SPACE awareness

OCEAN ACIDIFICATION

Learn how carbon dioxide makes the oceans acidic

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Curriculum topic
Oceans, biodiversity

Big idea of science
Earth is a system of systems which influences and is influenced by life on the planet

Keywords
carbon cycle, acidification, oceans, carbon dioxide, chemistry, pH value, surface layers, limestone, exoskeletons

Age range
10 - 16

Education level
Middle School, Secondary School

Time
45min

Group size
Group

Supervised for safety
Supervised

Cost
Average (5 - 25 EUR)

Location
Indoors (small, e.g. classroom)

Core 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 activity
Full enquiry

BRIEF DESCRIPTION

In this activity, the students use burning candles as a source of CO_2. This gas reacts with the water the candles are partially immersed in. The candles extinguish as soon as oxygen is depleted in the closed compartment. The reaction of the CO_2 with the water is witnessed by a changing colour of the indicator added to the water. Altogether, this experiment demonstrates the interplay between combustion carbon sources and CO_2 sinks like the oceans and how the result affects the ecosystem on Earth.

GOALS

The students learn that carbon dioxide produced by combustion reacts with the surface of waters. As a result, the pH value is reduced to the acidic realm. Although salty seawater is less affected by this process, it demonstrates that a rise of the CO_2 concentration in the atmosphere adds to the acidification of oceans.

LEARNING OBJECTIVES

The pupils will understand that the experiment is a simplified model of the acidification process happening in nature. The will learn that such a model is sufficient to – at least qualitatively – derive conclusions from the results that also apply to the situation on a global scale. The experiment is also useful to give an example of a chain of actions and reactions that leads to a consequence that is unwanted, sometimes unexpected and potentially harmful.

EVALUATION

Before the activity

After introducing the topic as suggested in the description of the activity, the teacher can probe the current knowledge of the students by asking some questions (also mentioned in the description).

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 (CO_2)

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

Question: Have you ever tested what happens when you put an egg in vinegar? Vinegar is a mild acid.
Possible answer: Vinegar dissolves the egg shell. It consists of limestone.

During the activity

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

Question: Why did the candles stop burning?
Answer: Oxygen is consumed until it is depleted.

Question: What gas did they produce? We exhale it when breathing.
Answer: The oxygen reacts with the carbon to form carbon dioxide, CO_2.

Question: How did the colour change? What pH value does it represent? Did the solution become basic or acidic?
Answer: The green solution is interspersed with yellowish streaks. The pH value is between 5 and 6, i.e. slightly acidic.

After the activity

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.

Question: If you look very closely, did the colour change all the way from top to bottom? (This depends on how much water was used.)
Answer: The reaction only took place at the surface, where the carbon dioxide gas touches the surface of the water.

Question: When you think about the carbon dioxide in the atmosphere reacting with the oceans, where would you expect the lowest pH values?
Answer: In the layers near the surface or/and in shallow waters.

MATERIALS

The number of items needed depends on whether this activity is done as a demonstration experiment carried out by the teacher alone or the students themselves, either individually or in groups.

- Distilled or demineralised water
- Transparent bowl (fireproof)
- Transparent bowl or tank used as cover (fireproof)
- 4 candles or tea lights
- Matches or lighter
- Universal pH indicator according to McCrumb (http://pubs.acs.org/doi/abs/10.1021/ac50075a004), see also: http://www.hometrainingtools.com/universal-indicator-30-ml and http://experilab.co.za/catalog/index.php?main_page=product_info&products_id=602

BACKGROUND INFORMATION

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.

