SPACE awareness

GLOBAL WARMING OF THE ATMOSPHERE

Discover how the surface of the earth heats the atmosphere

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Curriculum topic
Atmosphere, surface

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

Keywords
atmosphere, thermal radiation, warming, atmospheric windows, absorption, Copernicus, climate change

Age range
12 - 16

Education level
Middle School, Secondary School

Time
30min

Group size
Group

Supervised for safety
Unsupervised

Cost
Expensive (> 25 EUR)

Location
Indoors (small, e.g. classroom)

Core skills
Developing and using models, Planning and carrying out investigations, Analysing and interpreting data, Constructing explanations

Type of learning activity
Partial enquiry

BRIEF DESCRIPTION

A simple hands-on experiment that mimics the Earth's air-land system is used to demonstrate the heating rates of the air at different altitudes. The model is made of a transparent bottle with a blackened bottom and the bottleneck removed. The experiment simulates the thermal effects of solar radiation on the atmosphere and the land surface. The set-up is irradiated by a lamp for certain periods and the development of the temperature is measured with a thermometer. The students produce a diagram that illustrates how the atmosphere and the ground are affected by this and which of both heats faster.

GOALS

With this activity, the students learn:

- The Sun is the main heat source of the Earth.
- The atmosphere is mainly heated by infrared radiation re-emitted from the Earth's surface.
- Greenhouse gases interact with infrared radiation and contribute to additional warming of the atmosphere.
- Earth observation helps monitoring temperature evolution.
- How to carry out and analyse an experiment.

LEARNING OBJECTIVES

During the activity the students will be able to

- demonstrate that air next to a hot surface is heated stronger than air at higher altitudes.
- explain that Earth's atmosphere is effectively heated by the insolated surface.
- describe the effect of greenhouse gases to the temperature of the atmosphere.
- analyse a hands-on experiment that demonstrates how air is heated by radiation.

EVALUATION

The teacher can investigate the learning success by discussing the topics involved. The teacher can ask questions like:

- Imagine a sunny day in summer. What attains higher temperatures: the ground (asphalt, sand beach) or the air?
- When you fly in an airplane, is it usually colder or warmer outside than on the ground?
- A greenhouse is a transparent building in which one grows crops. Why does this work so well?
- Some gases in the atmosphere block heat from being released into space. They are called greenhouse gases. Why?
- How do you explain the different temperature readings you observed during the experiment?

MATERIALS

The tasks to be performed during the activity are best shared by two students per working group. For one experiment, the items needed are:

- Worksheet (one for each student)
- Strong lamp
- Stop watch
- Transparent container, higher than its diameter (e.g. transparent cup), dark bottom (e.g. black cardboard)
- 2 thermometers
- 2 paper clips
- Pen and paper
- Colour pencils
- Ruler
- Calculator

BACKGROUND INFORMATION

Global surface temperatures

A key phenomenon of the climate change we witness is the unusual speed of rising atmospheric temperatures. According to the latest climate models, we can expect atmospheric temperatures to rise above levels unprecedented for recent five million years (Figure 1).

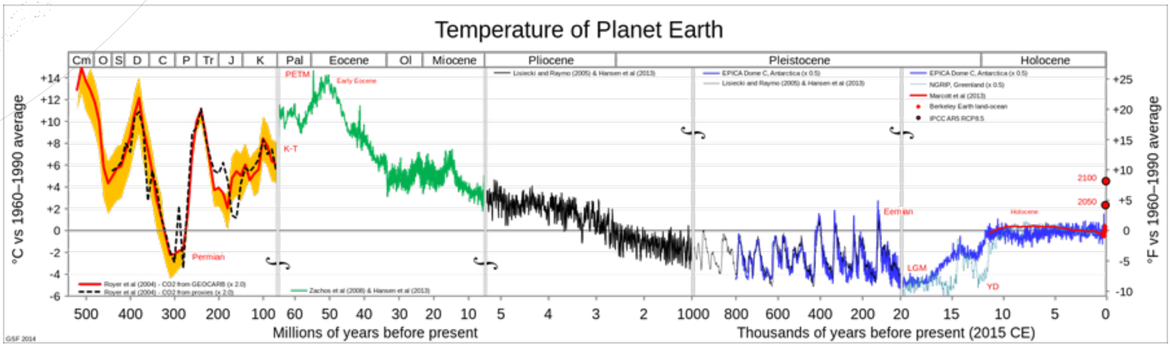

Figure 1: The viewgraph shows estimates of global average surface air temperature over the recent 540 million years since the first major proliferation of complex life forms on our planet. A substantial achievement of the last 30 years of climate science has been the production of a large set of actual measurements of temperature history (from physical proxies), replacing much of the earlier geological induction (i.e. informed guesses). The graph shows selected proxy temperature estimates (Credit: Glen Fergus, https://commons.wikimedia.org/wiki/File:All_palaeotemps.svg, "All palaeotemps", https://creativecommons.org/licenses/by-sa/3.0/legalcode).

Monitoring this quantity is one of the central objectives of the European Copernicus programme which uses ground based in situ measurements as well as satellite based remote sensing techniques. An example of what remote sensing can achieve is given in Figure 2, which provides a global map of the land surface temperature averaged over an entire month (March 2016). They have the advantage of being able to cover areas that cannot be probed by field measurements.

