Sea-level rise and extreme events: Insights from the *American Climate Prospectus*

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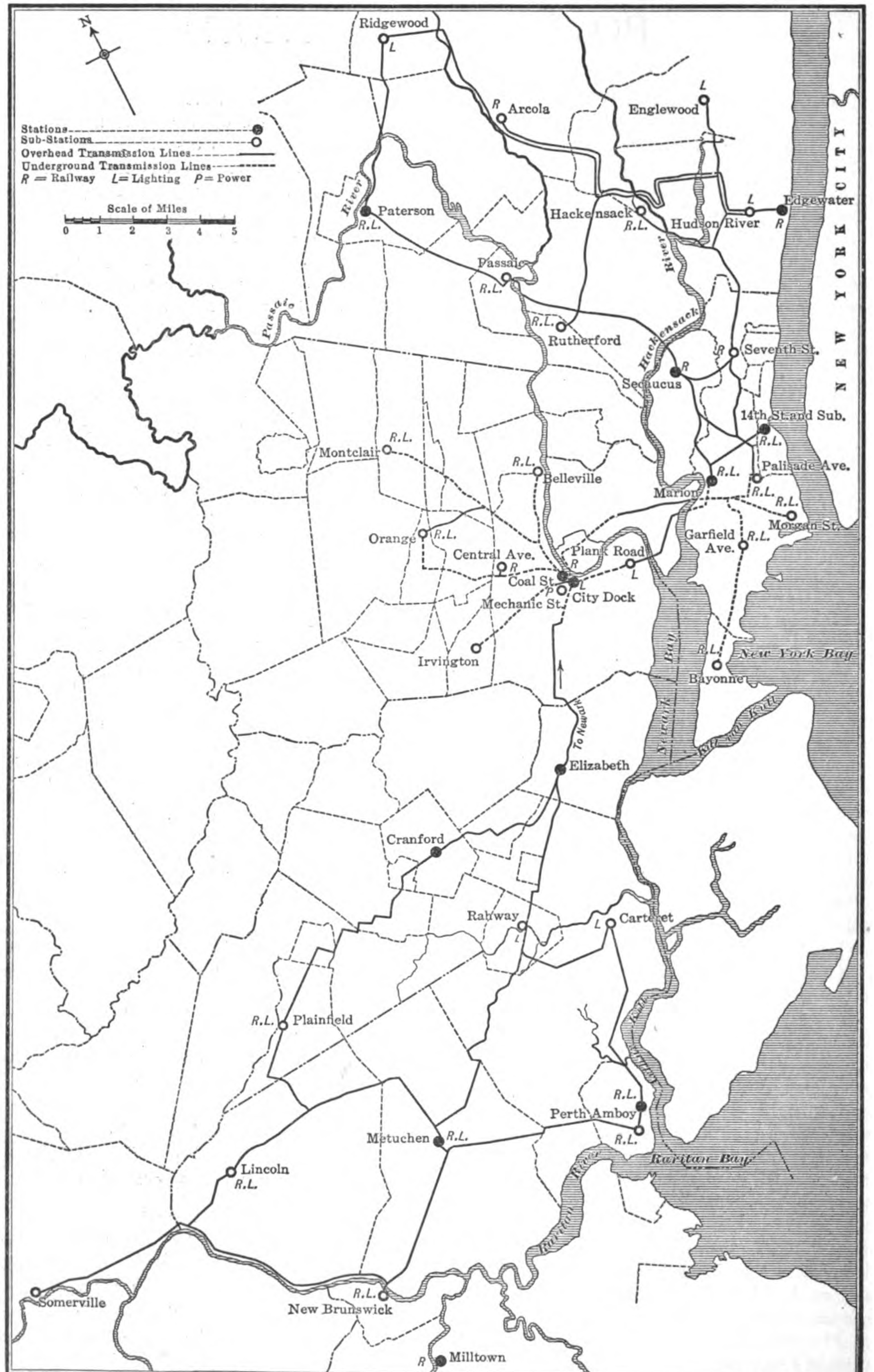
Climate Change Impacts/Integrated Assessment
Snowmass, CO • 22 July 2014



Power Generation—Map of Northern and Central Division Transmission Lines

Major Switching Stations Flooded During Sandy

(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]

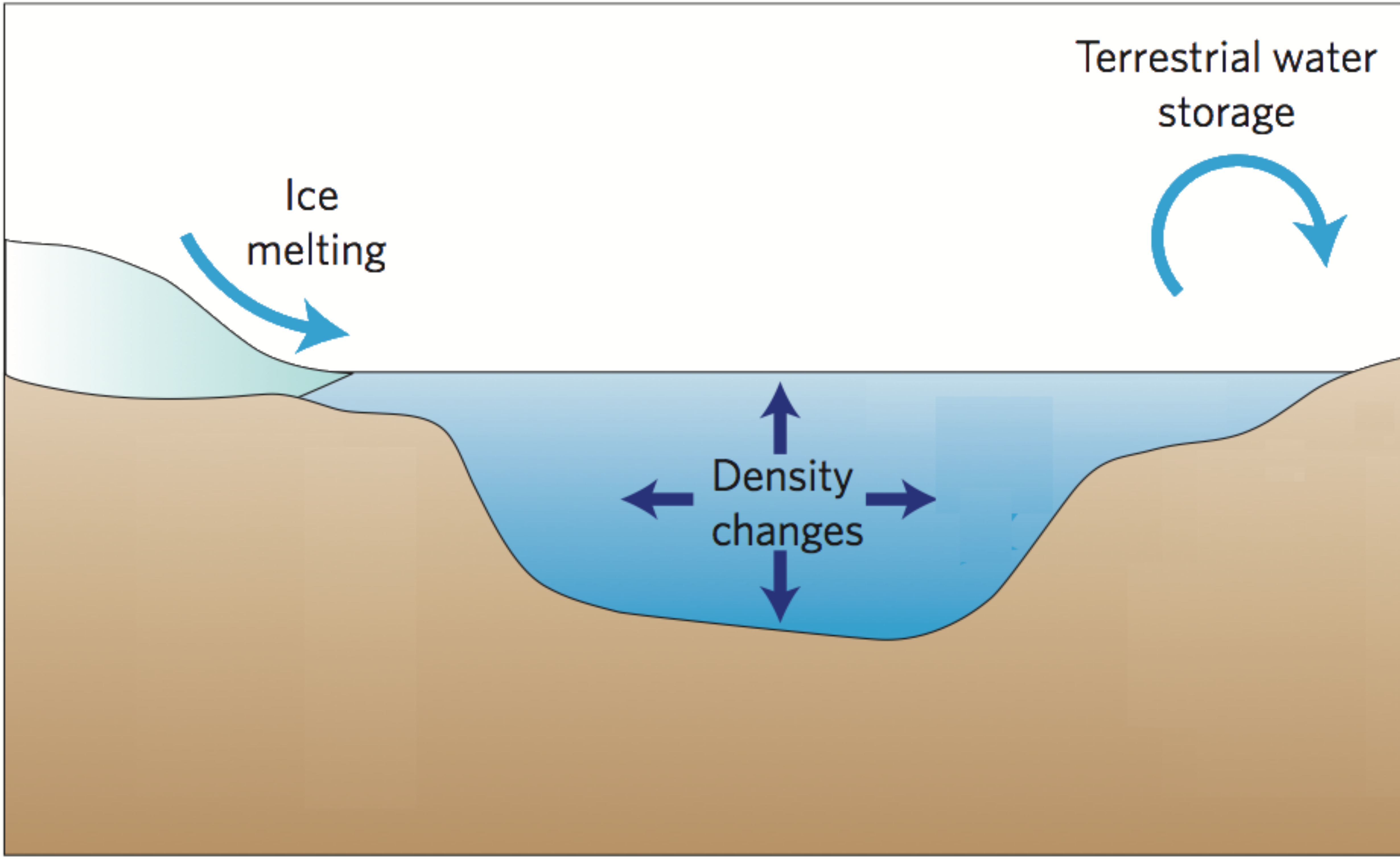
Source: PSE&G (2013)

Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites

Robert E. Kopp[1], Radley M. Horton[2], Christopher M. Little[3], Jerry X. Mitrovica[4], Michael Oppenheimer[3], D. J. Rasmussen[5], Benjamin H. Strauss[6] and Claudia Tebaldi[6,7]

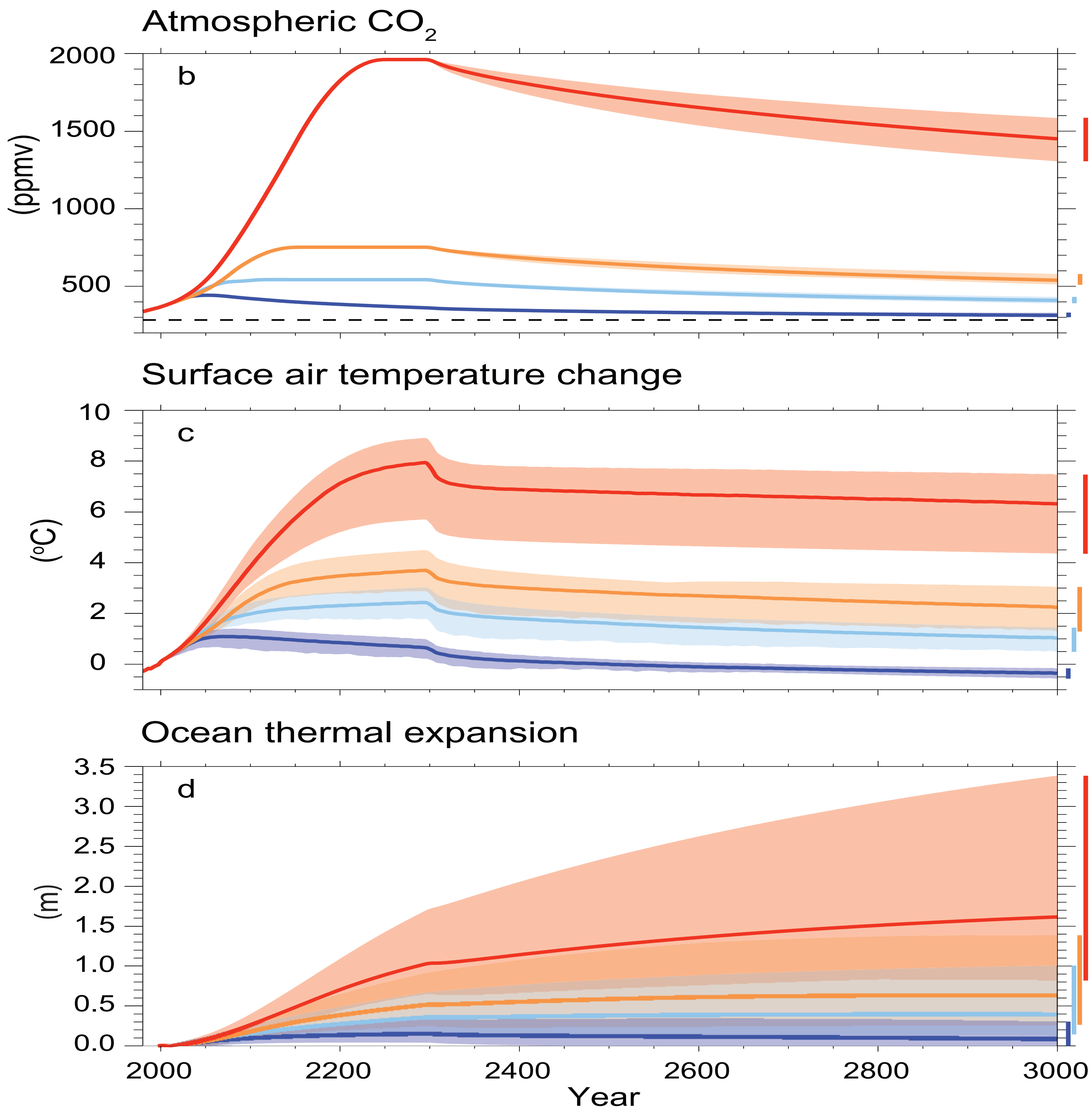
Kopp et al. (2014), Earth's Future

Sources of global sea-level change (and uncertainty)



Milne et al. (2009)

Thermal Expansion



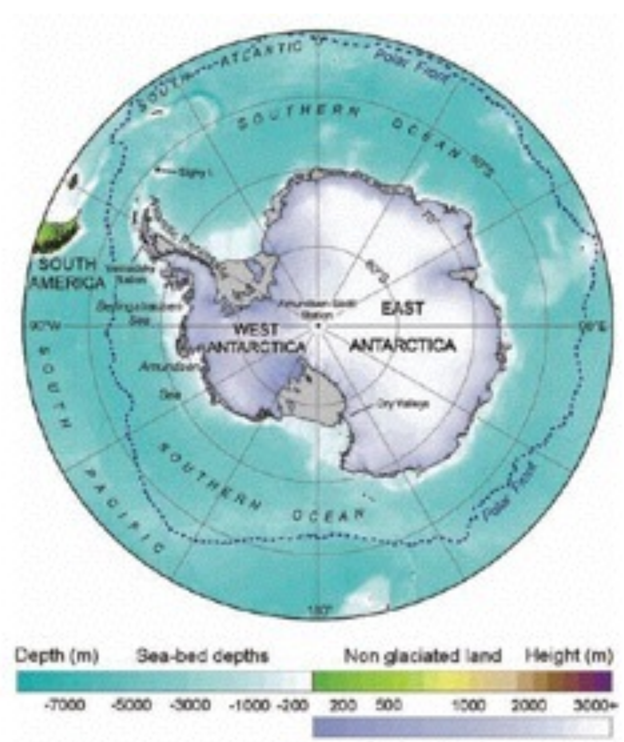
Compare observed thermal expansion of about 1.1 ± 0.3 mm/yr from 1993–2010

Collins et al. (2013)

Glacier and ice sheet melt

Total Hazard

Glaciers and ice caps	0.37 ± 0.02 m
Greenland Ice Sheet	7.4 m
West Antarctic + Antarctic Peninsula Ice Sheets	4.5 m
East Antarctic Ice Sheet	53.3 m

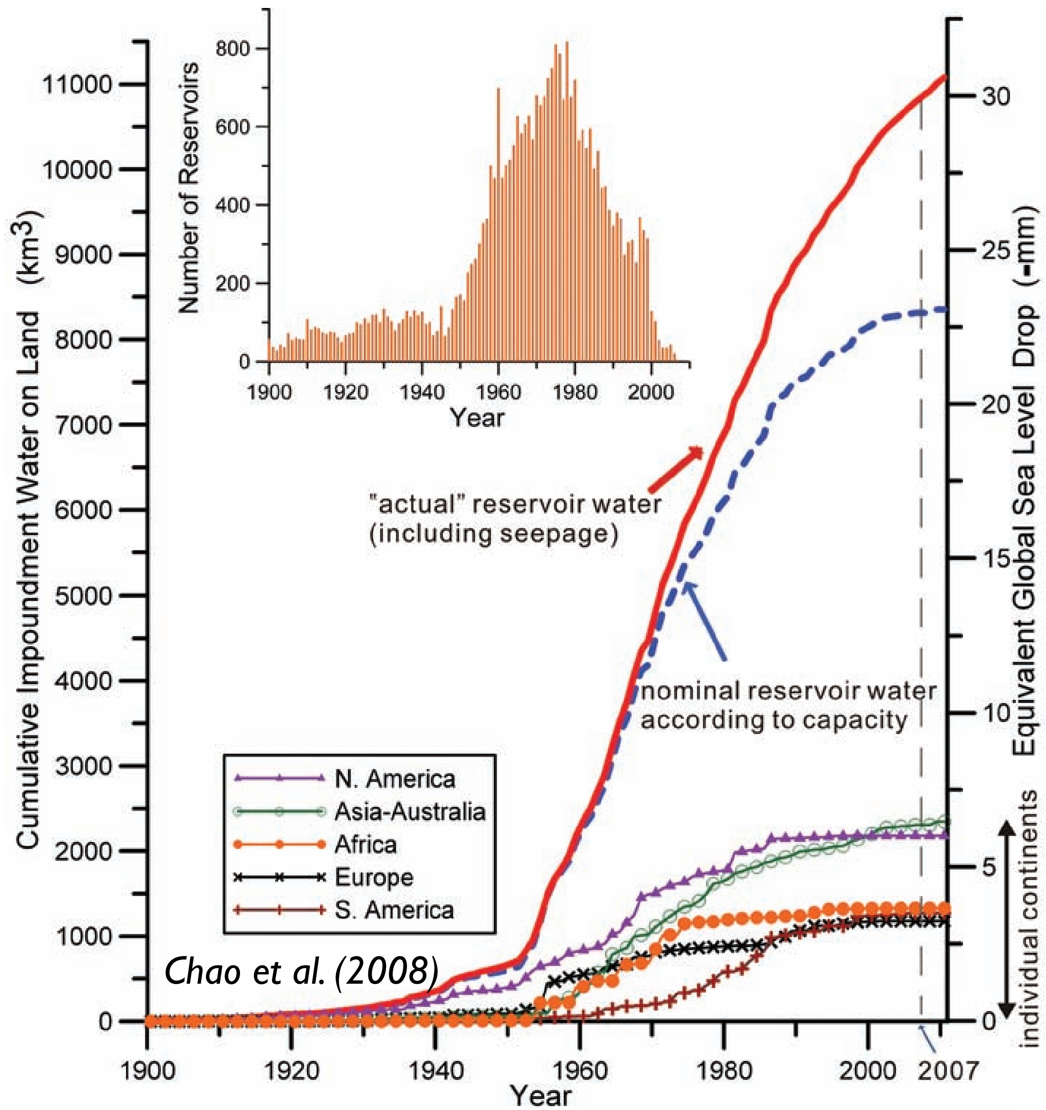


Maps by P. Fretwell (British Antarctic Survey)

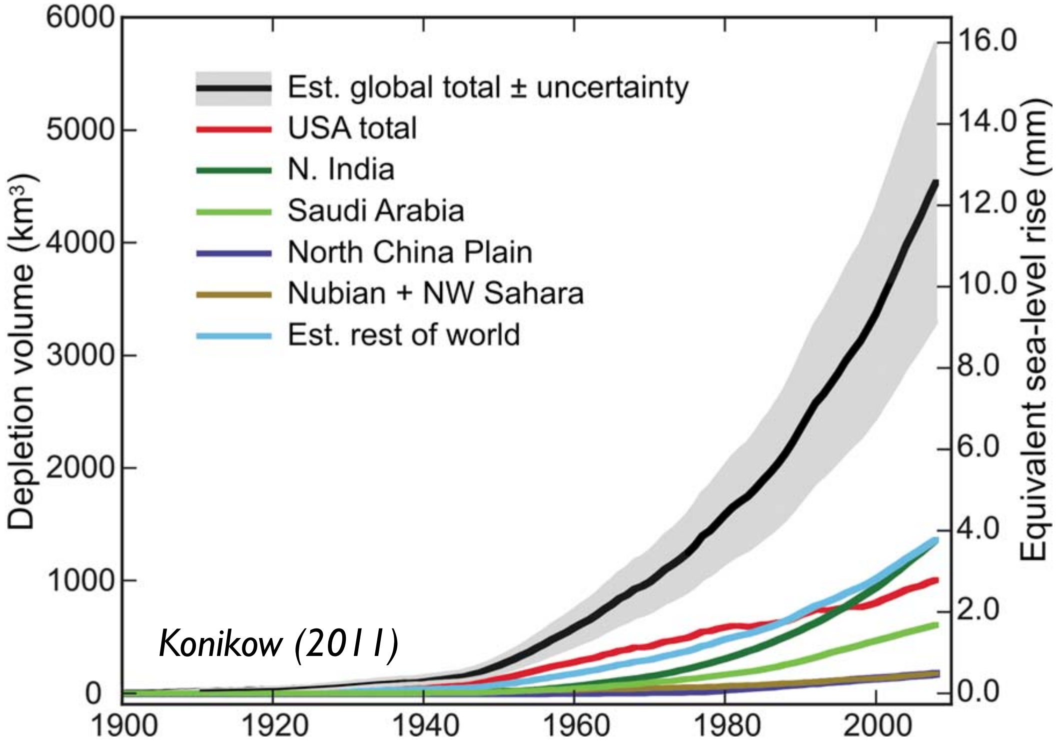
Marzeion et al. (2012); Bamber et al. (2013); Fretwell et al. (2013)

