Designing coastal defense strategies in an era of uncertain sea-level rise

D.J. Rasmussen

STEP PhD seminar, May 2019

Maeslant Surge Barrier, Netherlands

[Eastern Scheldt Storm Surge Barrier]

Research Area:
Engineered coastal flood defense in an era of sea-level rise

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“When to act?” & “the decision to build”: Political science/ Policy/ Environmental Law

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  - Modeling the return periods of extreme water levels
  - Characterizing uncertainty in future sea-level rise projections (under specific climate policies, like the Paris Agreement)

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[Eastern Scheldt Storm Surge Barrier]

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[IHNC-Lake Borgne Surge Barrier]

Overview

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1. Background/ motivation
   - What are the key processes driving sea-level rise and coastal flooding?

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   - What are the key processes driving sea-level rise and coastal flooding?
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3. Methods/ approach
4. Results

[IHNC-Lake Borgne Surge Barrier]

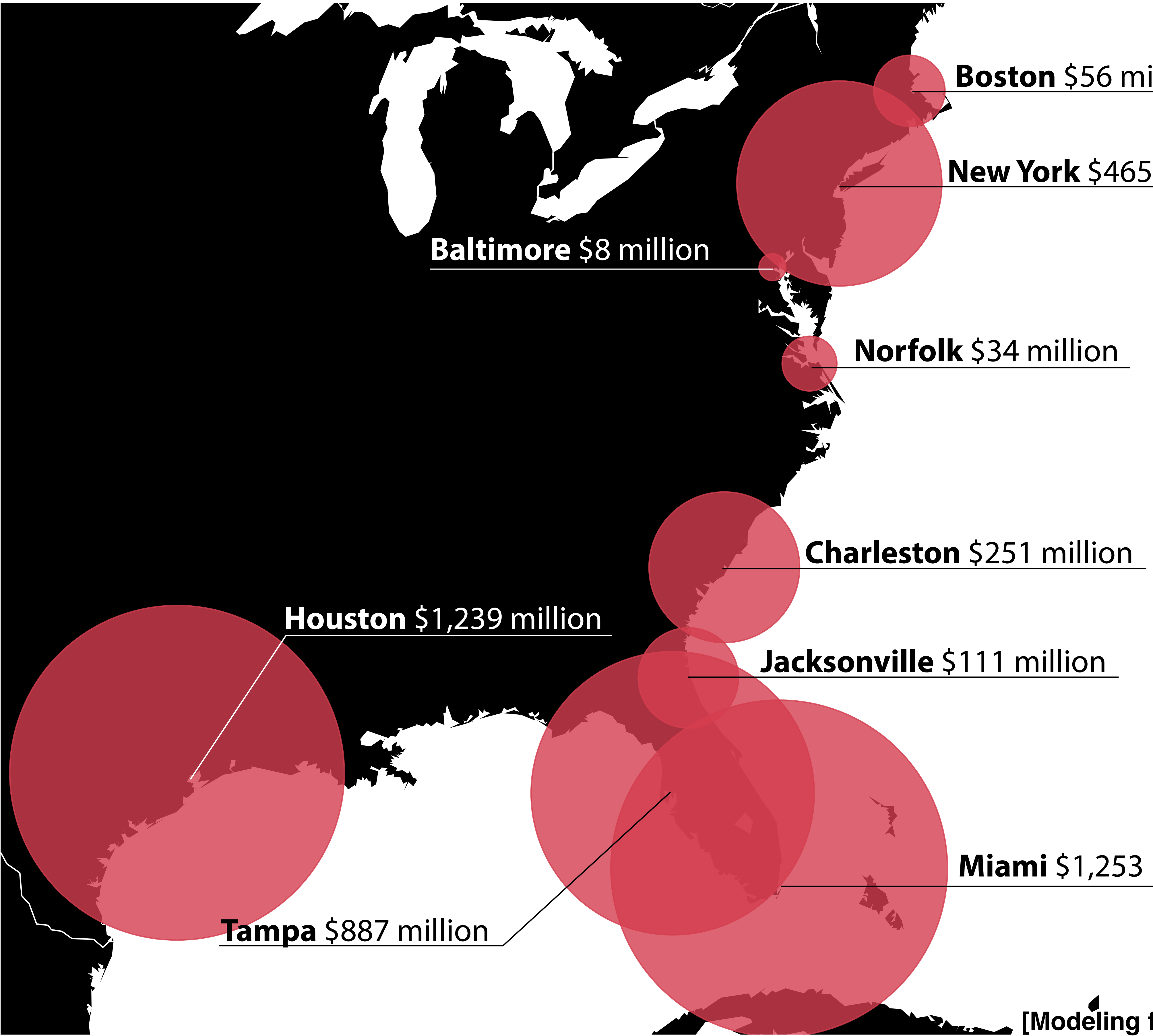
D.J. Rasmussen, R.E. Kopp, and M. Oppenheimer (in prep): **A damage allowance framework for calculating the design heights of coastal flood protection options under deeply uncertain future Antarctic ice melt.**

Available at : bit.ly/2VFd1nJ

[NY Times]

Cities around the eastern U.S. are exposed to coastal flood risk

Annual average loss due to flooding (present)



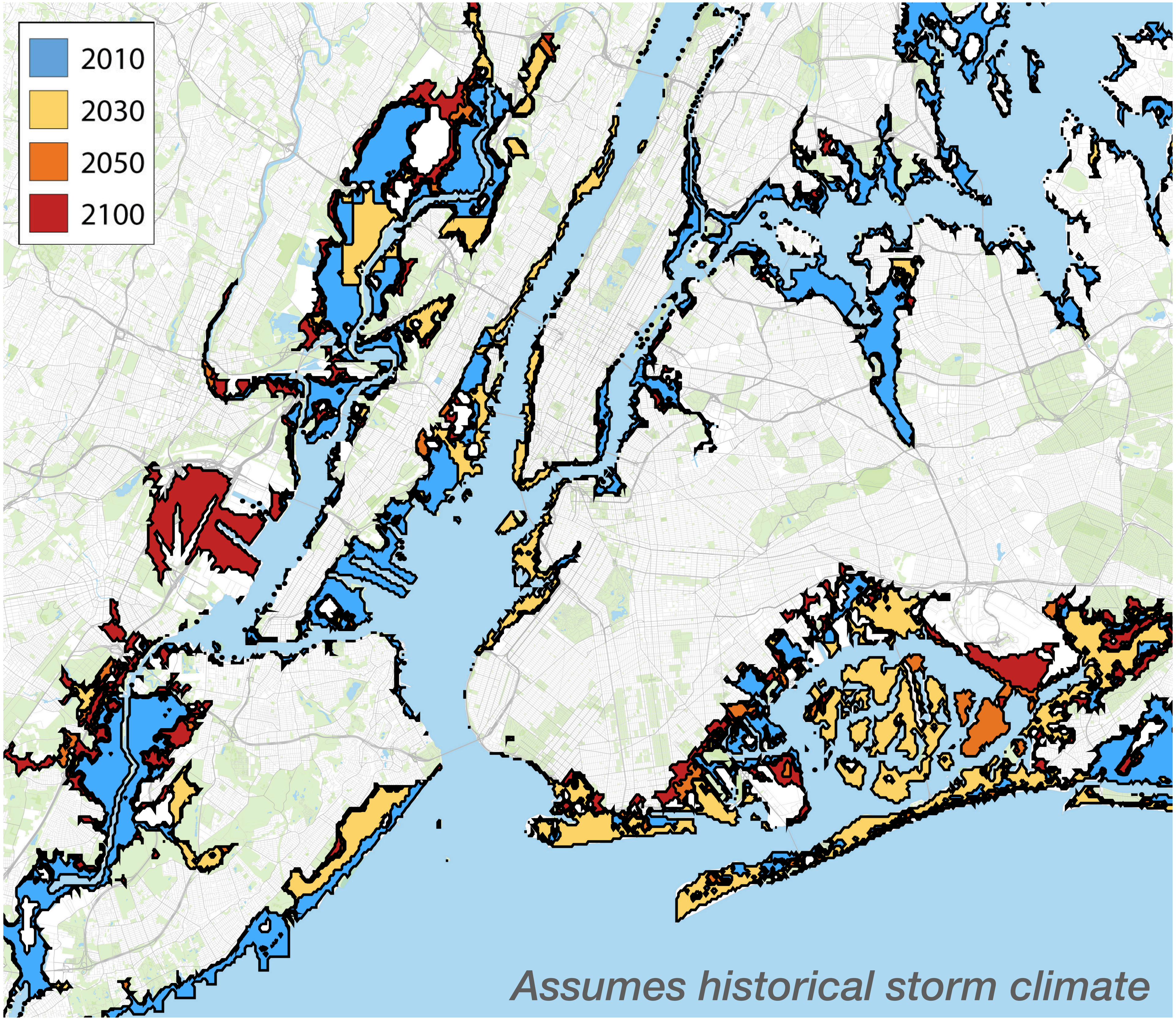
Risk

1. *Hazard*
2. *Exposure*
3. *Vulnerability*

[Modeling from Risk Management Solutions]

Sea-level rise leads to expanding flood zones

1% annual probability of flooding, New York City and New Jersey



[Climate Impact Lab; Houser et al., 2015]


So what can we do to
reduce coastal flood risk?
[Wikipedia]

[Josh Haner/The New York Times]


[Mexico Beach, Florida/ Hurricane Michael]
Accommodate/
Elevate

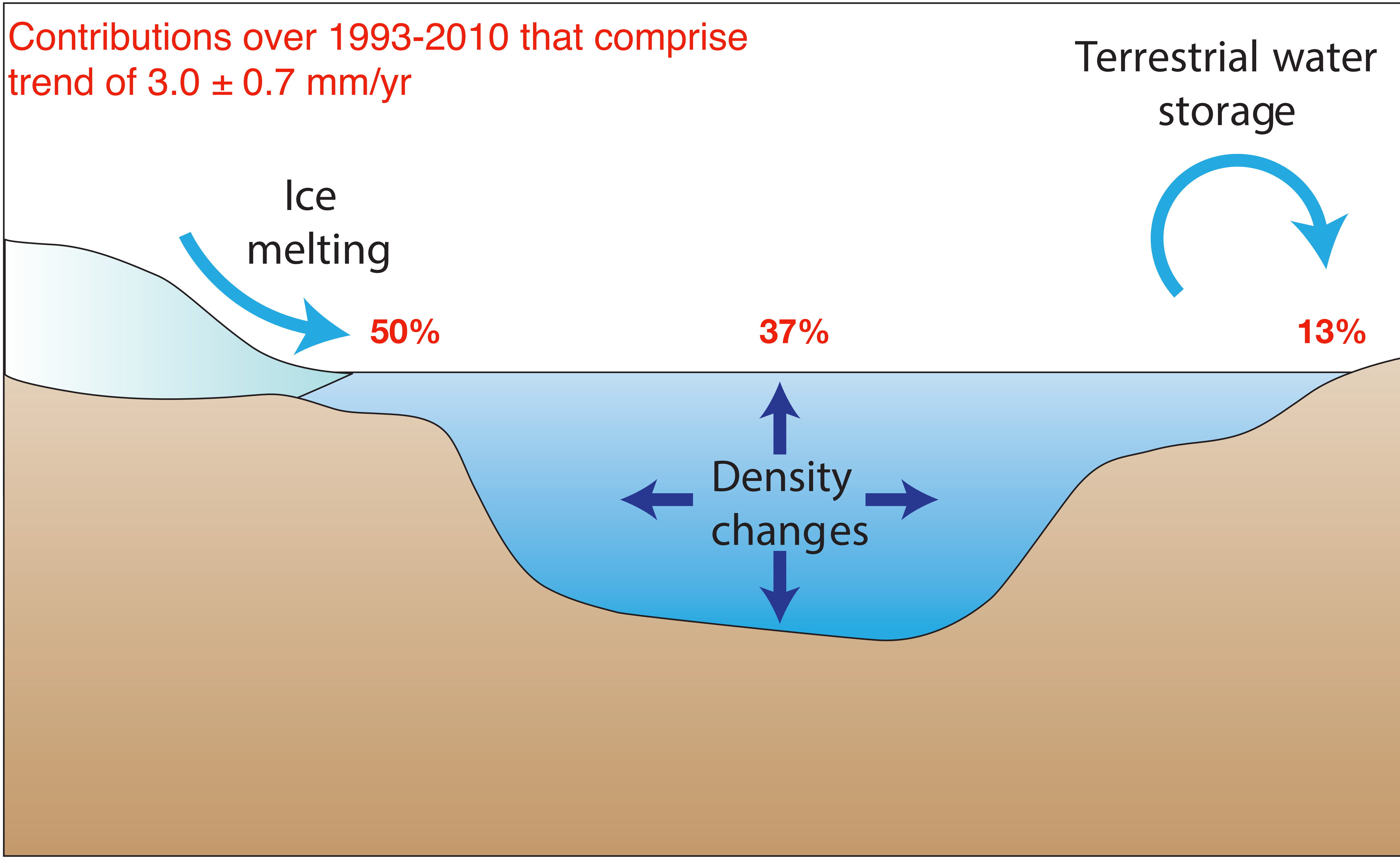
Protect

[Maeslant Surge Barrier]

The design of these strategies must consider the key processes that drive coastal flooding:

1. Changing mean sea-levels
2. Extreme events

Sources of global mean sea-level change



[Milne et al., 2009; IPCC AR5]

Local sea-level change is more complex

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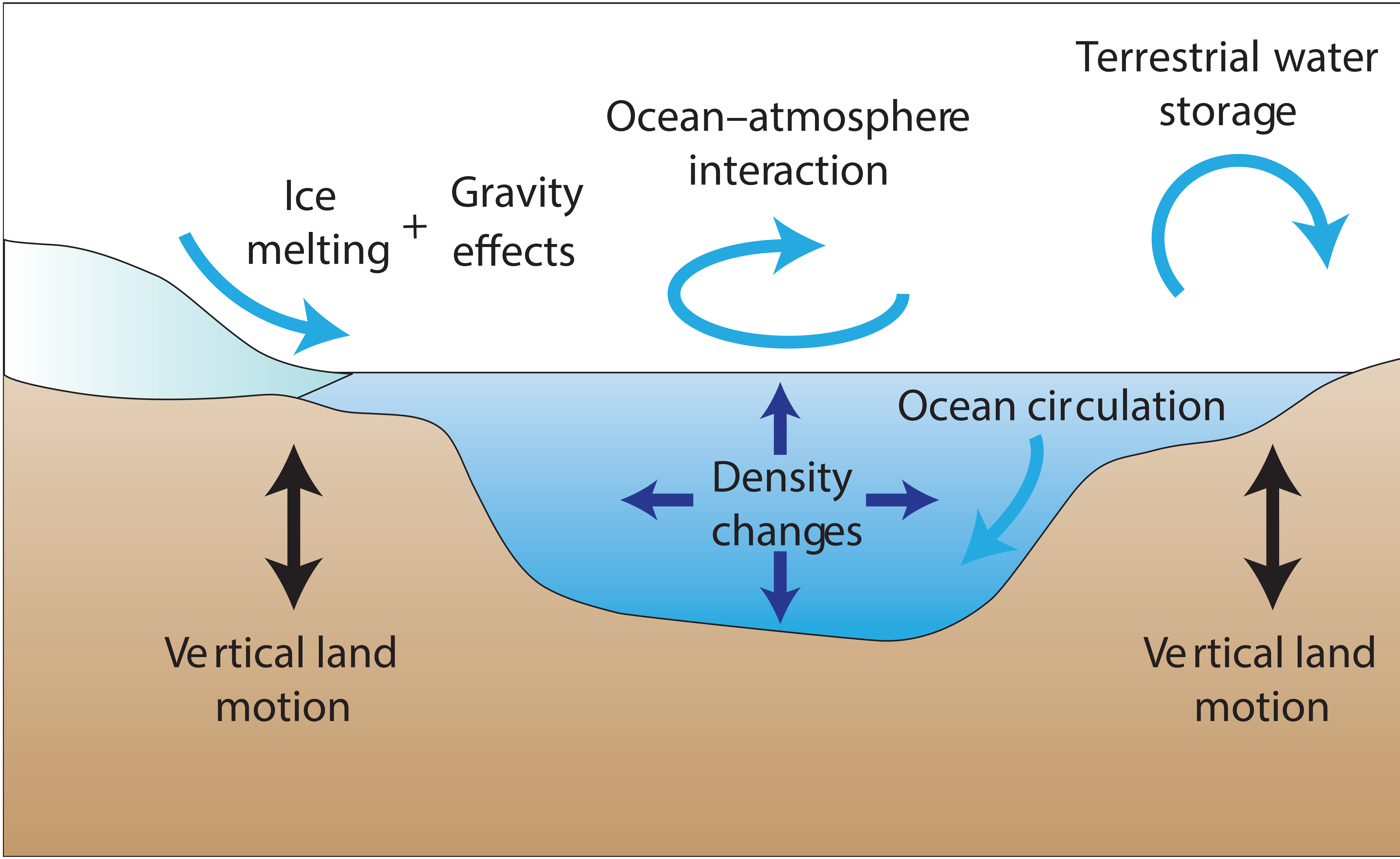

[Milne et al., 2009]

Future projections of sea-level rise

Approach: “bottom-up” accounting of components over time and their uncertainty

Global mean sea-level rise [Kopp et al., 2014]

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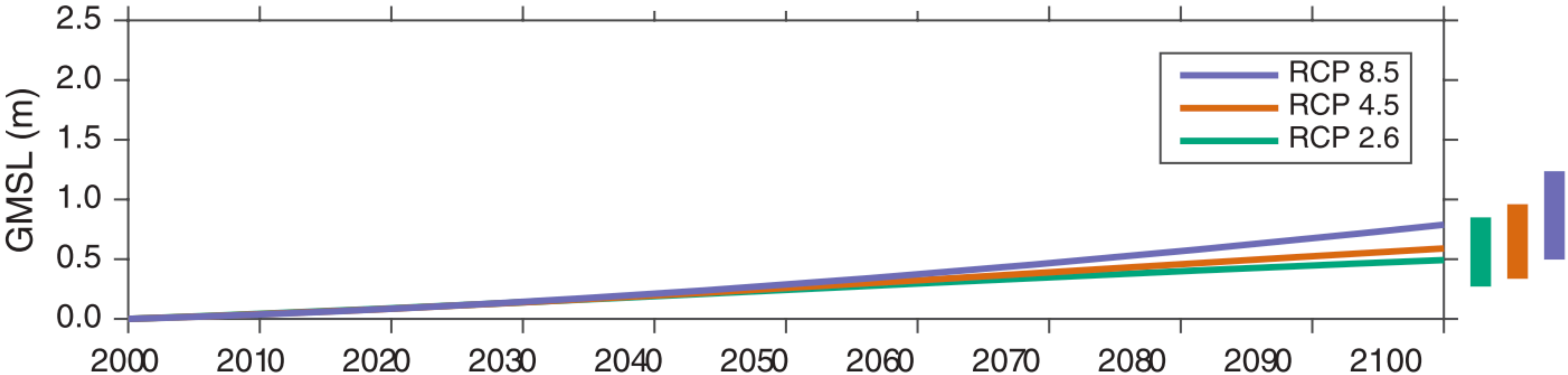
Amounts relative to 2000



Year	Projected global-mean SLR (90% probability range; RCP 8.5)
2030	0.1-0.2 m (0.3-0.6 ft)
2050	0.2-0.4 m (0.7-1.3 ft)
2100	0.5-1.2 m (1.6-4.0 ft)

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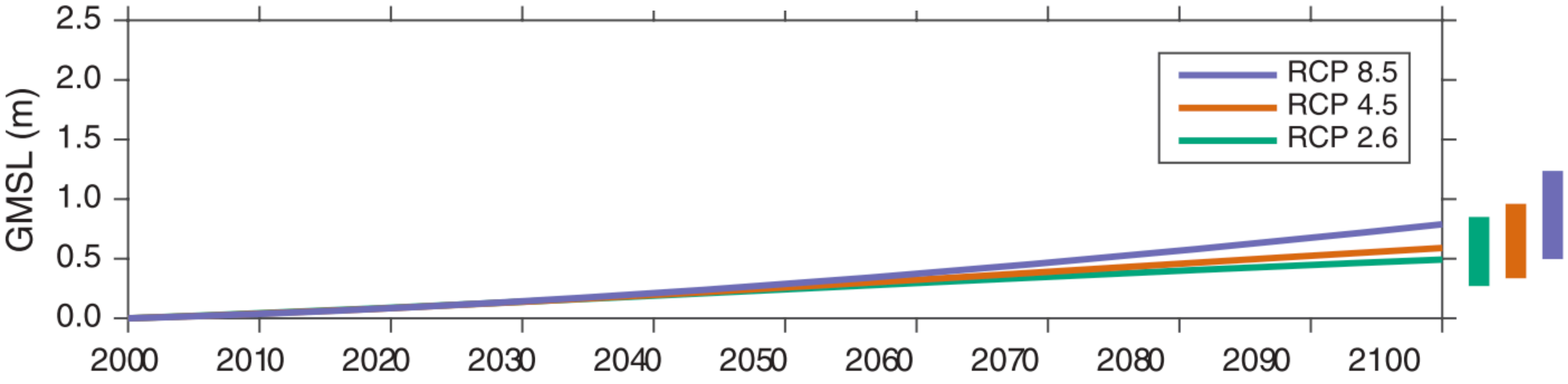

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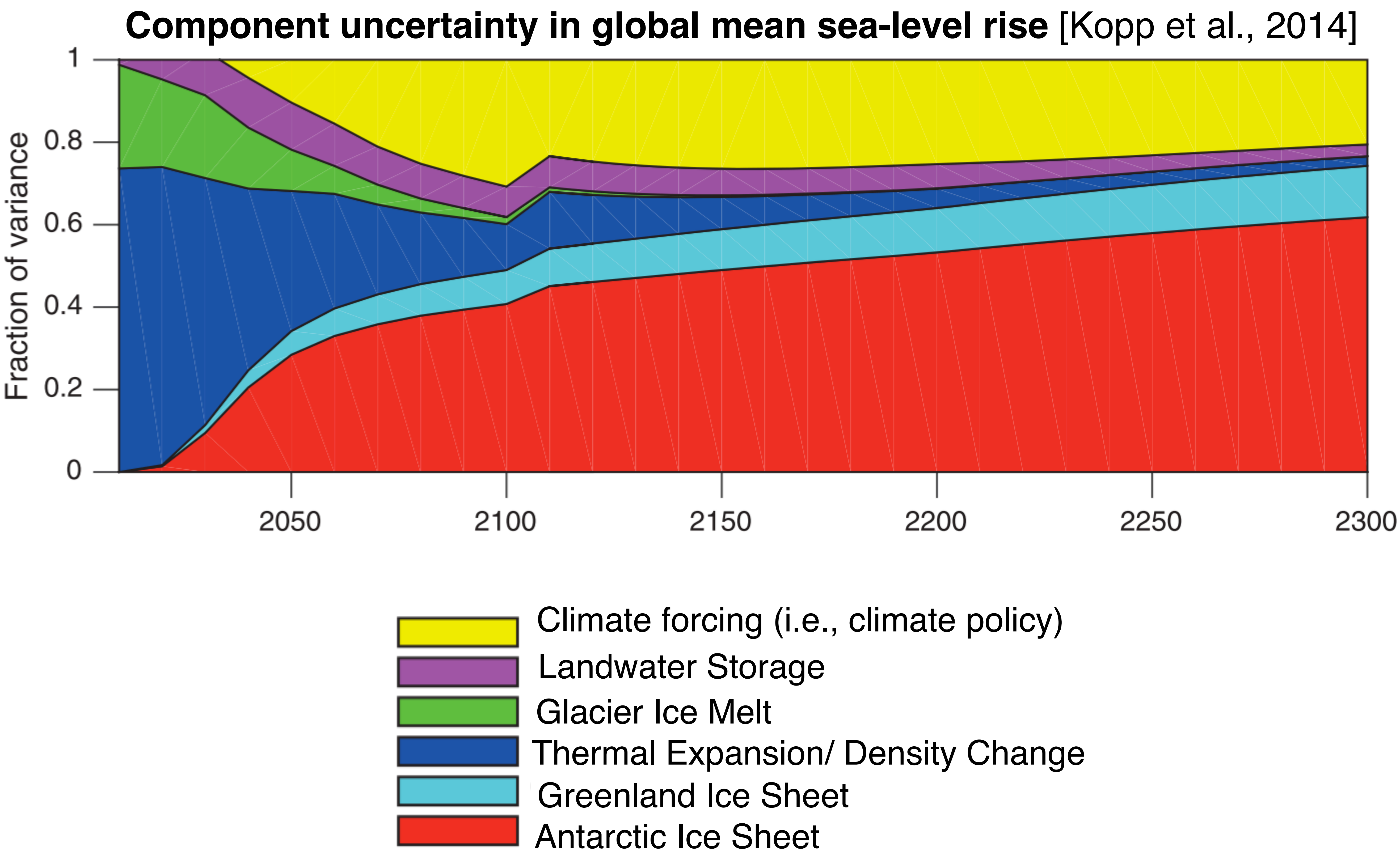
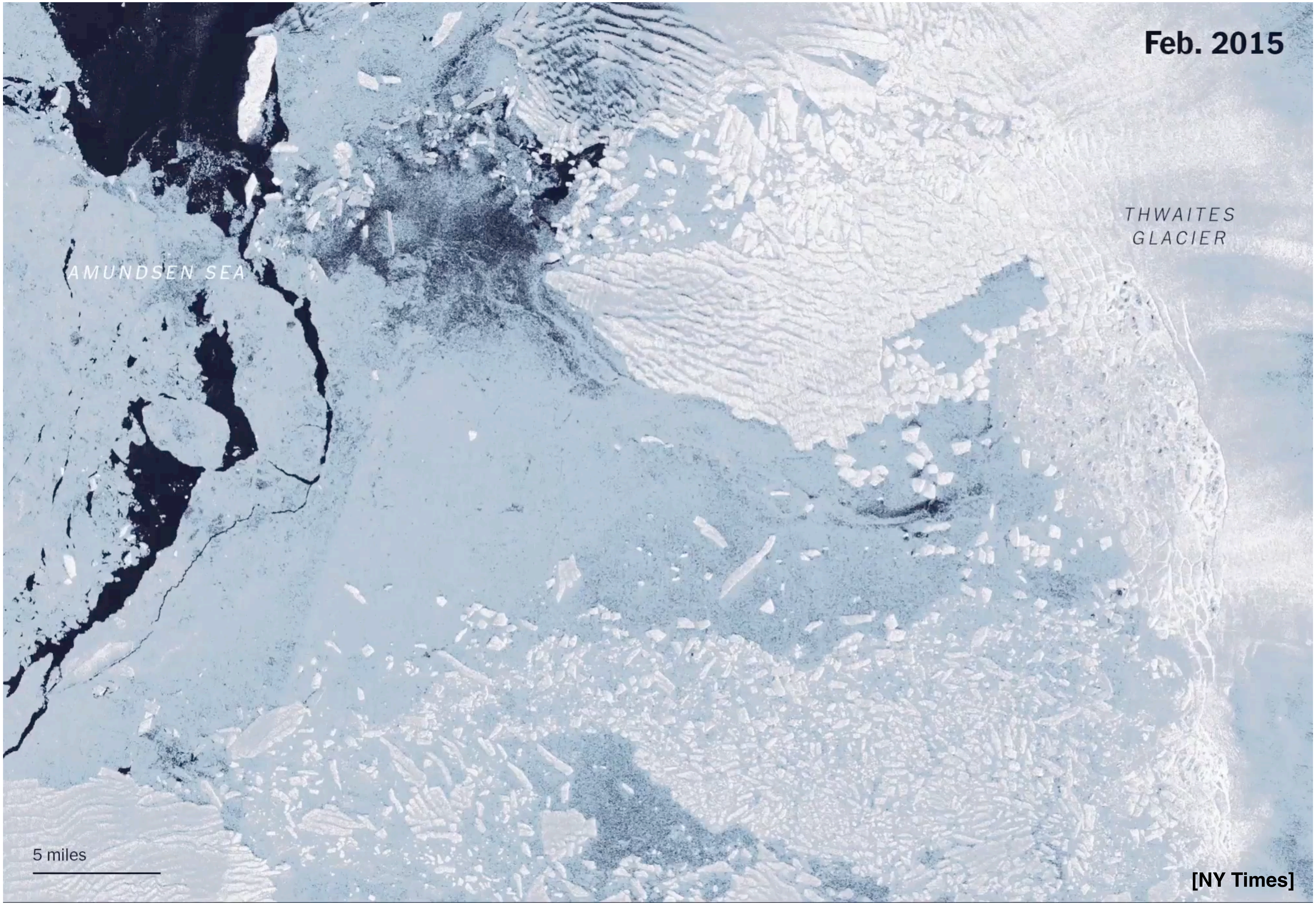
Amounts relative to 2000

The rate and amount of future sea-level rise is uncertain

Antarctic ice sheet dominates future sea-level rise uncertainty after 2050 (sea-level rise “wildcard”)

