Description of the experiment

Carbon dioxide in the climate system

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Motivation

Next to water vapour, carbon dioxide (CO_2) is the second most important greenhouse gas in the atmosphere. Carbon dioxide contributes about 30 % to the natural greenhouse effect on Earth. In the last decades, carbon dioxide has attracted particular attention due to climate change. Since the beginning of the industrialization, the carbon dioxide concentration in the atmosphere has continuously increased owing to the burning of fossil fuels such as coal, petrol and natural gas. Due to the associated amplification of the greenhouse effect, carbon dioxide is primarily responsible for the anthropogenic climate change. Additionally, the increased amount of carbon dioxide in the atmosphere is partially taken up by the oceans and leads to the acidification of the seas with severe consequences for the marine ecosystems.

The following experiments with the Monash Simple Climate Model (MSCM) can help to understand the effects of carbon dioxide on near-ground air temperature.

Model setup for the experiments

Depending on the user, the MSCM can be used in different levels of difficulty:

The standard version has 11 processes that can be switched on and off manually (see next page). However, some processes like diffusion or advection of water vapour and heat are not comprehensible for every user. Likewise, the term model correction is hard to grasp for non-professionals. Thus this version is rather suitable for advanced users (e.g. students or people with a strong background in climate physics).

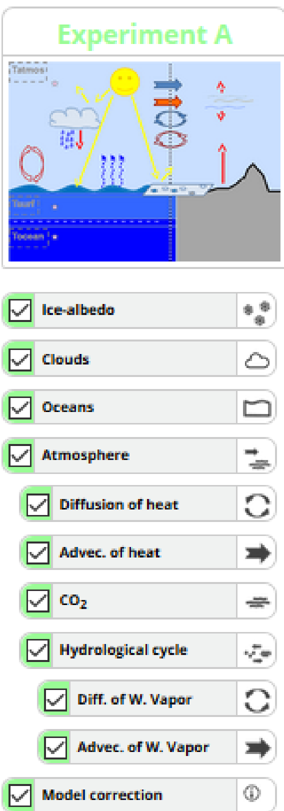
The basic version combines several processes from the standard version under one generic term so that the number of the processes that can be switched on and off reduces to 6 (see next page). The model correction, although not visible, is switched on, if the water cycle is switched on. This basic version is suitable for users without previous knowledge in climate physics.

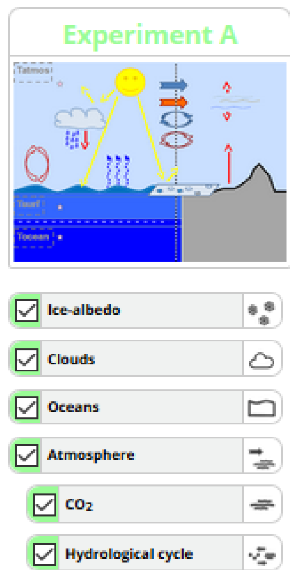
The experiments discussed here result in the same model performance for the standard as well as the basic version, because the processes not shown in the basic version are still incorporated in the model. Therefore, the experiments are outlined and explained only once in the section 'Model results and observations'.

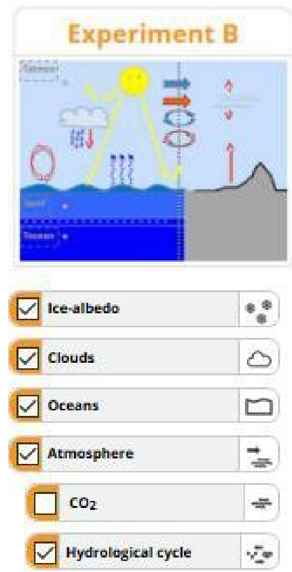
Processes switched ON in experiment A: **All processes**	Processes switched ON in experiment B: **All processes except 'CO_2'**

Following months will be compared:
January (Northern winter/ southern summer) and **July** (Northern summer/ southern winter)