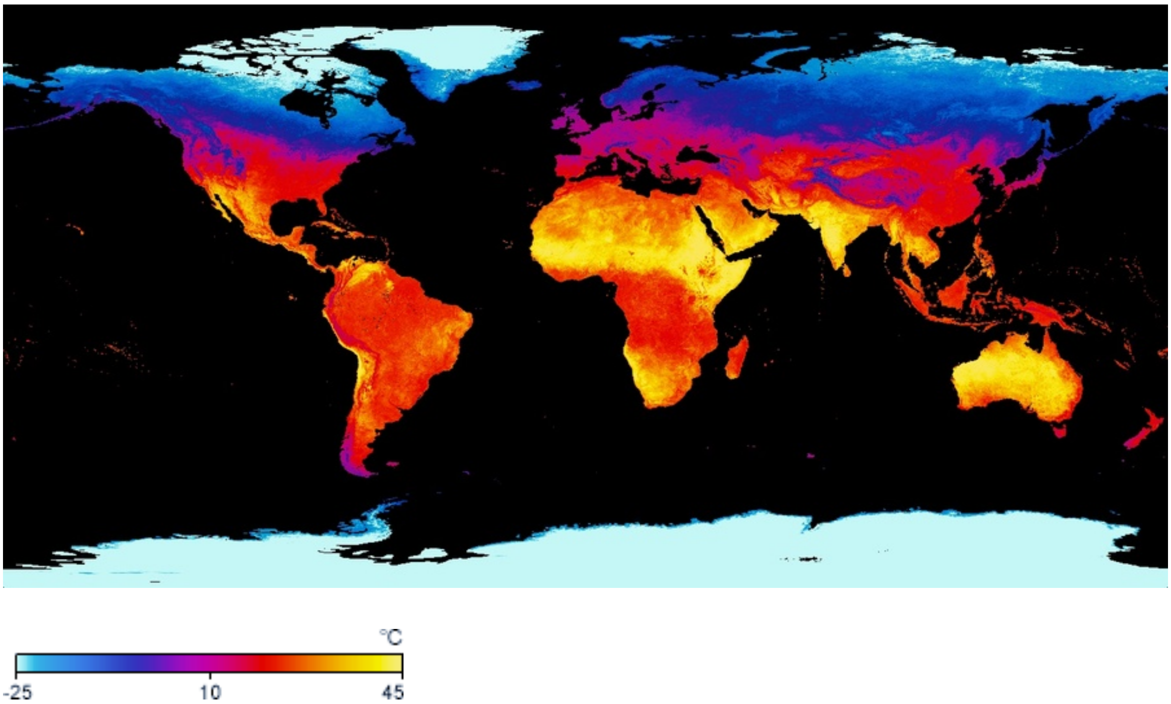

Figure 2: Averaged global land surface temperature map for March 2016 obtained with the

MODIS spectrograph on board NASA's Terra satellite of the EOS programme. The colour code indicates temperatures between -25°C and +45°C (Credit: NASA Near Earth Observations, http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD11C1_M_LSTDA).

In particular, the polar regions seem to be affected more strongly by warming than other regions (Figure 3). In order to model the energy budget and subsequently the temperature development from the past into the future, the processes of heating the land surface and the atmosphere must be determined on a global scale.

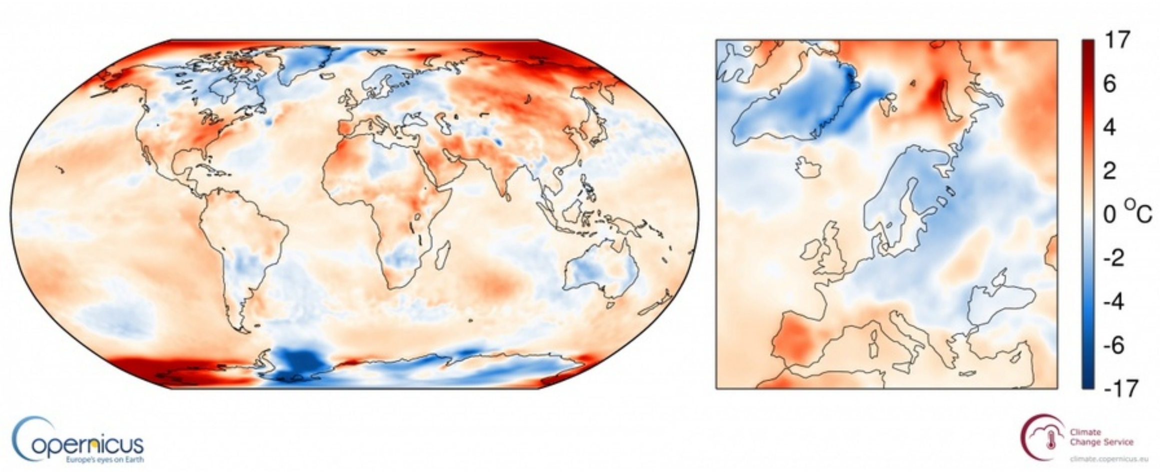

Figure 3: Surface air temperature anomaly for April 2017 relative to the April average for the period 1981-2010. (Source: ERA-Interim, credit: ECMWF, Copernicus Climate Change Service, https://climate.copernicus.eu/resources/data-analysis/average-surface-air-temperature-analysis/monthly-maps/april-2017)

Greenhouse gases

Air - to be more precise the molecules in the mix of gases which we call air – can only absorb light with a certain frequency or wavelength. These are the frequencies which cause the molecules of the air to vibrate (longitudinal and transverse oscillations). The following diagram shows the vibration modes of carbon dioxide:

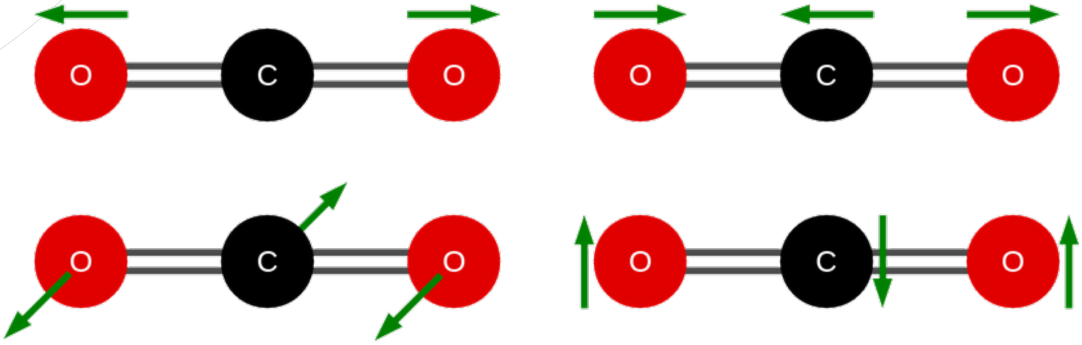

Figure 4: Basic vibrations realised as stretching (top) and bending (bottom) of the CO2 molecule (own work).

