Outline

1. From global mean sea level to coastal flooding

2. Polar ice sheets – the remaining major unknown

3. Probabilistic forecasts & future flood frequencies
Before we start...

**Major ongoing activities as of 2017**

My attempt for this talk is to use material published 2017 onwards only.
Major ongoing activities (international & U.S.) as of 2017

WCRP Grand Challenge: “Regional Sea Level and Coastal Impacts” [wcrp-climate.org]
- WCRP Global Sea Level Budget Group, *Earth Syst. Sci. Data*, 2018

USGCRP 4th National Climate Assessment [science2017.globalchange.gov]

NASA Sea Level Change Team – N-SLCT [sealevel.nasa.gov]
- Nerem et al., *Nature*, 2018

NOAA Tides & Currents [tidesandcurrents.noaa.gov]
- Sweet et al., 2017, 2018: Global and regional sea level rise scenarios for the U.S.

Ice sheet Mass Balance Intercomparison Exercise 2 [imbie.org]
- IMBIE Team (Shepherd et al.), *Nature*, 2018
Major ongoing activities (international & U.S.) as of 2017

Selected U.S. government agencies & reports:

- **U.S. DOD Strategic Environmental Research and Development Program**, 2017: The Impact of Sea-Level Rise and Climate Change on Department of Defense Installations on Atolls in the Pacific Ocean

- **U.S. NOAA, 2017**: Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold

- **U.S. EPA**: Climate Ready Estuaries [epa.gov/cre]

- **U.S. Army Corps of Engineers**: Planning for Changing Sea Levels [usace.army.mil/corpsclimate/Planning_for_Changing_Sea_Levels/]
Major ongoing activities (international & U.S.) as of 2017

Selected regional Efforts:

• New York City Panel on Climate Change Report 2015
• Climate Ready Boston: Coastal Resilience Solutions 2017
• Projected Sea Level Rise in Washington State - A 2018 Assessment
• California’s 4th Climate Assessment 2018
• Study of Environmental Arctic Change (SEARCH), Land Ice Action Team https://www.searcharcticscience.org

Valuable exercises that highlight what stakeholders need from scientists
What sea level?

From global sea level to coastal flooding
Global Mean vs. Regional Sea Level from Satellite Radar Altimetry

The satellite altimetric record, 1993-2017:

- linear trend: $3.1 \pm 0.3$ mm/a
- acceleration: $0.1 \pm 0.03$ mm/a$^2$

Up to factor of 5 differences between GMSL and regional sea level trend


State of the Climate 2017

AVISO (2018)
Regional sea level change

- steric changes
- barystatic (mass) changes
due to water input from
  - land ice
  - river runoff
  - global hydrological cycle
- static equilibrium gravitational fingerprints of present-day land ice loss
- glacial isostatic adjustment (GIA) due to post-glacial rebound (PGR)
- coupled atmosphere-ocean circulation variability
Relative Sea Level & Coastal Flooding (2/3)

**Storm surges/tides**
- atmospheric surges (barotropic response to atmospheric IB)
- (astronomical) tidal surges
- wind waves & swell:
  - wave set-up & swash

**Drivers**
- cyclone activity, frequency, intensification
- local sea level pressure extremes
- atmospheric modes of variability
- coastal erosion / morphology

---

Ezer & Atkinson (2014)
Vertical land motion and land loss

- land subsidence from
  - groundwater withdrawal
  - soil compaction
  - variations in sedimentation rates
- glacial isostatic adjustment (GIA) due to rebound of the Earth’s lithosphere and geoid changes following ice sheet mass drainage into the ocean
- wetland submergence

Sweet et al., NOAA (2017)
Thermosteric changes: Ocean Heat Content (OHC) trends

- Despite a possible surface warming slowdown (a.k.a. “hiatus”) during the early 2000’s OHC has increased unabated
- More than 90% of Earth’s excess energy is absorbed by the ocean
- OHC and implied steric sea level change are volumetric quantities, and as such a more robust climate indices than global mean surface temperature (GMST)
- Thermosteric trend: 1.3 ± 0.4 mm/a

