Lower Atmosphere

Basics

Unit 2
The greenhouse effect, light and the biosphere

When we speak about climate, most people think about global warming. And if we speak about global warming, most of us think about the greenhouse effect. The greenhouse effect is actually a naturally occurring process which has been affected by human activity.

1. greenhouse effect

Without the greenhouse effect, life wouldn't be possible on Earth.

2. greenhouse effect

The energy driving our climate comes from the Sun. In the first part of this unit we look at what happens to the solar energy as it passes through the atmosphere, as it hits clouds and when it reaches the surface of the Earth. We look at how this energy warms the Earth, how some of the energy is returned back into space and what effect clouds and greenhouse gases have. In the second part of this unit we look at the impact plant emissions have on our atmosphere, both during their growth and if they are burnt in vegetation fires.

Humans have enhanced the natural greenhouse effect and have changed the climate of the Earth.

supported by the International Max Planck Research School on Atmospheric Chemistry and Physics

Part 1: Greenhouse effect and light

Light and the greenhouse effect

Energy to power our planet comes from the Sun. But what happens to the sunlight on its way to Earth and what happens to the energy emitted from the surface of the Earth as it travels back into space?

The atmosphere has an influence on light

We learnt in the first unit of this topic that air consists of different gases, particles and water which can either exist in the gas phase or as liquid droplets. During a dust storm, when the sun is pale or on a rainy day, when clouds cover the sky, it's much darker than on a bright clear day without any clouds. But it's not only particles and clouds which affect how much light gets to the surface of the Earth, the gases in the air also influence the amount of sunlight which reaches the ground.

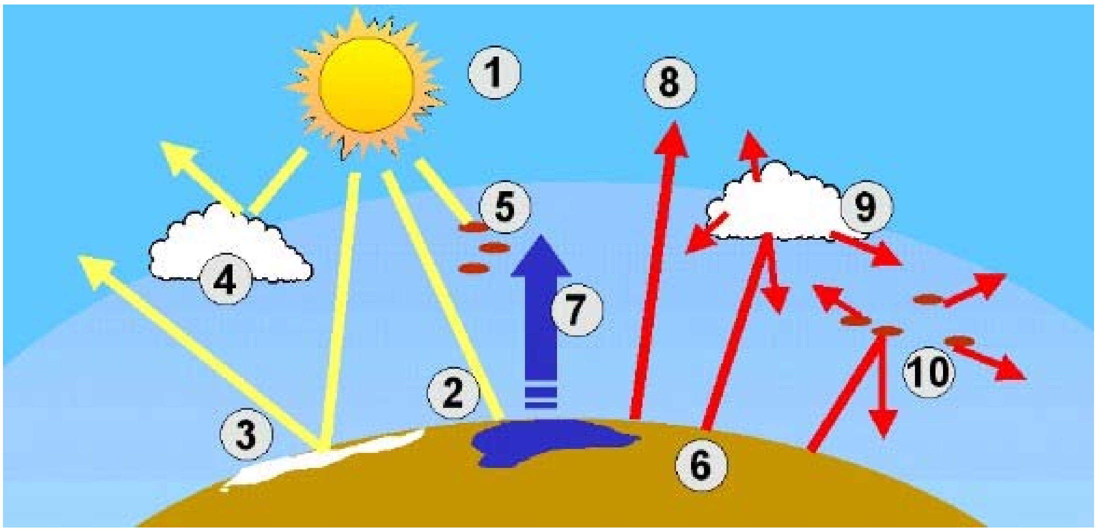
1. All energy comes from the sun.
Source: Freefoto.com

Energy is in balance

Sunlight warms the surface of the Earth. The water in the sea becomes warmer in summer and the streets get so hot in some places that its impossible to walk on them barefoot. Since the earth cannot store this heat forever, the warm Earth sends energy back into space. The sunlight which hits the Earth's surface is made up of high energy ultra-violet and visible radiation. The energy emitted from the surface of the Earth is infra-red or 'longwave radiation' and is less energetic than sunlight.