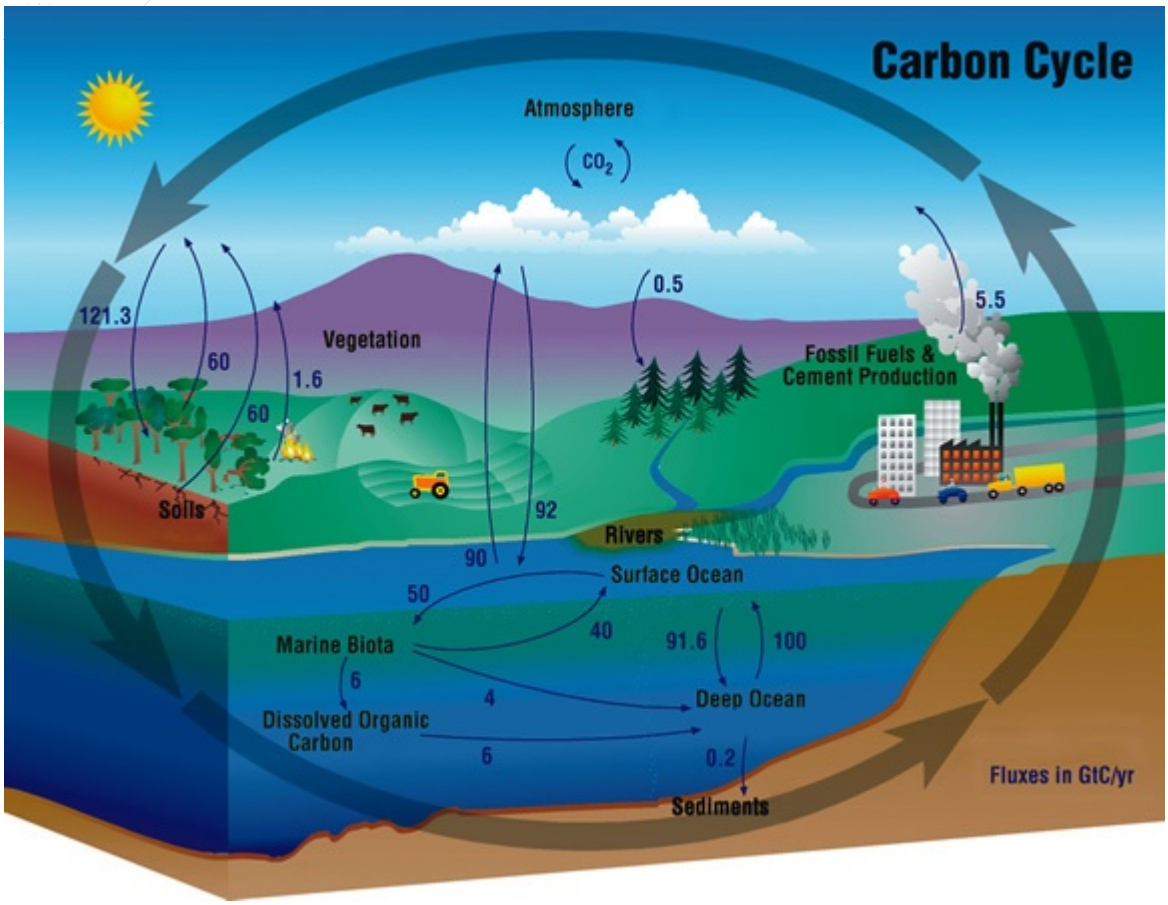


Figure 1: The annual flux of CO_2 in GigaTons (Gt) or billions of tons between each of the Earth's reservoirs. Each reservoir serves as both a source of and a sink for carbon, as indicated by opposing arrows. The carbon released by burning fossil fuels is an unbalanced contribution to the global carbon budget. The total contribution of carbon from the burning of fossil fuels has increased from 5.5 Gt to between 7 and 8 Gt from 2003 until 2007 (Credit: 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
Volcanos	Oceans and lakes
Organic decay	Vegetation by photosynthesis
Natural forest/bush fires	Reforestation
Fossil fuel production and combustion	Precipitation
Deforestation by fire clearing	Industrial winning of atmospheric gases
Waste incineration	Carbon capture and storage methods
Gas hydrates	
Waters	
Livestock	
Rice farming	
Manure management	
Waste management	
Industrial manufacturing	

