CLIMATE CHANGE TOOLKIT

The Thermal Expansion of Water and Sea Level Rise

Equipment

- Hot plate, stove top, or similar, to heat a pan of water
- Long-necked bottle (ex: soda, wine)
- Graduated cylinder/beaker/measuring cup, to measure volume of water in bottle
- Small grad cylinder/beaker/measuring cup to measure volume change
- Large beaker or sauce pan, to keep bottle from direct contact with stove/hot plate
- Thermometer – metal-stem digital kitchen thermometer or digital aquarium thermometer
- Masking tape
- Calculator or computer spread sheet

Why?

We observe thermal expansion every time we use a simple liquid-filled thermometer. Changing the temperature of a material changes its density, and also its volume. In a thermometer the change in volume forces the liquid to expand into a narrow tube, which is calibrated to show us the temperature. The same property applies to larger systems – like the water in the ocean – and is one of the principal concerns of climate change. There is a ***coefficient of thermal expansion*** that is unique to each material that determines how much the material will change volume when heated. In this activity we calculate the coefficient of thermal expansion for tap water.

What?

In this experiment we will heat tap water in a long-necked glass bottle to explore the relationship between temperature and volume of water. We can calculate the coefficient of thermal expansion for this system by measuring the initial volume, change in volume, and the initial and final temperatures. Once we have calculated the coefficient of thermal expansion for our tap water system we can ask additional questions about the role of thermal expansion in other systems, like the world's oceans.

Resources

- Video | In the Greenhouse #6 | Thermal Expansion & Sea Level Rise
  YouTube: https://youtu.be/7q2SGL_qmbg

How?

Materials expand when they are heated. For example, the air in a hot air balloon expands when it is heated. This lowers the density of the interior air and causes the balloon to rise. Water also expands when it is heated. If the water is held in a container – for example

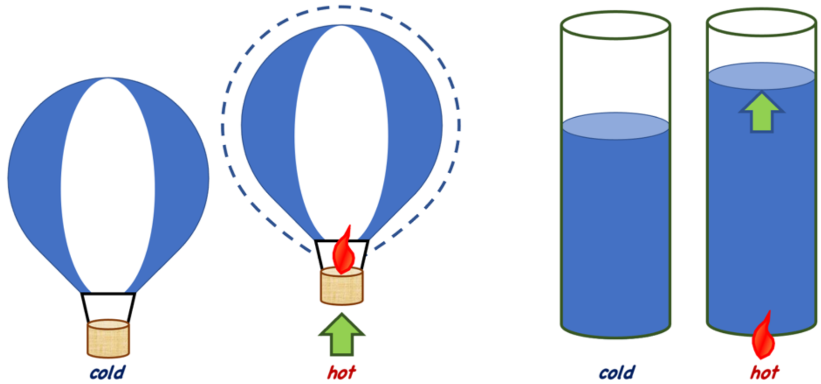
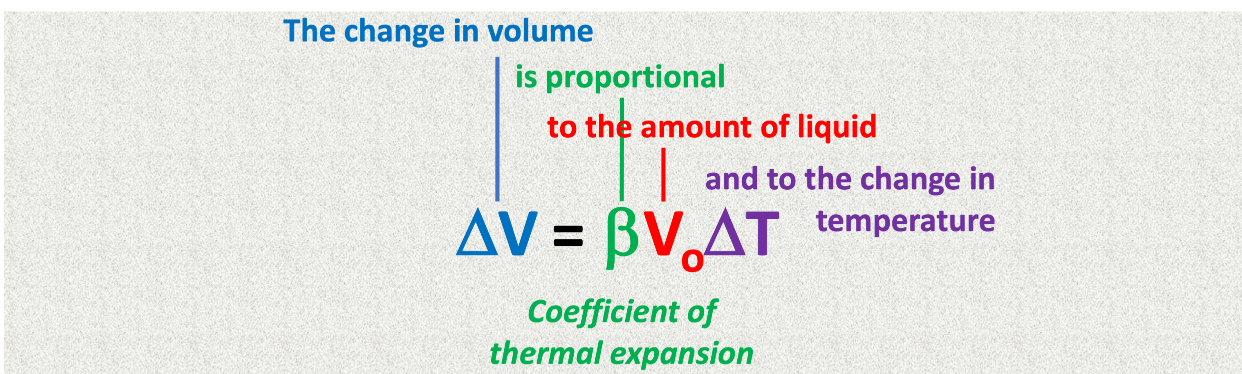


