Lecture02-Sea_Level

September 2, 2025

1 Lecture02 - Sea level - definition, short term and long term variations

Learning Objectives: mean sea level, the geoid, changes in mean sea level, tide, storm surge, climate change and sea level rise, sea level combining sediment process

Before class: - make sure you know how to access and run the class jupyternotebook (*.ipynb) on Google Colab

After class: - Assignment01.ipynb (due 09/08/2025 23:59PM EDT) - read more about sea level rise - and explore NOAA's sea level rise viewer to learn more about sea level rise and coastal flooding impacts - optional: finish watching How the tides REALLY work

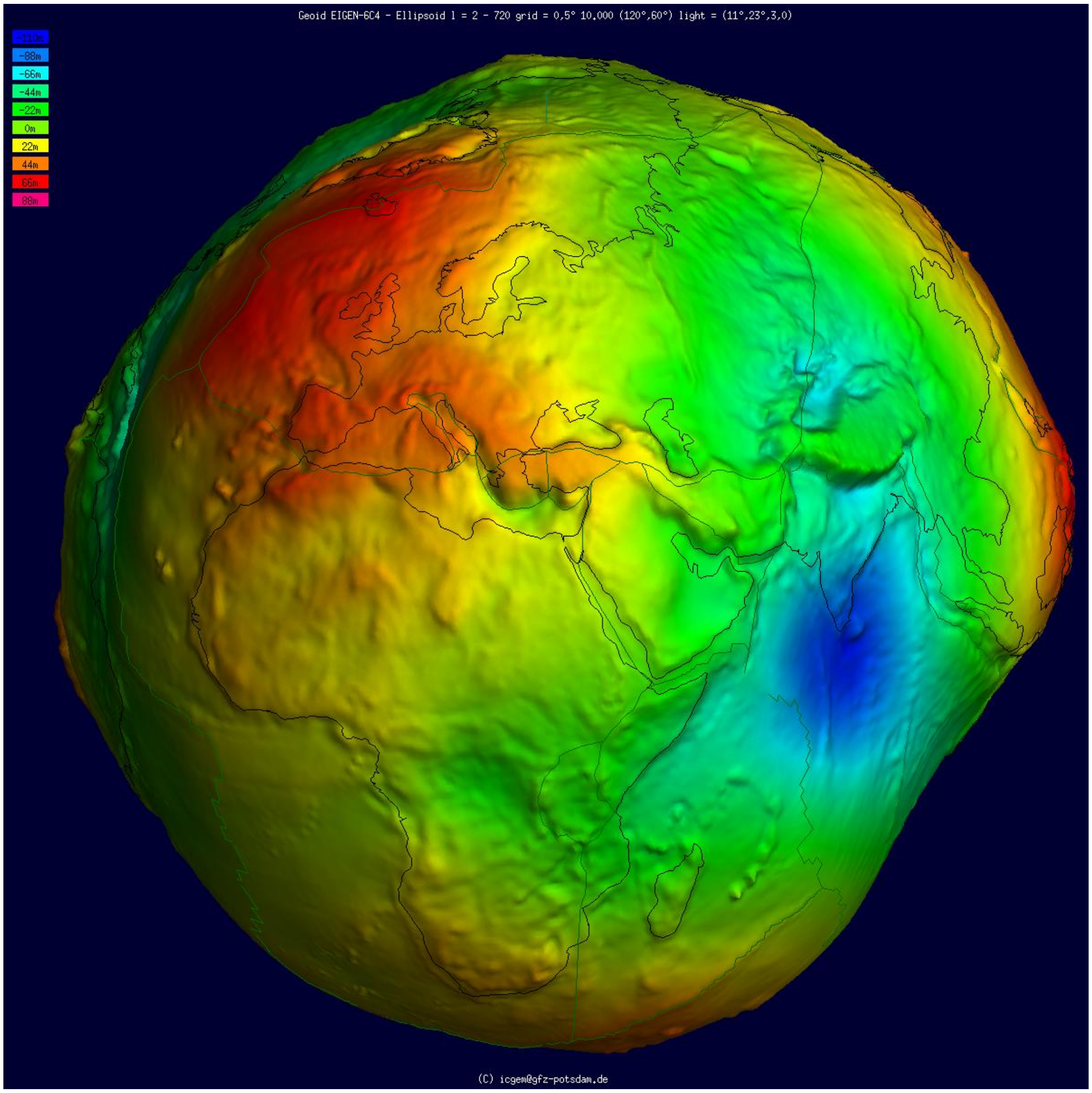
Reference:

- Textbook chapter 3, skip 3.4.3-3.4.4
- optional: BS 2.5

1.1 1. Water level definition and the geoid

The **geoid** (/ d i . d/ JEE-oyd) is the shape that the ocean surface (i.e., roughly fits the mean sea surface) would take under the influence of the gravity of Earth:

If one were to remove the tides and currents from the ocean, it would settle onto a smoothly undulating shape (rising where gravity is high, sinking where gravity is low). This irregular shape is called "the geoid," a surface which **defines zero elevation** so that we can measure precise surface elevations. The permanent deviation between the geoid and mean sea level is called **ocean surface topography**. Find more info here.



The SWOT satellite was launched in 2022 to map the topography world's oceans and its terrestrial surface waters at high resolution. Click here for video demo.

1.2 2. Short-term variations

The textbook definition of short-term changes ranges from hours to approximately 10^3 years. In this class, we heuristically define processes with timescales shorter than a few decades as short-term, and those longer as long-term.