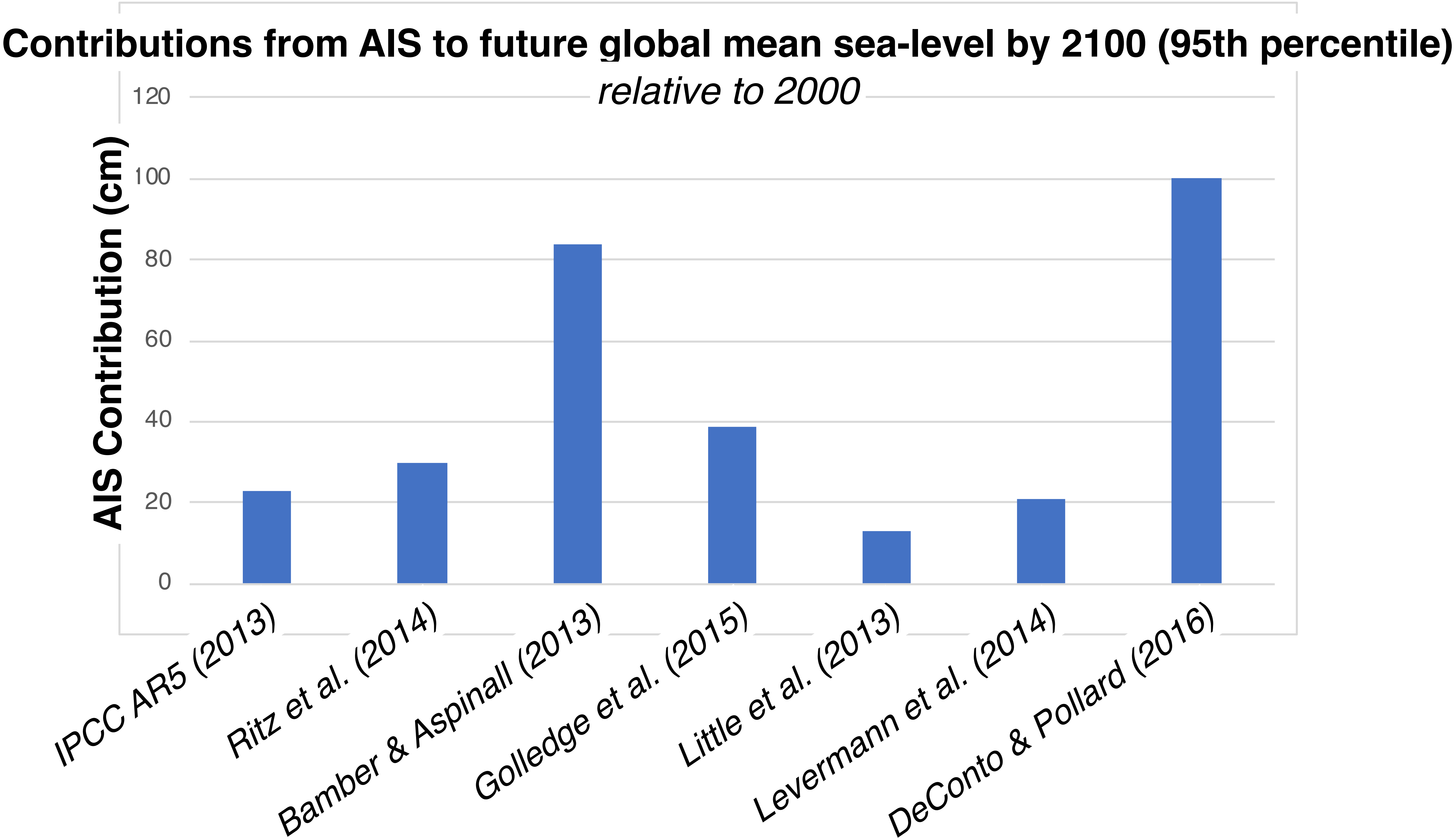


What happens in Antarctica doesn't stay in Antarctica…



Antarctic ice sheet (AIS) contribution to sea level is a rapidly evolving area of research, but remains deeply uncertain

“Deeply uncertain”: No single, unambiguous probability distribution of future Antarctic behavior exists

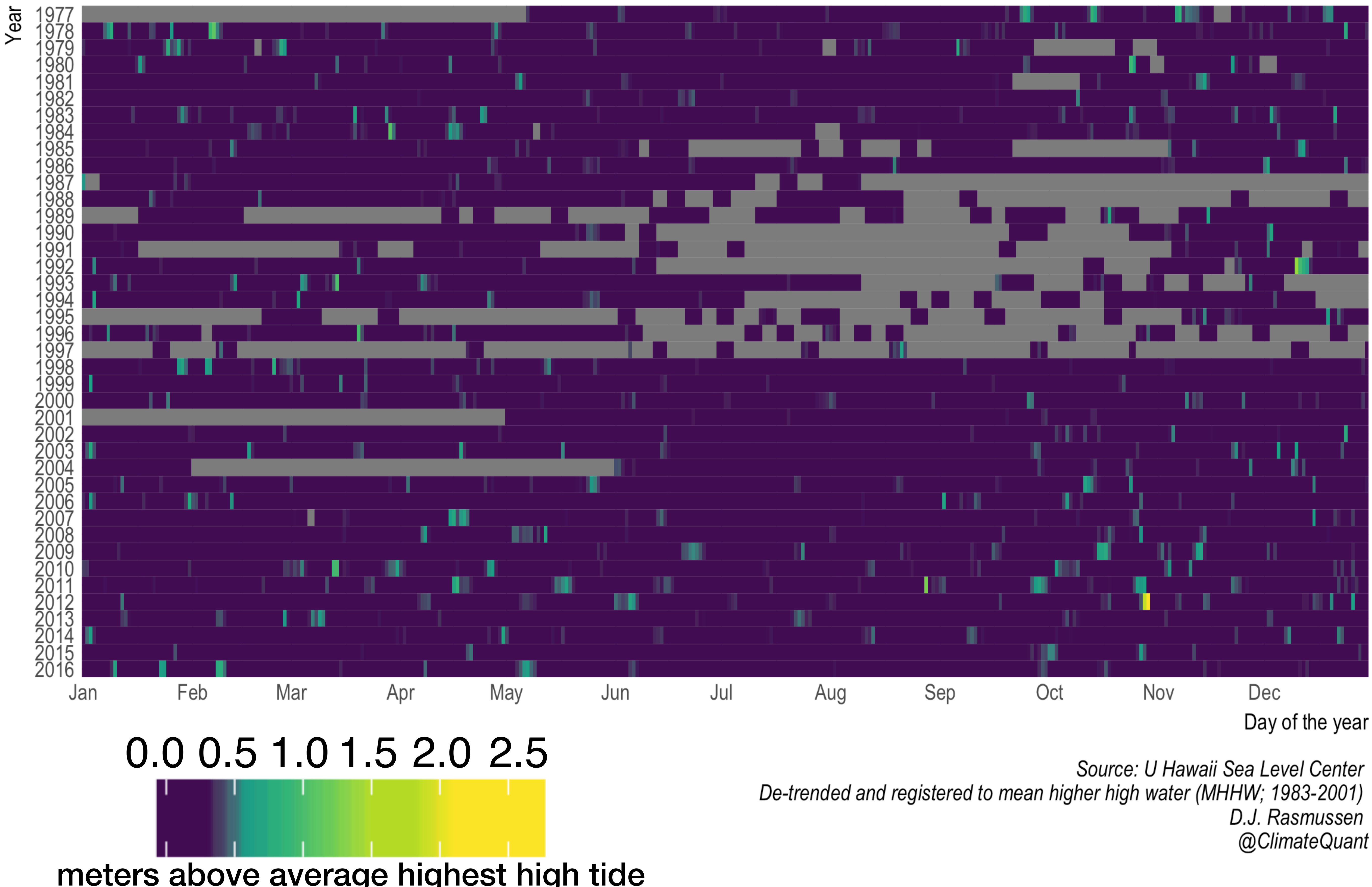


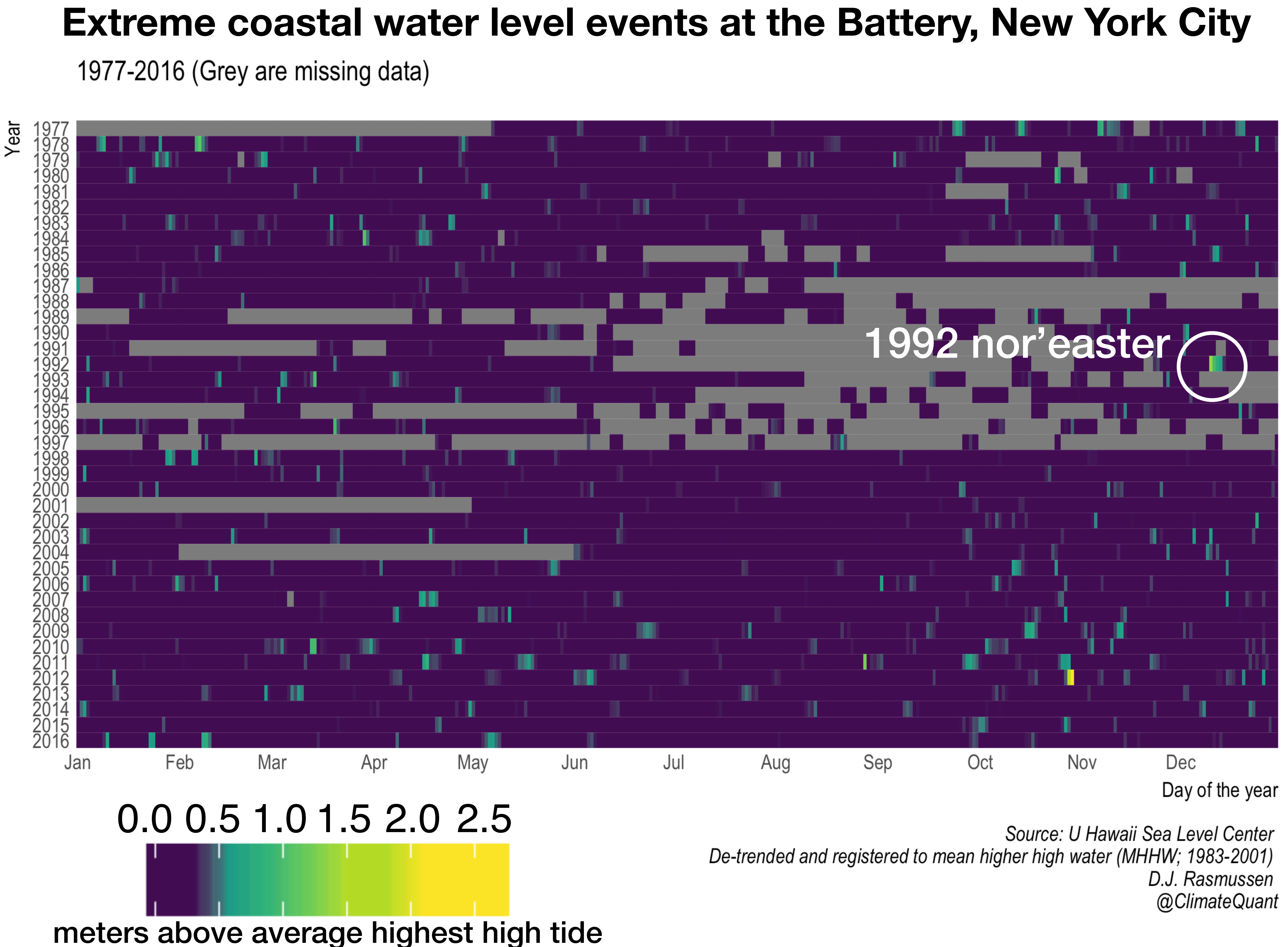
*****Applications using sea-level rise data (post-2050) should accommodate this ‘deep uncertainty’*****

2. extreme coastal water levels

Extreme coastal water level events at the Battery, New York City

1977-2016 (Grey are missing data)





Extreme coastal water level events at the Battery, New York City
1977-2016 (Grey are missing data)
Year
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1992 nor'easter
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Day of the year
0.0 0.5 1.0 1.5 2.0 2.5
meters above average highest high tide
Source: U Hawaii Sea Level Center
De-trended and registered to mean higher high water (MHHW; 1983-2001)
D.J. Rasmussen
@ClimateQuant

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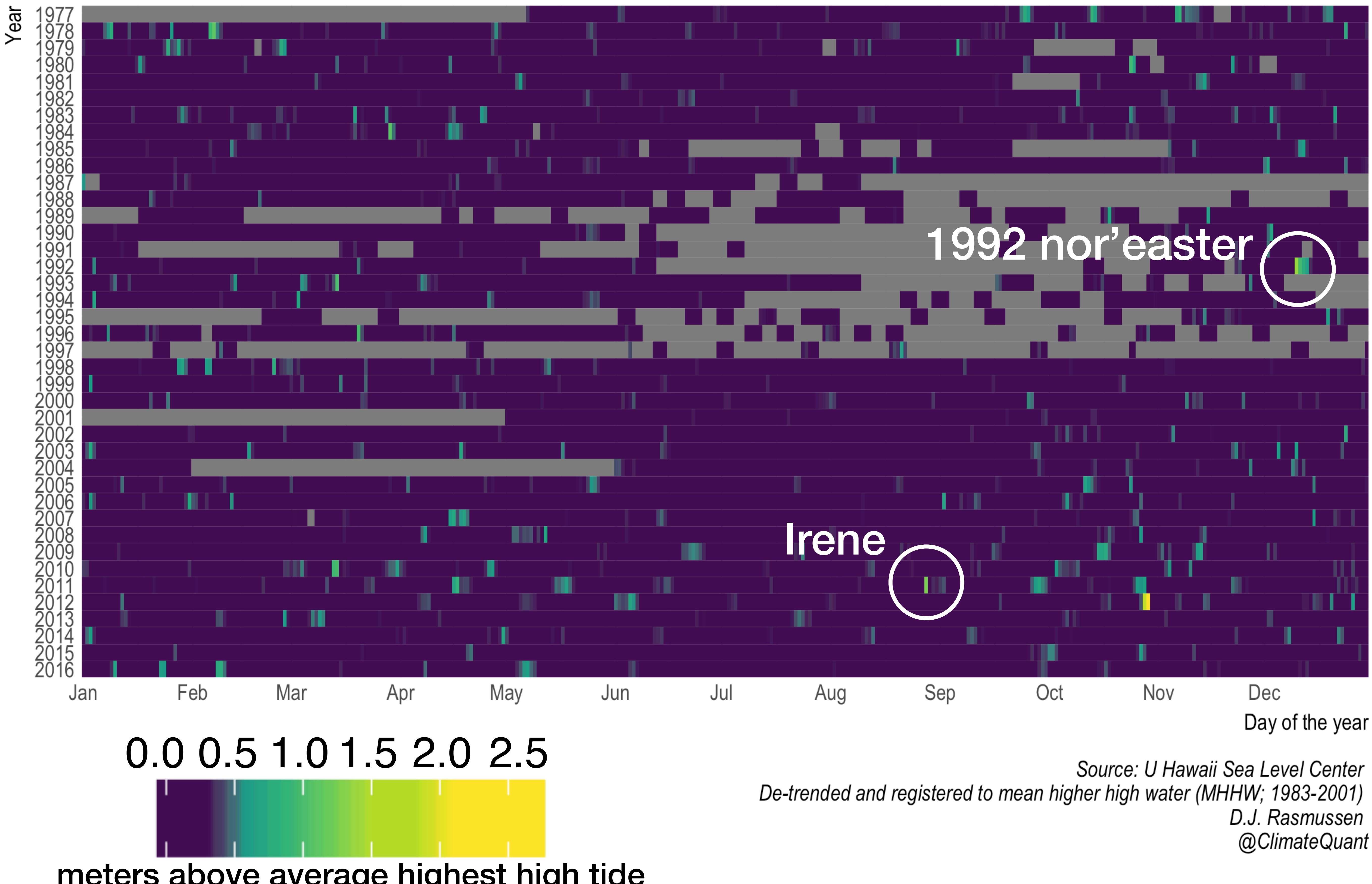

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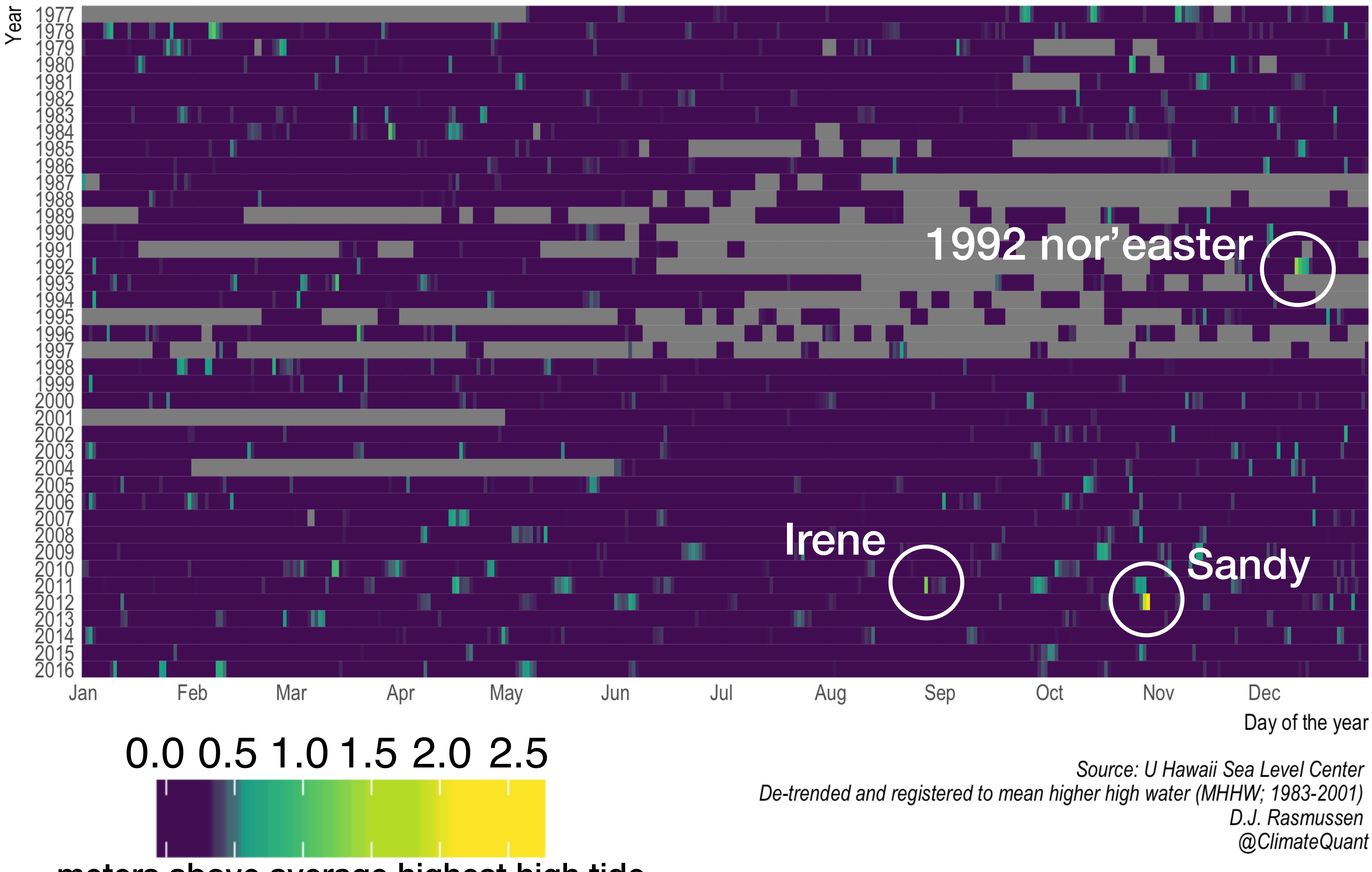

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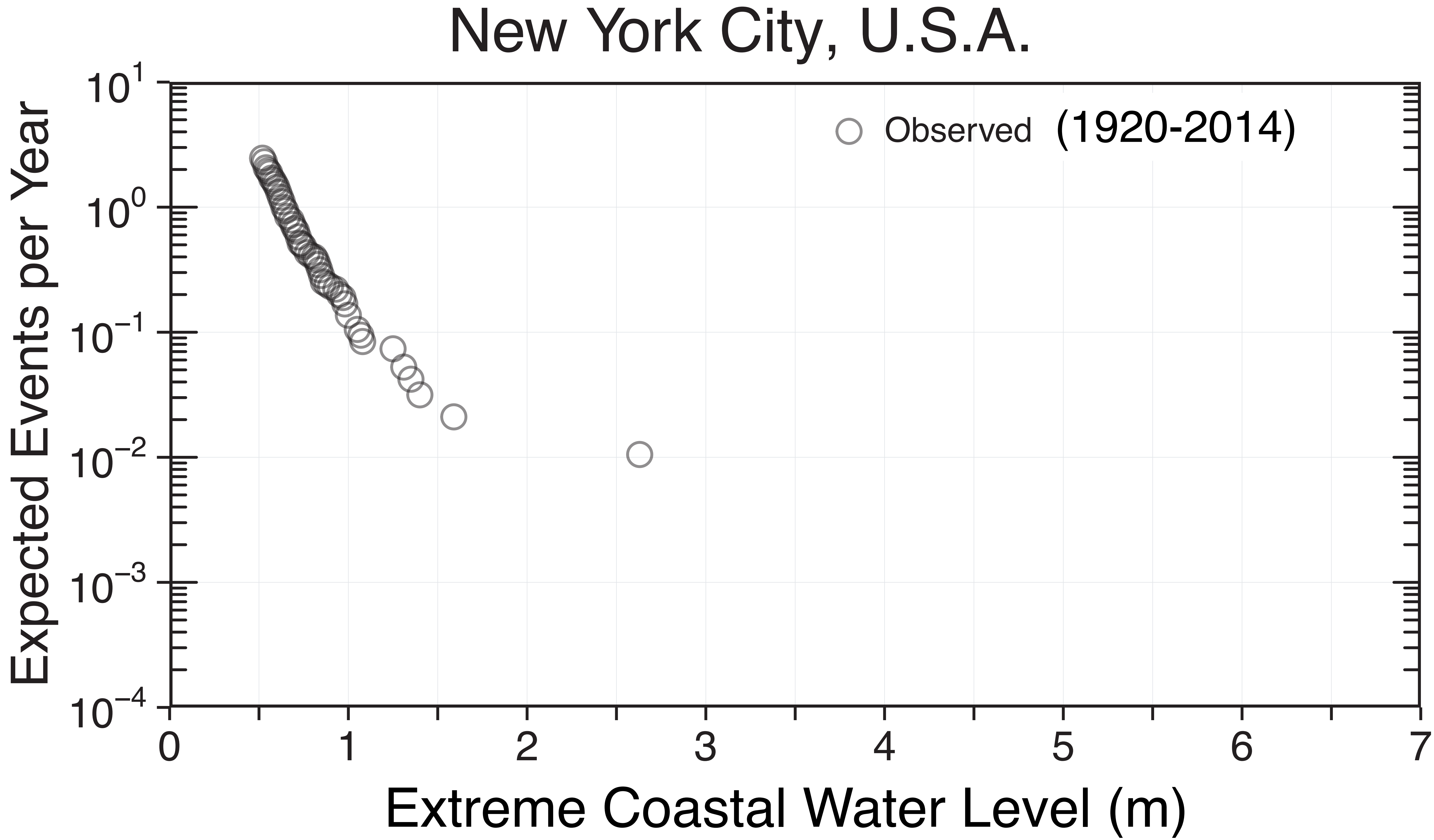
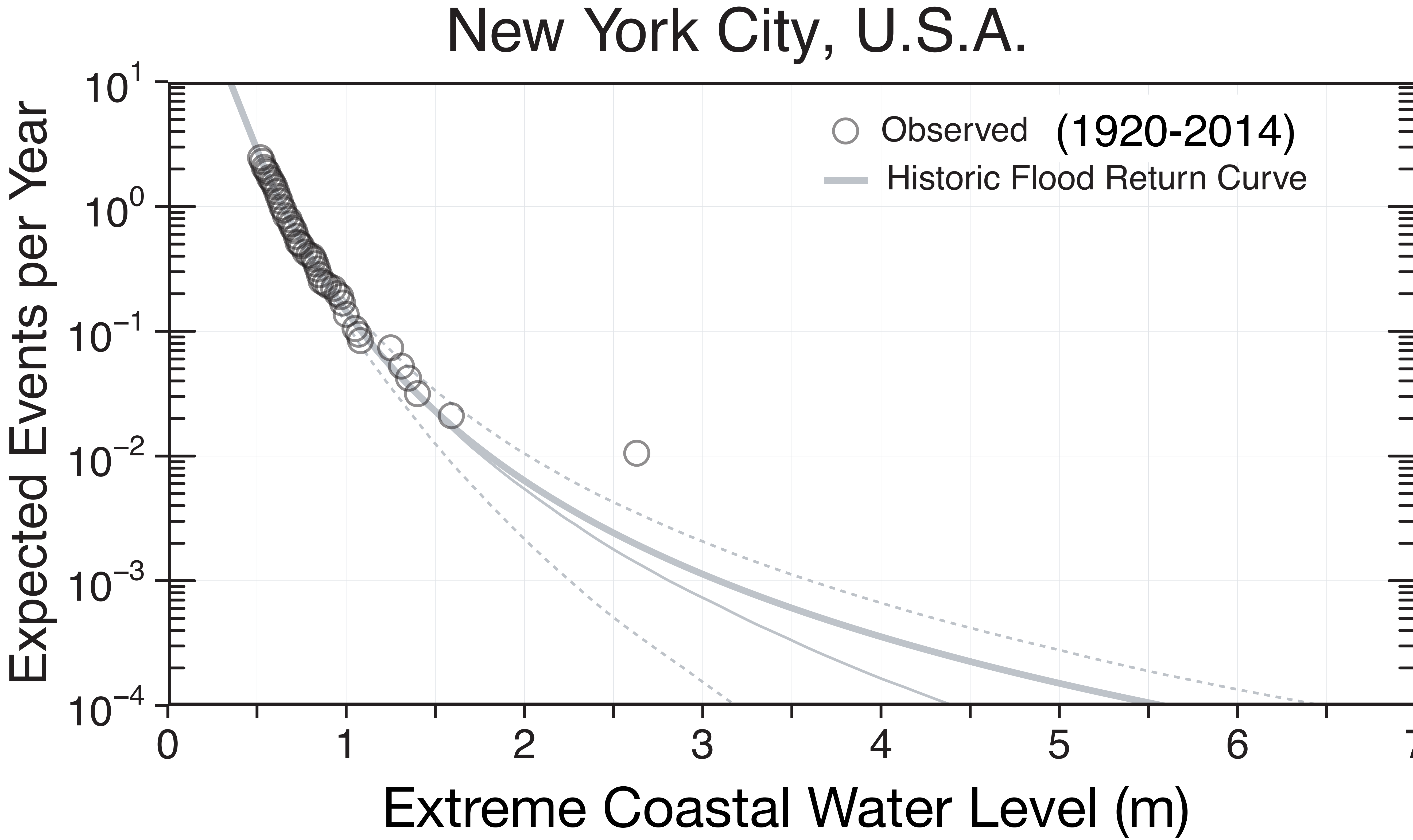
Long-term hourly records of sea level contain information about extreme water levels that can lead to flooding



[Rasmussen, Oppenheimer, and Kopp, in prep]

Extreme value theory used to fit a probability distribution to observed extreme sea levels



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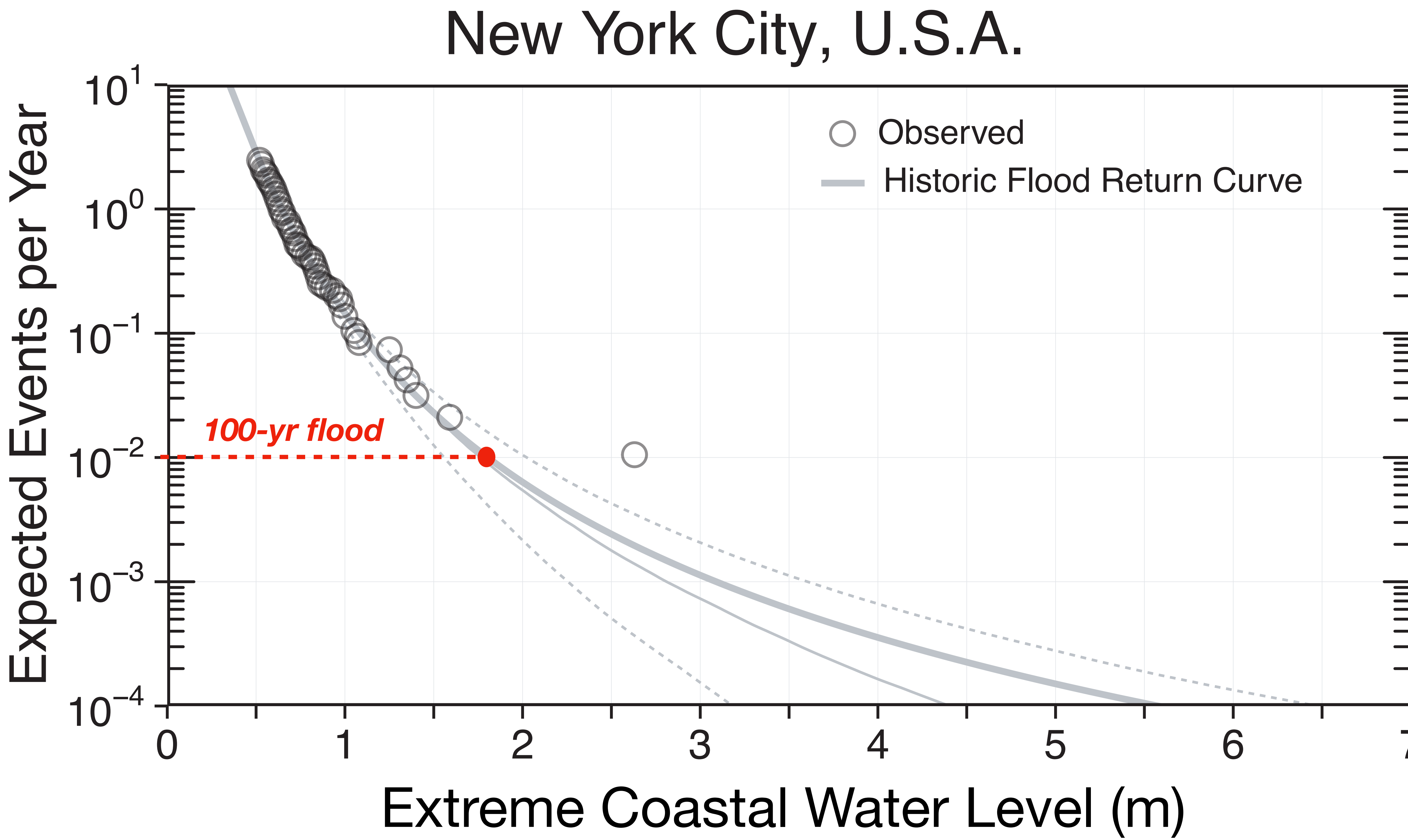
Return periods of water levels of various heights can be estimated



