Oceans as a Heat Reservoir

Background information

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).

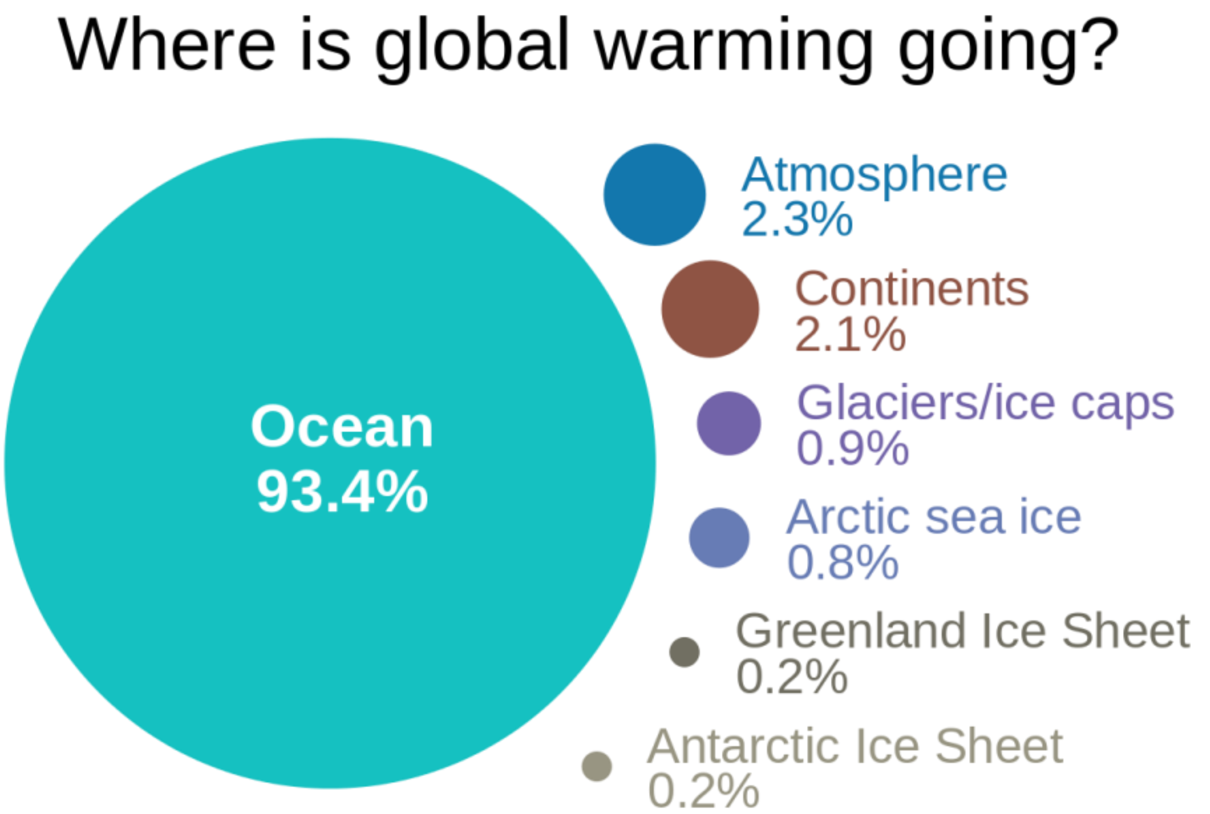

Figure 1: Amounts of energy added to the various parts of the climate system due to global warming, according to the 2007 IPCC AR(4) WG1 Sec 5.2.2.3 (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch5s5-2-2-3.html), (Credit: Skeptical Science, vectorised by User:Dcoetzee (https://commons.wikimedia.org/wiki/File:WhereIsTheHeatOfGlobalWarming.svg),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