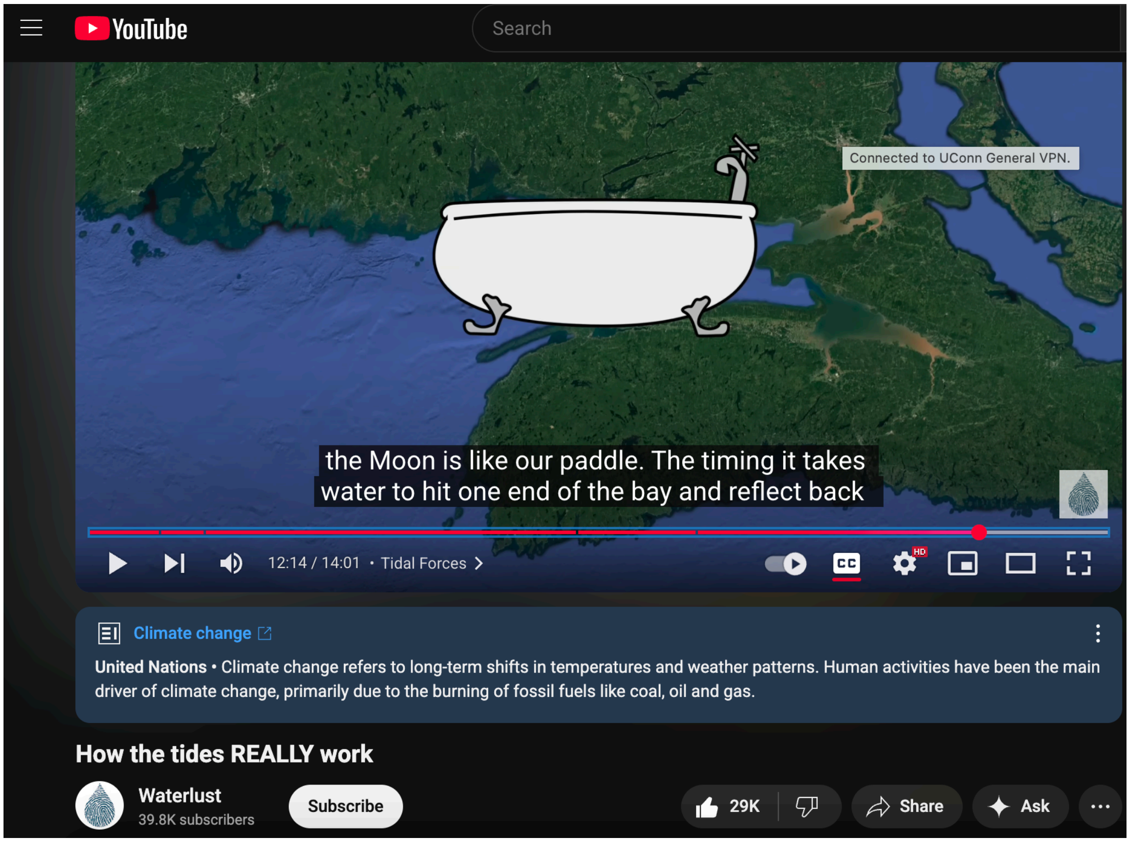
Table 3.1 *Major causes of sea level change and characteristic magnitude and time history. The magnitudes of change and time period are general and in some cases may fall outside the ranges indicated. Periodic and episodic changes result in a temporary deviation from mean sea level whereas continuous changes result in a change in the relative position of the sea and land.*

Name	Cause	Magnitude (m)	Time scale	Time history
surf beat	wave groups	0.05–0.5	30–300 seconds	periodic
seiche	oscillations in basin	0.02–0.75	seconds to hours	episodic periodic
tides	gravitational force of moon and sun	0.05–15	semi-diurnal or diurnal	periodic
wave set up (and set down)	wave momentum flux	0.05–0.75	hours-days	episodic
wind set up and storm surge	wind stress barometric pressure	0.05–3.0	hours-days	episodic
dynamic ocean temperature, currents	expansion and contraction due to temperature changes	0.05–0.5	days to months seasonal	episodic

1.2.1 1). Tide

Along ocean coasts tides produce a regular daily rise and fall of sea level that may range from a few decimetres to as much as 15m in a few places. These fluctuations are termed astronomical tides because they are produced by the **gravitational influence of the moon and sun**, and this distinguishes them from other short-term changes in sea level produced, for example, by strong winds or changes in barometric pressure which are sometimes termed meteorological tides. Basically, tides are very long-period **waves** that move through the oceans in response to the forces exerted by the moon and sun. Tides originate in the oceans and progress toward the coastlines where they appear as the regular rise and fall of the sea surface. When the highest part, or crest of the wave reaches a particular location, **high tide** occurs; **low tide** corresponds to the lowest part of the wave, or its trough. The difference in height between the high tide and the low tide is called the **tidal range**.

Let's watch a short video together to see tides in Fanny bay, Canada:



Chalk talk and Discussion: What is the net effect of gravity from Earth and moon on mass at surface of Earth? - Tide Generating Forces; and What is the ratio of the tidal force due to the Sun to that of the Moon at the Earth's surface?

Body	Mass (m)	Body	Radius (r)	Distance (d)
Sun	1.99×10^{30} kg	Earth	6.37×10^{6} m	1.50×10^{11} m
Moon	7.34×10^{22} kg	Earth	6.37×10^{6} m	3.84×10^{8} m
Earth	5.97×10^{24} kg	Moon	1.74×10^{6} m	3.84×10^{8} m

a. tidal type **Diurnal tides** occur primarily along the coast of Antarctica and the Indian Ocean and in parts of the eastern Arctic Archipelago. **Semi-diurnal tides** are common along much of the Atlantic and Arctic coasts and mixed tides are common in the northern Pacific.

Figure 3.8 Examples of tidal curves for one month showing each of the major tidal patterns (after Defant, 1962).

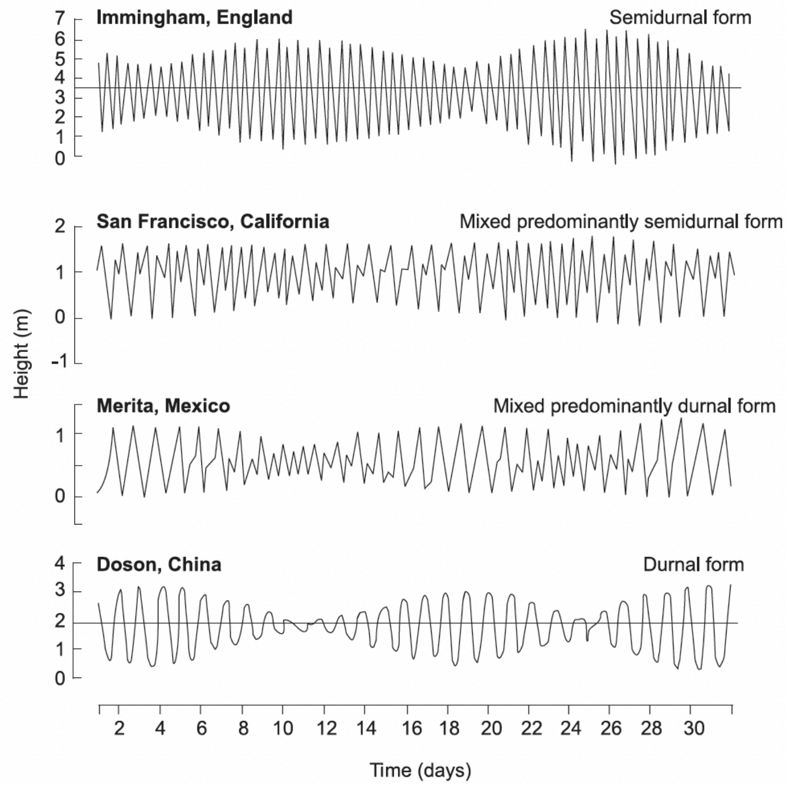
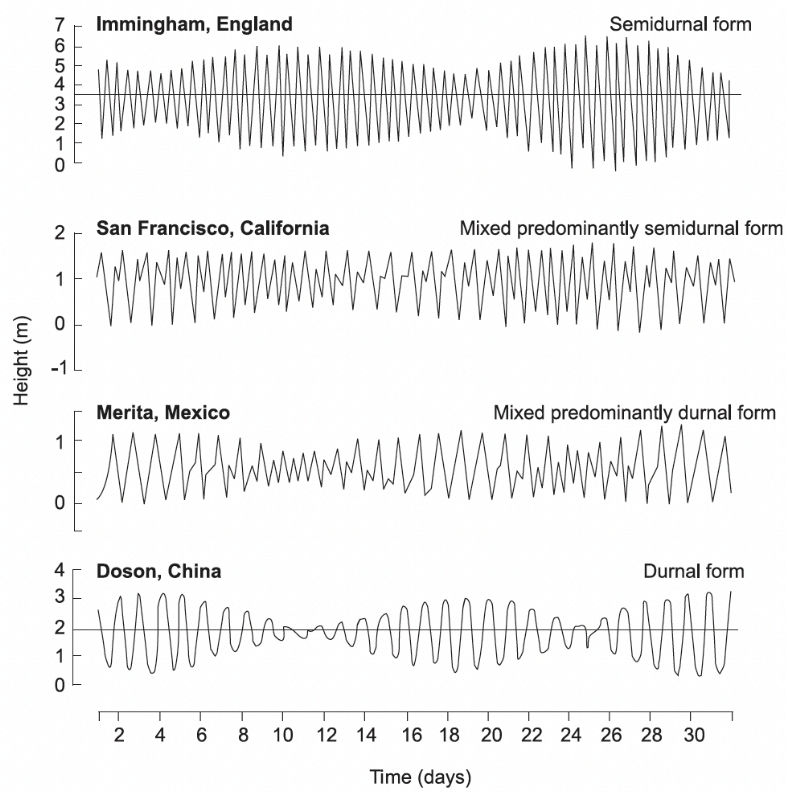


