Assessing Sea Level Rise at the Regional to Local Scale Using Earth Observations

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Team Lead of NASA Sea Level Change Team
August 24, 2021
Contributors to Sea Level Rise

- **Sea Level in Past:**
  - Mean Sea Level
  - Natural Variability
  + Tides, Waves, Winds
  - Moderate Safety
  - Gap
Contributors to Sea Level Rise

- **Sea Level Now:**
  - Mean Sea Level
  - Sea Level Rise
  - Natural Variability
  - Subsidence
    - Tides, Waves, Winds

Small Safety Gap

**LOCAL**
- Tides, Waves, Winds

**REGIONAL**
- Natural Variability (El Niño, Seasonal)

**GLOBAL**
- Sea Level Rise (Ice, Warming)
- Mean Sea Level

- Subsidence
Why is sea level rising globally?

• There are two reasons that sea level is rising on global scales:

  1. The ocean is warming $\rightarrow$ water expands (thermal expansion).

  2. Ice on land is melting and the melt water is going into the ocean.
Why is sea level rising globally?

Ice (GRACE-FO) + Thermal Expansion (Argo) = Total Sea Level (Altimetry)
How do we measure global sea level change?

- For the last century, tide gauges have been used to measure sea level change along the world’s coastlines.
- Challenges associated with combining these records and estimating global mean sea level.
How do we measure global sea level change?

• Since 1992, satellite altimeters have been used to measure sea surface height in the ocean.
• Continuous measurements with near-global coverage.
• Sentinel-6/Michael Freilich continues this record.
Satellite Altimetry
Satellite Altimetry
Global Mean Sea Level from Satellite Altimetry

GLOBAL MEAN SEA LEVEL (ALTIMETRY)

Source: GSFC/PDO DAAC
Sentinel-6 continues 27+ years of sea level measurement from space.

With the launch of Sentinel-6A/Michael Freilich and Sentinel-6B in 2025, this record will surpass 40 years in length.

Why is the long record important?
Global Mean Sea Level

Source: Frederikse et al. (2020); GSFC/PO.DAAC
Why is sea level rising globally?

Ice (GRACE-FO) + Thermal Expansion (Argo) = Total Sea Level (Altimetry)
GRACE and GRACE-FO

• Gravity Recovery & Climate Experiment (GRACE; 2002-2016) and GRACE Follow-On (GRACE-FO; 2018-pres.) measure gravity changes on Earth.
  • These satellites can tell us how much ice is being lost.
  • They also tell us about the movement of water on Earth.

https://earthobservatory.nasa.gov/
Greenland Ice Sheet Mass Loss
Antarctic Ice Sheet Mass Loss
Sea Level Change from Ice Loss

DIRECT MEASUREMENTS: 2002-PRESENT

Data source: Monthly measurements (average seasonal cycle removed). Credit: JPL

RATE OF CHANGE

↑ 2.1
(± 0.3) mm/yr
Why is sea level rising globally?

Ice (GRACE-FO) + Thermal Expansion (Argo) = Total Sea Level (Altimetry)
Argo Profiling Floats

• Since ~2005, Argo profiling floats have been measuring the temperature and salinity of the ocean from 0 to 2000 m below the surface.

• From these measurements we can estimate the impact of thermal expansion on sea level rise.
Sea Level Change from Thermal Expansion

STERIC HEIGHT
Credit: Scripps/JPL

RATE OF CHANGE

1.1
(± 0.2) mm/yr
Why is sea level rising globally?

Ice (GRACE-FO) + Thermal Expansion (Argo) = Total Sea Level (Altimetry)
Closing the Sea Level “Budget”

1.3 mm/year THERMAL EXPANSION TREND, 2005–2019
2.1 mm/year MASS INCREASE TREND, 2002–2019
3.3 mm/year TOTAL SEA LEVEL TREND, 1993–2019

THERMAL EXPANSION + GLOBAL OCEAN MASS
GLOBAL MEAN SEA LEVEL (ALTIMETRY)
GLOBAL OCEAN MASS (GRACE/GRACE-FO)
THERMAL EXPANSION (ARGO)

Sources: GSFC/PO DAAC, JPL, NOAA
Regional Sea Level Change

Sea Surface Height Maps from Radar Altimetry

Oct 1992
Regional Sea Level Change
Regional Sea Level Change

• Sea level changes on a wide range of space and time scales.
  • The ocean does not behave like a bathtub.
• Contributions to the pattern of regional sea level change:
  • Natural variability signals like El Niño-Southern Oscillation and North Atlantic Oscillation.
  • Ice-sheet “fingerprints”.