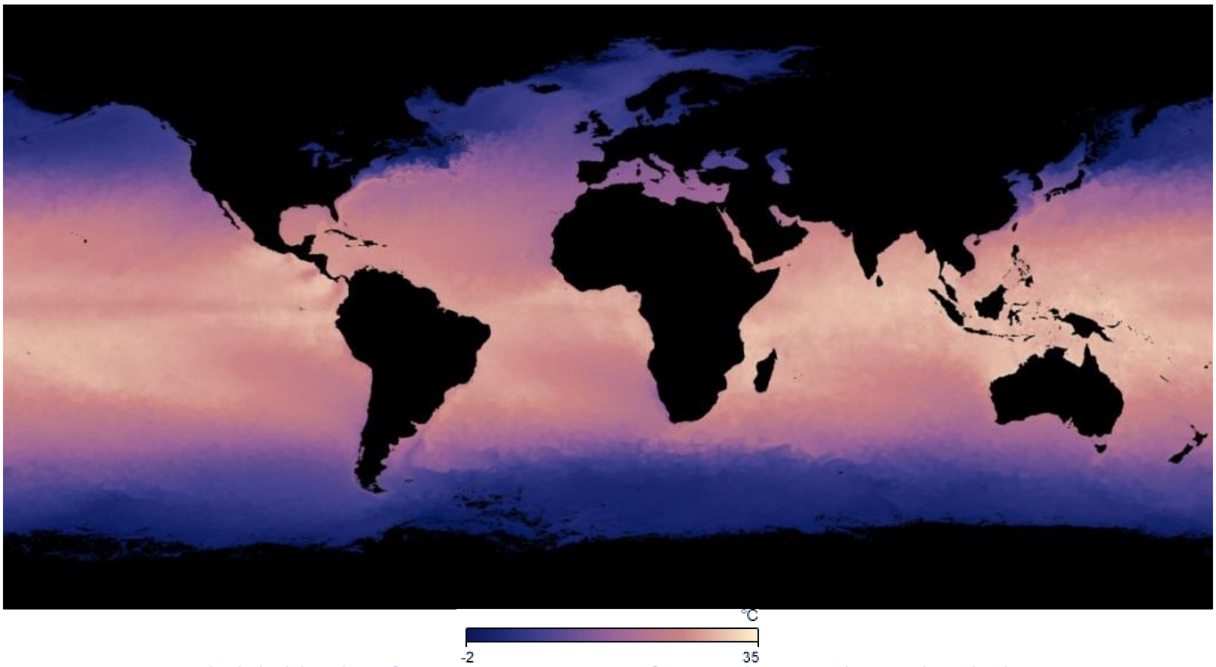

Figure 2: Averaged global land surface temperature map for March 2016 obtained with the MODIS spectrograph on board NASA's Aqua satellite of the EOS programme. The colour code indicates temperatures between -2°C and +35°C (NASA Near Earth Observations, http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYD28M).

The relevance to climate change

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

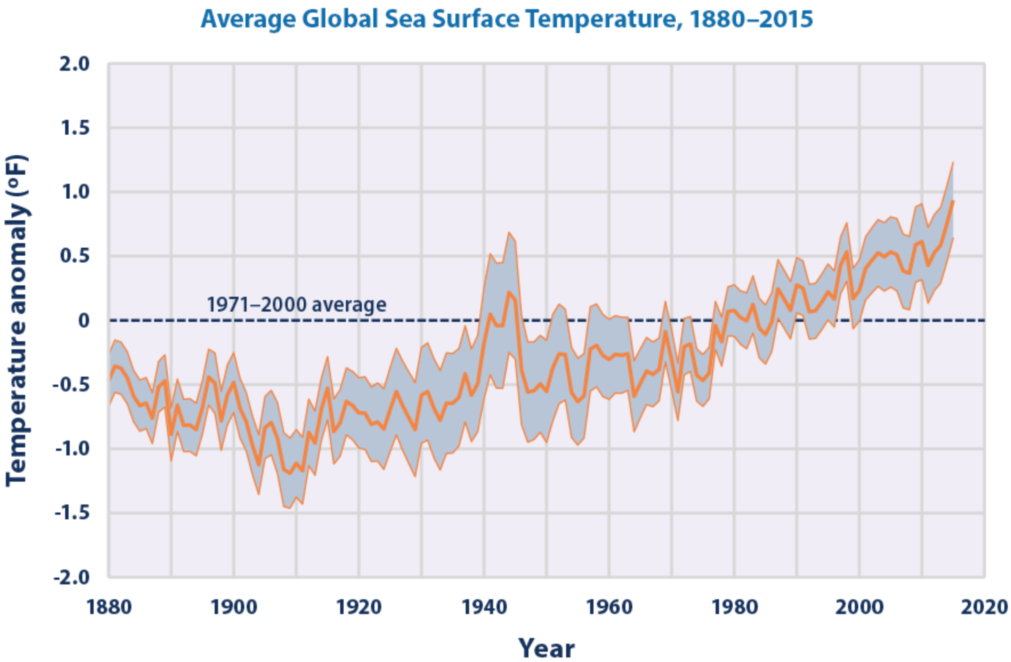

Figure 3: This graph shows how the average surface temperature of the world's oceans has changed since 1880. This graph uses the 1971 to 2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time. The shaded band shows the range 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.

