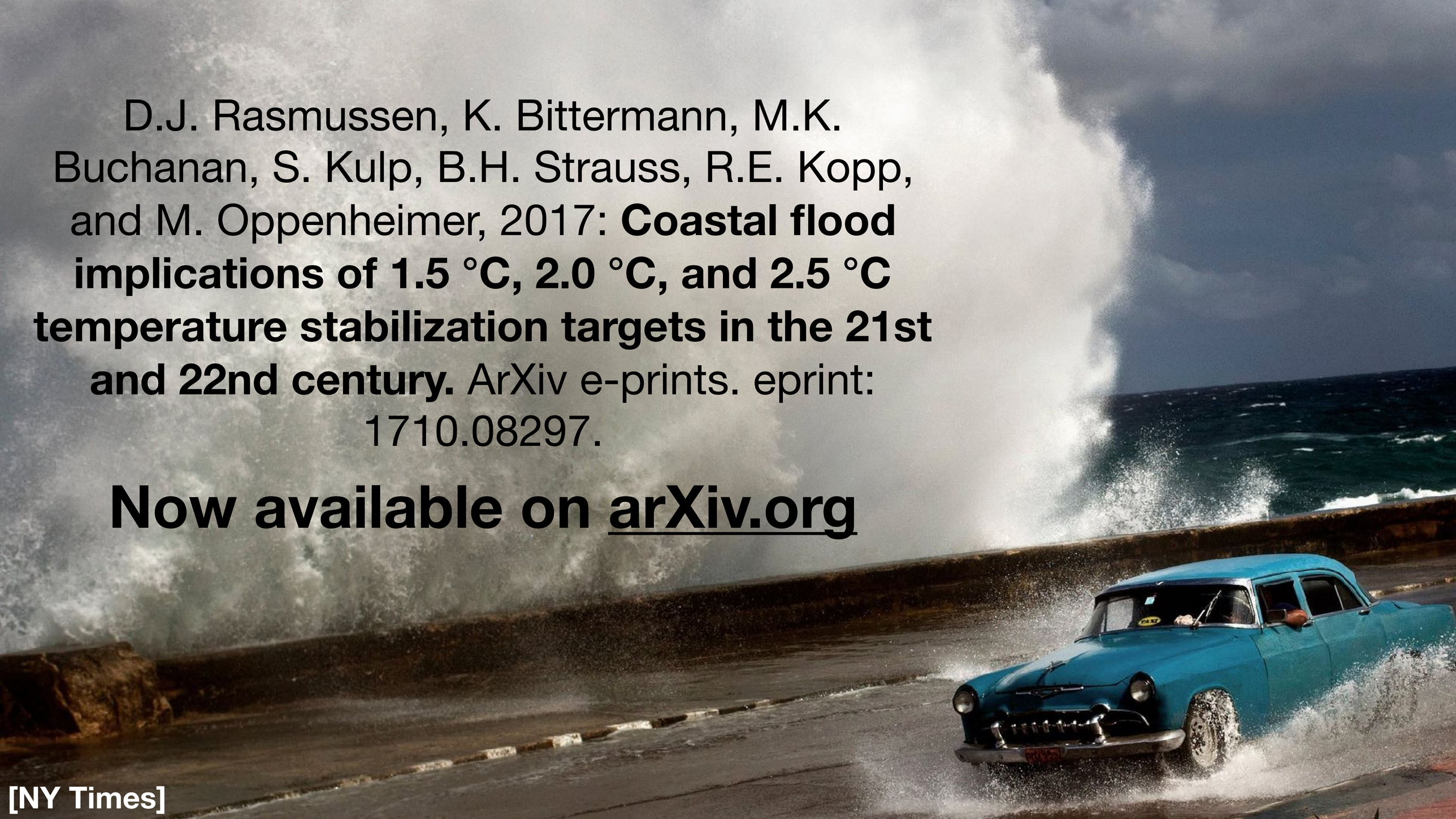
🌊 Coastal flood implications of 1.5 °C, 2 °C and 2.5 °C global mean temperature stabilization targets 🌊

D.J. Rasmussen, Klaus Bittermann, Maya K. Buchanan, Scott Kulp, Benjamin H. Strauss, Robert E. Kopp, Michael Oppenheimer



D.J. Rasmussen, K. Bittermann, M.K. Buchanan, S. Kulp, B.H. Strauss, R.E. Kopp, and M. Oppenheimer, 2017: **Coastal flood implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd century.** ArXiv e-prints. eprint: 1710.08297.

Now available on arXiv.org

[NY Times]

What’s so special with these temperatures: 1.5 °C, 2 °C and 2.5 °C? 🤷🏻‍♀️

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Goal: Stabilize global mean surface temperature (GMST) by limiting warming to *"well below 2.0 °C above pre-industrial levels"* and to further pursue efforts to *"limit the temperature increase to 1.5 °C above pre-industrial levels"* (UNFCCC, 2015)

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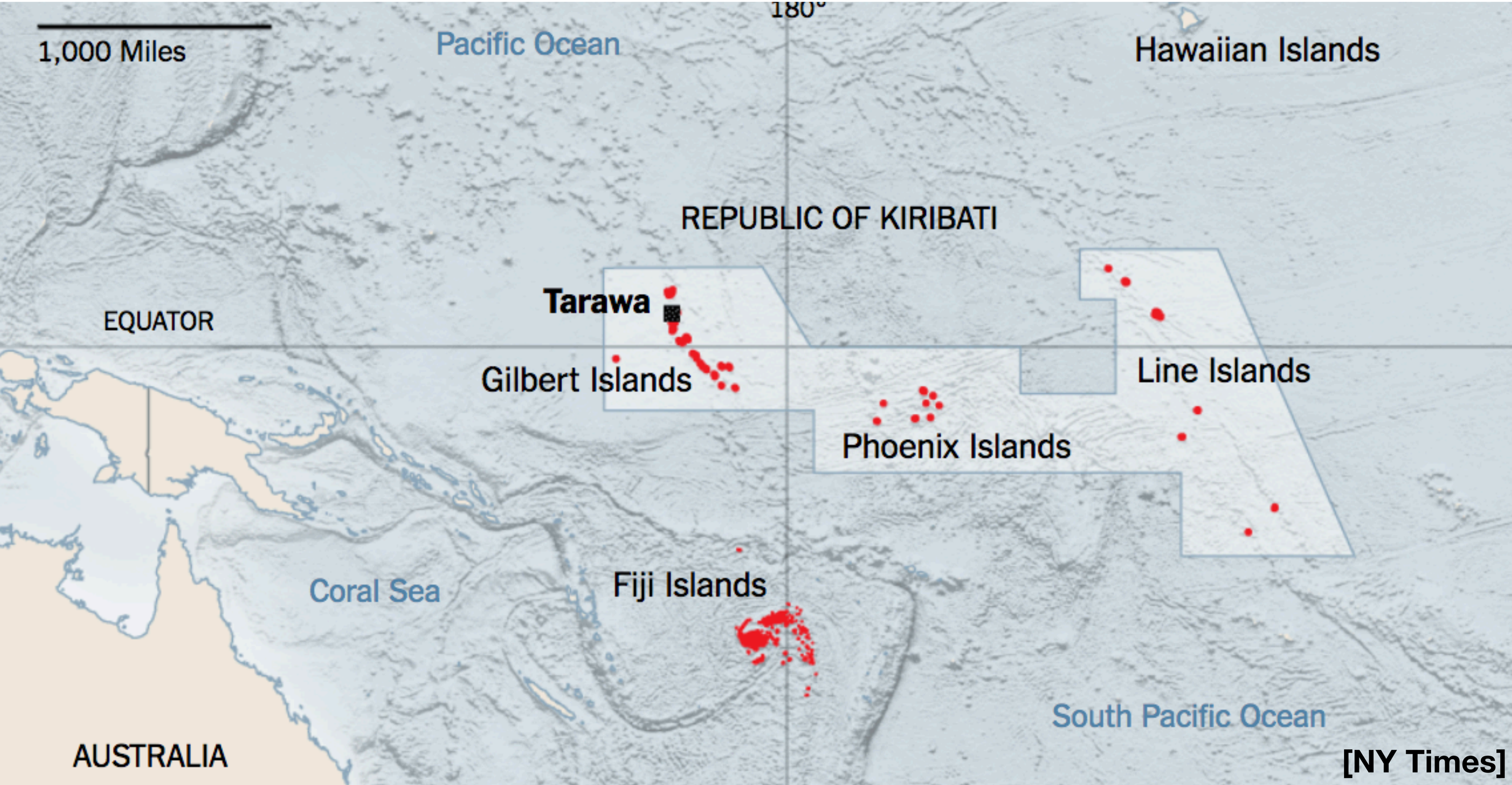
This study: include 2.5 °C to assess warmer temperature stabilizations

Small Island Developing States Advocated for 1.5 °C Target



[NY Times]

Tarawa

[NY Times]

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Flood Protection Contstruction

[NY Times]

Pre-Quiz

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Small island nations will experience the largest coastal flood benefits from 1.5 °C vs. 2.0 °C stabilization over this century. (T/F)

So what do temperature stabilization targets have to do with global sea levels?

Global mean surface temperature (GMST) increases global mean sea level (GSL)

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- Warmer surface temperatures increase rate of glacier and ice-sheet melt and fracturing

Higher sea levels imply permanent inundation

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…but first more frequent flooding

Stabilized Temperature 🌡️ ≠ Stabilized Sea Level 🌊

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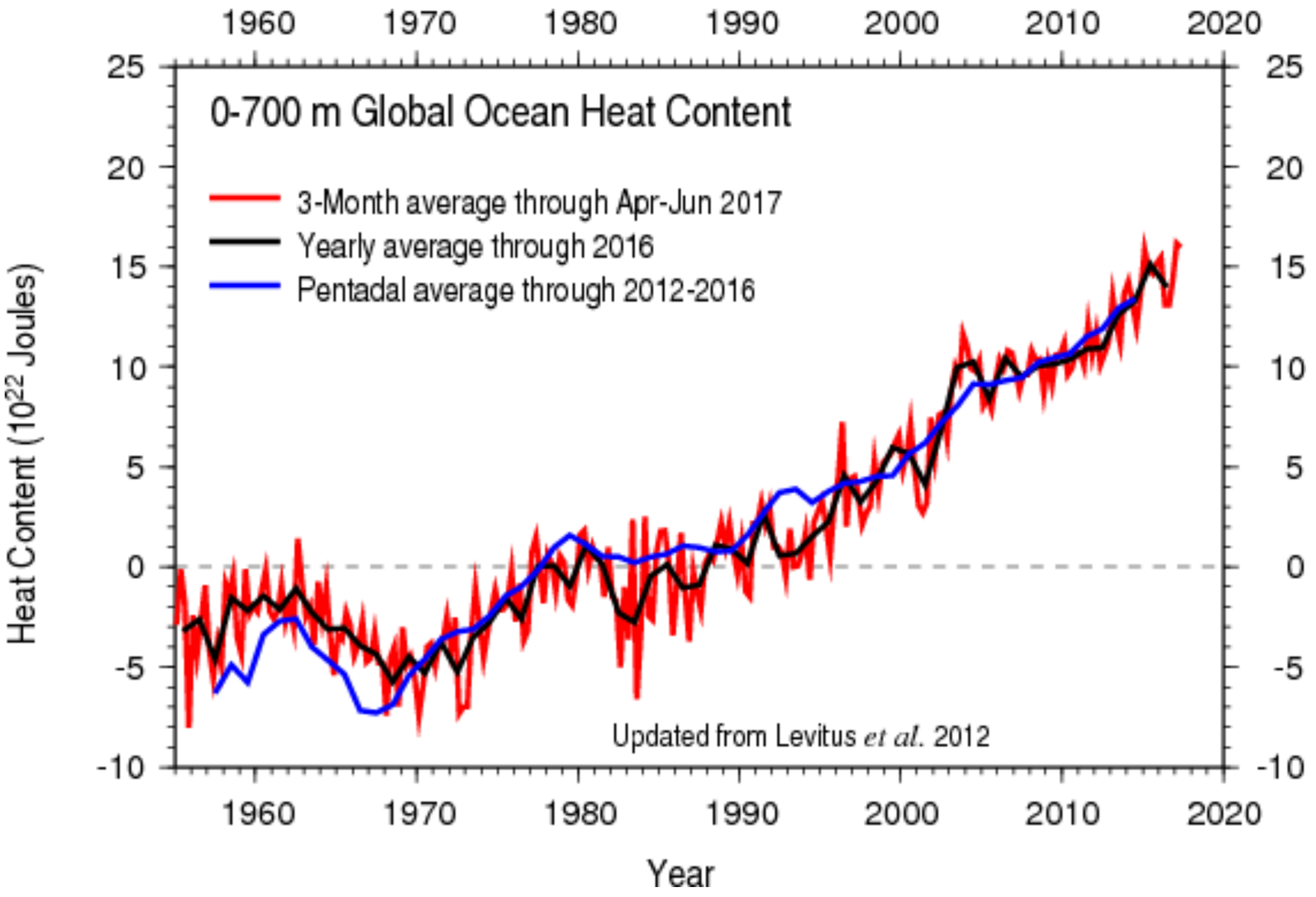

Ocean volume will continue to expand due to lag associated with the uptake of heat from the atmosphere to the ocean

“Thermal Expansion”

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Ice-sheets are slow to respond to a given forcing (as seen in paleo-record), so melting and fracturing likely to continue

[NY Times]

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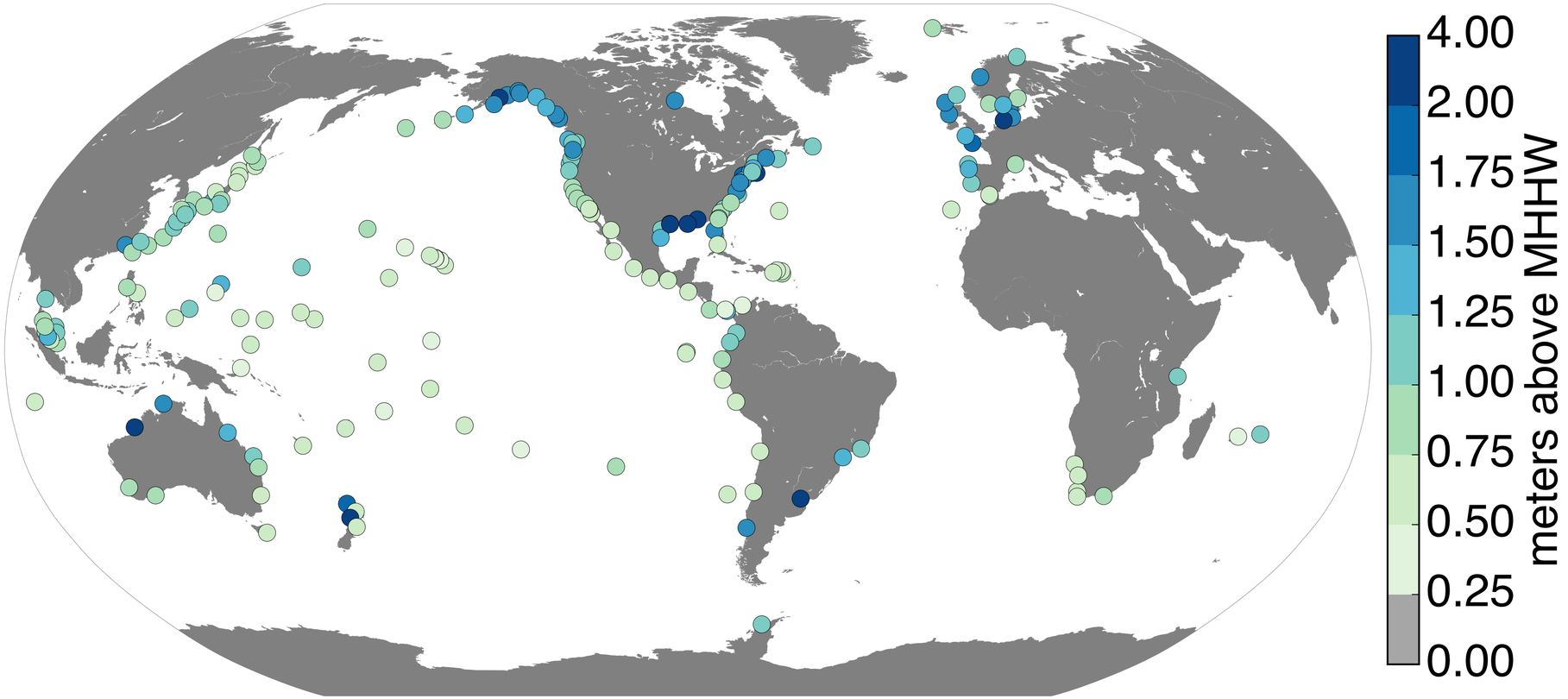
- Ocean volume will continue to expand due to lag associated with the uptake of heat from the atmosphere to the ocean
- Ice-sheets are slow to respond to a given forcing (as seen in paleo-record), so melting and fracturing likely to continue
- **GSL rise will increase the baseline height from which storm surges and astronomical tides occur**

Global sea level rise will increase the frequency of coastal floods (e.g., the 100-yr or 1%yr-1 flood)

Historical 100-yr Flood Height



[Rasmussen et al., in rev.]

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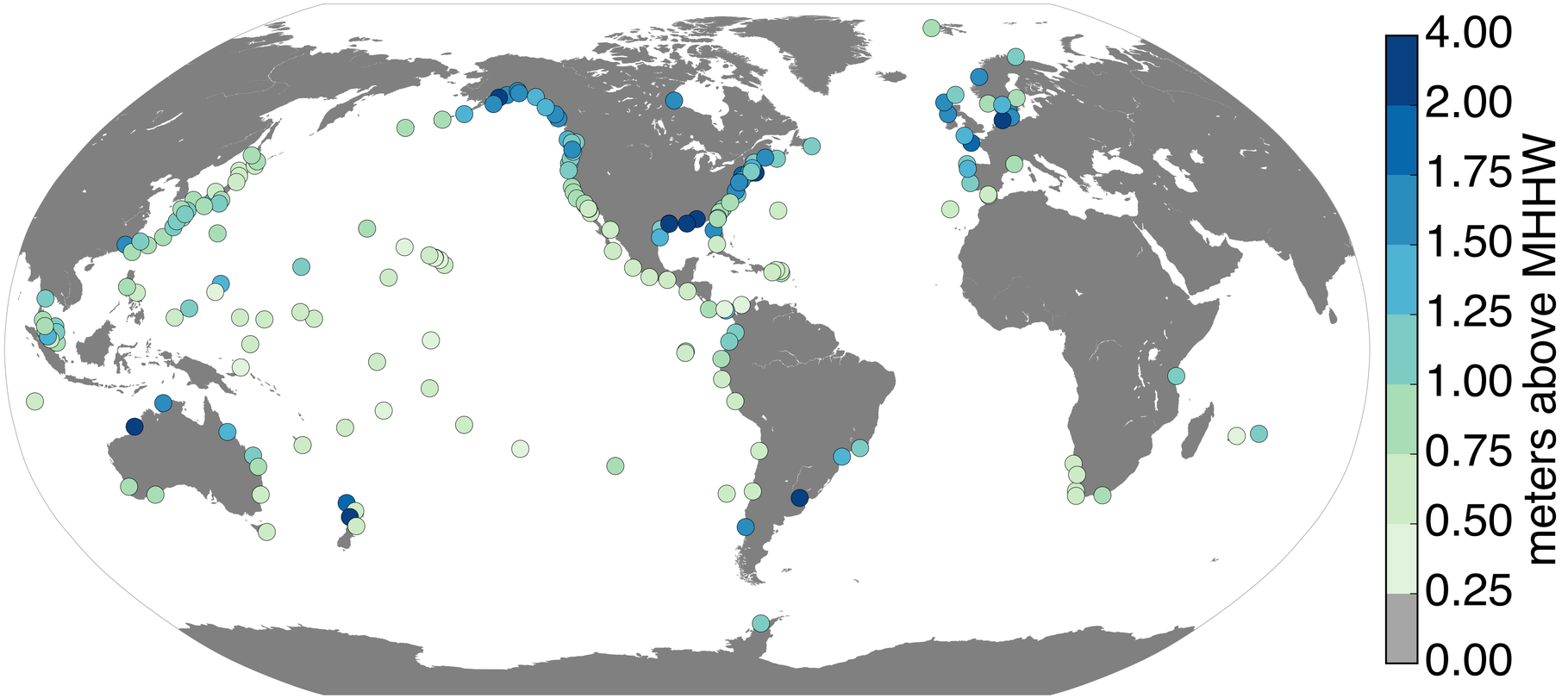

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Floods measured as “point” estimates — NOT spatially continuous

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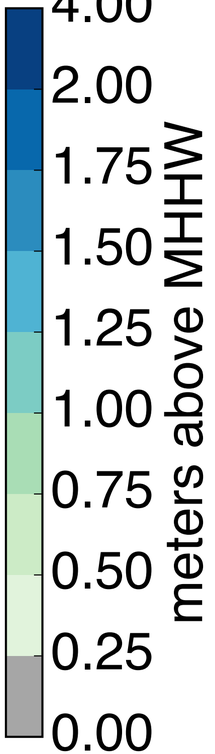

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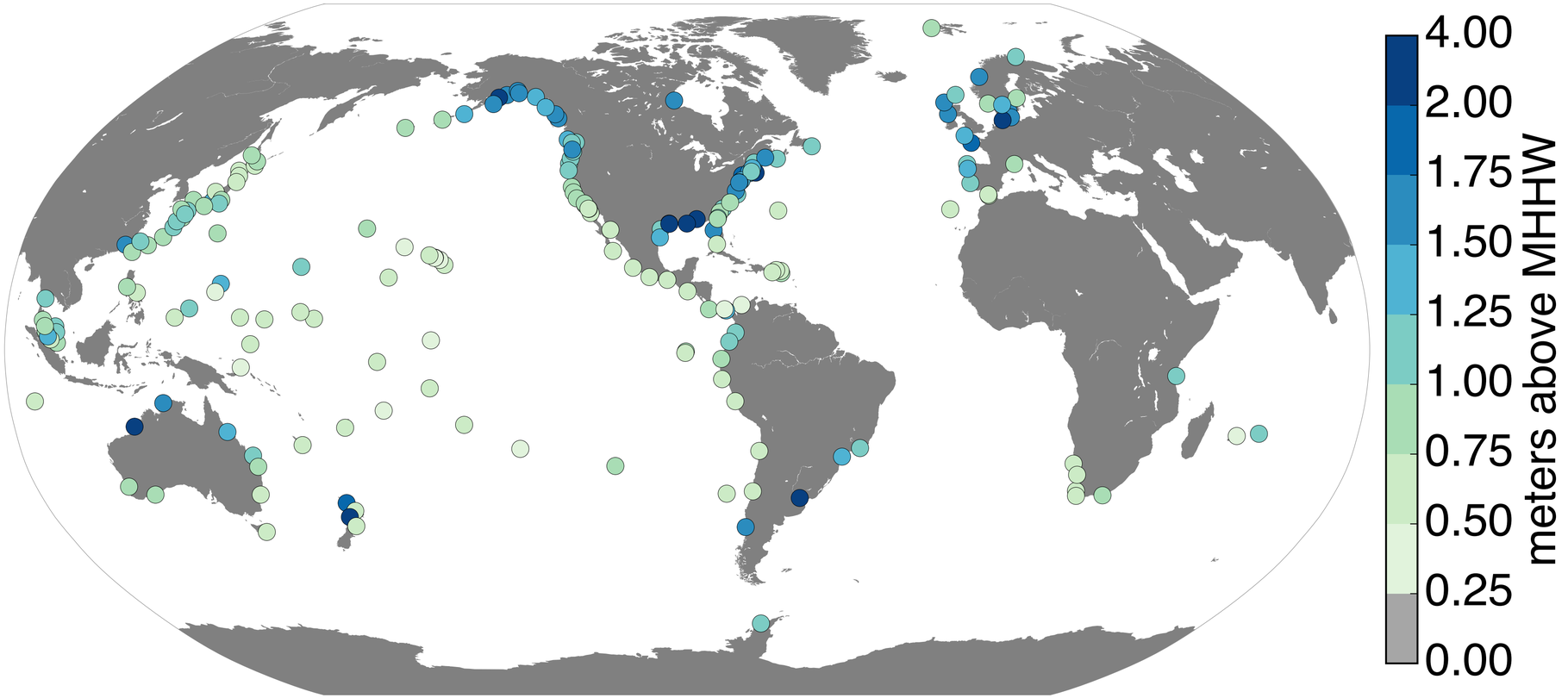

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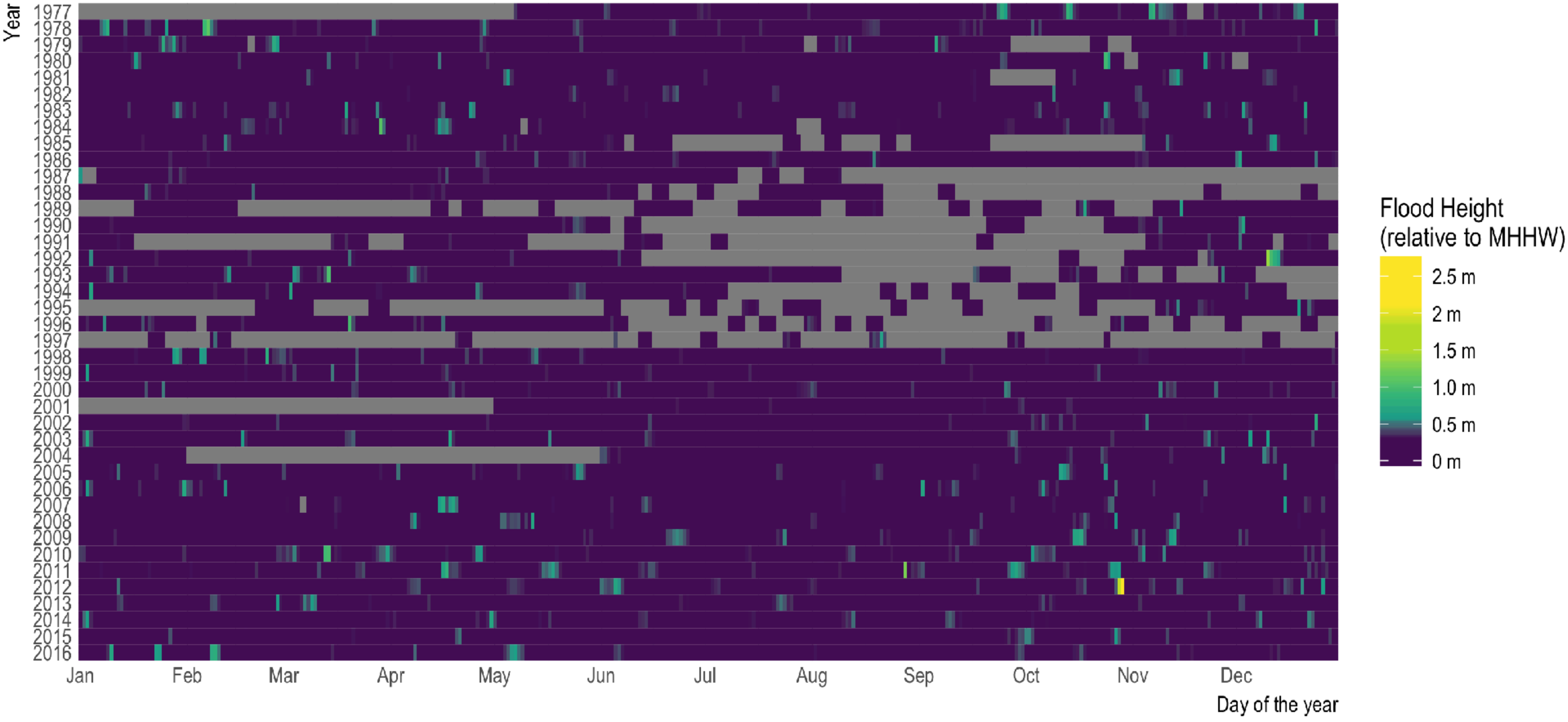
Floods measured as “point” estimates — NOT spatially continuous

Floods are defined as water height over MHHW (independent of damage)

Daily Flood Events at the Battery, New York City

1977-2016 (Grey are missing data)