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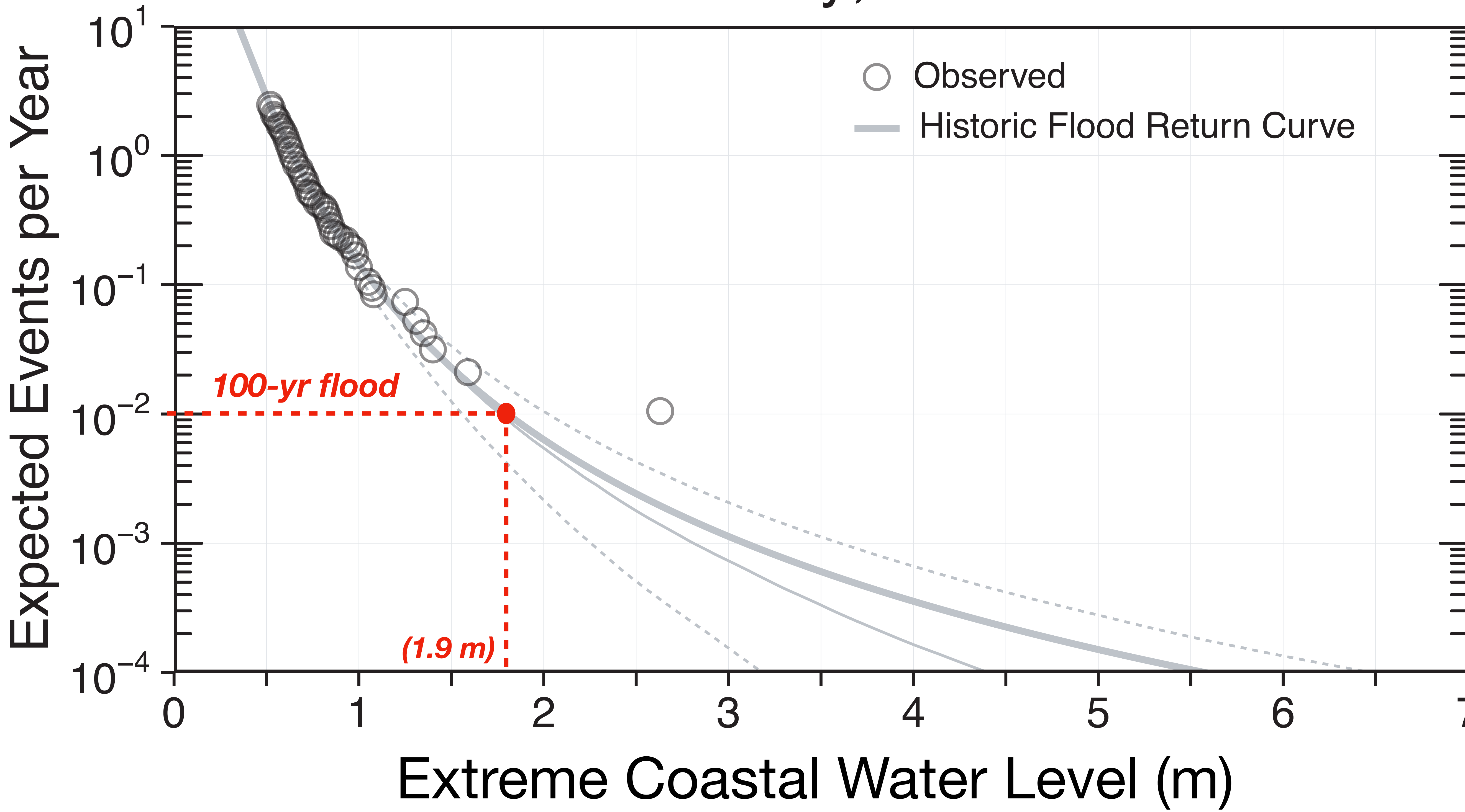
New York City, U.S.A.



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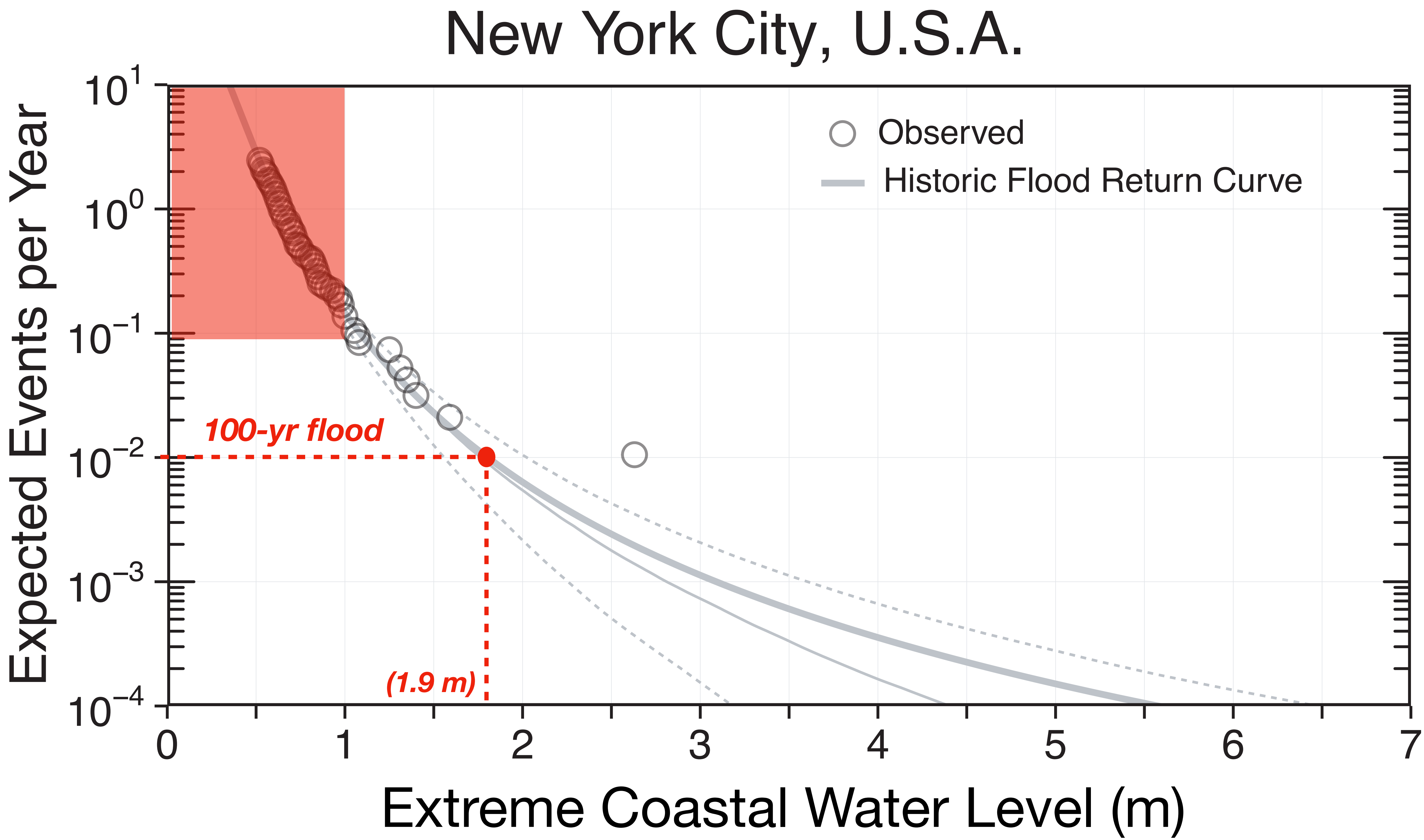
The most frequent events usually lead to minor damages



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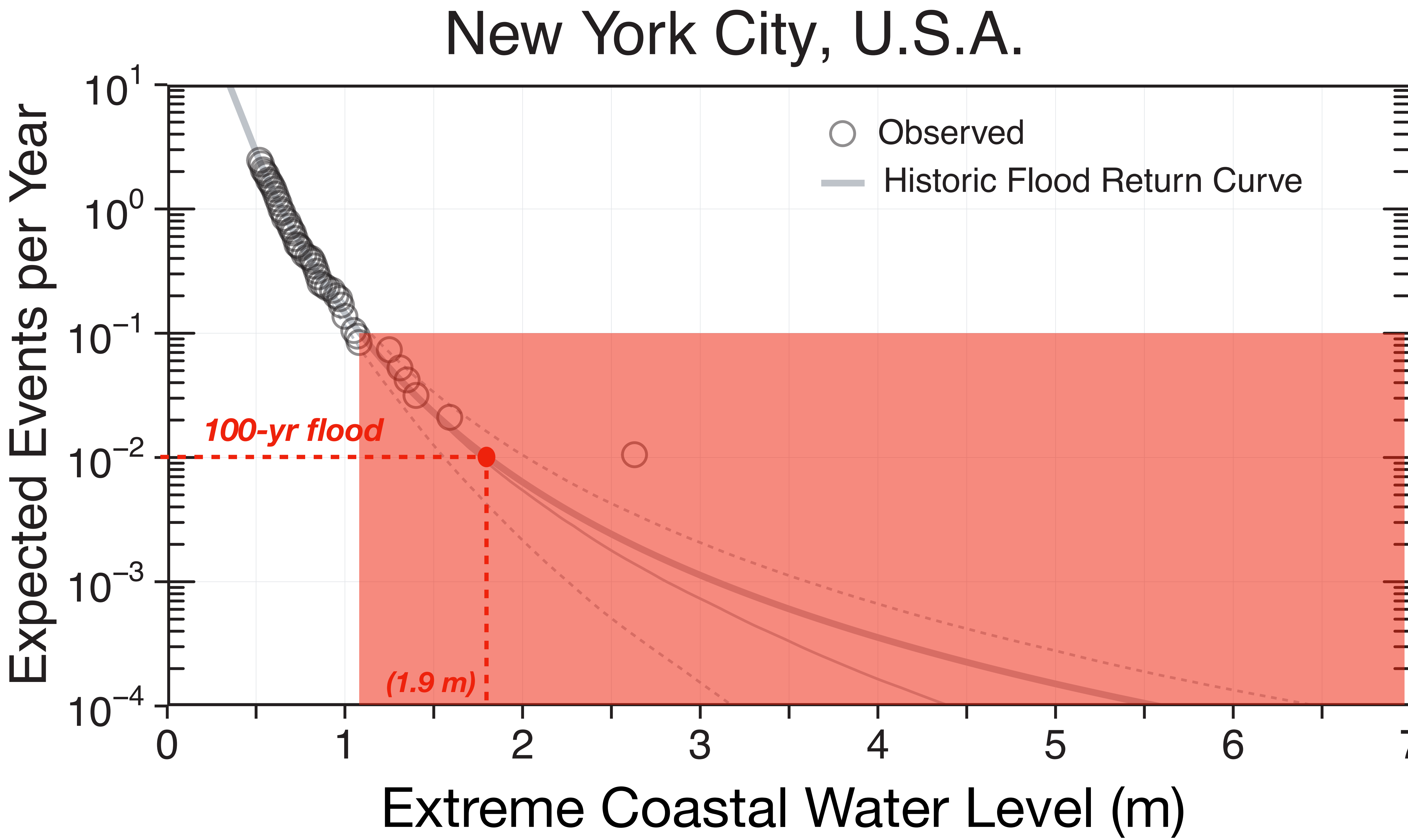
KEEP OUT
High tide flooding

Rare events can lead to catastrophic damage, if not well protected



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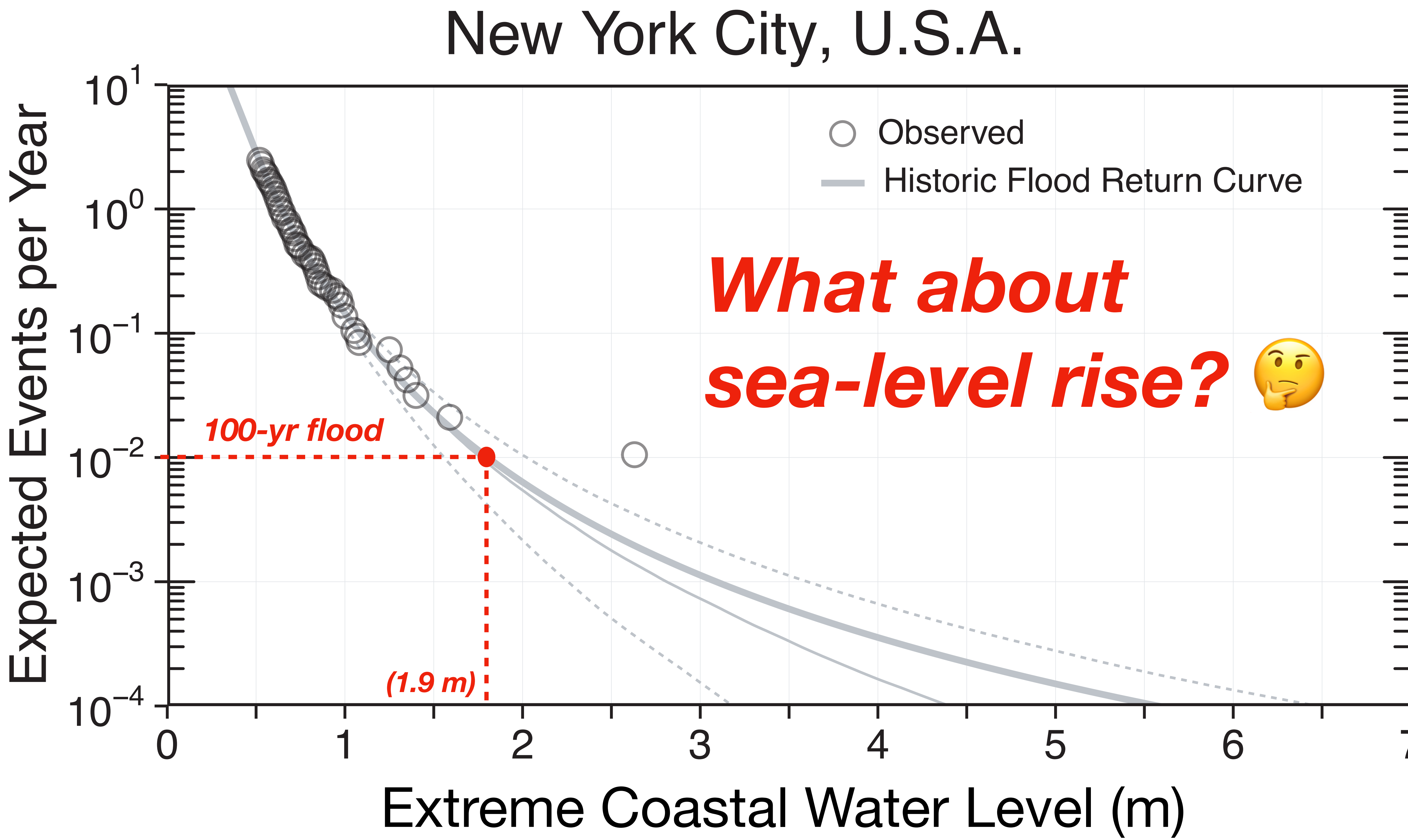
LaGuardia Airport (Nov. 1950)

South Ferry Subway (Oct. 2012)

Rare event flooding



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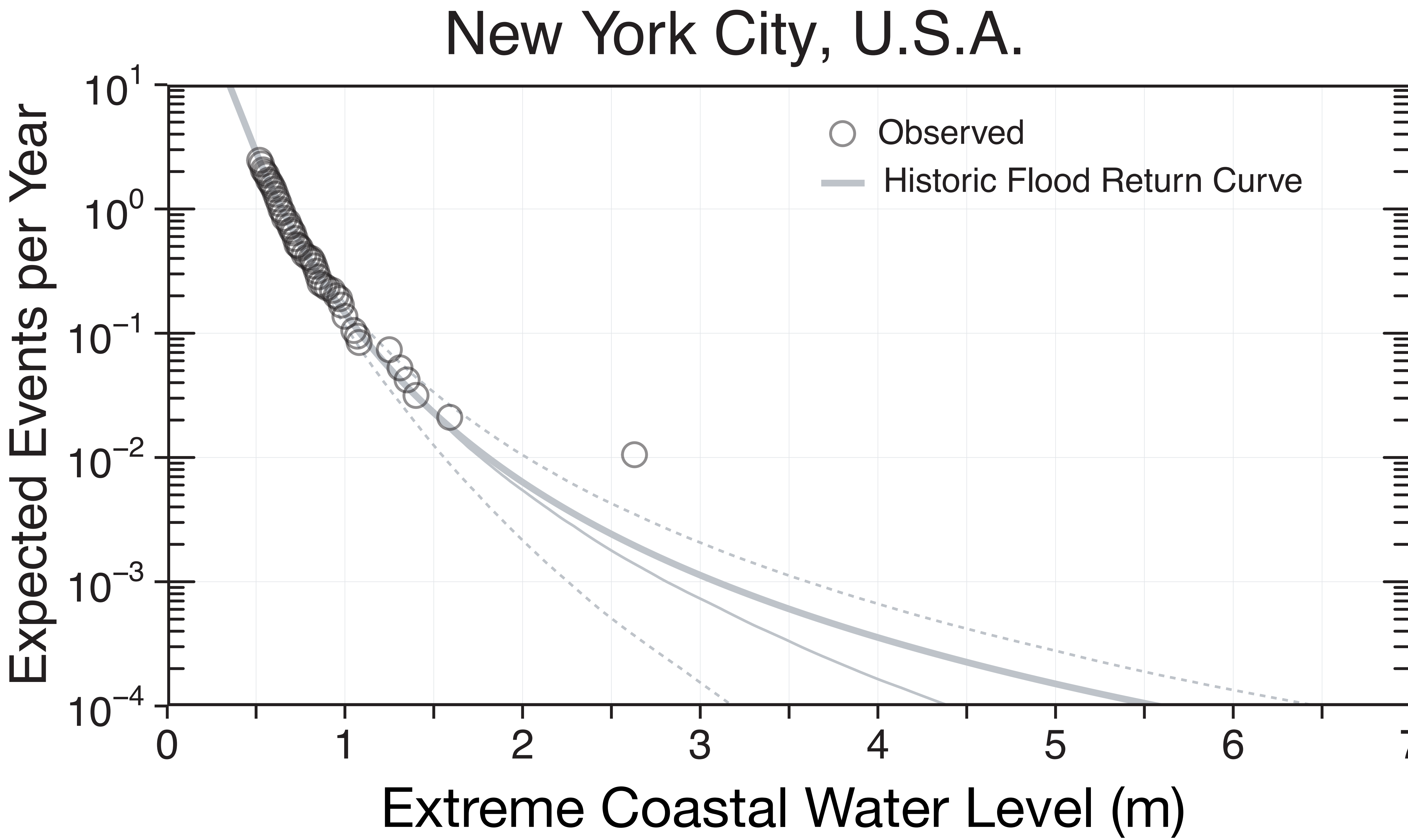

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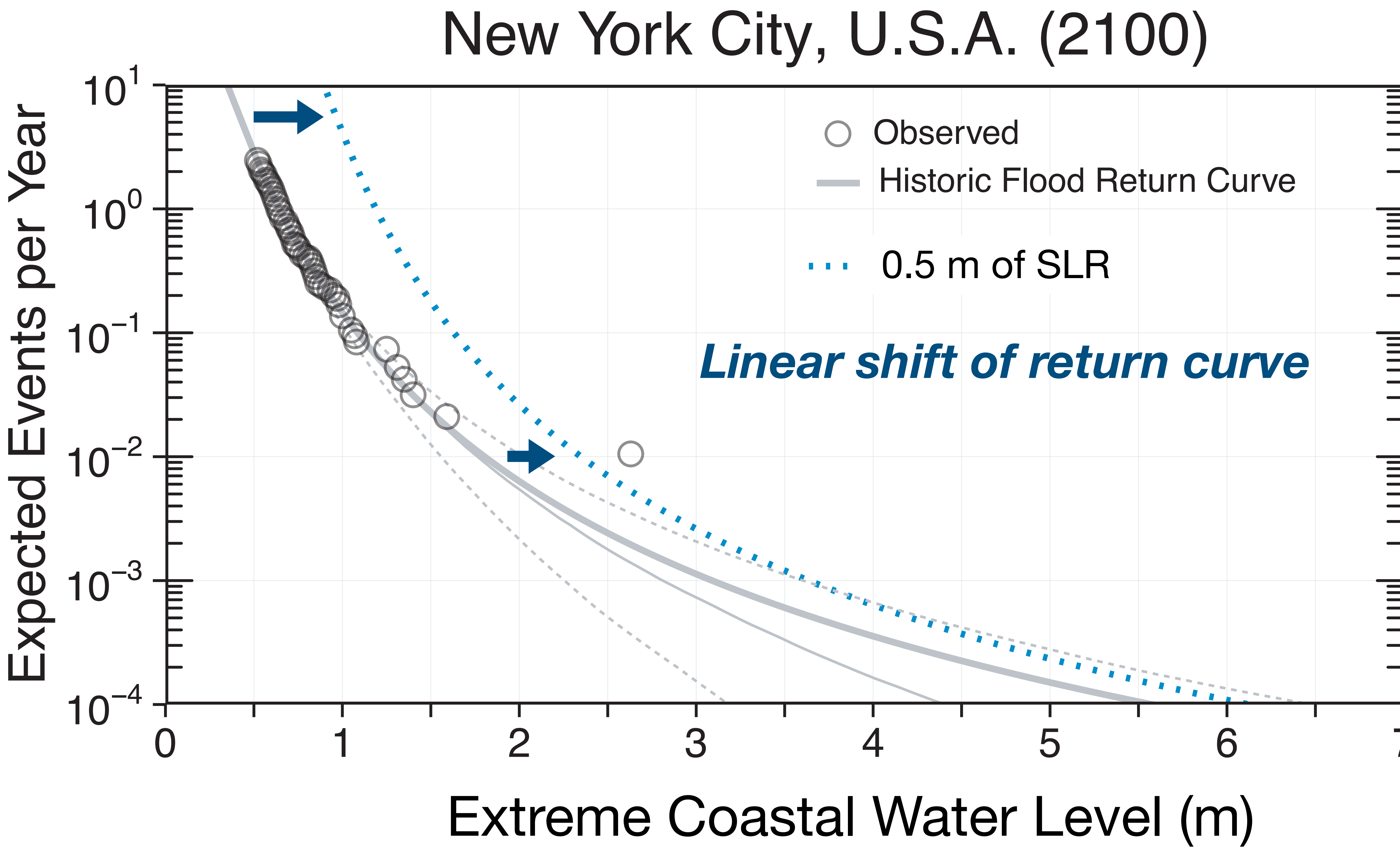
Sea-level rise increases the frequency of all extreme water level events



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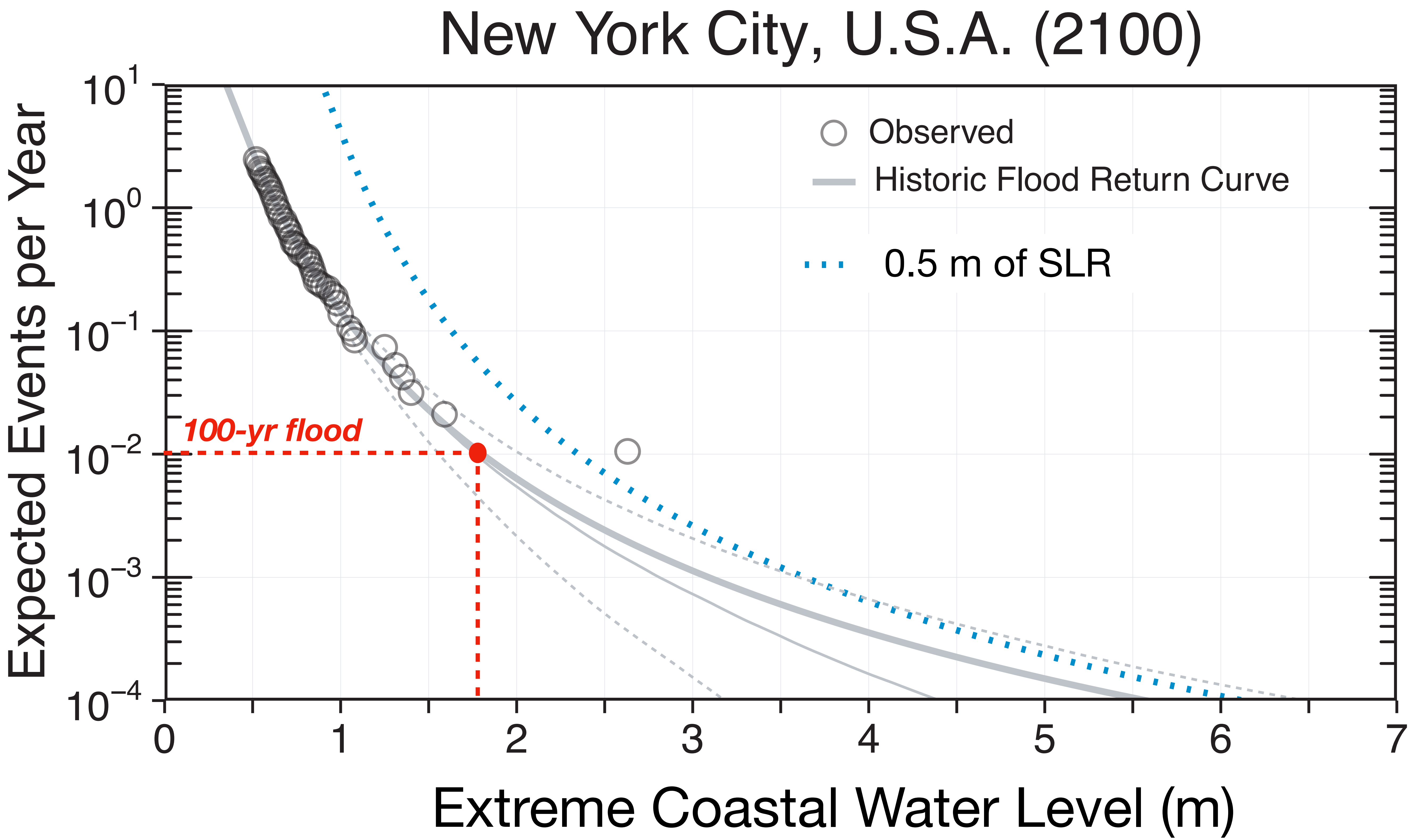

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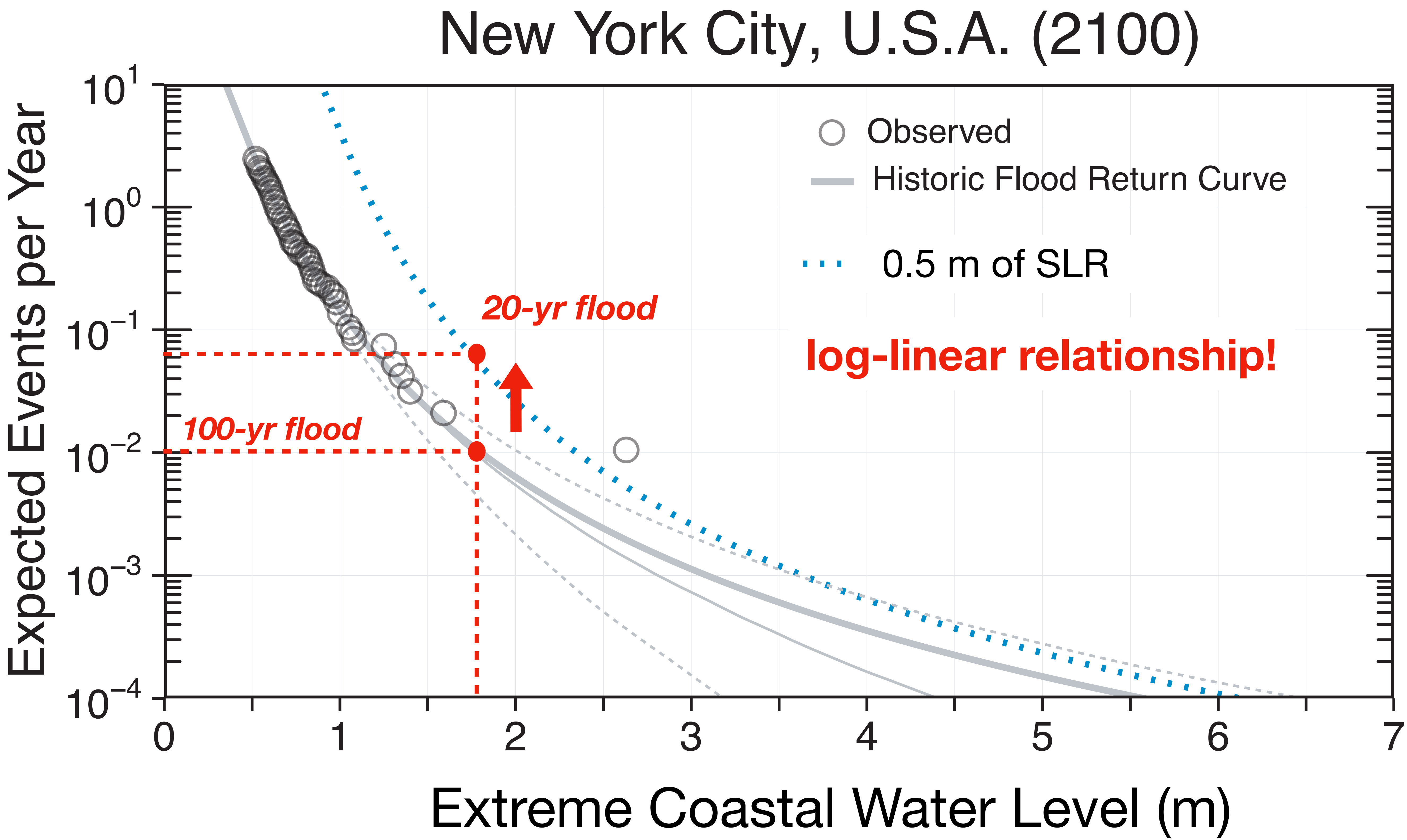