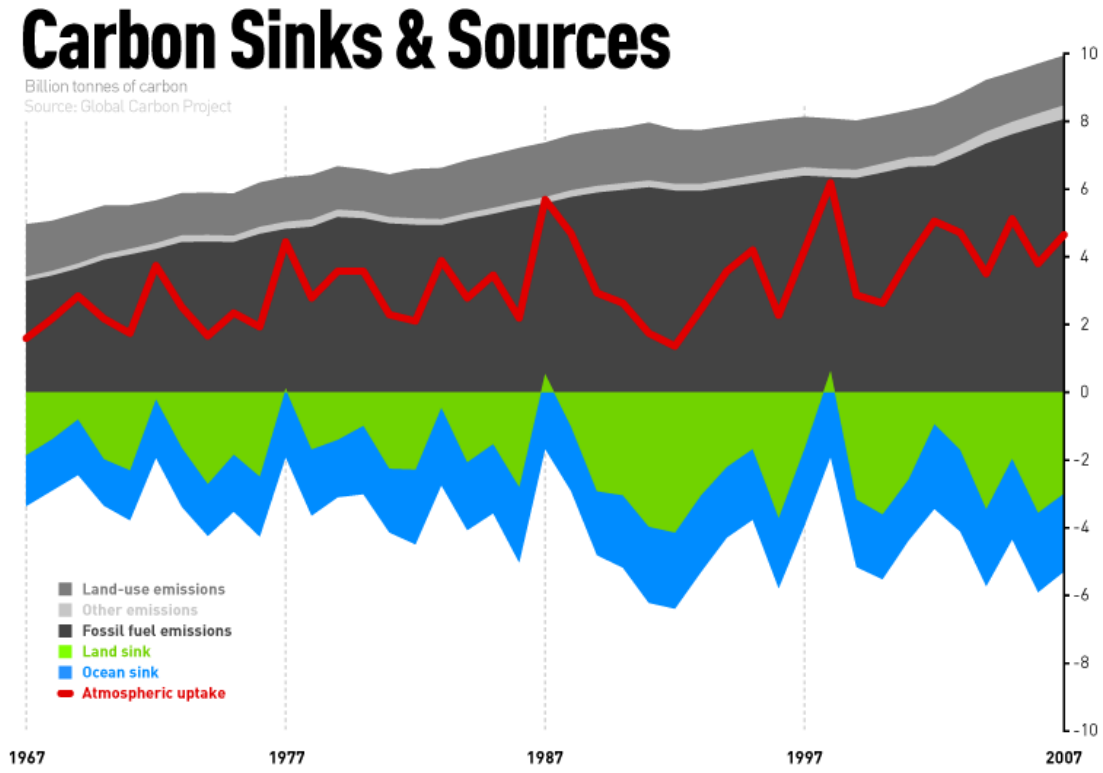


Figure 2: Evolution of the budget of carbon sinks and sources (Credit: climatesafety, https://www.flickr.com/photos/climatesafety/4745854611, https://creativecommons.org/licenses/by-nc/2.0/legalcode).

However, artificial interference by human activities constantly increases a net imbalance towards carbon sources leading to a growing concentration of carbon based greenhouse gases. As Figure 3 illustrates, the amount of atmospheric CO_2 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 we measure 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 help understand the effects of an increasing level of greenhouse gases released into the atmosphere.

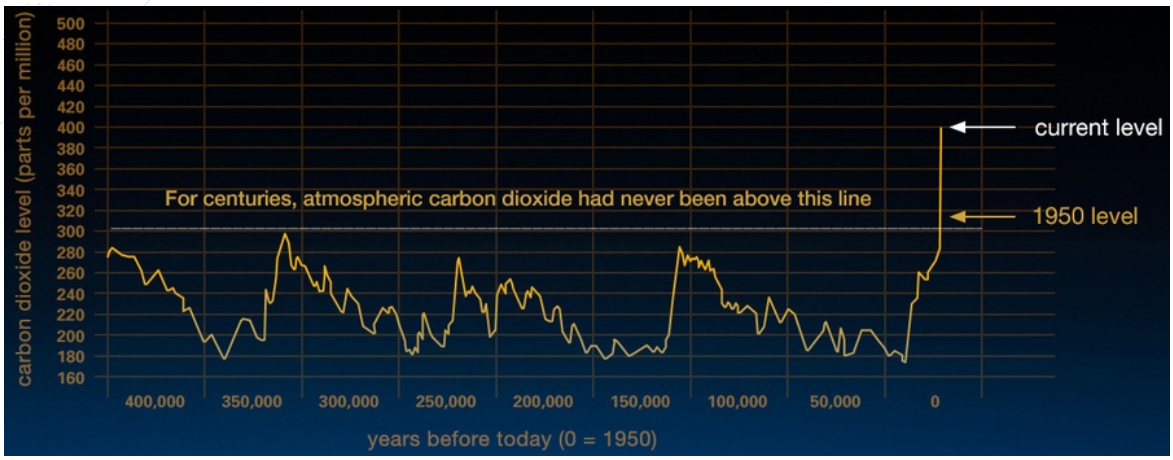


Figure 3: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO_2 has increased since the Industrial Revolution until February 2016. (Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record/NASA/JPL, http://climate.nasa.gov/evidence/, public domain).

The pH value

The pH value is a measure for the strength of acids. Its value represents the concentration of free hydron (H^+) or hydronium (H_3O^+) ions. The value is defined as:

$$pH = -\log_{10}\left(\frac{c(H_3O^+)}{\frac{mol}{l}}\right)$$

The concentration of hydronium ions $c(H_3O^+)$ is given in units of moles per litre. The mole is a standard unit for the amount of a given substance. There are indicators that change their colour depending on the pH value of the solution. This permits measuring the pH value.

