SPACE awareness

OCEANS AS A HEAT RESERVOIR

Learn how oceans store heat

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Lehrplanthema
Oceans, climate change

Übergeordnetes wissenschaftliches Konzept
Earth is a system of systems which influences and is influenced by life on the planet

Schlüsselwörter
thermal radiation, oceans, Earth, heat capacity, heat storage, temperature

Altersgruppe
12 - 19

Bildungsebene
Middle School, Secondary School

Zeit
1h

Gruppengröße
Group

Überwachung aus Sicherheitsgründen
Unsupervised

Kosten
Average (5 - 25 EUR)

Ort
Indoors (small, e.g. classroom)

Kernkompetenzen
Developing and using models, Planning and carrying out investigations, Analysing and interpreting data, Constructing explanations, Engaging in argument from evidence

Art der Lernaktivität
Partial enquiry

KURZBESCHREIBUNG

This activity demonstrates the heat storing capabilities of soil or sand and water which simulates similar processes on Earth. Both samples are irradiated with a strong lamp and the temperature variation is monitored as well as illustrated with a diagram. This model represents temperature changes on solar irradiation of both land and water on Earth. This demonstrates the heat storage capacity of the oceans on Earth.

ZIELE

With this activity the students will: *learn how different materials respond to heat.

- learn that water can store large amounts of heat very effectively.
- understand that oceans play an important role in capturing and storing heat that cannot contribute to the global atmospheric warming.
- learn how to measure and record data for subsequent graphical presentation and analysis.

LERNZIELE

During this activity, the students will be able to:

- describe that the Sun is the main heat source of the Earth.
- demonstrate that each substance responds to heat with a different temperature change.
- carry out an experiment that monitors temperature.
- analyse and interpret that data obtained during the experiment.

- demonstrate the relevance of the results to the Earth's climate.

BEWERTUNG

- After introducing the Sun-Earth system, ask the students what the main energy source of the Earth is.
- Discuss with the students their own experiences when heating different substances (air, water, …).
- Watch and supervise the students while they carry out the experiment described in this activity.
- Let the students discuss and visualise the results after translating the data into graphs.
- Let the students discuss the composition of the Earth's surface and their response to external solar heating. With the results of the experiment in mind, let them discuss the role of the oceans.

MATERIALIEN

Items needed for one experimental set-up (a group of at least two):

- Strong lamp
- Water
- Dirt, soil, or sand
- 2 bowls or trays (e.g. petri dishes)
- Stop watch
- Pen and paper
- Colour pencils
- Ruler
- Thermometer
- Calculator
- Anything the helps maintaining an upright orientation of the thermometer

HINTERGRUNDINFORMATIONEN

The oceans as a heat sink

The global warming caused by the increasing Greenhouse Effect is one of the biggest challenges of mankind. Different to other planets in the solar system, the Earth is covered by large oceans that make up for 2/3 of the total surface area. Therefore, they are an important player in the budget of heating and cooling. Oceans act as a heat sink, as they react slower and with less a temperature change than land masses do. As a result, the oceans store more than 90% of the total global heat (Figure 1).