- We have to learn an important rule:

If the Earth doesn't send back all the energy it receives from the Sun, more and more energy would accumulate on the Earth and it would become hotter and hotter. But this isn't the case. Energy is in balance. Radiation comes from the Sun. We call this radiation light (shown in yellow on the image). Radiation is sent back from the Earth and we call this infrared light or infrared radiation (shown in red).



2. What happens to radiation from the Sun? Author: Elmar Uherek.

What happens when solar radiation enters the atmosphere?

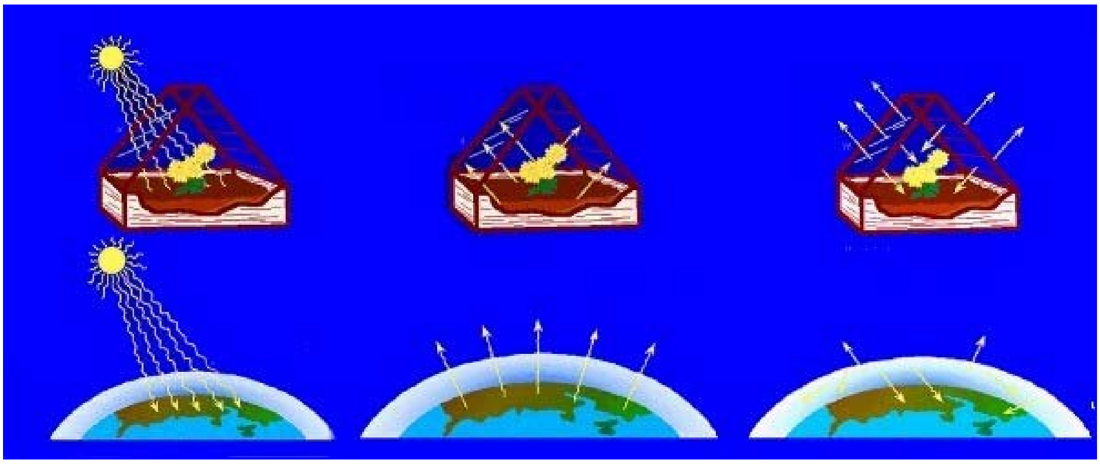
First, let us look what happens to the sunlight.
1. The Sun is the source of all radiation and energy coming to the Earth from space.
2. Part of the sunlight reaches the Earth's surface - the forests, oceans, deserts, savannah, cities, ice and snow.
3. The Earth's surface doesn't take up (absorb) all the sunlight, but sends (reflects) a certain part of it directly back into space. Very light coloured surfaces (e.g. ice and snow) are excellent reflectors.
4. Reflection doesn't just occur at the Earth's surface. Some light is reflected back into space by the top of the clouds and by particles in the air.
5. Absorption of sunlight doesn't only take place at the surface. Gas molecules and particles in the air also absorb sunlight.

The sunlight which reaches the Earth, warms its surface. The Earth sends this warmth back into space as infra-red heat radiation.

What happens to this heat radiation?

6. The warm surface of the Earth is a source of infra-red heat radiation to space.
7. A portion of this energy is used to evaporate water (think about a kettle - energy in the form of electricity is used to heat the liquid water up and in the process some is converted into water vapour or steam).
8. A small fraction of the infrared radiation goes directly back into space.
9. Clouds not only reflect sunlight, they also absorb and re-emit heat radiation from the Earth. A cloudy sky keeps the Earth warm, like a blanket.
10. Particles and gases in the air absorb infrared heat radiation. The gases are called greenhouse gases. They trap the heat near the ground.

We must take all these processes into account if we want to understand our climate. But why do we call it a greenhouse effect?



3. The greenhouse effect - compare the interaction of light in a greenhouse with that on Earth! Original source: NOAA.

The role of greenhouse gases in the atmosphere can be compared to the role of glass in a greenhouse. The glass lets the sunlight in and the light warms the soil and plants in the greenhouse. These send out heat radiation. When this heat radiation hits the glass, it doesn't pass back through like the sunlight, but is absorbed by the glass. So the glass heats up and this heat goes back into the greenhouse and it gets hotter. This is similar to what greenhouse gases in the atmosphere do. They let the sunlight in, but they don't let the heat radiation from Earth back out into space.

