

Handbook of
Global Warming



Shu Rucker

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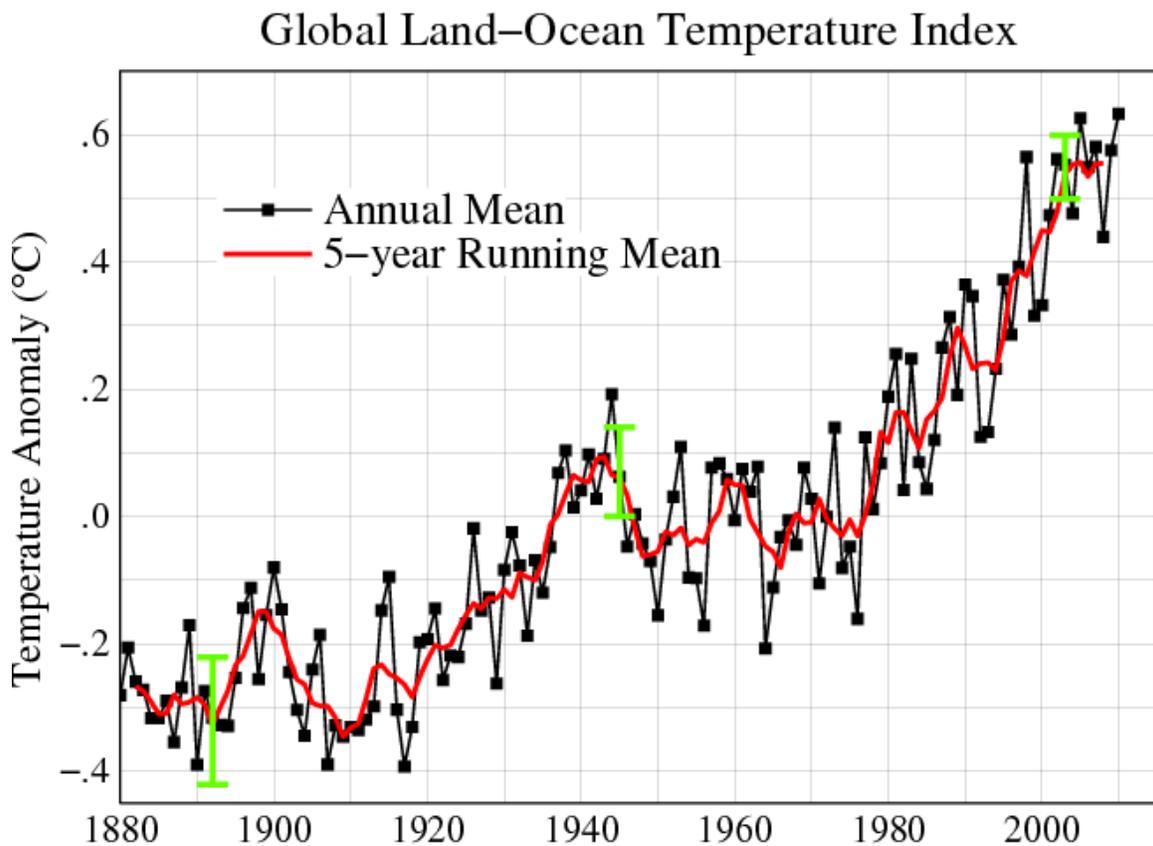
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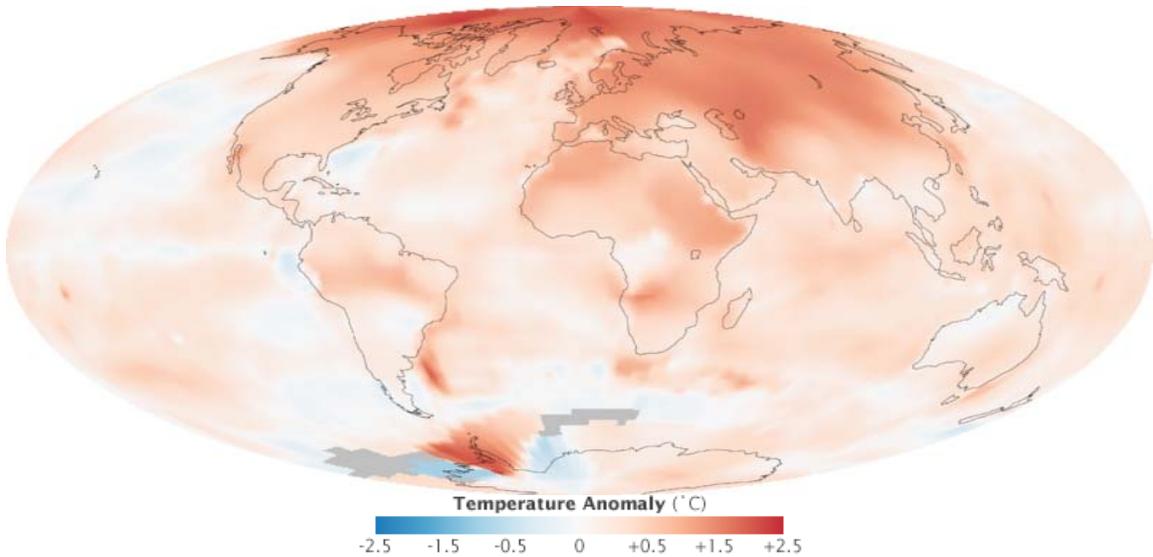
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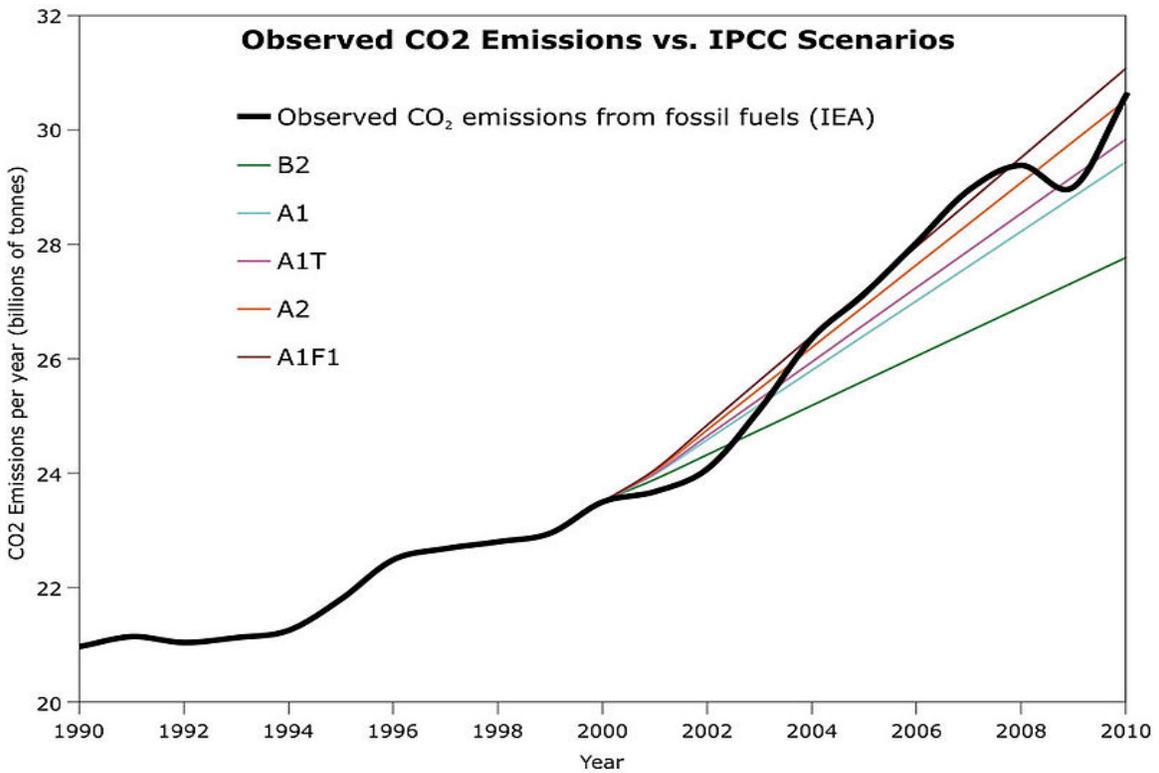
Global Warming



Global mean land-ocean temperature change from 1880-2010, relative to the 1951-1980 mean. The black line is the annual mean and the red line is the 5-year running mean. The green bars show uncertainty estimates.



The map shows the 10-year average (2000-2009) global mean temperature anomaly relative to the 1951-1980 mean. The largest temperature increases are in the Arctic and the Antarctic Peninsula.



Fossil fuel related CO₂ emissions compared to five of IPCC's emissions scenarios. The dips are related to global recessions. Data from IPCC SRES scenarios; Data spreadsheet included with International Energy Agency's "CO₂ Emissions from Fuel Combustion 2010 - Highlights"; and Supplemental IEA data.

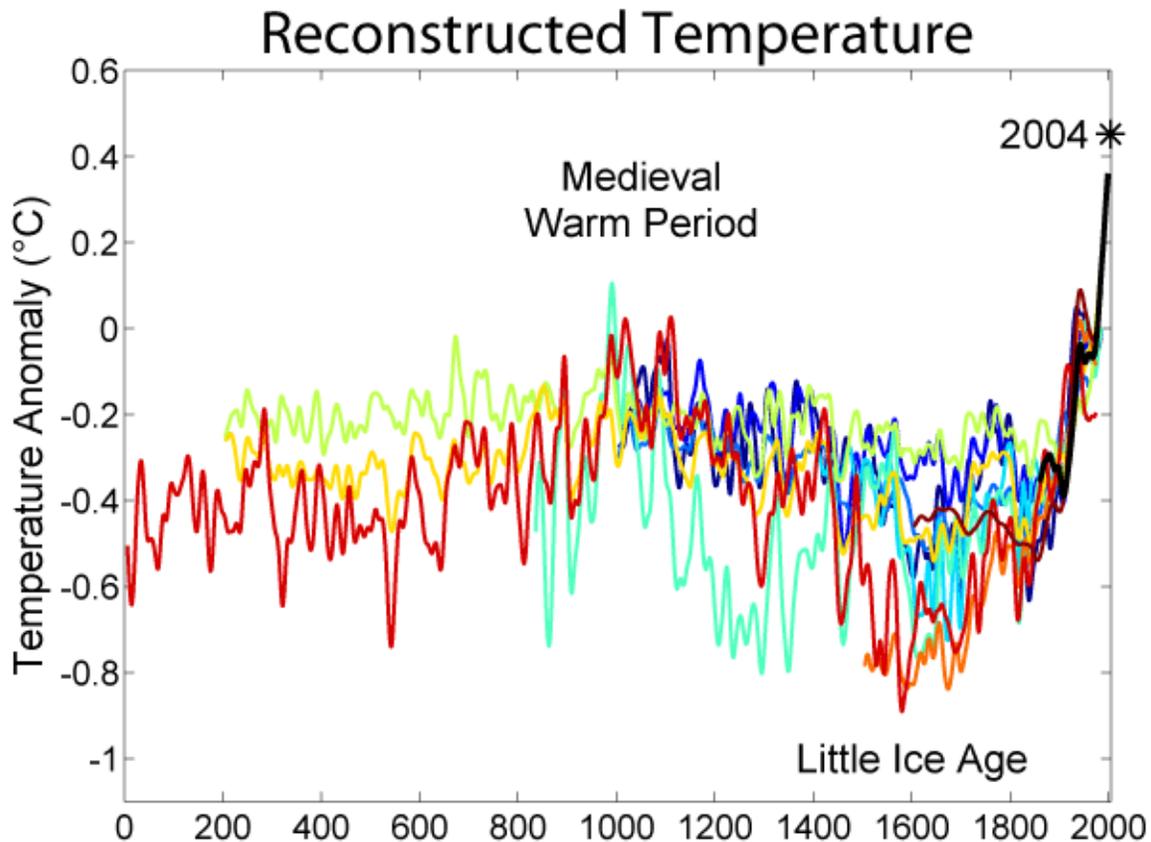
Global warming is the current rise in the average temperature of Earth's oceans and atmosphere and its projected continuation. The scientific consensus is that global warming is occurring and was initiated by human activities, especially those that increase concentrations of greenhouse gases in the atmosphere, such as deforestation and burning of fossil fuels. This finding is recognized by the national science academies of all the major industrialized countries and is not rejected by any scientific body of national or international standing.

Scientists directly measured the global surface temperature increase during the 20th century at about 0.74°C (1.33°F). Potential future warming is projected using computer models of the climate system and hypothetical amounts of greenhouse gas emissions for possible future worlds, published in 2000. Actual emissions since 2000 have equaled or exceeded the "A2 scenario", except for small dips during two global recessions. According to the 2007 report of the Intergovernmental Panel on Climate Change (IPCC), the "best estimate" of future warming for the A2 scenario is 3.4°C (6.1°F) by 2100, with a likely range from 2.0-5.4°C (3.6-9.7°F). This exceeds the 2°C threshold for dangerous climate change recognized by the United Nations Framework Convention on Climate Change, and warming from this century's emissions will extend well beyond 2100 due to the longevity of some greenhouse gases in the atmosphere.

An increase in global temperature will cause sea levels to rise and will change the amount and pattern of precipitation, probably including expansion of subtropical deserts. Warming is expected to be strongest in the Arctic and would be associated with continuing retreat of glaciers, permafrost and sea ice. Other likely effects of the warming include more frequent occurrence of extreme weather events including heatwaves, droughts and heavy rainfall events, species extinctions due to shifting temperature regimes, and changes in agricultural yields. Warming and related changes will vary from region to region around the globe, though the nature of these regional changes is uncertain. In a 4°C world, the limits for human adaptation are likely to be exceeded in many parts of the world, while the limits for adaptation for natural systems would largely be exceeded throughout the world. Hence, the ecosystem services upon which human livelihoods depend would not be preserved.

Proposed responses to global warming include mitigation to reduce emissions, adaptation to the effects of global warming, and geoengineering to remove greenhouse gases from the atmosphere or reflect incoming solar radiation back to space. The main international mitigation effort is the Kyoto Protocol, which seeks to stabilize greenhouse gas concentration to prevent a "dangerous anthropogenic interference". As of May 2010, 192 states had ratified the protocol. The only members of the UNFCCC that were asked to sign the treaty but have not yet ratified it are the USA and Afghanistan.

Temperature changes



Two millennia of mean surface temperatures according to different reconstructions, each smoothed on a decadal scale, with the instrumental temperature record overlaid in black.

Evidence for warming of the climate system includes observed increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The most common measure of global warming is the trend in globally averaged temperature near the Earth's surface. Expressed as a linear trend, this temperature rose by 0.74 ± 0.18 °C over the period 1906–2005. The rate of warming over the last half of that period was almost double that for the period as a whole (0.13 ± 0.03 °C per decade, versus 0.07 °C \pm 0.02 °C per decade). The urban heat island effect is estimated to account for about 0.002 °C of warming per decade since 1900. Temperatures in the lower troposphere have increased between 0.13 and 0.22 °C (0.22 and 0.4 °F) per decade since 1979, according to satellite temperature measurements. Temperature is believed to have been relatively stable over the one or two thousand years before 1850, with regionally varying fluctuations such as the Medieval Warm Period and the Little Ice Age.

Recent estimates by NASA's Goddard Institute for Space Studies (GISS) and the National Climatic Data Center show that 2005 and 2010 tied for the planet's warmest year since reliable, widespread instrumental measurements became available in the late 19th century, exceeding 1998 by a few hundredths of a degree. Current estimates by the

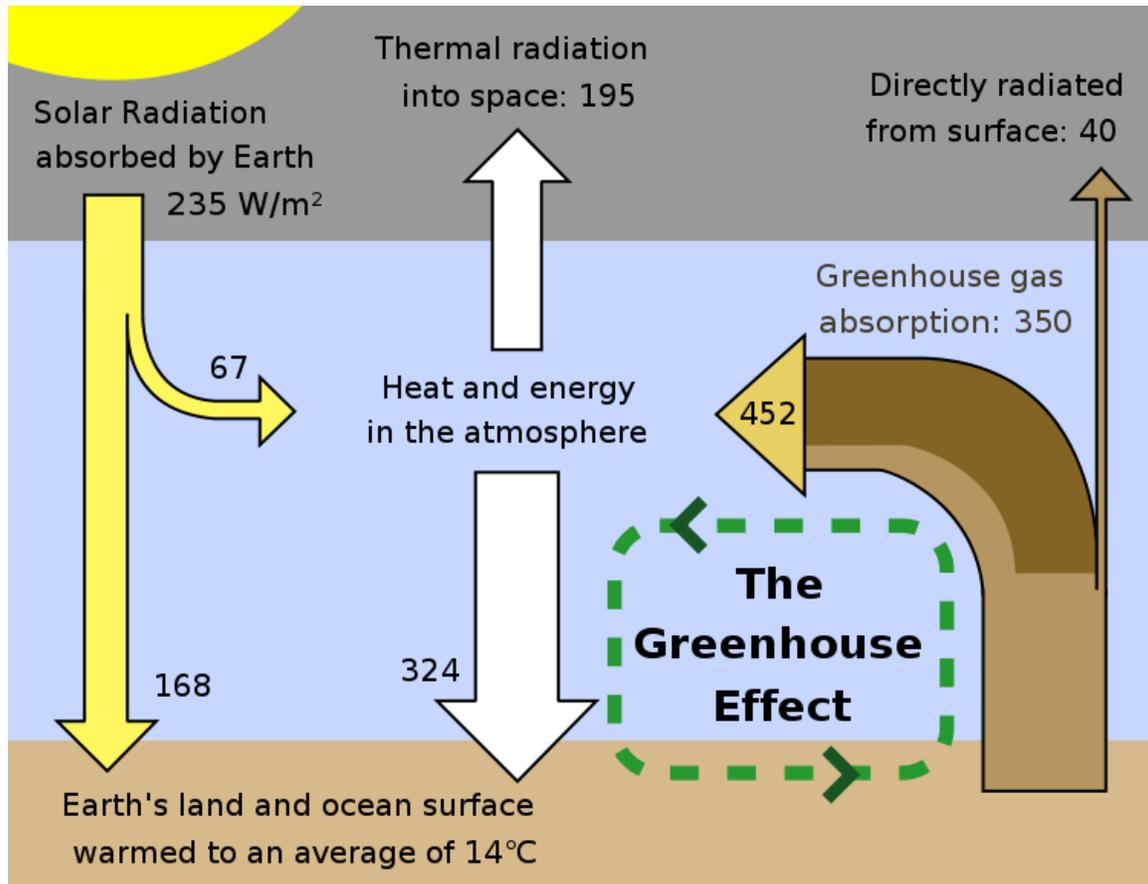
Climatic Research Unit (CRU) show 2005 as the second warmest year, behind 1998 with 2003 and 2010 tied for third warmest year, however, “the error estimate for individual years ... is at least ten times larger than the differences between these three years.” The World Meteorological Organization (WMO) *statement on the status of the global climate in 2010* explains that, “The 2010 nominal value of +0.53°C ranks just ahead of those of 2005 (+0.52°C) and 1998 (+0.51°C), although the differences between the three years are not statistically significant...”

Temperatures in 1998 were unusually warm because the strongest El Niño in the past century occurred during that year. Global temperature is subject to short-term fluctuations that overlay long term trends and can temporarily mask them. The relative stability in temperature from 2002 to 2009 is consistent with such an episode.

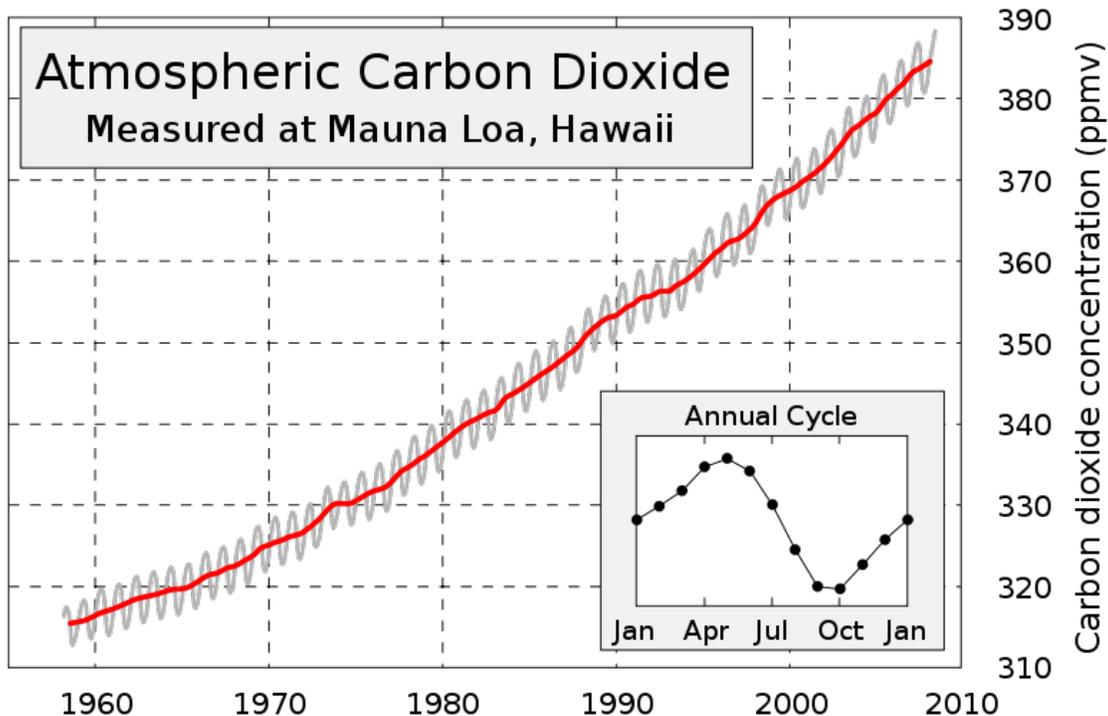
Temperature changes vary over the globe. Since 1979, land temperatures have increased about twice as fast as ocean temperatures (0.25 °C per decade against 0.13 °C per decade). Ocean temperatures increase more slowly than land temperatures because of the larger effective heat capacity of the oceans and because the ocean loses more heat by evaporation. The Northern Hemisphere warms faster than the Southern Hemisphere because it has more land and because it has extensive areas of seasonal snow and sea-ice cover subject to ice-albedo feedback. Although more greenhouse gases are emitted in the Northern than Southern Hemisphere this does not contribute to the difference in warming because the major greenhouse gases persist long enough to mix between hemispheres.

