National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

RMetS
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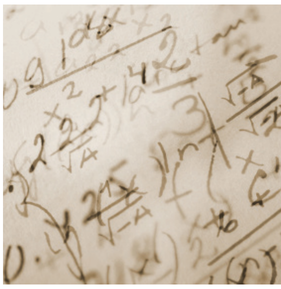
Report for Science Teachers

# Climate Change Updates

*10 New Figures from the 2013*
*Intergovernmental Panel on Climate Change*
*(IPCC)*



# List of Figures



## Glossary

This booklet and all the figures and Frequently Asked Questions referenced in this booklet may be downloaded from www.metlink.org

# All figures:

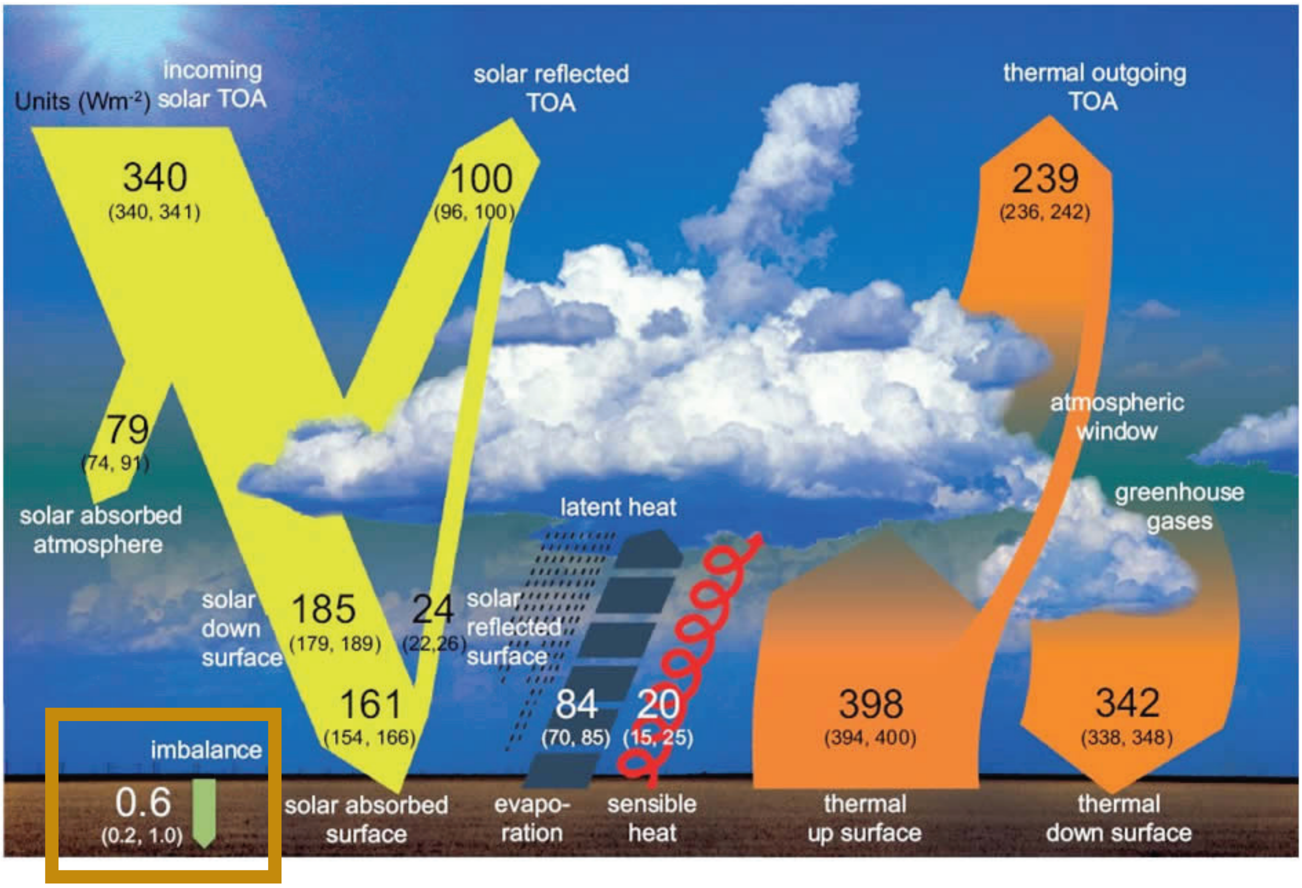
IPCC, 2013: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: Climate Change 2014: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. The IPCC reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change.

# 1. Earth's Energy Balance




*The current Global annual average flows of electromagnetic and other energy. The numbers show the movement of energy in W/m$^2$ (Watts per m$^2$) and their* ***uncertainty*** *(in brackets). The incoming sunlight (solar energy) at the Top Of the earth's Atmosphere (TOA) is 340 W/m$^2$, some of which is scattered back to space by clouds, the atmosphere or the surface (100 W/m$^2$). The rest is absorbed within the atmosphere and at the surface. The amount of energy absorbed by the surface determines its temperature (currently around 15 °C), which in turn determines the type (thermal) and amount (398 W/m$^2$) of energy emitted by the surface. Water at the surface evaporates, which requires energy, and moves into the atmosphere, where it condenses into water droplets or forms ice crystals, releasing latent heat energy. This transports energy from the surface into the atmosphere. Conduction and convection also move heat from the surface to the atmosphere. Most of the infra-red energy emitted by the surface is absorbed and re-emitted by gases in the atmosphere rather than escaping to space. The infra-red energy emitted to space (239 W/m$^2$) together with the reflected solar energy approximately balances the incoming solar energy.*

Since the last IPCC report, new space-borne instruments have begun collecting data, recording the energy exchanges between the Sun, Earth and Space. This has improved the accuracy of the information available to scientists. While it might be expected that it would be easier to make measurements of the movement of energy at the surface, it is the energy exchanges at the top of the atmosphere which are better known. They are measured directly by satellite sensors whereas surface measurements rely on instruments that are not spread evenly across the globe. Using information about cloud heights from space-borne radar and lidar instruments has allowed new estimates to be made of the thermal infrared radiation which reaches the surface.

Since 1950 the amount of solar radiation reaching the surface has been changing. Until the 1980s it was decreasing (dimming) because of an increase in atmospheric pollutants called **aerosols.** An aerosol is a colloid of either a solid or a liquid suspended in air and some of these cause the atmosphere to scatter sunlight back to space and can also can make clouds more reflective by increasing the number of water droplets in the clouds, which also increases the amount of sunlight reflected. Since then, national and international legislation has reduced the amount of aerosols which has increased the amount of solar radiation reaching the surface **(brightening).**