Part 2: Greenhouse Gases

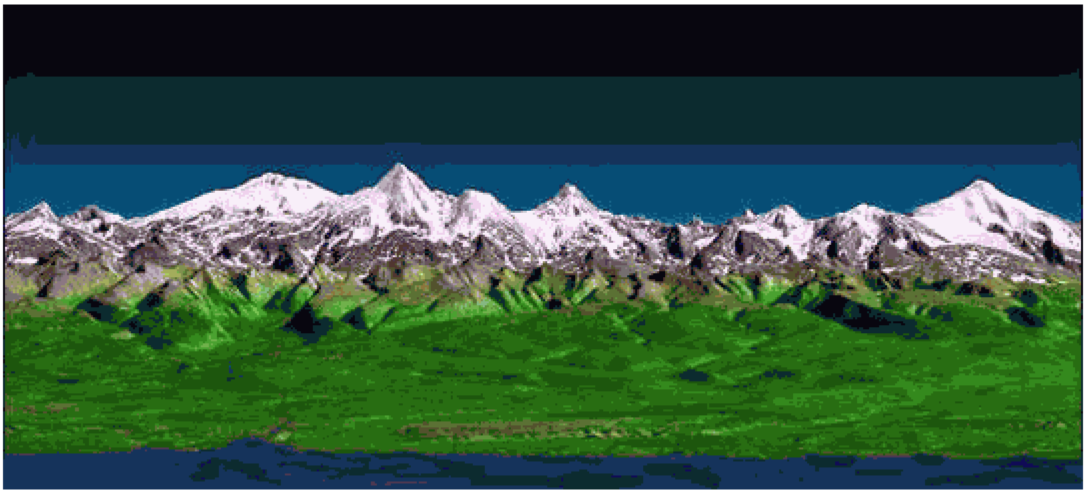
Greenhouse gases and their effect

The greenhouse effect is very important for life on Earth. The average temperature of the Earth is 15 °C, if there were no greenhouse gases in the air, the average temperature of the Earth would be about 30 °C lower.

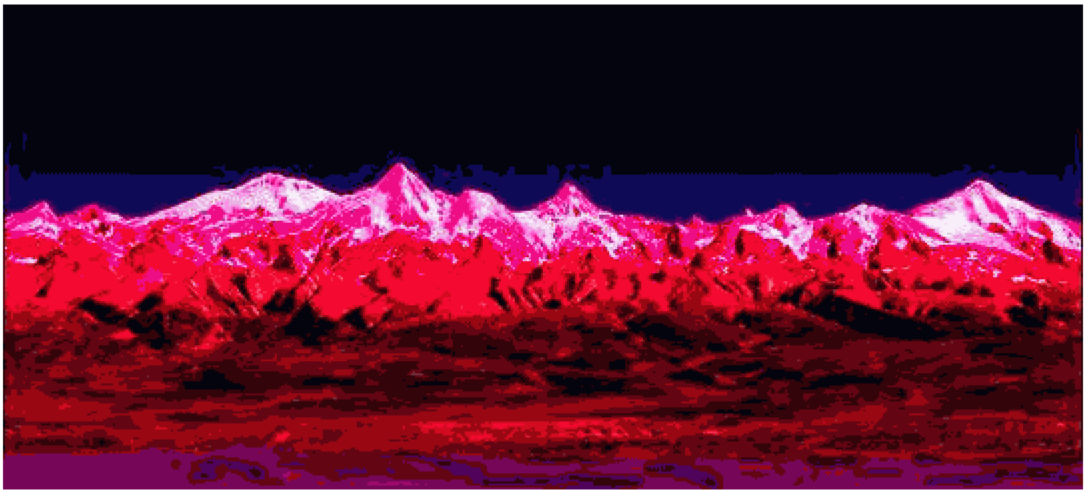
1. Greenhouse gases act like a pullover. Adapted from: fashion 3sat online.

We need a natural greenhouse effect. This acts like a pullover in winter which traps a warm layer of air around our body. However, if the pullover is too thick, we begin to sweat. By putting more and more greenhouse gases into the air, humans have enhanced the natural greenhouse effect and are making the Earth warmer. It's not the natural greenhouse effect which is causing global warming, it's the **additional** greenhouse effect caused by humans which is causing the trouble.

