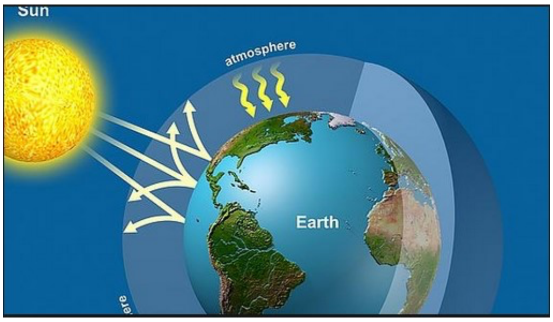


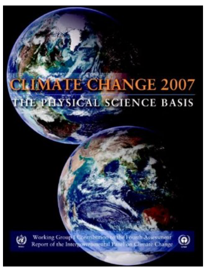
Principles of the Greenhouse Effect

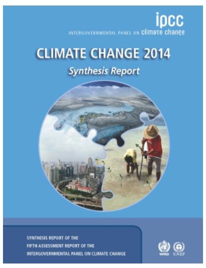
Rui Rosa

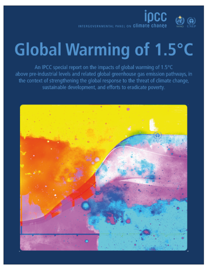
Laboratório Marítimo da Guia,
Faculdade de Ciências da Universidade de Lisboa
Email: rrosa@fc.ul.pt

http://www.ruirosalab.com

Working groups (EGRVM) Topics







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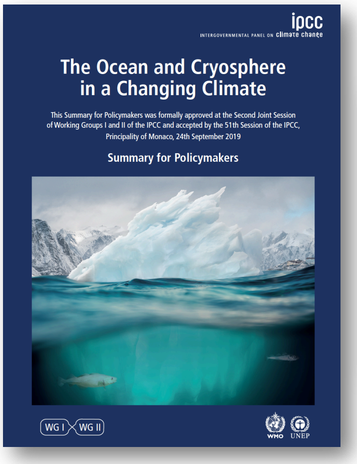

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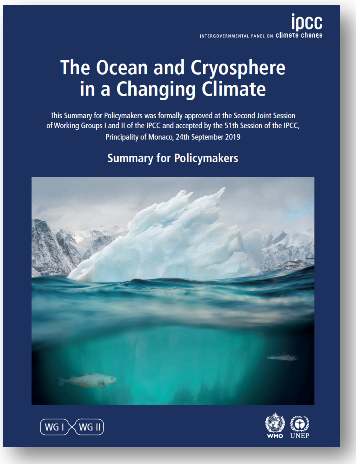

FINAL DRAFT Chapter 5 IPCC SR Ocean and Cryosphere

Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities

Coordinating Lead Authors: Nathaniel L. Bindoff (Australia), William W. L. Cheung (Canada), James G. Kairo (Kenya)

Lead Authors: Javier Arístegui (Spain), Valeria A. Guinder (Argentina), Robert Hallberg (USA), Nathalie Hilmi (Monaco/France), Nianzhi Jiao (China), Md saiful Karim (Australia), Lisa Levin (USA), Sean O'Donoghue (South Africa), Sara R. Purca Cuicapusa (Peru), Baruch Rinkevich (Israel), Toshio Suga (Japan), Alessandro Tagliabue (United Kingdom), Phillip Williamson (United Kingdom)

Contributing Authors: Sevil Acar (Turkey), Juan Jose Alava (Ecuador/Canada), Eddie Allison (United Kingdom), Brian Arbic (USA), Tamatoa Bambridge (French Polynesia), Inka Bartsch (Germany), Laurent Bopp (France), Philip W. Boyd (Australia/ United Kingdom), Thomas Browning (Germany/United Kingdom), Francisco P. Chávez (USA), Mine Cinar (USA), Daniel Costa (USA), Lijing Cheng (China), Omar Defeo (Uruguay), Salpie Djoundourian (Lebanon), Catia Domingues (Australia), Tyler Eddy (Canada), Sonja Endres (Germany), Alan Fox (UK), Christopher Free (USA), Thomas Frölicher (Switzerland), Jean-Pierre Gattuso (France), Gemma Gerber (South Africa), Charles Greene (USA), Nicolas Gruber (Switzerland), Gustaav Hallegraef (Australia), Matthew Harrison (USA), Sebastian Hennige (UK), Mark Hindell (Australia), Andrew Hogg (Australia), Taka Ito (USA), Tiff-Annie Kenny (Canada), Kristy Kroeker (USA), Lester Kwiatkowski (France/UK), Vicky Lam (China/Canada), Philippe LeBillon (Canada), Nadine Le Bris (France), Heike Lotze (Canada), Jennifer MacKinnon (USA), Annick de Marffy-Mantuano (Monaco), Patrick Martell (South Africa), Nadine Marshall (Australia), Kathleen McInnes (Australia), Jose Garcia Molinos (Japan/Spain), Serena Moseman-Valtierra (USA), Andries Motau (South Africa), Sandor Mulsow (Brazil), Kana Mutombo (South Africa), Andreas Oschlies (Germany), Muhammed Oyinlola (Nigeria), Elvira S. Poloczanska (Australia), Nicolas Pascal (France), Maxime Philip (France), Sarah Purkey (USA), Saurabh Rathore (India), Xavier Rebelo (South Africa), Gabrial Reygondeau (France), Jake Rice (Canada), Anthony Richardson (Australia), Ulf Riebesell (Germany), Christopher Roach (Australia), Joacim Rocklöv (Sweden), Murray Roberts (United Kingdom), Alain Safa (France), Sunke Schmidtko (Germany), Gerald Singh (Canada), Bernadette Sloyan (Australia), Karinna von Schuckmann (France), Manal Shehabi (England), Matthew Smith (USA), Amy Shurety (South Africa), Fernando Tuya (Spain), Cristian Vargas (Chile), Colette Wabnitz (France), Caitlin Whalen (USA)

Review Editors: Manuel Barange (South Africa), Brad Seibel (USA)

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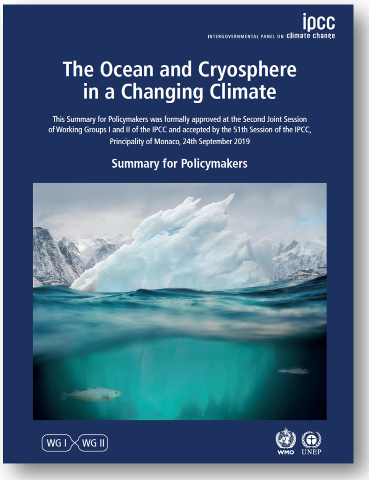

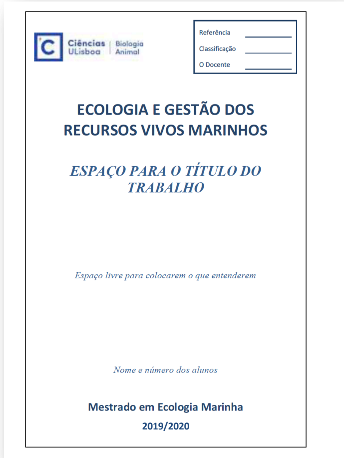

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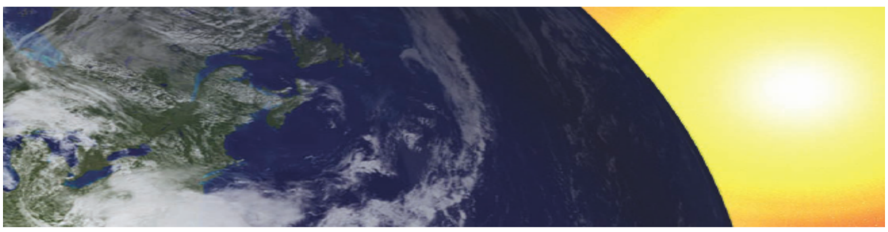
The greenhouse effect

THE BASIC principle of global warming :

-**Radiation energy** from the Sun that warms the Earth's surface and
- the **thermal radiation** from the Earth and the atmosphere that is radiated out to space.

On average these two radiation streams must balance.

If the balance is disturbed (for instance by an increase in atmospheric carbon dioxide) it can be restored by an increase in the Earth's surface temperature .



Radiation balance

To balance this incoming energy, the Earth itself must radiate on average the same amount of energy back to space in the form of thermal radiation.

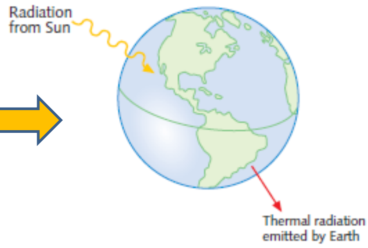


Figure 2.1 The radiation balance of planet Earth. The net incoming solar radiation is balanced on average by outgoing thermal radiation from the Earth.

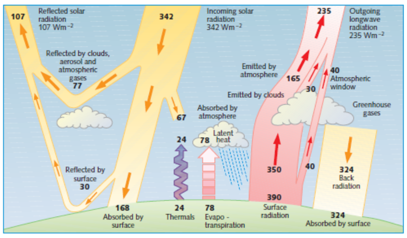
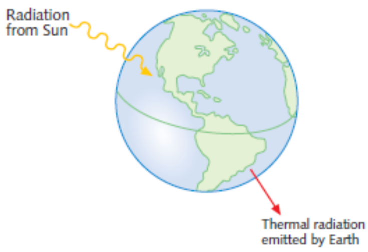


Figure 2.7 Components of the radiation (in watts per square metre) which on average enter and leave the Earth's atmosphere and make up the radiation budget for the atmosphere. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space.

Radiation balance

In a surface of 1 m^2 area outside the atmosphere and directly facing the Sun:

Radiant energy from the Sun falls on a rate of about **1370 watts** – about the power radiated by a reasonably sized domestic electric fire.



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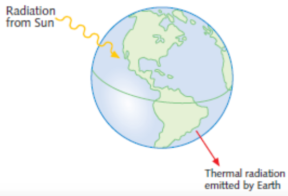
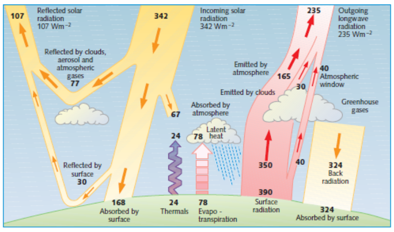
2. The greenhouse effect



However, few parts of the Earth's surface face the Sun directly and in any case for half the time they are pointing away from the Sun at night,

so that the average energy falling on one square metre of a level surface outside the atmosphere is only one-quarter of this 1 or about 342 watts.



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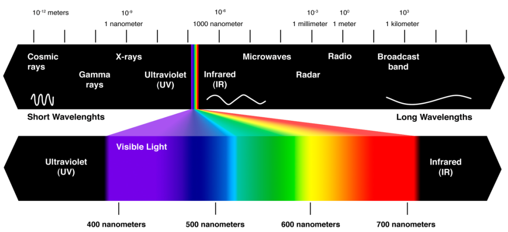


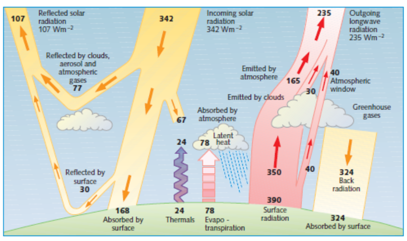
All objects emit this kind of radiation;

if they are hot enough we can see the radiation they emit.

The Sun at a temperature of about 6000 °C looks white;
an electric fire at 800 °C looks red.

Cooler objects emit radiation that cannot be seen by our eyes and which lies at wavelengths beyond the red end of the spectrum – infrared radiation (sometimes called long-wave radiation to distinguish it from the shortwave radiation from the Sun).

