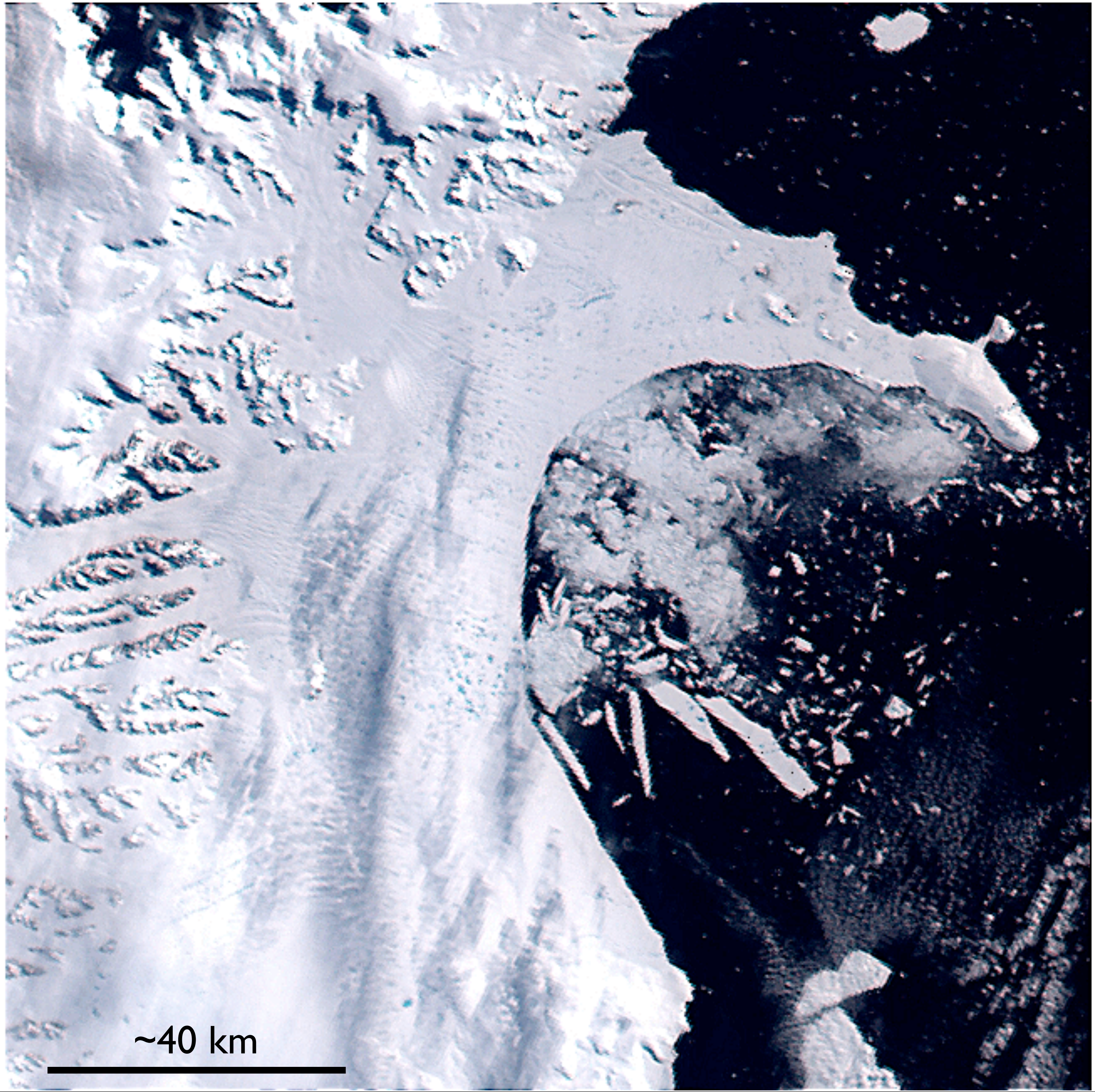


http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

It's still difficult for physical models to capture some key dynamics of ice sheet behavior.

Larsen B Ice Shelf

23 Feb. 2002

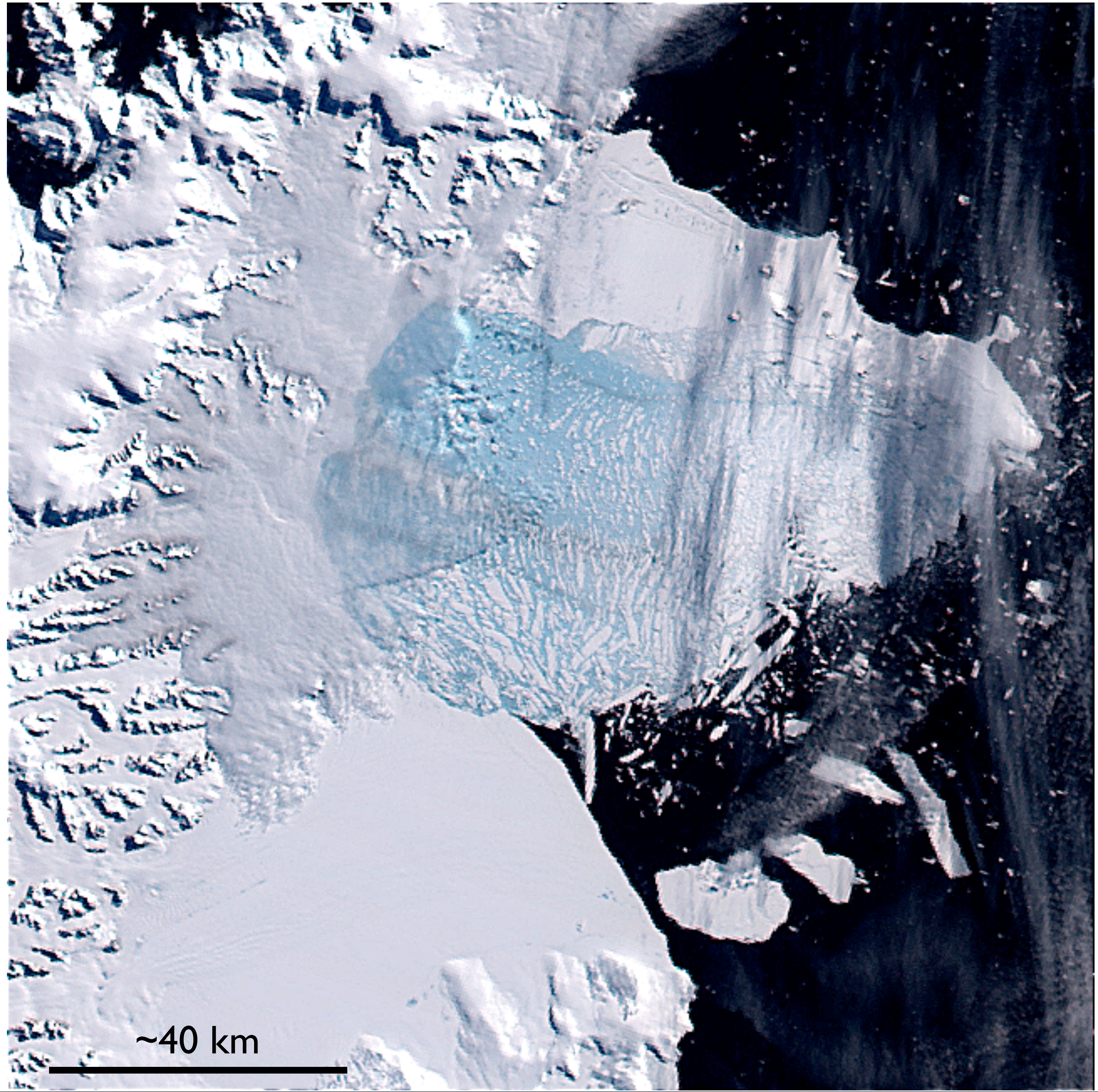


http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

It's still difficult for physical models to capture some key dynamics of ice sheet behavior.