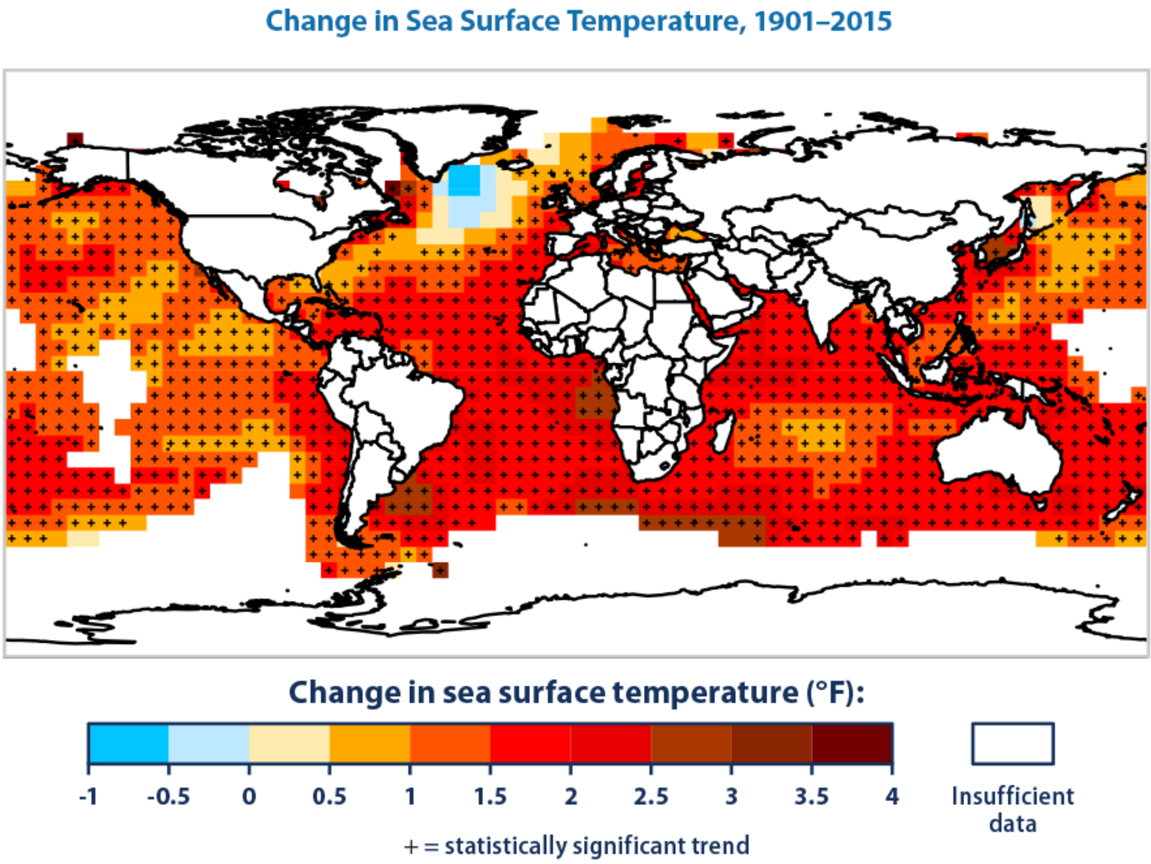

Figure 4: This map shows how average sea surface temperature around the world changed between 1901 and 2015. It is based on a combination of direct measurements and satellite measurements. A black "+" symbol in the middle of a square on the map means the trend shown is statistically significant. White 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).

Thermal radiation of bodies

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

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

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, it implies that any body with good heat absorption also releases heat well.