Standardversion	Basic version

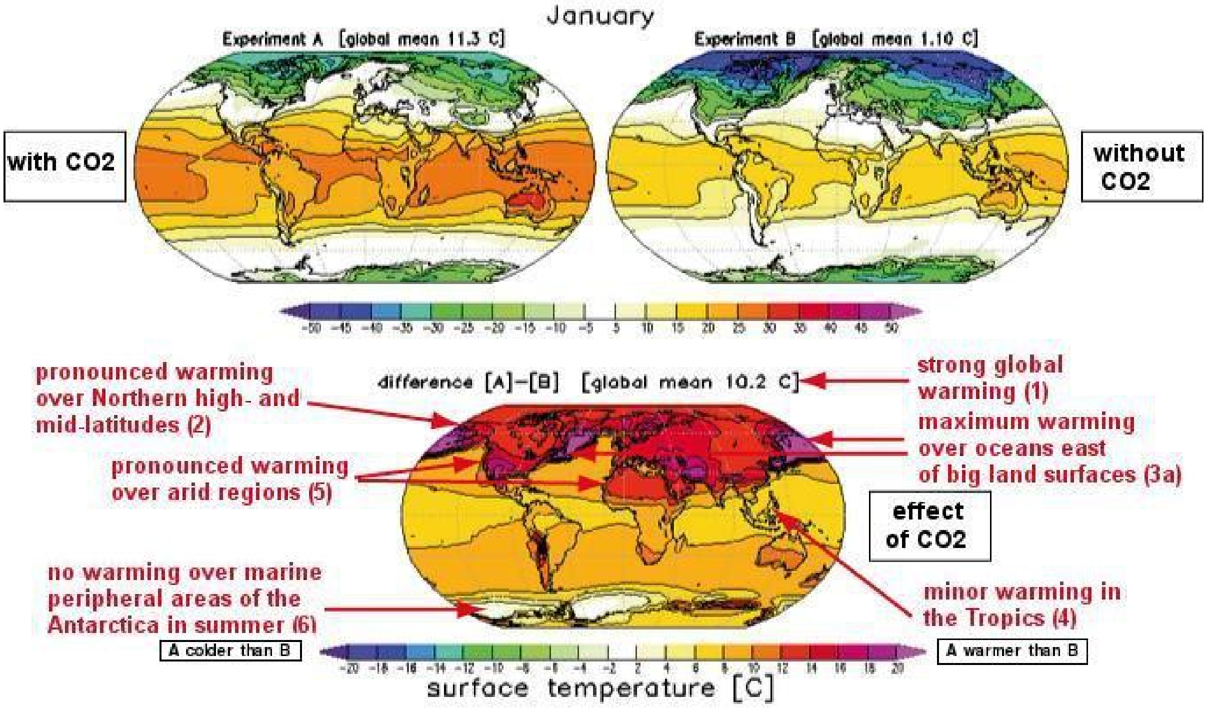




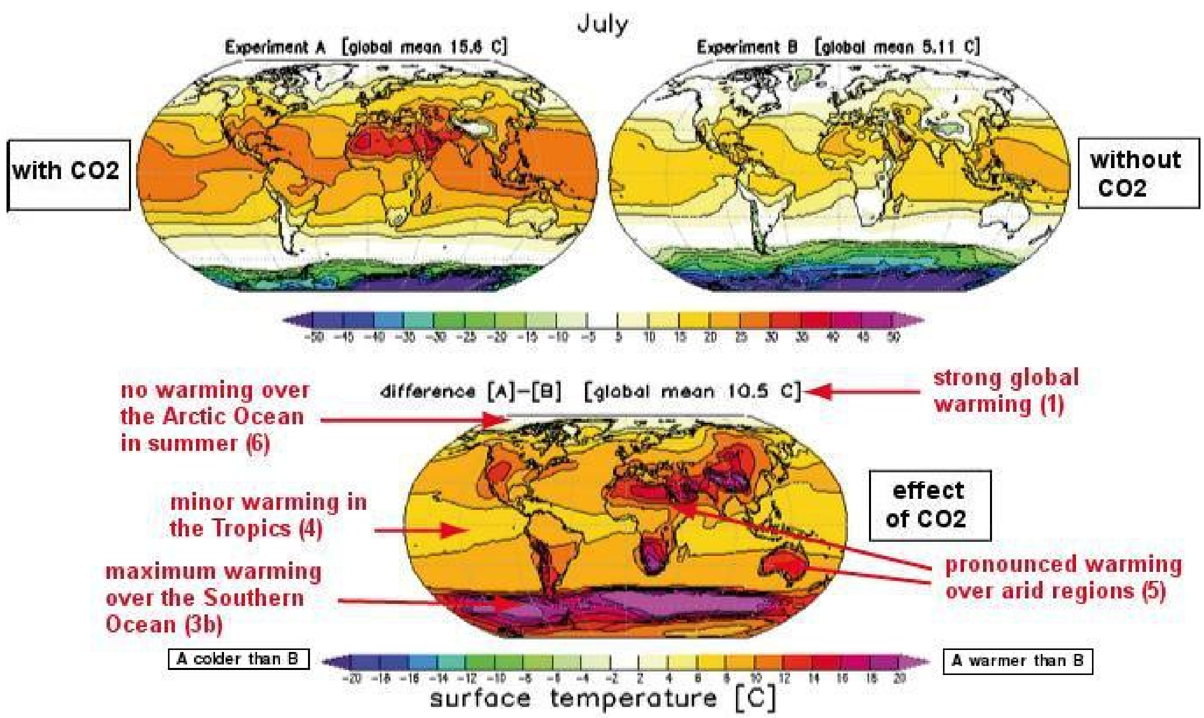


Model results and observations

JANUARY



JULY



Physical background and explanation of the model results

The long-lived greenhouse gas carbon dioxide is evenly distributed in the atmosphere. Without interactions with the other components of the climate system, the temperature on Earth **would increase homogeneously.** However, due to feedback mechanisms with other components of the climate system (primarily due to the ice-albedo and the water vapour feedback), the warming varies regionally, since ice and water vapour are distributed heterogeneously.
Due to the ice-albedo feedback, an increase in temperature caused by higher atmospheric CO_2-concentrations leads to a decrease in ice cover and thus to a declining albedo which in turn results in a higher absorption of radiation on the Earth's surface and an additional increase in temperature.
Due to the water vapour feedback, an increase in temperature leads to higher evaporation and a resulting increase in atmospheric water vapour concentration. Since water vapour is a greenhouse gas, this again leads to an increase in temperature.

Global observations

	Observation	Explanation
(1)	Global warming due to CO_2 (sign is positive).	Due to the greenhouse effect, carbon dioxide causes a global warming of about 10 °C. This is approximately equivalent to half of the greenhouse effect of atmospheric water vapour. This warming does not only result from the direct effect of CO_2 on radiation, but from feedbacks with ice and snow cover as well as with water vapour.

Regional observations

	Observation	Explanation
(2)	Pronounced warming due to CO_2 in the high and mid-latitudes in boreal winter.	1. Without CO_2, large ice- and snow covered areas would form in the high and mid-latitudes of the Northern Hemisphere. As a result, the temperature would drop below the freezing point. In experiment A, CO_2 warms the atmosphere so that ice- and snow-covered areas melt to a huge extent, resulting in a lower albedo and thus in an increasing warming of the atmosphere (ice-snow-albedo-effect). Due to the large land surfaces, this effect is more pronounced in northern than in the southern winter. 