Larsen B Ice Shelf

5 Mar. 2002

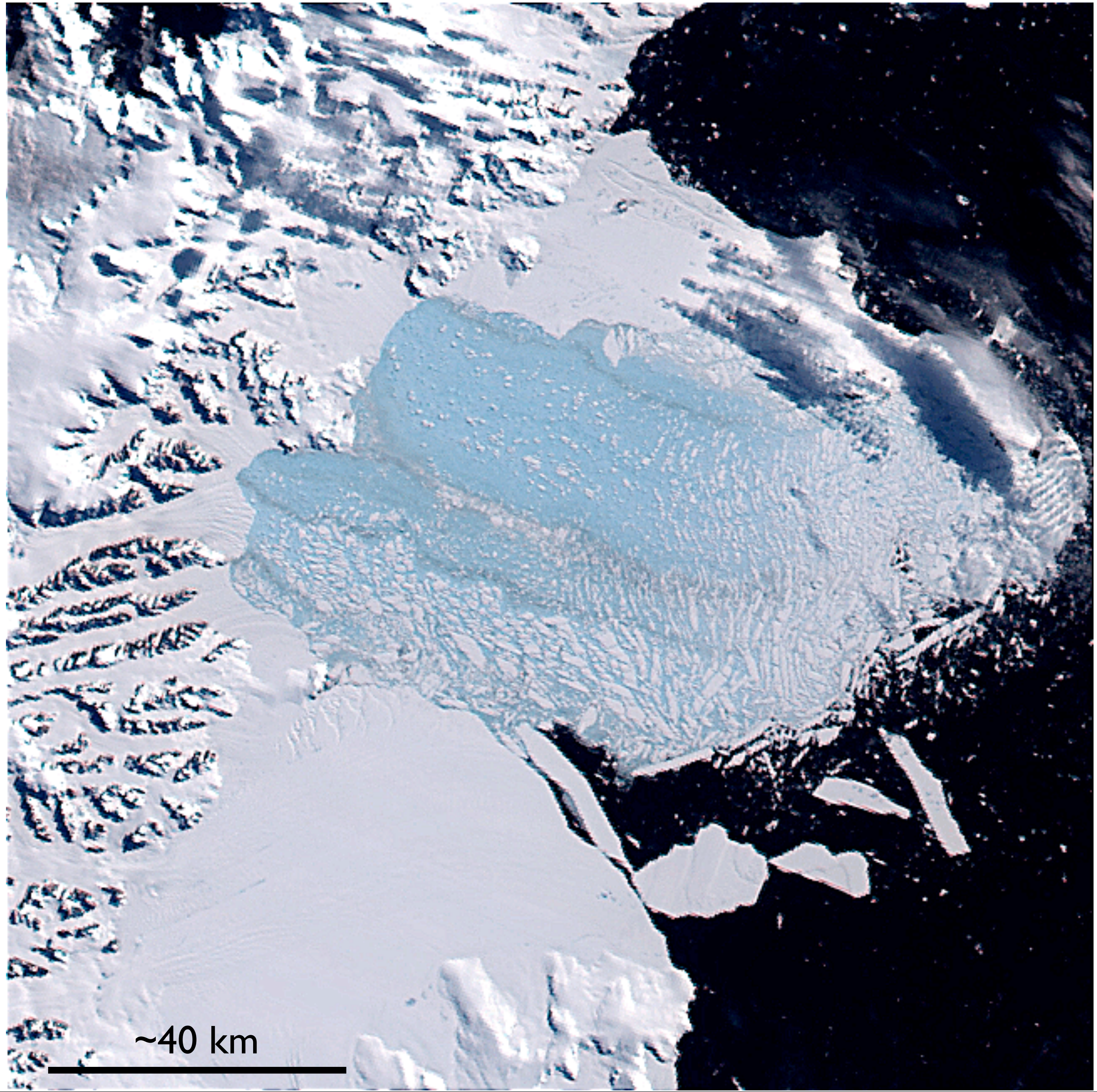


http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

It's still difficult for physical models to capture some key dynamics of ice sheet behavior.

