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

D.J. Rasmussen (dj.rasmussen@princeton.edu), M. K. Buchanan, M.Oppenheimer (Princeton), K. Bittermann (Tufts U. & PIK), S. Kulp, B. H. Strauss (Climate Central), R. E. Kopp (Rutgers)

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]


Historic Sea Level

Higher sea levels imply permanent inundation

...but first, more frequent flooding

Sea-level rise will increase the baseline height from which storm surges and astronomical tides occur

Coastal flooding: one of costliest impacts of climate change [Hsiang et al., 2017; Diaz, 2016]

Tropical Storm Ana (2015)

[NY Times]

Small island developing states have limited physical and economic means to adapt to sea level rise and coastal flooding

Kiribati

[NY Times]

We don't know the future coastal flood benefits of 1.5 °C, 2 °C, or 2.5 °C GMST stabilizations

We don’t know the future coastal flood benefits of 1.5 °C, 2 °C, or 2.5 °C GMST stabilizations

> 625 million people currently live in low-lying coastal areas (i.e., < 10 m elevation; Neumann et al., 2015)

Stabilized Temperature🌡️ ≠ Stabilized Sea Level 🌊

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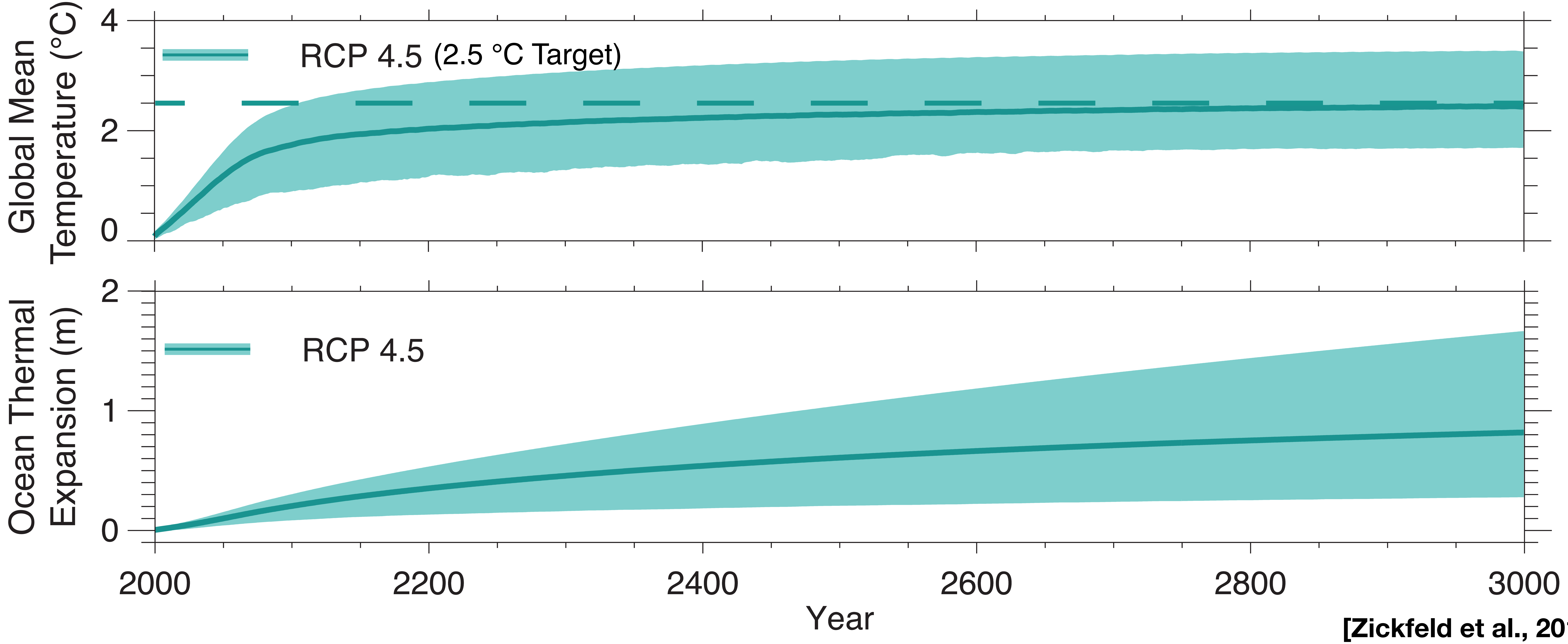


[Zickfeld et al., 2013]

Ocean volume will continue to expand (i.e., thermal expansion)

Uptake of heat from the atmosphere to the deep ocean is slow


Stabilized Temperature 🌡️ ≠ Stabilized Sea Level 🌊
Ice-sheets slow to respond to a given forcing so melting and fracturing are likely to continue…
[NY Times]

How we project future coastal flood probabilities:

How we project future coastal flood probabilities:

1.5 °C 🌊

2.0 °C 🌊

2.5 °C 🌊

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**

[Rasmussen et al., in rev.]

How we project future coastal flood probabilities:

1.5 °C 🌊

2.0 °C 🌊

2.5 °C 🌊

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

…"thermal expansion" and glacier components (Marzeion et al., 2012) from GCMs… but these are driven with Representative Concentration Pathways (RCPs)…

[Rasmussen et al., in rev.]

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

Approximates GMST stabilization (kind of…)

[Rasmussen et al., in rev.]

How we project future coastal flood probabilities:

1.5 °C 🌊

2.0 °C 🌊

2.5 °C 🌊

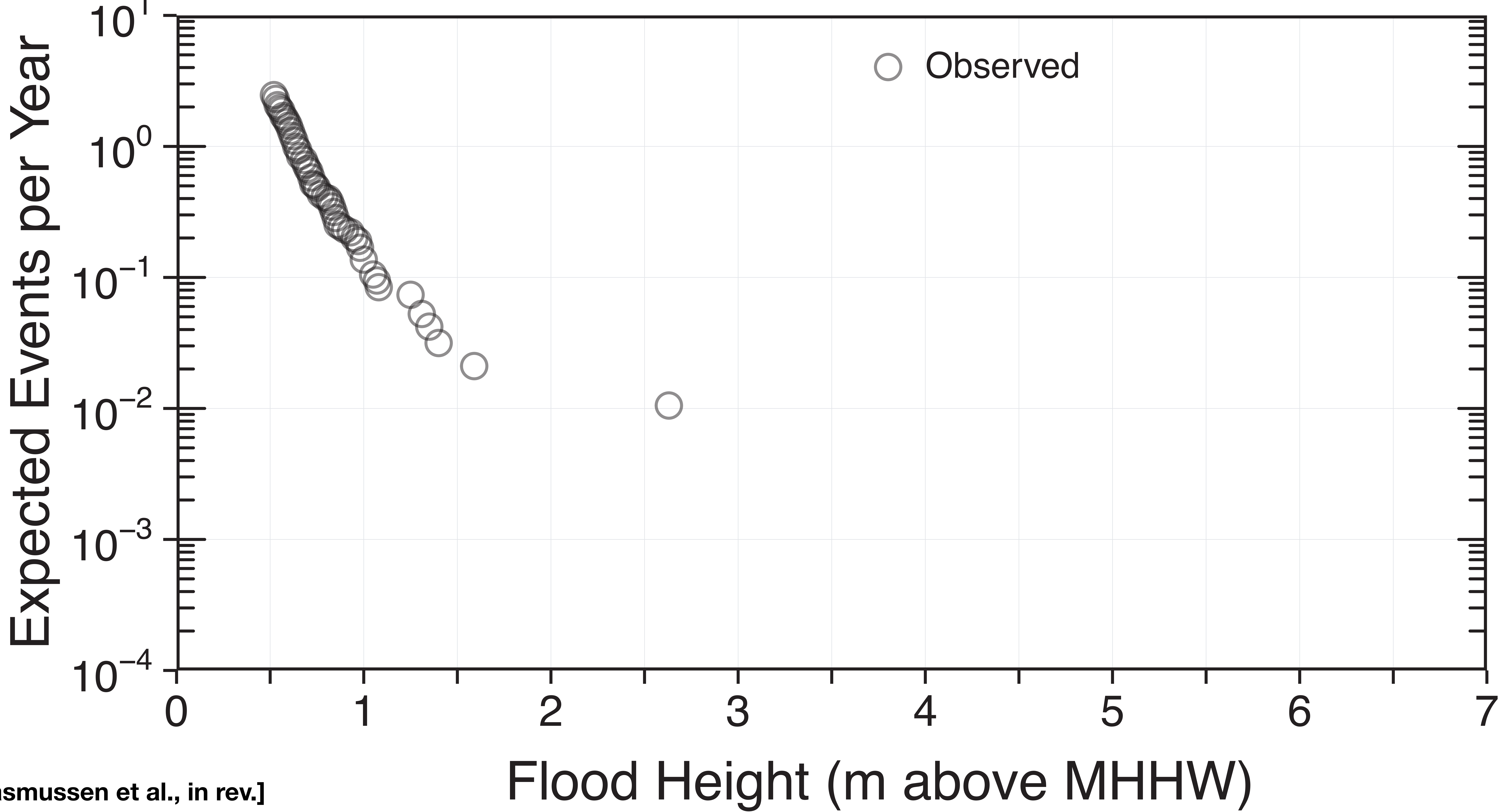
Global and Local Sea Level Rise (Kopp et al., 2014)

<u>**Historical**</u> Flood Probability Estimates

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

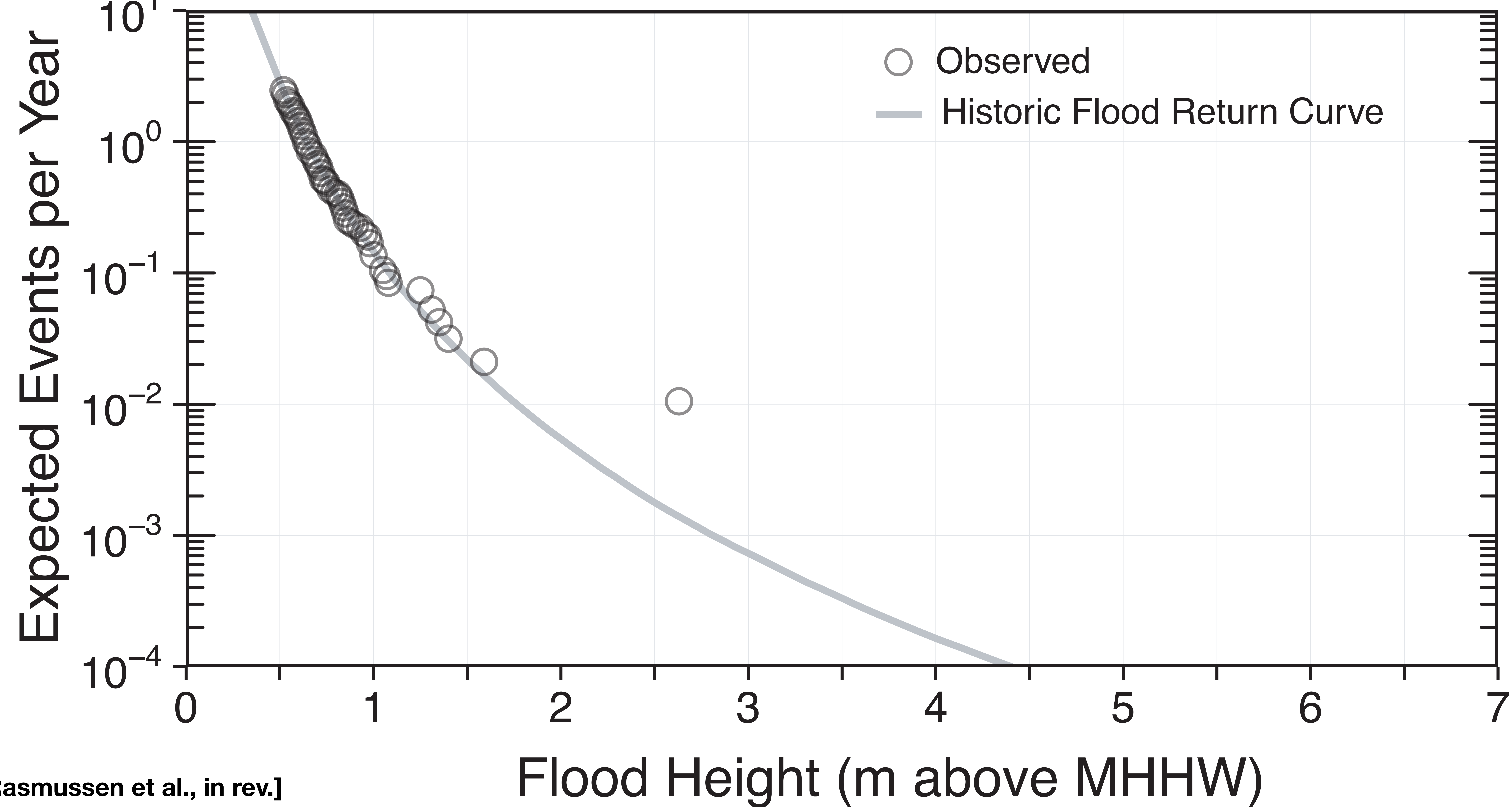
[Rasmussen et al., in rev.]

Example: New York City, U.S.A.



[Rasmussen et al., in rev.]

Example: New York City, U.S.A.



[Rasmussen et al., in rev.]

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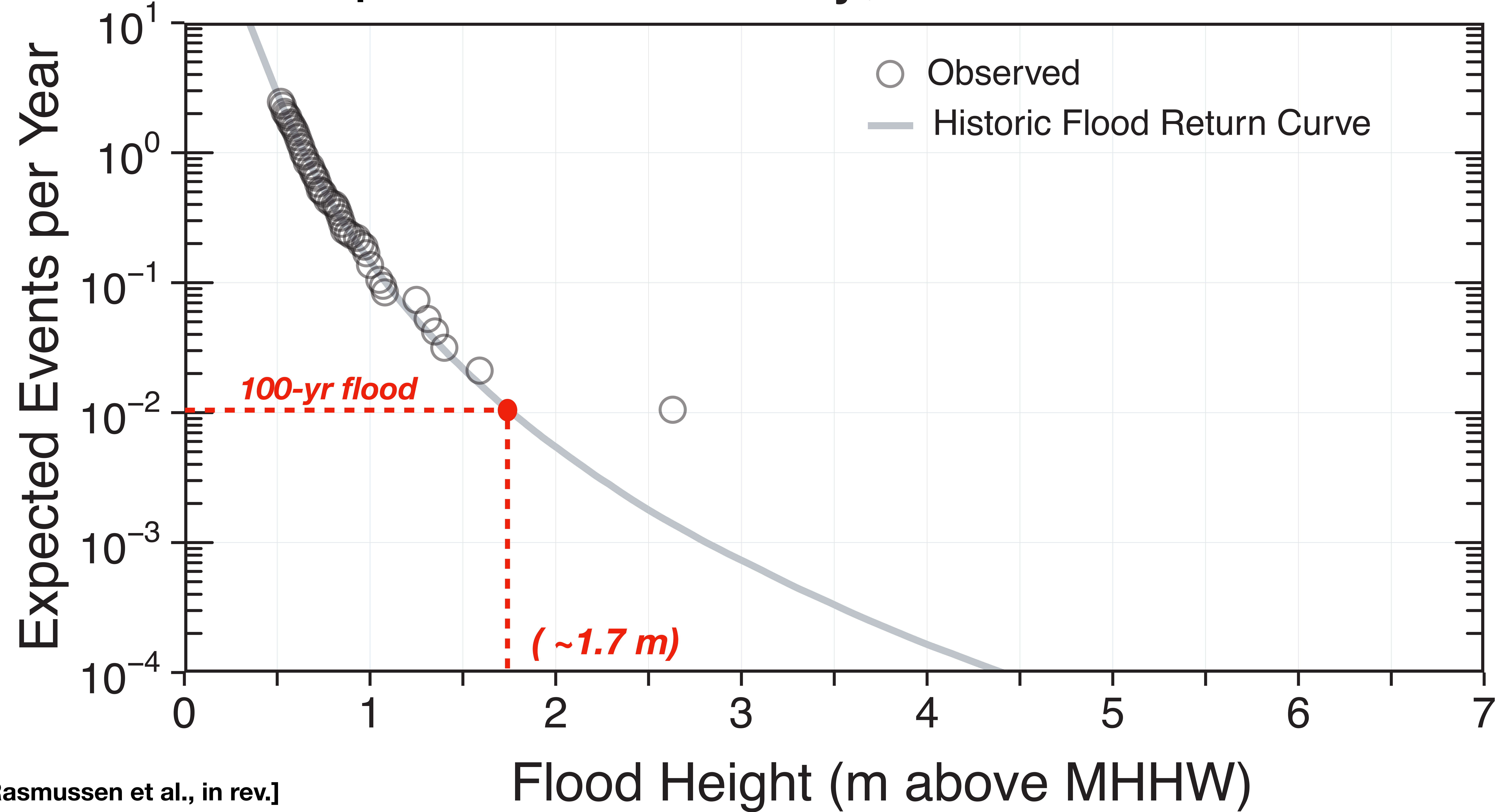


[Rasmussen et al., in rev.]

How we project future coastal flood probabilities:

1.5 °C 🌊

2.0 °C 🌊

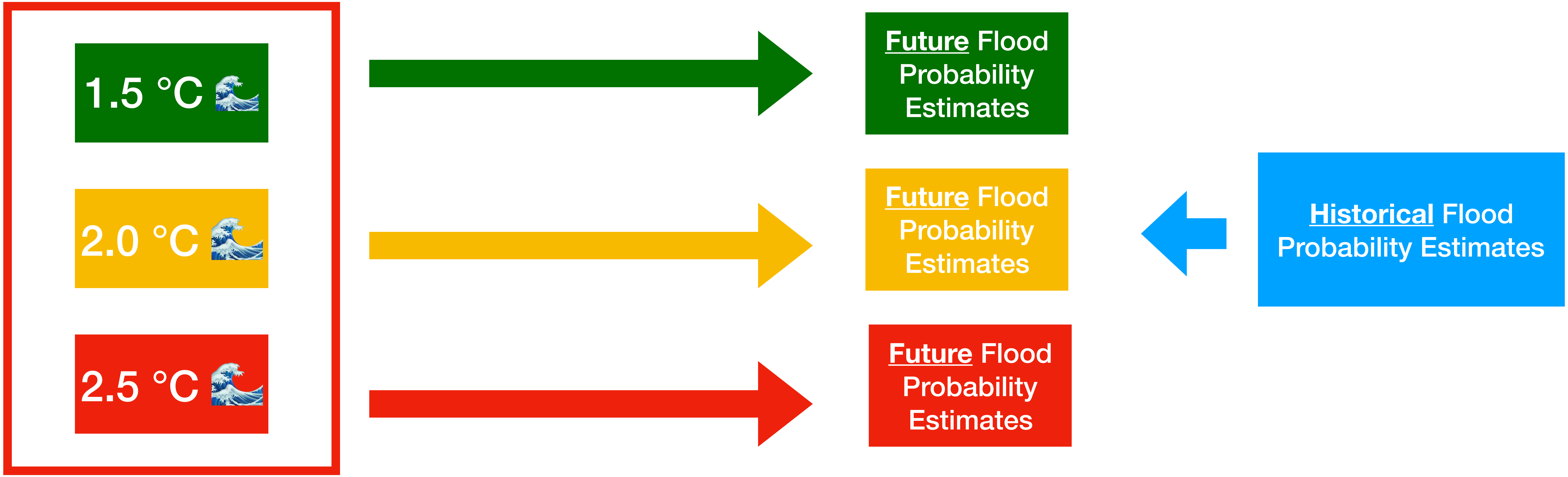
2.5 °C 🌊

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

Historical Flood Probability Estimates

[Rasmussen et al., in rev.]

