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# Climate and greenhouse gases

*By Michael Raupach and Paul Fraser*

**Key messages**

- Greenhouse gases (GHGs) influence the Earth's climate because they interact with flows of heat energy in the atmosphere.
- The main GHGs influenced directly by human activities are carbon dioxide ($CO_2$), methane, nitrous oxide, ozone, and synthetic gases. Water vapour, although an important GHG, is not influenced directly by human activities.
- The amount of warming produced by a given rise in GHG concentrations depends on 'feedback' processes in the climate system, which can either amplify or dampen a change. The net effect of all climate feedbacks is to amplify the warming caused by increasing $CO_2$ and other GHGs of human origin.
- The atmospheric level of $CO_2$ (the most important GHG influenced by human activities) rose from about 280 ppm in 1800 to 386 ppm in 2009, and is currently increasing at nearly 2 ppm per year.
- $CO_2$ levels are rising mainly because of the burning of fossil fuels and deforestation. Over half of this $CO_2$ input to the atmosphere is offset by natural $CO_2$ 'sinks' in the land and oceans, which constitute a massive natural ecosystem service helping to mitigate humanity's emissions.
- To have a 50:50 chance of keeping human-induced average global warming below 2°C, it will be necessary to stop almost all $CO_2$ emissions before cumulative emissions reach one trillion tonnes of carbon. The world has already emitted more than half of this quota since the industrial revolution, and (at current growth rates for $CO_2$ emissions) the rest will be emitted by the middle of this century.
- Climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes.

## Greenhouse gases and the Earth's climate

Life on Earth depends on the presence of greenhouse gases in the atmosphere to insulate our planet's surface against the chill of space. The main GHGs influenced directly by human activities are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), ozone ($O_3$), and synthetic gases, such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Water vapour is also a major greenhouse gas, but its concentration in the atmosphere is not influenced directly by human activities; rather, it is controlled mainly by the Earth's temperature.

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Greenhouse gases influence Earth's climate because they interact with energy flows. The atmosphere (including its GHGs) is largely transparent to the Sun's energy, most of which arrives in the form of light. At the Earth's surface, this energy is partly reflected and partly absorbed and re-radiated as heat. Paler ice- and snow-covered surfaces of the planet reflect much more energy than darker surfaces, such as forests and oceans. The GHGs in the atmosphere absorb and re-radiate much of the outgoing heat energy. At the same time, minute particles or droplets floating in the atmosphere, known as aerosols, act both to reflect incoming solar radiation (light) and to absorb and re-radiate outgoing heat.

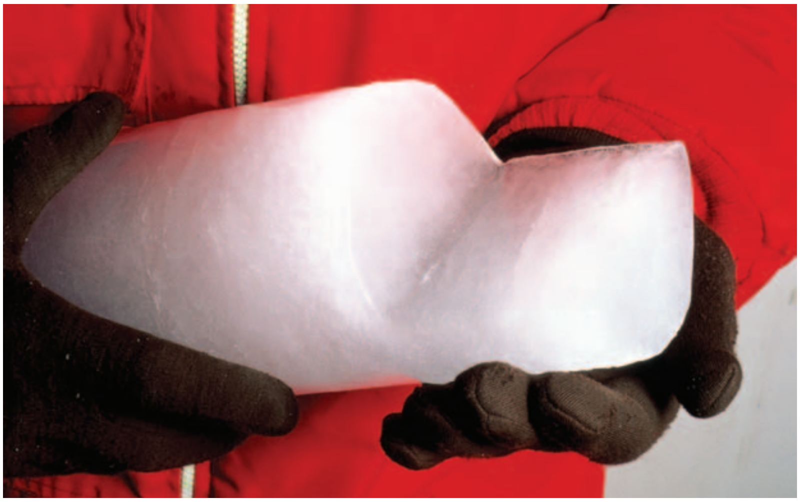
The Earth's climate is influenced by all of these factors, which together maintain the planet at about 32°C warmer than it would otherwise be. Their combined effect is measured by a quantity called net radiative forcing, which is basically the net rate of input of heat energy to the entire planet due to all the processes described above. Extra heat builds up in the atmosphere and oceans when the rate of energy input is positive, causing the planet to warm. The net radiative forcing in 2005 was +1.6 $W/m^2$ (Watts per square metre), with uncertainty discussed below.[1] This is equivalent to the energy input from running a 1 kW electric radiator on an area the size of a suburban block – day and night, all year round, for every block-sized patch of the entire planet's surface. It is this massive input of energy to the Earth's surface and lower atmosphere that is causing global temperatures to increase.

There are several important factors affecting the net radiative forcing, as shown in Figure 2.1 (2005 values). The contributions fall into three main groups:

- $CO_2$ contributes about 1.7 $W/m^2$
- the other GHGs, including methane, nitrous oxide, synthetic gases, and ozone, together contribute about 1.3 $W/m^2$
- aerosols, together with some other physical processes such as changes in the Sun's energy output and the brightness of the Earth's surface, have a net effect of reducing radiative forcing by 1.1 $W/m^2$. There is a significant degree of uncertainty in this estimate, however, because the effects of aerosols are complex. For example, dark aerosols, such as carbon in fire smoke, tend to absorb solar radiation and enhance warming, while pale-coloured aerosols, such as sulphate particles formed from many kinds of industrial emissions, reflect solar radiation back to space and exert a cooling effect.

The combination of these and other minor contributions gives a net positive radiative forcing of about 1.6 $W/m^2$, causing a net warming of the atmosphere. This is similar to the radiative forcing from $CO_2$ alone, because at present the contributions from non-$CO_2$ GHGs and from aerosols approximately cancel one another out. This approximate cancellation is unlikely to continue, because a probable future decrease in pollution-based aerosols in the atmosphere will reduce the negative (that is, cooling) aerosol contribution to radiative forcing, resulting in increased warming.

Figure 2.2 shows how the contributions to radiative forcing from the long-lived GHGs ($CO_2$, methane, nitrous oxide, and synthetic gases) have built up from 1900 to 2009, based on measurements from CSIRO,[2] the Advanced Global Atmospheric Gases Experiment (AGAGE) global GHG networks,[3] and CSIRO measurements of air trapped in Antarctic ice[4] and near-surface levels of ice known as firn.[5]