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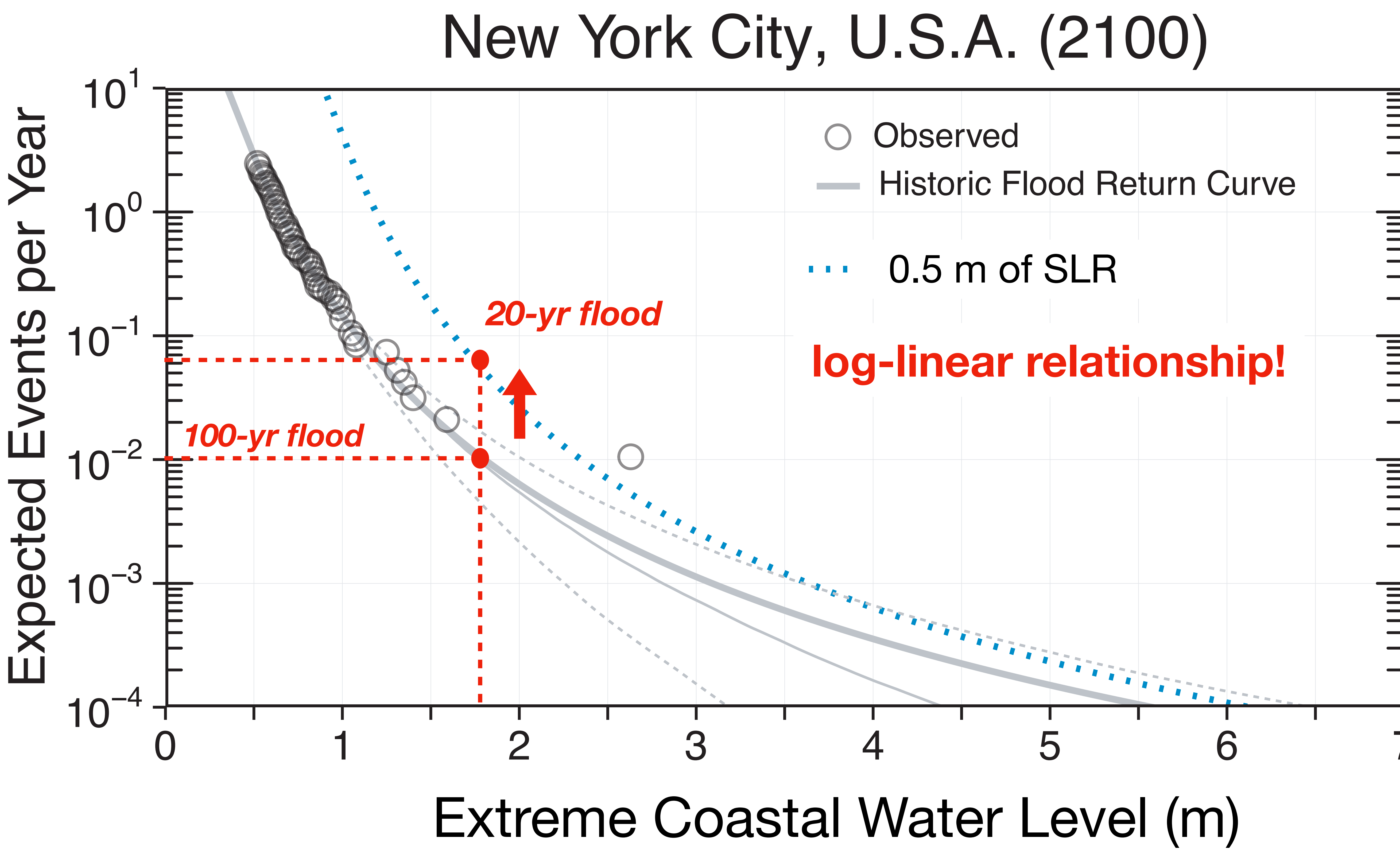


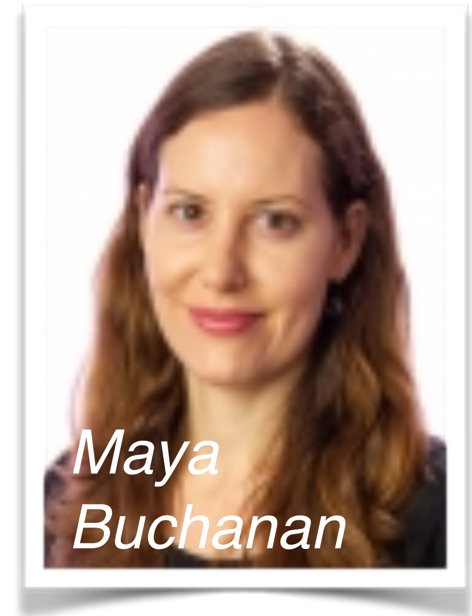
How to design to a 'moving' target?

A ‘flood allowance’ accommodates changing frequency of extreme water levels

[Hunter, 2012; Buchanan et al., 2016]

Flood allowance *(noun):* the vertical required to keep the expected number of extreme coastal water level events constant under uncertain sea-level change

Engineering metric: “How high to build the levee?”



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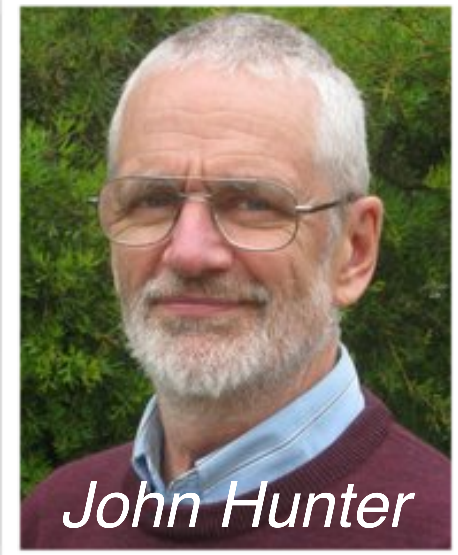
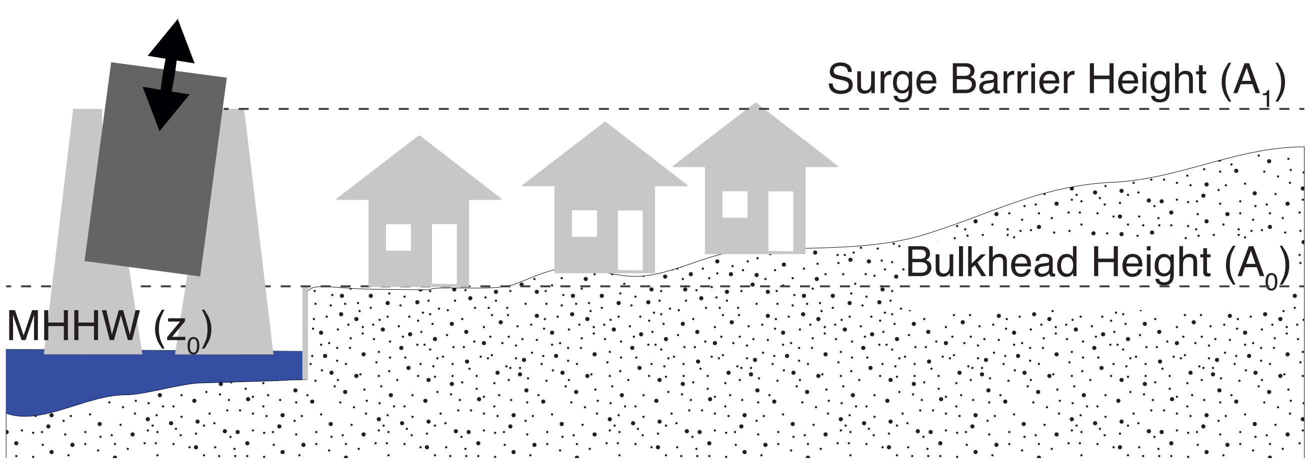


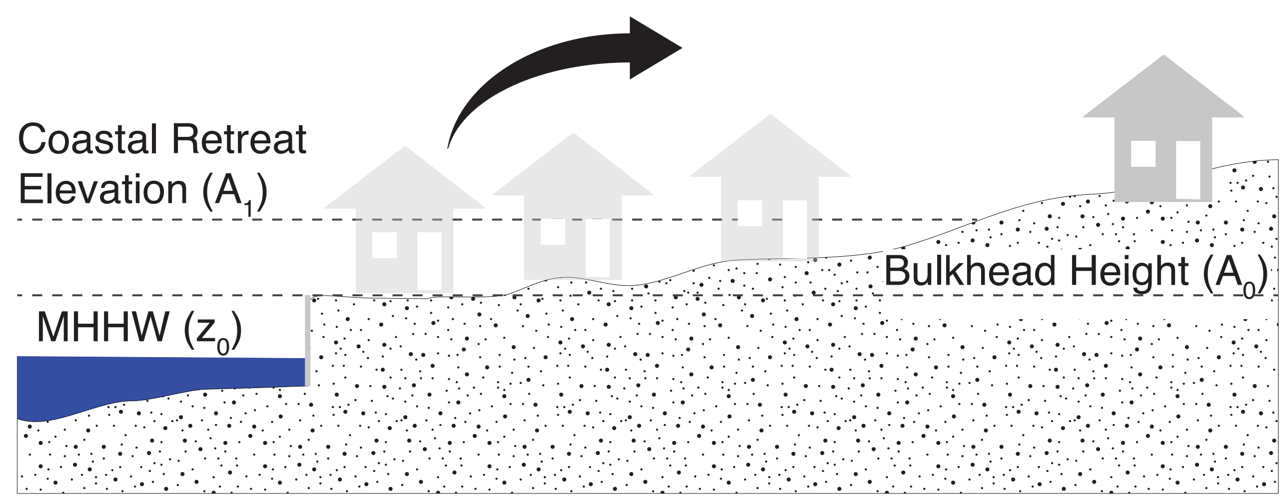
Engineering metric: “How high to build the levee?”

Examples:

Surge Barrier



Coastal Retreat



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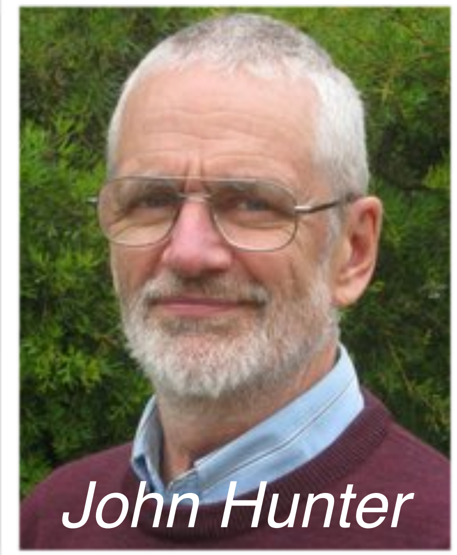

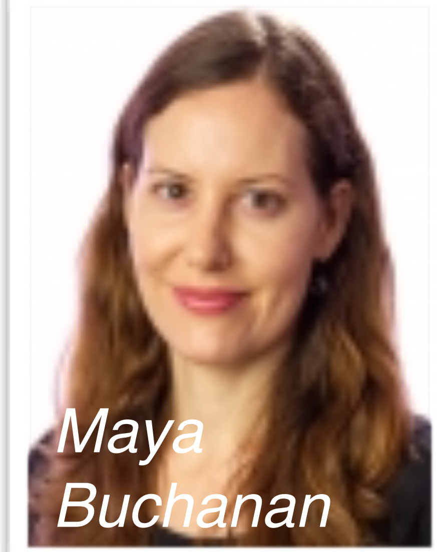

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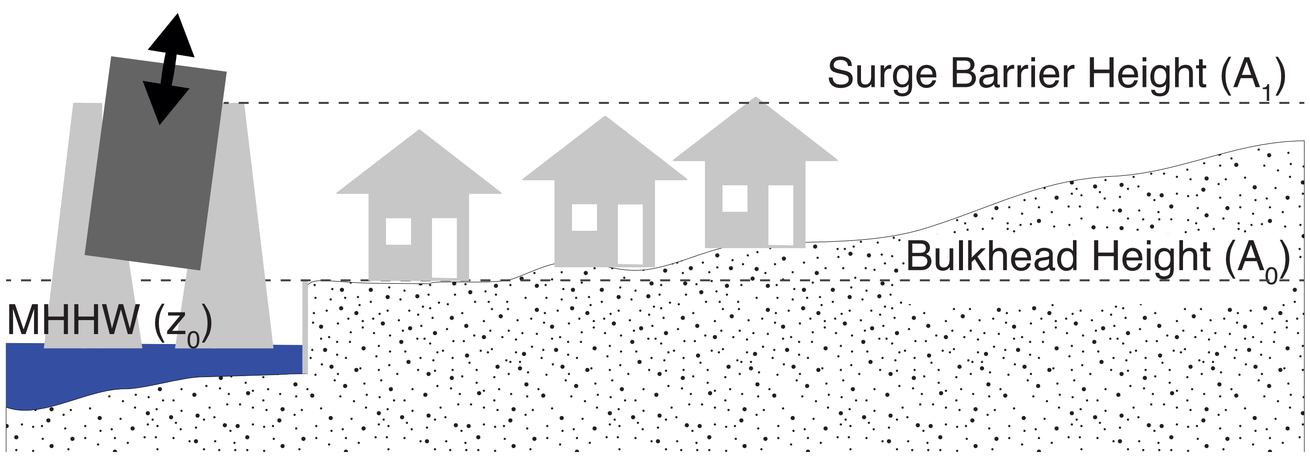

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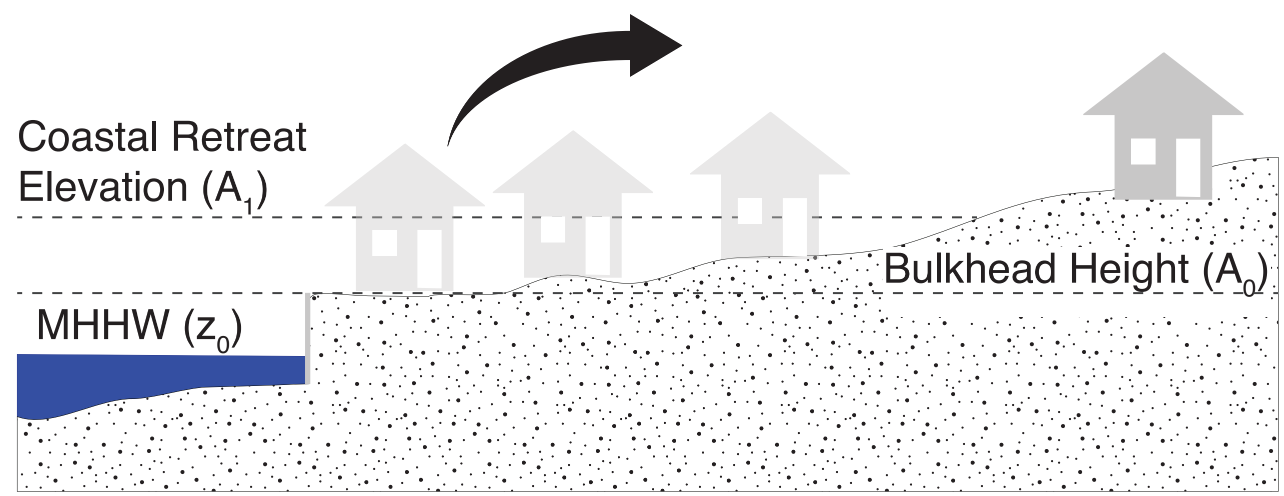

Type of flood allowances:

1. *For a given point in time (“instantaneous”)*
2. *Over a given time period (“design life”)*

Flood allowance illustrated with basic math

Sea-level rise increases exceedance probability of z: *f(z-Δ)*

$$f(z^*) = f(z^* - \Delta + A(z^*))$$

Height of extreme water level: $z^* = 1.9\ m$

Current exceedance probability of z*: $f(z^*) = 0.01$

Known amount of local sea-level rise: $\Delta = 0.5\ m$

Vertical adjustment to maintain f(z*): $A(z^*)$ *the "allowance"*

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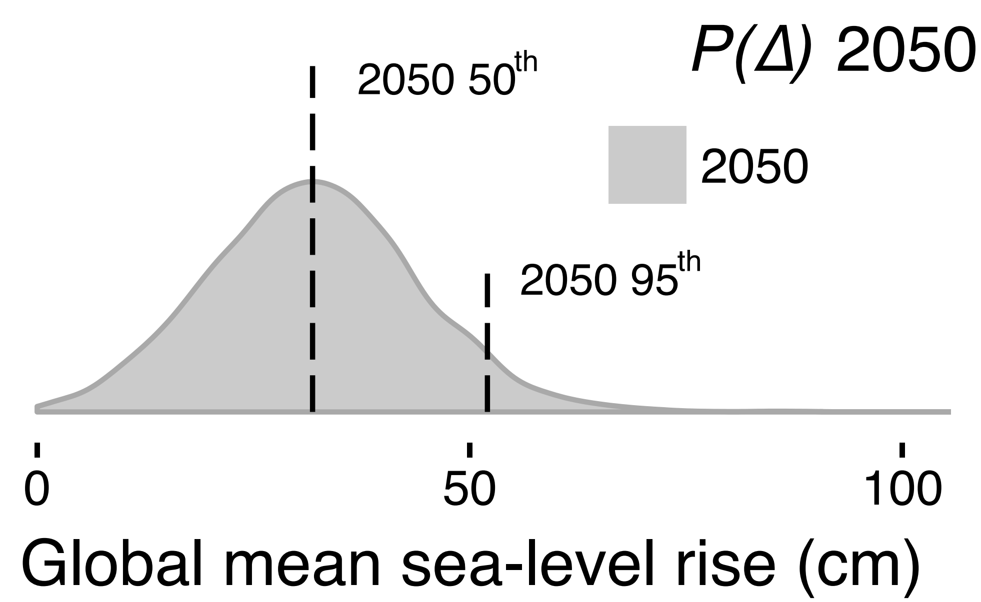
***Unknown* amount of local sea-level rise**



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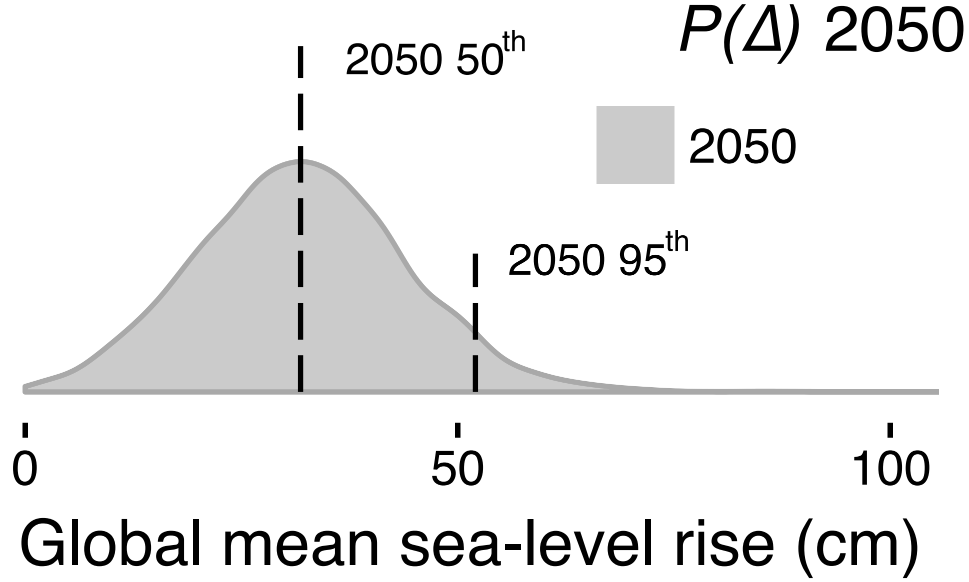
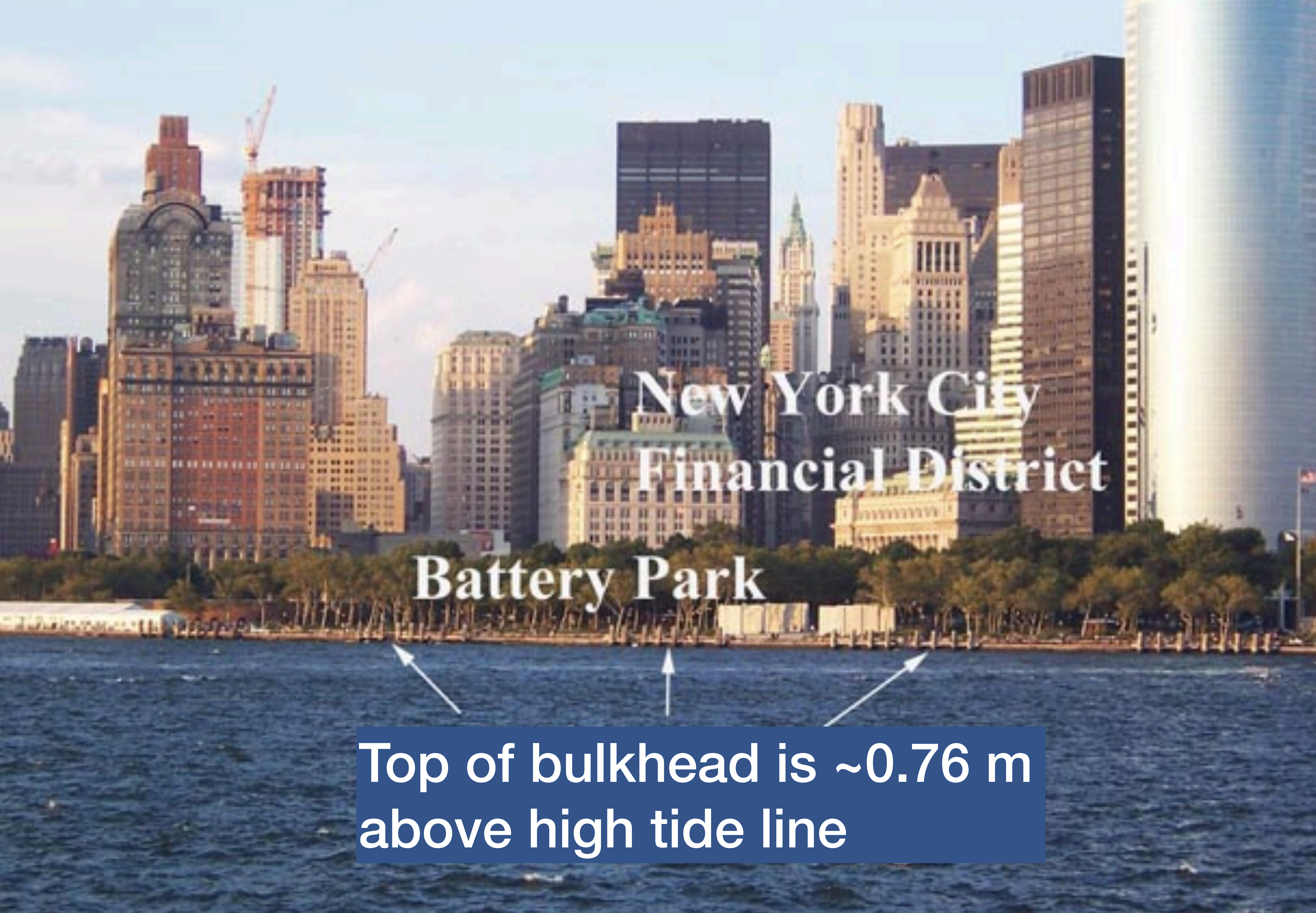


$$f(z^*) = \int_\Delta f(z^* - \Delta + A(z^*))P(\Delta)\,\mathrm{d}\Delta$$

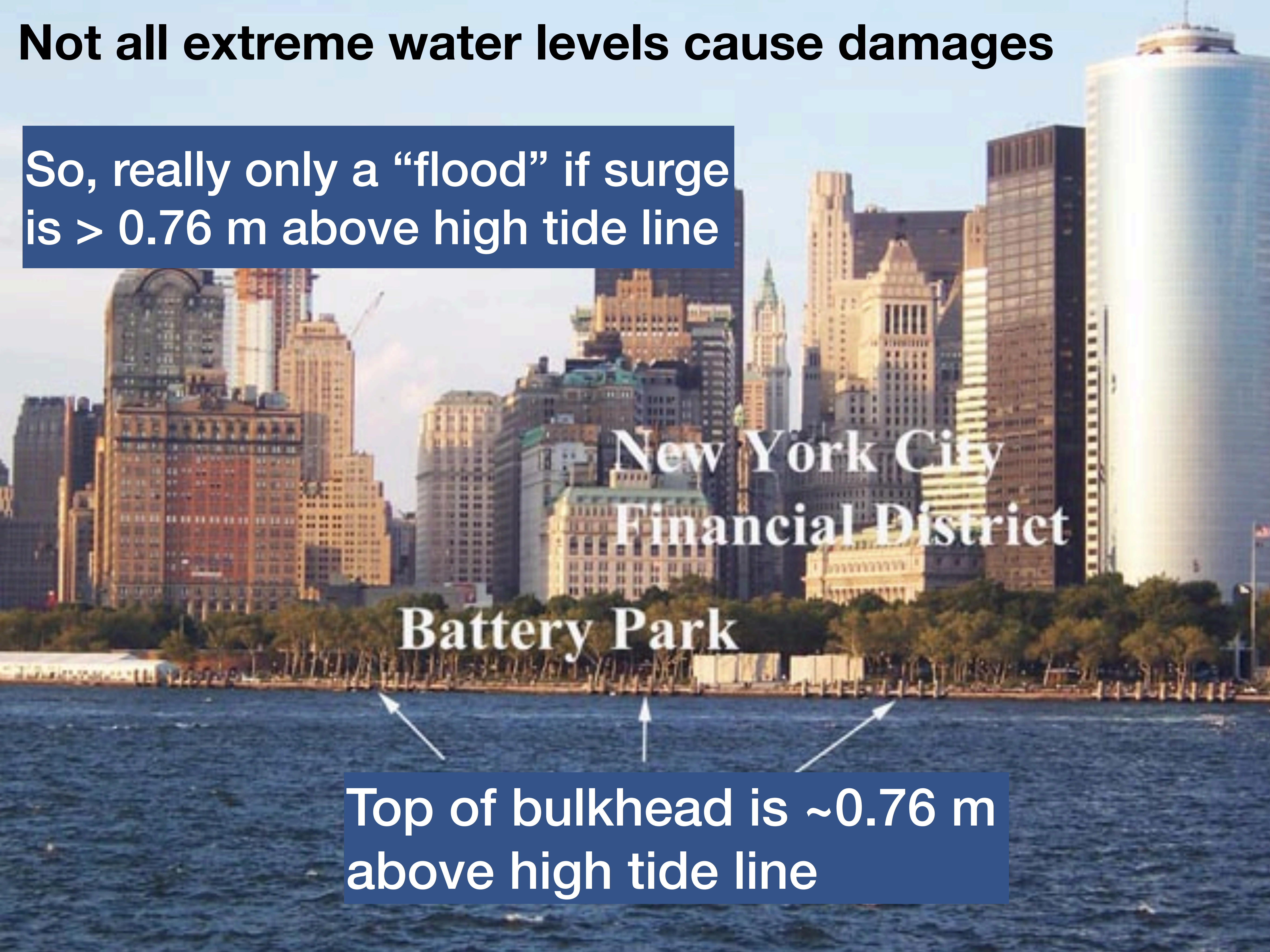
Solve for A numerically

Not all extreme water levels cause damages



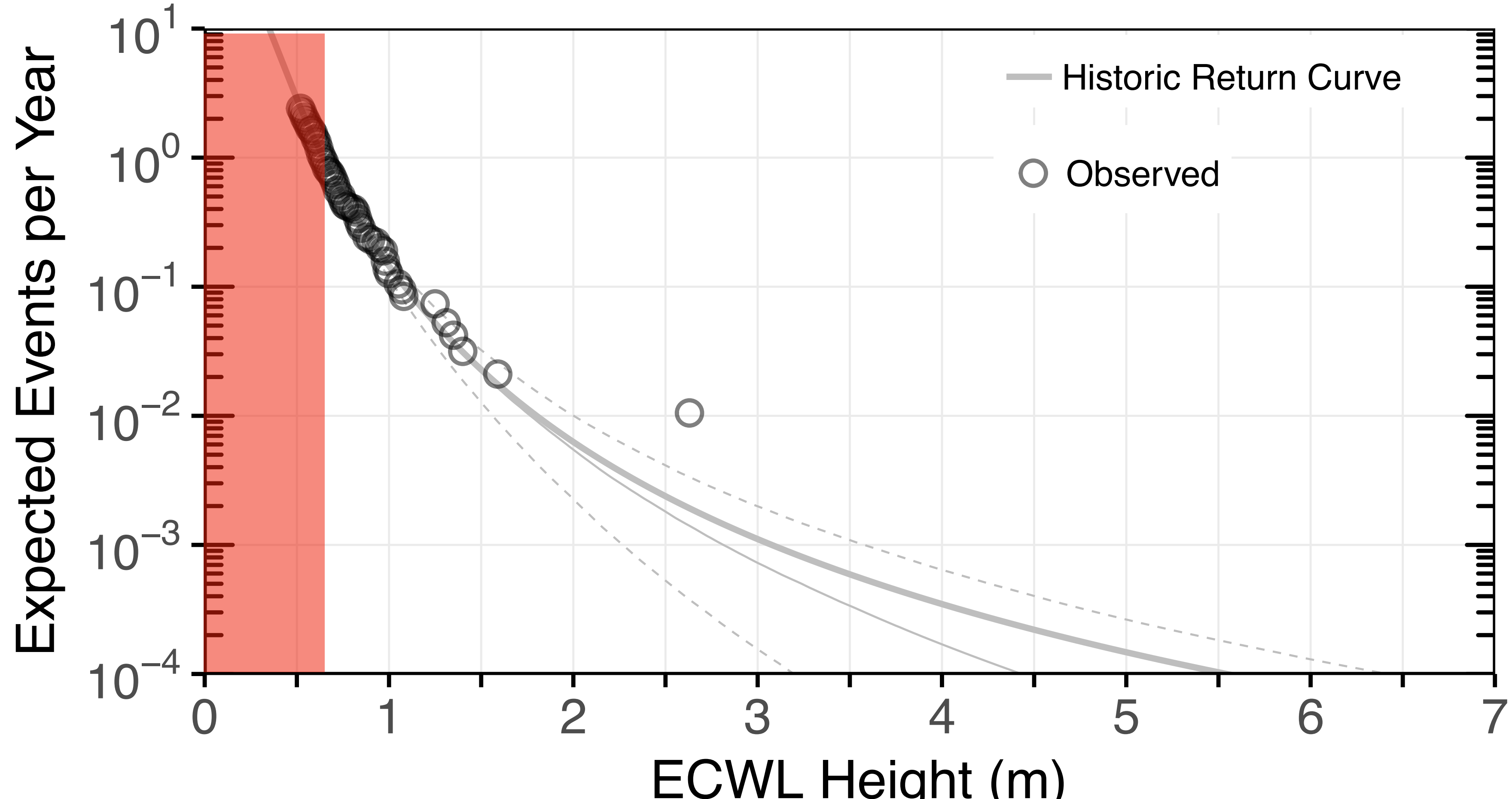
Not all extreme water levels cause damages

