Tidings of the Tides

The Climate Science Special Report (CSSR)
Chapter 12: Sea Level Rise
https://science2017.globalchange.gov/chapter/12/

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Key Message 1

Global mean sea level (GMSL) has risen by about 16-21 cm (7-8 in) since 1900, with about 7 cm (3 in) occurring since 1993.

From: Wuebbles et al. (2017): CSSR Chapter 1
Key Message 1 (continued):
Human-caused climate change has made a substantial contribution to GMSL rise since 1900...

Sweet et al. (2017) CSSR Ch. 12 [adaptation of Kopp et al., 2016]
Key Message 1 (continued):
...contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years.

Global Sea-Level Rise
What causes sea level to change?

- **Land/Water Storage**
  Changes in runoff and storage of surface and ground water affect sea levels

- **Thermal Expansion**
  As water warms, it expands

- **Land-Based Ice Melting**
  As glaciers, Greenland and Antarctica Ice Sheets melt, they add mass

After IPCC (2001)
Current ocean rise:

• thermal expansion (1/3)
• land ice melt (2/3)

This is a departure of 20th century component ratio

Global & Local Relative Sea Level Rise (SLR)

Water Level Stations  Satellite Altimeter  Gravity Measurements  ARGO Profilers

NOAA Relative Sea Level Trends

Relative SLR =
\[ \Delta \text{Ocean Height} \]
Vertical Land Motion

https://tidesandcurrents.noaa.gov/sltrends/sltrends.html
Key Message 2:

Relative to the year 2000, GMSL is *very likely* to rise by:

- 0.3–0.6 feet (9–18 cm) by 2030
- 0.5–1.2 feet (15–38 cm) by 2050
- 1.0–4.3 feet (30–130 cm) by 2100

Future pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century.
Assessed 90% conditional probability ranges (colored boxes) of RCP-based GMSL projections augmented (dashed lines) by the difference between the median Antarctic contribution of Kopp et al. (2014) and the median Antarctic projections of DeConto and Pollard (2016)
### Table 12.3. Interpretations of the Interagency GMSL rise scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Continuing current rate of GMSL rise, as calculated since 1993&lt;br&gt;Low end of <em>very likely</em> range under RCP2.6</td>
</tr>
<tr>
<td>Intermediate-Low</td>
<td>Modest increase in rate&lt;br&gt;Middle of <em>likely</em> range under RCP2.6&lt;br&gt;Low end of <em>likely</em> range under RCP4.5&lt;br&gt;Low end of <em>very likely</em> range under RCP8.5</td>
</tr>
<tr>
<td>Intermediate</td>
<td>High end of <em>very likely</em> range under RCP4.5&lt;br&gt;High end of <em>likely</em> range under RCP8.5&lt;br&gt;Middle of <em>likely</em> range under RCP4.5 when accounting for possible ice cliff instabilities</td>
</tr>
<tr>
<td>Intermediate-High</td>
<td>Slightly above high end of <em>very likely</em> range under RCP8.5&lt;br&gt;Middle of <em>likely</em> range under RCP8.5 when accounting for possible ice cliff instabilities</td>
</tr>
<tr>
<td>High</td>
<td>High end of <em>very likely</em> range under RCP8.5 when accounting for possible ice cliff instabilities</td>
</tr>
<tr>
<td>Extreme</td>
<td>Consistent with estimates of physically possible “worst case”</td>
</tr>
</tbody>
</table>

The SLR scenarios contextualized in terms of probabilistic projections (e.g., Kopp et al., 2014)
Key Message 2 (continued):
Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.

Ocean & atmospheric warming and modelling of marine ice sheet/cliff instabilities:
- ice-shelf hydrofracturing
- ice cliff failures

Credit: Jeff Goodell, Rolling Stone
Key Message 2 (continued):