Underestimated wind wave & swell effects on coastal sea level

Relative contribution of:
- waves (wind sea & swell)
- “altimetric sea level”
- atmospheric surges

to interannual-to-multidecadal coastal sea level variations (1993-2015)

Melet et al. (2018)
Before we discuss how these different pieces are put together in flooding frequency estimates, we look at largest remaining wildcard:
The largest remaining uncertainty:

**Sea level and polar ice sheets**
Sea level and polar ice sheets:

Sea level rise potential – some numbers

- Greenland: ~ 7 m
- East Antarctic Ice Sheet (EAIS): ~ 53 m (of which ~19 m marine-based)
- West Antarctic Ice Sheet (WAIS): ~ 3 to 5 m
- Glaciers and Ice Caps (GIC): ~ 0.5 m

IPCC reports:
- 1990: no mention of ice sheet dynamics (time scales thought too long)
- 1995: WAIS collapse mentioned as high risk / low probability event
- 2001: feedback emphasizing importance of ice dynamics all but ignored
- 2007: “dramatic” ice dynamics identified as main uncertainty and limitation for sea-level prediction
- 2013: ...
Sea level and polar ice sheets:

Sea level rise potential – some numbers

- Greenland: ~ 7 m
- East Antarctic Ice Sheet (EAIS): ~ 53 m (of which ~19 m marine-based)
- West Antarctic Ice Sheet (WAIS): ~ 3 to 5 m
- Glaciers and Ice Caps (GIC): ~ 0.5 m

IPCC reports:

- 1990: no mention of ice sheet dynamics (time scales thought too long)
- 1995: WAIS collapse mentioned as high risk / low probability event
- 2001: feedback emphasizing importance of ice dynamics all but ignored
- 2007: "dramatic" ice dynamics identified as main uncertainty and limitation for sea-level prediction
- 2013: ...
Sea level and polar ice sheets: Antarctica

Satellite remote sensing during the 2000’s reveals

- increased ice stream flow speed
- increased ice shelf thinning
- increased ice sheet mass loss

in West Antarctica

Paolo et al. (2015)
Rignot et al. (2008)
Sea level and polar ice sheets: Evidence from the Eemian (Last Interglacial)

130,000 to 115,000 years ago:
- atmospheric CO\textsubscript{2} concentrations below 280 p.p.m.v.
- global mean surface temperatures ~0 to 2 °C warmer than present
- GMSL 6–9 m higher than present
  - 1.5 to 2 m estimated from Greenland
  - 0.4 m estimated from thermosteric rise
  - requires substantial Antarctic contribution!

USGCRP (2017)
Mean AIS mass loss during 1992-2017: 109 ± 56 Gt/a
(Greenland is: 171 Gt/a; WCRP 2018)

Major uncertainties:
- SMB & GIA

West Antarctic ice sheet mass loss increased from 53 ± 29 Gt/a to 159 ± 26 Gt/a due to ocean-driven “melting”
Sea level and polar ice sheets:
Greenland Ice Sheet

• Lots to say, but will leave out ...
Sea level and polar ice sheets: How much – how fast?

Ice sheet dynamics & physics – major unknowns:
1. Marine ice sheet instability (MISI)
2. Marine Ice cliff instability (MICI)
3. Marine Ice shelf hydrofracturing
4. Decadal climate variability and circulation changes
5. Amplification of flood frequencies – extreme value statistics
Sea level and polar ice sheets: The West Antarctic Ice Sheet & marine ice sheet instability?

