SCIENCE FOR THE CLASSROOM

geomax

Issue 22 // Autumn 2017

The sixth element –

how scientists search for carbon

It was a spectacular experiment: In September 1991, four women and four men were locked into a gigantic glass dome structure in the Arizona desert. On an area about the size of two football fields, it enclosed a rain forest, a desert, a savannah, a marsh landscape, an ocean, fields and a residential area. The researchers aimed to spend two years in this artificial ecosystem, known as BIOSPHERE II – without outside air or food from outside. However, it wasn't to be. In contrast to calculations, the air in the high-tech glasshouse became thinner after only a few weeks. Oxygen input was necessary. Despite this, animals and plants gradually died. Ants and cockroaches, on the other hand, became a plague. After exactly two years and twenty minutes, the crew exited, exhausted and quarrelsome. The 200-million-dollar project had failed.

One reason for the failure was that natural interactions and vital cycles such as the oxygen and the **carbon cycle** were given insufficient consideration. At the Max Planck Institute for Biogeochemistry in Jena, scientists from various disciplines conduct research into just these substance cycles between Earth's surface, the atmosphere and the oceans. They are attempting to discover where, and to what extent, the different substances are stored and how substance fluxes are controlled. They simulate these processes on the computer. The principal question is: What influence do humans have on natural cycles and what are the consequences?

More than 7.55 billion people currently live on Earth (July 2017). On average, another 2 to 3 are added every second. More than half of the land area has already been modified by humans, with grave consequences for natural vegetation and biodiversity, the nature of soils and global substance cycles, such as that of carbon.

In nature, carbon in the form of **carbon dioxide** (CO_2) is in a constant state of exchange between the atmosphere, the hydrosphere (water and ice), the lithosphere (rocks) and the biosphere (flora and fauna) **(Fig. A)**. Some regions or ecosystems emit more CO_2 to the atmosphere than they absorb (**CO_2 sources**). Others, in contrast, store CO_2 by fixing it in the form of different carbon compounds (**CO_2 sinks**). Under natural conditions, global absorption and emission processes are nearly balanced. However, humans are destroying this equilibrium, predominantly by the combustion of coal, oil and gas. This releases enormous quantities of CO_2, previously stored in rocks over millions of years. Around 45 percent of these anthropogenic CO_2 emissions remain in the atmosphere, the rest is reabsorbed by the oceans and land biosphere.

The oceans play a central role here, particularly due to the good solubility of CO_2 in water. However, the capacity of the oceans declines with the increase of atmospheric CO_2 concentration. In addition, researchers are registering grave changes in aquatic chemistry: part of the dissolved CO_2 reacts to form carbonic acid, lowering the water's pH – the oceans are acidified. The pH of surface waters has already fallen from 8.2 to 8.1 as a result of CO_2 emissions. On the logarithmic pH scale, this means that water has become 30 percent more acid. **Ocean acidification** impairs calcium carbonate formation and results in the shells and skeletons of marine animals such as mussels, gastropods or corals literally dissolving.

Another part of the CO_2 in the oceans is fixed by marine plankton. When these creatures die, the organic material sinks to the sea floor, taking the carbon compounds with it. Around 25 percent of the carbon absorbed in the upper ocean because of photosynthesis sinks into the depths in this way – a process referred to as the **'biological pump'** by scientists. A small proportion is integrated in sediments, the rest is reconverted into dissolved inorganic carbon by decomposition processes and returns to the surface in rising water.

The largest carbon sink besides the oceans is the land biosphere. Plants fix large quantities of CO_2 by photosynthesis. The CO_2 returns to the atmosphere through respiration and the nutrient cycle between plants, animals and soil organisms, and does this considerably faster than in the marine carbon cycle. Enormous quantities of CO_2 are also released by fire, in particular slash-and-burn (see GEOMAX 3). Important CO_2 stores are simultaneously lost due to the continuing destruction of forests.

