Demystifying sea level rise and coastal flooding projections

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September 27, 2022
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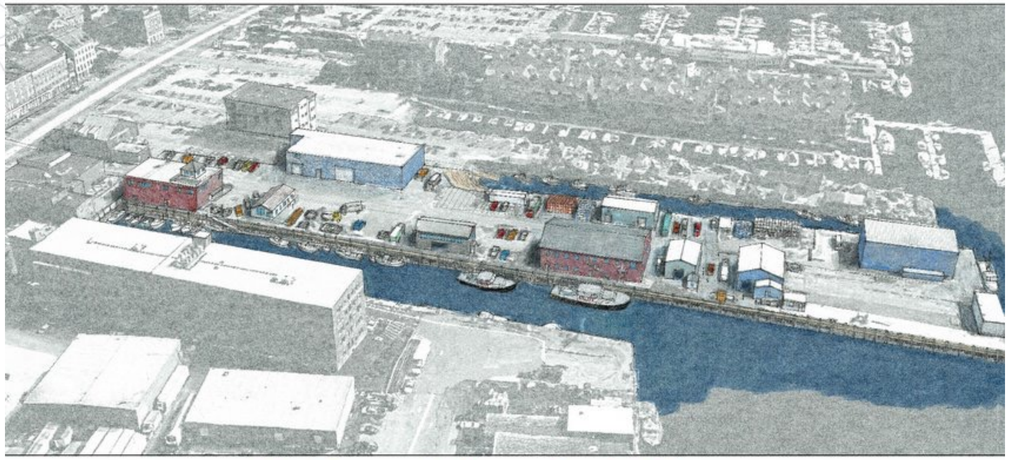
Gulf of Maine Research Institute
Science. Education. Community.

Coastal Hazards and Sea Level Rise Lab at Gulf of Maine Research Institute

Goal: Develop localized flood projections that can be used for community-scale planning along Maine's open coast and estuaries



Union Wharf
THE HEART OF PORTLAND'S WORKING WATERFRONT
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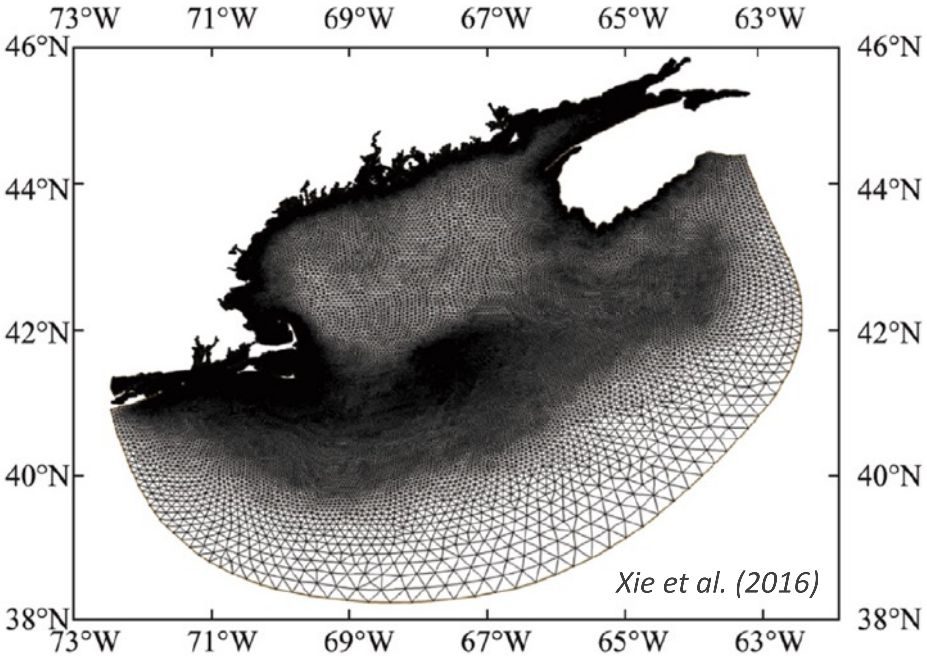

(a) Finite element grid

science.nasa.gov/learners/highlights

beaufortcountysc.gov/news

You are tasked with considering sea level rise and/or coastal flooding in project design or decision-making.

¯_(ツ)_/¯

< ShrugBot >

Outline

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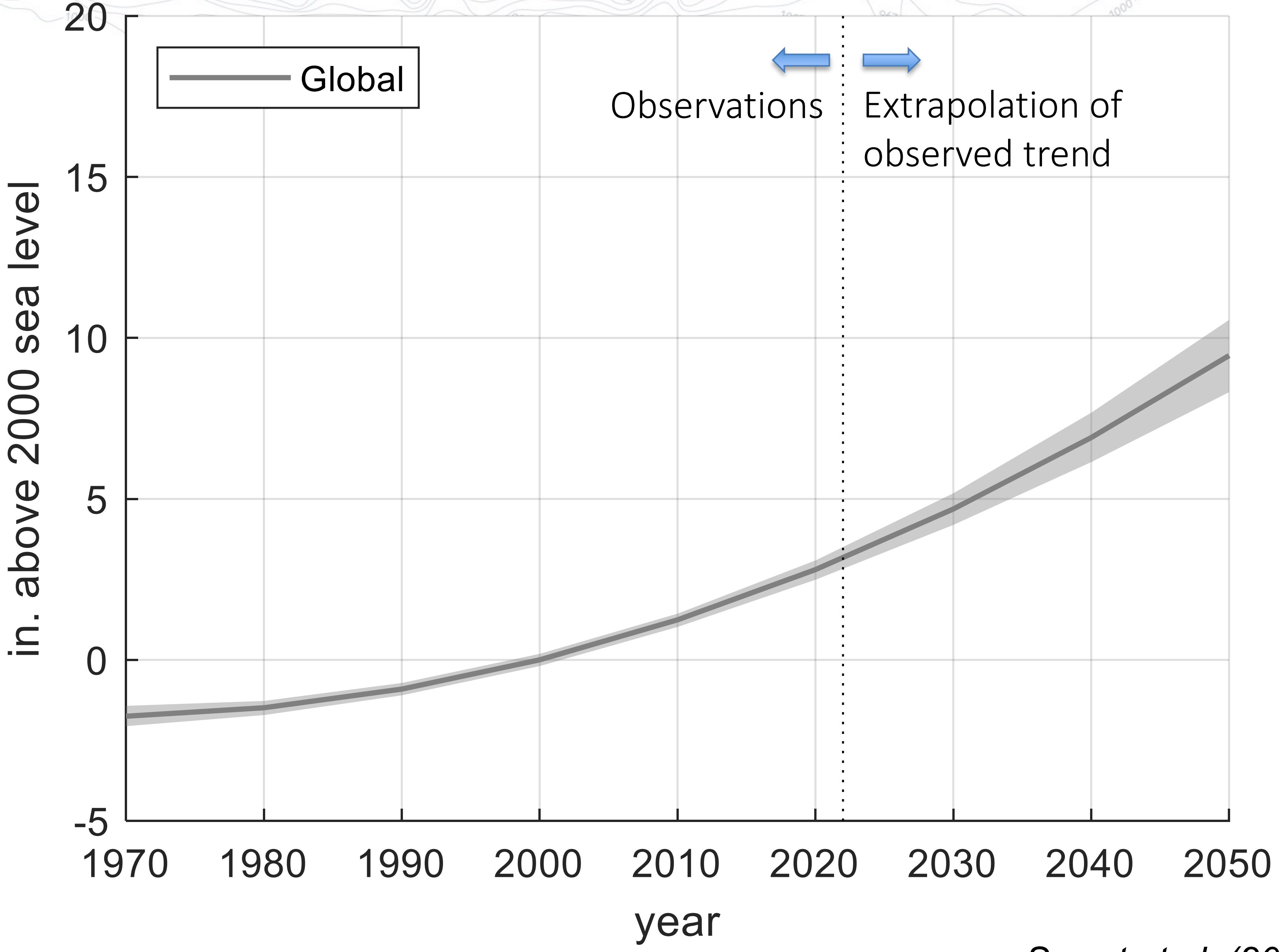
My goal: provide foundational knowledge for interpreting and choosing among available resources.

- Fundamental sea level science
- IPCC and U.S. Interagency Taskforce sea level rise projections (and context for the Maine state-adopted projections)
- Physical drivers of flooding
- High tide and extreme flooding projections

Sea level fundamentals



Sweet et al. (2022)

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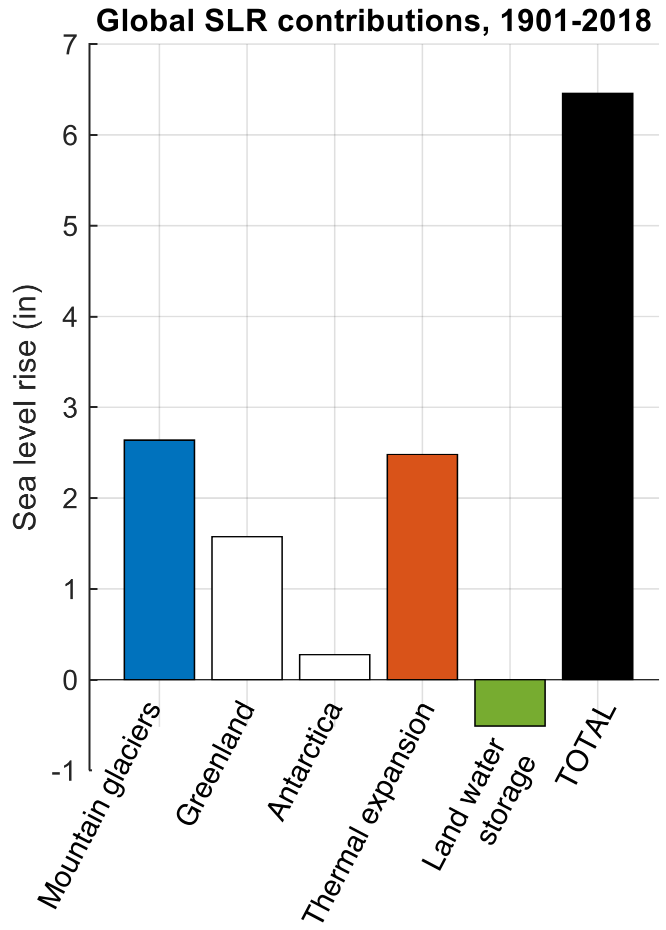
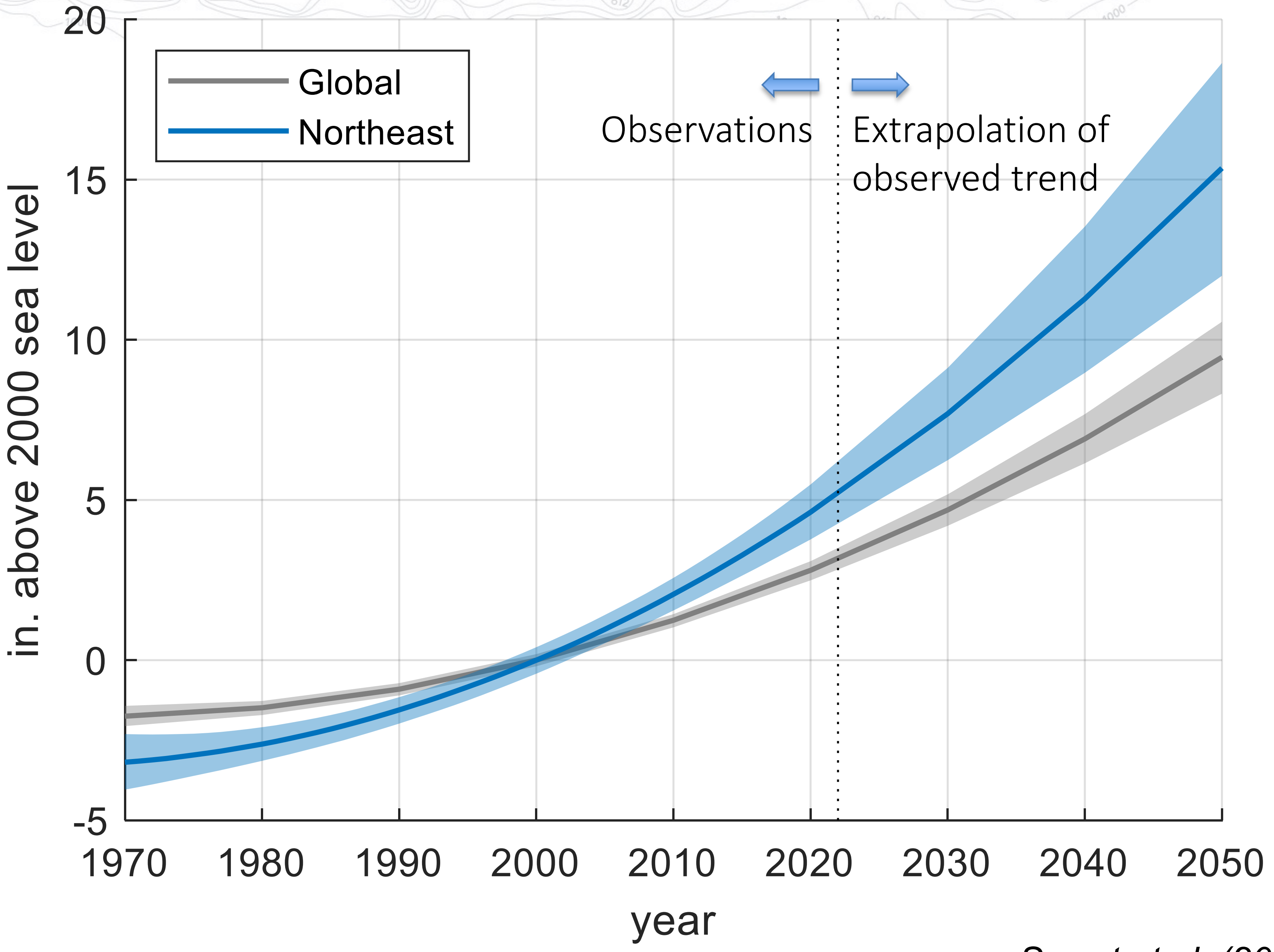


Fox-Kempner et al. (2021)



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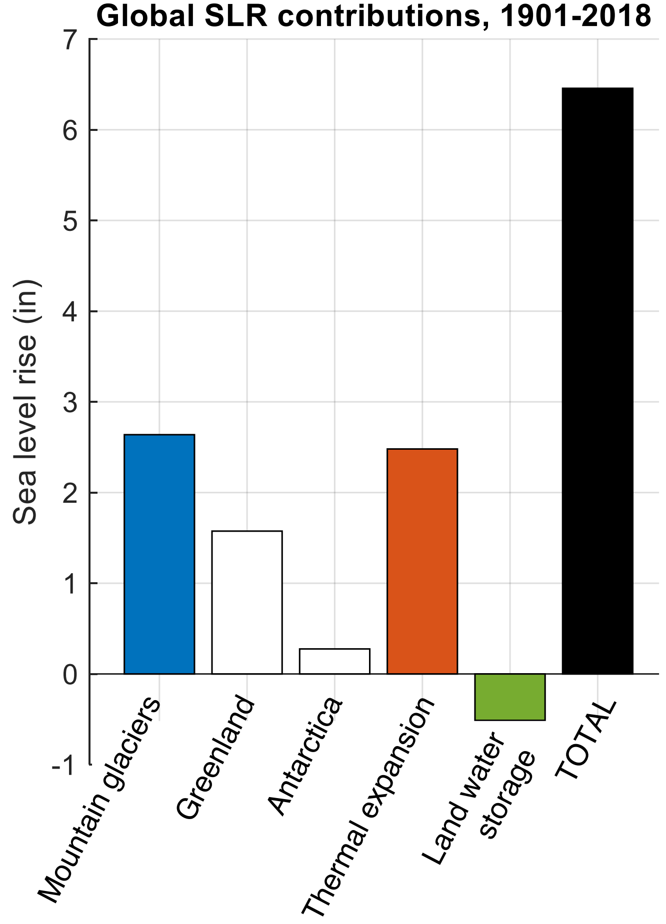