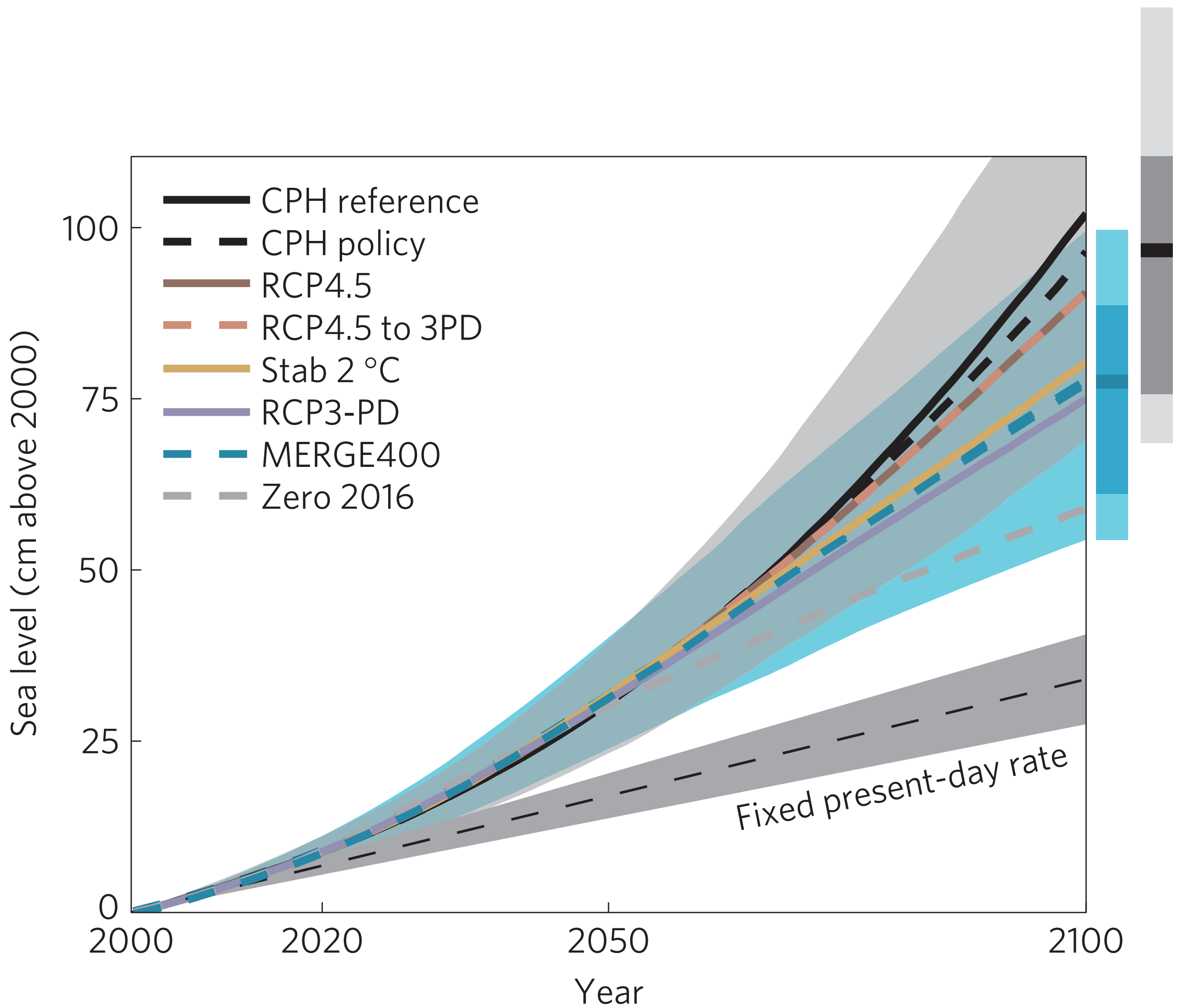
Larsen B Ice Shelf

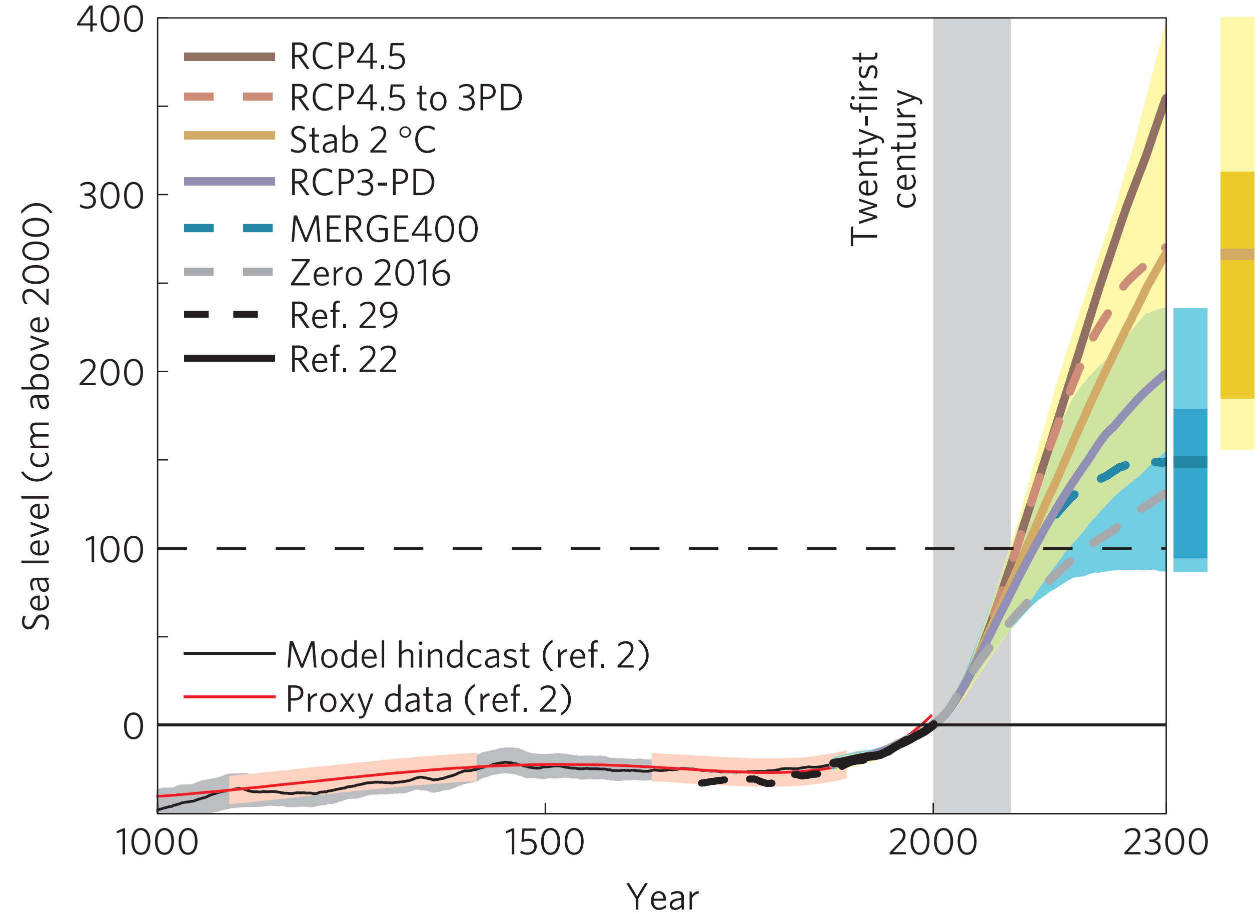
7 Mar. 2002



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

One alternative approach: Semi-empirical models look at past relationship between temperature, GSL





Projected SLR (90% probability range):

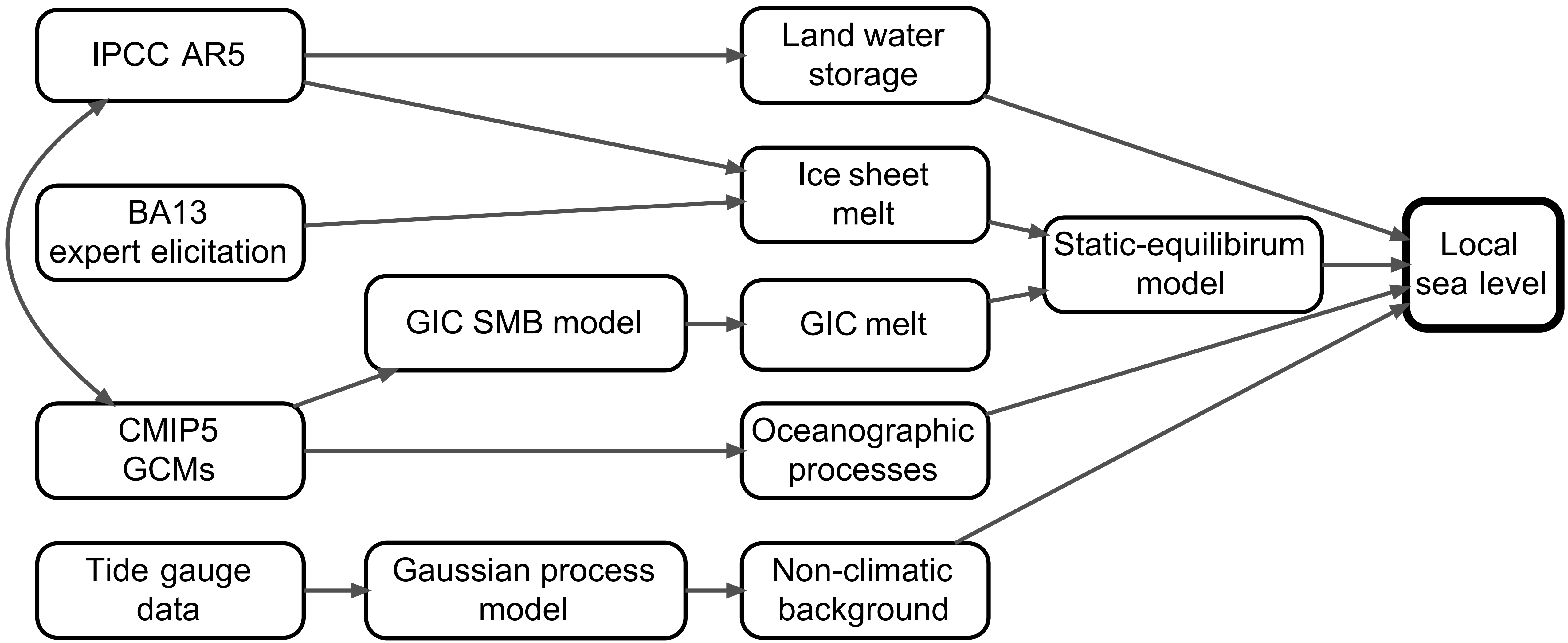
70-140 cm (28"-55") by 2100 under no policy

50-100 cm (20"-39") by 2100 under aggressive policy

***But:** current semi-empirical models project global (not local) changes and are calibrated against either short record or regional sea-level reconstructions, both from a time period when thermal expansion (and, regionally, ocean dynamics) dominated sea-level change*

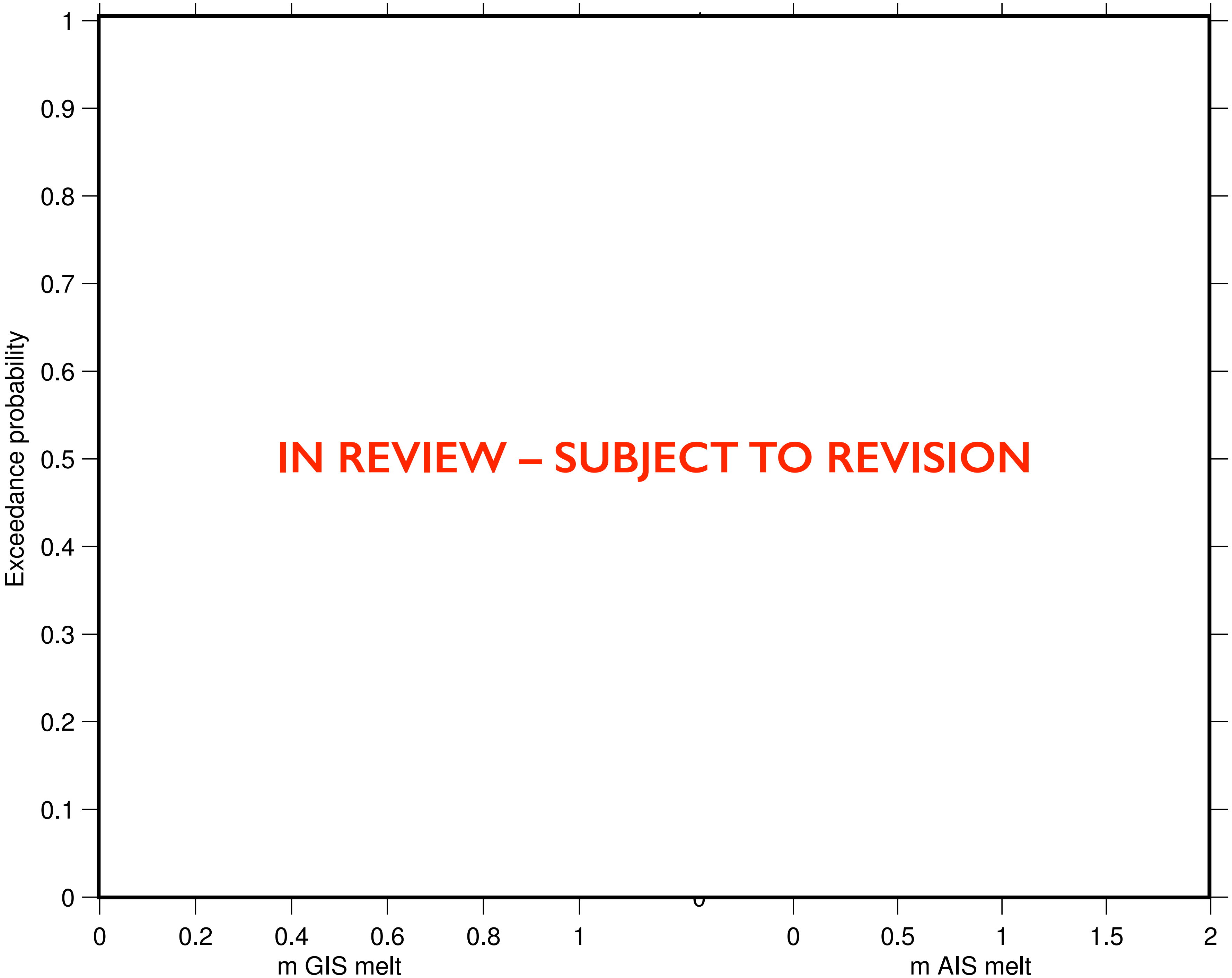
Schaeffer et al. (2012)