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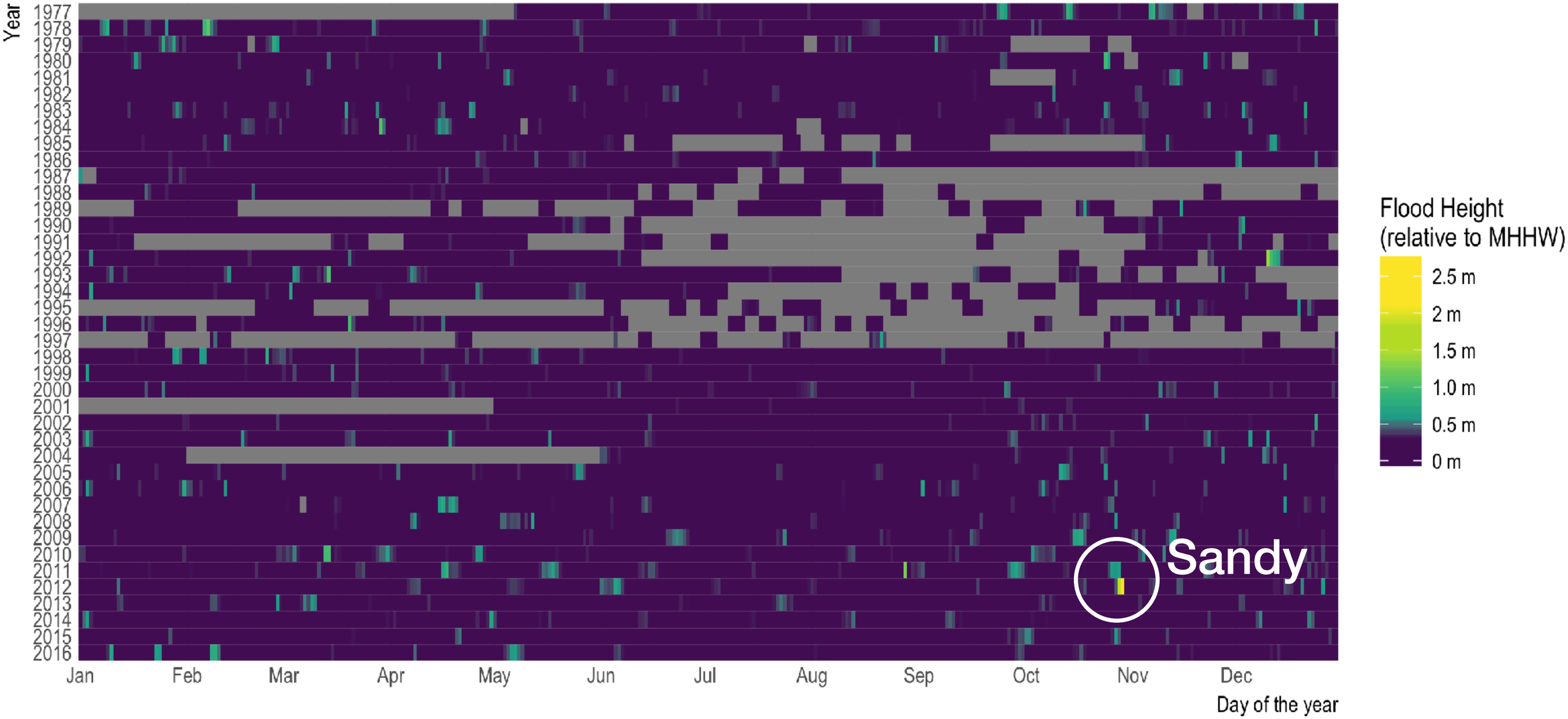

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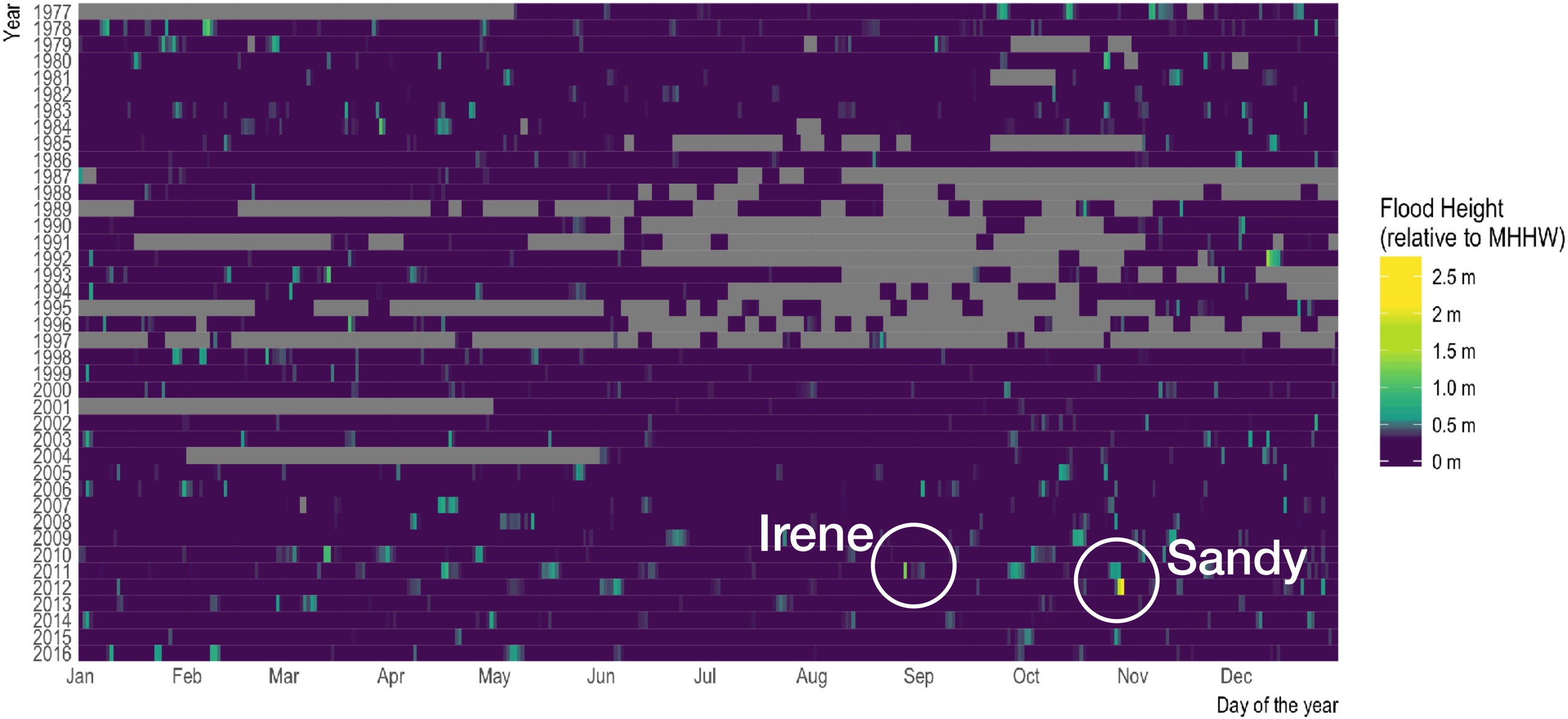

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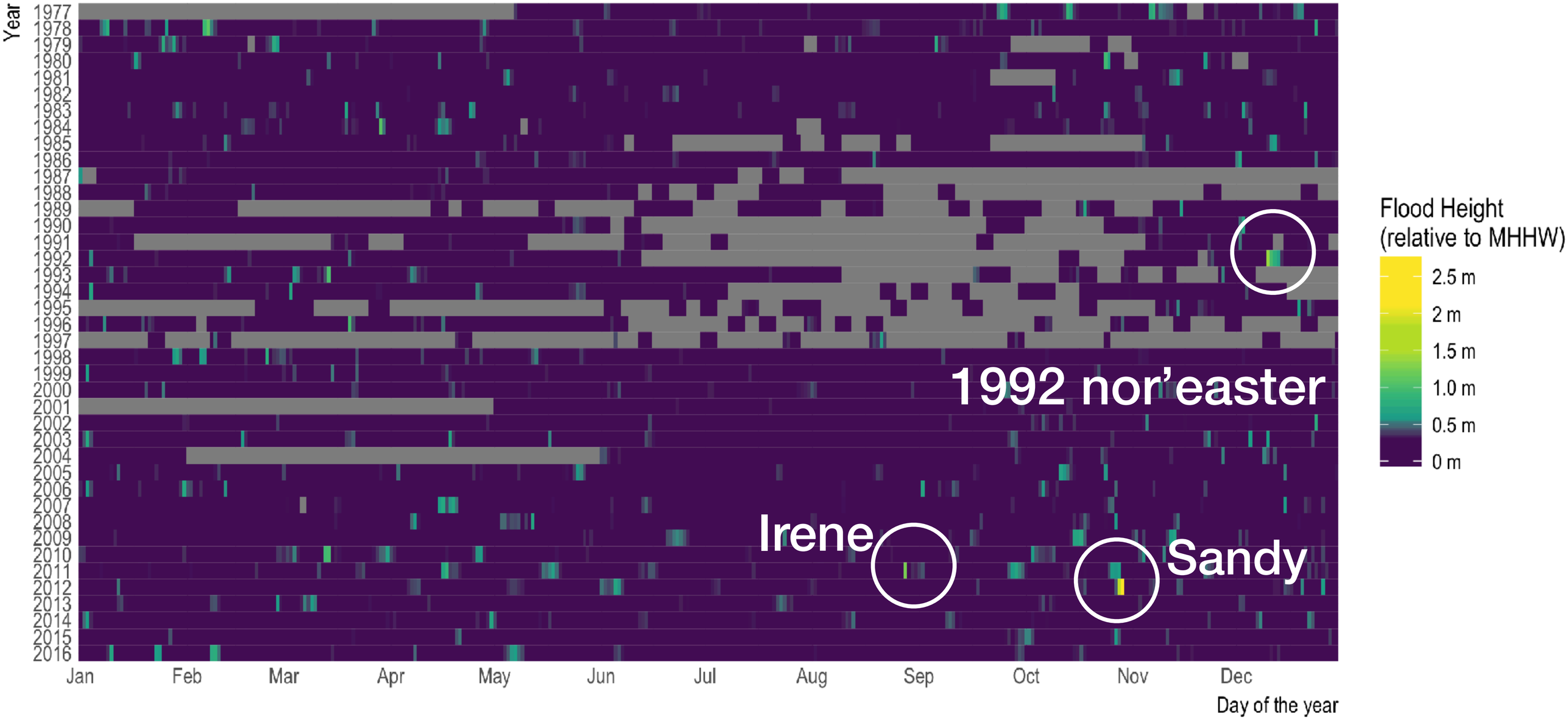
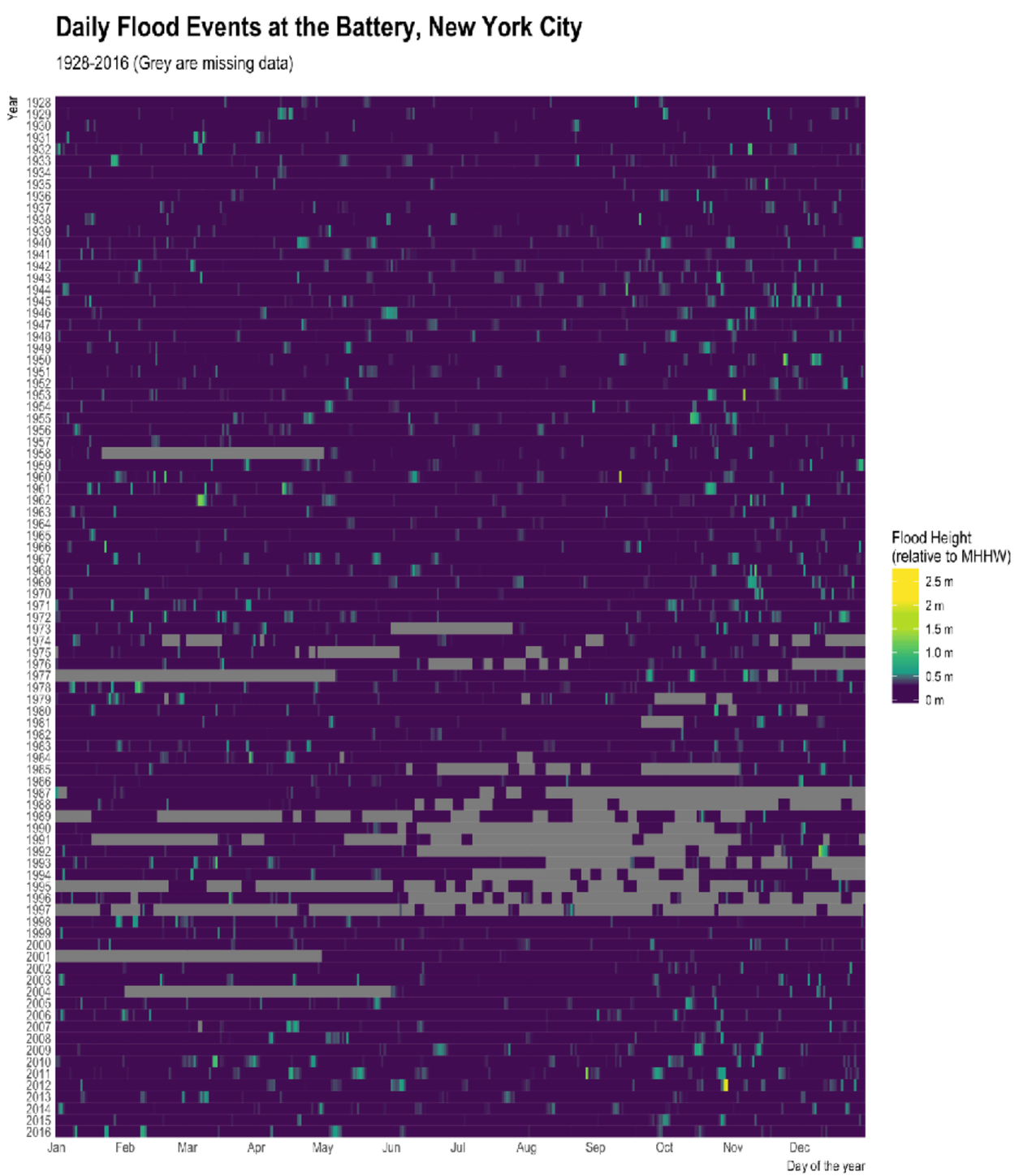


Zooming out… (1928—2016)

🌌“Sky full of… floods”?🌌

✨🌟💫✨🌟



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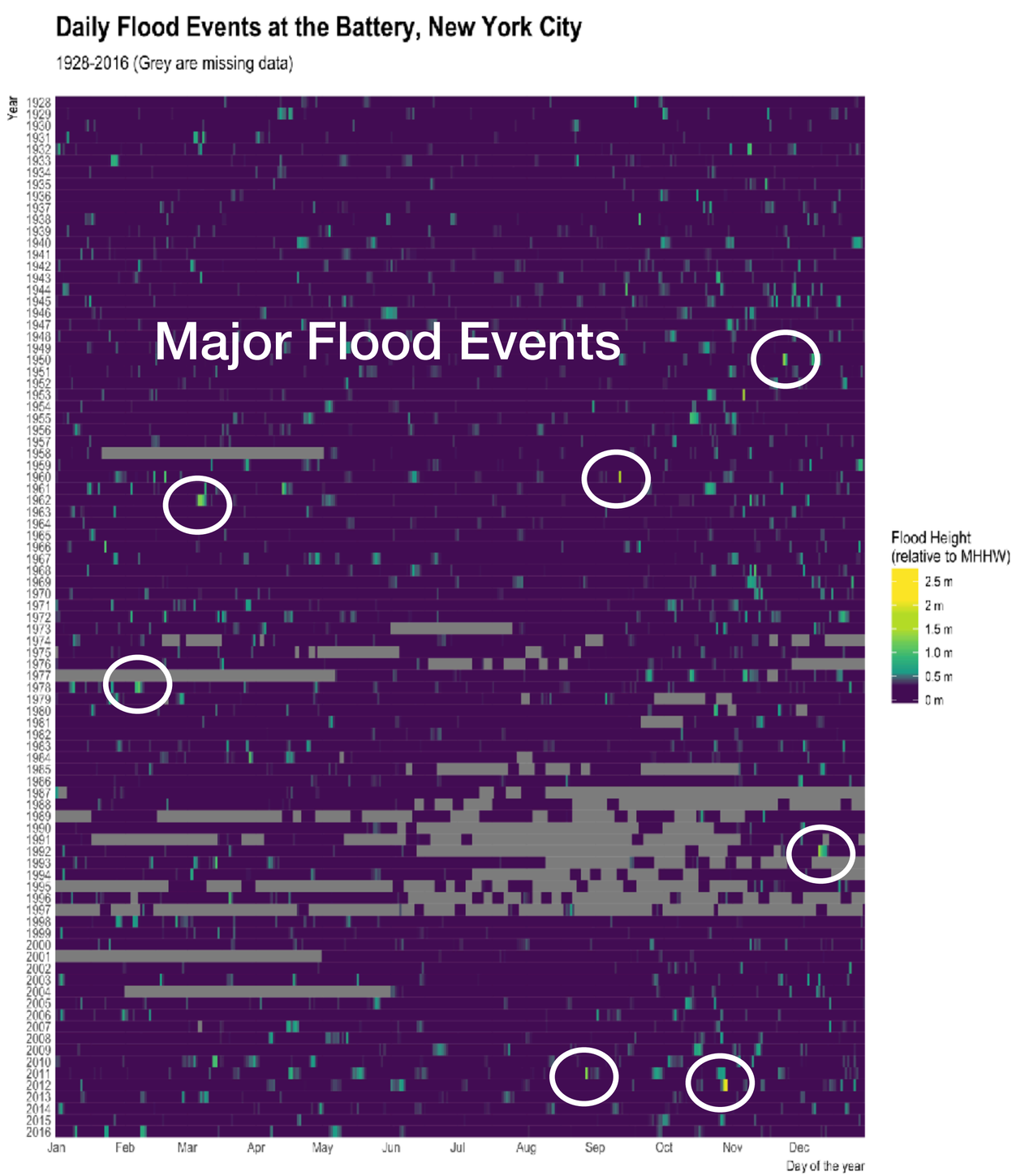
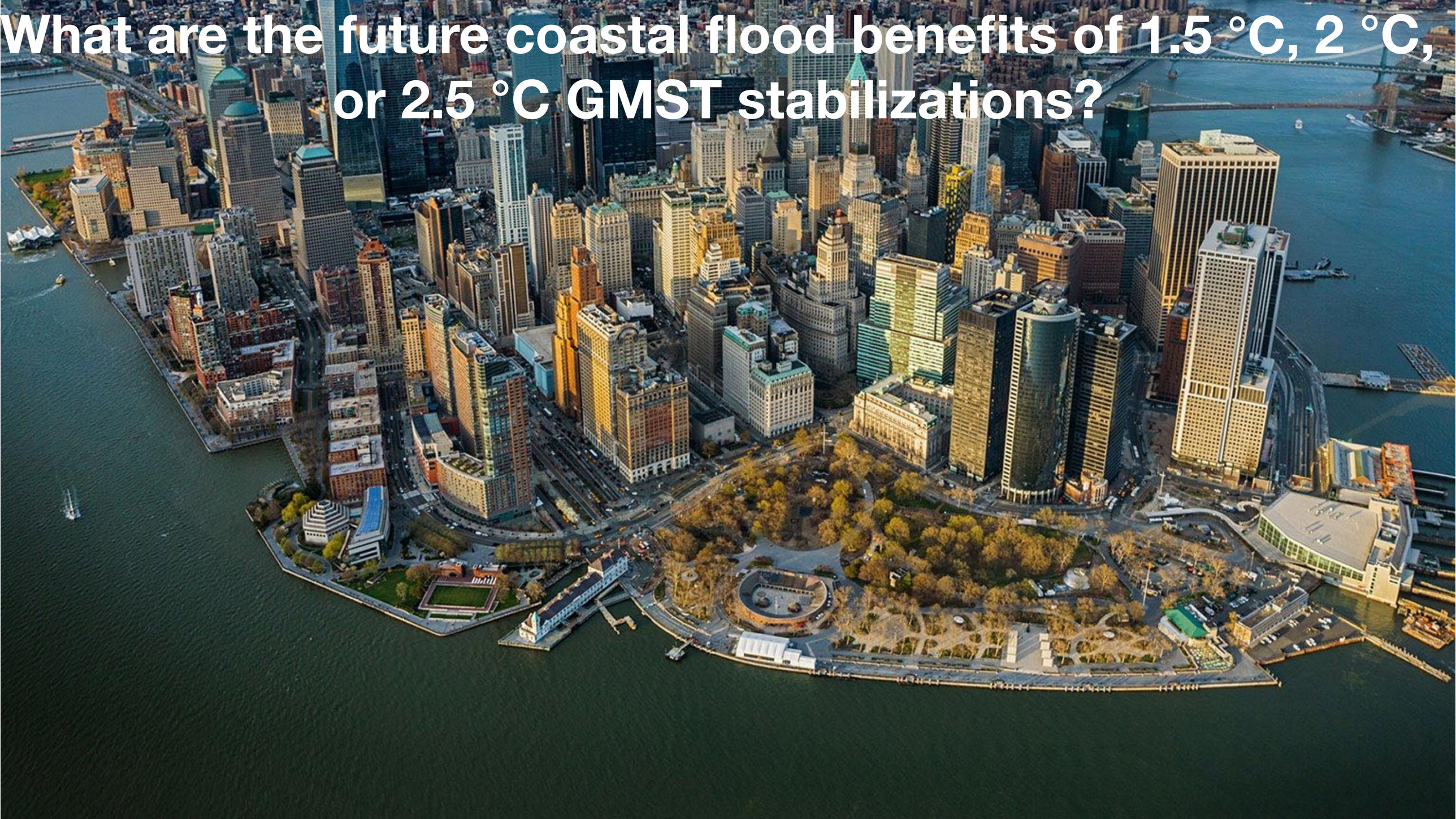


What are the future coastal flood benefits of 1.5 °C, 2 °C, or 2.5 °C GMST stabilizations?



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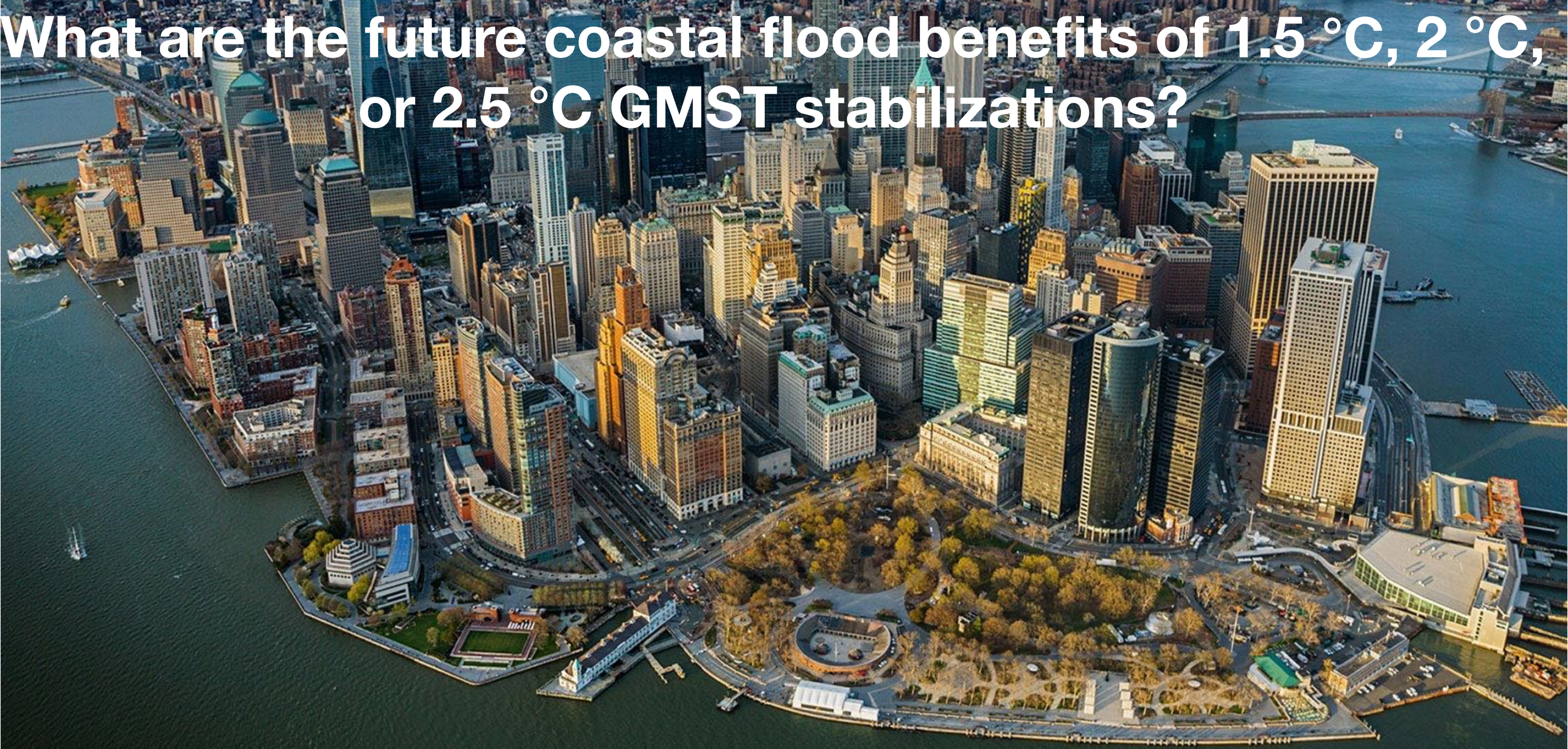

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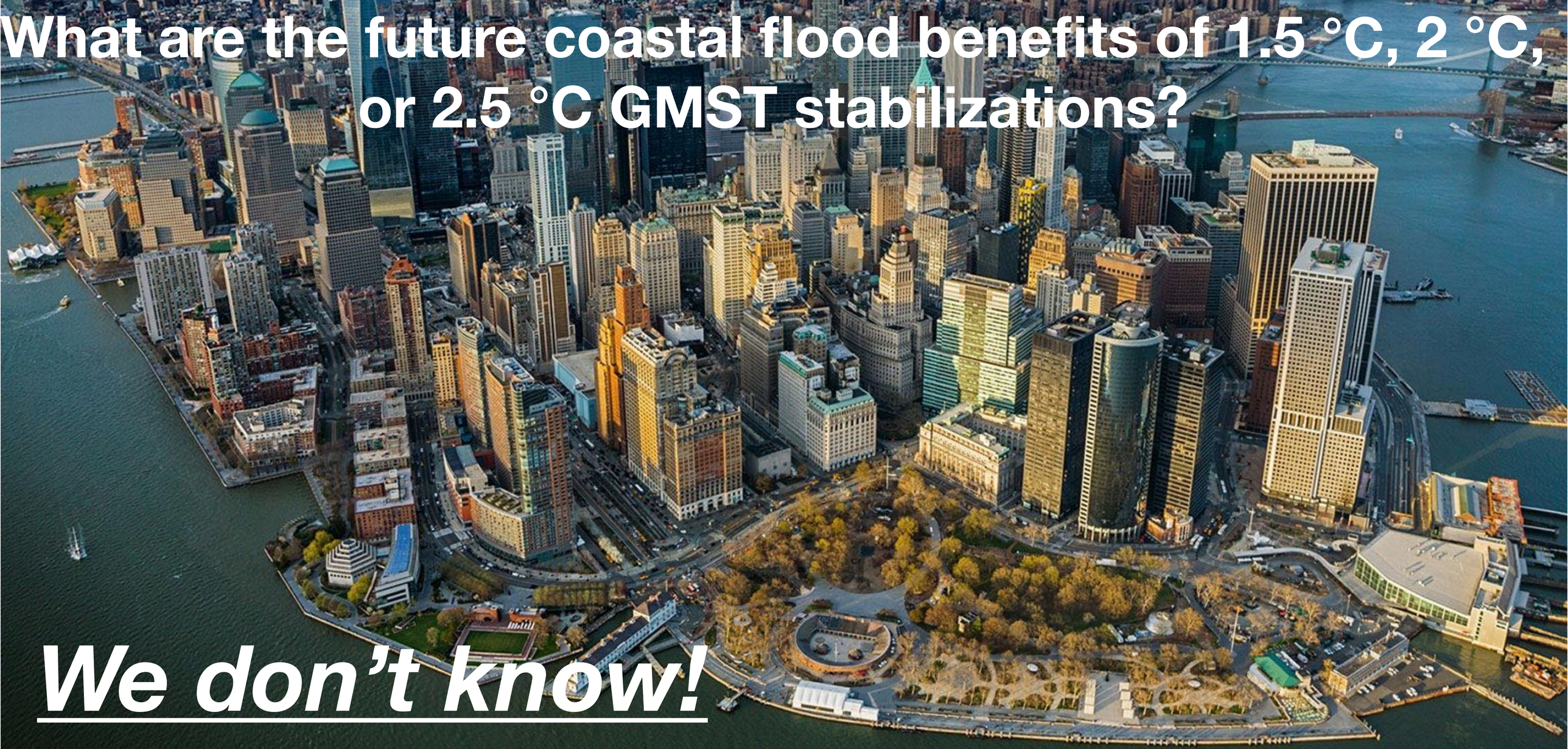

We don't know!