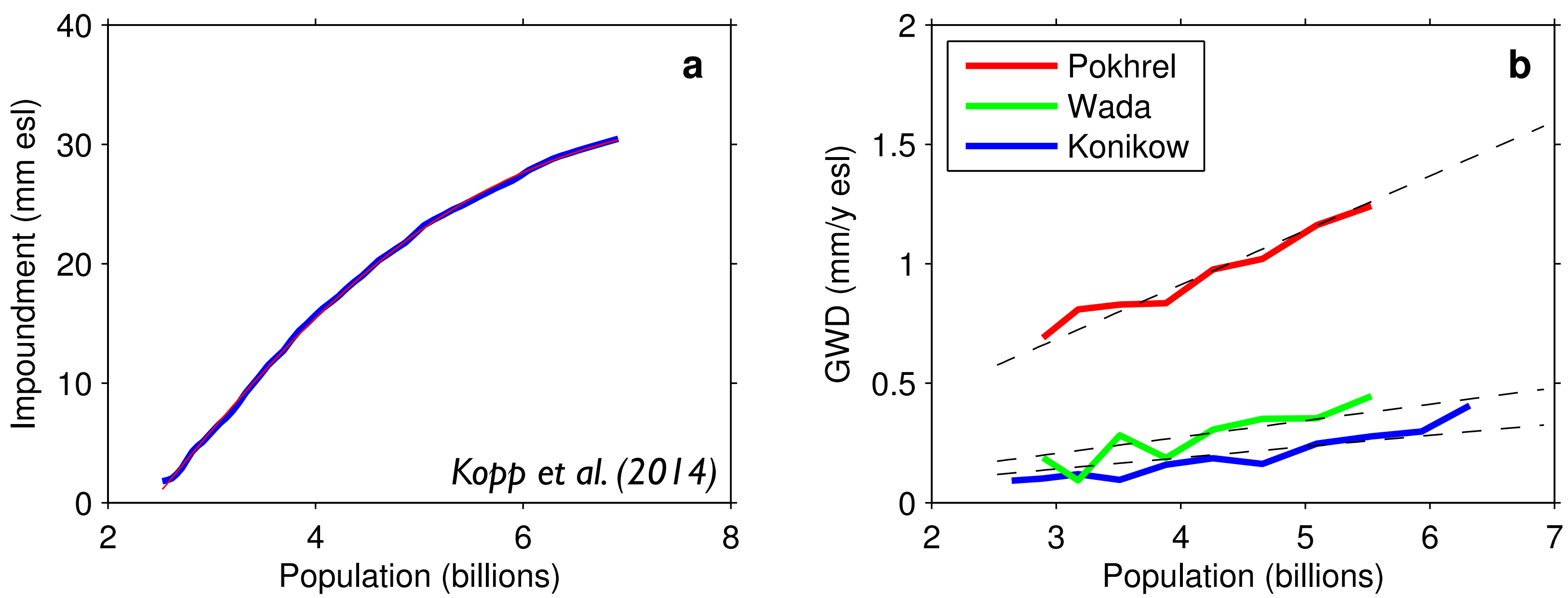
Land water storage

Dam construction

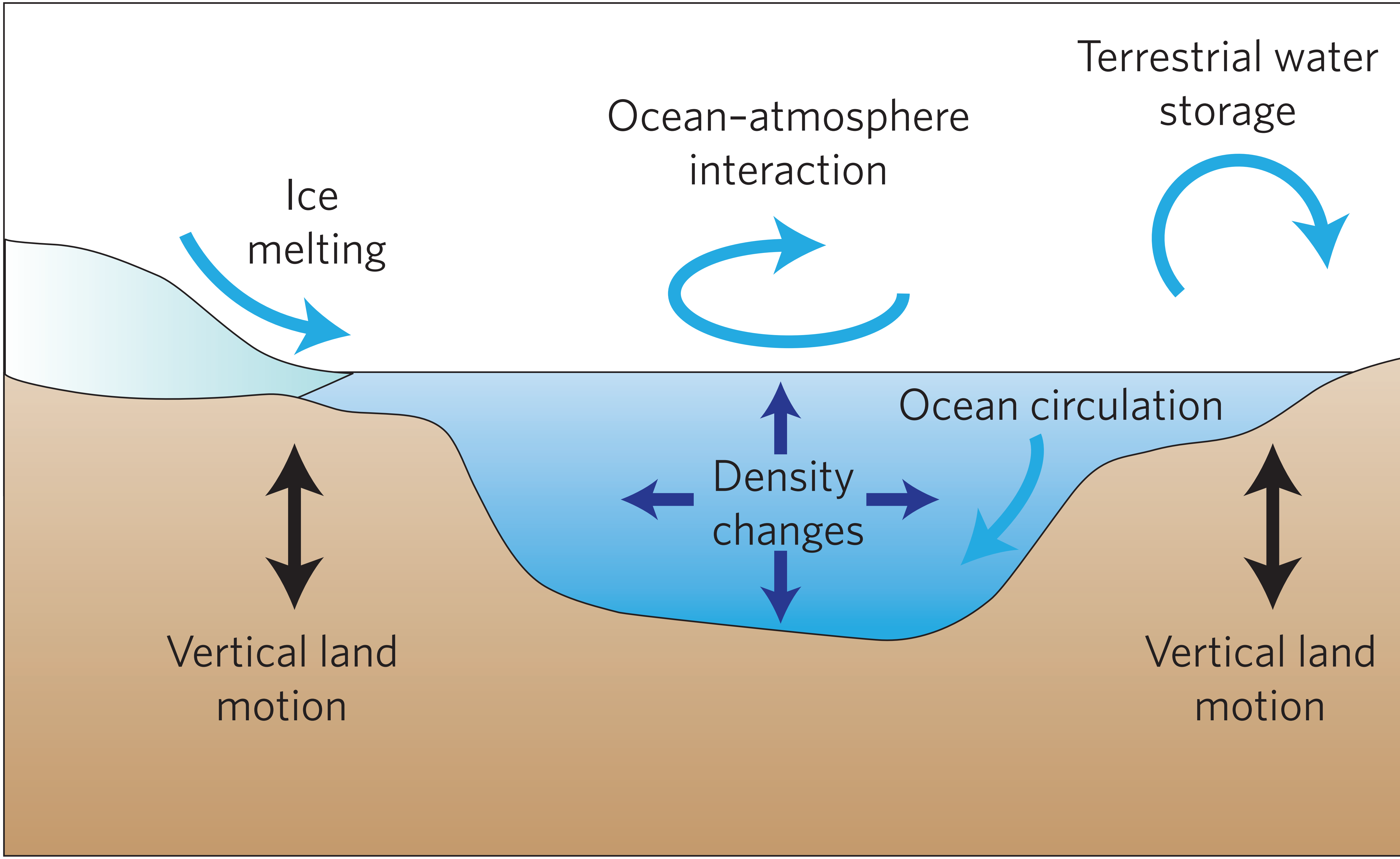


Groundwater withdrawal



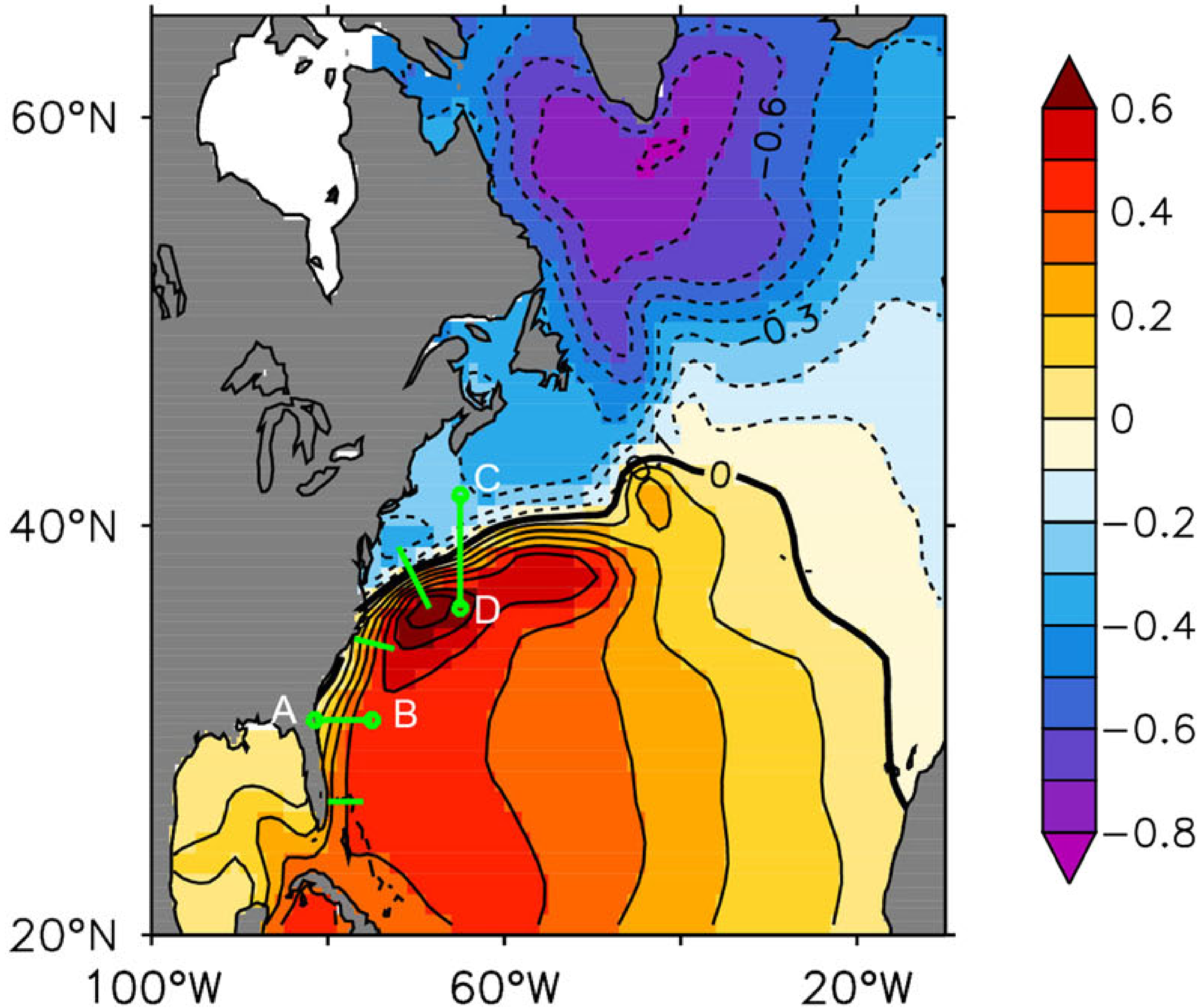


Sources of regional sea-level change (and uncertainty)



Milne et al. (2009)

Ocean circulation and ocean-atmosphere interaction

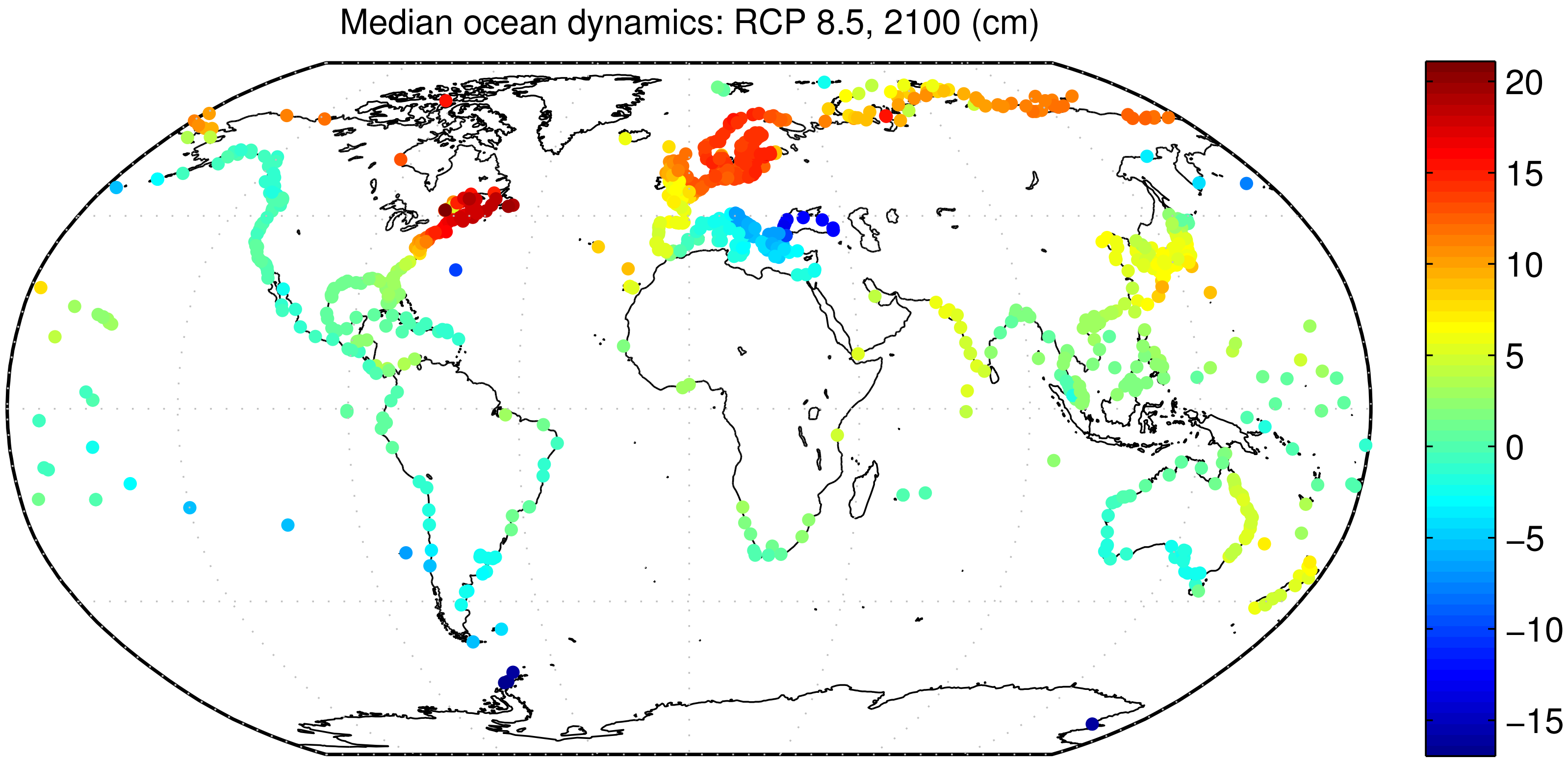


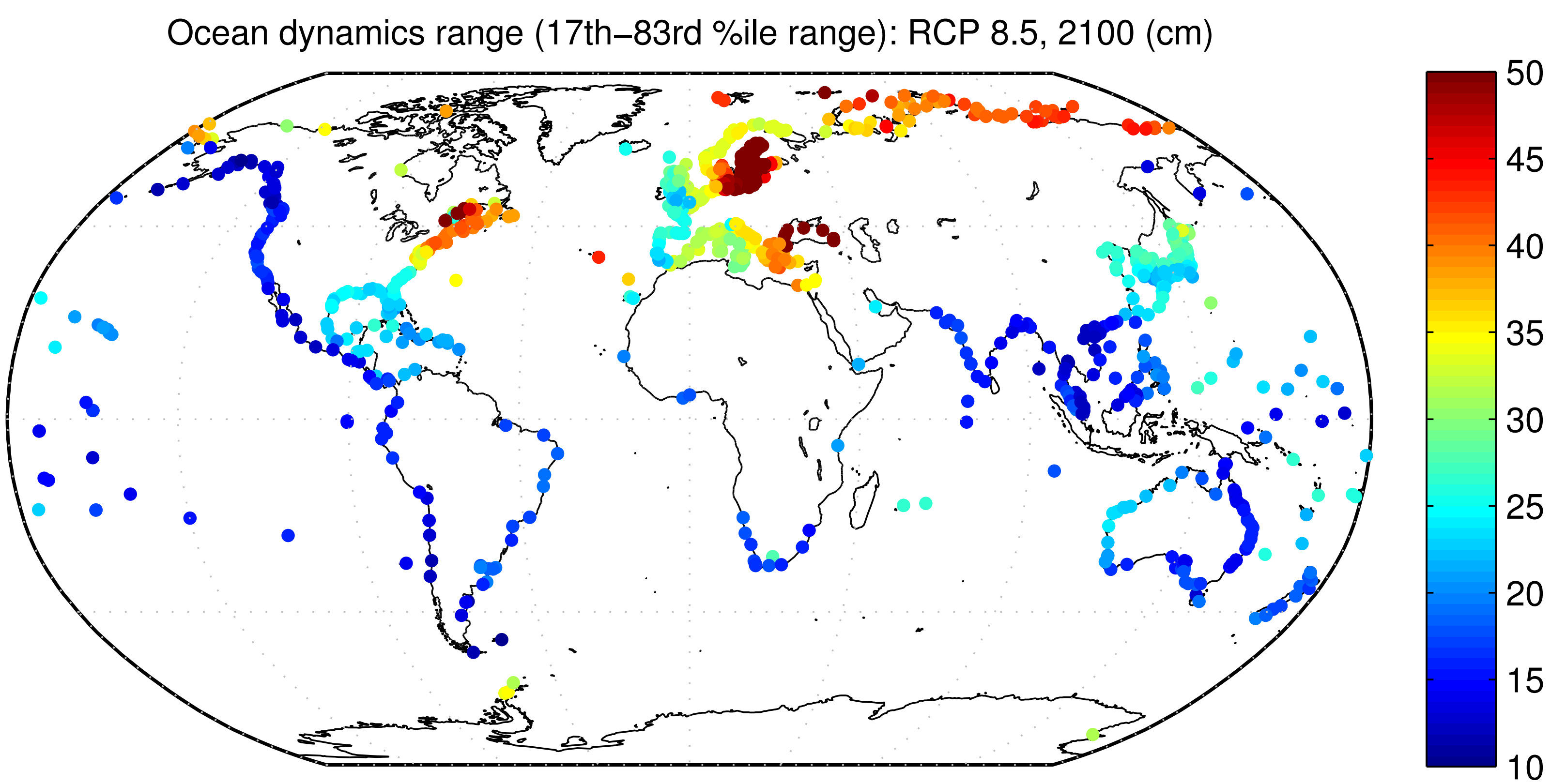
mean dynamic sea level, 1993-2010 (meters)

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.