Fox-Kempner et al. (2021)

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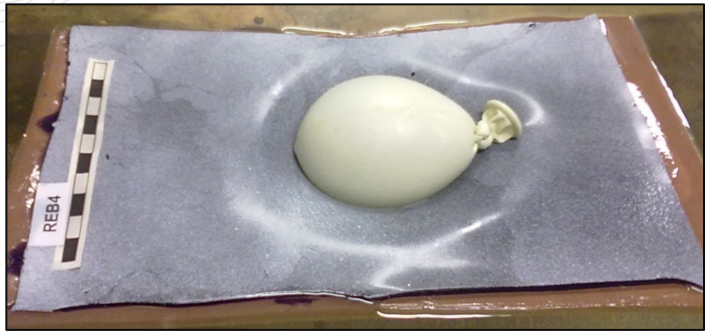
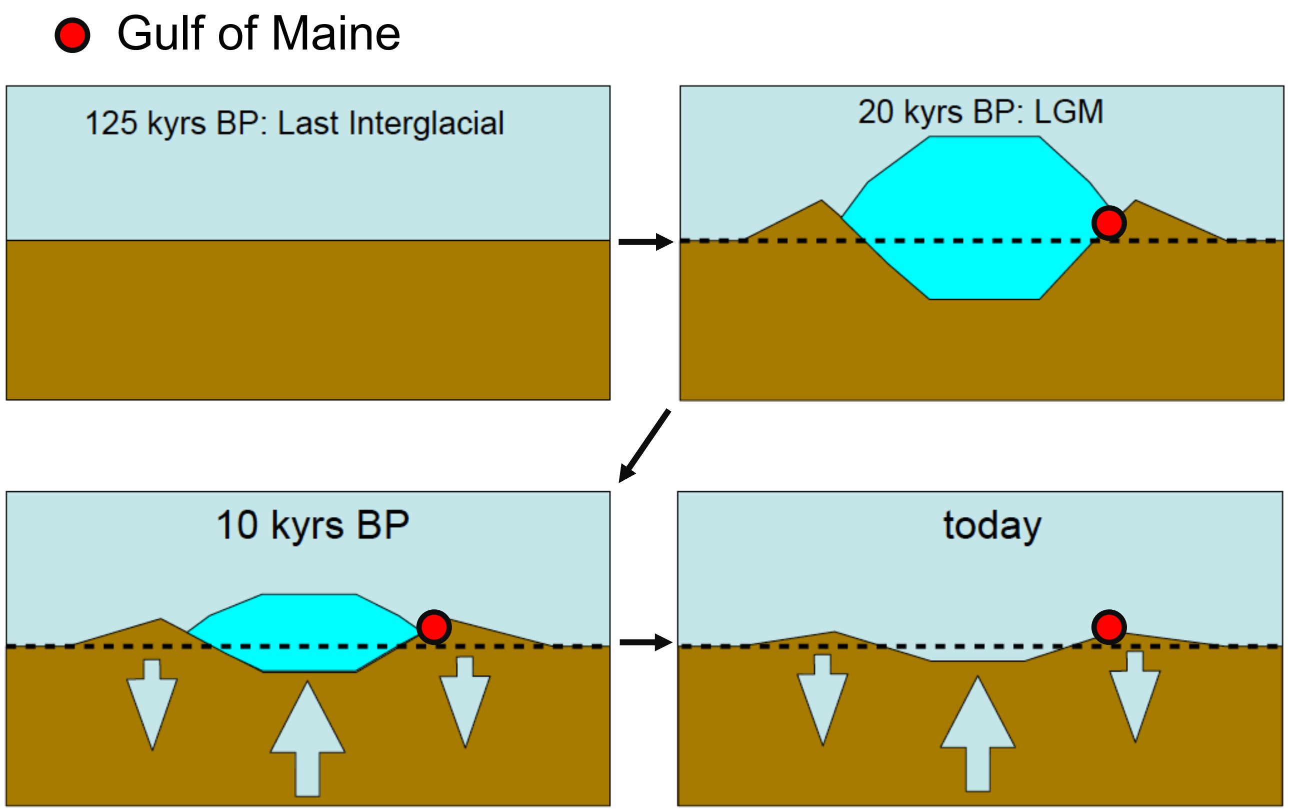
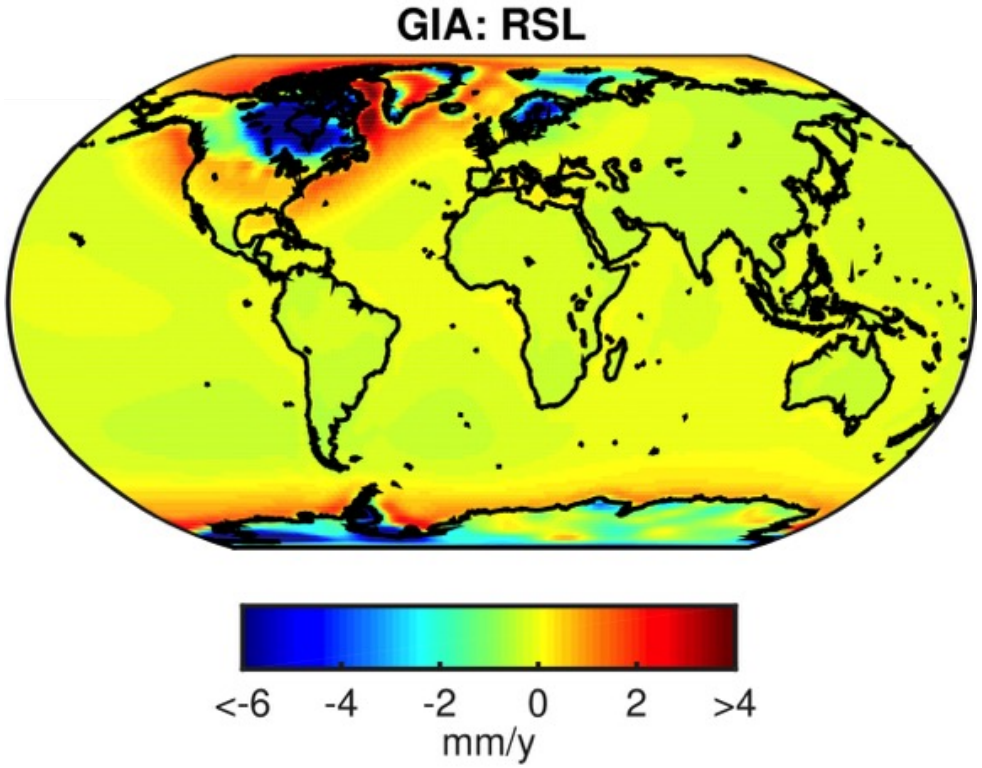
Glacio-isostatic adjustment (GIA)

The Gulf of Maine coast is subsiding (sinking) as the land surface adjusts from the last ice age

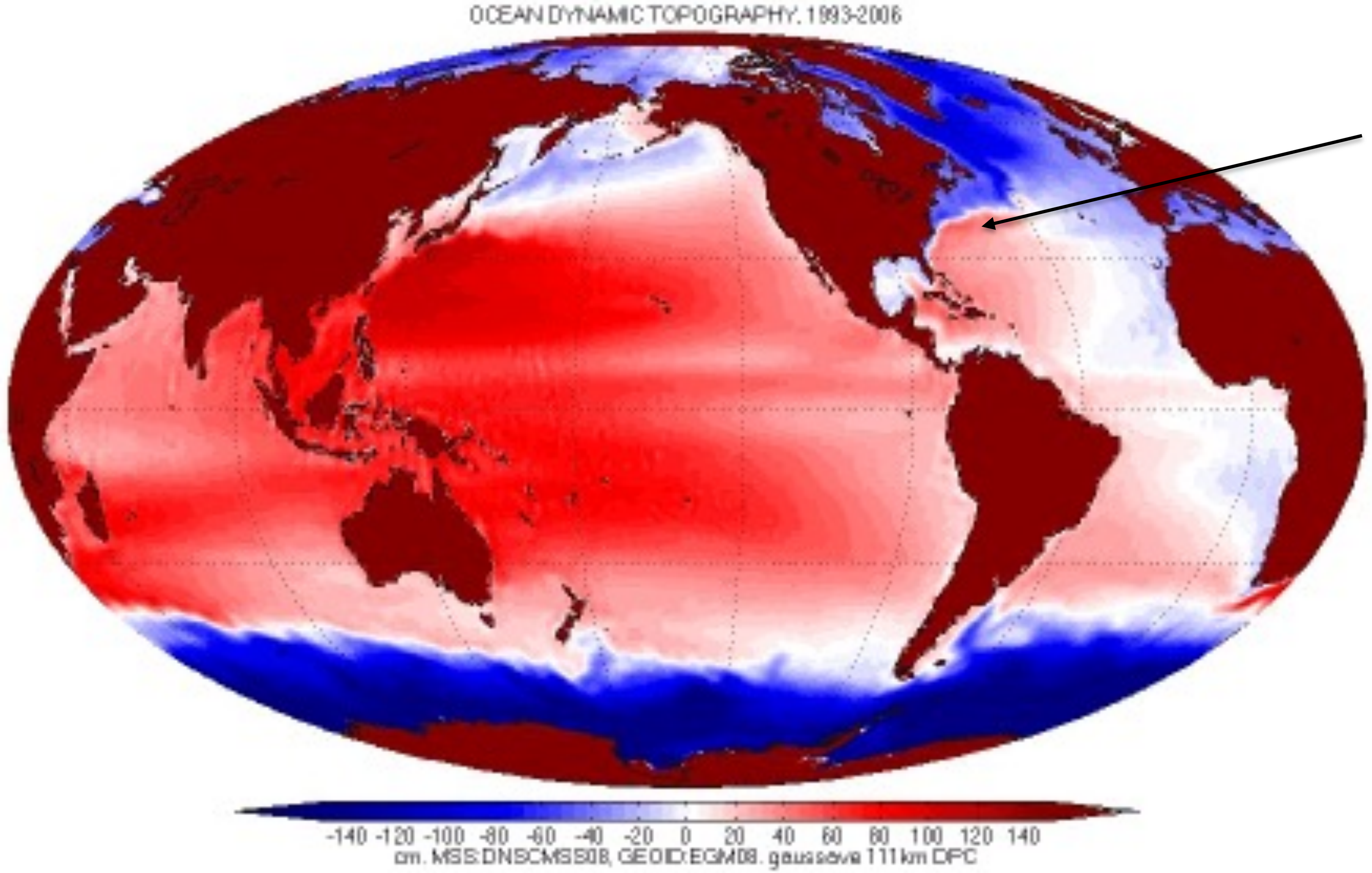






Credit: Paolo Stocchi, Bob Kopp

Currents and tides cause the ocean surface height to vary by several feet



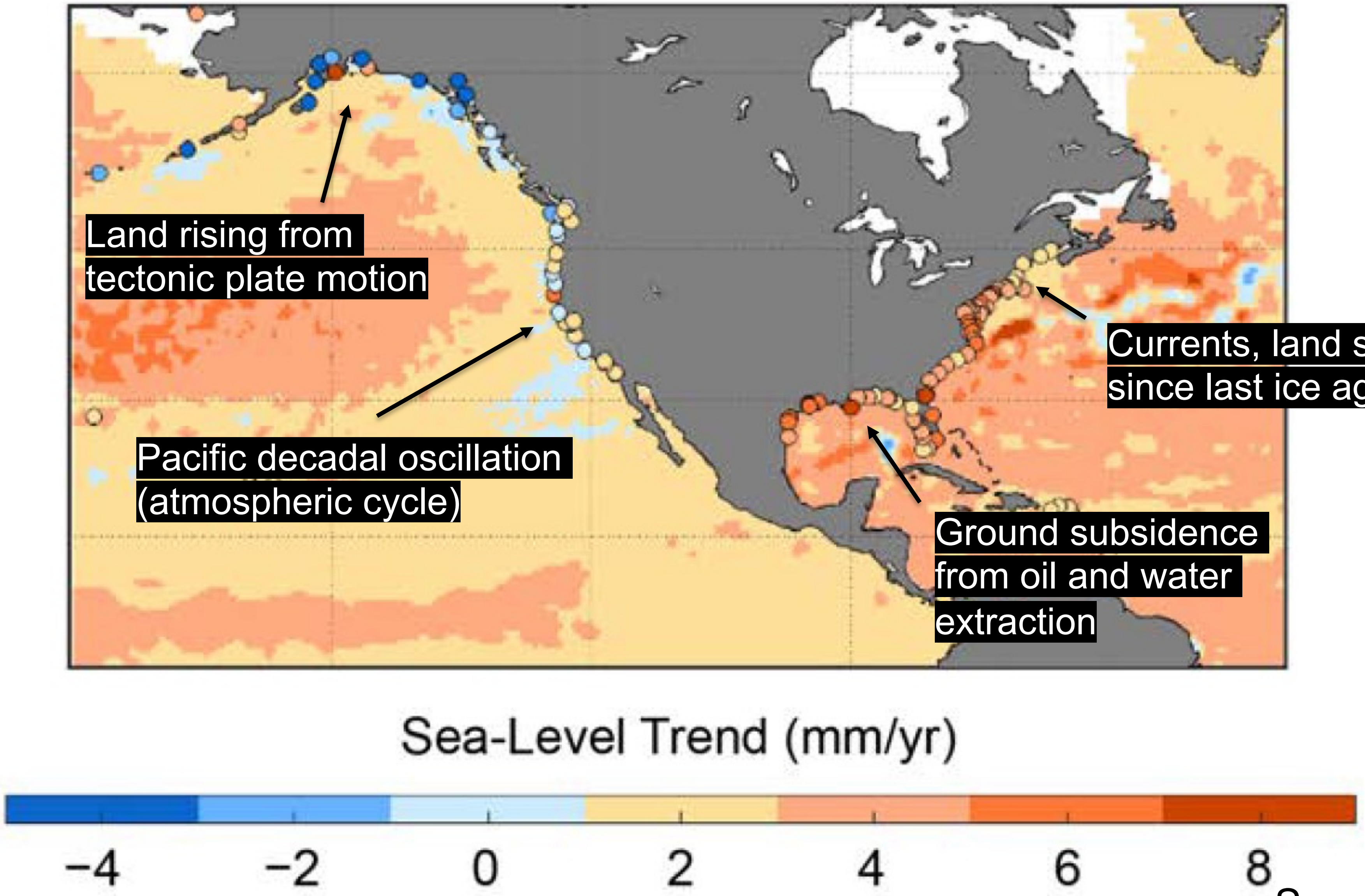
NASA JPL

As the Gulf Stream turns eastward, it “pulls” water away from the Atlantic Coast

Gulf stream is slowing down

→ Less water pulled from coast, and sea level increases along the Atlantic seaboard