How we project future coastal flood probabilities:

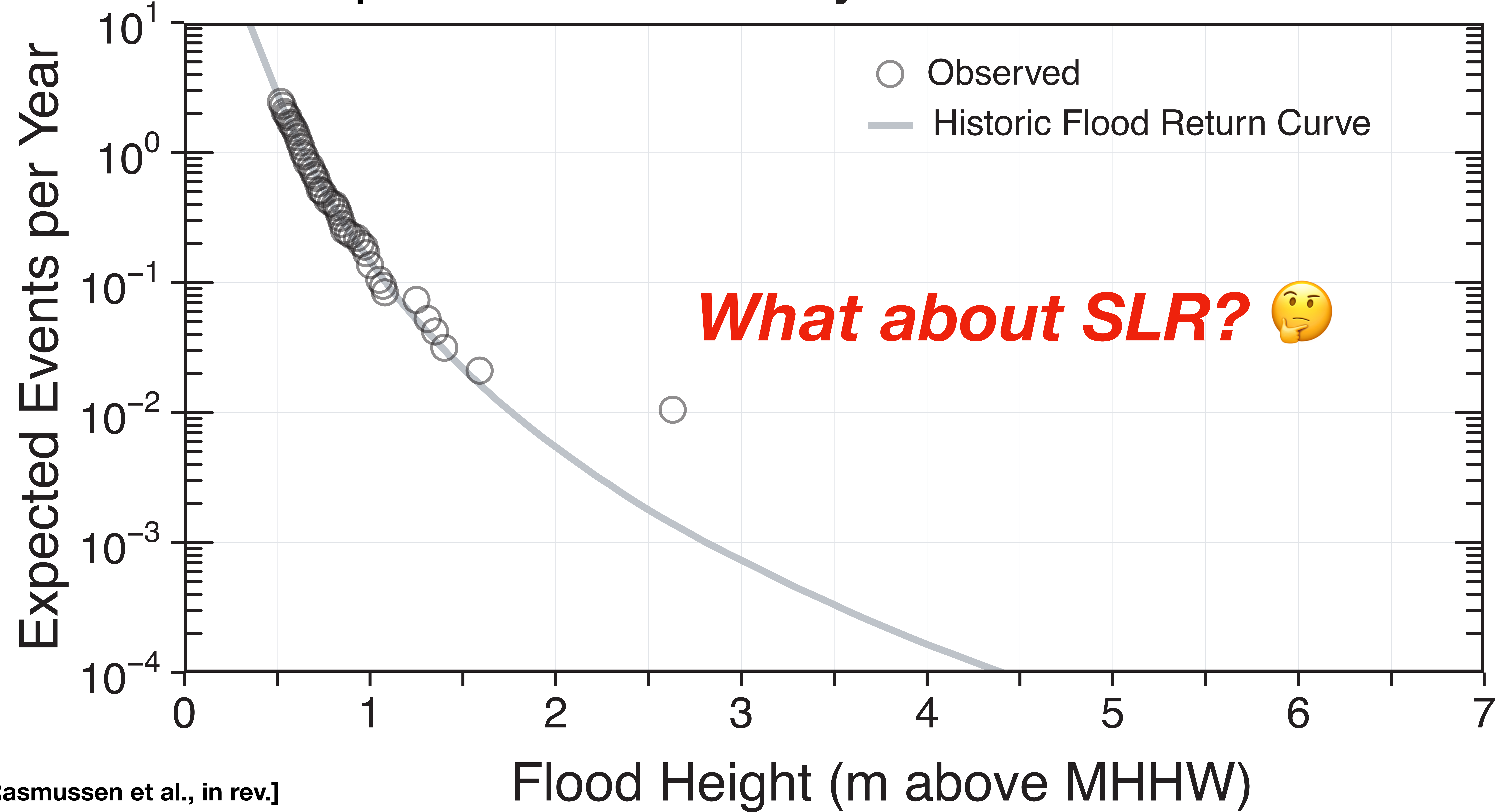


Global and Local Sea Level Rise (Kopp et al., 2014)

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

[Rasmussen et al., in rev.]

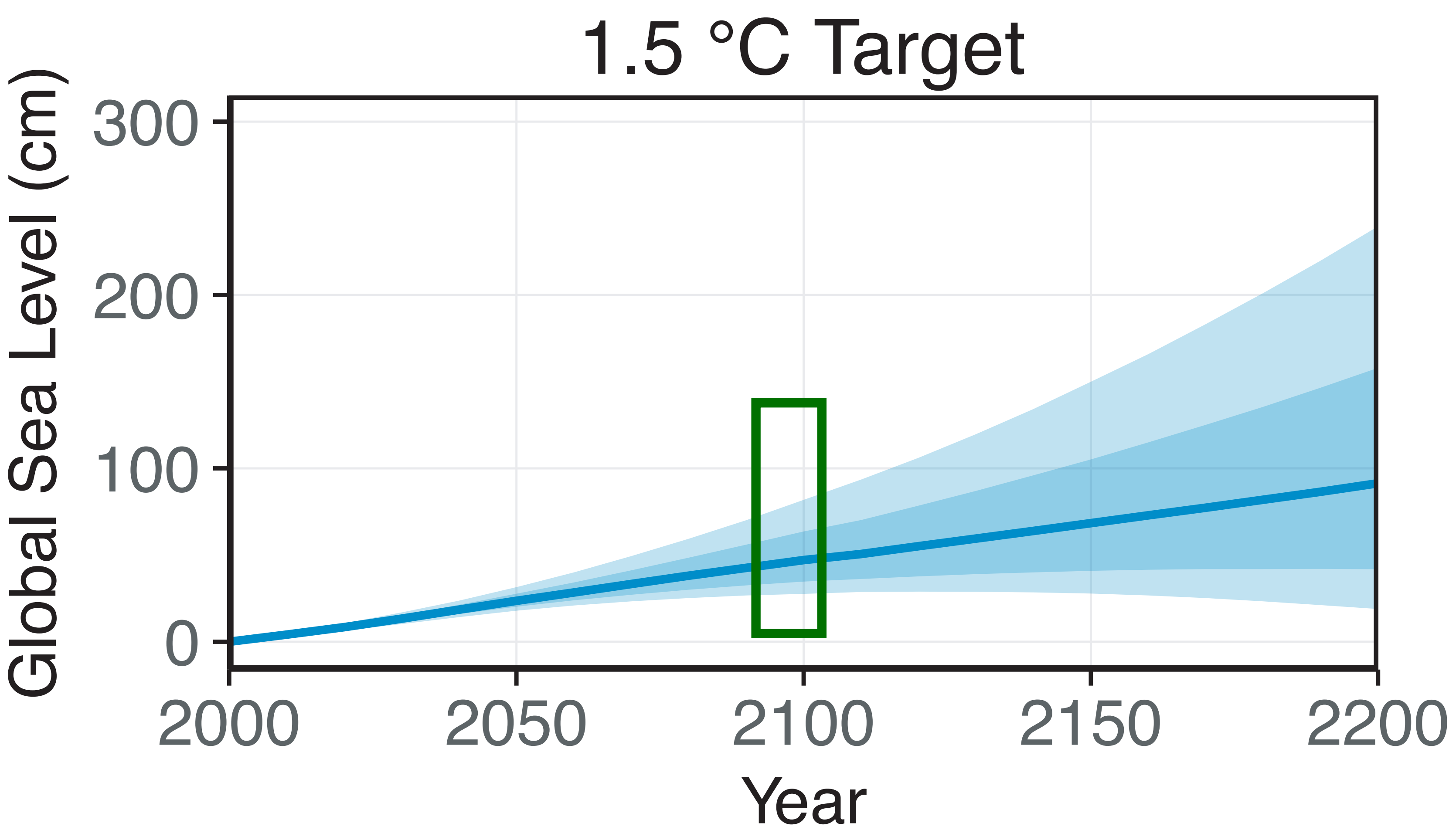
Example: New York City, U.S.A.



[Rasmussen et al., in rev.]

Example: New York City, U.S.A. (2100)
Observed
Historic Flood Return Curve
Historic + Median Local Sea-Level Rise (1.5 °C)
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.]

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

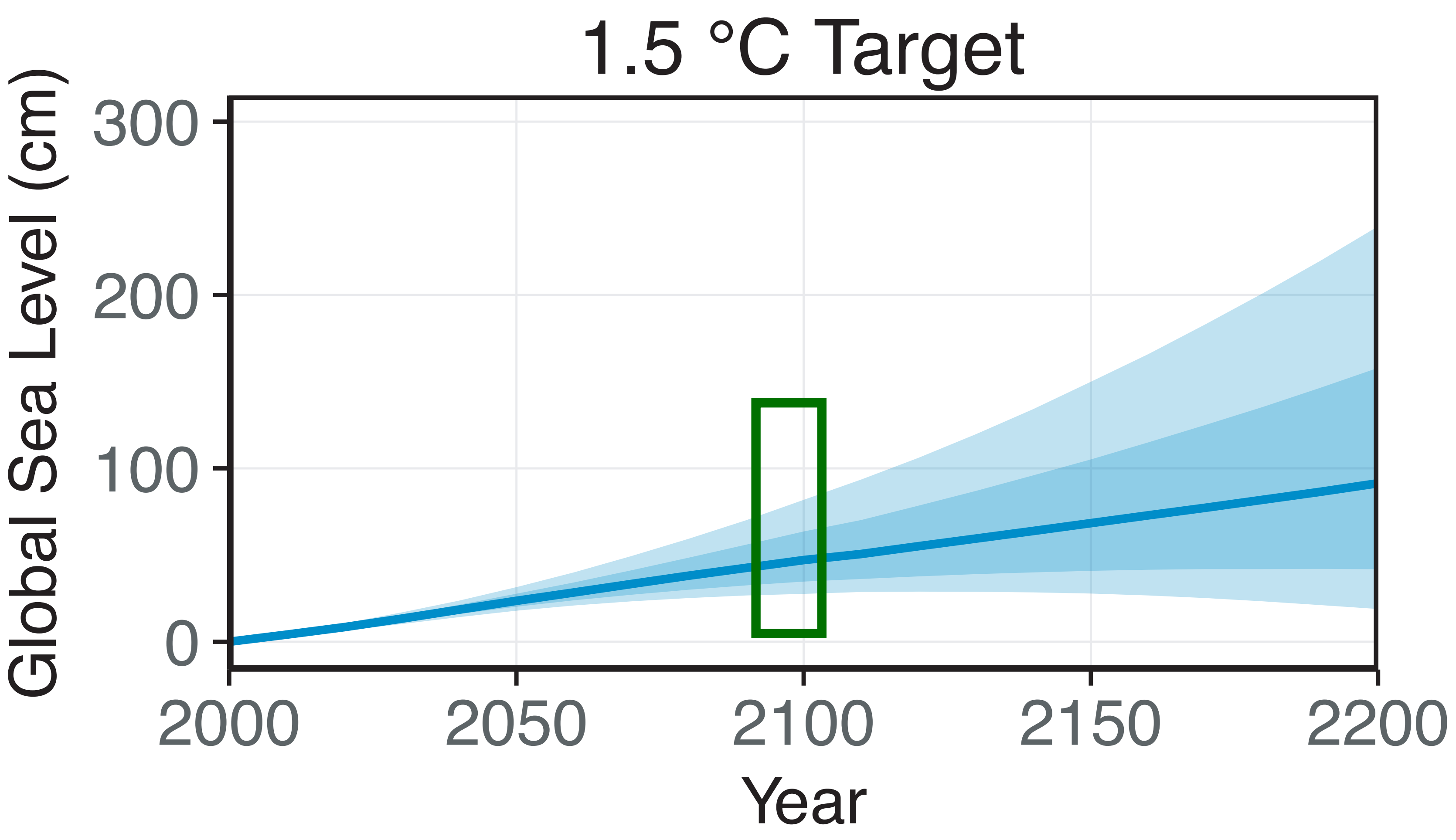


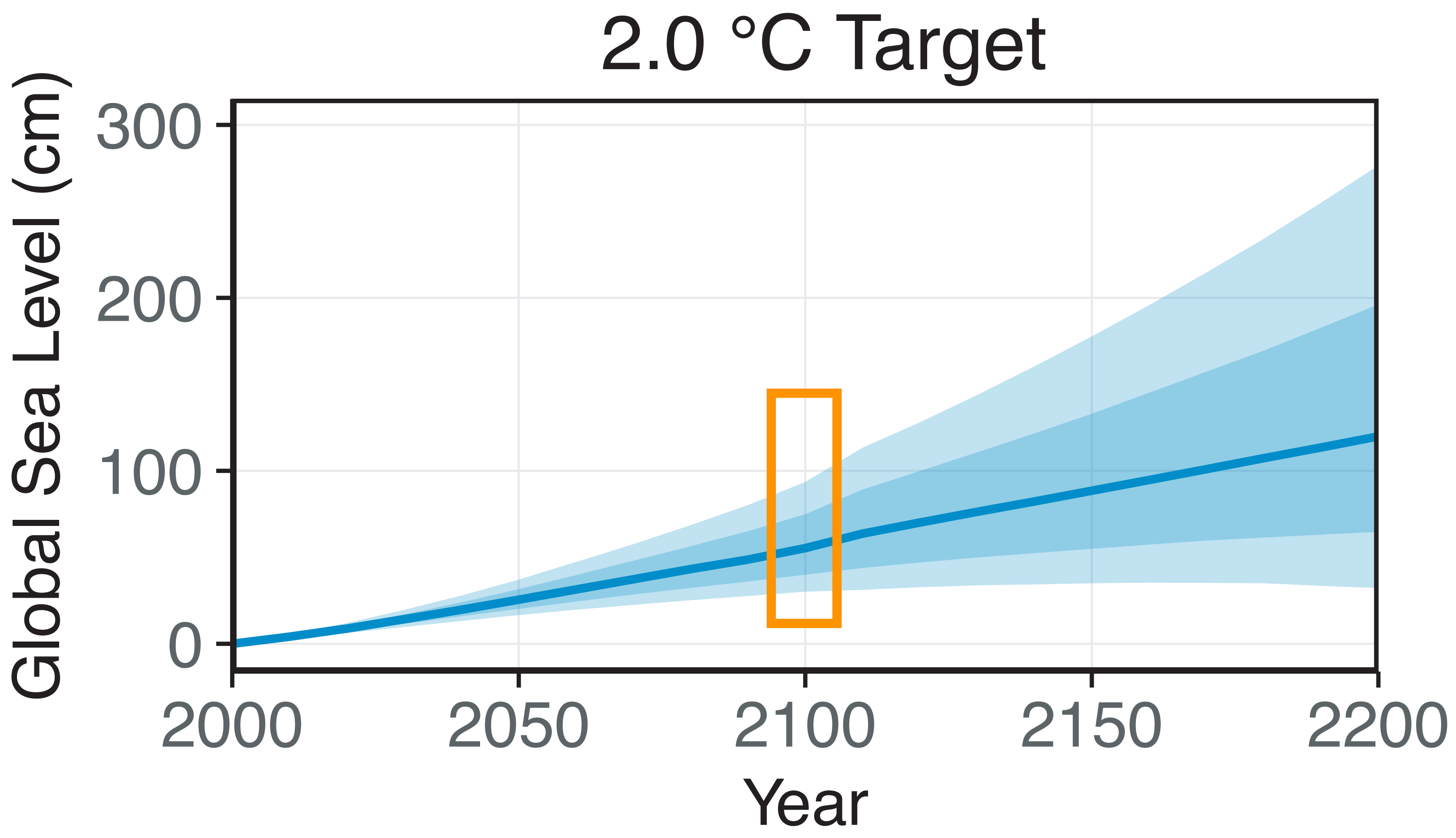
2100 GSL

cm	50th	17th-83rd	5th-95th
1.5 °C	47	35-64	28-82

[Rasmussen et al., in rev.]