Since we can't yet rely on physical models, we need to synthesize multiple lines of knowledge



Kopp et al. (in review)

Reconciliation of IPCC and expert elicitation



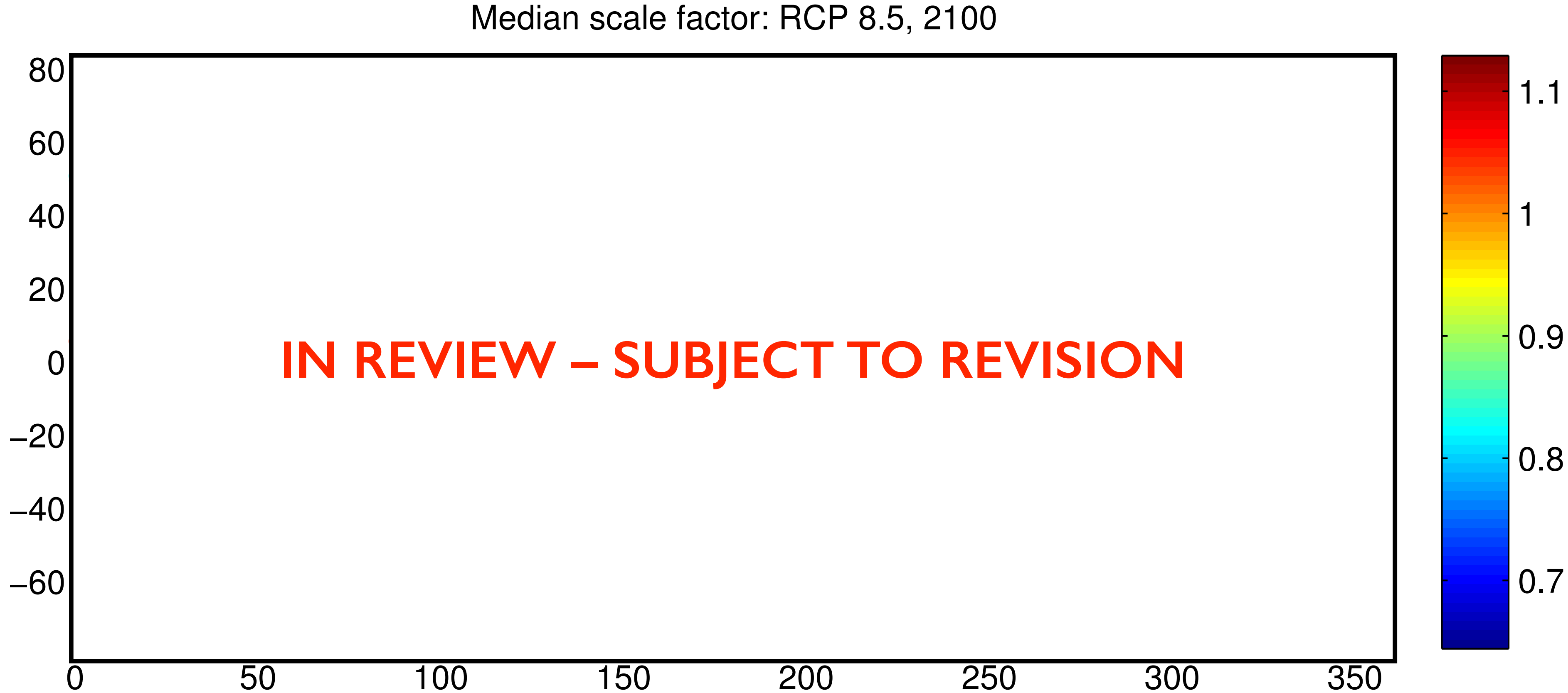
AIS mass loss
RCP 8.5, 2100

cm	Likely	1-in-20	1-in-200
AR5	-8–15		
BA	2–41	83	
Hybrid	-8–15	33	94

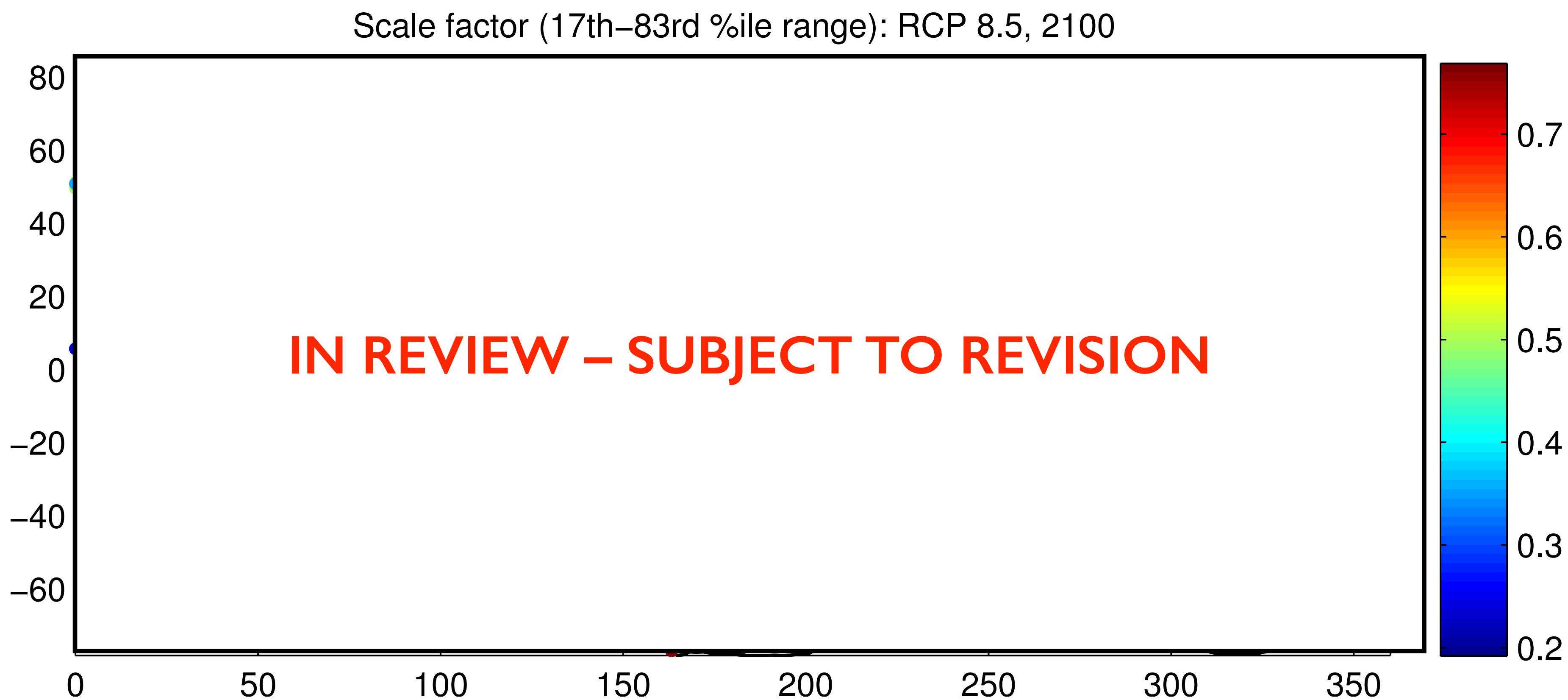
Note that IPCC provides only likely (67%) ranges – it does not attempt to estimate the tails of the ice sheet distribution. We accept the AR5 likely range and use BA expert elicitation to capture relationship between likely range and tails.