The oceans as a carbon sink

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

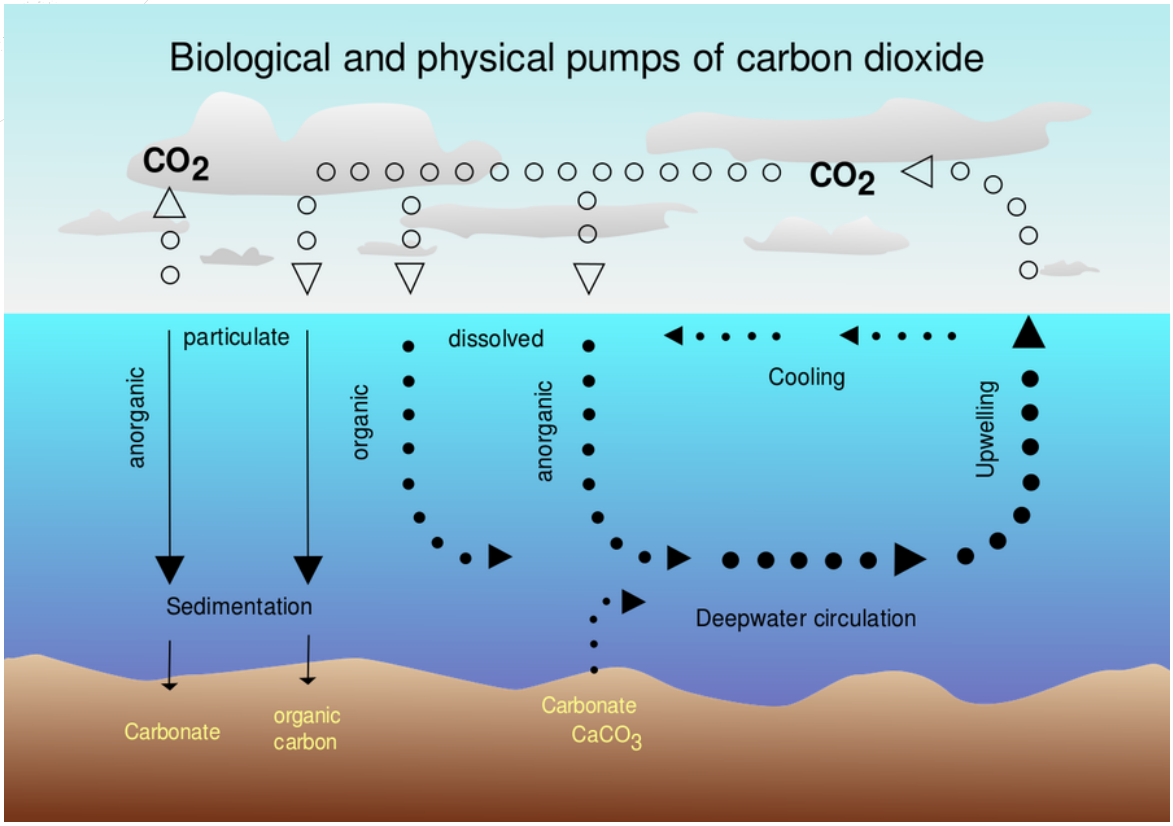


Figure 4: Air-sea exchange of carbon dioxide (Credit: McSush (modified), Hannes Grobe (original), https://commons.wikimedia.org/wiki/File:CO2_pump_hg.svg, https://creativecommons.org/licenses/by-sa/2.5/legalcode).

Although the ability of water capturing and storing CO_2 helps reducing greenhouse gases, it comes with a high price. Solving CO_2 in water changes the 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, among which is the hydron ion which also reacts to form the hydronium ion H_3O^+. The free hydron or hydronium ions are characteristic for 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.

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

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

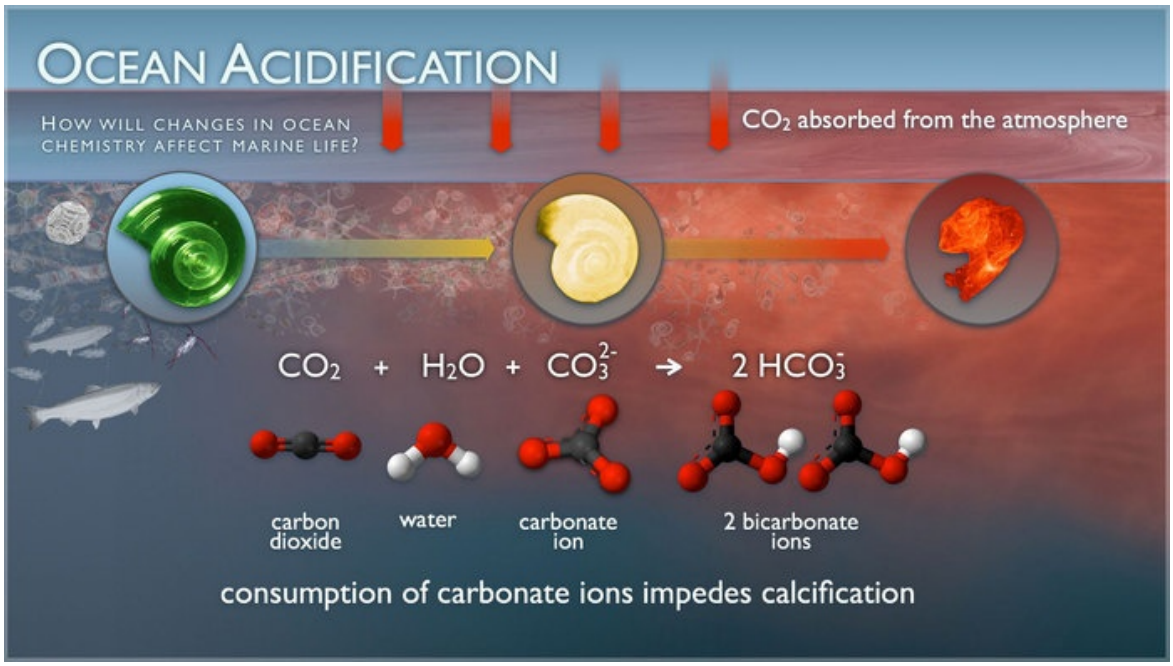


Figure 5: Illustration of how solving CO_2 in water consumes carbonate ions. It impedes calcification or even may lead to decalcification of sea shells (Credit: NOAA PMEL Carbon program, public domain).