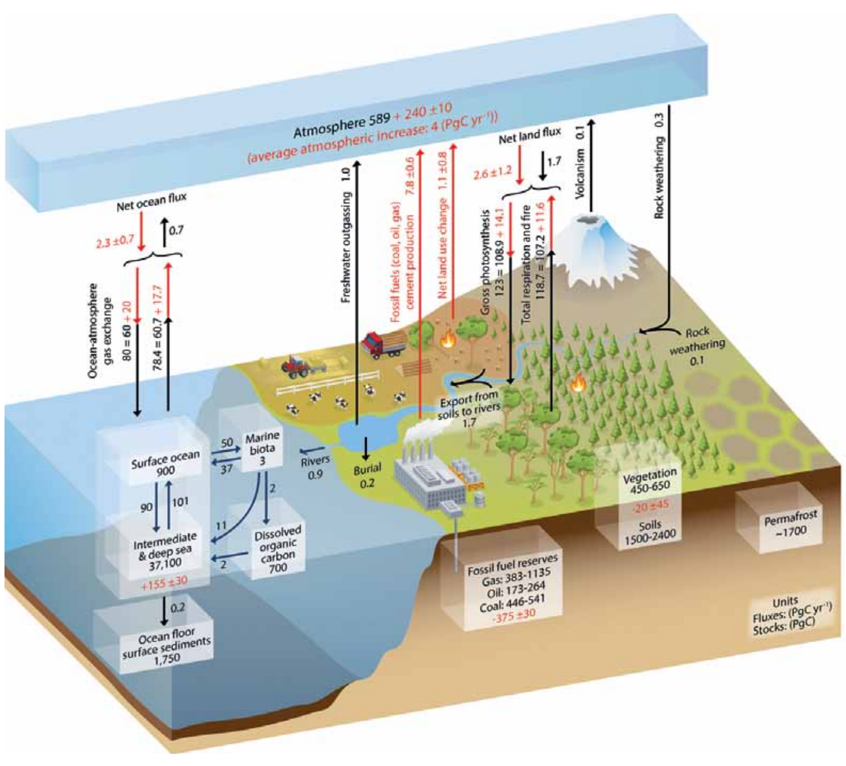
THE HUMAN FACTOR

CO_2 plays a decisive role for the global climate: Together with other trace gases and water vapour, it forms a layer in the troposphere allowing incident sunlight to pass through and keeping long-wave heat radiation on the Earth. Without this **natural greenhouse effect**, the average temperature on Earth would be a mere minus 18 °C instead of the current 15 °C. The **anthropogenic**, i.e. man-made **greenhouse effect**, in contrast, means that the Earth is getting warmer and warmer. In addition to CO_2, methane (CH_4) and dinitrogen oxide (N_2O) primarily contribute to this.

The concentration of CO_2 in the atmosphere has increased by more than a third since industrialization began, from 280 ppm (parts per million) to just over 400 ppm **Fig. B)**. The observed global temperatures of land and sea surfaces increased by 0.85 °C between 1880 and 2012. According to the scenarios investigated by the Intergovernmental Panel on Climate Change (IPCC), which range from strict climate protection to unhindered greenhouse gas emissions, the mean global surface temperature may increase by 0.9 to 5.4 °C by the end of this century compared to the pre-industrial age.

The consequences of **climate warming** can already be felt today: glaciers and the ice at the poles are melting, permafrost soils are thawing. The mean global sea level rose by approximately 19 cm between 1901 and 2010. Changes in extreme weather and climate events have been noted since 1950: cold temperature extremes are getting fewer, hot extremes are increasing. Unusually high sea levels or extreme precipitation are also becoming more frequent. Researchers, including those at the Max Planck Institute

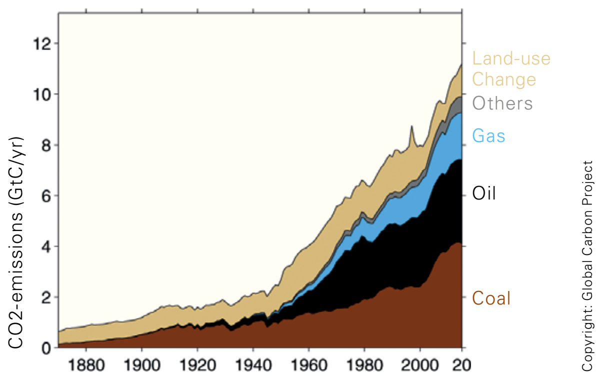
Fig. A: The global carbon cycle



The figures give the amount of stored carbon and the annual fluxes, measured in gigatonnes (Gt = billion tonnes). Black figures and arrows represent the pre-industrial era (around 1750), red represents anthropogenic fluxes (mean for the period 2000 to 2009). The figures in red in the carbon stores represent the total man-made changes during the industrial age (1750-2011). The illustration shows how much humans alter the global balance: the carbon content of the atmosphere is currently increasing by around 4 Gt per year.