So greenhouse gases do the same with the heat radiation from the Earth as a pullover does with our body in winter. They hold back the warmth and cause a warm layer to form around the Earth's surface.



2. Light coming from the Sun is mostly visible light, the dangerous ultra-violet part is absorbed by the ozone layer. This sunlight is either reflected back into space by the light coloured parts of the Earth's surface (ice, snow and clouds) or reaches the Earth's surface and heats it up (symbolised by the red colour). Author: Elmar Uherek.



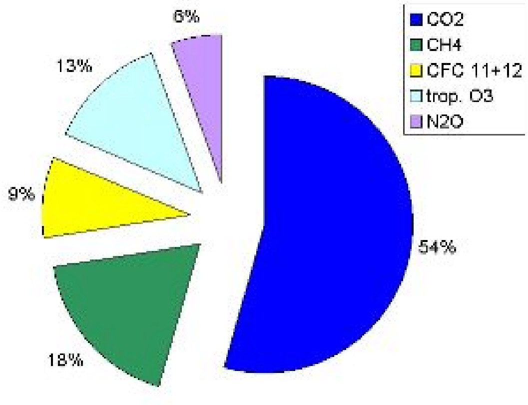
3. Warm infrared heat radiation (invisible to our eyes) is emitted by the Earth. Greenhouse gases in the atmosphere (symbolised by blue ellipses) absorb the infrared radiation and send part of the heat back to the Earth and part of it back into space. Author: Elmar Uherek.

4. Contributions of the tropospheric greenhouse gases to radiative forcing between 1750 (preindustrial times) and 2000. This is a measure of the additional greenhouse effect resulting from human activity. Carbon dioxide has the greatest effect. Author: Elmar Uherek. Values from IPCC TAR 2001 .

Radiative forcing of the additional greenhouse gases (1750 - 2000) values in W m^{-2}.
1.46 CO_2 (carbon dioxide)
0.48 CH_4 (methane)
0.24 CFC 11+12 (chlorofluorocarbons)
0.35 trop. O_3 (tropospheric ozone)
0.15 N_2O (nitrous oxide)

Which gases contribute to the greenhouse effect?

The most important greenhouse gas is water vapour (which accounts for about 60% of the greenhouse effect) but we don't think that concentrations of water vapour in the atmosphere have changed much over the past few centuries. So its unlikely that water vapour is responsible for the observed warming of our planet. However, human activity has dramatically increased the concentration of carbon dioxide in the atmosphere, from 280 ppm in preindustrial times to 370 ppm* today. Carbon dioxide is the second most important greenhouse gas in the atmosphere, contributing about 20% of the greenhouse effect. Concentrations of methane and ozone, which are also strong greenhouse gases, have also increased dramatically since the industrial revolution. Greenhouse gases are trace gases, and beside from CO_2, they account for less than one millionth of the total air mass. In some scientific publications the contribution of the greenhouse gases to the warming of the Earth is called 'radiative forcing'. It is measured in watts per square meter (W m^{-2}). Between 1750 (when the industrial revolution started) and today, the concentrations of greenhouse gases have increased dramatically as a result of human activity. The numbers on the right show the increase in radiative forcing during this time.
* 1ppm = 1 molecule of a gas in 1 million molecules of air



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Part 3: Emissions

Emissions from the biosphere

Most of us live in towns or villages, in areas surrounded by industry and dominated by cars and other transport. In densely populated European countries it's difficult to imagine that it's plants, not humans, which emit most of the organic (carbon based) compounds into the air globally. The biosphere is the part of the Earth where plants and animals live.

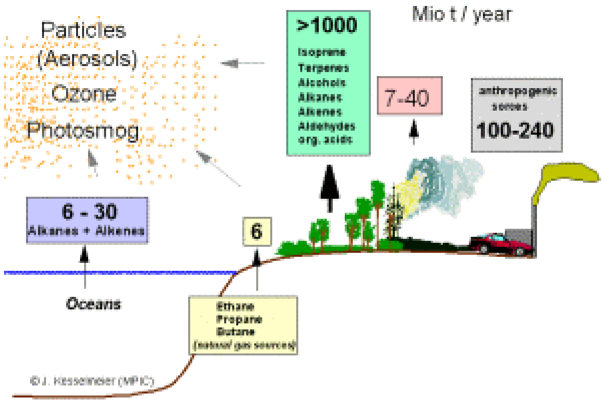
1. Rice paddy field - Bali, Indonesia
foto by: STRINGER/INDONESIA for Reuters

What is emitted by the biosphere?