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

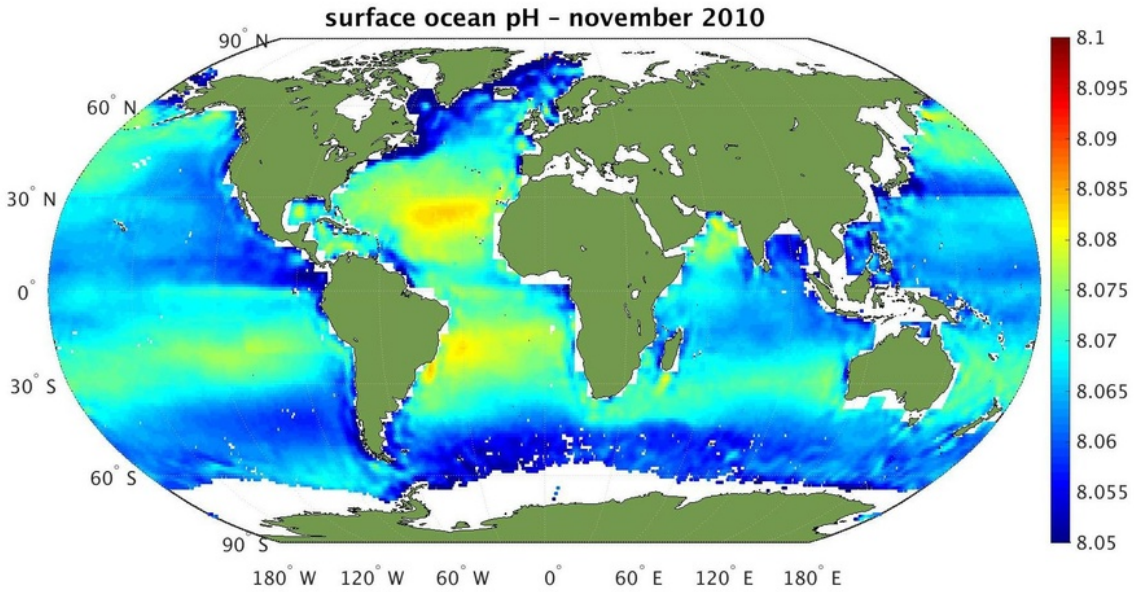


Figure 6: This map shows the first estimates of surface ocean pH using salinity data from ESA's SMOS with satellite sea-surface temperature measurements and additional auxiliary data. There is a spatial variation of the pH across the globe. Cold waters near the poles tend to be more acidic due to the ability of cold water to solve carbon dioxide better than warm water (Credit: 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 especially polar regions are stronger affected by acidification than others. This can be explained by the phenomenon of cold water being able to solve CO_2 better than warm water. Wide range water currents are known to connect the oceans of the world. As a consequence water is exchanged between latitudes, and so acidic, i.e. CO_2 rich, water is transported from the poles to the equator regions. The water is heated up on its way and releases part of the stored CO_2. Therefore, oceans can also be regarded as a regionally confined carbon source.

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

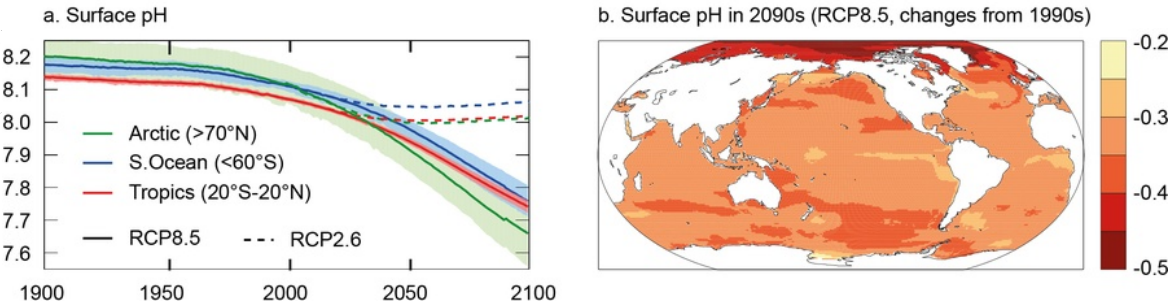


Figure 7: Historic and projected evolution of oceanic surface pH levels. The models were calculated for the most optimistic (RCP2.6, Representative Concentration Pathways) and the most pessimistic scenarios (RCP8.5) for the evolution of atmospheric CO_2. (a) Time series of surface pH shown as the mean (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 (Credit: IPCC Report, 2013, Working Group I, Chp. 6, p. 532, permission for reproduction granted).

This could have an effect on the food chain. The diet of a fish includes shellfish that typically possess an exoskeleton (e.g. mussels, crustaceans) that are vulnerable to acidic environments.

FULL ACTIVITY DESCRIPTION

Introduction

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

Question: What substances do you know that contain carbon?

Question: Do you know solid, liquid or gaseous substances that contain carbon?
Information: Many substances that burn contain carbon (e.g. candles, wood, natural gas, fuels, coal).