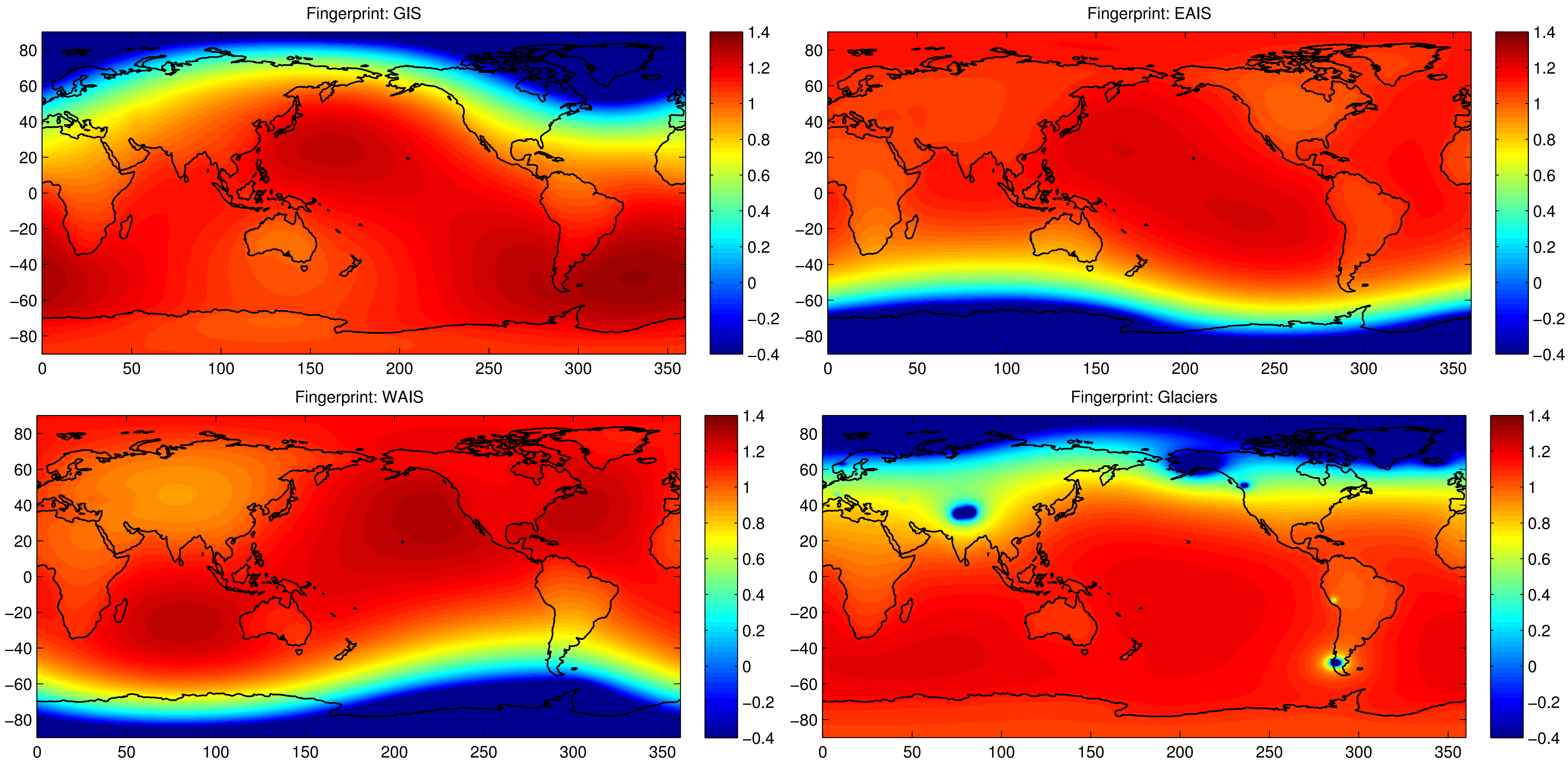
Yin and Goddard (2013)

CMIP5 projections of regional ocean dynamics



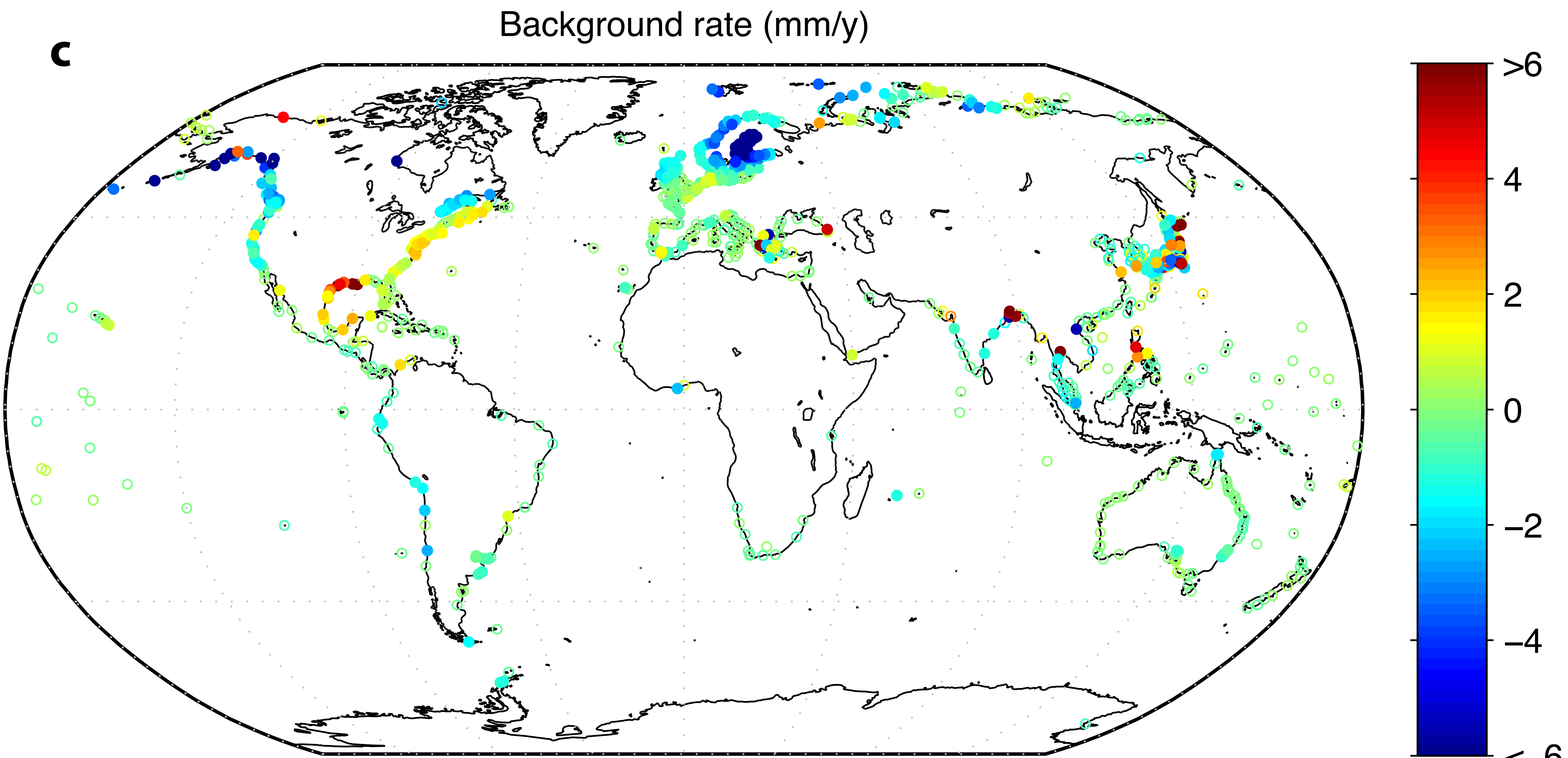


Static-equilibrium effects: Gravitational, rotational, and flexural changes caused by melting land ice



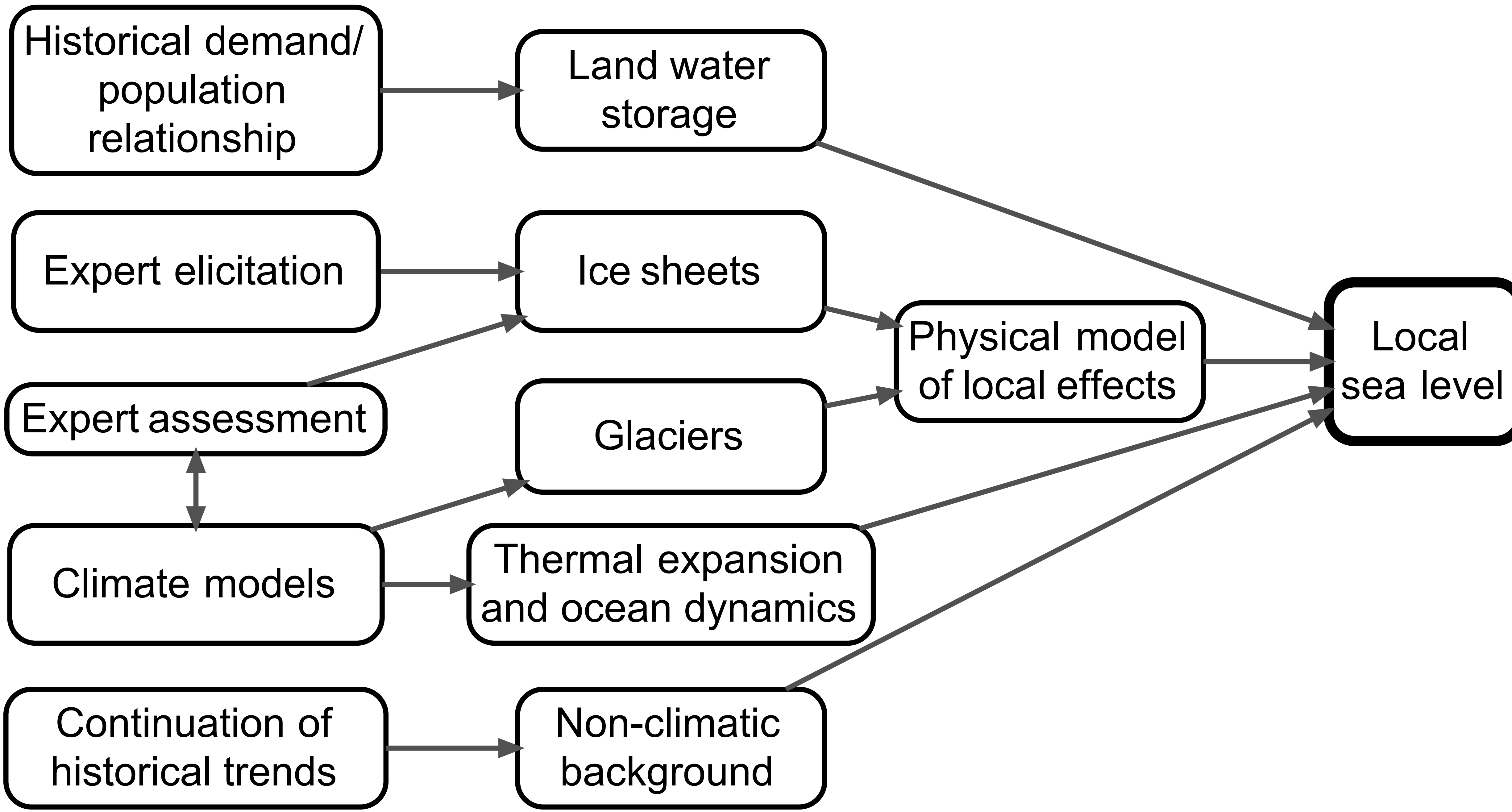
Kopp et al. (2014)

Sea levels are also rising because of glacial isostatic adjustment, tectonics, and fluid withdrawal.



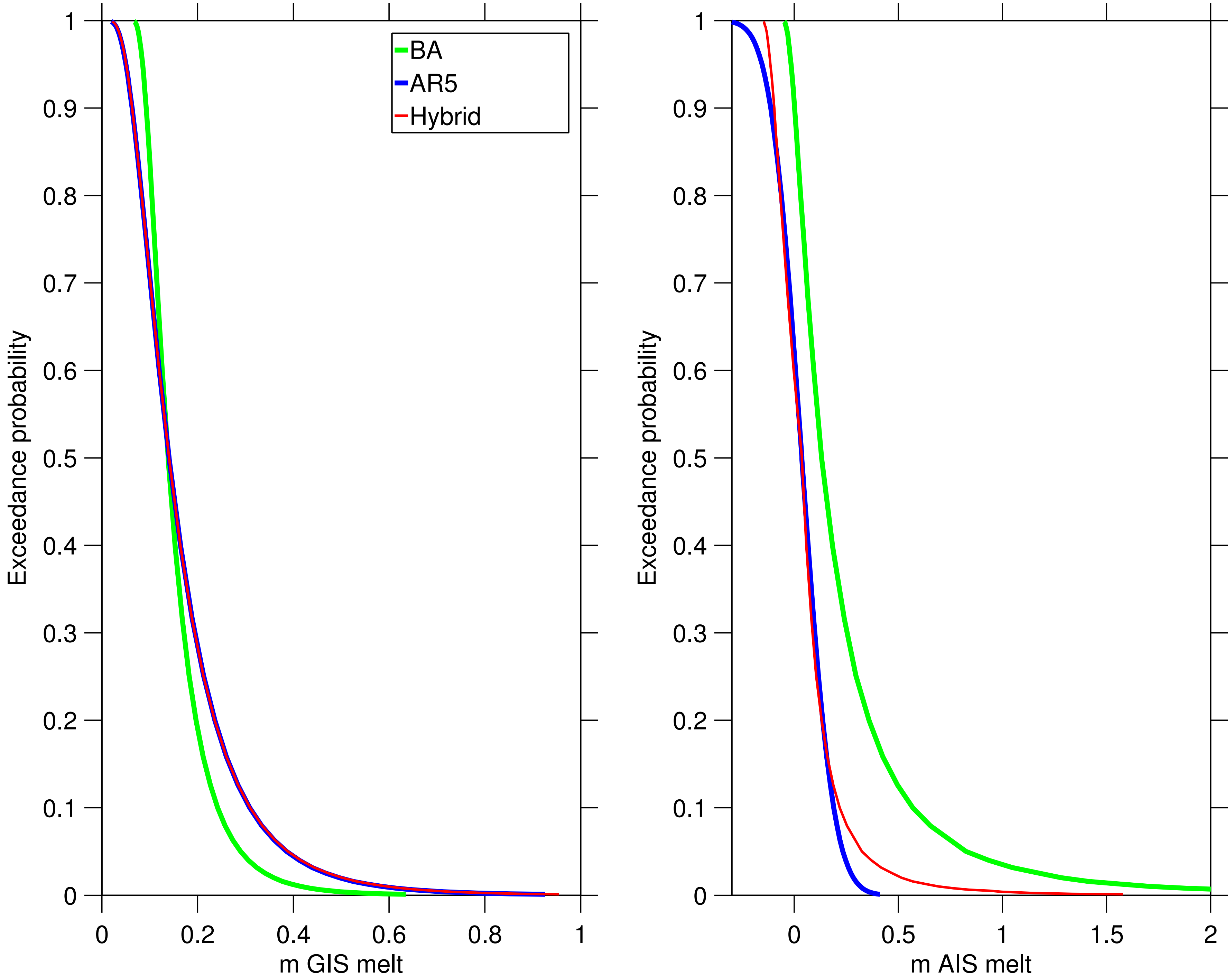
Kopp et al., 2014

Climate models don't project all the contributors to sea-level rise, and don't do all the ones they do include well, so we need to synthesize multiple lines of knowledge.



Kopp et al. (in review)

Reconciliation of IPCC and expert elicitation



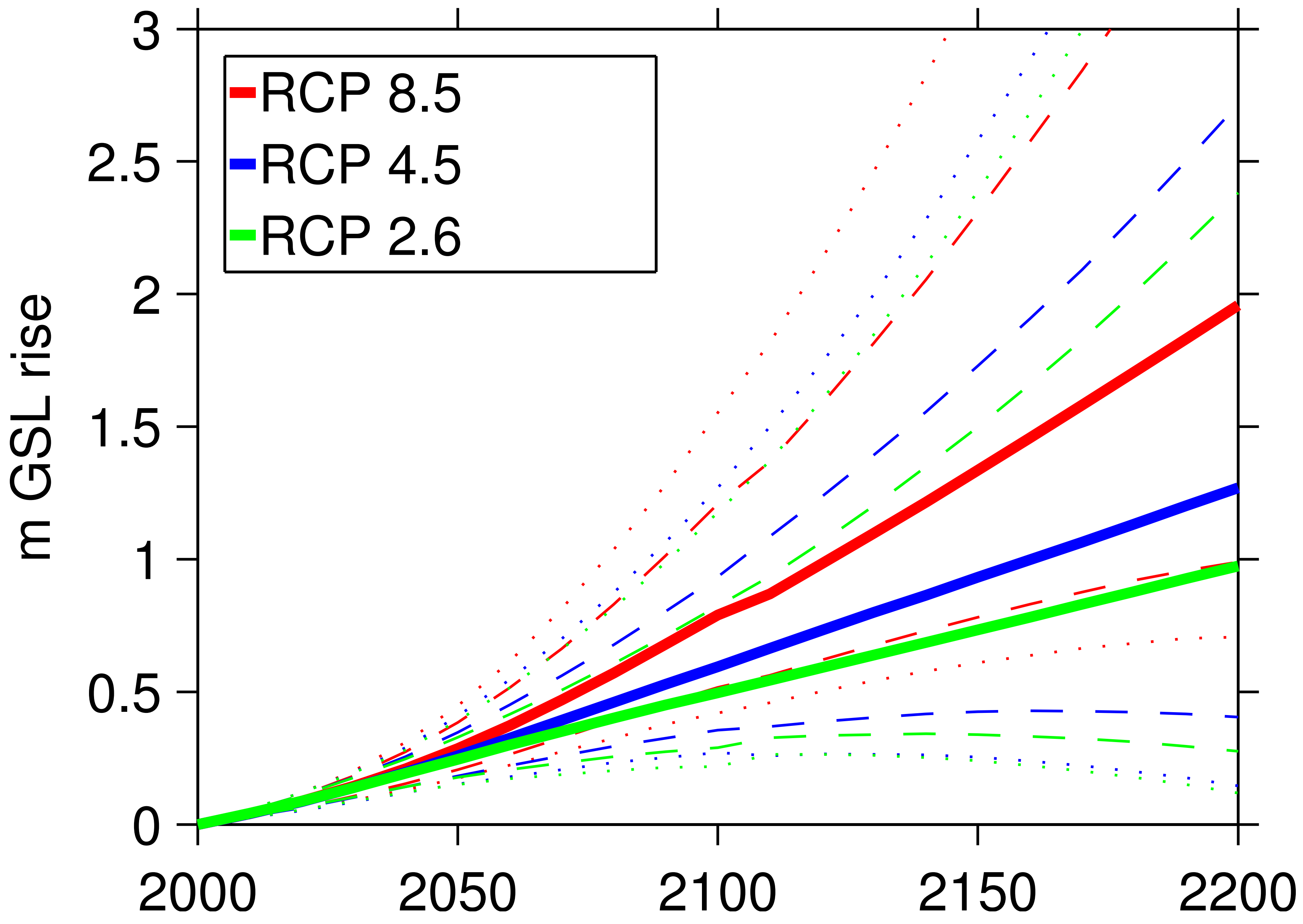
AIS mass loss
RCP 8.5, 2100

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.