Regardless of pathway, it is extremely likely that GMSL rise will continue beyond 2100.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2100</th>
<th>2120</th>
<th>2150</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.30 (1.0)</td>
<td>0.34 (1.1)</td>
<td>0.37 (1.2)</td>
<td>0.39 (1.3)</td>
</tr>
<tr>
<td>Intermediate-Low</td>
<td>0.50 (1.6)</td>
<td>0.60 (2.0)</td>
<td>0.73 (2.4)</td>
<td>0.95 (3.1)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1.0 (3.3)</td>
<td>1.3 (4.3)</td>
<td>1.8 (5.9)</td>
<td>2.8 (9.2)</td>
</tr>
<tr>
<td>Intermediate-High</td>
<td>1.5 (4.9)</td>
<td>2.0 (6.6)</td>
<td>3.1 (10)</td>
<td>5.1 (17)</td>
</tr>
<tr>
<td>High</td>
<td>2.0 (6.6)</td>
<td>2.8 (9.2)</td>
<td>4.3 (14)</td>
<td>7.5 (25)</td>
</tr>
<tr>
<td>Extreme</td>
<td>2.5 (8.2)</td>
<td>3.6 (12)</td>
<td>5.5 (18)</td>
<td>9.7 (32)</td>
</tr>
</tbody>
</table>

Table 12.5. Post-2100 extensions of the Interagency GMSL rise scenarios in meters (feet)
Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth’s gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion.

Key Message 3:

After IPCC (2001)

RSL rise from changes in Earth’s gravitational field and rotation from melting of land ice
Sweet et al., 2017 CSSR Ch12

RSL rise from changes in ocean circulation
Sweet et al., 2009 NOAA Report

RSL rise from vertical land motion
Sweet et al., 2017 NOAA Report

GPS-derived Vertical Land Motion

RSL rise from vertical land motion
Key Message 3 (con’t):

For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico.

In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska.
Key Message 3 (con’t):

For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along U.S. coasts outside Alaska.

Almost all U.S. coastlines experience > global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss.
Key Message 4:

As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called “nuisance floods”) have increased 5- to 10-fold since the 1960s in several U.S. coastal cities.
Bob Dylan...the (high) tides, they are a changing!

Years ago, flooding occurred during big storms.

Now, sunny day (nuisance) tidal flooding is rather common.

Example from Norfolk, VA

Typical reach of daily ‘tides’

Minor Flood Level

Example from Norfolk, VA
5-10 fold increase in minor flood frequencies (0.75-2.75 feet above high tide) since 1960s in multiple locations
Key Message 4 (continued): Rates of increase of tidal flooding are accelerating in over 25 Atlantic and Gulf Coast cities.

![Graph showing tidal flooding rates](image-url)

- **Norfolk, VA**
- **1960s**
- **2010s**
- **SLR**
- **Minor (Nuisance)**
- **Moderate**
- **Major**

- **Height above MHHW (m)**
  - -0.8
  - 0.0
  - 0.8

- **Highest Daily Tides in a Year (Probability)**

U.S. Global Change Research Program
Trend Characterization of High Tide (aka Nuisance) Flooding (using a nationally consistent threshold: ~1.75-2.0 feet above high tide)

From Sweet et al. (2018) NOAA Report(s)
Key Message 4 (con’t): Tidal flooding will continue increasing in depth, frequency, and extent this century.

From Sweet et al. (2018)
Key Message 4 (con’t): Tidal flooding will continue increasing in depth, frequency, and extent this century.

From Sweet et al. (2018)
Key Message 5:
Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor’easters.
Bye-bye Freeboard...Hello Flooding

Intermediate-Low (0.5 m) Scenario

Intermediate (1.0 m) Scenario

Decade when the 5-year event becomes the 0.2-year event

2020 2030 2040 2050 2060 2070 2080 2090 2100 <2200

Sweet et al. (2017): CSSR Chapter 12
Key Message 5 (continued):

A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected based solely on RSL rise.
Large uncertainties in contemporary estimates of extreme water levels (more certainty in lesser extreme event probabilities)

Some examples of methods to assess today’s rare event probabilities:
- dynamical simulations: US Army Corps of Engineers (left), FEMA BFE
- Regional statistical methods: DOD CARSWG
Concluding Remarks

1. The contemporary rate of global sea level rise of about 3 mm/year (1 inch every 8 years) is not expected to slow.

2. Global sea levels are very likely to rise between about 1 and 4 feet by 2100, dependent upon future ocean/atmospheric heating.

3. By 2100 (if not then, maybe by 2150...), global rise could top 2.5 m.

4. The overall amount of rise will continue to vary around the U.S. coastline (e.g., more rise in New York City than Seattle).

5. Flooding directly attributed to sea level rise is happening now.

6. Due to sea level rise, flood frequencies are now accelerating and expected to become much worse in the coming decades.

7. Extreme flooding will worsen due to sea level rise; stronger storms and compounding events (e.g., heavier rains, higher water tables, increased tide ranges) will worsen impacts.

8. EMISSIONS MATTER!!