The thermal inertia of the oceans and slow responses of other indirect effects mean that climate can take centuries or longer to adjust to changes in forcing. Climate commitment studies indicate that even if greenhouse gases were stabilized at 2000 levels, a further warming of about 0.5 °C (0.9 °F) would still occur.

External forcings



Greenhouse effect schematic showing energy flows between space, the atmosphere, and earth's surface. Energy exchanges are expressed in watts per square meter (W/m²).



This graph is known as the "Keeling Curve" and it shows the long-term increase of atmospheric carbon dioxide (CO₂) concentrations from 1958-2008. Monthly CO₂ measurements display seasonal oscillations in an upward trend; each year's maximum occurs during the Northern Hemisphere's late spring, and declines during its growing season as plants remove some atmospheric CO₂.

External forcing refers to processes external to the climate system (though not necessarily external to Earth) that influence climate. Climate responds to several types of external forcing, such as radiative forcing due to changes in atmospheric composition (mainly greenhouse gas concentrations), changes in solar luminosity, volcanic eruptions, and variations in Earth's orbit around the Sun. Attribution of recent climate change focuses on the first three types of forcing. Orbital cycles vary slowly over tens of thousands of years and at present are in an overall cooling trend which would be expected to lead towards an ice age, but the 20th century instrumental temperature record shows a sudden rise in global temperatures.

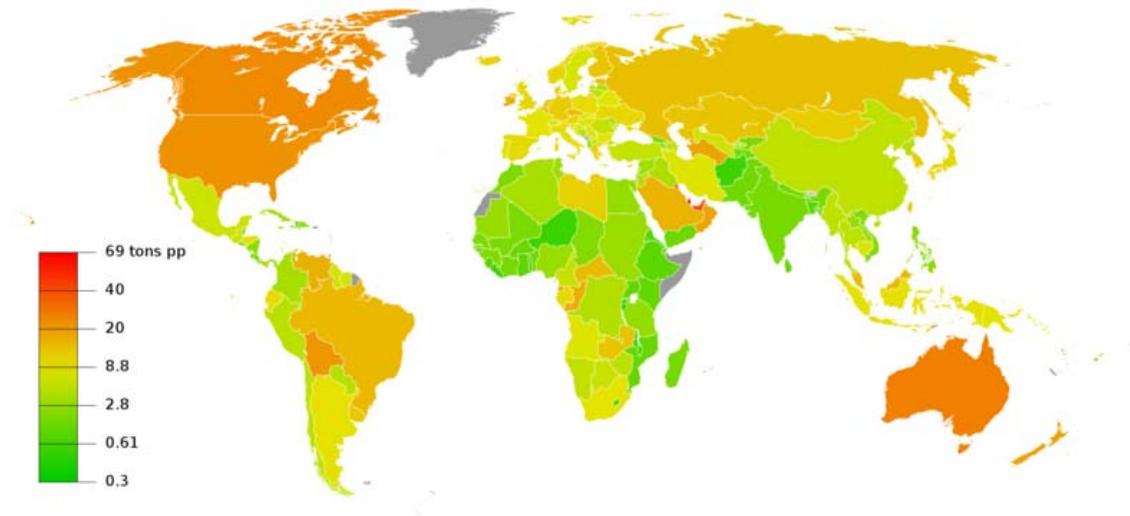
Greenhouse gases

The greenhouse effect is the process by which absorption and emission of infrared radiation by gases in the atmosphere warm a planet's lower atmosphere and surface. It was proposed by Joseph Fourier in 1824 and was first investigated quantitatively by Svante Arrhenius in 1896.

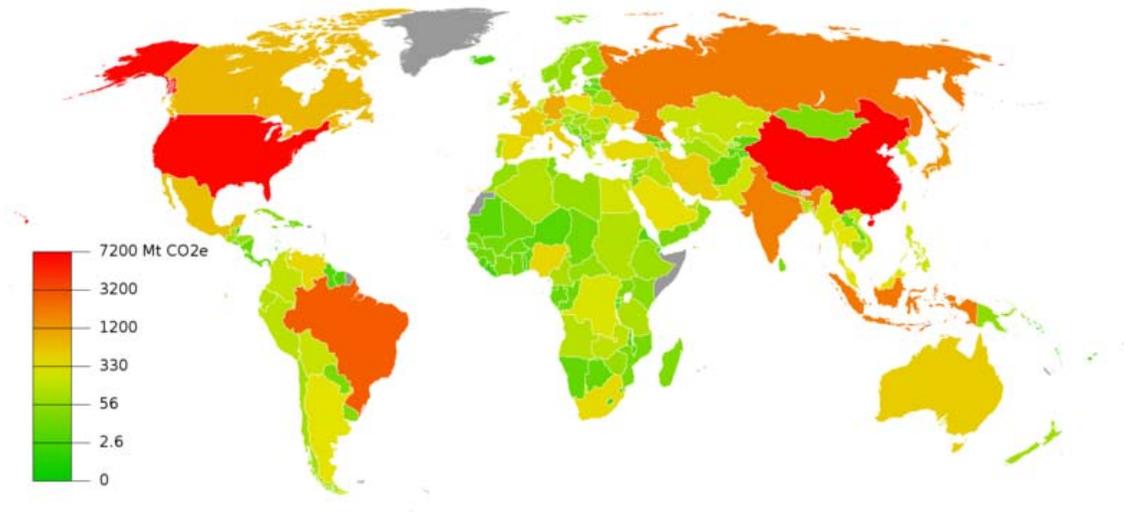
Naturally occurring greenhouse gases have a mean warming effect of about 33 °C (59 °F). The major greenhouse gases are water vapor, which causes about 36–70 percent

of the greenhouse effect; carbon dioxide (CO₂), which causes 9–26 percent; methane (CH₄), which causes 4–9 percent; and ozone (O₃), which causes 3–7 percent. Clouds also affect the radiation balance, but they are composed of liquid water or ice and so have different effects on radiation from water vapor.

Human activity since the Industrial Revolution has increased the amount of greenhouse gases in the atmosphere, leading to increased radiative forcing from CO₂, methane, tropospheric ozone, CFCs and nitrous oxide. The concentrations of CO₂ and methane have increased by 36% and 148% respectively since 1750. These levels are much higher than at any time during the last 800,000 years, the period for which reliable data has been extracted from ice cores. Less direct geological evidence indicates that CO₂ values higher than this were last seen about 20 million years ago. Fossil fuel burning has produced about three-quarters of the increase in CO₂ from human activity over the past 20 years. The rest of this increase is caused mostly by changes in land-use, particularly deforestation.



Per capita greenhouse gas emissions in 2005, including land-use change



Total greenhouse gas emissions in 2005, including land-use change

Over the last three decades of the 20th century, GDP per capita and population growth were the main drivers of increases in greenhouse gas emissions. CO₂ emissions are continuing to rise due to the burning of fossil fuels and land-use change. Emissions can be attributed to different regions. The two figures opposite show annual greenhouse gas emissions for the year 2005, including land-use change. Attribution of emissions due to land-use change is a controversial issue. For example, concentrating on more recent changes in land-use (as the figures opposite do) is likely to favour those regions that have deforested earlier, e.g., Europe.

Emissions scenarios, estimates of changes in future emission levels of greenhouse gases, have been projected that depend upon uncertain economic, sociological, technological, and natural developments. In most scenarios, emissions continue to rise over the century, while in a few, emissions are reduced. Fossil fuel reserves are abundant, and will not limit carbon emissions in the 21st century. Emission scenarios, combined with modelling of the carbon cycle, have been used to produce estimates of how atmospheric concentrations of greenhouse gases might change in the future. Using the six IPCC SRES "marker" scenarios, models suggest that by the year 2100, the atmospheric concentration of CO₂ could range between 541 and 970 ppm. This is an increase of 90-250% above the concentration in the year 1750.

The popular media and the public often confuse global warming with the ozone hole, i.e., the destruction of stratospheric ozone by chlorofluorocarbons. Although there are a few areas of linkage, the relationship between the two is not strong. Reduced stratospheric ozone has had a slight cooling influence on surface temperatures, while increased tropospheric ozone has had a somewhat larger warming effect.

Particulates and soot



Ship tracks over the Atlantic Ocean on the east coast of the United States. The climatic impacts from particulate forcing could have a large effect on climate through the indirect effect.

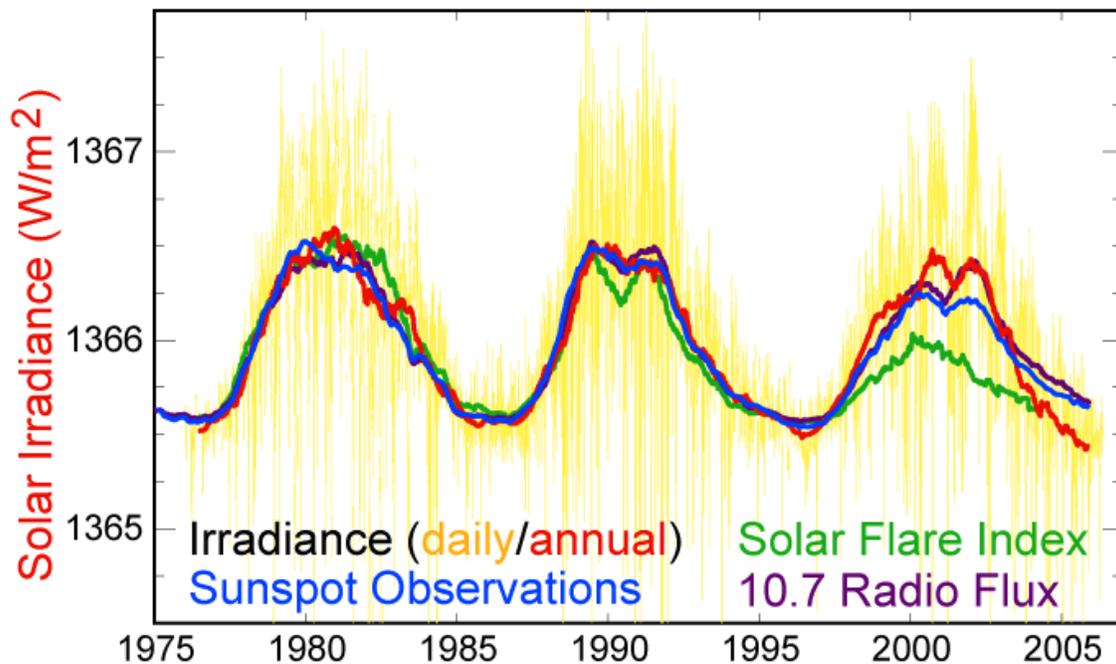
Global dimming, a gradual reduction in the amount of global direct irradiance at the Earth's surface, has partially counteracted global warming from 1960 to the present. The main cause of this dimming is particulates produced by volcanoes and human made pollutants, which exerts a cooling effect by increasing the reflection of incoming sunlight. The effects of the products of fossil fuel combustion—CO₂ and aerosols—have largely offset one another in recent decades, so that net warming has been due to the increase in non-CO₂ greenhouse gases such as methane. Radiative forcing due to particulates is temporally limited due to wet deposition which causes them to have an atmospheric lifetime of one week. Carbon dioxide has a lifetime of a century or more, and as such, changes in particulate concentrations will only delay climate changes due to carbon dioxide.

In addition to their direct effect by scattering and absorbing solar radiation, particulates have indirect effects on the radiation budget. Sulfates act as cloud condensation nuclei and thus lead to clouds that have more and smaller cloud droplets. These clouds reflect solar radiation more efficiently than clouds with fewer and larger droplets, known as the Twomey effect. This effect also causes droplets to be of more uniform size, which reduces growth of raindrops and makes the cloud more reflective to incoming sunlight,

known as the Albrecht effect. Indirect effects are most noticeable in marine stratiform clouds, and have very little radiative effect on convective clouds. Indirect effects of particulates represent the largest uncertainty in radiative forcing.

Soot may cool or warm the surface, depending on whether it is airborne or deposited. Atmospheric soot directly absorb solar radiation, which heats the atmosphere and cools the surface. In isolated areas with high soot production, such as rural India, as much as 50% of surface warming due to greenhouse gases may be masked by atmospheric brown clouds. When deposited, especially on glaciers or on ice in arctic regions, the lower surface albedo can also directly heat the surface. The influences of particulates, including black carbon, are most pronounced in the tropics and sub-tropics, particularly in Asia, while the effects of greenhouse gases are dominant in the extratropics and southern hemisphere.

Solar Cycle Variations



Satellite observations of Total Solar Irradiance from 1979-2006

Solar variation

Variations in solar output have been the cause of past climate changes. The effect of changes in solar forcing in recent decades is uncertain, but small, with some studies showing a slight cooling effect, while others studies suggest a slight warming effect.

Greenhouse gases and solar forcing affect temperatures in different ways. While both increased solar activity and increased greenhouse gases are expected to warm the troposphere, an increase in solar activity should warm the stratosphere while an increase

in greenhouse gases should cool the stratosphere. Radiosonde (weather balloon) data show the stratosphere has cooled over the period since observations began (1958), though there is greater uncertainty in the early radiosonde record. Satellite observations, which have been available since 1979, also show cooling.

A related hypothesis, proposed by Henrik Svensmark, is that magnetic activity of the sun deflects cosmic rays that may influence the generation of cloud condensation nuclei and thereby affect the climate. Other research has found no relation between warming in recent decades and cosmic rays. The influence of cosmic rays on cloud cover is about a factor of 100 lower than needed to explain the observed changes in clouds or to be a significant contributor to present-day climate change.

Studies in 2011 have indicated that solar activity may be slowing, and that the next solar cycle could be delayed. To what extent is not yet clear; Solar Cycle 25 is due to start in 2020, but may be delayed to 2022 or even longer. It is even possible that Sol could be heading towards another Maunder Minimum. While there is not yet a definitive link between solar sunspot activity and global temperatures, the scientists conducting the solar activity study believe that global greenhouse gas emissions would prevent any possible cold snap.

Feedback

Feedback is a process in which changing one quantity changes a second quantity, and the change in the second quantity in turn changes the first. Positive feedback increases the change in the first quantity while negative feedback reduces it. Feedback is important in the study of global warming because it may amplify or diminish the effect of a particular process.

The main positive feedback in global warming is the tendency of warming to increase the amount of water vapor in the atmosphere, a significant greenhouse gas. The main negative feedback is radiative cooling, which increases as the fourth power of temperature; the amount of heat radiated from the Earth into space increases with the temperature of Earth's surface and atmosphere. Positive and negative feedbacks are not imposed as assumptions in the models, but are instead emergent properties that result from the interactions of basic dynamical and thermodynamic processes.

Imperfect understanding of feedbacks is a major cause of uncertainty and concern about global warming. A wide range of potential feedback processes exist, such as Arctic methane release and ice-albedo feedback. Consequentially, potential tipping points may exist, which may have the potential to cause abrupt climate change.

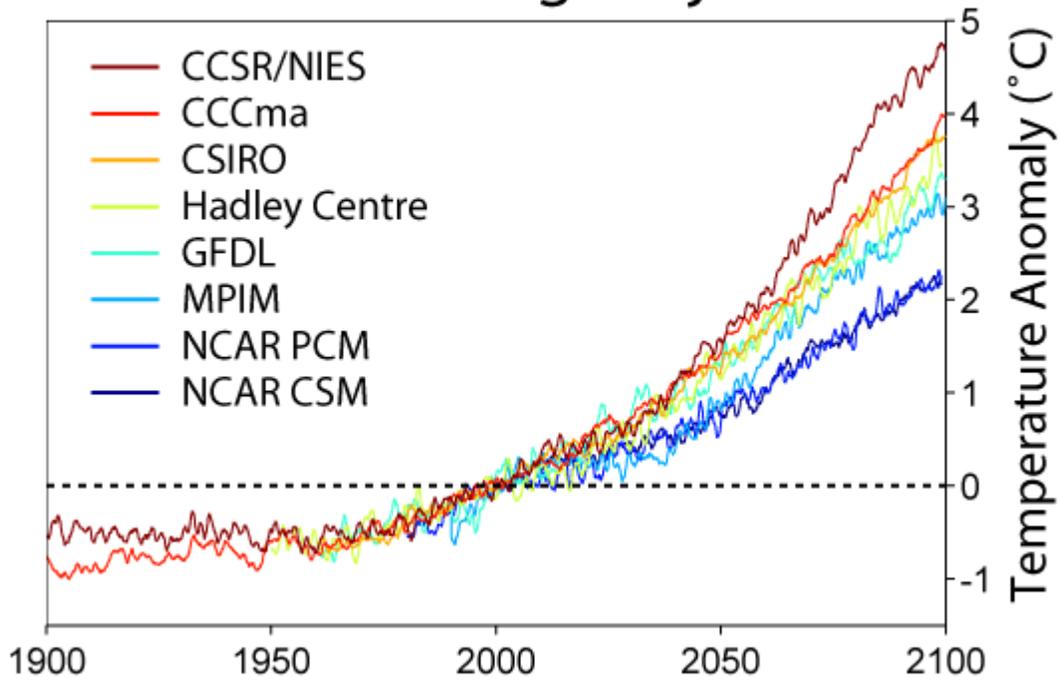
For example, the "emission scenarios" used by IPCC in its 2007 report primarily examined greenhouse gas emissions from human sources. In 2011, a joint study by NSIDC-(US) and NOAA-(US) calculated the additional greenhouse gas emissions that would emanate from melted and decomposing permafrost, even if policymakers attempt to reduce human emissions from the currently-unfolding A1FI scenario to the A1B

scenario. The team found that even at the much lower level of human emissions, permafrost thawing and decomposition would still result in 190 ± 64 Gt C of permafrost carbon being added to the atmosphere on top of the human sources. Importantly, the team made three extremely conservative assumptions: (1) that policymakers will embrace the A1B scenario instead of the currently-unfolding A1FI scenario, (2) that all of the carbon would be released as carbon dioxide instead of methane, which is more likely and over a 20 year lifetime has 72x the greenhouse warming power of CO₂, and (3) their model did not project additional temperature rise caused by the release of these additional gases. These very conservative permafrost carbon dioxide emissions are equivalent to about 1/2 of all carbon released from fossil fuel burning since the dawn of the Industrial Age, and is enough to raise atmospheric concentrations by an additional 87 ± 29 ppm, beyond human emissions. Once initiated, permafrost carbon forcing (PCF) is *irreversible*, is strong compared to other global sources and sinks of atmospheric CO₂, and due to thermal inertia will continue for many years even if atmospheric warming stops. A great deal of this permafrost carbon is actually being released as highly flammable methane instead of carbon dioxide. IPCC 2007's temperature projections did not take any of the permafrost carbon emissions into account and therefore underestimate the degree of expected climate change.

Other research published in 2011 found that increased emissions of methane, which over 20 years has 72x the greenhouse warming power of CO₂, could instigate significant feedbacks that amplify the warming attributable to the methane alone. The researchers found that a 2.5-fold increase in methane emissions would cause indirect effects that increase the warming 250% above that of the methane alone. For a 5.2-fold increase, the indirect effects would be 400% of the warming from the methane alone.