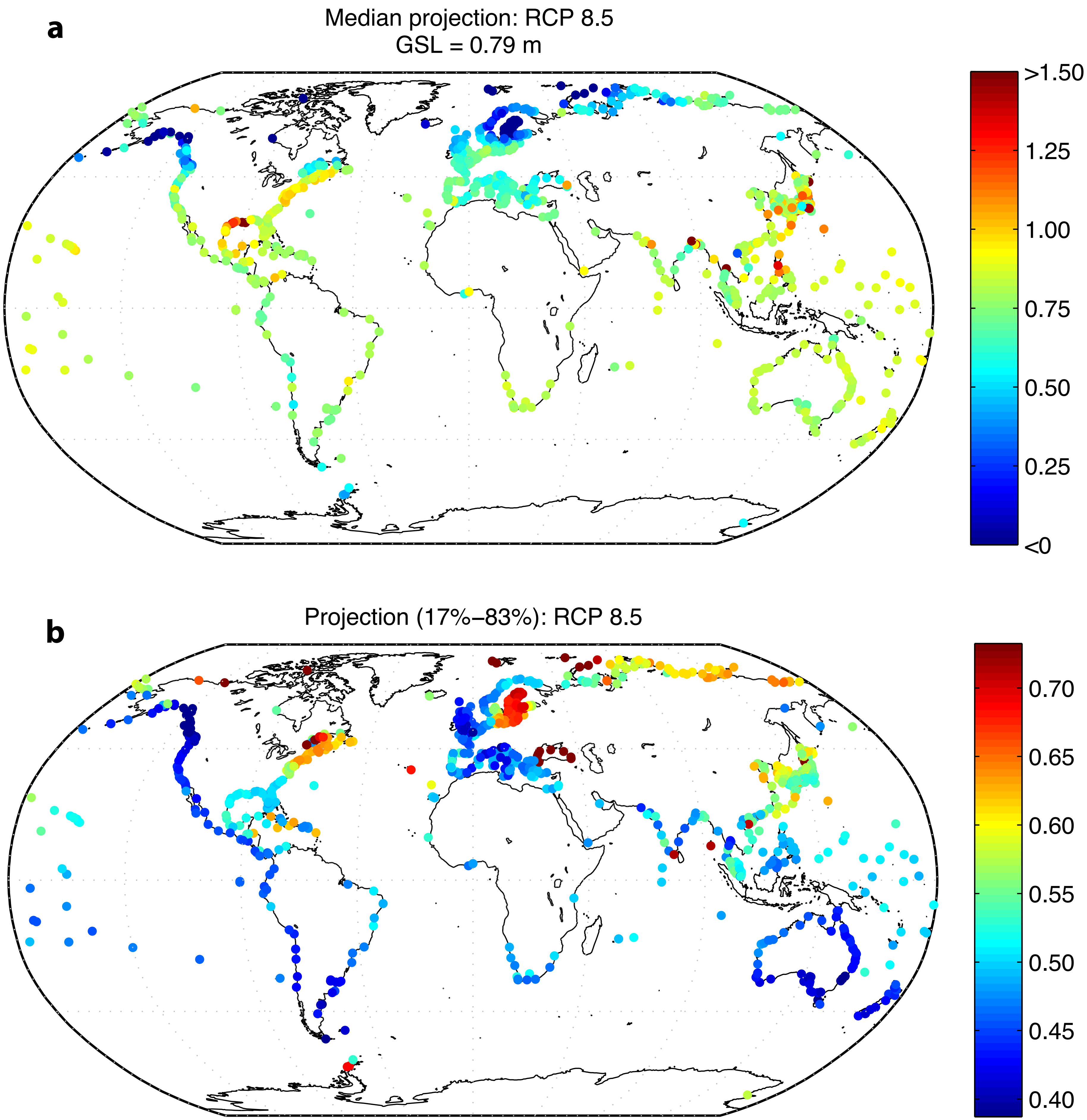
Kopp et al. (2014)

Projected global mean sea-level rise



	Likely	1-in-20	1-in-200	Max. possible
2050	0.8-1.1' (24-34 cm)	1.2' (38 cm)	1.6' (49 cm)	2.0' (60 cm)
2100, RCP 8.5	2.1-3.3' (62-100 cm)	4.0' (121 cm)	5.8' (176 cm)	8.0' (245 cm)
2100, RCP 2.6	1.2'-2.1' (37-65 cm)	2.7' (82 cm)	4.6' (141 cm)	6.9' (210 cm)

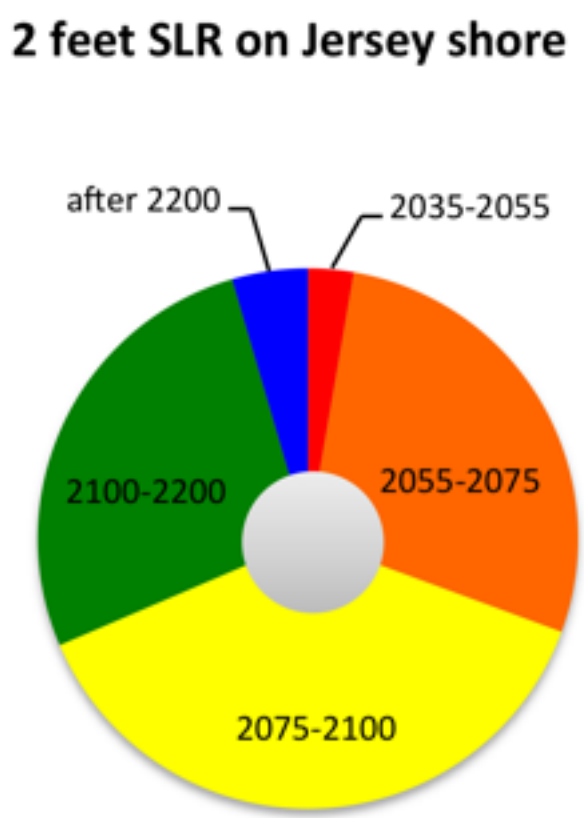
Kopp et al. (2014)

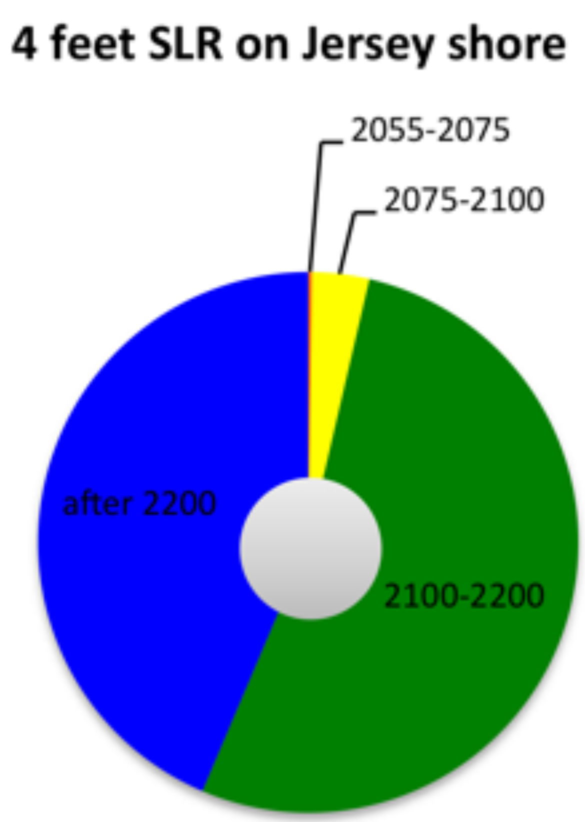


Projections vary globally

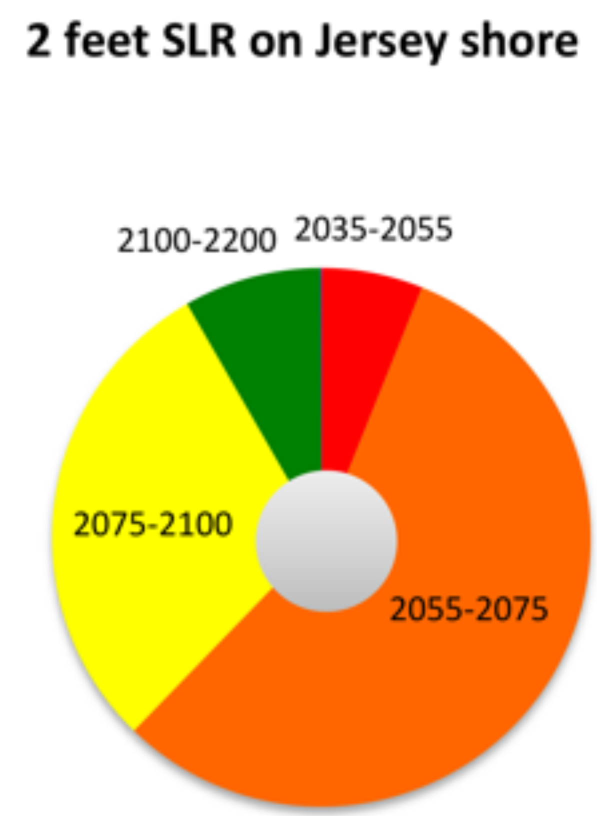
(RCP 8.5, 2100)

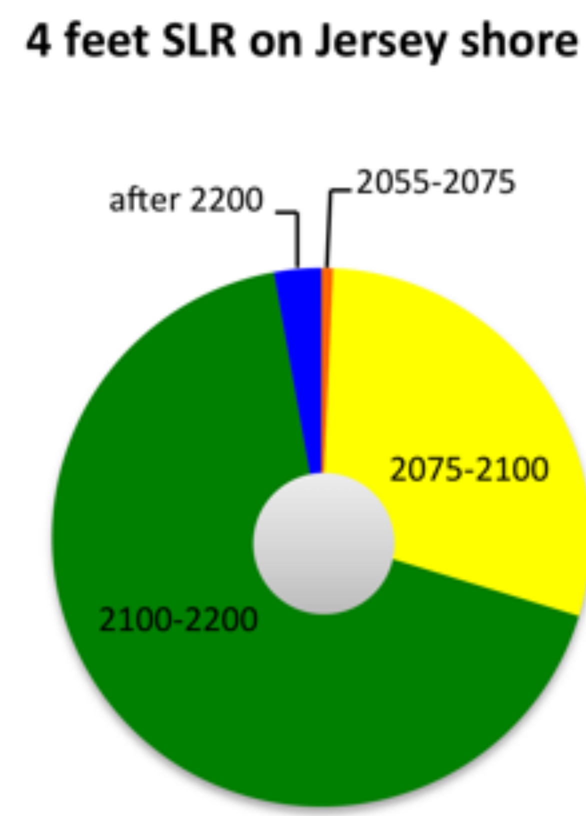
RCP 2.6


2 feet SLR on Jersey shore
after 2200
2035-2055
2100-2200
2055-2075
2075-2100

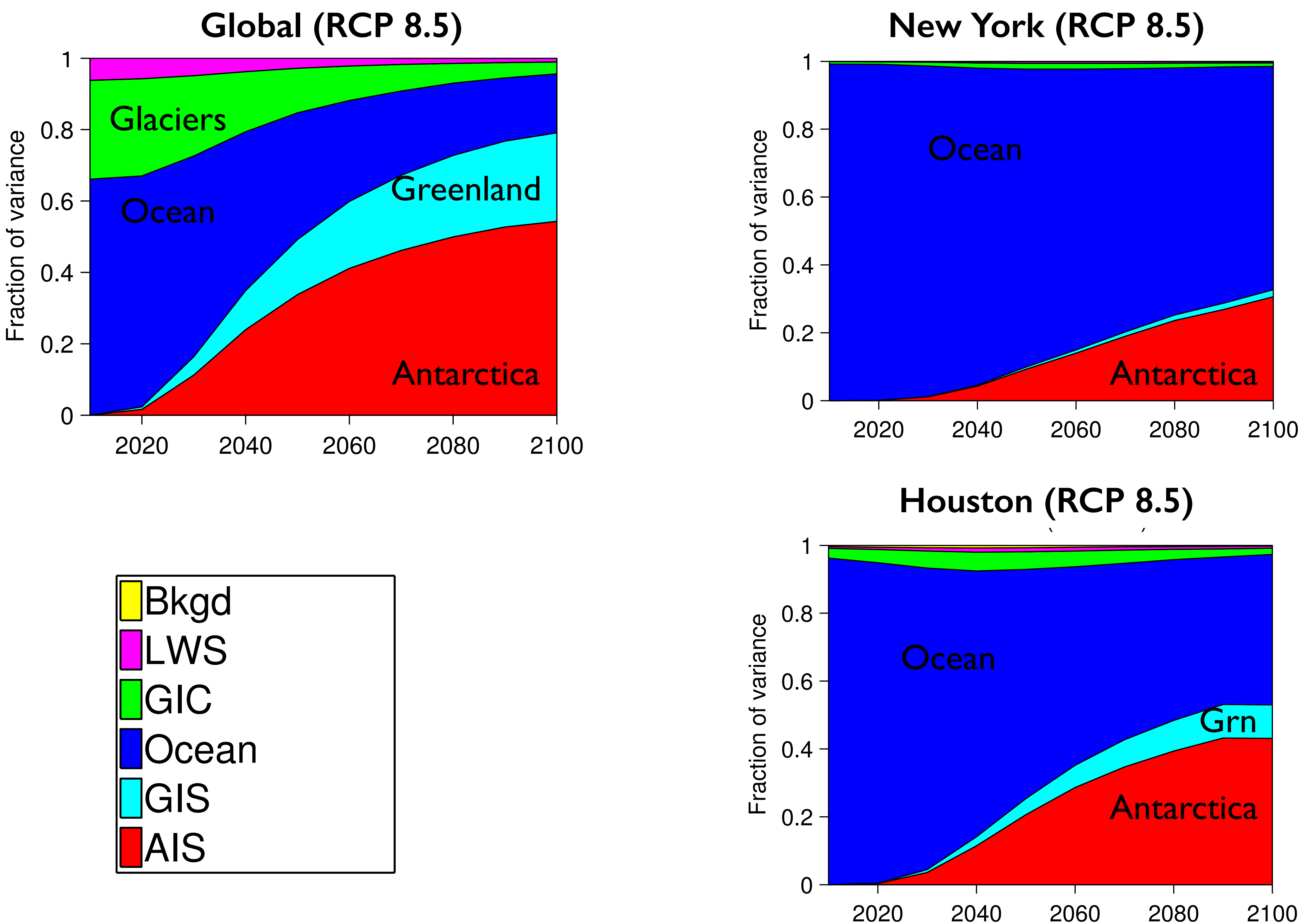

4 feet SLR on Jersey shore
2055-2075
2075-2100
after 2200
2100-2200

RCP 8.5


2 feet SLR on Jersey shore
2100-2200
2035-2055
2075-2100
2055-2075


4 feet SLR on Jersey shore
after 2200
2055-2075
2075-2100
2100-2200

Sources of uncertainty change over space and time



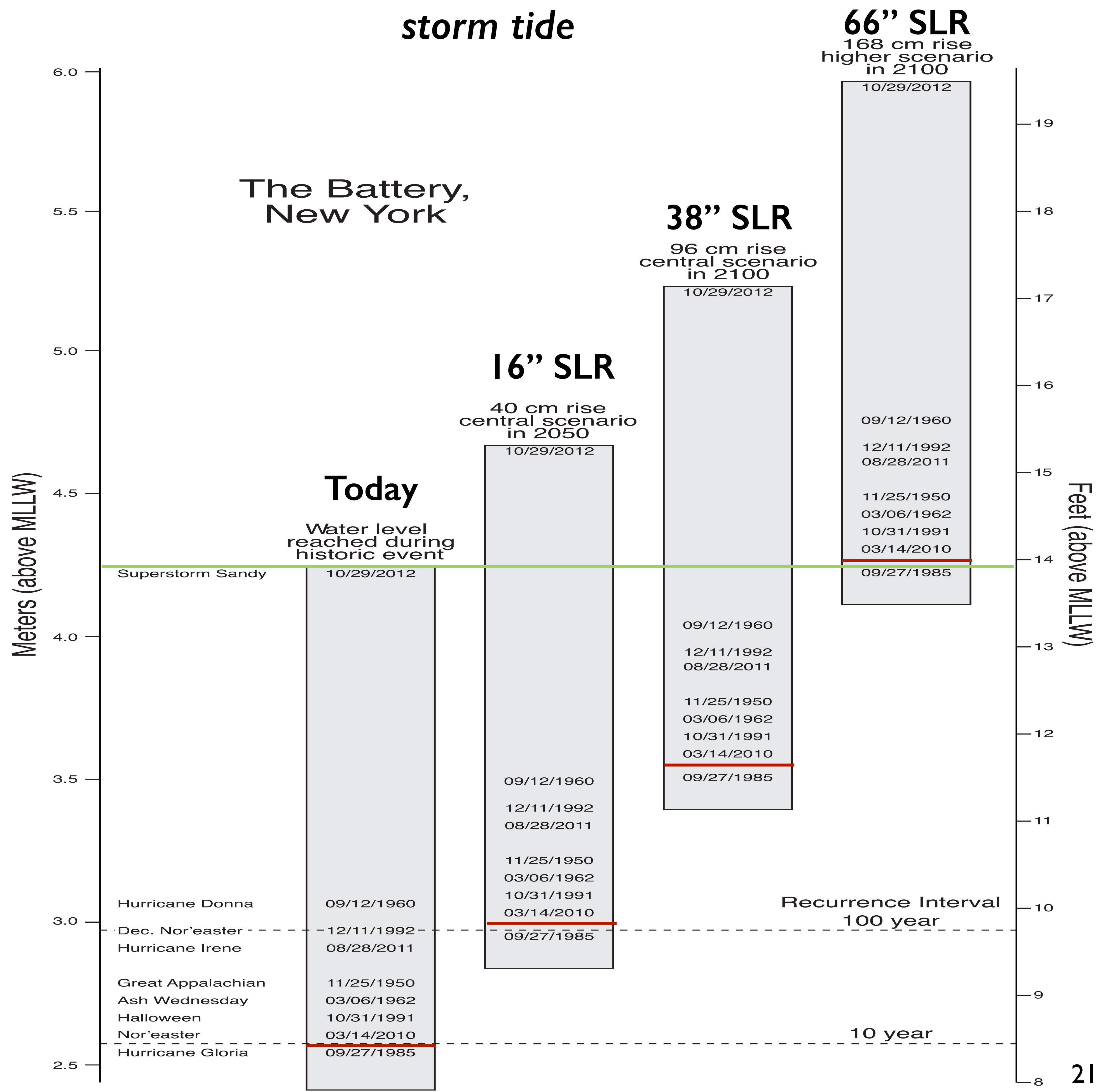
Kopp et al. (2014)

Coastal flooding

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)

