Lower Atmosphere

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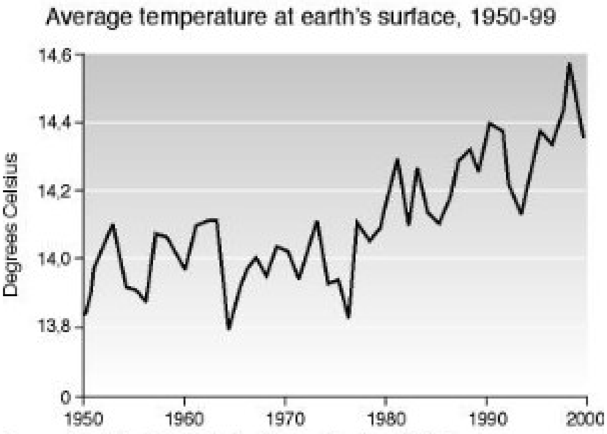
Unit 2

Radiation, greenhouse gases and the Greenhouse Effect

All the energy on Earth comes originally from the Sun. In this unit we look at what happens to solar energy in the atmosphere and what proportion of it actually reaches the surface of the Earth. We also look at the energy emitted back into space from the Earth.

So in this unit we look at the radiation budget of the Earth - how much energy enters and leaves the system.
We then study how increasing greenhouse gas concentrations have altered the radiation budget. We focus on carbon dioxide and methane, levels of which have increased dramatically as a result of human activity.
We also look in detail at the role of water vapour. We know that water vapour is the most important natural greenhouse gas but we are very unsure how it will affect global warming in the future.



Source: Goddard Institute for Space Studies (GISS)

Over the past few decades, the average temperature of the Earth has been increasing dramatically. Greenhouse gases are responsible for this. © NASA GISS.

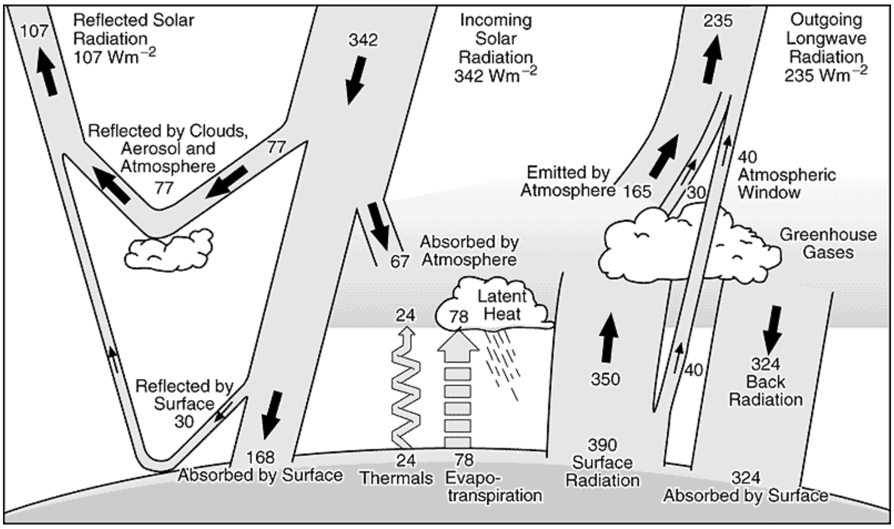
Part 1: Radiation

The Earth's radiation budget and the Greenhouse Effect

The climate system is driven by the energy from the Sun. Only a certain fraction of this energy reaches the surface of the Earth and causes warming. The rest of the solar energy is reflected back into space or absorbed by the atmosphere. In this section we look at how the Earth's radiation system works.

a) When we look at the radiation budget of the Earth, we can divide the system into three parts:
1) outer space
2) our atmosphere
3) the surface of the Earth
In each part of the system the amount of energy coming in equals the amount of the energy leaving. If this wasn't the case, one part of the system would become either warmer and warmer or colder and colder over time and this isn't happening. So the system is in equilibrium (balance).

b) Greenhouse gases do NOT produce energy. They help to generate an equilibrium state where the surface layer of the atmosphere is unusually warm.



1. The global radiation budget as published in IPCC TAR Chap. 1.2.1. In the following sections we try to understand the different energy transport systems which govern our climate.

The reality is a bit more complicated since the oceans react very slowly to changes in temperature. So if the temperature rises as a result of global warming, the atmospheric temperature increases rapidly but it takes much longer for the oceans to heat up. This means that until the oceans heat up fully, the Earth is in a state of disequilibrium. In the following sections we assume that the equilibrium situation has been reached and the Earth system is in balance.