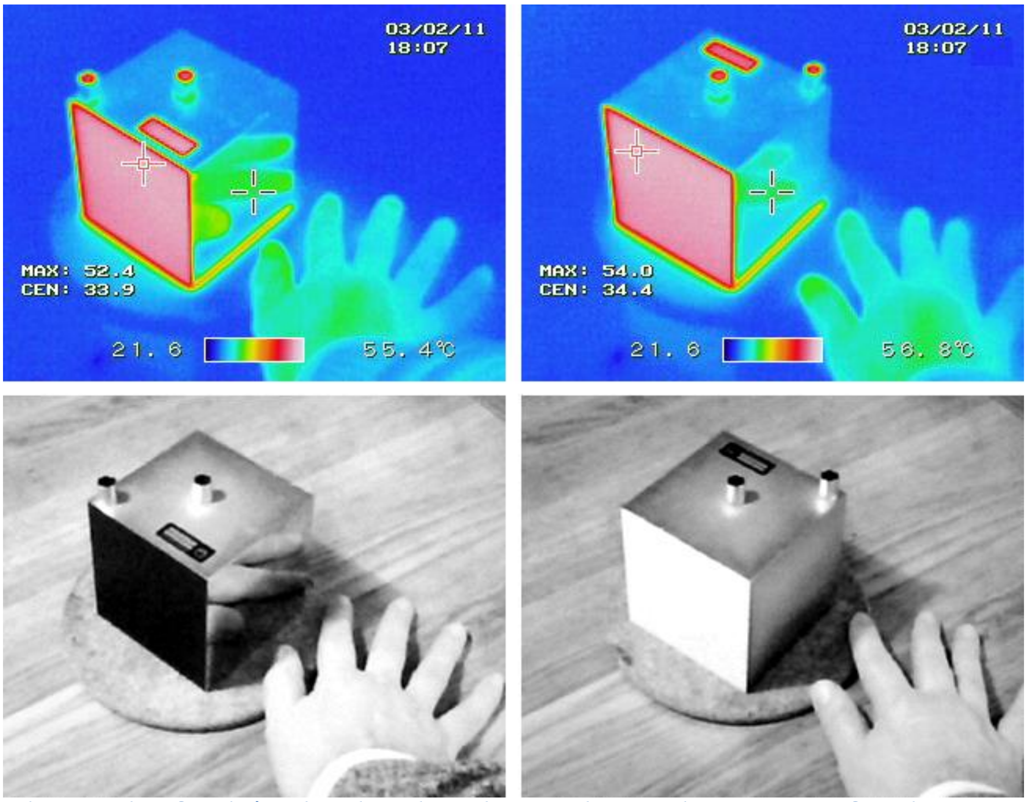

Figure 5: Photographs of Leslie's cube. The colour photographs are taken using an infrared camera; the black and white photographs underneath are taken with an ordinary camera. All faces of the cube are at the same temperature of about 55 °C. The face of the cube that has been painted has a large emissivity, which is indicated by the reddish colour in the infrared photograph. The polished face of the aluminium cube has a low emissivity indicated by the blue colour, and the reflected image of the warm hand is clear (Credit: Pieter Kuiper; https://commons.wikimedia.org/wiki/File:LesliesCube.png, public domain).

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 $\varepsilon(T)$.

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

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.

$$\Delta Q \propto \Delta T$$

Thought experiment

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

$$c = \frac{\Delta Q}{m \cdot \Delta T}$$

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:

$$[c] = 1 \frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{K}}$$

It is commonly listed in units of:

$$1 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}} = 1 \frac{\mathrm{J}}{\mathrm{g} \cdot \mathrm{K}}$$

With a value of $\mathrm{c_W} = 4.182 \frac{\mathrm{kJ}}{\mathrm{kg \cdot K}}$, water has a high specific heat capacity and thus is an excellent heat reservoir due to its simple and low priced availability.

Questions

We experience day and night and the different seasons. What causes the different temperatures associated with them?

How much of the Earth's surface is covered by water and how much by land (approximately)?

So, where does the insolation induce most of the heat?

The temperature changes between day and night in the deserts are very strong. Can you imagine why?

In comparison, how rapid does water respond to heating? Imagine a pot of water on a stove.

Activity

Materials needed:

- 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

This activity is part of a larger educational package called "Our Fragile Planet – The Climate Box". This box contains a collection of items that are needed to conduct the experiment (see pictures below).

