ASTROEDU

Peer-reviewed Astronomy Education Activities

Transforming water into acid... and back

Are our oceans turning to acid?

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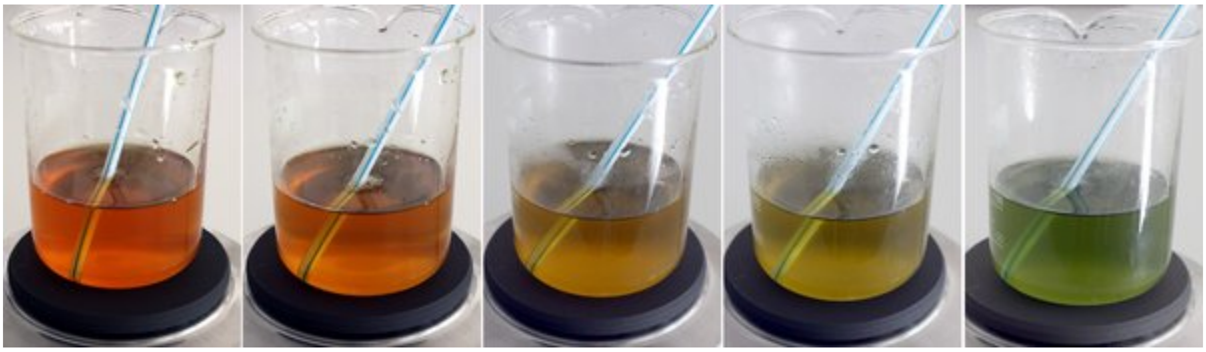


KEYWORDS

Oceans, Acidification, pH value, Carbon dioxide, Marine life, Carbon cycle, Chemistry

LOCATION

Small Indoor Setting (e.g. classroom)

AGE

10 - 16

LEVEL

Middle School

TIME

45min

GROUP

Group

SUPERVISED

Yes

COST

Medium Cost

SKILLS

Asking questions, Developing and using models, Planning and carrying out investigations, Analysing and interpreting data, Constructing explanations, Engaging in argument from evidence, Communicating information

TYPE OF LEARNING

Structured-inquiry learning, Traditional Science Experiment

GOALS

- The students learn how the dissolving of carbon dioxide in water can change it from a life-supporting to a life-threatening liquid.
- They will realise that the increased levels of CO2 not only drives the greenhouse effect but also affects the marine ecosystem through acidification.
- Oceans are a carbon sink that help mitigate the greenhouse effect, but they experience disadvantageous consequences on their own.
- The students learn that the amount of CO2 dissolved in water depends on its temperature.

LEARNING OBJECTIVES

The students will be able to - explain how carbon dioxide dissolved in water changes its chemical properties from neutral to acidic by measuring the pH value. - explain why a rising level of carbon dioxide in the atmosphere affects the chemical balance of the oceans by extrapolating the lab experiment in the activity to natural processes. - describe how the amount of dissolved carbon dioxide in water depends on its temperature by heating the acidic solution from the first activity.

BACKGROUND

The carbon cycle
The Earth is a dynamic system that exchanges energy and materials between different spheres and outer space. One of the important circulation systems is the carbon cycle. **Figure 1:** The annual flux of CO2 in GigaTons (Gt) or billions of tons between each of the Earth's reservoirs. Each reservoir serves as both a source of and a sink for carbon, as indicated by opposing arrows. The carbon released by burning fossil fuels is an unbalanced contribution to the global carbon budget. The total carbon from burning of fossil fuels has increased from 5.5 Gt to 7-8 Gt between 2003 and 2007 (NASA/AIRS, https://www.flickr.com/photos/atmospheric-infrared-sounder/8265010034, https://creativecommons.org/licenses/by/2.0/legalcode)

Carbon is altered chemically and its compounds attain different physical states. Usually, the exchange of carbon between the lithosphere, the hydrosphere, the biosphere and the atmosphere is maintained in a delicate and naturally balanced equilibrium, with carbon sources and carbon sinks being in constant interaction. Sinks and sources are defined as subsystems that capture carbon or release it into the atmosphere where they act as greenhouse gases like carbon dioxide or methane.

Table 1: Natural and artificial carbon sources and sinks.