Glaciology’s Grand Unsolved Problem

Sea level and polar ice sheets:
Ice sheet-ocean interactions in Greenland & Antarctica

- Warm subsurface water found at the grounding lines of both ice sheets
- *Thermodynamic* forcing elicits *dynamic* response

Joughin et al. (2012)
Sea level and polar ice sheets:
Ice sheet-ocean interactions in Greenland & Antarctica

- Warm subsurface water found at the grounding lines of both ice sheets
- Thermodynamic forcing elicits dynamic response

Joughin et al. (2012)
Sea level and polar ice sheets: Marine Ice Cliff Instability

- A newly proposed, plausible mechanism for accelerated ice sheet mass loss due to surface warming
- But remains heavily parameterized in current simulations

DeConto & Pollard (2016)
Sea level and polar ice sheets: Marine Ice Cliff Instability

Large uncertainties in:
- model resolution & initial conditions,
- simplified hybrid ice dynamics,
- parameterized
  - sub-ice melt & calving,
  - structural ice-margin failure,
- ancient sea-level estimates used in Large Ensemble analysis,

“The rates of ice loss simulated should not be viewed as actual predictions, but rather as possible envelopes of behaviour”

DeConto & Pollard (2016)
Sea level and polar ice sheets: Gravitational fingerprints

Normalized sea level fingerprints of West Antarctic Ice Sheet (WAIS) collapse

Farrell & Clark (1976)
Clark & Lingle (1977)
Conrad & Hager (1997)
Mitrovica et al. (2001)
Sea level and polar ice sheets: Gravitational fingerprints

Normalized sea level change with respect to eustatic sea level

\[ > 1: \text{sea level rise large than eustatic} \]

\[ > 0: \text{sea level rise (but lower than eustatic)} \]

\[ = 0: \text{no change} \]

\[ < 0: \text{sea level drop} \]

Impact of uncertainty due to underlying elastic vs. viscoelastic solid Earth model

Hay et al. (2017)
Sea level and polar ice sheets: Gravitational fingerprints

Dependence of fingerprints on spatial pattern of ice sheet mass loss, i.e. on where exactly within the ice sheet the ice is lost

“the adjoint”, or “the sensitivity kernel”
Putting it all together:

Probabilistic projections & compounding effects
### From global to regional to relative sea level

<table>
<thead>
<tr>
<th>Physical Process</th>
<th>Spatial Scale</th>
<th>Temporal Scale</th>
<th>Potential Magnitude (yearly)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td>Regional</td>
<td>Local</td>
</tr>
<tr>
<td>Wind Waves (e.g., dynamical effects, runup)</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Tsunami</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Storm Surge (e.g., tropical storms or nor’easters)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Seasonal Cycles</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ocean/Atmospheric Variability (e.g., ENSO response)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ocean Eddies, Planetary Waves</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ocean Gyre and Over-turning Variability (e.g., PDO response)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Land Ice Melt/Discharge</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vertical Land Motion</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Probabilistic projections of GMSL rise

Kopp et al. (2014)

Prior to MICI finding, and not including some other aspects.

<table>
<thead>
<tr>
<th>Table 1. GMSL Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>50</td>
</tr>
</tbody>
</table>

2100 — Components

<table>
<thead>
<tr>
<th></th>
<th>RCP 8.5</th>
<th>RCP 4.5</th>
<th>RCP 2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIC</td>
<td>18–24</td>
<td>11–24</td>
<td>7–29</td>
</tr>
<tr>
<td>GIS</td>
<td>14–8</td>
<td>5–39</td>
<td>3–70</td>
</tr>
<tr>
<td>AIS</td>
<td>4–8</td>
<td>11–33</td>
<td>14–91</td>
</tr>
<tr>
<td>TE</td>
<td>37–46</td>
<td>22–52</td>
<td>12–62</td>
</tr>
<tr>
<td>LWS</td>
<td>5–3</td>
<td>2–8</td>
<td>0–11</td>
</tr>
<tr>
<td>Total</td>
<td>79–100</td>
<td>52–121</td>
<td>39–176</td>
</tr>
</tbody>
</table>

Projections by year

<table>
<thead>
<tr>
<th>Year</th>
<th>RCP 8.5</th>
<th>RCP 4.5</th>
<th>RCP 2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>12–17</td>
<td>11–18</td>
<td>8–21</td>
</tr>
<tr>
<td>2050</td>
<td>29–34</td>
<td>21–38</td>
<td>16–49</td>
</tr>
<tr>
<td>2100</td>
<td>79–100</td>
<td>52–121</td>
<td>39–176</td>
</tr>
<tr>
<td>2150</td>
<td>130–180</td>
<td>80–230</td>
<td>60–370</td>
</tr>
<tr>
<td>2200</td>
<td>200–280</td>
<td>100–370</td>
<td>60–630</td>
</tr>
</tbody>
</table>