Sea level rise rate, 1993-2020

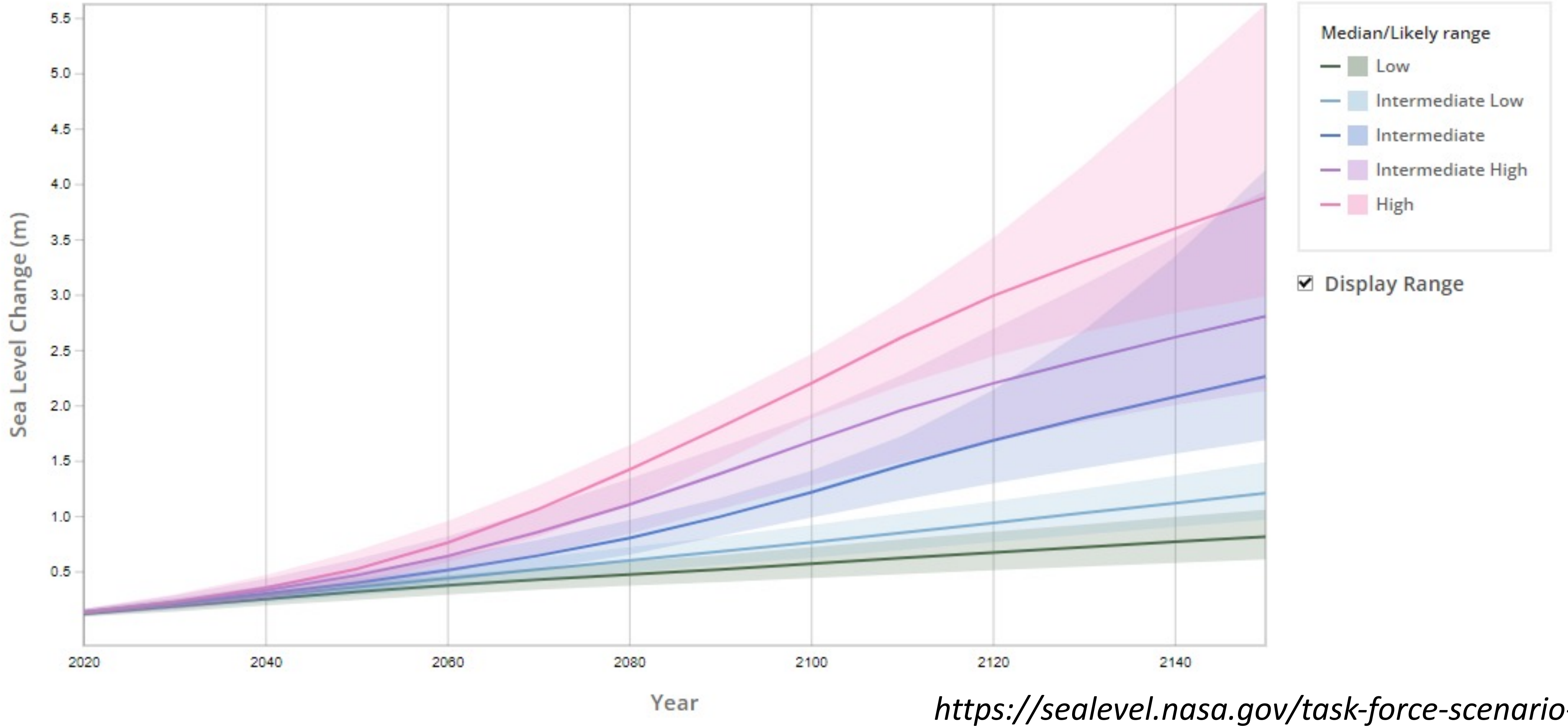


Sweet et al. (2022)

Sea level rise projections

A general point (don't worry about reading the axes)

2022 NOAA report: Northeast U.S. sea level rise projections



https://sealevel.nasa.gov/task-force-scenario-tool

Greenland: 1.6 inches so far, 23 ft potential

Antarctica: 0.2 inches so far; 187 ft potential

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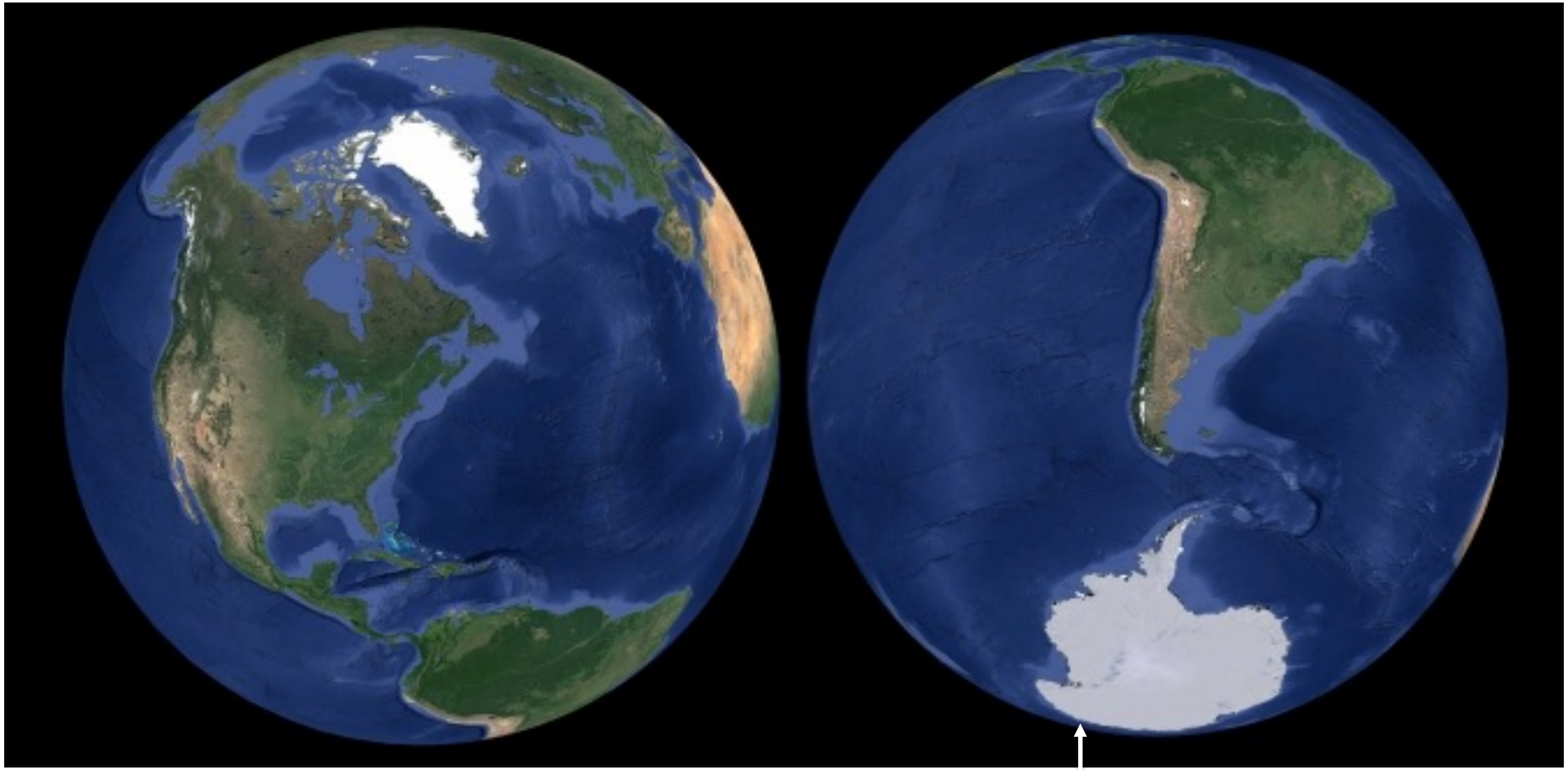
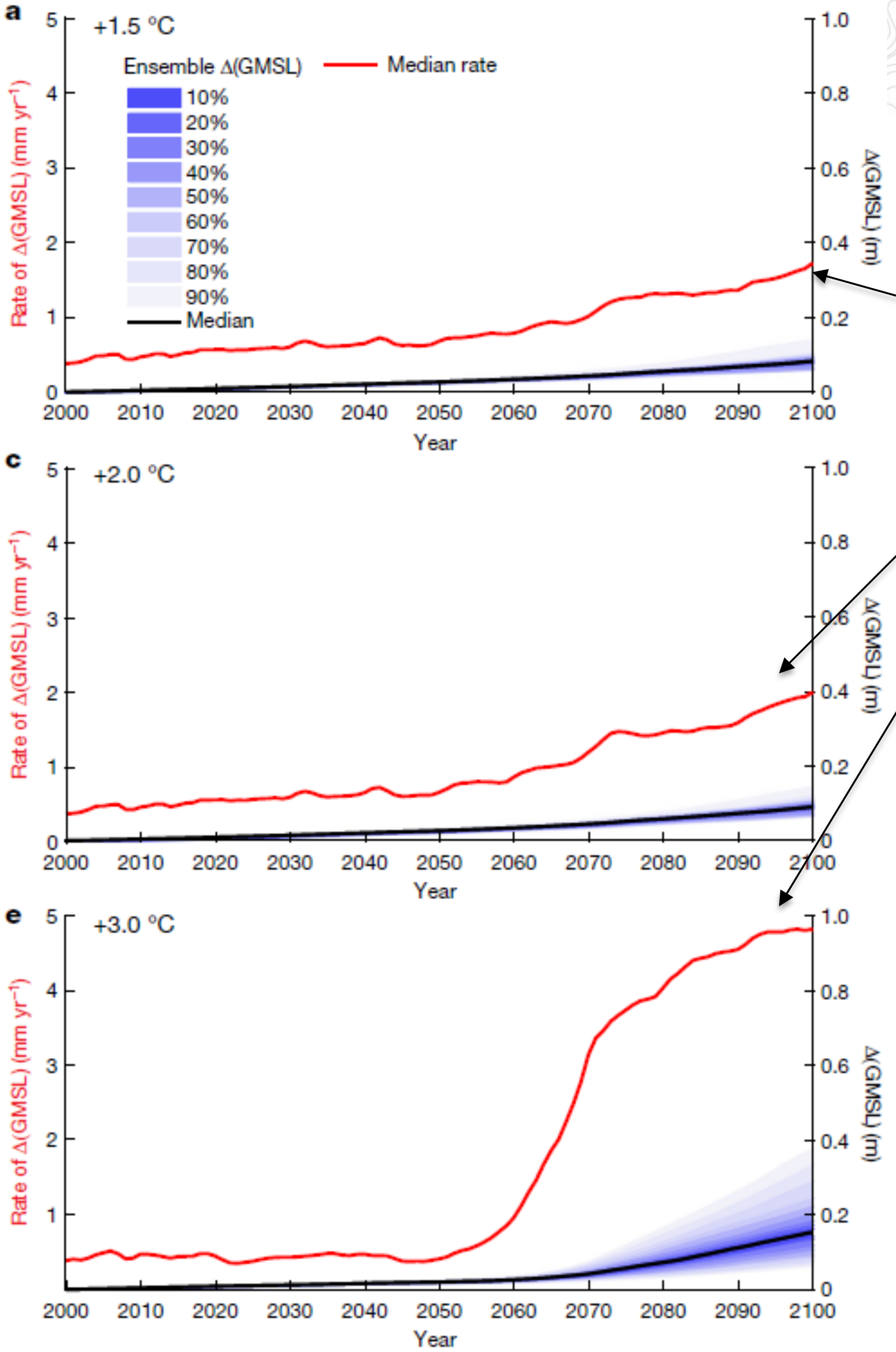


“Deeply uncertain ice sheet processes”



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Rate of sea level rise from Antarctica with 1.5, 2.0, and 3.0 degrees of warming

"These results demonstrate the possibility that rapid and unstoppable sea-level rise from Antarctica will be triggered if Paris Agreement targets are exceeded."

DeConto et al. (2021), *Nature*

Localized probabilistic projections

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AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE
10.1002/2014EF000239

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) major advances:

- Global mean sea level change → Local sea level change
- Likely sea level change → All probabilities, including tail risk

Parks, trails, etc. ← → Critical infrastructure

				Likely range					
		0.99	0.95	0.83	0.5	0.17	0.05	0.01	0.001
RCP8.5	2020	1	5	8	13	17	21	25	31
	2030	4	9	14	20	27	33	40	54
	2050	12	19	27	39	52	65	83	127
	2070	19	31	44	63	85	109	145	239
	2100	28	49	72	105	146	192	273	476
	2200	118	148	184	257	378	550	904	1,690
RCP4.5	2020	3	6	8	12	15	18	21	25
	2030	6	10	14	19	24	28	33	43
	2050	9	16	23	34	44	54	66	95
	2070	13	23	34	50	68	84	105	161
	2100	16	31	48	73	100	129	173	290
	2200	23	54	89	147	230	335	543	1,050
RCP2.6	2020	3	6	9	13	16	19	22	27
	2030	4	8	13	19	25	30	35	44
	2050	4	12	20	32	43	53	64	85
	2070	6	16	27	43	59	73	90	130
	2100	6	20	35	56	78	101	133	214
	2200	41	54	69	97	143	208	341	680

R. DeConto, H. Baranes, J. Woodruff, A. Halberstadt, R. Kopp. (2022), *Climate Change Impacts and Projections for the Greater Boston Area*

IPCC and U.S. Interagency Task Force

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U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force

- Sweet et al. (2017) → Fourth National Climate Assessment (NCA4)
- Sweet et al. (2022) → pending Fifth National Climate Assessment (NCA5)

Sometimes called "NOAA Projections." I'll call them "U.S. Projections"

- *Fifth Assessment Report* (AR5), Church et al. (2013)
- *Special Report on Oceans and Cryosphere in a Changing Climate* (SROCC), Oppenheimer et al. (2019)
- *Sixth Assessment Report* (AR6), Fox-Kempner et al. (2021)