Visible radiation **Infrared radiation**



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2. The greenhouse effect

The amount of thermal radiation emitted by the Earth's surface depends on its temperature – the warmer it is, the more radiation is emitted.

The amount of radiation also depends on how absorbing the surface is; the greater the absorption, the more the radiation.

Figure 2.1 The radiation balance of planet Earth. The net incoming solar radiation is balanced on average by outgoing thermal radiation from the Earth.

2. The greenhouse effect

The gases nitrogen and oxygen that make up the bulk of the atmosphere neither absorb nor emit thermal radiation.

Table 2.1 The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2007

Gas	Mixing ratio or mole fraction[a] expressed as fraction* or parts per million (ppm)
Nitrogen (N_2)	0.78*
Oxygen (O_2)	0.21*
Water vapour (H_2O)	Variable (0–0.02*)
Carbon dioxide (CO_2)	380
Methane (CH_4)	1.8
Nitrous oxide (N_2O)	0.3
Chlorofluorocarbons	0.001
Ozone (O_3)	Variable (0–1000)

[a]For definition see Glossary.

2. The greenhouse effect

It is the water vapour, carbon dioxide and some other minor gases present in the atmosphere in much smaller quantities that absorb some of the thermal radiation leaving the surface.

Table 2.1 The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2007

Gas	Mixing ratio or mole fraction[a] expressed as fraction[a] or parts per million (ppm)
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Ozone (O_3)	Variable (0–1000)

[a]For definition see Glossary.

2. The greenhouse effect

They act as a partial blanket for this radiation and causing the difference of 20 to 30 °C between the actual average surface temperature on the Earth (of about 15 °C) and the temperature that would apply if greenhouse gases were absent.

Table 2.1 The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2007

Gas	Mixing ratio or mole fraction[a] expressed as fraction[a] or parts per million (ppm)
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Ozone (O_3)	Variable (0–1000)

[a]For definition see Glossary.

2. The greenhouse effect

This blanketing is known as the natural greenhouse effect and the gases are known as greenhouse gases

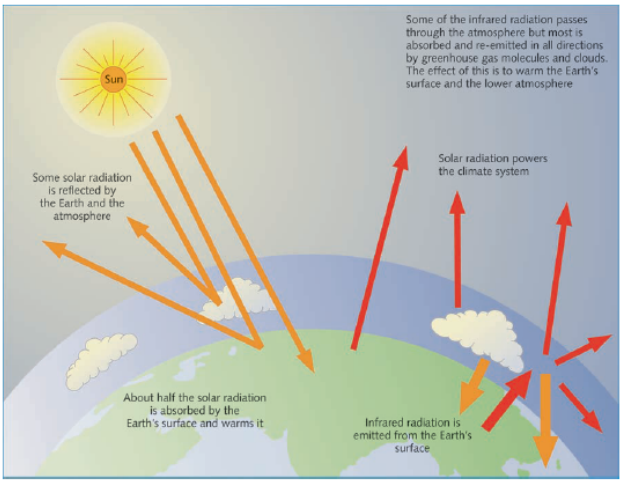

Figure 2.2 Schematic of the natural greenhouse effect.

2. The greenhouse effect

It is called 'natural' because all the atmospheric gases (apart from the chlorofl uorocarbons – CFCs) were there long before human beings came on the scene.

Table 2.1 The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2007

Gas	Mixing ratio or mole fraction[a] expressed as fraction* or parts per million (ppm)
Nitrogen (N_2)	0.78*
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Chlorofluorocarbons	0.001
Ozone (O_3)	Variable (0–1000)

[a]For definition see Glossary.

2. The greenhouse effect

The basic science of the greenhouse effect has been known since early in the nineteenth century when the similarity between the radiative properties of the Earth's atmosphere and of the glass in a greenhouse was first pointed out – hence the name 'greenhouse effect'.

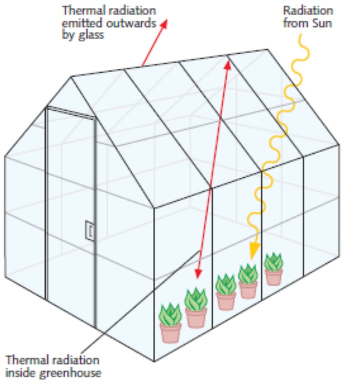


Figure 2.3 A greenhouse has a similar effect to the atmosphere on the incoming solar radiation and the emitted thermal radiation.

2. The greenhouse effect

The most important means of heat transfer is convection, in which less dense warm air moves upwards and more dense cold air moves downwards.

Convection is the concerted, collective movement of ensembles of molecules within fluids (e.g., liquids, gases)

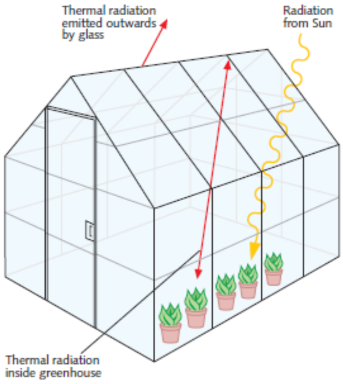
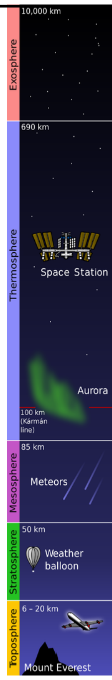


Figure 2.3 A greenhouse has a similar effect to the atmosphere on the incoming solar radiation and the emitted thermal radiation.

Atmosphere

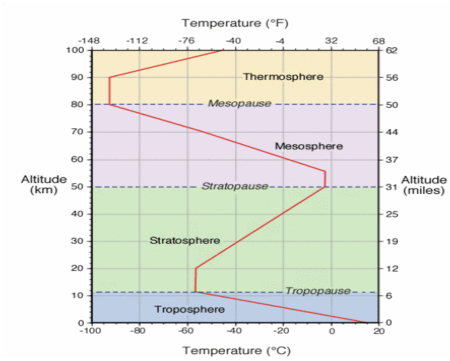
About **80 % of the total mass of the atmosphere is contained in troposphere**. It is also the layer where the majority of our weather occurs.

Maximum air temperature also occurs near the Earth's surface in this layer



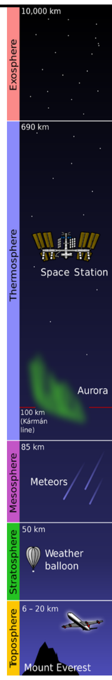
With increasing height, air temperature drops uniformly with altitude at a rate of approximately 6.5° Celsius per 1000 meters = Environmental lapse rate)

(taxa de decréscimo da temperatura com altitude)



Atmosphere

In the first 9 kilometers of the **stratosphere**, temperature remains constant with height - an isothermal layer.



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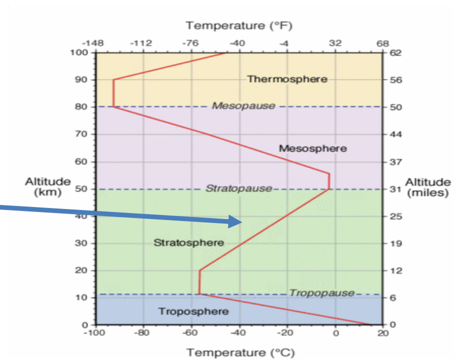
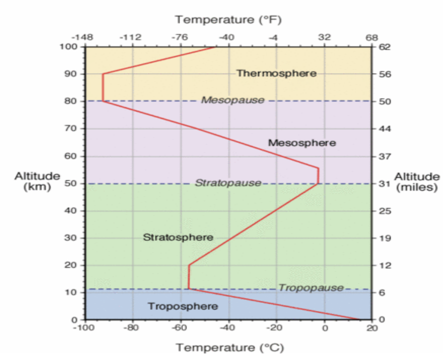
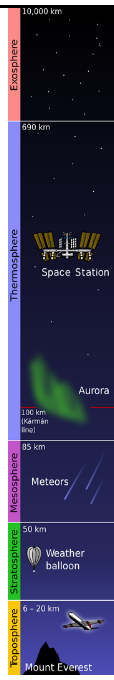


Atmosphere

From an altitude of 20 to 50 kilometers, temperature increases with an increase in altitude. The higher temperatures found in this region of the stratosphere occurs because of a localized concentration of [ozone gas molecules.](#) These molecules absorb ultraviolet sunlight creating heat energy that warms the stratosphere.

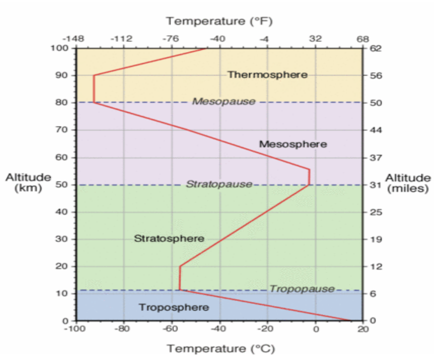


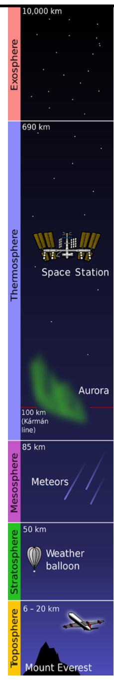


Atmosphere

[Ozone](#) is primarily found in the atmosphere at varying concentrations between the altitudes of 10 to 50 kilometers. This layer of ozone is also called the ozone layer.

The ozone layer is important to organisms at the Earth's surface as it protects them from the harmful effects of the sun's ultraviolet radiation. Without the ozone layer life could not exist on the Earth's surface.





2. The greenhouse effect

Because the greenhouse gases are cold, they emit correspondingly less radiation. What these gases have to do, therefore, is absorb some of the radiation emitted by the Earth's surface but then to emit much less radiation out to space.

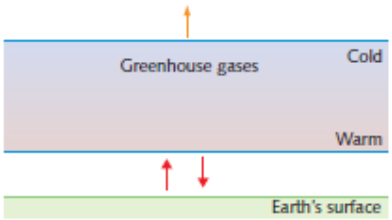


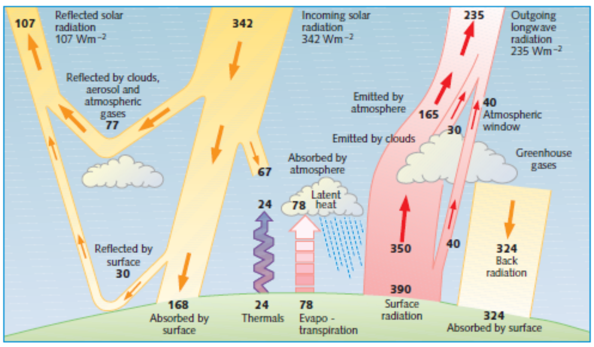
Figure 2.6 The blanketing effect of greenhouse gases.

They, therefore, act as a **radiation blanket** over the and help to keep it warmer than it would otherwise be.

2. The greenhouse effect

There needs to be a balance between the radiation coming in and the radiation leaving the top of the atmosphere

About half of the incoming solar radiation is absorbed by the Earth's surface (168 Wm2).



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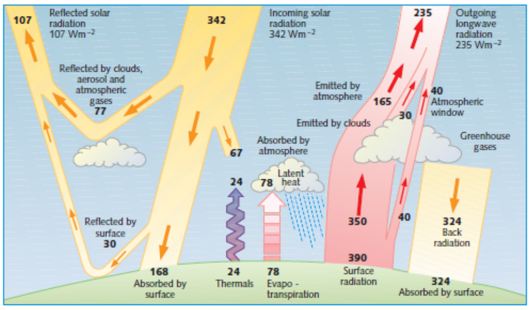
2. The greenhouse effect

This energy is transferred to the atmosphere:

1) by warming the air in contact with the surface (thermals – *colunas de ar ascendente*),
2) by evapotranspiration and
3) by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space.