Figure 3.8 Examples of tidal curves for one month showing each of the major tidal patterns (after Defant, 1962).



b. neap and spring tides All of the tidal curves in Figure 3.8 show a distinct variation in the amplitude of the tidal fluctuation that occurs over a period of a fortnight (two weeks). This is related to the relative positions of the two tide generating forces of the sun and the moon. The moon and the sun each produce two tidal waves. When the sun and the moon are aligned in a straight line as they are at the full and new moons (Figure 3.10) then these two waves are in phase and reinforce each other, producing higher high tides and lower low tides. When the sun and moon are aligned at right angles to each other, as they are at the first and third quarter, then the tidal waves are out of phase and tend to cancel each other. Because the solar component is much smaller than that of the lunar component it does not fully cancel it, leaving a diminished lunar tide. Tides with the largest range, which occur at the full and newmoons, are termed **spring tides** while those with a lower range associated with the first and third quarters of the moon are termed **neap tides**. The neap tidal range is on average about 40% lower than that of the spring tide.

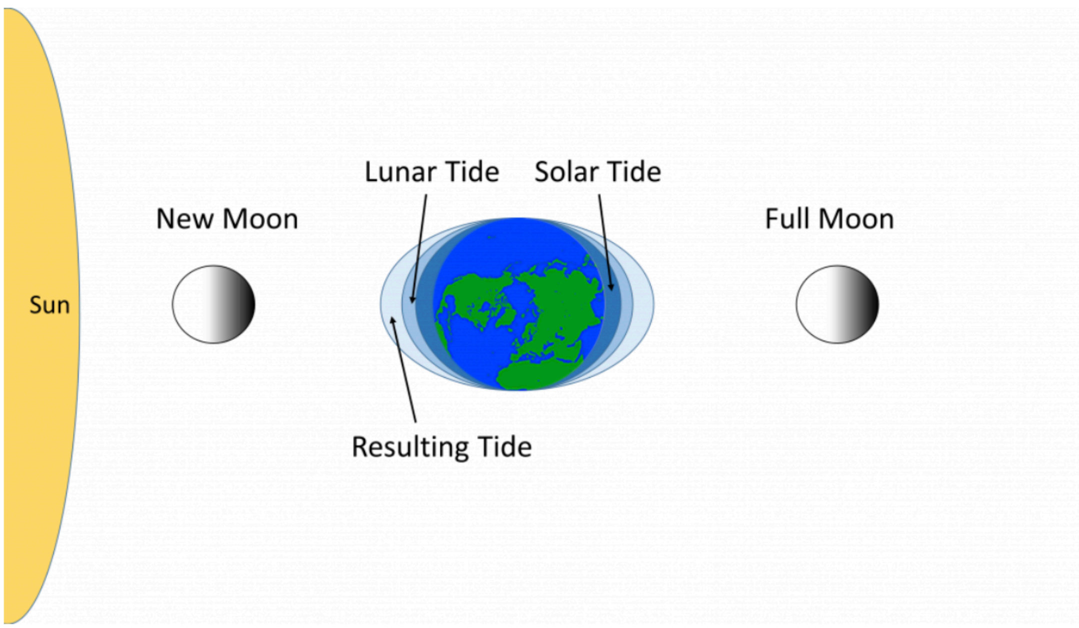


Figure 11.1.5 *Spring tides with high tidal ranges occur when the solar and lunar tides are added together during full and new moons when the Earth, sun and moon are aligned (PW).*

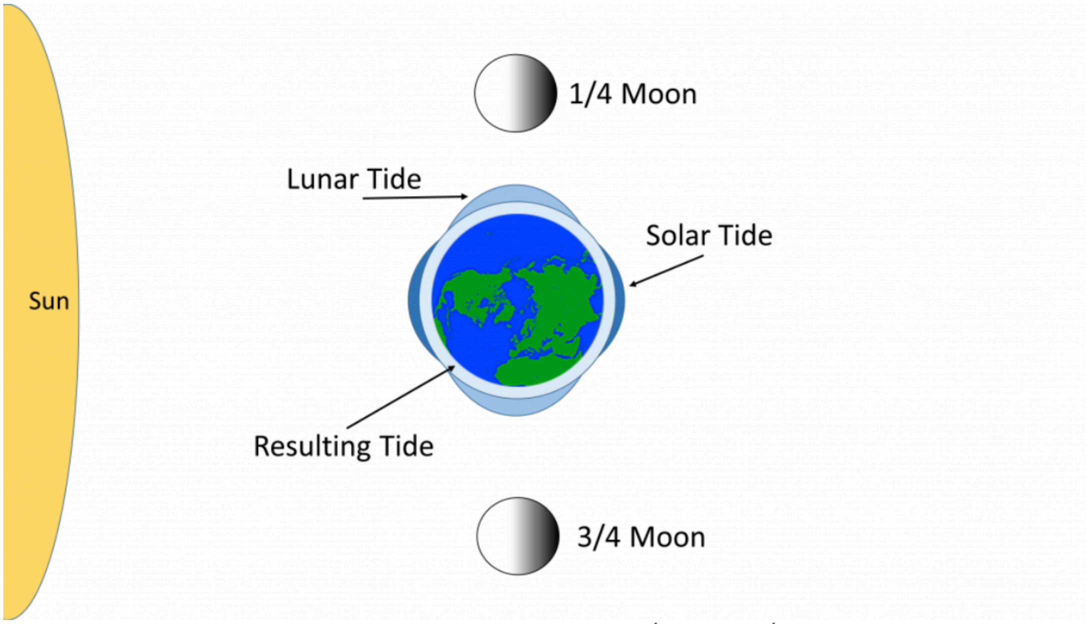


Figure 11.1.6 *Neap tides are created during 1/4 and 3/4 moons when the Earth, sun and moon are perpendicular to each other. The solar and lunar tides cancel each other out, resulting in a small tidal range (PW).*

c. tidal range The difference between the elevation of high and low tide is the tidal range and it controls the excursion of the water level on the coastline. The average **tidal range at spring tides** can be used as an important shoreline descriptor and it ranges from <0.5m in enclosed seas to over 15m in a few elongate estuaries and embayments.