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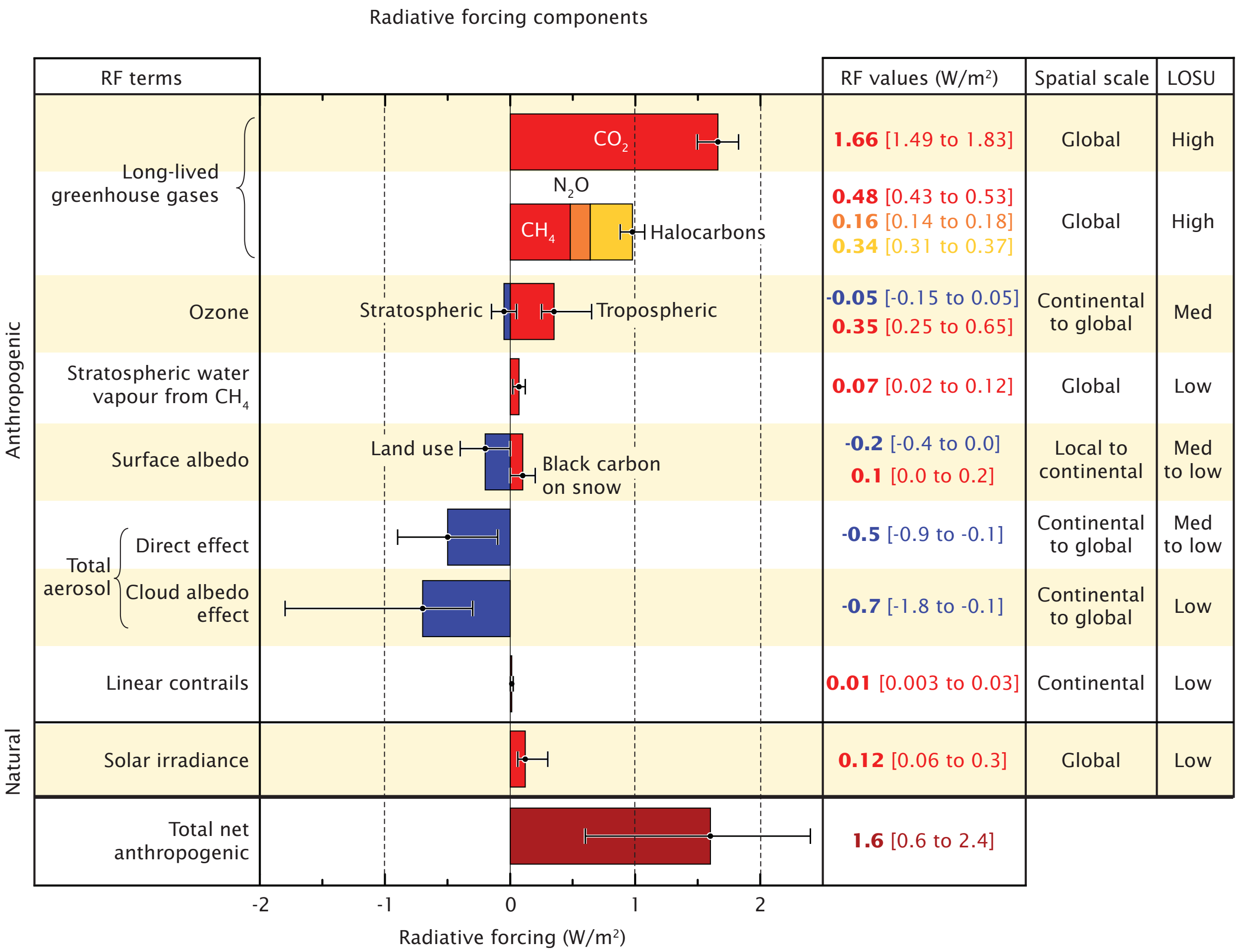
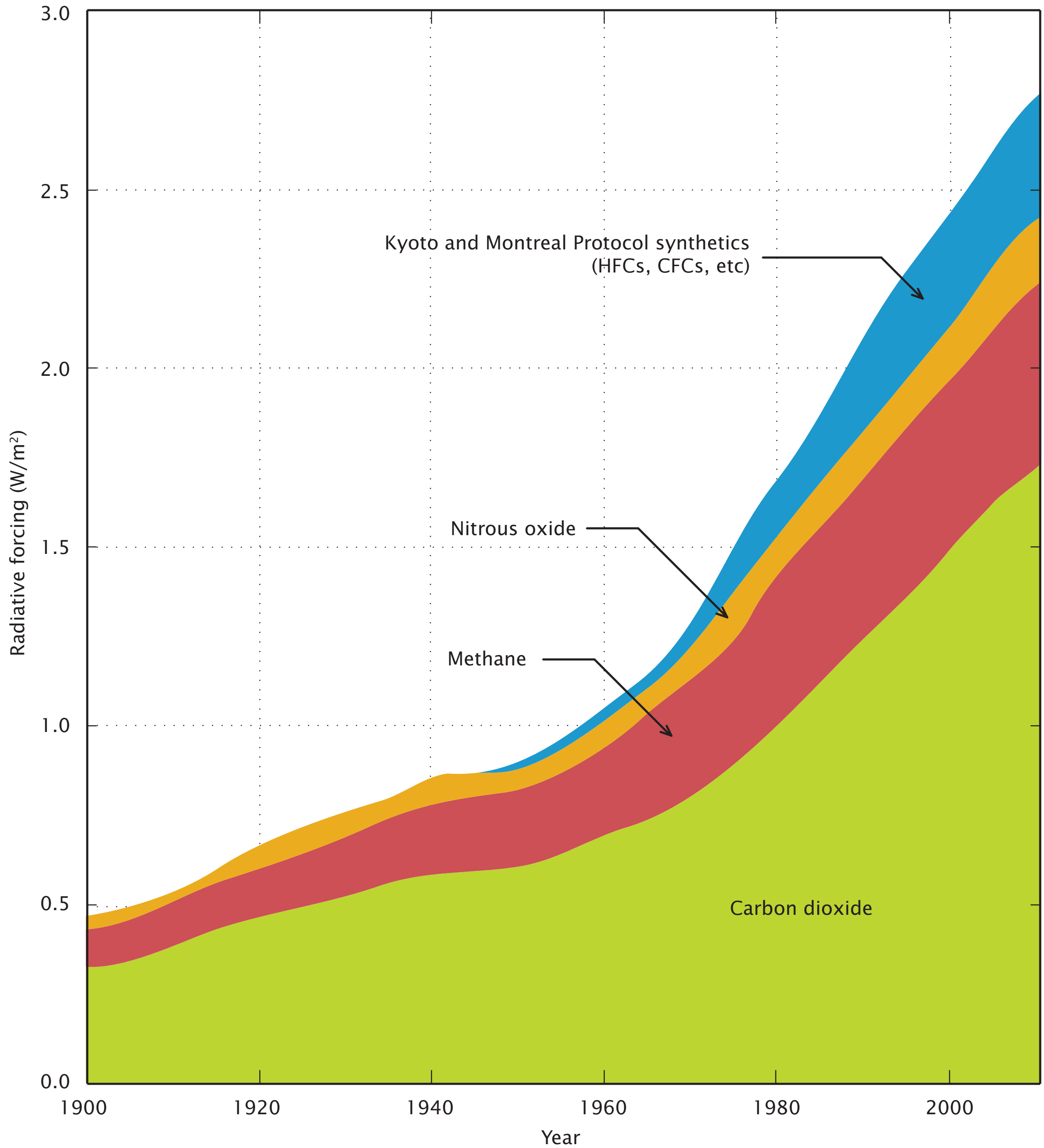