## Human activities are affecting the Earth's energy balance by;

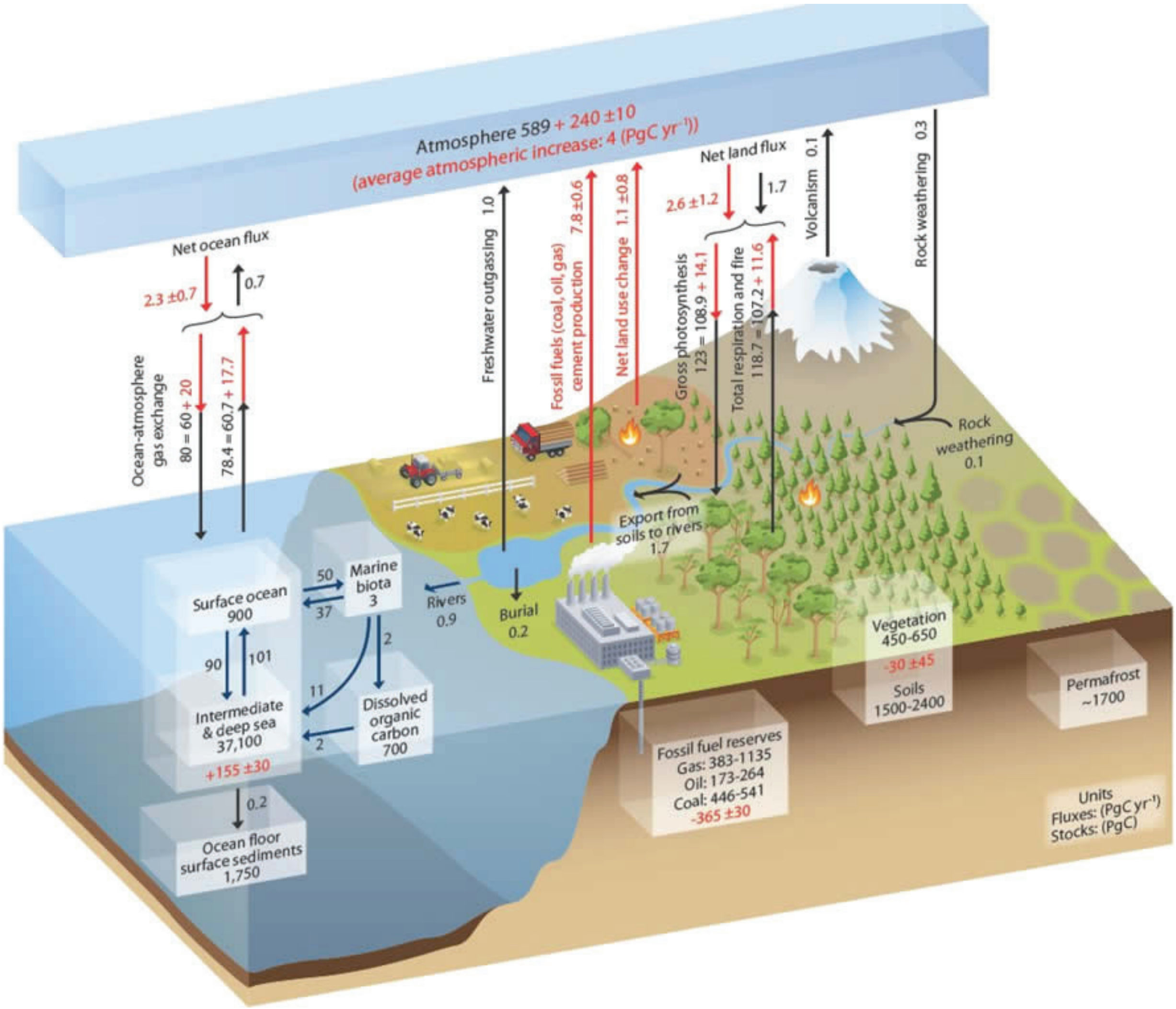
- changing the emissions and resulting atmospheric concentrations of greenhouse gases, such as carbon dioxide, which reduce the amount of infra-red radiation which escapes to space (the **Greenhouse effect**),
- changing the emissions and resulting atmospheric concentrations of aerosols which reflect and absorb the sun's radiation,
- changing land surface properties, which affects reflection, conduction and evaporation, by e.g. deforestation and increased urbanisation.

The result of these activities is that the sum of the energy leaving the top of the atmosphere is less (239+100 W/m2) than the energy entering it (340 W/m2). The imbalance is estimated to be about 0.6 W/m2. Most of this excess energy is absorbed at the surface (mainly by the oceans), as shown by the orange box, causing the observed increase in temperatures in the lower atmosphere and oceans.

## Summary

There is more energy entering the top of the atmosphere than is leaving it. This energy needs to go somewhere and most is causing a rise in temperature in the oceans and the atmosphere above. The warming is very likely to be caused by human activities such as the increase in carbon dioxide and other pollutants.

# 2. The Carbon Cycle




*The numbers represent carbon reservoirs in Petagrams of Carbon (PgC; $10^{15}$gC) and the annual exchanges in PgC/year. The black numbers and arrows show the pre-Industrial reservoirs and fluxes. The red numbers and arrows show the additional fluxes caused by humans averaged over 2000-2009, which include emissions due to the burning of fossil fuels, cement production and land use change (in total about 9 PgC/year). Some of this additional* ***anthropogenic*** *carbon is taken up by the land and the ocean (about 5 PgC/year) while the remainder is left in the atmosphere (4 PgC/year), causing rising atmospheric concentrations of $CO_2$. The red numbers in the reservoirs show the cumulative changes in* ***anthropogenic*** *carbon from 1750-2011; a positive change indicates that the reservoir has gained carbon.*

The global carbon cycle can be viewed as a series of reservoirs of carbon in the Earth System, which are connected by exchange fluxes of carbon. An exchange flux is the amount of carbon which moves between reservoirs each year.

There are two domains in the global carbon cycle, fast and slow. The fast domain has large exchange fluxes and relatively 'rapid' reservoir **turnovers**. This includes carbon on land in vegetation, soils and freshwater and in the atmosphere, ocean and surface ocean sediments. Reservoir **turnover** times (a measure of how long the carbon stays in the reservoir) range from a few years for the atmosphere to decades to millennia for the major carbon reservoirs of the land vegetation and soil and the various domains in the ocean.

The slow domain consists of the huge carbon stores in rocks and sediments which exchange carbon with the fast domain through volcanic emissions of $CO_2$, erosion and sediment formation on the sea floor. Reservoir turnover times of the slow domain are 10,000 years or longer.

Before the Industrial Era, the fast domain was close to a **steady state**. Data from **ice cores** show little change in the atmospheric $CO_2$ levels over millennia despite changes in land use and small emissions from humans. By contrast, since the beginning of the **Industrial Era** (around 1750), fossil fuel extraction and its combustion have resulted in the transfer of a significant amount of fossil carbon from the slow domain into the fast domain, causing a major perturbation to the carbon cycle.

In the atmosphere, $CO_2$ is the dominant carbon containing trace gas with a concentration of approximately 390.5 ppm in 2011, which corresponds to a mass of 828 PgC. Additional trace gases include methane ($CH_4$, currently about 3.7 PgC) and carbon monoxide (CO, around 0.2 PgC), with still smaller amounts of hydrocarbons, black carbon **aerosols** and other organic compounds.

The terrestrial biosphere reservoir contains carbon in organic compounds in vegetation (living biomass) (450 to 650 PgC) and in dead organic matter in litter and soils (1500 to 2400 PgC). There is an additional amount of old soil carbon in wetland soils (300 to 700 PgC) and in permafrost (1700 PgC).

$CO_2$ is removed from the atmosphere by plant **photosynthesis** (123±8 PgC/ year). Carbon fixed into plants is then cycled through plant tissues, litter and soil carbon and can be released back into the atmosphere by plant, microbial and animal respiration and other processes (e.g. forest fires) on a very wide range of time scales (seconds to millennia).

A significant amount of terrestrial carbon (1.7 PgC/year) is transported from soils to rivers. A fraction of this carbon is released as $CO_2$ by rivers and lakes to the atmosphere, a fraction is buried in freshwater organic sediments and the remaining amount (~0.9 PgC/ year) is delivered by rivers to the coastal ocean. Atmospheric $CO_2$ is exchanged with the surface ocean through gas exchange.

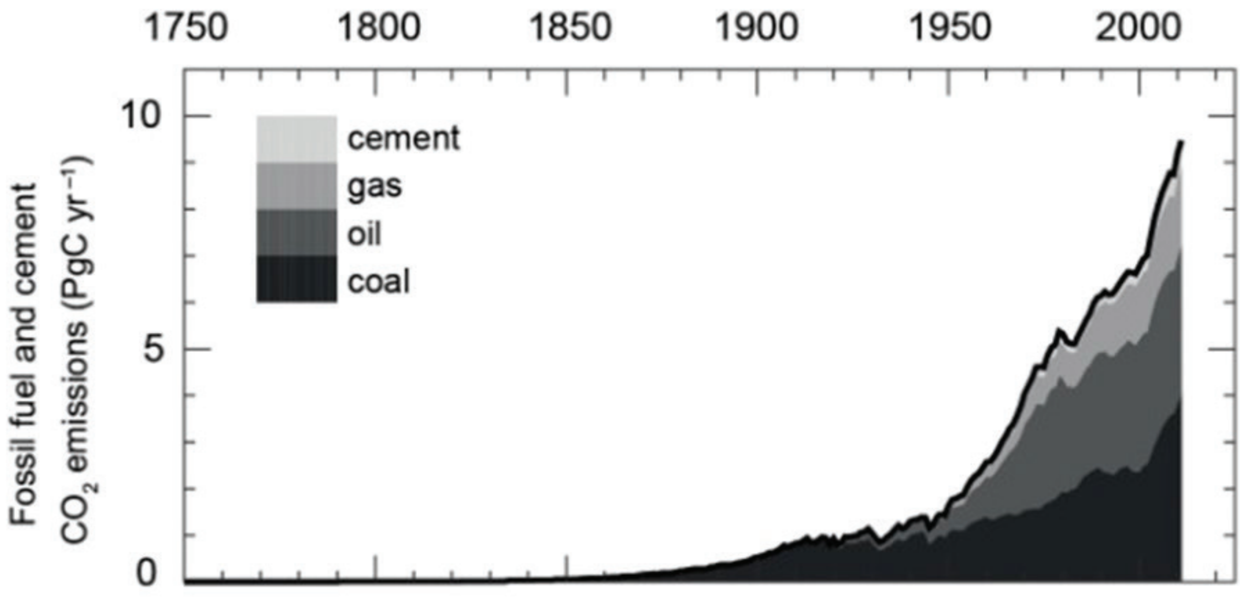
**Carbon is transported within the ocean by three mechanisms;**

(1) the **'solubility pump',**
(2) the **'biological pump',**
(3) the **'marine carbonate pump'**

## Summary

Carbon is cycled around in the environment from a number of stores or reservoirs by various processes. Some of these processes are natural such as photosynthesis; others are the result of human activity such as most burning of fossil fuels. Humans are moving carbon at a very high rate from stores where it would usually stay for tens of thousands of years. The processes to put the carbon back in such stores are much slower so carbon dioxide is building up in the atmosphere and oceans.