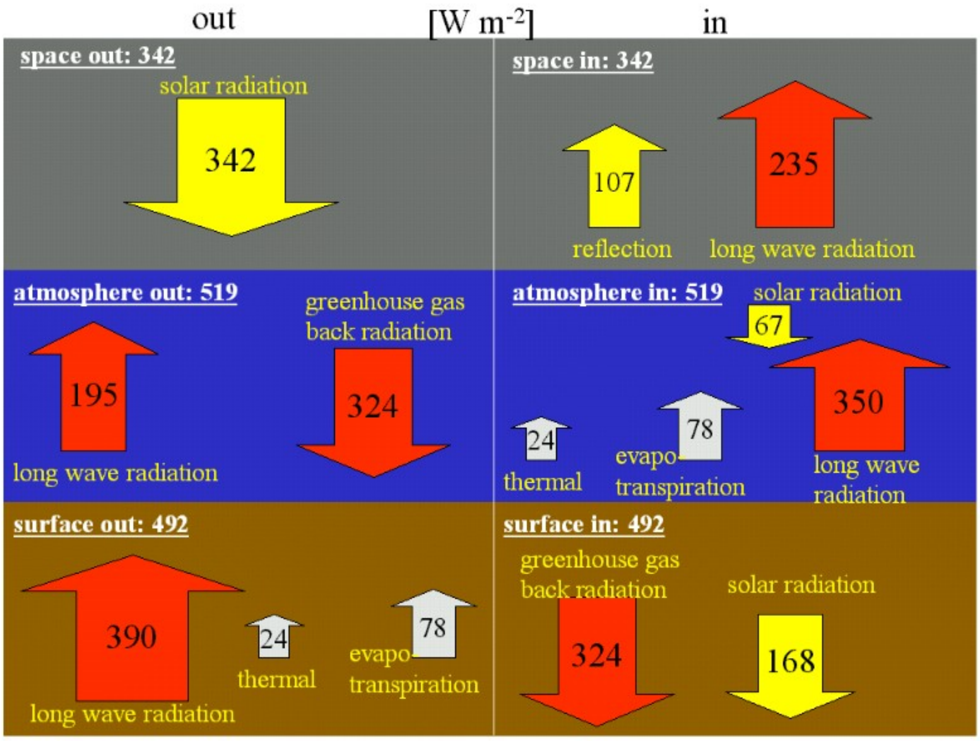
2. Greenhouse gases keep the planetary boundary layer warm in the same way as our clothes do in winter. Adapted from fashion 3sat online.

The role of greenhouse gases

We wear a jumper on a cold day to keep us warm. However, the jumper doesn't make the air any warmer or make our body produce more energy and the jumper doesn't produce energy itself! It simply sends part of the energy coming from our body back towards our skin causing a warm layer of air between the jumper and ourselves. This is exactly what greenhouse gases do. An increasing greenhouse effect doesn't mean that more energy comes from the Sun but that a larger proportion of the energy coming from the Earth's surface is sent back towards the surface allowing more heat to accumulate before it is released back into space.

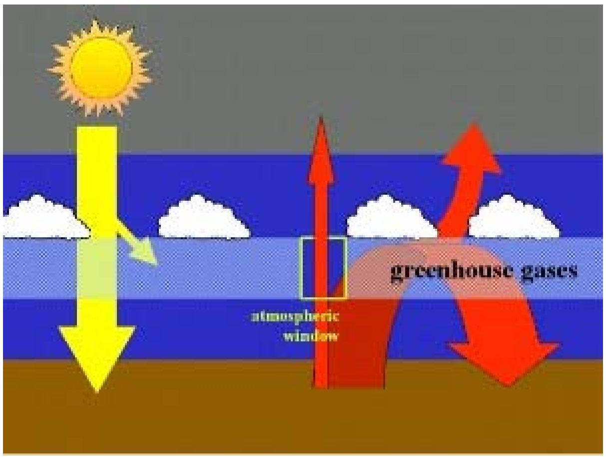
Understanding the energy budget

We measure the energy transferred into, or emitted from, a part of the system in watts per square metre (W m^{-2}). First, let us check that that the same amount of energy comes in and goes out of the system (here we simplify by leaving out the retarding effect of the oceans):
342 W m^{-2} of energy enters our atmosphere directly from the Sun. About 30% of this solar energy (107 W m^{-2}) is directly reflected back into space either from the clouds or from the surface of the Earth. This fraction of sunlight reflected directly back to space is known as the Earth's **albedo**, so the Earth has an average albedo of 0.3. Clouds and polar ice caps are the most efficient reflectors of solar radiation directly back into space.
Definition of albedo: *The ratio of the light reflected by a body to the light received by it. Albedo values range from 0 (pitch black) to 1 (perfect reflector).*



3. The energy balance for outer space, our atmosphere and the Earth's surface. Everything is in equilibrium. Solar radiation is shown in yellow and long wave infra-red radiation in red. A certain fraction of the energy is also needed for evaporation of water and thermal transfer.
Image: Elmar Uherek, data from IPCC TAR.

The remaining 235 W m^{-2} of energy from the Sun interacts either with the atmosphere or with the Earth's surface. It then returns to space as long wave infra-red radiation.

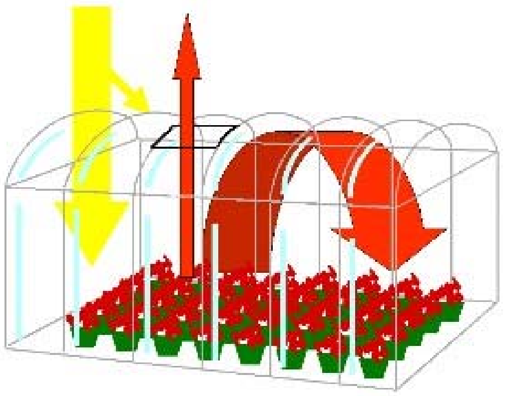


4. A reduced view of the Earth's radiation budget (reflection excluded) and an illustration of the atmospheric window. Image by Elmar Uherek.