Experimental set-up 1

Within this activity, you will measure the evolution of temperature of water and soil in time. You will be working in groups of two (or more). 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** **$\Delta\vartheta$ (°C)**
0			
1			
⋮			

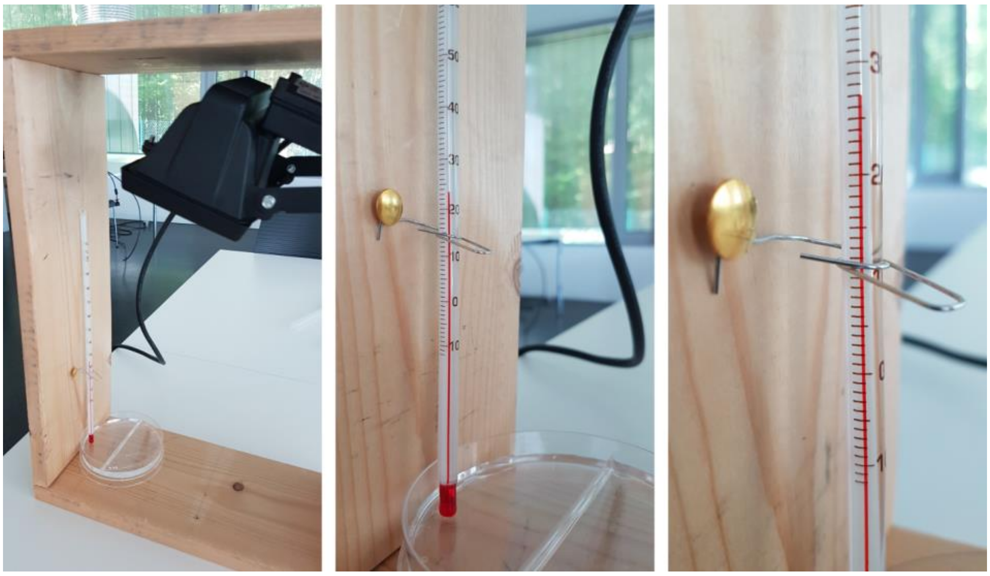

Figure 6: Experimental set-up for the temperature measurement of water. A petri dish is filled with water, and a thermometer is ready to measure the temperature. In order to maintain an upright position for the thermometer, it is attached to the frame with a pin and a paper clip. The lamp is set to illuminate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

Predictions

What do you think how the temperatures change after switching on the lamp?

After probing the water, you will use soil. Do you expect a different temperature response?

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.

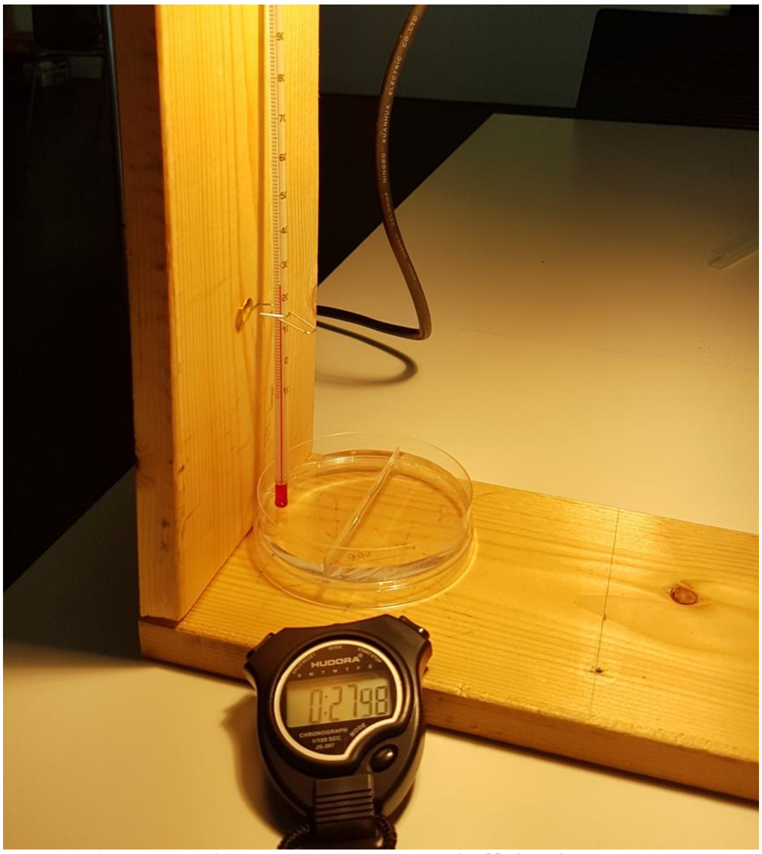

Figure 7: While illuminating the water, the temperature is read off the thermometer every minute (own work).