# 3. Sources of Anthropogenic Carbon Dioxide

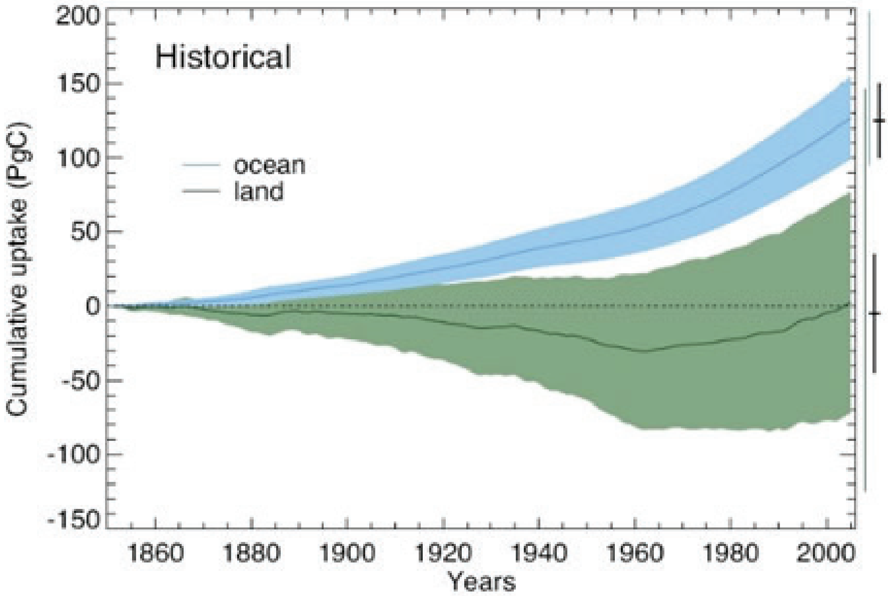



*Annual global **anthropogenic** $CO_2$ emissions (PgC/ year) from 1750 to 2011*

**Anthropogenic** $CO_2$ emissions to the atmosphere were 555 ± 85 PgC between 1750 and 2011. Of this, fossil fuel combustion and cement production contributed 375 ± 30 PgC and land use change (including deforestation, afforestation (planting new forest) and reforestation) contributed 180 ± 80 PgC. In 2002–2011, average fossil fuel and cement manufacturing emissions were 7.6 to 9.0 PgC/ year, with an average increase of 3.2%/ year compared with 1.0%/ year during the 1990s. In 2011, fossil fuel emissions were in the range of 8.7 to 10.3 PgC.

Emissions due to land use changes between 2002 and 2011 are dominated by tropical deforestation, and are estimated to range between 0.1 to 1.7 PgC/year. This includes emissions from deforestation of around 3 PgC/ year compensated by an uptake of around 2 PgC/year by forest regrowth (mainly on abandoned agricultural land).

The IPCC concluded that **the increase in $CO_2$ emissions from both fossil fuel burning and land use change are the dominant cause of the observed increase in atmospheric $CO_2$ concentration**. Globally, the combined natural land and ocean sinks of $CO_2$ kept up with the atmospheric rate of increase, removing 55% of the total anthropogenic emissions every year on average during 1958–2011. The ocean reservoir stored 155 ± 30 PgC. Vegetation biomass and soils stored 160 ± 90 PgC.

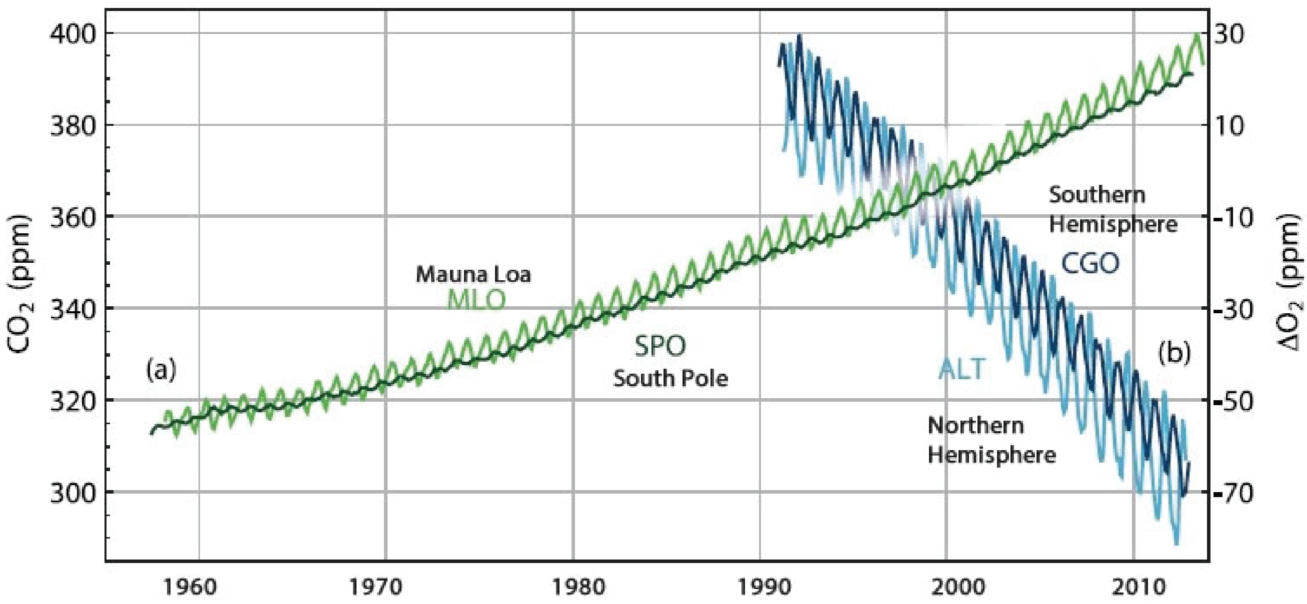



*Cumulative land and ocean uptake of carbon for the period 1850-2005. The thick line shows the mean and the shaded area shows one standard deviation. This shows that land was a net source of $CO_2$ to the atmosphere until around 1960, after which land becomes a net sink with more $CO_2$ being drawn down from the atmosphere into vegetation and soils than is released.*

## Summary

Since 1750 when the industrial revolution began, humans have produced carbon dioxide by burning fossil fuels and making cement. About half of this extra carbon dioxide has stayed in the atmosphere where it absorbs energy, preventing the energy escaping into space and so heating the planet. Some of the extra carbon dioxide has been taken up by the ocean.

# 4. Changing Carbon Dioxide and Oxygen Concentrations in the Atmosphere




*Concentrations of carbon dioxide and oxygen in the atmosphere Atmospheric concentration of a) carbon dioxide in parts per million by volume from Mauna Loa (MLO, light green) and the South Pole (SPO, dark green) from 1950 to 2013, and of b) changes in the atmospheric concentration of $O_2$ from the northern hemisphere (ALT, light blue) and the southern hemisphere (CGO, dark blue) relative to a standard value.*

## Carbon Dioxide

$CO_2$ increased by 40% from 278 ppm in 1750 to 390.5 ppm in 2011.

Most of the fossil fuel $CO_2$ emissions take place in the industrialised countries north of the equator. Consistent with this, the annual average atmospheric $CO_2$ measurement stations in the Northern Hemisphere (NH) record higher $CO_2$ concentrations than stations in the Southern Hemisphere (SH). As the difference in fossil fuel combustion between the hemispheres has increased, so has the difference in concentration between measuring stations at the South Pole and Mauna Loa (Hawaii, Northern Hemisphere).