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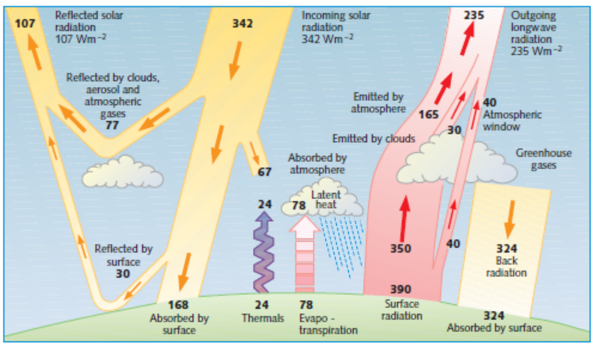
2. The greenhouse effect

Clouds effect

They reflect some of the incident radiation from the Sun back out to space. However, they also absorb and emit thermal radiation and have a blanketing effect similar to that of the greenhouse gases.



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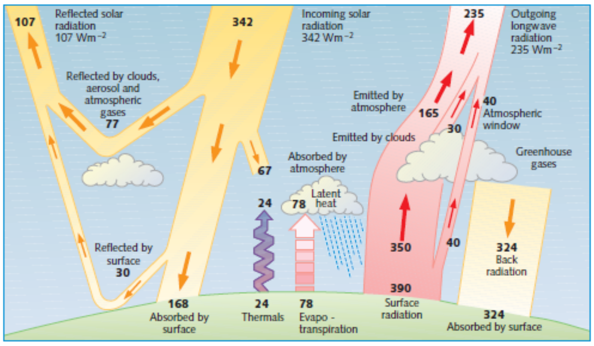
2. The greenhouse effect

Clouds effect

These two effects work in opposite senses: one (the reflection of solar radiation) tends to cool the Earth's surface and the other (the absorption of thermal radiation) tends to warm it.



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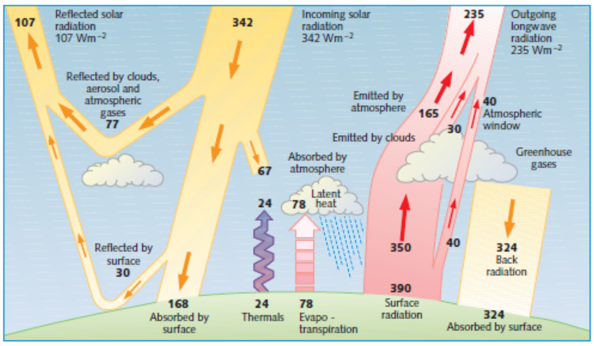
The greenhouse effect

Balance:

235 wm2 on average coming in (168+67) and 235 watts per square metre on average going out. The temperature of the surface and hence of the atmosphere above adjusts itself to ensure that this balance is maintained.



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Greenhouse gases

Industrial activity: a source of carbon dioxide and other gaseous and particulate pollution.

Greenhouse gases

The most important of the greenhouse gases is water vapour, but its amount in the atmosphere is not changing directly because of human activities.

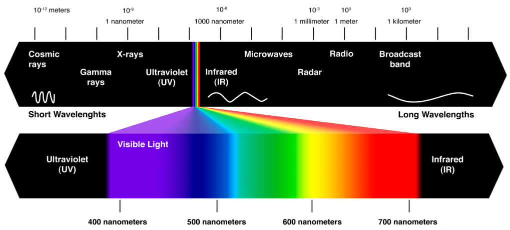
The important greenhouse gases that are directly influenced by human activities are **carbon dioxide, methane, nitrous oxide, the chlorofluorocarbons (CFCs) and ozone .**

This chapter will describe:
- what is known about the origin of these gases,
-how their concentration in the atmosphere is changing and how it is controlled.

Also considered will be **particles in the atmosphere** of anthropogenic origin, some of which can act to cool the surface.

4. Greenhouse gases

A picture of the transfer of radiation in the atmosphere may be obtained by looking at the thermal radiation emitted by the Earth and its atmosphere as observed from instruments on satellites orbiting the Earth.



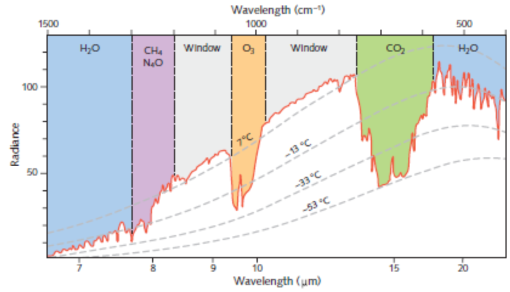


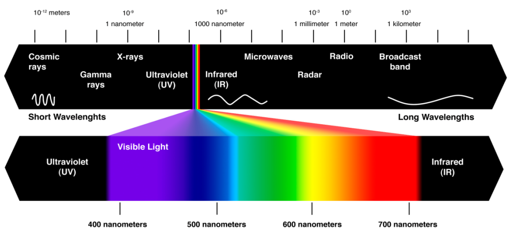
Figure 2.5 Thermal radiation in the infrared region (the visible part of the spectrum is between about 0.4 and 0.7 μm) emitted from the Earth's surface and atmosphere as observed over the Mediterranean Sea from a satellite instrument orbiting above the atmosphere, showing parts of the spectrum where different gases contribute to the radiation. Between the wavelengths of about 8 and 14 μm, apart from the ozone band, the atmosphere, in the absence of clouds, is substantially transparent; this is part of the spectrum called a 'window' region. Superimposed on the spectrum are curves of radiation from a black body at 7 °C, –13 °C, –33 °C and –53 °C. The units of radiance are watts per square metre per steradian per wavenumber.

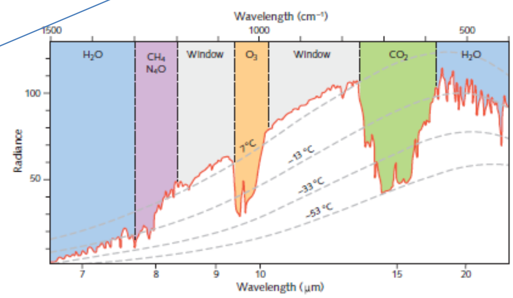
4. Greenhouse gases

Figure illustrated the regions of the infrared spectrum where the greenhouse gases absorb. Their importance as greenhouse gases depends both on:

-their concentration in the atmosphere;

- the strength of their absorption of infrared radiation.





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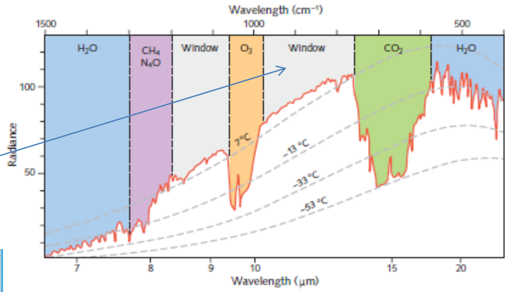
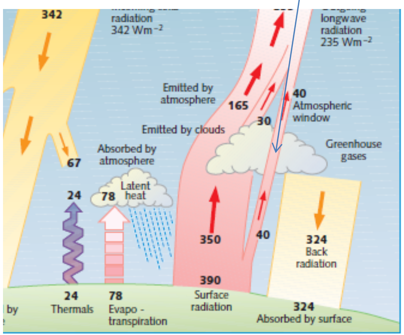
4. Greenhouse gases

At some wavelengths in the infrared the atmosphere – in the absence of clouds – is largely transparent, just as it is in the visible part of the spectrum.

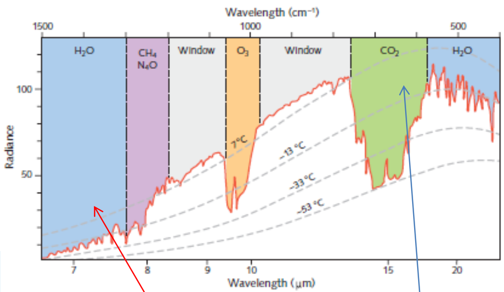


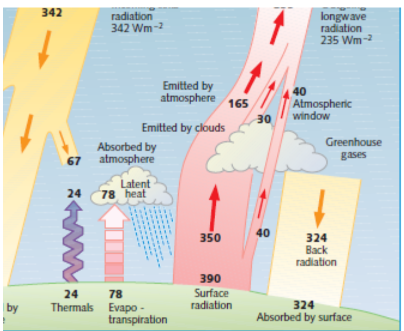


If our eyes were sensitive at these wavelengths we would be able to peer through the atmosphere to the Sun, stars and Moon above, just as we can in the visible spectrum.

4. Greenhouse gases

At these wavelengths all the radiation originating from the Earth's surface leaves the atmosphere.





At other wavelengths radiation from the surface is strongly absorbed by some of the gases present in the atmosphere, in particular by **water vapour** and carbon dioxide .

4. Greenhouse gases

Carbon dioxide is the most important of the greenhouse gases that are increasing in atmospheric concentration because of human activities.

If, for the moment, we ignore the effects of the CFCs and of changes in ozone, which vary considerably over the globe and which are therefore more difficult to quantify, the increase in:

- **carbon dioxide** has contributed about 72% of the enhanced greenhouse effect to date,

- **methane** (CH4) about 21%

- and **nitrous oxide** (N_2O) about 7%

4. Greenhouse gases

Carbon dioxide and the carbon cycle

Carbon dioxide provides the **dominant means** through which carbon is transferred in nature between a number of natural carbon reservoirs – a process known as the **carbon cycle**.

We contribute to this cycle every time we breathe. How?

Answer: Using the oxygen we take in from the atmosphere, carbon from our food is burnt and turned into carbon dioxide that we then exhale; in this way we are provided with the **energy we need to maintain our life.**

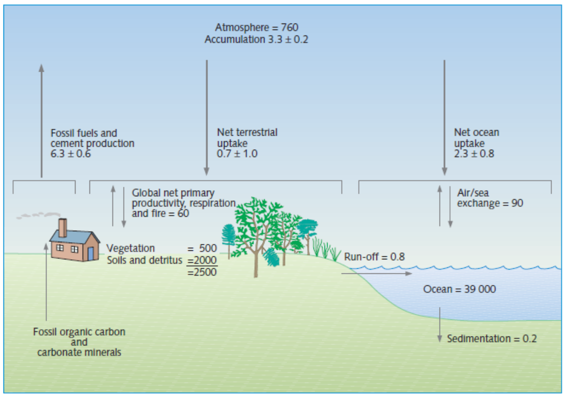
Animals contribute to atmospheric carbon dioxide in the same way; so do **fires**, and **decomposition of organic material** in the soil and elsewhere.