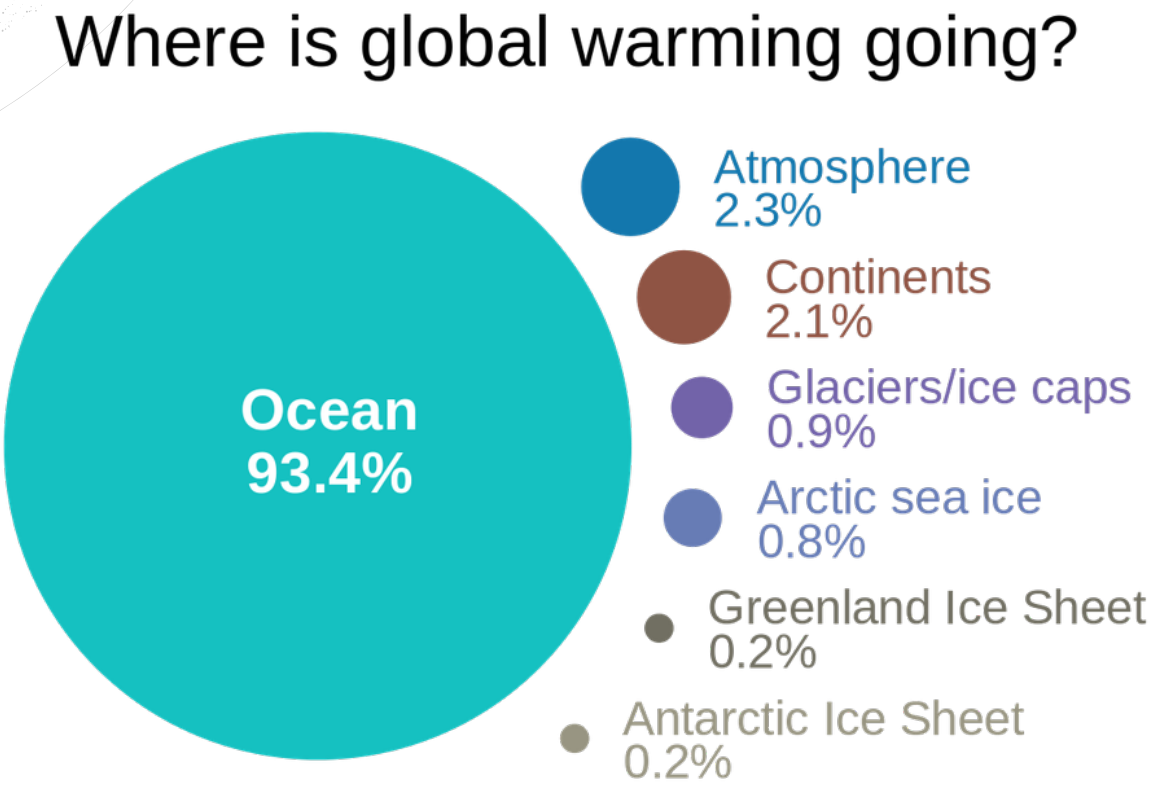


Figure 1: Amounts of energy added to the various parts of the climate system due to global warming, according to the 2007 IPCC AR(4) WG1 Sec 5.2.2.3 (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch5s5-2-2-3.html), (Skeptical Science, vectorised by User:Dcoetzee (https://commons.wikimedia.org/wiki/File:WhereIsTheHeatOfGlobalWarming.svg), „WhereIsTheHeatOfGlobalWarming", https://creativecommons.org/licenses/by/3.0/legalcode).

The temperature distribution of the waters on Earth is efficiently monitored from space by remote sensing Earth observation satellites. Monitoring the sea is one of the key objectives of Europe's Copernicus Earth observing programme.

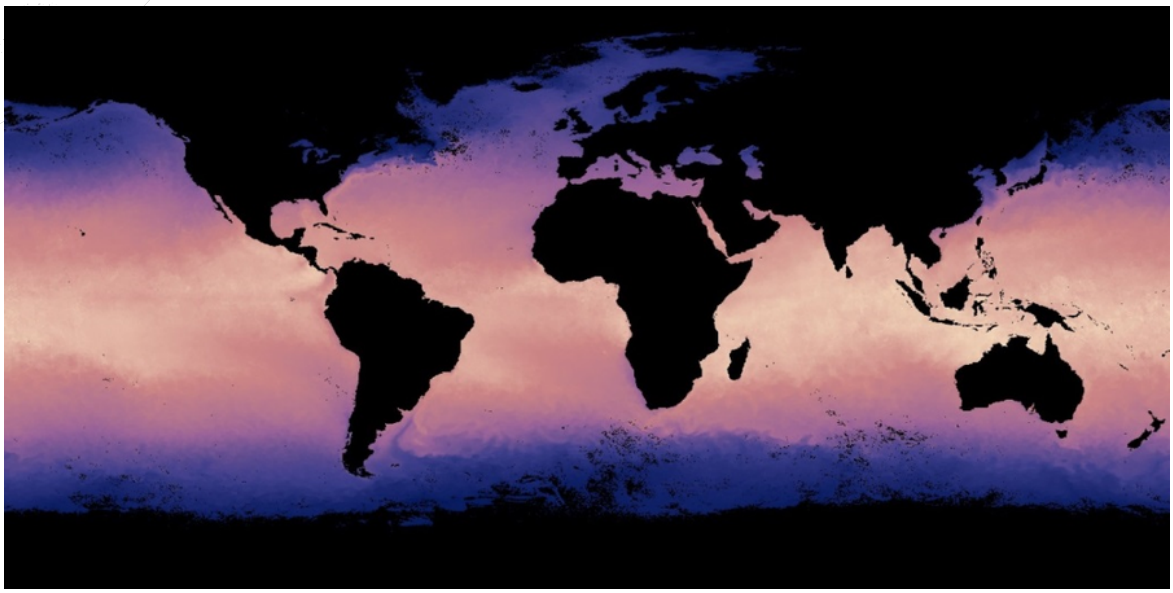


Figure 2: Averaged global land surface temperature map for March 2016 obtained with the MODIS spectrograph on board NASA's Aqua satellite of the EOS programme. The colour code indicates temperatures between -2°C and +35°C (Credit: NASA Near Earth Observations, http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYD28M).

The relevance to climate change

These monitoring programmes have provided evidence that just like the atmosphere the oceans are continuously warming up.