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





2100 GSL

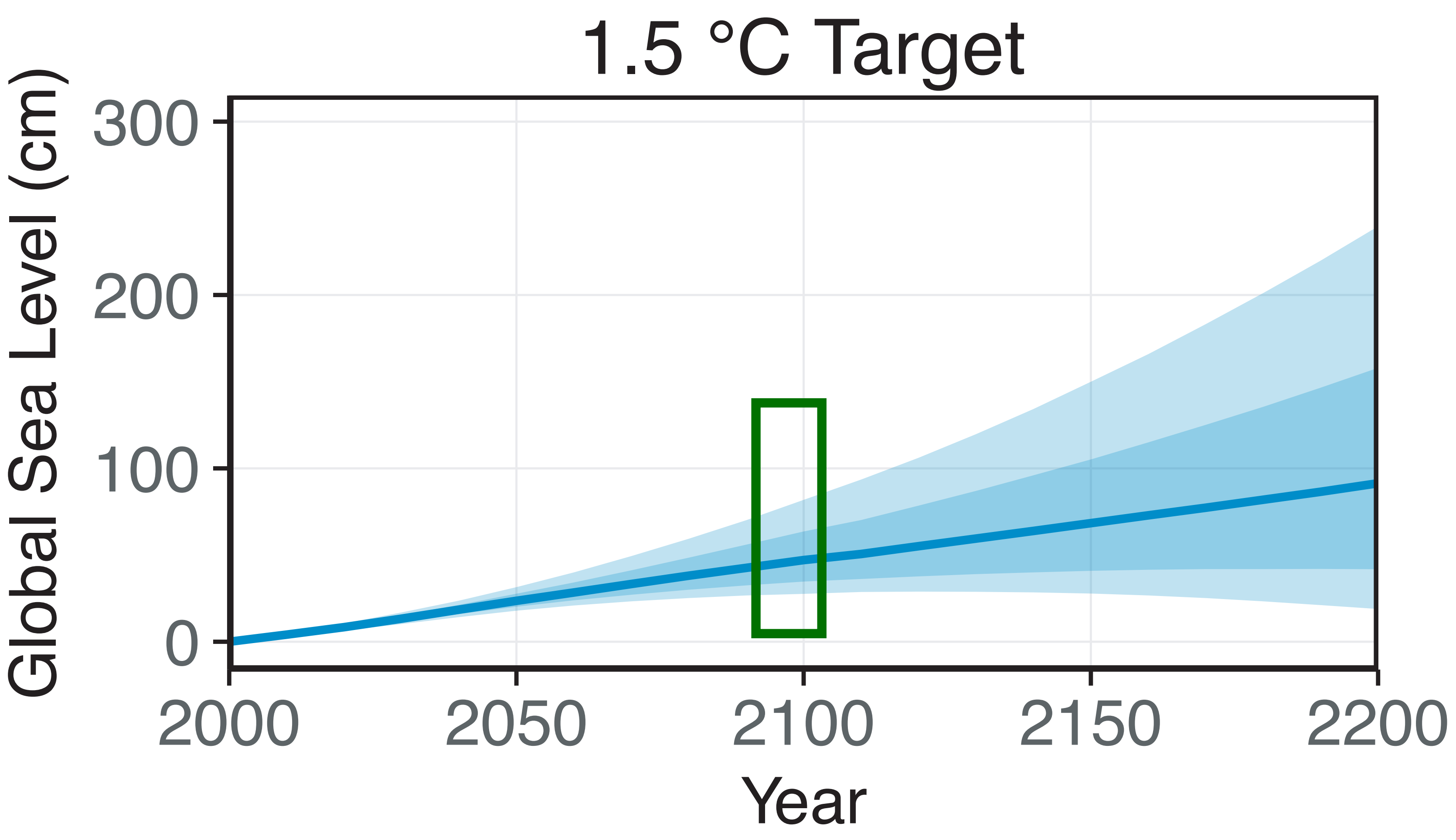
cm	50th	17th-83rd	5th-95th
1.5 °C	47	35-64	28-82

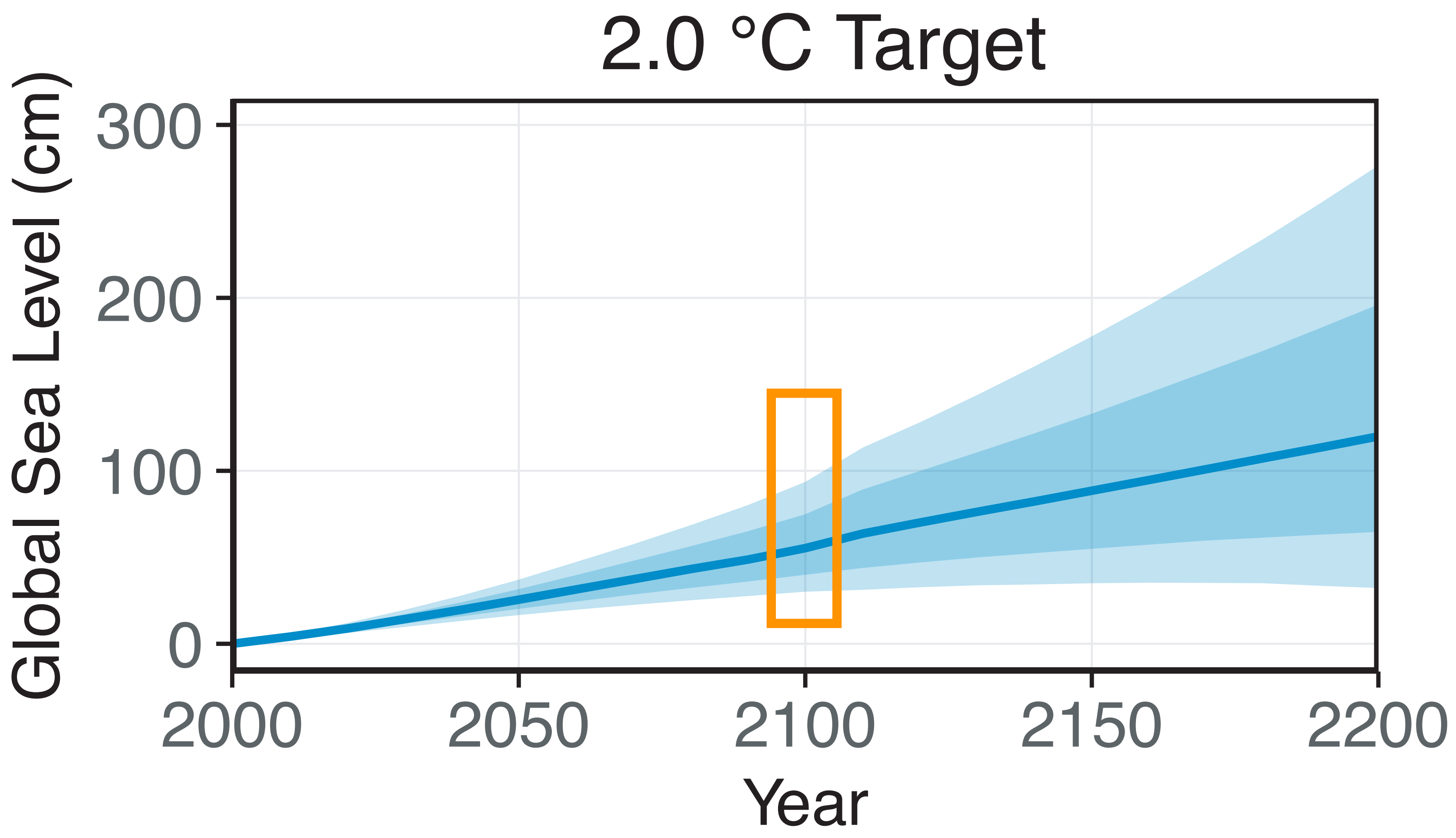
2100 GSL

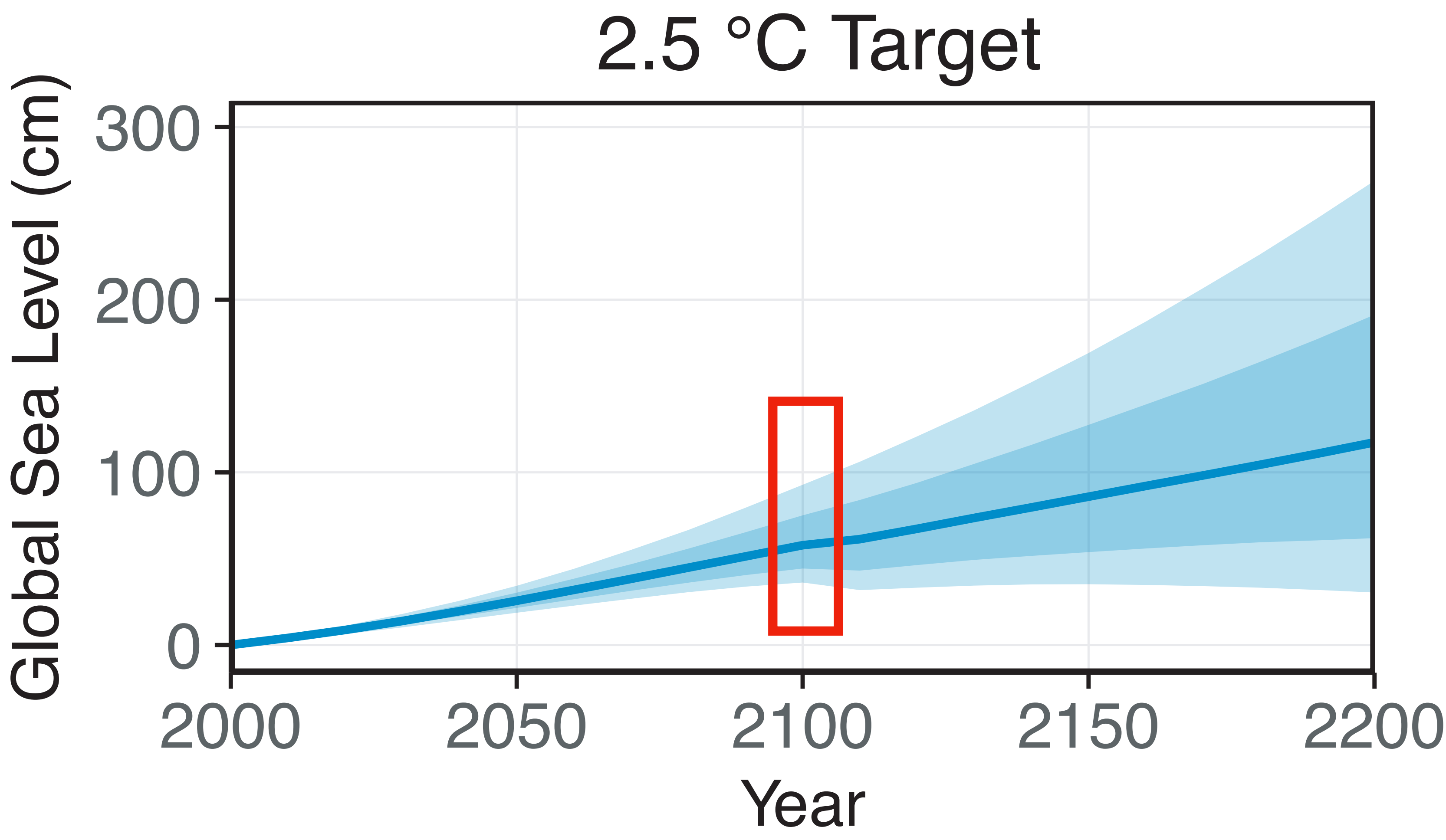
cm	50th	17th-83rd	5th-95th
2.0 °C	55	40-75	30-94

[Rasmussen et al., in rev.]

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







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2100 GSL

cm	50th	17th-83rd	5th-95th
2.5 °C	58	44-75	36-93

[Rasmussen et al., in rev.]

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

[Rasmussen et al., in rev.]

CLIMATE CENTRAL

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

Assumes people don't migrate…

[Rasmussen et al., in rev.]

CLIMATE CENTRAL

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

2.0 °C scenario (median SLR):

~60 million people *currently* reside in lands projected to be submerged by 2150

[Rasmussen et al., in rev.]

CLIMATE CENTRAL

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

2.0 °C scenario (median SLR):

~60 million people (current population of Italy)

[Rasmussen et al., in rev.]

CLIMATE CENTRAL

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

2.0 °C scenario (median SLR):

~500,000 *current* residents of Small Island Developing States

CLIMATE CENTRAL

[Rasmussen et al., in rev.]


2.0 °C scenario:
(median SLR)
~25% of the *current* population of the Marshall Islands projected to be submerged by 2150
[Rasmussen et al., in rev.]
https://www.logicum.co/landmarks-in-marshall-islands/

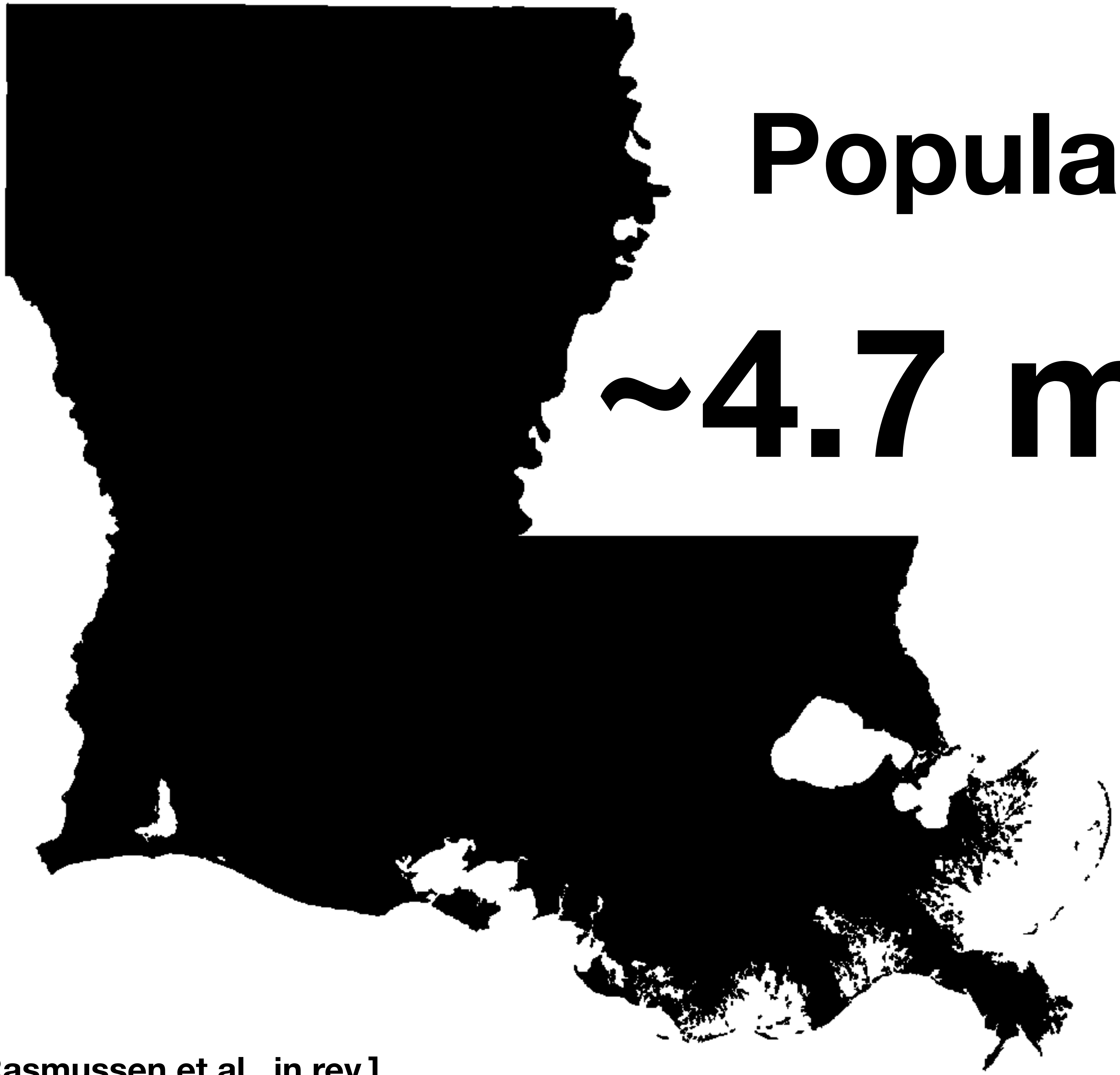
Who currently resides in areas at risk of being ***permanently*** inundated by future SLR?

1.5 °C scenario:

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

[Rasmussen et al., in rev.]

CLIMATE CENTRAL



Population of Louisiana:

~4.7 million (2016)

[Rasmussen et al., in rev.]

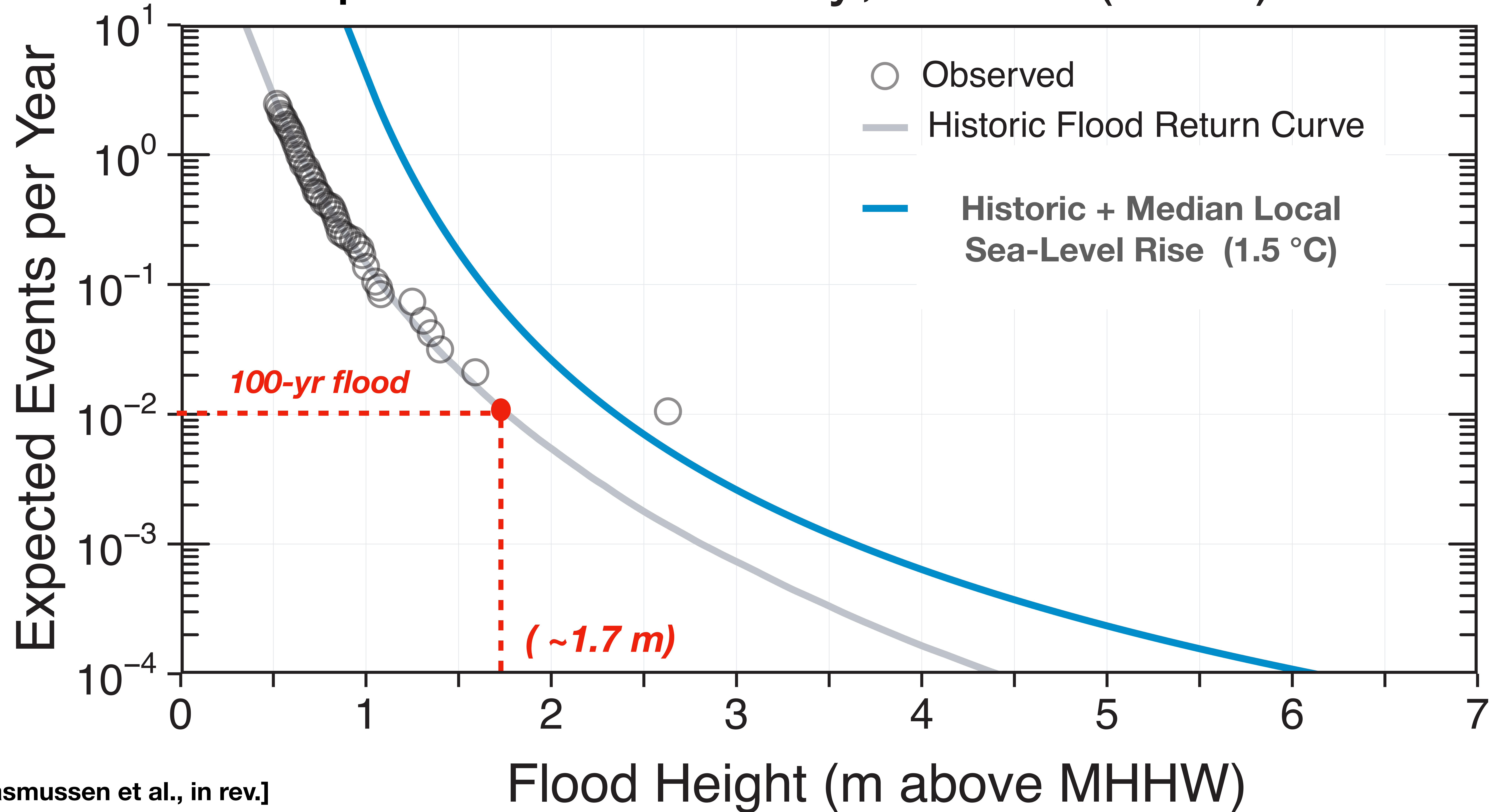

1.5 °C scenario:
(median SLR)
~1% of the *current* population of the Marshall Islands projected to be spared by 2150 (vs. 2.0 °C scenario)
[Rasmussen et al., in rev.]
https://www.logicum.co/landmarks-in-marshall-islands/

Flood Frequency Amplification Factors (AF)

[c.f., Buchanan et al., 2017]

$$\mathrm{AF} = \frac{\textbf{Future}\text{ Annual Expected Number of Floods}}{\textbf{Current}\text{ Annual Expected Number of Floods}}$$

Example: New York City, U.S.A. (2100)



[Rasmussen et al., in rev.]