4. Greenhouse gases

Carbon dioxide and the carbon cycle

Figure is a simple diagram of the way carbon cycles between the various
reservoirs –

i) the atmosphere,
ii) the oceans (including the ocean biota),
iii) the soil
and
iv) the land biota



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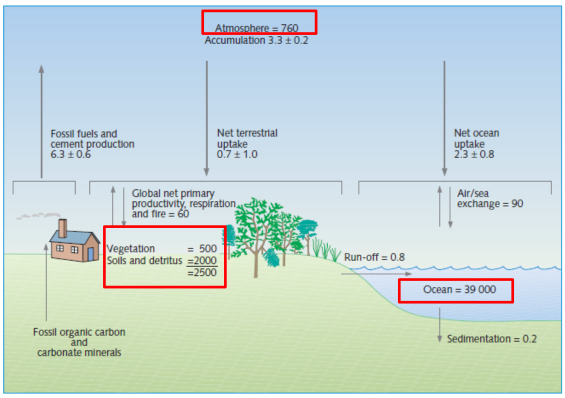
(biota - all living things: plants, trees, animals and so on – on land and in the ocean, which make up a whole known as the biosphere)

4. Greenhouse gases

Carbon dioxide and the carbon cycle

. The land and ocean reservoirs are much larger than the amount in the atmosphere;

small changes in these larger reservoirs could therefore have a large effect on the atmospheric concentration;



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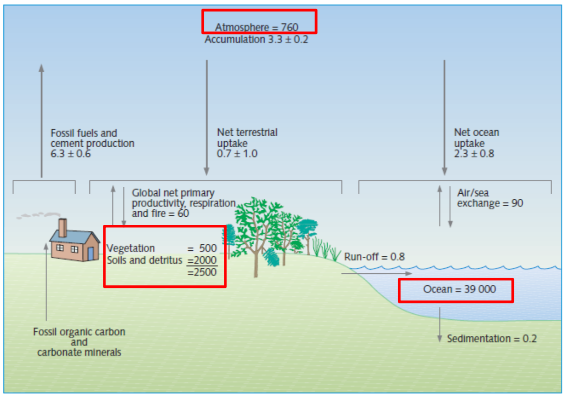
4. Greenhouse gases

Carbon dioxide and the carbon cycle

E.g. the release of just 2% of the carbon stored in the oceans would double the amount of atmospheric carbon dioxide.



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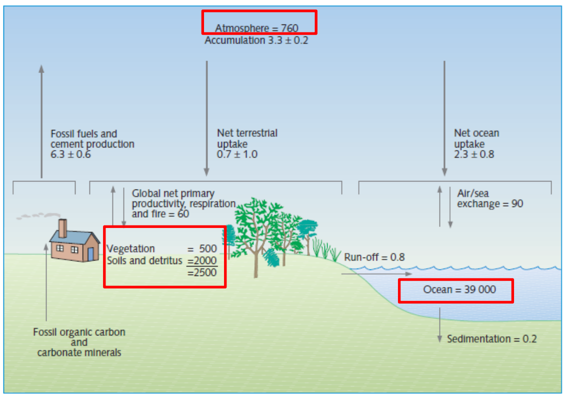
4. Greenhouse gases

Carbon dioxide and the carbon cycle

Carbon dioxide is not destroyed but redistributed among the various carbon reservoirs.

Carbon dioxide is therefore different from other greenhouse gases that are destroyed by chemical action in the atmosphere .



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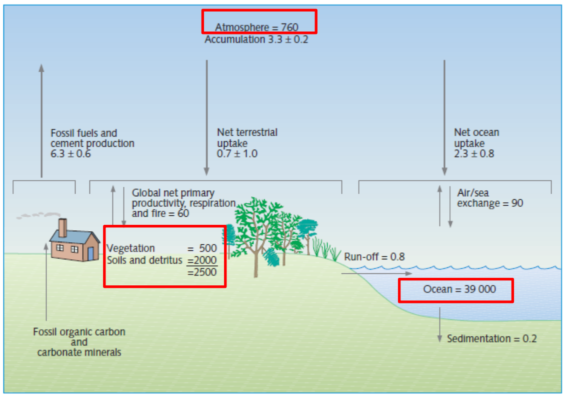
4. Greenhouse gases

Carbon dioxide and the carbon cycle

The carbon reservoirs exchange carbon between themselves on a wide range of timescales determined by their respective turnover times

They range from less **than a year to decades**
(for exchange with the top layers of the ocean and the land biosphere)
to millennia
(for exchange with the deep ocean or long-lived soil pools).



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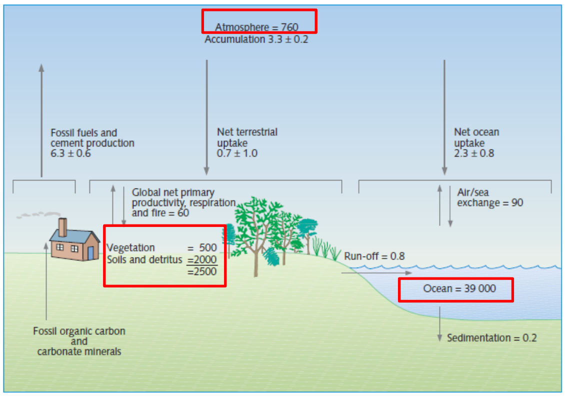
4. Greenhouse gases

Carbon dioxide and the carbon cycle

These timescales are generally much longer

than the average time a particular carbon dioxide molecule spends in the atmosphere,

which is only about four years.



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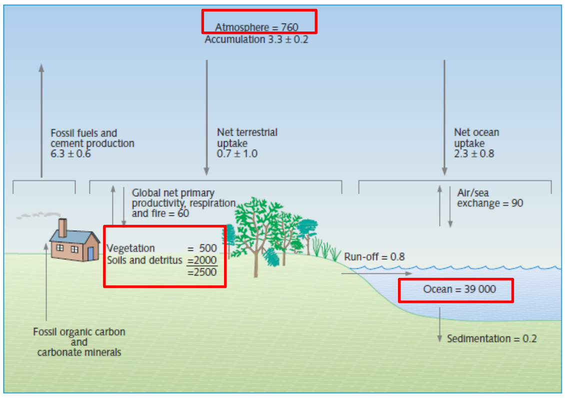
4. Greenhouse gases

Carbon dioxide and the carbon cycle

The **Industrial Revolution** disturbed this balance and since its beginning over **600 thousand million tonnes** (or gigatonnes, Gt) of carbon have been emitted into the atmosphere from fossil fuel burning.



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4. Greenhouse gases

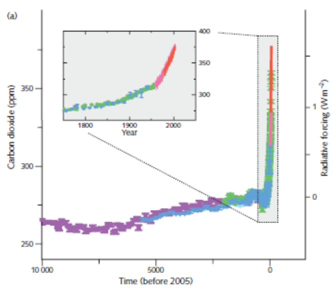
This has resulted in a concentration of CO2 in the atmosphere that has increased by about **36%**,

From **280 ppm** around 1700 to a value of over **410 ppm** at the present day.

A greater concentration than for at least 650 000 years

Data from Ice cores

Figure 3.2 Atmospheric carbon dioxide concentration. (a) Over the last 10 000 years (inset since 1750) from various ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). Corresponding radiative forcings shown on right-hand axis. (b) Annual changes in global mean and their five-year means from two different measurement networks (red and black stepped lines). The five-year means smooth out short-term perturbations associated with strong El Niño Southern Oscillation (ENSO) events in 1972, 1982, 1987 and 1997. The upper dark green line shows the annual increases that would occur if all fossil fuel emissions stayed in the atmosphere and there were no other emissions.



4. Greenhouse gases

Keeling curve

Accurate measurements (not ice cores) – only since 1959 from an observatory near the summit of Mauna Loa in Hawaii,

from 1995 to 2005 CO2 increased on average 1.9 ppm year-1.
(an increase from the average for the 1990s of about 1.5 ppm) although there are large variations from year to year

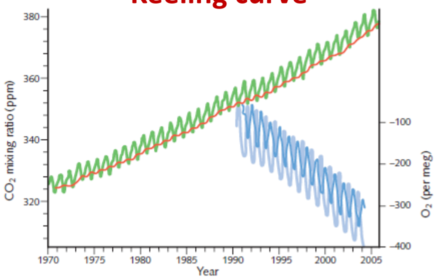


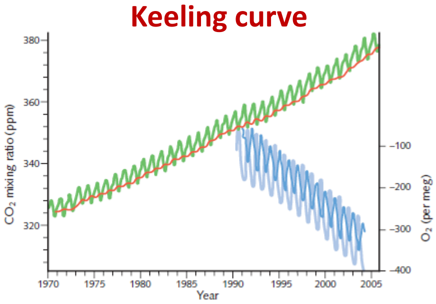
Figure 3.3 Carbon dioxide concentrations (monthly averages) observed from Mauna Loa, Hawaii, 19°N, green and from Baring Head, New Zealand, 41°S, red. Also shown are measurements of deviations in the O_2/N_2 ratio from an arbitrary reference multiplied by 10^6 from samples from Alert, Canada, 82°N, blue and from Cape Grim, Australia, 41°S, dark blue (after Manning and Keeling).

This increase spread through the atmosphere adds about 3.8 Gt to the atmospheric carbon reservoir each year.

4. Greenhouse gases

Keeling curve

Charles David Keeling directed this program to measure the concentrations of CO_2 in the atmosphere



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The value of the Mauna Loa record soon became readily apparent.

Within just a year or two, Charles David Keeling had shown that CO_2 underwent a regular seasonal cycle, reflecting the seasonal growth and decay of land plants in the northern hemisphere, as well as a regular long-term rise driven by the burning of fossil-fuels.

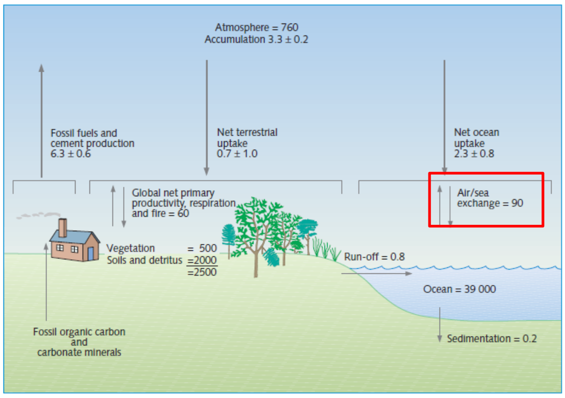
4. Greenhouse gases

Carbon dioxide and the carbon cycle

What happens in the oceans?

Carbon dioxide dissolves in water – ocean acidification;

Carbon dioxide is continually being exchanged with the air above the ocean across the whole ocean surface (about 90 Gt per year is so exchanged).



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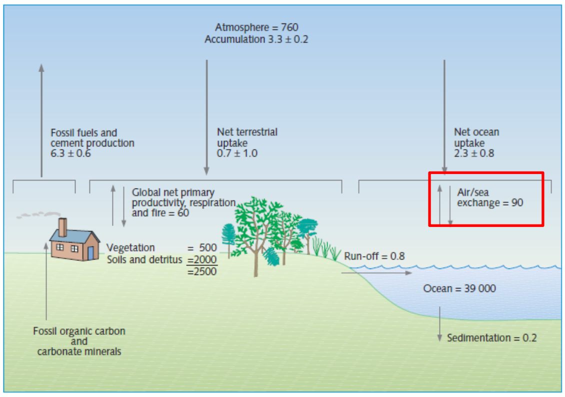
4. Greenhouse gases

Carbon dioxide and the carbon cycle

An equilibrium is established between the concentration of carbon dioxide dissolved in the surface waters and the concentration in the air above the surface.

The chemical laws governing this equilibrium are such that if the **atmospheric concentration** changes by 10% , the concentration in solution in the **water** changes by only **one-tenth** of this: **1%.**



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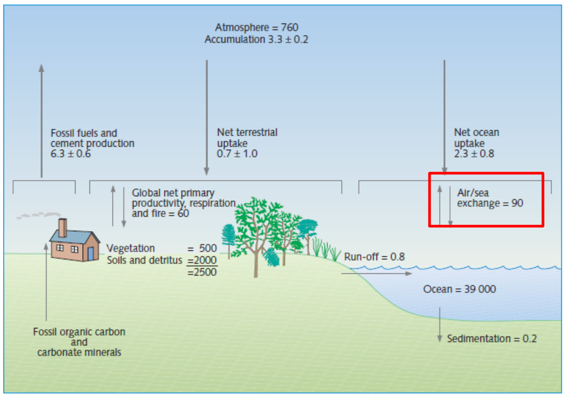
4. Greenhouse gases

Carbon dioxide and the carbon cycle

This change will occur quite rapidly in the upper waters of the ocean (top 100 m or so),
thus enabling part of the anthropogenic CO2 added to the atmosphere to be taken up quite rapidly.