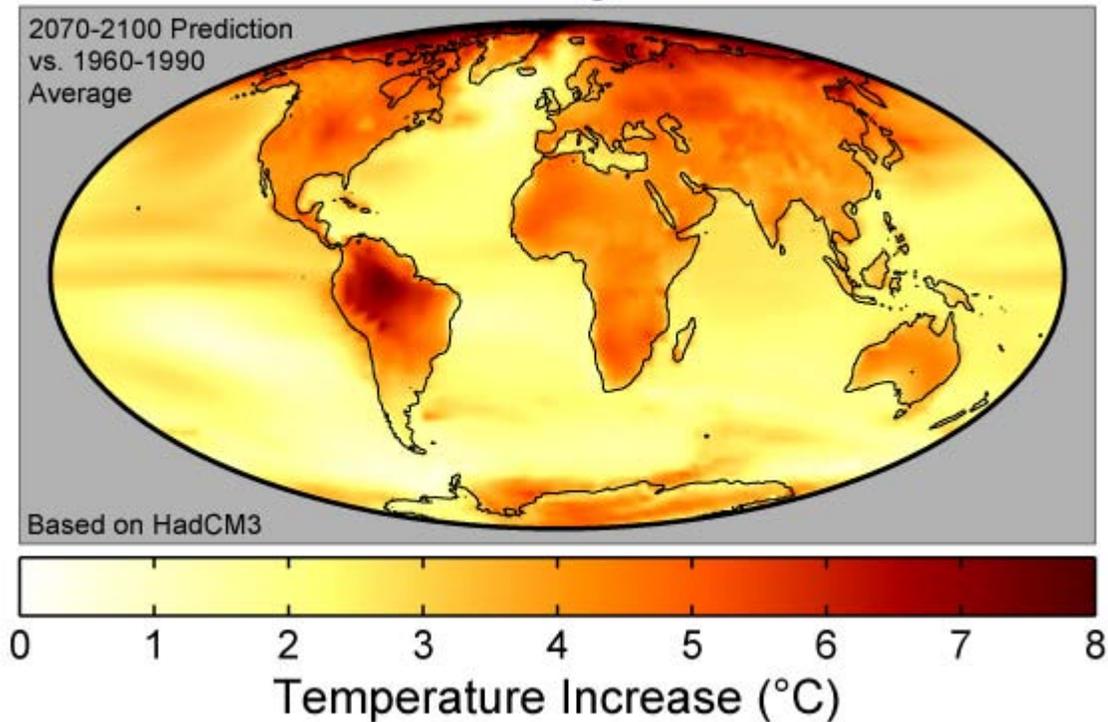
Climate models

Global Warming Projections



Calculations of global warming prepared in or before 2001 from a range of climate models under the SRES A2 emissions scenario, which assumes no action is taken to reduce emissions and regionally divided economic development.

Global Warming Predictions



The geographic distribution of surface warming during the 21st century calculated by the HadCM3 climate model if a business as usual scenario is assumed for economic growth and greenhouse gas emissions. In this figure, the globally averaged warming corresponds to 3.0 °C (5.4 °F).

A climate model is a computerized representation of the five components of the climate system: Atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Such models are based on physical principles including fluid dynamics, thermodynamics and radiative transfer. There can be components which represent air movement, temperature, clouds, and other atmospheric properties; ocean temperature, salt content, and circulation; ice cover on land and sea; the transfer of heat and moisture from soil and vegetation to the atmosphere; chemical and biological processes; and others.

Although researchers attempt to include as many processes as possible, simplifications of the actual climate system are inevitable because of the constraints of available computer power and limitations in knowledge of the climate system. Results from models can also vary due to different greenhouse gas inputs and the model's climate sensitivity. For example, the uncertainty in IPCC's 2007 projections is caused by (1) the use of multiple models with differing sensitivity to greenhouse gas concentrations, (2) the use of differing estimates of humanities' future greenhouse gas emissions, (3) any additional emissions from climate feedbacks that were not included in the models IPCC used to prepare its report, i.e., greenhouse gas releases from permafrost.

The models do not assume the climate will warm due to increasing levels of greenhouse gases. Instead the models predict how greenhouse gases will interact with radiative transfer and other physical processes. One of the mathematical results of these complex equations is a prediction whether warming or cooling will occur.

Recent research has called special attention to the need to refine models with respect to the effect of clouds and the carbon cycle.

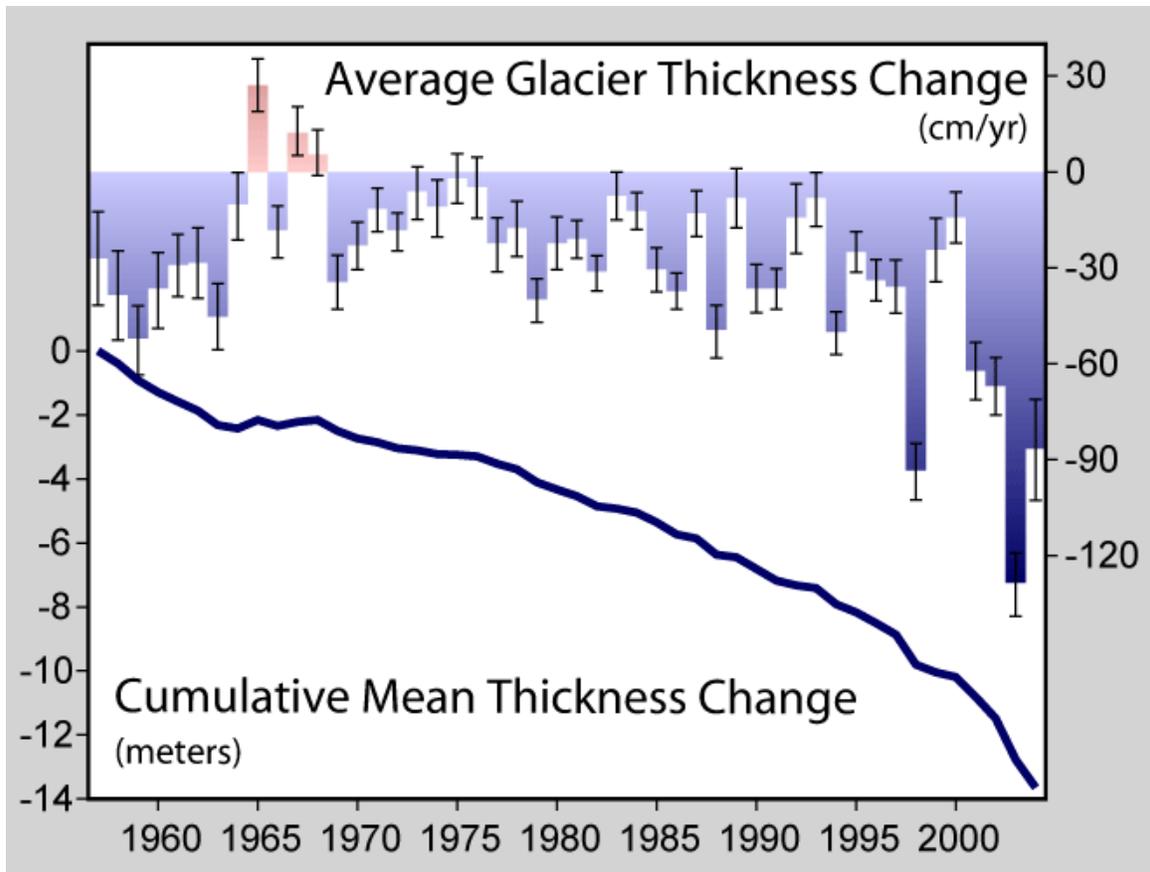
Models are also used to help investigate the causes of recent climate change by comparing the observed changes to those that the models project from various natural and human-derived causes. Although these models do not unambiguously attribute the warming that occurred from approximately 1910 to 1945 to either natural variation or human effects, they do indicate that the warming since 1970 is dominated by man-made greenhouse gas emissions.

The physical realism of models is tested by examining their ability to simulate current or past climates.

Current climate models produce a good match to observations of global temperature changes over the last century, but do not simulate all aspects of climate. Not all effects of global warming are accurately predicted by the climate models used by the IPCC. Observed Arctic shrinkage has been faster than that predicted. Precipitation increased proportional to atmospheric humidity, and hence significantly faster than current global climate models predict.

Attributed and expected effects

Global warming may be detected in natural, ecological or social systems as a change having statistical significance. Attribution of these changes e.g., to natural or human activities, is the next step following detection.



Sparse records indicate that glaciers have been retreating since the early 1800s. In the 1950s measurements began that allow the monitoring of glacial mass balance, reported to the WGMS and the NSIDC.

Natural systems

Global warming has been detected in a number of systems. Some of these changes, e.g., based on the instrumental temperature record, have been described in the section on temperature changes. Rising sea levels and observed decreases in snow and ice extent are consistent with warming. Most of the increase in global average temperature since the mid-20th century is, with high probability, attributable to human-induced changes in greenhouse gas concentrations.

Even with current policies to reduce emissions, global emissions are still expected to continue to grow over the coming decades. Over the course of the 21st century, increases in emissions at or above their current rate would very likely induce changes in the climate system larger than those observed in the 20th century.

In the IPCC Fourth Assessment Report, across a range of future emission scenarios, model-based estimates of sea level rise for the end of the 21st century (the year 2090-2099, relative to 1980-1999) range from 0.18 to 0.59 m. These estimates, however, were not given a likelihood due to a lack of scientific understanding, nor was an upper bound

given for sea level rise. Over the course of centuries to millennia, the melting of ice sheets could result in sea level rise of 4–6 m or more.

Changes in regional climate are expected to include greater warming over land, with most warming at high northern latitudes, and least warming over the Southern Ocean and parts of the North Atlantic Ocean. Snow cover area and sea ice extent are expected to decrease, with the Arctic expected to be largely ice-free in September by 2037. The frequency of hot extremes, heat waves, and heavy precipitation will very likely increase.

Ecological systems

In terrestrial ecosystems, the earlier timing of spring events, and poleward and upward shifts in plant and animal ranges, have been linked with high confidence to recent warming. Future climate change is expected to particularly affect certain ecosystems, including tundra, mangroves, and coral reefs. It is expected that most ecosystems will be affected by higher atmospheric CO₂ levels, combined with higher global temperatures. Overall, it is expected that climate change will result in the extinction of many species and reduced diversity of ecosystems.

Species migration

In 2010, a gray whale was found in the Mediterranean Sea, even though the species had not been seen in the North Atlantic Ocean since the 1700s. The whale is thought to have migrated from the Pacific Ocean via the Arctic. Climate Change & European Marine Ecosystem Research (CLAMER) has also reported that the *Neodenticula seminae* alga has been found in the North Atlantic, where it had gone extinct nearly 800,000 years ago. The alga has drifted from the Pacific Ocean through the Arctic, following the reduction in polar ice.

In the Siberian sub-arctic, species migration is contributing to another warming albedo-feedback, as needle-shedding larch trees are being replaced with dark-foliage evergreen conifers which can absorb some of the solar radiation that previously reflected off the snowpack beneath the forest canopy.

Social systems

Vulnerability of human societies to climate change mainly lies in the effects of extreme weather events rather than gradual climate change. Impacts of climate change so far include adverse effects on small islands, adverse effects on indigenous populations in high-latitude areas, and small but discernable effects on human health. Over the 21st century, climate change is likely to adversely affect hundreds of millions of people through increased coastal flooding, reductions in water supplies, increased malnutrition and increased health impacts.

Future warming of around 3 °C (by 2100, relative to 1990-2000) could result in increased crop yields in mid- and high-latitude areas, but in low-latitude areas, yields could decline,

increasing the risk of malnutrition. A similar regional pattern of net benefits and costs could occur for economic (market-sector) effects. Warming above 3 °C could result in crop yields falling in temperate regions, leading to a reduction in global food production. Most economic studies suggest losses of world gross domestic product (GDP) for this magnitude of warming.

Some areas of the world would start to surpass the wet-bulb temperature limit of human survivability with global warming of about 6.7°C (12°F) while a warming of 11.7°C (21°F) would put half of the world's population in an uninhabitable environment. In practice the survivable limit of global warming in these areas is probably lower and in practice some areas may experience lethal wet bulb temperatures even earlier, because this study conservatively projected the survival limit for persons who are out of the sun, in gale-force winds, doused with water, wearing no clothing, and not working.

Responses to global warming

Mitigation

Reducing the amount of future climate change is called mitigation of climate change. The IPCC defines mitigation as activities that reduce greenhouse gas (GHG) emissions, or enhance the capacity of carbon sinks to absorb GHGs from the atmosphere. Many countries, both developing and developed, are aiming to use cleaner, less polluting, technologies. Use of these technologies aids mitigation and could result in substantial reductions in CO₂ emissions. Policies include targets for emissions reductions, increased use of renewable energy, and increased energy efficiency. Studies indicate substantial potential for future reductions in emissions.

To limit warming to the lower range in the overall IPCC's "Summary Report for Policymakers" means adopting policies that will limit emissions to one of the significantly different scenarios described in the full report. This will become more and more difficult, since each year of high emissions will require even more drastic measures in later years to stabilize at a desired atmospheric concentration of greenhouse gases, and energy-related carbon-dioxide (CO₂) emissions in 2010 were the highest in history, breaking the prior record set in 2008.

Since even in the most optimistic scenario, fossil fuels are going to be used for years to come, mitigation may also involve carbon capture and storage, a process that traps CO₂ produced by factories and gas or coal power stations and then stores it, usually underground.

Adaptation

Other policy responses include adaptation to climate change. Adaptation to climate change may be planned, e.g., by local or national government, or spontaneous, i.e., done privately without government intervention. The ability to adapt is closely linked to social and economic development. Even societies with high capacities to adapt are still

vulnerable to climate change. Planned adaptation is already occurring on a limited basis. The barriers, limits, and costs of future adaptation are not fully understood.

Geoengineering

Another policy response is engineering of the climate (geoengineering). This policy response is sometimes grouped together with mitigation. Geoengineering is largely unproven, and reliable cost estimates for it have not yet been published. Geoengineering encompasses a range of techniques to remove CO₂ from the atmosphere or to block incoming sunlight. As most geoengineering techniques would affect the entire globe, the use of effective techniques, if they can be developed, would require global public acceptance and an adequate global legal and regulatory framework.

Views on global warming

There are different views over what the appropriate policy response to climate change should be. These competing views weigh the benefits of limiting emissions of greenhouse gases against the costs. In general, it seems likely that climate change will impose greater damages and risks in poorer regions.

Politics

Most countries are Parties to the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of the Convention is to prevent "dangerous" human interference of the climate system. As is stated in the Convention, this requires that GHG concentrations are stabilized in the atmosphere at a level where ecosystems can adapt naturally to climate change, food production is not threatened, and economic development can proceed in a sustainable fashion.

The Framework Convention was agreed in 1992, but since then, global emissions have risen. During negotiations, the G77 (a lobbying group in the United Nations representing 133 developing nations) pushed for a mandate requiring developed countries to "[take] the lead" in reducing their emissions. This was justified on the basis that: the developed world's emissions had contributed most to the stock of GHGs in the atmosphere; per-capita emissions (i.e., emissions per head of population) were still relatively low in developing countries; and the emissions of developing countries would grow to meet their development needs. This mandate was sustained in the Kyoto Protocol to the Framework Convention, which entered into legal effect in 2005.

In ratifying the Kyoto Protocol, most developed countries accepted legally binding commitments to limit their emissions. These first-round commitments expire in 2012. US President George W. Bush rejected the treaty on the basis that "it exempts 80% of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the US economy."

At the 15th UNFCCC Conference of the Parties, held in 2009 at Copenhagen, several UNFCCC Parties produced the Copenhagen Accord. Parties associated with the Accord (140 countries, as of November 2010) aim to limit the future increase in global mean temperature to below 2 °C. A preliminary assessment published in November 2010 by the United Nations Environment Programme (UNEP) suggests a possible "emissions gap" between the voluntary pledges made in the Accord and the emissions cuts necessary to have a "likely" (greater than 66% probability) chance of meeting the 2 °C objective. The UNEP assessment takes the 2 °C objective as being measured against the pre-industrial global mean temperature level. To having a likely chance of meeting the 2 °C objective, assessed studies generally indicated the need for global emissions to peak before 2020, with substantial declines in emissions thereafter.

The 16th Conference of the Parties (COP16) was held at Cancún in 2010. It produced an agreement, not a binding treaty, that the Parties should take urgent action to reduce greenhouse gas emissions to meet a goal of limiting global warming to 2 °C above pre-industrial temperatures. It also recognized the need to consider strengthening the goal to a global average rise of 1.5 °C.

Public opinion

In 2007–2008 Gallup Polls surveyed 127 countries. Over a third of the world's population was unaware of global warming, with people in developing countries less aware than those in developed, and those in Africa the least aware. Of those aware, Latin America leads in belief that temperature changes are a result of human activities while Africa, parts of Asia and the Middle East, and a few countries from the Former Soviet Union lead in the opposite belief. In the Western world, opinions over the concept and the appropriate responses are divided. Nick Pidgeon of Cardiff University said that "results show the different stages of engagement about global warming on each side of the Atlantic", adding, "The debate in Europe is about what action needs to be taken, while many in the U.S. still debate whether climate change is happening." A 2010 poll by the Office of National Statistics found that 75% of UK respondents were at least "fairly convinced" that the world's climate is changing, compared to 87% in a similar survey in 2006. A January 2011 ICM poll in the UK found 83% of respondents viewed climate change as a current or imminent threat, while 14% said it was no threat. Opinion was unchanged from an August 2009 poll asking the same question, though there had been a slight polarisation of opposing views.

A survey in October, 2009 by the Pew Research Center for the People & the Press showed decreasing public perception in the United States that global warming was a serious problem. All political persuasions showed reduced concern with lowest concern among Republicans, only 35% of whom considered there to be solid evidence of global warming. The cause of this marked difference in public opinion between the United States and the global public is uncertain but the hypothesis has been advanced that clearer communication by scientists both directly and through the media would be helpful in adequately informing the American public of the scientific consensus and the basis for it.

The U.S. public appears to be unaware of the extent of scientific consensus regarding the issue, with 59% believing that scientists disagree "significantly" on global warming.

By 2010, with 111 countries surveyed, Gallup determined that there was a substantial decrease in the number of Americans and Europeans who viewed Global Warming as a serious threat. In the United States, a little over half the population (53%) now viewed it as a serious concern for either themselves or their families; a number 10 percentage points below the 2008 poll (63%). Latin America had the biggest rise in concern, with 73% saying global warming was a serious threat to their families. That global poll also found that people are more likely to attribute global warming to human activities than to natural causes, except in the USA where nearly half (47%) of the population attributed global warming to natural causes.

On the other hand, in May 2011 a joint poll by Yale and George Mason Universities found that nearly half the people in the USA (47%) attribute global warming to human activities, compared to 36% blaming it on natural causes. Only 5% of the 35% who were "disengaged", "doubtful", or "dismissive" of global warming were aware that 97% of publishing US climate scientists agree global warming is happening and is primarily caused by humans.

Researchers at the University of Michigan have found that the public's belief as to the causes of global warming depends on the wording choice used in the polls.

Other views

Most scientists accept that humans are contributing to observed climate change. National science academies have called on world leaders for policies to cut global emissions. However, some scientists and non-scientists question aspects of climate-change science.

Organizations such as the libertarian Competitive Enterprise Institute, conservative commentators, and some companies such as ExxonMobil have challenged IPCC climate change scenarios, funded scientists who disagree with the scientific consensus, and provided their own projections of the economic cost of stricter controls. In the finance industry, Deutsche Bank has set up an institutional climate change investment division (DBCCA), which has commissioned and published research on the issues and debate surrounding global warming. Environmental organizations and public figures have emphasized changes in the current climate and the risks they entail, while promoting adaptation to changes in infrastructural needs and emissions reductions. Some fossil fuel companies have scaled back their efforts in recent years, or called for policies to reduce global warming.

Chapter- 2

Climate Change

Climate change is a long-term change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. It may be a change in average weather conditions or the distribution of events around that average (e.g., more or fewer extreme weather events). Climate change may be limited to a specific region or may occur across the whole Earth.

Terminology

The most general definition of *climate change* is a change in the statistical properties of the climate system when considered over long periods of time, regardless of cause. Accordingly, fluctuations over periods shorter than a few decades, such as El Niño, do not represent climate change.

The term sometimes is used to refer specifically to climate change caused by human activity, as opposed to changes in climate that may have resulted as part of Earth's natural processes, and the differentiation of these two causes, human impact vs. natural processes is a key component of the climate change debate.

The United Nations Framework Convention on Climate Change defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." In this latter sense, used especially in the context of environmental policy, climate change is synonymous with anthropogenic global warming.

Causes

Climate change reflects a change in the energy balance of the climate system, i.e. changes the relative balance between incoming solar radiation and outgoing infrared radiation from Earth. When this balance changes it is called "radiative forcing", and the calculation and measurement of radiative forcing is one aspect of the science of climatology. The processes that cause such changes are called "forcing mechanisms" .

Forcing mechanisms can be either "internal" or "external". Internal forcing mechanisms are natural processes within the climate system itself, e.g., the meridional turnover.

External forcing mechanisms can be either natural (e.g., changes in solar output) or anthropogenic (e.g., increased emissions of greenhouse gases).