> 625 million people currently live in low-lying coastal areas (Neumann et al., 2015)

How we project future coastal flood probabilities:

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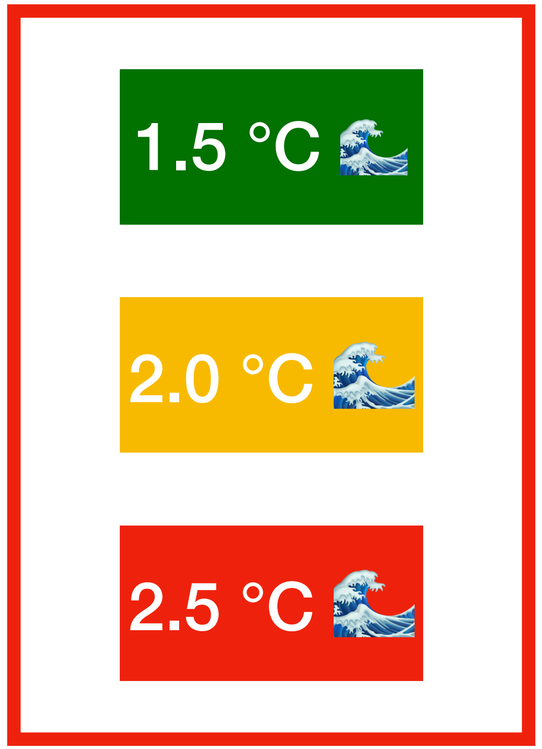

Global and Local Sea Level Rise (Kopp et al., 2014)

1. Generate local and global probabilistic SLR projections for 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilization using process-model framework of Kopp et al., 2014

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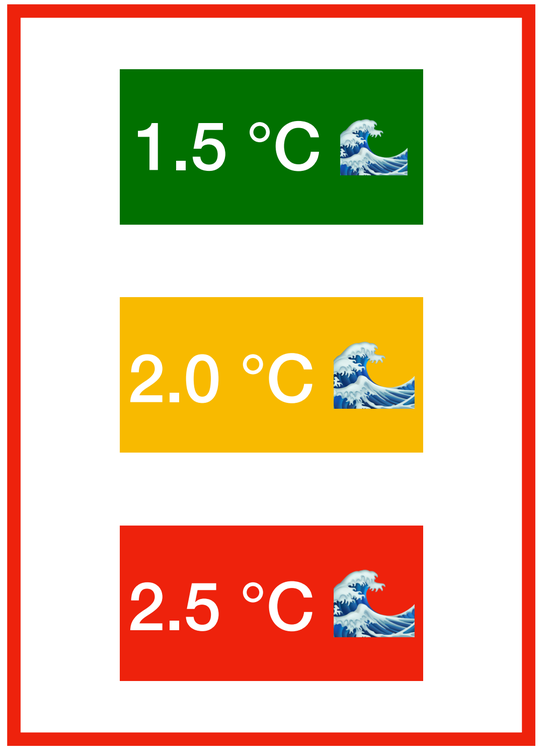
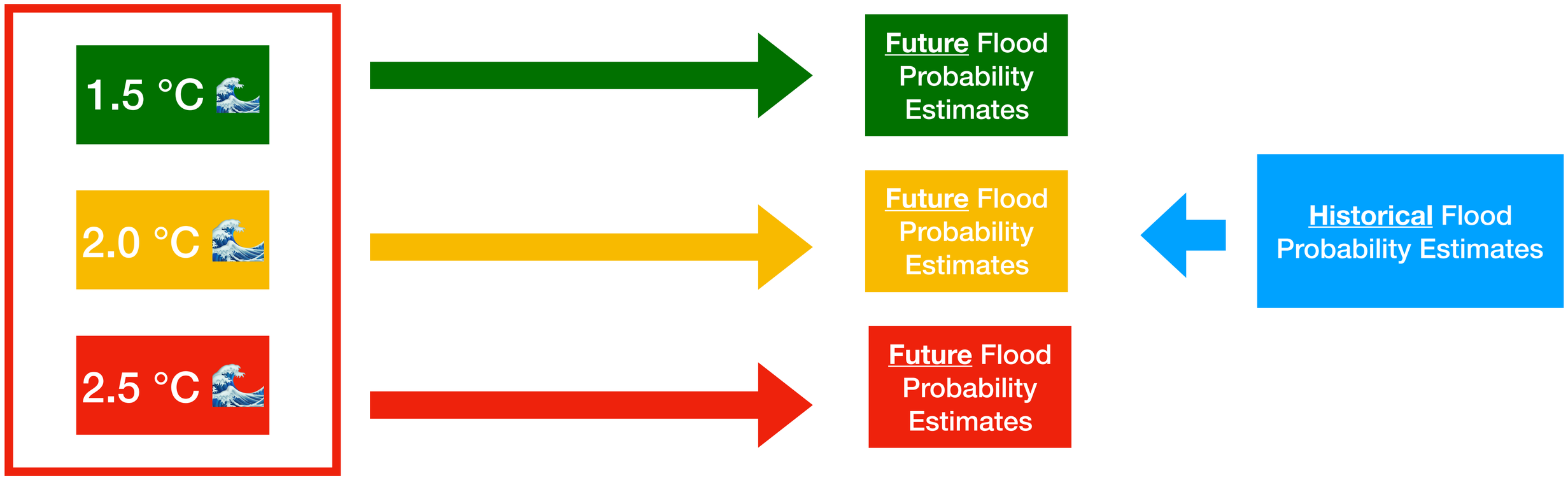


Global and Local Sea Level Rise (Kopp et al., 2014)

Historical Flood Probability Estimates

2. Estimate historical flood height probabilities (i.e., flood return periods)

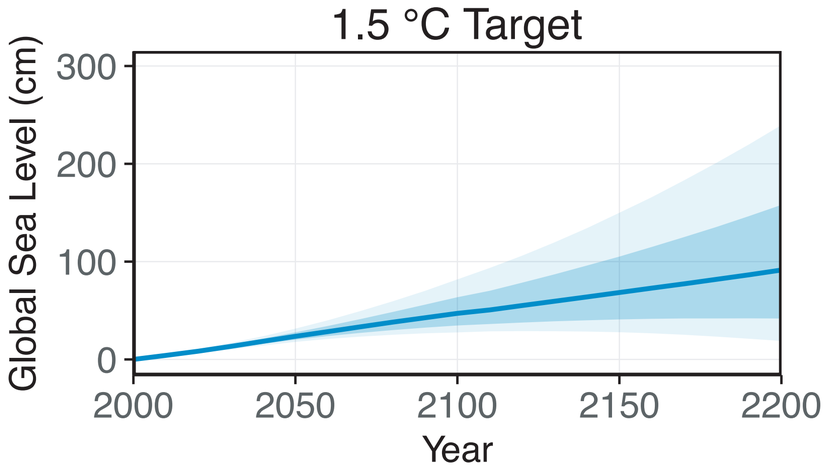
How we project future coastal flood probabilities:



Global and Local Sea Level Rise (Kopp et al., 2014)

3. Combine local SLR projections and historical flood probabilities to estimate probabilities of future coastal flood events

Global Mean Sea-Level (GSL) Rise Projections Increase with Temperature Stabilization



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1.5 °C	47	35-64	28-82

[Rasmussen et al., in rev.]

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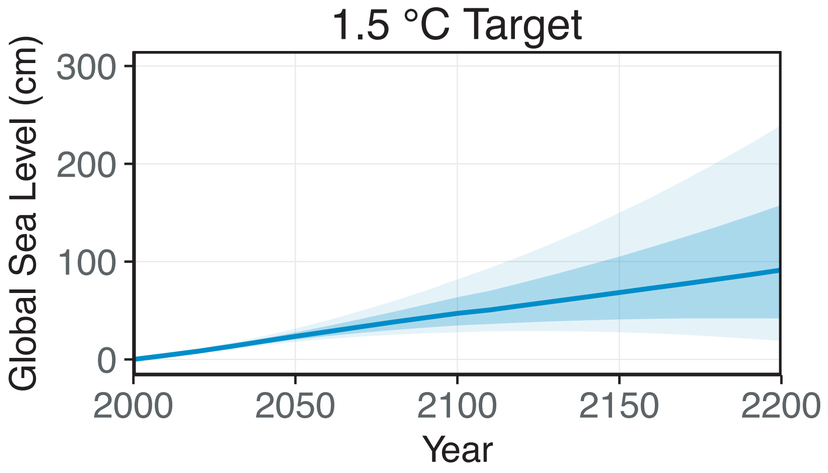

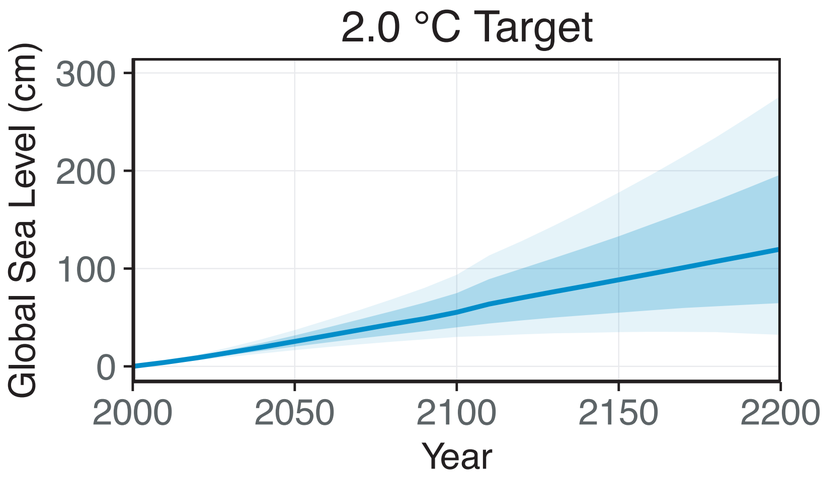

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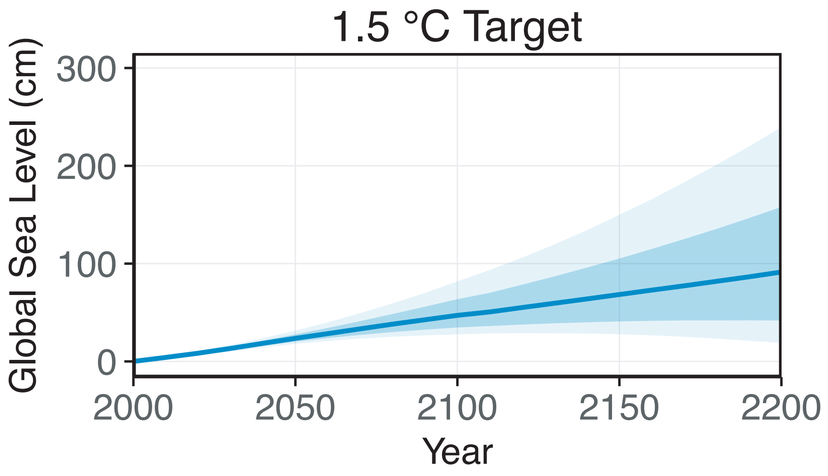

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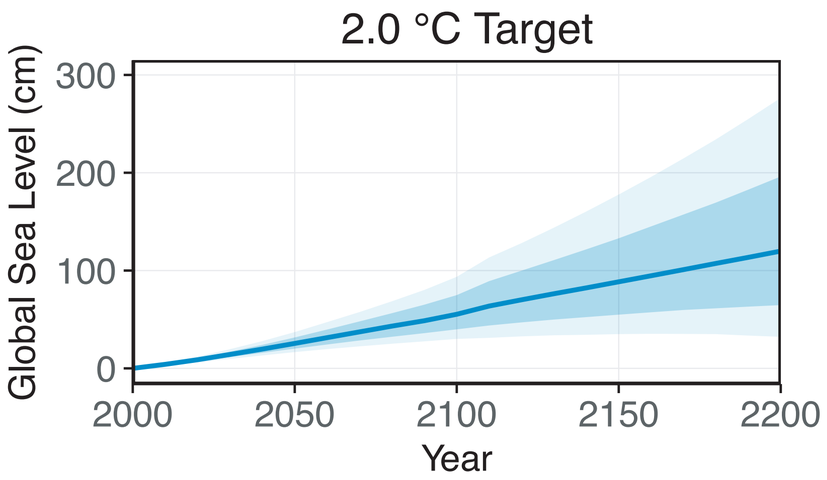

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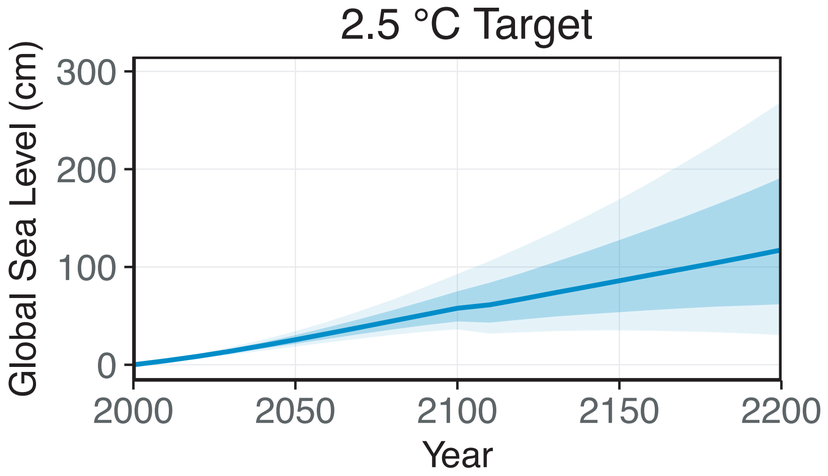

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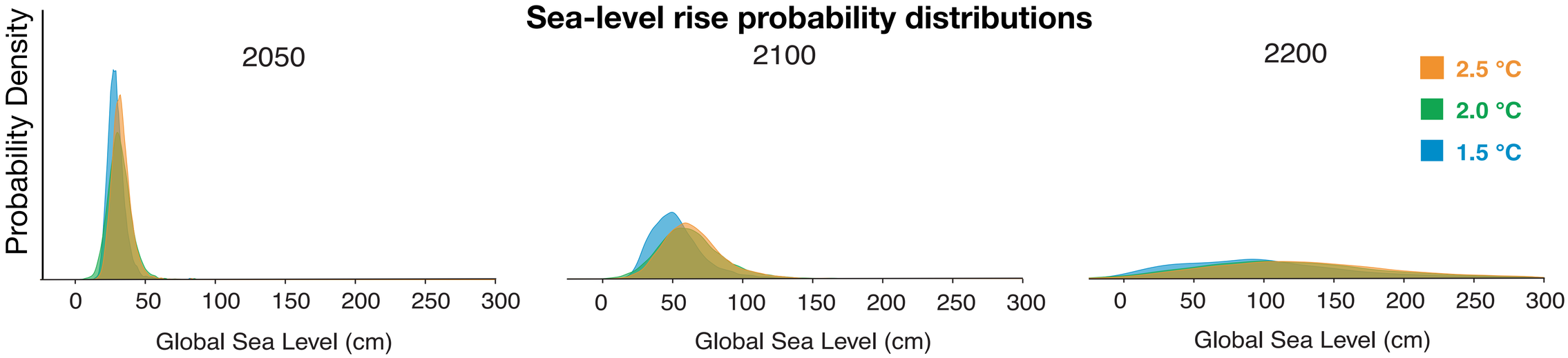
2.5 °C	58	44-75	36-93

[Rasmussen et al., in rev.]

Sea-level rise probability distributions



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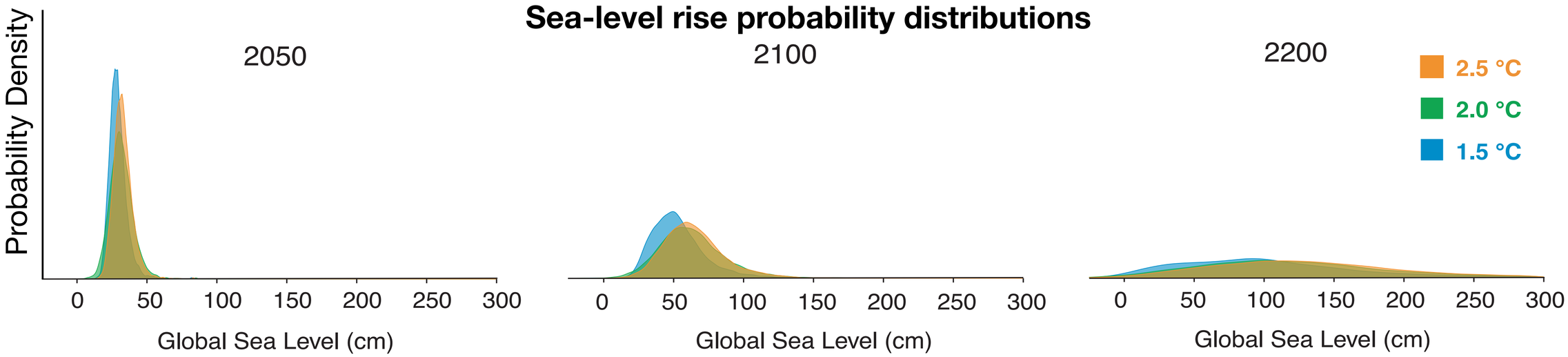
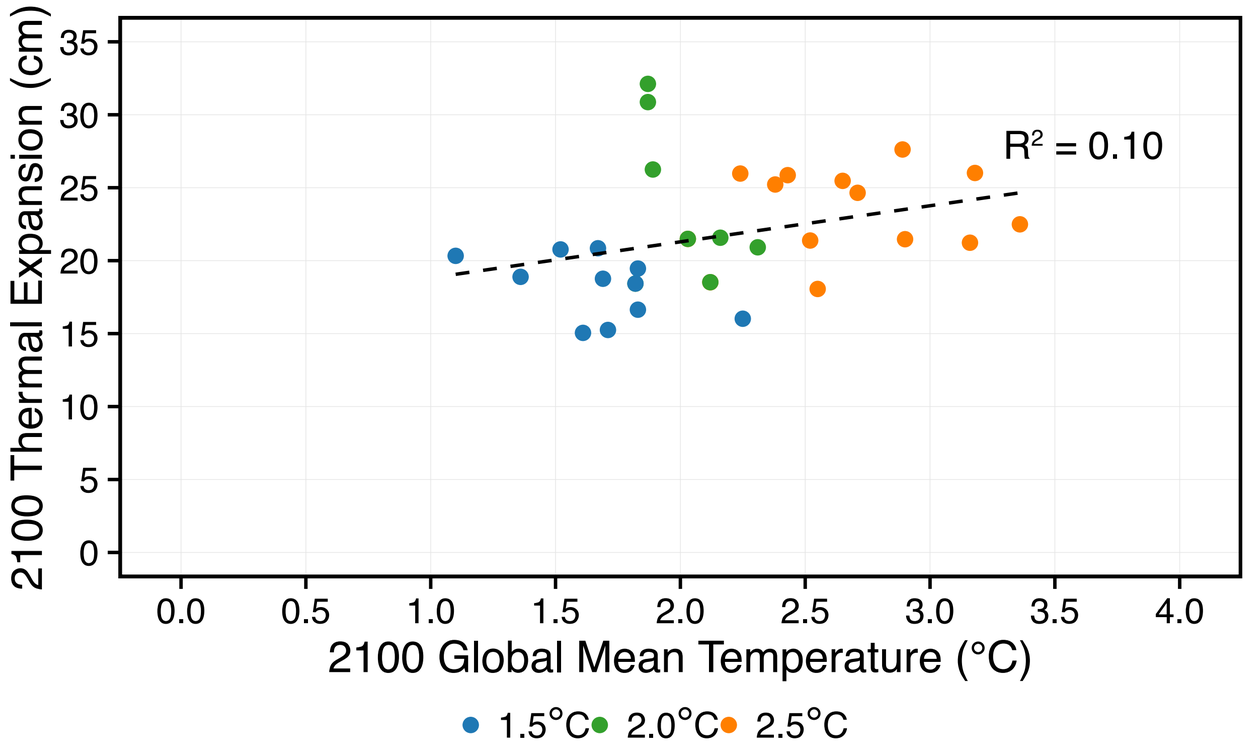


2.0 °C and 2.5 °C scenarios overlap b/c thermal expansion not strongly correlated with temperature across models



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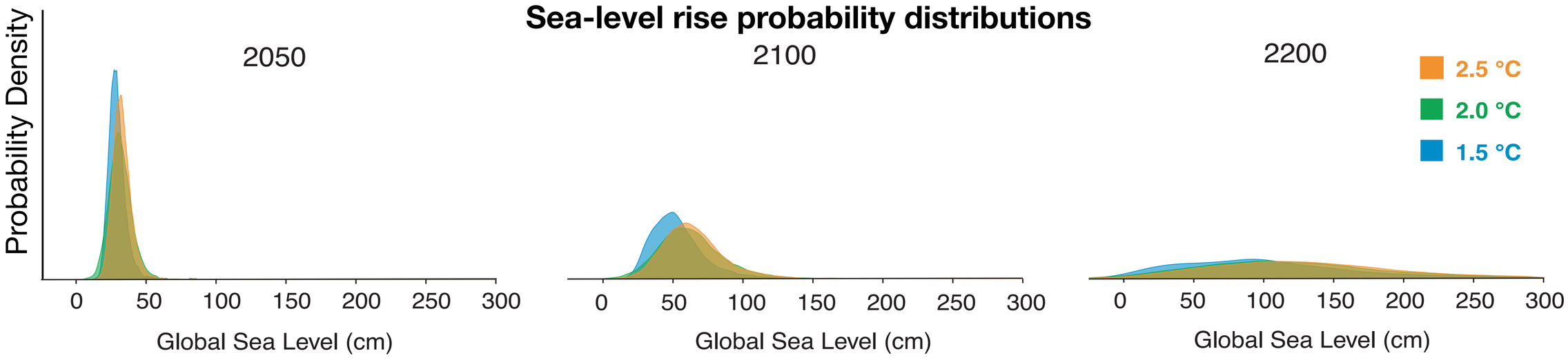

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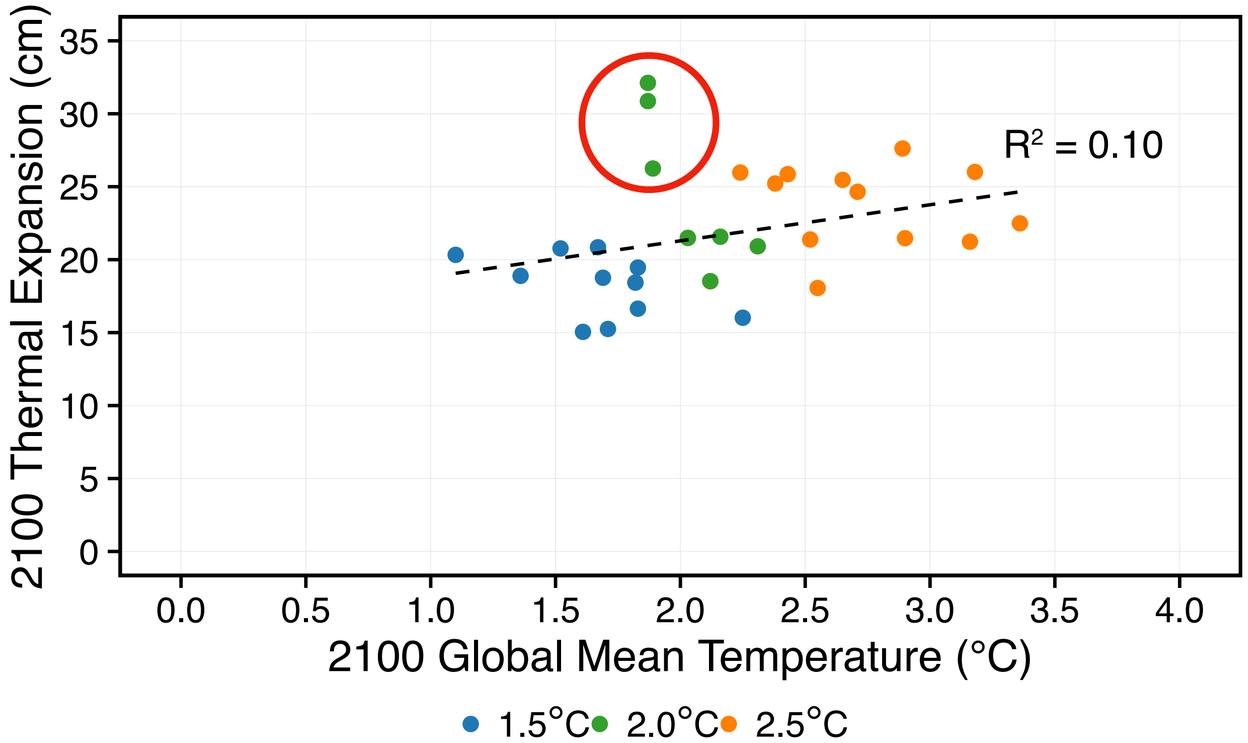

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Who currently resides in areas at risk of being *permanently* inundated by future SLR?

Approach:

CLIMATE CENTRAL

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How high will mean sea-level rise?

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1-arcsec SRTM 3.0 Digital Elevation Model (NASA, 2013)

What land is underwater?

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What land is underwater?

National population and boundary data (Bright et al., 2011)

Who lives there?