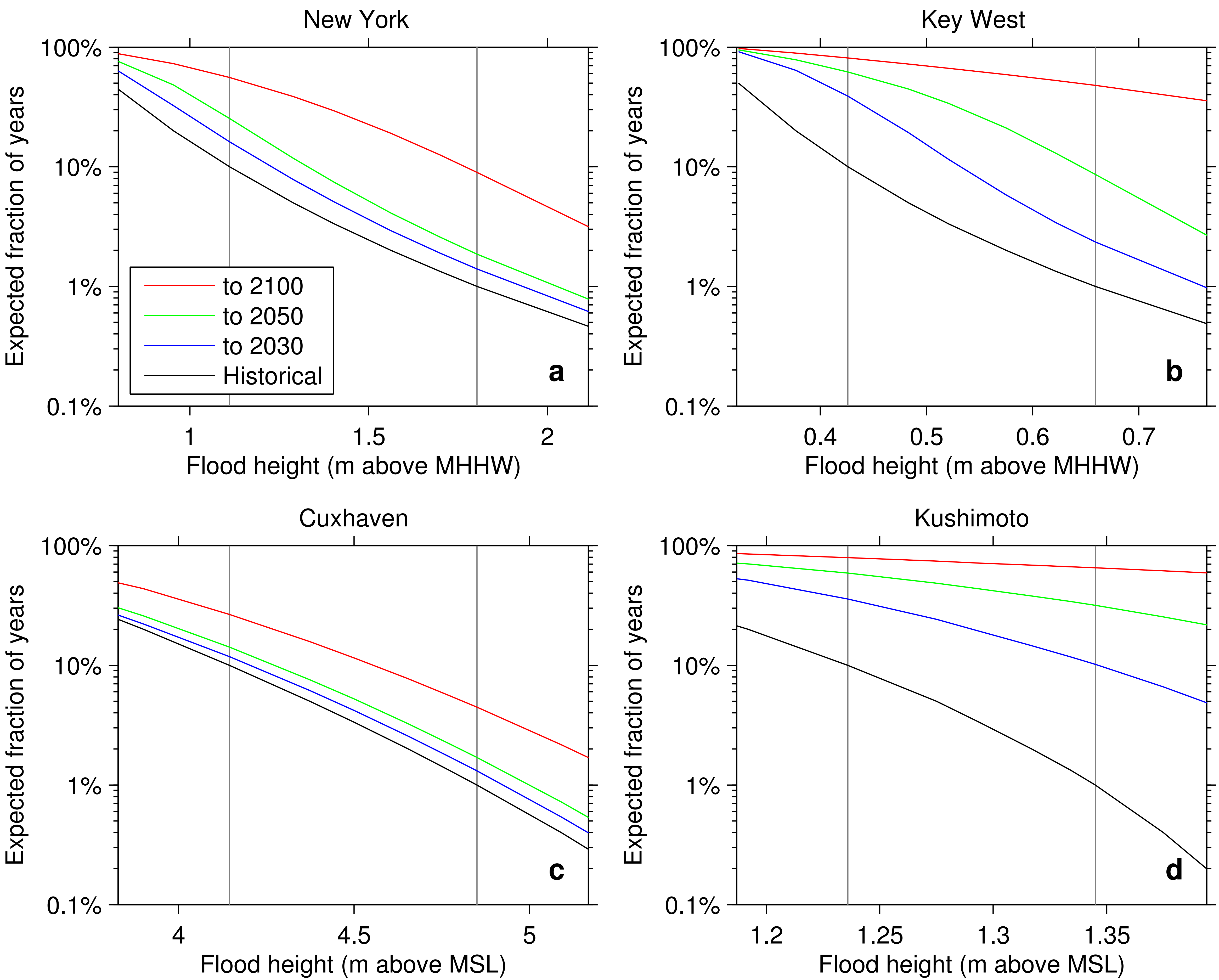
Coastal flooding

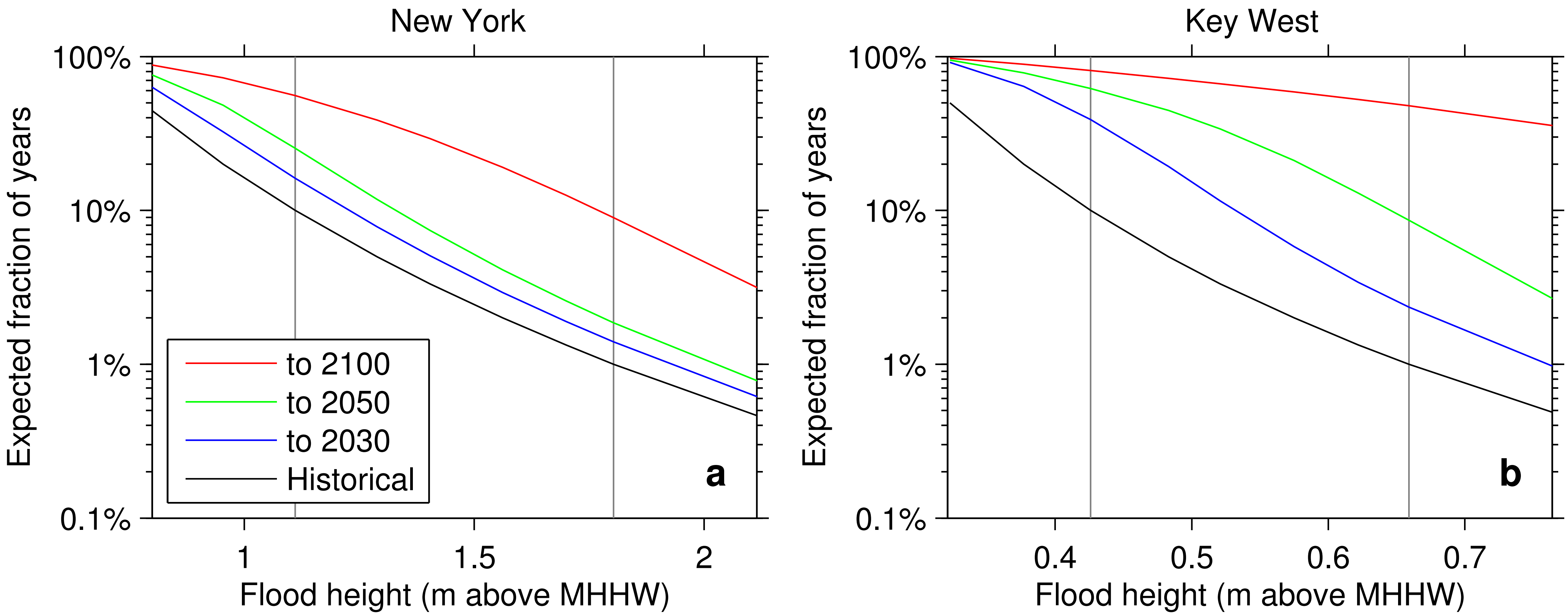
Areas submerged with 9' sea level rise plus storm surge (= Sandy today, 1-in-10 year storm w/5' sea-level rise)

<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)
http://sealevel.climatecentral.org/

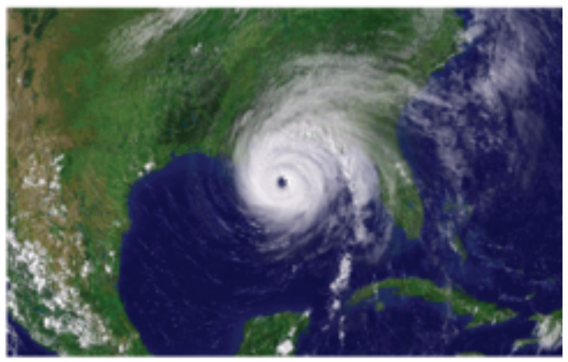

New York
Key West
Cuxhaven
Kushimoto
Expected fraction of years
100%
10%
1%
0.1%
Flood height (m above MHHW)
Flood height (m above MSL)
to 2100
to 2050
to 2030
Historical
a
b
c
d
1
1.5
2
0.4
0.5
0.6
0.7
4
4.5
5
1.2
1.25
1.3
1.35



Key West	'1-in-10 year'	'1-in-100 year'
2000–2030	12	0.7
2000–2050	31	3–4
2000–2100	81	40–50
No SLR, 2000–2100	10	1

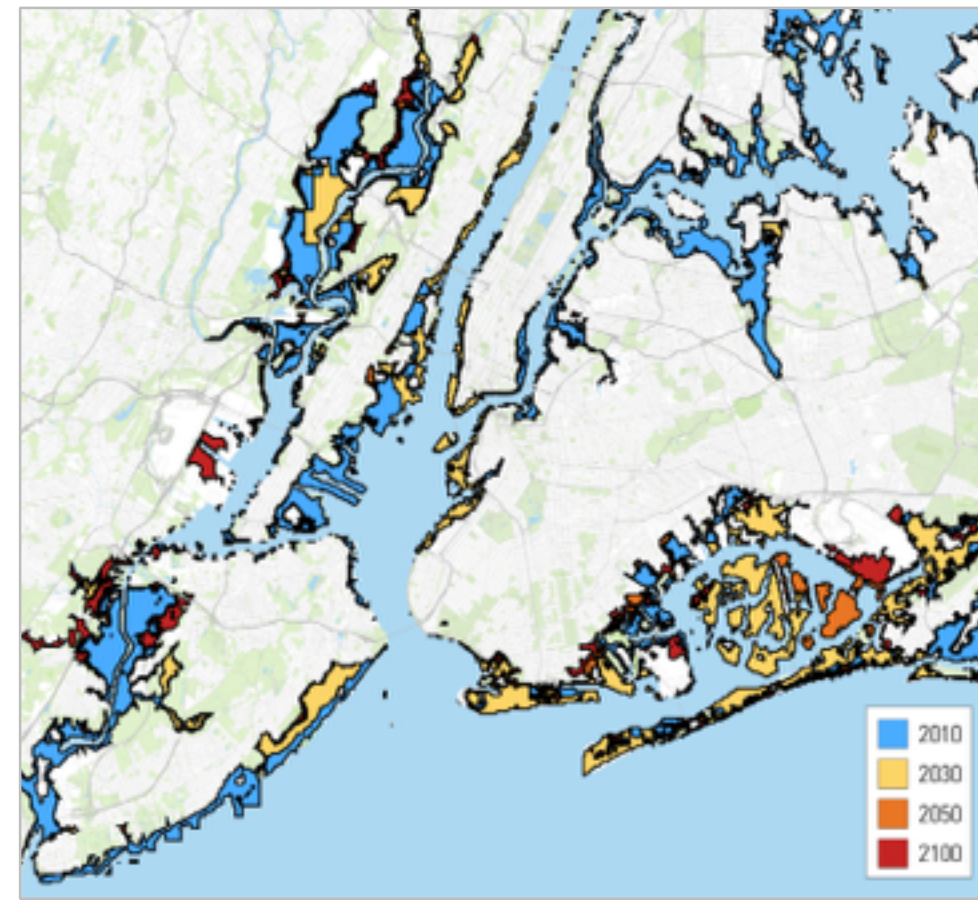
Coastal property

Tropical Cyclone Activity



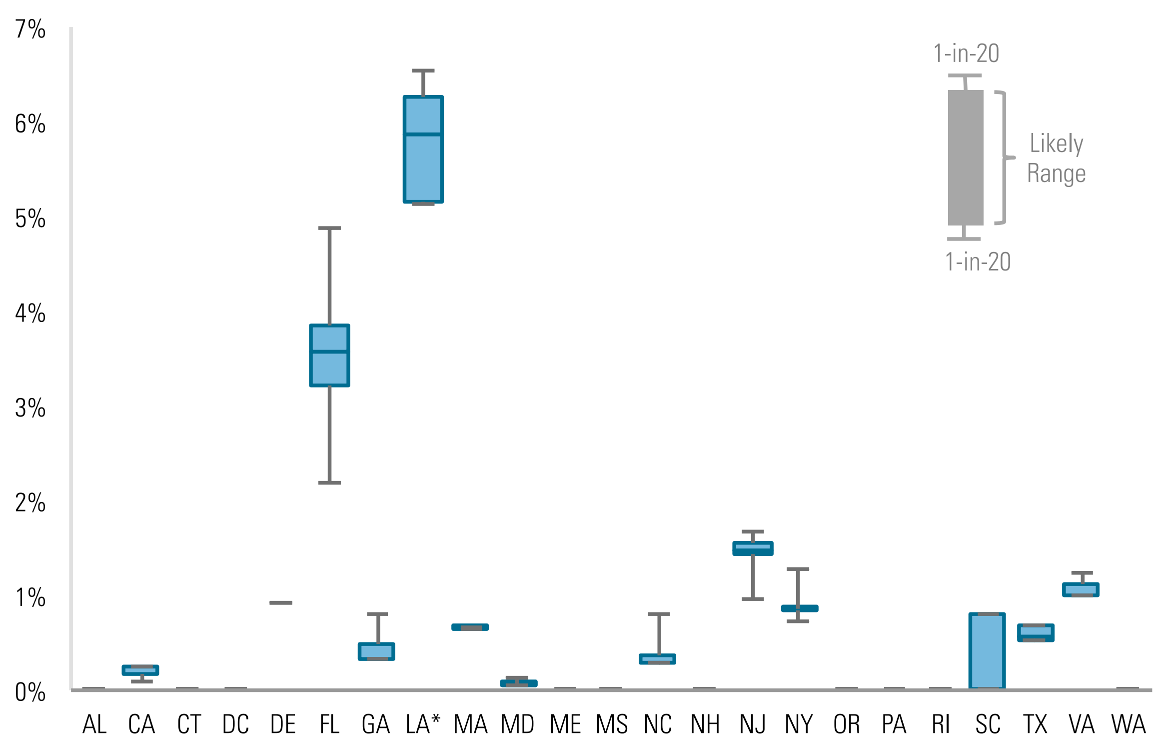
Sea-Level Rise

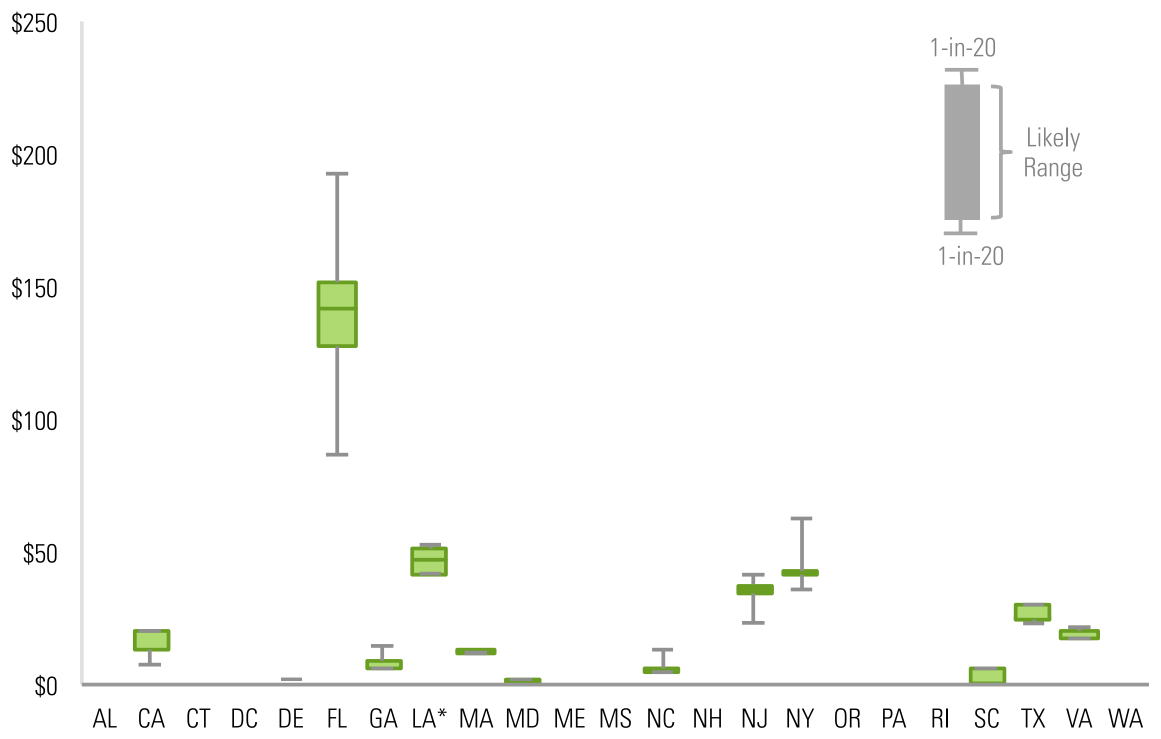
RMS North Atlantic Hurricane Model



Coastal property: property loss to SLR

Additional insurable property below mean higher high water, RCP 8.5 2050 (percent of statewide property/billion USD)

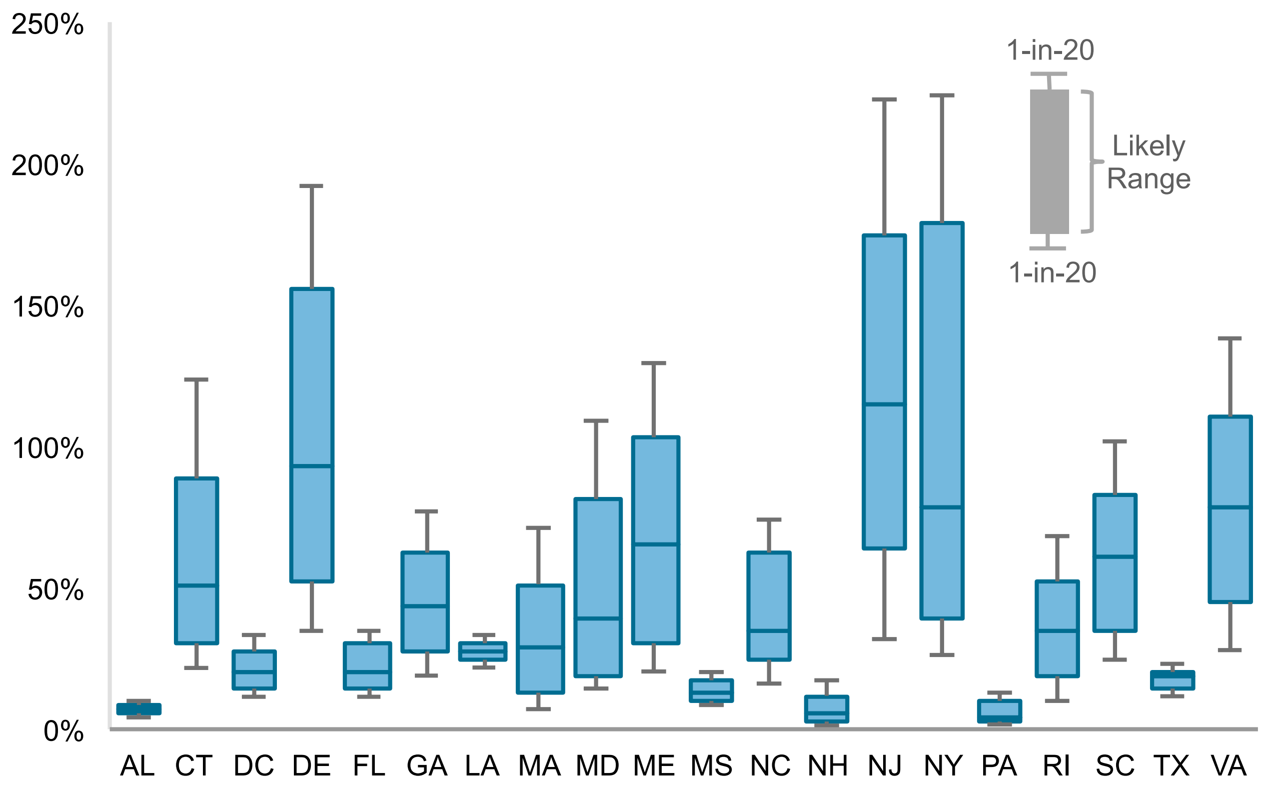




Probability	RCP 8.5		RCP 4.5		RCP 2.6	
	MSL	High Tide	MSL	High Tide	MSL	High Tide
1-in-100 chance above	$156	$523	$143	$472	$129	$456
1-in-20 chance above	$126	$465	$107	$400	$106	$397
Likely range	$66 to $106	$323 to $389	$62 to $85	$294 to $366	$62 to $85	$287 to $360
1-in-20 chance below	$61	$256	$60	$240	$60	$226
1-in-100 chance below	$52	$186	$51	$181	$50	$172

Coastal property: flood damage due to SLR

Average annual coastal flood damage (property + business interruption) RCP 8.5 2050 (percent/million USD increase)