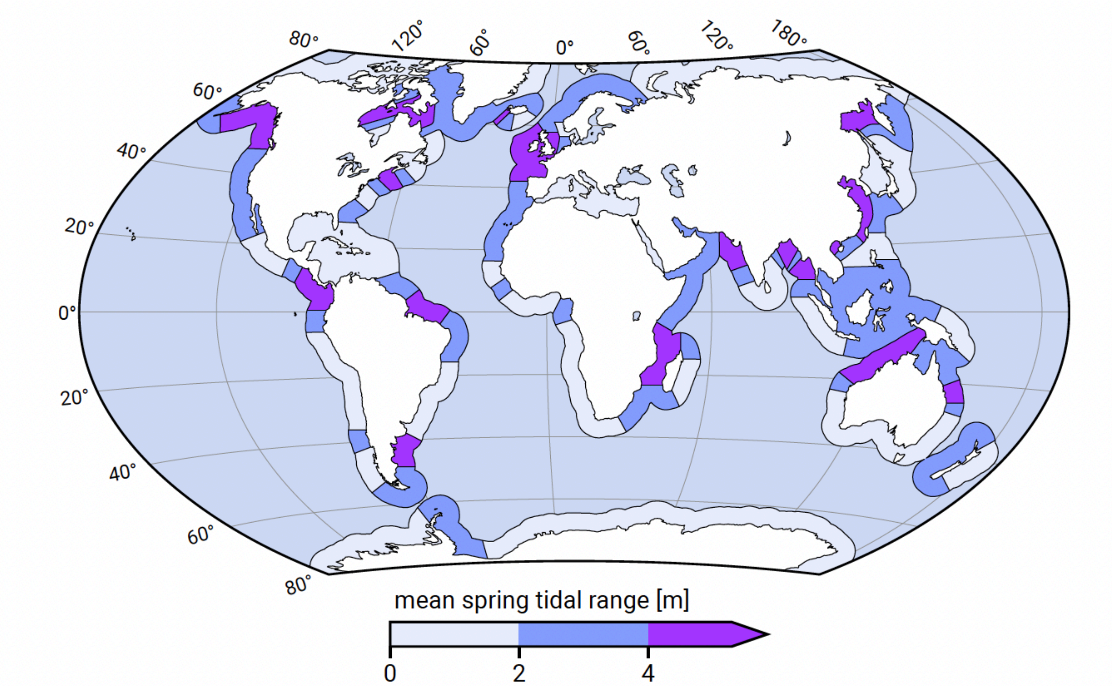


Figure 4.10: World distribution of mean spring tidal range (MHWS – MLWS). Tidal classification according to J. L. Davies and Clayton (1980).

d. tidal currents A horizontal movement of water often accompanies the rising and falling of the tide. This is called the tidal current. The incoming tide along the coast and into the bays and estuaries is called a flood current; the outgoing tide is called an ebb current. The strongest flood and ebb currents usually occur before or near the time of the high and low tides. The weakest currents occur between the **flood** and **ebb** currents and are called "**slack** water" or "slack current". In the open ocean tidal currents are relatively weak. Near estuary entrances, narrow straits and inlets, the speed of tidal currents can reach up to several kilometers per hour.

Table C.2: Terms related to tidal levels.

CD	Chart Datum
LAT	Lowest Astronomical Tide
HAT	Highest Astronomical Tide
MLW	Mean Low Water
MHW	Mean High Water
MSL	Mean Sea Level
MLWS	Mean Low Water Spring
MHWS	Mean High Water Spring
MLWN	Mean Low Water Neap
MHWN	Mean High Water Neap
MLLW	Mean Lower Low Water
MHHW	Mean Higher High Water
MHLW	Mean Higher Low Water
MLHW	Mean Lower High Water

e. tidal datums E.g., **MSL** – Mean Sea Level the average height of the sea measured over a long period of time. This is the average level which would exist in the absence of tides.
MHW – Mean High Water the average height of all high tides.
MHHW – Mean Higher High water the average height of the higher of the two daily high tides over a long period of time. When only one high water occurs per day, this is taken as the higher high water.
MHWS – Mean High Water Spring the long-term average of all high-water observations of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of tide is greatest, at full and new moon.
MLHW – Mean Lower High Water the mean of the lower of the two daily high waters over a long period of time. When only one high water occurs on most days, no value is printed in the MLHW column, indicating that the tide is usually diurnal.
The rest definition can be found in B.S. p529.

Let's take a look at water levels from a tidal gauge in New London here and tidal datums here..

Discussion: Describe the local characteristics of tides by identifying (1) the number of cycles in a day - the tidal type; (2) the variation in tidal elevation over a two week period - the springneap cycle; and (3) the difference in elevation between high and low tide - the tidal range.

Tidal Component	Period (solar hours)	Description	Nature
M2	12.42	Principal lunar	semi-diurnal
S2	12.00	Principal solar	semi-diurnal
N2	12.66	Larger lunar elliptic	semi-diurnal
K2	11.97	Luni-solar	semi-diurnal
K1	23.93	Luni-solar diurnal	diurnal
O1	25.82	Principal lunar diurnal	diurnal
P1	24.07	Principal solar diurnal	diurnal
Q1	26.87	Larger lunar elliptic	diurnal
MF	327.90	Lunar fortnightly	Long term
MM	661.30	Lunar monthly	Long term
SSA	4383.00	solar semi annual	Long term
M4	6.21		Compound
MS4	6.10		Compound

f. tidal constituents/components

[1]:
```
# %%capture

# # Install necessary packages and restart the kernel.
# !pip install pandas
# !pip install ipympl
# # resetart kernel
# import IPython
# IPython.Application.instance().kernel.do_shutdown(True) #automatically
 ↪restarts kernel
```

[2]:
```
# # to enable the jupyter widgets so that you can plot interactive figures
# from google.colab import output
# output.enable_custom_widget_manager()
```