A molecule is called to be IR active, if the vibration modifies the dipole moment. Only molecules that exhibit an electric dipole moment can interact with the incident electromagnetic wave. Hence, the stretching mode to the top left in Figure 4 is IR inactive. Other oscillations modify the dipole moment and are therefore IR active. Generally, an excitation can also occur as a superposition of different vibrational modes.

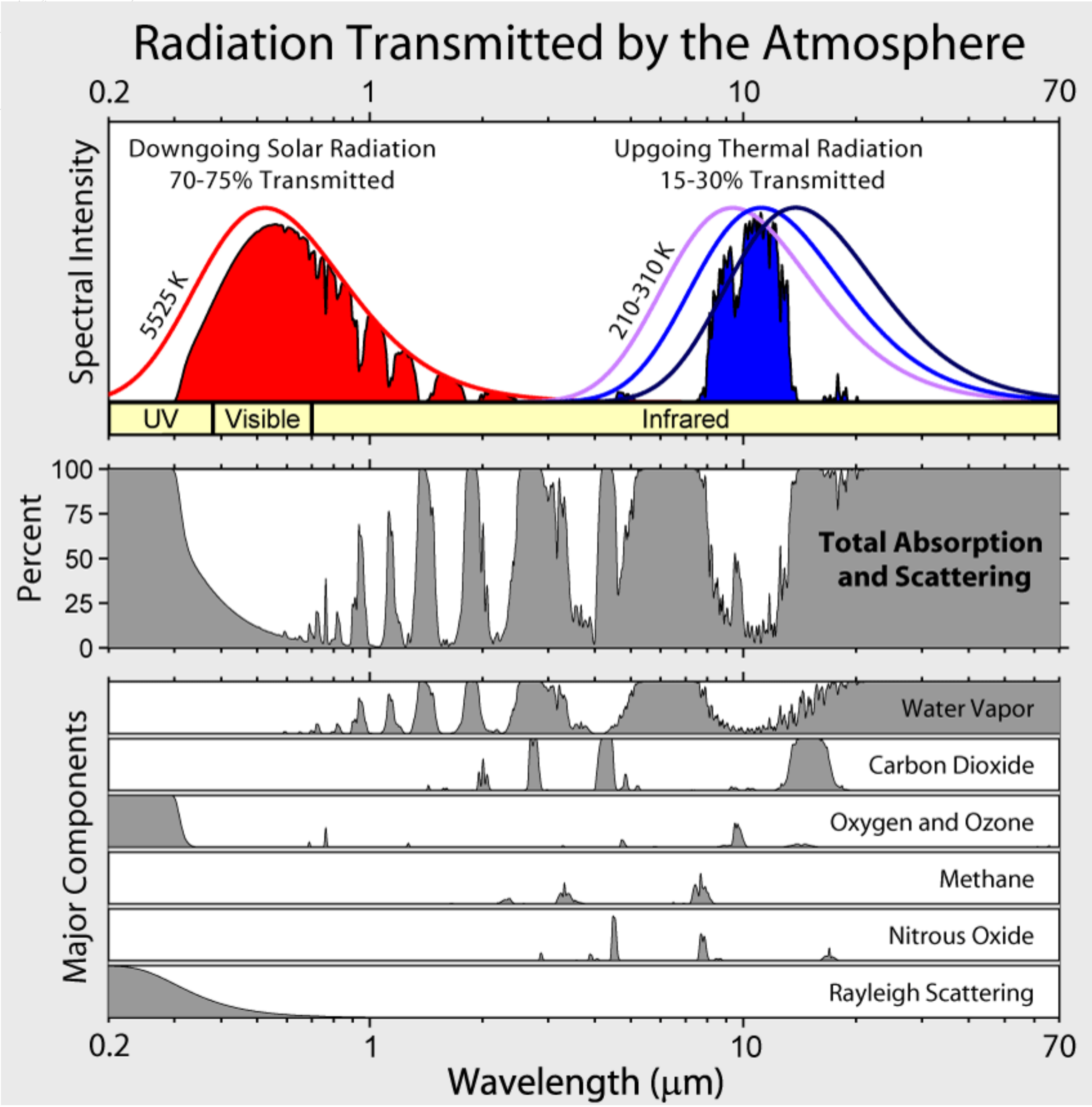

Figure 5: Absorption spectra of typical greenhouse gases and Rayleigh scattering at atmospheric aerosols (Credit: Robert A. Rohde, The Global Warming Art Project, https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.png, cropped, https://creativecommons.org/licenses/by-sa/3.0/legalcode).

Therefore, each atmospheric gas component only absorbs a part of the solar spectrum (Figure 5). The transmissivity of the atmosphere for a given wavelength is given in Figure 6. The cumulative effect on the atmospheric transmissivity is shown in Figure 6.