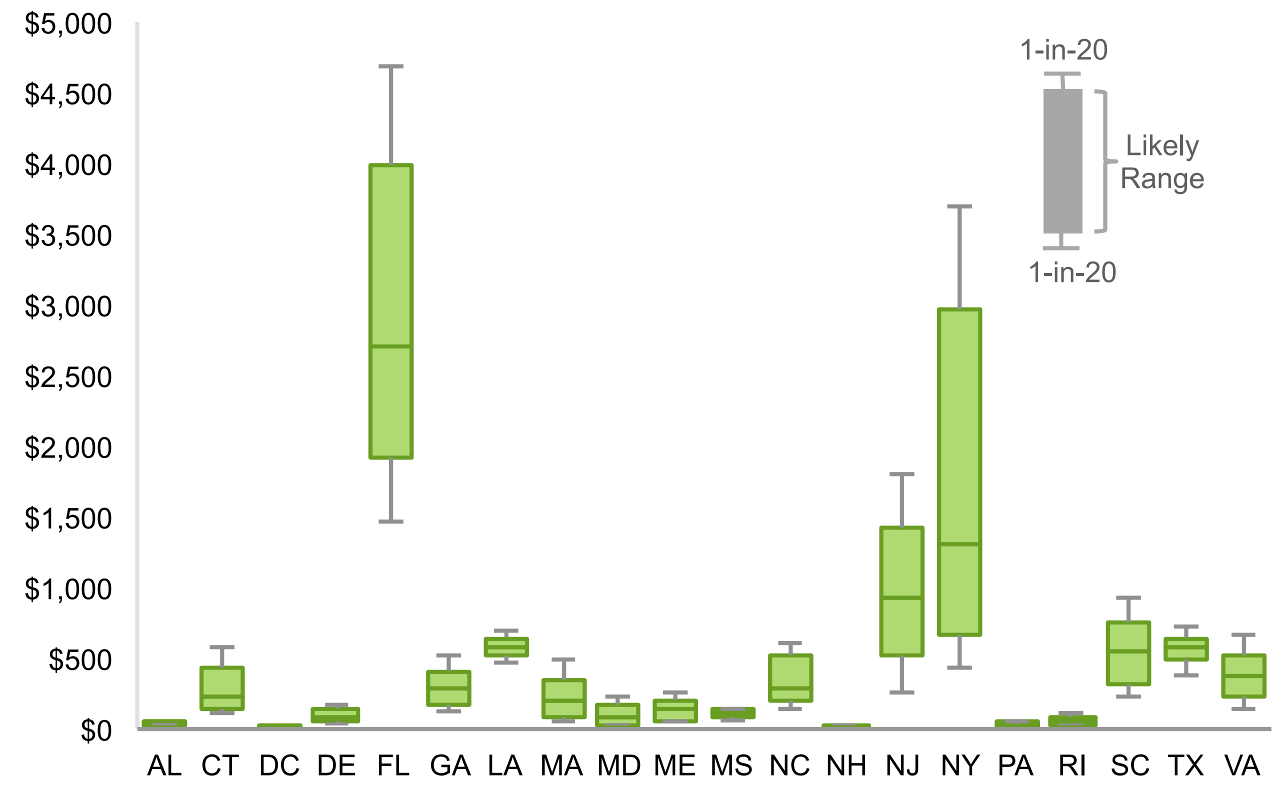
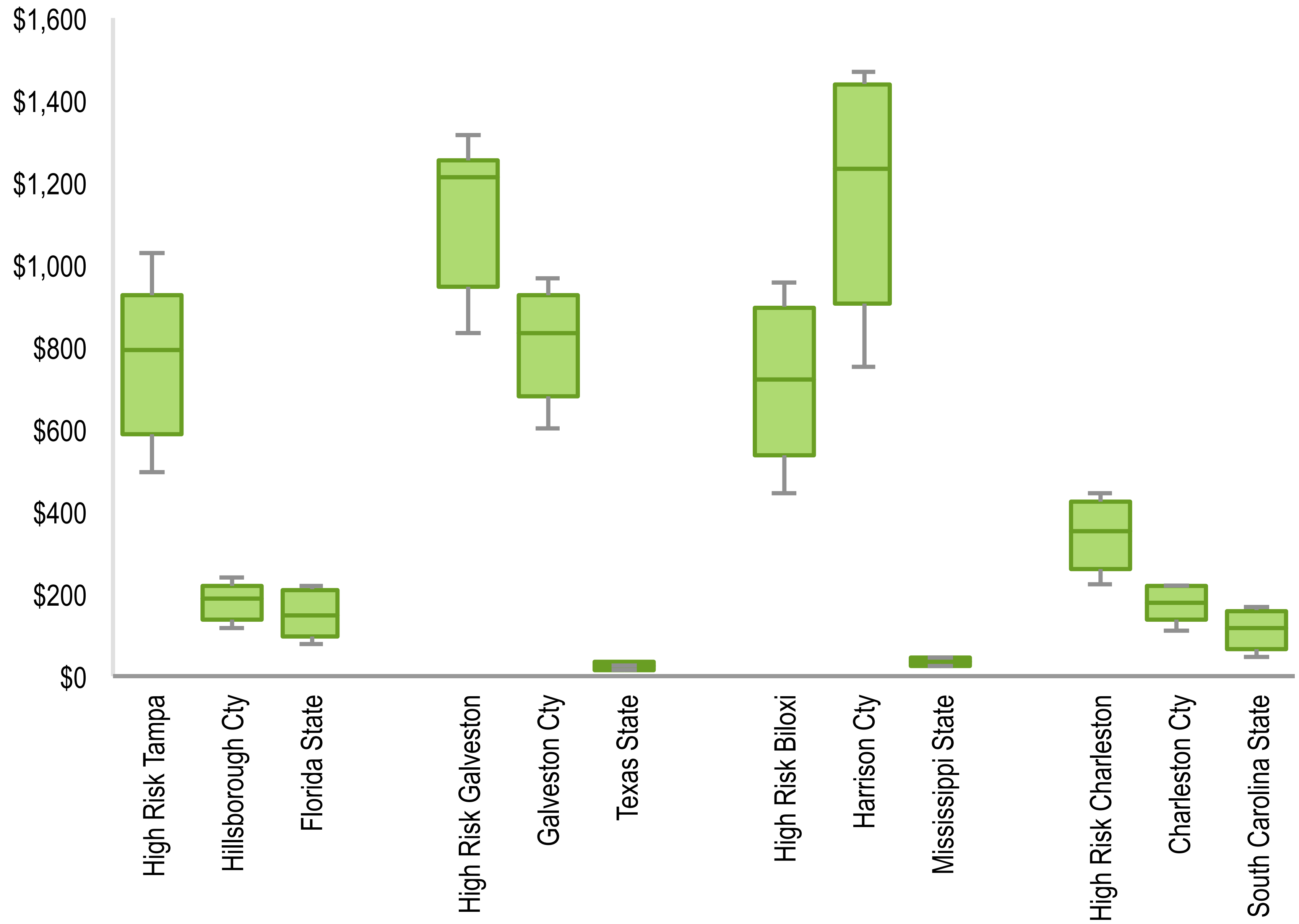


Table 1: Number of Stochastic Events "Hitting" a Country or a Combination of Countries

	U.S.	Canada	U.S. or Canada
Number of events	32,702	10,648	37,538

Coastal property: distribution of flood damages

Damages to high-risk coastal dwellings vs. county and state averages
RCP 8.5 2050 (dollars per capita)

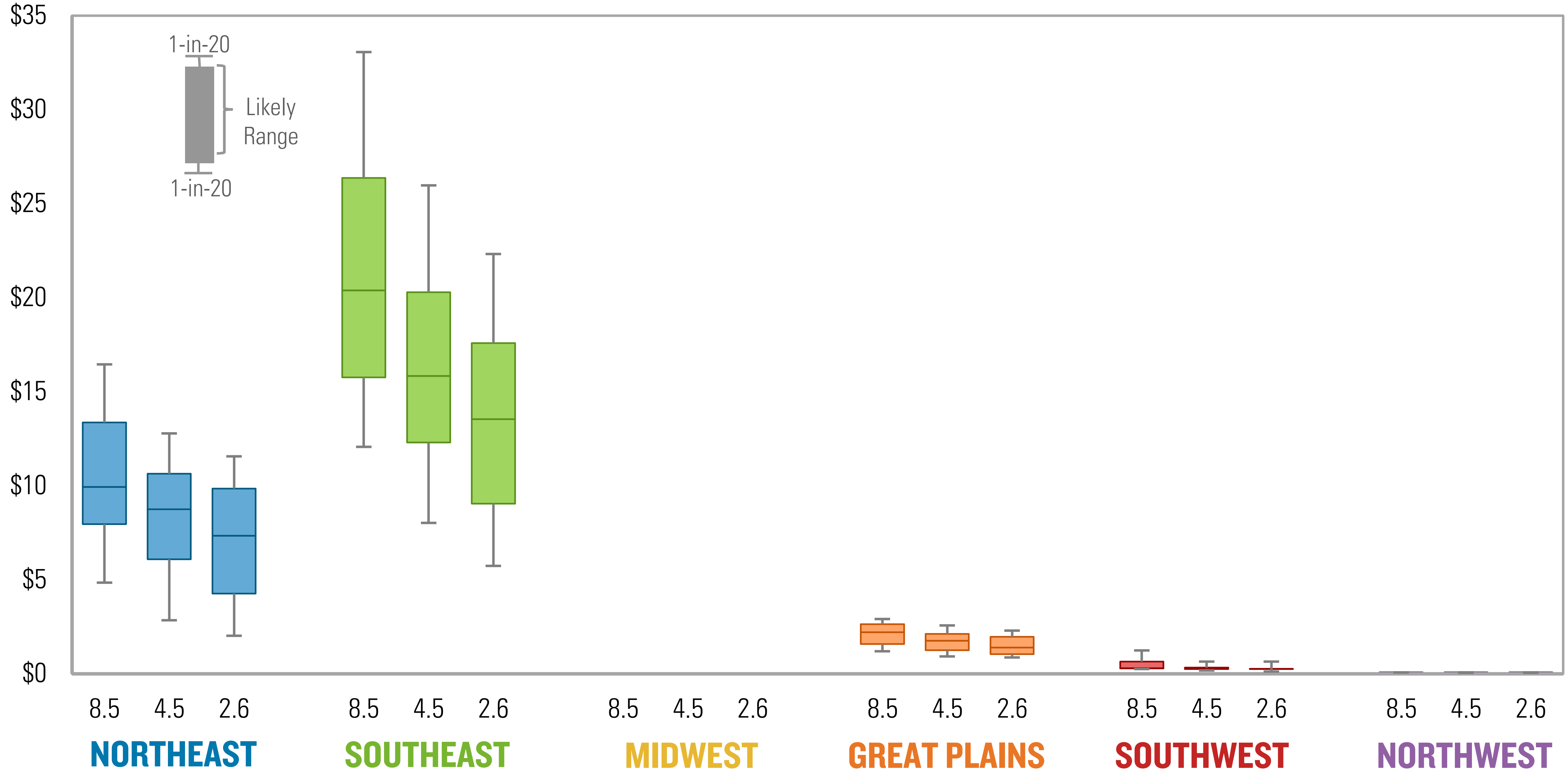


nationally ~ $50–$75/capita

Limited mitigation benefits in 21st century

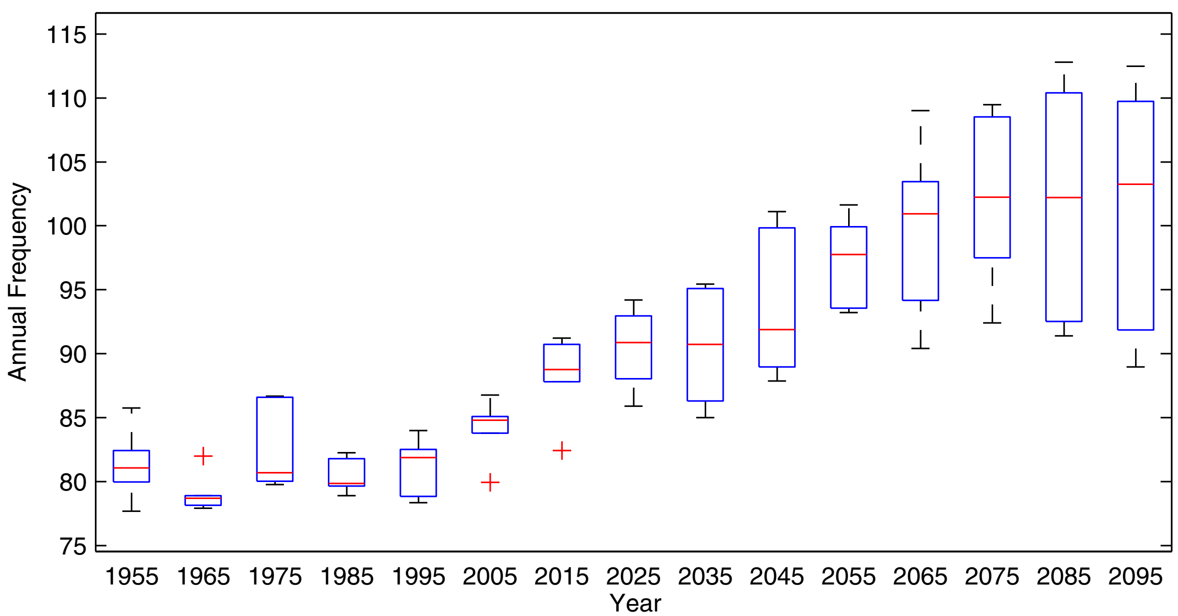
Figure 21.6: Change in average annual hurricane and inundation damage, 2080-2099

Billion 2011 USD

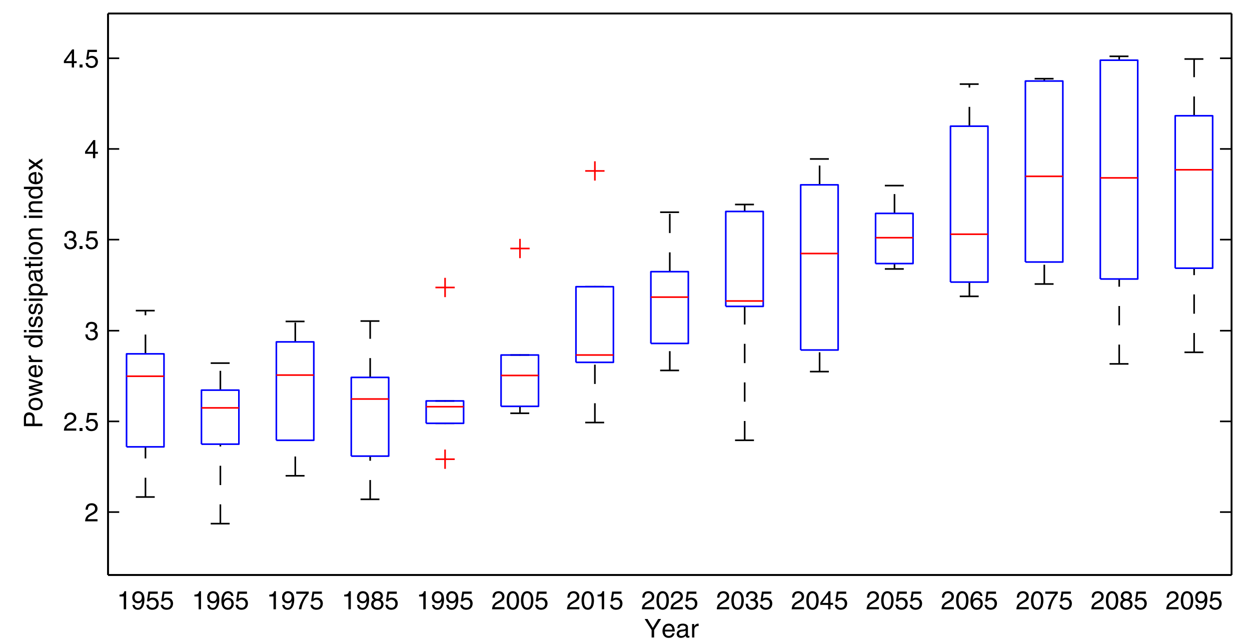


Projected changes in tropical cyclones
(Downscaled RCP 8.5)