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 your 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).

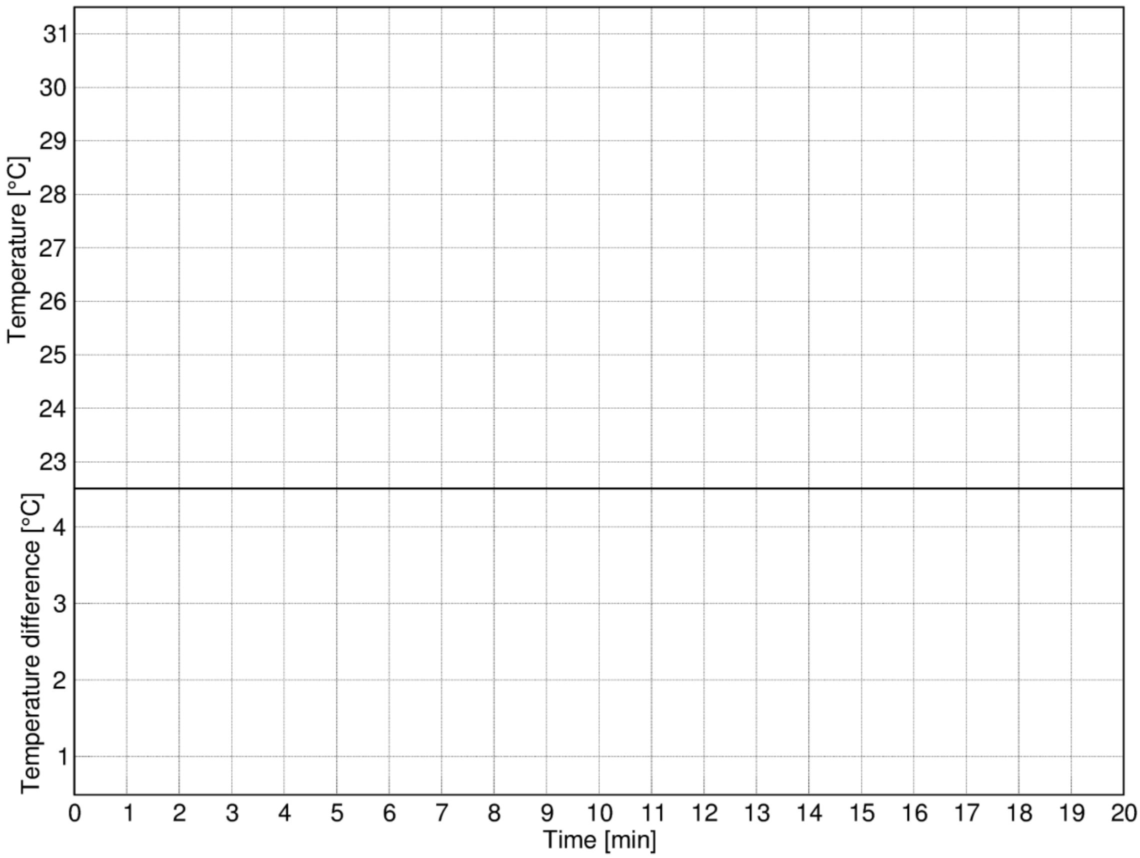

Figure 8: Template for the diagram to record the temperature measurements. The upper panel will contain the temporal evolution of the temperatures. The lower panel is reserved for plotting the difference between the two temperatures. Use different colours to represent the data (own work).

Experimental procedure 2

The procedure is the same as before.

- Take the first temperature measurement before switching on the lamp.
- Start the stop watch and switch on the lamp.
- For 10 minutes, take a measurement every minute and note down the value in corresponding column and line in the table.
- After 10 minutes, switch off the lamp and continue measuring the temperature as before.
- 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.

Conclusion

Describe and discuss the results with your group members or classmates. During the discussion, try to focus on the following questions.

How did the temperatures change while the lamp was switched on and off?

Do you recognise a difference between the two substances?

The temperatures rose differently. What is causing this? What changed between the experiments?

Imagine now the Earth with its oceans and continents. Describe how these components react to solar irradiation.

Can you determine the role the oceans have in the global climatic system? Think of what would happen with global temperatures without oceans.

What happens to the oceans, if the heating rate rises, while the cooling rate stays the same?