Other projections for 2100

<table>
<thead>
<tr>
<th></th>
<th>AR5</th>
<th>H14</th>
<th>J12</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>73–97</td>
<td>70–120</td>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>52–70</td>
<td>50–150</td>
<td>81–165</td>
<td>64–121</td>
</tr>
<tr>
<td></td>
<td>43–60</td>
<td>40–60</td>
<td>57</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>38–63</td>
<td>25–70</td>
<td>36–83</td>
<td>52–96</td>
</tr>
</tbody>
</table>

*TE: Thermal expansion, LWS: Land water storage, H14: Horton et al. [2014], J12: Jevrejeva et al. [2012], S12: Schaeffer et al. [2012].

All values are cm above 2000 CE baseline except for AR5, which is above a 1986–2005 baseline.
Probabilistic projections of GMSL rise

A compilation of probabilistic projections under different scenarios (RCP 2.6, 4.5, 8.5) and GMST stabilization pathways (Stab 1.5, 2.0) 5 – 95 percentiles

Horton et al. (2018)
Probabilistic projections of RSL rise

a) Six US interagency GMSL scenarios, the very likely ranges in 2100 for different RCPs (colored boxes), and lines augmenting the very likely ranges by the difference between the median Antarctic contribution of Kopp et al. (2014) and the various median Antarctic projections with MICI.

b) Relative sea level (RSL) rise in 2100 projected for the Interagency Intermediate Scenario (1-meter GMSL rise by 2100)
High tide flooding  
(a.k.a. nuisance flooding  
a.k.a. sunny day flooding)

Projected annual frequencies of high tide flooding in response to scenarios of global sea level rise

Scenarios are based on the U.S. Federal Interagency Sea Level Rise and Coastal Flood Hazard Task Force

N.B.: does not include
• wind wave & swell effects
• storm surges/cyclones
From global to local: 
**Allowances for evolving coastal flood risk**

- SLR allowance: the vertical buffer necessary to maintain an annual expected probability of occurrence (AEP)

**Here:**

1. use temporally dynamic, uncertain SLR projections
2. address deep uncertainty by using Limited Degree of Confidence metric
3. allowance for hydrologic design-life levels to accommodate different assets’ lifetimes in non-stationary risk management
From global to local: *Amplification* of flood frequencies with sea level rise

**amplification factor (AF):**
- measures change in expected frequency of a historic annual chance flood with SLR;
- a function of
  - storm/tidal surge changes
  - sea level rise

**emerging flood regime:**
- relationship between flood height and flood frequency changes under SLR

Buchanan et al. (2017)
Conclusions

• Robust evidence for GMSL rise, with acceleration in some components now detectable
• Regional signal may outpace global by up to factor 5
• Regional decadal signals still dominated by natural climate variability
• Polar ice sheets, in particular Antarctica carry large wildcard
  – new instability mechanisms amplify potential dynamic mass loss
  – remaining uncertainties also in gravitational sea level fingerprints
• Compounding effects that yield nonlinear amplification factors between sea level rise and coastal flooding frequencies
• Non-GIA related Vertical Land Motion may be important in regions (e.g., GoM)
• Probabilistic projections have come a long way, but it is important to understand what they account for, and what’s still missing
Outlook – polar ice sheets remain a large sea level wildcards

A multi-scale / multi-physics forward & inverse problem
A computational grand challenge
A scientific grand challenge

InSAR-based ice surface velocity observations

Reconstructed ice surface velocity field via inverse modeling
The End
References

References (cont’d)

• Sweet et al., 2017
• Sweet et al., 2018
Geocentric (“Absolute”) vs. Relative Sea Level (RSL)

Satellite altimetry and tide gauges do not measure the same “sea level”!
Global Mean vs. Regional Sea Level from Satellite Radar Altimetry

The satellite altimetric record, 1993-2017:
- linear trend: $3.1 \pm 0.3$ mm/a
- acceleration: $0.1 \pm 0.03$ mm/a$^2$

Up to factor of 5 differences between GMSL and regional sea level trend
Global Mean Sea Level (GMSL) rise

A superposition of many physical processes that need to be understood

What changes global mean sea level?