Carbon is the most important element in the living world. Chemicals, made up mainly of carbon and hydrogen, are called organic compounds. If you walk through a forest or a grassy area you smell many organic gases which are emitted by the trees, the grasses and the flowers. World-wide, more than one thousand million tonnes of organic compounds are emitted by plants. About half of this is a gas called isoprene. Another important group are the monoterpenes (~130 million tonnes per year) which give pine trees their characteristic smell. Plants emit these gases through their leaves and their needles, often in response to stress such as drought or high temperatures, but also during normal growth.

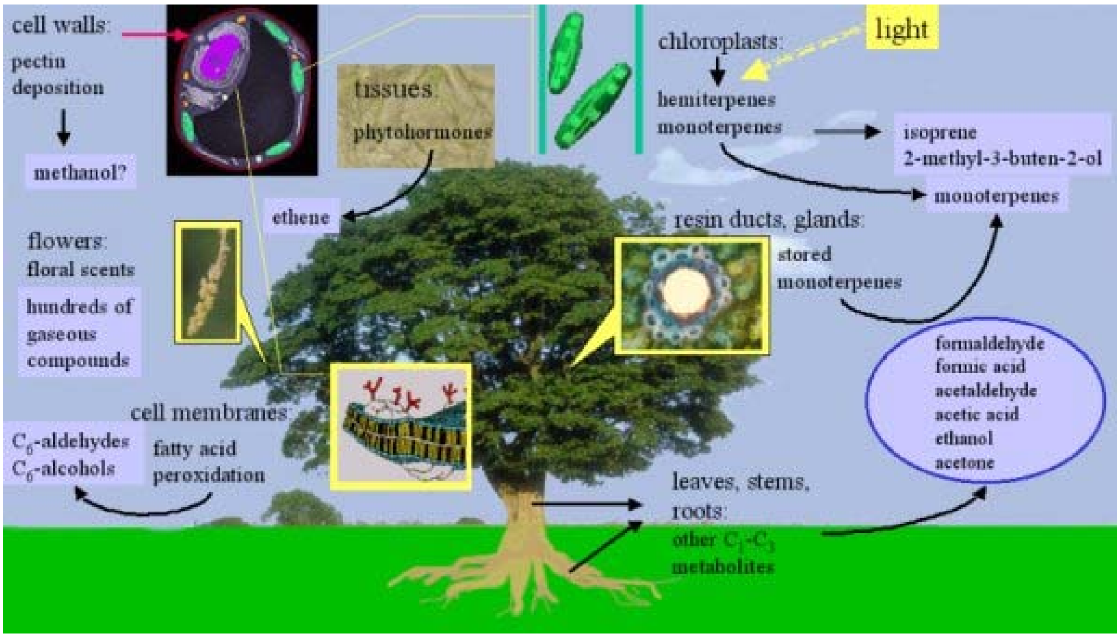
Methane (CH_4) is the simplest organic compound and about 200 million tonnes of it are produced naturally each year. Human activity roughly doubles this, with emissions from cows and rice paddies being important sources.

Organic compounds are also naturally emitted from the oceans. Single celled marine plants, known as phytoplankton, produce organic compounds which can be released from seawater into the air. One of the most important is dimethyl sulphide. About 45 million tonnes of this sulphur containing gas enters the air each year. Once in the air, it is converted to sulphuric acid and then to sulphate aerosol particles. This sulphuric acid plays a part in governing how acidic the atmosphere is and the sulphate aerosols help form clouds. So dimethyl sulphide is very important to our climate.



2. Global emissions of volatile organic compounds (VOC's) in millions of tonnes per year (methane and DMS not included). The compounds are emitted by the oceans, soils, from trees and plants, by fires and from human sources. Author: Jurgen Kesselmeier.