Carbon sources	Carbon sinks
Volcanoes	Oceans and Lakes
Organic decay	Vegetation by photosynthesis
Natural forest/ bush fires	Reforestation
Fossil fuel production and combustion	Precipitation
Deforestation by fire clearing	Industrial production of atmospheric gases
Waste incineration	Carbon capture and storage methods
Gas hydrates	
Waters	
Livestock	
Rice farming	
Manure management	
Waste management	
Industrial manufacturing	

Figure 2: Evolution of the budget of carbon sinks and sources (climatesafety, https://www.flickr.com/photos/ climatesafety/4745854611, https://creativecommons.org/licenses/by-nc/2.0/legalcode).

However, human activities constantly increase the imbalance in carbon sources, leading to a growing concentration of carbon-based greenhouse gases. As Figure 3 illustrates, the amount of atmospheric CO2 has increased dramatically since the beginning of the 20th century. The growth rate is unprecedented for the recent several hundred thousand years. There is a broad consensus among climatologists that this contributes significantly to the global warming seen today. Carbon dioxide concentrations can be measured both by sensors on ground and with dedicated Earth observation probes from space by remote sensing. Successful space programmes for monitoring greenhouse gases globally are Europe’s Envisat, Japan’s GoSat as well as NASA’s OCO-2 satellite. Europe’s Copernicus programme with its Sentinel satellites will also help understand the effects of increasing levels of greenhouse gases released into the atmosphere.

Figure 3: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO2 has increased since the Industrial Revolution until February

2016. (Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record/NASA/JPL, http://climate.nasa.gov/evidence/, public domain).

The pH value

The pH value is a measure of the strength of acids. Its value represents the concentration of free hydron ("H" ^+) or hydronium ("H" _3 "O" ^+) ions. The value is defined as:

The concentration of hydronium ions c(H3O $^+$ is given in units of moles per litre. The mole is a standard unit for the amount of a given substance. pH indicators change their colour depending on the pH value of the solution. This helps measure the pH value.

Oceans as a carbon sink

Up to 30-40% of manmade carbon dioxide is captured in oceans, rivers and lakes. The gas efficiently dissolves in water. Therefore, oceans are a very powerful and significant carbon sink.

Figure 4: Air-sea exchange of carbon dioxide (McSush (modified), Hannes Grobe (original), https://commons.wikimedia.org/wiki/File:CO2_pump_hg.svg, https://creativecommons.org/licenses/by-sa/2.5/legalcode).

Although the ability of water to capture and store CO_2 helps reduce greenhouse gases, it comes at a high price. The dissolution of CO_2 in water changes its chemistry. As a result, the water becomes more acidic. The acidification and its consequences can be split up into three chemical reactions. First, carbon dioxide and water form carbonic acid.

$CO_2 + H_2O \rightarrow H_2CO_3$

The acid is immediately split up into its ions, one of which is the hydron ion that reacts to form the hydronium ion $H3O^+$. The free hydron or hydronium ions are characteristic of an acid. This is reflected in the definition of the pH value (see above).

$H_2CO_3 \rightarrow H^+ + HCO_3^-$

The acidic solution reacts with carbonate ions that are abundant in ocean water. They are the building blocks e.g. for the exoskeletons of shellfish like snails, mussels as well as corals.

$H^+ + CO_3^{2-} \rightarrow HCO_3^-$

These reactions occur at the surface of water bodies like the oceans. As a result, the formation of carbonate compounds like lime is hindered, or in extreme cases, existing exoskeletons can even get dissolved. The net equation of the reaction chain is shown in Figure 5.

Figure 5: Illustration of how CO2 dissolved in water consumes carbonate ions. It impedes calcification or may even lead to decalcification of sea shells (NOAA PMEL Carbon program, NAOO public domain).

Although the salinity of sea water mitigates the effect of acidification, the tendency remains. Apart from in-situ sample measurements, new technologies are available to determine ocean pH levels on a global scale using remote sensing from Earth observation satellites (Figure 6).

Figure 6: This map shows the first estimates of surface ocean pH using salinity data from ESA's SMOS with satellite sea-surface temperature measurements and additional auxiliary data. There is a spatial variation of the pH across the globe. Cold waters near the poles tend to be more acidic because of the ability of cold water to better dissolve carbon dioxide than warm water (ESA/R. Sabia, http://www.esa.int/spaceinimages/Images/2015/01/Surface_ocean_pH, https://creativecommons.org/licenses/by-sa/3.0/igo/legalcode).