(NASA GSFC Visualization Studio)
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(VESL, sealevel.nasa.gov)
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New York City: 1.06 mm/yr
Sydney: 1.50 mm/yr

(VESL, sealevel.nasa.gov)
Coastal Subsidence

• In addition to the ocean rising, many coastal regions around the world are sinking. This contributes to a rise in relative sea level.
  • Groundwater withdrawal, glacial isostatic adjustments, and tectonics.

• Interferometric Synthetic Aperture Radar Analysis (InSAR) can be used to estimate this movement of land at high spatial resolutions.
  • Satellite measures change from one pass to another over the same location.
Coastal Subsidence

- NASA is using InSAR in coastal locations threatened by sea-level rise to estimate vertical land motion.

(Bekaert et al., 2016)
Assessing Coastal Impacts

- Sea level is a global problem, but the impacts are local.
  - Flooding
  - Coastal Erosion
  - Saltwater Intrusion
  - Coastal Migration
  - Exposed Infrastructure
- A wide range of sea level “processes” can lead to coastal impacts.
- Important to consider how these processes combine and the timescales on which they combine.
Coastal Impact Case Study: High Tide Flooding

- High-tide floods (HTF), previously known as nuisance floods, are already a problem along some U.S. coastlines.
- HTF is generally minor flooding that occurs at high tides in low-lying coastal locations (viewed as separate from storm-related flooding).
- HTF impacts coastal communities broadly, leading to business closures, transportation problems, and utility challenges.
- Accumulated effect over time can have a big impact on coastal infrastructure.
- Assessments of future HTF are critical for annual budgeting and long-term planning.
- Also, HTF is not always “minor”.

NOAA Technical Report, 2021
Coastal Impact Case Study: High Tide Flooding
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Hours above HTF Threshold in Norfolk, VA

(Hamlington et al., 2018)
Putting the Pieces Together

- In Thompson et al. (2021), a statistical framework was developed to assess the combined impact of the processes that drive HTF using the best available information on each process.
Sea Level Scenarios and Projections

<table>
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<tr>
<th>GMSL Scenario (meters)</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
<th>2120</th>
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<td>0.06</td>
<td>0.09</td>
<td>0.13</td>
<td>0.16</td>
<td>0.19</td>
<td>0.22</td>
<td>0.25</td>
<td>0.28</td>
<td>0.30</td>
<td>0.34</td>
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<tr>
<td>Intermediate-Low</td>
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<td>0.08</td>
<td>0.13</td>
<td>0.18</td>
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<td>0.35</td>
<td>0.45</td>
<td>0.50</td>
<td>0.60</td>
<td>0.73</td>
<td>0.95</td>
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<tr>
<td>Intermediate-High</td>
<td>0.05</td>
<td>0.10</td>
<td>0.19</td>
<td>0.30</td>
<td>0.44</td>
<td>0.60</td>
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<td>1.5</td>
<td>2.0</td>
<td>3.1</td>
<td>5.1</td>
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<tr>
<td>High</td>
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<td>0.11</td>
<td>0.21</td>
<td>0.36</td>
<td>0.54</td>
<td>0.77</td>
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<td>1.3</td>
<td>1.7</td>
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<td>0.41</td>
<td>0.63</td>
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<td>1.2</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
<td>3.6</td>
<td>5.5</td>
<td>9.7</td>
</tr>
</tbody>
</table>
Flooding Thresholds

a. NOAA Minor Flood Threshold

b. Minor Derived Flood Threshold

Above MHHW (m)

0
0.2
0.4
0.6
0.8
1

>1

0.3
0.5
0.7
0.9
1.1
1.3

>1.3

c. NOAA Moderate Flood Threshold
d. Moderate Derived Flood Threshold

Tidal Variations

Impact of the nodal cycle
NOAA intermediate SLR scenario
St. petersburg, FL

Height above MHW (cm)

-10
0
10
20
30
40

2020 2030 2040 2050

Highest astronomical tides
Mean SLR
Highest tides + SLR

14.1 cm
9.4 cm
8.9 cm
4.3 cm

18.6 year cycle

Tidal forces emphasize one higher tide per day
Larger angle between moon's orbit and equator

Tidal forces emphasize two similar high tides per day
Smaller angle between moon's orbit and equator

Note: The angles between the moon's orbit and equator have been modified.