CLIMATE CENTRAL

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Under 2.0 °C scenario:

- ~60 million people currently reside in lands projected to be submerged by 2150 (~1% of current global population)
- ~500,000 current residents of Small Island Developing States
- ~20% of the current population of the Marshall Islands

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Under 1.5 °C scenario:

- Total number of people residing in lands is reduced by ~5 million people from ~60 million (under 2.0 °C scenario)

CLIMATE CENTRAL

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Under 2.0 °C scenario:

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- ~500,000 *current* residents of Small Island Developing States
- ~7% of the *current* population of Kiribati

Assumes people don't move around…

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CLIMATE CENTRAL

Approach: estimating historical and future coastal flood probabilities

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- Observations de-trended (i.e. remove historical SLR) and made relative to mean higher high water (MHHW)

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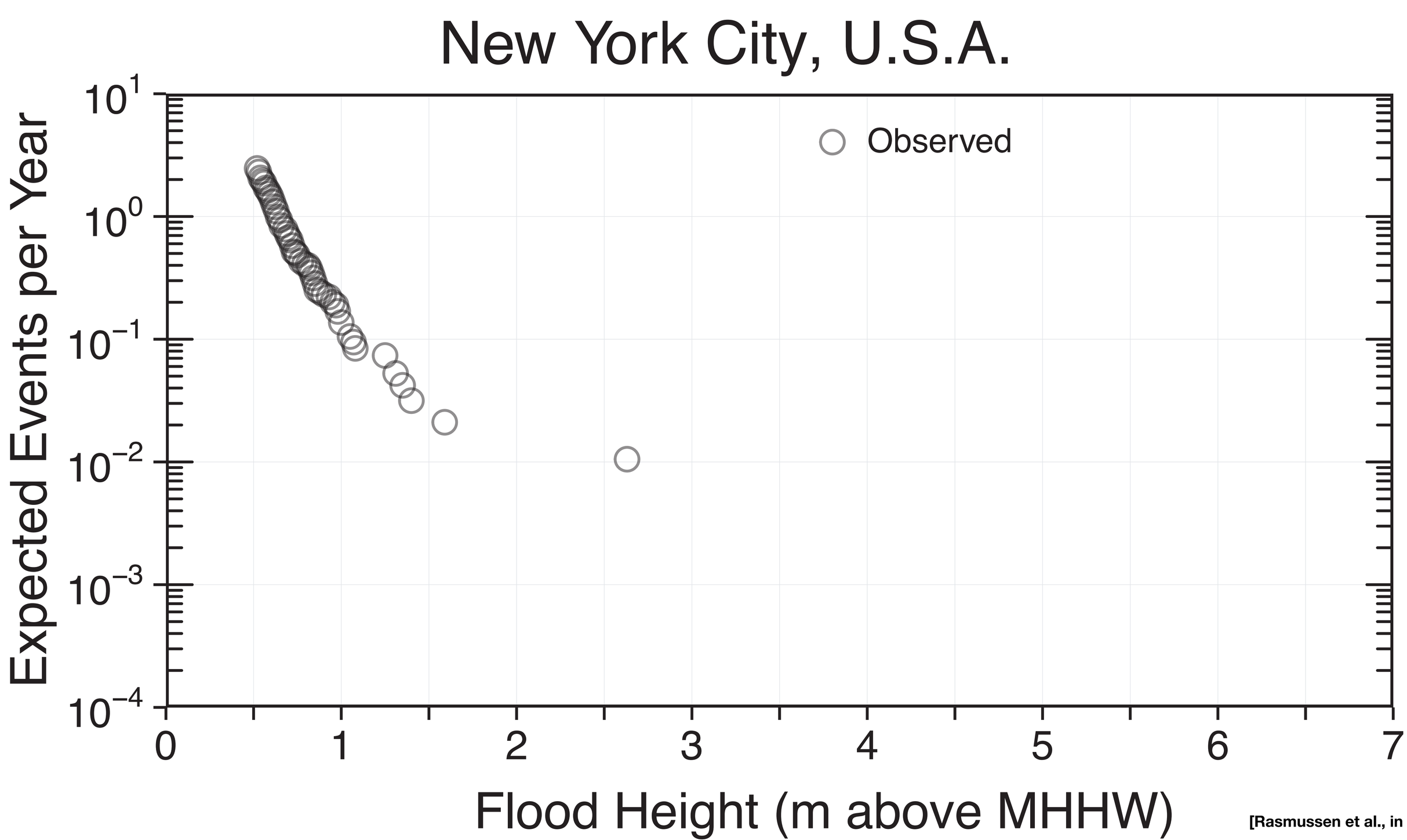
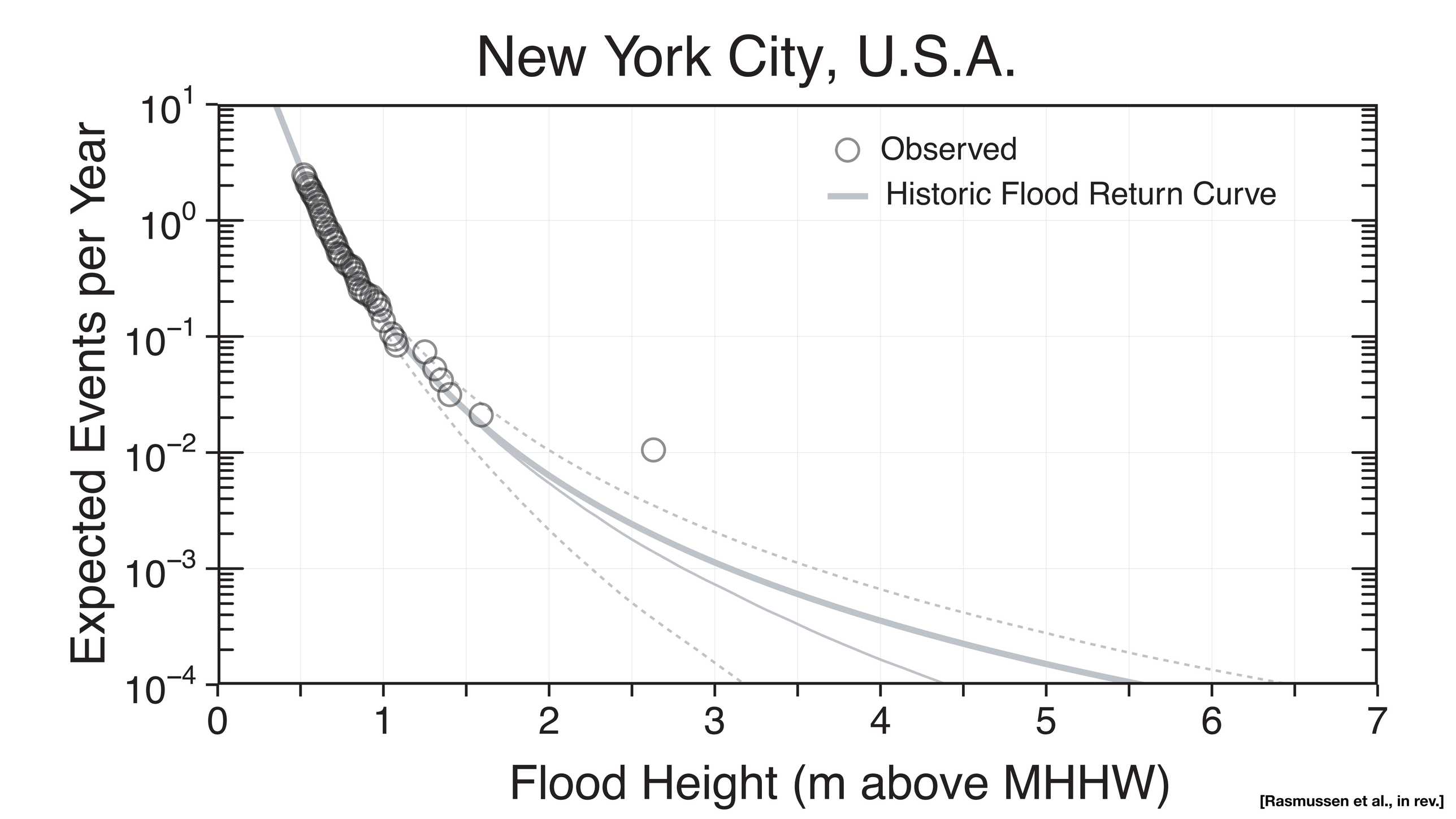
- Observations de-trended (i.e. remove historical SLR) and made relative to mean higher high water (MHHW)
- Estimate annual expected number of floods using method from Buchanan et al. (2016; 2017):
    - General Pareto Distribution (GPD)
    - GDP exceedances assumed to be a Poisson process
    - Sample GPD parameter uncertainty and the SLR uncertainty

New York City Flood Events

Case Study: New York City


New York City, U.S.A.
Observed
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
[Rasmussen et al., in rev.]



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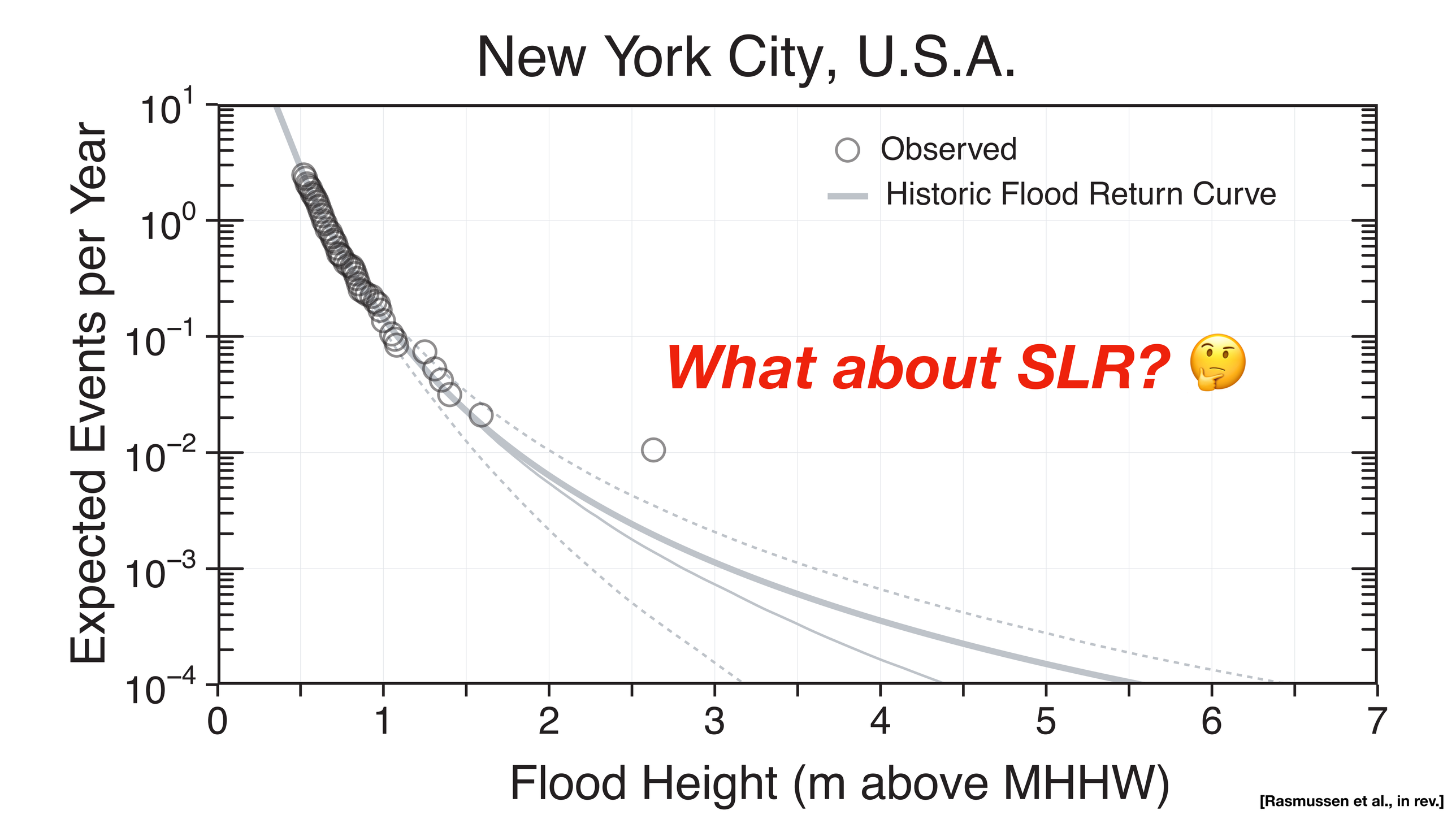

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What about Local SLR?

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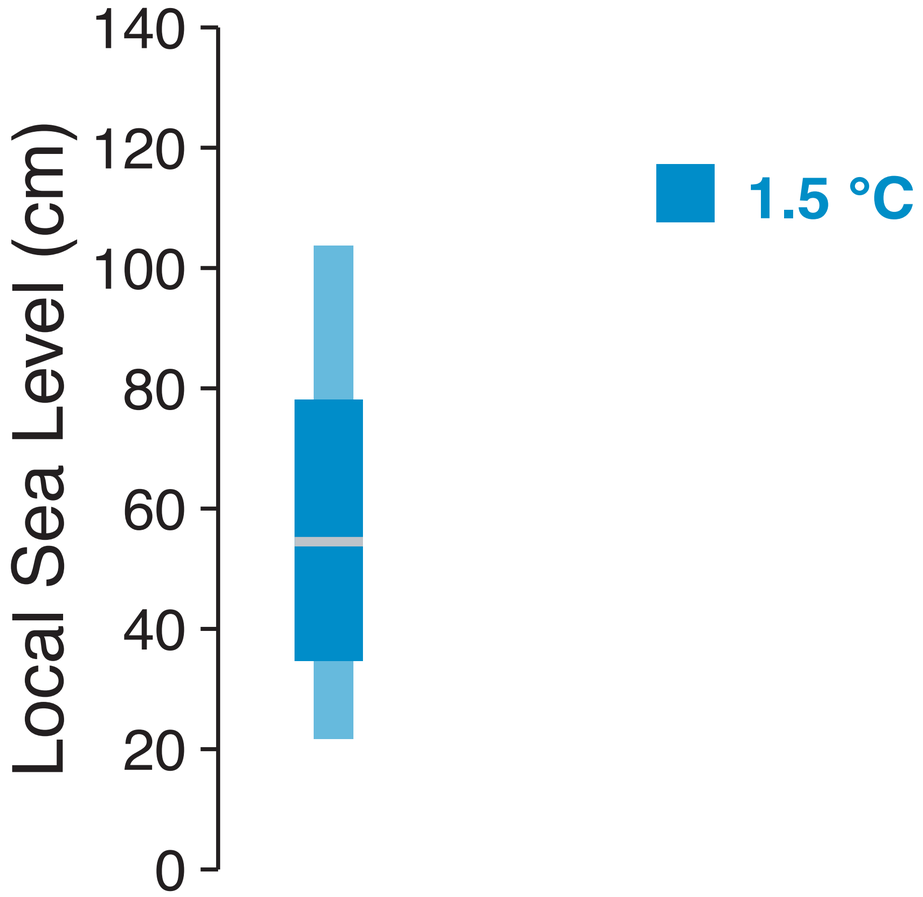

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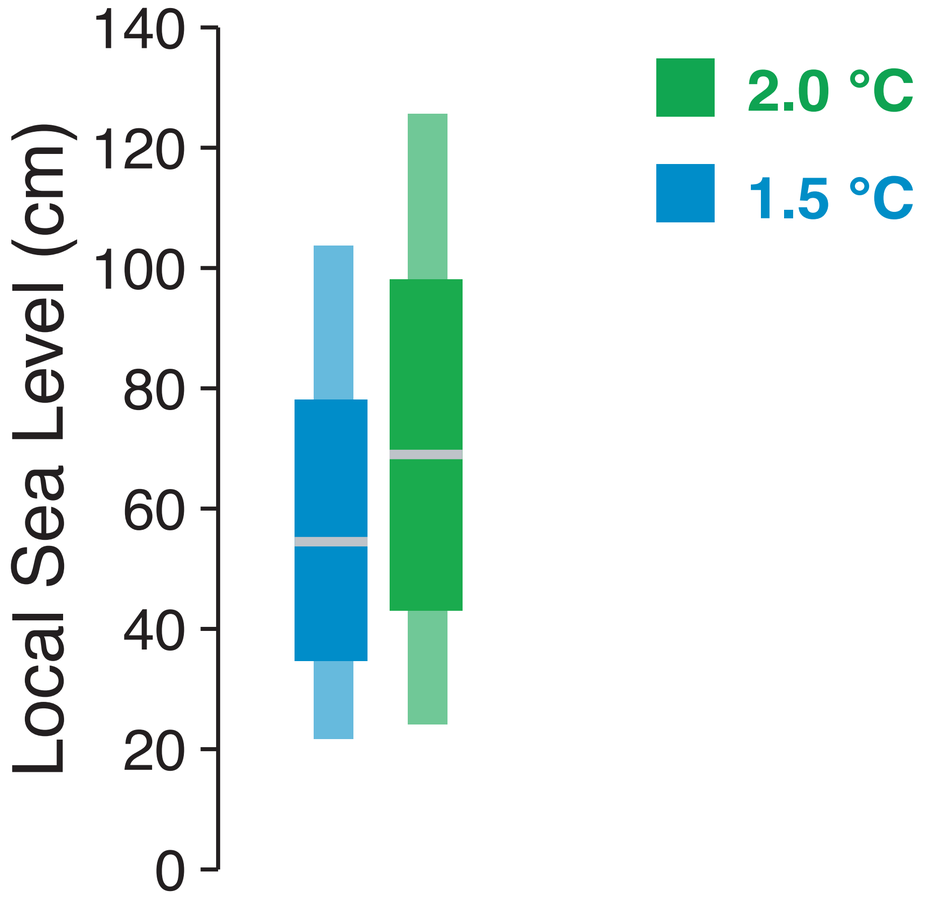

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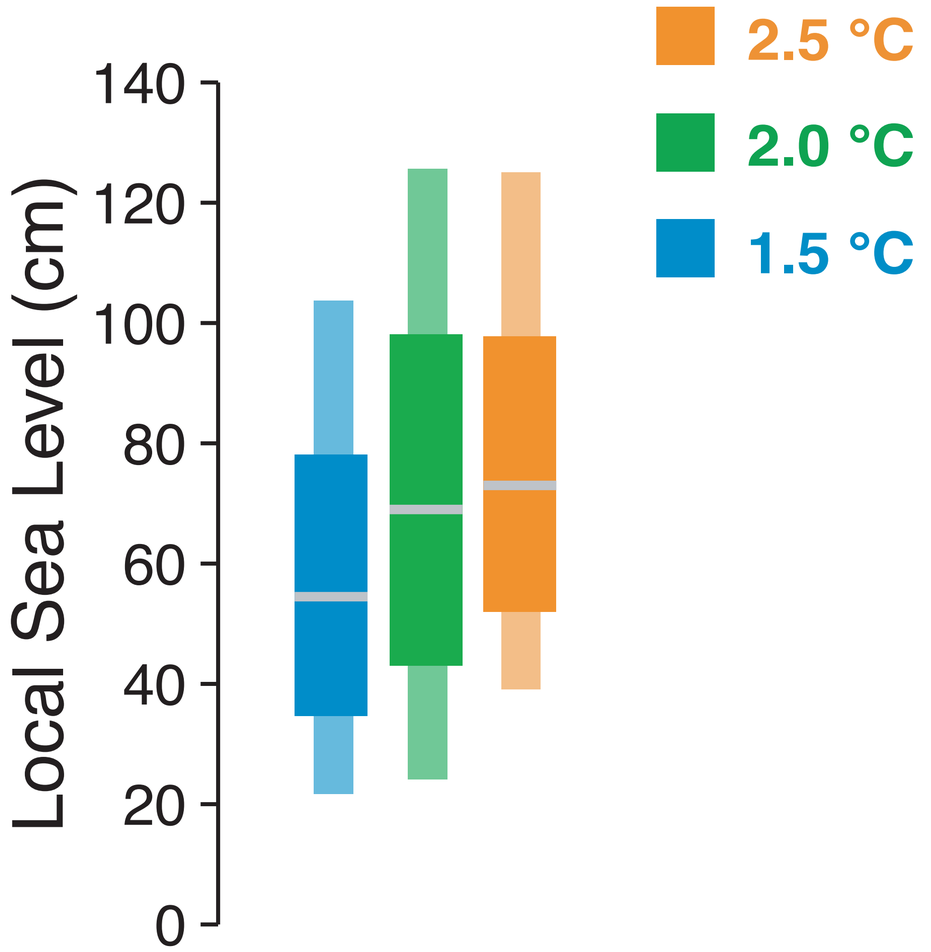

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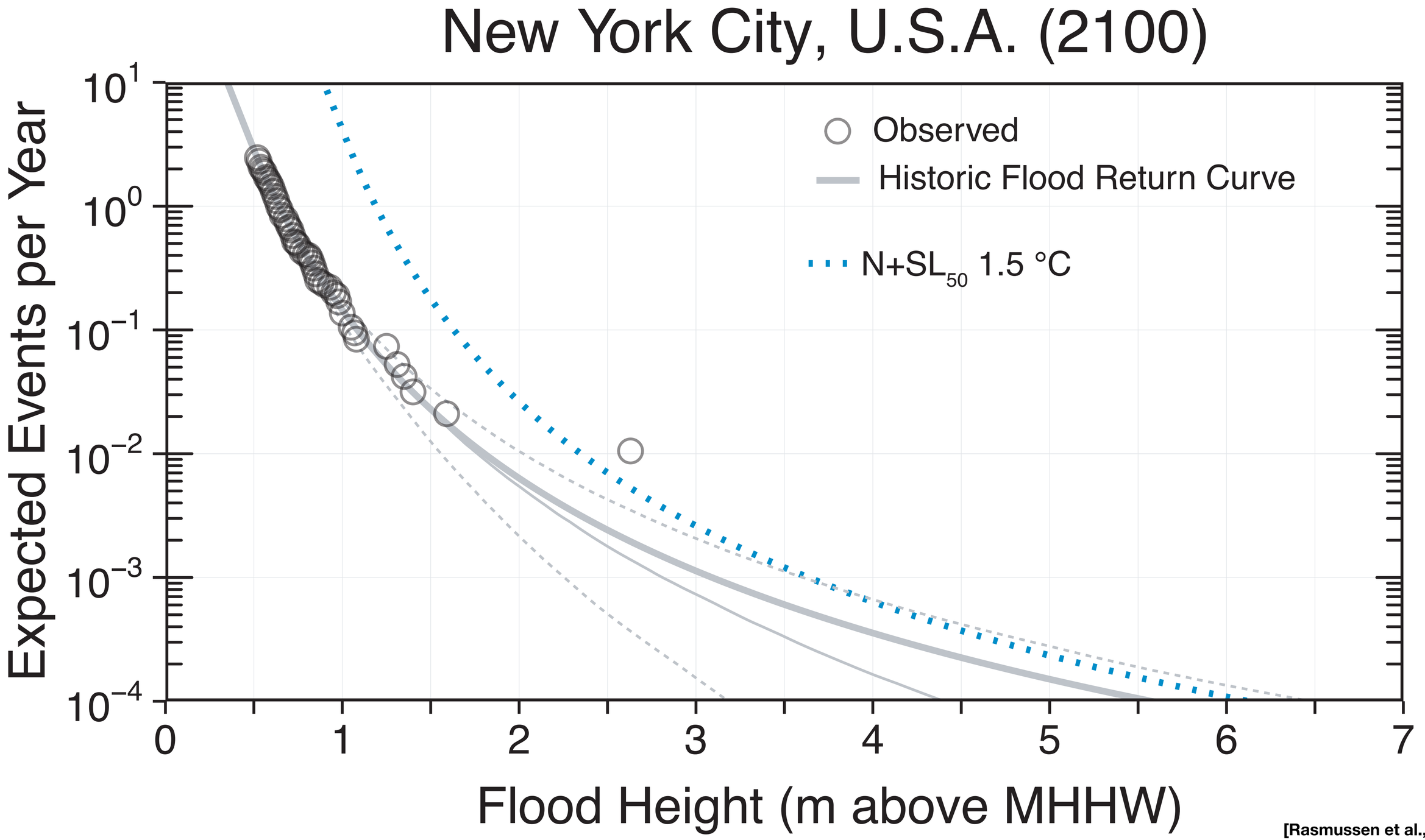

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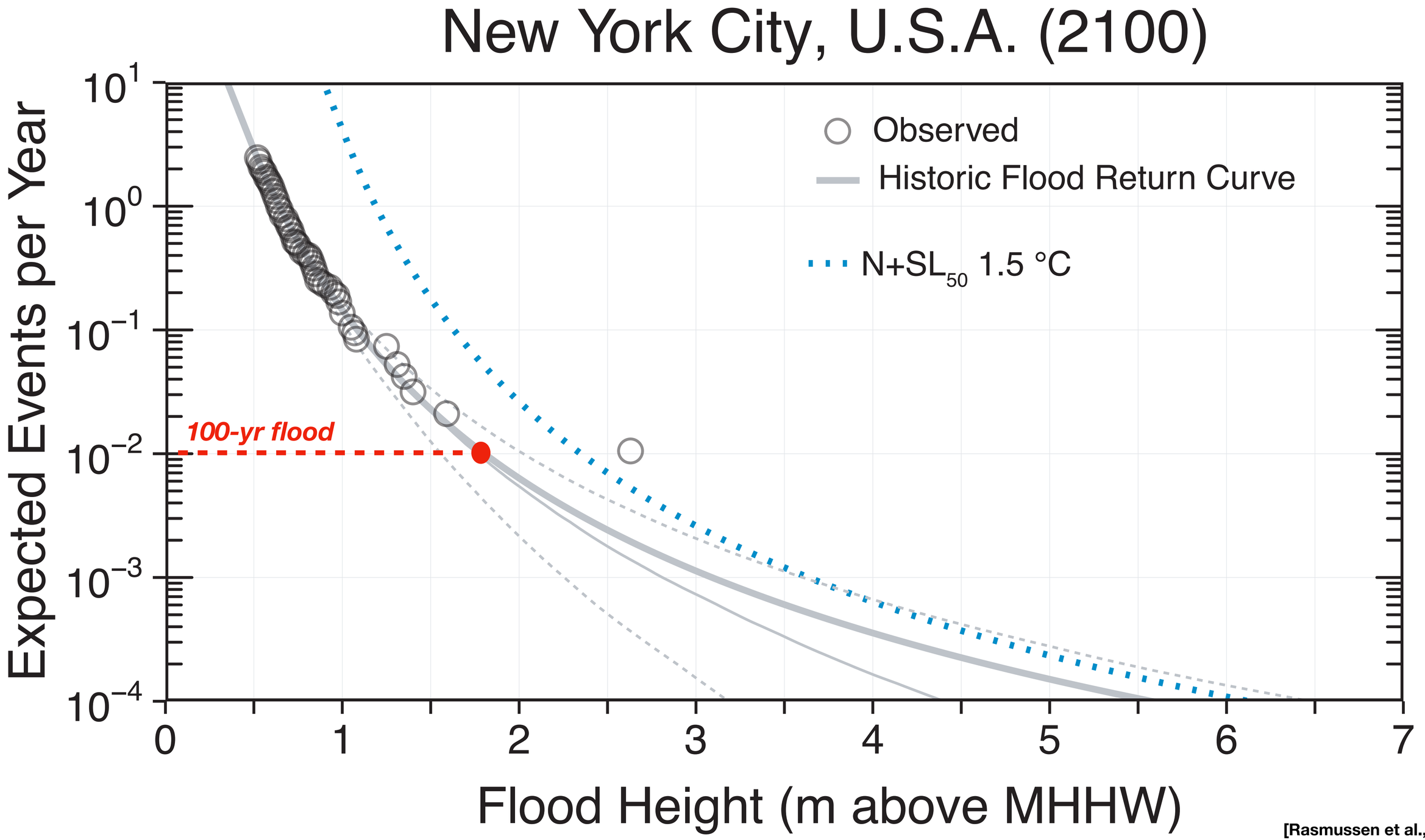

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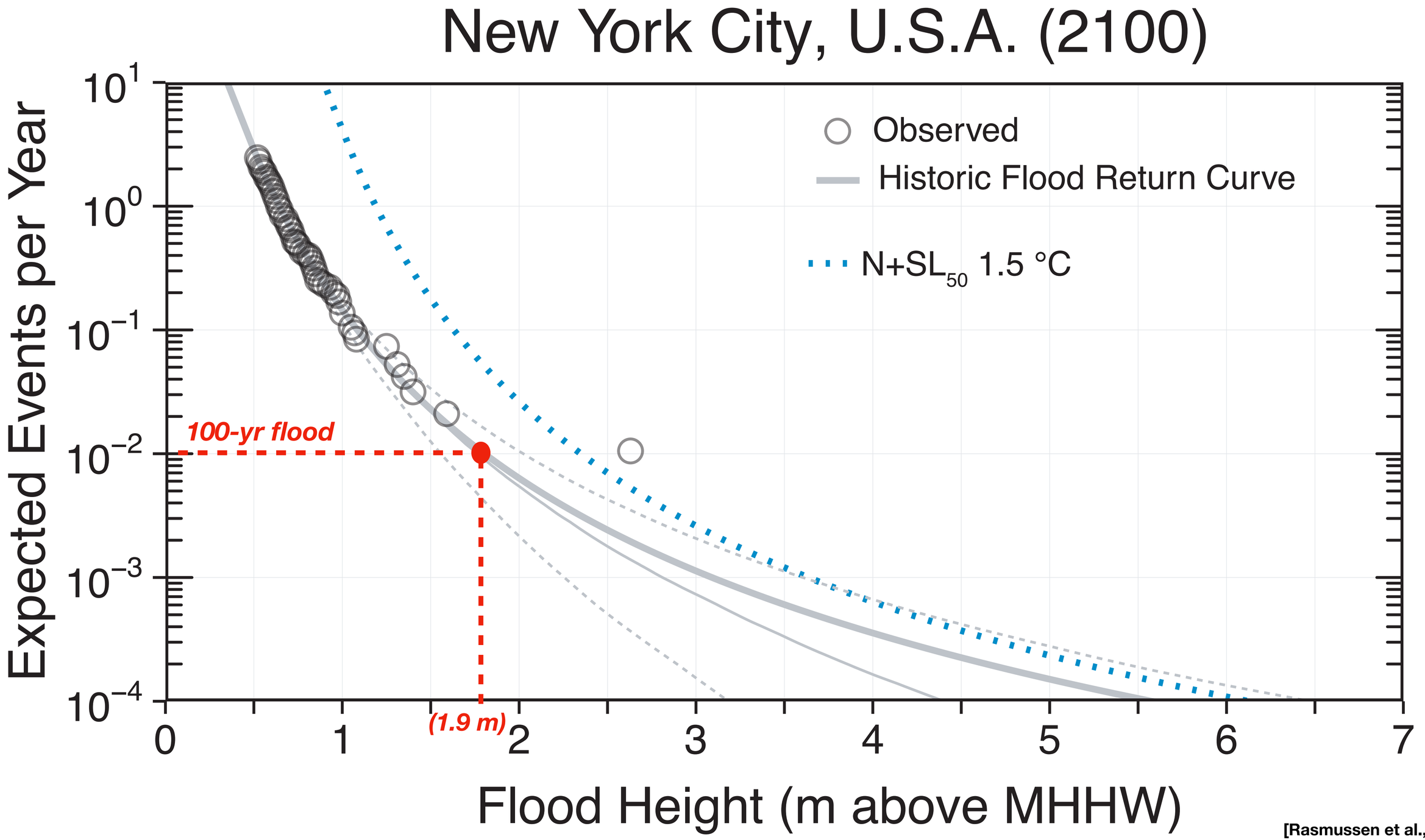

