CLIMATE CHANGE TOOLKIT

Sea Level Rise & the Thermal Expansion of Water

Standards
NGSS PS1.A: Structure & Properties of Matter
NGSS ESS3.D Global Climate Change
Grade Level: Middle & High School

Equipment
Video: https://youtu.be/7q2SGL_qmbg
Thermometer
Long-necked bottle (wine, soda, etc)
Large beaker (2- or 3-liter)
Graduated cylinder
Hot plate
Masking tape/sharpie

Overview
Earth scientists can observe the long-term record of rising and falling sea level in the landscape, in the rock record, and in the climate record preserved in ice cores. In real time a global network of tide gauges monitors the current rate of sea level change. One of the most important drivers of sea level change is a change in the amount of sea water stored on continents in the form of ice caps. A second very important cause of sea level change is the thermal expansion of water due to increasing water temperature.

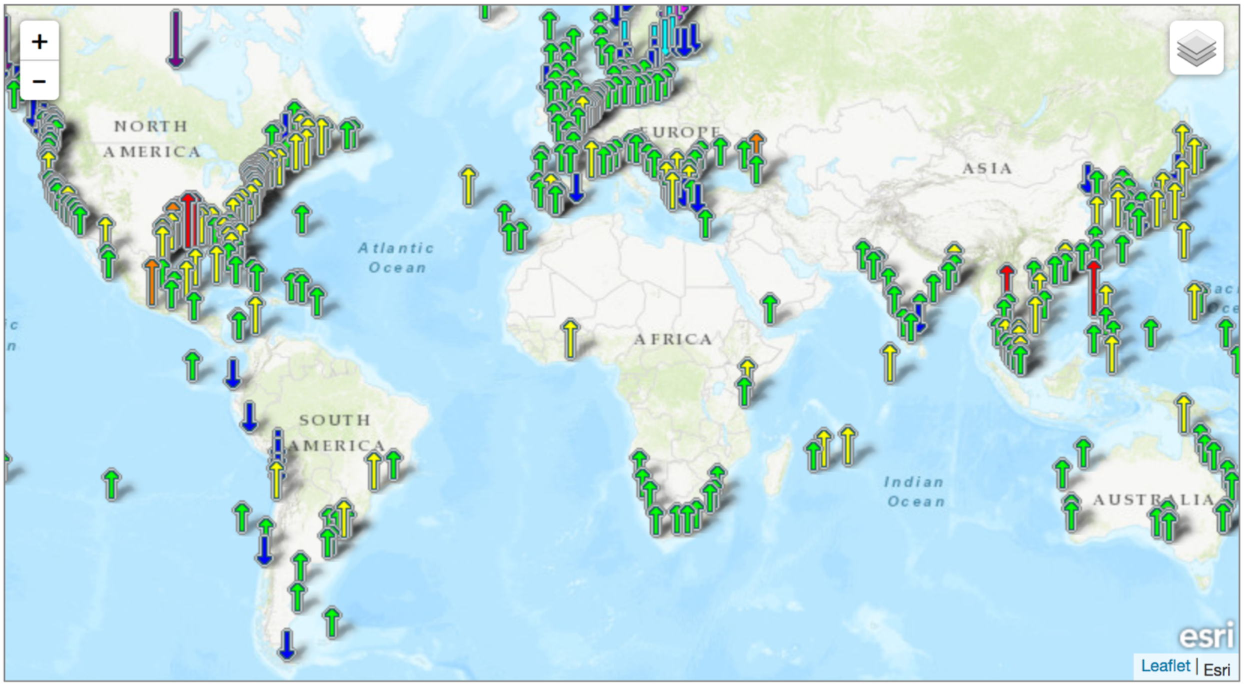
What?
A traditional glass thermometer shows changing temperature when the liquid it contains expands and contracts. Almost every material expands when it is warm and contracts when it is cold. A fixed amount of material – with a fixed mass – changes density when its volume changes:

$$\rho = m/V$$

where ρ = density, m = mass and V = volume. When the volume increases the density decreases. The amount that the volume changes is controlled by the temperature and a *coefficient of thermal expansion* that is particular to each substance:

$$\Delta V = \beta V_0 \Delta T$$

where β is the coefficient of thermal expansion and the Greek letter Δ signifies a change in temperature (T) and volume (V).



The map above illustrates relative sea level trends , with arrows representing the direction and magnitude of change. Click on an arrow to access additional information about that station.