1 Pg (petagram) ≙ 10^{15} grams
≙ 1 gigatonne ≙ 1 billion tonnes

Fig. B: Global CO_2 emissions



Until around 1950, land use changes were the primary cause of increasing atmospheric CO_2. Since then it has been the combustion of coal, oil and gas. Today, fossil fuels deliver more than 85% of global energy demand. This continues to increase rapidly. "Others" primarily includes all cement production emissions and those caused by flaring of unused gases.

for Chemistry, have calculated that many regions of North Africa and the Middle East may become uninhabitable as a result of extreme heat from 2050 onwards. Parts of Bangladesh or the Pacific island state of Kiribati, on the other hand, will be inundated in the foreseeable future. The number of **climate refugees** will therefore increase dramatically in future.

HAGGLING OVER THE GLOBAL CLIMATE

At the end of 2015, 195 states signed the **Paris climate accord**. To avert the worst consequences of climate change, global warming is to be limited to considerably less than 2 °C, if possible less than 1.5 °C. To achieve this, countries have undertaken to reduce net emissions of greenhouse gases to zero in the second half of the century. This means that only as much greenhouse gas may enter the atmosphere as is simultaneously removed – for example by tree planting. This would make the use of fossil fuels almost impossible.

The Paris Agreement is regarded as a milestone in the fight against global warming – only three countries are not participating: Syria, Nicaragua – and following the inauguration of the new President, Donald Trump, also the USA. The greatest problem with the Paris Agreement is that it is not legally binding, but is instead based on voluntary implementation in the individual countries. Only in this way was it possible to have as many countries around the globe as possible recognize the climate agreement. Each country therefore decides on its own contribution. However, national climate protection planning so far is not even remotely sufficient to limit global warming to 1.5 degrees.

Because CO_2 persists in the atmosphere for many millennia and warms the climate, previous emissions since the beginning of industrialisation also need to be considered. To still maintain a moderate probability of achieving the 2-degree target, only a maximum of around 760 billion tonnes (gigatonnes, Gt) of CO_2 may be emitted into the atmosphere between 2017 and 2100 (as of 1 Jan. 2017). The world currently emits around 40 Gt CO_2 annually – 1268 tonnes per second! The 1.5-degree target already appears utopian: according to a study in which the Max Planck Institute for Meteorology was involved, Earth will heat up by 1.1 °C by the end of the century, even if all emissions were abruptly stopped in 2017. At the current rate of emissions, it will be around another 15 to 30 years until the risk of exceeding the 1.5-degree target reaches a fifty percent probability of occurrence.

SCIENTISTS SEARCHING FOR CARBON

To facilitate climate forecasts and effective climate protection measures it is important to know how much CO_2 is released or 'disappears'. The team led by Julia Marshall, Research Group Leader at the Max Planck Institute for Biogeochemistry in Jena, therefore analyse the current spatial and temporal CO_2 exchange between the Earth's surface and the atmosphere: the CO_2 fluxes. They vary from year to year, region to region and from summer to winter. These fluctuations arise because natural carbon exchange processes, for example photosynthesis, the decay of organic substances in the soil or the dissolution and conversion of CO_2 in seawater, are affected by temperature and numerous other environmental factors.

In order identify the effects of the various factors, the researchers simulate actual processes with the aid of highly complex computer models. They incorporate both existing knowledge of the processes and their uncertainties. Field data from two different sources form the basis for the analyses: ground-based monitoring stations are capable of directly recording the concentrations of trace gases such as CO_2 **(Fig. C)**. They are operated by several international institutions, among them the Max Planck Institutes for Biogeochemistry and Chemistry. The fact that the stations are irregularly distributed around the globe and only deliver few data from climatically relevant regions such as the tropics or Siberia is problematic.

Satellite sensors deliver much better data coverage. The measuring principle is based on carbon dioxide's capacity to absorb reflected sunlight at specific wavelengths. The sensors can thus determine the total proportion of CO_2 molecules in the air column between the satellite and Earth's surface. If this proportion of CO_2 is divided by the number of air molecules in the column, we arrive at the column-integrated concentration for carbon dioxide, XCO_2.