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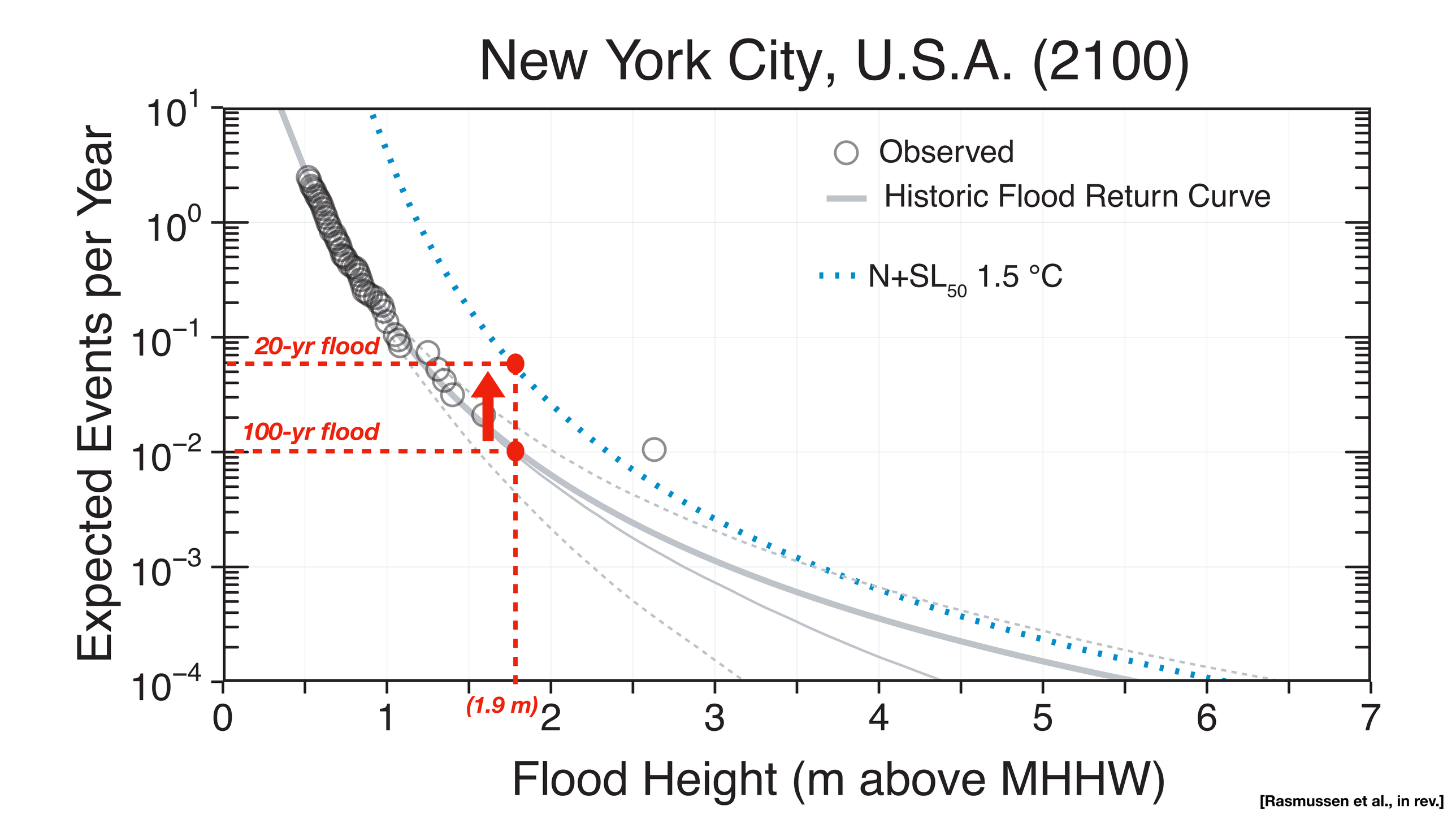
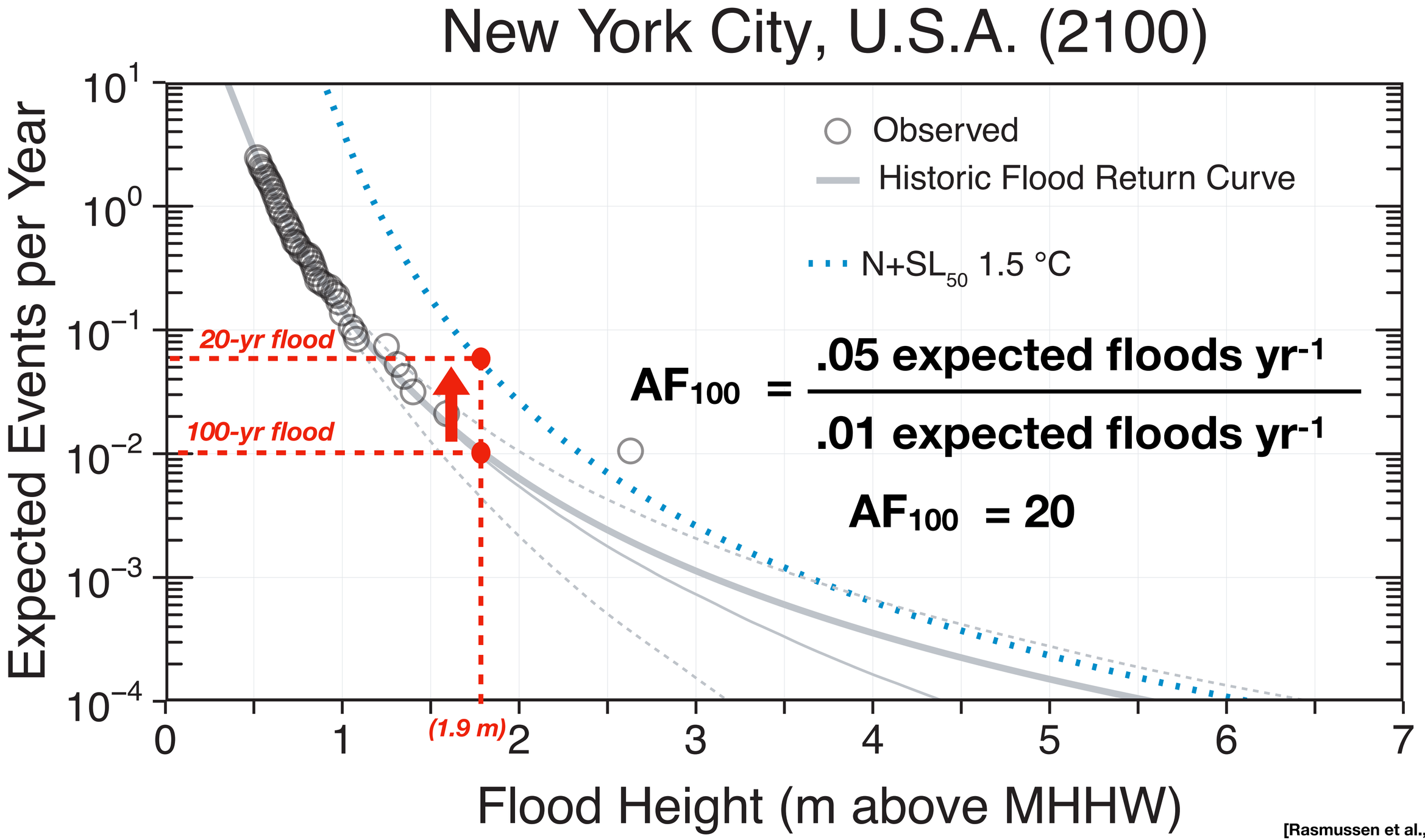

New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Observed
Historic Flood Return Curve
N+SL$_{50}$ 1.5 °C
20-yr flood
100-yr flood
(1.9 m)
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
[Rasmussen et al., in rev.]

Flood Frequency Amplification Factors (AF)

[i.e., Buchanan et al., 2017]

$$AF = \frac{\textbf{Future}\ \text{Annual Expected Number of Floods}}{\textbf{Current}\ \text{Annual Expected Number of Floods}}$$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10^{0}
10^{-1}
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2
3
4
5
6
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL$_{50}$ 1.5 °C
20-yr flood
100-yr flood
(1.9 m)
$AF_{100} = \frac{\text{.05 expected floods yr}^{-1}}{\text{.01 expected floods yr}^{-1}}$
$AF_{100} = 20$
[Rasmussen et al., in rev.]

Where are greatest benefits from 1.5 °C vs. 2.0 °C? (2100)

$$\text{AF ratio} = \frac{AF_{\text{100-yr, 2.0 °C}}}{AF_{\text{100-yr, 1.5 °C}}}$$

Larger AF ratios imply greater benefits from 1.5 °C over 2.0 °C

Where are greatest benefits from 1.5 °C vs. 2.0 °C? (2100)

Local flood benefits from 1.5 °C over 2.0 °C target (100-yr flood)

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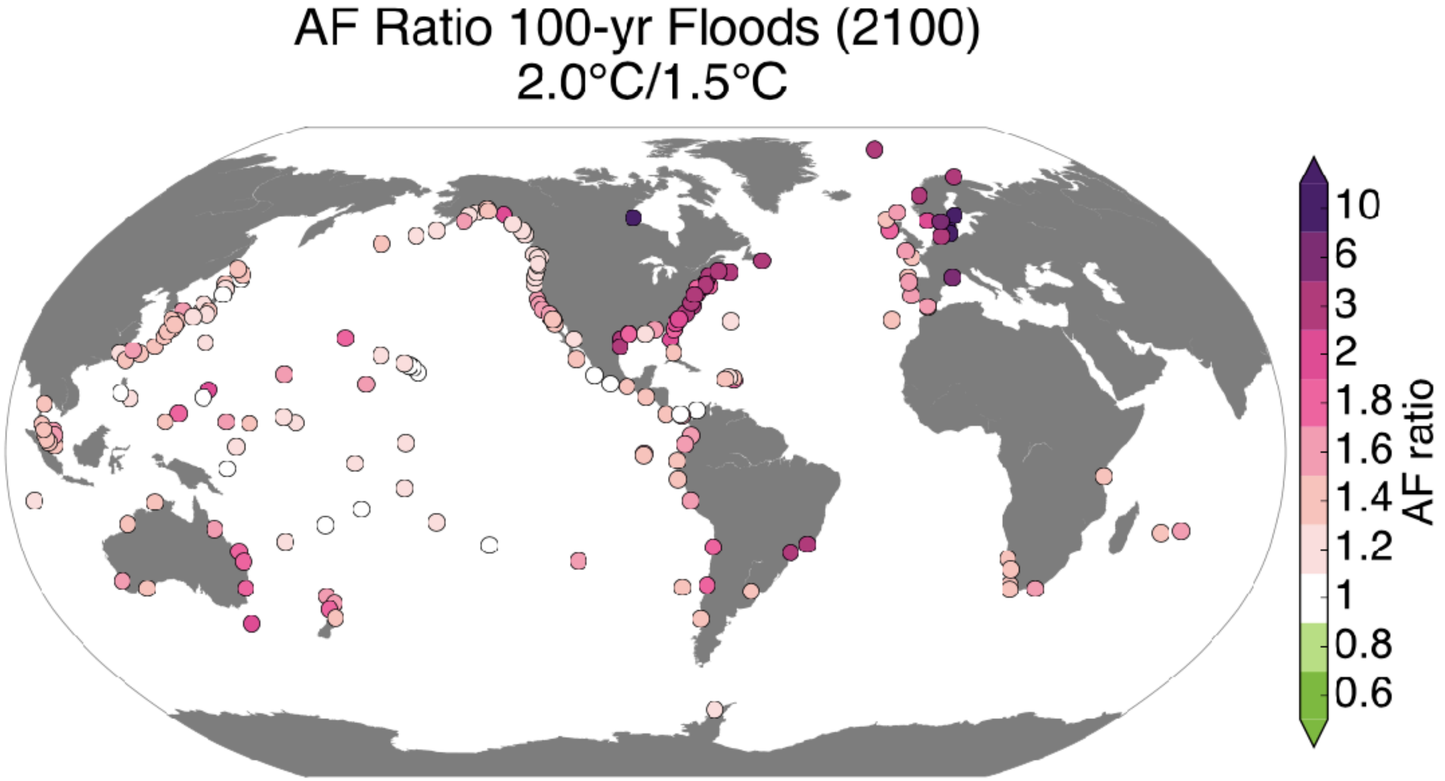

$$\text{AF ratio} = \frac{AF_{100\text{-yr, }\mathbf{2.0\ °C}}}{AF_{100\text{-yr, }\mathbf{1.5\ °C}}}$$

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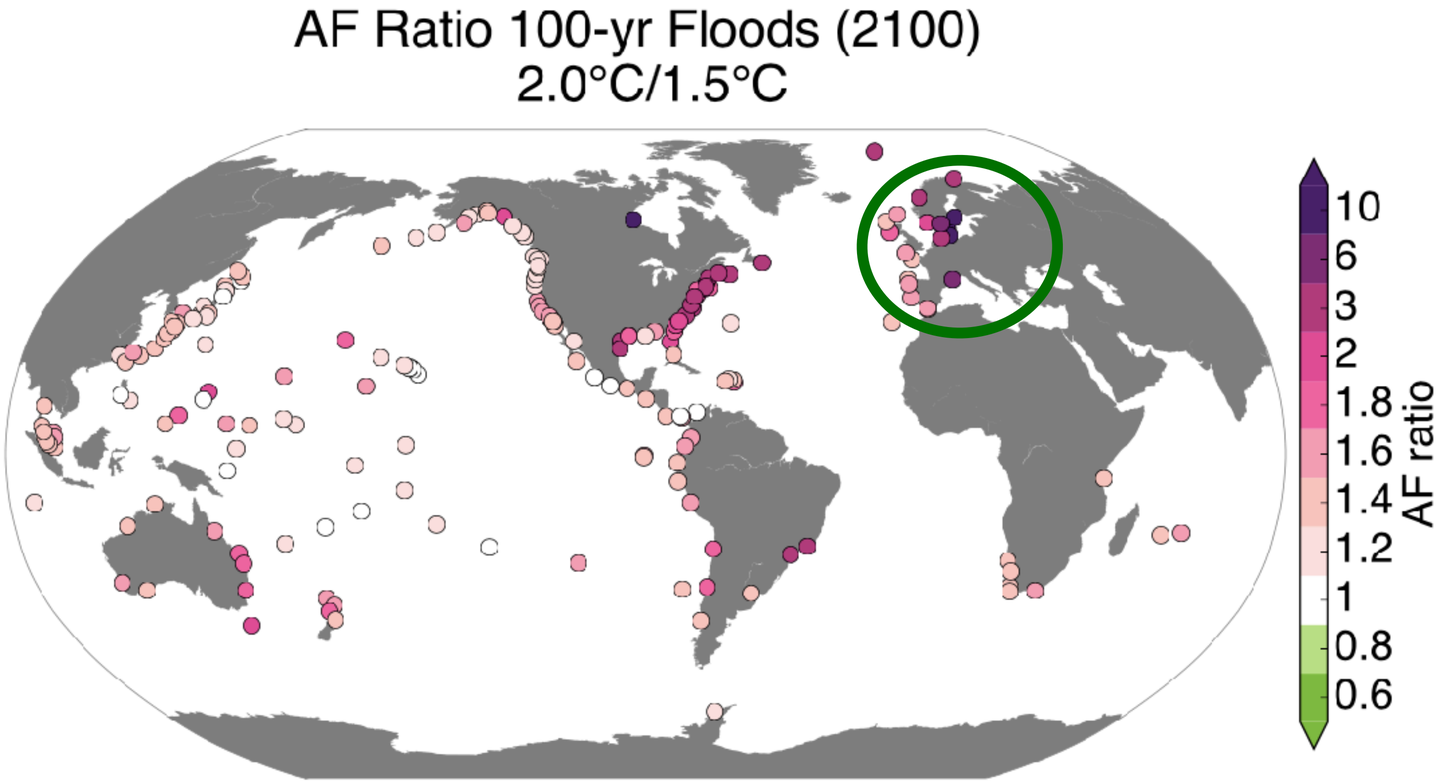

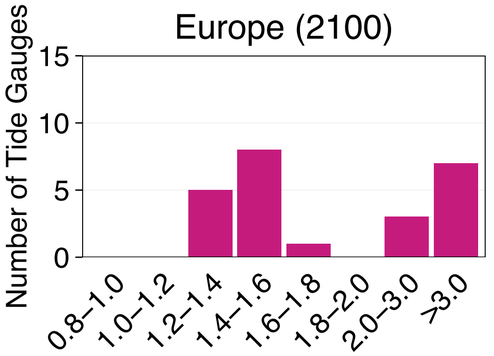

Increase in the number of 100-yr floods is reduced by roughly half for Eastern U.S. and Europe.

[Rasmussen et al., in rev.]

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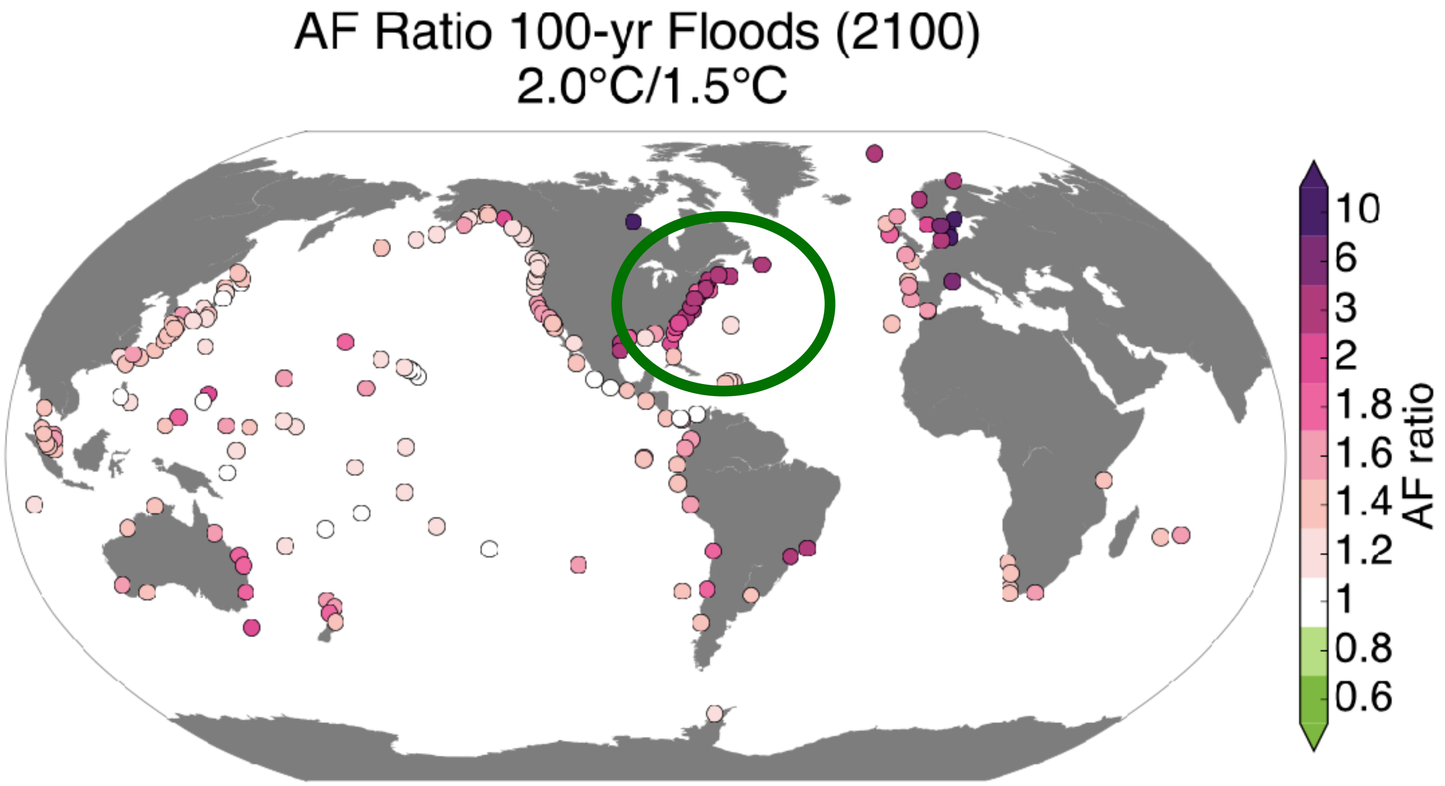

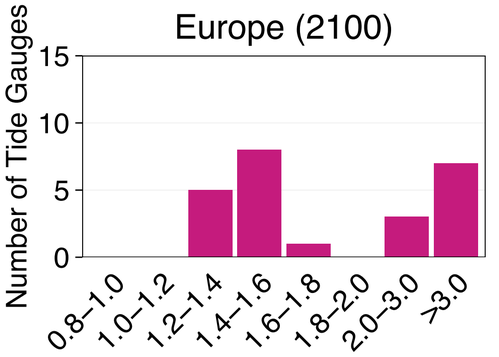

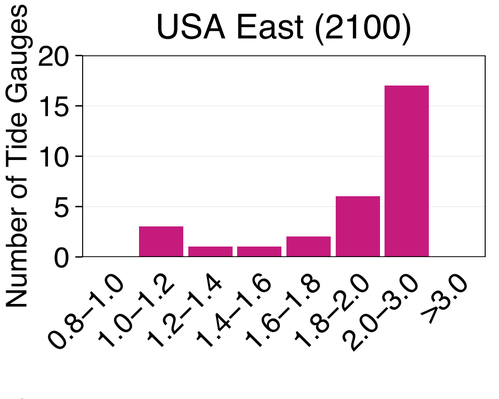

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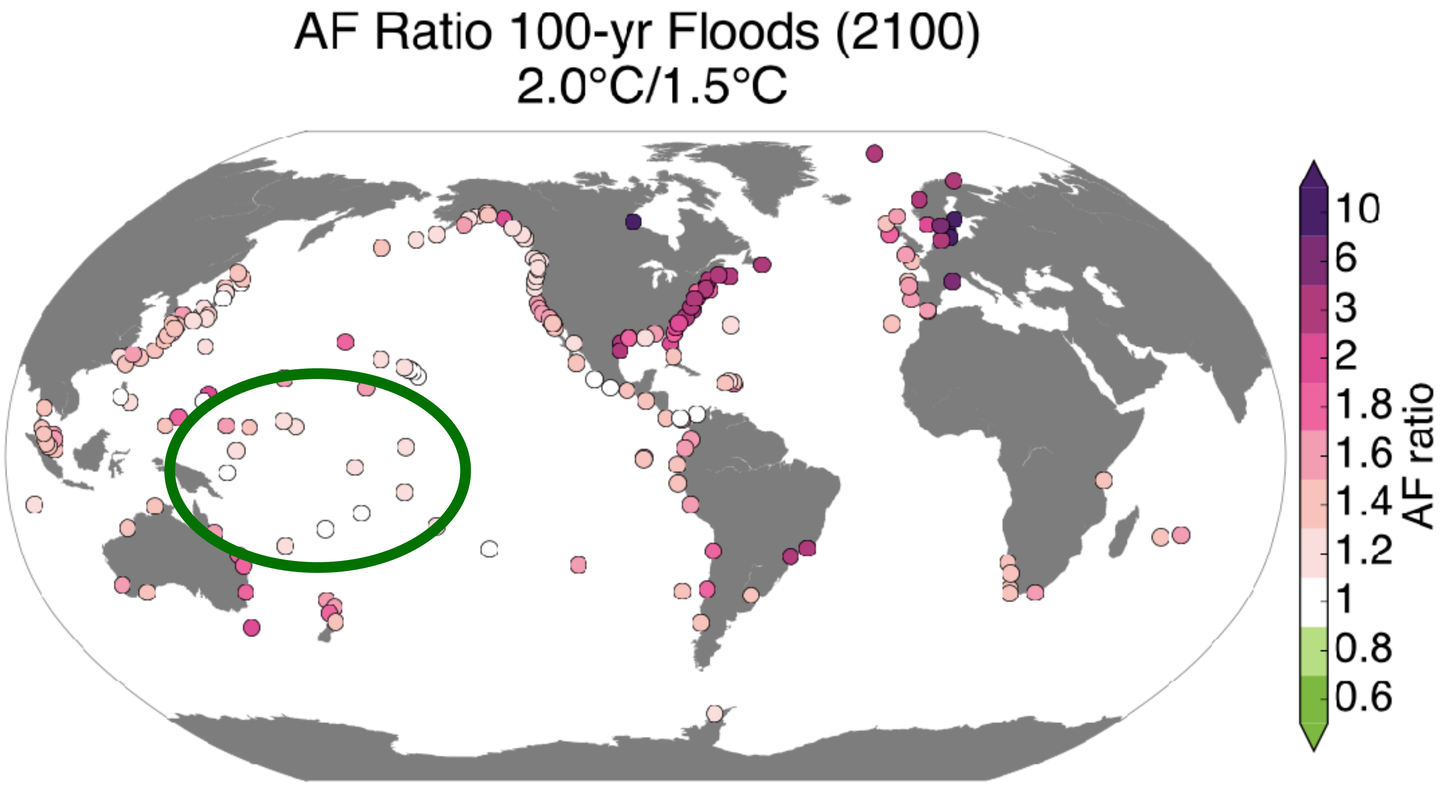