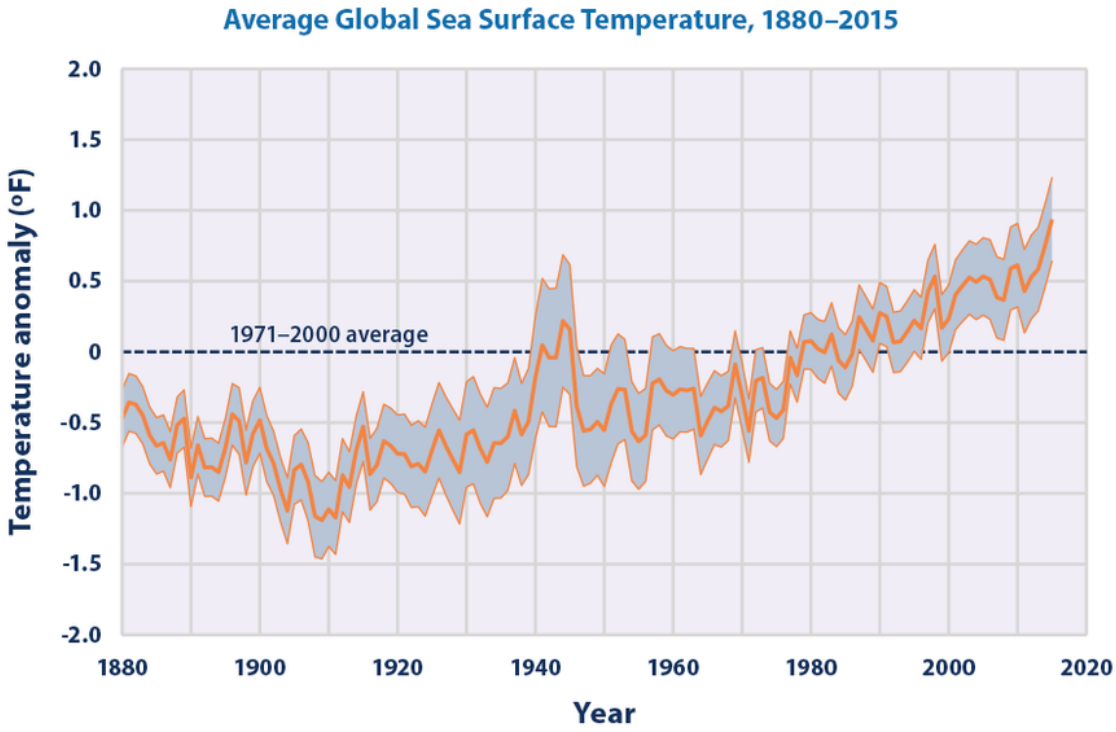


Figure 3: This graph shows how the average surface temperature of the world's oceans has changed since 1880. This graph uses the 1971 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time. The shaded band shows the range of uncertainty in the data, based on the number of measurements collected and the precision of the methods used (Credit: NOAA (National Oceanic and Atmospheric Administration). 2016. Extended reconstructed sea surface temperature (ERSST.v4). National Centers for Environmental Information. Accessed March 2016. www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst, https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature).

Suitable remote sensing campaigns can even analyse the spatial distribution of the warm-up process. Since the insolation (solar luminosity variations, orbital variations) does not change with the rates measured, natural causes can be excluded.