Kopp et al. (in review)

Different sites have different sensitivities to climatically-driven sea-level change



Median ratio of climatically-driven LSL change to climatically-driven GSL change



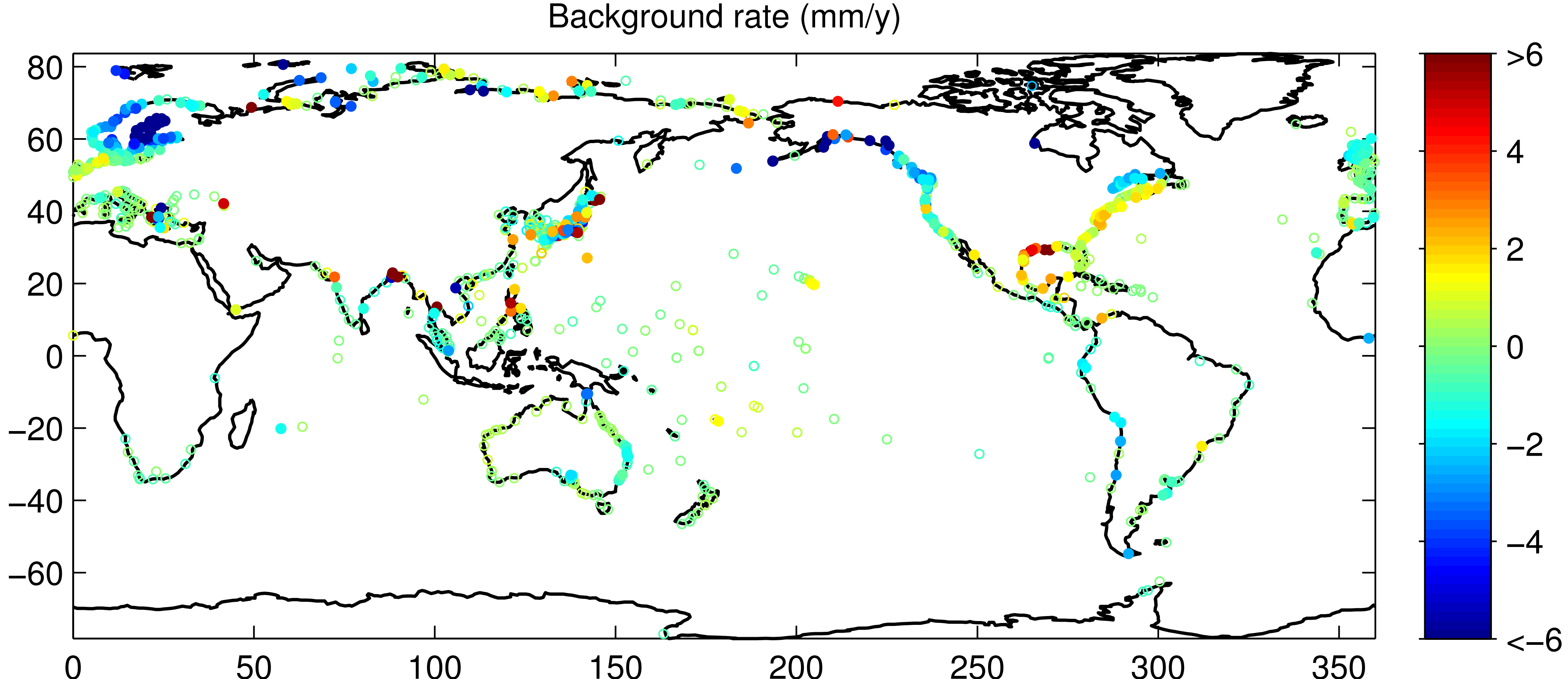
Spread in this ratio

Boston, MA:

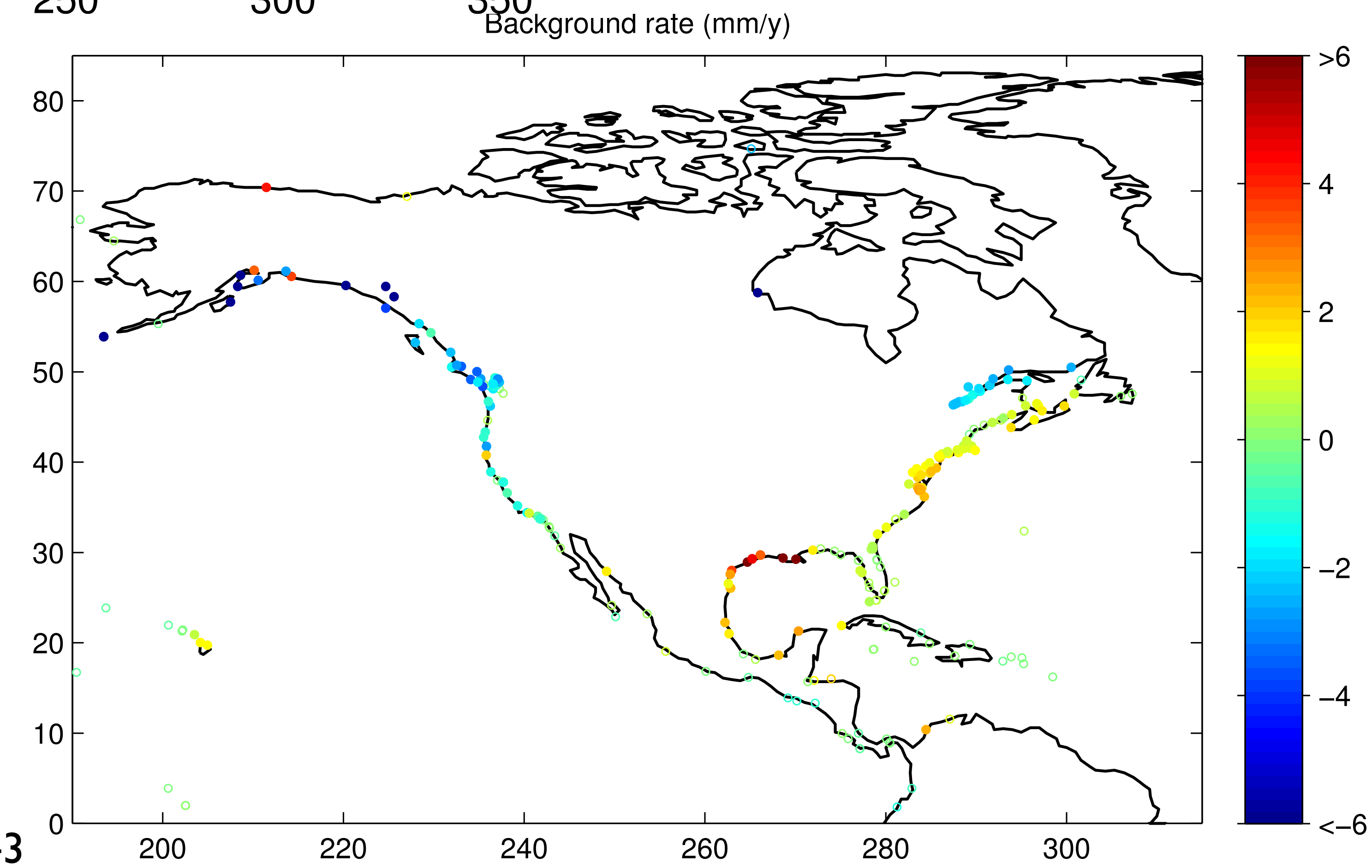
IN REVIEW – SUBJECT TO REVISION

Kopp et al. (in review)

Different sites also have different background rates of non-climatic sea level change