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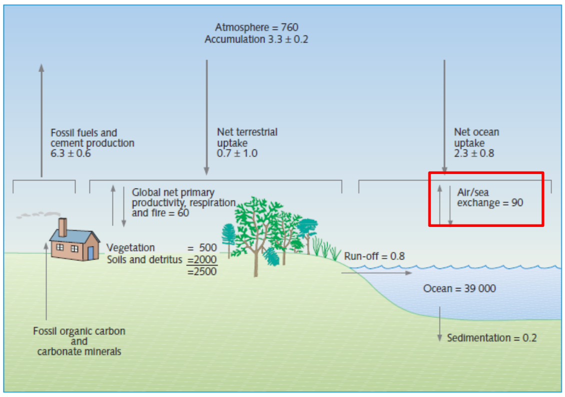
4. Greenhouse gases

Carbon dioxide and the carbon cycle

Absorption in the lower levels in the ocean takes longer;

mixing of surface water with water at lower levels takes up to several hundred years

or for the deep ocean over a thousand years!



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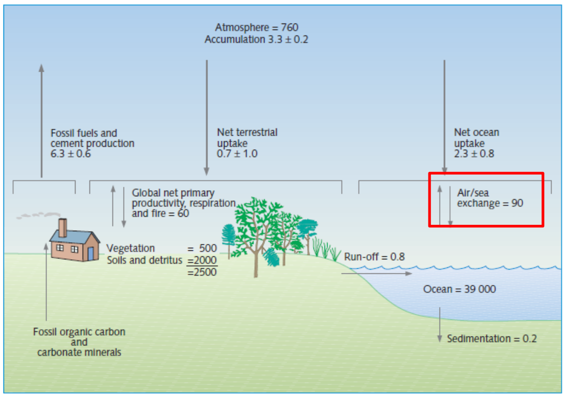
4. Greenhouse gases

Carbon dioxide and the carbon cycle

So the oceans do not provide as immediate a sink for increased atmospheric CO2 carbon dioxide as might be suggested by the size of the exchanges with the large ocean reservoir.

For short-term changes only the surface layers of water play a large part in the carbon cycle



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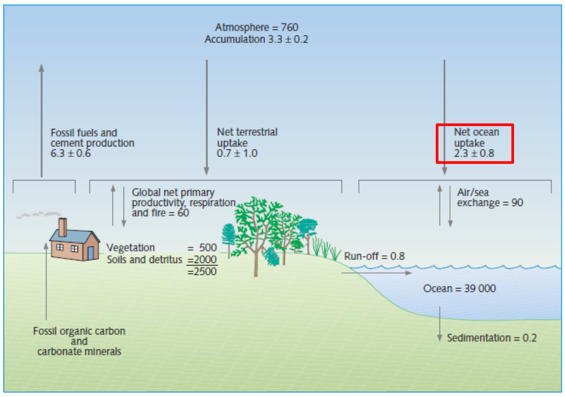
4. Greenhouse gases

Carbon dioxide and the carbon cycle

Nonetheless, it is estimated that about 2 Gt (± 0.8 Gt) of the carbon dioxide added to the atmosphere each year ends up in the oceans



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4. Greenhouse gases

Carbon dioxide and the carbon cycle

Summing up:

Natural Ocean Carbon Cycle

- The oceans contain about 50 times more CO_2 than the atmosphere and 19 times more than the land biosphere.

- CO_2 moves between the atmosphere and the ocean by molecular diffusion when there is a difference between CO_2 gas pressure (pCO_2) between the atmosphere and oceans. For example, when the atmospheric pCO_2 is higher than the surface ocean, CO_2 diffuses across the air-sea boundary into the sea water.

4. Greenhouse gases

Carbon dioxide and the carbon cycle

Natural Ocean Carbon Cycle

- The oceans are able to hold much more carbon than the atmosphere because most of CO_2 that diffuses into the oceans reacts with the water to form carbonic acid and its dissociation products, bicarbonate and carbonate ions .

- The conversion of CO_2 gas into nongaseous forms such as carbonic acid and bicarbonate and carbonate ions effectively reduces the CO_2 gas pressure in the water, thereby allowing more diffusion from the atmosphere.

- The oceans are mixed much more slowly than the atmosphere, so there are large horizontal and vertical changes in CO_2 concentration. In general, tropical waters release CO_2 to the atmosphere, whereas high-latitude oceans take up CO_2 from the atmosphere.

4. Greenhouse gases

Carbon dioxide and the carbon cycle

Natural Ocean Carbon Cycle

-CO_2 is also about 10 percent higher in the deep ocean than at the surface. The two basic mechanisms that control the distribution of carbon in the oceans are referred to as the

- **solubility pump** and the
- **biological pump**.

4. Greenhouse gases

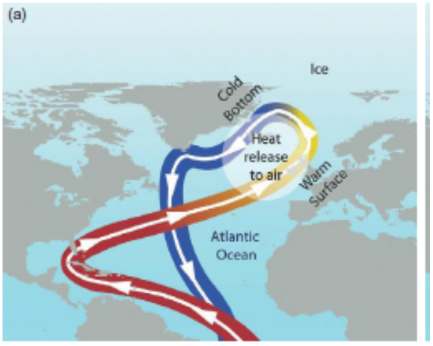
Carbon dioxide and the carbon cycle

Solubility Pump.

The solubility pump is driven by two principal factors. First, more than twice as much CO_2 can dissolve into cold polar waters than in the warm equatorial waters.

As major ocean currents (e.g., the Gulf Stream) move waters from the tropics to the poles, they are cooled and can take up more CO_2 from the atmosphere.

Second, the high latitude zones are also places where deep waters are formed. As the waters are cooled, they become denser and sink into the ocean's interior, taking with them the CO_2 accumulated at the surface



4. Greenhouse gases

Carbon dioxide and the carbon cycle

Biological Pump

Another process that moves CO_2 away from the surface ocean is called the biological pump.

Growth of marine plants (e.g., phytoplankton) takes CO_2 and other chemicals from sea water to make plant tissue. Zooplankton then provide the basis for the food web for all animal life in the sea. Because photosynthesis requires light, phytoplankton only grow in the near surface ocean, where sufficient light can penetrate.

Although most of the CO_2 taken up by phytoplankton is recycled near the surface, a substantial fraction, perhaps 30 percent, sinks into the deeper waters before being converted back into CO_2 by marine bacteria. Only about 0.1 percent reaches the seafloor to be buried in the sediments.

4. Greenhouse gases

Other greenhouse gases

Methane

Methane is the main component of natural gas.

Its common name used to be marsh gas

because it can be seen bubbling up from marshy areas where organic material is decomposing.

Rice paddy fields have an adverse environmental impact because of the large quantities of methane gas they generate. World methane production due to paddy fields has been estimated to be in the range of 30 to 90 million tonnes per year.

4. Greenhouse gases

Other greenhouse gases

Methane

Data from ice cores show that for at least 2000 years before 1800 its concentration in the atmosphere was about 700 ppb.

Since then its concentration has more than doubled to a value that the ice core record shows is unprecedented over at least the last 650 000 years.

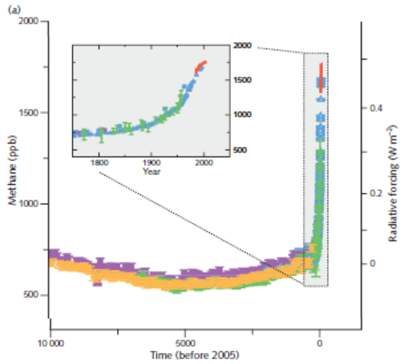


Figure 3.6 Change in (a) methane and (b) nitrous oxide concentration (mole fraction in ppb) over the last 10 000 years (insets from 1750) determined from ice cores (symbols with different colours from different studies) and atmospheric samples (red lines). Radiative forcing since the pre-industrial era due to the increases is plotted on the right-hand axes.

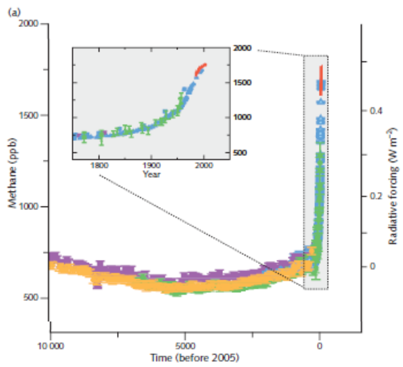
4. Greenhouse gases

Other greenhouse gases

Methane

Although the concentration of methane in the atmosphere is much less than that of carbon dioxide (only 1.775 ppm in 2005 compared with about 380 ppm for carbon dioxide),

its greenhouse effect is far from negligible. That is because the enhanced greenhouse effect caused by a molecule of methane is about <u>8x</u> that of a molecule of carbon dioxide .



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4. Greenhouse gases

Other greenhouse gases

Methane

The main natural source of methane is from wetlands.

A variety of other sources result directly or indirectly from human activities, for instance from leakage from natural gas pipelines and from oil wells, from generation in rice paddy fields, from enteric fermentation (belching) from cattle and other livestock, from the decay of rubbish in landfi ll sites and from wood and peat burning

Table 3.2 Estimated sources and sinks of methane in millions of tonnes per year. The first column of data shows the best estimate from each source; the second column illustrates the uncertainty in the estimates by giving a range of values

	Best estimate	Uncertainty
Sources		
Natural		
Wetlands	150	(90–240)
Termites	20	(10–50)
Ocean	15	(5–50)
Other (including hydrates)	15	(10–40)
Human-generated		
Coal mining, natural gas, petroleum industry	100	(75–110)
Rice paddies	60	(30–90)
Enteric fermentation	90	(70–115)
Waste treatment	25	(15–70)
Landfills	40	(30–70)
Biomass burning	40	(20–60)
Sinks		
Atmospheric removal	545	(450–550)
Removal by soils	30	(15–45)
Atmospheric increase	22	(35–40)

For some more recent estimates see Table 7.7 in Denman, K. L., Brasseur, G. *et al.*, Chapter 7, in Solomon *et al.* (eds.) *Climate Change 2007: The Physical Science Basis*. The figure for atmospheric increase is an average for the 1990s; note that from 1999 to 2005 the increase was close to zero.

Belching - is the release of gas from the digestive tract (mainly esophagus and stomach) through the mouth

4. Greenhouse gases

Other greenhouse gases

Methane

The main process for the removal of methane from the atmosphere is through chemical destruction.

It reacts with hydroxyl (OH) radicals, which are present in the atmosphere because of processes involving sunlight, oxygen, ozone and water vapour.

Table 3.2 Estimated sources and sinks of methane in millions of tonnes per year. The first column of data shows the best estimate from each source; the second column illustrates the uncertainty in the estimates by giving a range of values

	Best estimate	Uncertainty
Sources		
Natural		
Wetlands	150	(90–240)
Termites	20	(10–50)
Ocean	15	(5–50)
Other (including hydrates)	15	(10–40)
Human-generated		
Coal mining, natural gas, petroleum industry	100	(75–110)
Rice paddies	60	(30–90)
Enteric fermentation	90	(70–115)
Waste treatment	25	(15–70)
Landfills	40	(30–70)
Biomass burning	40	(20–60)
Sinks		
Atmospheric removal	545	(450–550)
Removal by soils	30	(15–45)
Atmospheric increase	22	(35–40)

For some more recent estimates see Table 7.7 in Denman, K. L., Brasseur, G. *et al.*, Chapter 7, in Solomon *et al.* (eds.) *Climate Change 2007: The Physical Science Basis*. The figure for atmospheric increase is an average for the 1990s; note that from 1999 to 2005 the increase was close to zero.