- Net temperature change (heat exchange with the atmosphere and sea floor)
- Addition/subtraction of fresh water (from atmosphere, land, ice)
- Change in ocean volume (crustal deformation / uplift)
- (Melting/formation of sea ice with non-zero salinity)
Regional/Relative Sea Level

What changes *regional sea level*? All global contributions, plus:

- *Local* addition/removal of fresh water
- *Local* wind & temperature shifts (atmosphere & ocean)
- Displacement of ocean currents (e.g., due to wind shifts)
- Gravity field changes due to mass redistribution ("gravitational sea level fingerprints")
- Tectonic uplift (GIA / PGR)
- Change in ocean load
Decadal natural climate variability & regional sea level

A large part of the decadal regional sea level pattern explained by circulation change in response to wind forcing variability

Miller & Douglas (2007)

Stammer et al. (2013)
Sea level and land hydrology

- Climate-driven changes in land water storage and their contributions to sea level rise
- Not assessed in IPCC AR5
- GRACE enables estimates

Reager et al. (2016)
Climate-driven changes in land water storage and their contributions to sea level rise

Not assessed in IPCC AR5

GRACE enables estimates

Climate variability-driven decadal gain in land water storage partly offset loss from land ice

Reager et al. (2016)
River discharge & coastal sea level along the US coast

Piecuch et al., PNAS, 2018
Satellite remote sensing during the 2000’s reveals

- increased ice stream flow speed
- increased ice shelf thinning
- increased ice sheet mass loss
Sea level and polar ice sheets: some history
First traverse of Antarctica during IGY 1957
Sea level and polar ice sheets: some history

First traverse of Antarctica during IGY 1957

First traverse of Antarctica during the International Geophysical Year IGY 1957

Structure of West Antarctica

The results of U.S. IGY oversnow traverses reveal the nature of a large portion of ice-covered Antarctica.

C. R. Bentley, A. P. Crary, N. A. Ostenso, E. C. Thiel

As part of its program for the International Geophysical Year and the IGY’s successor, International Geophysical Cooperation, the United States is conducting an extensive traverse program in Antarctica. Seven major parties were used by each party. The parties generally traveled 50 kilometers every day, stopping at regular intervals to read the gravimeter, the magnetometer, and the altimeters, and spent the alternate days making seismic and glaciological 870 pounds. These long refraction profiles provided, along with other valuable data, the wave velocities used for computing ice thickness.

Equipment

All traverses used the 24-trace Texas Instruments 7000B portable seismograph system with a basic frequency range of 5 to 500 cycles per second and with a selection of gain, filter, mixing, and automatic-gain-control settings that provided a large number of operating characteristics. Automatic gain control was very rarely used, and mixing only occasionally, with no appreciable improvement in the records. The parties were also equipped with two Vector geophone cables each having 12 take-outs at 30-meter intervals, and with a variety of geophones for measuring all...
Sea level and polar ice sheets: some history
The West Antarctic Ice Sheet & marine ice sheet instability?

• A slide on Mercer, Weertman, Hughes, Thomas, ...
Sea level and polar ice sheets: Amundsen Sea Embayment

Access to Byrd Subglacial Basin

- 3 to 5 m sea level rise potential
- Thwaites, Pine Island, Getz, …
- Simulated retreat for Thwaites:

Joughin et al. (2014)

Scambos et al. (2017)
Sea level and polar ice sheets: Amundsen Sea Embayment

Access to Byrd Subglacial Basin

- 3 to 5 m sea level rise potential
- Thwaites, Pine Island, Getz, …
- Simulated retreat for Thwaites: Scambos et al. (2017)

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley

Joughin et al. (2014)
Sea level and polar ice sheets:

Weddell Sea: Filchner-Ronne Ice Shelf

Access to Recovery Subglacial Basin

- Twenty-first-century warming of Filchner-Ronne ice-shelf cavity by a redirected coastal current
- Simulated evolution of near-bottom temperatures in the Weddell Sea suggests intrusion of warmer waters in mid-21st century.
- How realistic/likely?