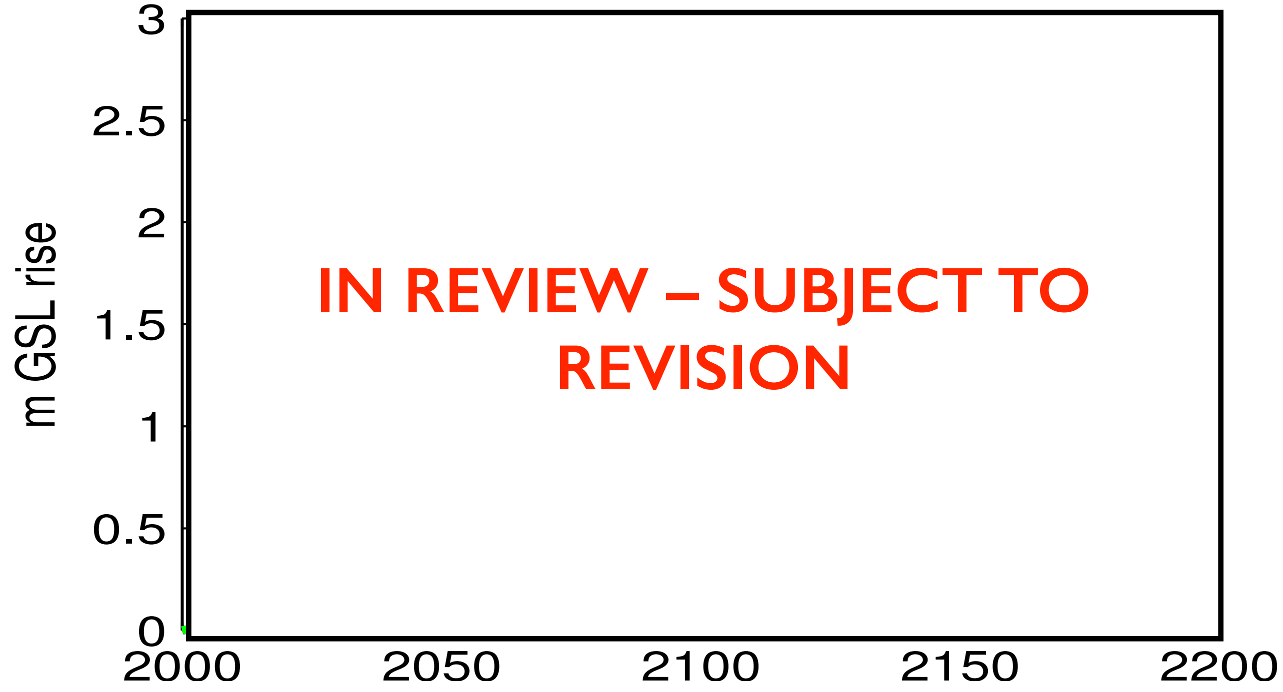


1 mm/y = 4”/century



Boston, MA:
IN REVIEW –
SUBJECT TO REVISION
Bkgd = 0.8 ± 0.3 mm/y

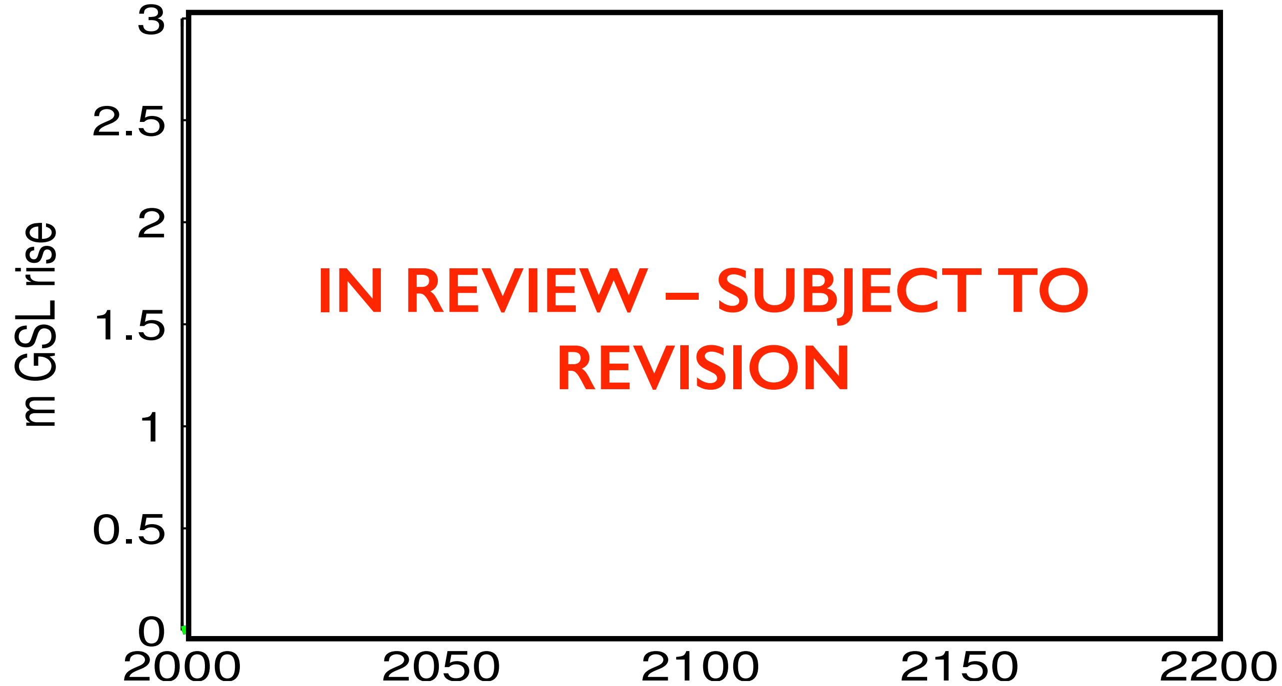
Kopp et al. (in review)



by 2050, RCP 8.5	Likely	1-in-20	1-in-200
Globally	IN REVIEW – SUBJECT TO REVISION		
New York, NY			
Norfolk, VA			
Boston, MA			

by 2100, RCP 8.5	Likely	1-in-20	1-in-200
Globally	IN REVIEW – SUBJECT TO REVISION		
New York, NY			
Norfolk, VA			
Boston, MA			

Kopp et al. (in review)



Aggressively reducing greenhouse gas emissions can shave about 1'-1.5' off of projected 21st century sea-level rise

by 2100, RCP 8.5	Likely	1-in-20	1-in-200
Globally			
New York, NY			
Norfolk, VA			
Boston, MA			

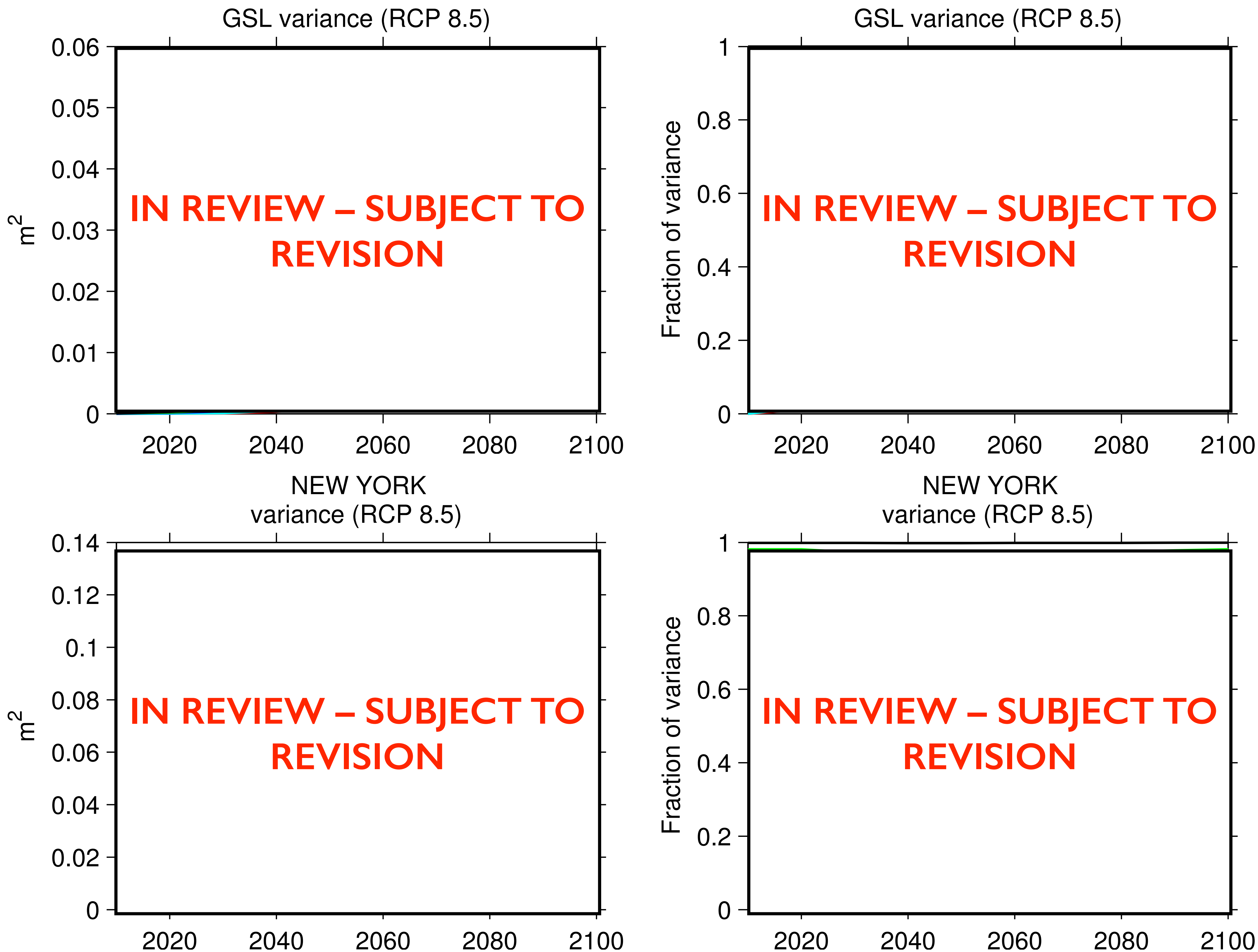
IN REVIEW – SUBJECT TO REVISION

by 2100, RCP 2.6	Likely	1-in-20	1-in-200
Globally			
New York, NY			
Norfolk, VA			
Boston, MA			