So if we want to understand how our climate system works and how it is likely to change in the future, it is important to look at emissions both from human activity and also from the biosphere. Here we look at three examples to show just how important plant emissions are to our climate.

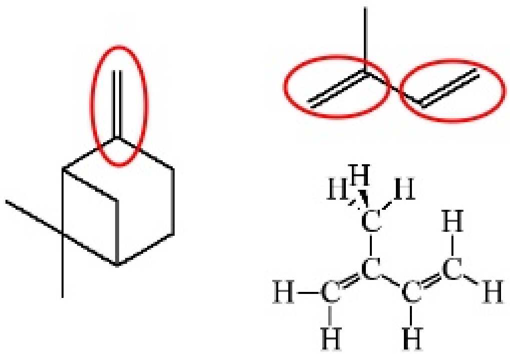


3. The tree as a source of organic compounds (after N. C. Hewitt; image Elmar Uherek). Plants emit a huge number of different chemical compounds into the air. Isoprene (emissions of around 500 million tonnes per year worldwide) and monoterpenes (emissions of 130 million tonnes per year worldwide) are the dominant species emitted.

4. Emissions of gases from trees and the conversion of these gases into fine aerosol particles is probably the cause of the blueish haze over the Great Smoky Mountains (USA).

Monoterpenes

Monoterpenes contribute to the smell of the forest and also to the smell of some fruits. They are made up of carbon and hydrogen and sometimes also contain oxygen. Many of them have very descriptive names, for example, limonene and pinene. They are produced most actively when the Sun rises on warm days and can either be stored or released directly into the air. Production of the compounds rises if the plant is stressed.



5. In this figure you can see the chemical structure of the monoterpene, beta-pinene (left), and of one of the most important natural organic compounds, isoprene (right). Both compounds are unsaturated. This means, they have C=C double bonds, highlighted by a red loop. In order to simplify complicated organic molecules, chemists ususally do not draw the C and H atoms. Isoprene is shown in both forms, without C and H atoms above and with C and H atoms below.

What happens to these compounds in the atmosphere?

Once they enter the atmosphere, monoterpenes react with hydroxyl radicals (OH) or ozone to form compounds which either deposit onto plants, the ground or react with other chemicals in the air to form aerosols (particles or liquid droplets in the air). Sometimes it's possible to see these aerosols forming as the reactions occur. The blue haze you see over forests is formed as aerosols are produced. The picture opposite shows a laboratory simulation of this. Some of the aerosols which are formed can act as cloud condensation nuclei and may start the formation of clouds.

6. Simulation of blue haze formation in the laboratory (carried out at MPI Mainz). The beam of a strong lamp helps us to see the smoke formed when ozone comes into contact with monoterpenes from pine needles.

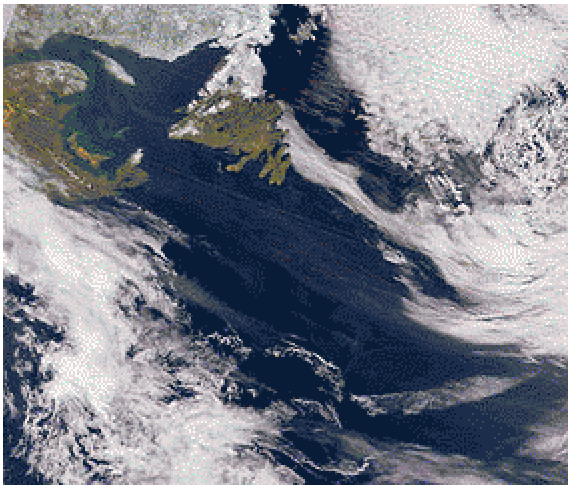
Nitrous oxide N_2O

7. Medicago varia (Fabaceae). This plant is used in agriculture to take up nitrogen from the air.
Photo: Patrick Knopf, spez. Botanik, Ruhr-Universität Bochum.