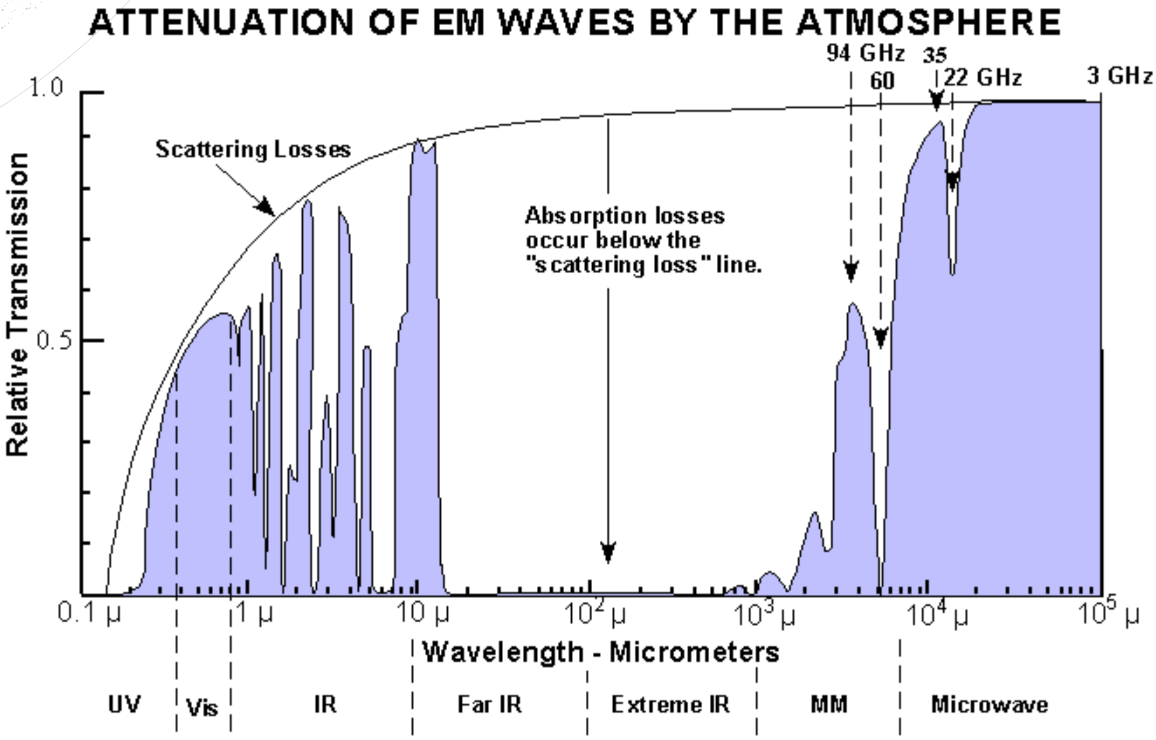

Figure 6: Relative atmospheric transmission (Credit: US Government, https://commons.wikimedia.org/wiki/File:Atmosph%C3%A4rische_Absorption.png, public domain).

The radiative energy budget of the Earth and the Greenhouse Effect

This means that air absorbs only a small part of the solar radiation directly. If it were different, the atmosphere would be quite opaque. The remaining radiation that hits the surface is partly absorbed and partly reflected. Figure 7 demonstrates that from the incoming solar radiation of 342 W/m^2 only 67 W/m^2 (20%) is directly absorbed by the atmosphere. From the remaining portion, 107 W/m^2 is reflected back into space. The surface absorbs 168 W/m^2, which is a factor of 2.5 more than what the atmosphere absorbs.

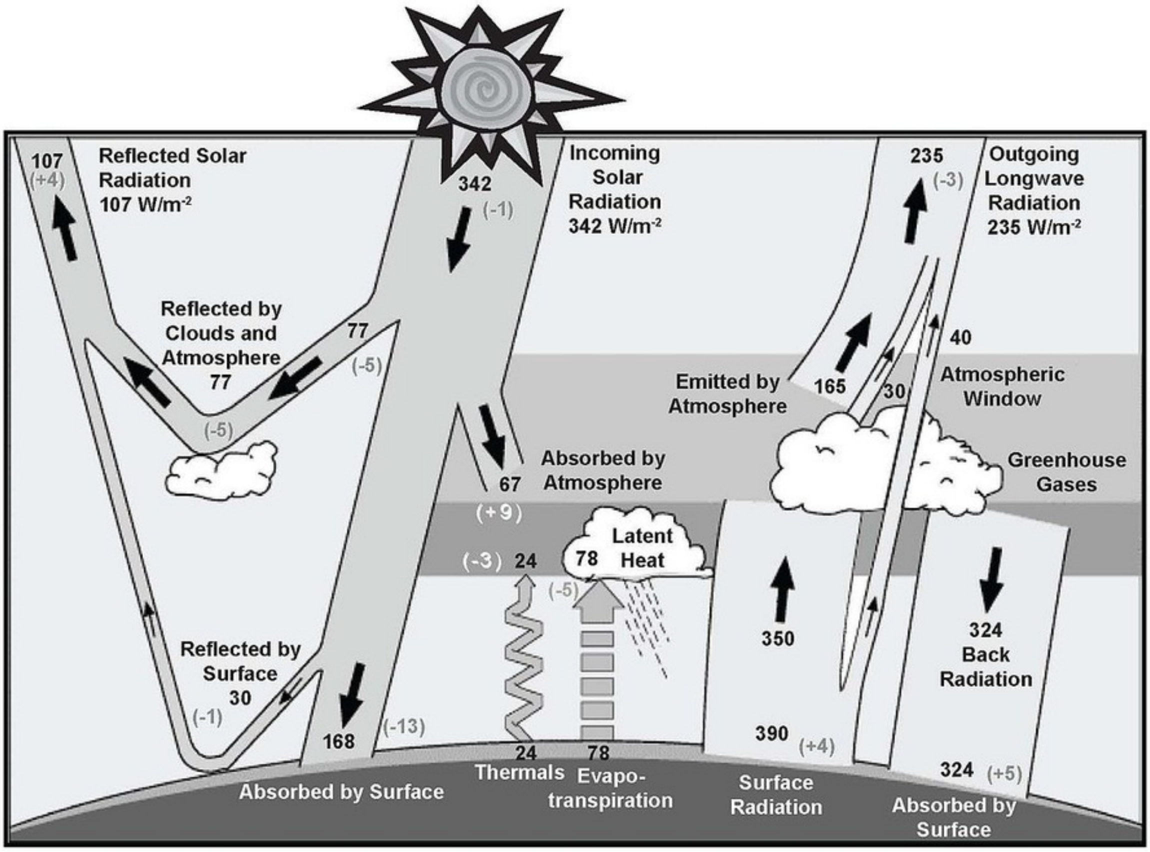

Figure 7: Radiation budget of the Earth (Credit: NASA, The Earth Observer. November - December 2006. Volume 18, Issue 6. page 38, after: Kiehl, J. T. and Trenberth, K. E. (1997). “Earth's Annual Global Mean Energy Budget”. Bulletin of the American Meteorological Association 78: 197-208, https://commons.wikimedia.org/wiki/File:Keihl_and_Trenberth_%281997%29SunClimateSystem.JPG, public domain).