When we look at the radiation budget, we see that the surface of the Earth absorbs more energy (492 W m^{-2}) than the total amount of energy coming from the Sun. If the system is in equilibrium this can't be true! So how does this happen? The atmosphere can either re-emit the energy it has absorbed back into space or send it back to the surface of the Earth. The presence of greenhouse gases in the atmosphere allows energy to be reflected back to the Earth making it appear that the system is unbalanced.

The atmospheric window

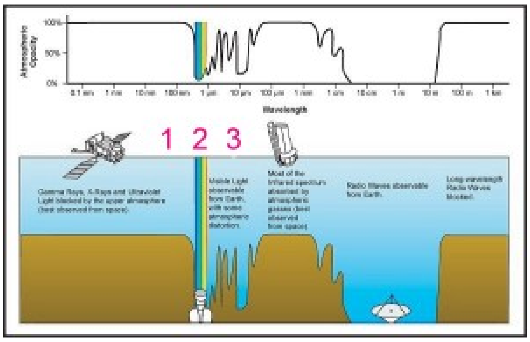
Only 40 W m^{-2} of energy is directly emitted as long wave infra-red radiation from the Earth's surface into space.



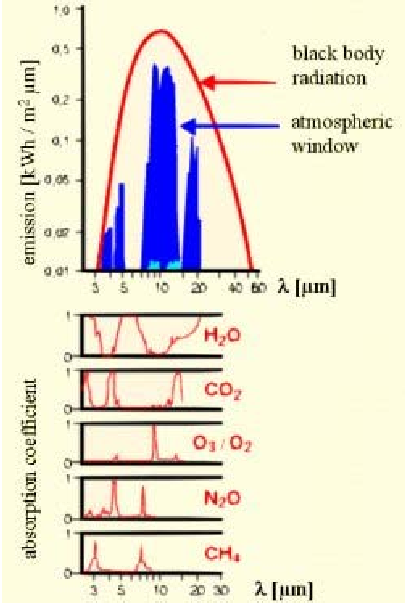
5. The model of a greenhouse. Illustration: Elmar Uherek.

Only a small amount of the infra-red radiation emitted from the surface of the Earth can escape directly into space. Most is absorbed by the greenhouse gases present in the atmosphere. There are a few gaps in the overlapping absorption spectra of water (which absorbs roughly 60%), carbon dioxide, methane, nitrous oxide, ozone and the other greenhouse gases where infra-red radiation can't be absorbed. The most important gaps are known as the atmospheric window. Put very simply, the infrared radiation can disappear into space like heat does through a window in the roof of a greenhouse.

The analogy of the greenhouse gases to the glass of a greenhouse is not perfect. The gases interact with light, while the glass is a solid barrier which also prevents convection so that heat is retained.



6. The interaction of electromagnetic waves with the atmosphere (how much radiation and which wavelengths pass through the atmosphere) means that certain parts of the atmosphere are opaque. In the image above, these parts are shown in brown. Of special interest is the near ultra-violet radiation (1), the visible light (2) and the near infra-red radiation (3). Ozone absorbs in the range 1 and makes the atmosphere opaque for dangerous UV-B radiation. Next to it, visible light (2) reaches the ground and lights our days and heats the Earth's surface. Infra-red radiation (3) from the Earth (see image on the right) can go back to space, but only in the areas which are not blocked. Firstly water and then carbon dioxide make parts of the infrared range opaque for the radiation from the Earth (greenhouse effect). If other gases (O_3, CH_4, N2O) absorb in the remaining 'atmospheric window' (see spectra right), they are very efficient greenhouse gases. Picture from NASA / IPAC.



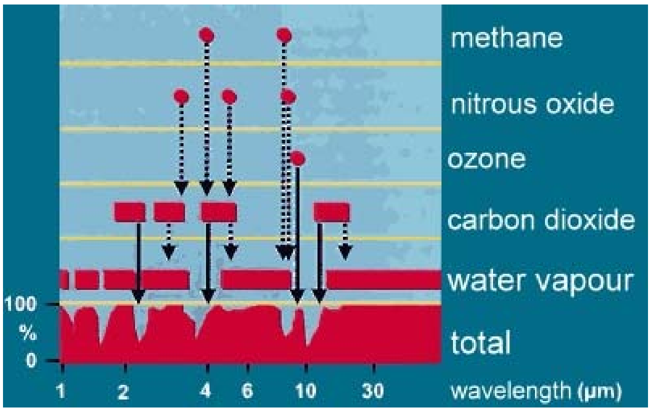
7. Only a fraction of the theoretical spectra of the Earth (so called black body radiation, shown in red) is really emitted into space. This fraction (shown in blue) is called the atmospheric window. The rest is absorbed primarily by water and carbon dioxide. Image adopted from Hamburger Bildungsserver.