Figure 1: Expansion of a hot air balloon (left) and a container of water (right).

in a bottle, or in a lake or the ocean basins – thermal expansion makes the water level rise. In this experiment we ask the question, "***How much*** does the water expand?" Working with your teacher you will set two parameters for this experiment, (1) how much water you will use, and (2) how much you will heat it. Then you can quantitatively measure the expansion of water and calculate its coefficient of thermal expansion.

When a material is heated, its change in volume is proportional to the amount of material and to the change in temperature. That idea can be expressed mathematically,



where the constant of proportionality is the coefficient of thermal expansion, commonly designated with the Greek letter **β**, and with units of K^{-1}, or "per degree." The initial volume is designated V_o, the volume change is ΔV and the temperature change is ΔT.

Procedure

The containers that you have available will determine the starting volume of the water. A soda bottle holds 350 ml while a wine bottle holds 750 ml. You don't need to start with exactly these amounts, but you ***do*** need to know exactly how much you start with.

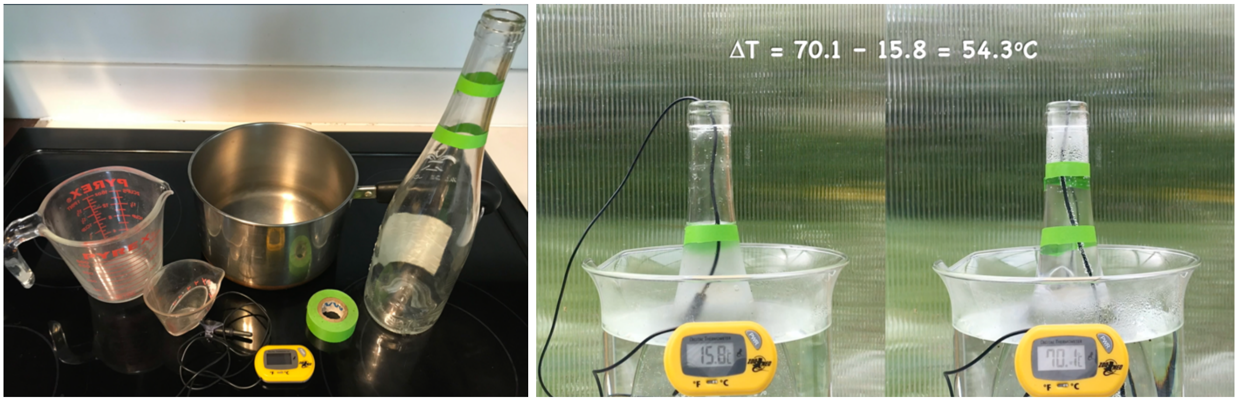


Figure 2: (Left) equipment needed for the experiment. (Right) 750 ml of water in a wine bottle before heating (lower green tape mark) and after heating (upper green tape). The temperature change is shown on the display of the thermometer stuck to the water bath.

(1) Add a known volume of room-temperature tap water to your bottle and place the thermometer in the bottle to measure the starting temperature. Keep the thermometer in the bottle and mark the water line with tape (wrap it all the way around the neck so that it doesn't come off when heated. Make sure that your bottle is full enough so that the water level is near the base of the narrow part of the neck (see example in Figure 2, and the Youtube video https://youtu.be/7q2SGL_qmbg).
(2) Working with your group and your teacher, set a maximum temperature that you will not exceed when you heat the water. The purpose of the temperature max is to make sure that any accident doesn't cause a serious injury to you or your partners.
(3) Working with your group, decide how you will measure the volume change of the water in the bottle.
(4) Record the starting volume and starting temperature in the Data Table below.
(5) Place the bottle (with the thermometer still in it) in a water bath and place the whole set-up on a hot plate or stove.
(6) Heat the apparatus until you observe a measurable change in the level of water in the bottle neck. Mark the new volume.
(7) Record the final temperature.
(8) Using the procedure that you decided on for measuring the new volume (or volume change), determine the volume change of the water. Determine the temperature change of the water.