IPCC projections: RCPs and SSPs

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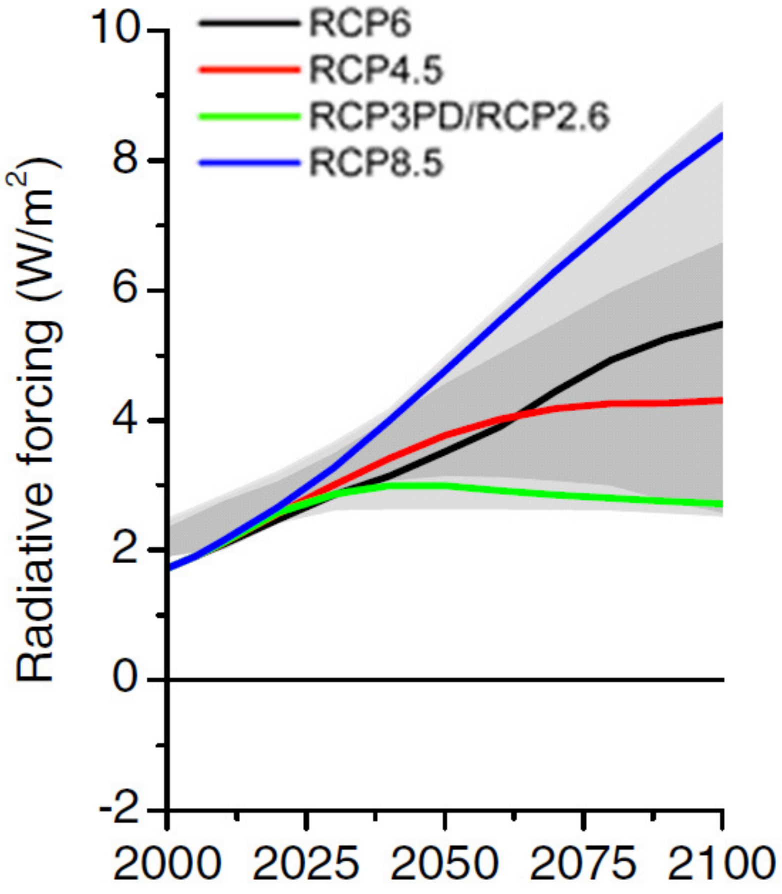
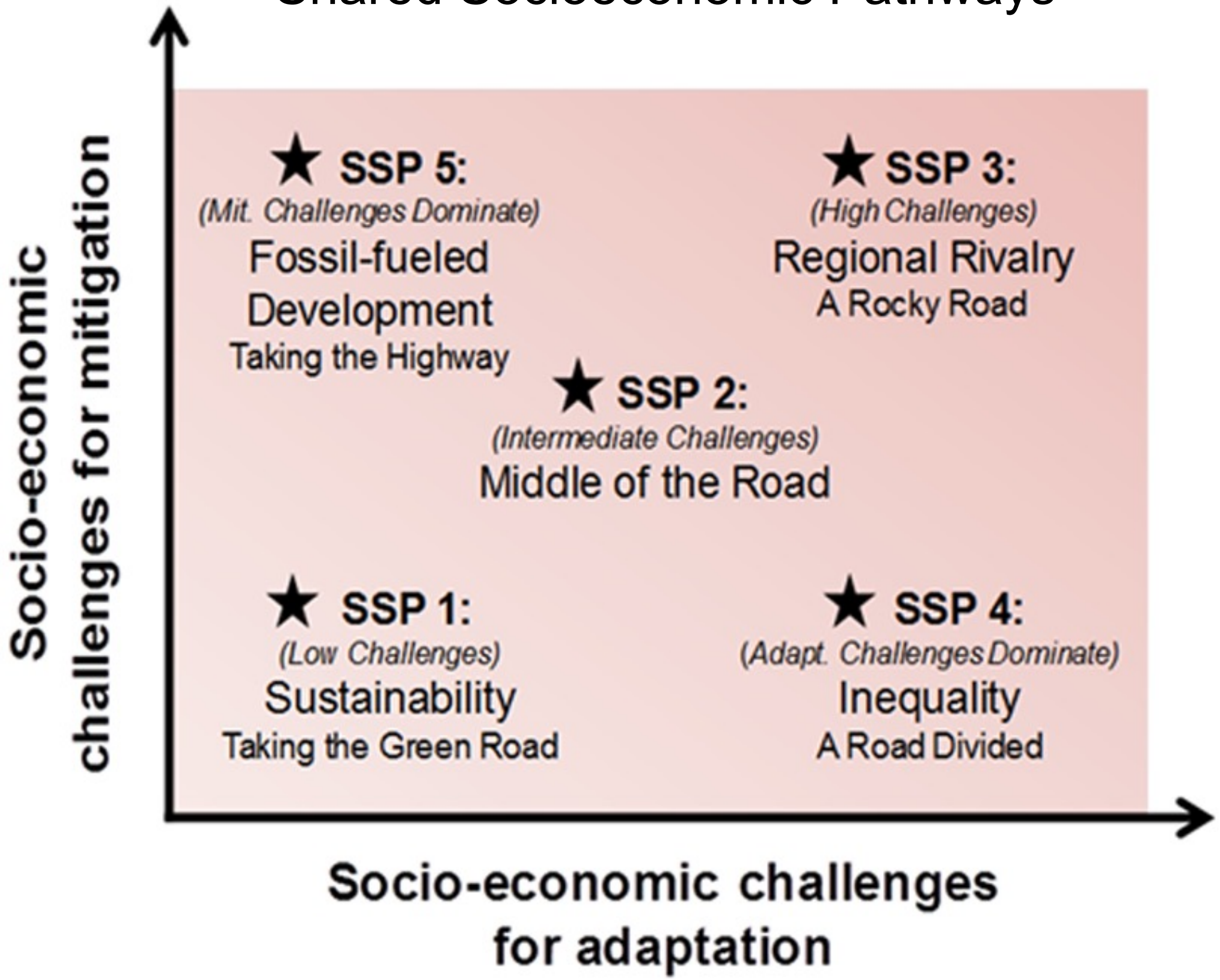
Representative Concentration Pathways



van Vuuren et al., 2011

Shared Socioeconomic Pathways



O'Neill et al., 2016

2017 and 2022 U.S. projections

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Scenario	Global mean sea level rise in 2100
Low	0.3 m / 1.0 ft
Intermediate-Low	0.5 m / 1.6 ft
Intermediate	1.0 m / 3.3 ft
Intermediate-High	1.5 m / 4.9 ft
High	2.0 m / 6.6 ft

Temporal trajectories and probabilities are consistent with IPCC AR6

Maine "commit to manage"

Uncertain ice sheet processes contribute significantly to SLR in the late 21st century and beyond

Maine "prepare to manage"

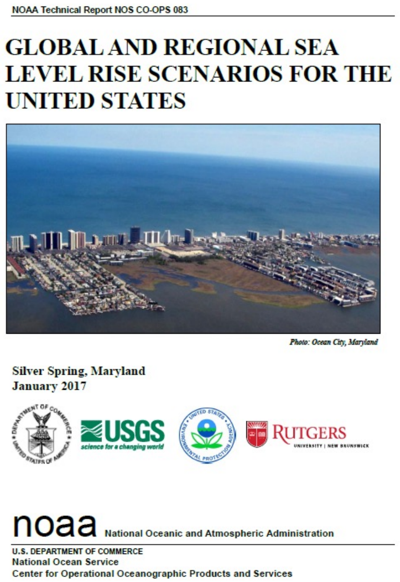
Note that the "Extreme" scenario from 2017 U.S. projections and NCA4 was dropped in 2022 U.S. projections / NCA5

Maine's "Commitment to manage"

0 ft	+1.5 ft	+4.0 ft
2000	*2050*	*2100*

Equivalent 2022 U.S. projections:

- +1.1 ft in 2050
- +3.5 ft in 2100


NOAA Technical Report NOS CO-OPS 083

GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES

Photo: Ocean City, Maryland

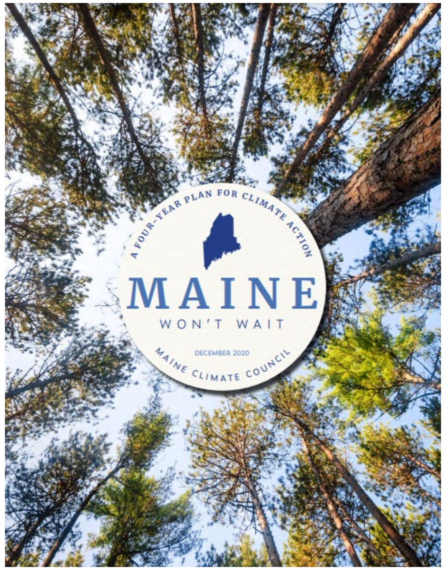
Silver Spring, Maryland
January 2017

noaa National Oceanic and Atmospheric Administration
U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

2017 NOAA Tech report
(2017 U.S. projections)


Scientific Assessment of Climate Change and Its Effects in Maine

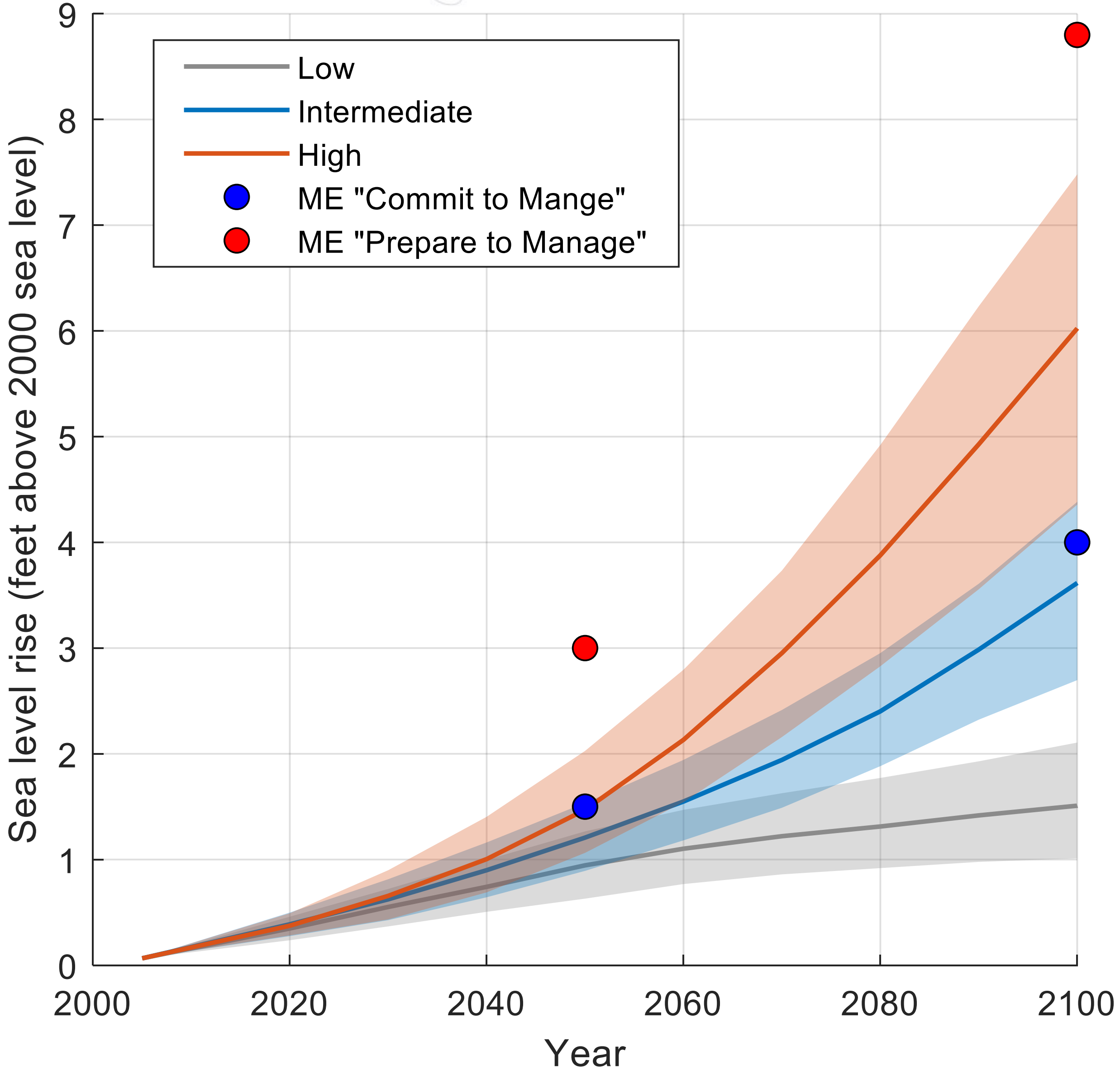
MAINE CLIMATE COUNCIL
SCIENTIFIC AND TECHNICAL SUBCOMMITTEE



Maine Climate Council adopts sea level planning targets based on Scientific and Technical Subcommittee (STS) report

Legal mandate to incorporate "commit to manage" scenarios into state agency regulations

2022 U.S. SLR projections, averaged across Maine gauges

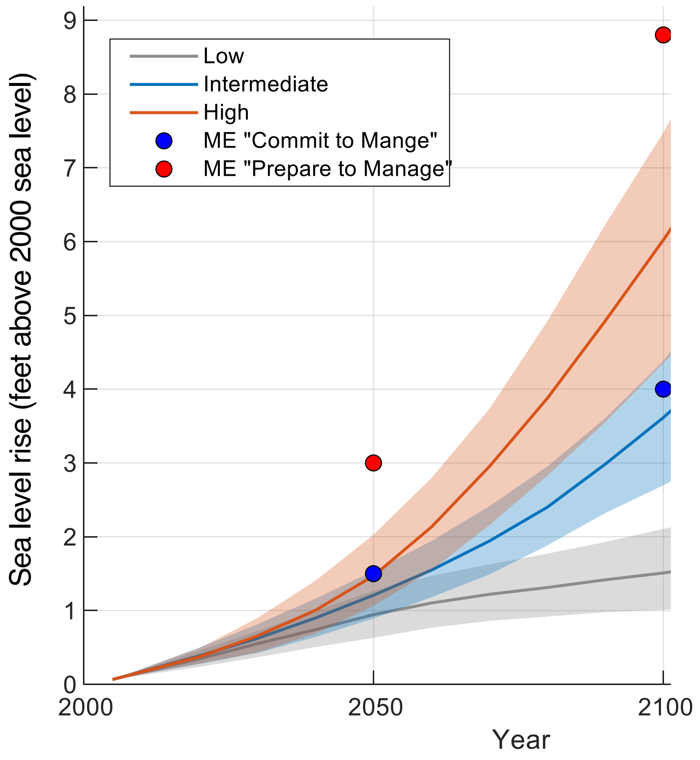


Equivalent 2022 U.S. projections:

- +1.1 ft in 2050
- +3.5 ft in 2100

The latest sea level projections are lower than Maine's targets. **Why?**

1. Uncertainty around the **timing** of when ice sheets become major contributors to sea level rise.
2. Better estimates of the relative contributions of Greenland vs. Antarctica.



Sea level rise (feet above 2000 sea level)
Year
0
1
2
3
4
5
6
7
8
9
2000
2050
2100
Low
Intermediate
High
ME "Commit to Mange"
ME "Prepare to Manage"

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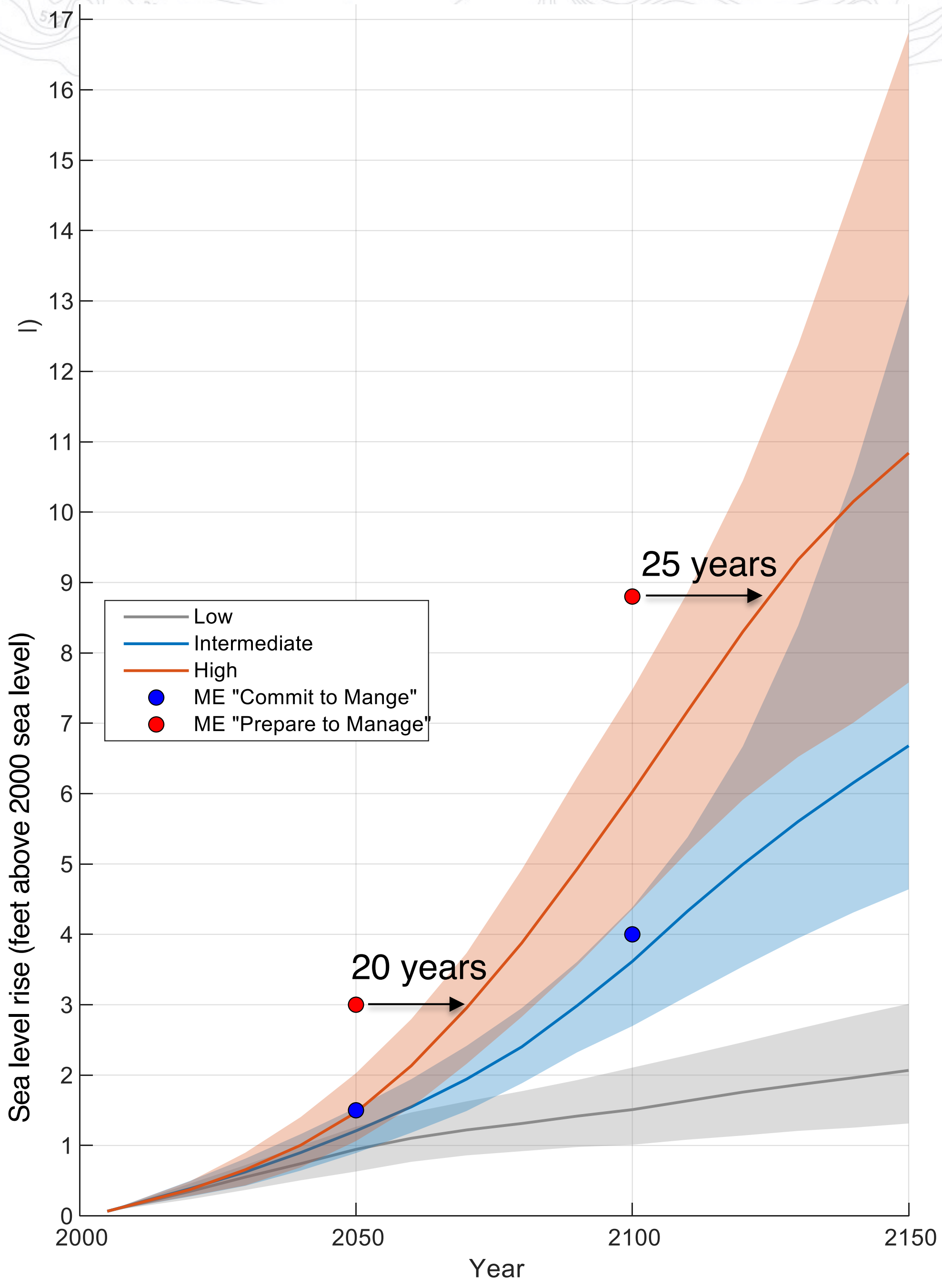