Part 2: CO2 CH4

The Greenhouse gases - carbon dioxide and methane

Although water vapour is the most important greenhouse gas, it's carbon dioxide and methane that normally make the headlines. The

concentration of these gases is far less than that of water vapour but they prevent particular wavelengths of infra-red heat radiation leaving the atmosphere. Their concentrations are also continuously increasing as a result of human activity.



Water vapour absorbs most wavelengths of the infra-red radiation emitted by the Earth's surface, trapping it as heat. At some wavelengths, however, the absorption is weak or close to zero allowing infra-red radiation to escape into space.

1. Absorption of water and other greenhouse gases.
Adapted from: Climate Website of the German Museum.

Other greenhouse gases absorb infra-red radiation at these wavelengths and reduce the amount of heat lost into space. Simply increasing the concentration of water vapour wouldn't have such a large effect on global warming as the presence of small amounts of these other greenhouse gases has.
These greenhouse gases are more efficient at trapping particular wavelengths of infra-red radiation than water vapour is.

So, the impact of a particular greenhouse gas on global warming depends not only on its concentration, but also on how efficiently it can trap infra-red radiation. The concept of a Global Warming Potential (GWP) was developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide (CO_2) was chosen as the reference gas.

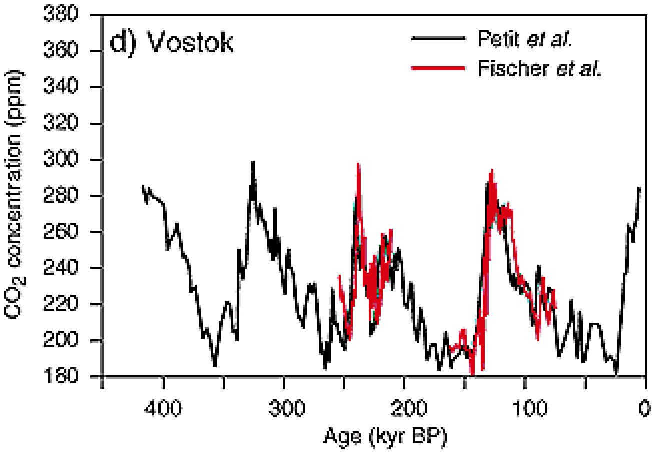
This table shows some of the most important greenhouse gases, their concentrations in 1750 (preindustrial times), in 1998 and their 100 year global warming potential (GWP) which indicates how efficient a greenhouse gas the chemical is. Data from IPCC TAR 2001:

Greenhouse gas	**abundance 1750**	**abundance 1998**	**100 year GWP**
carbon dioxide CO_2	280 ppm	365 ppm	1
methane CH_4	700 ppb	1745 ppb	23
nitrous oxide N_2O	270 ppb	314 ppb	296
tropospheric ozone* O_3	25 DU (10 ppb)	34 DU (30-40 ppb)	
CFC-11 $CFCl_3$	0	268 ppt	4600
CFC-12 CF_2Cl_2	0	533 ppt	10600

1 DU = Dobson Unit = 0.01 mm column of pure ozone
*since ozone is not evenly spread in the atmosphere, only rough assumptions of the average mixing ratios (in ppb) for the lower troposphere can be given.

The change in CO_2 emissions over time

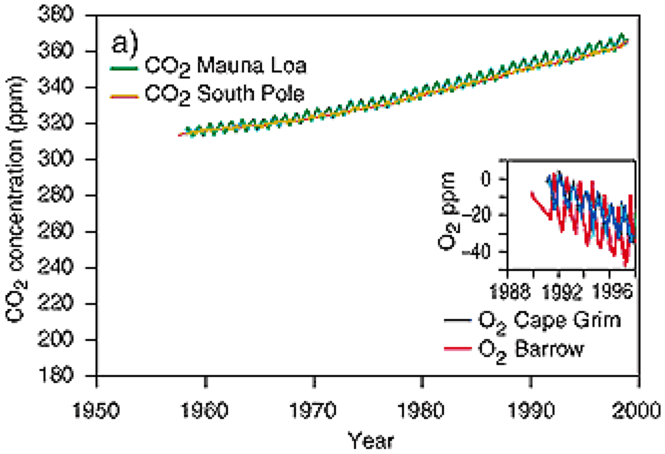
Analysis of air trapped within ice has allowed us to look at how CO_2 concentrations in the air have changed with time. Over the past 400,000 years atmospheric CO_2 concentrations ranged between 180 ppm during glacial times to 280 ppm during the interglacials. This trend changed with the beginning of industrialisation as a result of our increasing exploitation of fossil fuels (coal, oil, gas) as energy sources.



2. The atmospheric CO_2 trend over the last 400,000 years from analysis of the Vostok ice core. Source: IPCC TAR 2001 fig 3-2.

Since the industrial revolution, CO_2 emissions have increased exponentially and atmospheric concentrations are currently around 370 ppm. This rapid increase in CO_2 concentrations is primarily the result of human activity.