Belching - is the release of gas from the digestive tract (mainly esophagus and stomach) through the mouth

4. Greenhouse gases

Other greenhouse gases

Methane

The average lifetime of methane in the atmosphere is determined by the rate of this loss process. At about 12 years it is much shorter than the lifetime of carbon dioxide .

Table 3.2 Estimated sources and sinks of methane in millions of tonnes per year. The first column of data shows the best estimate from each source; the second column illustrates the uncertainty in the estimates by giving a range of values

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Belching - is the release of gas from the digestive tract (mainly esophagus and stomach) through the mouth

4. Greenhouse gases

Other greenhouse gases

Nitrous oxide

Nitrous oxide, used as a common anaesthetic and known as laughing gas, is another minor greenhouse gas.

Its concentration in the atmosphere of about 0.3 ppm is rising at about 0.25% per year and is about 16% greater than in pre-industrial times.

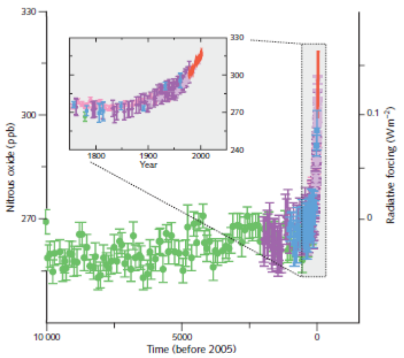


Figure 3.6 Change in (a) methane and (b) nitrous oxide concentration (mole fraction in ppb) over the last 10 000 years (insets from 1750) determined from ice cores (symbols with different colours from different studies) and atmospheric samples (red lines). Radiative forcing since the pre-industrial era due to the increases is plotted on the right-hand axes.

4. Greenhouse gases

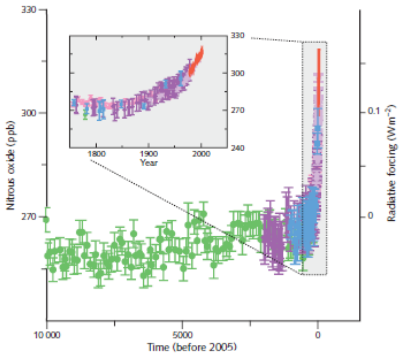
Other greenhouse gases

Nitrous oxide

The largest emissions to the atmosphere are associated with natural and agricultural ecosystems;

those linked with human activities are probably due to increasing fertiliser use.

Biomass burning and the chemical industry (for example, nylon production) also play some part.



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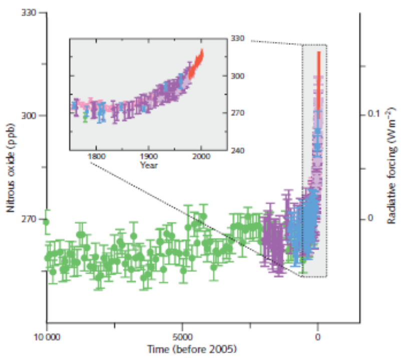
4. Greenhouse gases

Other greenhouse gases

Nitrous oxide

The sink of nitrous oxide is photodissociation in the stratosphere and reaction with electronically excited oxygen atoms, leading to an atmospheric lifetime of about 120 years .



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4. Greenhouse gases

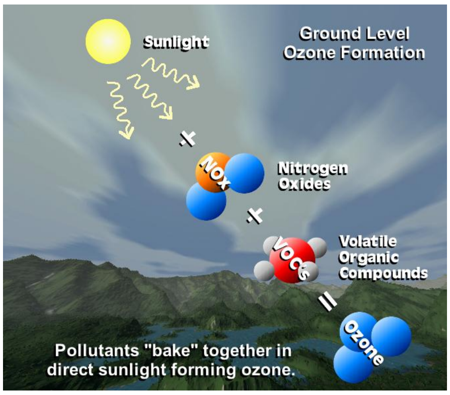
Other greenhouse gases

Nitrous oxide and ozone

Ozone is found in two places in the Earth's atmosphere.

1- Ozone in the Earth's upper atmosphere (stratosphere) protects life from harmful ultraviolet (UV) rays from the sun.

2- High concentrations of ozone found in the Earth's lower atmosphere (troposphere) are hazardous to life.



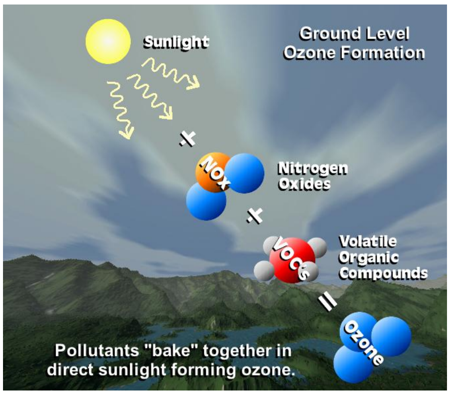
4. Greenhouse gases

Other greenhouse gases

Nitrous oxide and ozone

How is Tropospheric Ozone Created?

Ozone in the lower atmosphere (troposphere) is created through a series of reactions involving man-made chemical species such as Nitrogen oxides (NOx) and volatile organic compounds (VOCs). Chemical species that contribute to ground level ozone.



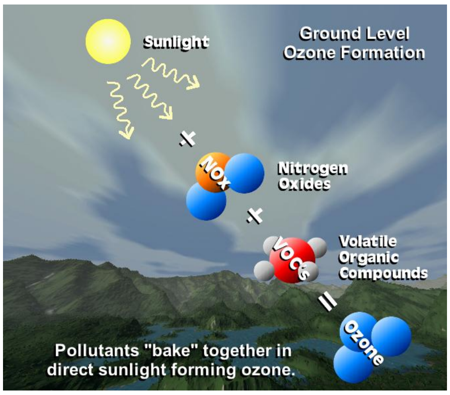
4. Greenhouse gases

Other greenhouse gases

Nitrous oxide and ozone

How does it affect me?

In high concentrations, ground level ozone is toxic to human tissue. When ozone levels get too high, the EPA issues "Code Red" days, on which humans should limit their time outdoors.



4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

The CFCs are man-made chemicals which, because they vaporise just below room temperature and because they are non-toxic and non-flammable, appear to be ideal for use in refrigerators, the manufacture of insulation and aerosol spray cans.

Since they are so chemically unreactive, once they are released into the atmosphere they remain for a long time – 100 or 200 years – before being destroyed.

4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

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4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

As their use increased rapidly through the 1980s their concentration in the atmosphere has been building up so that they are now present (adding together all the different CFCs) in about 1 ppb (part per billion – by volume).

This may not sound very much, but it is quite enough to cause two serious environmental problems.

The first problem is that they destroy ozone!!

Ozone (O_3), a molecule consisting of three atoms of oxygen, is an extremely reactive gas present in small quantities in the stratosphere.

4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

Ozone molecules are formed through the action of ultraviolet radiation from the Sun on molecules of oxygen.

On the other hand, they are in turn destroyed by a natural process as they absorb solar ultraviolet radiation at slightly longer wavelengths – radiation that would otherwise be harmful to us and to other forms of life at the Earth's surface.

↓

The amount of ozone in the stratosphere is determined by the balance between these two processes.

4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

What happens when CFC molecules move into the stratosphere is that some of the chlorine atoms they contain are stripped off, also by the action of ultraviolet sunlight.

↓

These chlorine atoms readily react with ozone, reducing it back to oxygen and adding to the rate of destruction of ozone. This occurs in a catalytic cycle – <u>one chlorine atom can destroy many molecules of ozone .</u>

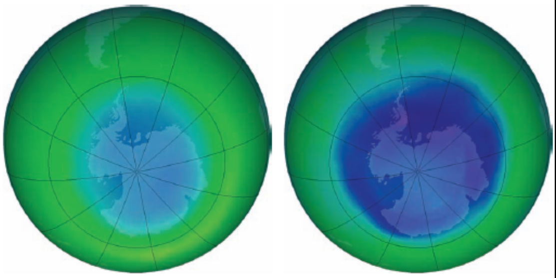
4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

The problem of ozone destruction was brought to world attention in 1985 when Joe Farman, Brian Gardiner and Jonathan Shanklin at the British Antarctic Survey

discovered a region of the atmosphere over Antarctica where, during the southern spring, <u>about half the ozone overhead disappeared.</u>



Ozone depletion can be seen by comparing ozone levels in September 1980 and September 2008. The dark blue and purple areas denote where the ozone layer is thinnest.

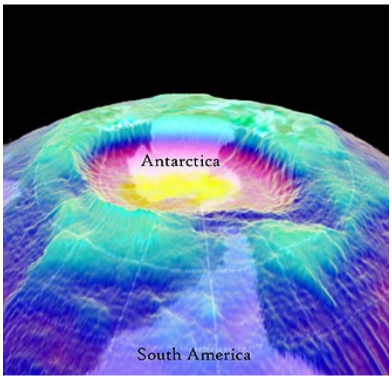
4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

Because of these serious consequences of the use of CFCs, international action has been taken.

Many governments have signed the Montreal Protocol set up in 1987 which, together with the **Amendments agreed in London in 1991 and in Copenhagen in 1992,** required that manufacture of CFCs be phased out completely by the year 1996 in industrialised countries and by 2006 in developing countries.



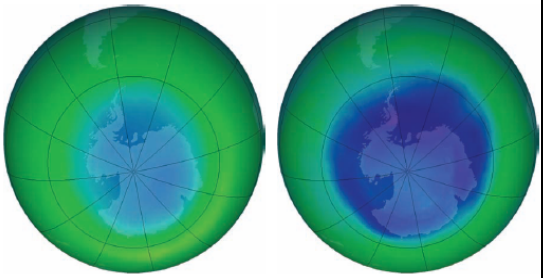
4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

Because of this action the concentration of CFCs in the atmosphere is no longer increasing.

However, since they possess a long life in the atmosphere, little decrease will be seen for some time and substantial quantities will be present well over 100 years from now .

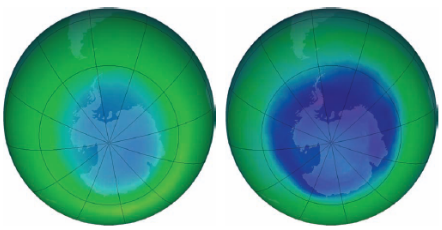


Ozone depletion can be seen by comparing ozone levels in September 1980 and September 2008. The dark blue and purple areas denote where the ozone layer is thinnest.

4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

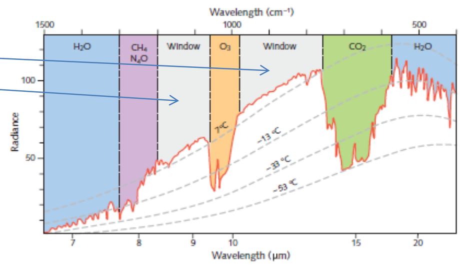


Ozone depletion can be seen by comparing ozone levels in September 1980 and September 2008. The dark blue and purple areas denote where the ozone layer is thinnest.

So much for the problem of ozone destruction.

The other problem with CFCs and ozone, the one which concerns us here, is that they are both greenhouse gases.

They possess absorption bands in the region known as the longwave atmospheric window where few other gases absorb.

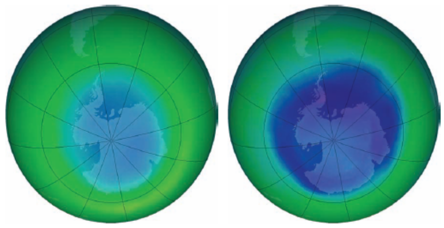


4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

Because, as we have seen, the CFCs destroy some ozone, the greenhouse effect of the CFCs is partially compensated by the reduced greenhouse effect of atmospheric ozone.



Ozone depletion can be seen by comparing ozone levels in September 1980 and September 2008. The dark blue and purple areas denote where the ozone layer is thinnest.