IN REVIEW – SUBJECT TO REVISION

Kopp et al. (in review)

Uncertainty in projections is usually dominated by Antarctica, and in some regions by ocean dynamics



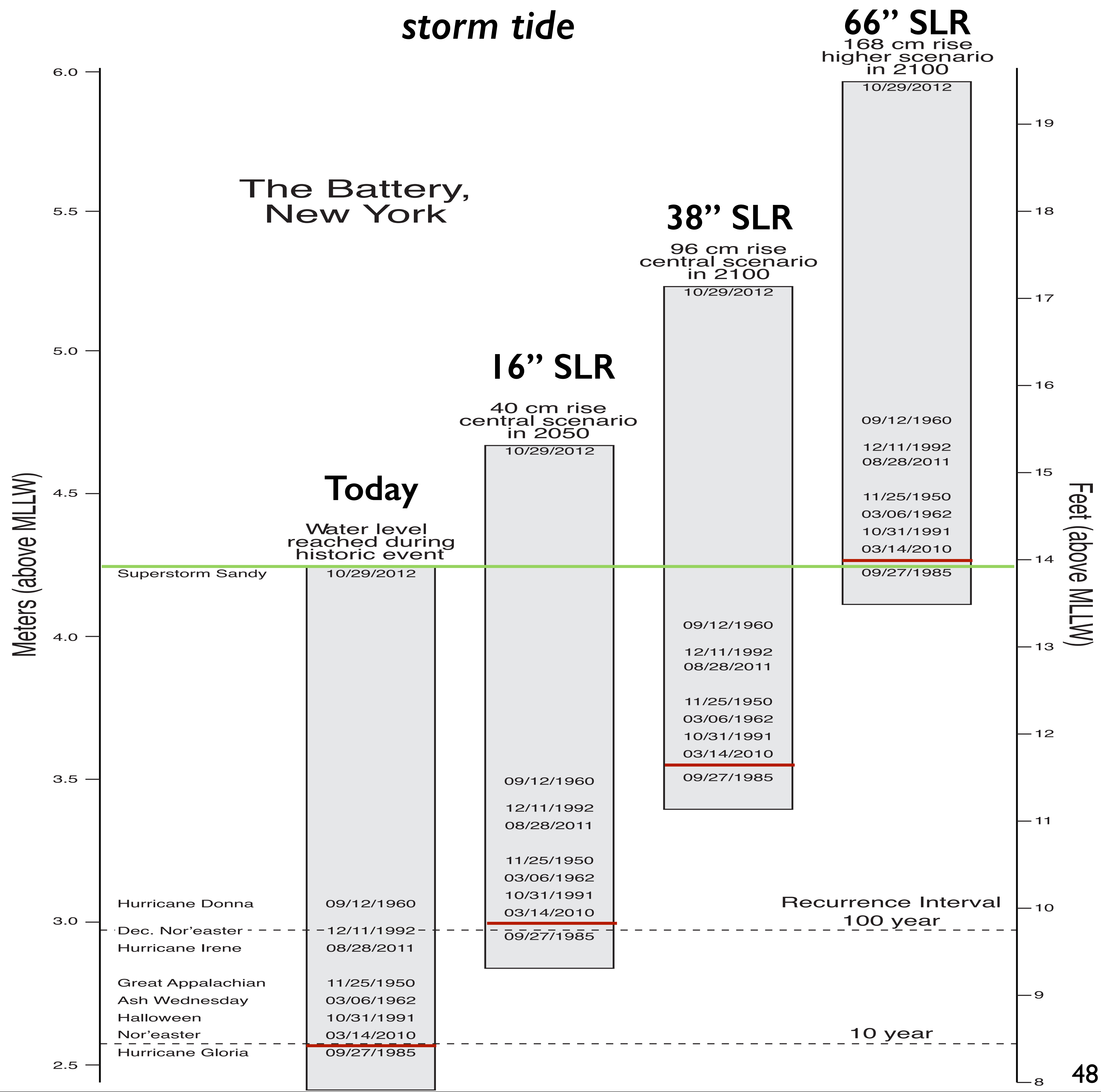
Kopp et al. (in review)

Implications for Flood Risk

Coastal flooding

Under a high sea-level rise scenario (~3% probability) for 2100 [at NYC: 5.5'], the flooding associated with a 10-year event will exceed Sandy's

Impacts of sea-level rise scenarios on storm tide



Miller et al. (2013)

Coastal flooding

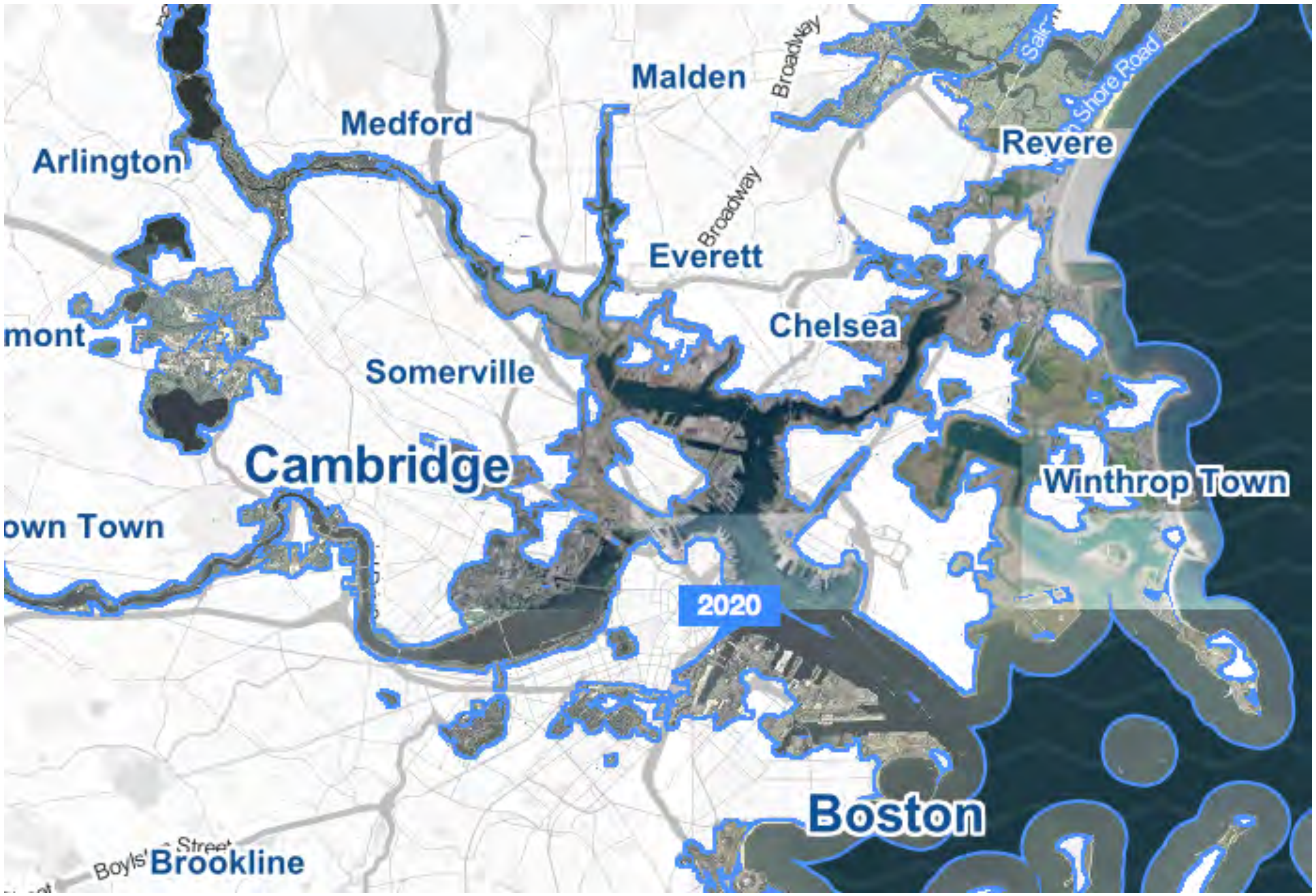
Areas submerged with 9' sea level rise plus storm surge (= Sandy today, 1-in-10 year storm w/5' sea-level rise)

<u>Below 9' in New York</u>

- $168 billion property
- 930 thousand people (1/3 high social vulnerability)
- 405 thousand housing units
- 65 fire and EMS stations
- 28 hospitals

Climate Central (2013)
<u>http://sealevel.climatecentral.org/</u>

What about Boston?