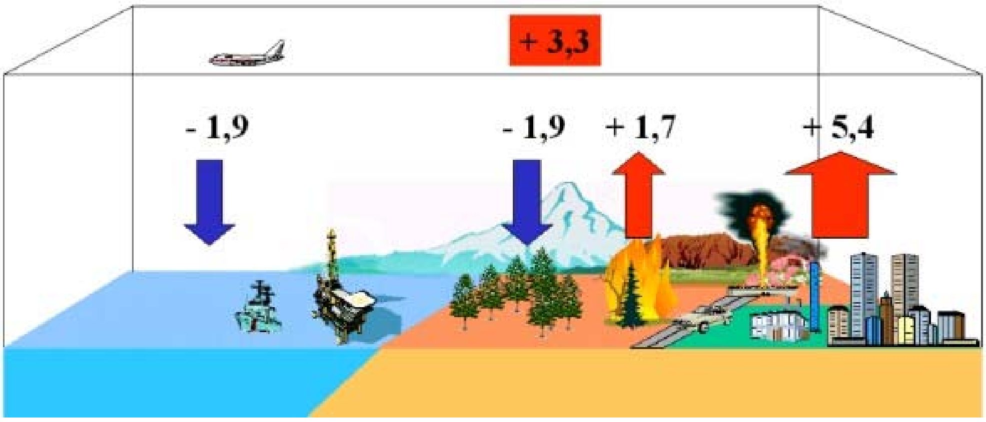
Every year several billion tons of carbon enter the atmosphere as CO_2. In the 1980's 5.4 ± 0.3 Pg C yr^{-1} was emitted, with this rising to 6.3 ± 0.4 Pg C yr^{-1} in the 1990's (1 Petagram C = Pg C = 1×10^{15} g = billion tonnes), most of which came from fossil fuel burning. Another 1.5 - 2 Pg C yr-1 enters the air as a result of land use changes, mostly from vegetation.



3. The CO_2 trend over the last few decades. The increase of CO_2 occurs in parallel with a slight decrease in atmospheric oxygen, as this is lost during the oxidation process. Source: IPCC TAR fig 3-2.

We know the magnitude of these CO_2 sources fairly well but are much more unsure where much of the CO_2 goes once it is emitted into the air.

About 3.2 to 3.3 ± 0.1 Pg C y^{-1} remains in the atmosphere. The oceans take up between 1 and 2 Pg C y^{-1} converting much of the carbon into carbonate and we assume that around 2 Pg C y^{-1} is taken up by growing vegetation. The amount of CO_2 taken up by plants is particularly unsure, it can easily vary by a factor of 2 from year to year and is related to different weather conditions, for example if an El Niño event occurs.



4. The CO_2 budget: Estimated average values for CO_2 sources and sinks for the 1980's in PgC y^{-1}. Fossil fuel burning and land use change are the major sources, vegetation and the ocean are the major sinks. Image by Elmar Uherek, data from IPCC TAR 2001.

The carbon cycle

Exchange of CO_2 between the biosphere and the atmosphere is on a much larger scale than indicated by the source and sink values shown above. About 270 Pg C y^{-1} is temporarily stored in plants during photosynthesis and about 60 Pg C y^{-1} fuels annual plant growth. This natural carbon cycle is in equilibrium so that all of the carbon stored temporarily and all the carbon which is needed for growth is returned to the atmosphere when the plants die and decompose or when they are burnt during biomass burning. This means that natural plant growth does not significantly alter CO_2 levels in the atmosphere. Rather, it is the additional CO_2 entering the atmosphere as a result of human activities that alters the natural equilibrium of the carbon system.

Sources of methane

5. a-d) Methane producing bacteria are active the stomachs of cows

and sheep. Source: www.freefoto.com

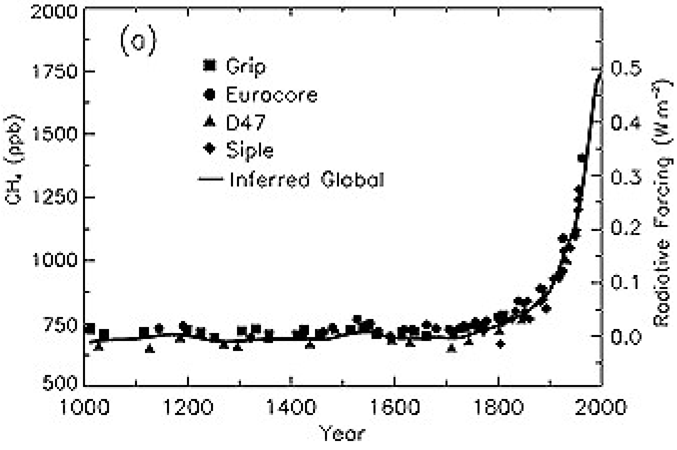
Methane is emitted from rice paddies

moors and other wetlands.

The globally averaged concentration of methane in the troposphere in 1998 was 1745 ppb. However, the magnitude of the exact sources are uncertain since emissions from wetlands are very variable and emissions from rice paddies have probably been overestimated (they may be just 40 Tg y^{-1}). The table below gives estimates of methane emissions from two different studies.