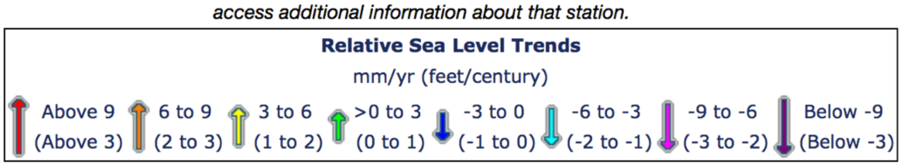


Figure 1: NOAA map of global tide gauges shows that sea level is rising almost everywhere, between 1-6mm/yr (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html).

How?

We will measure the volume expansion of water and calculate the coefficient of thermal expansion.

- Using a graduated cylinder, add 750ml of cold water to a wine bottle (355ml to a soda bottle). Use a piece of masking tape or permanent marker to mark the water level in the neck of the bottle.
- Place the full bottle in the beaker, and add water to the beaker to a level a few inches below the water level in the bottle.
- Measure the starting temperature of the water in the bottle in degrees Celsius and record it.
- Place the beaker-with-bottle on the hot plate and turn it on. Heat the beaker until the temperature rises ~50^{o}C.
- Record the final temperature.
- Mark the new water level on the bottle.

The hot water should expand into the neck of the bottle, with a new level higher than the starting level. To calculate the coefficient of thermal expansion we need to measure the change in volume. You can probably think of several ways to do this, one way is this:

- Remove the bottle from the beaker (careful, its hot) and empty the hot water from the bottle. Let the bottle cool, and add cold water to the level of the original watermark.
- Add 50ml of cold water to the graduated cylinder, and pour it slowly into the bottle until it reaches the second mark. Subtract the volume of water remaining in the cylinder from 50ml to find the volume added.
- Record the change in volume.

DATA TABLE

Initial Volume (Vo)		units:
Initial Temperature		units:
Final Temperature		
Temperature change ΔT		
Volume change ΔV		

To calculate the thermal expansion we'll need to re-arrange our equation from above:

$$\Delta V = \beta V_0 \Delta T \;\rightarrow\; \beta = \Delta V / V_0 \Delta T$$

Coefficient of thermal expansion, β		units:

Notice two things about the coefficient of thermal expansion. First, the number is very small. This makes sense if you look at the equation that defines the coefficient of thermal expansion. The numerator, ΔV, is a small number, while the denominator is the product of two large numbers ($V_0\Delta T$). This requires the result to be a very small number. Second, what are the units of the coefficient of thermal expansion? The answer is “per degree of temperature,” or 1/°C. Formally, we should measure temperature in Kelvin, but because Kelvin and Celsius are linearly related the more common Celsius units work for this experiment.

Several other aspects of thermal expansion are important to bear in mind. First, every material has its own characteristic thermal expansion properties. For example, water behaves differently than steel for a given temperature change. Also, the coefficient of thermal expansion depends not only on the composition of a material, but also on the pressure conditions and the temperature range. For instance, if you heat your bottle of water from 20-60°C you would calculate β=0.000385. If you heated the water from 60-100°C you would find β=0.000640.

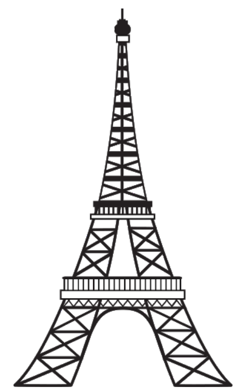


Figure 2: The 1000ft tall Eiffel Tower changes height by 6 inches from winter to summer because of the thermal expansion of its iron structure.

Why?
About half of the sea level rise observed over the last 30 years is because of the thermal expansion of seawater: ~1.5mm/yr from thermal expansion of the total ~3.0mm/yr.