Such maps also indicate that polar regions are more strongly affected by acidification than others. This is because cold water can better dissolve CO2 than warm water. Wide range water currents are known to connect the oceans of the world. As a consequence, water is exchanged between latitudes. So acidic, i.e. CO2 rich water, is transported from the poles to the equator regions. The water gets heated on its way and releases part of the stored CO2. Therefore, oceans can also be regarded as a regionally confined carbon source.

This influence of water temperatures has also been confirmed by data models that capture the past and projected evolution of global pH levels, as shown in the climate reports of the IPCC (Intergovernmental Panel on Climate Change, see Figure 7). All projections show a stronger acidification of the polar regions than other regions on Earth.

Figure 7: Past and projected evolution of oceanic surface pH levels. The models were calculated for the most optimistic (RCP2.6, Representative Concentration Pathways) and the most pessimistic scenarios (RCP8.5) for the evolution of atmospheric CO2. (a) Time-series of surface pH shown as the mean (solid line) and range of models (filled), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red) and the Southern Ocean (blue). (b) Map of the median model's change in surface pH from 1990 to 2090 (IPCC Report, 2013, Working Group I, Chp. 6, p. 532, permission for reproduction granted).

The impact of acidification on marine life

Growing acidification of the oceans and coastal regions endangers the delicate equilibrium of marine life. Several species grow exoskeletons with carbonatic structures (corals, sea snails, mussels, etc.). These carbonates, mostly limestone, dissolve under the influence of carbonic acid. For example, sea snails, also known as sea butterflies, are one of the victims of acidification (Figure 8). Their shell becomes more fragile, which for them is a life-threatening situation. Experiments have even shown that such creatures lose most of their shells after exposure to acidification levels expected in the near future. Since they are the basis of an entire food chain, their extinction may have a tremendous impact on a large portion of marine life.

Figure 8: In laboratory experiments, the shell of this sea snail dissolved over the course of 45 days in seawater adjusted to an ocean chemistry projected for the year 2100 (Credit: NOAA Environmental Visualization Laboratory (EVL), https://commons.wikimedia.org/wiki/File:Pterapod_shell_dissolved_in_seawater_adjusted_to_an_ocean_chemistry_projected_for_th
public domain).

Another example is microscopic, single-cell algae called coccolithophores (Figure 9). They form shells that consist of calcium carbonate scales. After they die, they sink to the sea floor. This process removes carbon from the global carbon cycle. If the formation of the carbonate shell is impeded, this carbon sink becomes less effective.

Figure 9: Image of a single coccolithophore cell produced with a high-resolution scanning electron microscope (Credit: Alison R. Taylor (University of North Carolina Wilmington Microscopy Facility) (https://commons.wikimedia.org/wiki/File:Emiliania_huxleyi_coccolithophore_(PLoS).png), https://creativecommons.org/licenses/by/2.5/legalcode).

FULL DESCRIPTION

INTRODUCTION

Introduce the topic by telling the students that carbon is the main element in living things. Each compound contains carbon atoms.

Question: What substances do you know that contain carbon?
Possible answers: coal, petrol, fuel, pencils, sugar, carbon dioxide, methane, ...

Question: Do you know solid, liquid or gaseous substances that contain carbon?
Possible answers: (see above)

Question: What is simplest gas that contains carbon and that is a product of combustion or organic decay? You even exhale it when breathing.
Answer: carbon dioxide (CO2)

The atmosphere of the Earth contains carbon dioxide whose level is constantly rising.

Question: What happens when carbon dioxide gets dissolved in water, as it happens with the oceans on Earth?
Possible answers: carbonated water, enriches water with carbonic acid

This is what we will find out with the next activity. It turns into an acid.

Question: What do acids do?
Possible answers: They can dissolve material.

Information:
The strength of an acid is measured by its pH value. The scale runs from 1 to 14. A neutral substance that is neither an acid nor a lye has values close to 7. The lower the value, the stronger the acid is. High values indicate lye. The pH value can be measured with indicators that change colour accordingly.

ACTIVITY 1

List of Material
The number of items corresponds to the number of students carrying out the experiments. One set consists of:

- Distilled or demineralised water
- Transparent cup or glass
- Straw
- Universal pH indicator according to McCrumb (provided with the activity package)
- As an alternative: pH indicator made from red cabbage https://www.youtube.com/watch?v=oG-pNRVHsc4 https://www.youtube.com/watch?v=OMXMIWybv8A

Hand out the items to the students. Let them perform the following tasks step by step. Warn them not to swallow the liquid.