Sources of methane (global emissions in Tera grams per year - 1 Tg = 10^{12} g):

Source (selected)	**Emissions [Tg CH_4 yr^{-1}]** (Hein *et al*., 1997)	**Emissions [Tg CH_4 yr^{-1}]** (Lelieveld *et al*., 1998)
wetlands + rice	325 (237 + 88)	225
energy sector	97	110
ruminants	90 (including waste treatment)	115
landfills	35	40
biomass burning	40	40
others	-	(70)
Total	**587**	**600**



6. The change in CH_4 concentrations in the atmosphere over time (mole fraction, in ppb = 10^{-9}) determined from ice cores, firn, and whole air samples plotted for the last 1000 years. Radiative forcing, approximated by a linear scale since the pre-industrial era, is plotted on the right axis. Source: IPCC TAR Fig. 4-1.

About 60% of methane emissions come from human activities such as agriculture, fossil fuel use and waste disposal. As a result of the growing contribution from human activity, the concentration of methane in the air has more than doubled over the past 1000 years.

The most important loss reaction for methane is the reaction with OH:
$OH + CH_4 \rightarrow CH_3 + H_2O$

But the reaction is rather slow and, as a result, the atmospheric lifetime of methane is long, around 8.4 years.

Methane hydrates

Enormous amounts of CH_4 are stored on Earth as methane hydrates. These are solid mixtures of ice and methane which are stable at high pressures and low temperatures and found under the oceans and in deeper layers of permafrost soil. About 10,000 Pg of carbon is estimated to be stored as methane hydrates, about double the amount of carbon stored as conventional fossil fuels (coal, oil and gas), so they represent a huge unused energy resource. Data from the Vostok ice core shows no evidence for large scale methane releases from these hydrates over the last 400,000 years. However, increasing surface temperatures as a result of global warming, may melt some of these methane hydrates releasing methane into the air and further enhance the greenhouse effect.

7. When methane hydrate melts, the methane released burns producing CO_2 and liquid water remains. (c) GEOMAR 2002 (German).

Part 3: Water

Water vapour and clouds

Water vapour is the most important greenhouse gas in the atmosphere and accounts for about 60% * of the total greenhouse effect. Until recently, Scientists assumed that the water vapour content of the atmosphere was more or less constant and that water vapour didn't contribute to the enhanced, human induced, greenhouse effect. However, as the Earth continues to warm, the amount of water vapour in the air will rise and water may cause greater warming in the future.

* some references suggest that tropospheric water (including the long wave absorption by clouds) is responsible for 80% of the greenhouse effect.

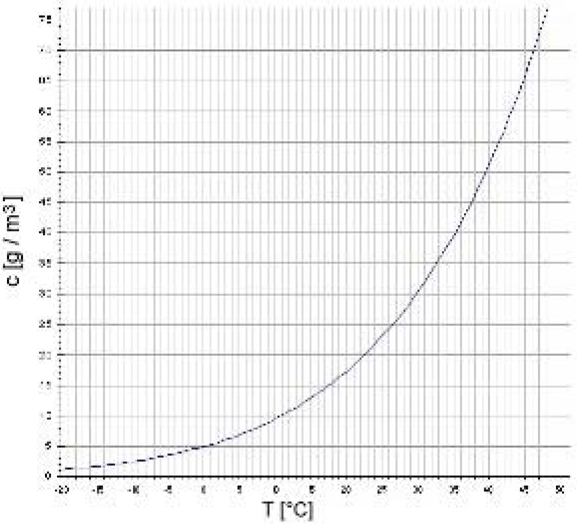
Probably the greatest uncertainties in future projections of climate arise because we don't know the impact of changing water vapour levels in the air and because we are unsure how clouds affect the amount of solar radiation reaching the surface of the Earth.

Saturation

The capacity of air to hold water vapour increases with temperature. Warmer air can take up more water. The saturation curve shows how much water air of a certain temperature can hold before condensation begins (i.e. a relative humidity of 100%). In the atmosphere, air is usually unsaturated. The relative humidity RH varies greatly and is given by the following equation:

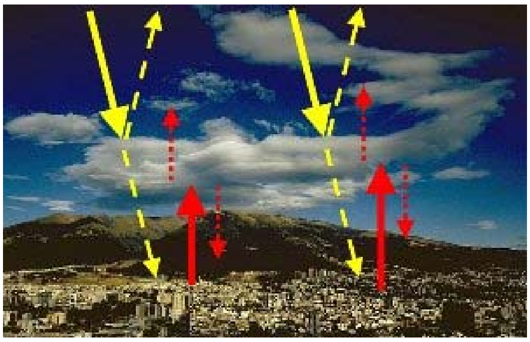
$$RH\,(\%) = \frac{p}{p_{sat}} \times 100$$

p = given partial vapour pressure of water
p_{sat} = saturated water vapour pressure, this depends strongly on the air temperature.



1. The water vapour saturation curve tells us the maximum amount of water the air can hold at a particular temperature (a relative humidity of 100%).

Generally, increasing air temperatures lead to increasing evaporation and more water vapour in the air. While ideal thermodynamic conditions are nearly fullfilled for evaporation processes in the tropospheric boundary layer (up to 1 to 2 km in altitude), conditions in the free troposphere above are much more complicated. It is here that the greenhouse potential of water vapour is likely to increase in the future.