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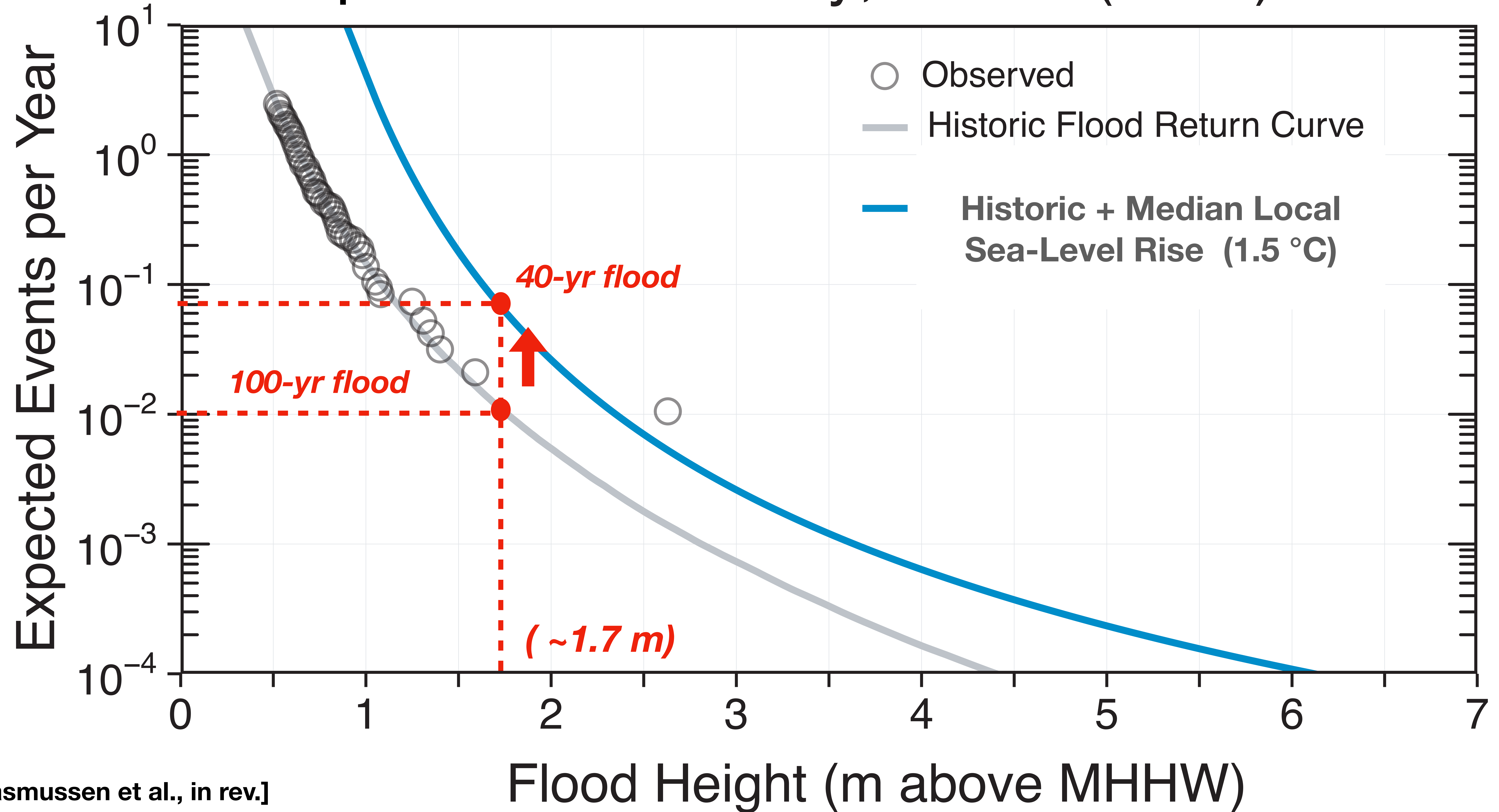


[Rasmussen et al., in rev.]

Flood Frequency Amplification Factors (AF)

[c.f., Buchanan et al., 2017]

$$AF = \frac{\textbf{Future}\text{ Annual Expected Number of Floods}}{\textbf{Current}\text{ Annual Expected Number of Floods}}$$

e.g., (100-yr flood)

$$\mathbf{AF_{100\text{-}yr,\ 1.5\ ^\circ C} = \frac{.025\ expected\ floods\ yr^{-1}}{.01\ expected\ floods\ yr^{-1}}}$$

$$\mathbf{AF_{100\text{-}yr,\ 1.5\ ^\circ C} = 2.5}$$

Estimating projected flood benefits from 1.5 °C vs. 2.0 °C

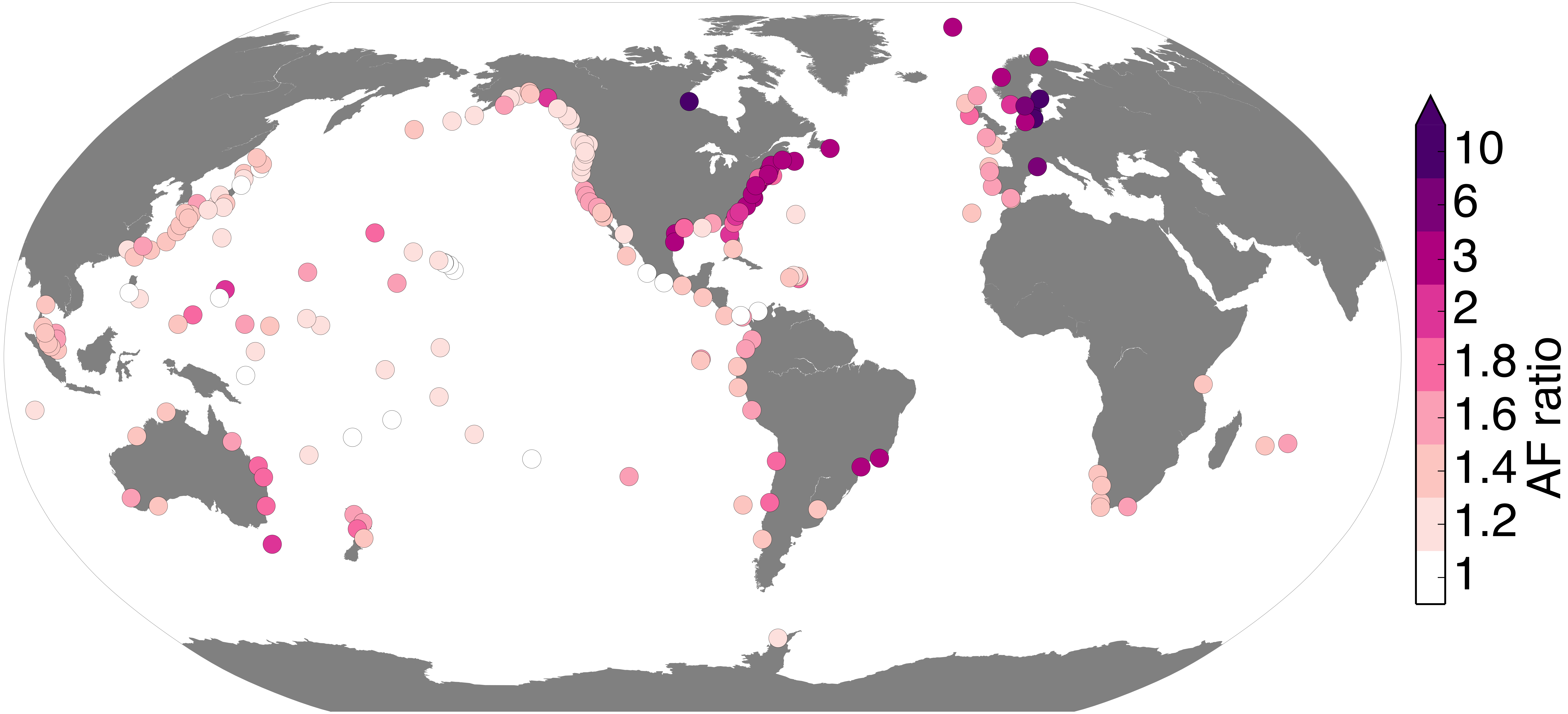
$$\text{AF ratio} = \frac{AF_{\text{100-yr, 2.0 °C}}}{AF_{\text{100-yr, 1.5 °C}}}$$

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)

Largest flood benefits in Eastern U.S. and Europe

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



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

[Rasmussen et al., in rev.]

Largest flood benefits in Eastern U.S. and Europe

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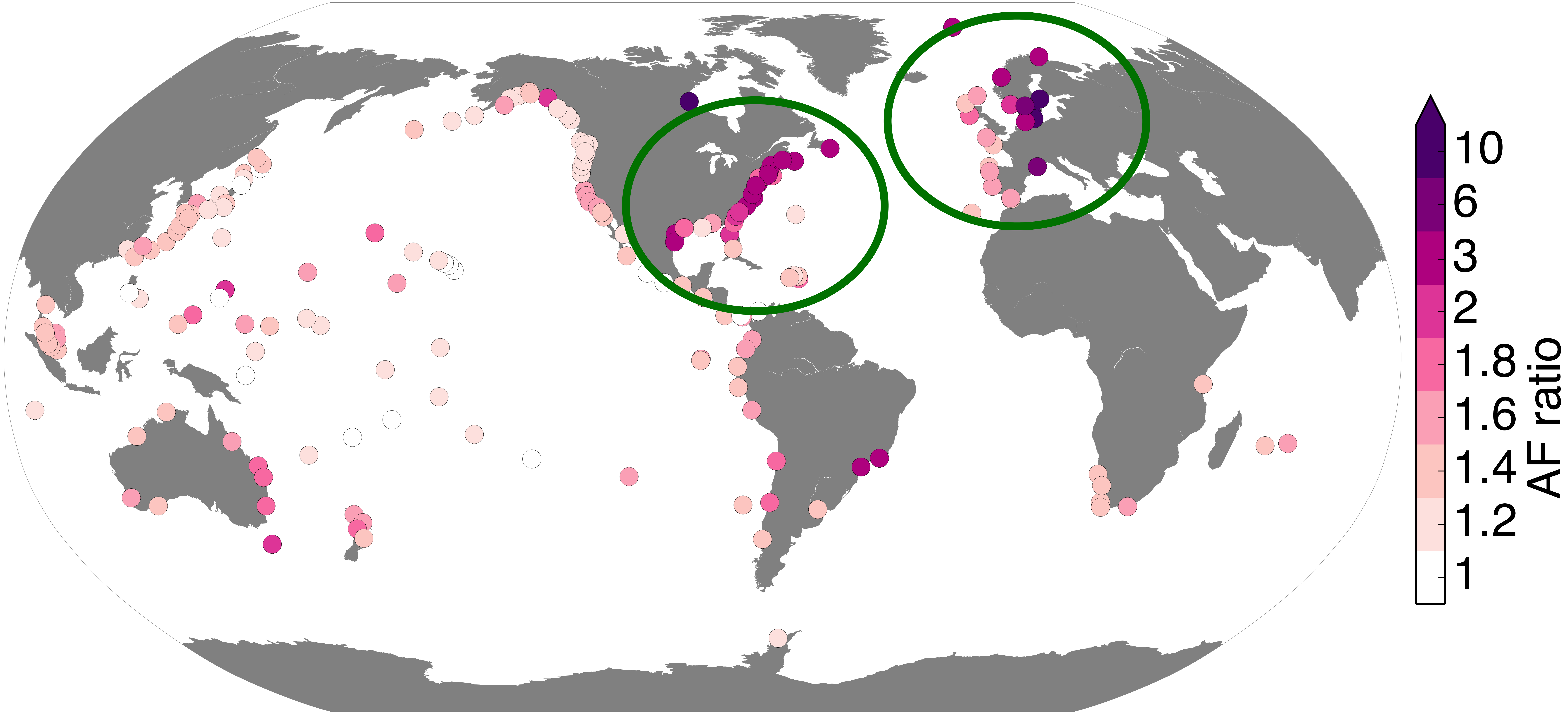

$$\text{AF ratio} = \frac{AF_{\text{100-yr, } \mathbf{2.0\ °C}}}{AF_{\text{100-yr, } \mathbf{1.5\ °C}}}$$

[Rasmussen et al., in rev.]

Key Takeaways:

- Relative to 2.0 °C, 1.5 °C may slow sea-level rise and reduce flood frequency, but will not stop it

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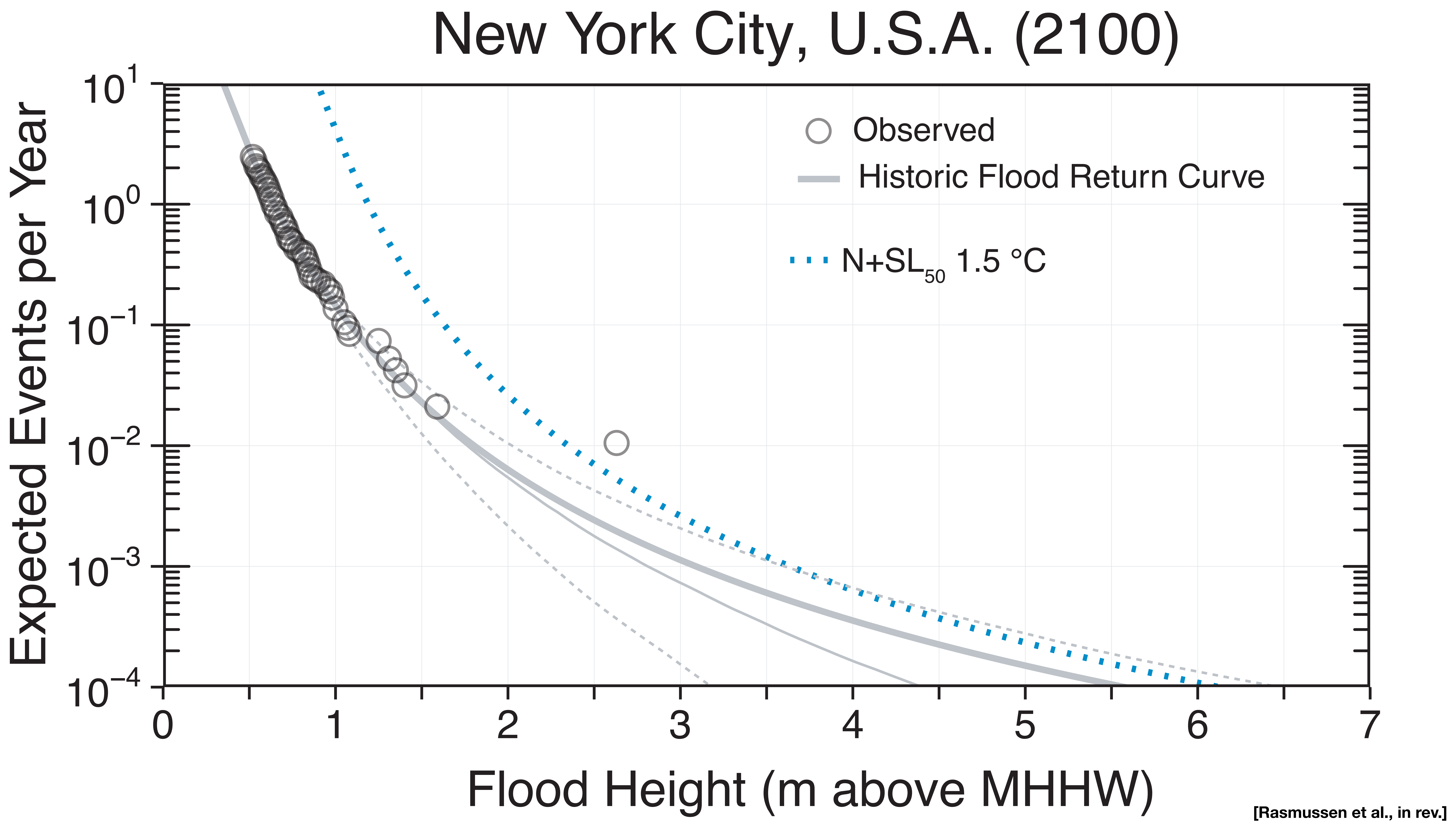
Key Takeaways:

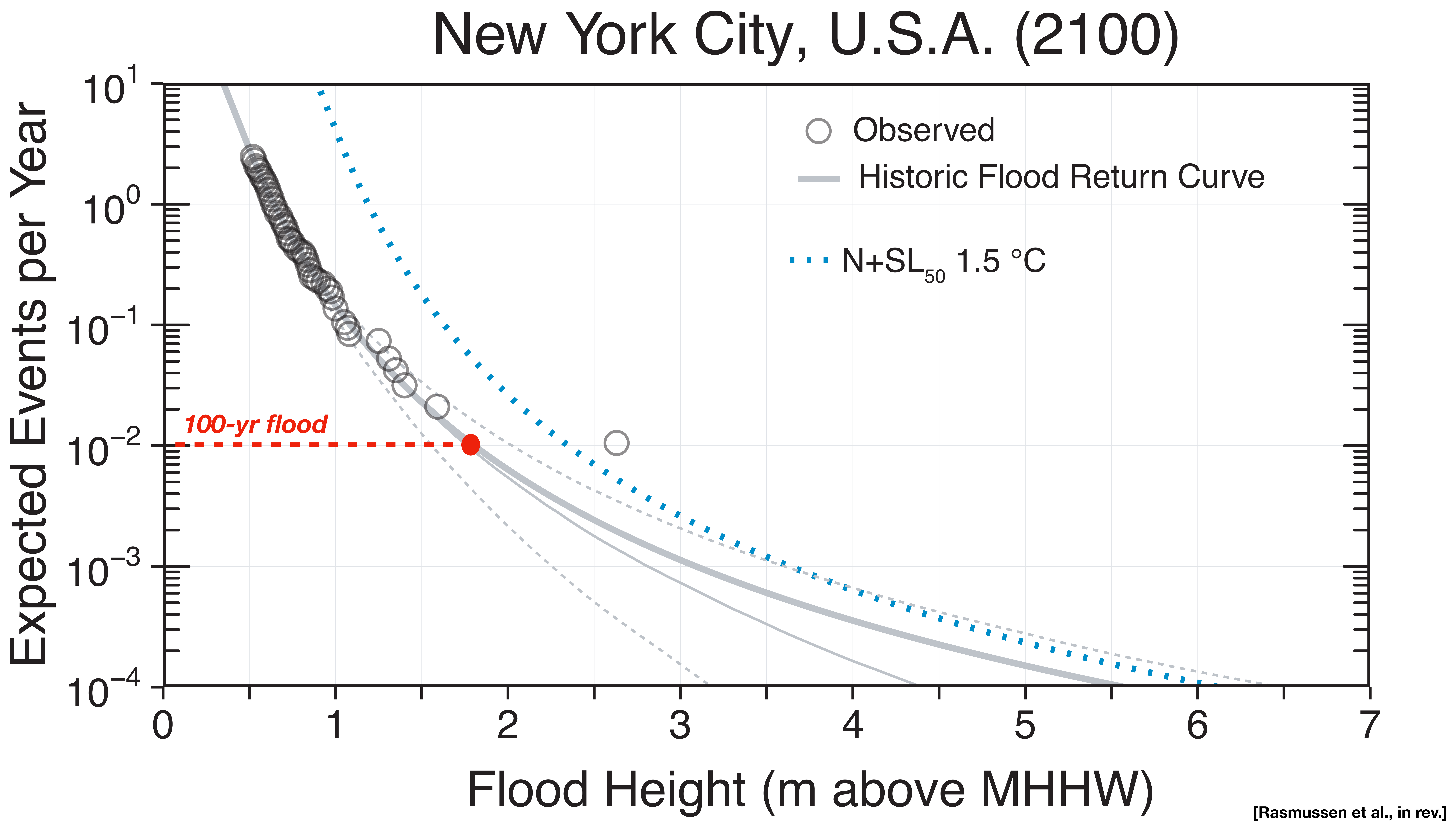
- Relative to 2.0 °C, 1.5 °C may slow sea-level rise and reduce flood frequency, but will not stop it
- By mid-22nd century, 2.0 °C target puts 5 million more people *currently residing* in low-elevation areas at risk of <u>permanent</u> inundation (relative to 1.5 °C)
- Under 1.5 °C, Europe and Eastern U.S. projected to have largest 100-yr flood amplification benefits (2100)

Contact: D.J. Rasmussen (dj.rasmussen@princeton.edu)

Sample AF calculation

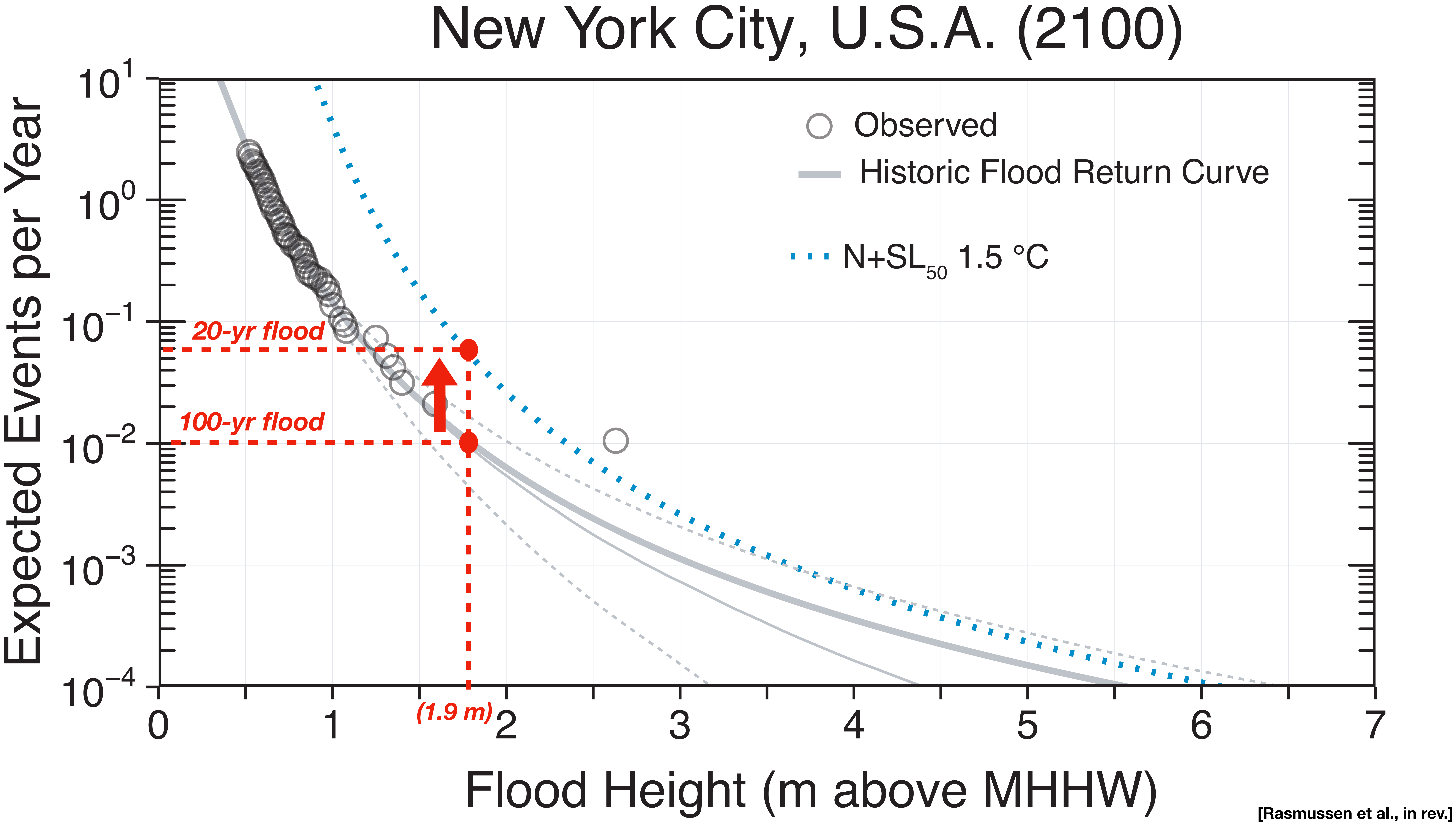


New York City, U.S.A. (2100)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
Expected Events per Year
Flood Height (m above MHHW)
10^1
10^0
10^−1
10^−2
10^−3
10^−4
0
1
2
3
4
5
6
7
[Rasmussen et al., in rev.]



New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
100-yr flood
10^1
10^0
10^−1
10^−2
10^−3
10^−4
0
1
2
3
4
5
6
7
[Rasmussen et al., in rev.]


New York City, U.S.A. (2100)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
100-yr flood
(1.9 m)
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.]


New York City, U.S.A. (2100)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
20-yr flood
100-yr flood
(1.9 m)
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
[Rasmussen et al., in rev.]

New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
20-yr flood
100-yr flood
(1.9 m)
AF100 = .05 expected floods yr-1 / .01 expected floods yr-1
AF100 = 20
[Rasmussen et al., in rev.]

Methods for inundation

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

Approach:

Gridded, probabilistic local SLR projections for global coastlines

How high will mean sea-level rise?

CLIMATE CENTRAL

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

Approach:

Gridded, probabilistic local SLR projections for global coastlines

→

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

How high will mean sea-level rise?

What land is underwater?

CLIMATE CENTRAL

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

Approach:

Gridded, probabilistic local SLR projections for global coastlines → 1-arcsec SRTM 3.0 Digital Elevation Model (NASA, 2013) → National population and boundary data (Bright et al., 2011)

How high will mean sea-level rise?

What land is underwater?

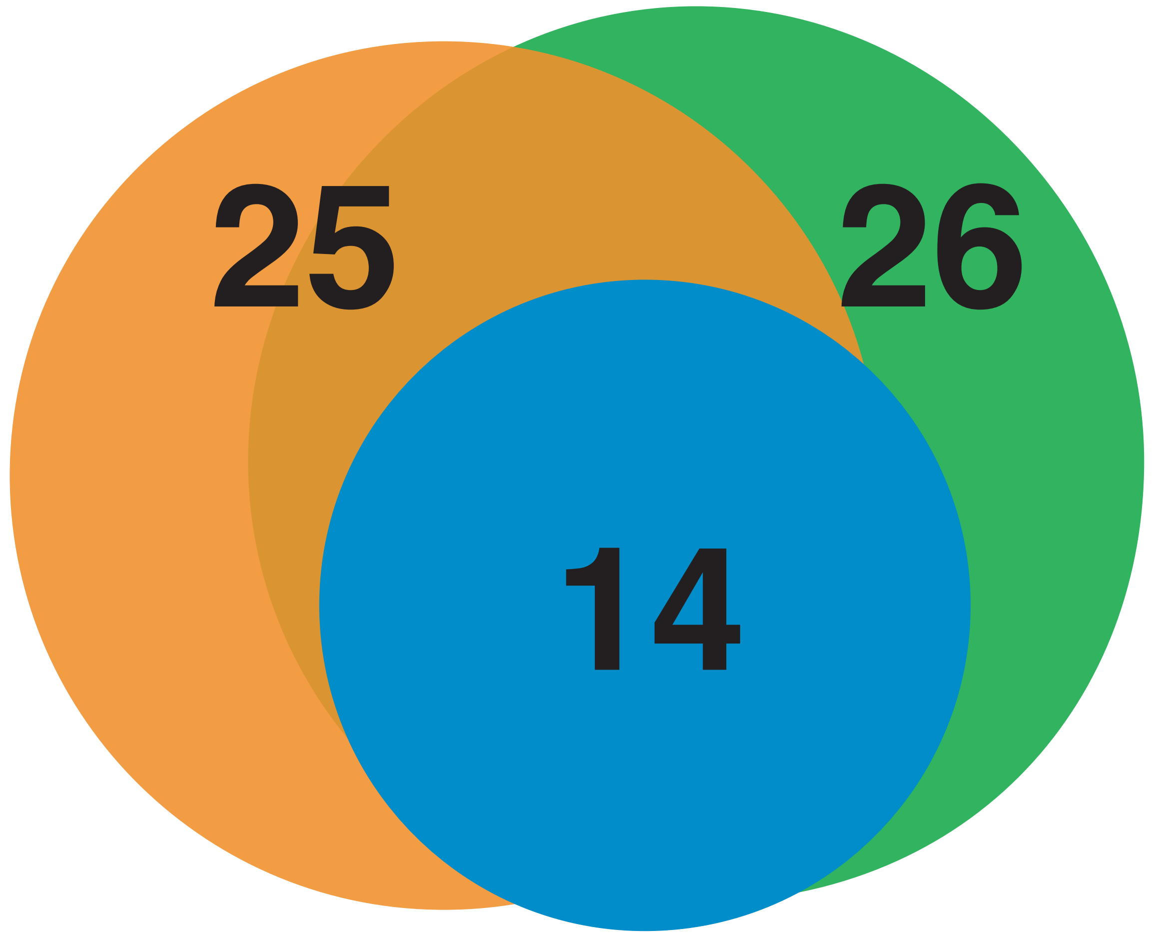
Who lives there?

CLIMATE CENTRAL

Number of annual expected floods (NYC; 2100)

10-yr floods per year

(1.09 m above MHHW)



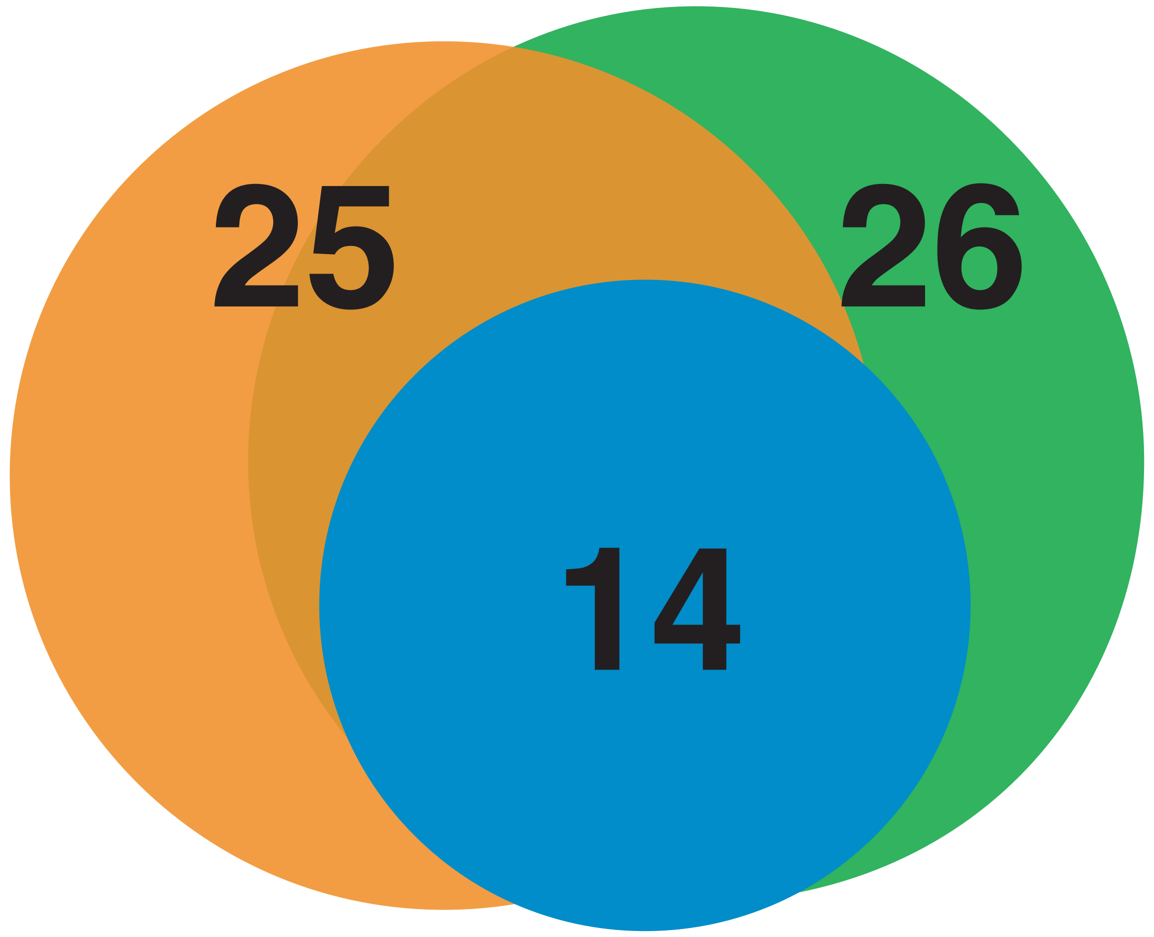
Current: 0.1
events per year

- 2.5 °C
- 2.0 °C
- 1.5 °C

Number of annual expected floods (NYC; 2100)

10-yr floods per year

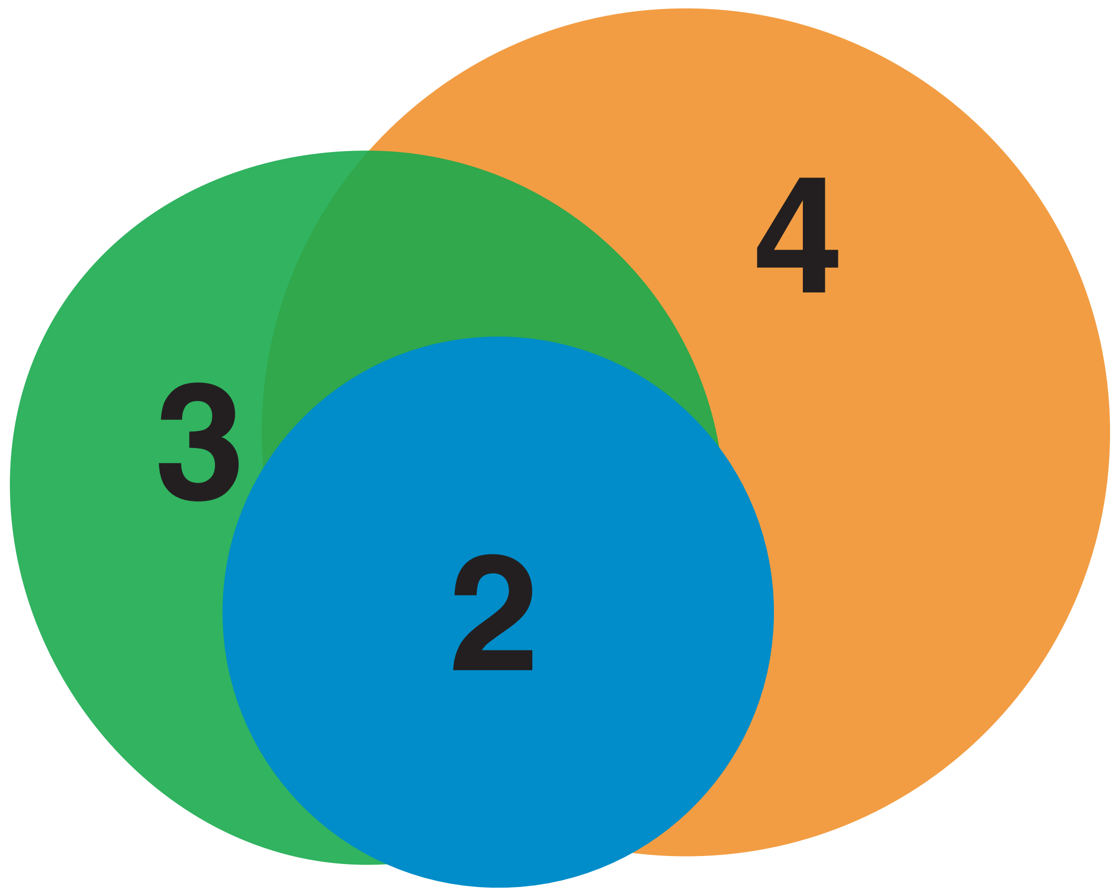
(1.09 m above MHHW)



Current: 0.1 events per year

100-yr floods per year

(1.86 m above MHHW)