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

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

Question: What happens with carbon dioxide, when it is solved in water, as it happens with the oceans on Earth?

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

Question: Have you ever tested what happens when you put an egg in vinegar? Vinegar is a mild acid.

Information:
The strength of an acid is measured with the pH value. The scale runs from 1 to 14. A neutral substance that is neither an acid nor 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

List of material

The number of items needed depends on whether this activity is done as a demonstration experiment carried out by the teacher alone or the students themselves, either individually or in groups.

- Distilled or demineralised water
- Transparent bowl (fireproof)
- Transparent bowl or tank used as cover (fireproof)
- 4 candles or tea lights
- Matches or lighter
- Universal pH indicator according to McCrumb (http://pubs.acs.org/doi/abs/10.1021/ac50075a004)

Hand out the items to the students. Let them perform the following tasks step by step.

Step 1: Put some water in the smaller transparent bowl. The water level should be slightly lower than the height of the candles.



Figure 8: Items needed for this activity.

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

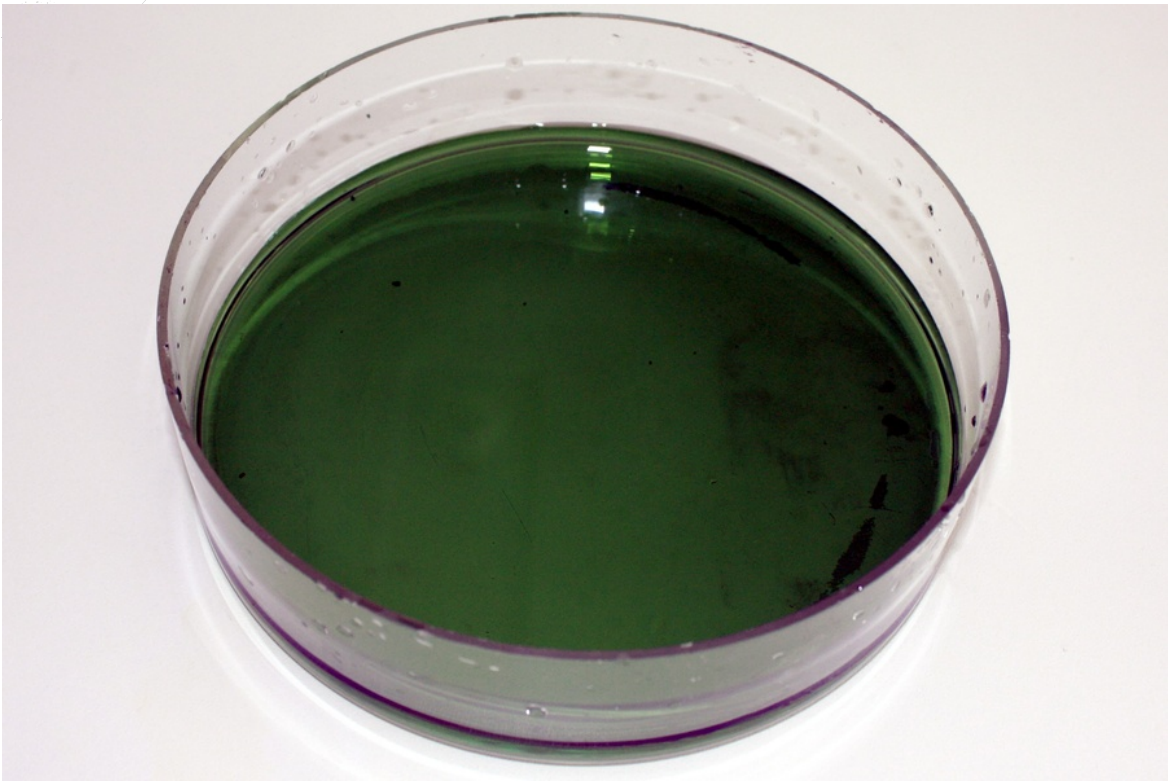


Figure 9: Distilled water in a bowl after adding some universal indicator. According to the colour, the pH value is between 7 and 8.

Question: What is the pH value? Is the liquid acidic or basic?