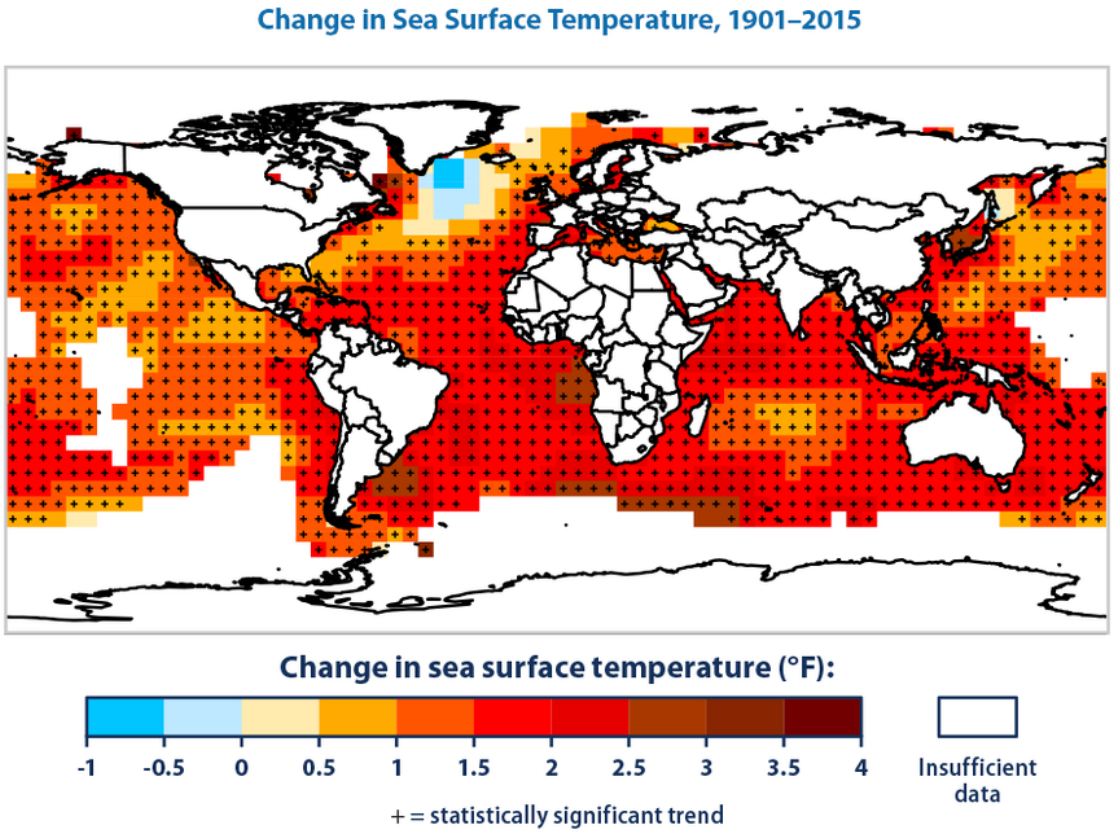


Figure 4: This map shows how average sea surface temperature around the world changed between 1901 and 2015. It is based on a combination of direct measurements and satellite measurements. A black "+" symbol in the middle of a square on the map means the trend shown is statistically significant. White areas did not have enough data to calculate reliable long-term trends (Credits: IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1, NOAA (National Oceanic and Atmospheric Administration). 2016. NOAA Merged Land Ocean Global Surface Temperature Analysis (NOAAGlobalTemp): Global gridded 5° x 5° data. National Centers

for Environmental Information. Accessed June 2016. www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp, https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature).

Thermic radiation of bodies

Any given body with a temperature above absolute zero, i.e. T>0 K radiates. According to Planck's Radiation Law (ideally for a black body) the distribution of frequencies of the emitted spectrum depends on the temperature.

$$U(\nu, T) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Integrating over all frequencies leads to the Radiation Law of Stefan Boltzmann which describes the total emitted power. In reality black bodies only exist up to a certain degree of approximation. Therefore, Kirchhoff's Radiation Law about the radiant power of any given body can be applied:

$$L_{\Omega\nu}(\beta, \varphi, \nu, T) = L^{o}_{\Omega\nu}(\nu, T) \cdot a'_{\nu}(\beta, \varphi, \nu, T)$$

This means that the radiant power $L_{\Omega\nu}(\beta,\varphi,\nu,T)$ of a given body is as large as the total radiant power of a black body $L^{o}_{\Omega,\nu}(\nu,T)$ having the same temperature and the same absorptivity $a_{\nu}'(\beta,\varphi,\nu,T)$. The spectral radiance and the absorptivity may also depend on the angle of incident radiation. Thus, according to Kirchhoff's Radiation Law, the radiant power of any given body is directly proportional to the radiant power of a black body with the same temperature. Furthermore, Kirchhoff's Radiation Law leads to the conclusion that with a given temperature a body with good heat absorption also releases heat well.

Stefan Boltzmann's Law

The Stefan Boltzmann's Law describes the emitted power of a black body radiating isotropically into all directions. For the total radiation power of a black body the following equation applies:

$$P = \sigma \cdot A \cdot T^4$$

A is the area of the radiating cross section of the body and σ is the Stefan Boltzmann's constant, a natural constant with the value of:

$$\sigma = \frac{2\pi^5 k_B^4}{15h^3c^2} = (5{,}670\,367 \pm 0{,}000\,013) \cdot 10^{-8}\,\frac{\mathrm{W}}{\mathrm{m^2K^4}}$$

Together with Kirchhoff's Radiation Law the Stefan Boltzmann's Radiation Law for any given body results to

$$P = \varepsilon(T) \cdot \sigma \cdot A \cdot T^4$$

with a temperature dependent emissivity ε(T).

The emissivity is a parameter that reflects the properties of the radiating substance and surface. For am given temperature, surfaces with different emissivity appear differently bright. As a result, the thermic radiation is also stronger.