The atmospheric $CO_2$ concentration increased by around 20 ppm during 2002–2011. T**his decadal rate of increase is higher than during any previous decade since direct atmospheric concentration measurements began in 1958.**

Because $CO_2$ uptake by photosynthesis occurs only during the growing season, whereas $CO_2$ release by respiration occurs nearly year-round, the greater land mass in the Northern Hemisphere imparts a characteristic 'sawtooth' seasonal cycle in atmospheric $CO_2$.

Past changes in atmospheric greenhouse gas concentrations can be determined with very high confidence from polar ice cores. During the 800,000 years prior to 1750, atmospheric $CO_2$ varied from 180 ppm during glacial (cold) up to 300 ppm during interglacial (warm) periods. Present-day (2011) concentrations of atmospheric carbon dioxide exceed this range. **The current rate of $CO_2$ rise in atmospheric concentrations is unprecedented with respect to the highest resolution ice core records of the last 22,000 years.**

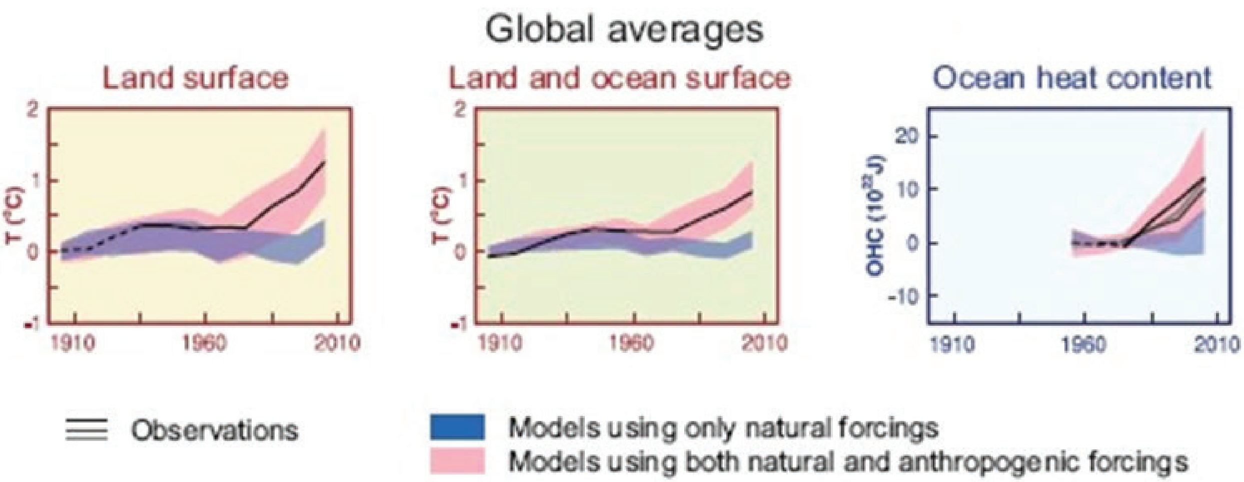
## Oxygen

Atmospheric oxygen is tightly coupled with the global carbon cycle. The burning of fossil fuels removes oxygen from the atmosphere. As a consequence of the burning of fossil fuels, atmospheric $O_2$ levels have been observed to decrease slowly but steadily over the last 20 years. Compared to the atmospheric oxygen content of about 21% this decrease is very small; however, it provides independent evidence that the rise in $CO_2$ must be due to an oxidation process, that is, fossil fuel combustion and/or organic carbon oxidation, and is not caused by volcanic emissions or a warming ocean releasing carbon dioxide ($CO_2$ is less soluble in warm water than cold). The atmospheric oxygen measurements also show the north–south concentration $O_2$ difference (higher in the south and mirroring the $CO_2$ north–south concentration difference) as expected from the greater fossil fuel consumption in the NH.

## Summary

The green line shows the changing concentration of carbon dioxide:  it is going steadily up, with seasonal fluctuations, consistent with the amount of fossil fuel combustion due to human activities. An additional piece of evidence to support that this is caused by the burning of fossil fuels is that the oxygen concentration is going down by a similar amount, suggesting that the oxygen is being used to produce carbon dioxide in a combustion reaction rather than the carbon dioxide coming from some other process such as volcanoes.

# 5. Are People Causing Climate Change?

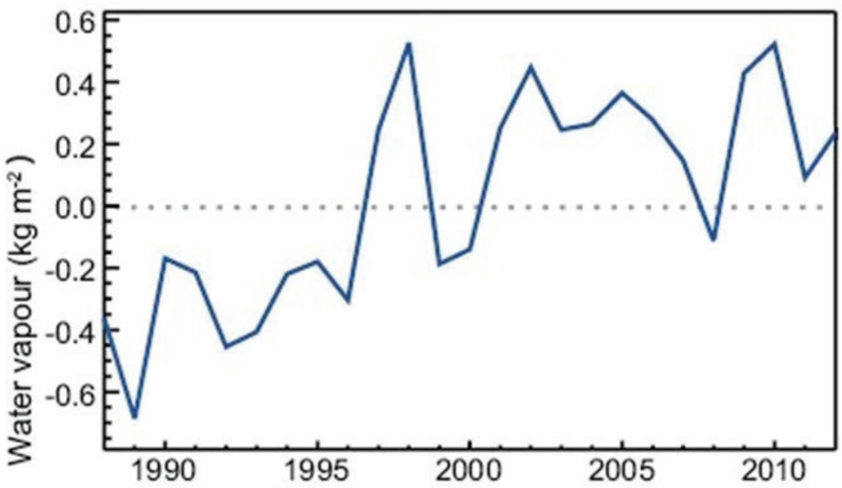



*A comparison of observed and modelled climate change in globally averaged surface air temperatures and upper ocean heat content. The values are decadal averages given relative to the 1880–1919 average surface temperatures and the 1960–1980 average upper ocean heat content. The observations are dashed where the coverage of observations is poor and* ***uncertainty*** *is larger. The model results shown are from a large collection of* ***climate models*** *from around the world, with shaded bands indicating the 5 to 95% confidence intervals.*

The causes of observed long-term changes in climate (on time scales longer than a decade) are assessed by determining whether the expected 'fingerprints' of different possible causes of climate change are found in observations. These fingerprints are patterns of change in temperature, or other climate variables, and are estimated using **climate model** simulations of the climate's response to specific '**forcing** factors' (any factor that influences global climate by heating or cooling the planet) which change the earth's energy balance. Some **forcing** factors are caused by purely natural processes, such as volcanic eruptions or variations in the brightness of the sun; other forcing factors are caused by human activities, such as emitting greenhouse gases.

By comparing the simulated fingerprint patterns with observed climate changes, scientists can determine which **forcing** factors have been most important. This work also takes into account natural fluctuations in the climate (known as 'natural **internal variability'**) that occur without any forcing.

The observed change in temperature in the latter half of the 20th century, shown by the black line in the figures, is larger than expected from just natural internal variability. Simulations driven only by natural factors (blue areas in the figures) fail to reproduce the temperature changes that were observed in the late 20th century. Only the simulations that include both forcing factors caused by human activities (including changes in greenhouse gases, stratospheric ozone and atmospheric **aerosol** pollution) and natural processes (pink areas) simulate the observed warming trend. Natural causes of change are still at work in the climate system, but the IPCC concluded that **" it is extremely likely that human activities caused more than half of the observed increase in global mean surface temperatures from 1951 to 2010".**