▲ ***Figure 2.1**: Global-average radiative forcing (RF) in 2005 (best estimates and 5–95% uncertainty ranges) with respect to 1750 for $CO_2$, $CH_4$, $N_2O$, and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term for a few years following an eruption. The range for linear contrails does not include other possible effects of aviation on cloudiness. Note that the total net human-induced radiative forcing (1.6 W/m²) is not a simple sum of components. Reproduced from Figure 2.4 of the IPCC (2007) Synthesis Report.*[1]




▲ ***Figure 2.2**: Global radiative forcing due to long-lived GHGs from 1900 to 2009 assessed from data measured in the CSIRO[2] and AGAGE[3] networks, which are archived annually in international GHG data archives [World Meteorological Organization World Data Centre for Greenhouse Gases, WMO-WDCGG: http://gaw.kishou.go.jp/wdcgg/ and US Dept of Energy Carbon Dioxide Information Analysis Center (CDIAC): htpp://cdiac.oprnl.gov] and from CSIRO measurements on air trapped in Antarctic ice[4] and firn.[5]*

Table 2.1 shows how CSIRO's measurements of the radiative forcing from these GHGs compare with those reported by the IPCC.[6] The small differences between the CSIRO and IPCC measurements result from the different global observational networks used by CSIRO (CSIRO and AGAGE) and IPCC (CSIRO, NOAA, and AGAGE). The CSIRO 2009 data are very likely to be almost identical to IPCC data for 2009, which are yet to be published.

**Table 2.1: Concentrations (ppm – parts per million molar; ppb – parts per billion molar) and radiative forcings ($W/m^2$) for 1998, 2005, and 2009 due to long-lived GHGs as reported by the IPCC[6] and calculated from data collected in the CSIRO[2] and AGAGE[3] networks**

| Gas | Concentrations | | | | | Radiative forcing | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1998 | | 2005 | | 2009 | 1998 | | 2005 | | 2009 |
| | IPCC | CSIRO | IPCC | CSIRO | CSIRO | IPCC | CSIRO | IPCC | CSIRO | CSIRO |
| $CO_2$ (ppm) | 366 | 366 | 379 | 379 | 386 | 1.47 | 1.46 | 1.66 | 1.65 | 1.76 |
| $CH_4$ (ppb) | 1763 | 1764 | 1774 | 1771 | 1789 | 0.48 | 0.49 | 0.48 | 0.49 | 0.50 |
| $N_2O$ (ppb) | 314 | 314 | 319 | 320 | 323 | 0.14 | 0.15 | 0.16 | 0.16 | 0.18 |
| Synthetic GHGs (ppb) | 1.27 | 1.33 | 1.32 | 1.33 | 1.35 | 0.33 | 0.33 | 0.34 | 0.33 | 0.34 |
| Total | | | | | | 2.42 | 2.43 | 2.64 | 2.65 | 2.77 |

*North Sullivan Photography/CSIRO*

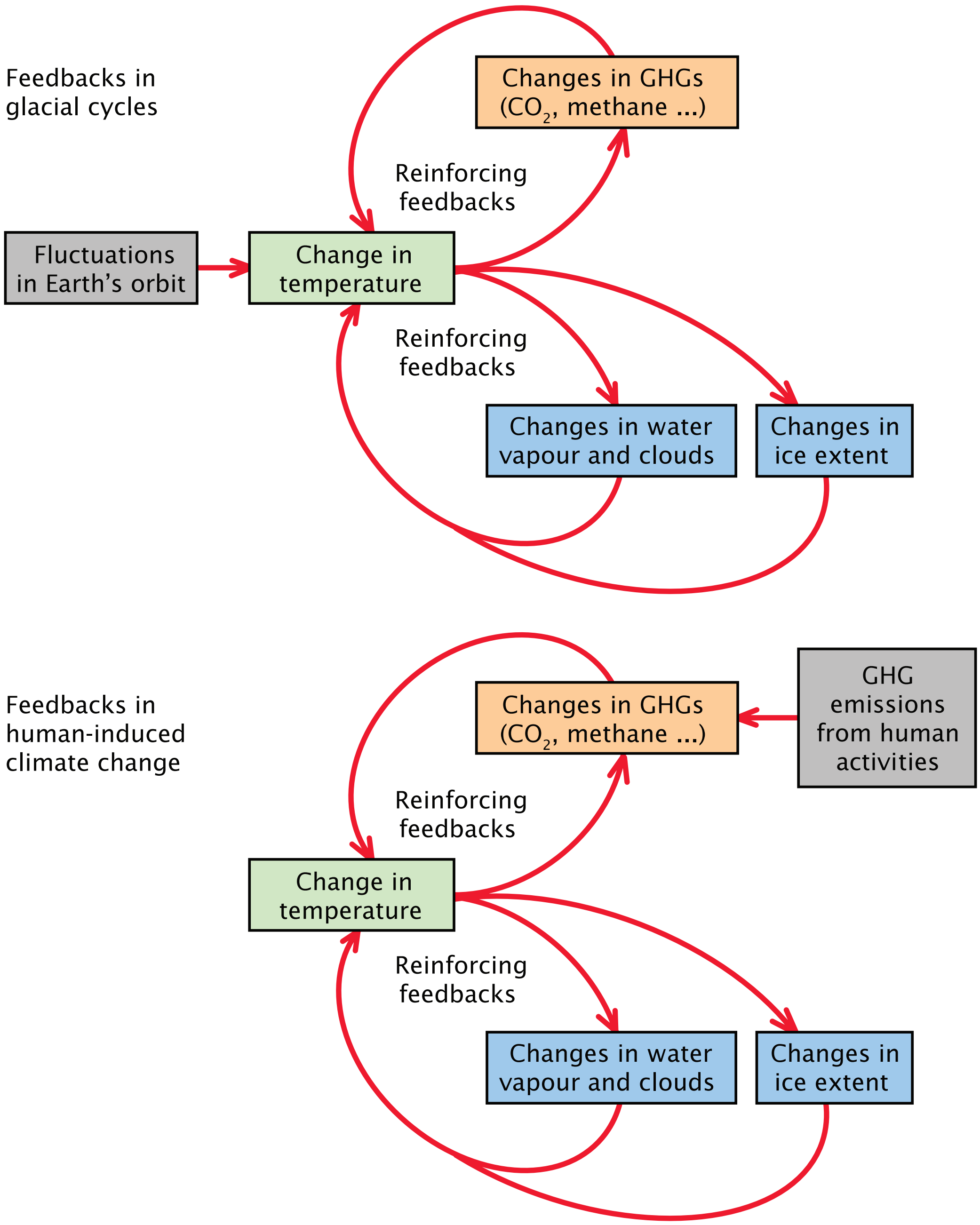
## Feedbacks in the climate system

Knowledge of the radiative forcing tells us how much extra energy the Earth is retaining in the lower atmosphere, but it does not tell us the resulting warming. The amount of warming depends on many internal 'feedbacks' in the climate system. These are processes whereby a change in one component of the system ripples through to other components and back again, either to reinforce or dampen the original change.