[3]:
```python
# import python libraries
import pandas as pd
import numpy as np
from matplotlib import cm
import matplotlib.pyplot as plt
```

[4]:
```python
# load one month of sea level data from New London tidal guage (https://
↪tidesandcurrents.noaa.gov/stationhome.html?id=8461490)
df = pd.read_csv('../data/lecture02/NewLondon_sl_20250801-0830_6min.csv')
df
```

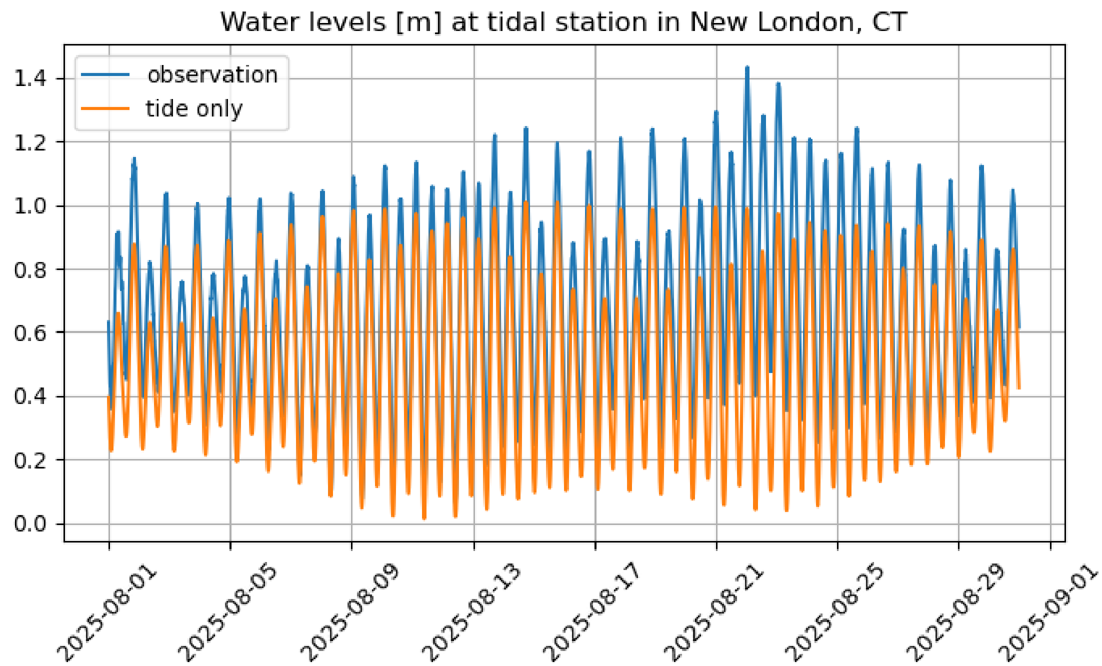
[4]:
```
             Date Time (GMT)  Predicted (ft)  Preliminary (ft) Verified (ft)
0     2025/08/01       00:00           1.297              2.07             -
1     2025/08/01       00:06           1.254              2.01             -
2     2025/08/01       00:12           1.212              1.95             -
3     2025/08/01       00:18           1.170              1.83             -
4     2025/08/01       00:24           1.129              1.76             -
…            …        …             …                …             …
7195  2025/08/30       23:30           1.554              2.17             -
7196  2025/08/30       23:36           1.515              2.13             -
7197  2025/08/30       23:42           1.475              2.10             -
7198  2025/08/30       23:48           1.436              2.07             -
7199  2025/08/30       23:54           1.396              2.02             -

[7200 rows x 5 columns]
```

[5]:
```python
# convert date and time to datetime
time = pd.to_datetime(df["Date"]+'T'+df["Time (GMT)"])
# convert sea level data to meters
sea_level_p = df["Predicted (ft)"].values*0.3048
sea_level = df["Preliminary (ft)"].values*0.3048
```

[6]:
```python
# plot sea level
# %matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(8,4))
ax.plot(time, sea_level, label="observation")
ax.plot(time, sea_level_p, label="tide only")
plt.xticks(rotation=45) # Rotates X-axis ticks by 45 degrees
plt.title("Water levels [m] at tidal station in New London, CT")
ax.grid(True) # add grids
ax.legend() # add legends
```

[6]:
```
<matplotlib.legend.Legend at 0x31af9b4d0>
```



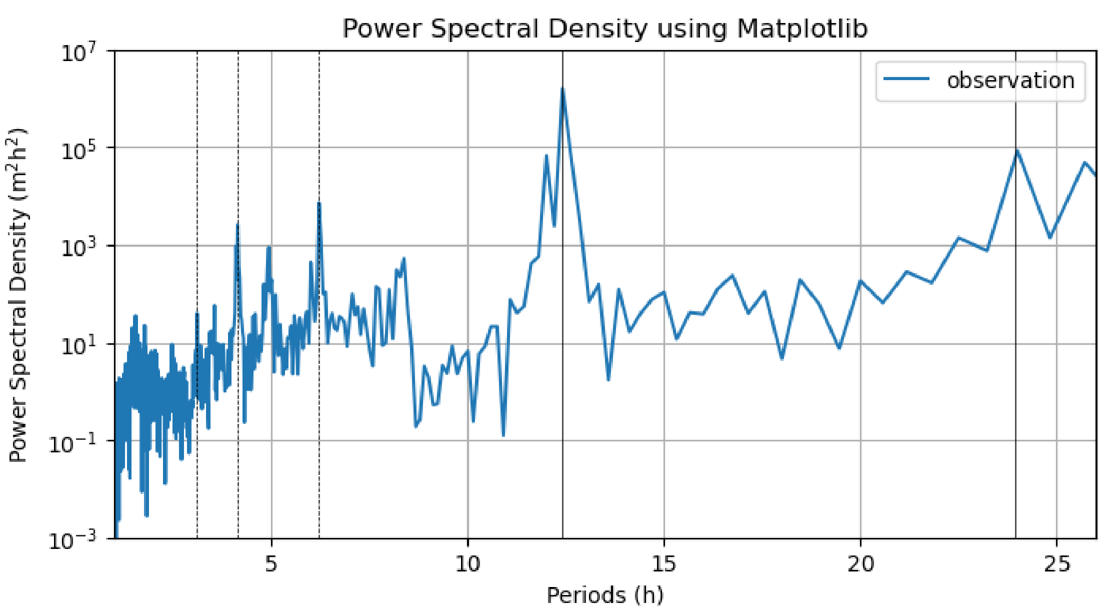
[7]:
```
# plot power spectral density of sea level
# %matplotlib widget
fs = 10  # Sampling frequency (in 1/hour)
# fast fourier transform of data
freqs = np.fft.fftfreq(time.size, 1/fs) # Generate frequencies
periods = 1/freqs
idx = np.argsort(freqs)
# power spectral for observed sea level
ps = np.abs(np.fft.fft(sea_level))**2 # by definiation, power spectral is the
 ↪squred FFT components
# power spectral for only tidal components
ps_p = np.abs(np.fft.fft(sea_level_p))**2
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(8,4))
# plot power spectral for both observed sea level and tidal prections
ax.plot(periods[idx], ps[idx], label="observation")
# ax.plot(periods[idx], ps_p[idx], label="tide only")
# plot M2 and K1 tidal frequencies
ax.plot([12.42, 12.42], [1e-3, 1e7], color='k', linewidth=.5) # M2 period 12.42
 ↪hours
ax.plot([23.93, 23.93], [1e-3, 1e7], color='k', linewidth=.5) # K1 period 23.93
 ↪hours
# higher harmonics are generated as a result of non-linear effects in
 ↪shallowing coastal waters and tidal basins
```

```
ax.plot([12.42/2, 12.42/2], [1e-3, 1e7], color='k', linewidth=.5,␣
↪linestyle='--') # M4
ax.plot([12.42/3, 12.42/3], [1e-3, 1e7], color='k', linewidth=.5,␣
↪linestyle='--') # M6
ax.plot([12.42/4, 12.42/4], [1e-3, 1e7], color='k', linewidth=.5,␣
↪linestyle='--') # M8

plt.title('Power spectrum ')
ax.set_yscale('log') # Set the y-axis to a logarithmic scale
ax.set_xlim([1, 26])
ax.set_ylim([1e-3, 1e7])
ax.set_xlabel(r'Periods (h)')
ax.set_ylabel(r'Power Spectral Density (m$^2$h$^2$)')
plt.title('Power Spectral Density using Matplotlib')
ax.grid(True)
ax.legend()
```

```
/var/folders/hs/5g3czpn50rn8rpb6b51001lm0000gp/T/ipykernel_59538/1762946375.py:6
: RuntimeWarning: divide by zero encountered in divide
  periods = 1/freqs
```