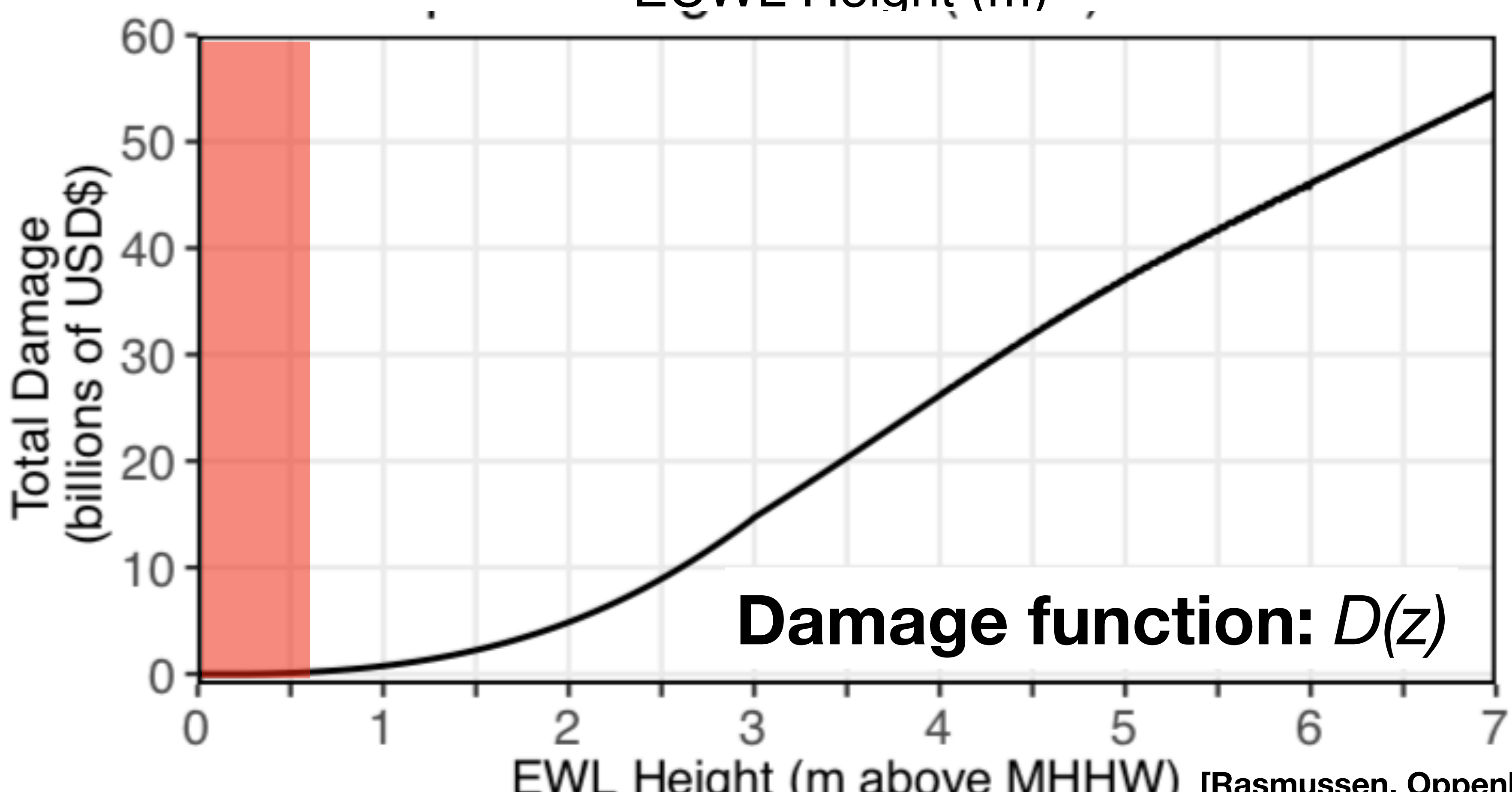
So, really only a “flood” if surge is > 0.76 m above high tide line



Top of bulkhead is ~0.76 m above high tide line

Not all extreme water levels cause damages

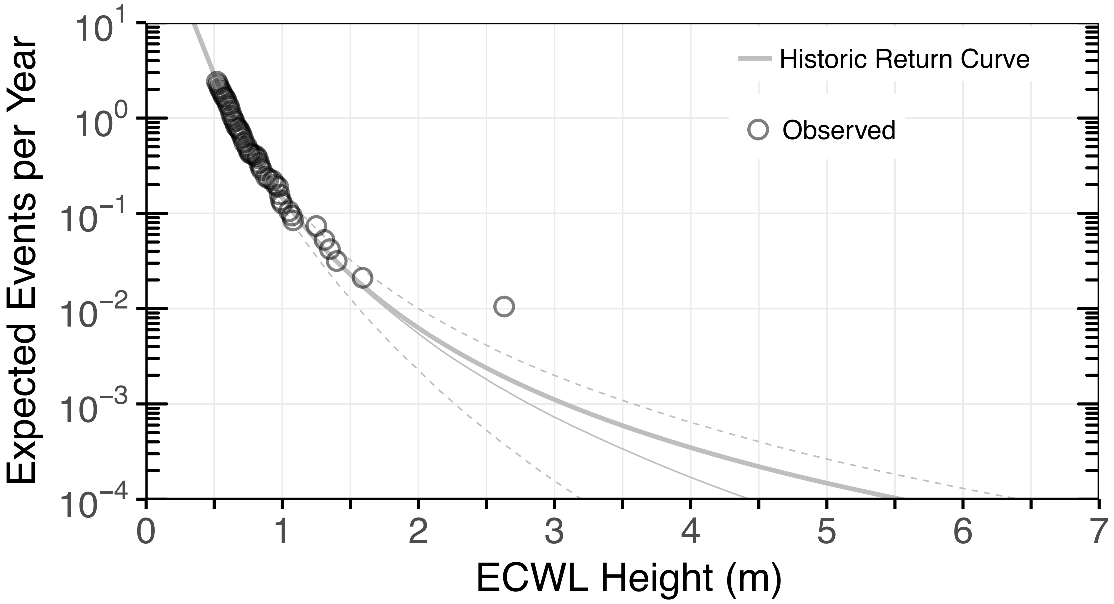




[Rasmussen, Oppenheimer, and Kopp, in prep]

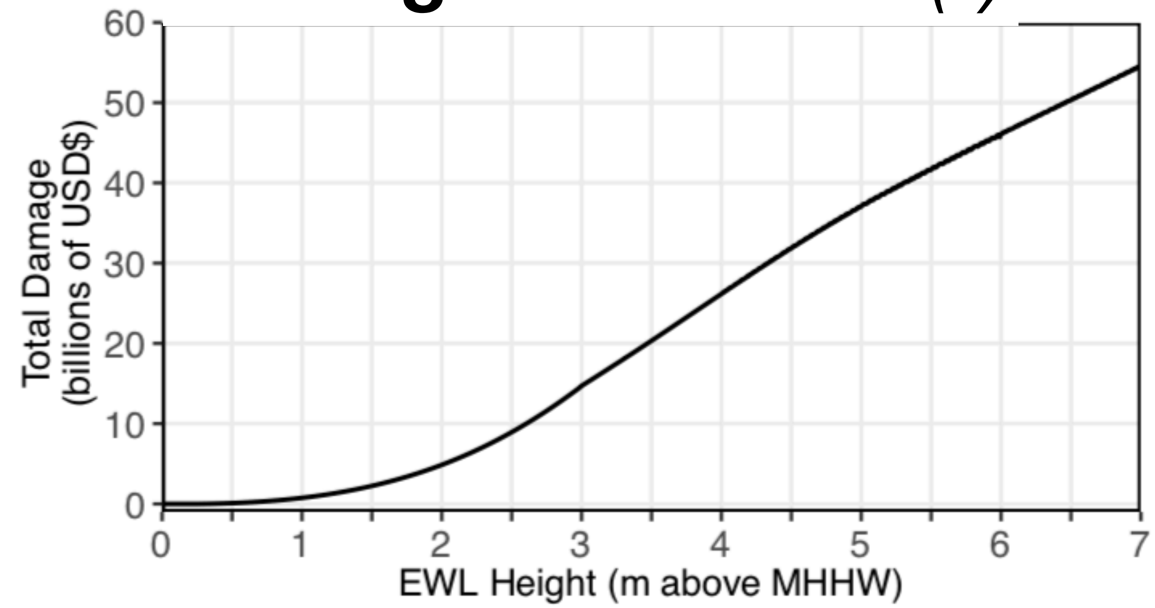
Coastal managers may be more interested in financial metrics

Probability of water level z: *f(z)*



X

Damage function: *D(z)*



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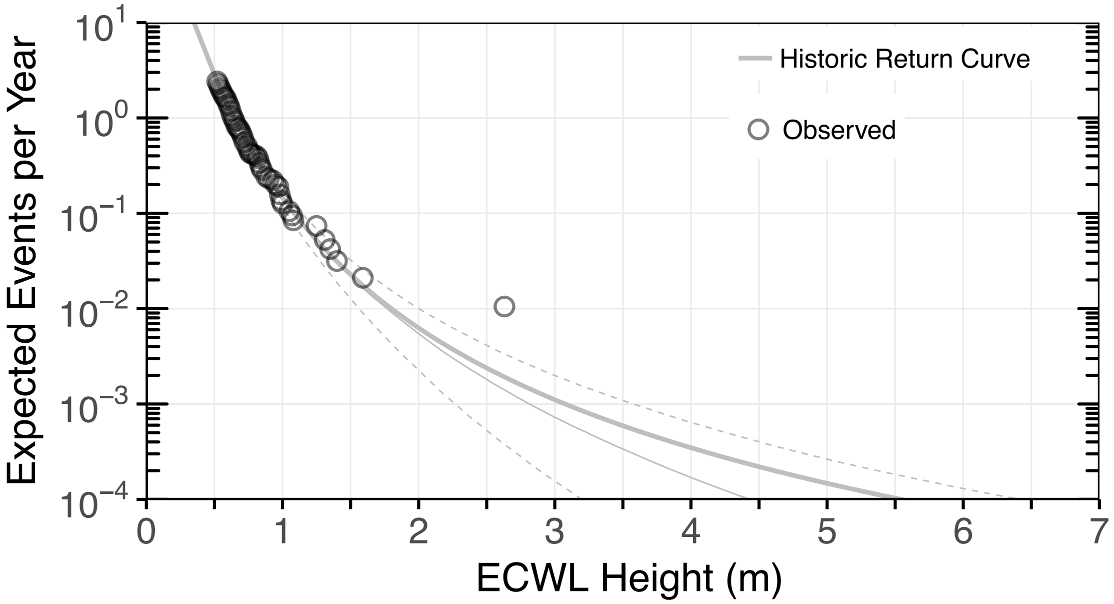
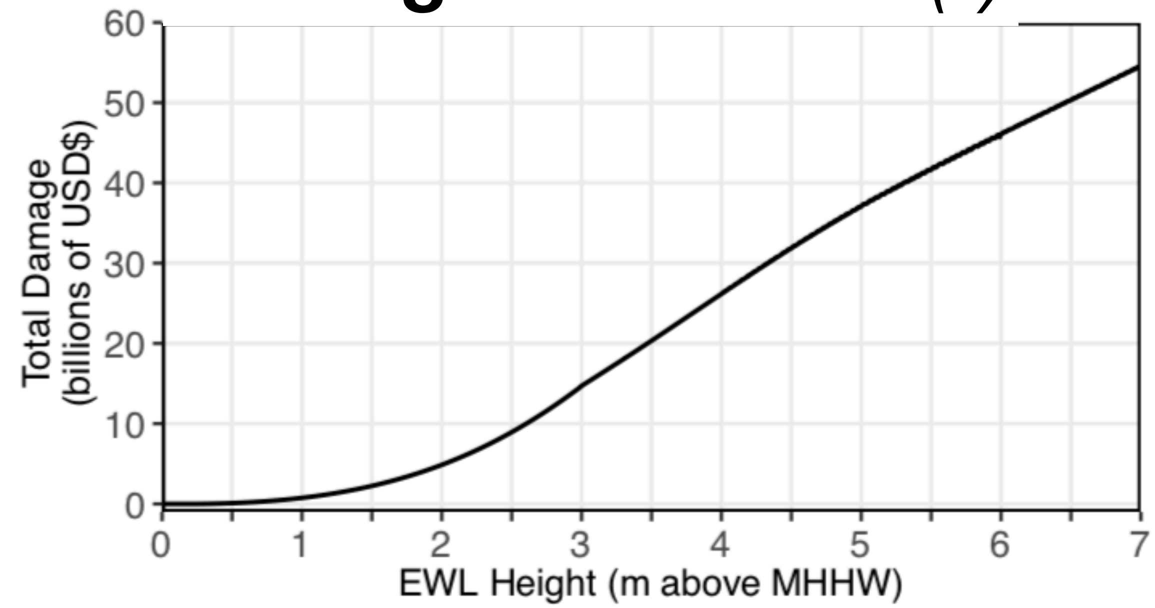


X

Damage function: *D(z)*



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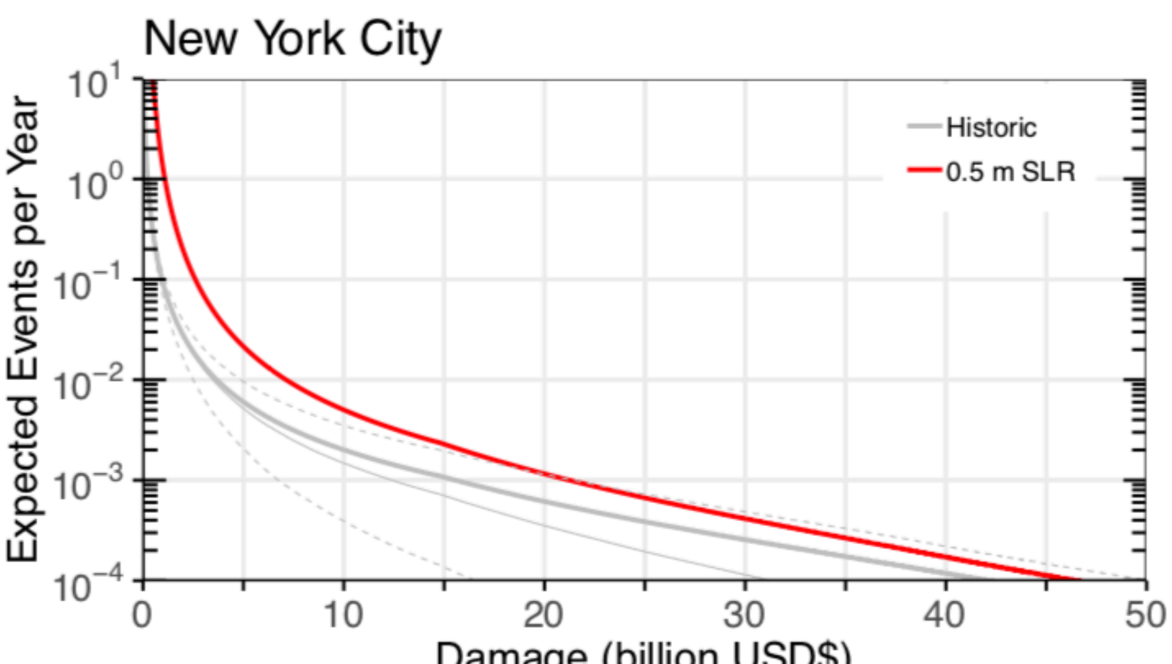

[Rasmussen, Oppenheimer, and Kopp, in prep]

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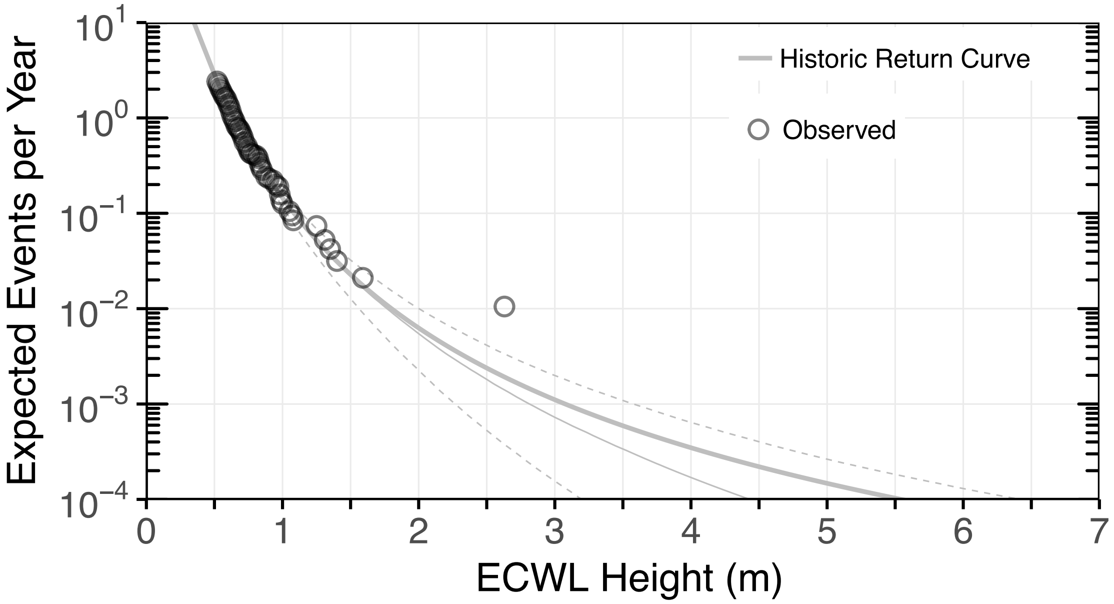

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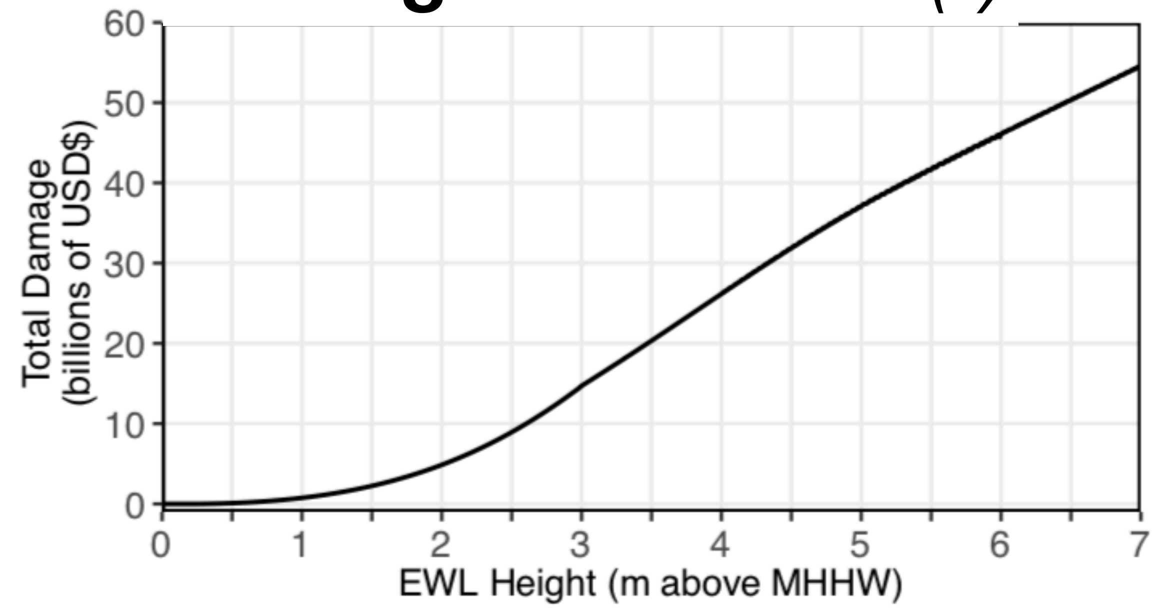

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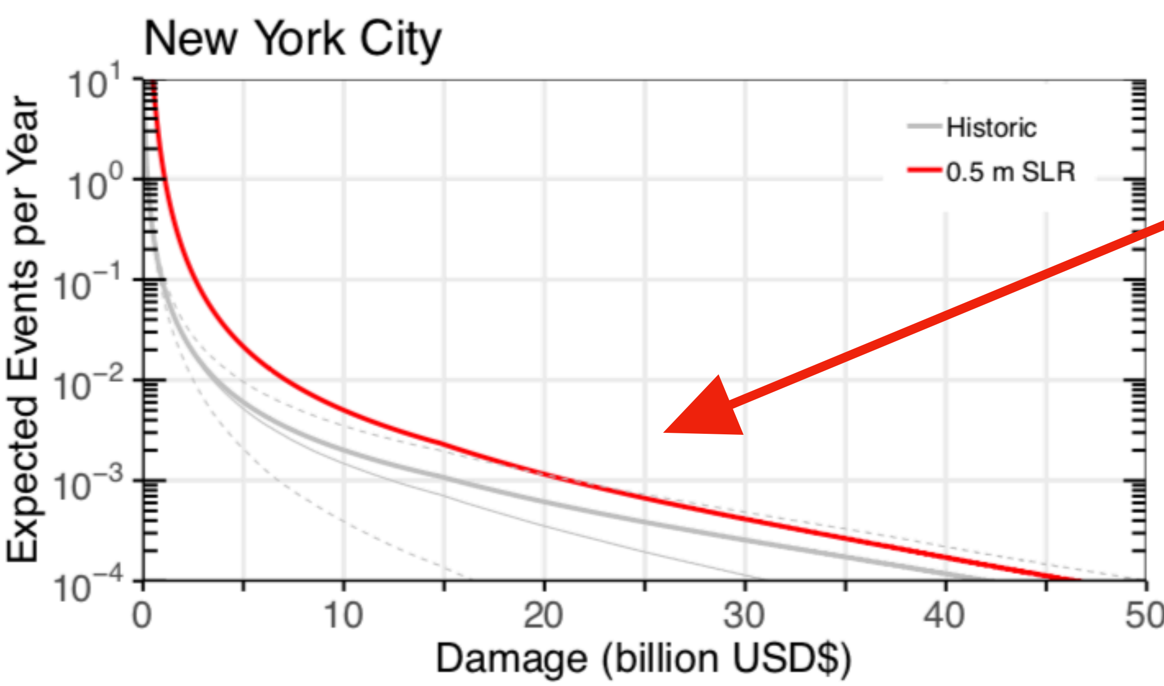

Area under each curve is the annual average loss (AAL)

$$\mathbb{E}[\mathrm{D}(z)] = \int_z \mathrm{D}(z) f(z)\, \mathrm{d}z$$

[Rasmussen, Oppenheimer, and Kopp, in prep]

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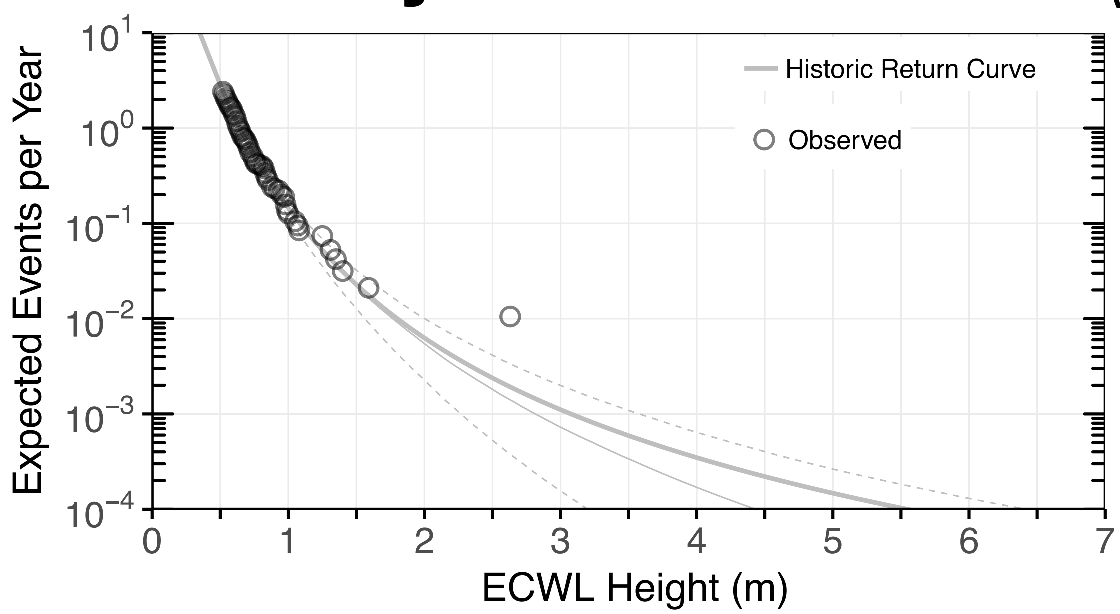

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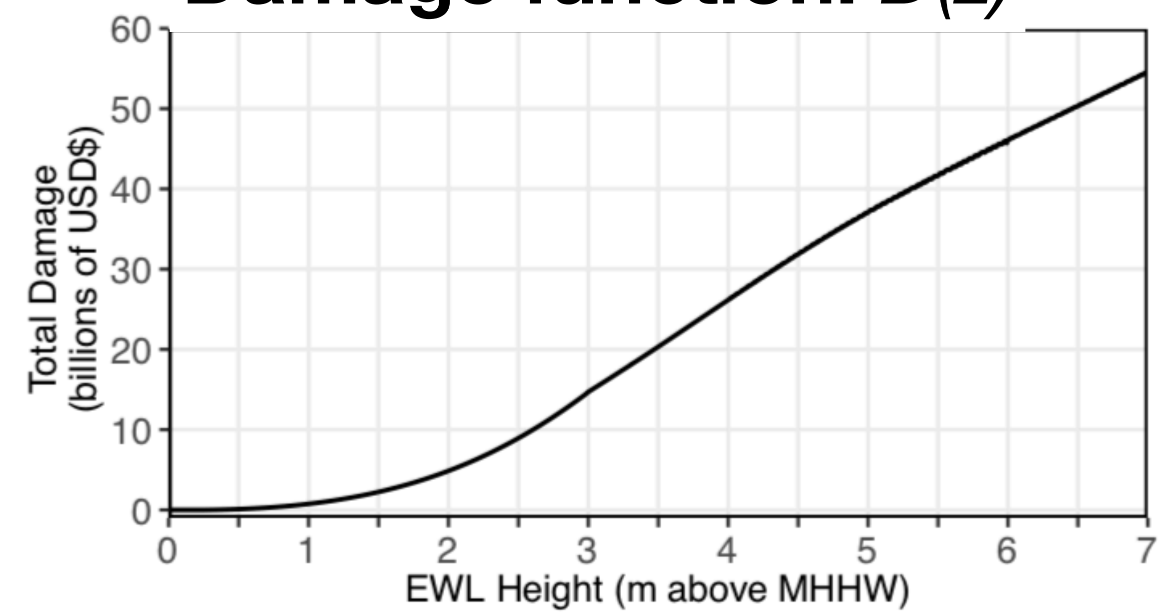