This portion heats up the surface and is transformed into heat, i.e. IR radiation that is released into the atmosphere again. Without any atmosphere, this heat would be radiated into space. Since the Earth has an atmosphere, it is heated, and in particular close to the surface, where the heat is released. In addition, greenhouse gases are especially sensitive to IR radiation. They are excited into vibrational modes that store the energy for a small time period. When those modes decay, the IR radiation is released again, but this time in all directions, e.g. also towards the ground, and adds to the heating that is caused by the insolation directly. As a result, greenhouse gases effectively prevent parts of the heat released from the Earth’s surface from being radiated into space.

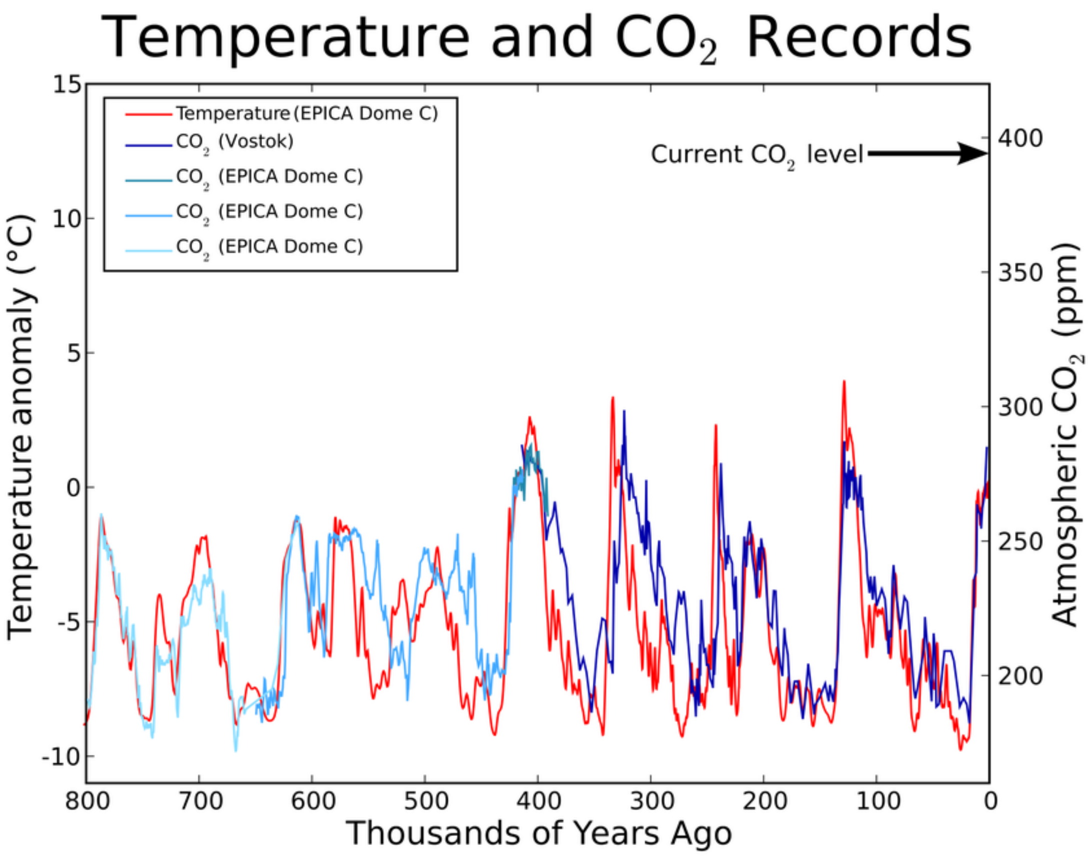

Figure 8: This figure shows historical carbon dioxide (right axis) and reconstructed temperature (as a difference from the mean temperature for the last 100 years) records based on Antarctic ice cores, providing data for the last 800,000 years. The indicated level of CO2 abundance in the atmosphere is obsolete and has passed the 400 ppm margin (Credit: Leyland McInnes, https://commons.wikimedia.org/wiki/File:Co2-temperature-records.svg, https://creativecommons.org/licenses/by-sa/3.0/legalcode).

Present day concentrations of carbon dioxide, a potent greenhouse gas, are already well above 400 ppm (parts per million, https://www.esrl.noaa.gov/gmd/ccgg/trends/) which is by far the highest value for the last 800,000 years (Figure 8).

As a consequence, any increase of the concentration of greenhouse gases inevitably leads to a rise of heat that remains inside the Earth's climatic system. Over time, this leads to an increase of temperatures of the surfaces, the atmosphere, and the oceans.

Solar contribution

Naturally, one might suspect other phenomena that contribute to the global warming like e.g. variations in the solar radiative power. The details of interaction between the solar radiative power with the Earth's atmosphere is quite complex (https://science.nasa.gov/science-news/science-at-nasa/2013/08jan_sunclimate). Nevertheless, the activity of the Sun, i.e. the number of sunspots, is usually understood as one driver of the variable solar luminosity. However, even if this contributes to the overall energy budget of the Earth, there is no observed correlation between the solar activity and the global temperature increase (Figure 9).