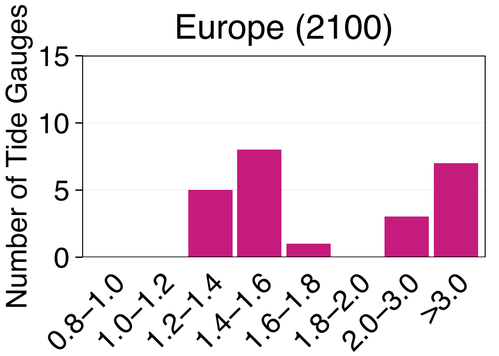

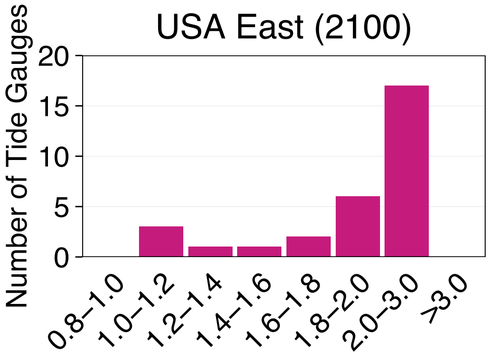

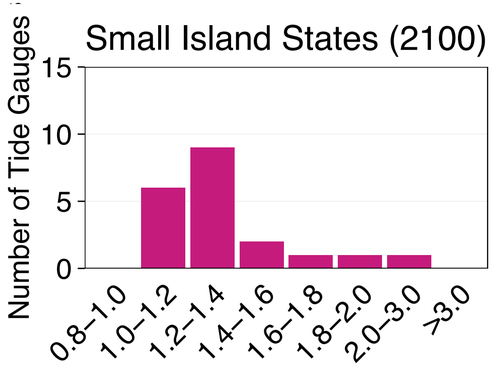

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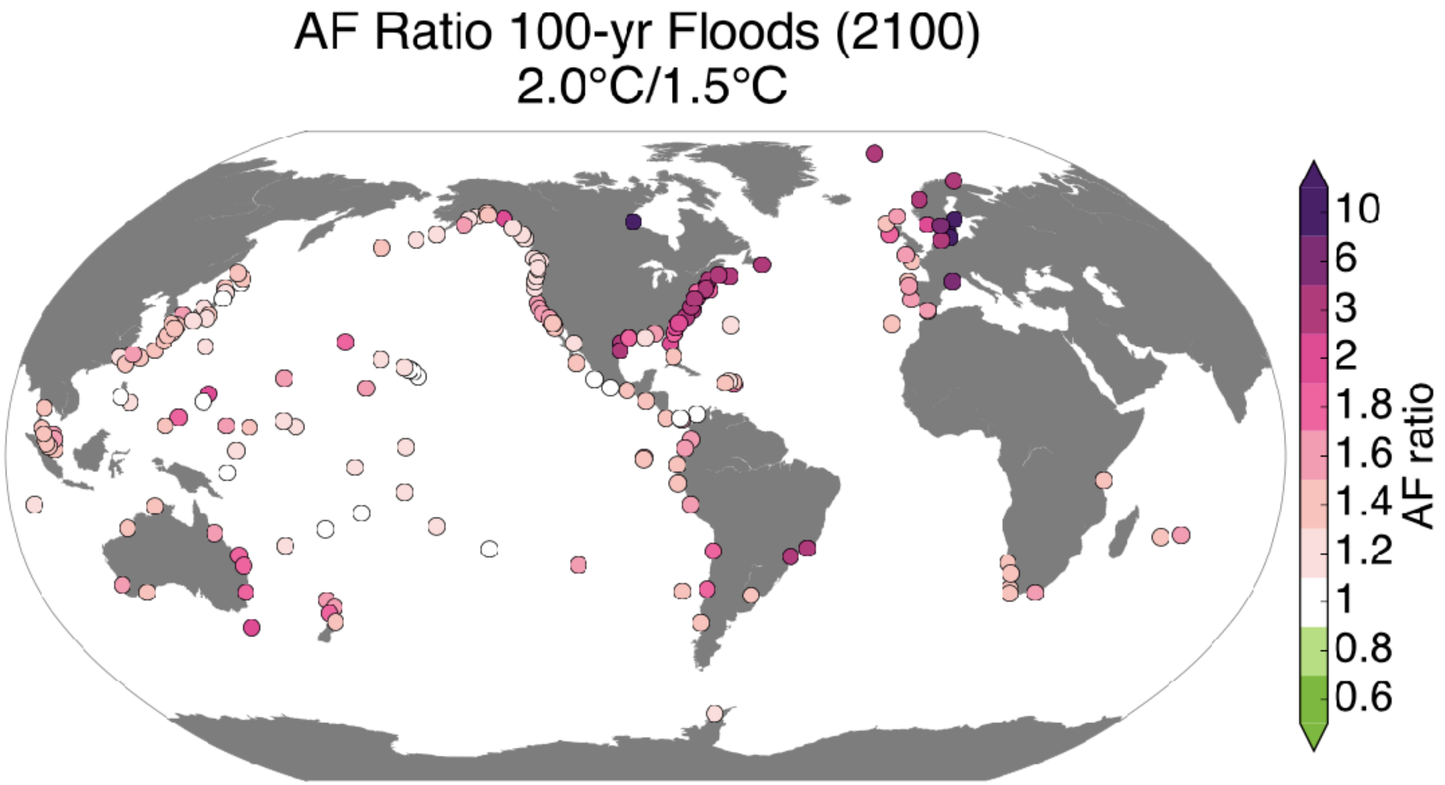
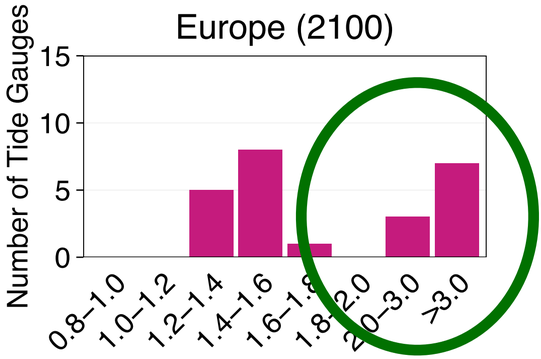
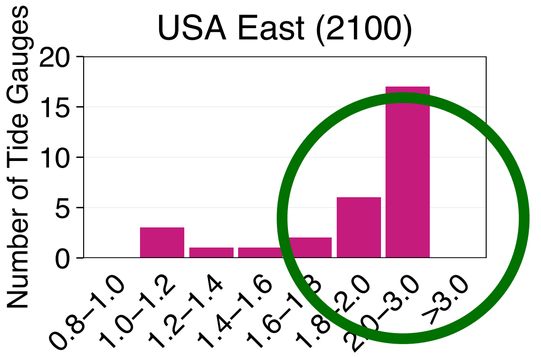
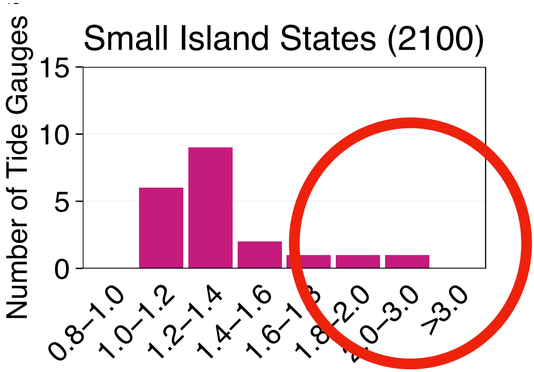


More tide gauges with larger benefits





less benefit



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Post-Quiz

The Paris Agreement will stabilize coastal flood frequency in the 21st century. (T/F)

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False. GSL will continue to rise…

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Assuming 1.5 °C stabilization, what fraction of the world's current population is living in areas that will be permanently submerged by 2150?

a) 10% b) 5% c) 1% d) < 0.5%

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~60-70 million

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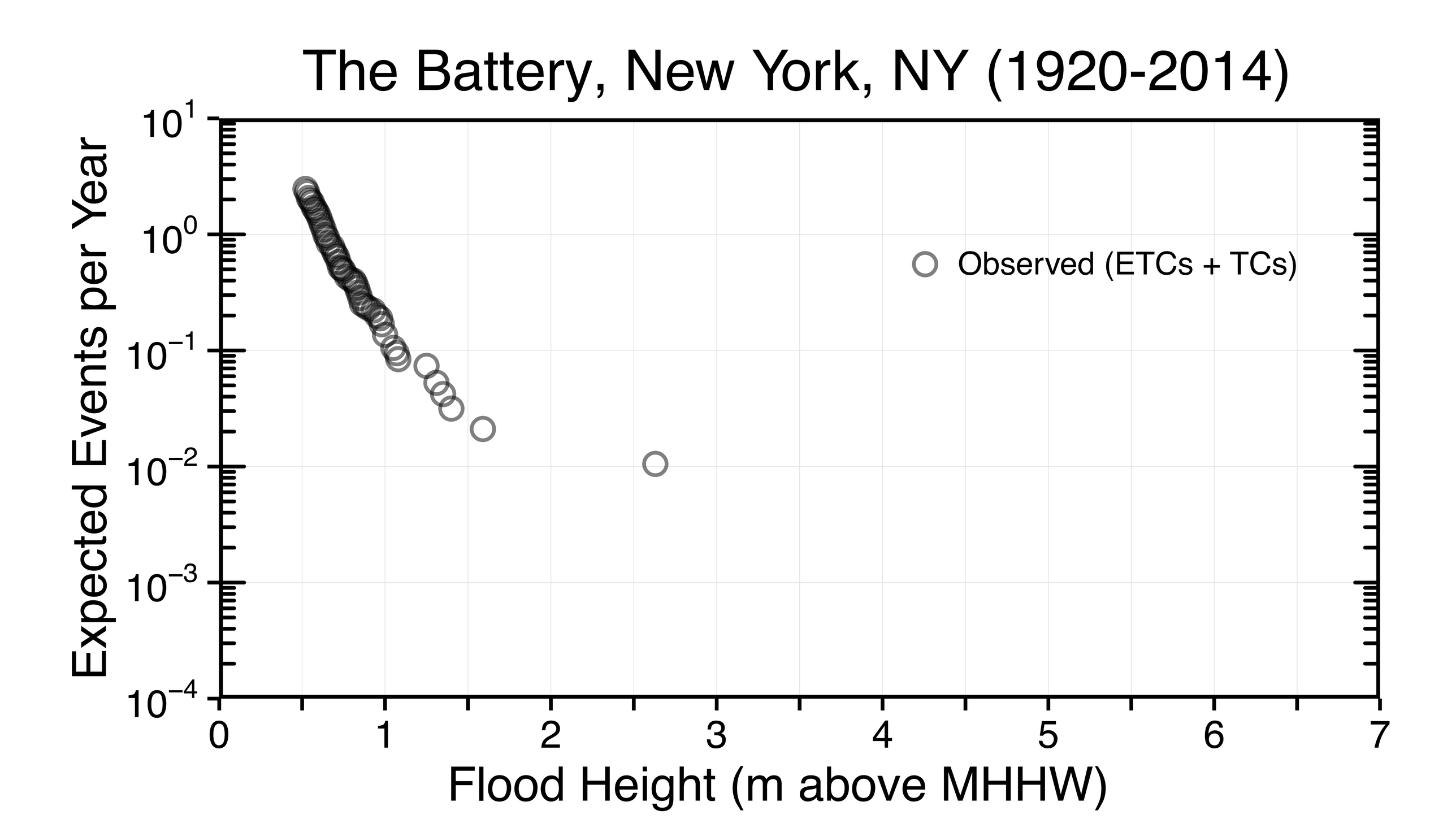
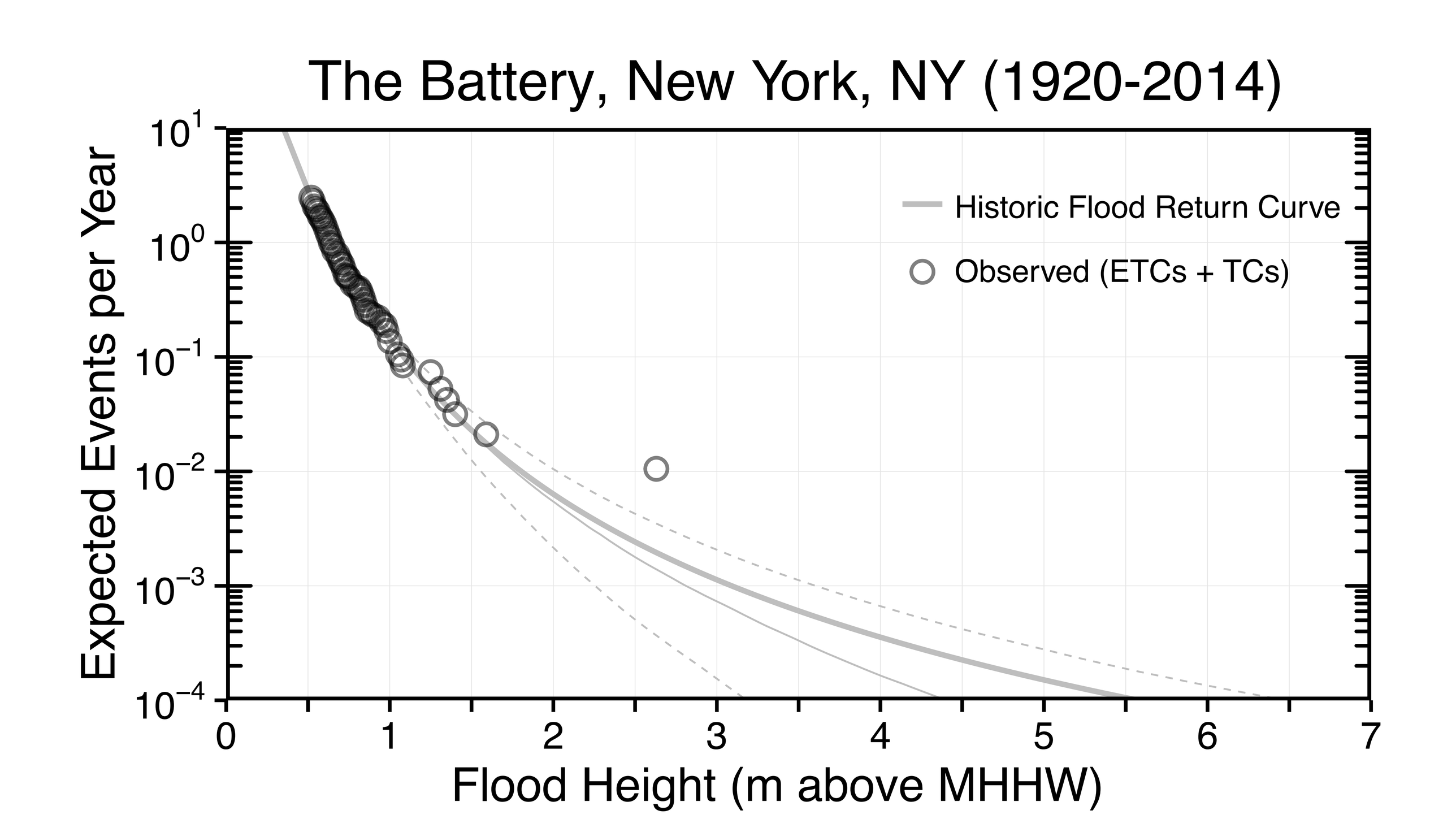
False. U.S.A. and Europe largest projected benefit

Separate extra-tropical cyclones from tropical cyclones…


The Battery, New York, NY (1920-2014)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed (ETCs + TCs)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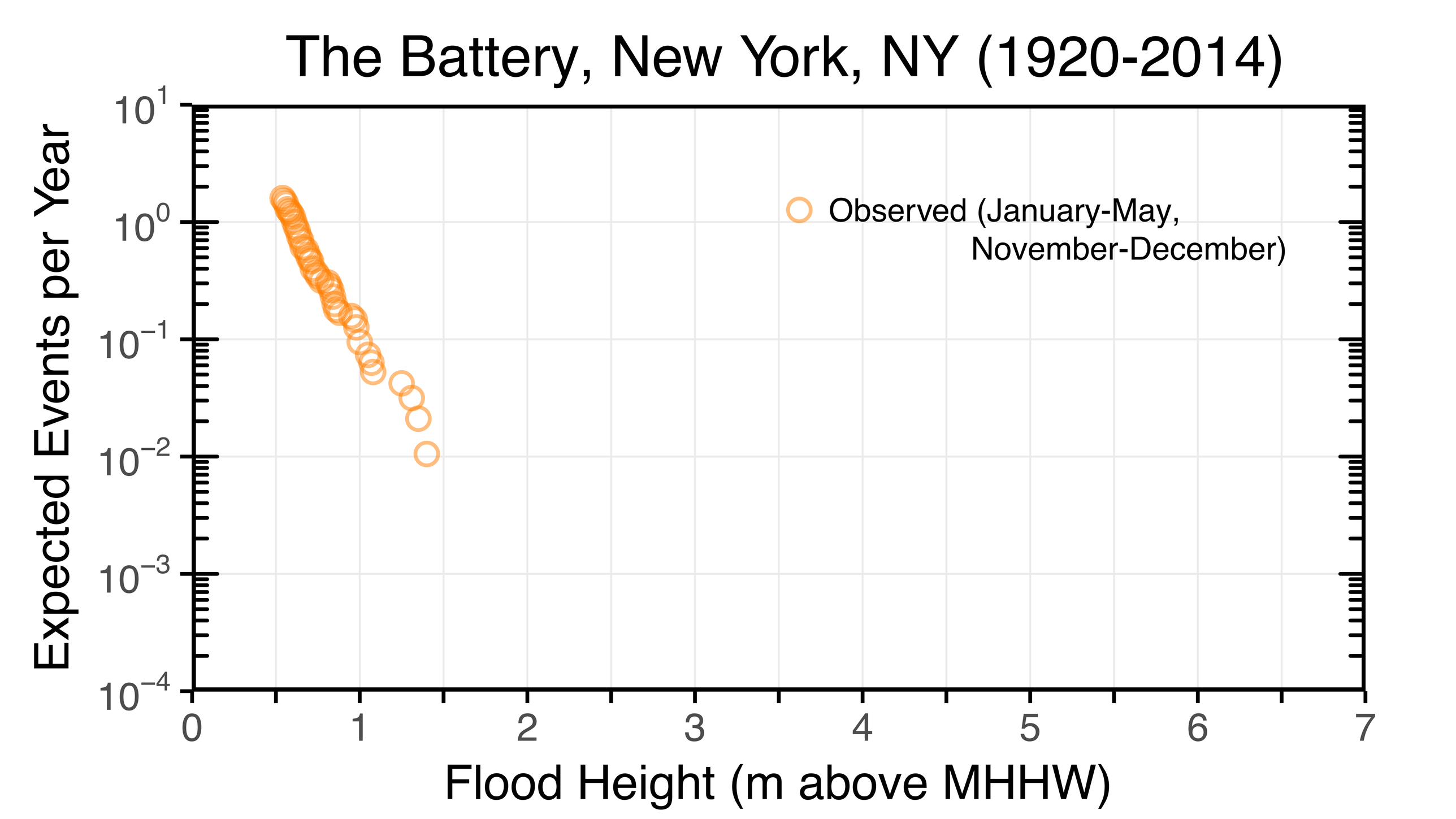
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Historic Flood Return Curve
Observed (ETCs + TCs)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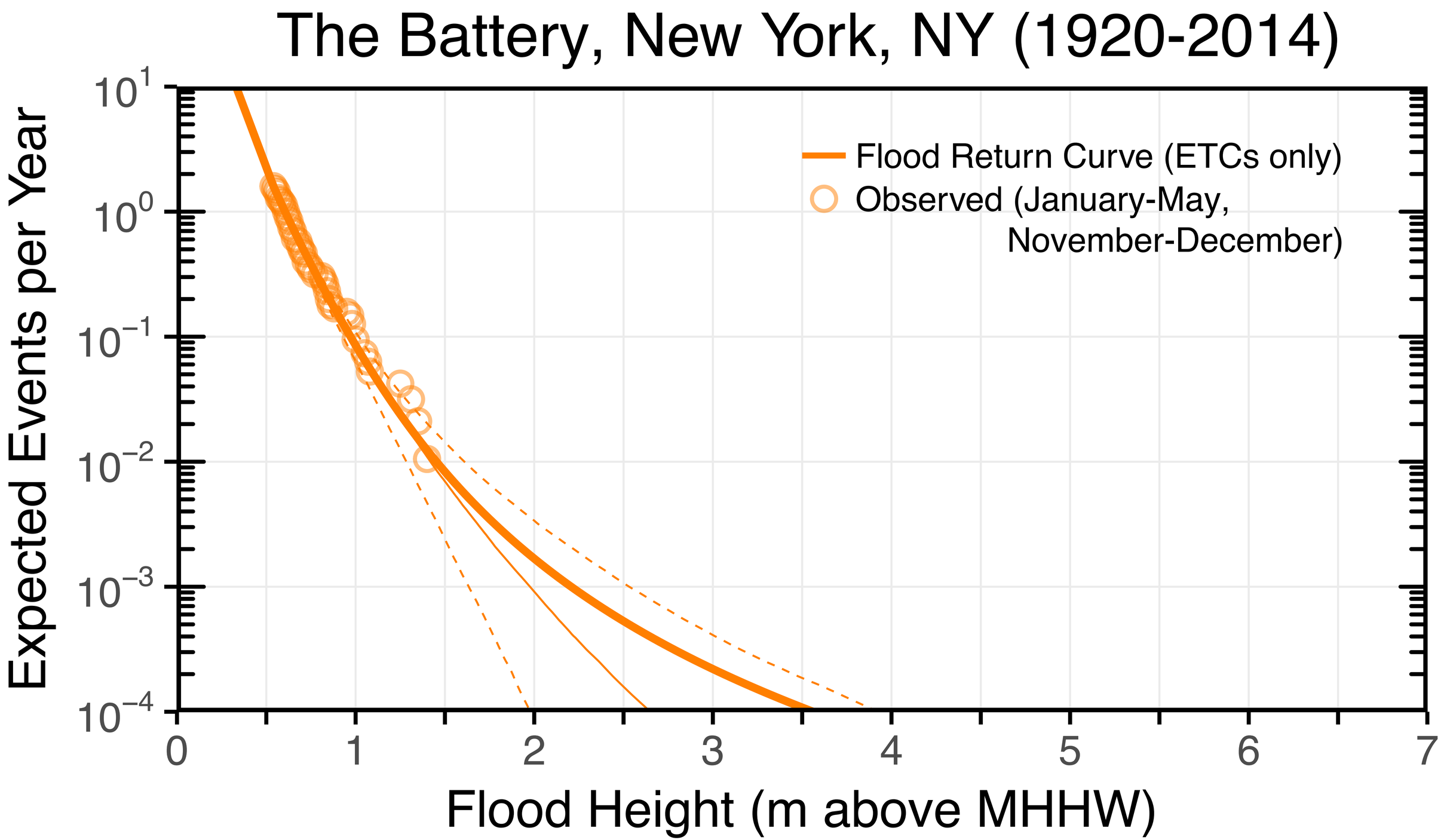
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed (January-May, November-December)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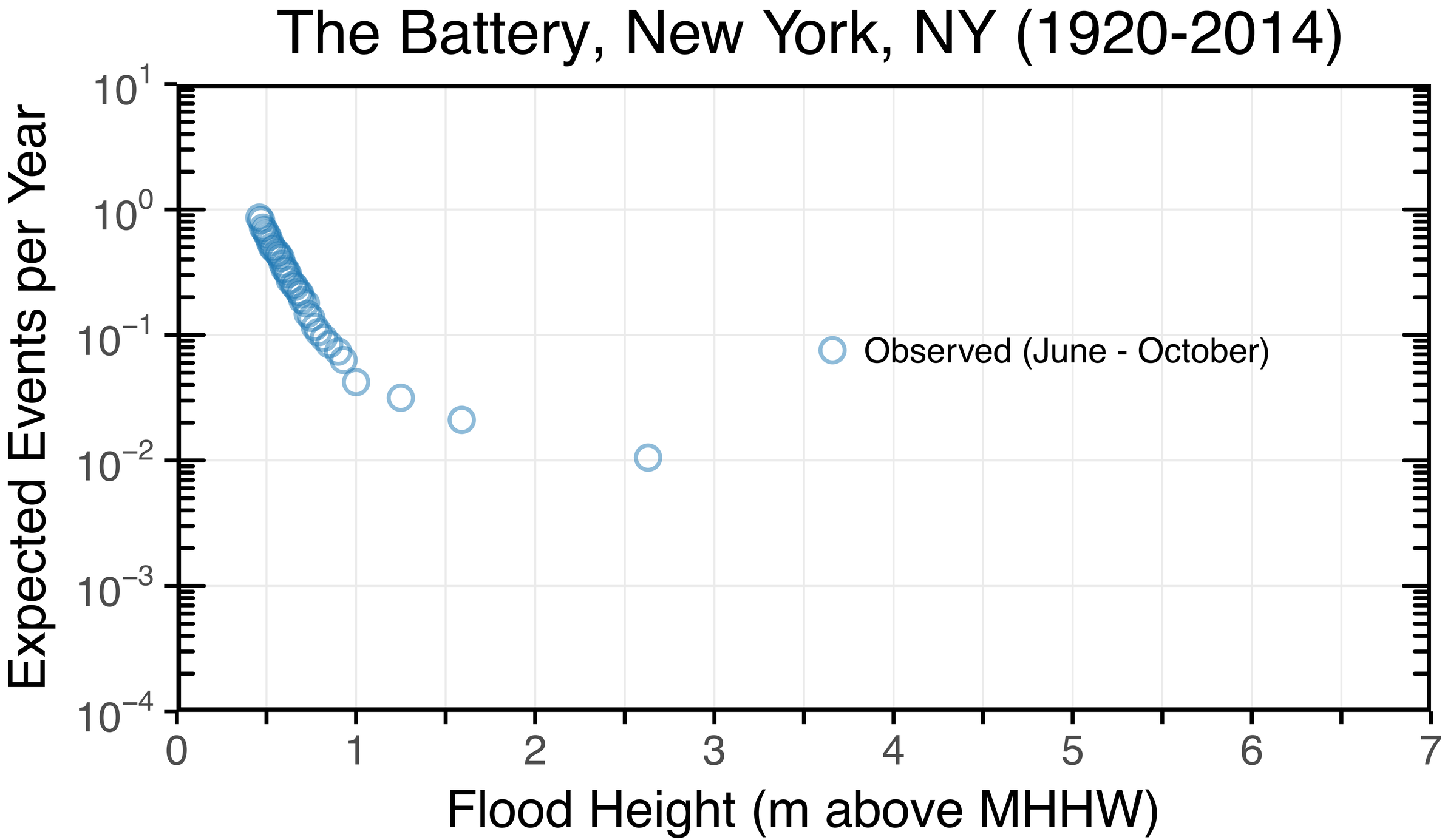
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Flood Return Curve (ETCs only)
Observed (January-May, November-December)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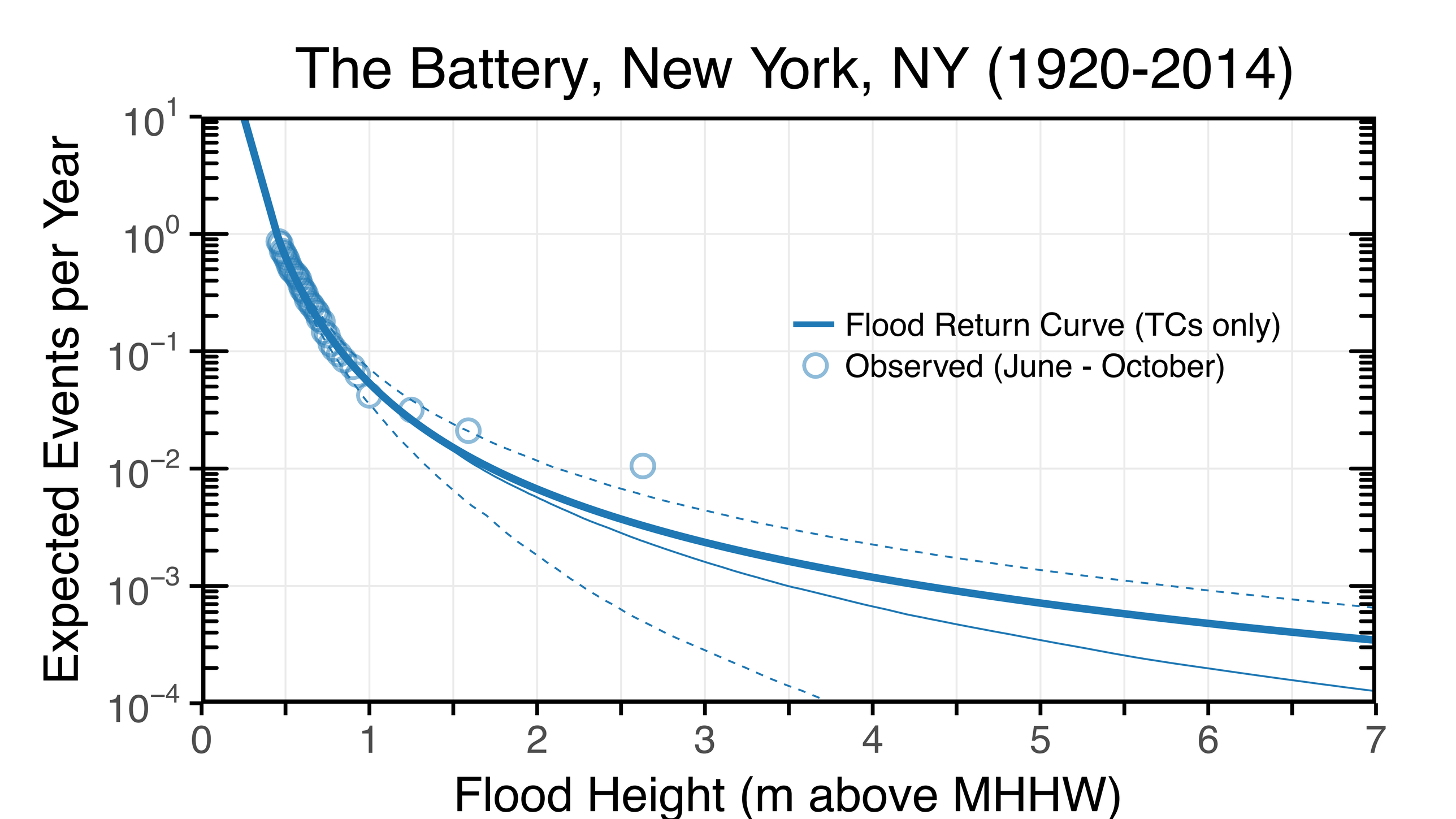
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed (June - October)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10^{1}
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4
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Flood Height (m above MHHW)
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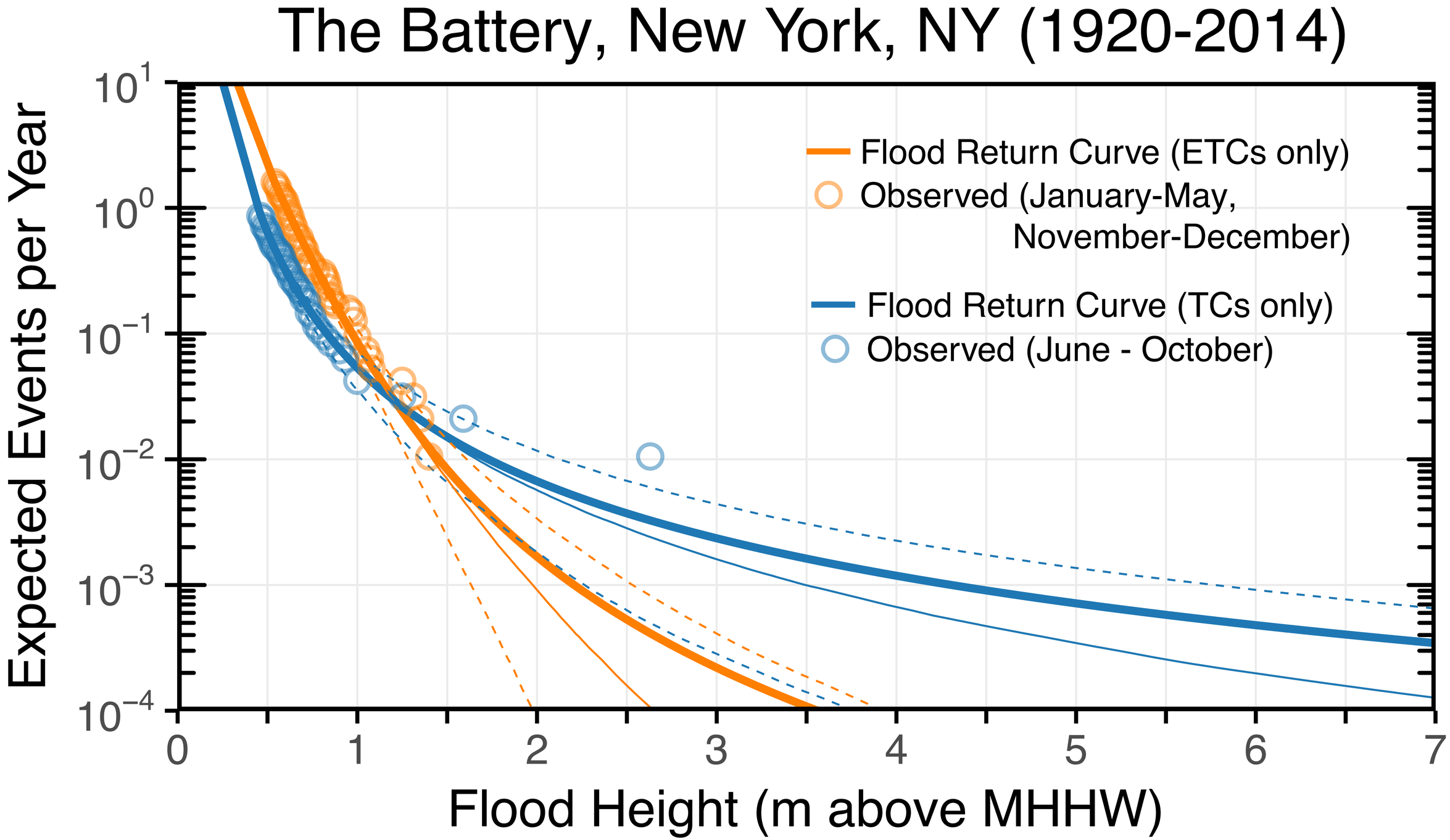
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10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
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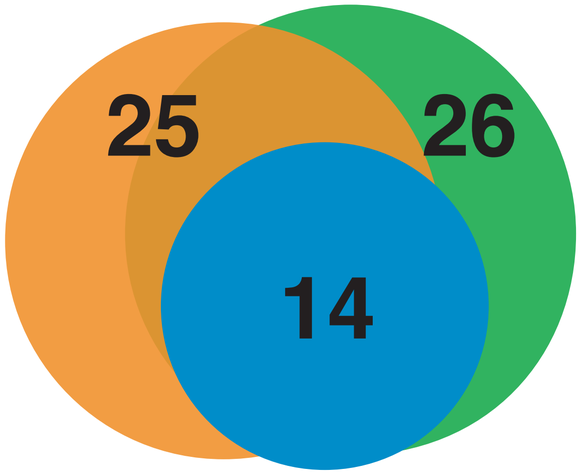
3
4
5
6
7
Flood Height (m above MHHW)
Flood Return Curve (ETCs only)
Observed (January-May, November-December)
Flood Return Curve (TCs only)
Observed (June - October)