Hellmer et al. (2012); Golledge et al. (2017)
Access to Aurora Subglacial Basin

- 3.5 to 6.5 m sea level rise potential
- Major unknowns:
  - bedmap geometry
  - oceanic variability

Greenbaum et al. (2015)
Sea level and polar ice sheets: Ross Sea Embayment

Access to Wilkes Subglacial Basin

- ...

Wilson et al. (2018)
Sea level and polar ice sheets: Marine Ice Cliff Instability

DeConto & Pollard (2016)
A note on glaciers & ice caps

Gardner et al. (2013)
Observed long-term (> 30 yr) relative sea level trend

Sweet et al., NOAA (2018)
Solid ice discharge (icebergs) from Greenland

- Based on observations for 1992 onward (feature-tracking via SAR and optical imagery)
- Least-squares interpolation from individual sparse measurements from 1958 onward

Example: Store Gletscher, West Greenland

Bamber et al., GRL (2018)
High tide flooding (Sweet et al., 2018)

a.k.a. nuisance flooding
a.k.a. sunny day flooding

Projected annual frequencies of high tide flooding in response to scenarios of global sea level rise

Scenarios are based on the U.S. Federal Interagency Sea Level Rise and Coastal Flood Hazard Task Force

N.B.: does not include
- wind wave & swell effects
- storm surges/cyclones
From global to local: The concept of *compounding effects*

- Simultaneous or sequential occurrence of extreme or non-extreme event add (or amplify) to lead to extreme event or impact
- US flood hazard assessment has been based on *univariate* extreme event analysis (one driver at a time)
- Coastal flooding risk due to
  - “background” sea level rise
  - storm & tidal surge (with or without wind waves)
  - river runoff (including intermittent intense precip.)
  - vertical land motion

From global to local: Allowances for evolving coastal flood risk

- **SLR allowance**: the vertical buffer necessary to maintain an annual expected probability of occurrence (AEP)

Here:

1. use temporally dynamic, uncertain SLR projections
2. address deep uncertainty by using a Limited Degree of Confidence metric
3. allowance for hydrologic design-life levels to accommodate different assets’ lifetimes in non-stationary risk management
From global to local: Non-GIA related Vertical Land Motion (VLM)

Three ways to estimate VLM:

1. **Blue**: GIA model ICE-5G (Peltier et al. 2015), used in IPCC AR5
2. **Green**: tide gauges and altimetry
3. **White**: GPS


Wöppelmann & Marcos (2016)
N.B.: Temporal variability in flood frequency

High tide flood frequency varies

- seasonally in response to a spatially varying mixture of
  - rhythmic astronomical tides (‘tidal forcing’),
  - repetitive seasonal mean sea level cycles, and
  - less-predictable episodic changes in wind and ocean currents that are nontidal in origin

- year-to-year due to
  - large-scale changes in weather and ocean circulation patterns, such as during the El Niño Southern Oscillation (ENSO).
N.B.: U.S. coastal cities & flood frequency tipping point

- many U.S. coastal cities are close to a tipping point with respect to flood frequency
- only 0.3 m to 0.7 m separates
  - infrequent damaging-to-destructive flooding from a regime of high tide flooding, or
  - minor floods from moderate and major floods.
- This suggests a particular interpretation for ‘freeboard’ and other engineering adaptive methods as the desired level of protection in terms of flood type, in both the present and future.
What’s not in the box

• Uncertainty in sea level fingerprints
• Uncertainty due to Marine Ice Cliff Instability
• Uncertainty in sub-ice shelf melt rates & amplifiers
• Uncertainty due to increase in tropical cyclone strength or frequency
• Uncertainty due to non-GIA Vertical Land Motion (VLM)