As shown in Figure 2.3, feedback processes connect the atmospheric levels of GHGs ($CO_2$, methane, and others), water vapour, cloudiness, the extent of polar ice caps, and global temperature. The global average concentration of water vapour quickly increases in response to an increase in global temperature, due to the increased water-retaining capacity of a warmer atmosphere. Because water vapour is a GHG, the original warming is amplified. This reinforcing feedback approximately doubles the amount of warming that would otherwise be produced by a given amount of radiative forcing. A second, much slower, reinforcing feedback arises from the interaction between the surface area of polar ice caps and global temperature: as warming initiates a melting of the ice, the consequent darkening of the surface (as land or ocean from under the ice is exposed) leads to the absorption of more radiation, and thus further warming. A third important class of feedbacks involves the natural cycles of greenhouse gases, such as $CO_2$ and methane, which respond to temperature and moisture in ways that can amplify an initial warming.

The net effect of all these processes is a set of feedbacks that have an overall reinforcing effect. A doubling in $CO_2$ from pre-industrial levels (280 ppm) to around 550 ppm without feedbacks would result in a global warming of about 1ºC. Factoring in the effects of water vapour and other 'fast' feedbacks, however, means that a $CO_2$ doubling will amplify the long-term average warming to about 3ºC. This important number, called the 'fast climate sensitivity', is somewhat uncertain and could vary between 2º and 4.5ºC according to IPCC estimates based on a range of climate models.[1]

The conclusion that water vapour and related feedbacks have an overall amplifying effect is critical. It can be substantiated entirely independently from climate models using ice-core records of climate fluctuations over the last 850 000 years.[7] These show that small fluctuations in the Earth's orbit around the Sun led to large changes in global temperature through the same set of feedbacks that operates to amplify the climate change from human emissions of $CO_2$ and other GHGs. These records yield a value of about 3ºC for fast climate sensitivity to a doubling of $CO_2$, similar to the estimates from various climate models.[7]




▲ ***Figure 2.3****: There are close connections between global temperature, atmospheric water vapour and cloudiness, the extent of polar ice caps, and levels of greenhouse gases in the atmosphere. When one of these is disturbed, such as by human activity, the others react through processes that amplify the original disturbance until a new, different, climate equilibrium is reached. The disturbance driving the glacial cycles over the last million years came mainly from fluctuations in the Earth's orbit around the Sun (grey box in upper diagram). This changed temperatures (green box), in turn changing water vapour and ice caps (blue boxes), and greenhouse gas levels (orange box). The disturbance in modern climate change comes largely from human-induced changes in atmospheric* $CO_2$ *and other greenhouse gas levels (grey box in lower diagram). The disturbance is amplified by similar reinforcing processes in both cases.*[8]

## The carbon dioxide budget of the Earth's atmosphere

Radiative forcing from carbon dioxide is the largest single contributor to human-induced climate change (Figures 2.1, 2.2). Half a century or more of atmospheric measurements testify to a steady rise in $CO_2$ concentrations in the Earth's atmosphere. Measurements have been taken at places such as Mauna Loa, Hawaii (since 1956) and Cape Grim, Tasmania (since 1976), the latter as part of a joint Australian Bureau of Meteorology and CSIRO program to study global atmospheric composition. Furthermore, tiny air bubbles trapped in ice and firn cores taken from places such as Law Dome in Antarctica reveal what the atmosphere was like in earlier times.[4] Together, all these measurements allow us to trace the dramatic rise in $CO_2$ levels from about 280 ppm before the start of the industrial era around 1800 to 386 ppm in 2009 (Figure 2.4). $CO_2$ levels rose through the decade 2000–2009 at an average rate of almost 2 ppm per year, although the rate fluctuates from year to year.

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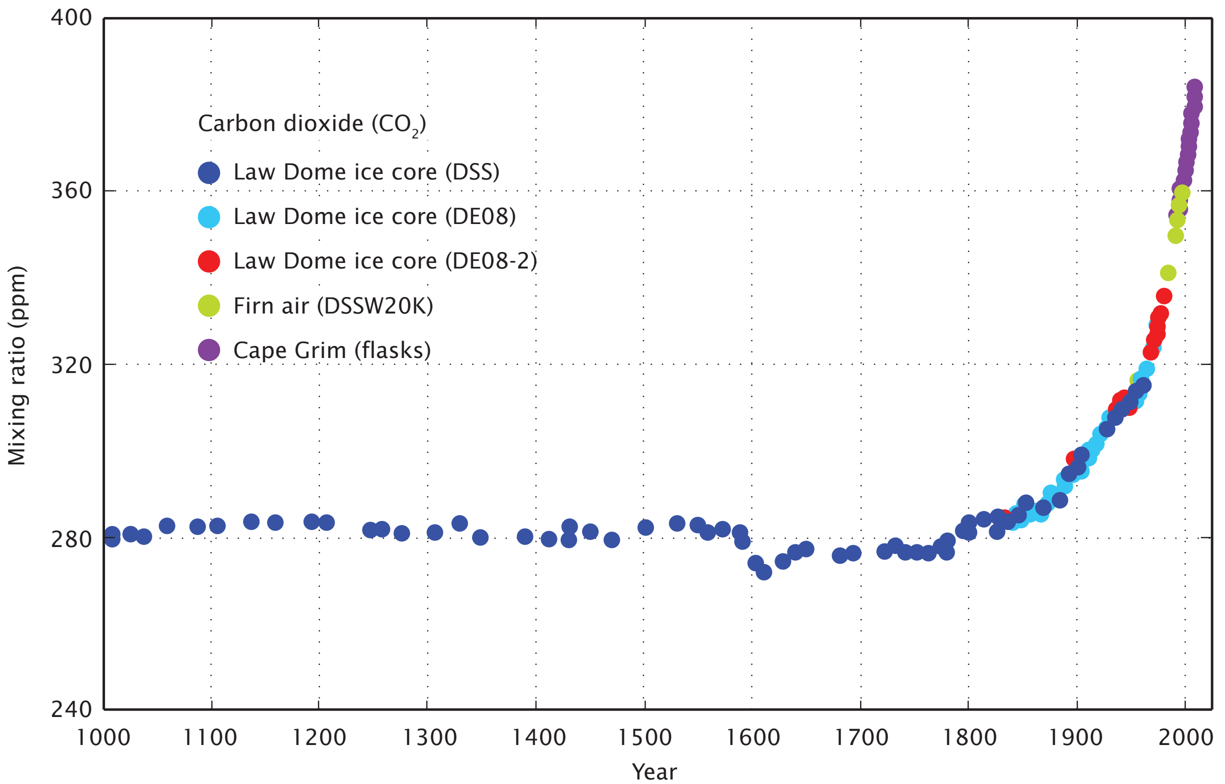
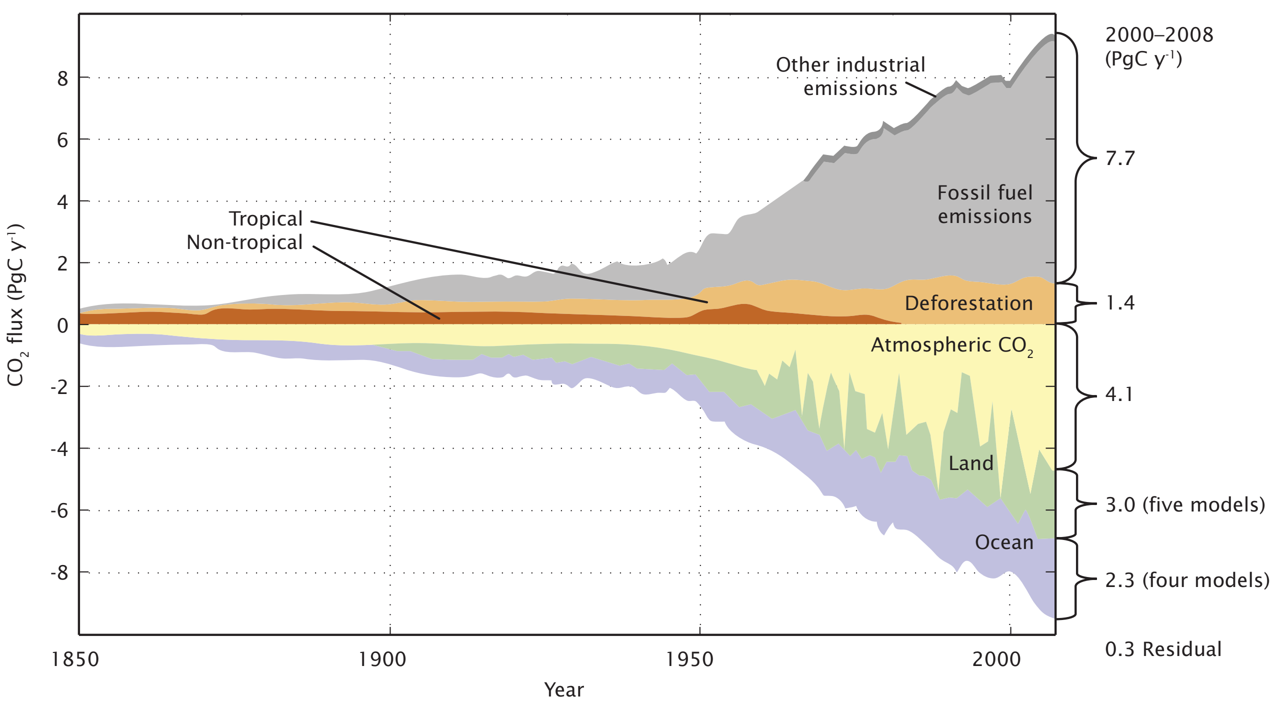