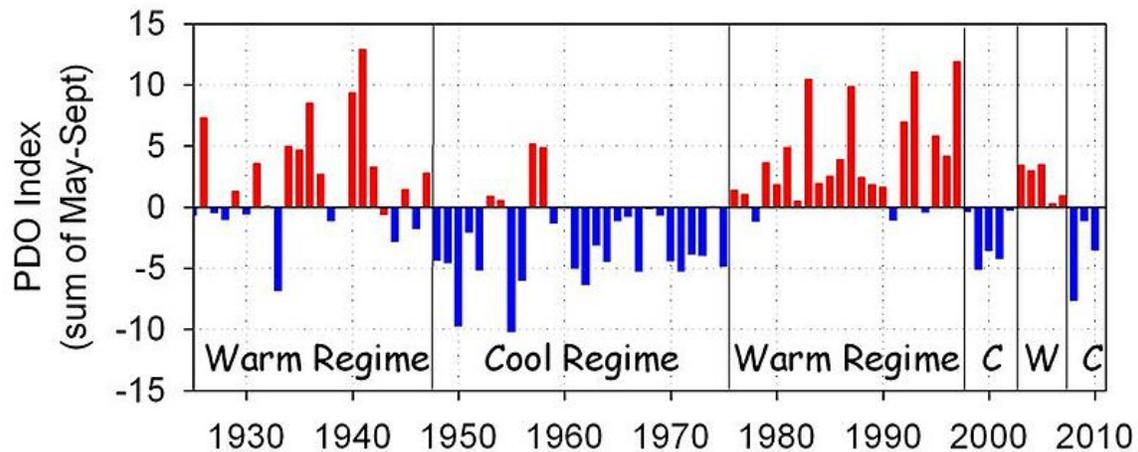
Whether the initial forcing mechanism is internal or external, the response of the climate system might be fast (e.g., a sudden cooling due to airborne volcanic ash reflecting sunlight), slow (e.g. thermal expansion of warming ocean water), or a combination (e.g., sudden loss of albedo in the arctic ocean as sea ice melts, followed by more gradual thermal expansion of the water). Therefore, the climate system can respond abruptly, but the full response to forcing mechanisms might not be fully developed for centuries or even longer.

In addition, there are many climate change feedbacks that can either intensify or reduce a warming or cooling trend.

Internal forcing mechanisms

Natural changes in the components of earth's climate system and their interactions are the cause of internal climate variability, or "internal forcings." Scientists generally define the five components of earth's climate system to include Atmosphere, hydrosphere, cryosphere, lithosphere (restricted to the surface soils, rocks, and sediments), and biosphere.

Ocean variability



Pacific Decadal Oscillation 1925 to 2010

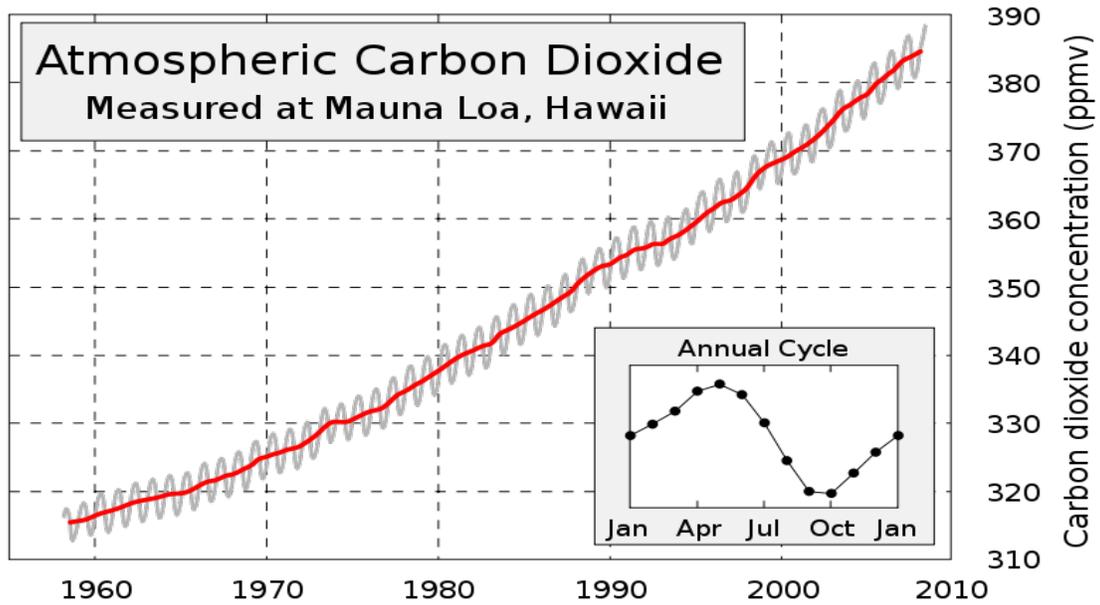
The ocean is a fundamental part of the climate system, some changes in it occurring at longer timescales than in the atmosphere, lasting hundreds of times more and having very high thermal inertia (such as the ocean depths still lagging today in temperature adjustment from the Little Ice Age).

Short-term fluctuations (years to a few decades) such as the El Niño-Southern Oscillation, the Pacific decadal oscillation, the North Atlantic oscillation, and the Arctic oscillation, represent climate variability rather than climate change. On longer time scales, alterations to ocean processes such as thermohaline circulation play a key role in redistributing heat by carrying out a very slow and extremely deep movement of water, and the long-term redistribution of heat in the world's oceans.

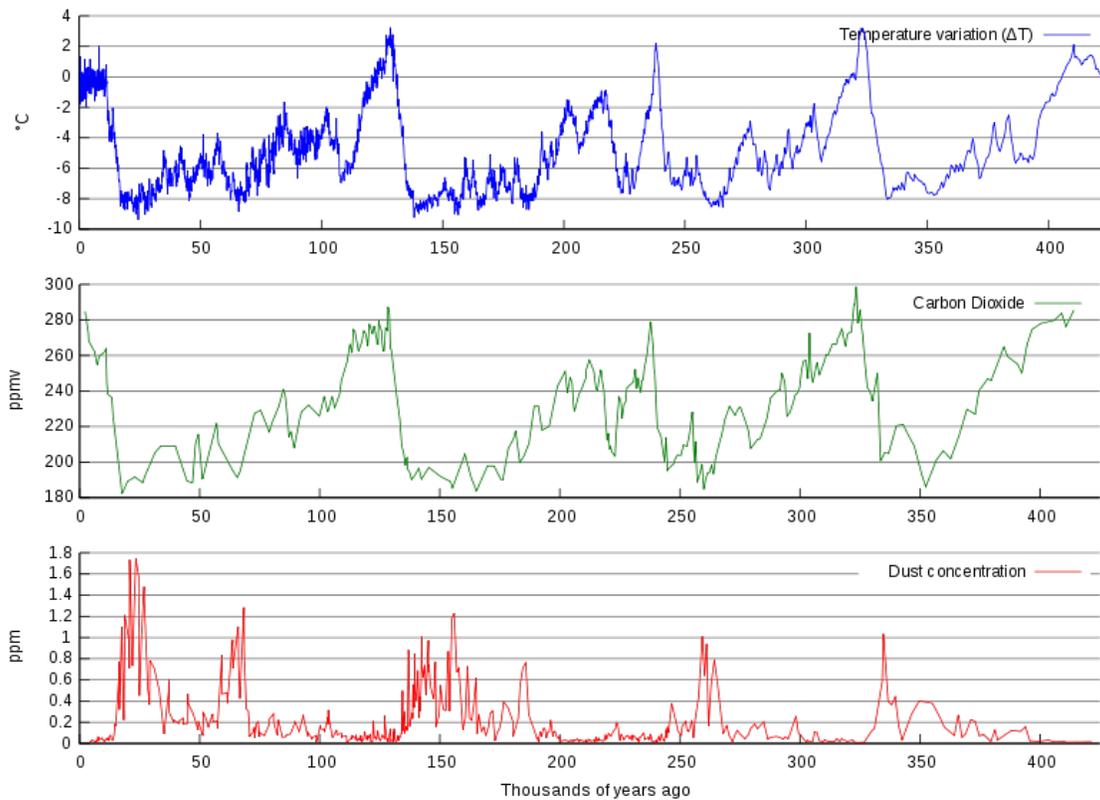


A schematic of modern thermohaline circulation. Tens of millions of years ago, continental plate movement formed a land-free gap around Antarctica, allowing formation of the ACC which keeps warm waters away from Antarctica.

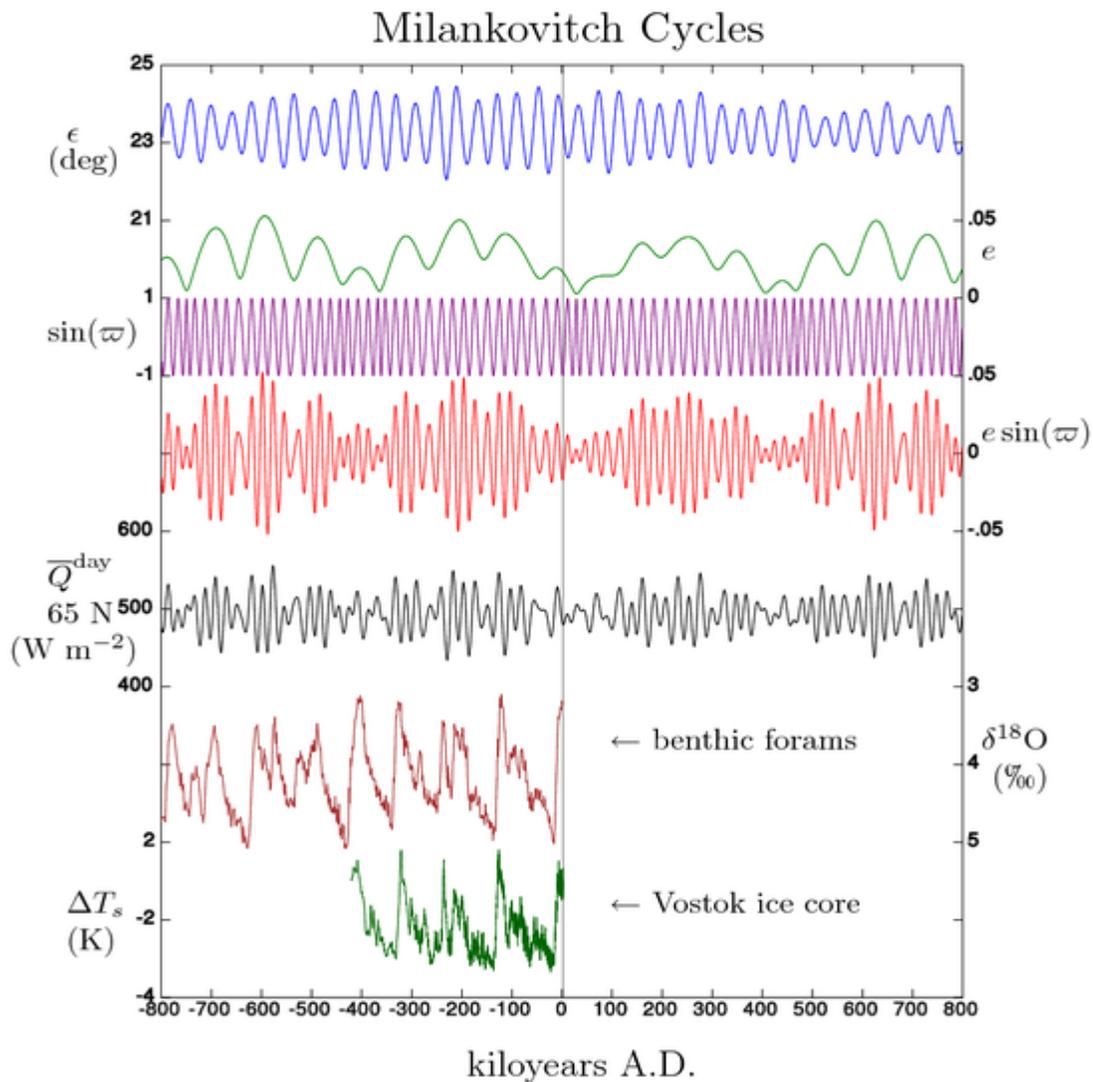
External forcing mechanisms



Increase in Atmospheric CO₂ Levels



Variations in CO₂, temperature and dust from the Vostok ice core over the last 450,000 years



Milankovitch cycles from 800,000 years ago in the past to 800,000 years in the future

Human influences

In the context of climate variation, anthropogenic factors are human activities which affect the climate. The scientific consensus on climate change is "that climate is changing and that these changes are in large part caused by human activities," and it "is largely irreversible."

“Science has made enormous inroads in understanding climate change and its causes, and is beginning to help develop a strong understanding of current and potential impacts that will affect people today and in coming decades. This understanding is crucial because it

allows decision makers to place climate change in the context of other large challenges facing the nation and the world. There are still some uncertainties, and there always will be in understanding a complex system like Earth's climate. Nevertheless, there is a strong, credible body of evidence, based on multiple lines of research, documenting that climate is changing and that these changes are in large part caused by human activities. While much remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of alternative explanations."

— *United States National Research Council, Advancing the Science of Climate Change*

Consequently, the debate is shifting onto ways to reduce further human impact and to find ways to adapt to change that has already occurred and is anticipated to occur in the future.

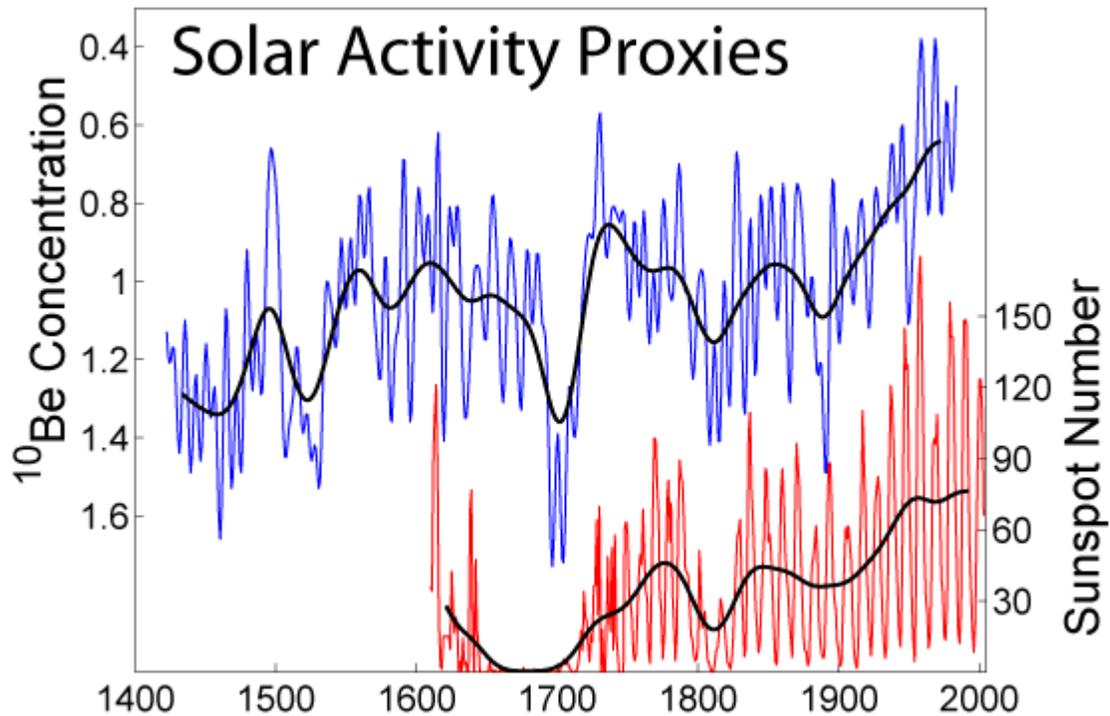
Of most concern in these anthropogenic factors is the increase in CO₂ levels due to emissions from fossil fuel combustion, followed by aerosols (particulate matter in the atmosphere) and cement manufacture. Other factors, including land use, ozone depletion, animal agriculture and deforestation, are also of concern in the roles they play - both separately and in conjunction with other factors - in affecting climate, microclimate, and measures of climate variables.

Orbital variations

Slight variations in Earth's orbit lead to changes in the seasonal distribution of sunlight reaching the Earth's surface and how it is distributed across the globe. There is very little change to the area-averaged annually averaged sunshine; but there can be strong changes in the geographical and seasonal distribution. The three types of orbital variations are variations in Earth's eccentricity, changes in the tilt angle of Earth's axis of rotation, and precession of Earth's axis. Combined together, these produce Milankovitch cycles which have a large impact on climate and are notable for their correlation to glacial and interglacial periods, their correlation with the advance and retreat of the Sahara, and for their appearance in the stratigraphic record.

The IPCC notes that Milankovitch cycles drove the ice age cycles; CO₂ followed temperature change "with a lag of some hundreds of years"; and that as a feedback amplified temperature change. The depths of the ocean have a lag time in changing temperature (thermal inertia on such scale). Upon seawater temperature change, the solubility of CO₂ in the oceans changed, as well as other factors impacting air-sea CO₂ exchange.

Solar output



Variations in solar activity during the last several centuries based on observations of sunspots and beryllium isotopes. The period of extraordinarily few sunspots in the late 17th century was the Maunder Minimum.

The sun is the predominant source for energy input to the Earth. Both long- and short-term variations in solar intensity are known to affect global climate.

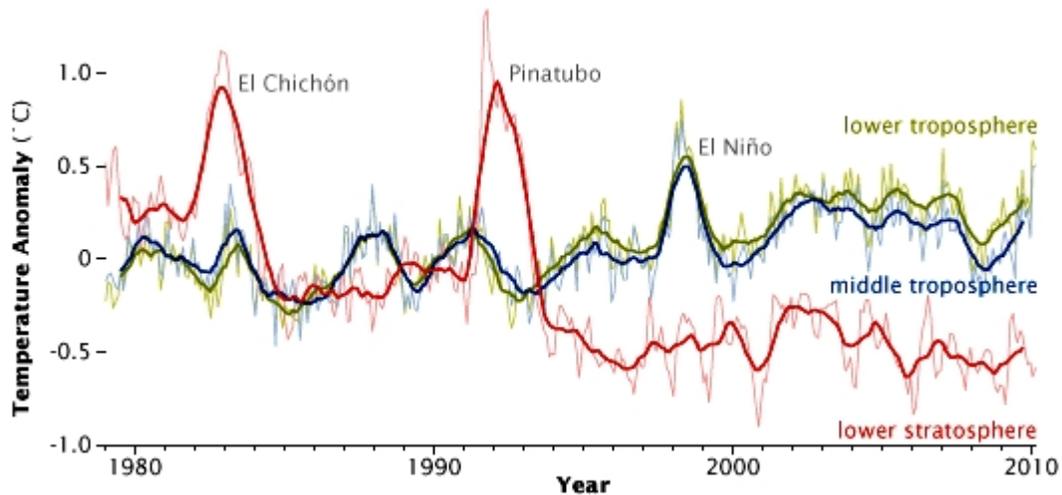
Three to four billion years ago the sun emitted only 70% as much power as it does today. If the atmospheric composition had been the same as today, liquid water should not have existed on Earth. However, there is evidence for the presence of water on the early Earth, in the Hadean and Archean eons, leading to what is known as the faint young sun paradox. Hypothesized solutions to this paradox include a vastly different atmosphere, with much higher concentrations of greenhouse gases than currently exist. Over the following approximately 4 billion years, the energy output of the sun increased and atmospheric composition changed. The oxygenation of the atmosphere around 2.4 billion years ago was the most notable alteration. Over the next five billion years the sun's ultimate death as it becomes a red giant and then a white dwarf will have large effects on climate, with the red giant phase possibly ending any life on Earth that survives until that time.

Solar output also varies on shorter time scales, including the 11-year solar cycle and longer-term modulations. Solar intensity variations are considered to have been influential in triggering the Little Ice Age, and some of the warming observed from 1900 to 1950. The cyclical nature of the sun's energy output is not yet fully understood; it

differs from the very slow change that is happening within the sun as it ages and evolves. Research indicates that solar variability has had effects including the Maunder Minimum from 1645 to 1715 A.D., part of the Little Ice Age from 1550 to 1850 A.D. which was marked by relative cooling and greater glacier extent than the centuries before and afterward. Some studies point toward solar radiation increases from cyclical sunspot activity affecting global warming, and climate may be influenced by the sum of all effects (solar variation, anthropogenic radiative forcings, etc).

Interestingly, a 2010 study *suggests*, “that the effects of solar variability on temperature throughout the atmosphere may be contrary to current expectations.”

Volcanism



In atmospheric temperature from 1979 to 2010, determined by MSU NASA satellites, effects appear from aerosols released by major volcanic eruptions (El Chichón and Pinatubo). El Niño is a separate event, from ocean variability.

Volcanic eruptions release gases and particulates into the atmosphere. Eruptions large enough to affect climate occur on average several times per century, and cause cooling (by partially blocking the transmission of solar radiation to the Earth's surface) for a period of a few years. The eruption of Mount Pinatubo in 1991, the second largest terrestrial eruption of the 20th century (after the 1912 eruption of Novarupta) affected the climate substantially. Global temperatures decreased by about 0.5 °C (0.9 °F). The eruption of Mount Tambora in 1815 caused the Year Without a Summer. Much larger eruptions, known as large igneous provinces, occur only a few times every hundred million years, but may cause global warming and mass extinctions.