Again, it’s **timing.**

Accessing 2022 U.S. projections

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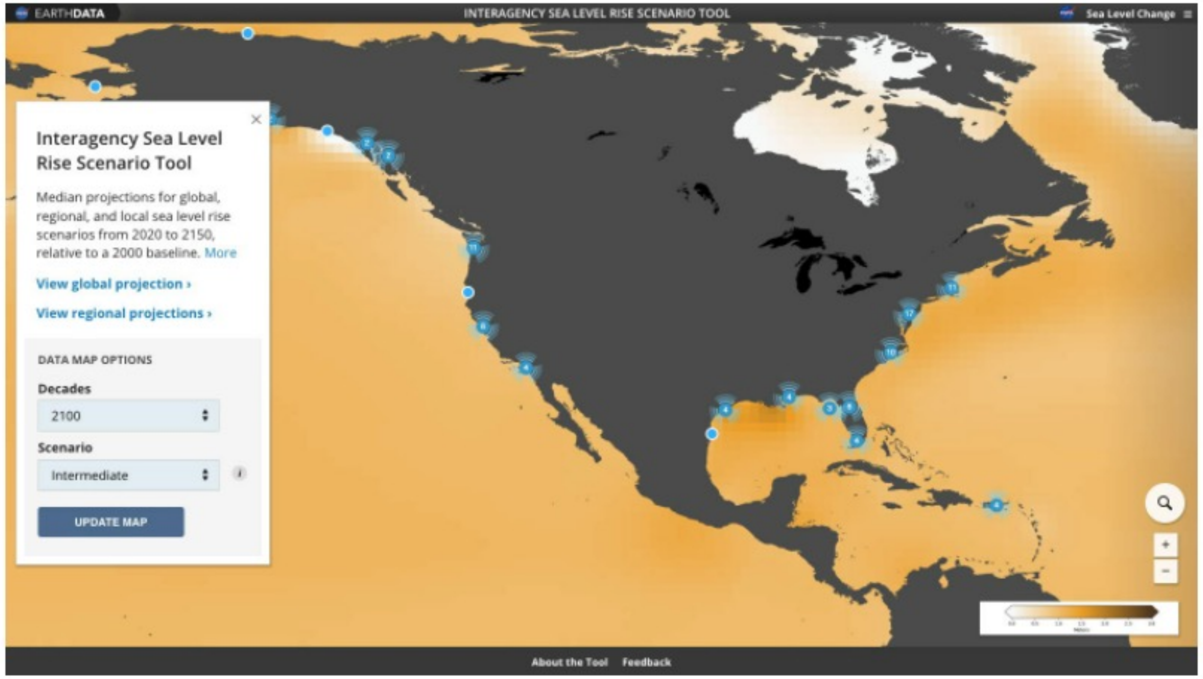
SEA LEVEL CHANGE
Observations from Space

Interagency Sea Level Rise Scenario Tool



LAUNCH

2022 U.S. projections at the Portland gauge

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sl_taskforce_scenarios_psmsl_id_183 (4).xlsx - Protected View

psmsl_id	process	Units	scenario	quantile	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
183	total	mm	Low	17	58.4627	98.46271	135.4627	168.4627	202.4627	230.4627	243.4627	257.4627	262.4627	280.4627	297.4627	312.4627	322.4627	334.4627
183	total	mm	Low	50	91.46271	148.4627	207.4627	260.4627	305.4627	338.4627	364.4627	391.4627	416.4627	448.4627	480.4627	506.4627	534.4627	563.4627
183	total	mm	Low	83	126.4627	200.4627	281.4627	361.4627	420.4627	463.4627	501.4627	548.4627	599.4627	649.4627	705.4627	755.4627	805.4627	852.4627
183	total	mm	IntLow	17	65.46271	106.4627	156.4627	210.4627	269.4627	323.4627	369.4627	413.4627	442.4627	488.4627	533.4627	581.4627	623.4627	668.4627
183	total	mm	IntLow	50	101.4627	164.4627	234.4627	305.4627	373.4627	437.4627	495.4627	554.4627	603.4627	671.4627	742.4627	809.4627	879.4627	951.4627
183	total	mm	IntLow	83	139.4627	225.4627	316.4627	403.4627	482.4627	561.4627	631.4627	707.4627	796.4627	884.4627	977.4627	1071.463	1174.463	1277.463
183	total	mm	Int	17	70.46271	114.4627	180.4627	249.4627	331.4627	425.4627	539.4627	669.4627	780.4627	907.4627	1028.463	1154.463	1262.463	1361.463
183	total	mm	Int	50	104.4627	173.4627	252.4627	340.4627	443.4627	559.4627	698.4627	869.4627	1062.463	1273.463	1471.463	1658.463	1823.463	1979.463
183	total	mm	Int	83	138.4627	230.4627	331.4627	441.4627	565.4627	704.4627	865.4627	1060.463	1294.463	1593.463	1983.463	2499.463	3142.463	3914.463
183	total	mm	IntHigh	17	67.46271	116.4627	186.4627	279.4627	390.4627	513.4627	658.4627	809.4627	940.4627	1097.463	1238.463	1374.463	1512.463	1616.463
183	total	mm	IntHigh	50	105.4627	181.4627	277.4627	395.4627	539.4627	713.4627	917.4627	1152.463	1393.463	1621.463	1818.463	1989.463	2135.463	2316.463
183	total	mm	IntHigh	83	139.4627	245.4627	374.4627	527.4627	707.4627	931.4627	1177.463	1443.463	1738.463	2060.463	2419.463	2777.463	3082.463	3508.463
183	total	mm	High	17	72.46271	117.4627	191.4627	301.4627	451.4627	633.4627	843.4627	1064.463	1306.463	1554.463	1771.463	1943.463	2107.463	2292.463
183	total	mm	High	50	102.4627	182.4627	289.4627	424.4627	622.4627	870.4627	1161.463	1483.463	1806.463	2150.463	2498.463	2807.463	3047.463	3262.463
183	total	mm	High	83	137.4627	258.4627	411.4627	587.4627	824.4627	1112.463	1468.463	1857.463	2240.463	2654.463	3139.463	3736.463	4412.463	5083.463

A key detail: baselines/datums

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It is standard for water level baselines/datums to be calculated over 19-year periods to incorporate cyclical astronomical, oceanic, and atmospheric variability.

Local tidal datums and flood thresholds from NOAA CO-OPS / NWS:

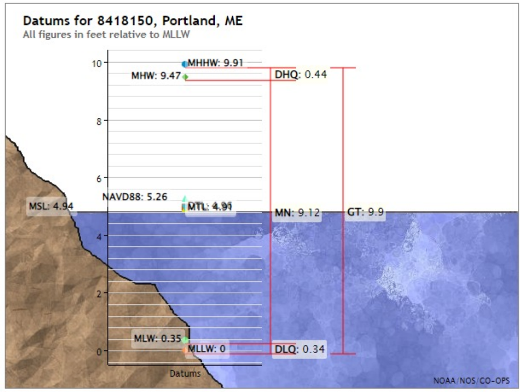
1992 baseline (1983-2001), i.e. present NTDE

Elevations on Mean Lower Low Water

Station: 8418150, Portland, ME
Status: Accepted (Apr 17 2003)
Units: Feet
Control Station:

T.M.: 0
Epoch: 1983-2001
Datum: MLLW

Datum	Value	Description
MHHW	9.91	Mean Higher-High Water
MHW	9.47	Mean High Water
MTL	4.91	Mean Tide Level
MSL	4.94	Mean Sea Level
DTL	4.96	Mean Diurnal Tide Level
MLW	0.35	Mean Low Water
MLLW	0.00	Mean Lower-Low Water
NAVD88	5.26	North American Vertical Datum of 1988
STND	-8.55	Station Datum
GT	9.90	Great Diurnal Range
MN	9.12	Mean Range of Tide
DHQ	0.44	Mean Diurnal High Water Inequality
DLQ	0.34	Mean Diurnal Low Water Inequality
HWI	3.59	Greenwich High Water Interval (in hours)
LWI	9.75	Greenwich Low Water Interval (in hours)
Max Tide	14.13	Highest Observed Tide
Max Tide Date & Time	02/07/1978 10:30	Highest Observed Tide Date & Time
Min Tide	-3.45	Lowest Observed Tide
Min Tide Date & Time	11/30/1955 17:18	Lowest Observed Tide Date & Time
HAT	11.97	Highest Astronomical Tide
HAT Date & Time	05/19/2034 04:06	HAT Date and Time
LAT	-2.12	Lowest Astronomical Tide
LAT Date & Time	01/14/2036 22:42	LAT Date and Time



Showing datums for
8418150 Portland, ME

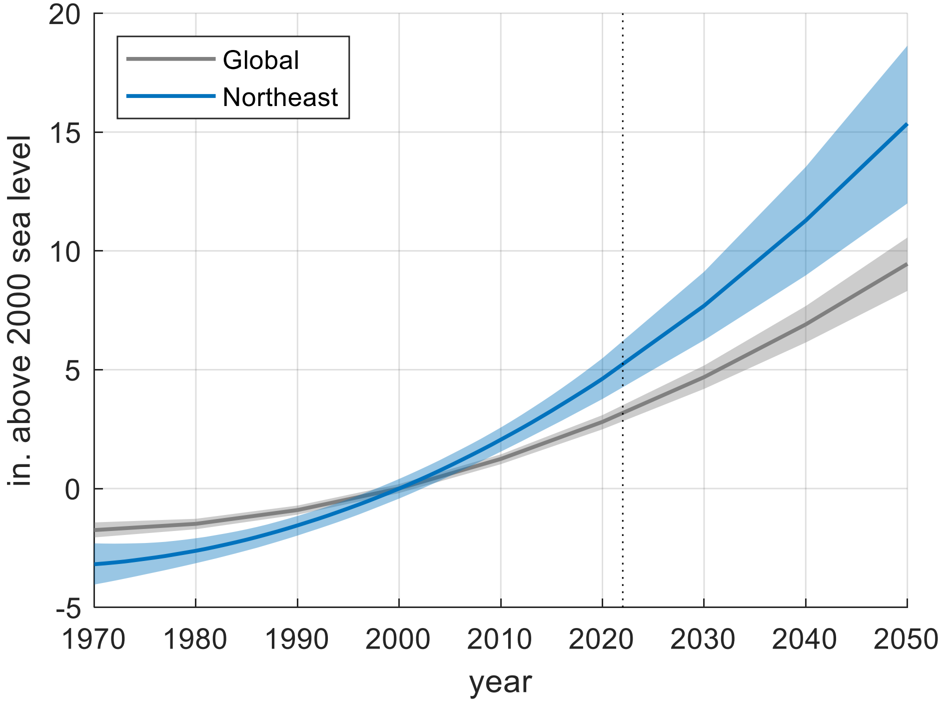
Datum
MLLW

Data Units ◉ Feet
○ Meters

Epoch ◉ Present (1983-2001)
○ Superseded (1960-1978)

U.S. and IPCC sea level rise projections baselines:

SROCC: 1995 (1986-2005)
AR6: 2004 (1995-2014)
2022 U.S.: 2000 (1991-2010)



Coastal Flooding

High tide "nuisance" flooding

Extreme flooding

Physical drivers of flooding (high tide flooding)

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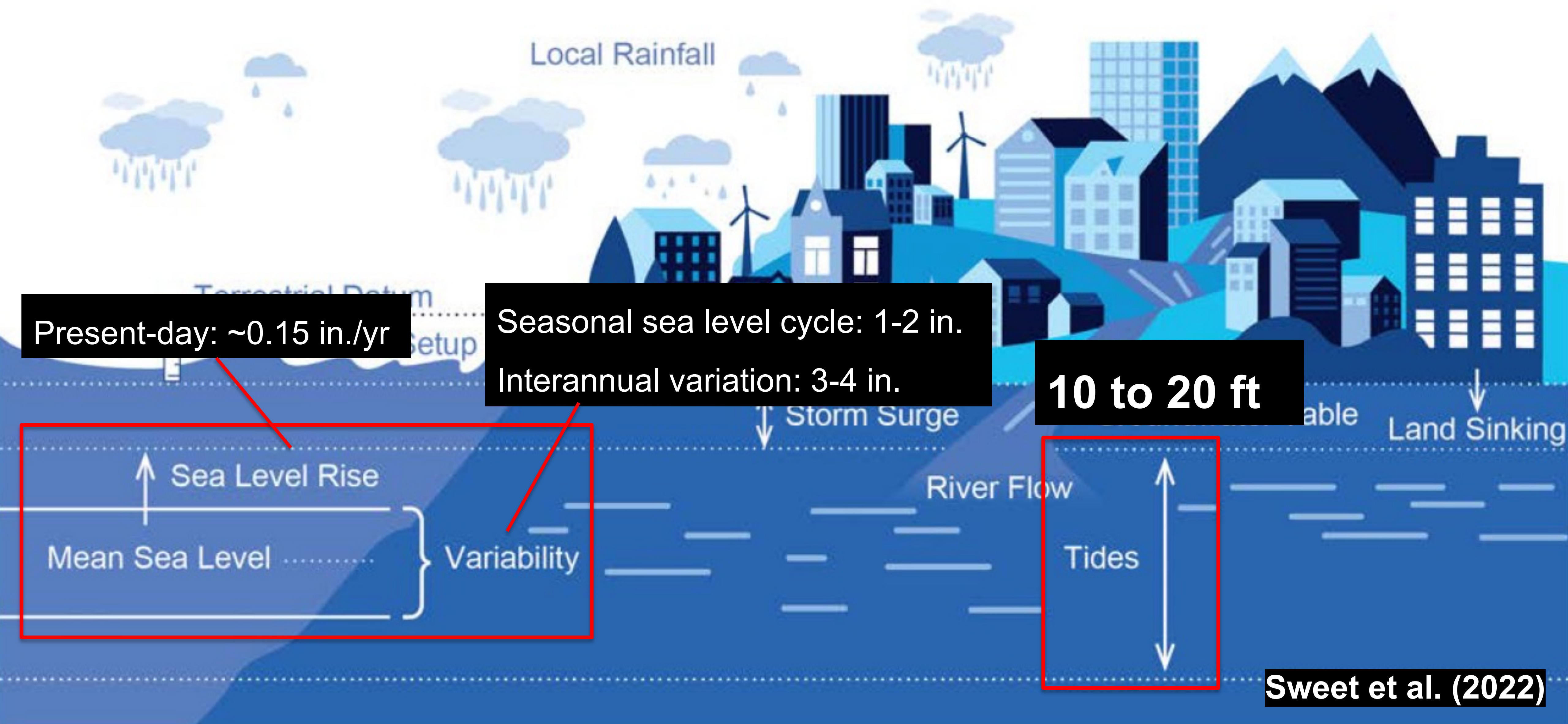