Nitrogen is an important chemical element in the biosphere since it's a fundamental component of proteins and DNA. Plants take up the nitrogen they need from the ground (as nitrate or ammonium) and some bacteria help make nitrogen gas available to plants in a process known as nitrogen fixation. Bacteria, however, also breakdown nitrate to form the gas nitrous oxide which is released into the air. Nitrous oxide is extremely stable, isn't destroyed in the troposphere and, as a result, makes it all the way into the stratosphere, the next layer of our atmosphere. In the stratosphere it plays a part in reactions which deplete the ozone layer. Emissions of nitrous oxide have increased over time due to increasing use of fertilisers in agriculture. Roughly 15 million tonnes are emitted world-wide each year.

Dimethyl sulphide

Tiny sulphate containing aerosol particles allow clouds to form over the oceans. But where does this sulphate come from? Phytoplankton produce sulphur containing compounds to help them survive the very salty conditions in the sea. One of the by-products of this process is a gas called dimethyl sulphide. This gas enters the atmosphere and, once in the air, it is converted into sulphuric acid and then to sulphate aerosols.



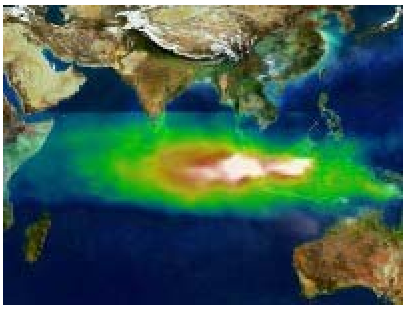
8. Visualisation of chlorophyll from phytoplankton. The satellite image shows the Atlantic Ocean east of Canada. The animation switches to a visualisaton of the phytoplankton in the sea (increasing numbers from blue to red). Some of these phytoplankton emit dimethyl sulfide into the air. Source: SEAWIFS Project.

So emissions from the biosphere are fundamentally important to our climate.

Part 4: Fire

Vegetation fires

Fires are a natural part of life on Earth, occurring when there are droughts and lightning strikes. These fires allow vegetation to naturally regenerate. Nowadays most fires are, unfortunately, caused by humans particularly in the tropics. When large areas of vegetation are burnt, we call the process biomass burning.
Fires started by humans are often the result of carelessness or even arson. Many, however, are started deliberately so humans can use the land. For example, large areas of the tropical rain forest have been burnt so that the land can be used for agriculture.



1. Pollution detected by the TOMS satellite over Indonesia and the Indian Ocean on 22nd October 1997. Image courtesy NASA GSFC Scientific Visualization Studio. http://svs.gsfc.nasa.gov

Huge fires destroyed vast areas of the Indonesian rain forest in 1997. So much air pollution resulted from these fires that it could be seen by satellites in space. The white colour in the image shows the smoke particles coming directly from the burning vegetation and the green, yellow and red colours show the tropospheric ozone which was also produced. The ozone forms when hydrocarbons and nitrogen oxides (NO and NO_2) produced by the fire react in the presence of sunlight.

So fires not only change the landscape, they also change the chemical composition of the air.

What is emitted by fires?

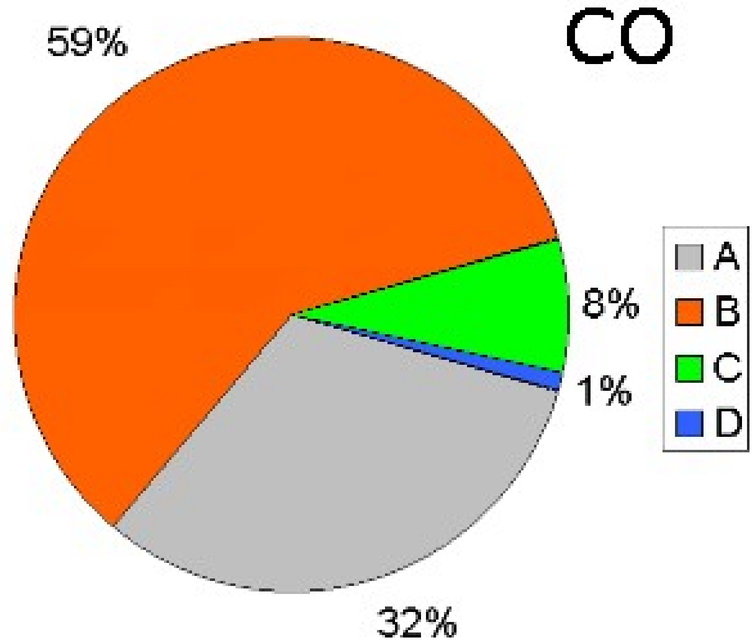
Many gases are emitted into the air when plants are burnt. Some examples of these gases include: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO + NO_2 = NOx) and simple organic hydrocarbons with methane (CH_4) the most abundant.
Particulate compounds are also formed. These are dominated by organic carbon compounds and soot carbon.
Biomass burning is an important contributor to the global atmospheric budgets of CO and NOx. If old forests containing large amounts of vegetation are burnt, a lot of CO_2 is emitted into the air. Savannah (grassland) fires, on the other hand, can be an overall sink for CO_2, since the soot carbon is