Step 1: Pour some water in the glass.

Figure 10: Items required for the first part of the activity.

Step 2: Add a few drops of the indicator until the solution turns green.

Question: What is the pH value of the liquid? Is it acidic or basic?
Answer: The pH value is 8, which means the water is neutral or slightly basic.

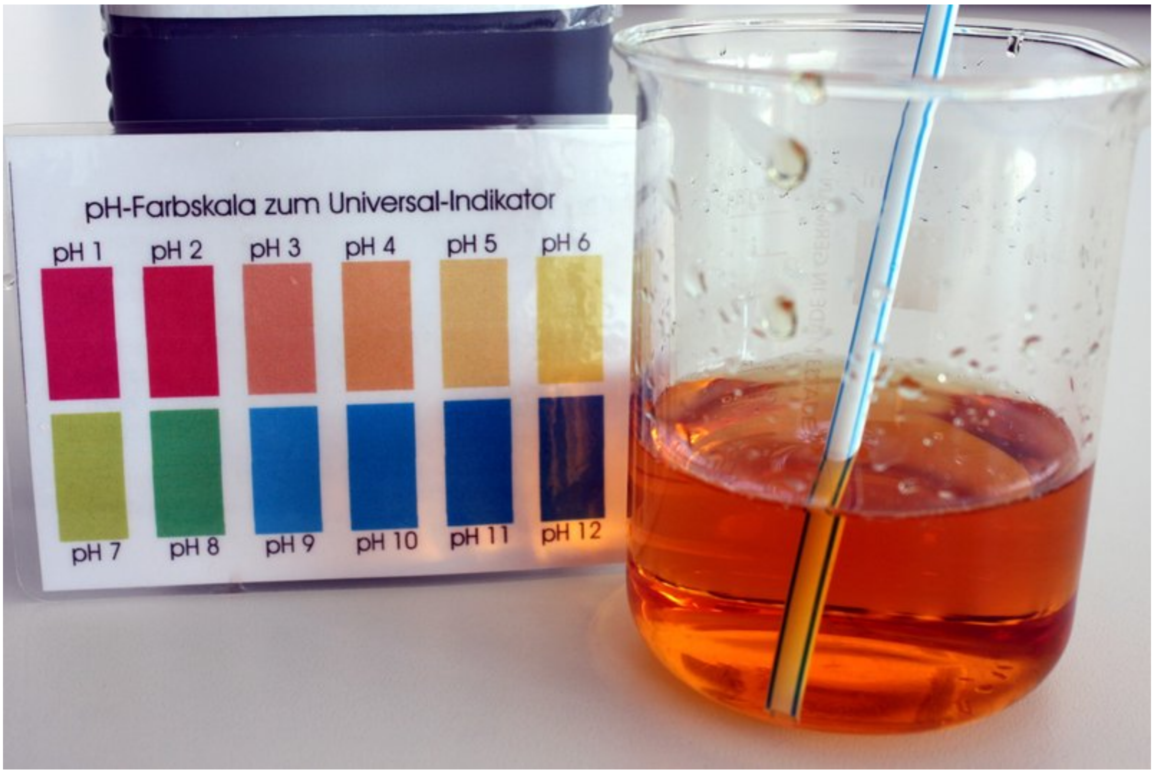
Figure 11: The water after the addition of some pH indicator has a pH value of 8.

Step 3: Use the straw und blow gently into the solution. Take care that it does not spill out of the glass. Continue until the colour of the indicator stops changing.

Figure 12: Blowing air into the liquid introduces carbon dioxide, which slowly changes the pH value.

Step 4: Compare the final colour with the pH table of the indicator and determine the pH value.

Figure 13: After blowing for several minutes, the colour stops changing. In this example, a pH value of 3 was reached. This indicates that the liquid changed to acidic carbonated water.



Question: What is the pH value you reached? Did the water become acidic or basic?
Answer: The pH value is … (3 in the example given in Figure 14). This is quite acidic.

Question: What do acids do with other substances?
Answer: Acids have the power to dissolve certain substances.

Information:
In this case, the students produced carbonic acid. In nature, the products react with limestone, which chemically is calcium carbonate. It is the building block of the exoskeletons of many marine creatures like sea snails, mussels or corals.