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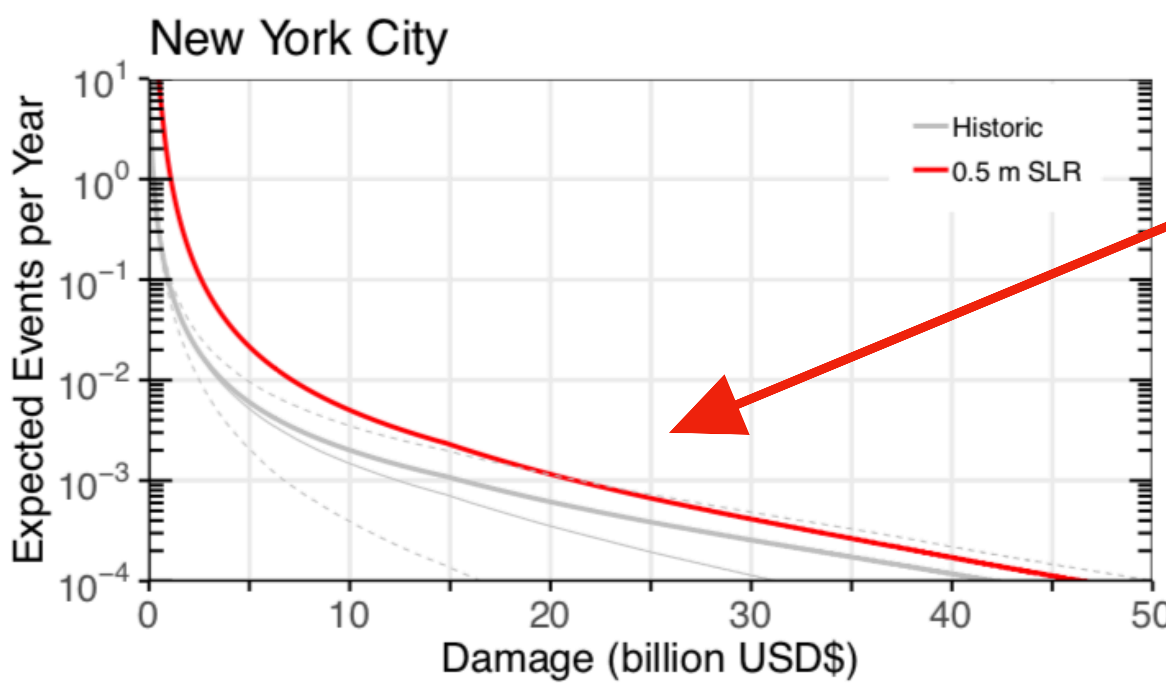

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Present-day AAL for New York City ~ $0.5 billion

AAL for New York City with 0.5 m of sea-level rise ~ $1.5 billion

[Rasmussen, Oppenheimer, and Kopp, in prep]

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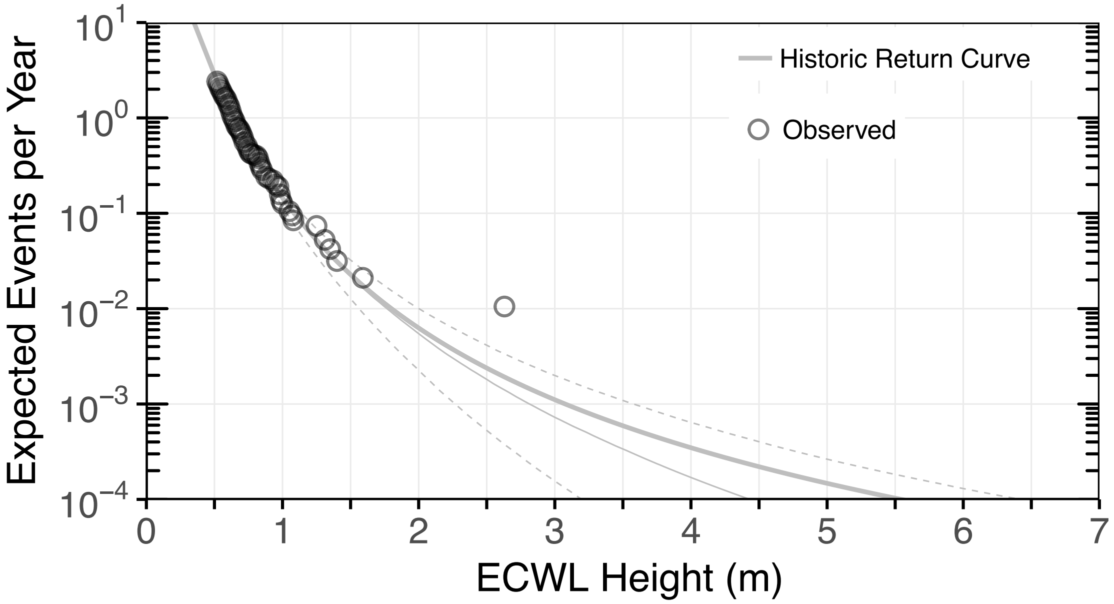

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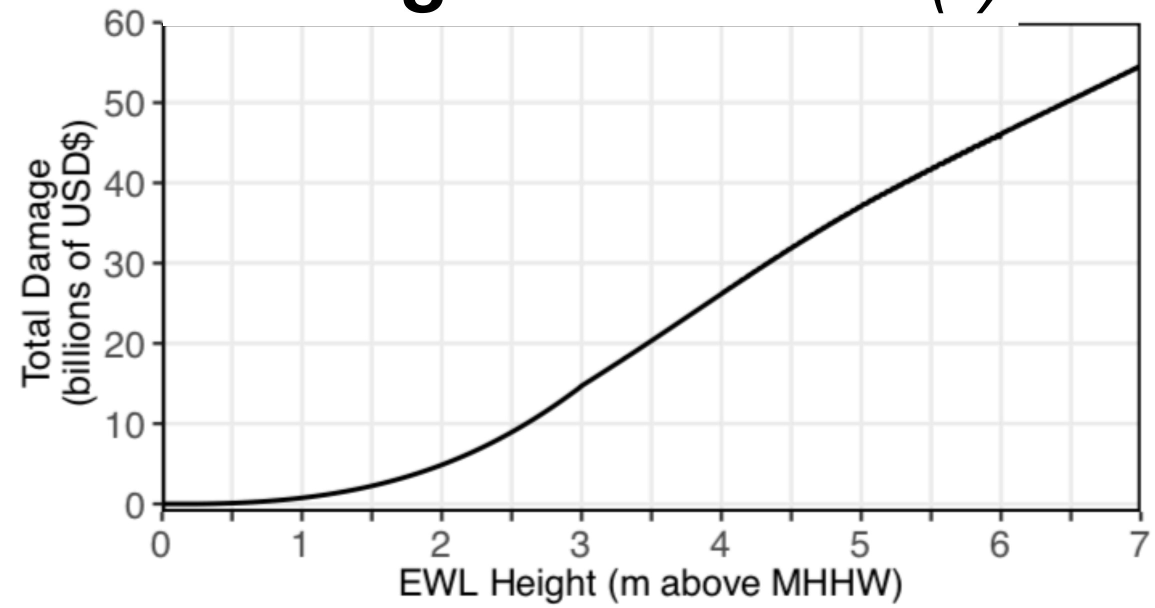

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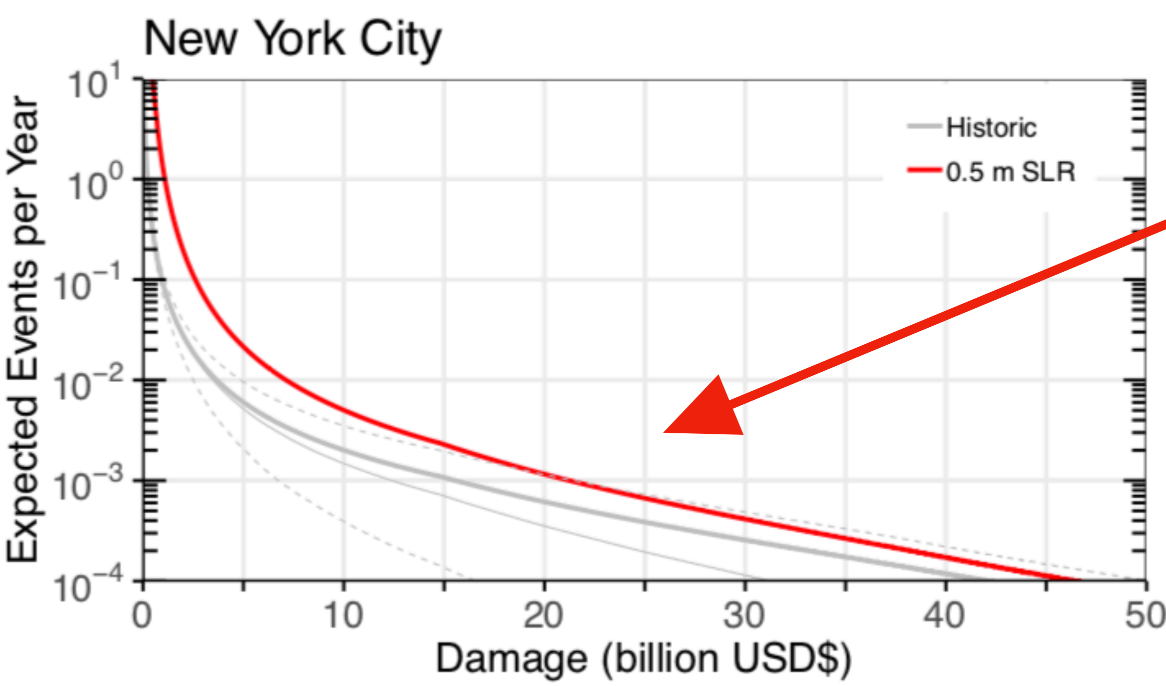

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How to maintain the current AAL as sea-levels rise?

[Rasmussen, Oppenheimer, and Kopp, in prep]

Research questions

#1: How to incorporate deeply uncertain projections of AIS into a framework to design coastal flood defenses?

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#2: How to account for damages in flood allowances?

#1: How to incorporate deeply uncertain projections of AIS into a framework to design coastal flood defenses?

Unknown **amount of local sea-level rise:** *P(Δ)*

$$f(z^*) = \int_{\Delta} f(z^* - \Delta + A(z^*)) P(\Delta) \, \mathrm{d}\Delta$$

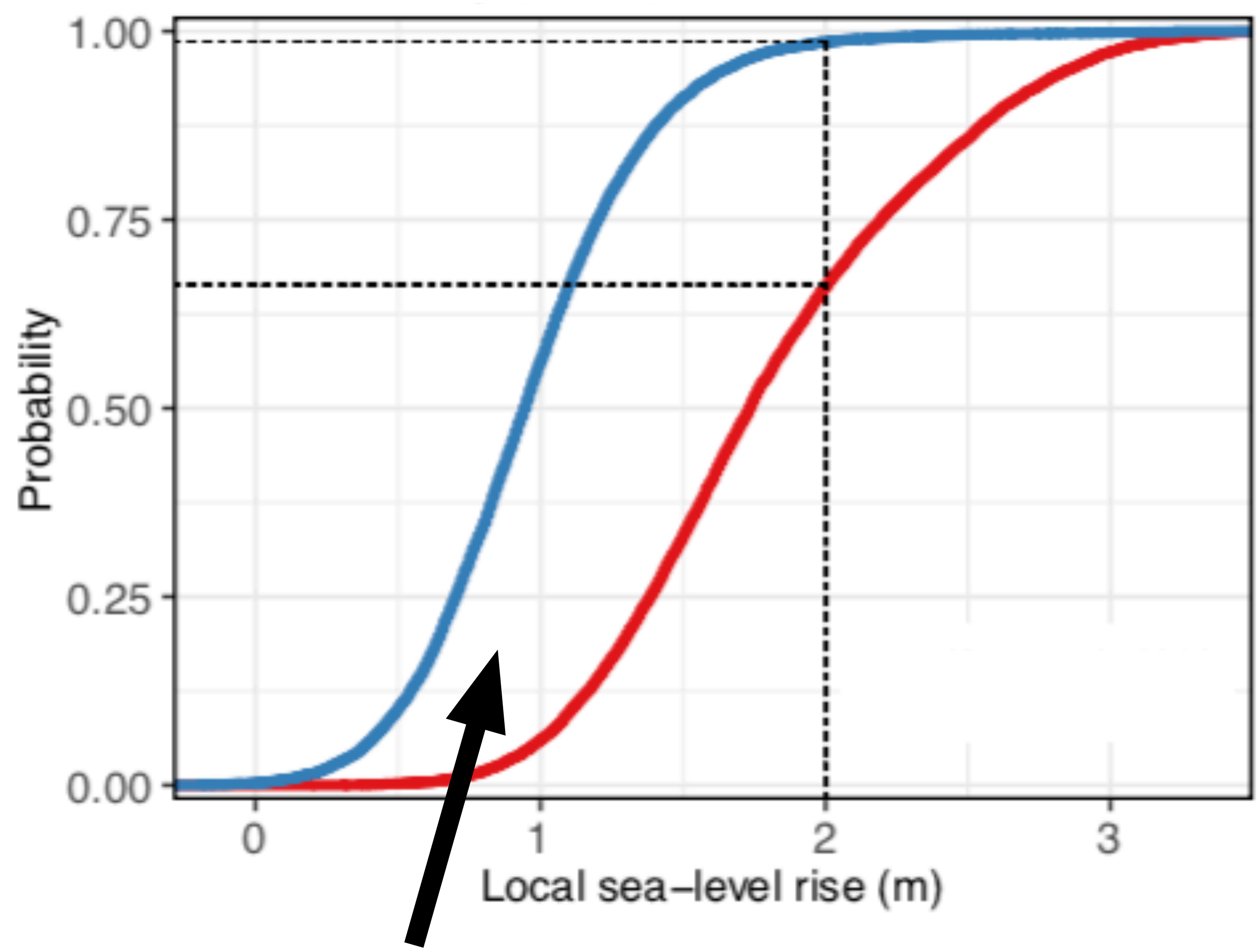
Objective: **Create an 'effective' probability distribution** $\tilde{P}(\Delta)$ **based on a** ***subjective view*** **of future Antarctic behavior**

“Possibilistic” approaches can be used to express incertitude

e.g., a probability box, or ‘p-box’

[Baudrit et al., 2007; Le Cozannet et al., 2017]

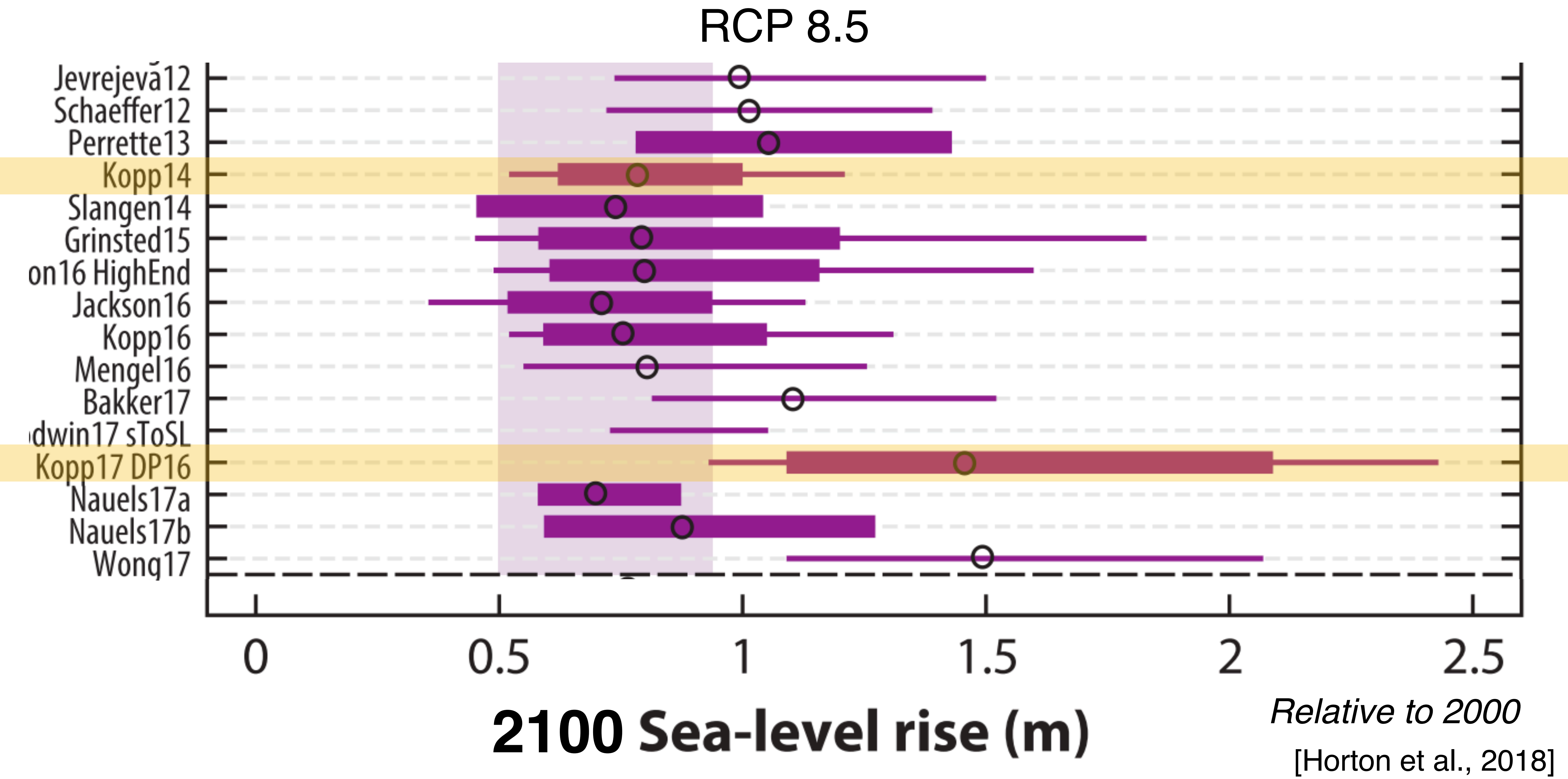
The ‘p-box’ is defined by CDFs



‘True’ value of 2100 sea-level rise lies somewhere in-between the CDFs

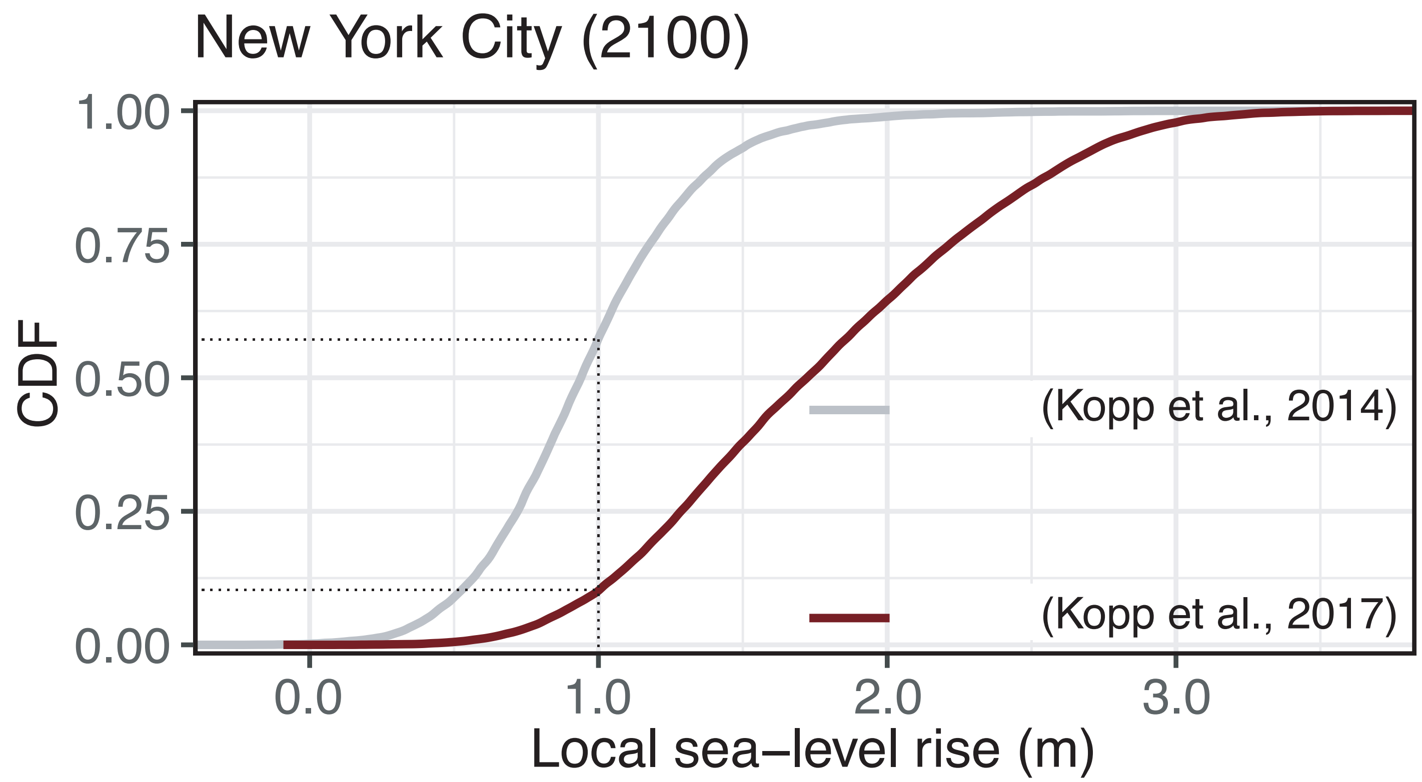
How to choose CDF bounds?

Kopp et al. (2014) and Kopp et al. (2017) span the range of possible sea-level rise values



Kopp et al. 2014 & 2017 frameworks identical, except for treatment of Antarctic ice melt

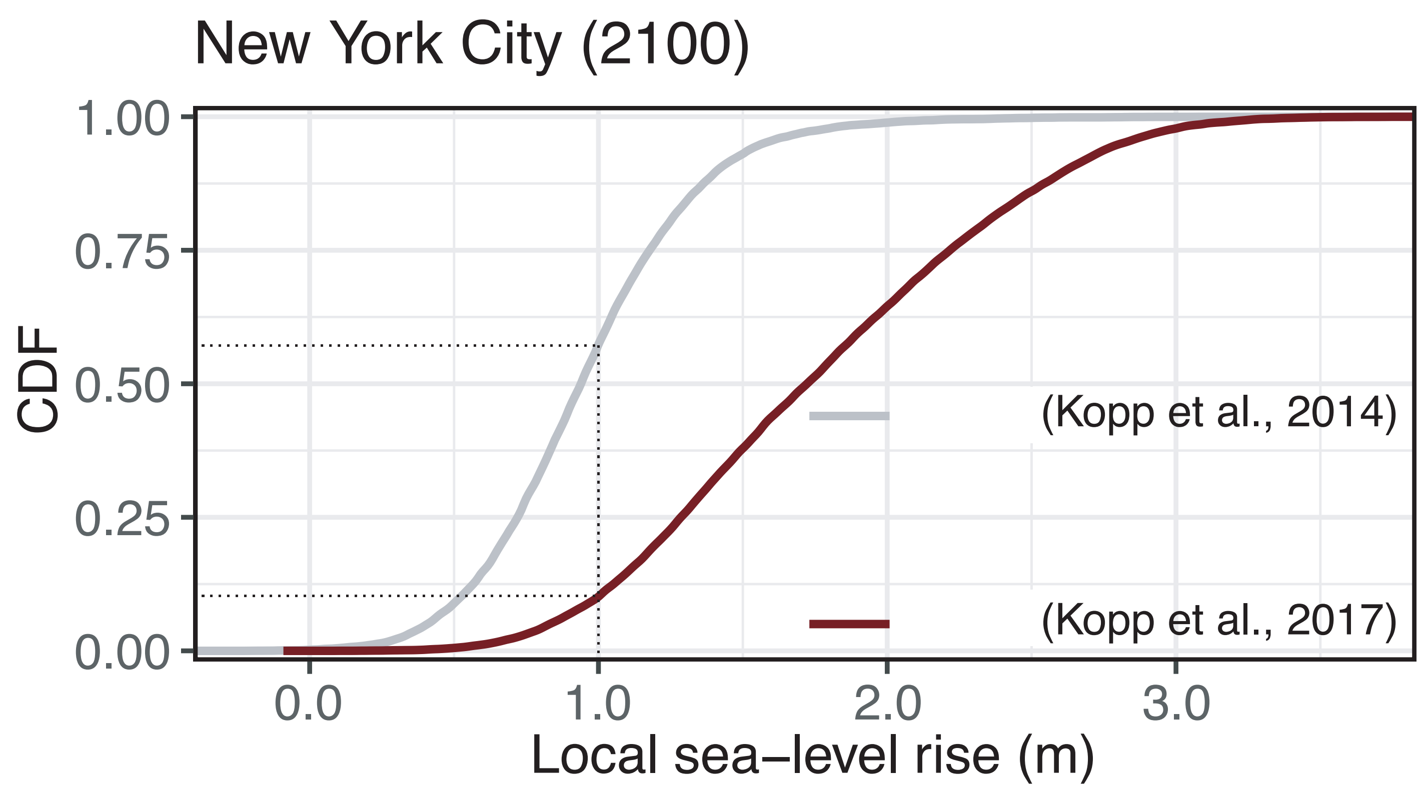
“Possibilistic” approaches can be used to express incertitude



Probability of 1-m of local sea-level rise: 45% - 90%

[Rasmussen, Oppenheimer, and Kopp, in prep]

“Possibilistic” approaches can be used to express incertitude



Two parameters:

1. Maximum 2100 AIS contribution: AIS_{max} [25, 50, 100, 150, 175 cm]

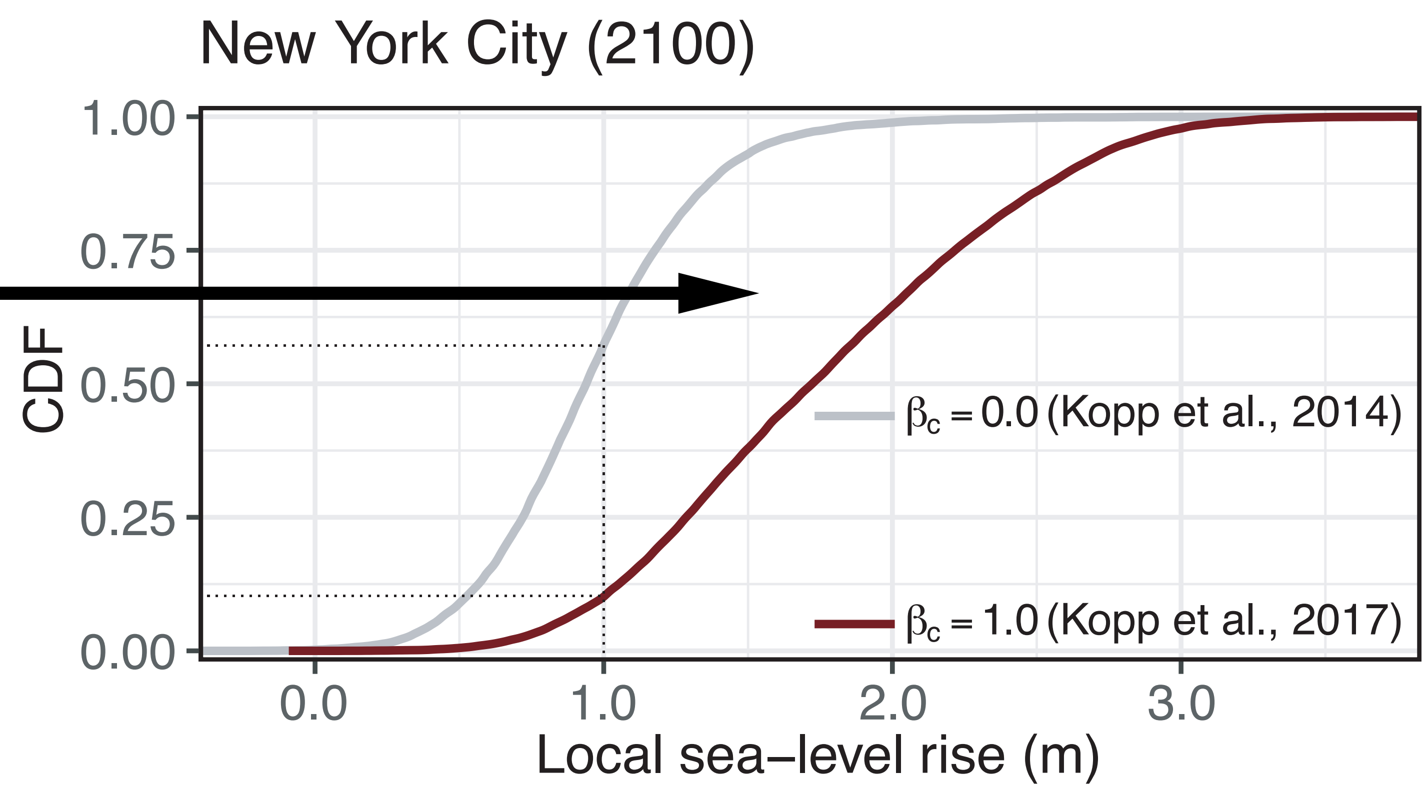
   (i.e., where to cut off the tail of the AIS distribution)

2. Likelihood of AIS collapse initiation: β_c [0-1]

[Rasmussen, Oppenheimer, and Kopp, in prep]

“Possibilistic” approaches can be used to express incertitude

β_c produces curves in between CDF bounds



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Effective SLR probability distribution: $\tilde{P}(\beta_c, \mathrm{AIS}_{max}, t)$

$$\tilde{P}(\beta_c, \mathrm{AIS}_{max}, t) = \beta_c P_{high}(\mathrm{AIS}_{max}, t) + (1 - \beta_c) P_{low}(\mathrm{AIS}_{max}, t)$$