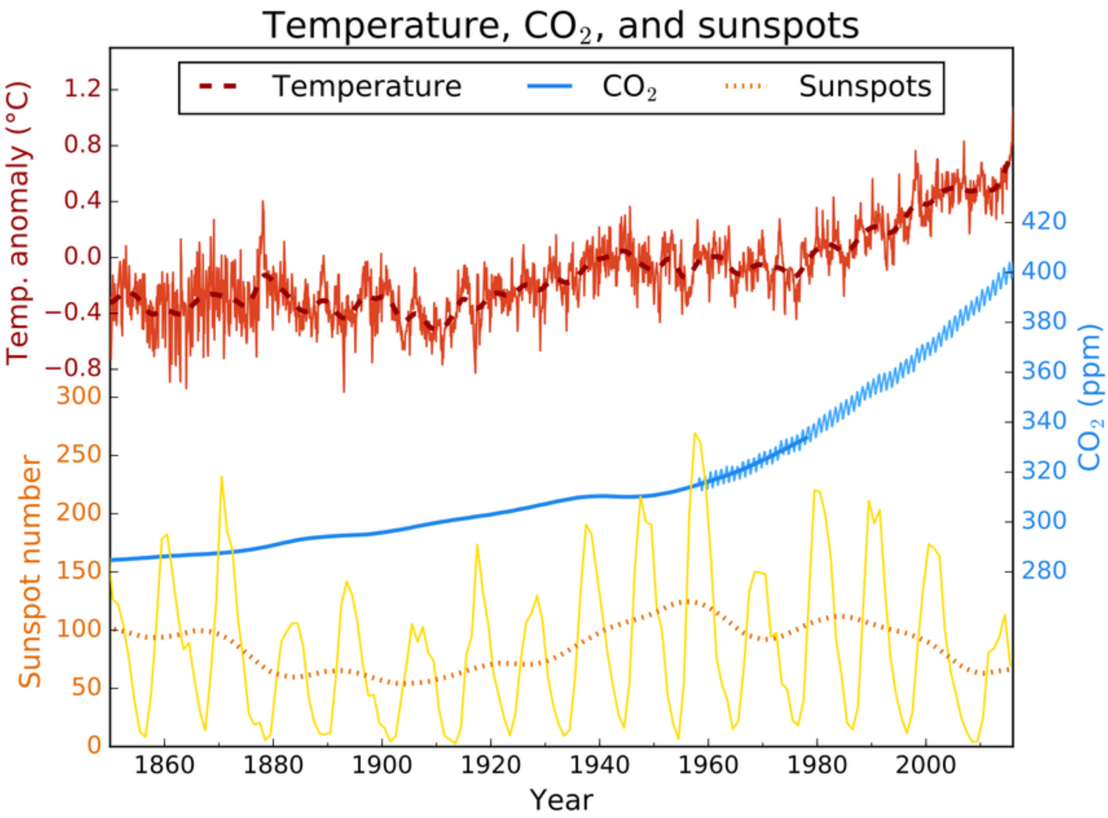

Figure 9: Correlation analysis of the contributions of the greenhouse gas carbon dioxide and the solar activity to the global increase of atmospheric temperatures (Credit: Adrien F. Vincent, https://commons.wikimedia.org/wiki/File:Mpl_example_temp_co2_sun.svg, https://creativecommons.org/licenses/by-sa/4.0/legalcode).

FULL ACTIVITY DESCRIPTION

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: Imagine a sunny day in summer. What attains higher temperatures: the ground (asphalt, sand beach) or the air?
A: Usually the ground is hotter than the air. The asphalt can melt. You can burn your feet when walking on hot sand.

Q: When you fly in an airplane, is it usually colder or warmer outside than on the ground?
A: The air temperature is lower at higher altitudes. The airplane windows are cold when you touch them.

Q: A greenhouse is a transparent building in which one grows crops. Why does this work so well?
A: Light gets in, but the heat and the heated air cannot escape. Therefore, greenhouses can grow crops at higher temperatures than the ones outside.

Q: Some gases in the atmosphere block heat from being released into space. They are called greenhouse gases. Why?
A: They have just the same effect as a greenhouse. The heat that normally would escape into space is trapped inside the atmosphere. As a result, it heats up.

With the students, discuss the following possible choices.

The atmosphere is heated by one of the following possibilities:

- Light passes the air without resistance and only warms up the ground.
  Would this be the case, only a few processes would be able to contribute to the temperature of the atmosphere. We would measure much lower temperatures than we do.
- Light is completely absorbed by the air and only warms up the air.
  Would this be the case, i.e. light being completely absorbed by the atmosphere, it would be completely opaque and no sunlight would hit the ground.
- Light is partly absorbed by the air and partly by the ground and warms-up both.
  Reality often happens to be a mixture of both extremes. With this experiment, we will demonstrate, whether the air or the ground absorbs the major part of the radiation.

Find arguments for and against the individual statements.

Activity: Warm air

Materials needed for a group of two:

- Worksheet (one for each student)
- Strong lamp
- Stop watch
- Transparent container, higher than its diameter (e.g. transparent cup), dark bottom (e.g. black cardboard)
- 2 thermometers
- 2 paper clips
- Pen and paper
- Colour pencils
- Ruler

- Calculator

Experimental set-up

It would be best, if students worked in groups of two to share responsibilities. They will measure the evolution of two temperature readings.