Nonlinear relationship between SLR and flooding

or, a little bit of SLR = a lot more flooding

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Minor flooding in Portland under Maine sea level rise scenarios

	2000	2050	2100
Minor high tide flooding days/year	~3	99–140	357–363
Sea level rise	0 ft	+1.5 ft	+4.0 ft

https://sealevel.nasa.gov/flooding-days-projection/

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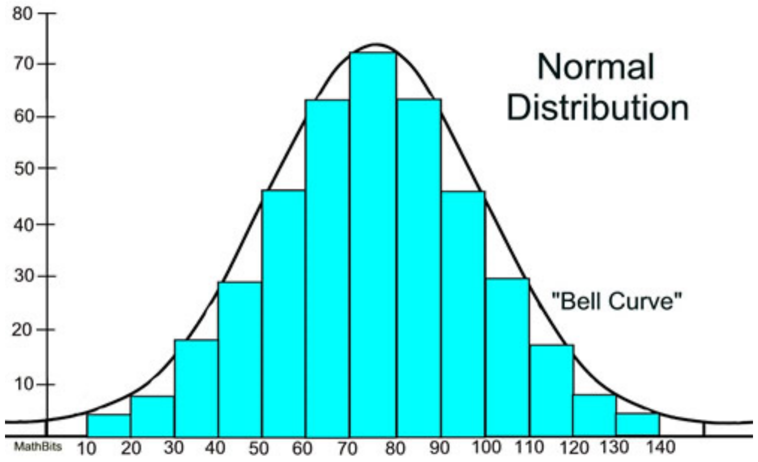

https://mathbitsnotebook.com/Algebra2/Statistics/STnormalDistribution.html

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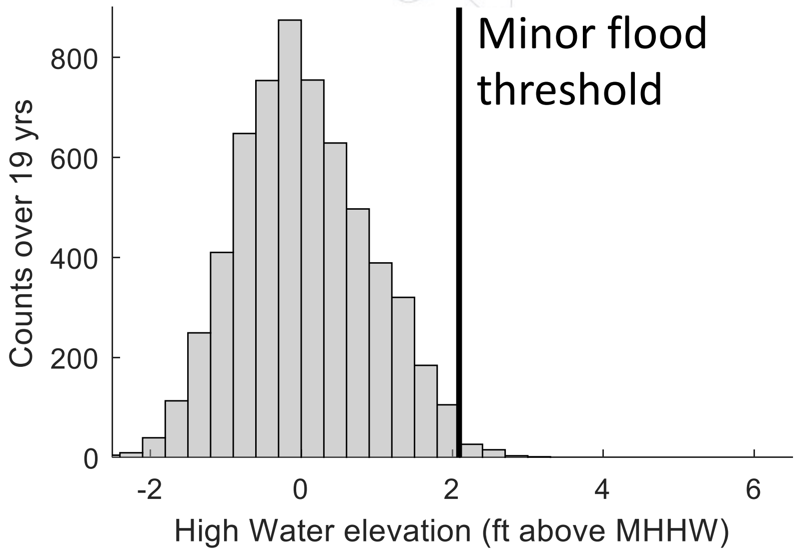
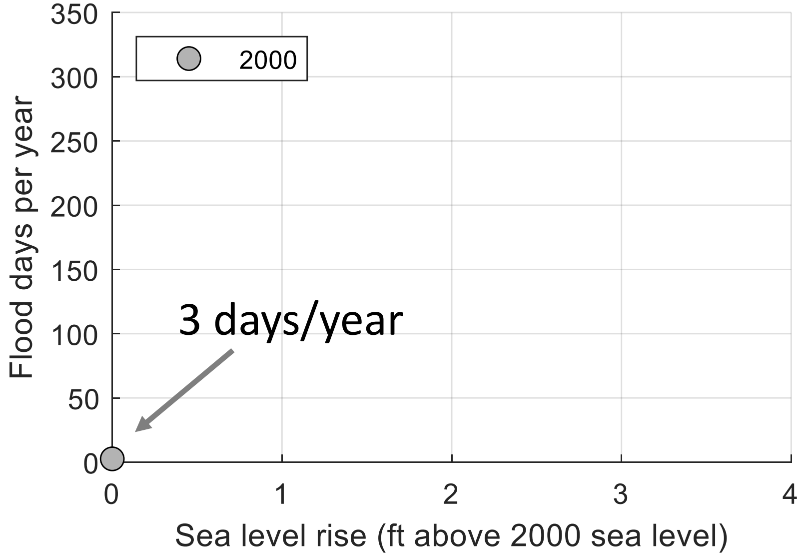
Distribution of daily highest predicted tide





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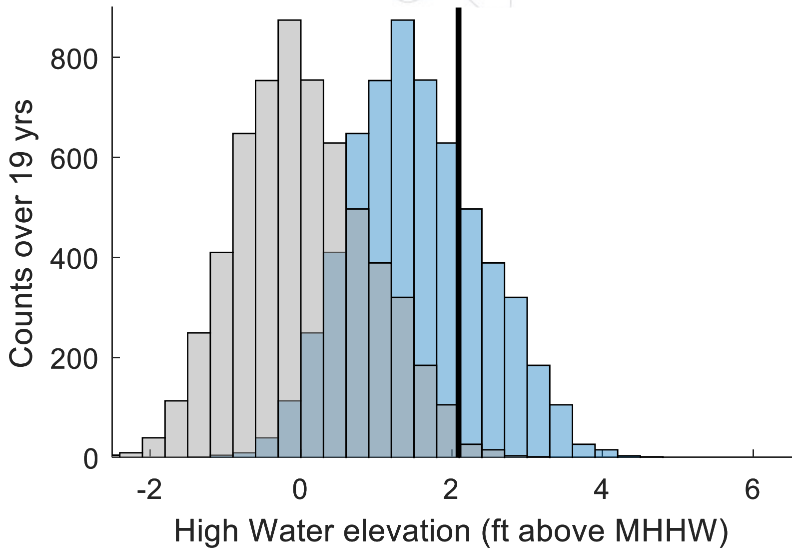

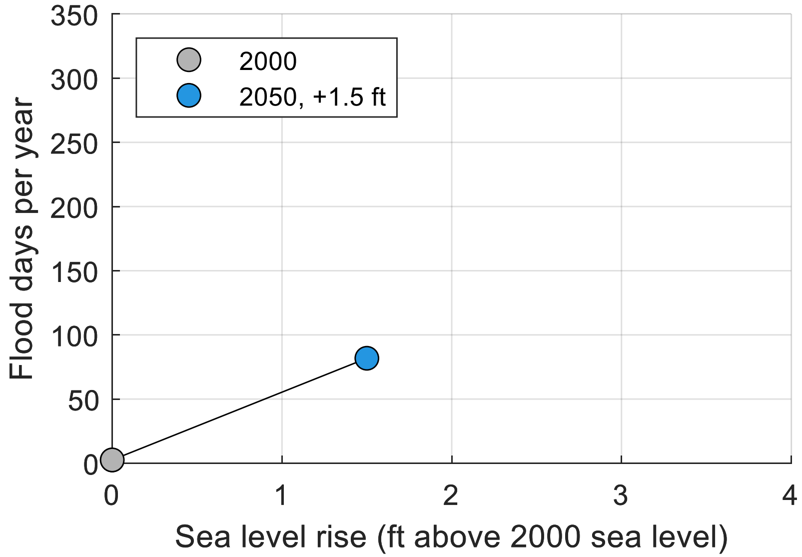

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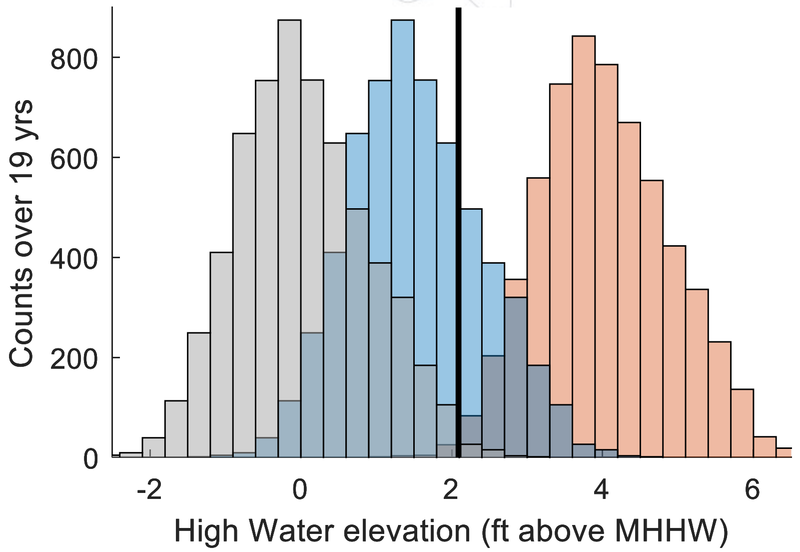
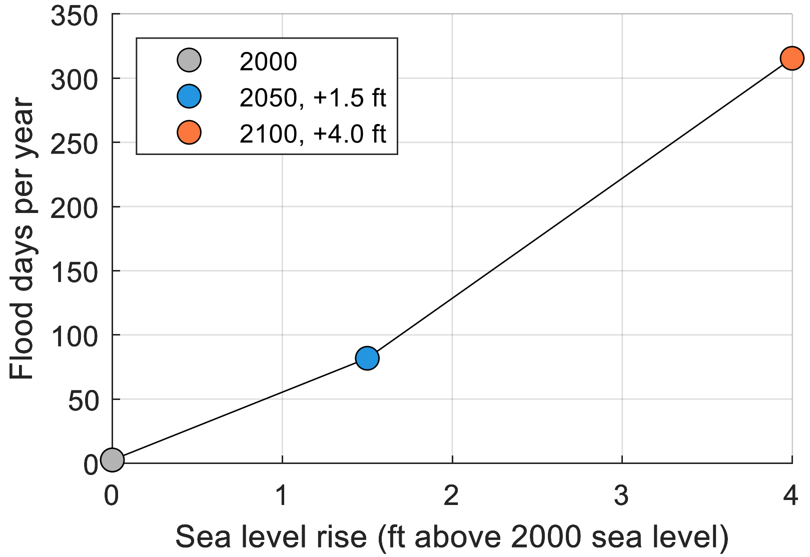




Minor flooding in Portland under Maine sea level rise scenarios

Minor high tide flooding days/year	~3	99–140	357–363
Sea level rise	0 ft	+1.5 ft	+4.0 ft
Year	*2000*	*2050*	*2100*

https://sealevel.nasa.gov/flooding-days-projection/

Maine Geological Survey flood hazard tool

Gulf of Maine Research Institute

1983-2001 Highest Astronomical Tide + 1.2, 1.6, 3.9, 6.1, 8.8, and 10.9 ft of sea level rise above 2000 mean sea level

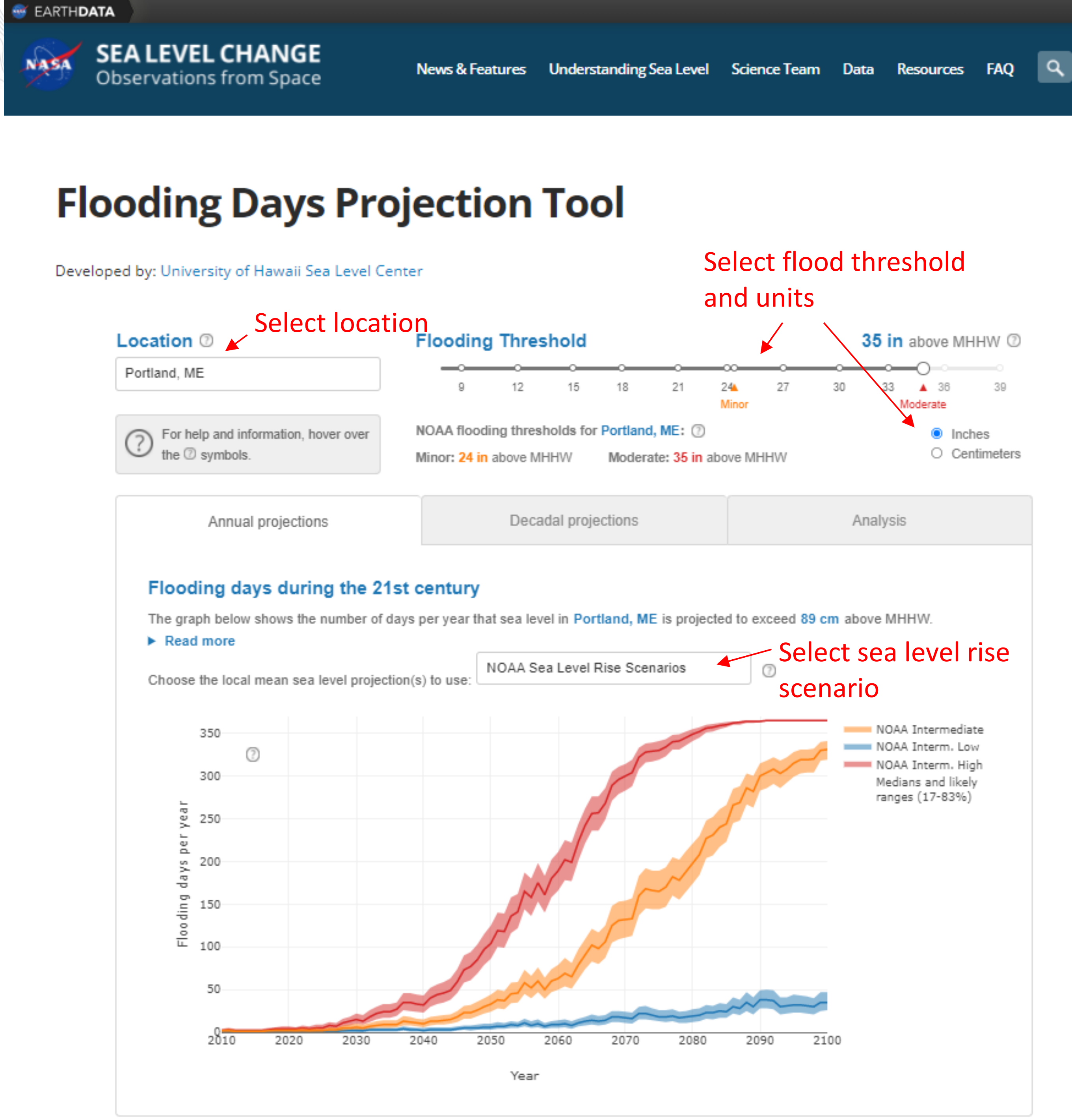
“Bathtub” mapping on top of LiDAR

https://www.maine.gov/dacf/mgs/hazards/slr_ss

High tide flooding projections: Thompson et al. (2021)