Number of annual expected floods (NYC; 2100)

10-yr floods per year

(1.09 m above MHHW)



Current: 0.1
events per year

2.5 °C

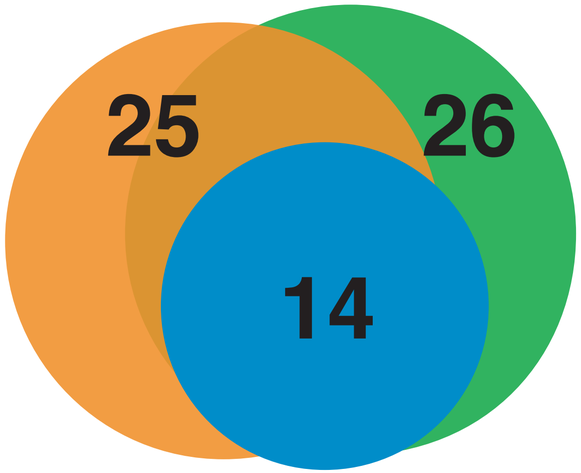
2.0 °C

1.5 °C

Number of annual expected floods (NYC; 2100)

10-yr floods per year

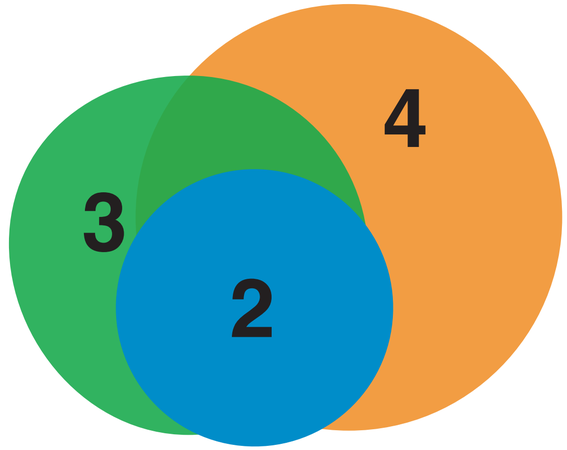
(1.09 m above MHHW)



Current: 0.1
events per year

100-yr floods per year

(1.86 m above MHHW)



Current: 0.01 events per year

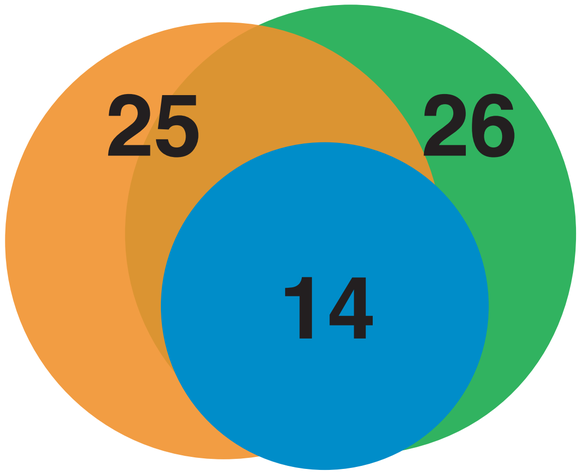
2.5 °C

2.0 °C

1.5 °C

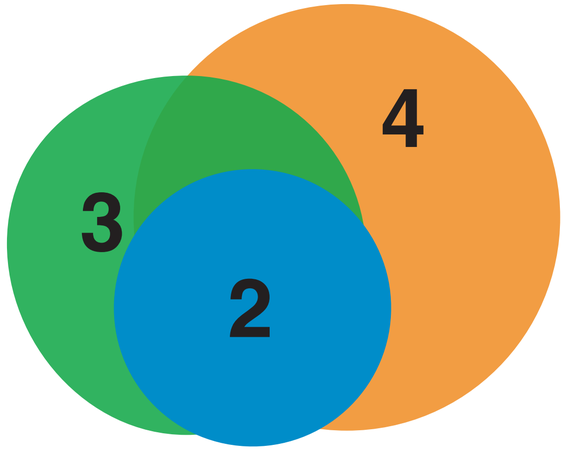
Number of annual expected floods (NYC; 2100)

10-yr floods per year
(1.09 m above MHHW)



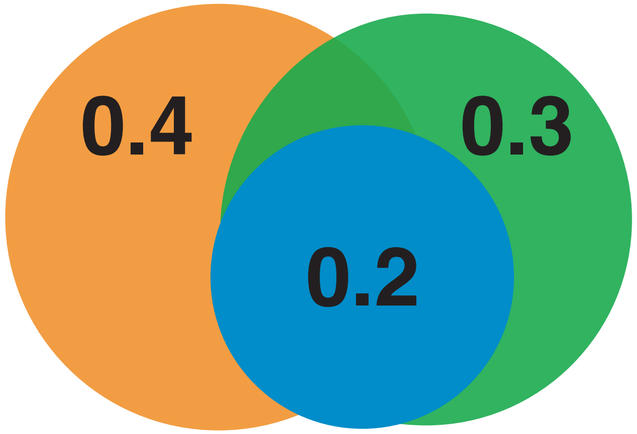
Current: 0.1
events per year

100-yr floods per year
(1.86 m above MHHW)



Current: 0.01 events per year

500-yr floods per year
(2.61 m above MHHW)



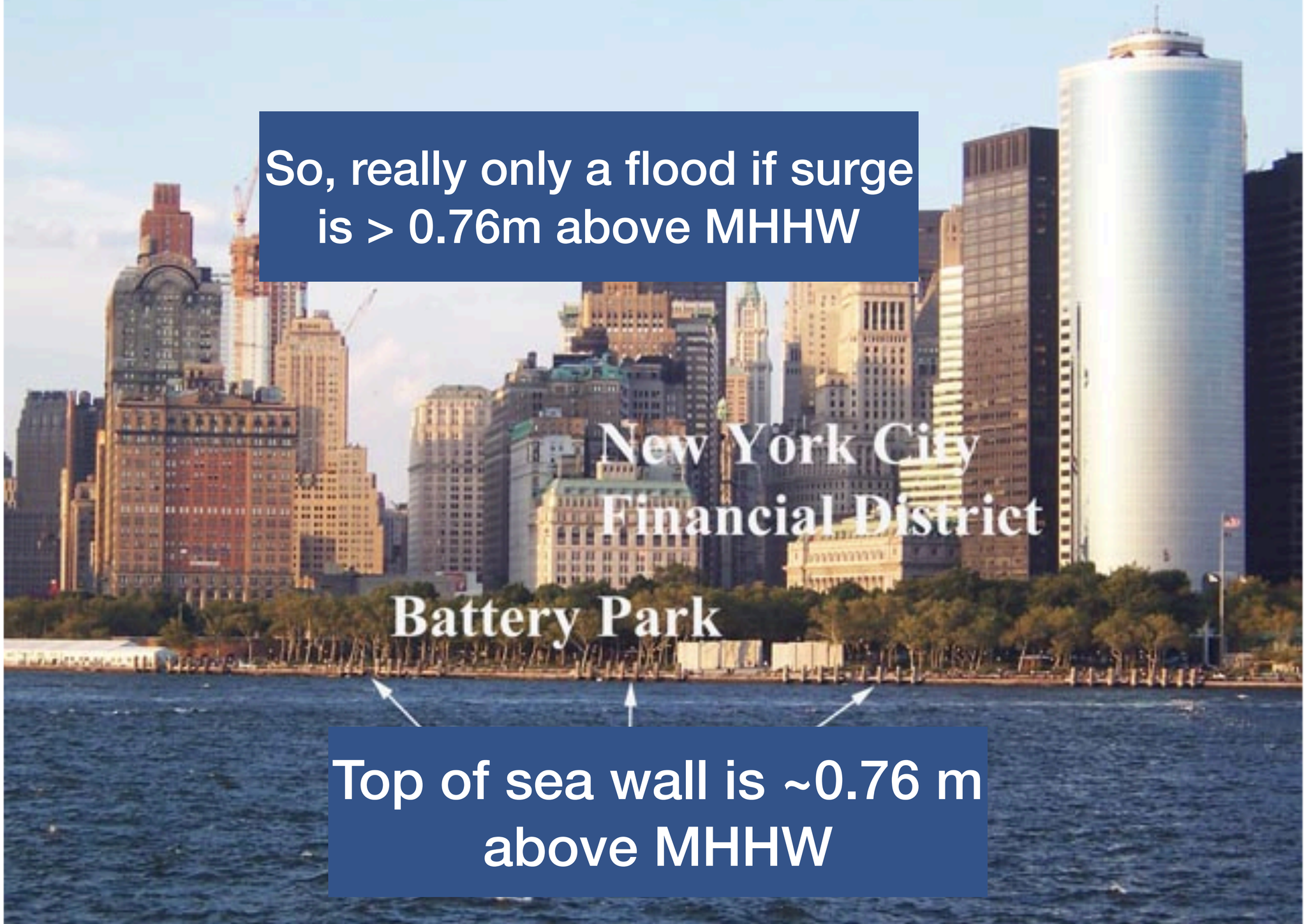
Current: 0.002 events per year

2.5 °C

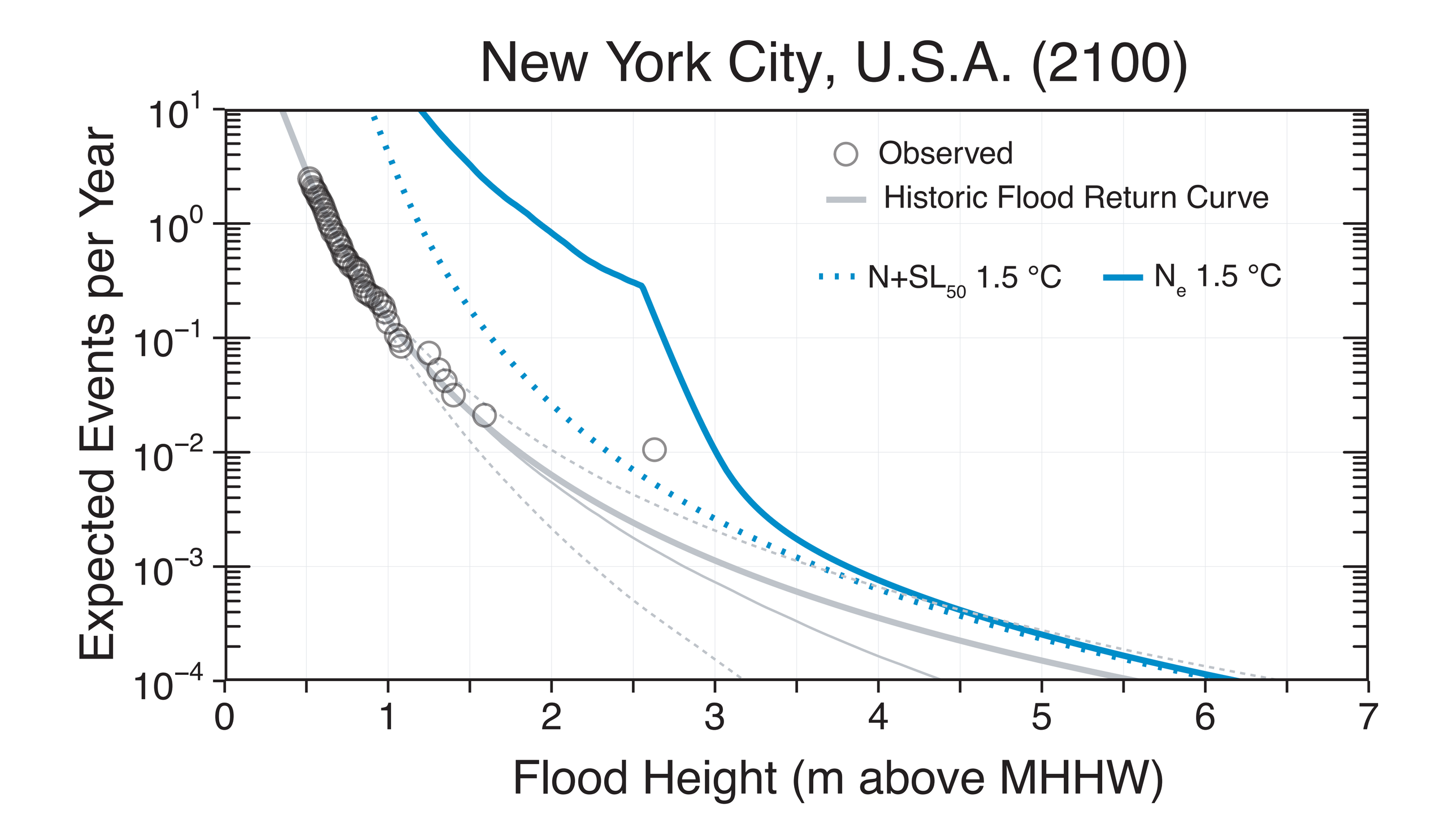
2.0 °C

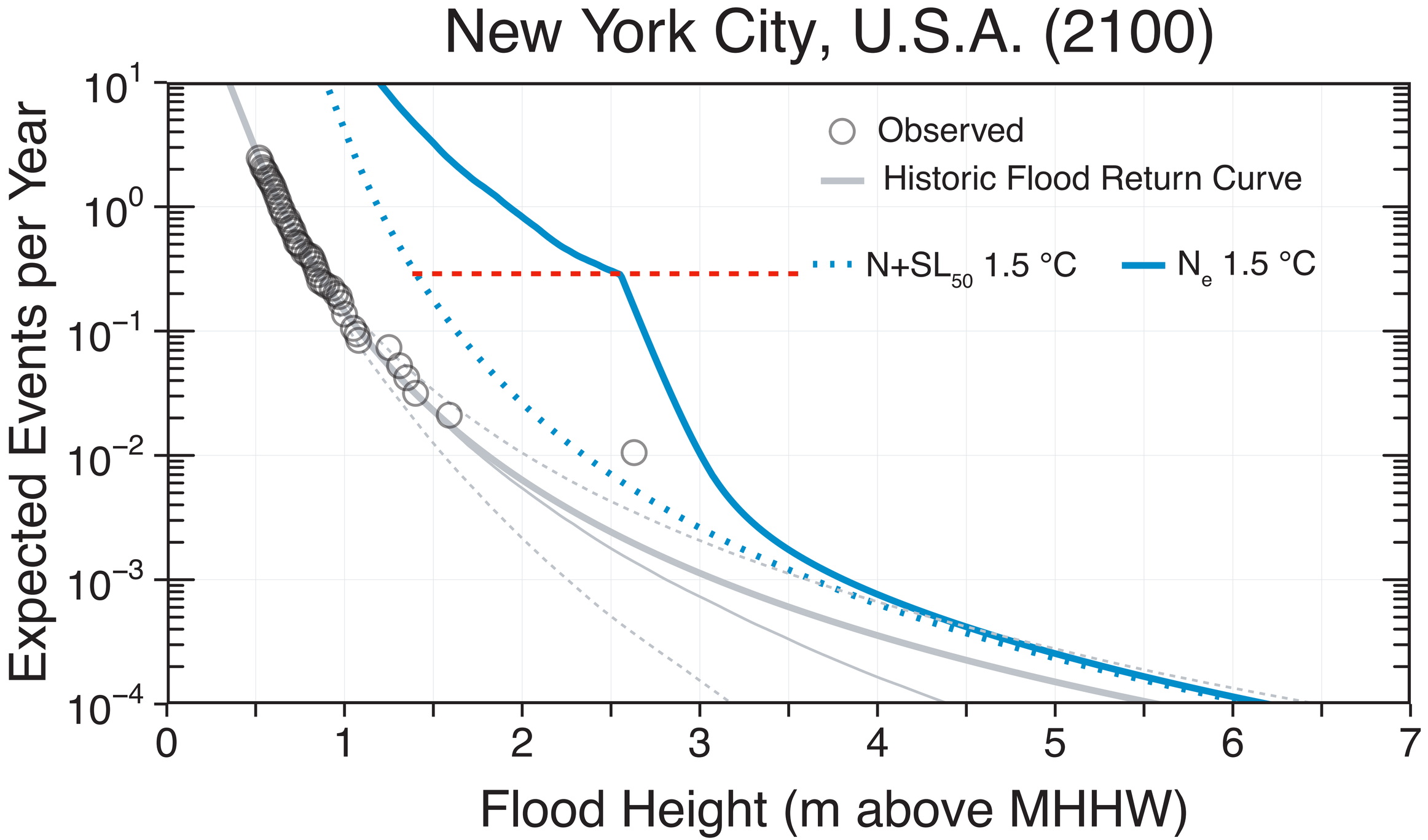
1.5 °C


New York City
Financial District
Battery Park
Top of sea wall is ~0.76 m
above MHHW


So, really only a flood if surge is > 0.76m above MHHW
New York City
Financial District
Battery Park
Top of sea wall is ~0.76 m above MHHW


TWA


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL$_{50}$ 1.5 °C
N$_e$ 1.5 °C


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
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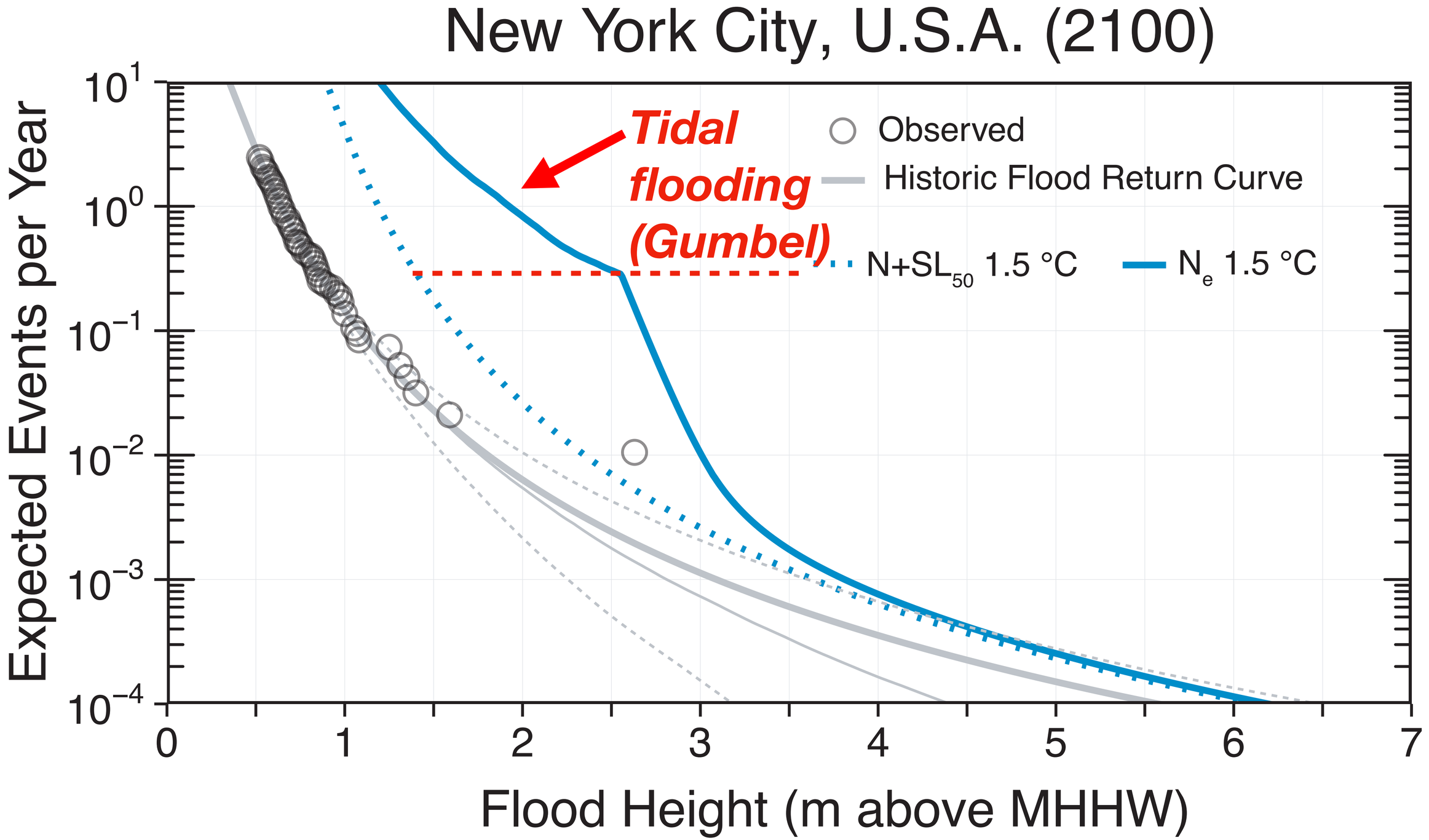
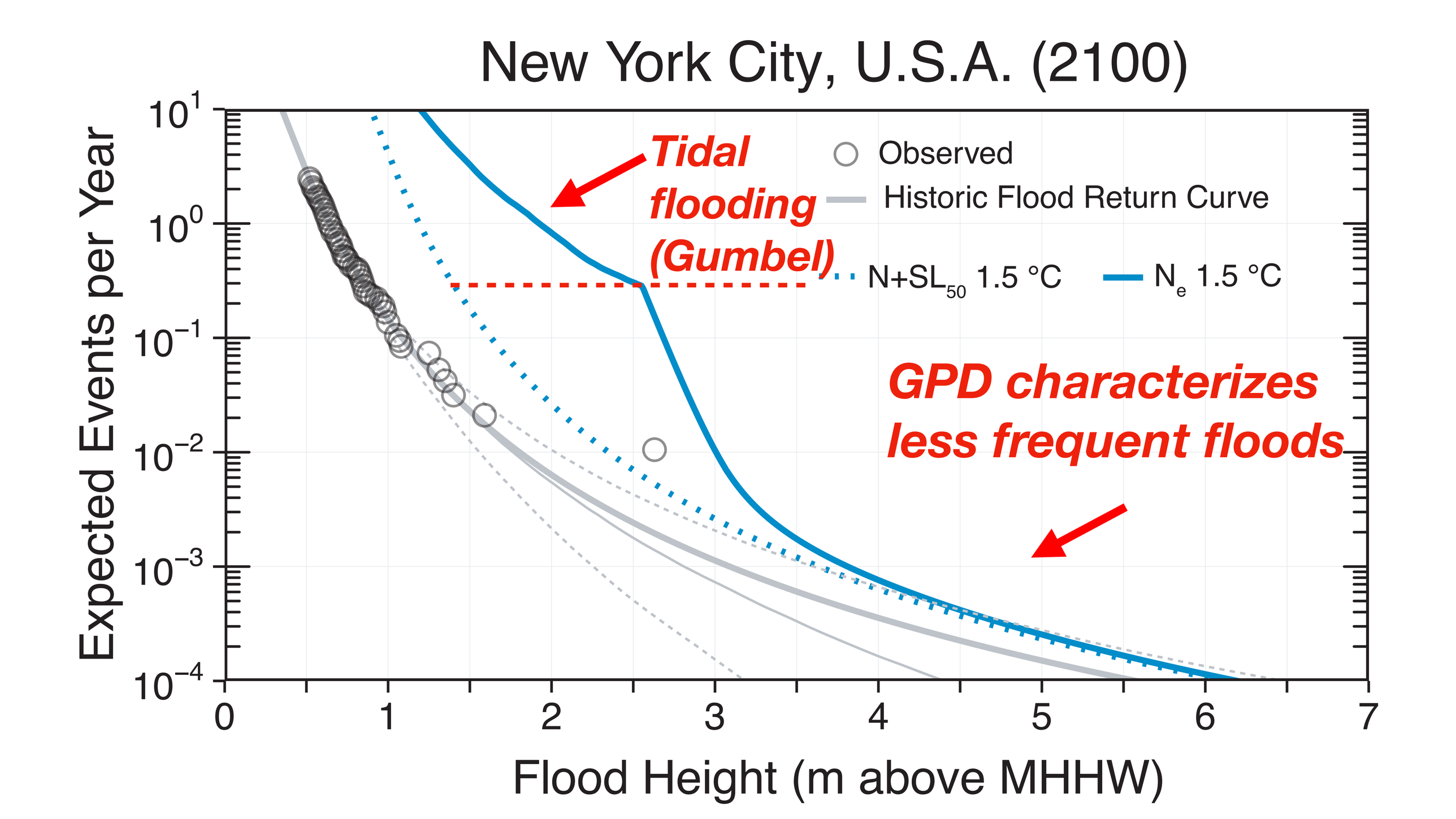
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL$_{50}$ 1.5 °C
N$_e$ 1.5 °C