The first satellite sensor capable of measuring greenhouse gases such as carbon dioxide and methane near the Earth's surface at high-resolution was SCIAMACHY *(SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY)*. It operated between 2002 and 2012 on the European environmental satellite ENVISAT. Its measurements led to a new understanding of methane sources, but also displayed systematic errors and uncertainties in the XCO_2 measurements. This made data analysis more difficult, especially considering that independent measurements to facilitate validation were not available. The Japanese satellite GOSAT *(Greenhouse Gases Observing Satellite)* has been registering XCO_2 and XCH_4 (methane) with substantially less measurement uncertainty since 2009; in addition, the NASA satellite OCO-2 *(Orbiting Carbon Observatory 2)* has

Fig. C Climate research at a loft height

© MPI für Biogeochemie/Michael Hilscher

Some the ground-based monitoring stations are located on high towers, such as ZOTTO *(Zotino Tall Tower Observatory)*, shown here, in the Siberian taiga. At 304 metres, its steel structure is almost as tall as the Eiffel Tower. Here, the precision instruments used to monitor carbon dioxide, methane and other greenhouse gases reach air layers free of local influences. This allows conclusions on climate processes in much larger regions to be drawn. ZOTTO has been operating since 2006 and is operated by the Max Planck Society together with Russian partners.

been measuring XCO_2 at an even greater spatial resolution since 2014. A disadvantage of the satellite sensors is that clouds and darkness limit the monitoring period over the whole year, returning considerably fewer measurements in winter at higher latitudes.

TROUBLESHOOTING CLIMATE DETECTIVES

The Max Planck researchers have already generated a wealth of data with both monitoring methods. However, interpretation of the data is anything but simple: for example, if one compares the satellite-based CO_2 flux estimates (GOSAT fluxes) with those based on ground-based network measurements (flux network measurements), significant differences result. “The GOSAT fluxes indicate that the tropics represent a large CO_2 source for the atmosphere, in contrast to the flux network measurements. In comparison, the temperate northern latitudes absorb substantially more CO_2 from the atmosphere”, explains Julia Marshall.

How do these differences come about? Interestingly, the ground- and satellite-based flux estimates begin to converge if only satellite monitoring data recorded within a defined distance to the ground-based monitoring station are incorporated in the analyses. That is, the discrepancies are obviously the result of the differing spatial data coverage. Experimental analyses confirm this. They revealed that the sparsely distributed ground-based monitoring stations cannot reflect the true spatial distribution of the CO_2 fluxes. This speaks for the reliability of the GOSAT measurements.

Researchers are currently collecting independent reference measurements to validate the GOSAT fluxes. The data originate from remote sensing and airborne missions, including HALO (*High Altitude and Long Range Research Aircraft)*, in which the Max Planck Institutes for Biogeochemistry, Chemistry and Meteorology participate. Here too, however, the results must be probed for possible error sources. Because remote sensing data can only be acquired by satellite in cloud-free conditions, scientists are investigating whether this can lead to distortions in the calculated CO_2 fluxes: “When the Sun shines, the vegetation at our latitudes absorbs more CO_2 through photosynthesis than if the skies are cloudy. The reverse is often the case in the tropics”, says Julia Marshall. The researchers test how this affects the analyses in complex simulations. The Jena-based researchers also support the development of new satellite missions, for example the Franco-German mission MERLIN *(Methane Remote Sensing LIDAR Mission)*, scheduled to start in 2021 and aimed at monitoring atmospheric methane. Beginning in 2025, several ESA satellite launches are planned as part of the Copernicus Earth observation programme, to record atmospheric CO_2 at even greater resolution. In future, for example, climate researchers aim to detect anthropogenic CO_2 sources in this way.

Key words

Carbon cycle, carbon dioxide, global warming, greenhouse gas, natural/anthropogenic greenhouse effect, CO2 sources, CO2 sinks, ocean acidification, biological pump, Paris Agreement

Recommended reading

Mojib Latif, Klima, Fischer Kompakt 2015

Recommended links

The time window for the 1.5-degree target is closing: www.mpg.de/11431699

My contribution to Arctic sea ice melt: www.mpg.de/10817029

Climate-exodus expected in the Middle East and North Africa: www.mpg.de/10481936

Max-Planck-Gesellschaft, Communication Department | e-mail: presse@gv.mpg.de | Editing: Dr. Christina Beck | Text: Dr. Elke Maier | Art direction: www.haak-nakat.de