https://sealevel.nasa.gov/flooding-days-projection/

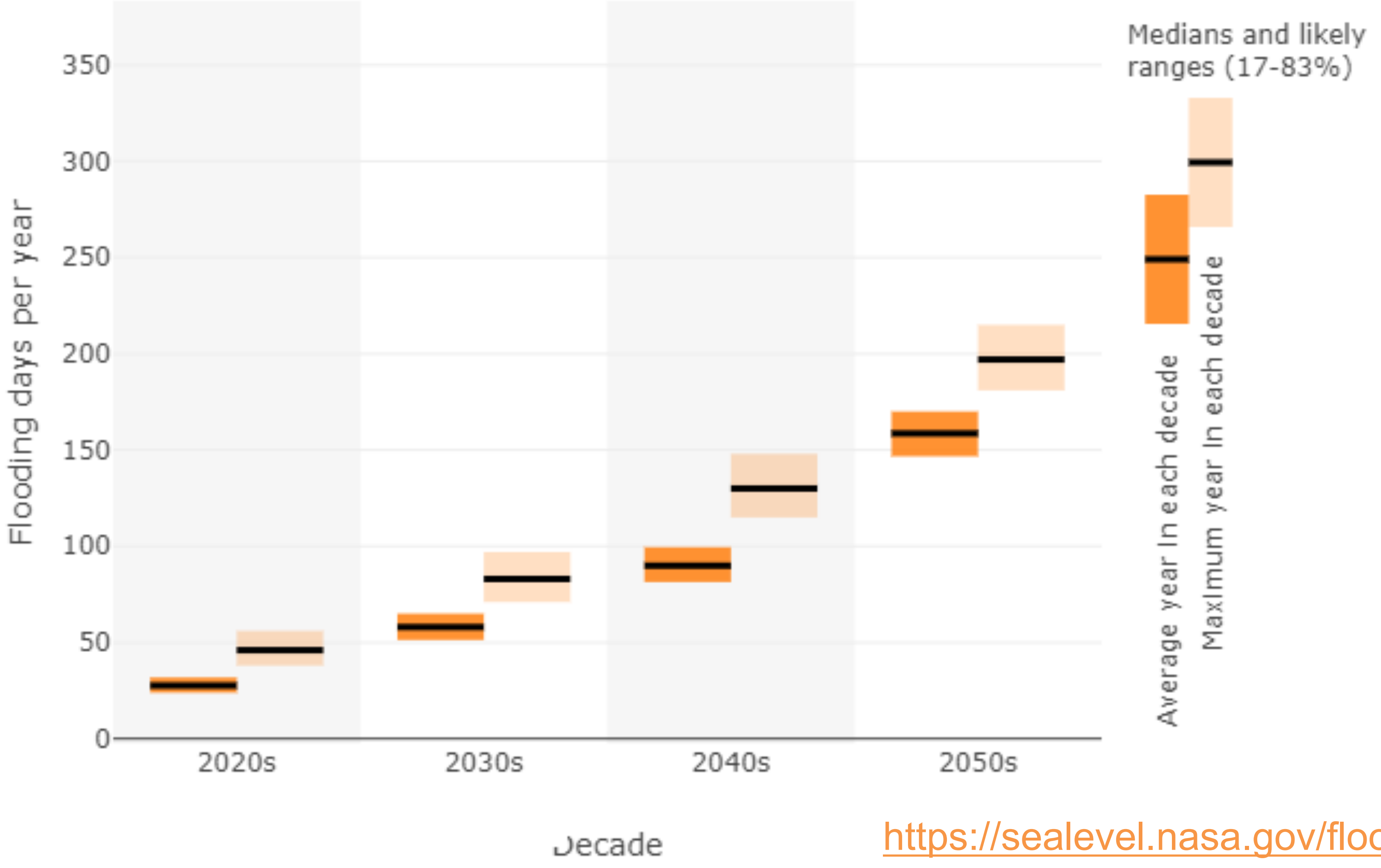
- Includes sea level rise projections, future tide predictions, and year-to-year sea level variability (due to predictable, cyclical variations in climate)
- Available at 89 U.S. tide gauges, and projections are specific to each location.



High tide flooding projections: Thompson et al. (2021)

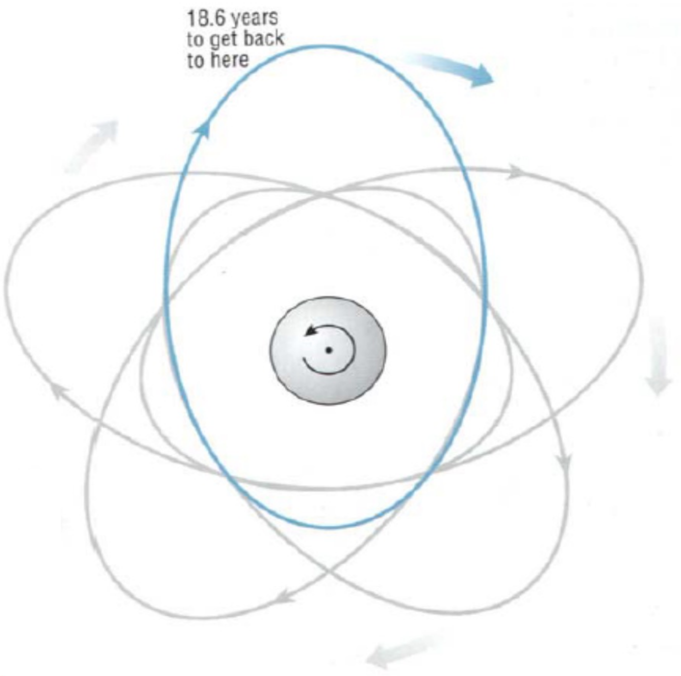
Gulf of Maine Research Institute

Portland tide gauge, 2017 U.S. Intermediate sea level rise scenario



https://sealevel.nasa.gov/flooding-days-projection/

Tide range changes over an 18.6-year lunar cycle. In Portland, the cycle varies the height of the year's highest high tides (the top 10%) by about 2 inches.



That doesn't seem like much, BUT it does impact high tide flooding throughout the Gulf of Maine

The New York Times

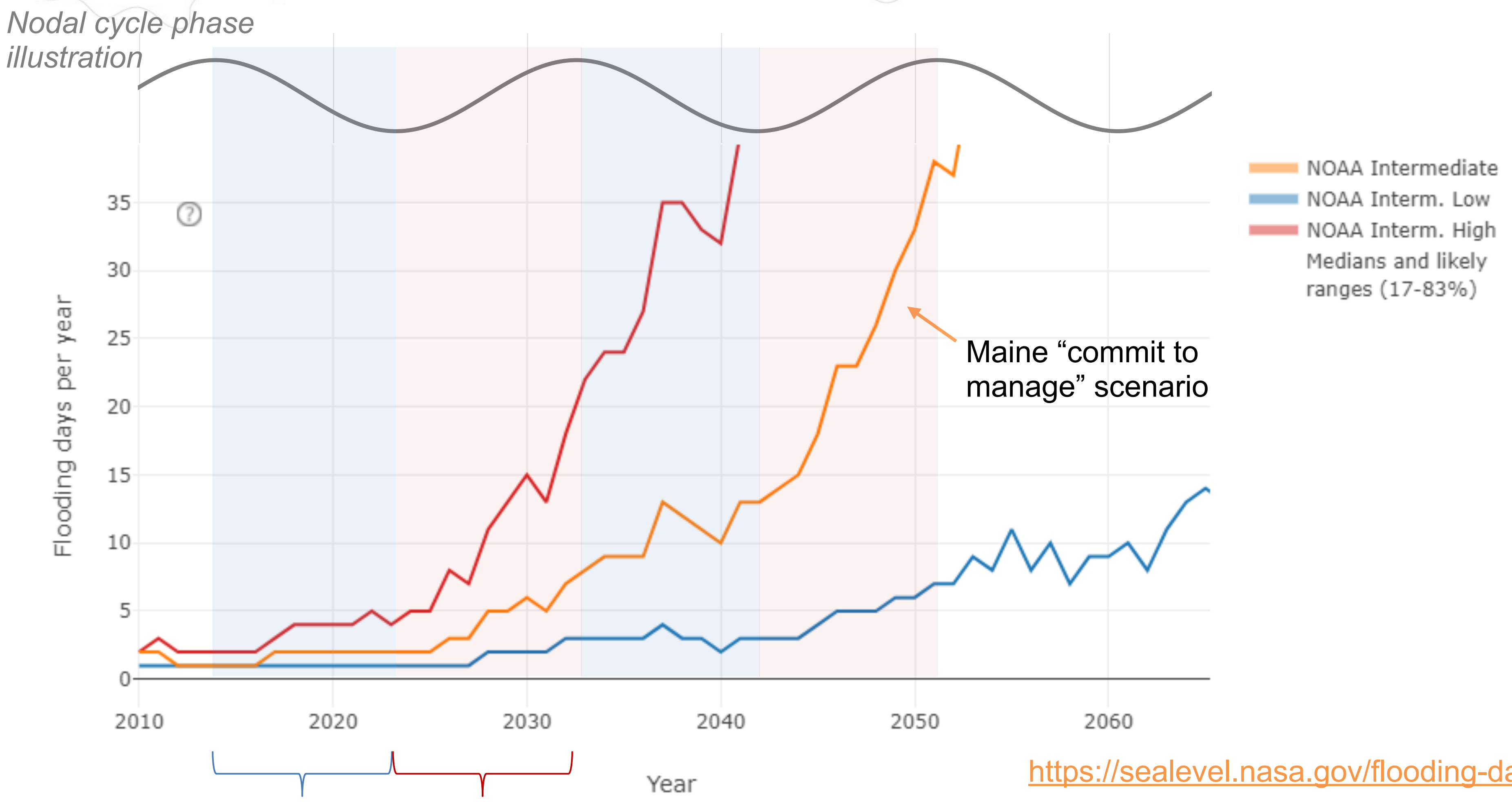
How the Moon 'Wobble' Affects Rising Tides

Scientists say it's less like a wobble and more like a slow, predictable cycle. And while the phenomenon will contribute to rising tides caused by climate change, it is just one of many factors.

The moon's orbital plane is at a slight incline relative to the Earth's, creating a so-called wobble effect. NASA tried to reassure the public: "There's nothing new or dangerous about the wobble." Dave Sanders for The New York Times

High tide flooding projections: Thompson et al. (2021)

Gulf of Maine Research Institute



https://sealevel.nasa.gov/flooding-days-projection/

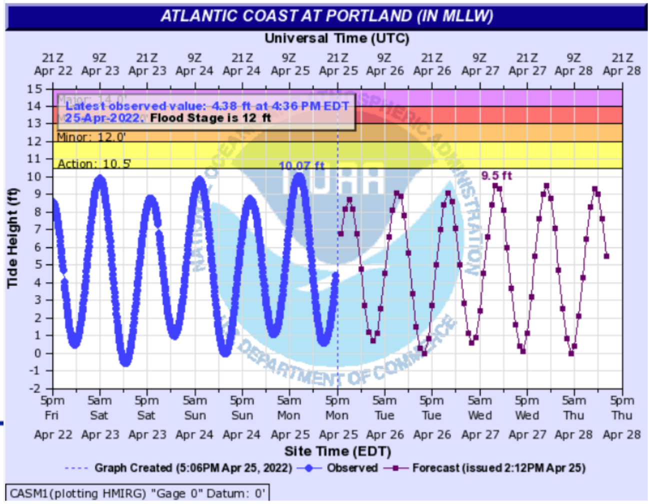
Through the early part of this decade, the nodal cycle is decreasing from a maximum to a minimum, and the increase in flooding days per year plateaus as **the decrease in tide range counteracts sea level rise.**

In 2023, tide range will start increasing again, and we can expect an **acceleration in the increase in high tide flooding days** over the next decade.

High tide flooding thresholds

Gulf of Maine Research Institute

1. Observational thresholds – established by emergency managers and NOAA weather forecast offices



National Weather Service

Advanced Hydrologic Prediction Service

Flood Impacts & Photos

If you notice any errors in the below information, please contact our Webmaster

13.8 Water will enter and flood businesses along and near the Portland Pier. Water will be nearly two feet deep along Granite Point Road in Biddeford and Mile Stretch Road will be flooded. Roads and businesses will also flood in Wells and Kennebunkport.

13 Water will reach the tailpipes of cars at businesses near the Portland Pier. At this elevation, a foot of water will also cover Granite Point Road in Biddeford

12.5 Water will be eight to ten inches deep along several low lying side streets and wharfs along Portland Harbor with water up to the bottom of doors in parking lots east of the Portland Peir. Water will be eight to 10 inches deep covering Marginal Way in Portland with six to eight inches of water on Somserset Street.

12 Flooding four to six inches deep occurs along the wharfs and most vulnerable side streets near the Portland Pier. Coastal flooding begins on Marginal Way and Somerset Street, especially if combined with heavy rainfall.

High tide flooding thresholds

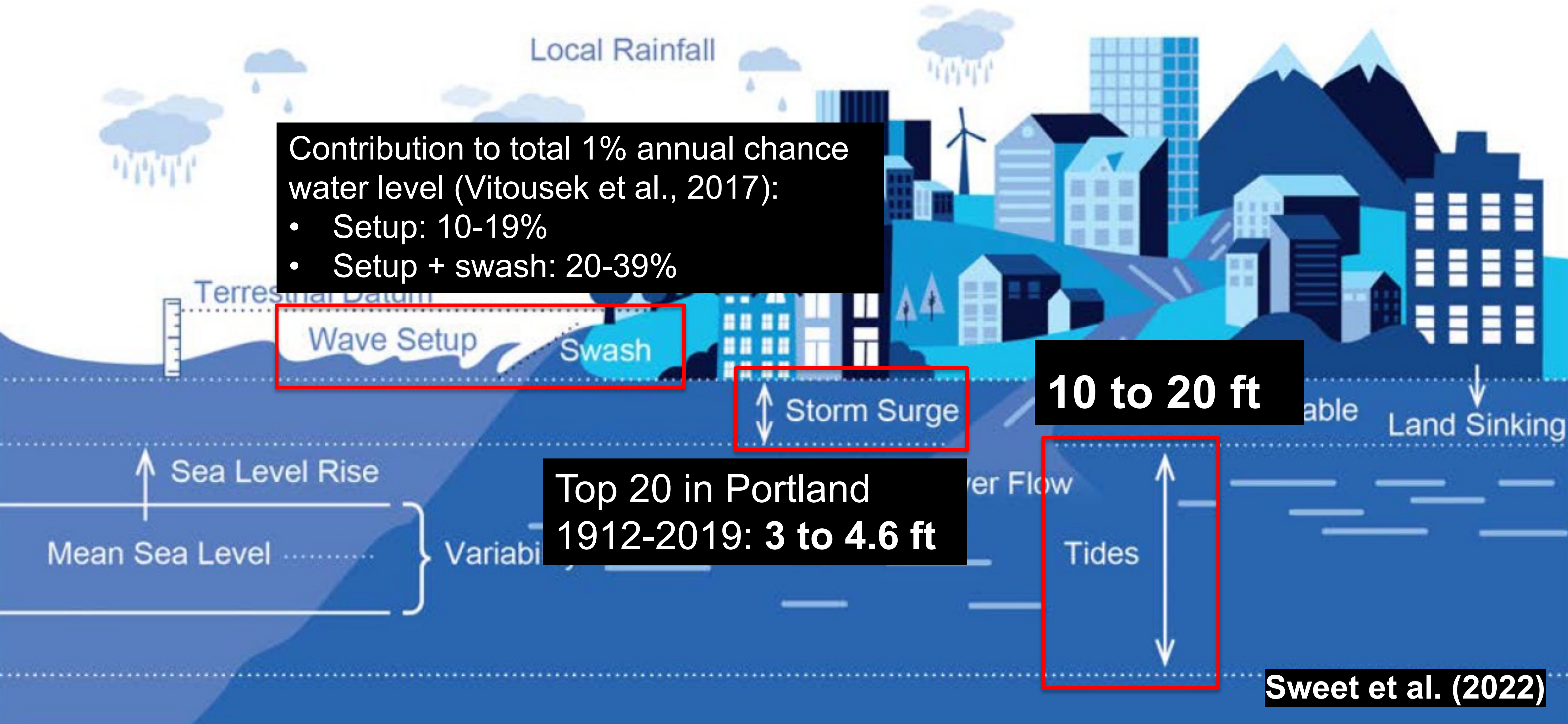
Gulf of Maine Research Institute

1. Observational thresholds – established by emergency managers and NOAA weather forecast offices

2. Sweet et al. (2018) Empirical thresholds = function of great diurnal tide range (GT), or MHHW – MLLW
   - Minor = 1.04 * GT + 0.50 m
   - Moderate = 1.03 * GT + 0.80 m
   - Major = 1.04 * GT + 1.17 m