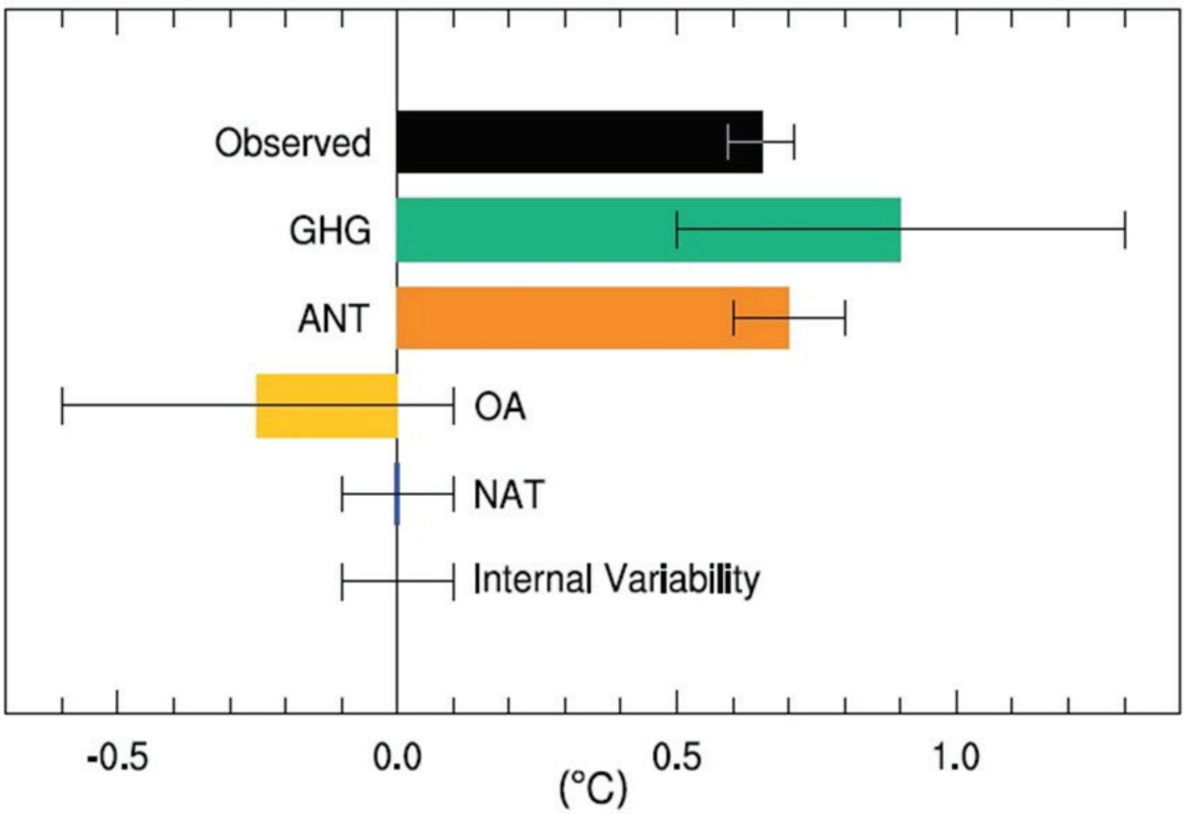

*Global and annual averages of atmospheric water vapour over ocean surfaces, shown relative to the average for the period 1988-2007.*

Evidence of climate change is also seen in other variables. Since the last IPCC report, satellite evidence has shown an increase in the amount of water vapour in the **troposphere**, the lowest part of the atmosphere. The year-to-year variability and long term trend in atmospheric water vapour content are closely linked to changes in global sea surface temperature, partly because warmer temperatures cause increased evaporation.

## Summary

Climate scientists use models to predict what will happen to the temperature in the future – these models can also be used to try to find out what caused the changes seen in the recent past. They strongly suggest that the change in climate since the 1950s is mostly due to human activity.

# 6. Quantifying the Causes of Recent Climate Change




*The black bar shows the trend in global mean surface temperature from 1951-2010. The coloured lines show how each factor is thought to have contributed to this rise. The thin black lines (whiskers) show the assessed likely ranges in the data and the coloured bars show the mid-points of these ranges for the contributions from: well-mixed greenhouse gases (GHG, green), other* ***anthropogenic forcing*** *factors (OA, yellow), combined anthropogenic forcing factors (ANT, orange), natural forcing factors (NAT, blue) and natural internal (i.e. unforced) variability. Other anthropogenic forcing factors include emissions of* ***aerosols*** *and non-greenhouse gases, and land use change. Natural forcing factors include changes in the sun's energy output and volcanic emissions.*

The IPCC concluded that **"it is extremely likely that human activities caused more than half of the observed increase in global mean surface temperatures from 1951 to 2010."**

The quantitative contributions to the observed warming over the period 1951-2010 are estimated using **climate model** simulations which include different forcing factors. Forcing factors influence global climate by heating or cooling the planet. The figure shows that the increase in well-mixed greenhouse gases (primarily $CO_2$) contributed a global mean surface warming between 0.5°C and 1.3°C, with a central estimate of 0.9°C. This warming contribution was partly offset by the contribution of other **anthropogenic** forcing factors (OA) which probably cooled the climate. As a result, the central estimate for the contribution from combined (greenhouse gas plus other anthropogenic) forcing factors is lower at 0.7°C, which is similar to the observed warming of 0.6-0.7°C. The contributions from natural forcing factors and **internal variability,** due to naturally variable processes within the climate system, are assessed to be small.

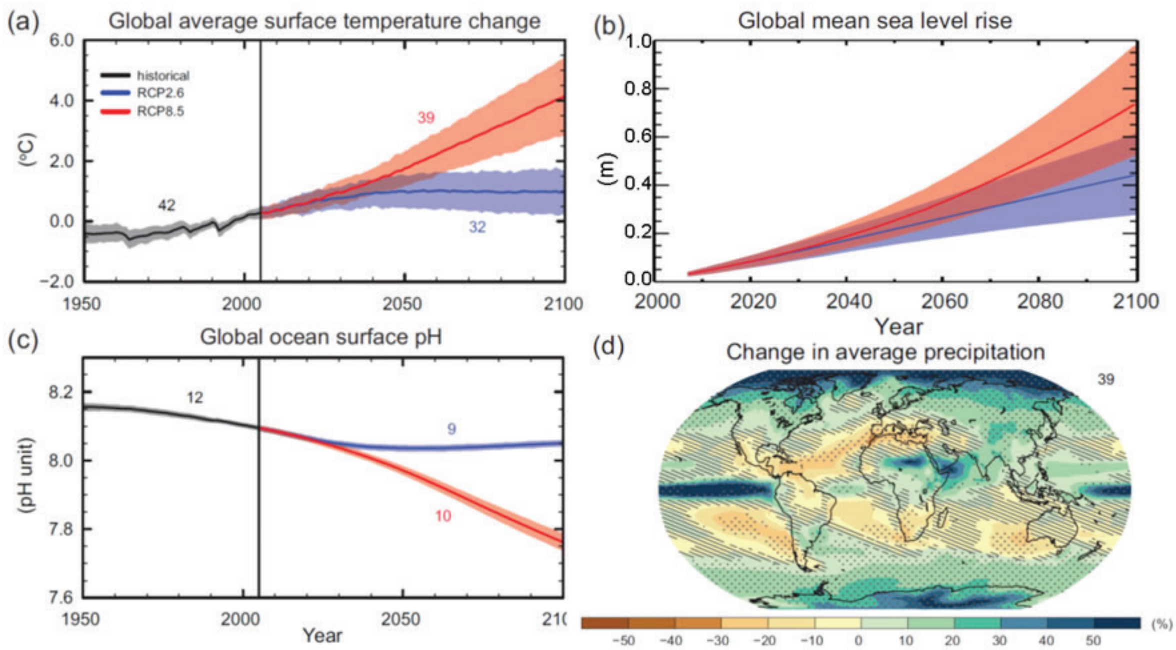
A major contribution to other anthropogenic forcing (OA) is from **aerosols**, which are small particles of liquids or solids dispersed through the air. These come from both natural and human sources, and can affect the climate in multiple and complex ways through their interactions with radiation and clouds. Some **aerosols** scatter and reflect solar radiation and therefore tend to the cool the climate, whilst others absorb solar radiation causing warming. The balance between cooling and warming depends on the properties of the aerosol (such as its colour) and local environmental conditions. Overall, models and observations indicate that **anthropogenic aerosols** have exerted a cooling influence on the Earth since pre-industrial times, which has masked some of the global mean warming from greenhouse gases that would have occurred in their absence.

The observed global mean surface temperature has shown a much smaller increasing linear trend over the past 15 years than over the past 30 to 60 years with the trend over 1998–2012 estimated to be around one third to one half of the trend over 1951–2012. Even with this '**hiatus'** in the surface temperature trend, the 2000-2010 decade has been the warmest in the instrumental record. The IPCC concluded that this '**hiatus**' is probably the result of both a cooling contribution from natural internal variability and a reduced trend in natural forcing (volcanic eruptions and a downward phase of the 11 year solar cycle). During the '**hiatus**', the climate system has continued to accumulate energy, for example energy accumulation in the oceans has caused the global mean sea level to continue rising.

## Summary

Climate scientists have tried to work out how much of the change in temperature since the 1950s is due to various factors. They suggest that very little is due to natural variability and most is due to human activity, mainly the industrial emissions of greenhouse gases. The thin black lines show the estimated error ranges in the calculations.