▲ ***Figure 2.4***: *Southern Hemisphere atmospheric $CO_2$ levels over the past 1000 years, sourced from CSIRO data.*[2, 4]

Why are $CO_2$ levels rising as they are? The amount of $CO_2$ accumulating in the Earth's atmosphere is determined by the balance between inflows and outflows: in other words, a '$CO_2$ budget'. For several millennia before the industrial revolution started around 1800, the $CO_2$ budget of the atmosphere was nearly in balance: natural inflows (transfers of carbon from land and ocean systems into the atmosphere as $CO_2$, together with small contributions from volcanic activity) were approximately equal to natural outflows (transfers of carbon out of the atmosphere into land and ocean systems). This nearly balanced budget meant that $CO_2$ levels in that atmosphere did not change significantly over centennial time scales (Figure 2.4).

Since around 1800, there has been an additional large inflow of $CO_2$ to the atmosphere from emissions due to human activities, including contributions from (1) the burning of fossil fuels (coal, oil, and gas), (2) cement production and other industrial processes, and (3) deforestation or land clearing (occurring now almost entirely in tropical regions). This inflow is partly offset by natural $CO_2$ 'sinks' in the land and oceans. The land $CO_2$ sink derives from an imbalance between plant growth (through photosynthesis) and plant decay. Several factors are responsible: the stimulation of photosynthesis by increasing atmospheric $CO_2$ levels (though other nutrients must also be available for a sustained increase in plant growth); forest regrowth after deforestation that occurred many decades ago; changes in fire regimes; and changes in ecosystem structure, such as the replacement of tropical C4 grasses by woody C3 plants that store more biomass. The ocean $CO_2$ sink occurs because $CO_2$ dissolves in ocean waters (also increasing ocean acidity) when atmospheric $CO_2$ concentrations are higher than those at the ocean's surface. This dissolved carbon is then transported to the deep ocean both by overturning circulations and by the sinking of dead organisms that have derived their carbon by consuming phytoplankton (tiny photosynthesising organisms that convert $CO_2$ to organic carbon).

Figure 2.5 shows how the inflows and outflows of $CO_2$ interact to produce the current rapid increase in atmospheric $CO_2$ levels in the atmosphere.[9, 10] In the period 2000–2008, 82% of humanity's $CO_2$ emissions came from the burning of fossil fuels, primarily coal, oil, and gas, and 3% from other industrial sources. These emissions together grew by 3.4% per year.[10] The remaining 15% of emissions, from deforestation, were steady. We know these emissions originate from human activity because of chemical 'fingerprints' in the atmosphere, such as the oxygen level and the fractions of carbon isotopes ($^{13}C$ and $^{14}C$) in $CO_2$, which all indicate that the origin of the increased $CO_2$ is largely fossil fuels. For example, the observed decrease with time of the carbon isotope ratio ($^{13}C/^{12}C$) in the atmosphere is consistent with the impact of a fossil fuel source, because the $^{13}C/^{12}C$ ratio in fossil carbon is lower than that in the atmosphere. Such approaches also help to determine the magnitude of the terrestrial and oceanic $CO_2$ sinks.




▲ ***Figure 2.5**: Sources and sinks of atmospheric $CO_2$. Those above the zero-line represent anthropogenic additions to the atmosphere (inflows); those below are sinks for $CO_2$ (outflows), together with the accumulation in the atmosphere. Units are in petagrams of carbon per year (Pg = petagram; 1 petagram = $10^{15}$ grams = 1 billion tonnes). The small residual reflects minor discrepancies in independent measurements of different terms.*[10]

Land and ocean $CO_2$ sinks respectively removed 30% and 25% of all anthropogenic $CO_2$ emissions over the period 2000–2008,[9–11] leaving about 45% to accumulate in the atmosphere. The Earth's $CO_2$ sinks, in both land and oceans, thus constitute a massive ecosystem service that helps to mitigate humanity's emissions.