Physical drivers of flooding (extreme flooding)

Gulf of Maine Research Institute



Contribution to total 1% annual chance water level (Vitousek et al., 2017):
- Setup: 10-19%
- Setup + swash: 20-39%

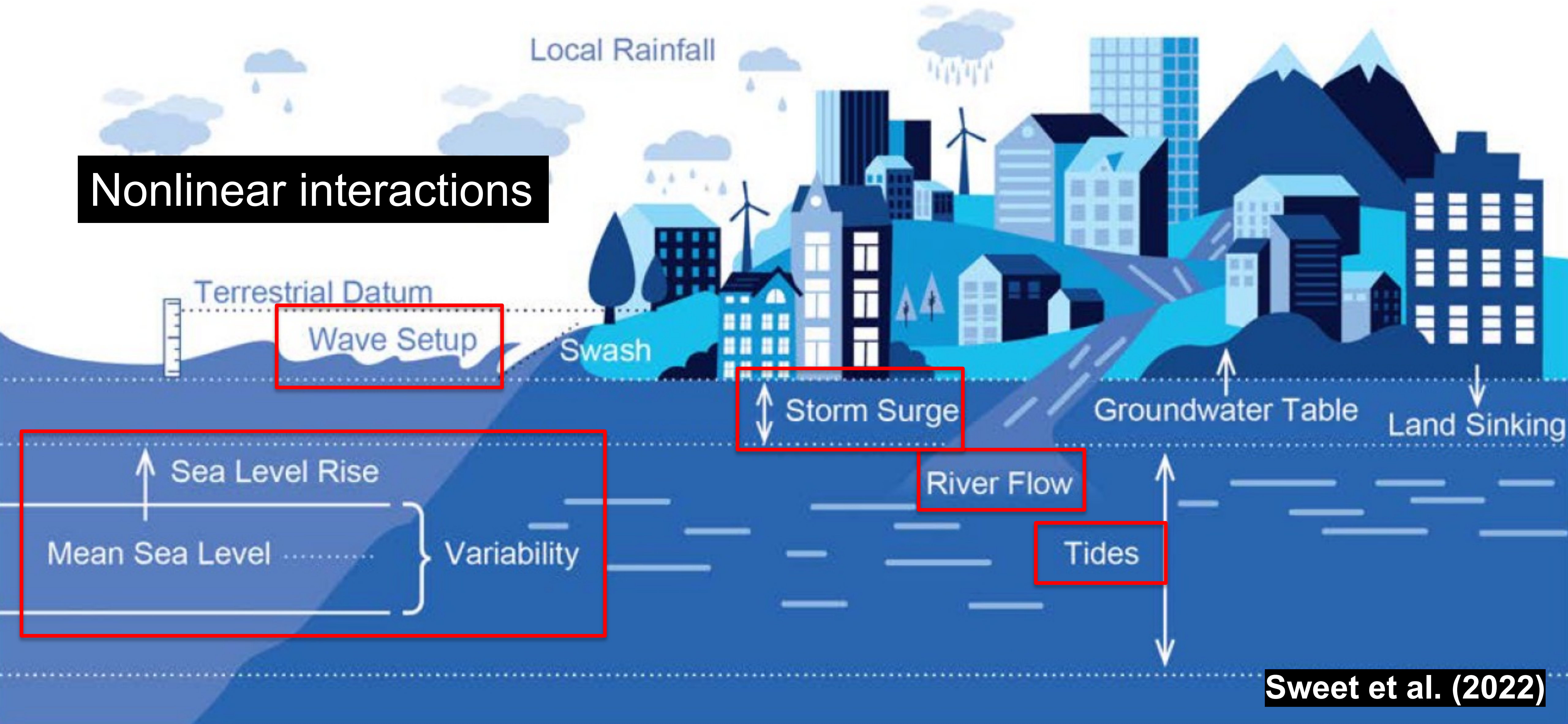
10 to 20 ft

Top 20 in Portland 1912-2019: **3 to 4.6 ft**

Sweet et al. (2022)

Physical drivers of flooding (extreme flooding)

Gulf of Maine Research Institute



Sweet et al. (2022)

Extreme flooding statistics

Two primary approaches:

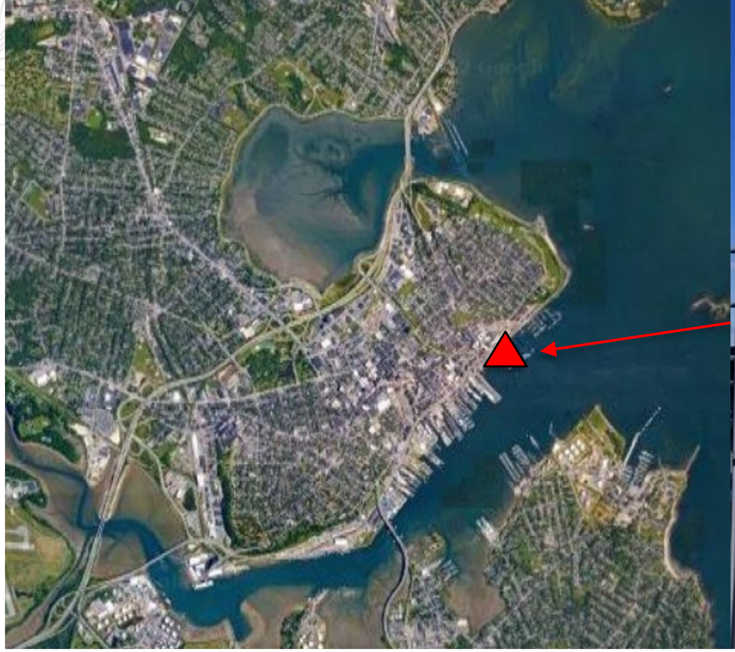
1. Tide gauge-based statistics
2. Dynamic modeling

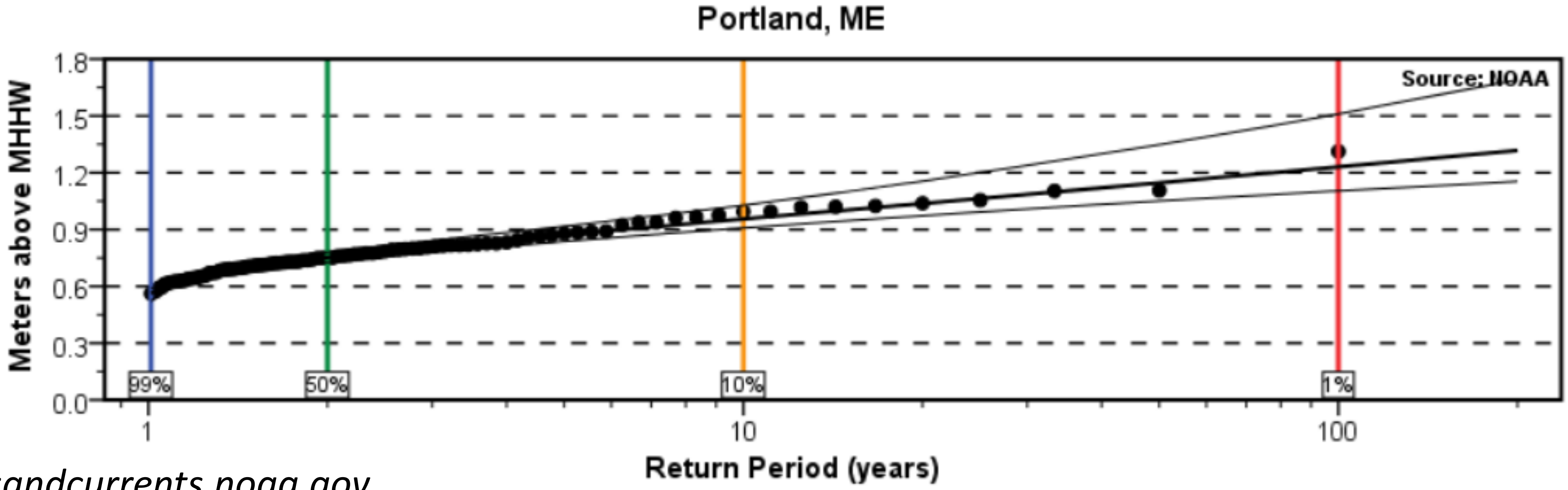
Extreme flooding statistics

Two primary approaches:

1. Tide gauge-based statistics

Most accurate for a point location, but does not provide lateral inundation information and usually sheltered from wave processes





tidesandcurrents.noaa.gov

Extreme flooding statistics

Two primary approaches:

1. Tide gauge-based statistics

   a) **NOAA CO-OPS GEVs (tidesandcurrents.noaa.gov):** present-day statistics for stations with >30 years of data

   b) **USACE Sea Level Change Calculator:** NOAA GEVs + various SLR scenarios

   c) **Sweet et al. (2022):** 1-degree gridded extreme water levels (EWLs) for 0.01 – 10 events/year with guidance on localizing and combining with sea level rise projections

Important considerations:

- No wave processes
- Taking vertical information and applying it laterally
- Does not consider nonlinear impacts of sea level rise, but these are sometimes small compared to uncertainty in SLR

Extreme flooding statistics

Gulf of Maine Research Institute

Two primary approaches:

1. Tide gauge-based statistics → Maine Silver Jackets model (Portland, South Portland, Damariscotta)

2. Dynamic modeling

- *Specific storm/SLR scenarios (e.g. what would the January 2018 Nor'easter look like on top of 1.5 ft SLR?)*
- *Probabilistic storms and tides + discrete SLR scenarios* → Statewide MaineDOT model

Statistically representative storm set
TCs, ETCs, present and future climatology

Sea level rise scenarios

Phase with tides

↓

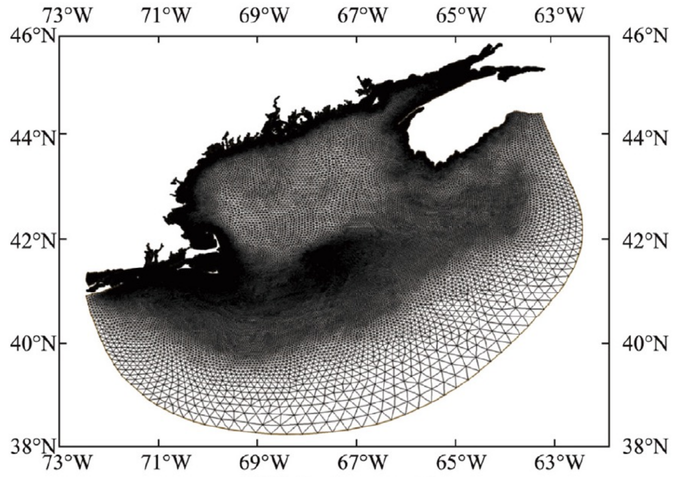
Coupled surge/wave/river model

↓

Statistical model

↓

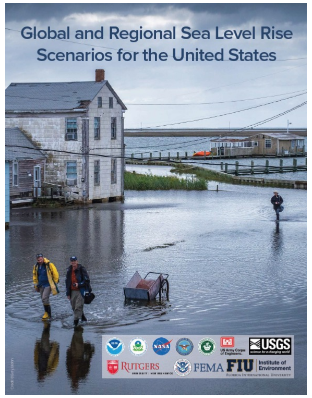
Extreme water level probabilities at all model nodes



(a) Finite element grid

Xie et al. (2016)

Take-home messages



Recommended reading:

Sweet et al. (2022)

And always be mindful of baselines/datums

Sea level rise

- Uncertainty: ice sheets and human decision-making
- Use or reference to probabilistic, localized NOAA or IPCC scenarios, considering timeline and risk tolerance

Coastal flooding

- Which physical drivers of flooding are included?
- Tide gauge-based statistics: most accurate at a single, wave-sheltered point, but challenging to extend
- Dynamic modeling: rapidly developing

Thanks

hbaranes@gmri.org

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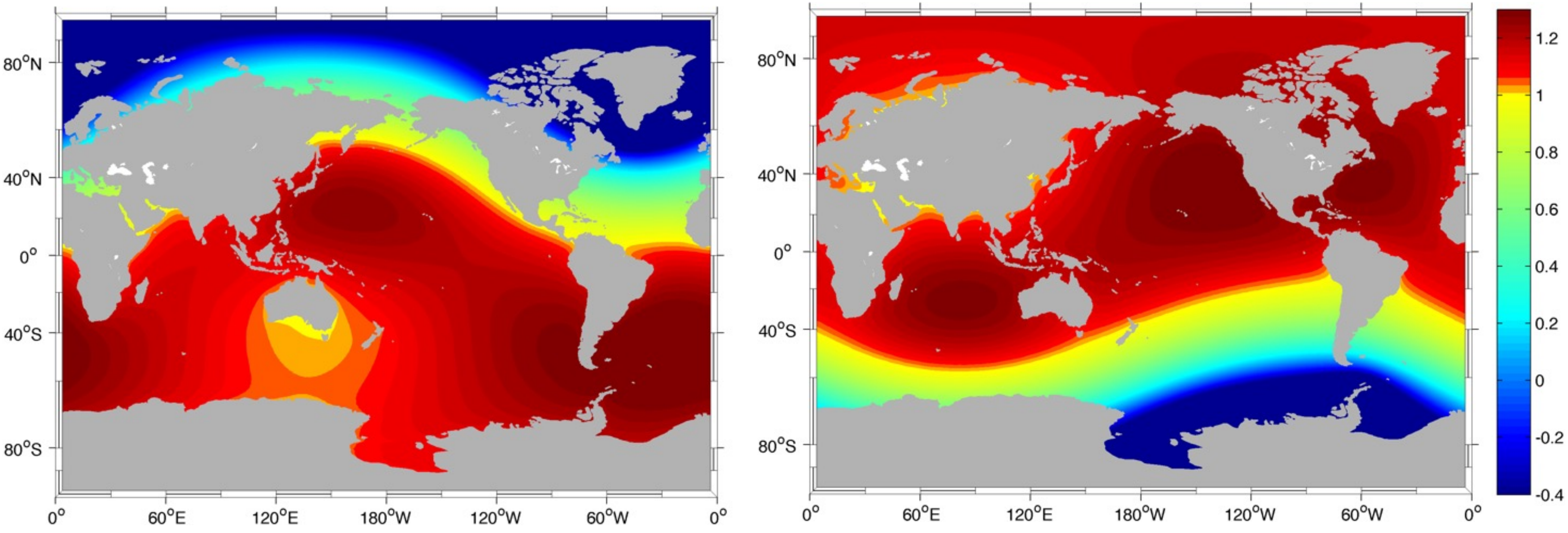
Science. Education. Community.

Sea level "fingerprints"

Gulf of Maine Research Institute



Credit: Carling Hay; Mitrovica et al. 2011

Gravitational and Earth rotational effects on relative sea level, caused by an equivalent ice mass loss from Greenland (left) or West Antarctica (right).