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Climate change, greenhouse gases and radiative forcing

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Overview

- Human emissions of greenhouse gases (GHGs) and aerosols create an energy imbalance at the top of the atmosphere. GHGs cause warming by trapping infrared radiation from the Earth's surface; aerosols have a cooling effect by reflecting incoming sunlight back into space. There are other important influences also such as the impact of aerosols on clouds, the effects of black carbon (soot) and airplane condensation trails.
- The size of this energy imbalance is measured by the radiative forcing, which for long lived greenhouse gases in 2011 was 2.83 [2.54 to 3.12] W per m^2. This is an increase of 0.20 [0.18 to 0.22] since the IPCC's last assessment report in 2007 (AR4). There is high confidence that anthropogenic aerosols have offset a high proportion of the greenhouse gas forcing.
- Carbon dioxide has been the dominant contributor of the long-lived GHGs, with a radiative forcing of 1.82 [1.63 to 2.01] W per m^2, an increase of about 0.3 W per m^2 per decade over the past 15 years. Carbon dioxide stays in the atmosphere for a long period of time so cumulative emissions are particularly important to its impact on the climate.
- The contribution of methane to the radiative forcing is now 0.48 [0.43 to 0.53] W per m^2, an increase of 2% since AR4. Nitrous oxide concentration has increased by 6% since AR4 and now contributes a radiative forcing of 0.17 [0.15 to 0.19] W per m^2. The radiative forcing from all halocarbons (including CFCs and HFCs) is 0.36 W m^2; there has been a reduction in the radiative forcing from CFCs but an increase in the contribution of their replacements.
- The (negative) effective radiative forcing due to anthropogenic aerosols is −0.9 [−1.9 to −0.1] W per m^2. This is consistent with multiple lines of evidence suggesting less negative estimates for aerosol-cloud interactions than those discussed in AR4.
- The representative Concentration Pathways (RCPs) in the IPCC's Fifth Assessment Report (AR5) cover a range of possible future emissions trajectories. RCP2.6 is a strong mitigation scenario while RCP8.5 is an emissions intensive one, with carbon dioxide levels of 933ppm by 2100. These scenarios are not predictions; the actual emissions path we follow in the 21st Century will depend on the extent to which there is effective national and international mitigation action. Current CO_2 emissions appear to be in line with those in RCP8.5.
- AR5 says that limiting climate change will require "substantial and sustained" reductions of greenhouse gas emissions.

Basics of electromagnetic radiation

The Earth is warmed by energy from the Sun which emits visible light and other forms of electromagnetic radiation such as ultraviolet (UV) and infra-red. Electromagnetic radiation can be thought of as packets of energy called photons. Each photon has a characteristic wavelength associated with it. The smaller the wavelength, the more energetic is the photon. The surface of the Sun is at a temperature of around 5500°C. This means that most of the electromagnetic radiation the sun emits is in the form of visible light, with some at higher and lower wavelengths. The Earth is much cooler and emits mainly infrared radiation - the sort of light that is picked up by night vision binoculars.

How atmospheric composition changes the climate

The atmosphere is pretty much transparent to the higher energy visible light from the Sun, although about 30 per cent is reflected directly back into space without warming the planet by clouds, atmospheric aerosols and the surface itself. The atmosphere, however, is a very good absorber of the infrared radiation that is re-emitted from the surface of the Earth. Most of this effect is due to water vapour in the atmosphere, but atmospheric carbon dioxide also makes an important contribution along with some other greenhouse gases.

This trapped radiation is re-emitted both upwards into the atmosphere and also back down to the Earth's surface. This means that the surface of the planet receives more energy than it would without an atmosphere and it warms until an equilibrium is established in which the emission of infrared radiation to space is equal to the solar energy flow into the Earth. Without this natural greenhouse effect, the Earth's surface would be some 33°C cooler.

Why is the level of greenhouse gases in the atmosphere important?