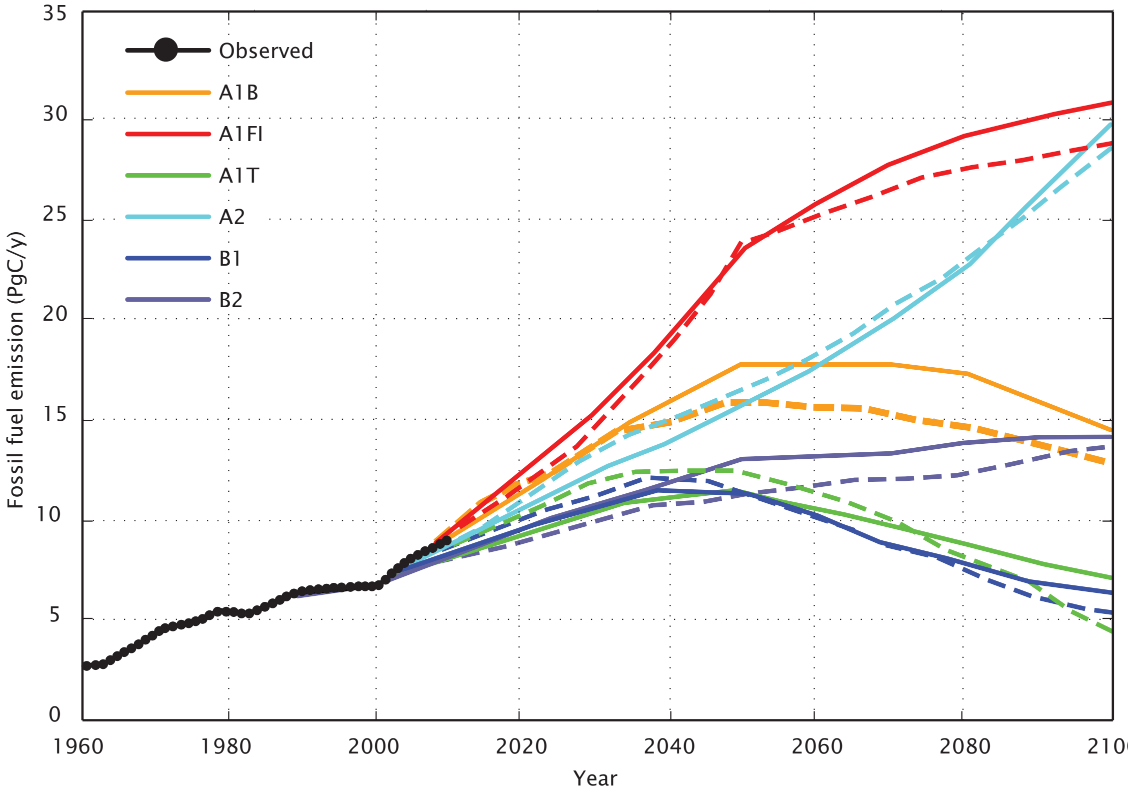
The fraction of $CO_2$ emissions staying in the atmosphere (about 45%) is known as the airborne fraction, or AF. There has been a small increasing trend in the AF over the period from 1960 to 2008,[9–11] which indicates that even though the land and ocean $CO_2$ sinks are continuing to grow with the rise in atmospheric $CO_2$, they are progressively 'losing the race' against the even more rapidly growing emissions. This is occurring for many reasons,[12] both for land and ocean sinks. For instance, on land, plants experience 'diminishing returns' in extra $CO_2$-induced growth with rising concentrations of atmospheric $CO_2$. On the oceans, climate change and ozone depletion drive stronger winds over the Southern Ocean – the largest ocean carbon sink – which may cause deep carbon-rich waters to upwell and release their $CO_2$ back into the atmosphere, thus reducing the net sink. An important consequence of the increasing AF is that the ecosystem service provided by the Earth's $CO_2$ sinks in soaking up a steady fraction of our $CO_2$ emissions has diminished in recent decades.

## Trends in $CO_2$ emissions from fossil fuels

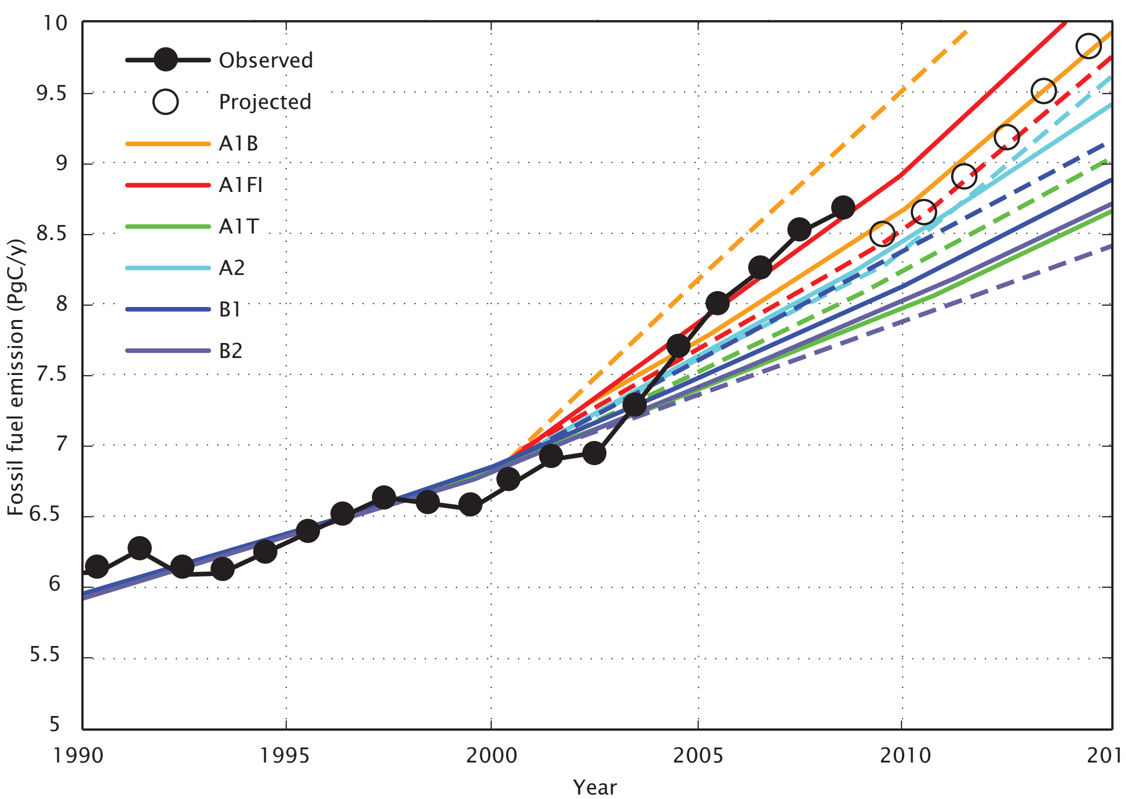
Critical to the rate of future climate change is how $CO_2$ emissions from the burning of coal, oil, and gas evolve over the coming decades. Figure 2.6 shows past emissions back to 1960 and a range of possible future scenarios out to 2100, as modelled by the IPCC in its *Special Report on Emissions Scenarios (SRES)*.[13] These scenarios involve assumptions about demographic, economic, and technological factors likely to influence future economic development and greenhouse gas emissions. Scenarios depend on factors such as rates of population increase, global economic growth, and humanity's relative success or failure at slowing emissions from the burning of coal, oil, and gas.