First considering the CFCs on their own, a CFC molecule added to the atmosphere has a greenhouse effect 5000 to 10 000 times greater than an added molecule of carbon dioxide.

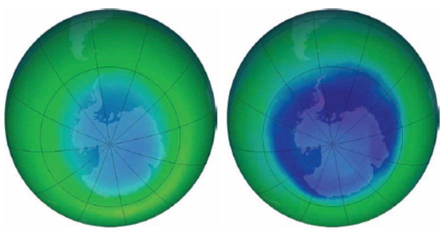
Thus, despite their very small concentration compared, for instance, with carbon dioxide, they have a significant greenhouse effect.

4. Greenhouse gases

Other greenhouse gases

Chlorofluorocarbons (CFCs) and ozone

Ozone depletion is concentrated at high latitudes while the greenhouse effect of the CFCs is uniformly spread over the globe.



Ozone depletion can be seen by comparing ozone levels in September 1980 and September 2008. The dark blue and purple areas denote where the ozone layer is thinnest.

In tropical regions there is virtually no ozone depletion so no change in the ozone greenhouse effect.

At mid latitudes, very approximately, the greenhouse effects of ozone reduction and of the CFCs compensate for each other.

In polar regions, the reduction in the greenhouse effect of ozone more than compensates for the greenhouse warming effect of the CFCs

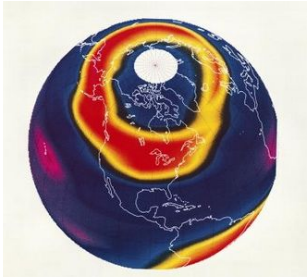
4. Greenhouse gases

Other greenhouse gases

Other halocarbons

As CFCs are phased out, they are being replaced to some degree by other halocarbons
– hydrochlorofluorocarbons (HCFCs) and
- Hydrofluorocarbons (HFCs).

In Copenhagen in 1992, the international community decided that **HCFCs** would also be phased out by the year 2030.



While being less destructive to ozone than the CFCs, they are still greenhouse gases.

The **HFCs contain no chlorine or bromine**, so they do not destroy ozone and are not covered by the Montreal Protocol.

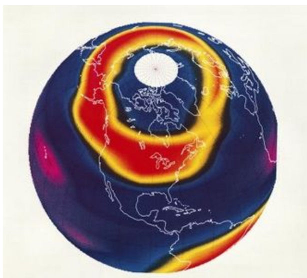
4. Greenhouse gases

Other greenhouse gases

Other halocarbons

Because of their shorter lifetime (~ typically tens (dezenas) rather than hundreds of years,

the concentration in the atmosphere of both the HCFCs and the HFCs,
and therefore their contribution to global warming for a given rate
of emission,
will be less than for the CFCs!!



However, since their rate of manufacture could increase substantially their potential contribution to greenhouse warming is being included alongside other greenhouse gases

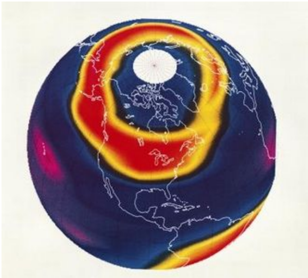
4. Greenhouse gases

Other greenhouse gases

Other halocarbons

Concern has also extended to some other related compounds which are greenhouse gases,
-perfluorocarbons (e.g. CF_4 , C_2F_6) and
- sulphurhexafluoride (SF_6), which are produced in some industrial processes.

Because they possess very long atmospheric lifetimes, probably more than 1000 years, all emissions of these gases accumulate in the atmosphere and will continue to influence climate for thousands of years.



They are also therefore being included as potentially important greenhouse gases .

4. Greenhouse gases

Particles in the atmosphere

Small particles suspended in the atmosphere (often known as *aerosol*) affect its energy balance because they both absorb radiation from the Sun and scatter it back to space.

Definition of aerosol(s) - A collection of airborne solid or liquid particles with a typical size between 0.01 and 10 µm that reside in the atmosphere from periods of hours to days or months. They may be natural or anthropogenic in origin.
They influence climate directly through absorbing or scattering radiation or indirectly by acting as cloud condensation nuclei.

4. Greenhouse gases

Particles in the atmosphere

We can easily see the effect of this on a bright day in the summer with a light wind when downwind of an industrial area.

Although no cloud appears to be present, the Sun appears hazy.

It is called 'industrial haze'.

4. Greenhouse gases

Particles in the atmosphere

Under these conditions a significant proportion of the sunlight incident at the top of the atmosphere **is being lost as it is scattered back and out of the atmosphere** by the millions of small particles (typically between 0.001 and 0.01 mm in diameter) in the haze.

4. Greenhouse gases

Particles in the atmosphere

Atmospheric particles come from a variety of sources.

-natural causes:
-1) blown off the land surface, especially in desert areas,

-2) forest fires

- 3) from volcanoes – **the Pinatubo volcano which erupted in 1991 provides a good example.**

4. Greenhouse gases

Particles in the atmosphere

- Other particles arise from human activities.

Over the past ten years a large number of observations especially from satellite-borne instruments have provided much needed information about:

- the aerosol distribution from both natural and anthropogenic sources in both space and time

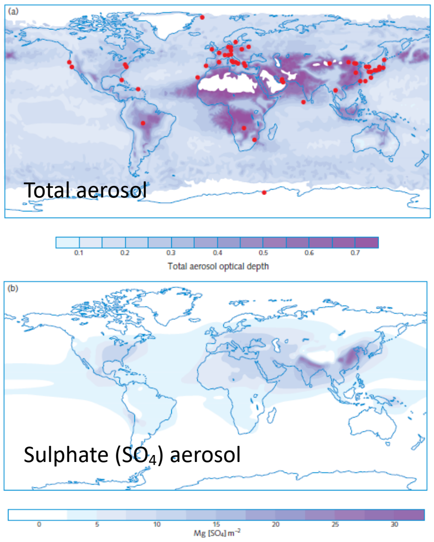


Figure 3.7 Distribution of atmospheric aerosols. (a) Total aerosol optical depth at a mid-visible wavelength (for definition see Glossary) due to natural plus anthropogenic aerosols determined from observations by the satellite instrument MODIS, averaged from August to October 2001. Also indicated are the locations of aerosol lidar network sites (red circles). (b) The amount of sulphate (SO_4) aerosol in the atmosphere in mg[SO_4] m^{-2} from human activities, 'background' non-explosive volcanoes and natural di-methyl sulphate (DMS) from ocean plankton, averaged over the decade of the 1990s calculated by the Hadley Centre model HadGEM1.

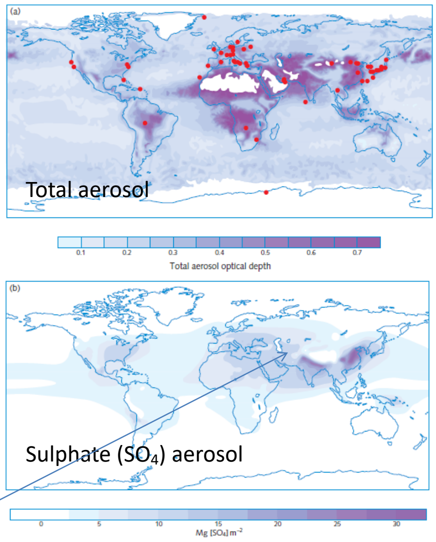
4. Greenhouse gases

Particles in the atmosphere

The most important of the aerosols from anthropogenic sources are:

- **sulphate particles** that are formed as a result of chemical action on **sulphur dioxide**, a gas that is produced in large quantities by power stations and other industries in which coal and oil are burnt.

These particles remain in the atmosphere only for about five days on average, their effect is mainly confined to regions near the sources, i.e. the major industrial regions of the northern hemisphere



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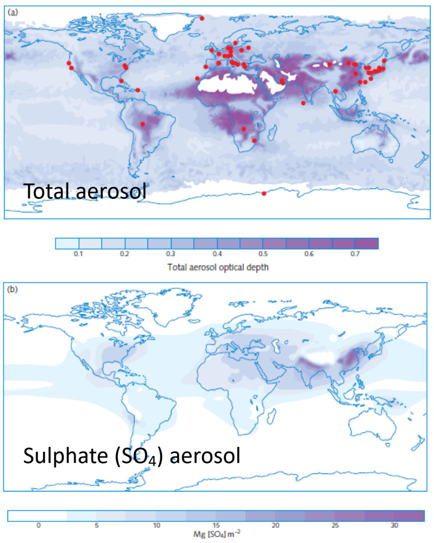
4. Greenhouse gases

Particles in the atmosphere

Sulphate particles scatter sunlight and provide a negative forcing, globally averaged estimated as −0.4 ± 0.2 W m −2 .

Over limited regions of the northern hemisphere the radiative effect of these particles **is comparable** in size, **although opposite in effect**, to that of human-generated greenhouse gases up to the present time.



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4. Greenhouse gases

Particles in the atmosphere

Figure 3.8 illustrates a model estimate of the substantial effect on global atmospheric temperature of removing all sulphate aerosol in the year 2000.

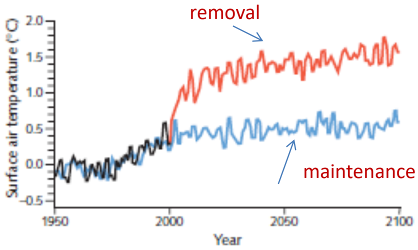


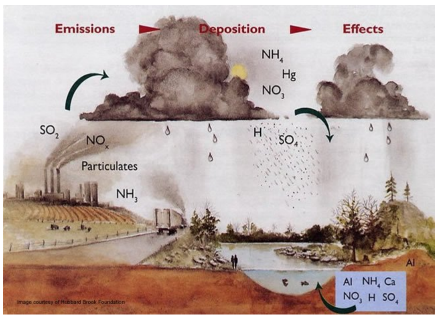
Figure 3.8 A model calculation of the effect on global mean surface air temperature of removing all sulphate aerosols in the year 2000 (red line) compared with maintaining the global burden of sulphate aerosols at the 2000 level for the twenty-first century (blue line).

4. Greenhouse gases

Particles in the atmosphere

An important factor that will influence the future concentrations of sulphate particles is '**acid rain**' pollution, caused mainly by the **sulphur dioxide emissions**.

This leads to the degradation of forests and fish stocks in lakes especially in regions downwind of major industrial areas.

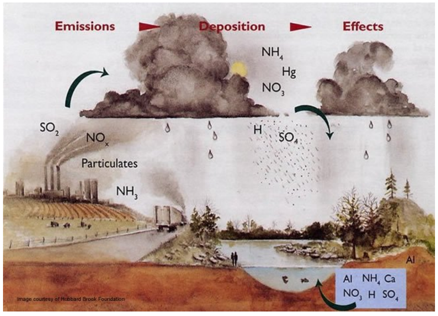


4. Greenhouse gases

"Acid rain"

Broad term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids.

The precursors, or chemical forerunners, of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion.

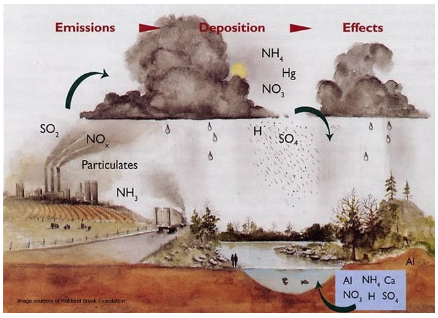


4. Greenhouse gases

"Acid rain"

In the United States, roughly 2/3 of all SO_2 and 1/4 of all NO_x come from electric power generation that relies on burning fossil fuels, like coal.

Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid.



4. Greenhouse gases

Particles in the atmosphere

At a global scale, sulphur emissions are likely to rise **much less** rapidly than emissions of carbon dioxide.