Use the equation for thermal expansion to calculate the coefficient of thermal expansion (β) for your experiment:

$$\Delta V = \beta V_o \Delta T$$

(9) Enter your result in the data table below.

Data Table

	Volume (liters)	Temperature (C)	Coefficient of Expansion (T^{-1})
Initial Volume (Vo)	V_o=		
Volume change (ΔV)	ΔV=		
Initial Temp (T_1)		T_1=	
Final Temp (T_2)		T_2=	
Temp Change (ΔT)		ΔT=	
Coefficient of Expansion (β)			β=

Taking it one more step…

Photo (above): The Eiffel Tower in Paris is taller in the summer than in the winter due to the thermal expansion of its iron structure. Typical annual temperature variations cause the tower to increase in height by about 15cm (6") in the summer as opposed to winter. Also, because the sun shines on one side at a time, the sunny side also expands with respect to the three shady sides, causing the tower to tilt, so that the summit actually moves in a circle (diameter ~15cm) in opposition to the movement of the sun over the course of a day. (https://www.toureiffel.paris/en/news/history-and-culture/why-does-eiffel-tower-change-size)

The coefficient of thermal expansion is not a universal constant. It varies as a function of the materials that we might examine, and for each material the coefficient varies as a function of the ambient temperature and pressure. For example, the coefficient of thermal expansion of the iron in the Eiffel Tower is different from that of fresh water, and the coefficient of thermal expansion is different for fresh water and for salt water.

The temperature variation for the volumetric coefficient of expansion for fresh water and sea water is shown in the table below:

Volumetric Expansion Coefficients for Fresh Water and Sea Water

Temperature ℃	Fresh Water **β** (/℃)	Sea Water **β** (/℃)
0 ℃	-0.000050 /℃	0.000051
4	0	0.000101
10	0.000088	0.000167
20	0.000207	0.000257
30	0.000303	0.000334
40	0.000385	
50	0.000457	
60	0.000522	
70	0.000582	
80	0.000640	
90	0.000695	

All these different values might seem messy or confusing, but they are really important. Almost everything we build has to accommodate thermal expansion in order to remain standing. Because this is so important, materials scientists and engineers have worked for centuries to figure out expansion coefficients for every possible material in every possible environment; thus these are quantities that we know ***very*** well. A walk across any bridge should reveal the metal expansion joints engineered into the construction to accommodate seasonal and daily temperature changes, and the expansion gaps between the steel rails on a railroad track give rise to the characteristic "clickety-clack" sound of moving trains.

Thermal expansion in the built environment is all around us, even if we don't think a lot about it. Thermal expansion in the natural environment is equally important, and in the 21st century the thermal expansion of sea water is a parameter that will impact millions of people globally.

In this experiment we used a very small volume of water and heated it over a very large temperature range. In the natural world it is more common for a large volume of water to be heated over a very small temperature range. The goal of this experiment is to give you experience with thermal expansion so that we can learn about systems that are beyond our ability to measure directly. The most important such system is the change in volume of ocean water in response to changes in global temperature.

Data for the Ocean

Surface area	3.619×10^{14} m^2
Total volume	1.335×10^{18} m^3

Table 1. Volumes of the World's Oceans from ETOPO1

Download Table 1 as a .PDF

	Area+ (km2)	% Ocean Area	Volume (km^3)	% Ocean Volume	Avg. Depth (m)	Max Depth (m)
Arctic Ocean	15,558,000	4.3	18,750,000	1.4	1205	5567
Atlantic Ocean	85,133,000	23.5	310,410,900	23.3	3646	8486
Baltic Sea	***406,000***	***0.1***	***20,900***	***0.0***	***51***	***392***
Mediterranean	***2,967,000***	***0.8***	***4,390,000***	***0.3***	***1480***	***5139***
North Atlantic	***41,490,000***	***11.5***	***146,000,000***	***10.9***	***3519***	***8486***
South Atlantic	***40,270,000***	***11.1***	***160,000,000***	***12.0***	***3973***	***8240***
Indian Ocean	70,560,000	19.5	264,000,000	19.8	3741	7906
Pacific Ocean	161,760,000	44.7	660,000,000	49.4	4080	10,803
North Pacific	***77,010,000***	***21.3***	***331,000,000***	***24.8***	***4298***	***10,803#***
South Pacific	***84,750,000***	***23.4***	***329,000,000***	***24.6***	***3882***	***10,753***
South China Sea	6,963,000	1.9	9,880,000	0.7	1419	7352
Southern Ocean*	21,960,000	6.1	71,800,000	5.4	3270	7075
Total:	**361,900,000¤**	**100.0**	**1,335,000,000**	**100.0**	**3688**	**10,803**
error estimates	0.10%		1%			