▸ ***Figure 2.6****: $CO_2$ emissions from fossil fuels[14, 15] measured in petagrams of carbon emitted per year (see Figure 2.5 caption for definition of petagrams). Observed data are shown as black and grey points. Solid coloured lines are average future emissions in six scenario families from the* IPCC Special Report on Emissions Scenarios (SRES).[13] *Corresponding dashed coloured lines denote marker scenarios used in IPCC climate change projections.[1] Scenarios are rescaled slightly to match actual emissions over the period 1990–2000. The upper (a) and lower (b) panels show the periods 1960–2100 and 1990–2015, respectively. Open circles in (b) are estimated emissions based on Gross World Product (GWP) projections[16] and an assumed carbon intensity of the economy (emissions/GWP) scaled to 2008 and reducing at 1.2%/year, the average value for 2000–2008.*

(a)


Observed
A1B
A1FI
A1T
A2
B1
B2
Fossil fuel emission (PgC/y)
0
5
10
15
20
25
30
35
1960
1980
2000
2020
2040
2060
2080
2100
Year

(b)


Observed
Projected
A1B
A1FI
A1T
A2
B1
B2
Fossil fuel emission (PgC/y)
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
1990
1995
2000
2005
2010
2015
Year

An important feature is seen in the lower part of Figure 2.6, which focusses on the 25-year period 1990–2015. This highlights a jump in fossil-fuel emissions growth[15] that took place soon after 2000. From 2000 to 2007, the growth rate of observed emissions was 3.4% per year, which exceeds almost all assumed scenarios generated in the late 1990s. This pulse of $CO_2$ emissions growth is attributable to strong global economic growth centred in China, India, and other rapidly developing economies, and the lack of effective reductions in emissions in developed countries. The pattern of growing emissions over the past two decades (whether a shorter term rapid increase in the early 2000s or a longer term increase starting in the 1990s) is an evolving research topic.[17]

The global financial crisis of 2008–2009 caused a temporary slowdown in global emissions growth, which is discernible in a dip in the upward trend of the line formed by the open circles in Figure 2.6. This dip was equivalent to about 6 weeks' worth of total global emissions. Allowing for the dip, the average growth rate in fossil-fuel emissions over the whole decade 2000–2009 was still high, at 3.0%. Assuming a return to rapid worldwide economic growth after the financial crisis, high growth in emissions is liable to continue unless rapid steps are taken to reduce the carbon intensity of the global economy.[14]

## Budgets for other greenhouse gases

There is a similar global budget for the second most influential greenhouse gas, methane.[12] Here the dominant natural source (input to the budget) is wetlands, with a smaller natural source from termite activity. Additional major sources arise from human activities, through agriculture (rice and ruminant livestock production), waste disposal in landfill, gas leaks from pipelines and coal mines, and biomass burning. In recent decades, sources from human activities have exceeded the combined natural sources by two-fold or more. The main sink for methane is chemical degradation in the atmosphere.

*Willem van Aken/CSIRO*

The average atmospheric methane level in 2009 was 1789 parts per billion – more than twice what it was in the pre-industrial era. There has been little growth in methane levels over the past decade, suggesting that methane emissions and their removal from the atmosphere by oxidation to $CO_2$ are coming into balance. This has been attributed in part to a gradual reduction of leaks from natural gas pipelines and from other industrial sources such as coal mining and landfill sites.

The nitrous oxide concentration in 2009 was 323 ppb, about 20% above its pre-industrial level. The dominant human-influenced source is agriculture. Emissions of nitrous oxide, like $CO_2$, continue unabated.

There has also been significant radiative forcing (about 0.16 W/m$^2$) caused by synthetic GHGs – largely chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs) – as shown in Figure 2.2. The aggregate atmospheric concentration of these gases has recently stopped growing, but growth in concentrations is likely to resume[18] because of the large projected growth in future emissions of HFCs, which are currently widely used in modern refrigerators and air-conditioners. Ironically, HFCs were introduced to replace the use of the CFCs, which were causing stratospheric ozone depletion.

## Greenhouse gases and climate in the future

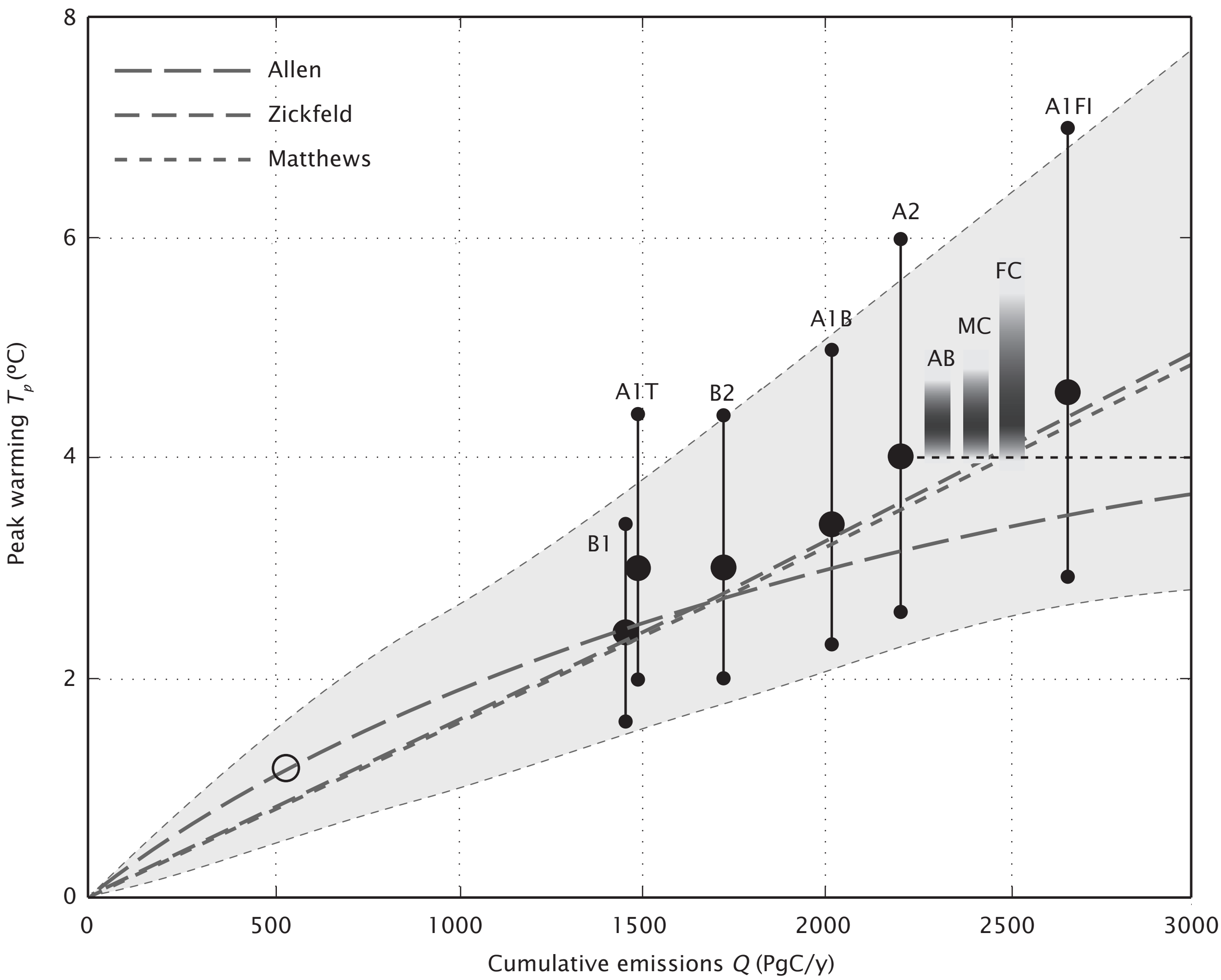
Whether climate change is 'dangerous' is a complex issue because different global regions will be affected in different ways. Nevertheless, a globally averaged warming of 2ºC above pre-industrial temperatures is widely used as a benchmark[19] at which the effects of climate change start to have dangerous risks and impacts. Chapters 1 and 3 describe some of these in more detail, such as sea-level rise, increased frequency of extreme weather, and so on.