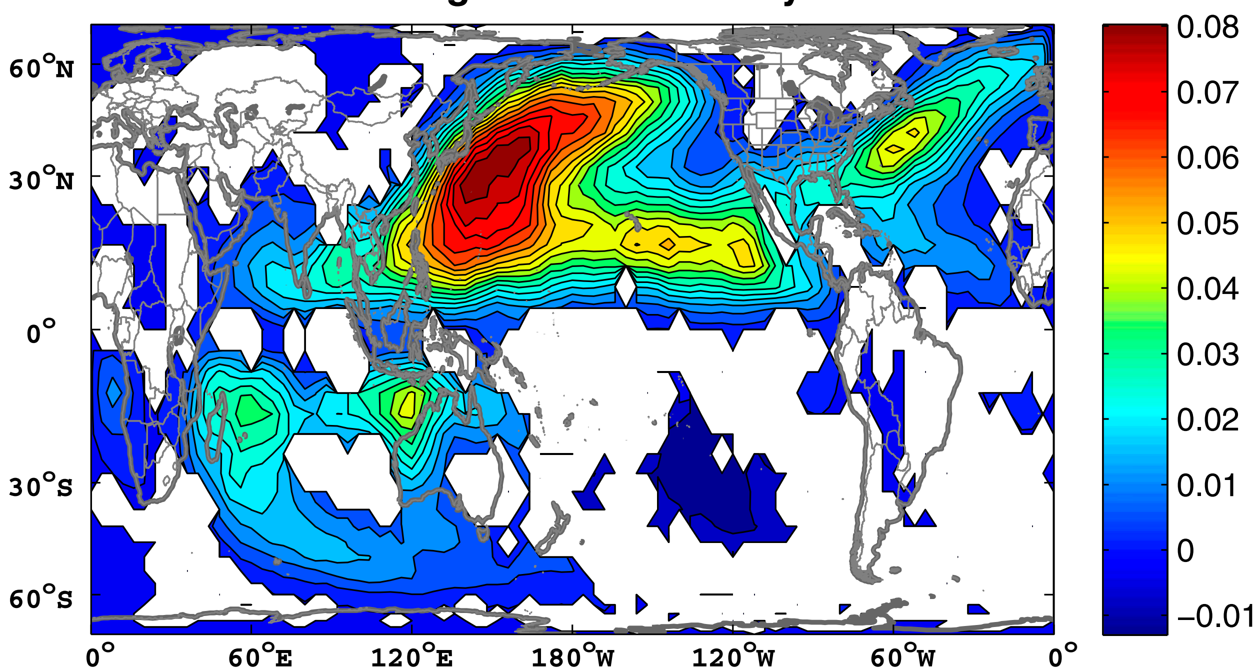
Frequency

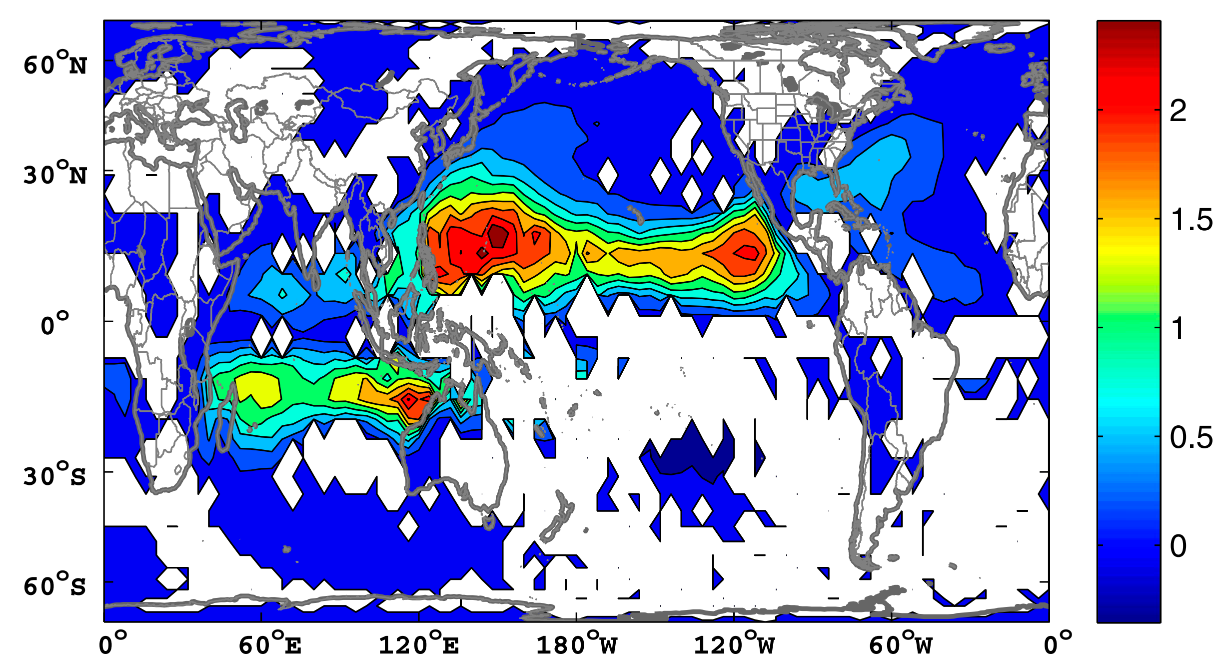


Power density index



Change in Track Density

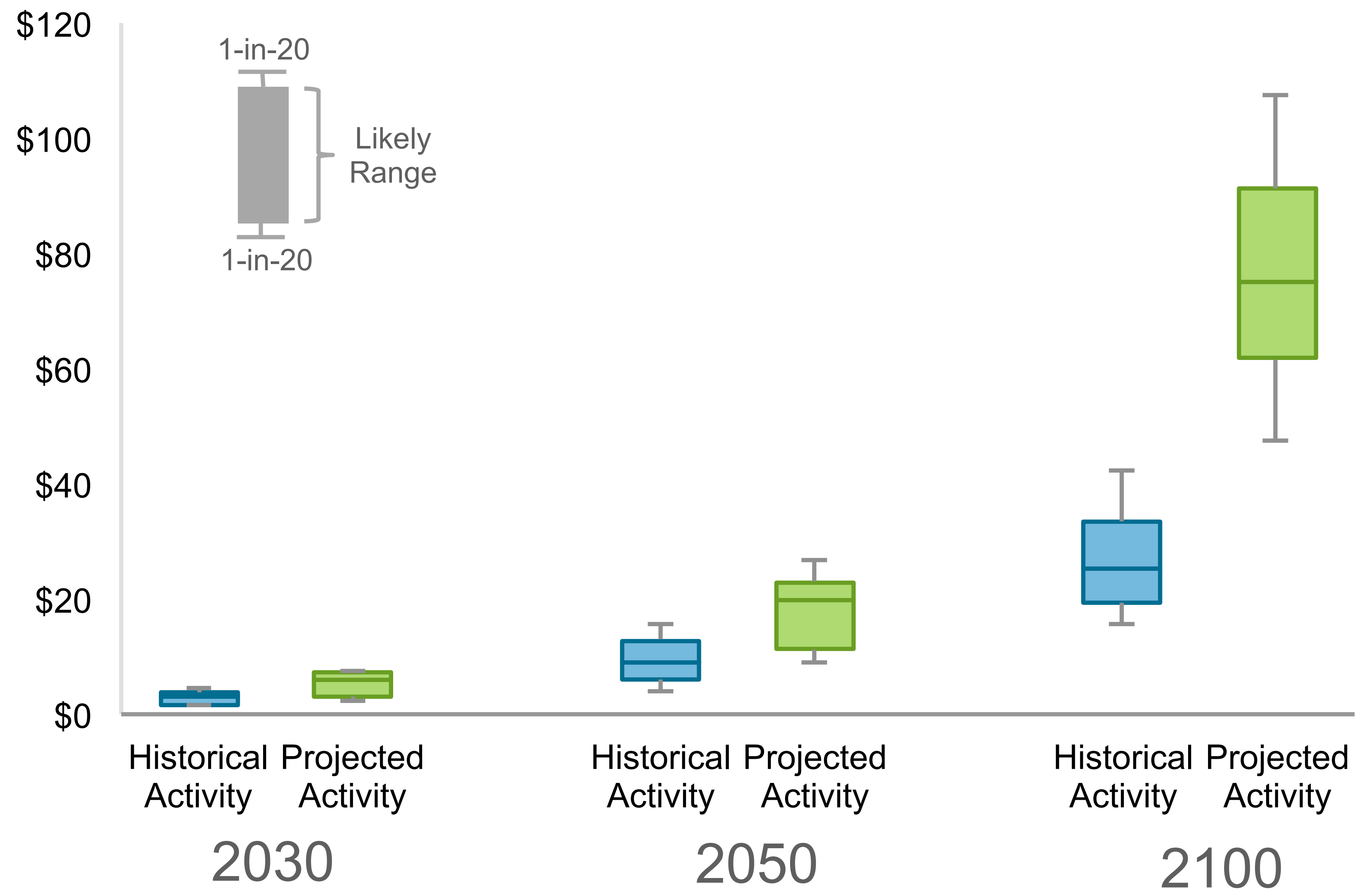




Emanuel et al. (2013)

Coastal property: Effects of changes in storm intensity

Effect of reweighting storms based on projected frequency/intensity
RCP 8.5 (billion USD)



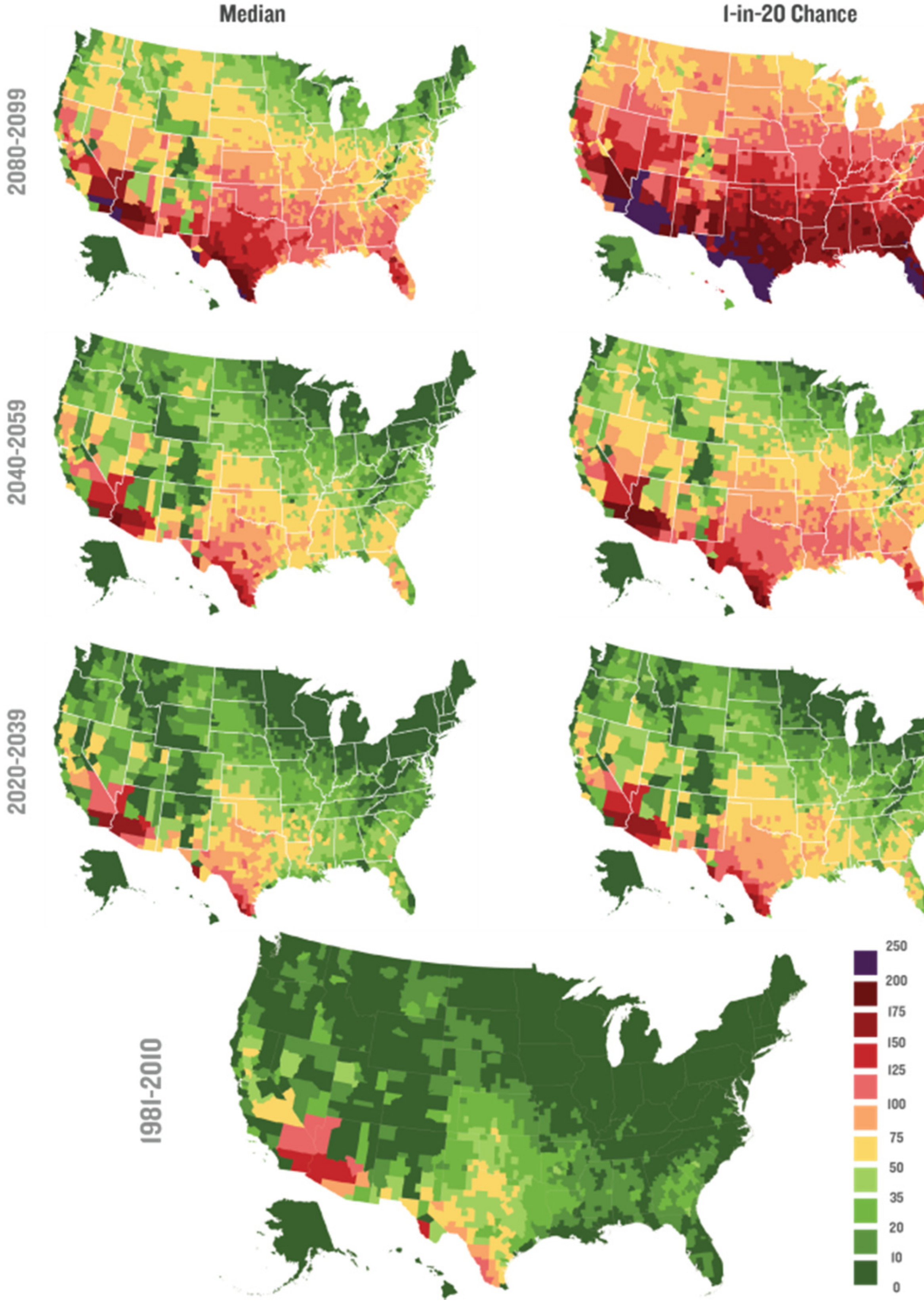
Some other extremes

Increasing extreme heat days

Days >35°C per year

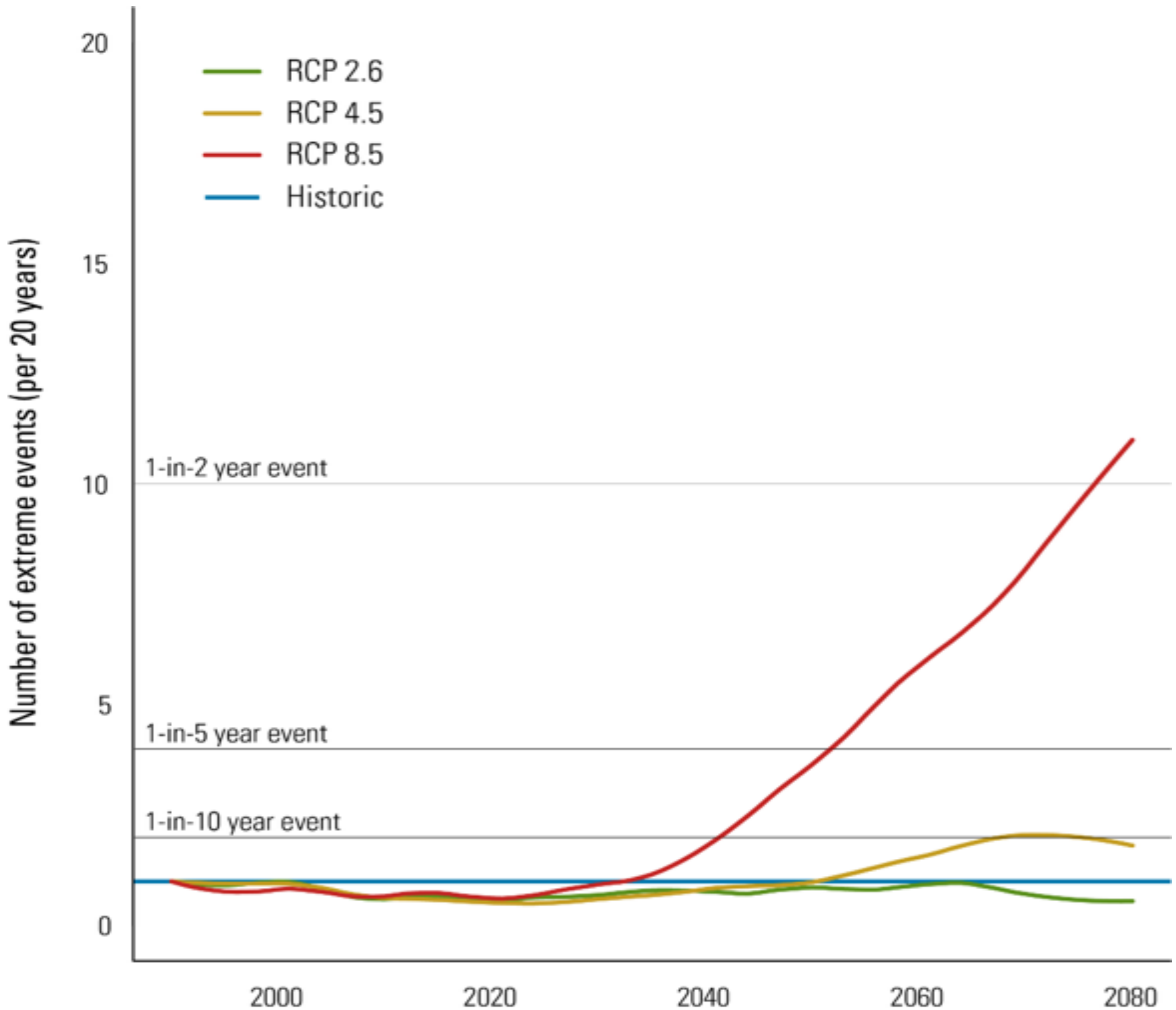
Figure 4.4: Increasing numbers of extreme hot days

Number of days with maximum temperatures above 95°F, RCP 8.5



Dangerous heat extremes become the new norm

1-in-20 year heat-related mortality expected 1-in-5 years by mid-century, 1-in-2 years by late century



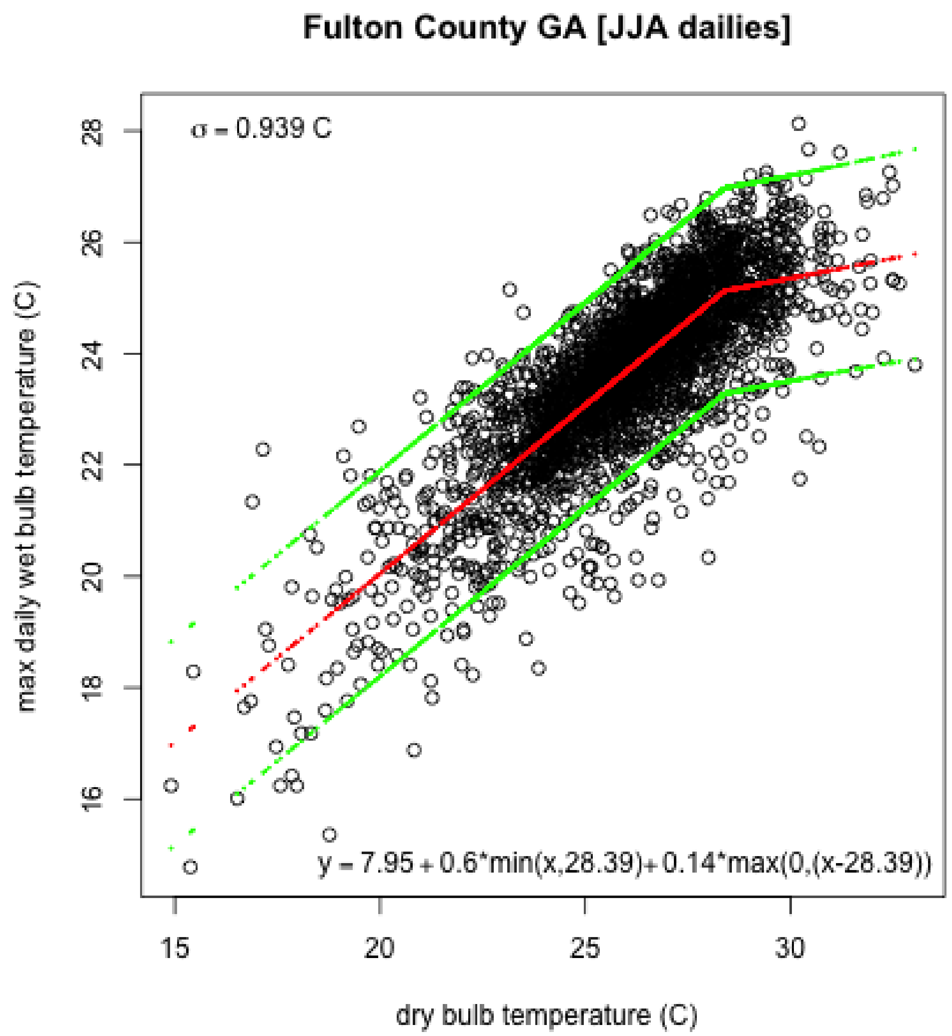
American Climate Prospectus Humid Heat Stroke Index

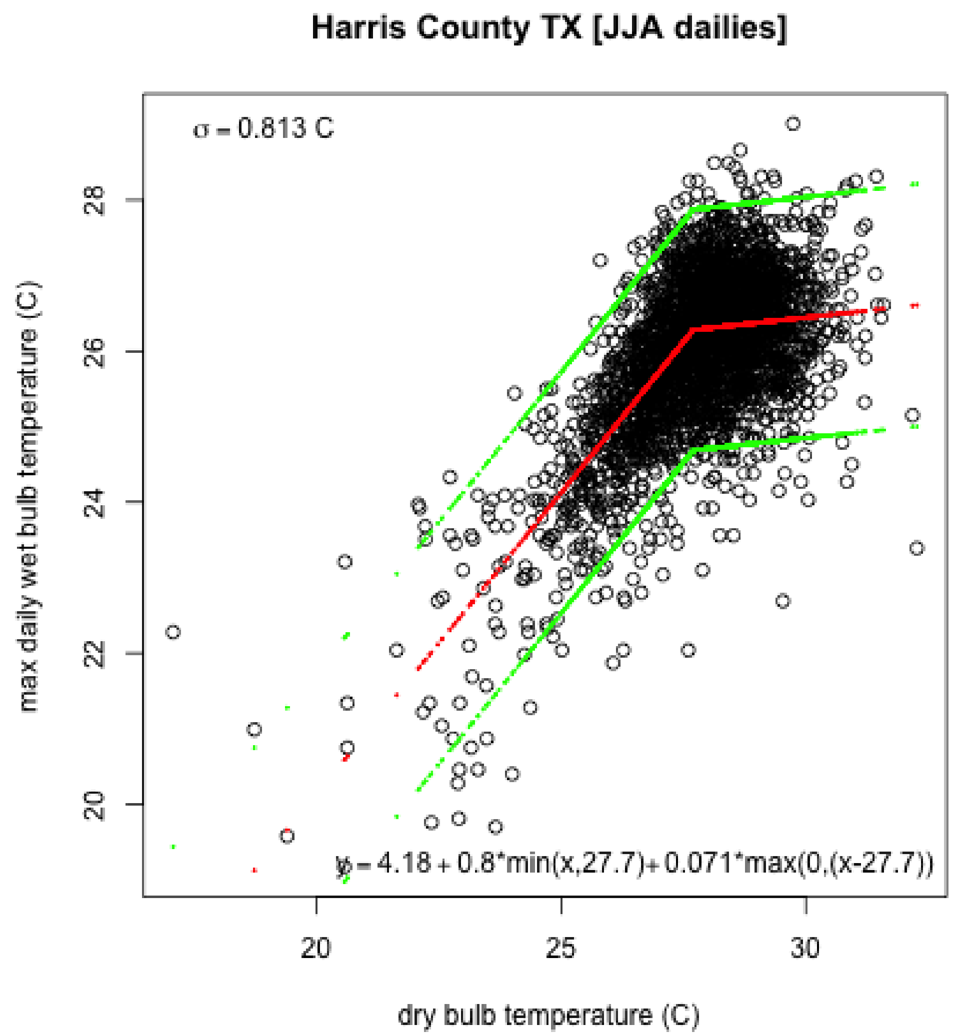
"It's not just the heat, it's the humidity"

ACP HHSI	Peak Wet Bulb Temperature	Description (hottest part of day)
I	74°F-80°F	Uncomfortable. Typical of much of summer in the Southeast.
II	80°F-86°F	Dangerous. Typical of most humid parts of Texas and Louisiana in hottest summer month, and most humid summer days in Washington and Chicago.
III	86°F-92°F	Extremely dangerous. Comparable to Midwest during peak days of 1995 heat wave.
IV	>92°F	Extraordinarily dangerous. Exceeds all U.S. historical records. Heat stroke likely for fit individuals after less than one hour of moderate activity in the shade.