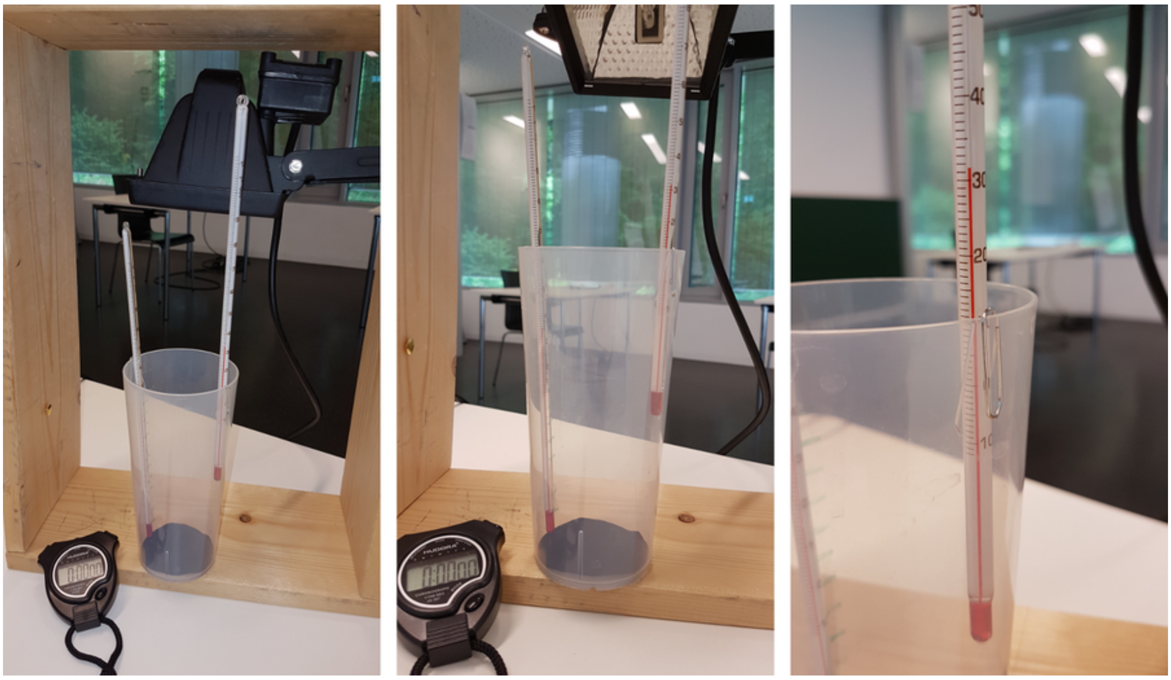

Figure 10: Experimental set-up (own work).

1. Put a piece of circular black cardboard at the bottom of the transparent cup.
2. Attach the two thermometers to the cup. You can use paper clips (see Figure 10). One thermometer should probe the temperature close to the bottom of the cup, while the other should be positioned to probe the air about half way between the bottom and the top.
3. Place the cup below the lamp so that the thermometers will be irradiated under a grazing angle. This will minimise direct heating.
4. Prepare a data table for filling in the measurements. It should allow for 11 lines of data and four columns (see Table 1).

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

Time t (min)	Bottom ϑ (°C)	Half way ϑ (°C)	Difference Δϑ (°C)
0			
1			
…			

Q: What do you think how the temperatures change after switching on the lamp?
A: The temperatures rise as long as the lamp is on.

Q: Do you expect a different temperature response between the bottom and the point half way between the bottom and the top of the cup?
A: The heating rates will be different, and the thermometer near the bottom of the cup will measure higher temperatures.

Experimental procedure

1. Take the first temperature measurement before switching on the lamp.
2. Switch on the lamp and start the stop watch.
3. Every minute, write down the temperatures (in parallel by the two students).
4. Continue for 10 minutes.
5. After 10 minutes, switch off the lamp.

Figure 11: While illuminated, the temperatures are read off the thermometers every minute

(own work).

Analysis

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

1. Prepare a diagram (e.g. Figure 12, 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 40°C.
2. Insert the data into the diagram. For each measurement, add a small cross at the coordinate that matches the time and the temperature. Use different colours for the two thermometers.
3. Connect the data points of the diagram
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 (e.g. Figure 12, lower panel).
6. Fill that diagram with the corresponding data

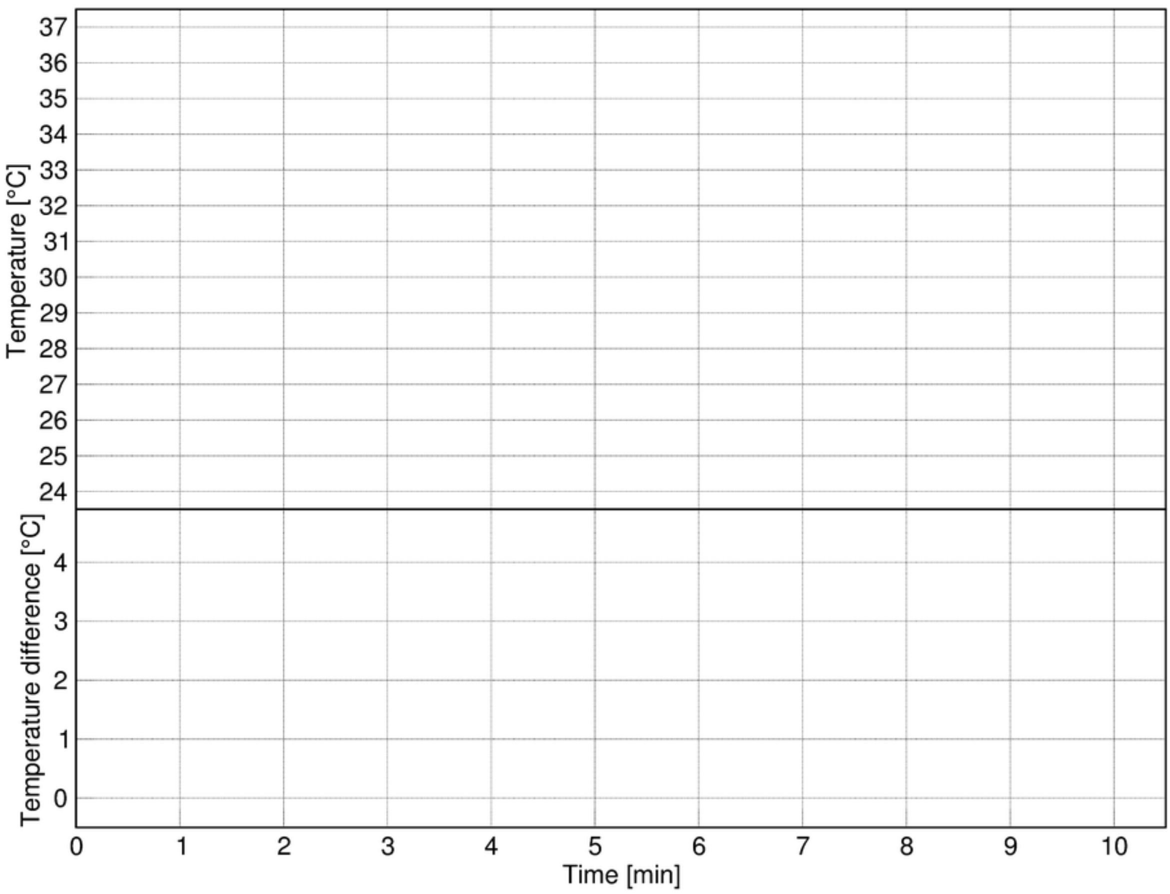

Figure 12: Template for the diagram to record the temperature measurements. The upper panel will contain the temporal evolution of the temperatures. The lower panel is reserved for plotting the difference between the two temperatures. Use different colours to represent the data (own work).