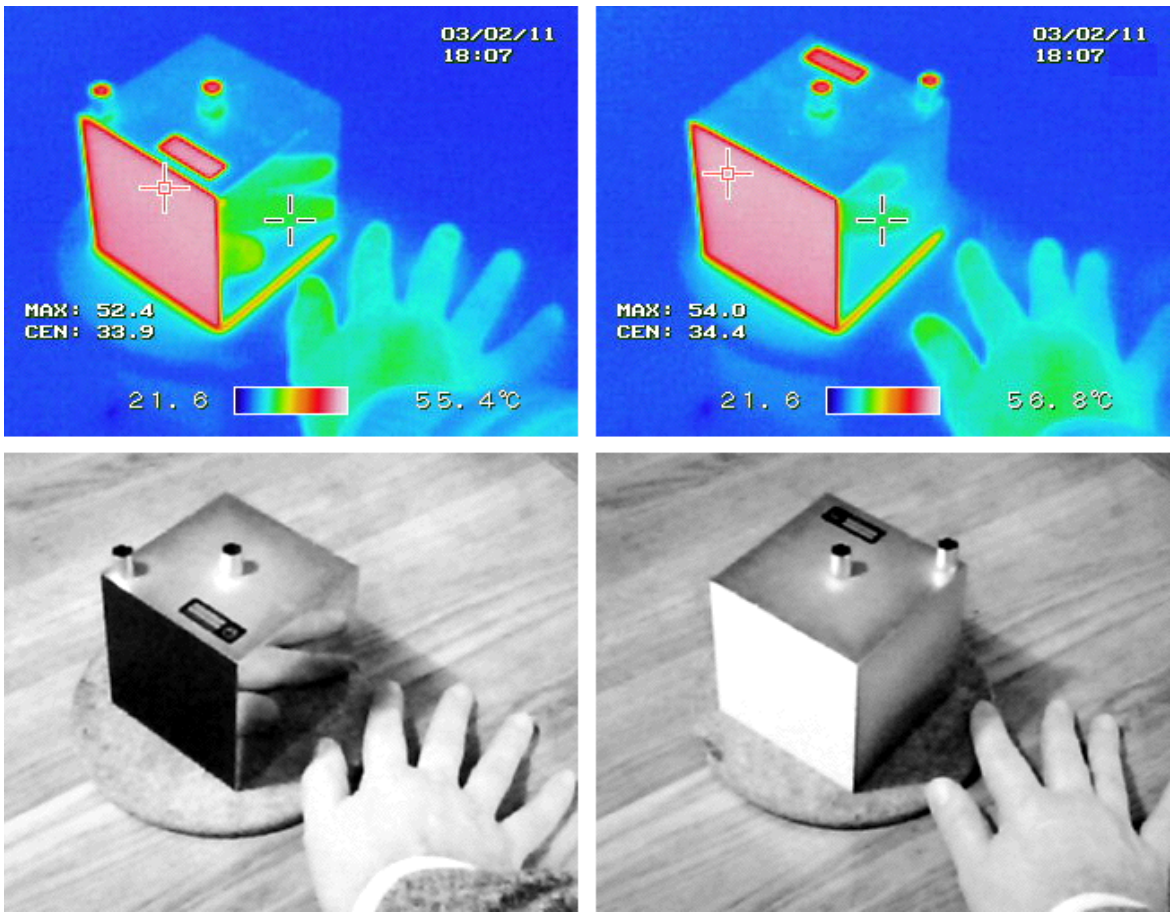


Figure 3: Photographs of Leslie's cube. The color photographs are taken using an infrared camera; the black and white photographs underneath are taken with an ordinary camera. All faces of the cube are at the same temperature of about 55°C. The face of the cube that has been painted has a large emissivity, which is indicated by the reddish color in the infrared photograph. The polished face of the aluminum cube has a low emissivity indicated by the blue color, and the reflected image of the warm hand is clear (Credit: Pieter Kuiper; https://commons.wikimedia.org/wiki/File:LesliesCube.png).

Heat capacity

If heat Q is added to liquids (or other material in general), their temperature T rises. Both increases (ΔQ, ΔT) are directly proportional to each other.

$\Delta Q \propto \Delta T$

Demonstration experiment
An immersion heater with the radiative power P within a certain period of time Δt will add energy to the liquid according to:

$\Delta Q = \kappa \cdot P \cdot \Delta t$

In this case κ is a dimensionless quantity with $\kappa \in [0;1]$, corresponding to the percentage of the energy transformed and absorbed by the liquid.

$\Delta Q \propto P \cdot \Delta t$

means that the energy needed by the immersion heater is directly proportional to the temperature change ΔT.

Remark: This experiment also works with a water filled paper cup, positioned over the flame of a Bunsen burner.

If you double the amount of liquid with m being the mass, you find the following correlation:

$\Delta Q \propto m$

In summary, the following is valid

$\Delta Q \propto m \cdot \Delta T$

with a proportionality constant

$c = \Delta Q / (m \cdot \Delta T)$

The quantity c is called specific heat capacity. It depends on the material. The dependence on the temperature is neglected in this example. The unit of the specific heat capacity is:

$[c] = 1\ J/(kg \cdot K)$

It is commonly listed in units of:

$1\ kJ/(kg \cdot K) = 1\ J/(g \cdot K)$

With a value of c_W = 4.182 kJ/(kg·K) water has a high specific heat capacity and thus is an excellent heat reservoir due to its simple and low priced availability.

Cooling process of materials

The cooling process of a given body with the temperature T(t) and an environmental temperature U(t) can be described with the following differential equation

$$\frac{\mathrm{d}T(t)}{\mathrm{d}t} = -k \cdot T(t) + k \cdot U(t)$$

with the initial condition $T(t_0)=T_0$. Provided the environmental temperature is constant, the differential equation describes an exponential decline (or an exponential increase). The cooling constant k is given as:

$$k = \frac{\alpha A}{mc}$$

It depends on the heat capacity, the mass of the body, the area of the interacting surface cross section and the heat transfer coefficient α. Applied to our experiment this means that due to its higher heat capacity water cools down more slowly.

VOLLSTÄNDIGE BESCHREIBUNG DER AKTIVITÄT

Preparations

Edit the background information in the worksheet document to match the knowledge of the students. Younger students might not need the detailed thermodynamic equations.

Introduction

Introduce the role of the Sun as the main heat source of the Earth along the following discussion and questions.

Q: We experience day and night and the different seasons. What causes the different temperatures associated with them?
A: The Sun provides the heating.

Q: How much of the Earth's surface is covered by water and how much by land (approximately)?
A: About 71% is covered by water.

Q: So, where does the insolation induce most of the heat?
A: The oceans.

Q: The temperature changes between day and night in the deserts are very strong. Can you imagine why?
A: The solid surface absorbs the heat and gets warm quickly. If something heats up very rapidly, it also cools down at a very high rate. In addition, deserts usually lack the "blanket" of clouds that prevent the heat from being released into space.

Q: In comparison, how rapid does water respond to heating? Imagine a pot of water on a stove.
A: This is a rather slow process.