# 7. Projected Effects of Increased Levels of Greenhouse Gases




***Climate Model*** *simulations of the change in*

*(a) global annual mean surface temperature (°C difference relative to 1986-2005 average),*

*(b) sea level (m difference),*

*(c) ocean acidity (pH) and*

*(d) precipitation (% change by 2081–2100 relative to 1986-2005).*

*The shading indicates an* ***uncertainty*** *range for simulations of the past (grey) and for two different future scenarios - a low* ***emissions scenario*** *where carbon emissions are rapidly cut (RCP2.6, blue) and a high emissions scenario (RCP8.5, red)*

There will be further warming and changes in all components of the climate system if the concentrations of greenhouse gases continue to rise. To limit climate change will require substantial and sustained reductions of greenhouse gas emissions, similar to the low emissions (RCP2.6, blue) scenario. Although warming will continue to exhibit year-to-year and decade-to-decade variability, global mean surface temperatures for 2081–2100 will be higher than in 1986–2005 even under the low emissions scenario. The ranges derived from the model simulations are 0.3°C to 1.7°C for a low **emissions scenario** (the blue line) **and 2.6°C to 4.8°C for the high emissions scenario (red line). Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C above pre-industrial temperatures unless future emissions are very low.**

Scientists are confident that the Arctic region will warm more rapidly than the global mean, and that average warming over land will be larger than over the oceans.

By 2100, with high emissions (red), model projections suggest global sea levels will have risen 0.52 to 0.98 m on average, with a rate during 2081 to 2100 of 8 to 16 mm/ year.

The projected decrease in surface ocean pH by the end of 21st century is 0.06 to 0.07 (blue) and 0.30 to 0.32 (red). This increase in ocean acidity is due to $CO_2$ (an acidic gas) dissolving in the oceans and could affect marine ecosystems.

There are likely to be changes to rainfall patterns in many areas around the globe. Areas near the poles (high latitudes) and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation by the end of this century. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will probably increase by the end of this century. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, because as global mean surface temperature increases, there is more energy and water vapour in the atmosphere.

By the mid-21st century, the magnitudes of the projected changes are substantially affected by the choice of emissions scenario. The various scenarios considered involve a wide range of technological, socioeconomic, and institutional trajectories, but it may be that the actual future does not fit within this projected range. Delaying **mitigation** efforts will make it substantially harder to achieve low longer-term emissions levels.

## Beyond 2100

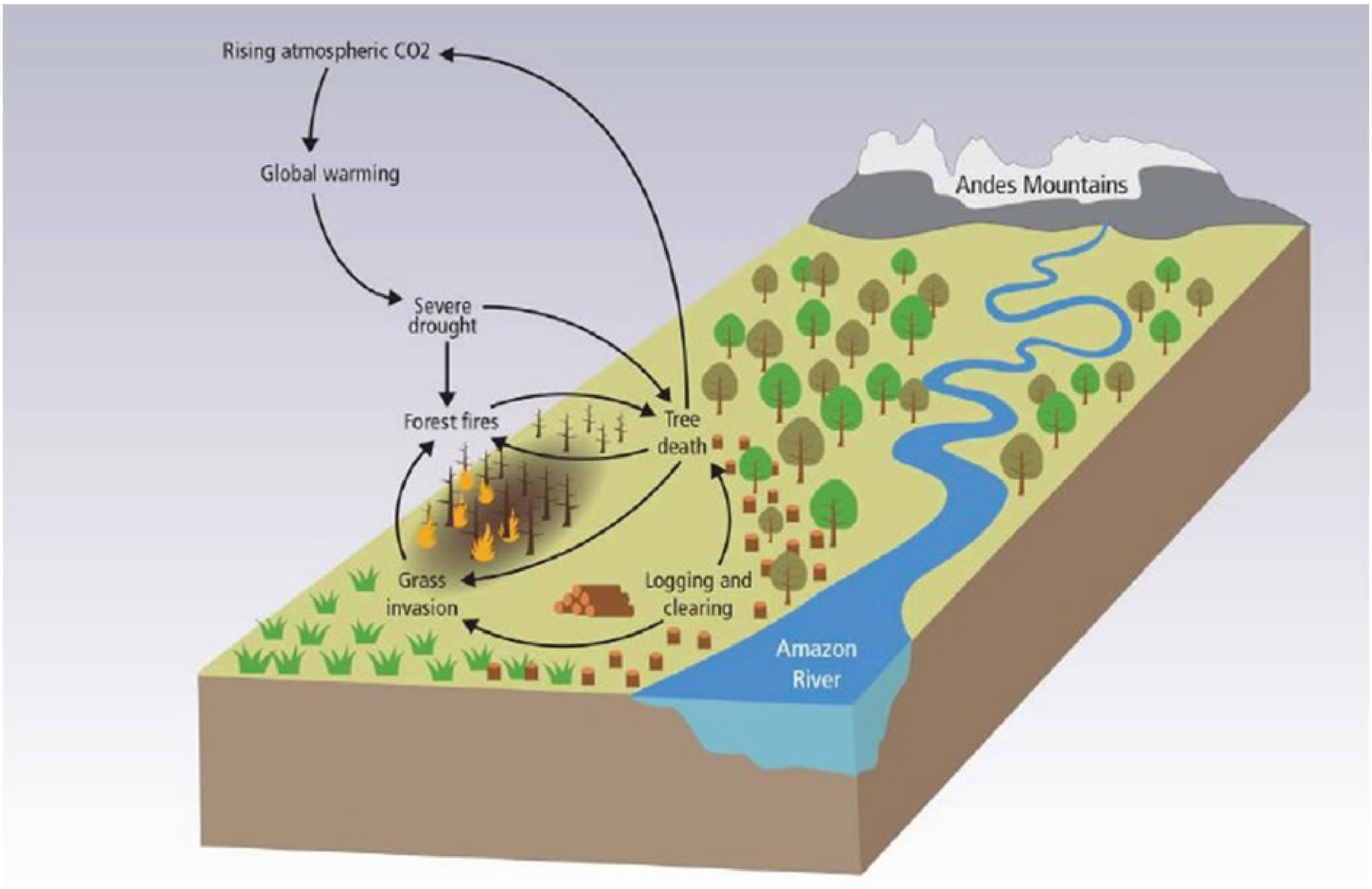
Warming will continue beyond 2100 except in the case of a low **emissions scenario**. A higher likelihood of remaining below a given warming target (such as 2°C), will require lower cumulative greenhouse gas emissions. Most other aspects of climate change will also persist for many centuries even if anthropogenic emissions of greenhouse gases are reduced to zero. Stabilization of global temperature does not imply stabilization for all aspects of the climate system. Processes related to vegetation change, changes in the ice sheets, deep-ocean warming and associated sea level rise have long time scales as do potential **feedbacks** linking, for example, ocean and the ice sheets. Ocean acidification will continue for many hundreds of years into the future as the oceans continue to take up atmospheric $CO_2$. Land ecosystem carbon cycle changes will manifest themselves beyond the end of the 21st century. It is virtually certain that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion continuing for centuries to millennia. Reducing emissions earlier rather than later, for the same cumulative total, leads to a lower eventual global mean sea level rise.

Issues of equity, justice, and fairness arise with respect to **mitigation** and **adaptation**. Countries' past and future contributions to the accumulation of greenhouse gases in the atmosphere are different, and countries also face varying challenges and circumstances, and have different capacities to address, mitigate and adapt. Mitigation and adaptation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods, and equitable sustainable development.

## Summary

Scientists use models to try to predict what might happen in the future if levels of carbon dioxide continue to rise. These show temperatures and sea levels rising and the pH of the sea falling as the sea becomes more acidic due to an increase in the concentration of carbon dioxide. Rainfall patterns change, but these vary with some areas seeing more and others less rain.