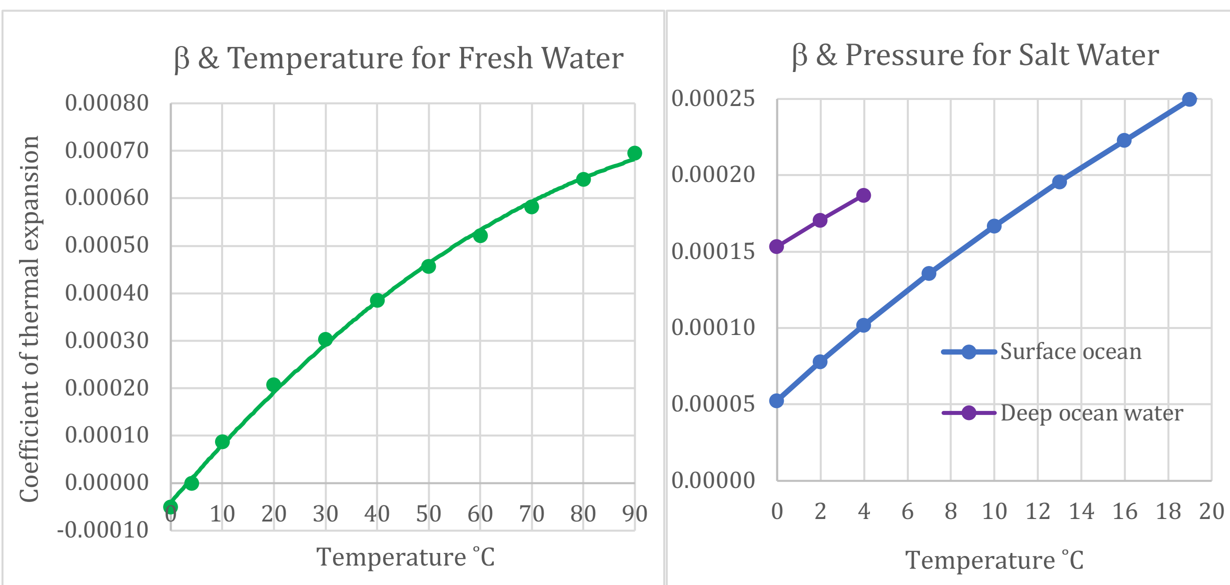


Figure 3: Graphs that show the variation of the coefficient of thermal expansion for fresh water (left) and sea water (right). In the ocean, deep water is under pressure, and so has a different coefficient of thermal expansion at a given temperature than the surface water.

We can use the coefficient of thermal expansion of deep ocean water to calculate thermal sea level rise for different changes in temperature. We choose the deep ocean because there is a whole lot more of it than the shallow surface. From the graph above, we will use β for the average temperature of the deep ocean, 2°C. We also need to know the total volume of water in the global ocean, and its surface area, so that we can solve for sea level rise:

$\beta = 0.0001707$
$V_{ocean} = 1.4 \times 10^{18} m^3$
$Area_{ocean} = 3.6 \times 10^{14} m^2$

We'll do the calculation for a series of different possible ocean temperature increases, from 0.1°C – 0.5°C, using the equation above: $\Delta V = \beta V_0 \Delta T$

Note that this equation gives us the change in volume of the ocean for each temperature increment. Since volume = area x height, we'll use the surface area of the ocean to calculate the height of sea level rise.

DATA TABLE: *fill in the green cells*

β	Vo	ΔT	ΔV	Area	SL Height (m)
0.0001707	$1.375 \times 10^{18} m^3$	**0.1°C**		$3.62 \times 10^{14} m^2$	
0.0001707	$1.375 \times 10^{18} m^3$	**0.2°C**		$3.62 \times 10^{14} m^2$	
0.0001707	$1.375 \times 10^{18} m^3$	**0.3°C**		$3.62 \times 10^{14} m^2$	
0.0001707	$1.375 \times 10^{18} m^3$	**0.4°C**		$3.62 \times 10^{14} m^2$	
0.0001707	$1.375 \times 10^{18} m^3$	**0.5°C**		$3.62 \times 10^{14} m^2$	

Data in Context
If you convert your sea level numbers to more familiar units – like inches – you will find that the values range from a few inches to over a foot of sea level rise due to thermal expansion. As we mentioned above, melting glacial ice also contributes to sea level rise. Thermal expansion causes about 40% of the observed rise, with melting ice responsible for the rest. Data from the Intergovernmental Panel on Climate Change (IPCC) show projected

sea levels for three different assumptions about future greenhouse gas emissions; a low-emission scenario, moderate emissions, and high emissions. You can see in Figure 4 that the calculations you did fit within these scenarios.