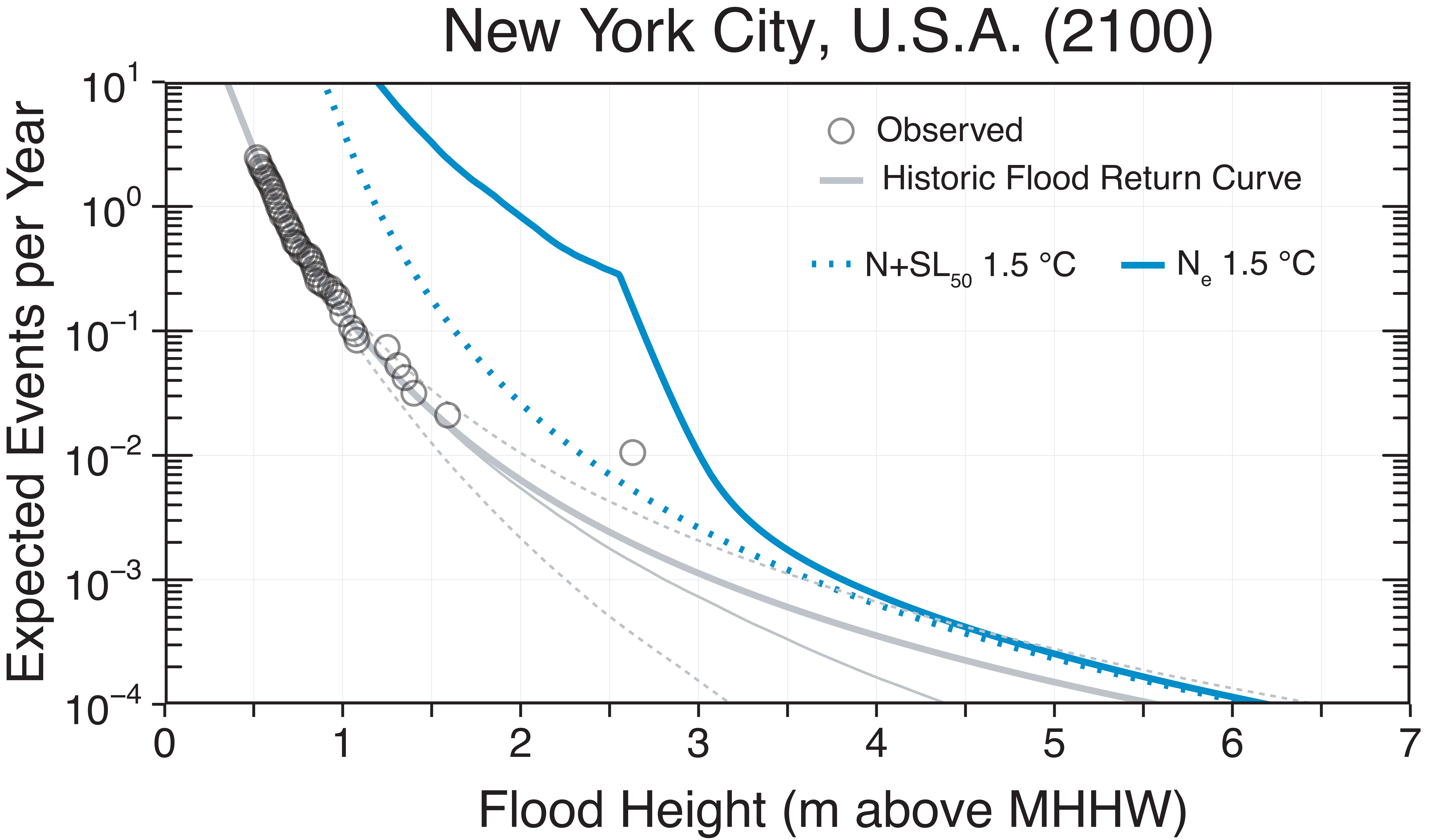
Current: 0.01 events per year

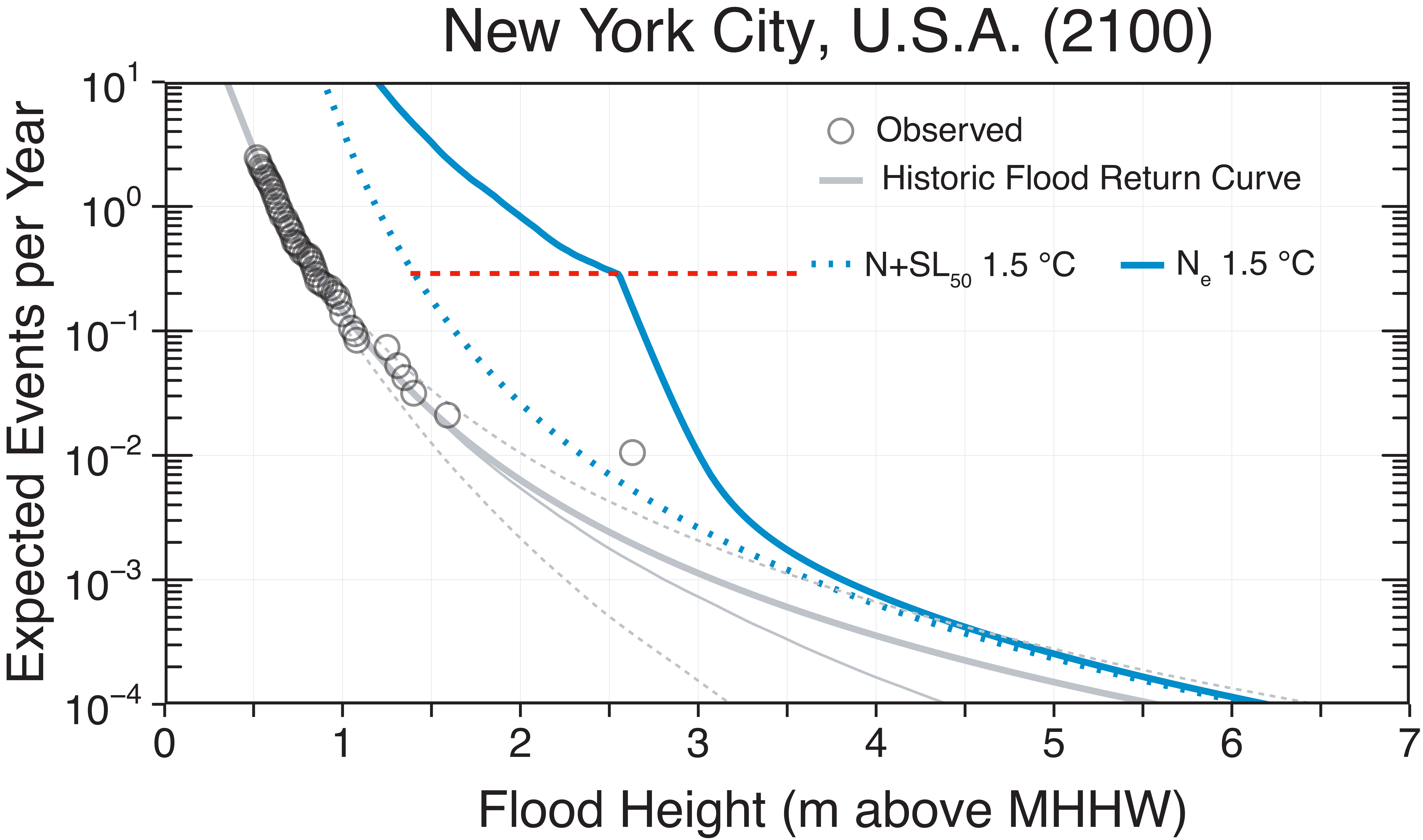
2.5 °C

2.0 °C

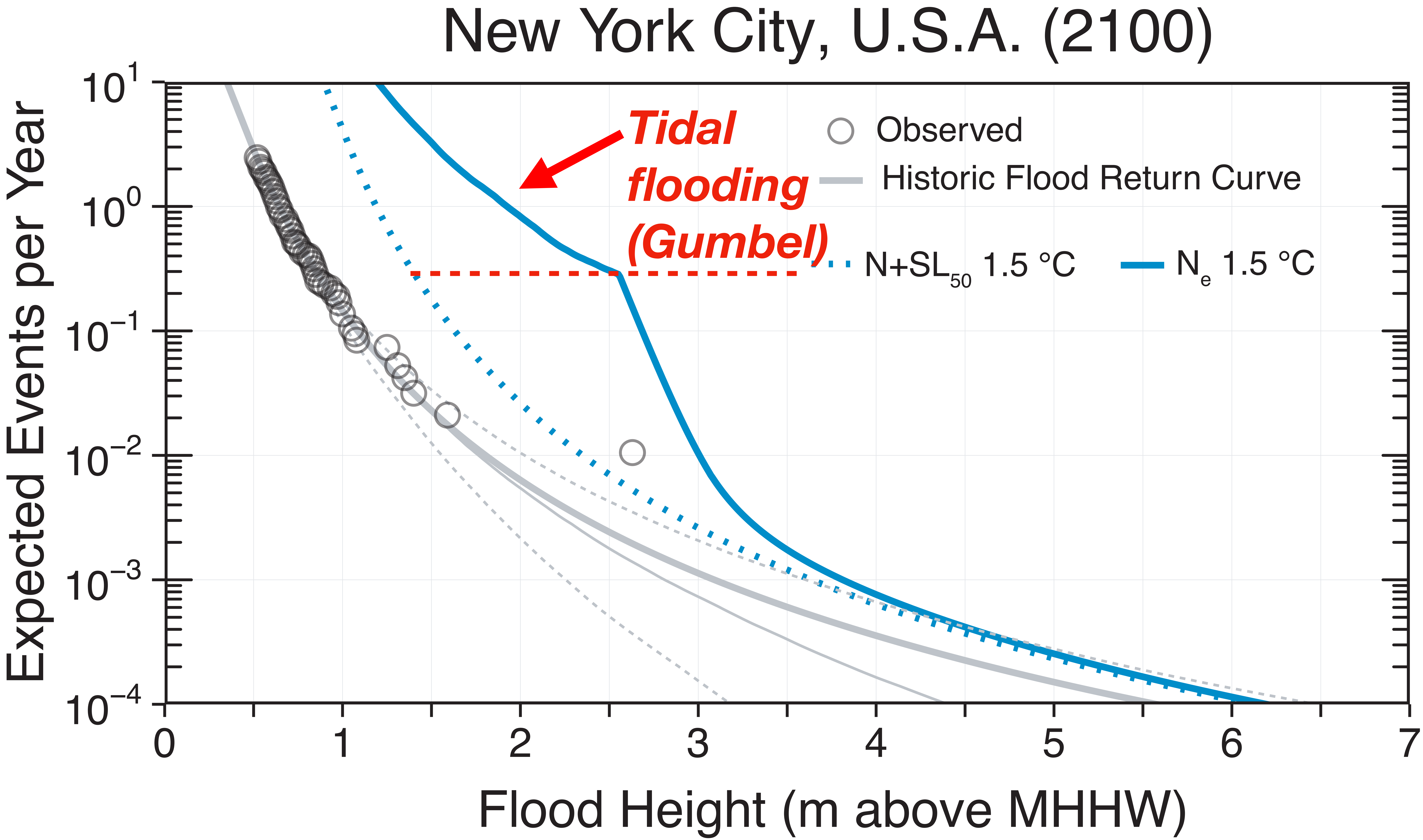
1.5 °C

Number of annual expected floods (NYC; 2100)
10-yr floods per year
(1.09 m above MHHW)
25
26
14
Current: 0.1 events per year
500-yr floods per year
(2.61 m above MHHW)
0.4
0.3
0.2
Current: 0.002 events per year
100-yr floods per year
(1.86 m above MHHW)
4
3
2
Current: 0.01 events per year
2.5 °C
2.0 °C
1.5 °C

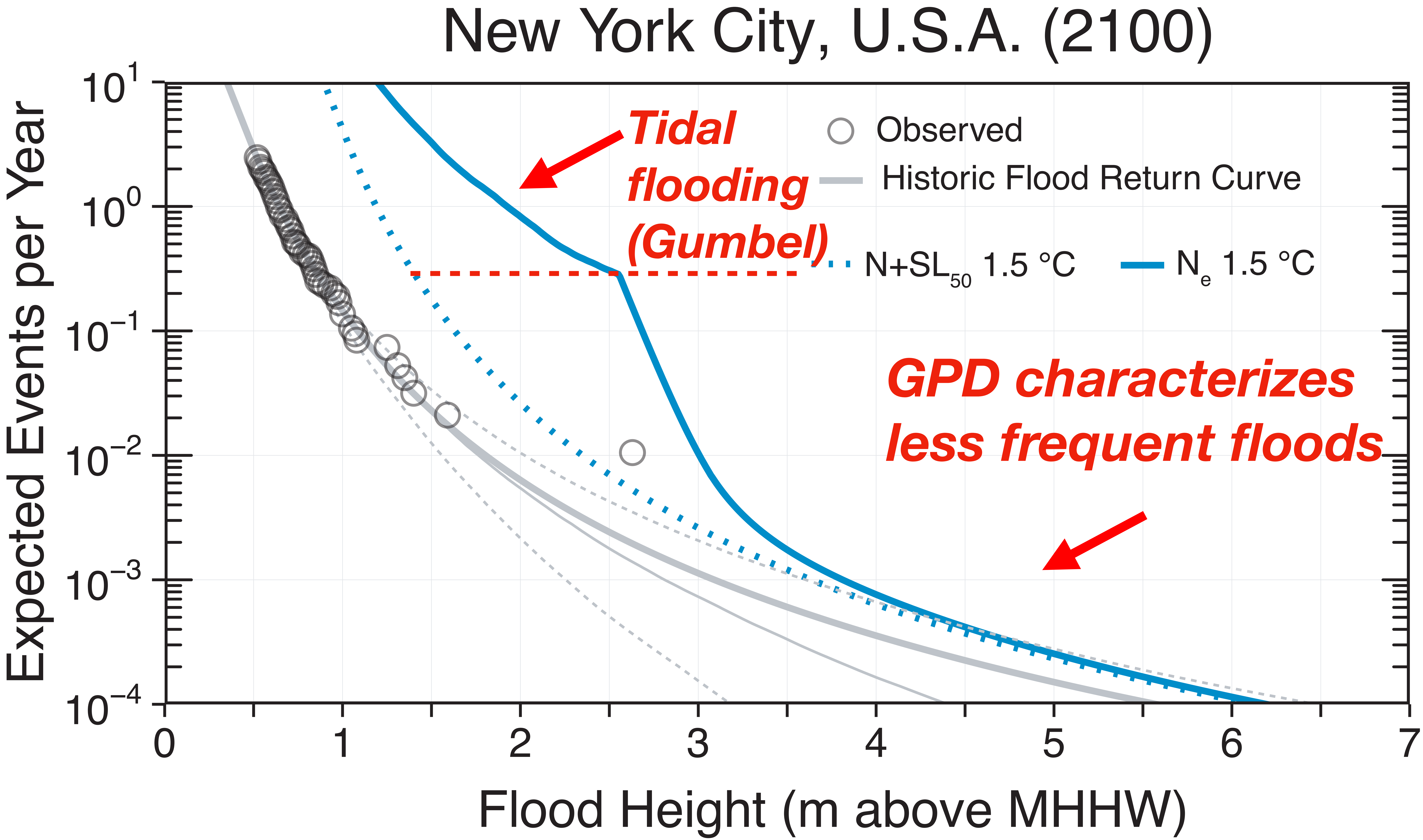

New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
Ne 1.5 °C
10^1
10^0
10^−1
10^−2
10^−3
10^−4
0
1
2
3
4
5
6
7



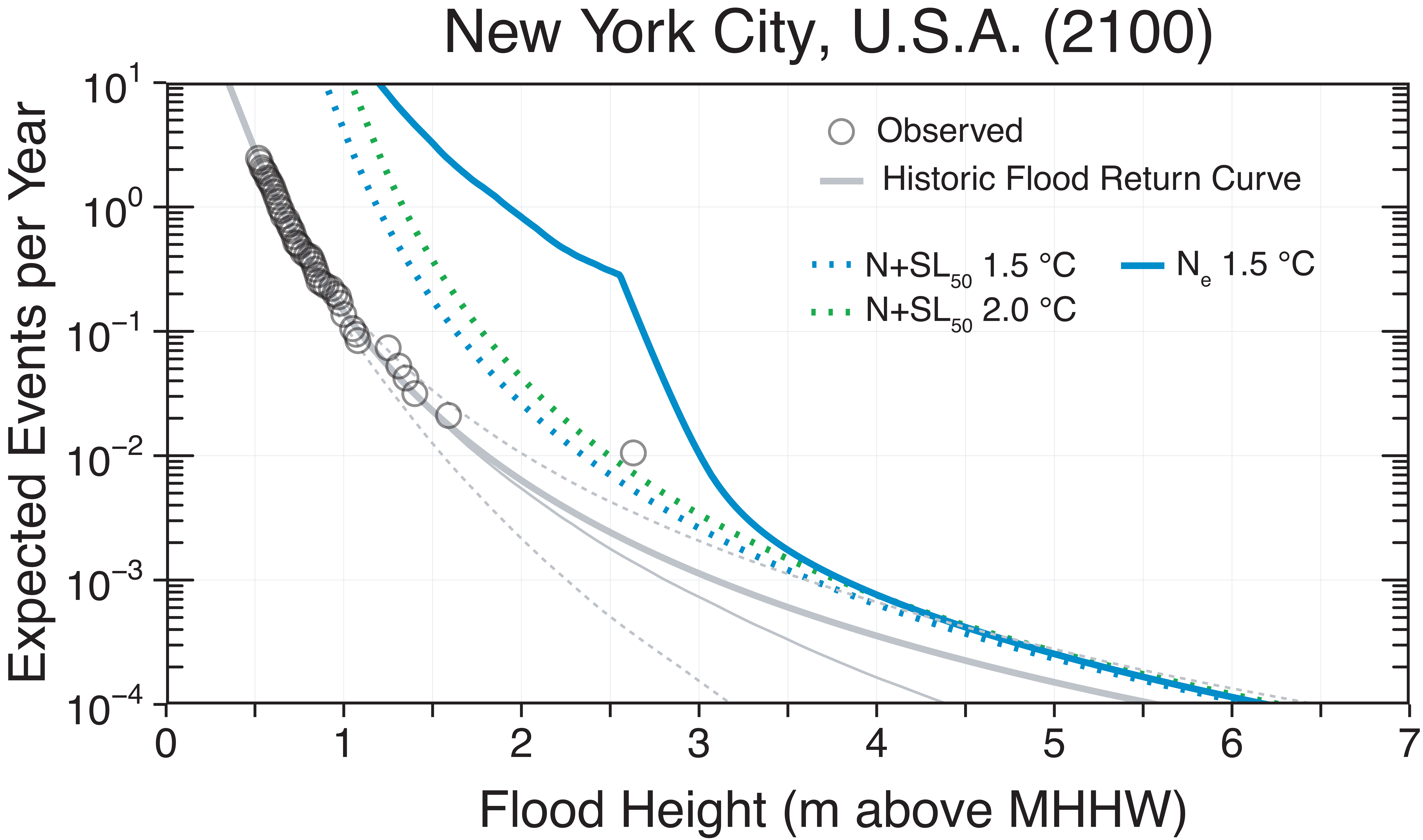
New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
Observed
Historic Flood Return Curve
$N+SL_{50}$ 1.5 °C
N_e 1.5 °C