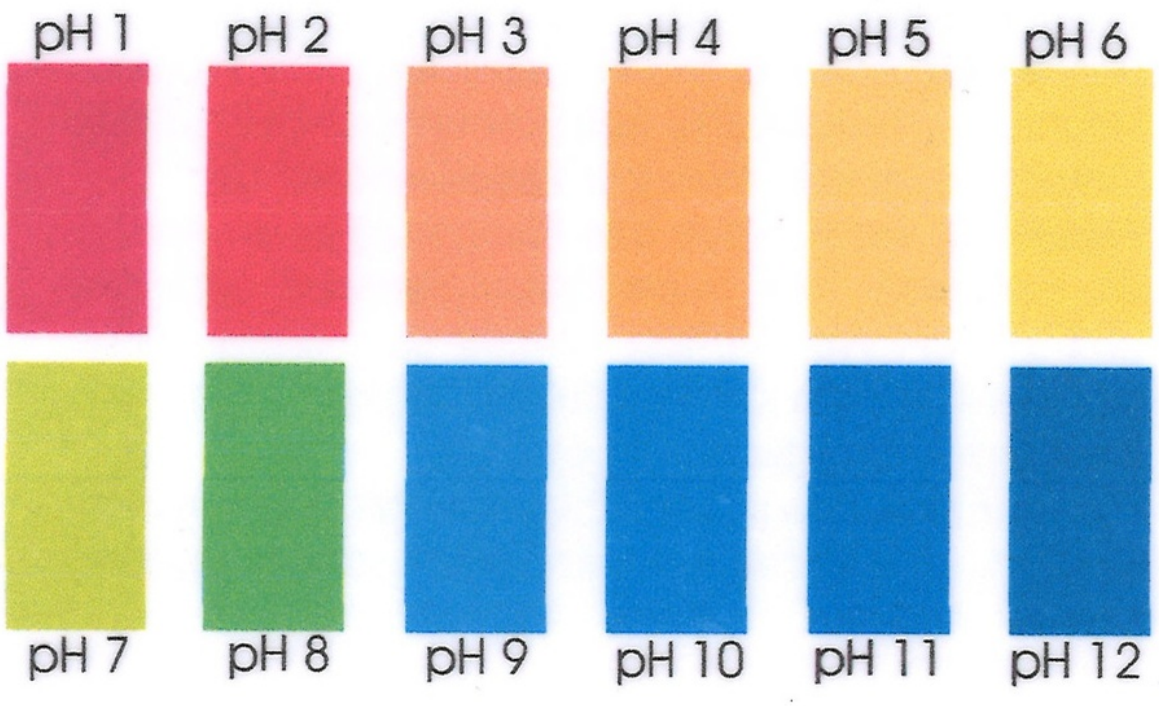


**Figure 10:* Colours the universal indicator attains for pH values

Step 3: Place the candles inside the bowl.

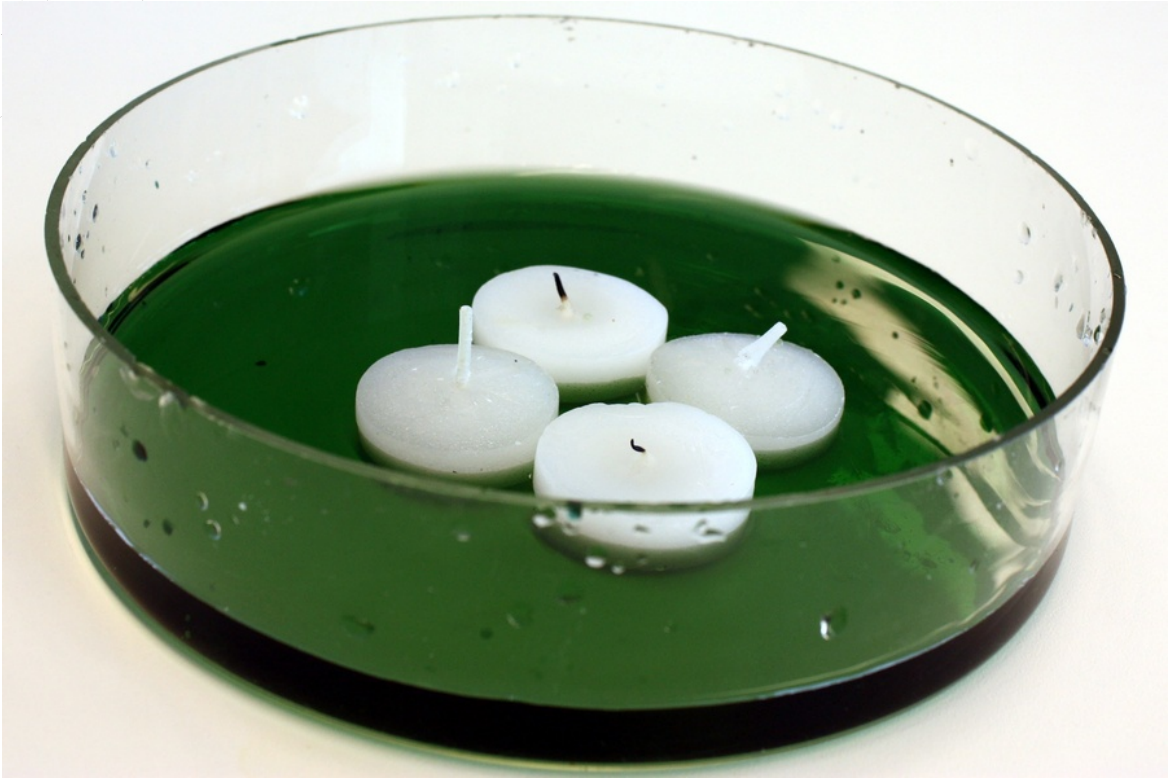


Figure 11: Candles are added to the bowl.

Step 4: Ignite the candles. Wait until they burn steadily and put the second and larger container over the bowl with the candles.



*_Figure 12:_ Candles are ignited and the bowl is covered with an airtight and fireproof transparent cover.