[7]: <matplotlib.legend.Legend at 0x31b29b610>



1.2.2 2) Storm surge

Storm surges are elevations of the water surface with time- and spatial scales equal to those of the large **storm** fields that generate them. They are generated by the low atmospheric pressure and high wind speeds in a storm field. Storm surges can cause severe flooding because the water will pile up against the coast when they approach the coast. The highest storm surges tend to occur in shallow, gently sloping coastal areas and in semi-enclosed bays and estuaries. (side note: Storm surge may be referred to as a meteorological tide, as in high tide, accompanying the storm.)

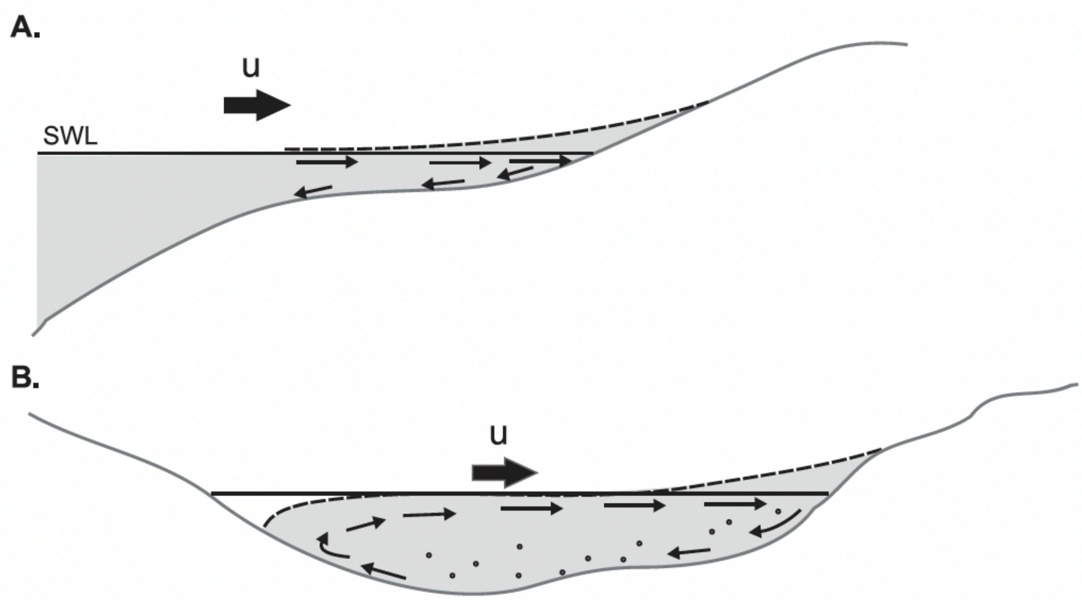
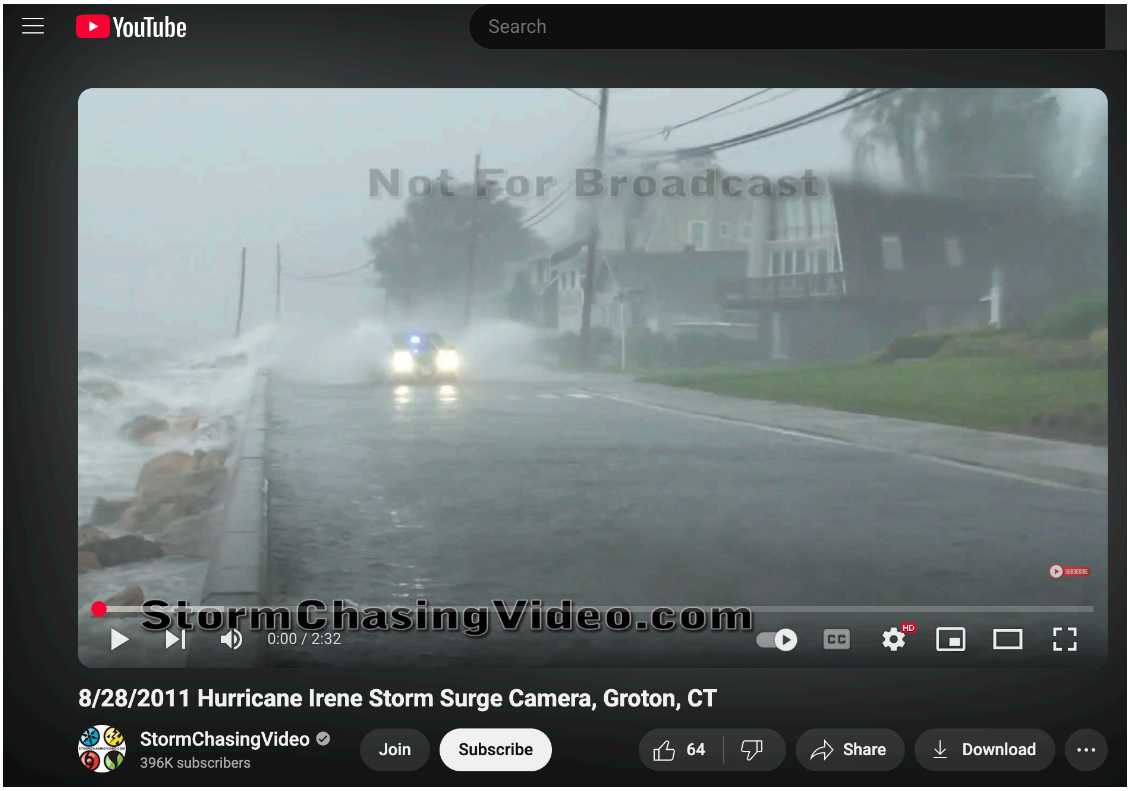