# 8. The Impact of Rising CO2 on Plants and Ecosystems

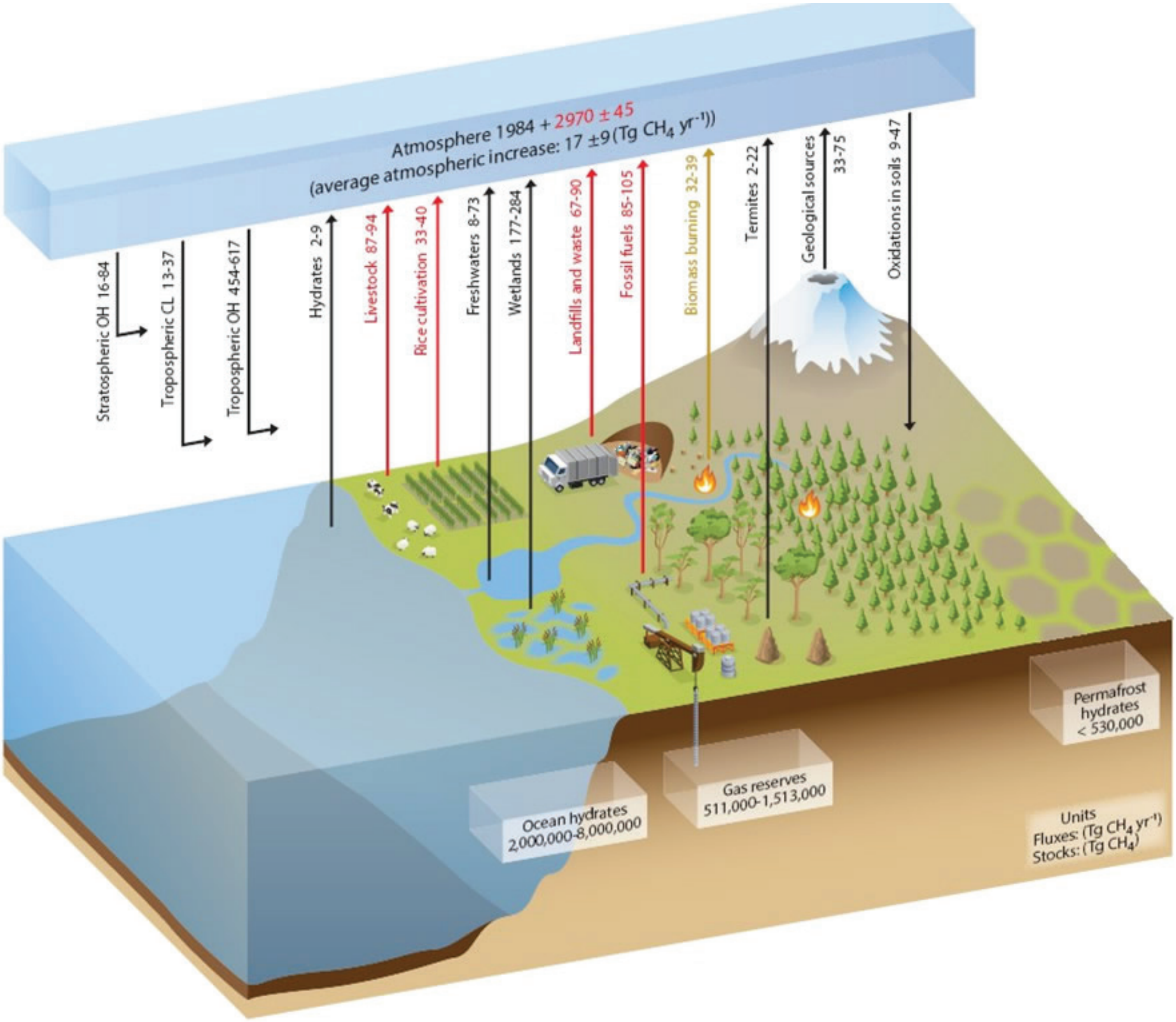



*The forests of the Amazon Basin are already being altered through severe droughts, changes in land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive* ***feedbacks,*** *and create the potential for a large-scale* ***tipping point.*** *For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin.*

There is a high risk that the large magnitudes and high rates of climate change this century will result in abrupt and irreversible regional-scale changes to terrestrial and freshwater ecosystems, especially in the Amazon and Arctic, leading to additional climate change.

There are plausible mechanisms, supported by experimental evidence, observations, and **climate model** simulations, for the existence of ecosystem **tipping points** in the rainforests of the Amazon basin. Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century. However, a projected increase in severe drought episodes, together with land-use change and forest fires, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems. This would risk reducing biodiversity in an important ecosystem, and would reduce the amount of carbon absorbed from the atmosphere through photosynthesis. Large reductions in deforestation, as well as wider application of effective wildfire management lower the risk of abrupt change in the Amazon.

# 9. The Methane Cycle




*Global Methane cycle*

*The numbers show the 2000-2009 estimates for annual methane fluxes (changes) in Teragrams ($10^{12}$g) of Methane (Tg($CH_4$) per year and methane reserves in Tg($CH_4$). The methane reserves are the atmosphere, hydrates on land, hydrates in the ocean floor and gas reserves. Methane hydrates are solids similar to ice with methane trapped in the crystal structure of water. The black arrows show natural fluxes, red arrows show fluxes directly caused by human activities since 1750 and brown arrows denote a combined natural and* ***anthropogenic*** *flux. Human activities may also have an indirect effect on natural fluxes, for example through land use change.*

Methane absorbs infrared radiation more strongly per molecule compared to $CO_2$. On the other hand, the methane **turnover time** is less than 10 years in the **troposphere** (much less than for $CO_2$).

The sources of $CH_4$ at the surface of the Earth include

(1) Natural emissions of fossil $CH_4$ from geological sources (marine and terrestrial seepages, geothermal vents and mud volcanoes).
(2) Emissions caused by leakages from fossil fuel extraction and use (natural gas, coal and oil industry).
(3) Pyrogenic sources resulting from incomplete burning of fossil fuels and plant biomass (both natural and anthropogenic fires).

(4) Biogenic sources including natural emissions predominantly from wetlands, from termites and very small emissions from the ocean. **Anthropogenic** biogenic emissions occur from rice paddy agriculture, ruminant livestock (such as cows), landfills, man-made lakes and wetlands and waste treatment. In general, biogenic $CH_4$ is produced from organic matter under low oxygen conditions by the fermentation processes of some microbes.

Atmospheric $CH_4$ is removed mainly by atmospheric chemical reactions with OH radicals. A smaller amount of $CH_4$ is removed in the **stratosphere** through reaction with chlorine and oxygen radicals and by oxidation in well aerated soils.

For the decade of 2000–2009 methane emissions were 177 to 284 Tg($CH_4$)/year for natural wetlands emissions, 187 to 224 Tg($CH_4$)/ year for agriculture and waste (rice, animals and waste), 85 to 105 Tg($CH_4$)/ year for fossil fuel related emissions, 61 to 200 Tg($CH_4$)/year for other natural emissions including geological, termites and fresh water emissions, and 32 to 39 Tg($CH_4$)/ year for biomass and biofuel burning. Anthropogenic emissions account for 50 to 65% of total emissions.

Climate driven fluctuations of $CH_4$ emissions from natural wetlands are the main drivers of the global inter-annual variability of $CH_4$ emissions, with a smaller contribution from the variability in emissions from biomass burning during high fire years.

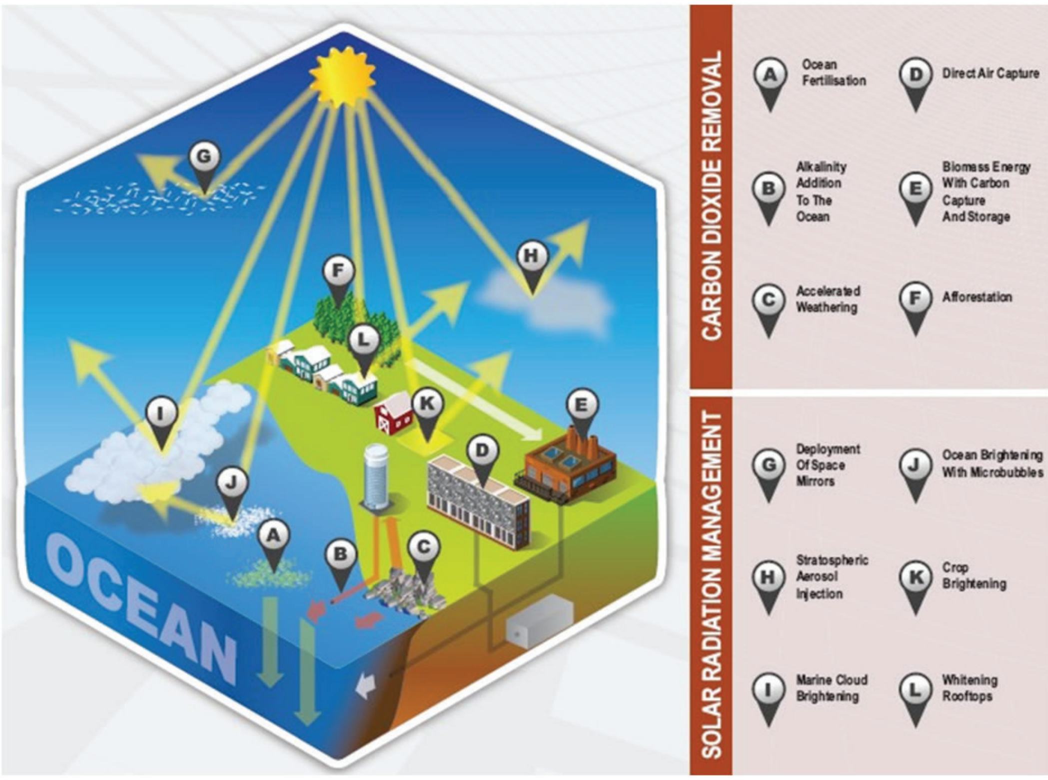
## Atmospheric Methane Concentrations

Past changes in atmospheric greenhouse gas concentrations can be determined with very high confidence from polar ice cores. Between 1750 and 2011, $CH_4$ increased by 150% from 722 ppb to 1803 ppb. Present-day (2011) concentrations of atmospheric methane ($CH_4$) exceed the range of concentrations recorded in ice cores during the past 800,000 years. **The current rate of increase in atmospheric concentration of $CH_4$ is also unprecedented with respect to the highest resolution ice core records of the last 22,000 years.**

### Summary

Methane concentrations in the atmosphere are rising which is problematic as methane causes more warming per molecule in the atmosphere than carbon dioxide. The methane concentration is a lot lower than the carbon dioxide concentration but is higher than it has been in at least the last 800 000 years.