Volcanoes are also part of the extended carbon cycle. Over very long (geological) time periods, they release carbon dioxide from the Earth's crust and mantle, counteracting the uptake by sedimentary rocks and other geological carbon dioxide sinks. The US Geological Survey estimates are that volcanic emissions are at a much lower level than the effects of current human activities, which generate 100-300 times the amount of carbon dioxide emitted by volcanoes. A review of published studies indicates that annual

volcanic emissions of carbon dioxide, including amounts released from mid-ocean ridges, volcanic arcs, and hot spot volcanoes, are only the equivalent of 3 to 5 days of human caused output. The annual amount put out by human activities may be greater than the amount released by supereruptions, the most recent of which was the Toba eruption in Indonesia 74,000 years ago.

Although volcanoes are technically part of the lithosphere, which itself is part of the climate system, IPCC explicitly defines volcanism as an external forcing agent.

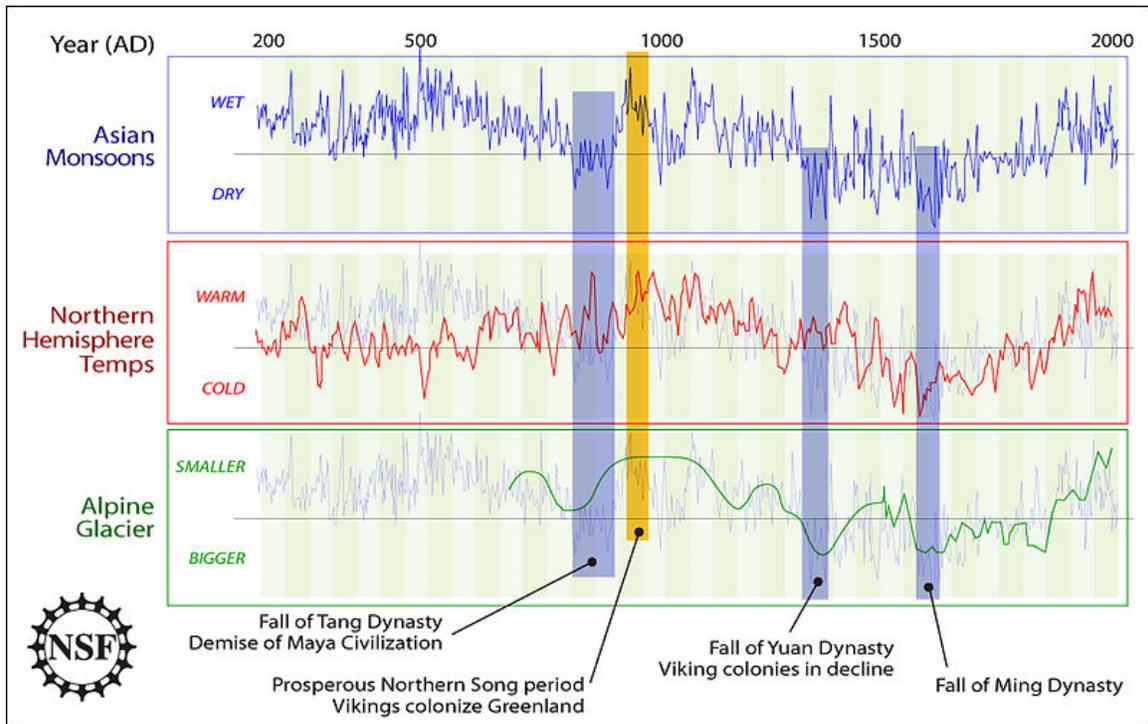
Plate tectonics

Over the course of millions of years, the motion of tectonic plates reconfigures global land and ocean areas and generates topography. This can affect both global and local patterns of climate and atmosphere-ocean circulation.

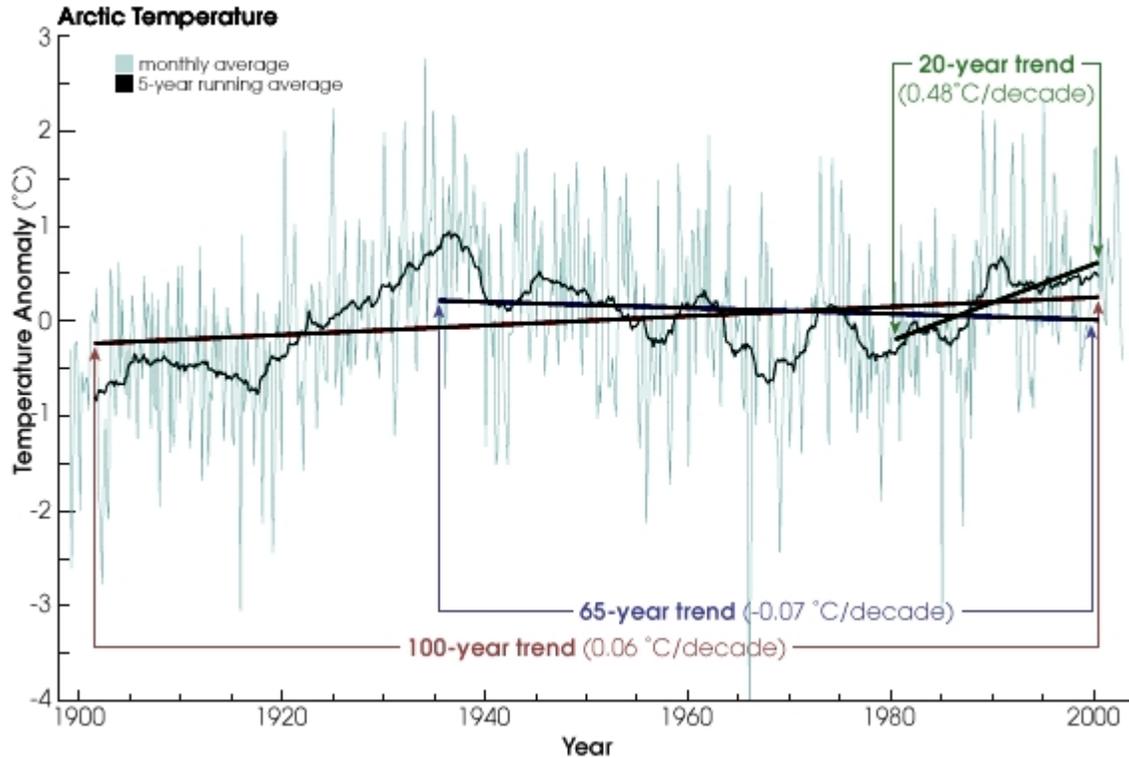
The position of the continents determines the geometry of the oceans and therefore influences patterns of ocean circulation. The locations of the seas are important in controlling the transfer of heat and moisture across the globe, and therefore, in determining global climate. A recent example of tectonic control on ocean circulation is the formation of the Isthmus of Panama about 5 million years ago, which shut off direct mixing between the Atlantic and Pacific Oceans. This strongly affected the ocean dynamics of what is now the Gulf Stream and may have led to Northern Hemisphere ice cover. During the Carboniferous period, about 300 to 360 million years ago, plate tectonics may have triggered large-scale storage of carbon and increased glaciation. Geologic evidence points to a "megamonsoonal" circulation pattern during the time of the supercontinent Pangaea, and climate modeling suggests that the existence of the supercontinent was conducive to the establishment of monsoons.

The size of continents is also important. Because of the stabilizing effect of the oceans on temperature, yearly temperature variations are generally lower in coastal areas than they are inland. A larger supercontinent will therefore have more area in which climate is strongly seasonal than will several smaller continents or islands.

Physical evidence for and examples of climatic change



Comparisons between Asian Monsoons from 200 A.D. to 2000 A.D. (staying in the background on other plots), Northern Hemisphere temperature, Alpine glacier extent (vertically inverted as marked), and human history as noted by the U.S. NSF.



Arctic temperature anomalies over a 100 year period as estimated by NASA. Typical high monthly variance can be seen, while longer-term averages highlight trends.

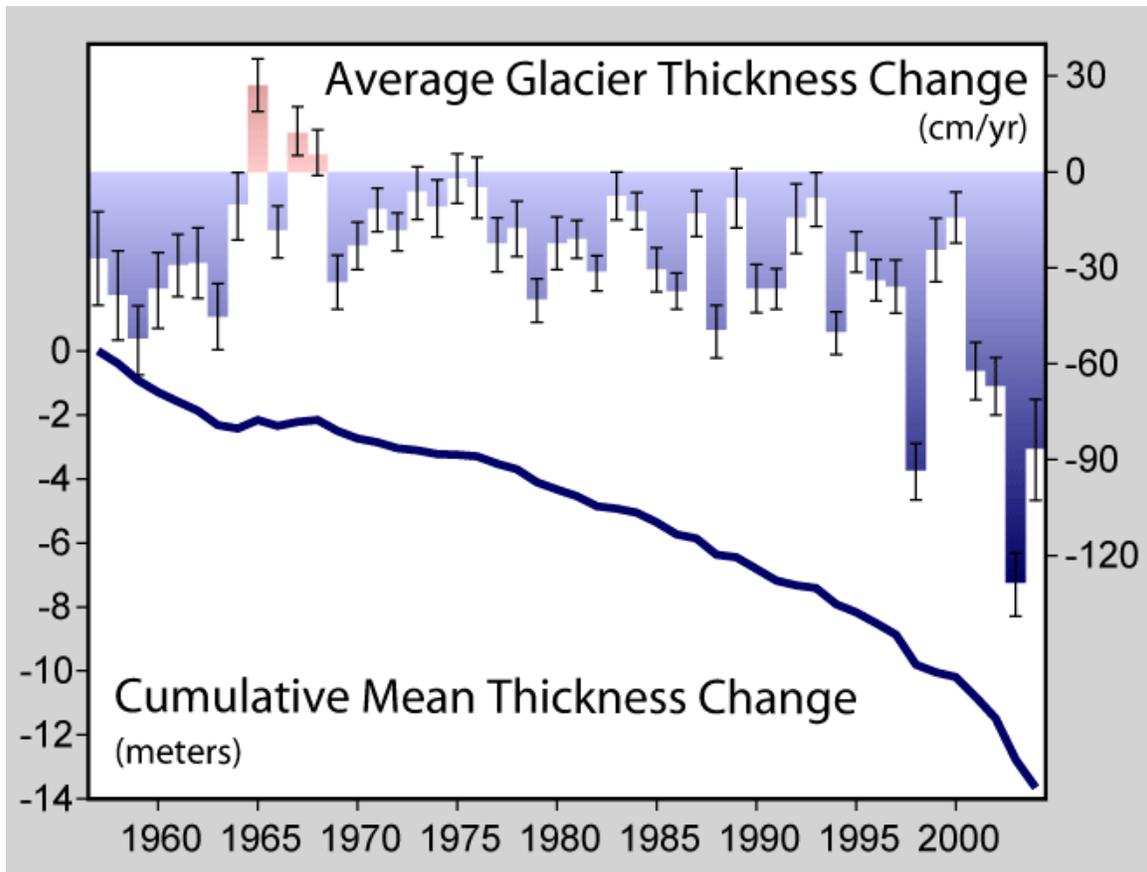
Evidence for climatic change is taken from a variety of sources that can be used to reconstruct past climates. Reasonably complete global records of surface temperature are available beginning from the mid-late 19th century. For earlier periods, most of the evidence is indirect—climatic changes are inferred from changes in proxies, indicators that reflect climate, such as vegetation, ice cores, dendrochronology, sea level change, and glacial geology.

Temperature measurements and proxies

The instrumental temperature record from surface stations was supplemented by radiosonde balloons, extensive atmospheric monitoring by the mid-20th century, and, from the 1970s on, with global satellite data as well. The $^{18}\text{O}/^{16}\text{O}$ ratio in calcite and ice core samples used to deduce ocean temperature in the distant past is an example of a temperature proxy method, as are other climate metrics noted in subsequent categories.

Historical and archaeological evidence

Climate change in the recent past may be detected by corresponding changes in settlement and agricultural patterns. Archaeological evidence, oral history and historical documents can offer insights into past changes in the climate. Climate change effects have been linked to the collapse of various civilizations.



Decline in thickness of glaciers worldwide over the past half-century

Glaciers

Glaciers are considered among the most sensitive indicators of climate change. Their size is determined by a mass balance between snow input and melt output. As temperatures warm, glaciers retreat unless snow precipitation increases to make up for the additional melt; the converse is also true.

Glaciers grow and shrink due both to natural variability and external forcings. Variability in temperature, precipitation, and englacial and subglacial hydrology can strongly determine the evolution of a glacier in a particular season. Therefore, one must average over a decadal or longer time-scale and/or over a many individual glaciers to smooth out the local short-term variability and obtain a glacier history that is related to climate.

A world glacier inventory has been compiled since the 1970s, initially based mainly on aerial photographs and maps but now relying more on satellites. This compilation tracks more than 100,000 glaciers covering a total area of approximately 240,000 km², and preliminary estimates indicate that the remaining ice cover is around 445,000 km². The World Glacier Monitoring Service collects data annually on glacier retreat and glacier mass balance. From this data, glaciers worldwide have been found to be shrinking

significantly, with strong glacier retreats in the 1940s, stable or growing conditions during the 1920s and 1970s, and again retreating from the mid 1980s to present.

The most significant climate processes since the middle to late Pliocene (approximately 3 million years ago) are the glacial and interglacial cycles. The present interglacial period (the Holocene) has lasted about 11,700 years. Shaped by orbital variations, responses such as the rise and fall of continental ice sheets and significant sea-level changes helped create the climate. Other changes, including Heinrich events, Dansgaard–Oeschger events and the Younger Dryas, however, illustrate how glacial variations may also influence climate without the orbital forcing.

Glaciers leave behind moraines that contain a wealth of material—including organic matter, quartz, and potassium that may be dated—recording the periods in which a glacier advanced and retreated. Similarly, by tephrochronological techniques, the lack of glacier cover can be identified by the presence of soil or volcanic tephra horizons whose date of deposit may also be ascertained.

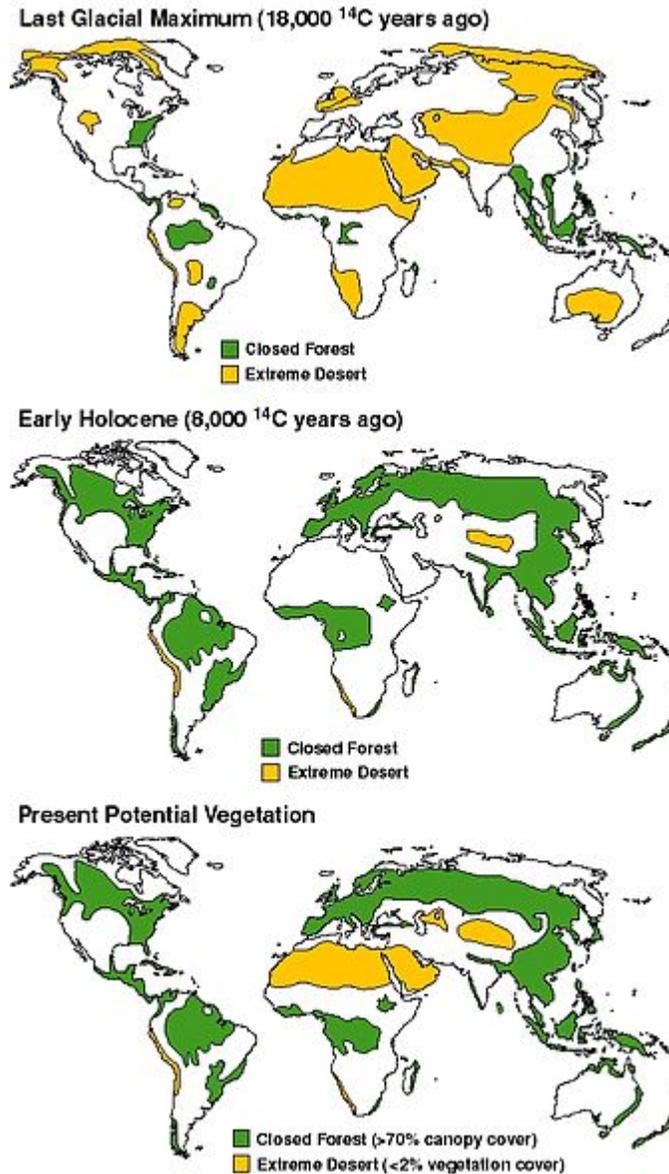
Vegetation

A change in the type, distribution and coverage of vegetation may occur given a change in the climate. Some changes in climate may result in increased precipitation and warmth, resulting in improved plant growth and the subsequent sequestration of airborne CO₂. Larger, faster or more radical changes, however, may result in vegetation stress, rapid plant loss and desertification in certain circumstances. An example of this occurred during the Carboniferous Rainforest Collapse (CRC), an extinction event 300 million years ago. At this time vast rainforests covered the equatorial region of Europe and America. Climate change devastated these tropical rainforests, abruptly fragmenting the habitat into isolated 'islands' and causing the extinction of many plant and animal species.

Satellite data available in recent decades indicates that global terrestrial net primary production increased by 6% from 1982 to 1999, with the largest portion of that increase in tropical ecosystems, then decreased by 1% from 2000 to 2009.

Pollen analysis

Palynology is the study of contemporary and fossil palynomorphs, including pollen. Palynology is used to infer the geographical distribution of plant species, which vary under different climate conditions. Different groups of plants have pollen with distinctive shapes and surface textures, and since the outer surface of pollen is composed of a very resilient material, they resist decay. Changes in the type of pollen found in different layers of sediment in lakes, bogs, or river deltas indicate changes in plant communities. These changes are often a sign of a changing climate. As an example, palynological studies have been used to track changing vegetation patterns throughout the Quaternary glaciations and especially since the last glacial maximum.



Top: Arid ice age climate

Middle: Atlantic Period, warm and wet

Bottom: Potential vegetation in climate now if not for human effects like agriculture

Precipitation

Past precipitation can be estimated in the modern era with the global network of precipitation gauges. Surface coverage over oceans and remote areas is relatively sparse, but, reducing reliance on interpolation, satellite data has been available since the 1970s. Quantification of climatological variation of precipitation in prior centuries and epochs is less complete but approximated using proxies such as marine sediments, ice cores, cave stalagmites, and tree rings.

Climatological temperatures substantially affect precipitation. For instance, during the Last Glacial Maximum of 18,000 years ago, thermal-driven evaporation from the oceans onto continental landmasses was low, causing large areas of extreme desert, including polar deserts (cold but with low rates of precipitation). In contrast, the world's climate was wetter than today near the start of the warm Atlantic Period of 8000 years ago.

Estimated global land precipitation increased by approximately 2% over the course of the 20th century, though the calculated trend varies if different time endpoints are chosen, complicated by ENSO and other oscillations, including greater global land precipitation in the 1950s and 1970s than the later 1980s and 1990s despite the positive trend over the century overall. Similar slight overall increase in global river runoff and in average soil moisture has been perceived.

Dendroclimatology

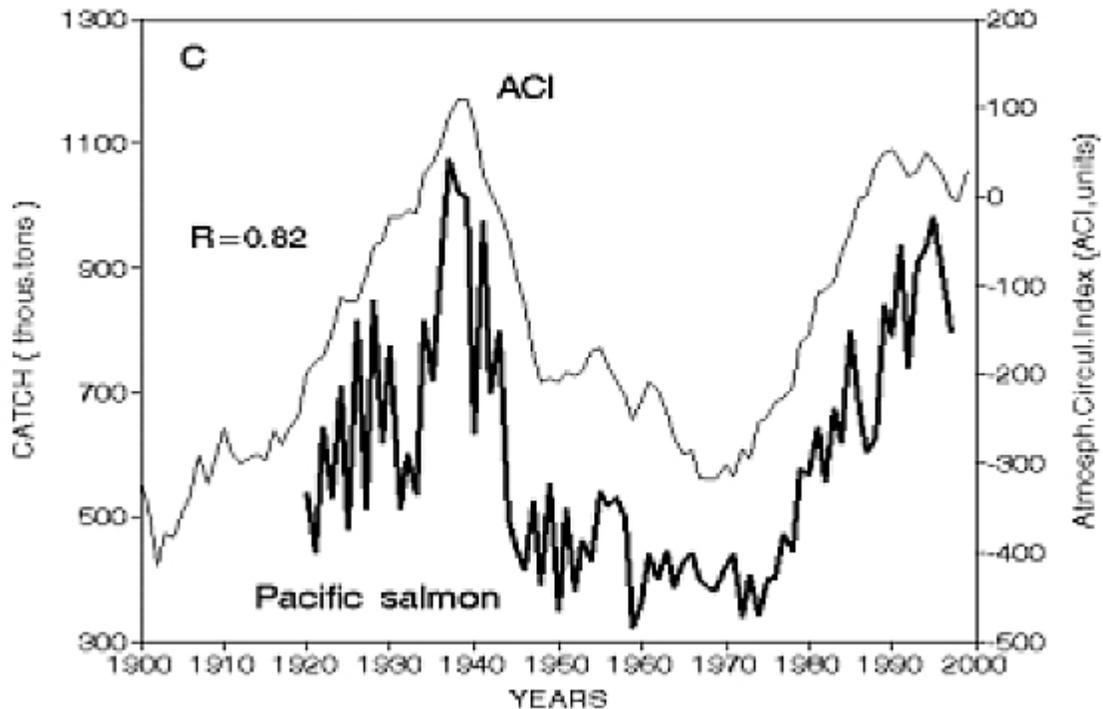
Dendroclimatology is the analysis of tree ring growth patterns to determine past climate variations. Wide and thick rings indicate a fertile, well-watered growing period, whilst thin, narrow rings indicate a time of lower rainfall and less-than-ideal growing conditions.