[Rasmussen, Oppenheimer, and Kopp, in prep]

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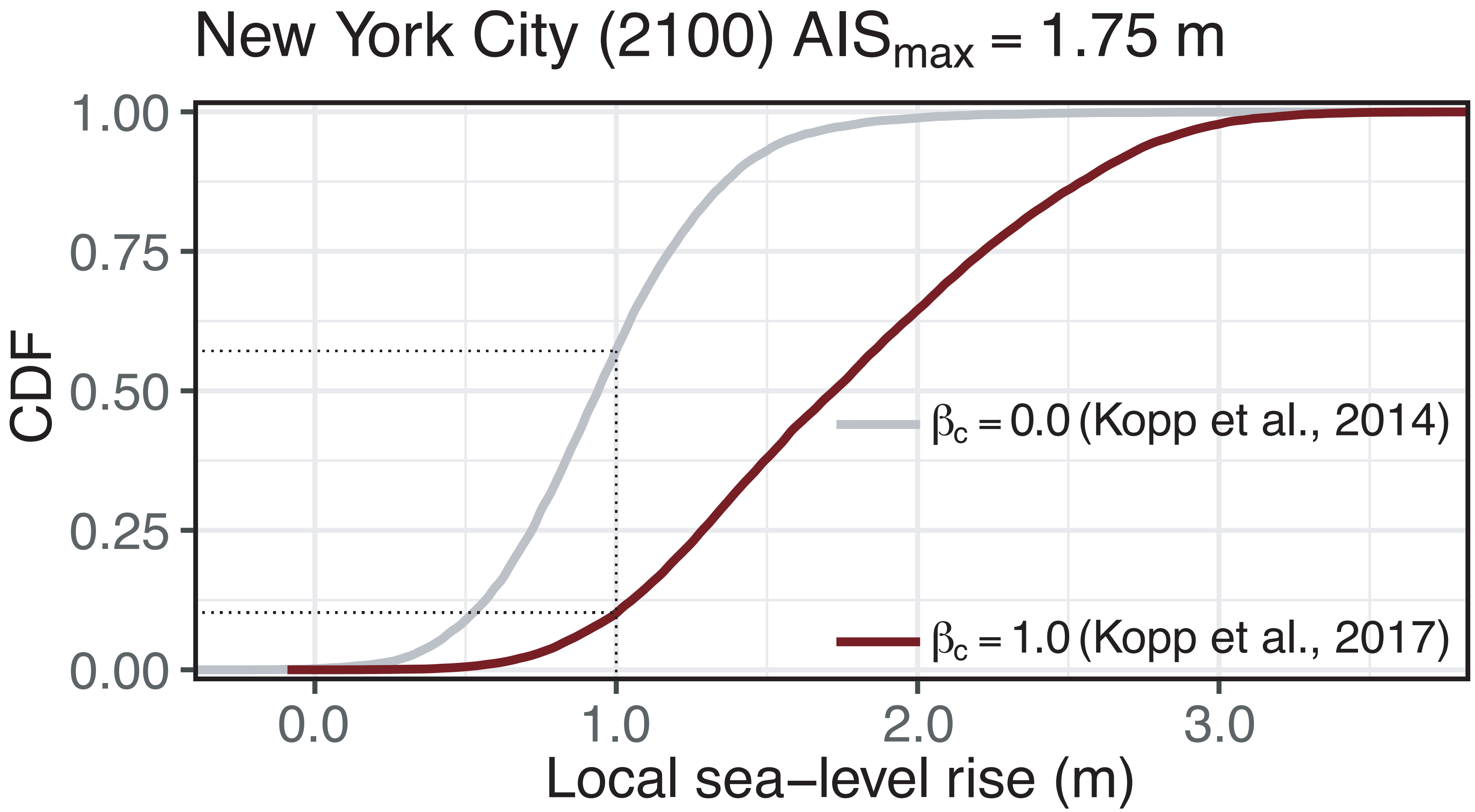
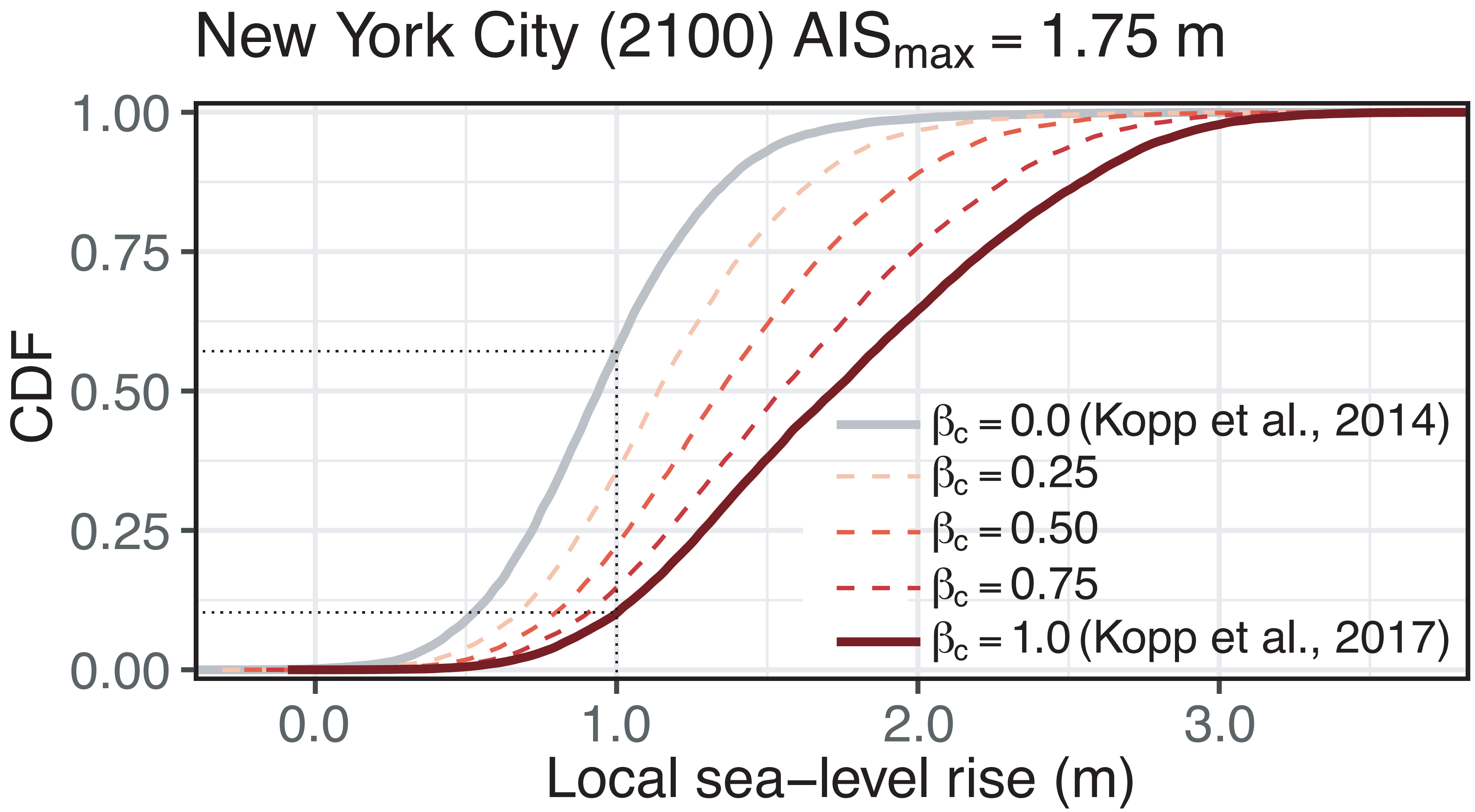
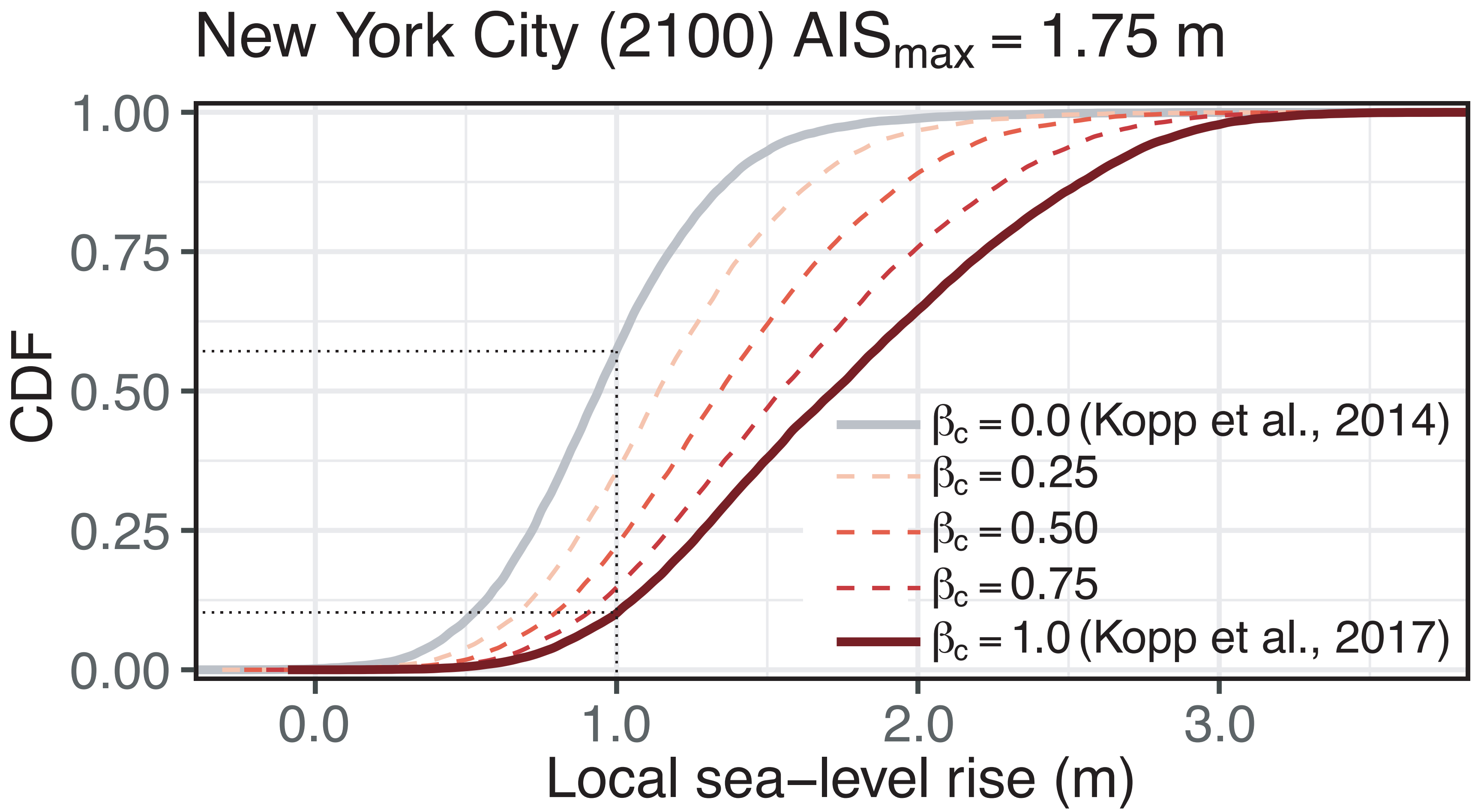
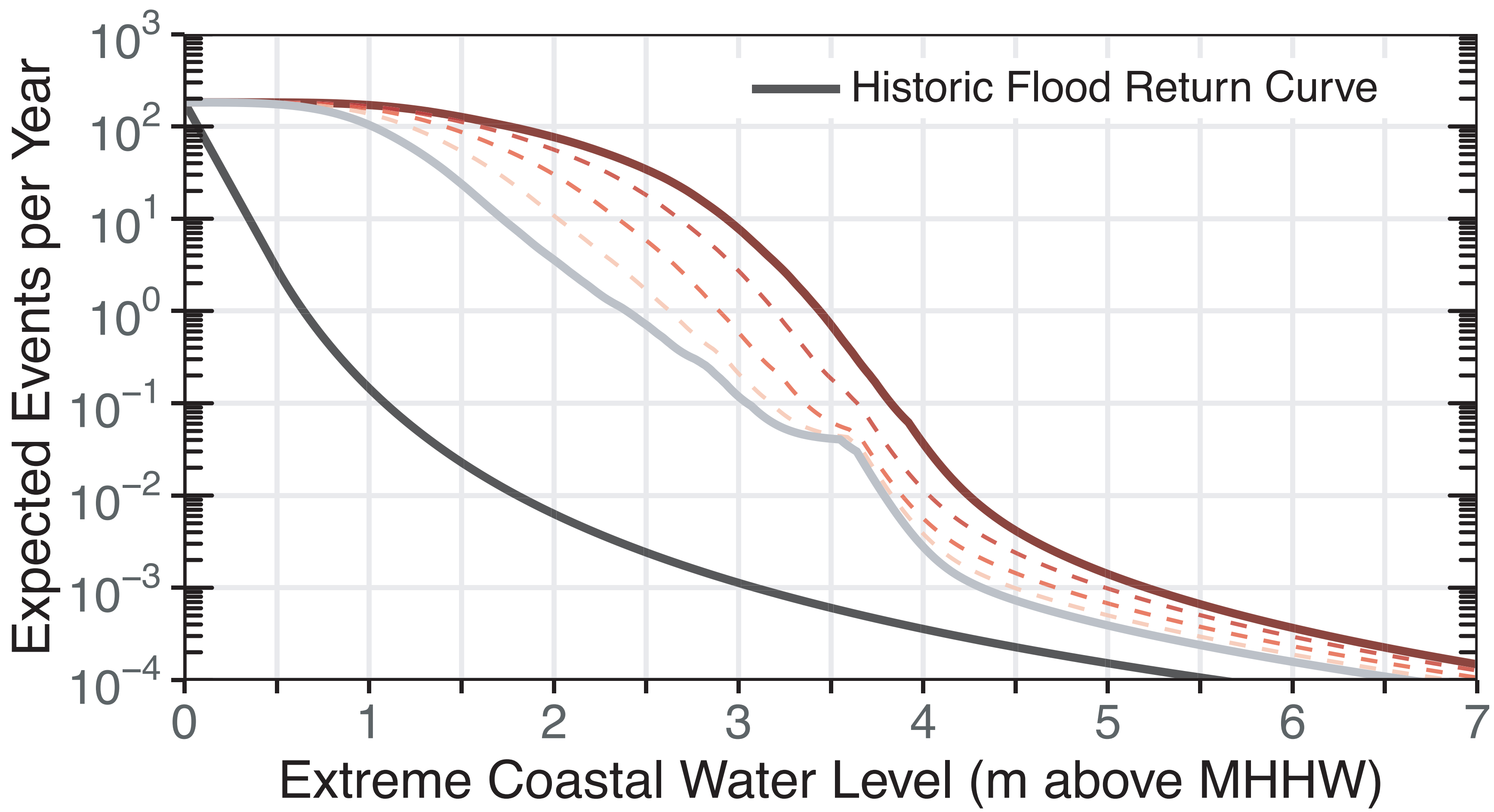



New York City (2100) AIS_{max} = 1.75 m
CDF
1.00
0.75
0.50
0.25
0.00
0.0
1.0
2.0
3.0
Local sea–level rise (m)
$\beta_c = 0.0$ (Kopp et al., 2014)
$\beta_c = 0.25$
$\beta_c = 0.50$
$\beta_c = 0.75$
$\beta_c = 1.0$ (Kopp et al., 2017)

[Rasmussen, Oppenheimer, and Kopp, in prep]





#2: How to account for damages in flood allowances?

Our answer: ’damage allowance’

[Rasmussen, Oppenheimer, and Kopp, in prep]

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$$\int_z \int_\Delta D^*(z) f(z-\Delta) \tilde{P}(\Delta) \, \mathrm{d}\Delta \, \mathrm{d}z = \int_z D(z) f(z) \, \mathrm{d}z$$

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Damage function: *D(z)*

Probability of water level z: *f(z)*

[Rasmussen, Oppenheimer, and Kopp, in prep]

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"Protected" damage function: *D*(z)*

D(z) takes on different forms based on protection strategy*

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Probability of water level z: *f(z)*

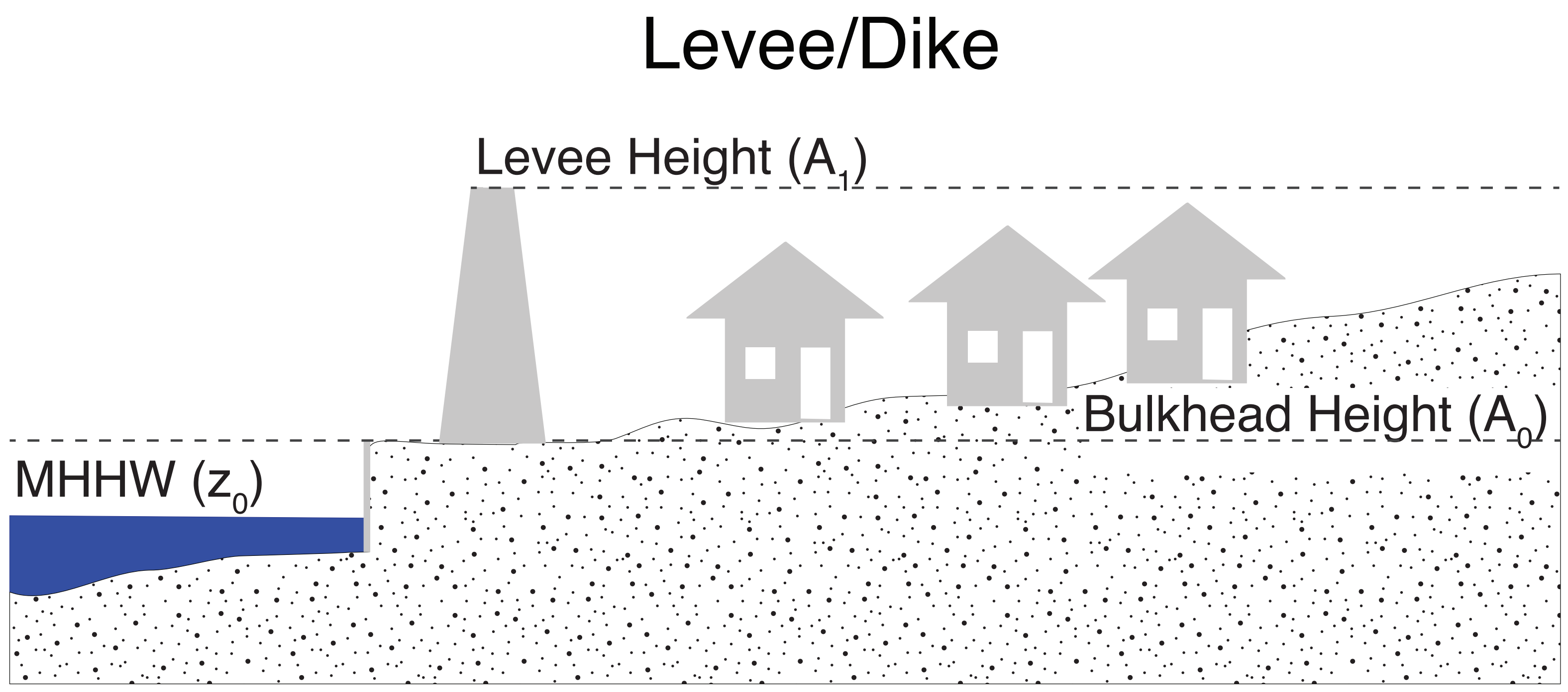
***Unknown* amount of local sea-level rise:** $\tilde{P}(\Delta)$

Objective: find a "protected" damage function *D*(z)* that produces an AAL that is equal to a given target

Strategies: elevation, levee/dike, storm surge barrier, coastal retreat

[Rasmussen, Oppenheimer, and Kopp, in prep]

Example damage allowance calculation for a levee/dike



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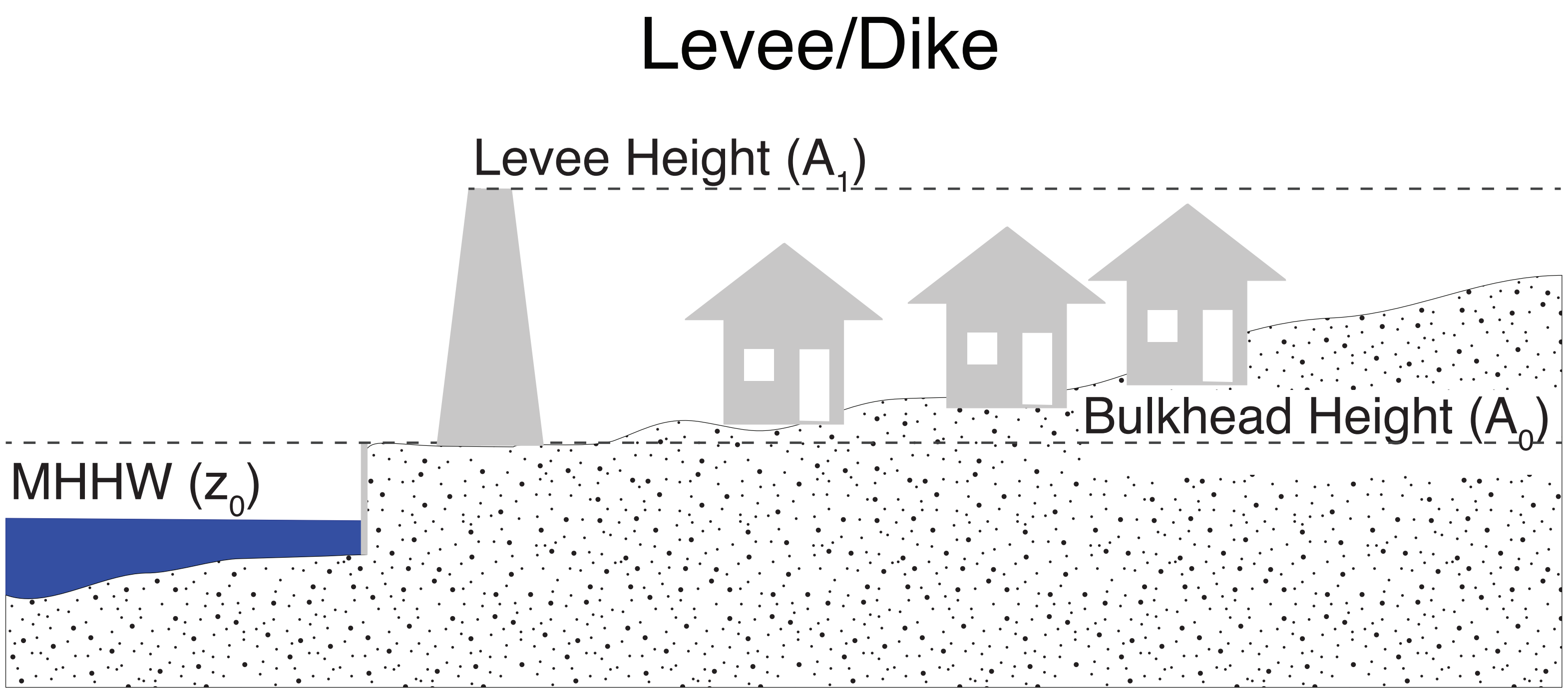

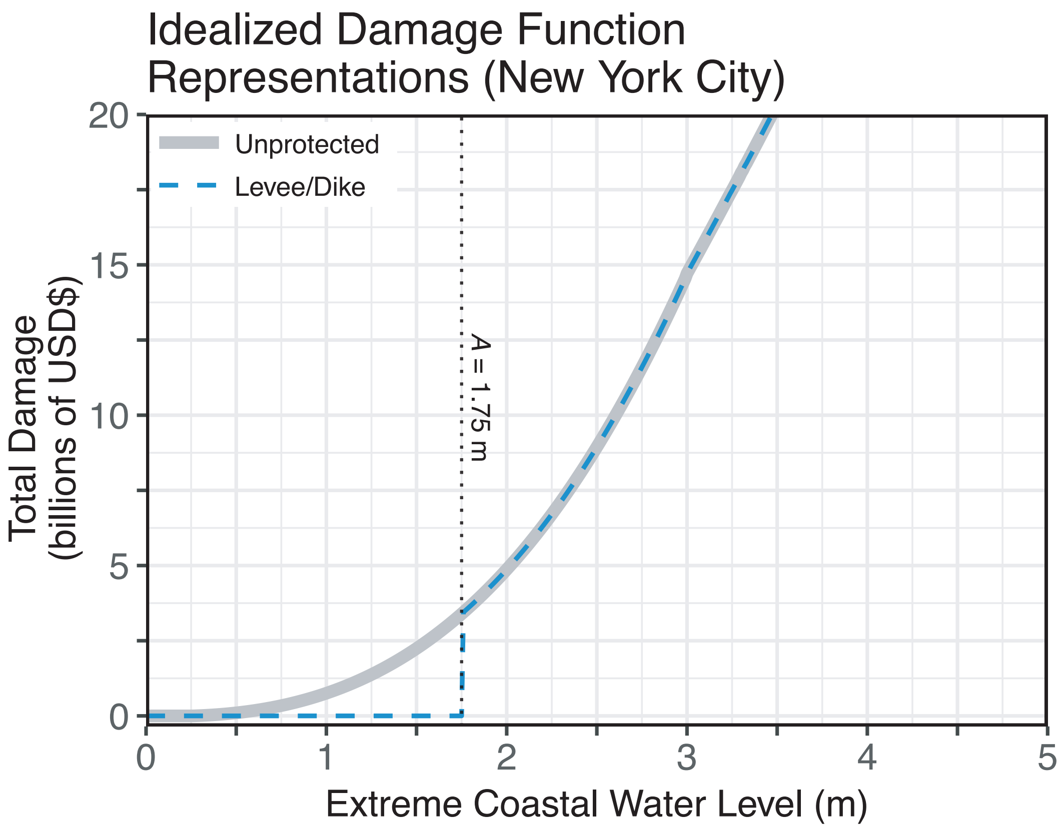

"Protected" damage function: $D^*(z)$

$$D^*(z) = p_f(z, A)D(z)$$

[Rasmussen, Oppenheimer, and Kopp, in prep]

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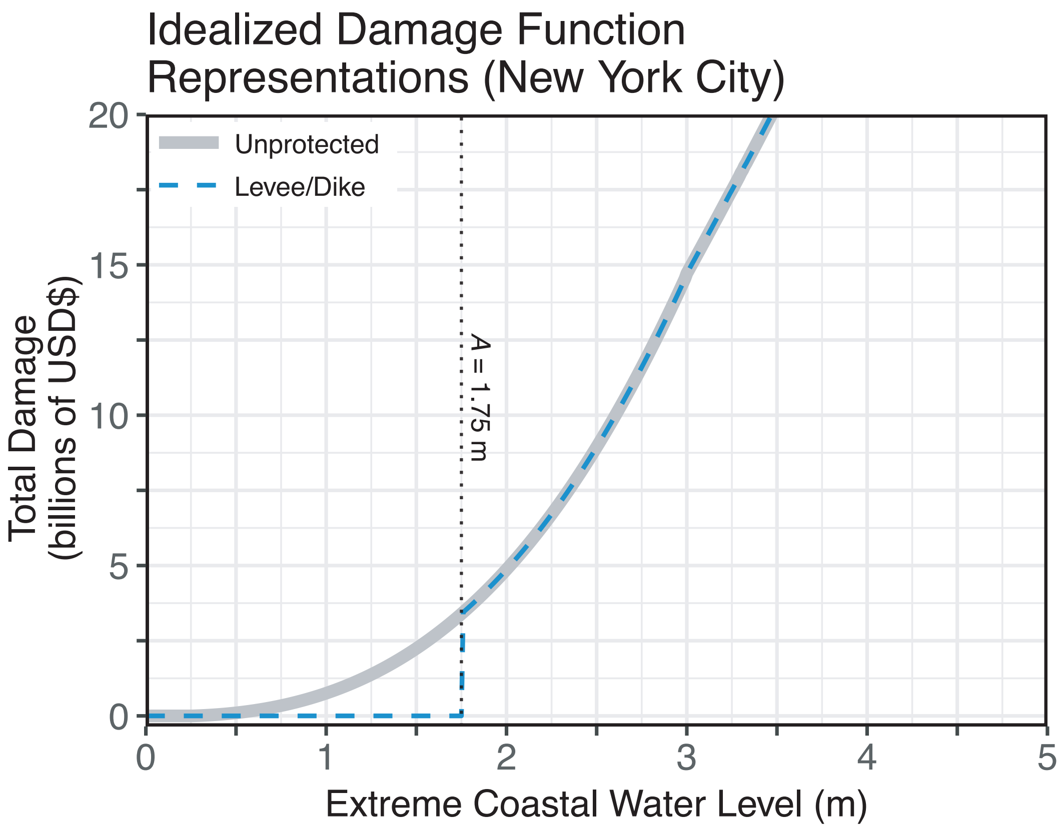