2. In addition, the water vapour feedback comes into effect: The atmosphere, already warmed by atmospheric CO_2 and the ice-albedo-feedback, can take up more water vapour, which results in an additional warming of the atmosphere.
(3 a	Maximum warming in	Over the oceans east of the large land masses in the Northern

+ b)	Northern Hemisphere winter due to CO_2 above the ocean eastern of big land surfaces in Northern Hemisphere. In Southern Hemisphere winter maximum warming over the Southern Ocean all around the Antarctica.	Hemisphere, masses of cold air would lead to a formation of big sea ice areas without CO_2. Due to the ice-albedo-feedback, these air masses would cool even further. With CO_2, the ice-free ocean can take up more radiation and release more heat to the atmosphere. Similarly, without the greenhouse effect of CO_2, the sea ice around the Antarctica would extend further north. Similar to 3a, the sea-ice-albedo-feedback would start to take effect.
(4)	Relatively low warming in the Tropics due to CO_2.	Compared to the greenhouse effect due to the high water vapour concentration in the Tropics, the greenhouse effect due to CO_2 is mild. Water vapour and CO_2 absorb thermal radiation to some extent on the same wavelengths (see Figure 1). The fraction of radiation already absorbed by water vapour in those wavelength-ranges cannot be absorbed by CO_2 anymore. Hence, the greenhouse effect of CO_2 is considerably lower in areas with high atmospheric water vapour.

Additional figures

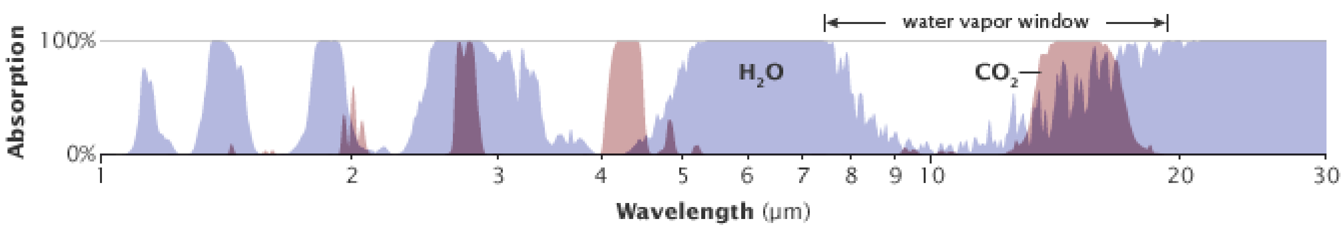


Figure 1: Absorption patterns of carbon dioxide (red) and water vapour (blue). Source: NASA Earth Observatory: Climate Forcings and Global Warming. http://earthobservatory.nasa.gov/Features/EnergyBalance/page7.php

Helpful articles to work on the exercises:

Article	Topic
Carbon cycle	The global carbon cycle
Carbon dioxide projections	Future changes in carbon dioxide concentrations
Observed carbon dioxide values	Observed values for carbon dioxide from Mauna Loa