The cumulative total amount of $CO_2$ emitted from all human sources in the past 250 years is now around 530 billion tonnes. To have a 50:50 chance of keeping global warming below 2ºC, it will be necessary to stop almost all $CO_2$ emissions before our cumulative emissions reach 1000 billion (one trillion) tonnes.[20–22] If $CO_2$ emissions keep growing at their present (2000–2010) rate, we will emit another 470 billion tonnes by around 2045. If we stabilise emissions from the present time (2010) onward without further growth, we will reach 1000 billion tonnes by around 2060. Any further emission leads to a greater chance of dangerous climate change. However, 50:50 is not good odds when it comes to avoiding danger; to improve those odds, the cap on cumulative emissions needs to be lower.

This underlines the fact that climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes. The level of risk we incur is directly related to the strength and speed of our actions. It also makes it clear that setting and adhering to clearly defined targets is an important way of reducing risks of harm from climate change.

The assessment of risk from climate change, and its relationship to future greenhouse gas emissions, is made more complicated by uncertainties about the magnitude and speed of the response of climate to a given radiative forcing. These uncertainties stem mainly from the feedbacks illustrated in Figure 2.3. Although feedback processes can either reinforce or dampen climate change, the risks associated with these two possibilities are not evenly distributed: reinforcing feedbacks are particularly important because they lead to increased risks of very serious outcomes.

Figure 2.7 includes an assessment of the way that several processes might affect the peak warming induced by a given cumulative input of $CO_2$.




▲ ***Figure 2.7**: Peak warming from pre-industrial times, plotted against cumulative emissions of $CO_2$ (in petagrams of carbon per year) from both fossil fuels and land-use change, from 1750 to the far future. Dashed and dotted lines[20, 23, 24] represent the most likely warming from three studies in 2009, and the shaded band represents an uncertainty range. Current assessments are that warming is likely to fall within this range. Solid points show IPCC scenarios for 2100,[1] with uncertainty bars giving likely ranges. Shaded bars[14] show ranges of possible effects, relative to the IPCC A2 scenario as a reference, from FC (coupled carbon-climate feedbacks on carbon sink strength), MC (mobilisation of previously immobile carbon pools), and AB (release of aerosol brake). All ranges are indicative only. Open circle shows cumulative emissions to 2008 and the resulting peak warming of 1.2ºC (including 0.7ºC of warming observed to date plus 0.5ºC of committed warming with radiative forcing stabilised at 2008 levels).[1]*

### *Feedbacks on land and ocean $CO_2$ sinks*

The influence of climate change on land and ocean $CO_2$ sinks occurs both through changes in atmospheric composition, particularly rising $CO_2$, and changes in climate, particularly the averages and distributions of temperature and rainfall. Recent studies[25, 26] have found that feedbacks between carbon dioxide concentrations and changes in climate tend to increase warming, but the possible range of responses remains large. An additional factor is that there are limits to the supply of nutrients (e.g. nitrogen and phosphorus), which are essential to maintain the land $CO_2$ sink. The uncertainty in consequent warming is conservatively indicated by the 'FC' bar in Figure 2.7.

### *Mobilisation of carbon from disturbed pools*

Vast quantities of carbon currently lie locked up in huge natural reservoirs that can be disturbed by climate change, causing release of this carbon into the atmosphere as either $CO_2$ or methane, hence further accelerating warming. One such reservoir is the carbon locked up in frozen soils in the Arctic region, which is estimated at nearly 1700 billion tonnes in total.[27] Thawing as a result of warming over the next 100 years could release around 100 billion tonnes of this carbon to the atmosphere as $CO_2$ or methane.[28] Another large quantity of carbon exists in tropical peatland soils, mainly in South-East Asia – around 30 billion tonnes of this carbon could be released as $CO_2$ or methane by drainage or fire.[29] Net releases of carbon from forest ecosystems are also possible through fire, insect attack, and ecological transitions such as conversion of tropical forests to grasslands. An as yet unquantified risk exists in frozen deposits of ancient methane beneath the Arctic seabed. The 'MC' bar in Figure 2.7 shows a conservative range for the overall warming consequences of these risks.

### *Release of the 'aerosol brake'*

Some types of aerosols help to cool the Earth and offset the effect of radiative forcing, as described earlier. It is still highly uncertain how large this effect may be but it is possible that measures taken to improve air quality in the world's big cities could reduce the amount of sulphate aerosols entering the atmosphere and so release the 'aerosol brake' (that is, cooling effect) on warming.[30] A possible range for the resulting additional warming is shown by the 'AB' bar in Figure 2.7.

Unfortunately, these uncertainties act mainly to further increase warming, although by how much remains unclear. The possibility exists that there are further unidentified, but significant, dampening and reinforcing feedbacks.

## Conclusion

There is a great deal of evidence that the Earth's climate has warmed over the last century. It is very likely that the primary cause of this warming is the emission of greenhouse gases ($CO_2$ and others) due to a range of human activities and the resulting increase in the concentrations of greenhouse gases in the atmosphere.

Climate models indicate that it is also very likely that warming and other climate changes will continue and accelerate through the coming century if emissions of greenhouse gases continue to increase. Our growing understanding of the feedbacks that can both dampen and reinforce climate change suggest that, in aggregate, these feedbacks reinforce the warming trend. Ultimately, there is always a difficult-to-quantify risk of crossing an important threshold and triggering serious, unexpected change that is potentially irreversible for a long time.

Climate change will pose an increased risk to human wellbeing in the future. The nature and consequences of the effects on ocean and air temperatures, sea-level rise, frequency of extreme events, ecosystems, agriculture, and more are described in the following chapters.

## Further reading

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