Experimental set-up 1

It would be best, if students worked in groups of two to share responsibilities. They will measure the evolution of the temperature of illuminated water and soil in time. To assure similar conditions for both substances, the experiment is carried out in two steps.

1. Fill one tray with water and the other with soil or sand. The amounts should be the same.
2. Place the tray filled with water below the lamp
3. Immerse the thermometer inside the water. Its orientation should be as parallel as possible to the angle of irradiation. This grazing angle helps to reduce direct heating of the thermometer.

4. Let the substances assume room temperature.
5. In the meantime, prepare a data table for filling in the measurements. It should allow for 21 lines of data and four columns (see Table 1).
6. The first column lists numbers from 0 to 20 (minutes).

Table 1: First lines of the data table, including header.

Time t (min)	Water ϑ (°C)	Soil ϑ (°C)	Difference Δϑ (°C)
0			
1			
...			

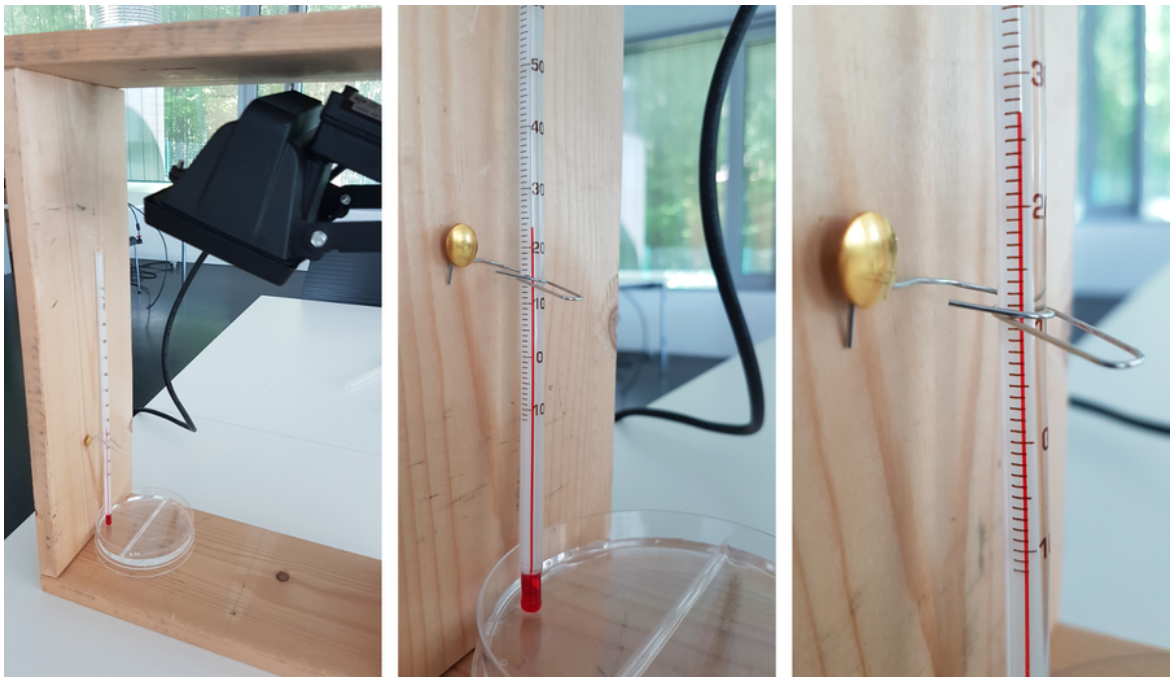


Figure 6: Experimental set-up for the temperature measurement of water. A petri dish is filled with water, and a thermometer is ready to measure the temperature. In order to maintain an upright position for the thermometer, it is attached to the frame with a pin and a paper clip. The lamp is set to illuminate the dish (own work).

Q: What do you think how the temperatures change after switching on the lamp?
A: The temperature rises as long as the lamp is on. After switching it off, the water will cool down again.

Q: After probing the water, you will use soil. Do you expect a different temperature response?
A: The rates of heating and cooling will be different.



Figure 7: While illuminating the water, the temperature is read off the thermometer every minute (own work).

Experimental procedure 1

The procedure is the same for both experiments. Begin with water.

1. Take the first temperature measurement before switching on the lamp.
2. Start the stop watch and switch on the lamp (Figure 7).

3. For 10 minutes, take a measurement every minute and note down the value in corresponding column and line in the table.
4. After 10 minutes, switch off the lamp and continue measuring the temperature as before.
5. Stop measuring after 20 minutes altogether. You should have 10 temperatures with the light switched on and 10 for the light switched off.
6. Exchange the water tray with the one filled with soil.

Analysis 1

The data are analysed by producing a diagram that shows the time elapsed during the experiment vs. the temperatures measured.

While one of the students of any working group continues to fill the data into diagram (Figure 8), the other prepares the second experiment with the soil.