# 10. Could Geoengineering Counteract Climate Change?




*An overview of some proposed* ***geoengineering*** *methods*

***Carbon Dioxide Removal methods:***

*(A) nutrients are added to the ocean (ocean fertilization), which increases oceanic productivity in the surface ocean and transports a fraction of the resulting biogenic carbon downward;*

*(B) solid minerals which are strong bases add alkalinity to the ocean, which causes more atmospheric $CO_2$ to dissolve;*

*(C) the weathering rate of silicate rocks is increased, producing dissolved carbonate minerals which are transported to the ocean;*

*(D) atmospheric $CO_2$ is captured chemically, and stored either underground or in the ocean;*

*(E) biomass is burned at an electric power plant with carbon capture, and the captured $CO_2$ is stored either underground or in the ocean;*

*(F) $CO_2$ is captured through afforestation and reforestation to be stored in land ecosystems.*

***Solar Radiation Management methods:***

*(G) reflectors are placed in space to reflect solar radiation;*

*(H)* ***aerosols*** *are injected in the* ***stratosphere;***

*(I) marine clouds are seeded in order to be made more reflective;*

*(J) microbubbles are produced at the ocean surface to make it more reflective;*

*(K) more reflective crops are grown; and*

*(L) roofs and other built structures are whitened.*

The most direct approach to reducing the effects of **anthropogenic** climate change is **reducing greenhouse gas emissions**. However, a number of '**geoengineering'** approaches have also been proposed as temporary, or additional, interventions. Geoengineering – also called climate engineering – is defined as a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change.

Theory, model simulations and observations suggest that some **Solar Radiation Management (SRM) methods** which reduce the amount of solar radiation reaching the Earth's surface could substantially offset a global temperature rise and partially offset some other impacts of climate change. However, regionally, SRM would not precisely offset the temperature and rainfall changes caused by elevated greenhouse gases.

Numerous side effects, risks and shortcomings from SRM have been identified. For example:

- SRM might produce a small but significant decrease in global precipitation (with larger differences on regional scales).
- Stratospheric **aerosol** SRM could cause modest polar stratospheric ozone depletion.
- As long as GHG concentrations continued to increase, the SRM would also need to increase, exacerbating side effects. In addition, scaling SRM to substantial levels would carry the risk that if the SRM were terminated for any reason, surface temperatures would increase rapidly (within a decade or two) to values consistent with the greenhouse gas **forcing**, which would stress systems sensitive to the rate of climate change.
- SRM would not compensate for ocean acidification from increasing $CO_2$.
- There could also be other as yet unanticipated consequences.

Novel ways to remove $CO_2$ from the atmosphere on a large scale are termed **Carbon Dioxide Removal (CDR) methods.** These methods have biogeochemical and technological limitations to their potential. Uncertainties make it difficult to quantify how much $CO_2$ emissions could be offset by CDR on a human time scale. CDR would probably have to be deployed at large-scale for at least one century to be able to significantly reduce atmospheric $CO_2$. A major **uncertainty** is the capacity to store carbon securely with sufficiently low levels of leakage. In addition, it is virtually certain that the removal of $CO_2$ by CDR will be partially offset by outgassing of $CO_2$ from the ocean and land ecosystems.

CDR methods can also have associated climatic and environmental side effects:

- A large-scale increase in vegetation coverage, for instance through afforestation or energy crops, could alter surface characteristics, such as surface reflectivity. Some modelling studies have shown that afforestation in seasonally snow-covered boreal regions could in fact accelerate global warming, whereas afforestation in the tropics may be more effective at slowing global warming.
- Enhanced vegetation productivity may increase emissions of $N_2O$, which is a more potent greenhouse gas than $CO_2$.
- Ocean-based CDR methods that rely on biological production (i.e., ocean fertilization) would have numerous side effects on ocean ecosystems, ocean acidity and may produce emissions of non- $CO_2$ greenhouse gases such as methane.

## Summary

One way of reducing the carbon dioxide concentration in the atmosphere is to reduce emissions. This is not popular globally and other solutions have been considered. There are potential problems with these – including that nobody would really know what might happen and who might suffer as a result of these ideas being tried.

# Glossary

## Adaptation

The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

## Aerosols

A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm, that reside in the atmosphere for at least several hours. Many act as surfaces for water droplets and ice crystals to form on.

## Anthropogenic

Resulting from or produced by human activities.

## Biological pump

The process of transporting carbon from the ocean's surface layers to the deep ocean by the primary production of marine phytoplankton, which converts dissolved inorganic carbon (DIC), mainly $CO_2$, and nutrients into organic matter through photosynthesis.

## Climate

The average weather, or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind.

## Climate Model

A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

## Energy Budget

The Earth is a physical system with an energy budget that includes all gains of incoming energy and all losses of outgoing energy. The Earth's energy budget is determined by measuring how much energy comes into the Earth system from the Sun, how much energy is lost to space, and accounting for the remainder on Earth and energy flows between the atmosphere and the ocean or land surface.

## Emissions Scenario

A plausible representation of the future development of emissions of substances that potentially influence the earth's energy budget (e.g., greenhouse gases, aerosols) and are based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.

## Feedback

An interaction in which a perturbation (change) in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is increased. For example, melting ice can expose dark-coloured land. The dark-coloured land absorbs more heat than the white ice, leading to further warming and melting. This is positive feedback.

## Forcings

Forcing represents any external factor that influences global climate by heating or cooling the planet. They may be either natural or anthropogenic. Natural forcings include volcanic eruptions, solar variations and orbital forcing; the amount of solar energy reaching Earth changes with orbital parameters eccentricity, tilt and precession of the equinox. Anthropogenic forcing include changes in the composition of the atmosphere and land use change.

## Geoengineering

A broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management) or (2) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (Carbon Dioxide Removal).

## Greenhouse Gas

Atmospheric gases that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, the atmosphere, and by clouds.

## Internal variability

Variations in the mean state and other statistics (such as the occurrence of extremes) of the climate on all spatial and time scales beyond that of individual weather events, due to natural, unforced processes within the climate system. Because the climate systems has components with very different response times complex dependencies, the components are never in equilibrium and are constantly varying. An example of internal variability is El Niño, a warming cycle in the Pacific Ocean which has a big impact on the global climate, resulting from the interaction between atmosphere and ocean in the tropical Pacific.

## Mitigation

A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

## Reconstruction

Approach to reconstructing the past temporal and spatial characteristics of a climate variable from predictors. The predictors can be instrumental data if the reconstruction is used to infill missing data or proxy data if it is an indirect measure used to develop paleoclimate reconstructions.

## Solubility pump

An important physicochemical process that transports dissolved inorganic carbon from the ocean's surface to its interior. Because carbon dioxide is more soluble in colder water, and the thermohaline circulation of the oceans is driven by cold, dense water sinking at high latitudes, deep water contains more dissolved inorganic carbon.

## Stratosphere

The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

## Tipping point

A hypothesized critical threshold when global or regional climate changes rapidly from one stable state to another stable state. The tipping point event may be irreversible.

## Troposphere

The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height.

## Turnover time

A measure of how long a component stays in a reservoir. It is the ratio of the mass M of a reservoir (e.g., a gaseous compound in the atmosphere) and the total rate of removal S from the reservoir: $T = M/S$. For each removal process, separate turnover times can be defined. In soil carbon biology, this is referred to as Mean Residence Time.

## Uncertainty

A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour.

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# Report for Science Teachers