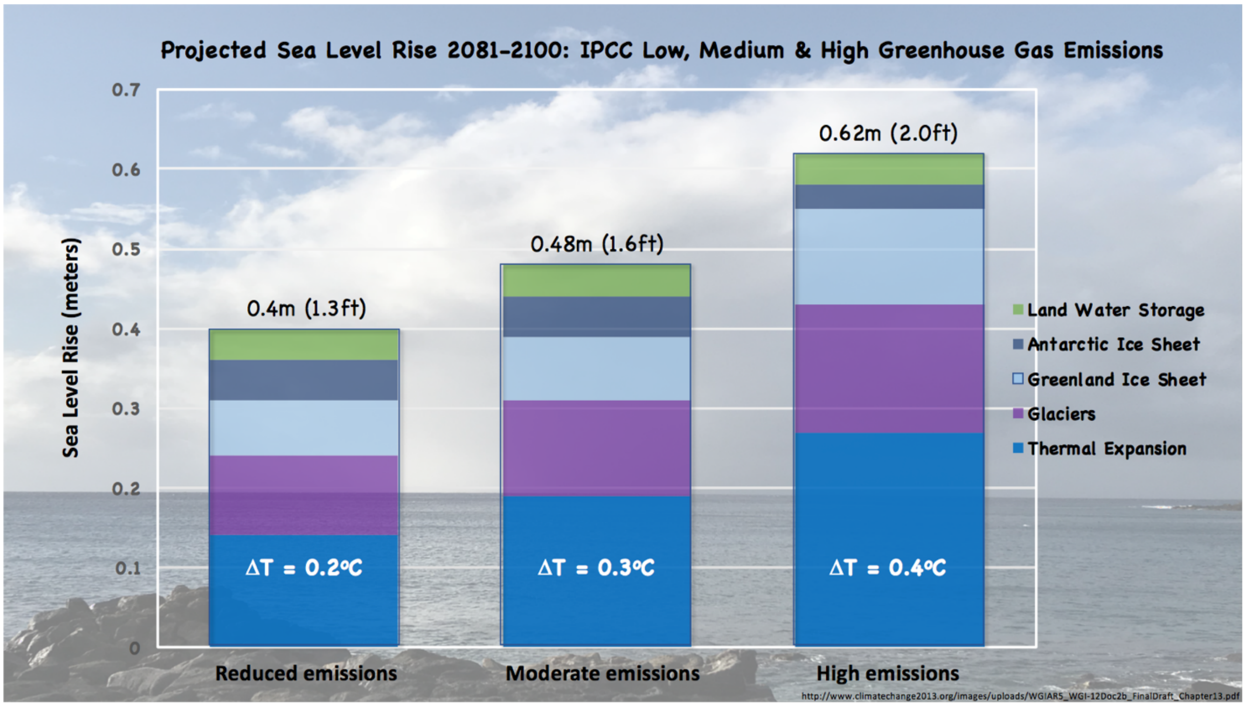


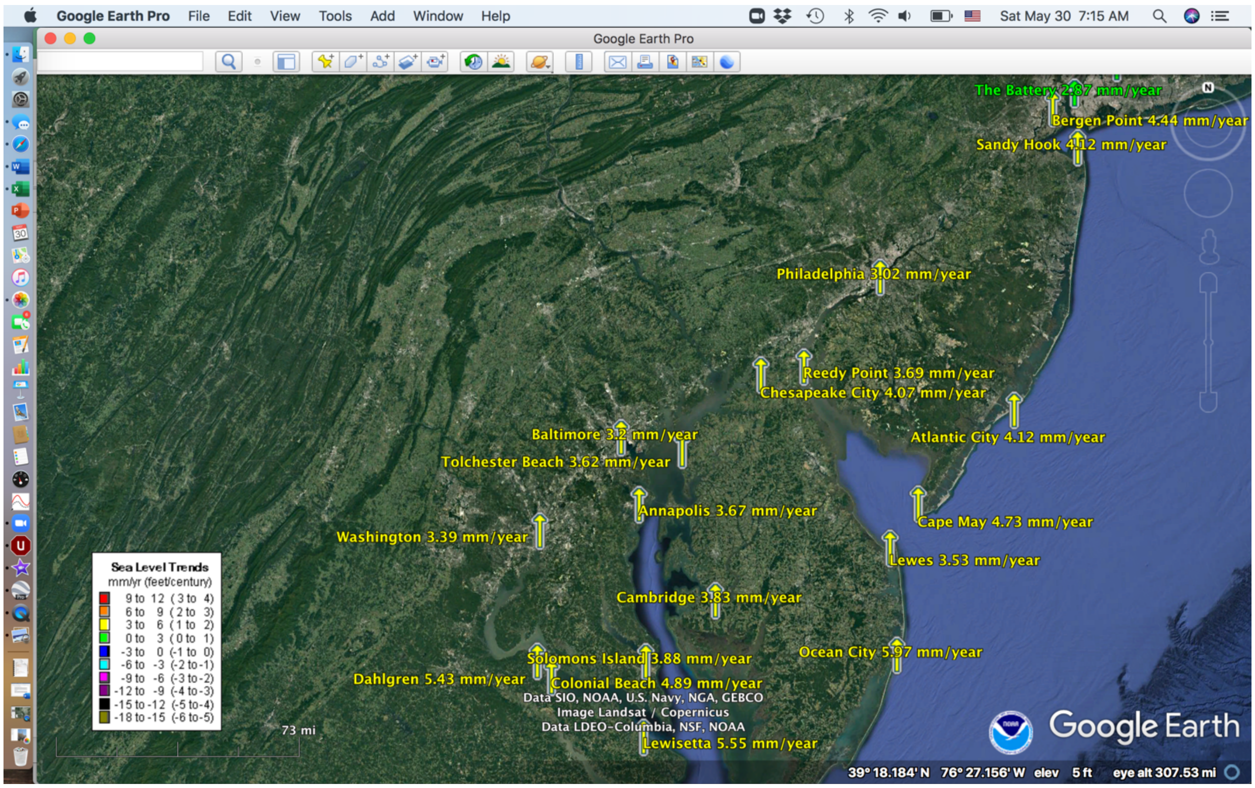
Figure 4: Projected sea level rise, 2081-2100, for low, medium and high greenhouse gas emission scenarios. About 40% of the projected rise is due to the thermal expansion of sea water.