2. Savanna fire in an open tree savanna in Central Kenya. Source: Global Fire Monotoring Centre

partially stored as sediment on the ground and the fresh grass in the burned area takes up CO_2 as it grows.

Example: Carbon monoxide (CO)

The pie chart gives an overview of global sources for atmospheric carbon monoxide (Tg stands for teragram and one teragram is one million tonnes). Biomass burning dominates the global CO budget.
A: Technological = 400 Tg CO per year
B: Biomass burning = 748 Tg CO per year
C*: Terrestrial biosphere = 100 Tg CO per year
D: Oceans = 13 Tg CO per year
* mainly from the degradation of plant material in soils.
The 1996 IPCC estimates for the amount of CO emitted from the oceans and all soils is between 80 and 360 Tg CO per year.
About 20% of the global nitrogen oxide emissions are due to vegetation fires. Since NOx contributes to ozone formation, high ozone concentrations are often found in the plumes from fires.



3. Sources of carbon monoxide (CO). Chart by Elmar Uherek.

Land use change

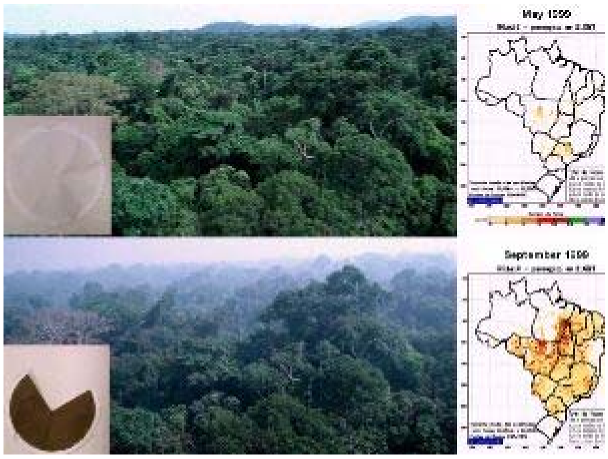
When forests are converted into farmland, towns or roads humans destroy the original vegetation and cause an irreversible conversion of the organic plant material into carbon dioxide. This type of **land use change** has occurred extensively in the rain forests in Africa and Brazil. The photograph below shows a measurement station at Rodônia in Brazil.

3. Photograph by Greg Roberts of a measurement site in the province of Rodônia in Brazil and an image of the region from space from the LANDSAT satellite.

4. Satellite image from Jacques Descloitres, MODIS Land Rapid Response Team / NASA visible Earth.

The satellite picture opposite shows the location of the measurement site (marked with an arrow) in the south-central Amazon Basin. A large road was built through the area in 1968 from which settlers and loggers started to clear the forest. The extensive deforestation (in a typical "fishbone" pattern) is visible from satellite.

Biomass burning takes place during the dry season (in Brazil this is from June to November). The photographs compare the situation during the wet season in May 1999 (top) and in September 1999. The maps show the incidence of forest fires in Brazil in the different seasons. The figure also shows aerosol samples collected in these months. While filters collected in the wet season are usually clean after sampling, they are completely black from soot carbon and organic material in the fire season. 90% of the CO_2 emissions from land use change are due to such forest fires.



5. Photographs taken by Greg Roberts during field campaigns from the measurement tower above (location: 10° 004' S, 61° 058' W).