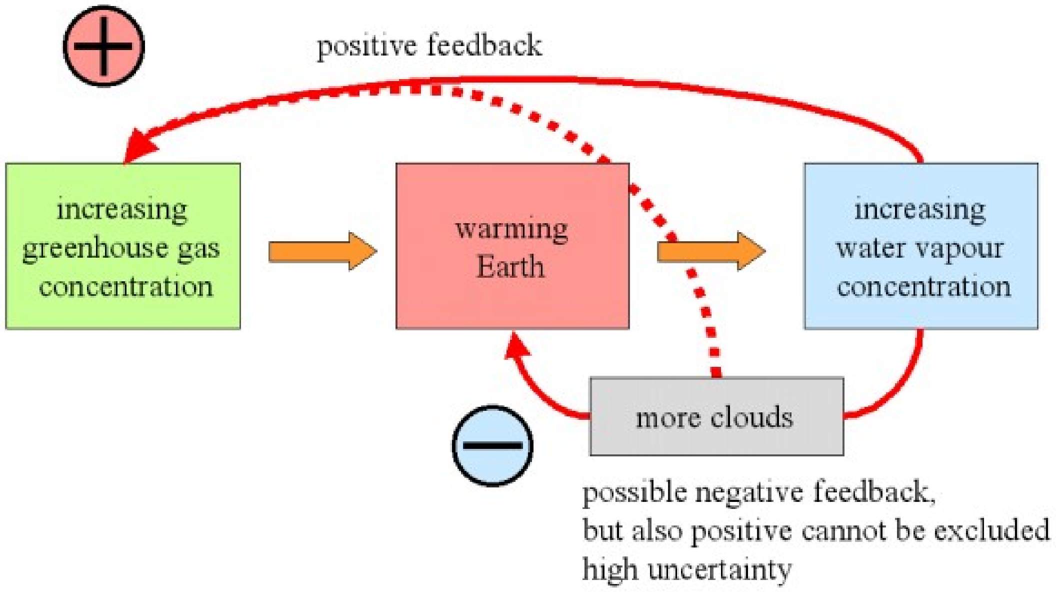
2. Clouds partially reflect solar radiation from the sun back into space (shown in yellow), but also absorb infra-red radiation from the surface of the Earth (shown in red) and return it to the Earth in the same way a greenhouse gas does. Picture source: Karlsruher Wolkenatlas (c) Bernhard Mühr.

Cloud formation

The consequence of increasing humidity is an increase in cloud cover. Clouds interact in two ways with radiation. On the one hand, they act like greenhouse gases, absorbing infra-red radiation from the Earth and trapping the heat in the lower atmosphere. On the other hand, they increase the Earth's albedo by reflecting incoming solar radiation back into space before it reaches the Earth, effectively cooling the planet. It strongly depends on the type of cloud which effect is strongest but it is assumed that, on average, the cooling effect dominates.

Twofold feedback

So global warming is likely to both increase the water vapour content of the air and increase cloud formation. These two effects are likely to have opposite feedback effects. One probably leads to further warming, the other to cooling, although the role of high clouds is still unsure.



3. Feedbacks in the water cycle.

Global warming leads to higher water vapour concentrations and more water vapour leads to further warming - a positive feedback effect leading to higher and higher temperatures. However increasing water vapour concentrations also leads to more clouds. An increase in clouds probably leads to a cooling since clouds can reflect incoming solar radiation back into space. However, some computer models suggest that high clouds may have a positive feedback effect and may encourage further warming. Our knowledge about clouds is not yet sufficient to explain exactly how they affect climate.

Uncertainties

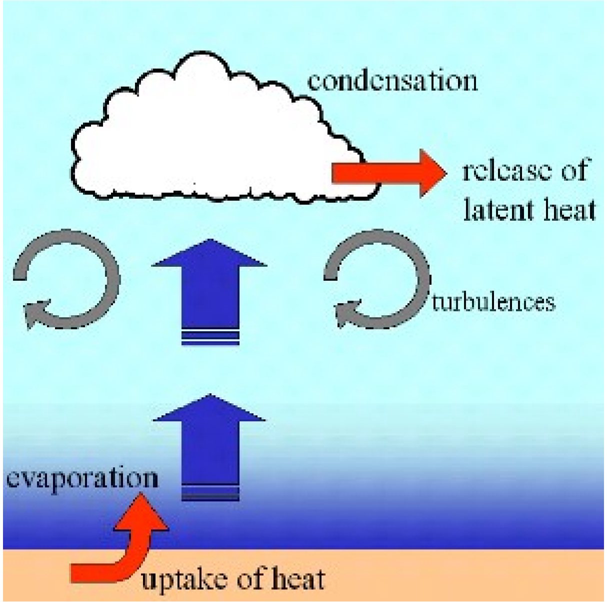
Large differences in the amount of cloud which forms and the amount of water vapour in the atmosphere are seen on regional scales. These scales are often smaller than the grid size used in climate models, so climate models don't take into account every cloud which appears in the atmosphere.
The affect of water vapour and clouds on climate is also uncertain because many models also don't take into account:

- large scale dynamics
- sub-grid scale dynamics
- microphysics
- differences in cloud droplet size
- the cloud temperature

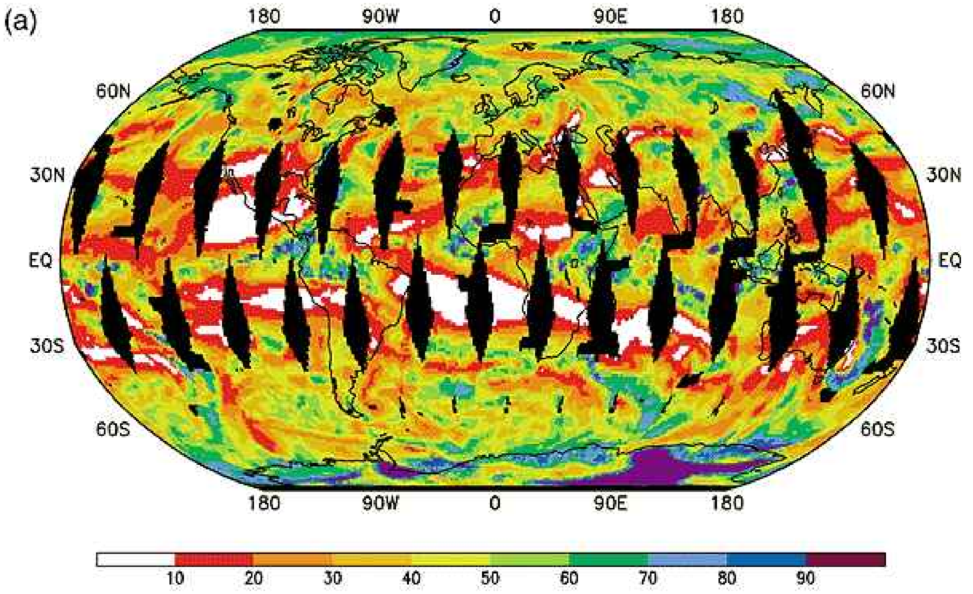
and many others.

The atmosphere is very dynamic and nowhere near a state of equilibrium. Latitute also affects how moisture is transported through the atmosphere:

1. convection (vertical transport) is most important in the tropics, where high cumulonimbus clouds are formed
2. large scale wave motions occur at mid and higher latitudes, where stratiform clouds dominate
3. advection (horizontal transport) is the dominant process in the dry areas between the tropics and the mid-latitudes.



4. Water vapour as part of a dynamic atmosphere. Source EU

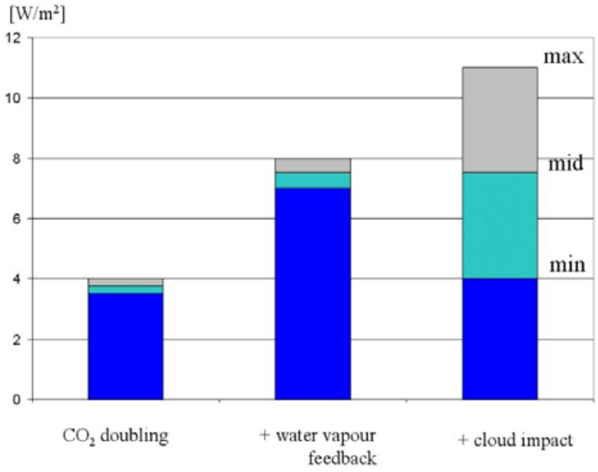


5. Global relative humidity distribution [%] in the free troposphere between 600 and 250 hPa. Attention: Read this map carefully! The free troposphere over the South Pole is more saturated than the free troposphere over the tropics relative to the possible maximum saturation, but it contains by far less water per cubic meter, i.e. in absolute values. Source: IPCC TAR Fig. 7-1.

Estimations of the water vapour and cloud feedback effects

Current estimations say that if we increase CO_2 concentrations in the air to 560 ppm (double the preindustrial level of 280 ppm), the average temperature of the Earth will increase by between 1.5 and 4.5 °C. This wide range in estimates is mainly because the overall effect of clouds on our climate is still so uncertain.

A doubling of CO_2 without any other change would lead to an additional radiative forcing of 3.5 to 4 W m^{-2}, equivalent to a temperature increase of 1.2 °C. This value doubles to between 7 and 8 W m^{-2} if we take into account the positive feedback effect of water vapour alone. We now need to add in the impact of clouds, these may lead to a slight cooling of the planet (regarded as most likely) or to an additional warming. The uncertainty in this term is estimated to be between -3 and +3 W m^{-2} leading to an overall radiative forcing of about 4 to 11 W m^{-2} for a doubling of CO_2 or a temperature increase between 1.5 and 4.5 °C.



6. Radiative forcing estimate for a doubling of CO_2, with and without water vapour and cloud feedback effects. Data from IPCC TAR Chapter 7.

Comparing this range in possible temperatures to the 1.2 °C temperature rise which is estimated to come from the CO_2 rise alone, you get an idea just how important it is to understand the impact of water vapour on our climate.