While a sea level rise of 1-2 feet by the end of the century might seem small, there are some familiar places around the world where sea level rise of that magnitude is already having an effect on coastal communities. One of these is Washington DC, where over the last 100 years tide gauges show a sea level rise of 1.11ft. This is enough to cause localized flooding twice a day at high tide. The areas impacted are the Tidal Basin – home to Washington's iconic cherry trees and the national memorials to presidents Thomas Jefferson and Franklin Delano Roosevelt (Figure 5).

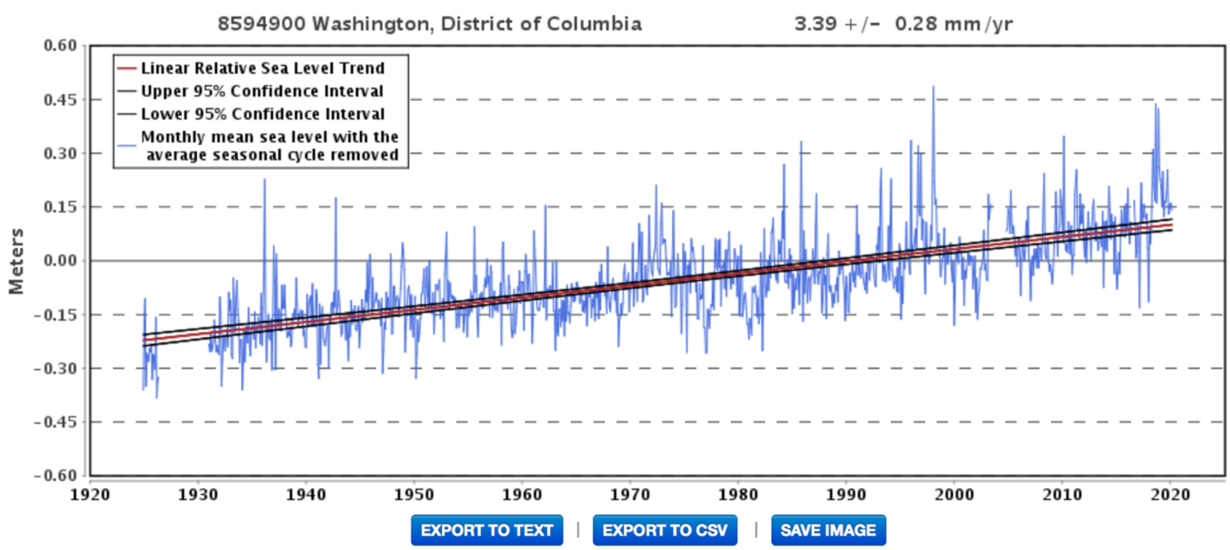
Figure 5: The Tidal Basin, Washington DC, near the Thomas Jefferson Memorial. Paths are flooded and benches are unusable twice a day, every day, during high tides.

Figure 6 (following page): Map of tide gauges on the US Mid-Atlantic coast from New York City (Battery Park) to southern Virginia, and graph of 100-year record of sea level rise for the Washington DC tide gauge.

References
IPCC Special Report on the Ocean & Cryosphere
https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/
The Physics Hypertextbook https://physics.info/expansion/
NOAA tide gauges *https://tidesandcurrents.noaa.gov/sltrends/sltrends.html*



Relative Sea Level Trend
8594900 Washington, District of Columbia



The relative sea level trend is 3.39 millimeters/year with a 95% confidence interval of +/- 0.28 mm/yr based on monthly mean sea level data from 1924 to 2019 which is equivalent to a change of 1.11 feet in 100 years.