American Climate Prospectus Humid Heat Stroke Index

Projections based on empirically-calibrated relationship between wet bulb and dry bulb temperatures

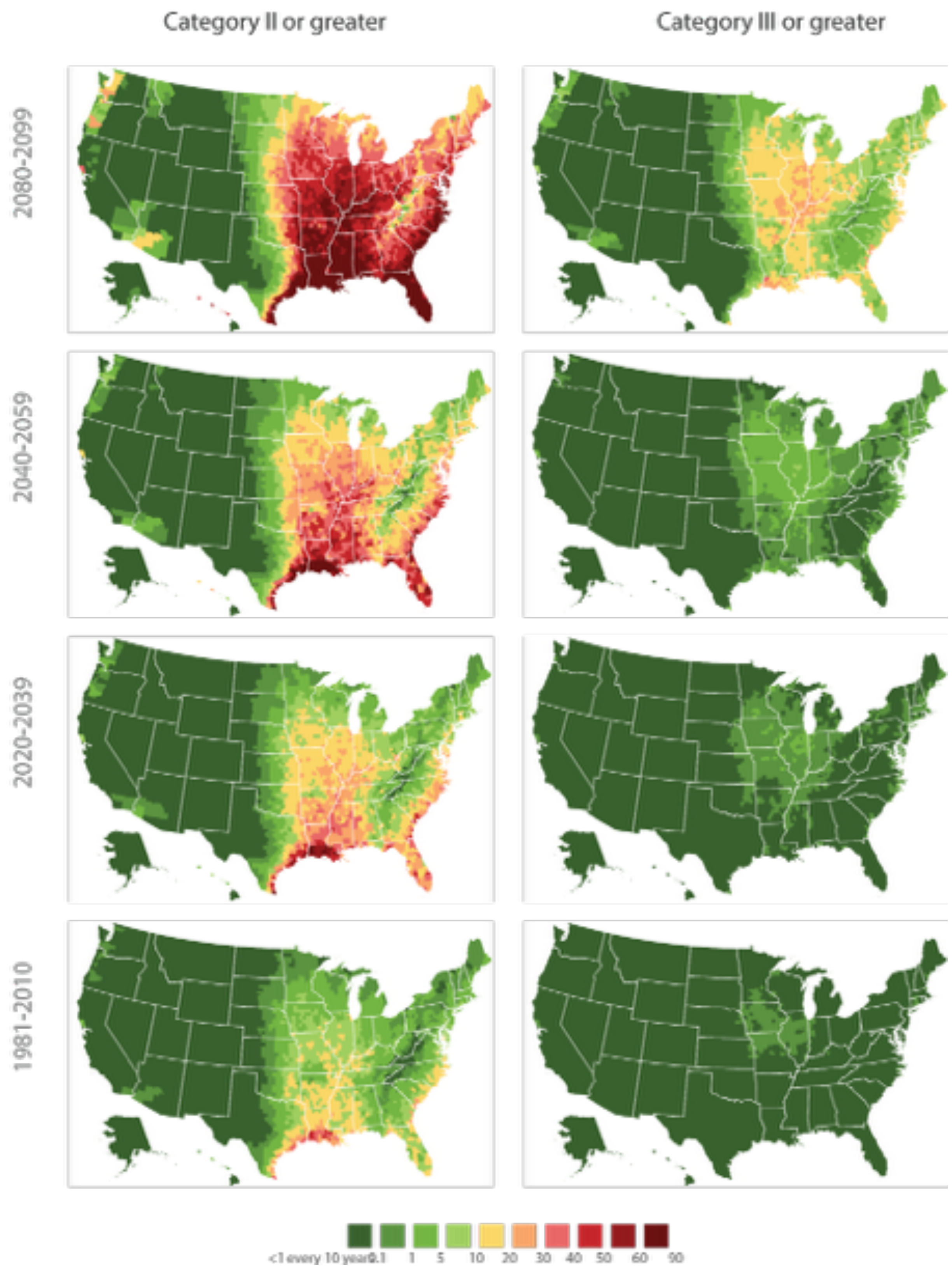


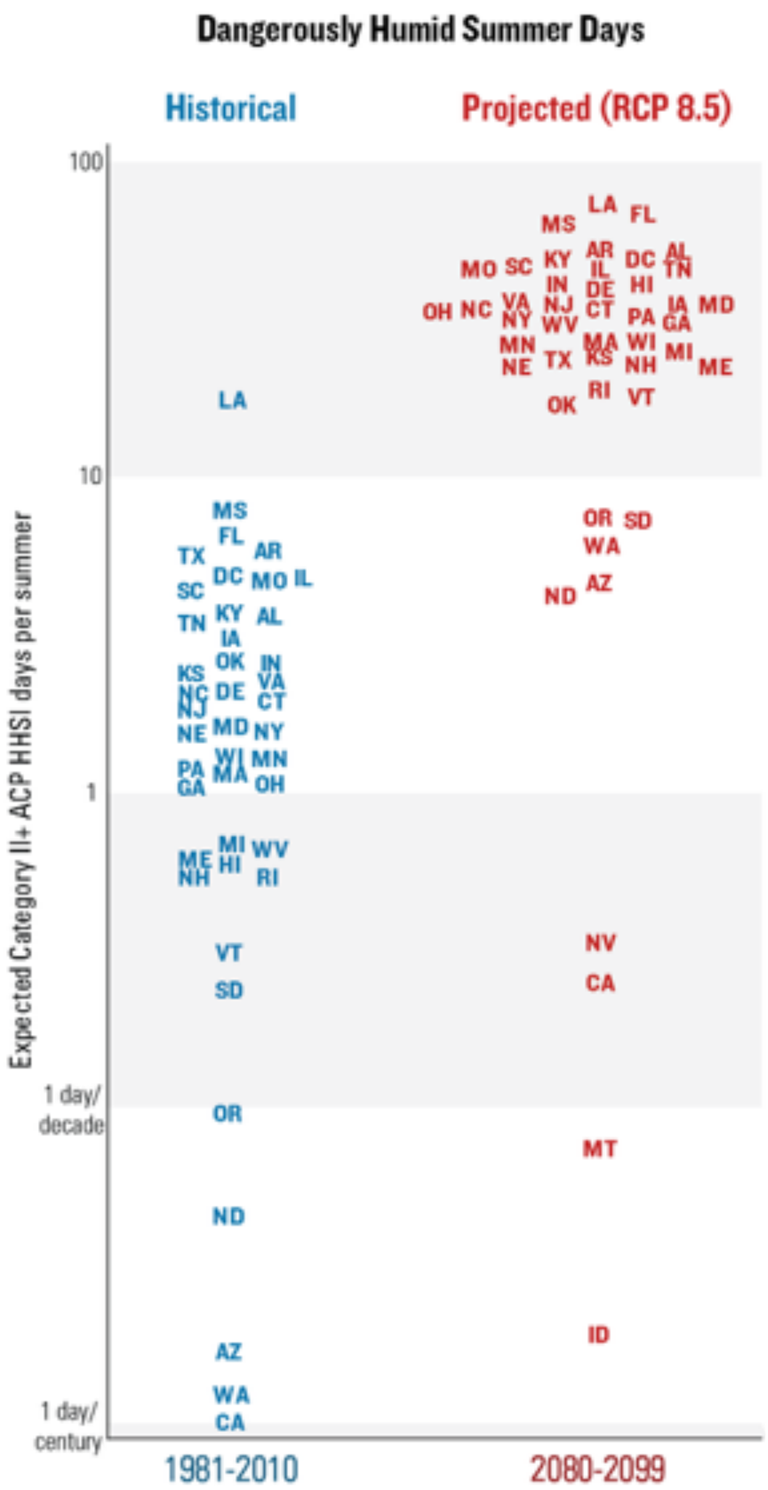


$$T_w(T_d, \Delta T_f) \quad = \quad T_w(T_d - \Delta T_f) + \beta_0 \Delta T_f$$

American Climate Prospectus Humid Heat Stroke Index

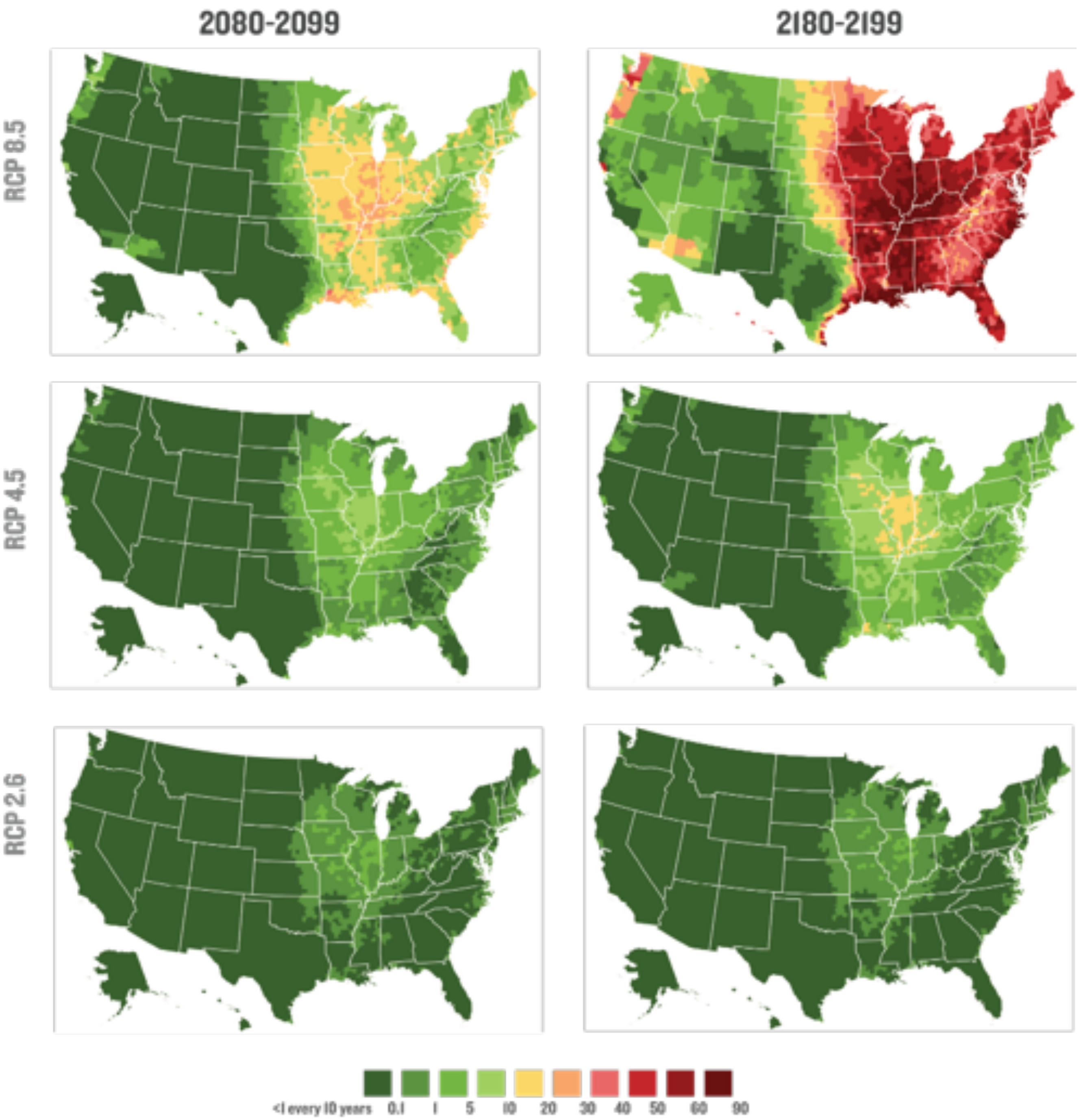
Expected number of Category 2+ (dangerous) and Category 3+ (extremely dangerous) in a typical year under RCP 8.5



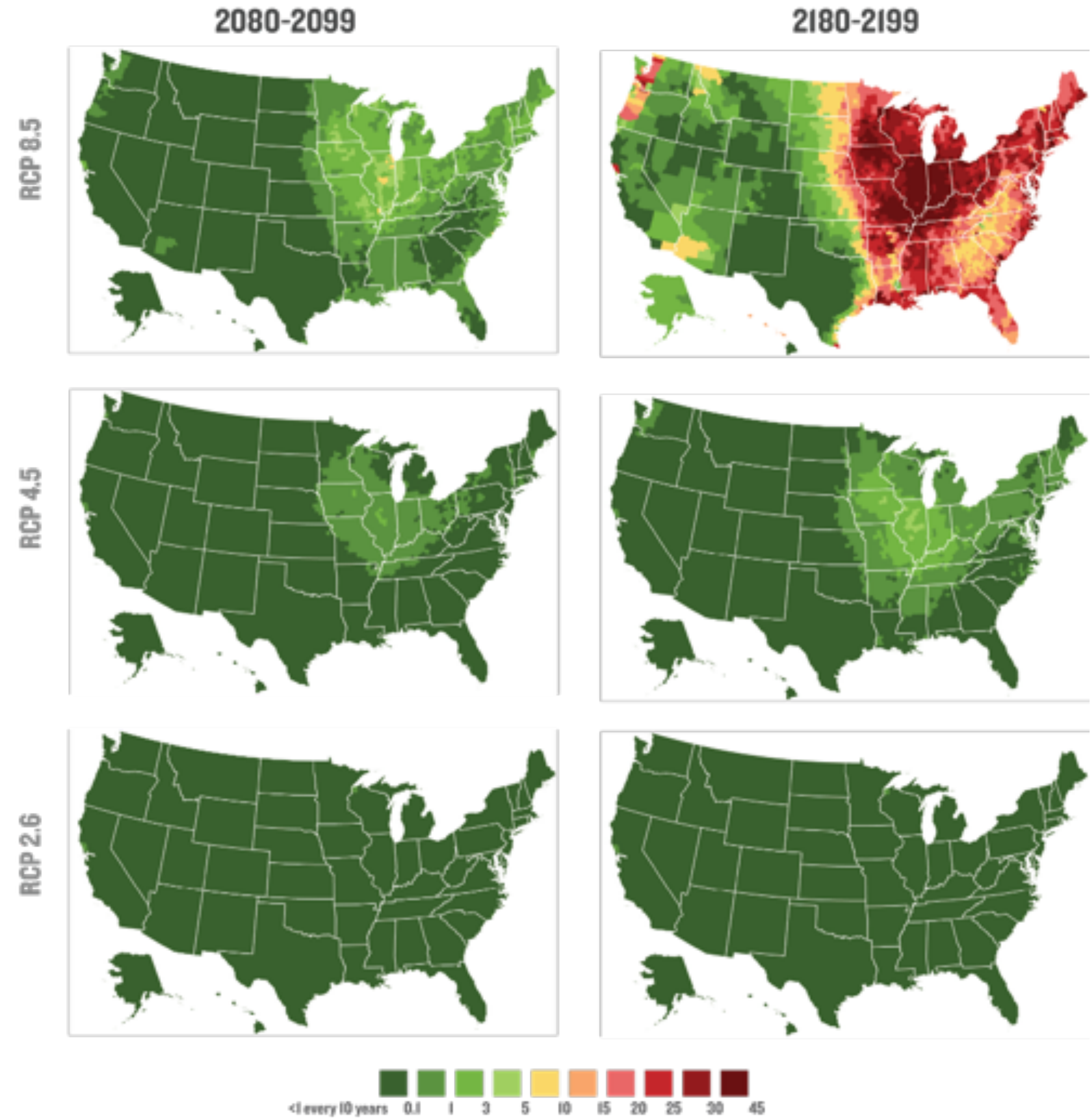


American Climate Prospectus Humid Heat Stroke Index

Category 3+ (Extremely dangerous)



Category 4 (Extraordinarily dangerous)

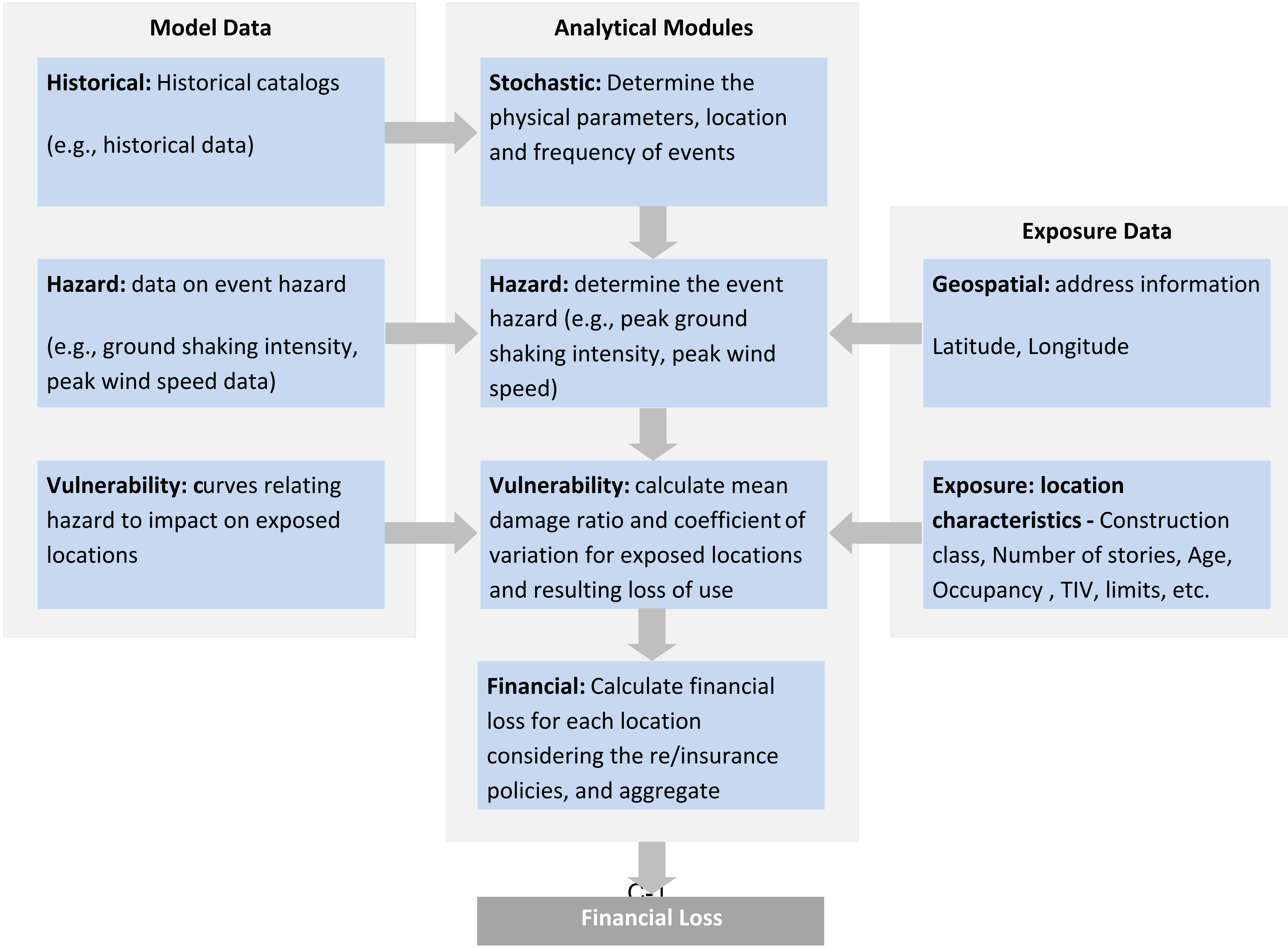


Note difference in scales above 3/year!

Takeaways

- Sea-level rise is uncertain and geographically variable, but we can produce reasonable PDFs for local sea-level change.
- When combined with flood return periods, SLR means more frequent flooding, sometimes dramatically slow.
- Combined with property + hydrodynamic models, we can estimate the cost of both SLR (in US median, likely ~$300-$400 billion by 2050 lost property) and its effects on storms (likely ~$6-$13 billion/year by 2050).
- More intense hurricanes – and perhaps all hurricanes – are likely to become more frequent, ~doubling expected annual losses by mid-century and ~tripling by 2100.
- Extreme heat and humidity days will become more common, with extraordinarily dangerous Cat 4 days starting to be expected in parts of the country by the end of the century under RCP 8.5.

Figure 1: The RMS Modeling Process



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