Step 5: Wait until the candles go out.



Figure 13: After a few minutes, the candles are extinguished by the lack of oxygen.

Question: Why did the candles stop burning?

Question: What gas did they produce? We exhale it when breathing.

Step 6: Wait a few minutes and observe the colour of the solution.



Figure 14: After a few minutes with the cover still on, the solution with the indicator begins to change colour.

Step 7: Remove the cover 10 to 15 minutes after the candles stopped burning.

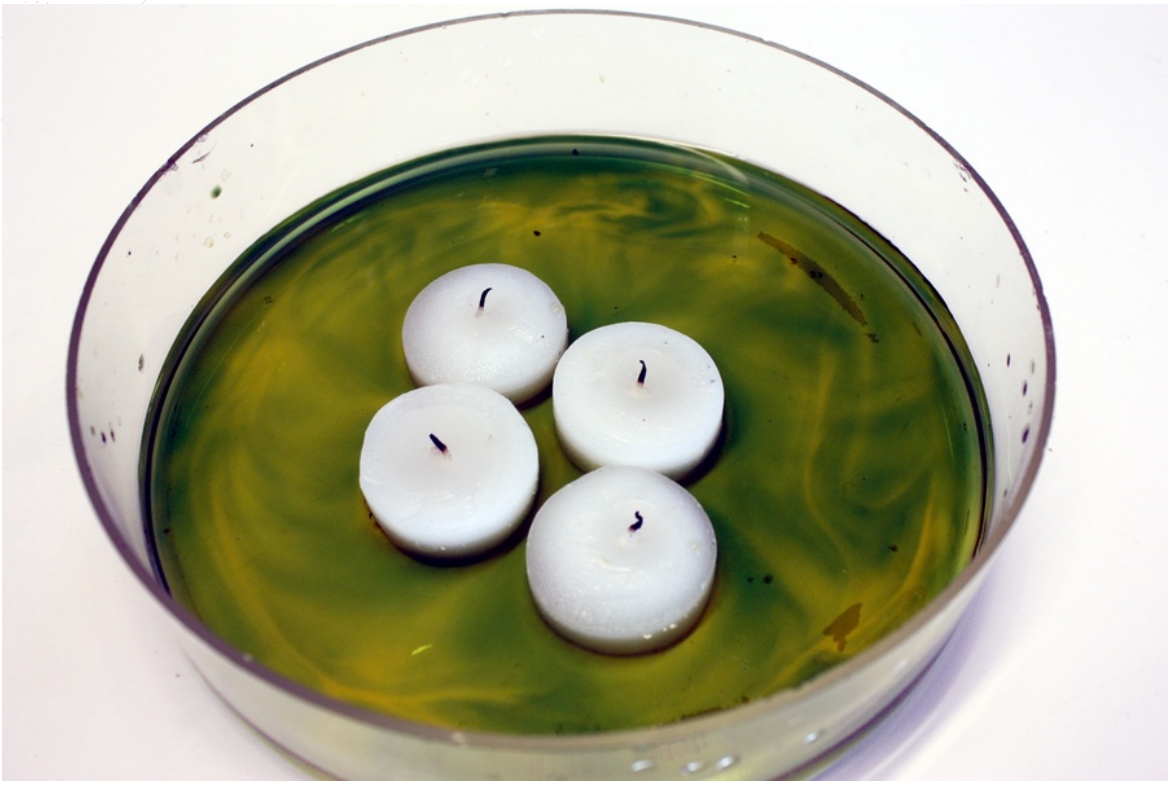


Figure 15: After 10 to 15 minutes, the recolouring has progressed enough that the cover can be removed. The colour has changed from green to yellow indicating a change of the pH value from neutral to acidic.

Question: How did the colour change? What pH value does it represent? Did the solution become basic or acidic?

Information: In this case, the carbon dioxide produced by the candles turned into 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.

Question: What happens to marine creatures with exoskeletons made of limestone, when the water becomes more acidic?

Question: If you look very closely, did the colour change all the way from top to bottom? (This depends on how much water was used.)

Question: When you think about the carbon dioxide in the atmosphere reacting with the oceans, where would you expect the lowest pH values?

Information:
The actual level of acidification is closely linked to the water temperature and the salinity of water. High temperatures and high salinity levels reduce the process of acidification; low temperatures and low salt concentrations support it. This means that especially the Arctic Sea is vulnerable to acidification. The water is very cold and the melting ice is a constant supply of salt free freshwater that remains at the surface.

CURRICULUM

Space Awareness curricula topics (EU and South Africa)

Our fragile planet, Oceans, biodiversity

CONCLUSION

Candles burn to produce carbon dioxide that reacts with the surface layer of a water bath. A pH indicator allows monitoring the change of the pH value. This experiment is a rather realistic analogy of what happens to water when exposed to the main greenhouse gas, carbon dioxide, i.e. it solves the gas and becomes more acidic. This is a threat to marine species like corals and snails who build exoskeletons by building limestone structures. Limestone is dissolved by carbonic acid.

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