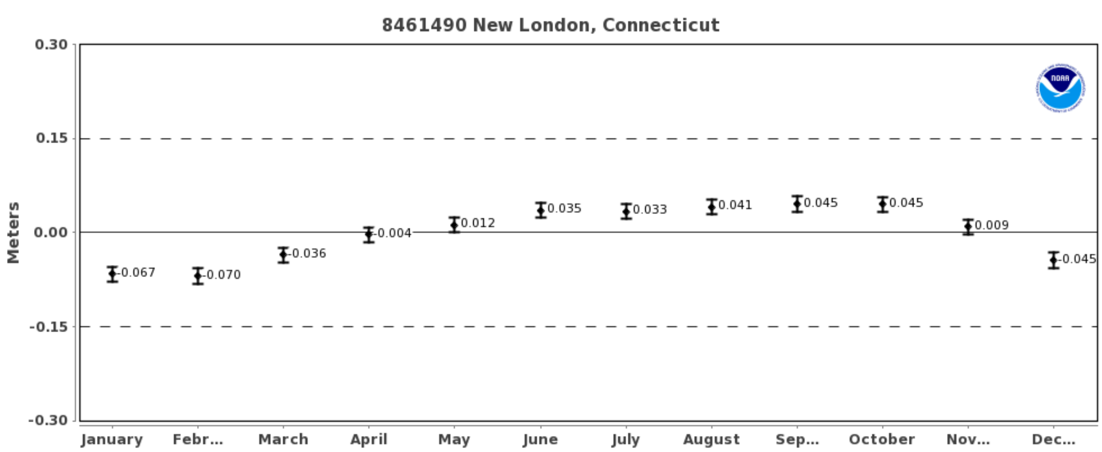
Figure 3.20 Storm surge generated by onshore winds: (A) surge effects on an open coast; (B) positive and negative surge in a lagoon or lake.

Let's watch a short video together to see what storm surge looked like during Hurricane Irene:



1.2.3 3) Seasonal to Interannal variations in pressure and wind patterns

Seasonal cycles in sea level occur as a result of fluctuations in **barometric pressure** (movement of high atmospheric pressure center, e.g., the Azores High above the subtropical Atlantic Ocean), **wind stress**, sea surface temperatures, and changes in location of ocean currents (shift of the Gulf Stream). For example, the monthly mean sea level along the U.S. Mid-Atlantic Coast varies seasonally, reaching a minimum in January and a maximum in September, but has changed significantly on multi-decadal timescales due to changes in wind stress.[1]



Interannal variation : Sea level changes in the Pacific occur as a result of changes in pressure, winds and ocean currents collectively associated with **El Niño** events. The 1982-83 El Niño event produced a wave of higher sea level 0.4-0.5m high which travelled fromwest to east across the Pacific and affected many coastal areas of North, Central and South America. Typically El Niño events result in a rise of 0.1-0.2m in sea level along the California coast and northward into Oregon (Komar and Enfield, 1987, see below Figure).

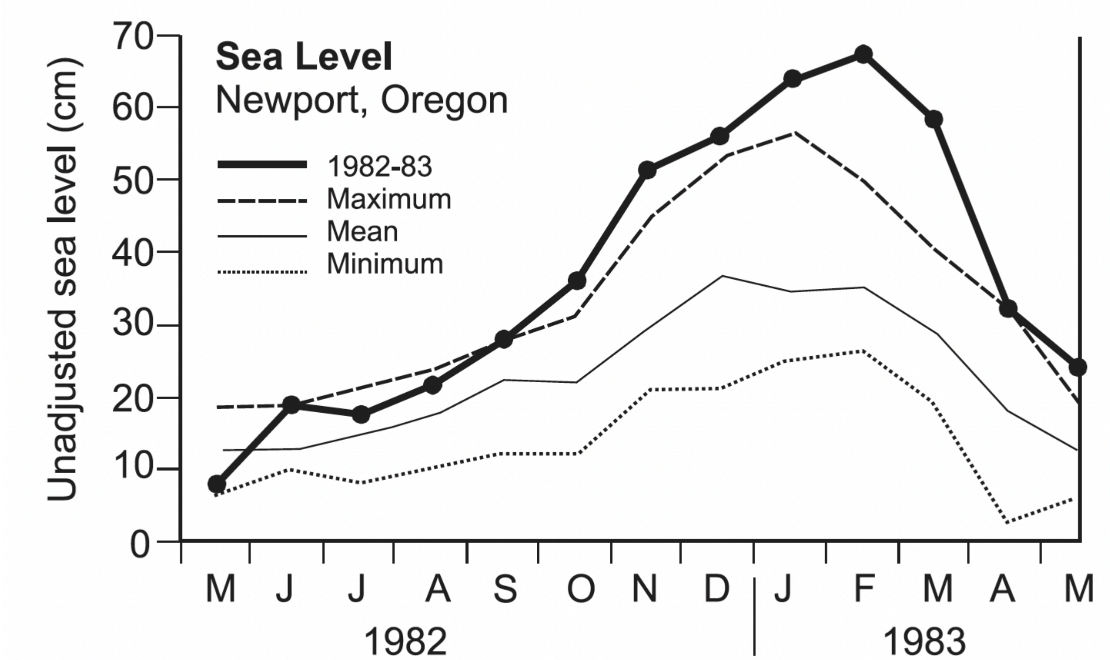


Figure 3.19 Monthly average sea level at Newport, Oregon, during the 1982–83 El Niño event compared to the maxima, average and minima previously measured. (Komar and Enfield, 1987).

1.3 3. Long-term variations

1.3.1 1) Global warming induced sea level rise

In the past century tide gauge data are available for an increasing number of stations worldwide and these provide measurements with a precision on the order of 2 cm. Gauges with a record of more than 50 years offer an opportunity to filter out annual- and decadal-scale dynamic variations and thus to determine recent trends in sea level.