1. Prepare a diagram (e.g. Figure 8, upper panel) with two axes. The horizontal axis lists the time elapsed during the experiment, the vertical axis lists the temperatures. Be prepared for a temperature range between 20 and 35°C.
2. While the thermometer assumes room temperature again, insert the data into the diagram. For each measurement, add a small cross at the coordinate that matches the time and the temperature.
3. Connect the data points of the diagram

Experimental set-up 2

Let the students prepare the second experiment in just the same way as the first (Figure 9). Instead of water, the students will probe the soil (dirt, sand).

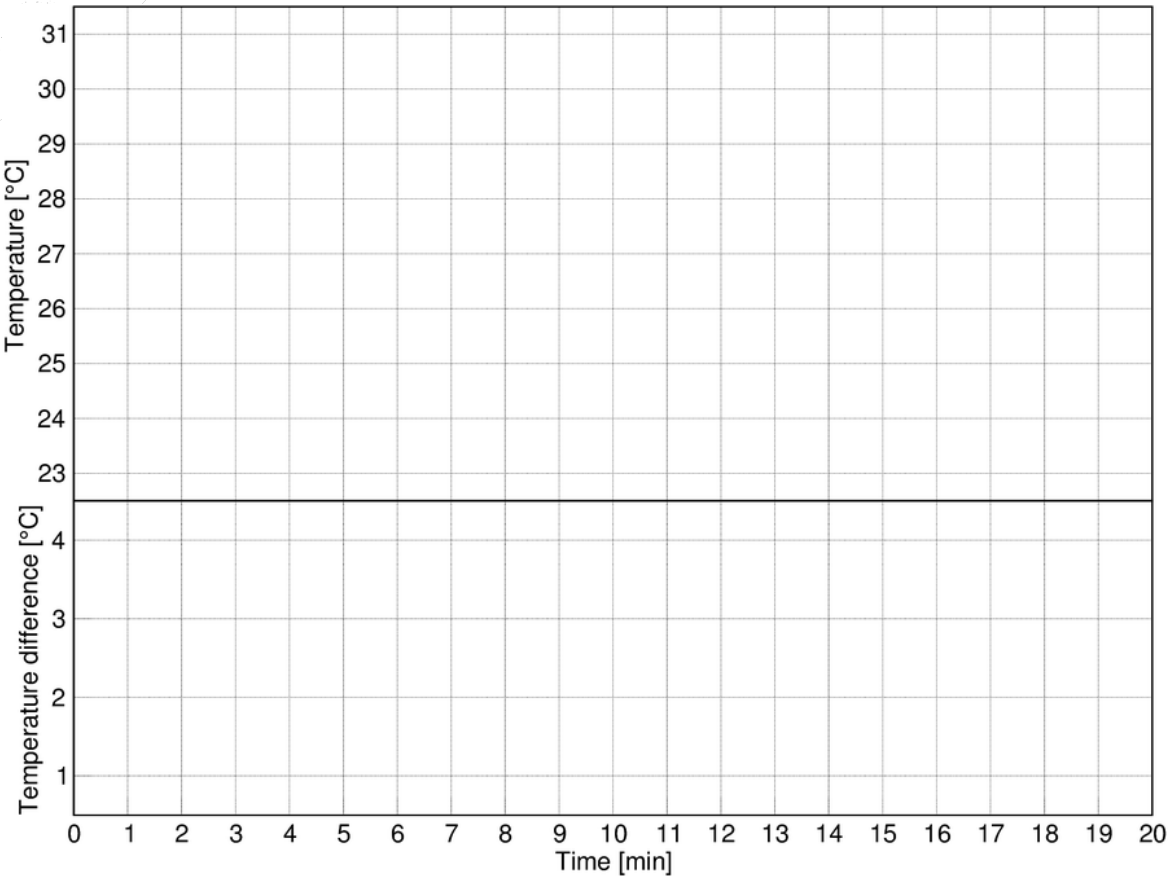


Figure 8: Template for the diagram to record the temperature measurements. The upper panel will contain the temporal evolution of the temperatures. The lower panel is reserved for plotting the difference between the two temperatures. Use different colours to represent the data (own work).

Experimental procedure 2

The procedure is the same as before.

1. Take the first temperature measurement before switching on the lamp.
2. Start the stop watch and switch on the lamp.
3. For 10 minutes, take a measurement every minute and note down the value in corresponding column and line in the table.
4. After 10 minutes, switch off the lamp and continue measuring the temperature as before.
5. Stop measuring after 20 minutes altogether. You should have 10 temperatures with the light switched on and 10 for the light switched off.



Figure 9: The set-up of the second experiment is the same as for the one with water, but this time the petri dish is filled with dirt, sand, or soil (own work).

Analysis 2

1. As before, add the new data to the diagram.
2. Connect the data points.
3. In the diagram, indicate the ranges, when the lamp was switched on and when it was switched off.
4. For each time step, calculate the temperature difference and add it to the table.
5. Prepare a second diagram that shows the temporal evolution of that difference.
6. Fill that diagram with the corresponding data.