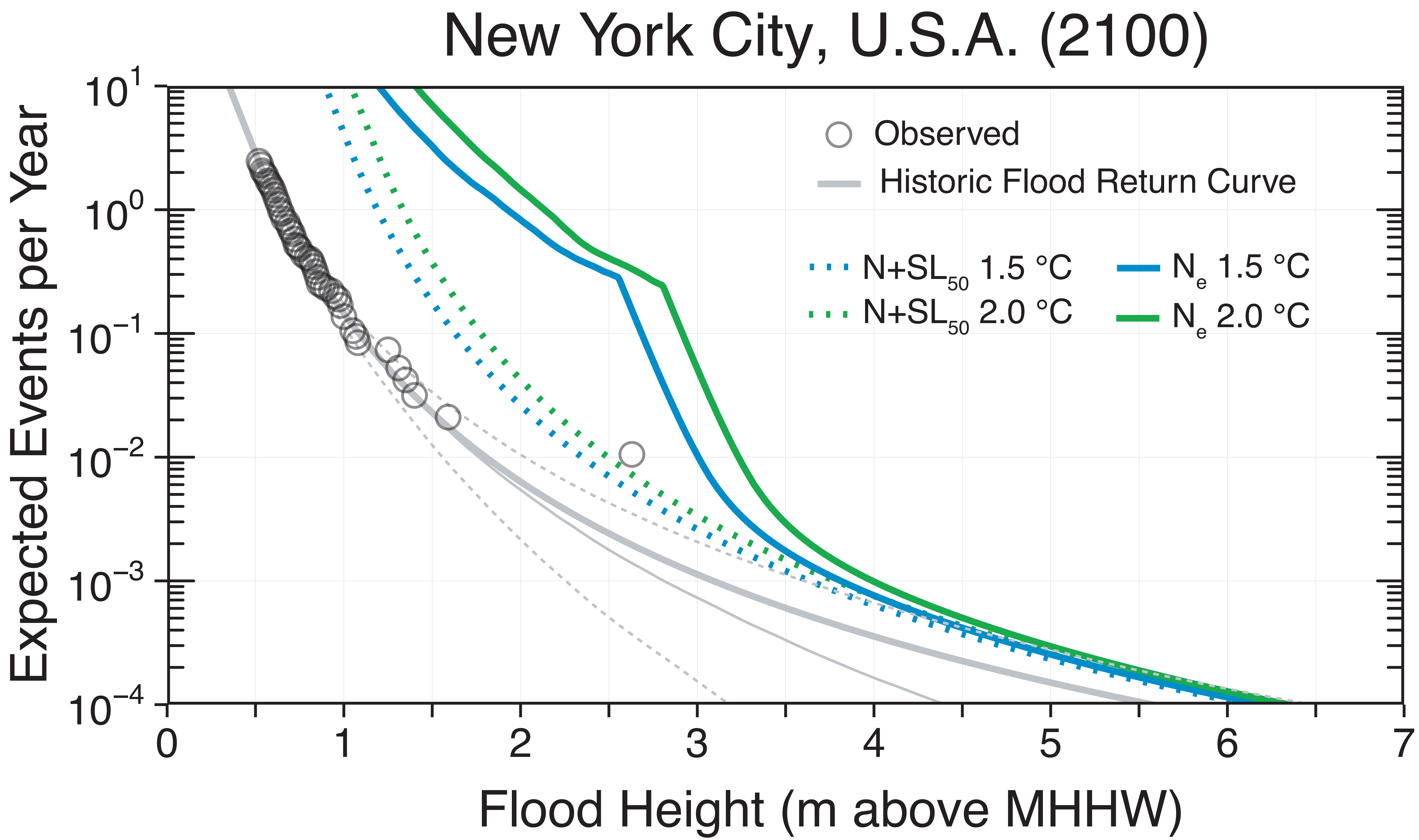
New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
Tidal flooding (Gumbel)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
Ne 1.5 °C
10^1
10^0
10^−1
10^−2
10^−3
10^−4
0
1
2
3
4
5
6
7

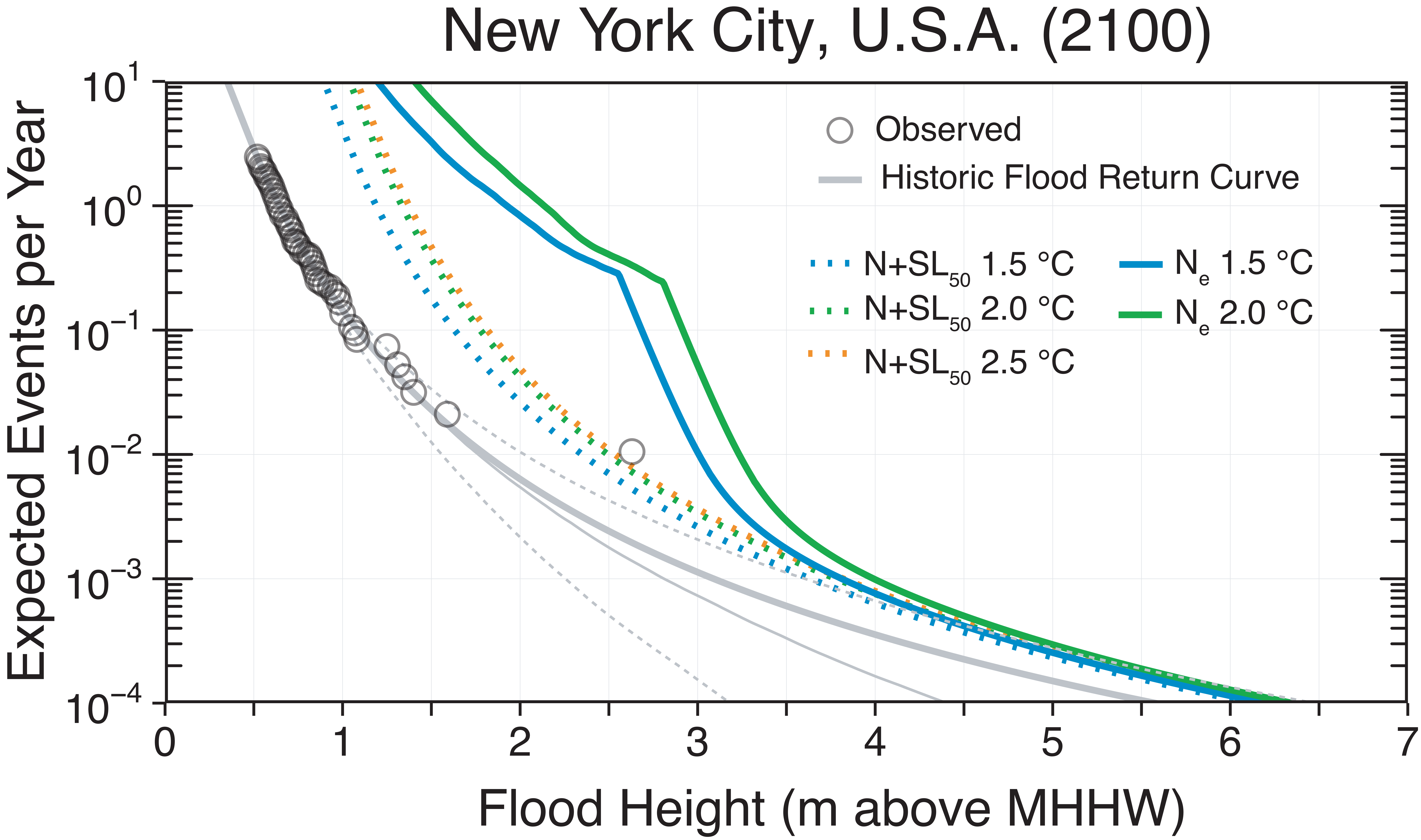


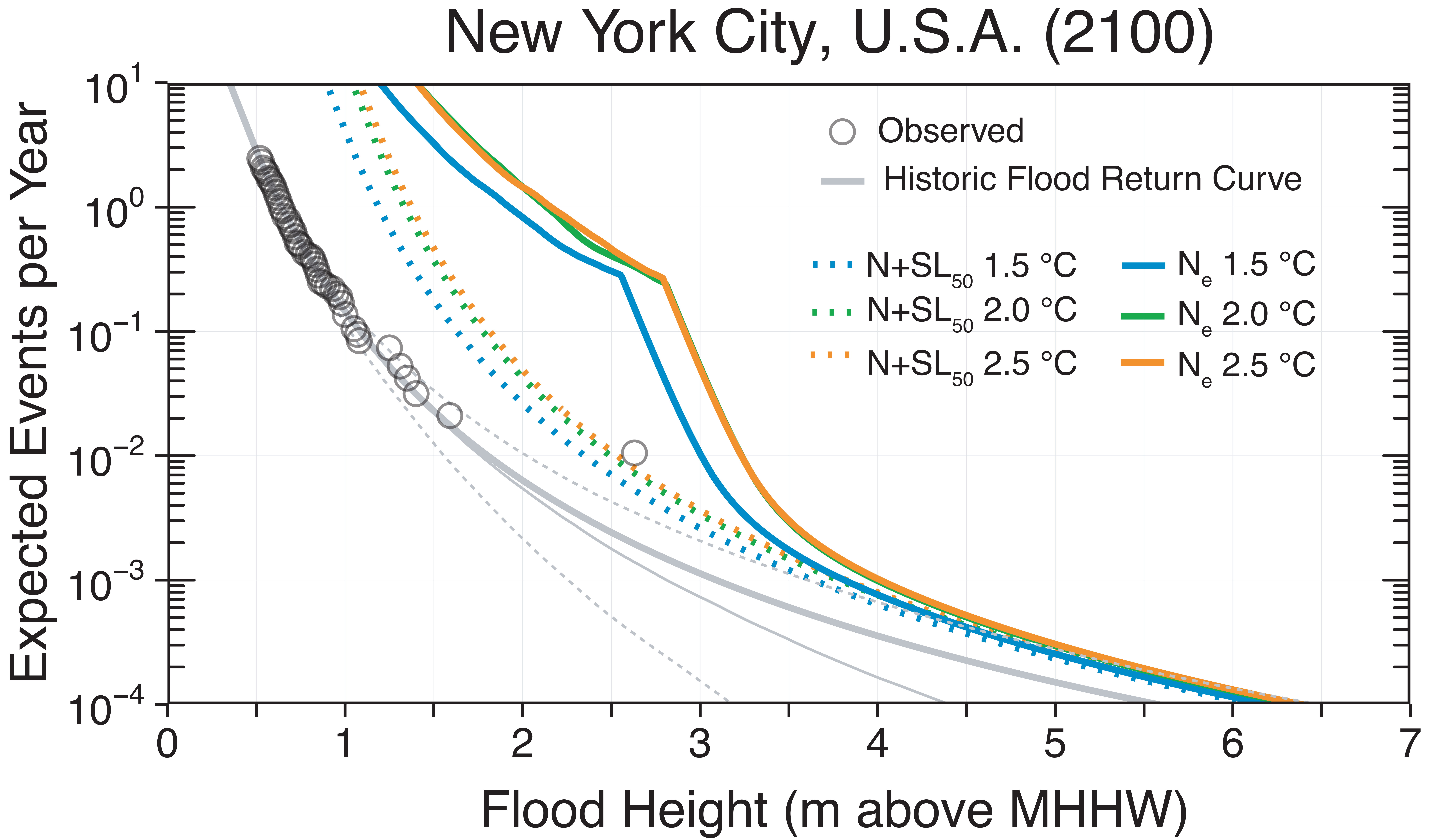
New York City, U.S.A. (2100)
Expected Events per Year
Flood Height (m above MHHW)
Tidal flooding (Gumbel)
GPD characterizes less frequent floods
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
Ne 1.5 °C



New York City, U.S.A. (2100)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
N+SL50 2.0 °C
Ne 1.5 °C
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)


New York City, U.S.A. (2100)
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
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
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
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)
Observed
Historic Flood Return Curve
N+SL50 1.5 °C
N+SL50 2.0 °C
N+SL50 2.5 °C
Ne 1.5 °C
Ne 2.0 °C
Ne 2.5 °C
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)

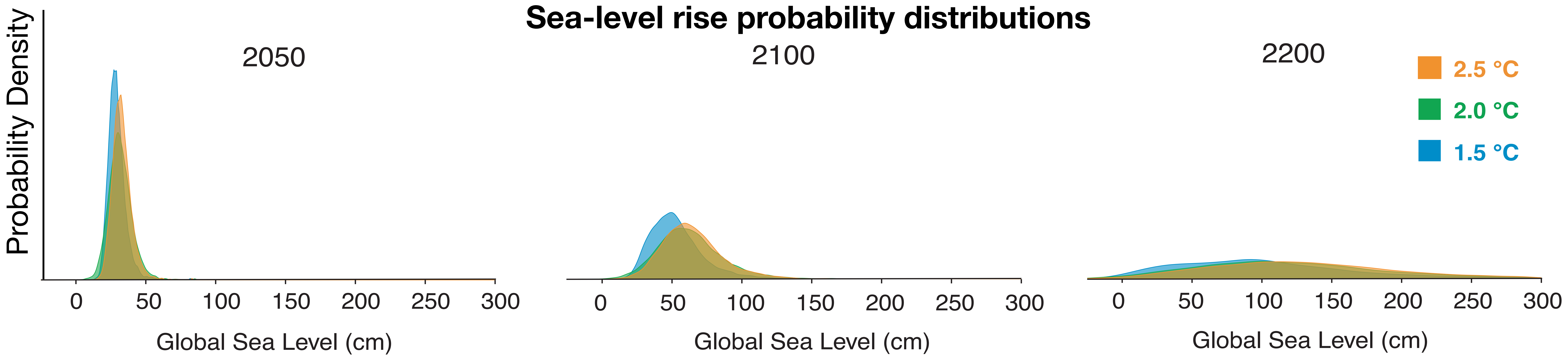
Global Mean Sea-Level (GSL) Rise Projections

GSL projections for 2100 with RCPs (for comparison)

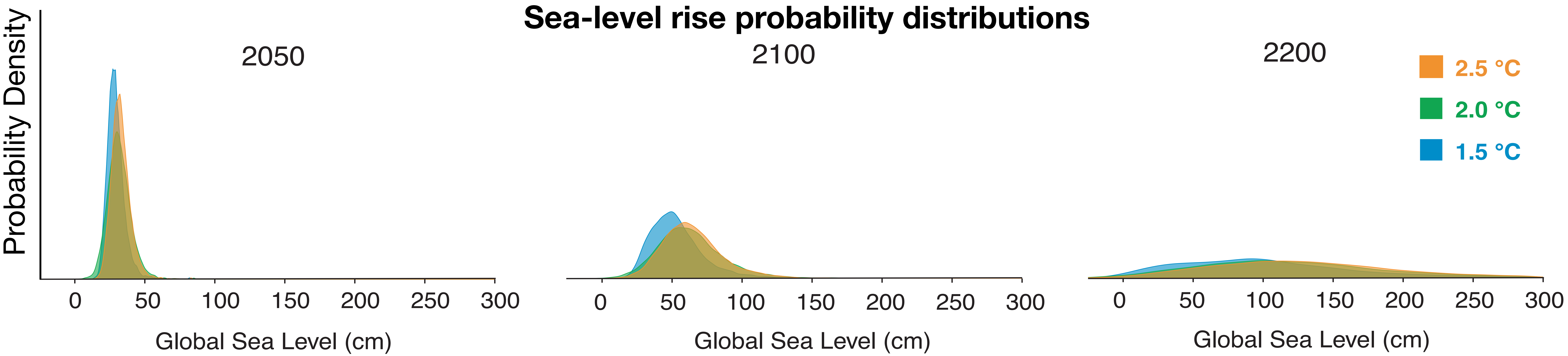
cm	50th	17th-83rd	5th-95th
1.5 °C	47	35-64	28-82
RCP2.6	50	37-65	29-82
RCP4.5	59	45-77	36-93

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

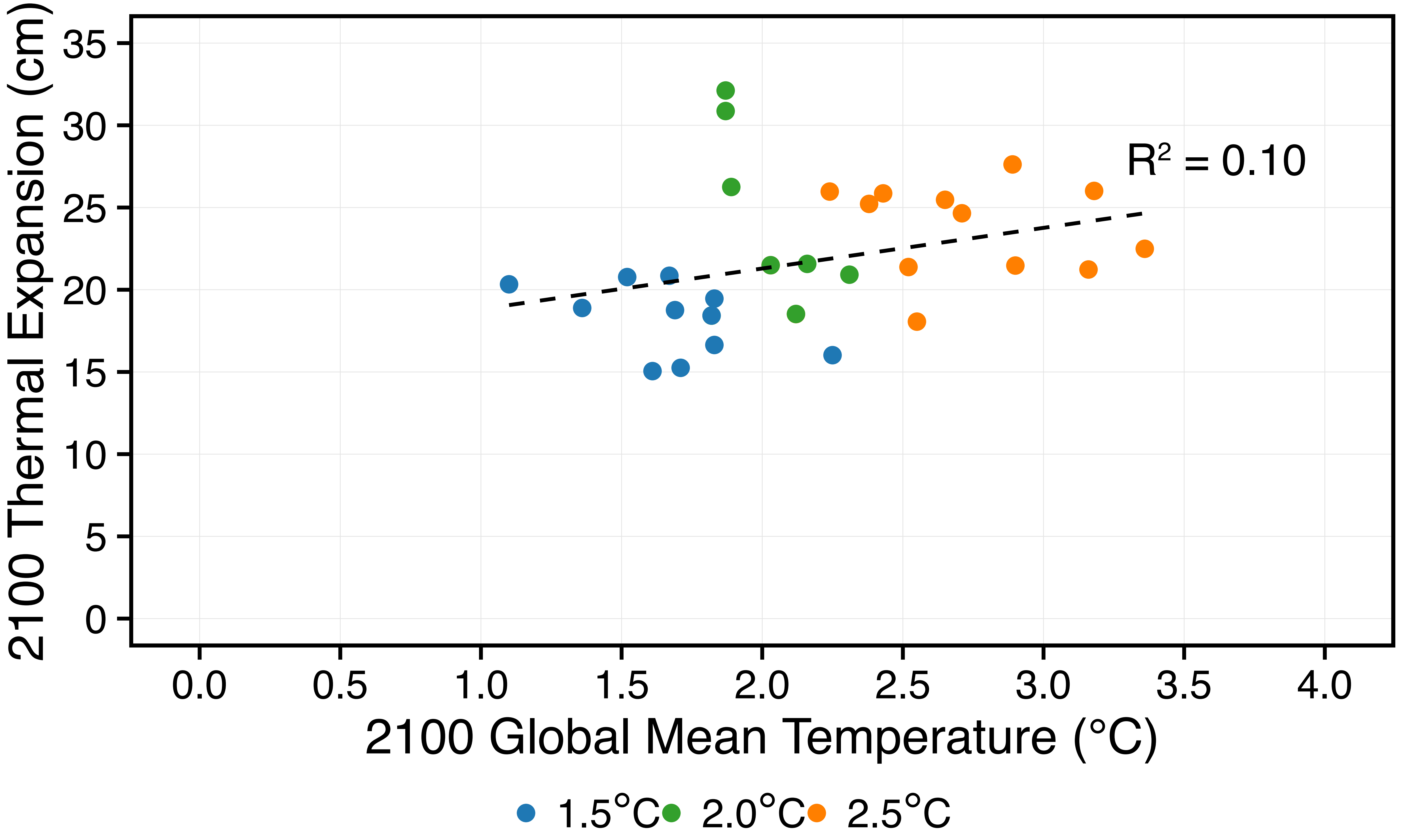
cm	50th	17th-83rd	5th-95th
2.5 °C	58	44-75	36-93
RCP4.5	59	45-77	36-93
RCP8.5	79	62-100	52-121