Ice cores

Analysis of ice in a core drilled from an ice sheet such as the Antarctic ice sheet, can be used to show a link between temperature and global sea level variations. The air trapped in bubbles in the ice can also reveal the CO₂ variations of the atmosphere from the distant past, well before modern environmental influences. The study of these ice cores has been a significant indicator of the changes in CO₂ over many millennia, and continues to provide valuable information about the differences between ancient and modern atmospheric conditions.

Insects

Remains of beetles are common in freshwater and land sediments. Different species of beetles tend to be found under different climatic conditions. Given the extensive lineage of beetles whose genetic makeup has not altered significantly over the millennia, knowledge of the present climatic range of the different species, and the age of the sediments in which remains are found, past climatic conditions may be inferred.



Variation in Pacific salmon catch over the 20th century and correlation with a climate-related Atmospheric Circulation Index (ACI) as estimated by the U.N. FAO.

Fish

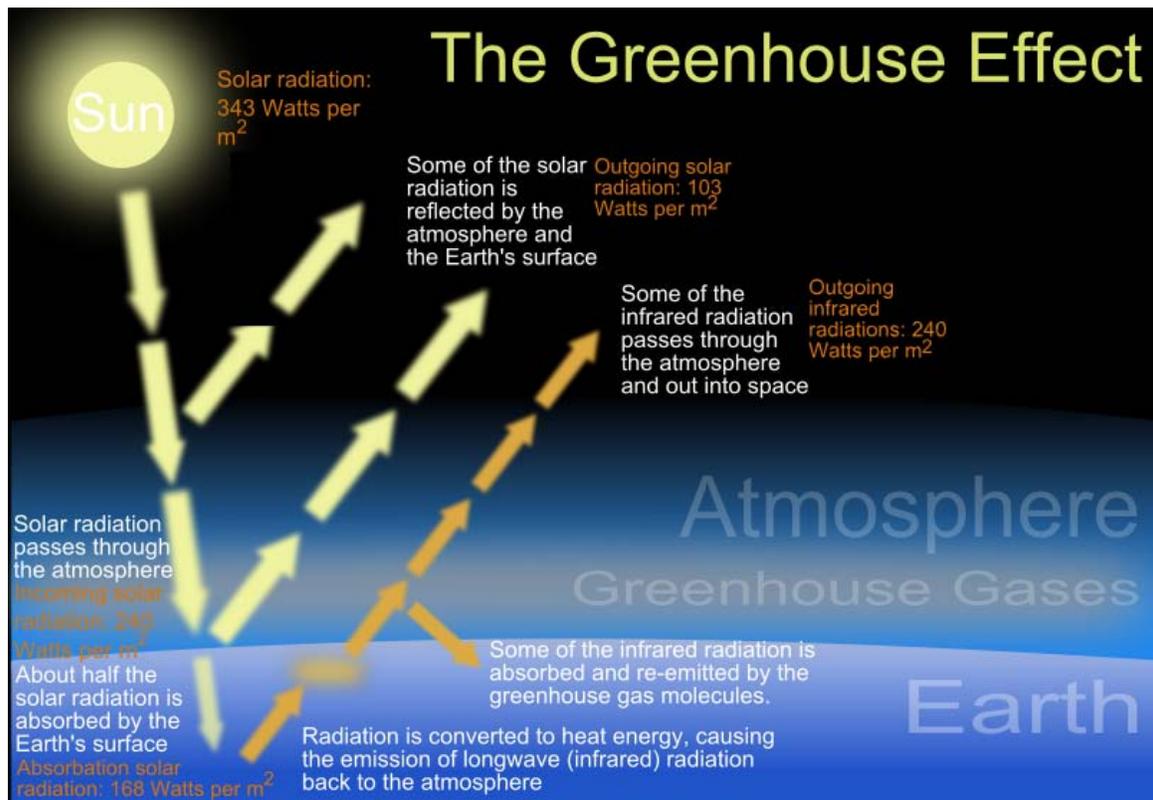
While far from the only factor involved, very substantial relationships have been observed between climatic conditions and the historical abundance of fish species. Changes in the primary productivity of autotrophs in the oceans can affect marine food webs.

Sea level change

Global sea level change for much of the last century has generally been estimated using tide gauge measurements collated over long periods of time to give a long-term average. More recently, altimeter measurements — in combination with accurately determined satellite orbits — have provided an improved measurement of global sea level change. To measure sea levels prior to instrumental measurements, scientists have dated coral reefs that grow near the surface of the ocean, coastal sediments, marine terraces, ooids in limestones, and nearshore archaeological remains. The predominant dating methods used are uranium series and radiocarbon, with cosmogenic radionuclides being sometimes used to date terraces that have experienced relative sea level fall.

Chapter- 3

Greenhouse Gas



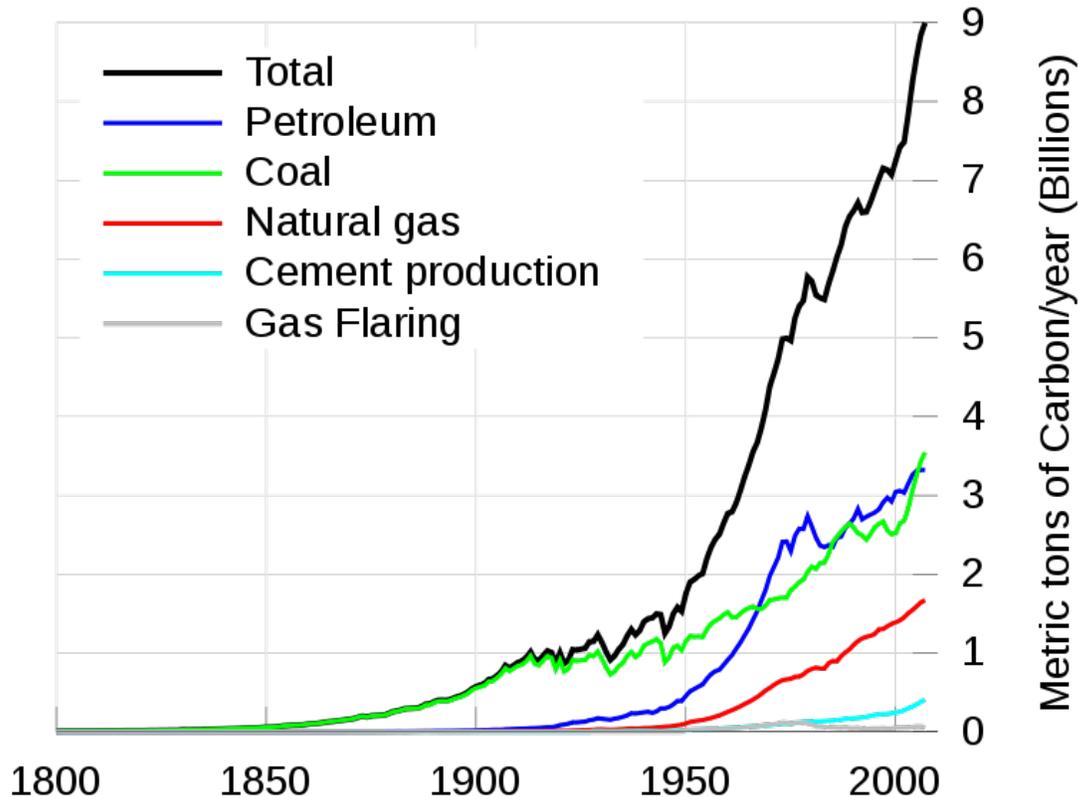
Simple diagram of greenhouse effect

A **greenhouse gas** (sometimes abbreviated **GHG**) is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. In the Solar System, the atmospheres of Venus, Mars, and Titan also contain gases that cause greenhouse effects. Greenhouse gases greatly affect the temperature of the Earth; without them, Earth's surface would be on average about 33 °C (59 °F) colder than at present.

Since the beginning of the Industrial revolution, the burning of fossil fuels has contributed to the increase in carbon dioxide in the atmosphere from 280ppm to 390ppm,

despite the uptake of a large portion of the emissions through various natural "sinks" involved in the carbon cycle. Unlike other pollutants, carbon dioxide emissions do not result from inefficient combustion: CO₂ is a product of ideal, stoichiometric combustion of carbon. At present, the emissions of carbon are directly proportional to fossil-fuel based energy consumption. Since 2000 fossil fuel related carbon emissions have equaled or exceeded the IPCC's "A2 scenario", except for small dips during two global recessions.

Greenhouse effects in Earth's atmosphere



Modern global anthropogenic carbon emissions

In order, the most abundant greenhouse gases in Earth's atmosphere are:

- water vapor
- carbon dioxide
- methane
- nitrous oxide
- ozone

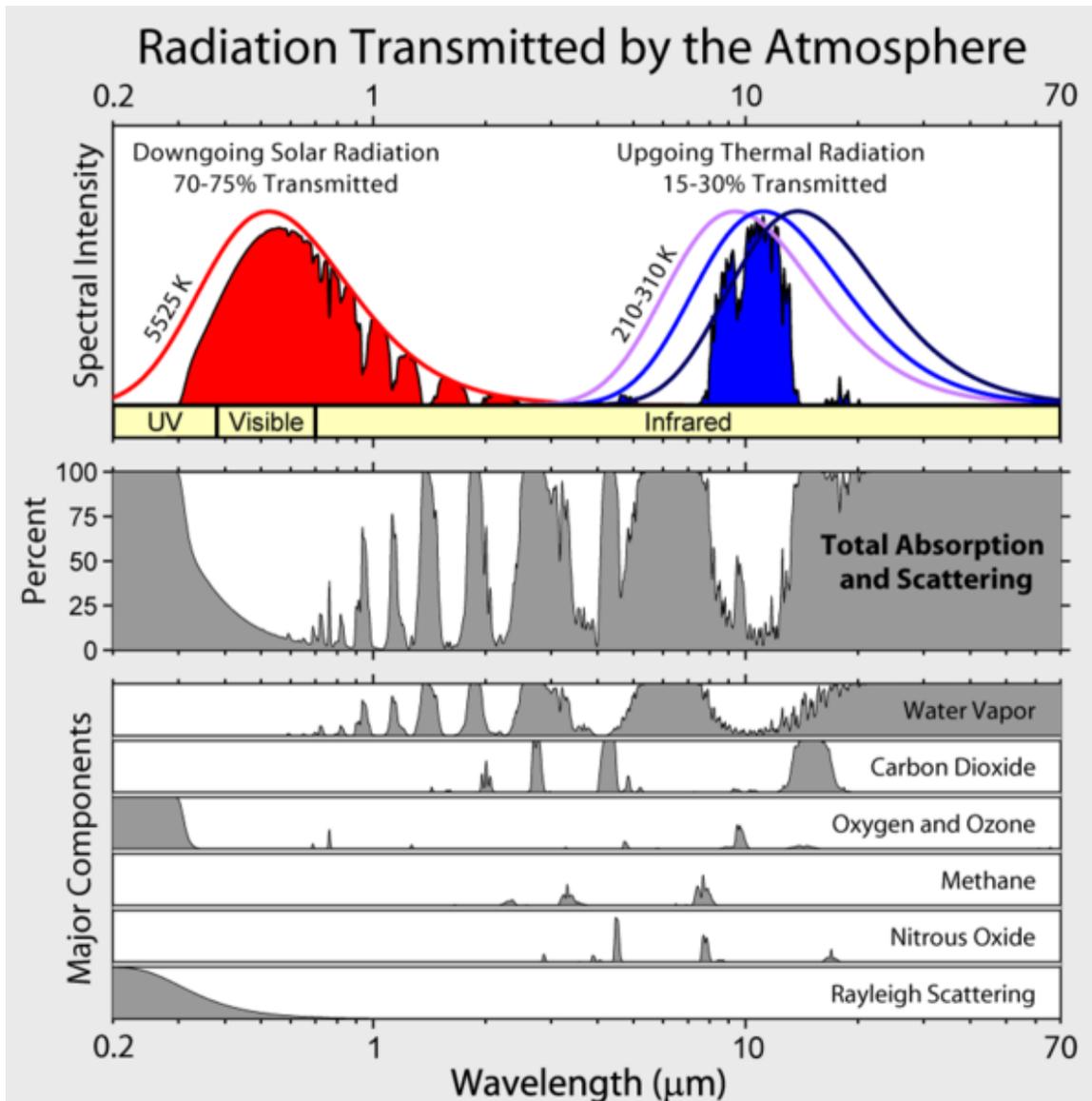
The contribution to the greenhouse effect by a gas is affected by both the characteristics of the gas and its abundance. For example, on a molecule-for-molecule basis methane is about 72 times stronger greenhouse gas than carbon dioxide over a 20 year time frame

but it is present in much smaller concentrations so that its total contribution is smaller. When these gases are ranked by their contribution to the greenhouse effect, the most important are:

Gas	Formula	Contribution (%)
Water vapor	H ₂ O	36 – 72 %
Carbon dioxide	CO ₂	9 – 26 %
Methane	CH ₄	4 – 9 %
Ozone	O ₃	3 – 7 %

It is not possible to state that a certain gas causes an exact percentage of the greenhouse effect. This is because some of the gases absorb and emit radiation at the same frequencies as others, so that the total greenhouse effect is not simply the sum of the influence of each gas. The higher ends of the ranges quoted are for each gas alone; the lower ends account for overlaps with the other gases. The major non-gas contributor to the Earth's greenhouse effect, clouds, also absorb and emit infrared radiation and thus have an effect on radiative properties of the greenhouse gases.

In addition to the main greenhouse gases listed above, other greenhouse gases include sulfur hexafluoride, hydrofluorocarbons and perfluorocarbons. Some greenhouse gases are not often listed. For example, nitrogen trifluoride has a high global warming potential (GWP) but is only present in very small quantities.

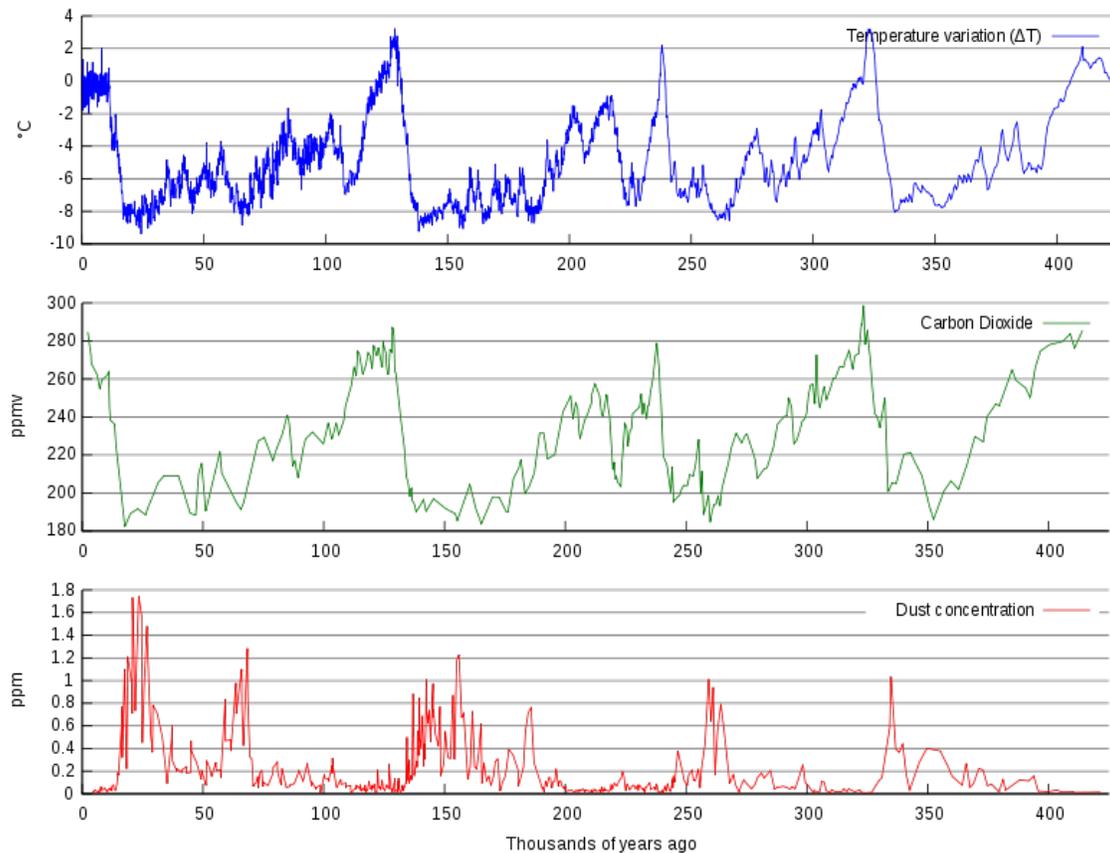


Atmospheric absorption and scattering at different electromagnetic wavelengths. The largest absorption band of carbon dioxide is in the infrared.

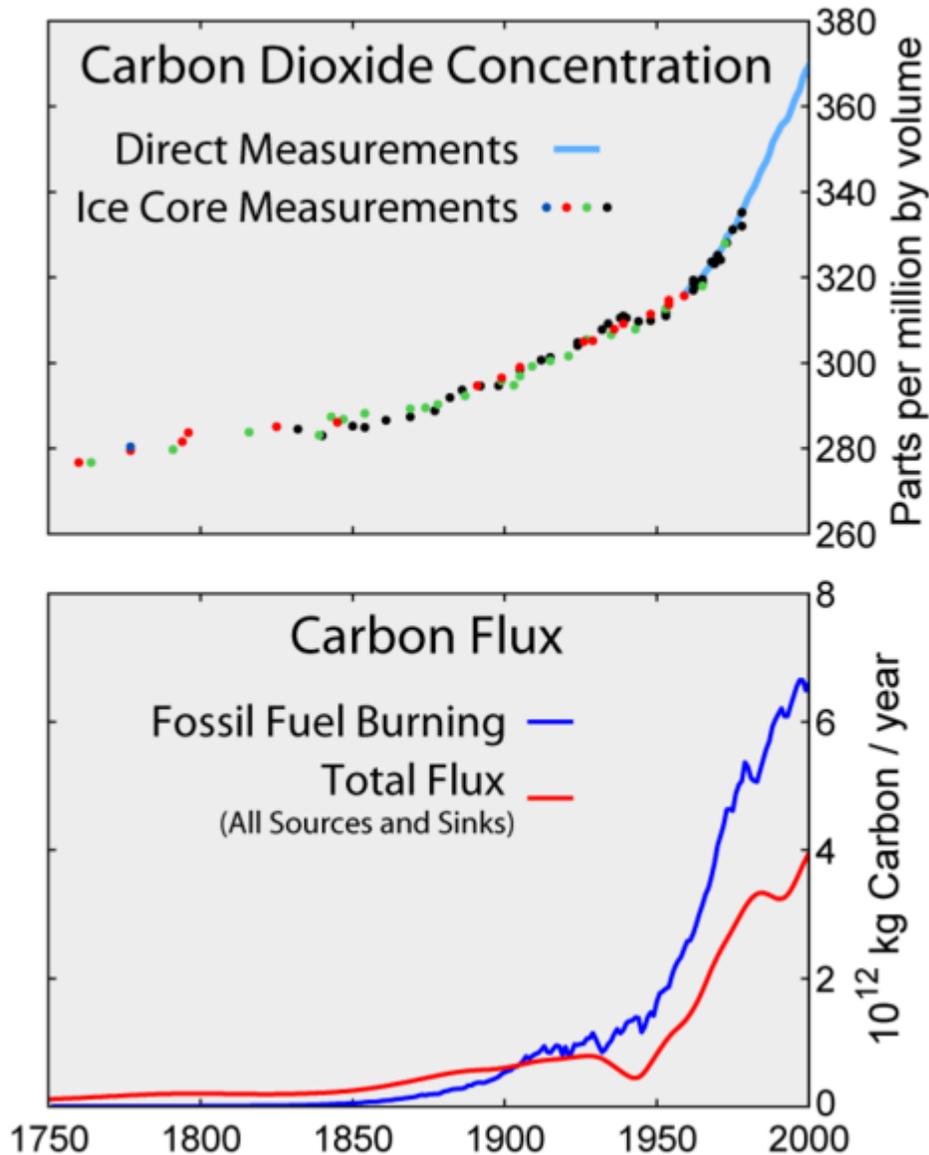
Although contributing to many other physical and chemical reactions, the major atmospheric constituents, nitrogen (N_2), oxygen (O_2), and argon (Ar), are not greenhouse gases. This is because molecules containing two atoms of the same element such as N_2 and O_2 and monatomic molecules such as Ar have no net change in their dipole moment when they vibrate and hence are almost totally unaffected by infrared light. Although molecules containing two atoms of different elements such as carbon monoxide (CO) or hydrogen chloride (HCl) absorb IR, these molecules are short-lived in the atmosphere owing to their reactivity and solubility. As a consequence they do not contribute significantly to the greenhouse effect and are not often included when discussing greenhouse gases.