Since industrialisation, levels of greenhouse gases in the atmosphere have risen due to human activities such as burning of fossil fuels and deforestation. Carbon dioxide is now at a level not seen for over 800,000 years, with CO_2 concentrations briefly reaching 400 parts per million (by volume - ppmv) during 2013. Methane levels have also increased dramatically. This rapid increase has intensified the greenhouse effect, leading to further warming of the planet. Increase in carbon dioxide (CO_2) levels since about 1750 is responsible for most of this human impact on the greenhouse effect, but other greenhouse gases (GHGs) also contribute.

We measure the strength of different GHGs by their contribution to what is known as "radiative forcing". This is a measure of the energy imbalance between the incoming solar and outgoing infrared radiation at the top of the atmosphere caused by the GHGs. If we stopped further emissions of GHGs tomorrow, the system would gradually return to equilibrium at a warmer surface temperature and the energy balance would return to zero.

Radiative forcing is measured in units of Watts per square metre (Wm^{-2}). Different GHGs vary in how strongly they absorb infrared radiation and hence have different effects on radiative forcing. They also have very different lifetimes. The longer the lifetime of the gas, the more evenly distributed it will be throughout the atmosphere due to natural weather processes. Carbon dioxide is a very long-lived and well-mixed gas, though there are some spatial and temporal variations depending on the photosynthetic activity of plants and large centres of economic activity. Of the well mixed greenhouse gases, methane and nitrous oxide (N_20) are the second and third highest contributors to global warming.

One measure by which different GHGs can be compared is the so-called global warming potential (GWP), which is the warming potential of a greenhouse gas compared to carbon dioxide, usually over a 100 year period. On this basis, methane has a GWP of 28 and N_2O has a GWP of 265. Methane only has a lifetime in the atmosphere of about 12 years, and N_2O about 120 years. The lifetime of carbon dioxide is not defined in general because it depends on physical processes that act on different timescales, but a significant fraction of any CO_2 released into the atmosphere will result in elevated CO_2 levels for many hundreds of years.

The increase in radiative forcing due to greenhouse gases is partially offset by the increased reflection of incoming light from the Sun due to the direct effects of sulphate aerosols from fossil fuel burning or volcanic activity. Black carbon (soot) from incomplete combustion has a positive effect on forcing. Aerosols also influence the development and properties of clouds, by providing particles on which atmospheric moisture can condense[1].

Through their impact on radiation, aerosols in particular influence the atmospheric temperature profile and cloud properties on a much shorter timescale than the response of the ocean to climate change. AR5 therefore uses both the concept of Radiative Forcing (RF) and that of Effective Radiative Forcing (ERF) that allows for rapid adjustments to changes in atmospheric composition for all relevant variables except global mean surface temperature, ocean temperature and sea ice cover. For most influences on the Earth's energy budget, the RF and ERF are similar in value; they are however significantly different for aerosols due to their influence on clouds and snow/ice cover on land. Where there is a difference between these two measures, AR5 says that ERF has been shown to be a better indicator of the global mean surface temperature response to changes in atmospheric composition.

Because carbon dioxide is long lived, the cumulative level of CO_2 emissions over time, rather than their atmospheric concentration or emission rates, has been found to have special significance in determining the maximum level of global mean surface temperature increase.

Carbon dioxide emissions are currently following IPCC's highest emissions scenarios from AR4 or the RCP8.5 scenario from AR5. This means that emissions need to be curbed significantly if we wish to avoid temperature increases exceeding 2^{o}C.

What other factors influence radiative forcing?

Radiative forcing varies naturally, mainly due to volcanic activity and solar cycles. The fluctuations in radiative forcing due to solar cycles are much smaller in magnitude than the radiative forcing associated with anthropogenic greenhouse gas emissions. Volcanic eruptions can induce significant decrease in radiative forcing, but they only last for a year or two.

[1] Clouds too have an impact on the radiative forcing since high clouds generally amplify the greenhouse effect, while low clouds tend to moderate it. But these effects are a climate feedback, not a forcing. See the accompanying note on climate sensitivity for details.