In fact, they are likely to fall during the twenty-first century to below their 2000 value

thus also removing part of the offset they are currently providing against the increase in radiative forcing from greenhouse gases .

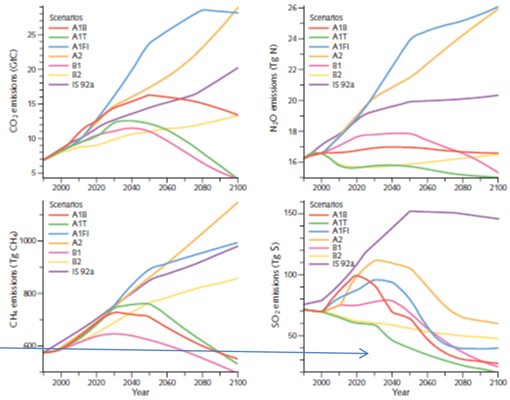


Figure 6.1 Anthropogenic emissions of carbon dioxide, methane, nitrous oxide and sulphur dioxide for the six illustrative SRES scenarios, A1B, AIT, A1FI, A2, B1 and B2. For comparison the IS 92a scenario is also shown.

4. Greenhouse gases

Particles in the atmosphere

Yet,
the radiative forcing from particles **can be positive or negative** depending on the nature of the particles.

For instance, soot (dust) particles from fossil fuel burning absorb sunlight and possess a positive forcing globally averaged estimated as 0.2 ± 0.15 W m−2 .

Other smaller anthropogenic contributions to aerosol radiative forcing come from biomass burning (e.g. the burning of forests), organic carbon particles from fossil fuel and nitrate and mineral dust particles.

4. Greenhouse gases

Particles in the atmosphere

That is why in Figure 3.11 estimates are given of the **total radiative forcing from aerosol** *particles together with the* associated uncertainty .

LOSU – "Level scientific understanding"

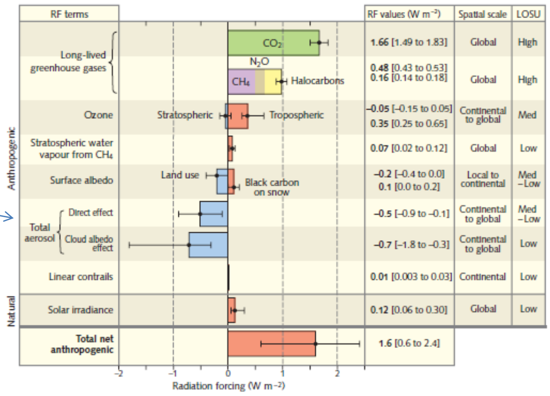


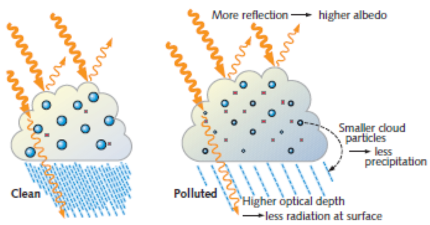
Figure 3.11 Global, annual mean radiative forcings (W m^{-2}) due to a number of agents for the period from pre-industrial (1750) to 2005. The size of the rectangular bar denotes a best estimate value; the horizontal lines indicate estimates of the uncertainty (90% confidence) ranges. To each forcing an indication is given of the geographical extent (spatial scale) and a 'level of scientific understanding' (LOSU) index is accorded. This latter represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the mechanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing.

4. Greenhouse gases

Particles in the atmosphere

So far for aerosol we have been describing ***direct* radiative forcing. But,** There is a further way by which particles in the atmosphere could influence the climate:

Figure 3.9 Schematic illustrating the cloud albedo and lifetime indirect effect on radiative forcing. Larger numbers of smaller particles in polluted clouds lead to more reflection of solar radiation from the cloud top, less radiation at the surface, less precipitation and a longer cloud lifetime.



Their effect on cloud formation that is described as *indirect* radiative forcing.

(It arises from the influence of the number of particles and their size on cloud radiative properties)

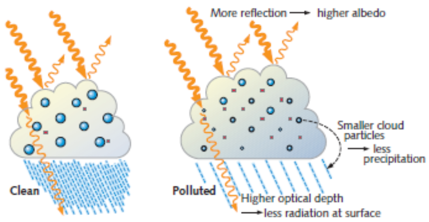
4. Greenhouse gases

Particles in the atmosphere

If particles are present in large numbers when clouds are forming, the resulting cloud consists of a large number of smaller drops similar to what happens as polluted fogs form in cities.

Such a cloud will be more highly reflecting to sunlight than one consisting of larger particles.

Figure 3.9 Schematic illustrating the cloud albedo and lifetime indirect effect on radiative forcing. Larger numbers of smaller particles in polluted clouds lead to more reflection of solar radiation from the cloud top, less radiation at the surface, less precipitation and a longer cloud lifetime.



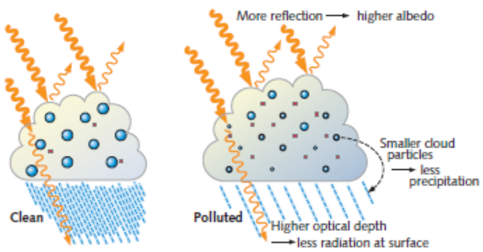
4. Greenhouse gases

Particles in the atmosphere

Further the droplet size and number influence:

-the precipitation efficiency,
- the lifetime of clouds, and
- hence the geographic extent of cloudiness

Figure 3.9 Schematic illustrating the cloud albedo and lifetime indirect effect on radiative forcing. Larger numbers of smaller particles in polluted clouds lead to more reflection of solar radiation from the cloud top, less radiation at the surface, less precipitation and a longer cloud lifetime.



4. Greenhouse gases

Particles in the atmosphere

LOSU – "Level scientific understanding"

Substantial uncertainty therefore remains in estimates of their magnitude

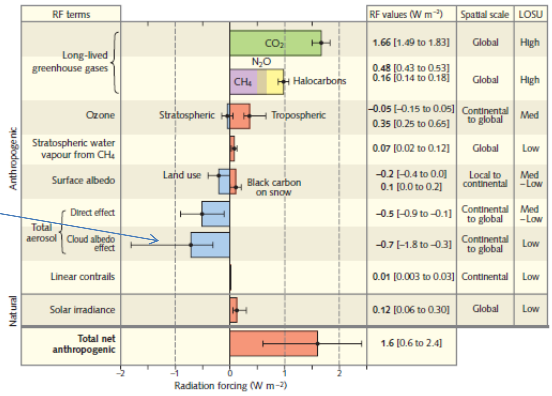


Figure 3.11 Global, annual mean radiative forcings (W m⁻²) due to a number of agents for the period from pre-industrial (1750) to 2005. The size of the rectangular bar denotes a best estimate value; the horizontal lines indicate estimates of the uncertainty (90% confidence) ranges. To each forcing an indication is given of the geographical extent (spatial scale) and a 'level of scientific understanding' (LOSU) index is accorded. This latter represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the mechanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing.

4. Greenhouse gases

Particles in the atmosphere

LOSU – "Level scientific understanding"

A particular effect on cloudiness arises from aircraft flying in the upper troposphere

which influence high cloud cover through their emissions of water vapour and of particles that can act as nuclei on which condensation can occur.

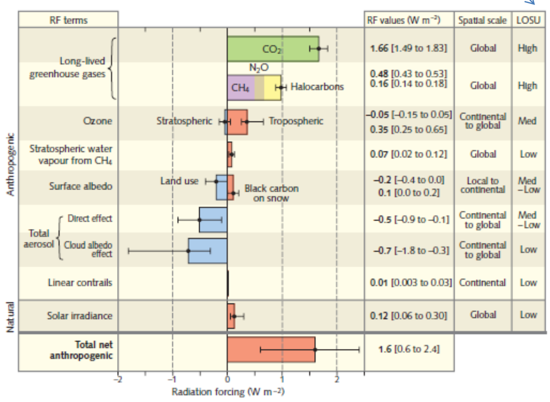


Figure 3.11 Global, annual mean radiative forcings (W m⁻²) due to a number of agents for the period from pre-industrial (1750) to 2005. The size of the rectangular bar denotes a best estimate value; the horizontal lines indicate estimates of the uncertainty (90% confidence) ranges. To each forcing an indication is given of the geographical extent (spatial scale) and a 'level of scientific understanding' (LOSU) index is accorded. This latter represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the mechanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing.

4. Greenhouse gases

Particles in the atmosphere

Extensive formation of contrails (***vapor trails***) in the upper troposphere
by aircraft frequently occurs;

Persistent contrails also tend to lead to increased overall cloudiness in the region where the contrails have formed. This is called ***aviation induced cloudiness***

LOSU – "Level scientific understanding"

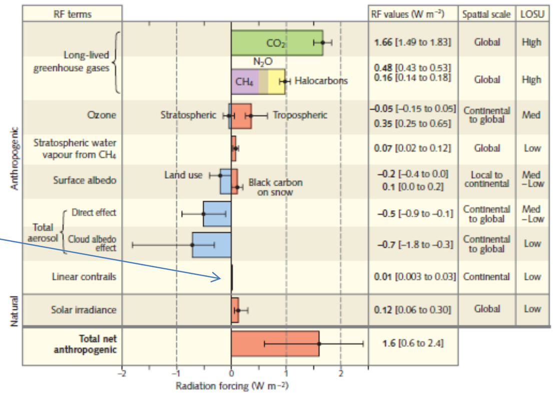


Figure 3.11 Global, annual mean radiative forcings (W m^{-2}) due to a number of agents for the period from pre-industrial (1750) to 2005. The size of the rectangular bar denotes a best estimate value; the horizontal lines indicate estimates of the uncertainty (90% confidence) ranges. To each forcing an indication is given of the geographical extent (spatial scale) and a 'level of scientific understanding' (LOSU) index is accorded. This latter represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the mechanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing.

4. Greenhouse gases

Summary

• The dominant forcing for climate change over the last two centuries has been that from the increase of long-lived greenhouse gases, especially carbon dioxide.

• Since the mid twentieth century, significant offset to the positive forcing from greenhouse gases has arisen from negative forcing due to aerosols, especially from sulphates.

• Significant progress has been made in the understanding and estimating of indirect aerosol forcing since the 2001 IPCC report – although substantial uncertainties remain.

4. Greenhouse gases

Summary

• Other smaller forcings are due to changes in ozone (stratospheric and tropospheric), stratospheric water vapour and land surface albedo and persistent contrails from aircraft.

Definition of albedo - The fraction of light reflected by a surface, often expressed as a percentage. Snow-covered surfaces have a high albedo level; vegetation-covered surfaces have a low albedo, because of the light absorbed for *photosynthesis.*

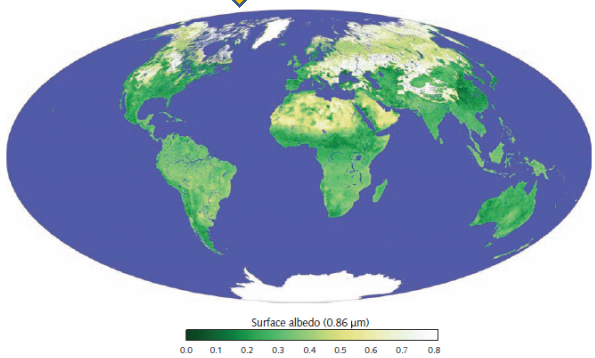


Figure 3.12 Global surface albedo for the period 1–16 January 2002, showing the proportion of incoming solar radiation that is reflected from the Earth's surface at a wavelength of 0.86µm. (Data from MODIS instrument on NASA's Terra satellite; visualisation by Eric Moody, RS Information Systems Inc.)