Late 19th century scientists experimentally discovered that N_2 and O_2 do not absorb infrared radiation (called, at that time, "dark radiation") while, at the contrary, water, as true vapour or condensed in the form of microscopic droplets suspended in clouds, CO_2 and other poly-atomic gaseous molecules do absorb infrared radiation. It was recognized in the early 20th century that the greenhouse gases in the atmosphere caused the Earth's overall temperature to be higher than it would be without them. During the late 20th century, a scientific consensus has evolved that increasing concentrations of greenhouse gases in the atmosphere are causing a substantial rise in global temperatures and changes to other parts of the climate system, with consequences for the environment and human health.

Natural and anthropogenic sources



400,000 years of ice core data



Top: Increasing atmospheric carbon dioxide levels as measured in the atmosphere and reflected in ice cores. Bottom: The amount of net carbon increase in the atmosphere, compared to carbon emissions from burning fossil fuel.

Aside from purely human-produced synthetic halocarbons, most greenhouse gases have both natural and human-caused sources. During the pre-industrial Holocene, concentrations of existing gases were roughly constant. In the industrial era, human activities have added greenhouse gases to the atmosphere, mainly through the burning of fossil fuels and clearing of forests.

The 2007 Fourth Assessment Report compiled by the IPCC (AR4) noted that "changes in atmospheric concentrations of greenhouse gases and aerosols, land cover and solar radiation alter the energy balance of the climate system", and concluded that "increases in

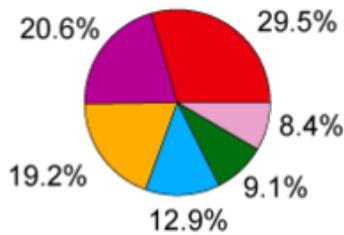
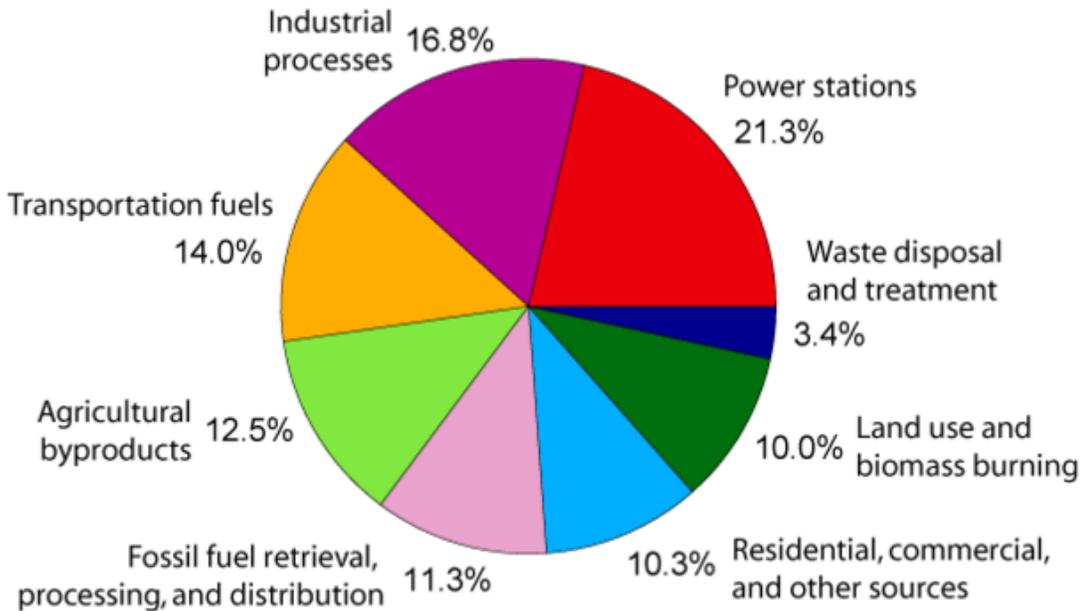
anthropogenic greenhouse gas concentrations is very likely to have caused most of the increases in global average temperatures since the mid-20th century". In AR4, "most of" is defined as more than 50%.

Gas	Preindustrial level	Current level	Increase since 1750	Radiative forcing (W/m²)
Carbon dioxide	280 ppm	388 ppm	108 ppm	1.46
Methane	700 ppb	1745 ppb	1045 ppb	0.48
Nitrous oxide	270 ppb	314 ppb	44 ppb	0.15
CFC-12	0	533 ppt	533 ppt	0.17

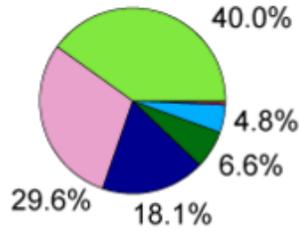
Ice cores provide evidence for variation in greenhouse gas concentrations over the past 800,000 years. Both CO₂ and CH₄ vary between glacial and interglacial phases, and concentrations of these gases correlate strongly with temperature. Direct data does not exist for periods earlier than those represented in the ice core record, a record which indicates CO₂ mole fractions staying within a range of between 180ppm and 280ppm throughout the last 800,000 years, until the increase of the last 250 years. However, various proxies and modeling suggests larger variations in past epochs; 500 million years ago CO₂ levels were likely 10 times higher than now. Indeed higher CO₂ concentrations are thought to have prevailed throughout most of the Phanerozoic eon, with concentrations four to six times current concentrations during the Mesozoic era, and ten to fifteen times current concentrations during the early Palaeozoic era until the middle of the Devonian period, about 400 Ma. The spread of land plants is thought to have reduced CO₂ concentrations during the late Devonian, and plant activities as both sources and sinks of CO₂ have since been important in providing stabilising feedbacks. Earlier still, a 200-million year period of intermittent, widespread glaciation extending close to the equator (Snowball Earth) appears to have been ended suddenly, about 550 Ma, by a colossal volcanic outgassing which raised the CO₂ concentration of the atmosphere abruptly to 12%, about 350 times modern levels, causing extreme greenhouse conditions and carbonate deposition as limestone at the rate of about 1 mm per day. This episode marked the close of the Precambrian eon, and was succeeded by the generally warmer conditions of the Phanerozoic, during which multicellular animal and plant life evolved. No volcanic carbon dioxide emission of comparable scale has occurred since. In the modern era, emissions to the atmosphere from volcanoes are only about 1% of emissions from human sources.

Anthropogenic greenhouse gases

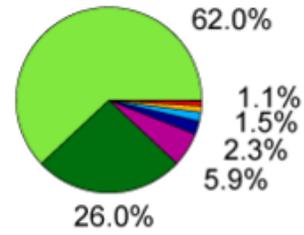
Annual Greenhouse Gas Emissions by Sector



Carbon Dioxide
(72% of total)

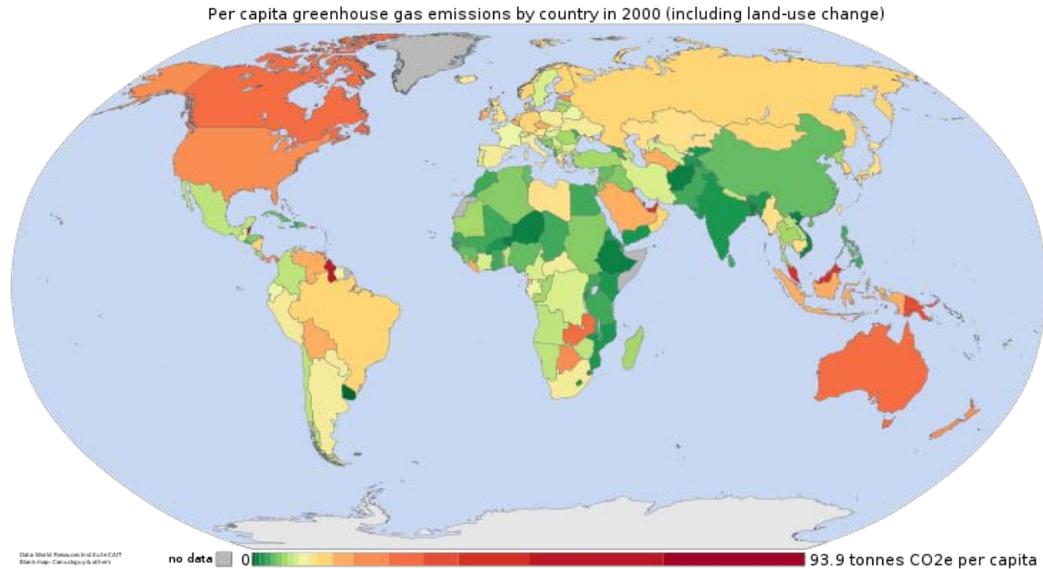


Methane
(18% of total)



Nitrous Oxide
(9% of total)

Global anthropogenic greenhouse gas emissions broken down into 8 different sectors for the year 2000



Per capita anthropogenic greenhouse gas emissions by country for the year 2000 including land-use change

Since about 1750 human activity has increased the concentration of carbon dioxide and other greenhouse gases. Measured atmospheric concentrations of carbon dioxide are currently 100 ppm higher than pre-industrial levels. Natural sources of carbon dioxide are more than 20 times greater than sources due to human activity, but over periods longer than a few years natural sources are closely balanced by natural sinks, mainly photosynthesis of carbon compounds by plants and marine plankton. As a result of this balance, the atmospheric mole fraction of carbon dioxide remained between 260 and 280 parts per million for the 10,000 years between the end of the last glacial maximum and the start of the industrial era.

It is likely that anthropogenic warming, such as that due to elevated greenhouse gas levels, has had a discernible influence on many physical and biological systems. Warming is projected to affect various issues such as freshwater resources, industry, food and health.

The main sources of greenhouse gases due to human activity are:

- burning of fossil fuels and deforestation leading to higher carbon dioxide concentrations in the air. Land use change (mainly deforestation in the tropics) account for up to one third of total anthropogenic CO₂ emissions.
- livestock enteric fermentation and manure management, paddy rice farming, land use and wetland changes, pipeline losses, and covered vented landfill emissions leading to higher methane atmospheric concentrations. Many of the newer style fully vented septic systems that enhance and target the fermentation process also are sources of atmospheric methane.
- use of chlorofluorocarbons (CFCs) in refrigeration systems, and use of CFCs and halons in fire suppression systems and manufacturing processes.

- agricultural activities, including the use of fertilizers, that lead to higher nitrous oxide (N₂O) concentrations.

The seven sources of CO₂ from fossil fuel combustion are (with percentage contributions for 2000–2004):

Seven main fossil fuel combustion sources	Contribution (%)
Liquid fuels (e.g., gasoline, fuel oil)	36 %
Solid fuels (e.g., coal)	35 %
Gaseous fuels (e.g., natural gas)	20 %
Cement production	3 %
Flaring gas industrially and at wells	< 1 %
Non-fuel hydrocarbons	< 1 %
"International bunker fuels" of transport not included in national inventories	4 %

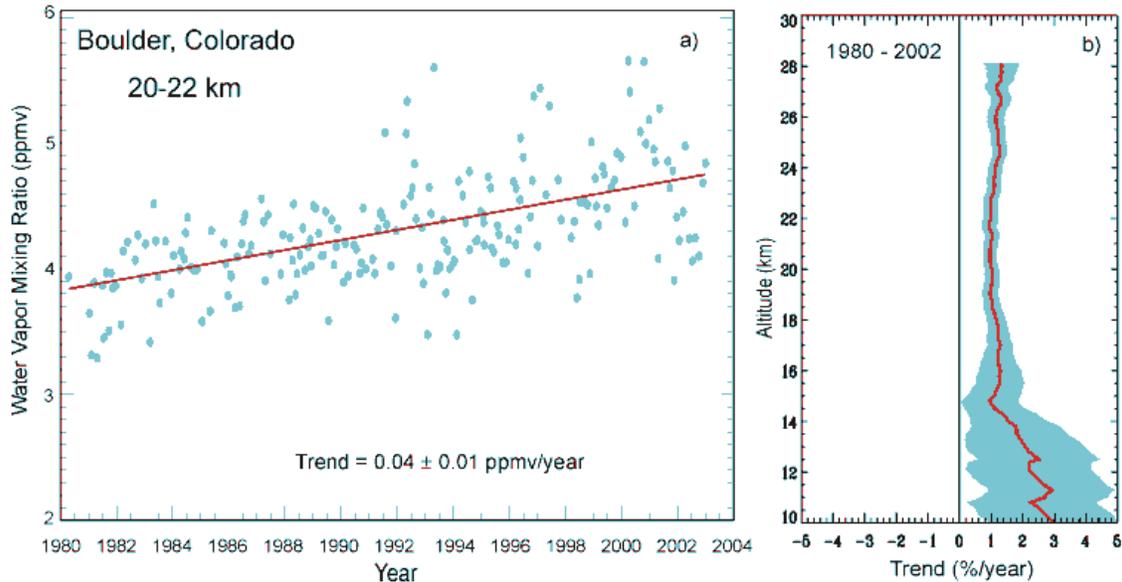
The US Environmental Protection Agency (EPA) ranks the major greenhouse gas contributing end-user sectors in the following order: industrial, transportation, residential, commercial and agricultural. Major sources of an individual's greenhouse gas include home heating and cooling, electricity consumption, and transportation. Corresponding conservation measures are improving home building insulation, installing geothermal heat pumps and compact fluorescent lamps, and choosing energy-efficient vehicles.

Carbon dioxide, methane, nitrous oxide and three groups of fluorinated gases (sulfur hexafluoride, HFCs, and PFCs) are the major greenhouse gases and the subject of the Kyoto Protocol, which came into force in 2005.

Although CFCs are greenhouse gases, they are regulated by the Montreal Protocol, which was motivated by CFCs' contribution to ozone depletion rather than by their contribution to global warming. Note that ozone depletion has only a minor role in greenhouse warming though the two processes often are confused in the media.

On December 7, 2009, the US Environmental Protection Agency released its final findings on greenhouse gases, declaring that "greenhouse gases (GHGs) threaten the public health and welfare of the American people". The finding applied to the same "six key well-mixed greenhouse gases" named in the Kyoto Protocol: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

Role of water vapor



Increasing water vapor in the stratosphere at Boulder, Colorado

Water vapor accounts for the largest percentage of the greenhouse effect, between 36% and 66% for clear sky conditions and between 66% and 85% when including clouds. Water vapor concentrations fluctuate regionally, but human activity does not significantly affect water vapor concentrations except at local scales, such as near irrigated fields. The atmospheric concentration of vapor is highly variable, from less than 0.01% in extremely cold regions up to 20% in warm, humid regions.

The average residence time of a water molecule in the atmosphere is only about nine days, compared to years or centuries for other greenhouse gases such as CH_4 and CO_2 . Thus, water vapor responds to and amplifies effects of the other greenhouse gases. The Clausius-Clapeyron relation establishes that air can hold more water vapor per unit volume when it warms. This and other basic principles indicate that warming associated with increased concentrations of the other greenhouse gases also will increase the concentration of water vapor. Because water vapor is a greenhouse gas this results in further warming, a "positive feedback" that amplifies the original warming. Eventually other earth processes offset these positive feedbacks, stabilizing the global temperature at a new equilibrium and preventing the loss of earth's water through a Venus-like runaway greenhouse effect.

Atmospheric concentration

Atmospheric concentrations of greenhouse gases, and their increases, are determined by the balance between sources (emissions of the gas from human activities and natural systems) and sinks (the removal of the gas from the atmosphere by conversion to a different chemical compound. The proportion of an emission (e.g. CO_2) remaining in the

atmosphere after a specified time is the "Airborne fraction". More precisely, the annual AF is the ratio of the atmospheric CO₂ increase in a given year to that year's total emissions, and calculate that of the average 9.1 PgC y⁻¹ of total anthropogenic emissions from 2000 to 2006, the AF was 0.45. For CO₂ the AF over the last 50 years (1956–2006) has been increasing at 0.25 ± 0.21%/year.

Measurements from Antarctic ice cores show that before industrial emissions started atmospheric CO₂ mole fractions were about 280 parts per million (ppm), and stayed between 260 and 280 during the preceding ten thousand years. Carbon dioxide mole fractions in the atmosphere have gone up by approximately 35 percent since the 1900s, rising from 280 parts per million by volume to 387 parts per million in 2009. One study using evidence from stomata of fossilized leaves suggests greater variability, with carbon dioxide mole fractions above 300 ppm during the period seven to ten thousand years ago, though others have argued that these findings more likely reflect calibration or contamination problems rather than actual CO₂ variability. Because of the way air is trapped in ice (pores in the ice close off slowly to form bubbles deep within the firm) and the time period represented in each ice sample analyzed, these figures represent averages of atmospheric concentrations of up to a few centuries rather than annual or decadal levels.

Since the beginning of the Industrial Revolution, the concentrations of most of the greenhouse gases have increased. For example, the mole fraction of carbon dioxide has increased from 280ppm by about 36% to 380 ppm, or 100 ppm over modern pre-industrial levels. The first 50 ppm increase took place in about 200 years, from the start of the Industrial Revolution to around 1973; however the next 50 ppm increase took place in about 33 years, from 1973 to 2006.

Recent data also shows that the concentration is increasing at a higher rate. In the 1960s, the average annual increase was only 37% of what it was in 2000 through 2007.

The other greenhouse gases produced from human activity show similar increases in both amount and rate of increase. Many observations are available online in a variety of Atmospheric Chemistry Observational Databases.

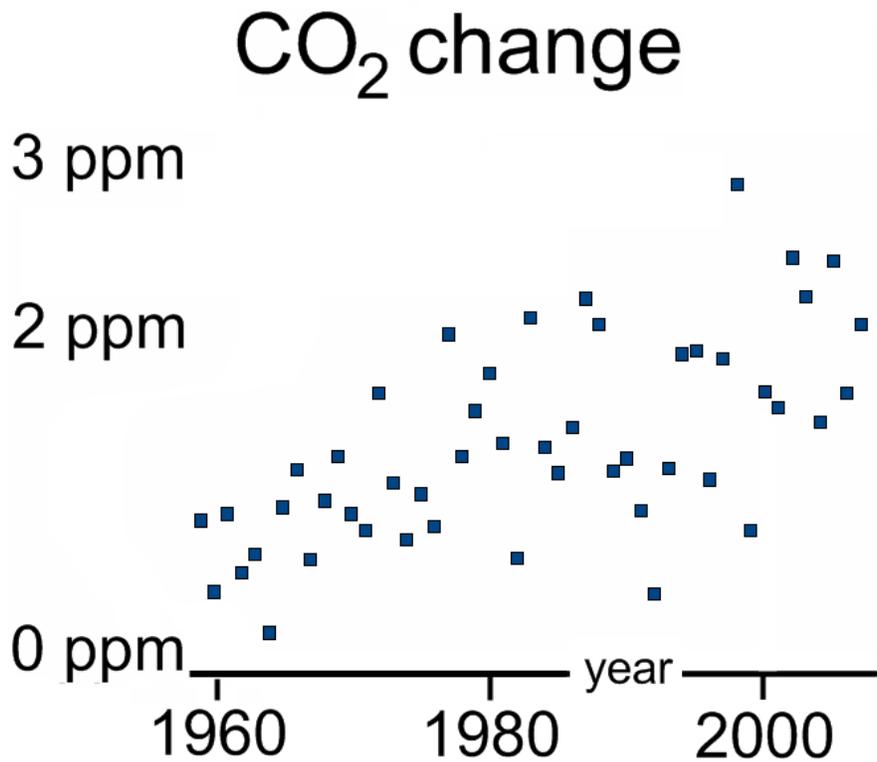
Gas	Relevant to radiative forcing			Radiative forcing (W/m ²)
	Current (1998) Amount by volume	Increase (absolute, ppm) over pre-industrial (1750)	Increase (relative, %) over pre-industrial (1750)	
Carbon dioxide	365 ppm (383 ppm, 2007.01)	87 ppm (105 ppm, 2007.01)	31 % (38 %, 2007.01)	1.46 (~1.53, 2007.01)
Methane	1745 ppb	1045 ppb	150 %	0.48
Nitrous	314 ppb	44 ppb	16 %	0.15

oxide

Relevant to both radiative forcing and ozone depletion; all of the following have no natural sources and hence zero amounts pre-industrial

Gas	Current (1998) Amount by volume	Radiative forcing (W/m²)
CFC-11	268 ppt	0.07
CFC-12	533 ppt	0.17
CFC-113	84 ppt	0.03
Carbon tetrachloride	102 ppt	0.01
HCFC-22	69 ppt	0.03

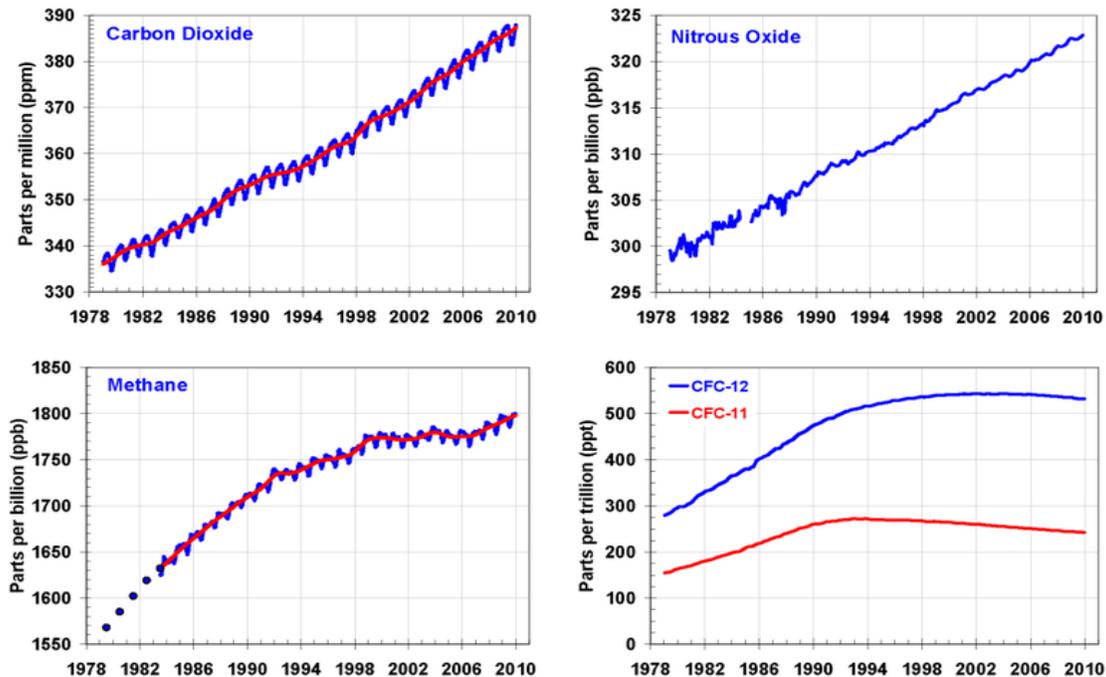
Greenhouse gas emissions ("sources")



Recent year-to-year increase of atmospheric CO₂

At present, the two primary sources of CO₂ emissions are from burning coal used for electricity generation and petroleum used for motor transport.