Land use change can have an impact on the reflectivity of the land which changes its radiative forcing. Aeroplanes produce contrails (condensation trails), particularly when they induce cirrus cloud, which give a small positive radiative forcing (in addition to the direct effect of the carbon dioxide emissions associated with aviation).

International policies on atmospheric pollutants

There are two different sets of international activities aimed at limiting levels of atmospheric pollutants that are relevant here. The UN Framework Convention on Climate Change (UNFCCC, 1992) established the basis for international action on climate change and the associated Kyoto Protocol (which was signed in 1997, but only entered into force in 2005) is an international agreement to reduce emissions in certain developed countries of the six so-called Kyoto gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

The UNFCCC built on the success of the Montreal Protocol of 1987, to protect the Earth's ozone layer. The latter has been successful in reducing the levels of chlorofluorocarbons (CFCs) that both deplete ozone and also are very powerful greenhouse gases in their own right, as are some of their successors. The global warming potential and lifetime of these gases varies significantly across the individual gases (see Table 1).

What does the Fifth Assessment Report (AR5) say about observed levels of greenhouse gases?

Well mixed greenhouse gases

- It is certain that the increasing concentrations of well mixed greenhouse gases especially carbon dioxide have increased radiative forcing further between 2005 and 2011. The radiative forcing of well mixed greenhouse gases in 2011 was 2.83 [2.54 to 3.12][2] W per m^2. This is an increase of 0.20 [0.18 to 0.22] since the last assessment in 2007 (AR4).
- The growth rate in the radiative forcing from well mixed greenhouse gases has been slower over the last decade compared to the 70s and 80s due to a slower increase in non-CO_2 radiative forcing.
- Carbon dioxide levels have increased from around 278 parts per million (ppm) in 1750 to 390.5 ppm in 2011. The radiative forcing due to carbon dioxide is 1.82 [1.63 to 2.01] W per m^2. This has increased by slightly less than 0.3 W per m^2 per decade over the past 15 years. CO_2 is the dominant contributor to the increase in greenhouse gas radiative forcing over the past 15 years.
- There has been an increase in methane concentrations since 2007. Methane concentrations have increased from 720 [695 to 745] parts per billion (ppb) in 1750 to 1803 [1799 to 1807] ppb in 2011. There is very high confidence that this increase is

[2] The range in square brackets is the 90% uncertainty interval. This is expected to have a 90% likelihood of covering the value being estimated. There is an estimated 5% likelihood that the value could be above the range given and 5% likelihood that the value could be below that range. A best estimate of the value is given where available. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate.

due to human activity, primarily from cattle farming, fossil fuel extraction and use, rice paddies, landfills and waste. The contribution of methane to the radiative forcing is now 0.48 [0.43 to 0.53] W per m^2, an increase of 2 per cent since AR4.

- The N_2O concentration has increased by 6 per cent since AR4 and now contributes a radiative forcing of 0.17 [0.15 to 0.19] W per m^2. N_2O is now likely the third highest well mixed greenhouse gas contributor to radiative forcing; the third highest was CFC-12 which has continued to fall in concentration.
- The radiative forcing from all halocarbons is 0.36 W m^2; there has been a reduction in the radiative forcing from CFCs but an increase in the contribution of their replacements, especially HCFC-22.

Short lived greenhouse gases

- Levels of tropospheric ozone were likely increasing in the 1990s. Since then, it has continued to increase over Asia and flattened over Europe. All ozone (both tropospheric and atmospheric) contributes 0.35 [0.15 to 0.55] W per m^2 of radiative forcing.
- There is high confidence that anthropogenic aerosols have offset a substantial proportion of the greenhouse gas forcing. The effective radiative forcing due to anthropogenic aerosols is −0.9 [−1.9 to −0.1] W per m^2: this incorporates aerosol-radiation interactions and aerosol-cloud interactions. This is consistent with multiple lines of evidence suggesting less negative estimates for aerosol-cloud interactions than those discussed in AR4.
- AR5 also reported a positive radiative forcing of 0.04 [0.02 to 0.09] W m^{-2} (low confidence) due to the impact of black carbon (soot) on the albedo of snow and ice.