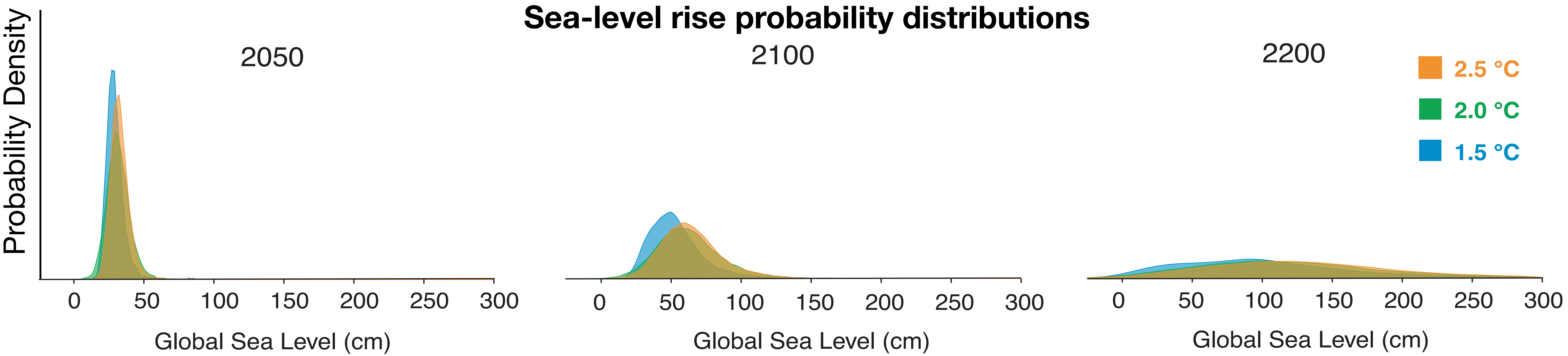
[Rasmussen et al., in rev.]



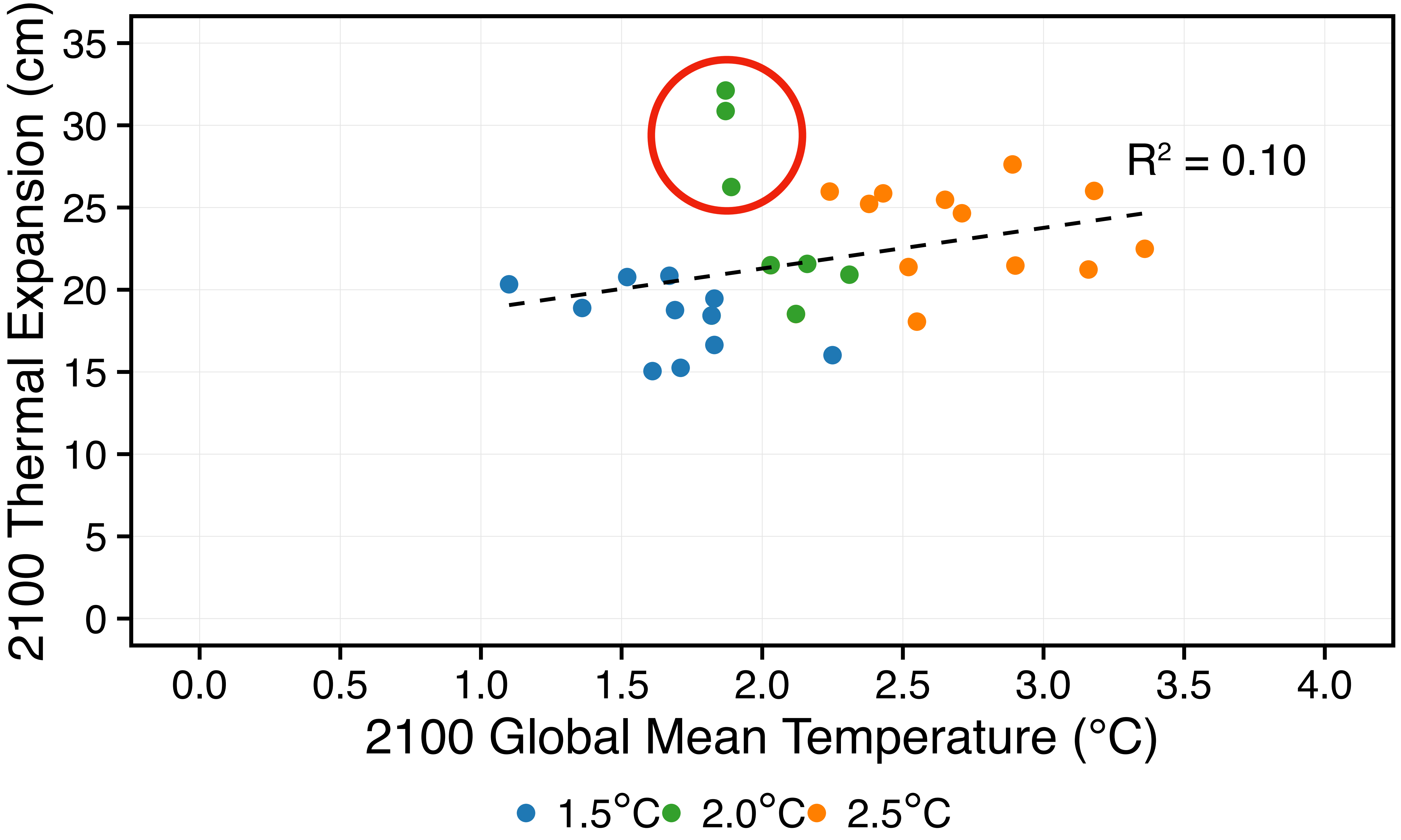
2.0 °C and 2.5 °C scenarios overlap b/c thermal expansion not strongly correlated with temperature across models



[Rasmussen et al., in rev.]



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

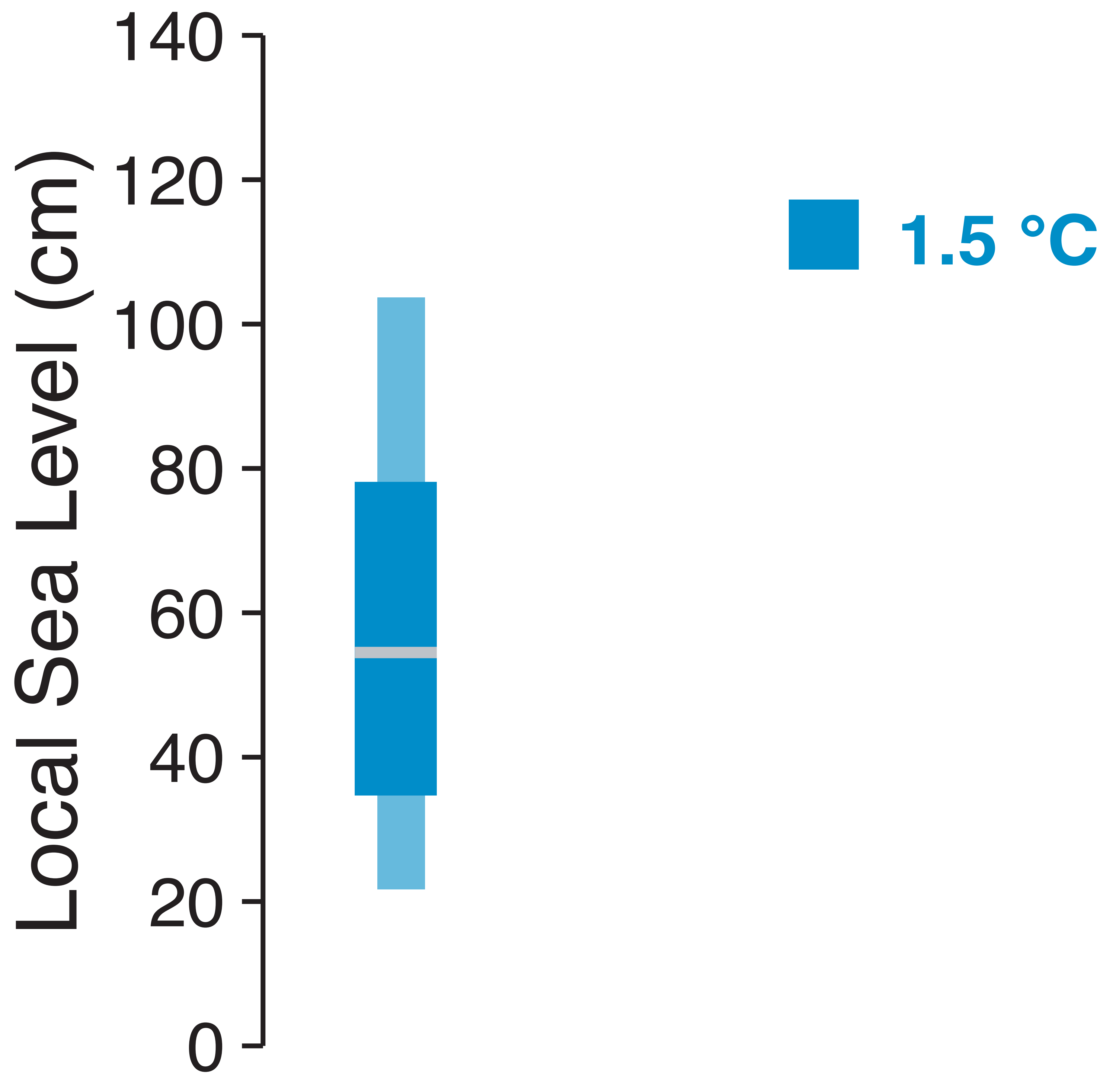


[Rasmussen et al., in rev.]

What about Local SLR?

Case Study: New York City

Local Sea-Level Rise Projections:

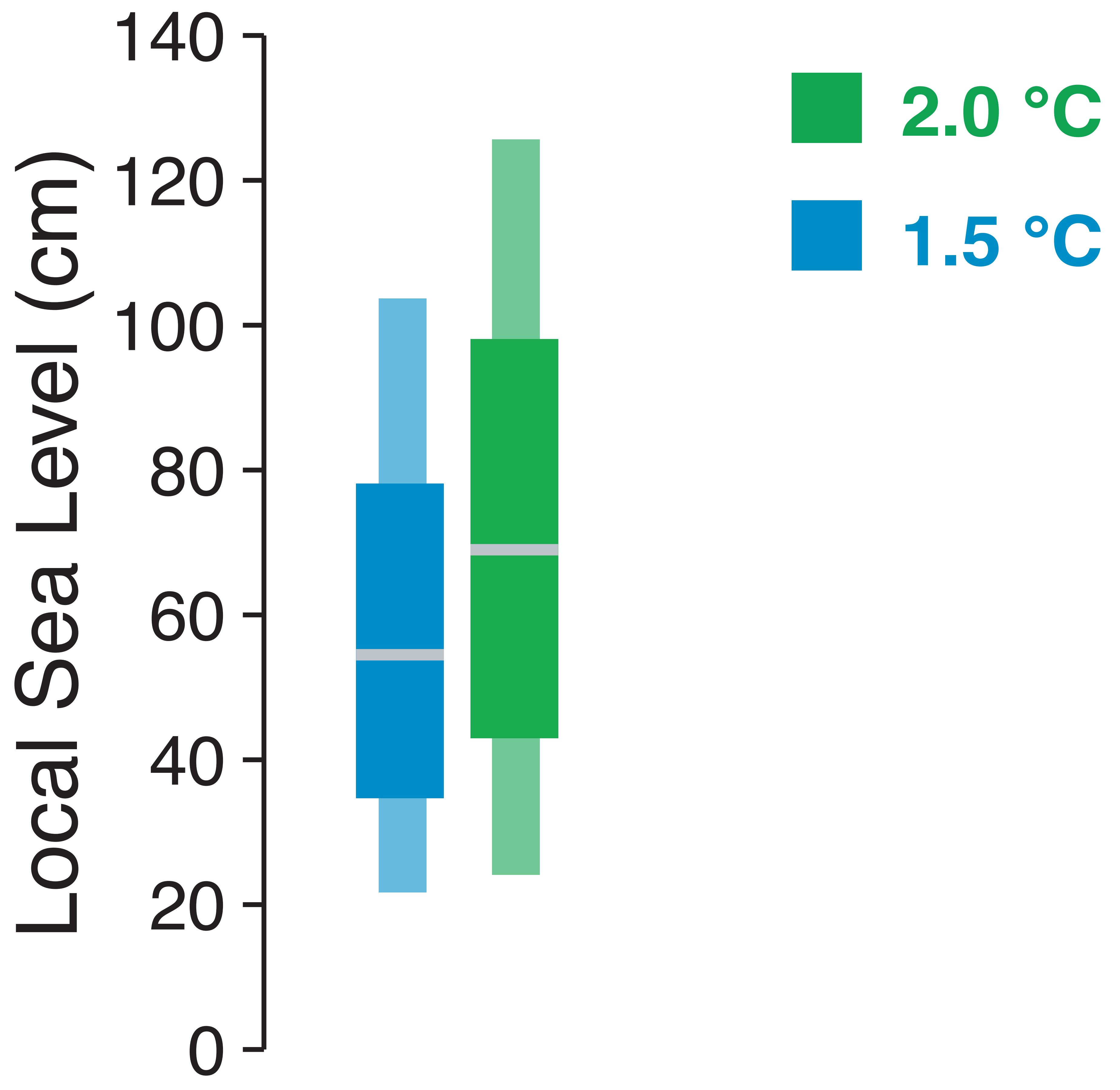


[Rasmussen et al., in rev.]

What about Local SLR?

Case Study: New York City

Local Sea-Level Rise Projections:

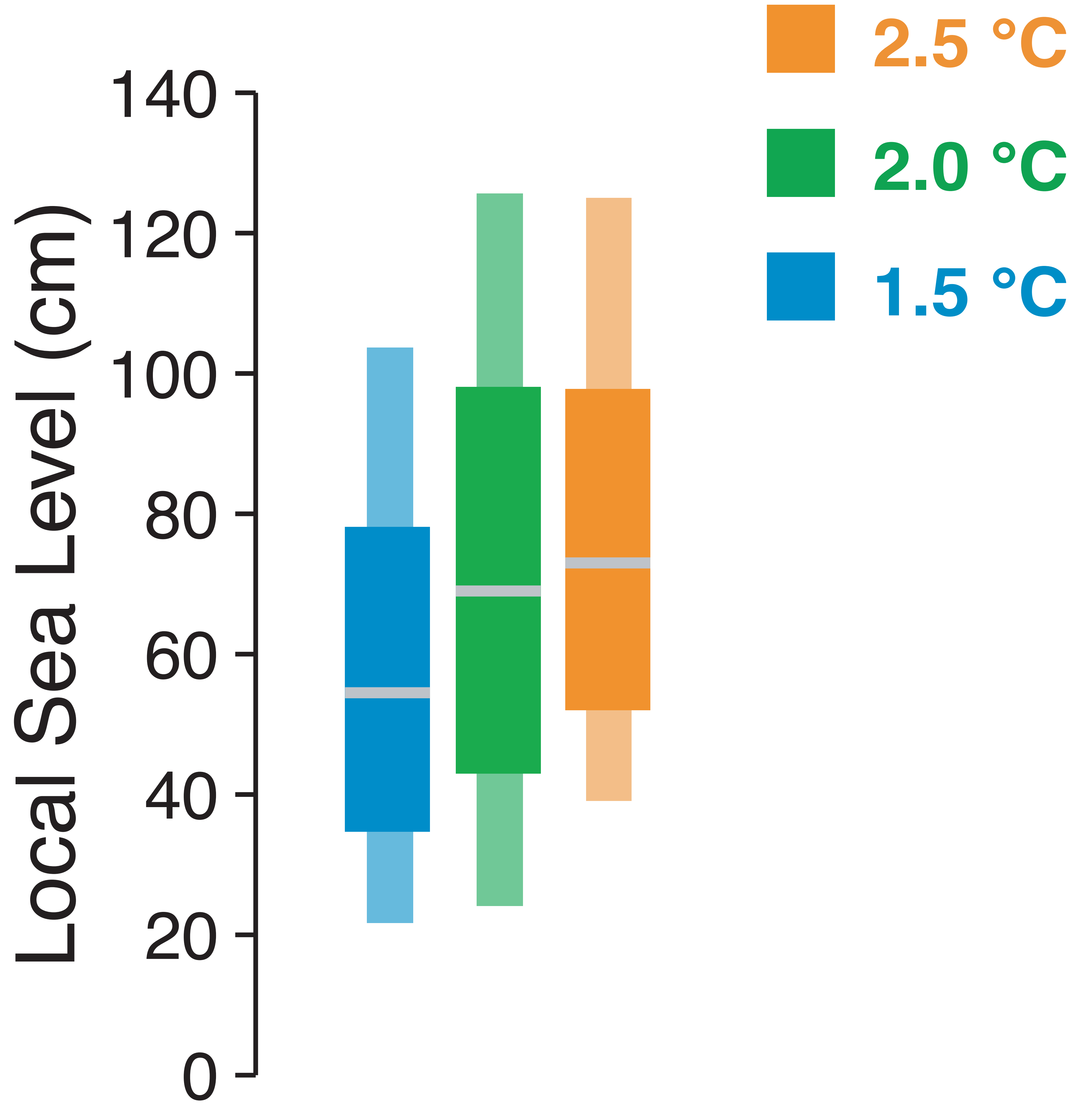


[Rasmussen et al., in rev.]

What about Local SLR?

Case Study: New York City

Local Sea-Level Rise Projections:



[Rasmussen et al., in rev.]