https://www.ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html

In its 2021 Assessment Report (IPCC AR6) the Intergovernmental Panel on Climate Change presented five climate change scenarios, each based on a range of assumptions about human greenhouse gas emissions over the next century. The scenarios range from very-low and low emissions through intermediate, high, and very high emissions. Each set of greenhouse gas emissions drives a temperature increase and subsequent sea level increase.

We can select representative temperature increases for sea water and use an appropriate coefficient of thermal expansion for the ocean to calculate the contribution to sea level rise from the thermal expansion of sea water. The calculation for a 0.2°C increase in the temperature of the ocean is shown in the figure below.

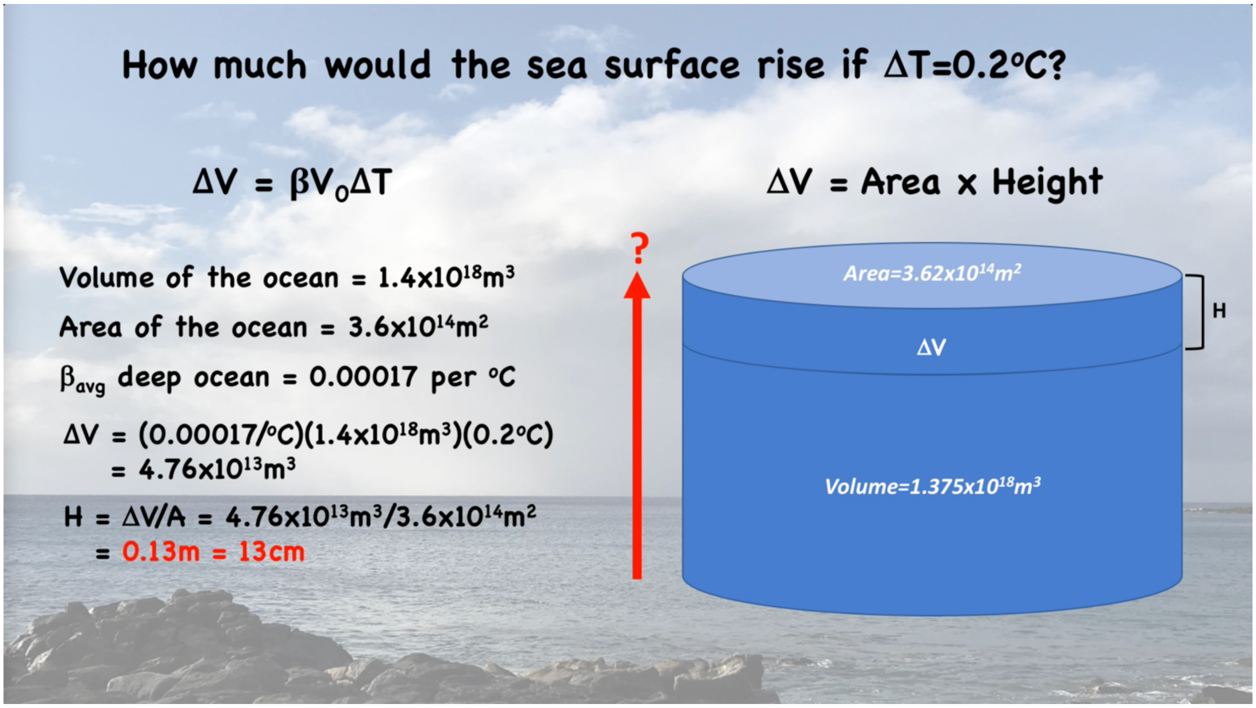


Figure 3: Sample calculation for ΔT=0.2C.