Q: Describe your observations. Did you notice a difference between the two temperature readings?
A: The temperature near the bottom rose faster and attained a higher value at the end. Perhaps, the students will also notice that the heating rate declined in time.

Conclusion

Q: Discuss the results with your classmates. Why are the two temperatures different?
A: Land absorbs the solar radiation better than air and thus warms up quicker. This again heats the air directly above.

Q: Can you explain why the heating rate declines during the measurement?
A: The air experiences a competition between heating and cooling. At some point, an equilibrium will be reached.

Q: Imagine the processes for the situation between the surface and the atmosphere. Which contribution heats the air more?
A: Transferring this conclusion to the Earth, this means that although the air can absorb part of the solar radiation directly, it is by far smaller than the part which is absorbed by the radiation emitted by the hot ground.

Q: Summarise the process how the lower atmospheric layers are heated.
A: The ground absorbs the major part of the solar radiation and warms up. The heat is emitted from the ground via infrared radiation which in turn heats the air more efficiently than direct light.

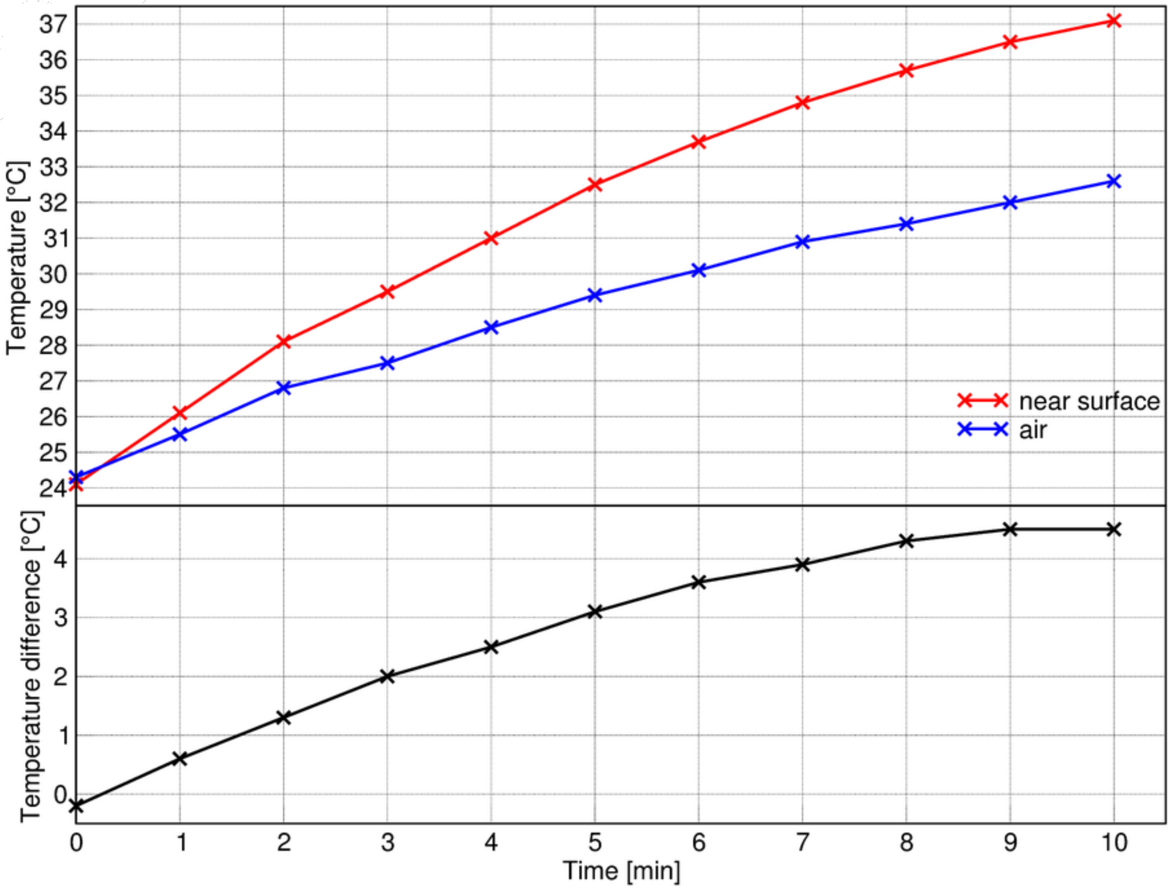

Figure 13: Example development of the temperatures of the air half way between the bottom and the top (blue) and just above the bottom (red) of the plastic cup. The black curve below depicts the evolution of the difference between the two temperatures (not revealed to the students in the worksheet, own work).

CURRICULUM

Space Awareness curricula topics (EU and South Africa)

Our fragile planet, Atmosphere, surface

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

- Composition and structure
- Atmosphere
- Climate change
- Surface
- Satellites

ADDITIONAL INFORMATION

This activity is part of a larger educational package called “Our Fragile Planet – The Climate Box”.

CONCLUSION

With this activity, the students will carry out a hands-on experiment that teaches them that air can only absorb part of the light for heating directly. Instead, the surface absorbs the major part and thus is heated more effectively. This in turn heats the atmospheric layers close to the surface.

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