In order to show the impact of ocean acidification by CO2, let the students watch the following videos:

The Other Carbon Dioxide Problem (Duration: 3:57) https://youtu.be/9EaLRcVdTbM

Sea Change: The Pacific's perilous turn (Duration: 9:03) https://goo.gl/Hu5y4q

Question: What happens to marine creatures with exoskeletons made of limestone, when the water becomes more acidic?
Possible answers: The limestone is dissolved by carbonic acid.

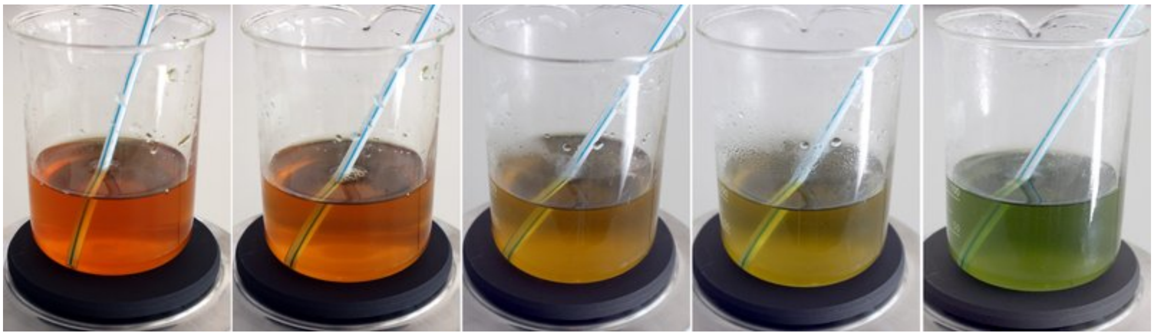
ACTIVITY 2

Question: Do you know how to neutralise the solution, i.e. change the acid into neutral water again? The teacher can help by explaining that the gas in sparkling water and sodas is carbon dioxide too. What happens to them when keeping them open at room temperature for a while?
Possible answers: drive out the carbon dioxide by waiting for a long time or support by heating

The following experiment can be carried out as a demonstration by the teacher, if there is the possibility that the students might hurt themselves when heating the solution. Otherwise, hand out heaters or stoves and turn them on.

Put the glass with the acidic solution on the heater. After heating it for several minutes, the liquid starts to change colours. Avoid boiling! Eventually, the colour should turn to green, indicating neutralisation. The different shades of the colour are shown in Figure 14.

Figure 14: On heating the acidic liquid, the colour starts to change again. The acidification is reversed because carbon dioxide is driven out of the liquid. Warm water cannot store as much carbon dioxide as water at lower temperatures.



Question: Do you see a change while heating the solution?
Answer: Yes, the colour changes.

Question: What is the pH value you reached?
Answer: The pH is back to a neutral value of 7 or 8.

Question: What happens to ocean water when it is transported from polar to equatorial regions?
Answers: It heats up.

Question: Which waters can store more carbon dioxide? Polar or equatorial?
Answers: Polar

Question: So, what happens to the carbon dioxide dissolved in the ocean?
Answer: It is released into the atmosphere.

EVALUATION

Ask students which gas is produced by burning organic material or when we exhale.

Carry out the first activity. This shows the students how carbon dioxide blown into water makes it acidic.

Ask the students how the oceans react when they are in constant contact with an atmosphere whose carbon dioxide levels are constantly rising.

Ask the students about the power of acids.

Ask the students how the dissolved carbon dioxide can be driven out of the solution by recalling their own experience like keeping soda or carbonated water at room temperature.

Ask the students how the percentage of carbon dioxide in the atmosphere will be affected if both the atmosphere and the oceans keep warming up.

CURRICULUM

ADDITIONAL INFORMATION

CONCLUSION

The students turn neutral water into a carbonic acid by introducing carbon dioxide by blowing into the solution. Afterwards, they neutralise the solution by heating, which releases the dissolved carbon dioxide. This experiment is an analogy of what happens to water when it is exposed to the main greenhouse gas, carbon dioxide, i.e. it absorbs the gas and becomes more acidic. This is a threat to marine species like corals and snails who develop exoskeletons by building limestone structures. Limestone is dissolved by carbonic acid. In the end, the students see that warm water can store less carbon dioxide which in turn is less acidic. However, ocean water is transported from polar to low latitude regions. On its way, it releases carbon dioxide that cannot be stored as the water gets heated.

CITATION

Nielbock, M., , *Transforming water into acid... and back*, astroEDU, 1634 doi: 10.14586/astroedu/1634

ACKNOWLEDGEMENT

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