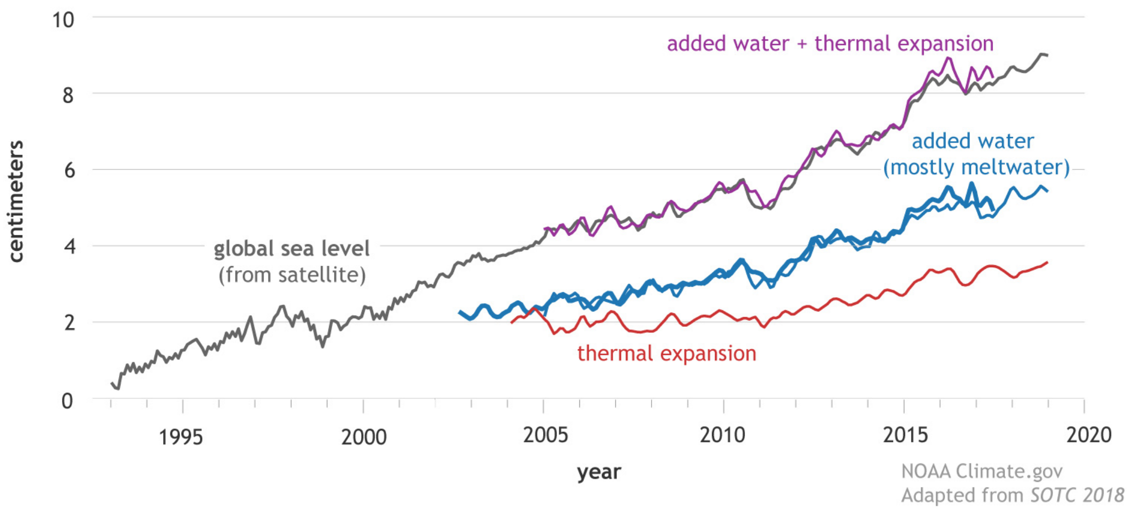
Let's take a look at sea level trends from a tidal gauge in New London here, where the relative sea level trend is 2.93 millimeters/year based on monthly mean sea level data from 1938 to 2024, which is equivalent to a change of 0.96 feet in 100 years.

1.3.2 2) Major contributors to present global sea level rise

- steric height variations produced by the **expansion** or contraction of the water in the oceans as a result of changing temperature and density;

- variations in the mass of water in the oceans. In this case the major process is **melting** of glaciers and snow packs worldwide, and particularly melting of the Greenland and Antarctic ice sheets.

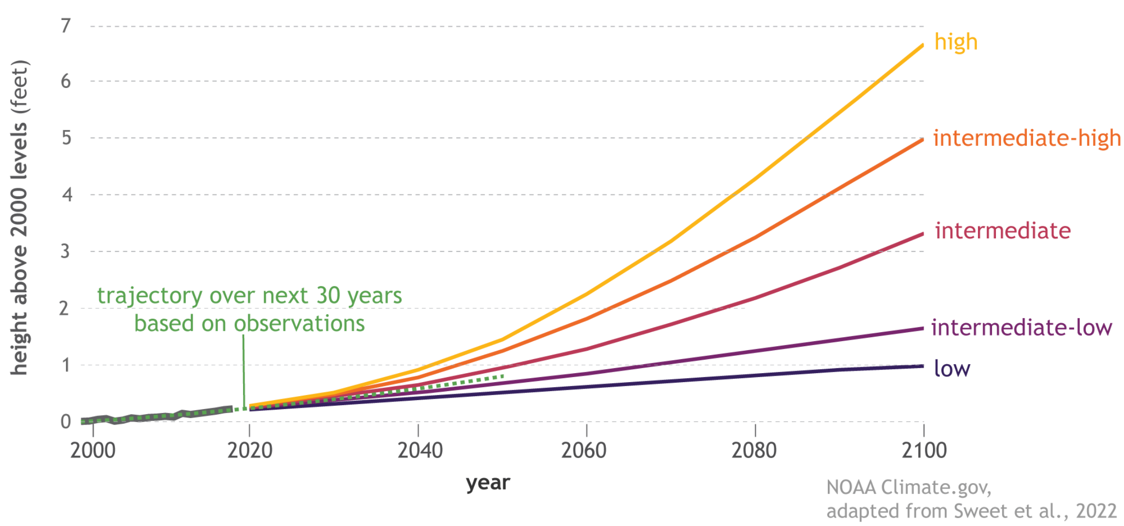
Contributors to global sea sea level rise (1993–2018)



1.3.3 3) Future projections

Every four or five years, NOAA leads an interagency task force that reviews the latest research on sea level rise and issues a report on likely— and 'unlikely but plausible'—amounts future sea level rise for different greenhouse gas and global warming pathways. In the 2022 report, the task force concluded that even on the pathway with the lowest possible greenhouse gas emissions and warming (1.5 degrees C), global mean sea level would rise at least 0.3 meters (1 foot) above 2000 levels by 2100. On a pathway with very high rates of emissions that trigger rapid ice sheet collapse, sea level could be as much as 2 meters (6.6 feet) higher in 2100 than it was in 2000.

Possible pathways for future sea level rise



One piece of good news: the task force concluded that an extreme possibility (8.2 feet above 2000 levels by 2100) that they couldn't rule out at the time of their 2017 report appears to be less likely based on the latest science. Now the bad news: the report reaffirmed that many parts of the United States can expect their local rate and overall amount of sea level rise to exceed the global average.

Let's take a look at global distribution of sea level trends here and

Discussion: The sea level trends difference in 1) U.S. vs the rest of the world; 2) East coast vs. West coast of the U.S. vs. Gulf coast; 3) why it matters

1.4 4. Combining Sediment process

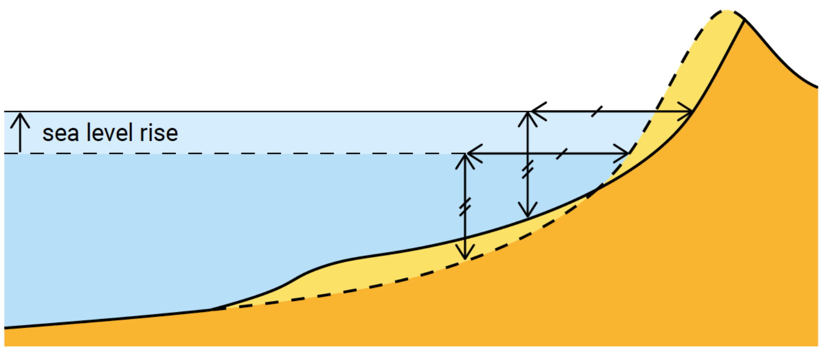


Figure 2.22: Bruun effect: the profile shape remains the same (the length of the vertical and horizontal lines respectively is constant), but the profile moves up and landward as a result of sea level rise. The volume of sediment eroded from the upper profile is equal to the deposited volume in deeper water.

Read Swelling Seas and Shifting Shores

1.5 References

[1]. Yang, J., & Chen, K. (2025). Profound changes in the seasonal cycle of sea level along the United States Mid-Atlantic Coast. Geophysical Research Letters, 52, e2024GL112273. https://doi.org/10.1029/2024GL112273

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