Thompson et al., 2021
Coastal Impact Case Study: High Tide Flooding

Projected HTF days
NOAA Intermediate SLR scenario

Honolulu, HI
Threshold: NOAA minor
2027 → 2037: Δ = 2 days per year
2037 → 2047: Δ = 63 days per year

Boston, MA
Threshold: NOAA moderate
2031 → 2041: Δ = 6 days per year
2041 → 2051: Δ = 48 days per year

La Jolla, CA
Threshold: NOAA minor
2023 → 2033: Δ = 1 day per year
2033 → 2043: Δ = 49 days per year

St. Petersburg, FL
Threshold: NOAA minor
2023 → 2033: Δ = 6 days per year
2033 → 2043: Δ = 67 days per year

Thompson et al., 2021
Coastal Impact Case Study: High Tide Flooding

Ten-year increases in HTF following YOIs

SLR scenario: NOAA Intermediate
Threshold: NOAA minor

Region
- Pacific Islands
- California
- Oregon and Washington
- Gulf of Mexico
- Atlantic Coast, south
- Atlantic Coast, north
- Caribbean

Ten-year multiplier
- $2x$
- $5x$
- $\geq 10x$

Ten-year increase in HTF days

YOI

2020 2030 2040 2050 2060 2070 2080 2090 2100

SLR scenario: NOAA Intermediate
Threshold: NOAA moderate

Region
- Pacific Islands
- California
- Oregon and Washington
- Gulf of Mexico
- Atlantic Coast, south
- Atlantic Coast, north
- Caribbean

Ten-year multiplier
- $2x$
- $5x$
- $\geq 10x$

Ten-year increase in HTF days

YOI

2020 2030 2040 2050 2060 2070 2080 2090 2100

Thompson et al., 2021
Coastal Impact Case Study: High Tide Flooding

Cluster of HTF days
NOAA Intermediate SLR scenario

Honolulu, HI
Threshold: NOAA minor

Boston, MA
Threshold: NOAA moderate

La Jolla, CA
Threshold: NOAA minor

St. Petersburg, FL
Threshold: NOAA minor

Five-year average
Five-year peak season (three-month period)
Five-year peak month

Thompson et al., 2021
Satellites will play a critical role in monitoring these processes and providing important information to decision-makers and planners.

What can NASA do to provide “useful” information?

To meet this challenge, NASA created the NASA Sea Level Change Team (N-SLCT) in 2014.
- 70+ scientists from government and academia.
- Web portal at sealevel.nasa.gov was created as part of this effort.

Two Goals:
- Science: Provide improved forecasts of sea level across a range of timescales.
- Outreach: Connect with practitioners and stakeholders to define and provide ‘useful’ sea-level information.
Satellite and Integrated Product Demo

- Full list of data tools on NASA sea level portal can be found here: [https://sealevel.nasa.gov/data/tools](https://sealevel.nasa.gov/data/tools).
- As a demonstration of how these tools and data can be combined to understand past, present, and future sea level, let’s take a look at:
  1. Data Analysis Tool: [https://sealevel.nasa.gov/data_tools/1](https://sealevel.nasa.gov/data_tools/1)
  2. Virtual Earth System Laboratory: [https://sealevel.nasa.gov/data_tools/2](https://sealevel.nasa.gov/data_tools/2)
  3. Sea Level Evaluation and Assessment Tool: [https://sealevel.nasa.gov/data_tools/16](https://sealevel.nasa.gov/data_tools/16)
  4. IPCC AR6 Sea Level Projection Tool: [https://sealevel.nasa.gov/data_tools/17](https://sealevel.nasa.gov/data_tools/17)
  5. Flooding Days Projection Tool: [https://sealevel.nasa.gov/data_tools/15](https://sealevel.nasa.gov/data_tools/15)
Homework and Certificate

• One homework assignment:
  – Answers must be submitted via Google Form, accessed from the ARSET website.
  – Homework will be made available on August 26th.
  – Due date for homework: September 15, 2021

• A certificate of completion will be awarded to those who:
  – Attend all live webinars
  – Complete the homework assignment by the deadline
  – You will receive a certificate approximately two months after the completion of the course from: marines.martins@ssaihq.com
Contacts

Trainers:

– Benjamin Hamlington:
  benjamin.d.hamlington@jpl.nasa.gov

Training Webpage:


ARSET Website:

– https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset

Follow us on Twitter @NASAARSET
Questions

• Please enter your questions in the Q&A box. We will answer them in the order they were received.

• We will post the Q&A to the training website following the conclusion of the webinar.
Thank You!