New York City, U.S.A. (2100)
Tidal flooding (Gumbel)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
Ne 1.5 °C
Expected Events per Year
Flood Height (m above MHHW)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
1
2
3
4
5
6
7


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
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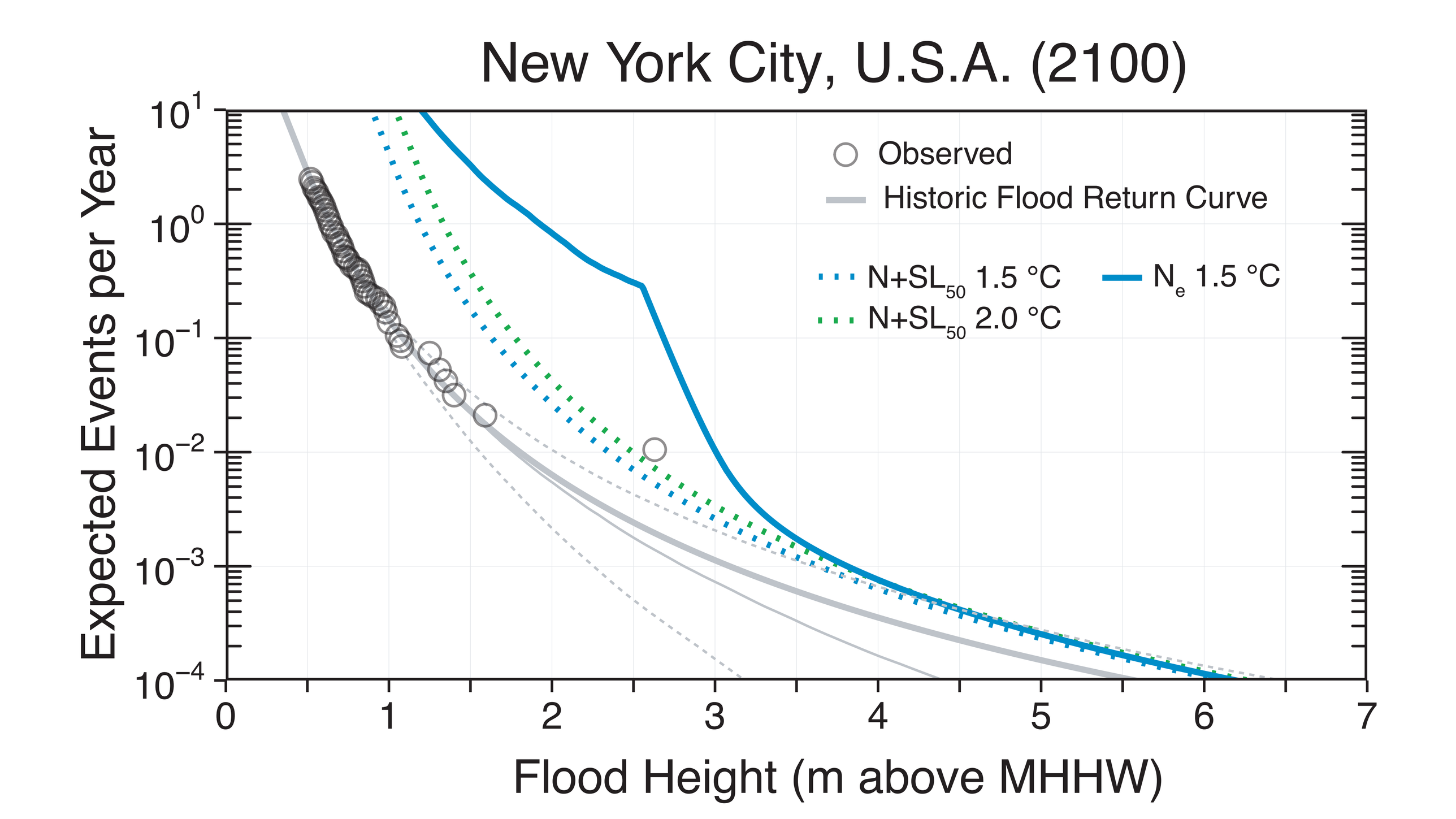
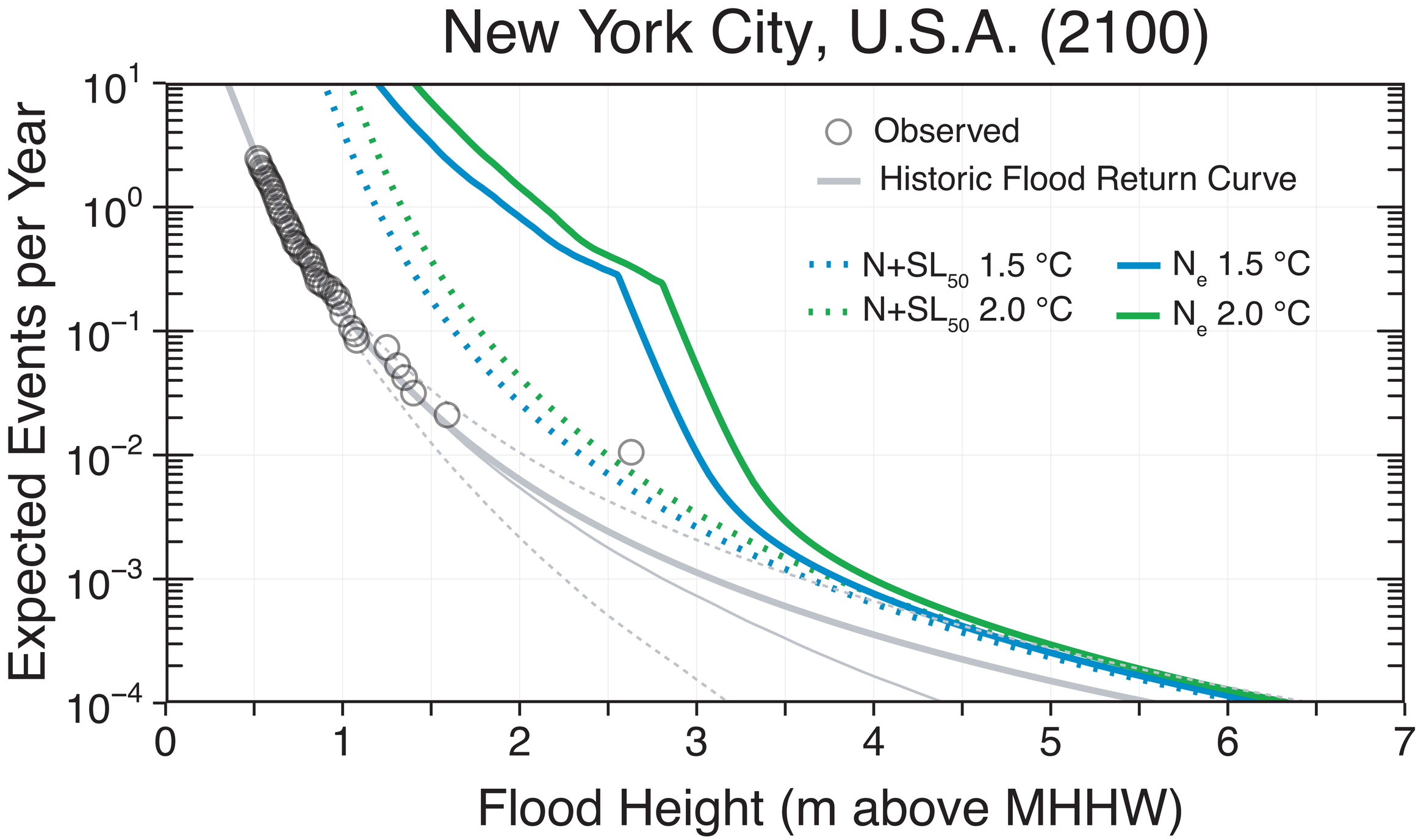
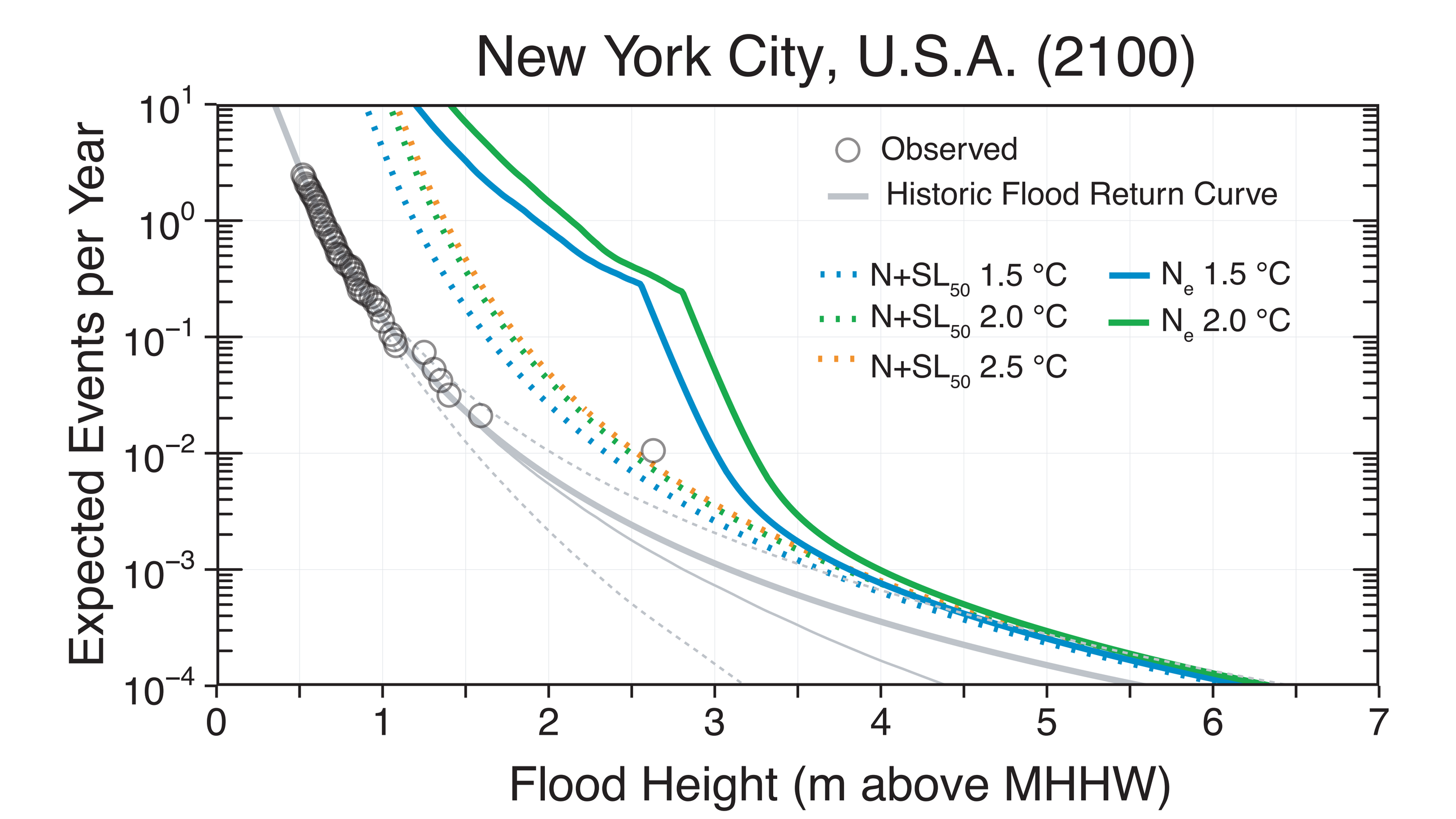
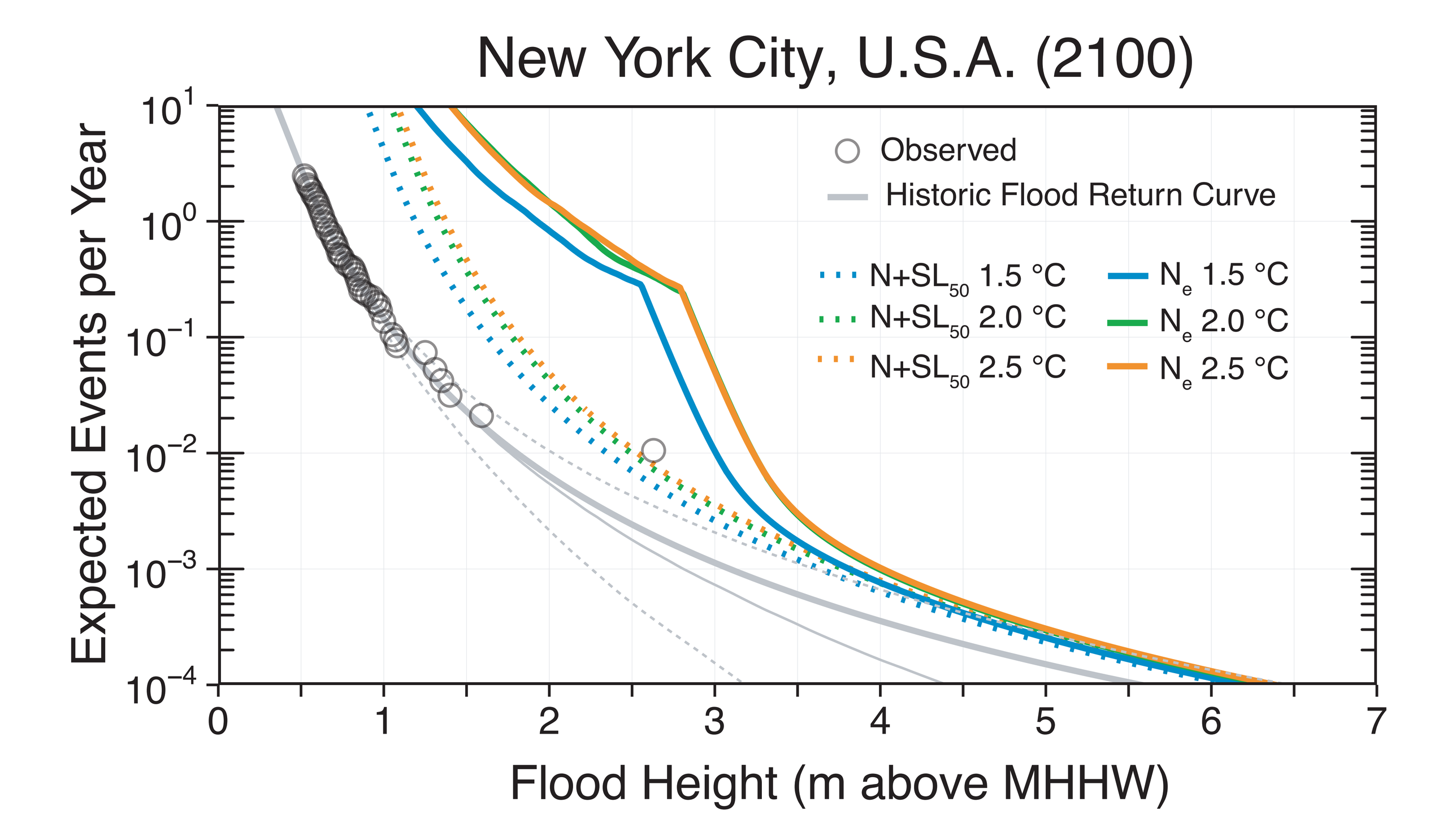
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Tidal flooding (Gumbel)
Observed
Historic Flood Return Curve
N+SL$_{50}$ 1.5 °C
N$_e$ 1.5 °C
GPD characterizes less frequent floods


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
$N+SL_{50}$ 1.5 °C
N_e 1.5 °C
$N+SL_{50}$ 2.0 °C


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
$N+SL_{50}$ 1.5 °C
$N+SL_{50}$ 2.0 °C
N_e 1.5 °C
N_e 2.0 °C


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
$N+SL_{50}$ 1.5 °C
$N+SL_{50}$ 2.0 °C
$N+SL_{50}$ 2.5 °C
N_e 1.5 °C
N_e 2.0 °C


New York City, U.S.A. (2100)
Expected Events per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
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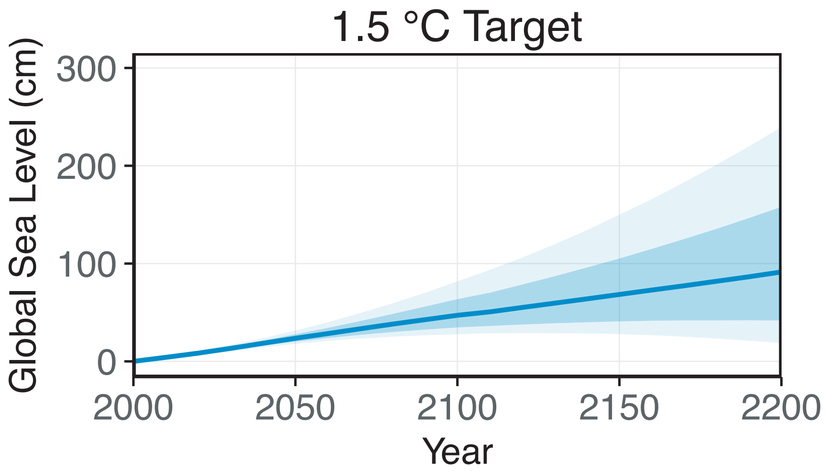
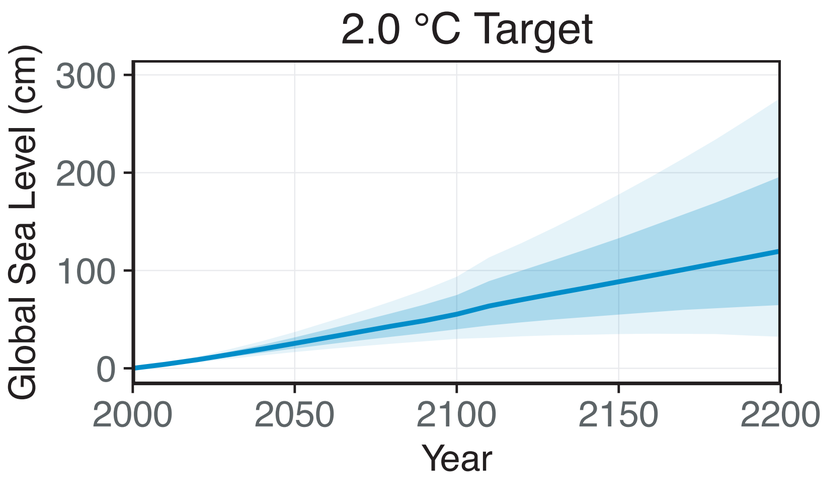
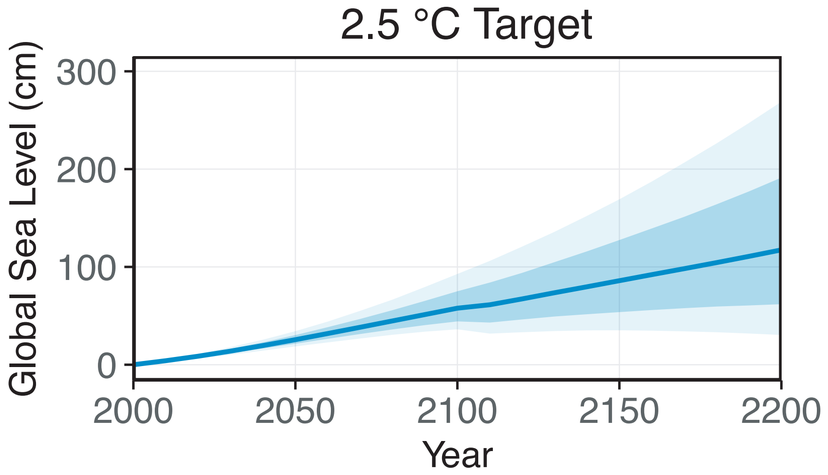
7
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
$N+SL_{50}$ 1.5 °C
$N+SL_{50}$ 2.0 °C
$N+SL_{50}$ 2.5 °C
N_e 1.5 °C
N_e 2.0 °C
N_e 2.5 °C

Global Mean Sea-Level (GSL) Rise Projections







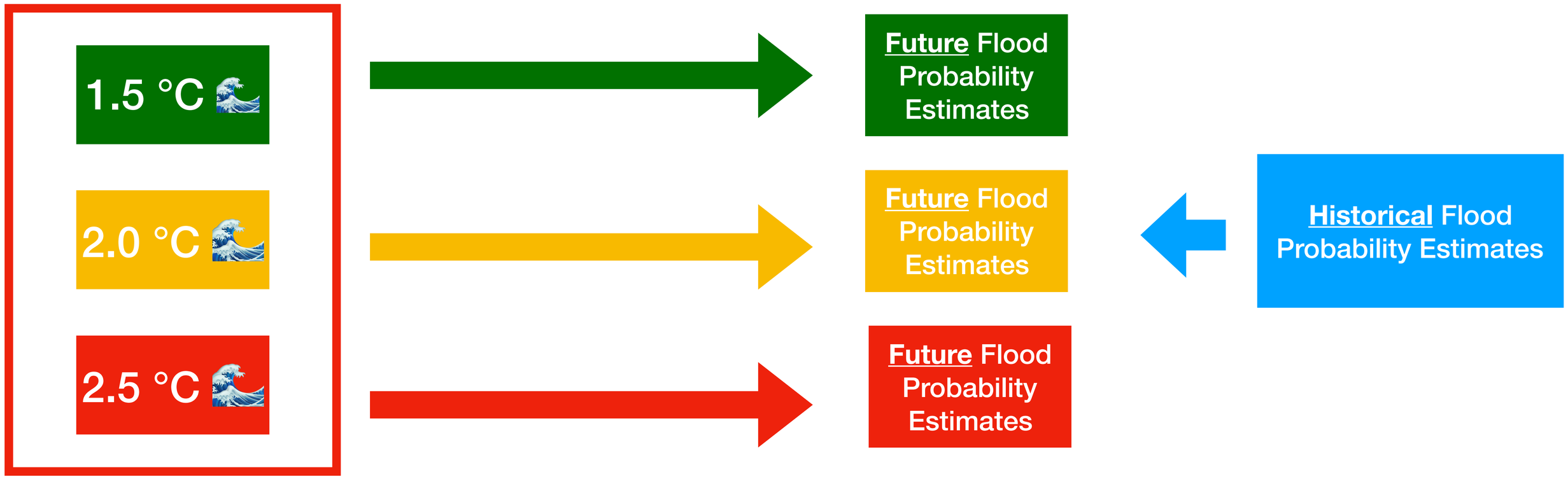
GSL projections for 2100 with RCPs (for comparison)

cm	50th	17th-83rd	5th-95th
1.5 °C	47	35-64	28-82
RCP2.6	50	37-65	29-82
RCP4.5	59	45-77	36-93

cm	50th	17th-83rd	5th-95th
2.0 °C	55	40-75	30-94
RCP2.6	50	37-65	29-82
RCP4.5	59	45-77	36-93

cm	50th	17th-83rd	5th-95th
2.5 °C	58	44-75	36-93
RCP4.5	59	45-77	36-93
RCP8.5	79	62-100	52-121

How we project future coastal flood probabilities:



Global and Local Sea Level Rise (Kopp et al., 2014)

Global and Local Sea Level Rise projections require climate model (GCM) output…

GCM output is conditional on Representative Concentration Pathways (RCPs)…

RCPs: climate policy scenarios?

GCM output is conditional on Representative Concentration Pathways (RCPs)…

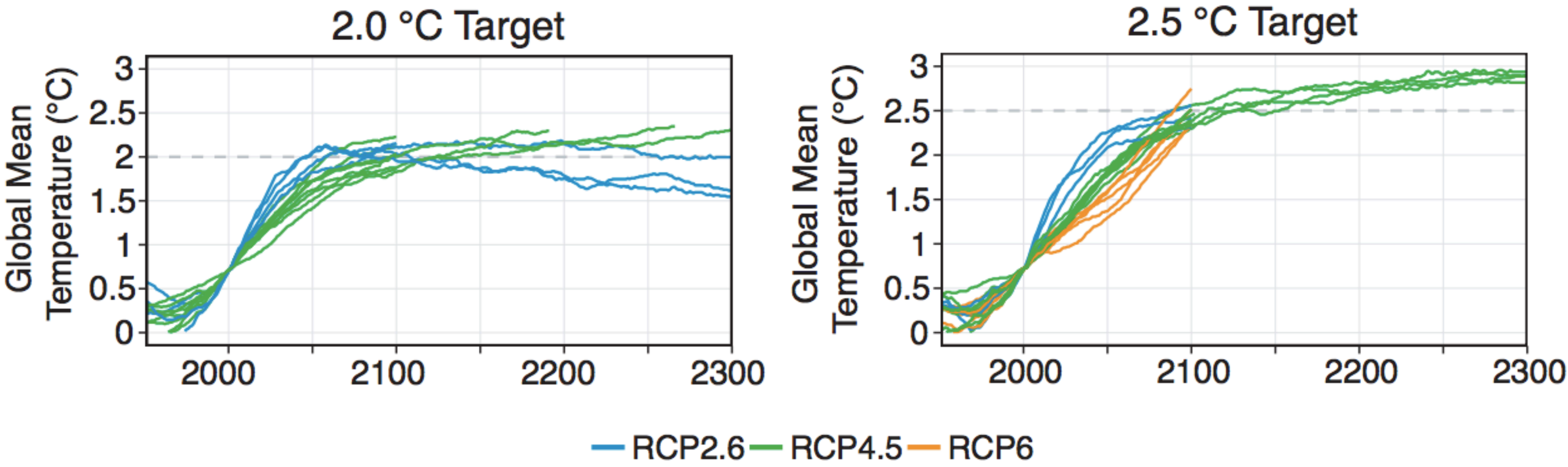
RCPs: climate policy scenarios?

No!

Representative of a *range* of possible emissions and forcing scenarios

Not a specific emissions target or climate policy (such as a global mean temperature stabilization)

Solution: group GCM output based on 2100 Global mean surface temperature (GMST) instead of RCP…



Approximates GMST stabilization (kind of…)