Table 1: The observed levels of greenhouse gas concentrations in 1765 and 2000, and the projected levels in 2050 and 2100 under RCP2.6 and RCP8.5. Source: Meinshausen (2011) and IPCC WGI AR5 (2013).

Gas	1765	2000	2050 RCP 2.6	2050 RCP 8.5	2100 RCP 2.6	2100 RCP 8.5	Lifetime	GWP*	Example emissions sources
Carbon dioxide CO_2 (ppm)	278	369	443	541	421	936	Long lived **	1	Electricity generation, transport, heating and deforestation
Methane CH_4 (ppb)	722	1,751	1,452	2,740	1,254	3,751	12.4 years	28	Agriculture and waste, and fossil fuel extraction
Nitrous oxide N_2O (ppb)	273	316	342	367	344	435	121 years	265	Fertilizer
HFCs, PFCs, SF_6 (in terms of HFC-134a equivalent, measured in ppt)	0	81	599	839	862	1,402	HFCs: 2 days—242 years, PFCs: 1 day —50,000 years, SF_6: 3,200 years	HFCs: 1 —12,400, PFCs: 2—11,100, SF_6: 23,500	Refrigeration
Ozone depleting substances (in terms of CFC-12 equivalent measured in ppt)	0	999	567	652	267	229	CFCs: 45 years—1,020 years	CFCs: 4,660-13,900	Refrigeration

*GWP=global warming potential over 100 years (i.e. the warming potential compared to carbon dioxide) without inclusion of climate-carbon feedbacks in response to emissions of the indicated non-CO_2 gases (climate-carbon feedbacks in response to the reference gas CO_2 are always included).

**The lifetime of carbon dioxide is not defined in general because different processes occur on different timescales, but a large proportion of carbon dioxide emissions will persist in the atmosphere for centuries so cumulative emissions are important to its impact.

Lifetime and GWP figures are from AR5.

Other anthropogenic contributions to radiative forcing

- Land use changes are responsible for additional anthropogenic radiative forcing of −0.15 [−0.25 to -0.05] W m^{-2}. The changes in CO_2 associated with deforestation have been incorporated into the CO_2 emissions total above.
- In aviation, the combined contrail and contrail cirrus cloud effective radiative forcing is 0.05 [0.02 to 0.15] W m^{-2}.

Natural fluctuations in radiative forcing

- The change in radiative forcing due to solar activity between most recent (2008) minimum and the 1986 minimum was -0.04 [−0.08 to 0.00] W m^{-2}.
- Volcanoes emit stratospheric aerosols that reduce radiative forcing for a few years after major eruption. There were several small eruptions between 2008 and 2011 which resulted in a radiative forcing of −0.10 [−0.13 to −0.07] W m^{-2}. The last major eruption, Mt Pinatubo in 1991, caused a RF of about −3.7 W m^{-2} for one year.

What does AR5 say about future levels of greenhouse gases?

AR5 uses four Representative Concentration Pathway (RCP) emissions scenarios. These scenarios assume total radiative forcing by 2100 of 2.6, 4.5, 6 or 8.5 W per m^2. The observed levels of greenhouse gases in 1765 and 2000, and the levels in 2050 and 2100 under RCP2.6 and RCP8.5 are given in Table 1. The RCP scenarios include some degree of mitigation (efforts to keep emissions down or reduce them) so some of the gas concentrations decrease over time. RCP2.6 in particular is a very strong mitigation scenario, while in RCP8.5 CO_2 concentrations grow rapidly throughout the century reaching around 936 ppm by 2100. The RCP emissions scenarios are not predictions and are not assigned probabilities; they are plausible future scenarios to be used as a benchmark for scientific research and for policy discussions.

AR5 says limiting climate change will require “substantial and sustained” reductions in greenhouse gas emissions.

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