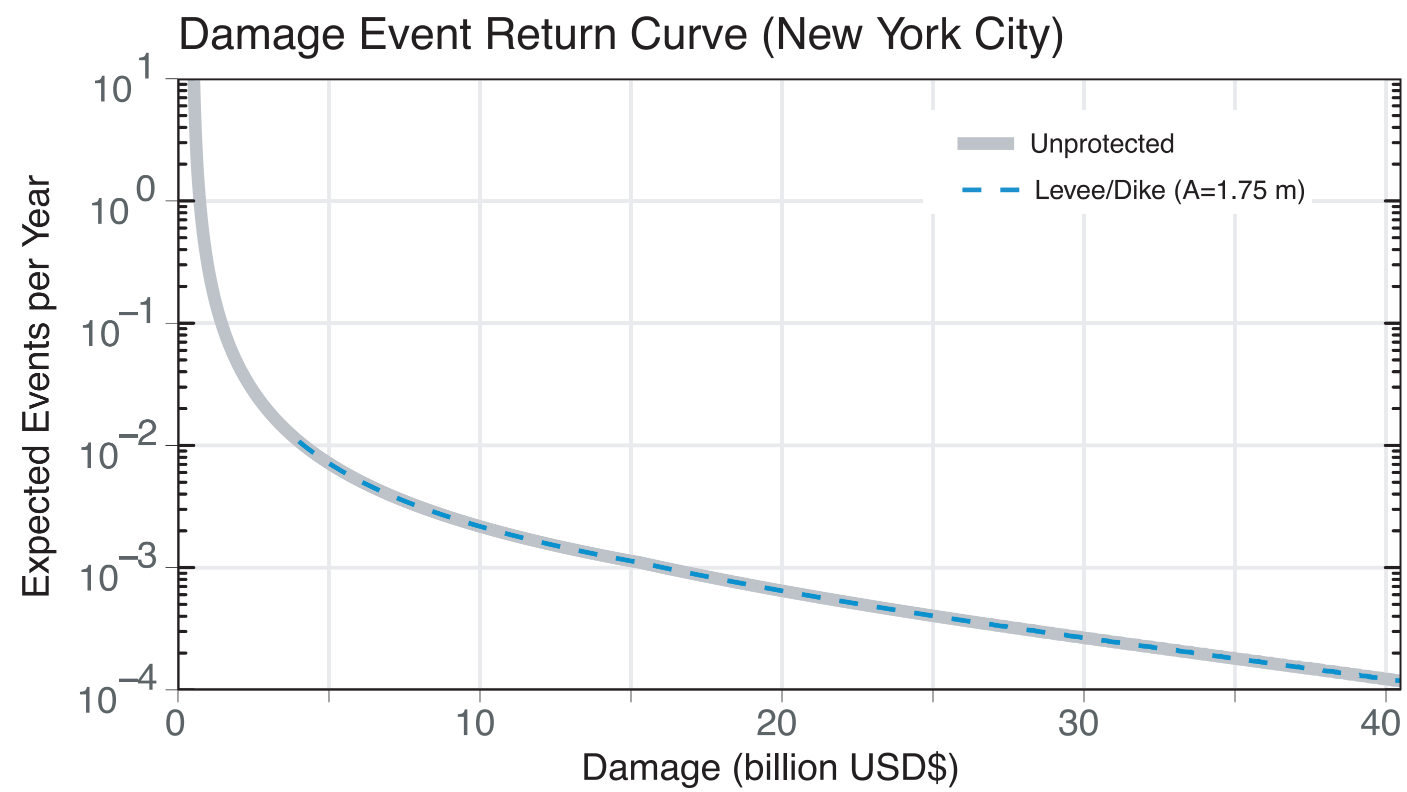

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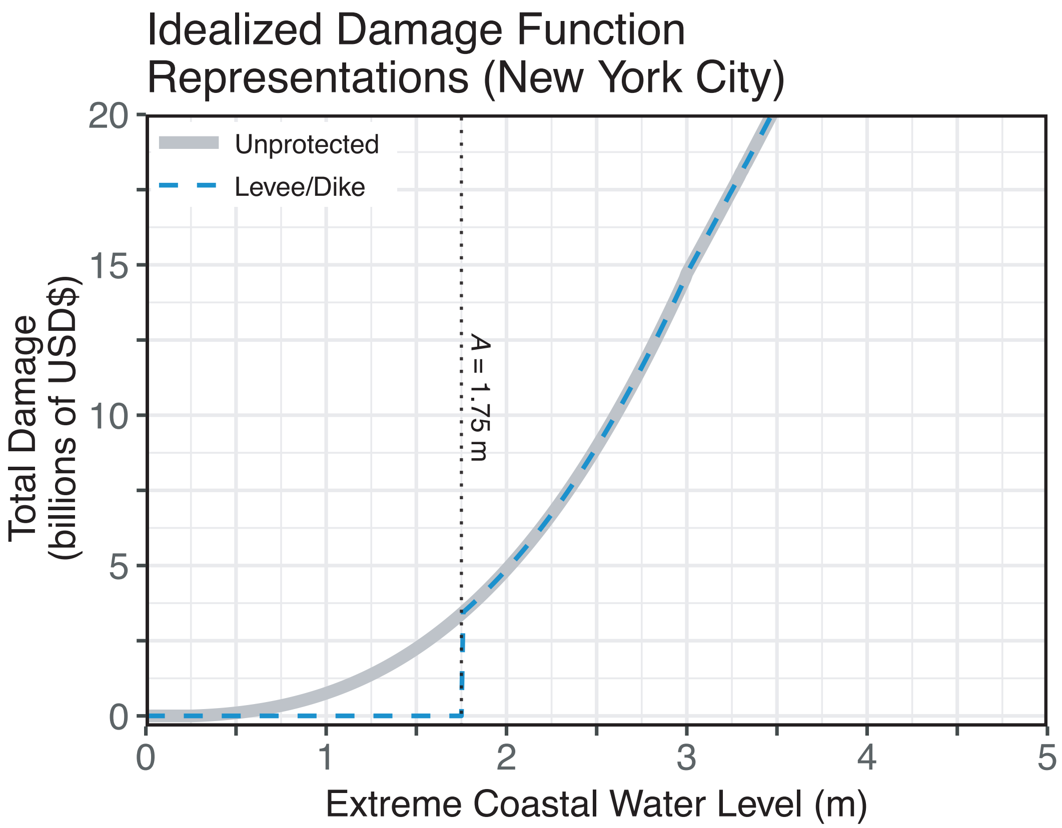

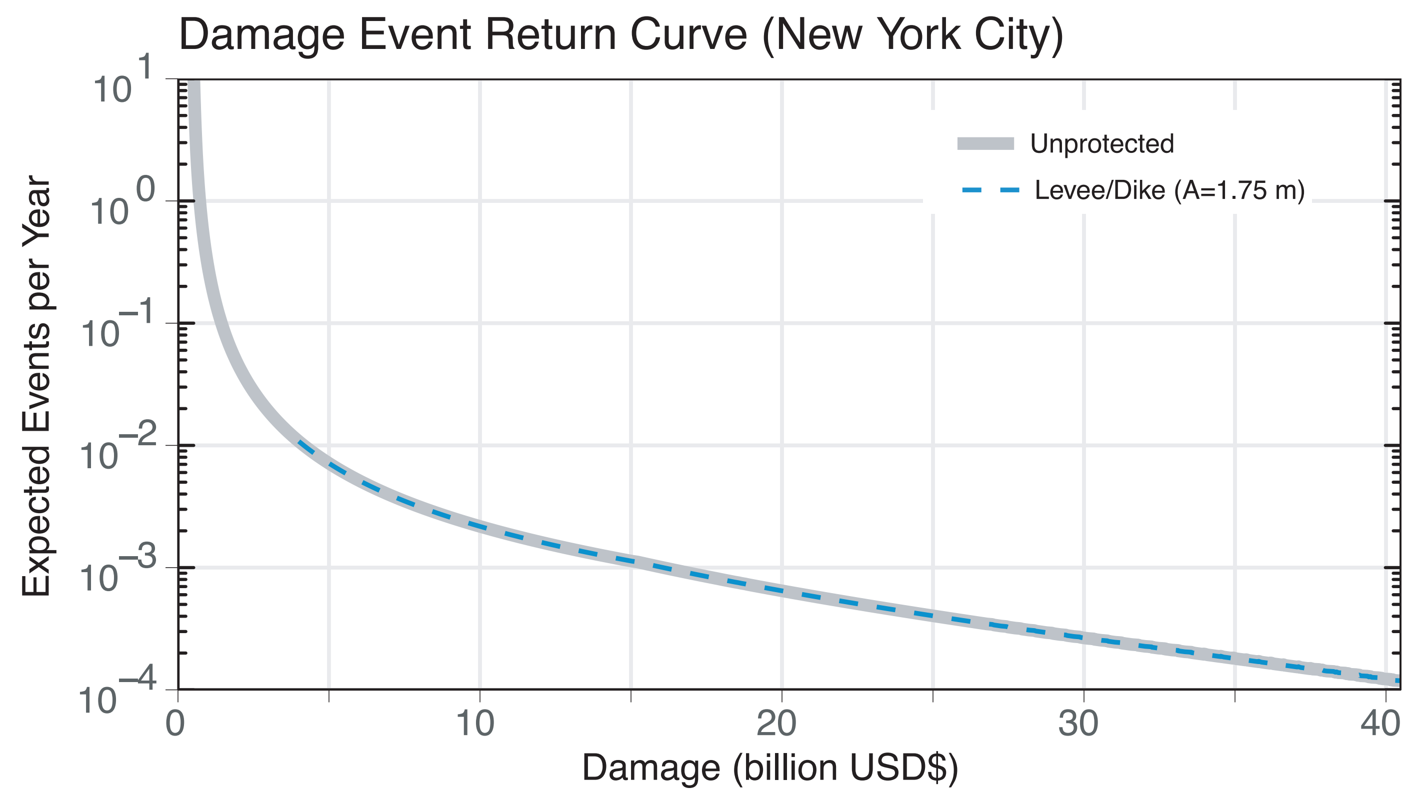

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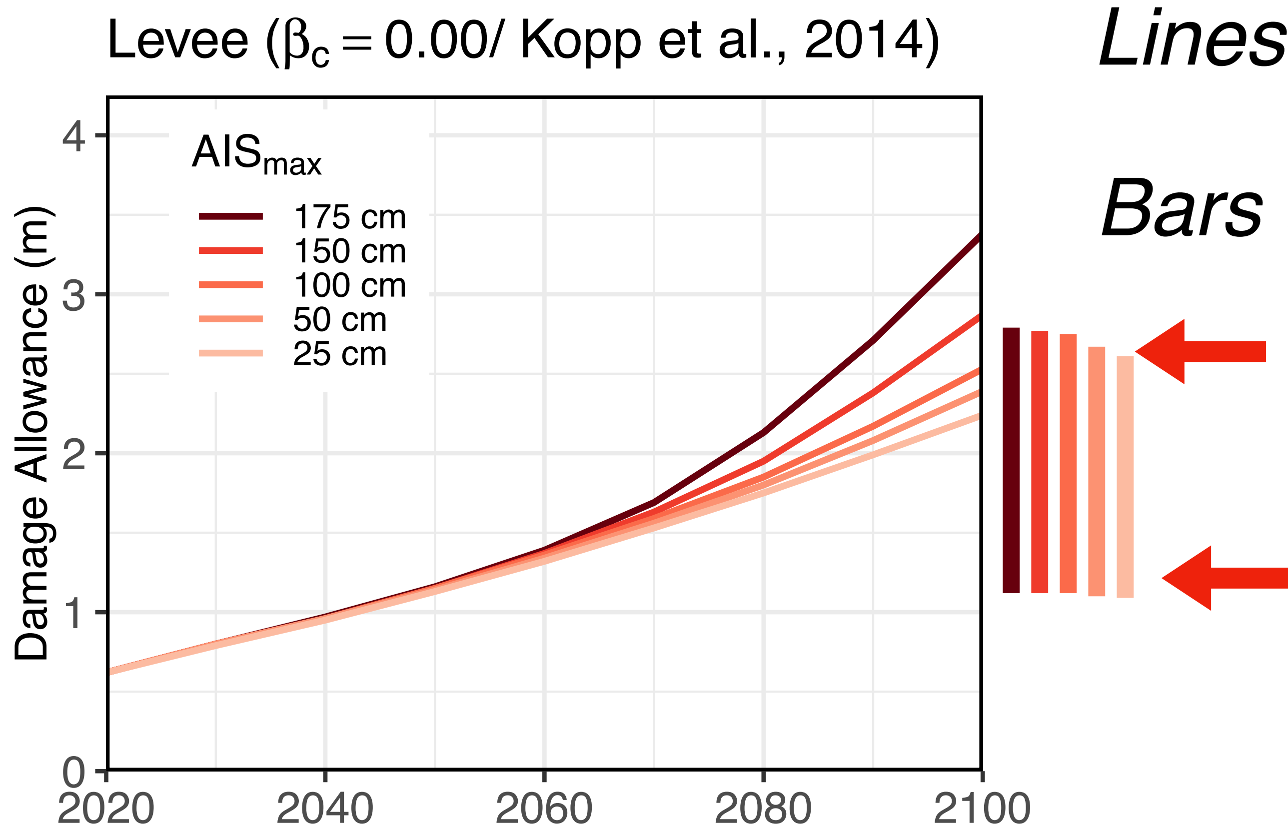
Solve for A numerically

[Rasmussen, Oppenheimer, and Kopp, in prep]

Damage allowance for levee/dike strongly depends on where the ‘tail’ of the AIS is cut off (i.e., AIS_{max})

‘instantaneous’ allowance



Lines = full PDF of sea-level rise

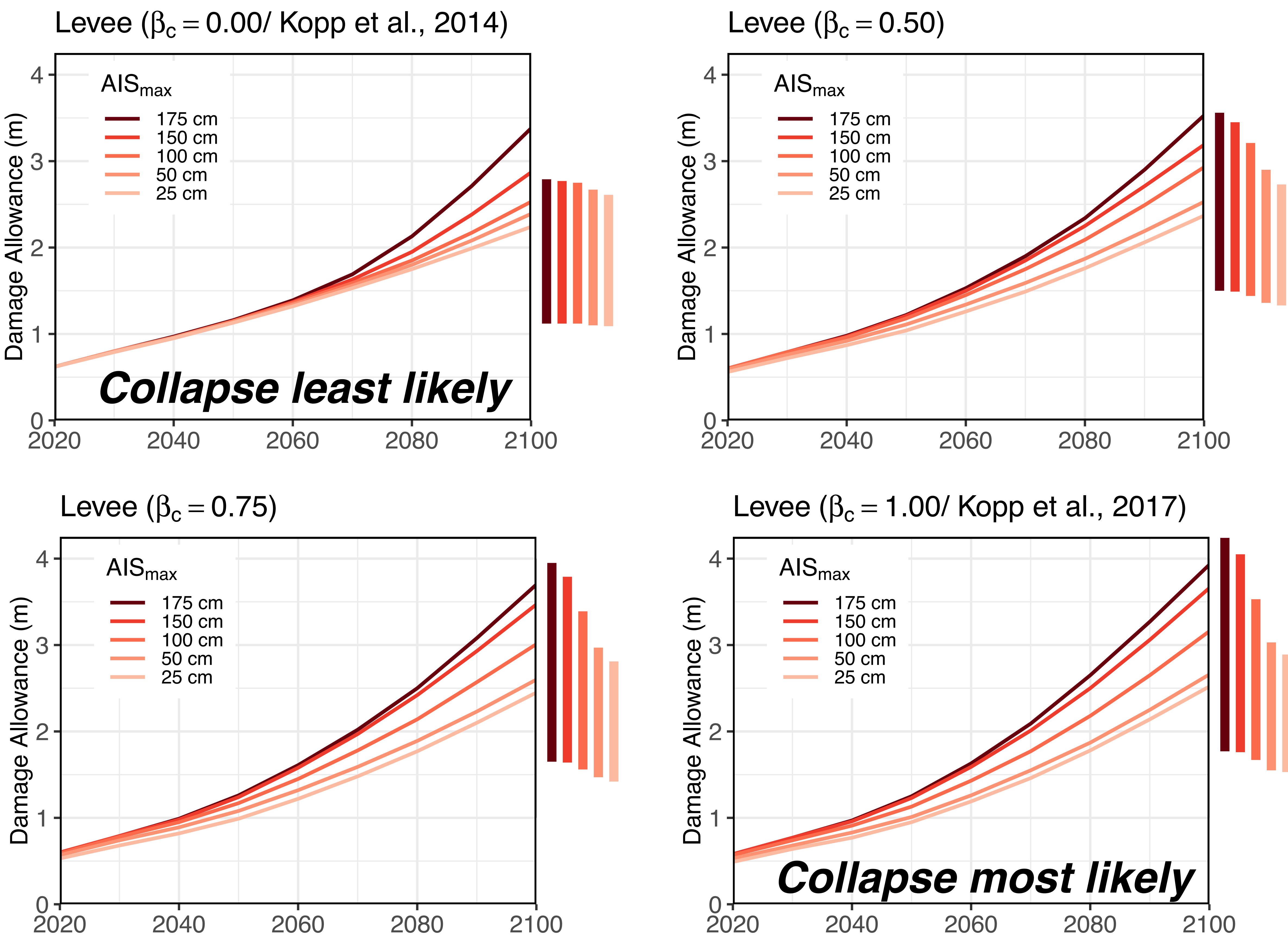
Bars =

95th percentile of sea-level rise

5th percentile of sea-level rise

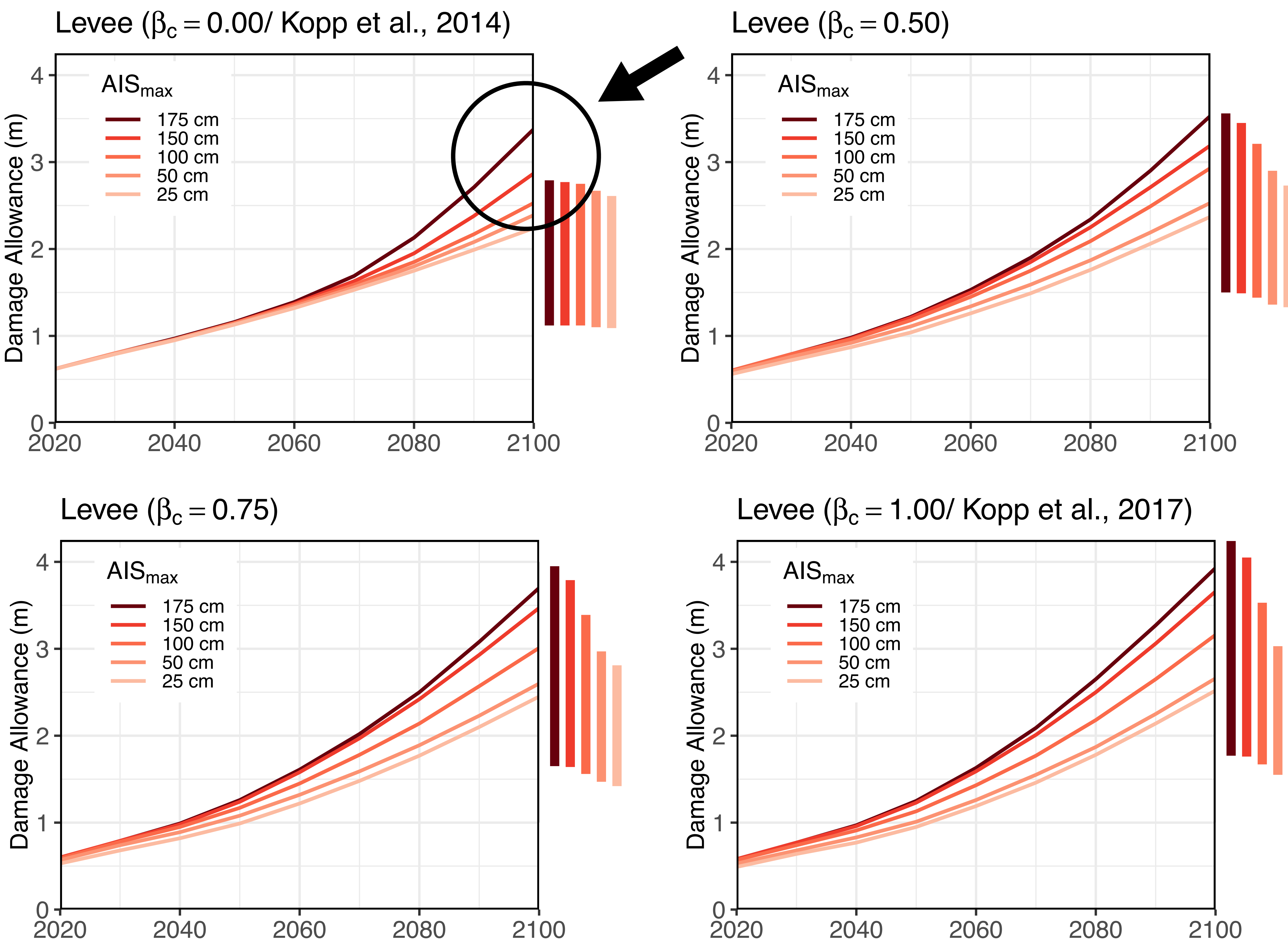
[Rasmussen, Oppenheimer, and Kopp, in prep]

Damage allowance for levee/dike also depends on perceived likelihood of AIS collapse (i.e., β_c)



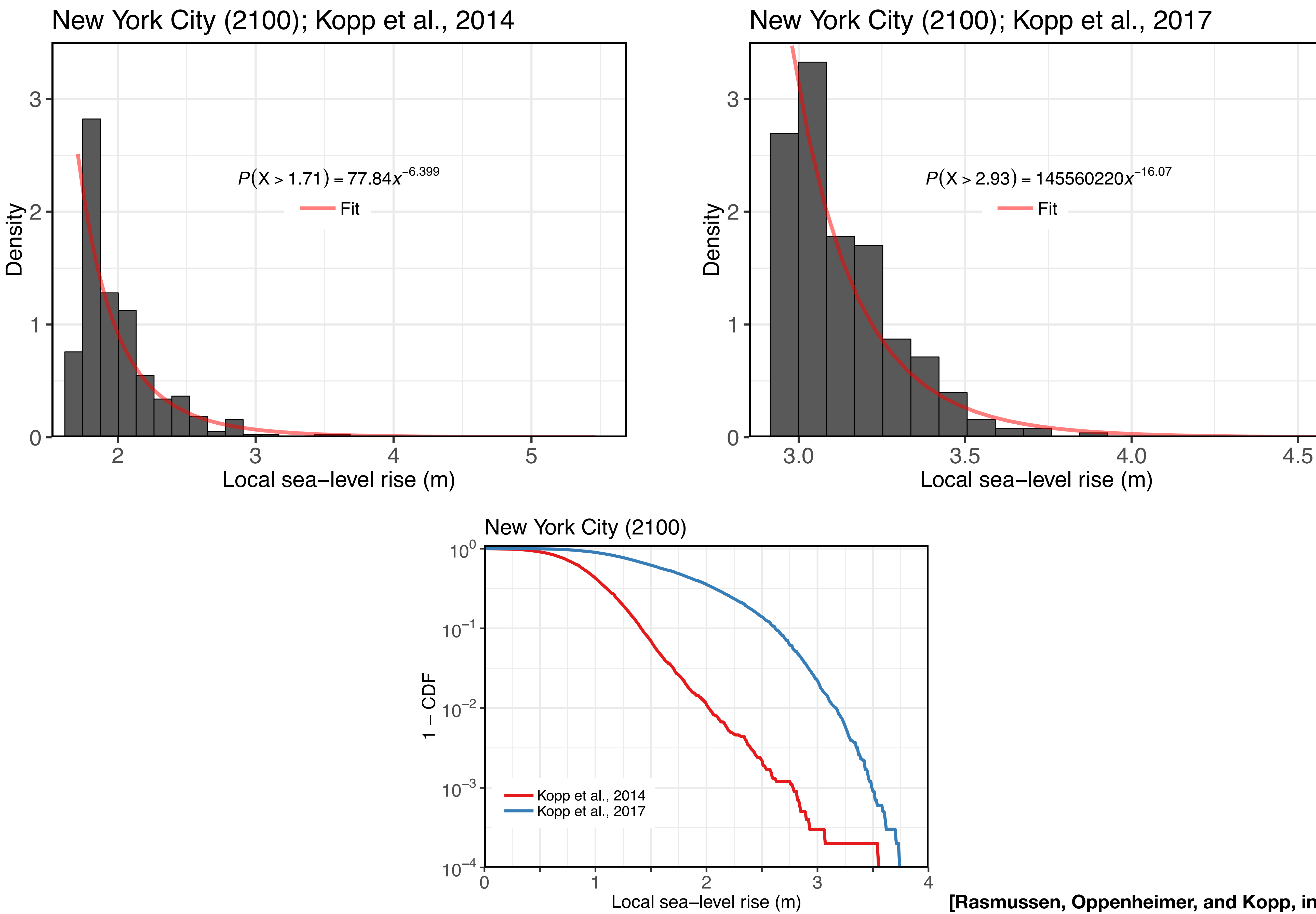
[Rasmussen, Oppenheimer, and Kopp, in prep]

Expected values driven by sea level extremes in tail



[Rasmussen, Oppenheimer, and Kopp, in prep]

Length of the tail on the sea-level rise PDF matters



[Rasmussen, Oppenheimer, and Kopp, in prep]

Lessons learned:

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‘Damage allowances’ are another tool for coastal risk manager’s or engineer’s tool box

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Subjective assessment of AIS stability necessary under deep uncertainty

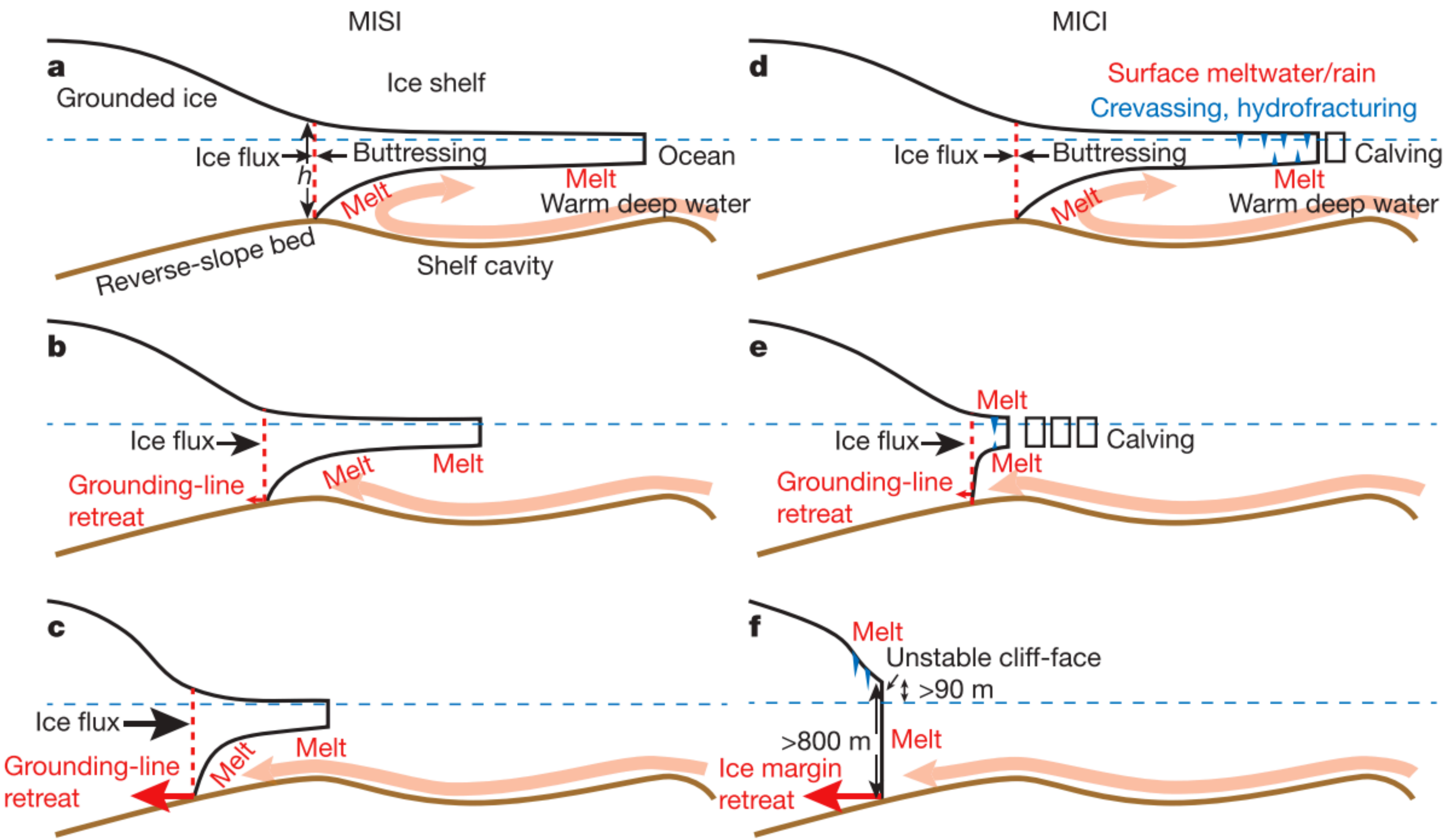
Lessons learned:

‘Damage allowances’ are another tool for coastal risk manager’s or engineer’s tool box

Planners must be cognizant of deep uncertainty, and recognize when it should be taken into account (e.g., beyond 2050)

Subjective assessment of AIS stability necessary under deep uncertainty

There is value in reducing this uncertainty in terms of lower levee heights that are less expensive



MISI
MICI
a
Grounded ice
Ice shelf
Ice flux
h
Buttressing
Ocean
Melt
Melt
Warm deep water
Reverse-slope bed
Shelf cavity
b
Ice flux
Grounding-line retreat
Melt
Melt
c
Ice flux
Grounding-line retreat
Melt
Melt
d
Surface meltwater/rain
Crevassing, hydrofracturing
Ice flux
Buttressing
Calving
Melt
Melt
Warm deep water
e
Melt
Ice flux
Calving
Melt
Grounding-line retreat
f
Melt
Unstable cliff-face
>90 m
>800 m
Melt
Ice margin retreat