Sea Level Rise for Projected Ocean Warming Scenarios

ΔTemperature (°C)	ΔVolume (m^3)	ΔSea Level (m)
0.2	$4.54x10^{13}$	0.13
0.3		
0.4		

(10) Using the ocean area and volume data (small table, above) calculate the sea level rise from thermal expansion predicted for temperature changes of 0.3C and 0.4C.

When projecting global sea level rise, thermal expansion accounts for just under half of the rise, while water inputs from melting ice caps and glaciers is a little more than half. If you double your results for each temperature, you will have a good estimate for the total sea level rise. These results are well-aligned with the IPCC scenarios shown in the figure below.

NOTE: Climate scientists talk a lot about limiting climate change to 1.5C above the pre-industrial global average temperature. The temperatures that we are working with here are the temperature of the water in the **ocean**, which is *only part* of the global average.

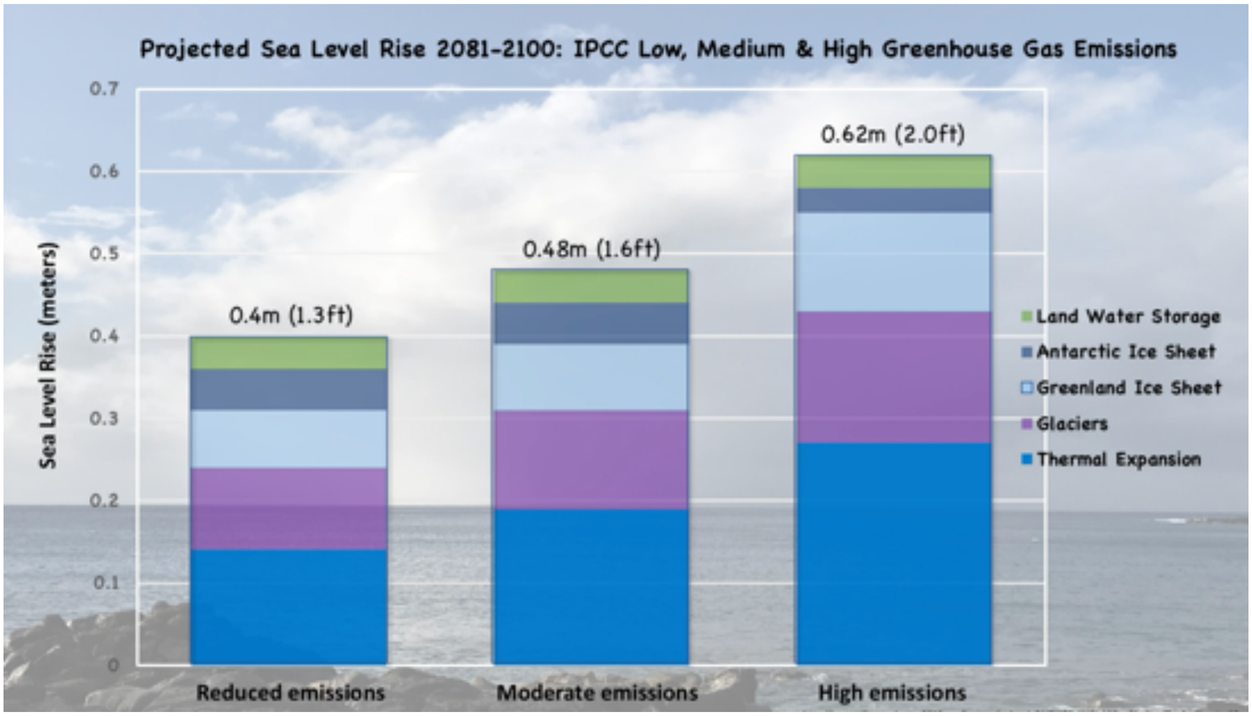


Figure 4: Results of three emissions scenarios from the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate

Why does this matter? The sea level rise projections might appear to be small, but they are in fact significant, for several reasons:

- Lowlying coastal zones are home to nearly one billion people
- The impact of severe storms is exacerbated by higher sea levels
- Infrequent coastal hazard events increase in frequency with higher sea level

Can you think of other reasons?

Sea level changes are monitored globally in real time. If you're interested, check that out here: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html