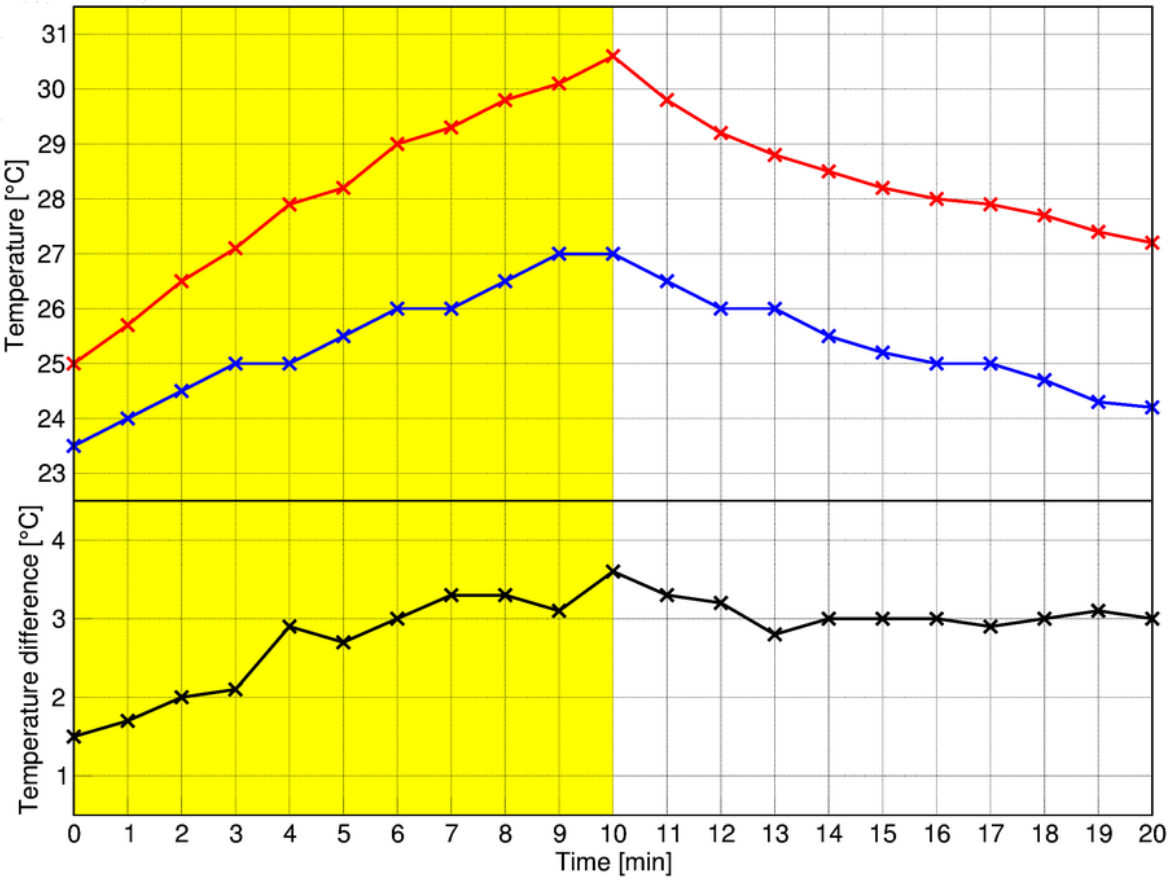


Figure 10: Example development of the temperatures of water (blue) and soil (red). The black curve below depicts the evolution of the difference between the two temperatures (not revealed to the students in the worksheet, own work).

Conclusion

Describe and discuss the results with your group members or classmates.

Q: How did the temperatures change while the lamp was switched on and off?
A: The temperature rises while the substances were illuminated, and they cooled down, as soon as the lamp was off.

Q: Do you recognise a difference between the two substances?
A: The water heats up less and more slowly.

Remark: It should also cool down more slowly. However, the particular conditions of the experimental set-up may influence the cooling process, e.g. high room temperature.

Q: The temperatures rose differently. What is causing this? What changed between the experiments?
A: Everything stayed the same, except the substance to be probed. The observed difference must be caused by the properties of the substances.

Q: Imagine now the Earth with its oceans and continents. Describe how these components react to solar irradiation.
A: During daytime, the cross section of the Earth facing the Sun is irradiated, and land masses and water are heated. During night-time heat is emitted. Oceans warm up and cool down more slowly than continents.

Q: Can you determine the role the oceans have in the global climatic system? Think of what would happen with global temperatures without oceans.
A: The oceans have a dampening effect on the global warming, as they can store heat that otherwise wold lead to higher global temperatures.

Q: What happens to the oceans, if the heating rate rises, while the cooling rate stays the same?
A: The temperature rises.

LEHRPLAN

Space Awareness curricula topics (EU and South Africa)

Our fragile planet, Oceans, climate change

This activity is part of Space Awareness category “Our fragile planet” and related to the curricula topics:

- Composition and structure
- Climate change
- Surface
- Oceans

ZUSÄTZLICHE INFORMATIONEN

This activity is part of a larger educational package called “Our Fragile Planet – The Climate Box”. The consequences of thermal expansion of water are highlighted in the activity “Oceans on the Rise”.

FAZIT

With this activity, pupils learn how and why oceans on Earth can store heat more effectively than land due to its high heat capacity. Therefore, the oceans can mitigate part of the global warming caused by the Greenhouse Effect. The activity simulates this behaviour by two samples of soil and water that are illuminated by a strong lamp. The recorded temperature change is generally slower for water than for soil.

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