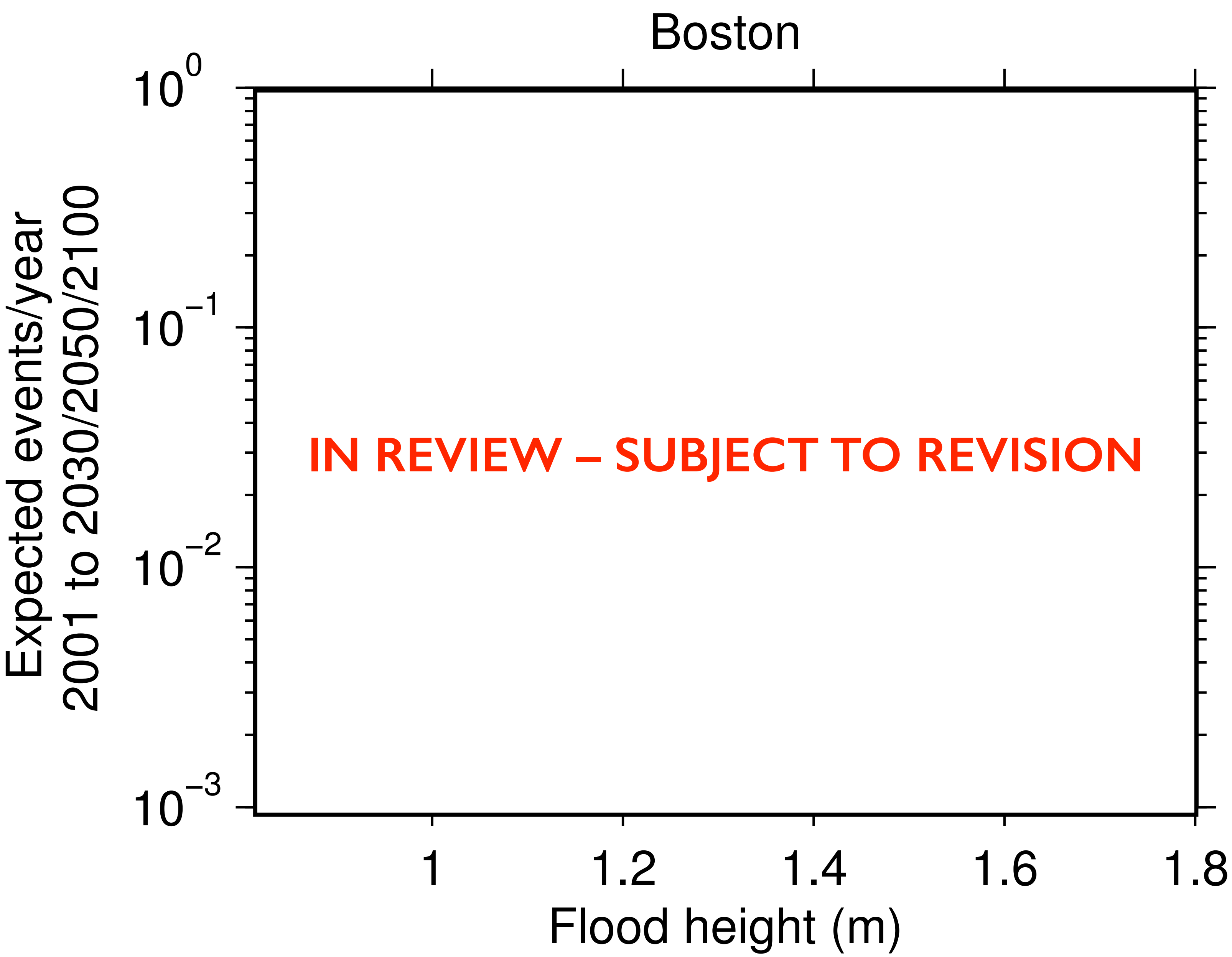
Boston:

Current 100-year flood elevation: 5.5' above MHHW

(about 40,000 people in Boston and Cambridge)

Climate Central (2012)
http://sealevel.climatecentral.org/

Rethinking flood risk



	'1-in-10 year'	'1-in-100 year'
2000–2030	IN REVIEW – SUBJECT TO REVISION	
2000–2050		
2000–2100		
No SLR, 2000–2100		

Ranges indicate expected events under different forcing pathways.

What matters is not just next year's flood risk;
it's the integrated flood risk over the lifetime of a project
and what the consequences of flooding are.

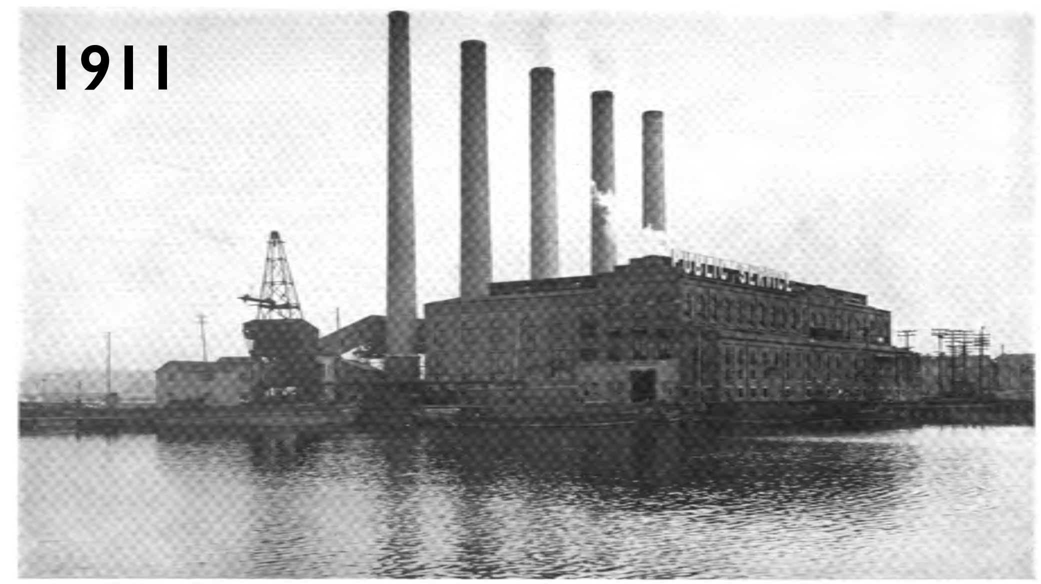
Kopp et al. (in review)

Power Generation—Map of Northern and Central Division Transmission Lines

Remember: infrastructure decisions can last a long time!

Marion Power Station, Jersey City, NJ
Built by the Public Service Electric Co. in 1905
Retired as generating station in 1961;
Succeeded by Hudson Generating Station

Marion Switching Station flooded in 2011 during Irene and 2012 during Sandy



View of Marion Power Station from West Bank of Hackensack River

Remember: infrastructure decisions can last a long time!

<u>Major Switching Stations Flooded During Sandy</u>

(Red = close to location on 1911 map)

1. Bayonne
2. Bayway [Elizabeth]
3. Deans [North Brunswick]
4. Essex [Newark]
5. Federal Square [Newark]
6. Hudson [Jersey City]
7. Jersey City
8. Kearny
9. Linden
10. Marion [Jersey City]
11. Metuchen
12. Newark
13. Sewaren
14. South Waterfront [Jersey City]

Source: PSE&G (2013)

Some cautions

- Different approaches to estimate the sea-level rise probability distribution will give somewhat different answers; ultimately, we need better process models but aren't there yet.
- Flood recurrence probabilities are based on historical data for the Boston tide gauge; historical storms imperfectly sample the true probability distribution, and the Boston tide gauge is not a perfect substitute for the whole region.
- Modeling of the hydrodynamics of flood inundation and of sediment transport is needed to more accurately characterize flood risks.

Nonetheless: it's clear that sea-level rise will dramatically reshape flood risk over the course of this century.

So what do we do?

seasideheightsnjonline.com

Do we rebuild unchanged (and assume the rest of the country will continue to subsidize indefinitely)?

Do we harden?

Maeslantkering, the Netherlands

Photo by www.aerolin.nl


Bay Head, NJ
NorthJersey.com

Do we raise (and otherwise modify our communities to be resilient to occasional flooding)?


Do we retreat
and raze?

How do we decide?

- *Technocratically*, e.g., through land use policy informed by benefit-cost analysis?
- *Economically,* e.g., with market tools such as accurately-priced, long-term flood insurance?
- *Democratically*, e.g., through deliberative community processes?

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My answer: Yes, we do all three, informed by risk assessments that reflect our best available knowledge.

The one thing we can't do is wish (or legislate) sea-level rise away.