Regional and national attribution of emissions



Major greenhouse gas trends

There are several different ways of measuring GHG emissions

Some variables that have been reported include:

- Definition of measurement boundaries. Emissions can be attributed geographically, to the area where they were emitted (the territory principle) or by the activity principle to the territory that caused the emissions to be produced. These two principles would result in different totals when measuring for example the importation of electricity from one country to another or the emissions at an international airport.
- The time horizon of different GHGs. Contribution of a given GHG is reported as a CO₂ equivalent; the calculation to determine this takes into account how long that gas remains in the atmosphere. This is not always known accurately and calculations must be regularly updated to take into account new information.
- What sectors are included in the calculation (e.g. energy industries, industrial processes, agriculture etc.). There is often a conflict between transparency and availability of data.
- The measurement protocol itself. This may be via direct measurement or estimation; the four main methods are the emission factor-based method, the mass balance method, the predictive emissions monitoring system and the continuing emissions monitoring systems. The methods differ in accuracy, but also in cost and usability.

The different measures are sometimes used by different countries in asserting various policy/ethical positions to do with climate change (Banuri *et al.*, 1996, p. 94). This use of different measures leads to a lack of comparability, which is problematic when monitoring progress towards targets. There are arguments for the adoption of a common measurement tool, or at least the development of communication between different tools.

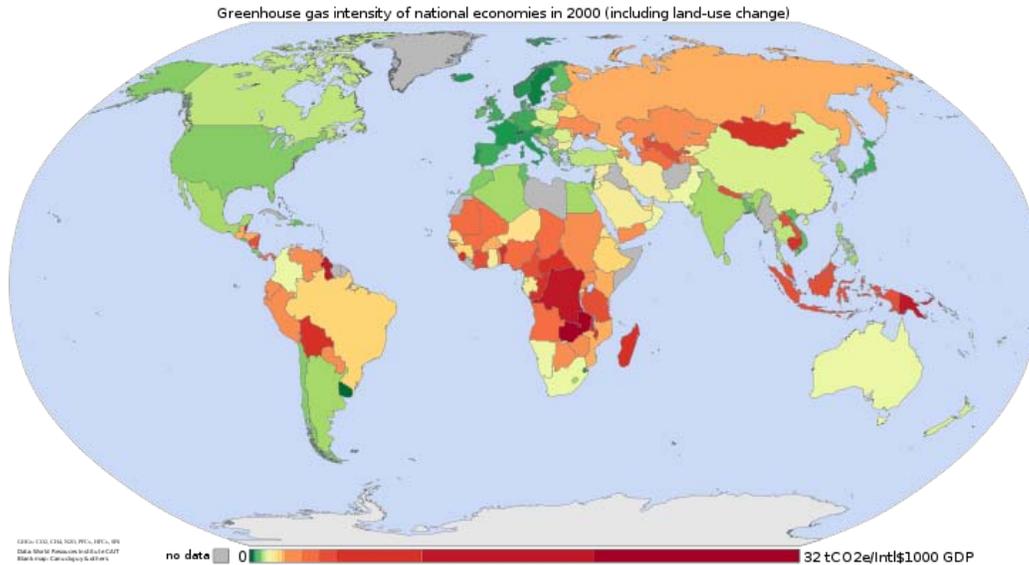
Emissions may be measured over long time periods. This measurement type is called historical or cumulative emissions. Cumulative emissions give some indication of who is responsible for the build-up in the atmospheric concentration of GHGs (IEA, 2007, p. 199).

The national accounts balance would be positively related to carbon emissions. The national accounts balance shows the difference between exports and imports. For many richer nations, such as the United States, the accounts balance is negative because more goods are imported than they are exported. This is mostly due to the fact that it is cheaper to produce goods outside of developed countries, leading the economies of developed countries to become increasingly dependent on services and not goods. We believed that a positive accounts balance would mean that more production was occurring in a country, so more factories working would increase carbon emission levels.

Emissions may also be measured across shorter time periods. Emissions changes may, for example, be measured against a base year of 1990. 1990 was used in the United Nations Framework Convention on Climate Change (UNFCCC) as the base year for emissions, and is also used in the Kyoto Protocol (some gases are also measured from the year 1995) (Grubb, 2003, pp. 146, 149). A country's emissions may also be reported as a proportion of global emissions for a particular year.

Another measurement is of per capita emissions. This divides a country's total annual emissions by its mid-year population (World Bank, 2010, p. 370). Per capita emissions may be based on historical or annual emissions.

Greenhouse gas intensity and land-use change



Greenhouse gas intensity in 2000 including land-use change

The figure opposite is based on data from the World Resources Institute, and shows a measurement of GHG emissions for the year 2000 according to greenhouse gas intensity and land-use change. Herzog *et al.* (2006, p. 3) defined greenhouse gas intensity as GHG emissions divided by economic output. GHG intensities are subject to uncertainty over whether they are calculated using market exchange rates (MER) or purchasing power parity (PPP) (Banuri *et al.*, 1996, p. 96). Calculations based on MER suggest large differences in intensities between developed and developing countries, whereas calculations based on PPP show smaller differences.

Land-use change, e.g., the clearing of forests for agricultural use, can affect the concentration of GHGs in the atmosphere by altering how much carbon flows out of the atmosphere into carbon sinks. Accounting for land-use change can be understood as an attempt to measure “net” emissions, i.e., gross emissions from all GHG sources minus the removal of emissions from the atmosphere by carbon sinks (Banuri *et al.*, 1996, pp. 92–93).

There are substantial uncertainties in the measurement of net carbon emissions. Additionally, there is controversy over how carbon sinks should be allocated between different regions and over time (Banuri *et al.*, 1996, p. 93). For instance, concentrating on more recent changes in carbon sinks is likely to favour those regions that have deforested earlier, e.g., Europe.

Cumulative and historical emissions

Top-5 historic CO₂ contributors by region over the years 1800 to 1988 (in %)

Region	Industrial CO ₂	Total CO ₂
OECD North America	33.2	29.7
OECD Europe	26.1	16.6
Former USSR	14.1	12.5
China	5.5	6.0
Eastern Europe	5.5	4.8

The table above is based on Banuri *et al.* (1996, p. 94). Overall, developed countries accounted for 83.8% of industrial CO₂ emissions over this time period, and 67.8% of total CO₂ emissions. Developing countries accounted for industrial CO₂ emissions of 16.2% over this time period, and 32.2% of total CO₂ emissions. The estimate of total CO₂ emissions includes biotic carbon emissions, mainly from deforestation. Banuri *et al.* (1996, p. 94) calculated per capita cumulative emissions based on then-current population. The ratio in per capita emissions between industrialized countries and developing countries was estimated to be more than 10 to 1.

Including biotic emissions brings about the same controversy mentioned earlier regarding carbon sinks and land-use change (Banuri *et al.*, 1996, pp. 93–94). The actual calculation of net emissions is very complex, and is affected by how carbon sinks are allocated between regions (an equity consideration), and the dynamics of the climate system.

The International Energy Agency (IEA, 2007, p. 201) compared cumulative energy-related CO₂ emissions for several countries and regions. Over the time period 1900-2005, the US accounted for 30% of total cumulative emissions; the EU, 23%; China, 8%; Japan, 4%; and India, 2%. The rest of the world accounted for 33% of global, cumulative, energy-related CO₂ emissions.

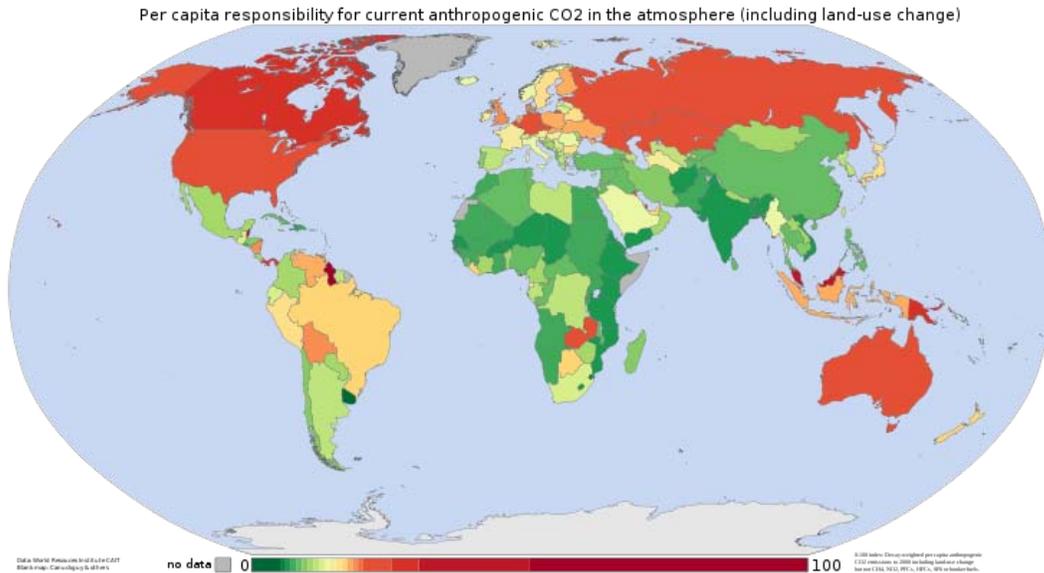
Changes since a particular base year

In total, Annex I Parties managed a cut of 3.3% in GHG emissions between 1990 and 2004 (UNFCCC, 2007, p. 11). Annex I Parties are those countries listed in Annex I of the UNFCCC, and are the industrialized countries. For non-Annex I Parties, emissions in several large developing countries and fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) GHG emissions have increased rapidly over this period (PBL, 2009).

The sharp acceleration in CO₂ emissions since 2000 to more than a 3% increase per year (more than 2 ppm per year) from 1.1% per year during the 1990s is attributable to the lapse of formerly declining trends in carbon intensity of both developing and developed nations. China was responsible for most of global growth in emissions during this period. Localised plummeting emissions associated with the collapse of the Soviet Union have

been followed by slow emissions growth in this region due to more efficient energy use, made necessary by the increasing proportion of it that is exported. In comparison, methane has not increased appreciably, and N₂O by 0.25% y⁻¹.

Annual and per capita emissions



Per capita responsibility for current anthropogenic atmospheric CO₂

At the present time, total annual emissions of GHGs are rising (Rogner *et al.*, 2007). Between the period 1970 to 2004, emissions increased at an average rate of 1.6% per year, with CO₂ emissions from the use of fossil fuels growing at a rate of 1.9% per year.

Today, the stock of carbon in the atmosphere increases by more than 3 million tonnes per annum (0.04%) compared with the existing stock. This increase is the result of human activities by burning fossil fuels, deforestation and forest degradation in tropical and boreal regions.

Per capita emissions in the industrialized countries are typically as much as ten times the average in developing countries (Grubb, 2003, p. 144). Due to China's fast economic development, its per capita emissions are quickly approaching the levels of those in the Annex I group of the Kyoto Protocol (PBL, 2009). Other countries with fast growing emissions are South Korea, Iran, and Australia. On the other hand, per capita emissions of the EU-15 and the USA are gradually decreasing over time. Emissions in Russia and the Ukraine have decreased fastest since 1990 due to economic restructuring in these countries.

Energy statistics for fast growing economies are less accurate than those for the industrialized countries. For China's annual emissions in 2008, PBL (2008) estimated an uncertainty range of about 10%.

Top emitters

In 2005, the world's top-20 emitters comprised 80% of total GHG emissions. Tabulated below are the top-5 emitters for the year 2005 (MNP, 2007). The second column is the country's or region's share of the global total of annual emissions. The third column is the country's or region's average annual per capita emissions, in tonnes of GHG per head of population:

Top-5 emitters for the year 2005

Country or region	% of global total annual emissions	Tonnes of GHG per capita
China ^b	17 %	5.8
United States ^a	16 %	24.1
European Union-27 ^a	11 %	10.6
Indonesia ^c	6 %	12.9
India	5 %	2.1

Table footnotes:

- These values are for the GHG emissions from fossil fuel use and cement production. Calculations are for carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and gases containing fluorine (the F-gases HFCs, PFCs and SF₆).
- These estimates are subject to large uncertainties regarding CO₂ emissions from deforestation; and the per country emissions of other GHGs (e.g., methane). There are also other large uncertainties which mean that small differences between countries are not significant. CO₂ emissions from the decay of remaining biomass after biomass burning/deforestation are not included.
- ^a Industrialised countries: official country data reported to UNFCCC.
- ^b Excluding underground fires.
- ^c Including an estimate of 2000 million tonnes CO₂ from peat fires and decomposition of peat soils after draining. However, the uncertainty range is very large.

Embedded emissions

One way of attributing greenhouse gas (GHG) emissions is to measure the embedded emissions (also referred to as "embodied emissions") of goods that are being consumed. Emissions are usually measured according to production, rather than consumption (Helm *et al.*, 2007, p. 3). Under a production-based accounting of emissions, embedded emissions on imported goods are attributed to the exporting, rather than the importing, country. Under a consumption-based accounting of emissions, embedded emissions on imported goods are attributed to the importing country, rather than the exporting, country.

Davis and Caldeira (2010, p. 4) found that a substantial proportion of CO₂ emissions are traded internationally. The net effect of trade was to export emissions from China and other emerging markets to consumers in the US, Japan, and Western Europe. Based on annual emissions data from the year 2004, and on a per-capita consumption basis, the top-5 emitting countries were found to be (in tCO₂ per person, per year): Luxembourg (34.7), the US (22.0), Singapore (20.2), Australia (16.7), and Canada (16.6).

Effect of policy

Rogner *et al.* (2007) assessed the effectiveness of policies to reduce emissions (mitigation of climate change). They concluded that mitigation policies undertaken by UNFCCC Parties were inadequate to reverse the trend of increasing GHG emissions. The impacts of population growth, economic development, technological investment, and consumption had overwhelmed improvements in energy intensities and efforts to decarbonize (energy intensity is a country's total primary energy supply (TPES) per unit of GDP (Rogner *et al.*, 2007). TPES is a measure of commercial energy consumption.

Projections

Based on then-current energy policies, Rogner *et al.* (2007) projected that energy-related CO₂ emissions in 2030 would be 40-110% higher than in 2000. Two-thirds of this increase was projected to come from non-Annex I countries. Per capita emissions in Annex I countries were still projected to remain substantially higher than per capita emissions in non-Annex I countries. Projections consistently showed a 25-90% increase in the Kyoto gases (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) compared to 2000.

IEA (2007, p. 199) estimated future cumulative energy-related CO₂ emissions for several countries. Their reference scenario projected cumulative energy-related CO₂ emissions between the years 1900 and 2030. In this scenario, China's share of cumulative emissions rises to 16%, approaching that of the United States (25%) and the European Union (18%). India's cumulative emissions (4%) approach those of Japan (4%).

Relative CO₂ emission from various fuels

One liter of gasoline, when used as a fuel, produces 2.32 kg (1.3 cubic meters) of carbon dioxide, a greenhouse gas. One US gallon produces 19.4 lb (172.65 cubic feet)

Mass of carbon dioxide emitted per quantity of energy for various fuels

Fuel name	CO ₂ emitted (lbs/10 ⁶ Btu)	CO ₂ emitted (g/10 ⁶ J)
Natural gas	117	50.30
Liquefied petroleum gas	139	59.76
Propane	139	59.76
Aviation gasoline	153	65.78
Automobile gasoline	156	67.07
Kerosene	159	68.36
Fuel oil	161	69.22
Tires/tire derived fuel	189	81.26

Wood and wood waste	195	83.83
Coal (bituminous)	205	88.13
Coal (subbituminous)	213	91.57
Coal (lignite)	215	92.43
Petroleum coke	225	96.73
Coal (anthracite)	227	97.59

Removal from the atmosphere ("sinks")

Natural processes

Greenhouse gases can be removed from the atmosphere by various processes, as a consequence of:

- a physical change (condensation and precipitation remove water vapor from the atmosphere).
- a chemical reactions within the atmosphere. For example, methane is oxidized by reaction with naturally occurring hydroxyl radical, OH \cdot and degraded to CO $_2$ and water vapor (CO $_2$ from the oxidation of methane is not included in the methane Global warming potential). Other chemical reactions include solution and solid phase chemistry occurring in atmospheric aerosols.
- a physical exchange between the atmosphere and the other compartments of the planet. An example is the mixing of atmospheric gases into the oceans.
- a chemical change at the interface between the atmosphere and the other compartments of the planet. This is the case for CO $_2$, which is reduced by photosynthesis of plants, and which, after dissolving in the oceans, reacts to form carbonic acid and bicarbonate and carbonate ions.
- a photochemical change. Halocarbons are dissociated by UV light releasing Cl \cdot and F \cdot as free radicals in the stratosphere with harmful effects on ozone (halocarbons are generally too stable to disappear by chemical reaction in the atmosphere).

Negative emissions

There are a number of technologies that remove emissions of greenhouse gases from the atmosphere. Most widely analysed are those which remove carbon dioxide from the atmosphere, either to geologic formations such as bio-energy with carbon capture and storage and carbon dioxide air capture, or to the soil as in the case with biochar. It has been pointed out by the IPCC, that many long-term climate scenario models require large scale manmade negative emissions in order to avoid serious climate change.

Impact of a given gas on climate sensitivity

Atmospheric lifetime

Aside from water vapor, which has a residence time of about nine days, major greenhouse gases are well-mixed, and take many years to leave the atmosphere. Although it is not easy to know with precision how long it takes greenhouse gases to leave the atmosphere, there are estimates for the principal greenhouse gases. Jacob (1999) defines the lifetime τ of an atmospheric species X in a one-box model as the average time that a molecule of X remains in the box. Mathematically τ can be defined as the ratio of the mass m (in kg) of X in the box to its removal rate, which is the sum of the flow of X out of the box (F_{out}), chemical loss of X (L), and deposition of X (D) (all in kg/sec):

$$\tau = \frac{m}{F_{out} + L + D}$$

The atmospheric lifetime of a species therefore measures the time required to restore equilibrium following an increase in its concentration in the atmosphere. Individual atoms or molecules may be lost or deposited to sinks such as the soil, the oceans and other waters, or vegetation and other biological systems, reducing the excess to background concentrations. The average time taken to achieve this is the mean lifetime. The atmospheric lifetime of CO₂ is often incorrectly stated to be only a few years because that is the average time for any CO₂ molecule to stay in the atmosphere before being removed by mixing into the ocean, photosynthesis, or other processes. However, this ignores the balancing fluxes of CO₂ into the atmosphere from the other reservoirs. It is the net concentration changes of the various greenhouse gases by *all sources and sinks* that determines atmospheric lifetime, not just the removal processes.

Global warming potential

The global warming potential (GWP) depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime. GWP is measured relative to the same **mass** of CO₂ and evaluated for a specific timescale. Thus, if a gas has a high radiative forcing but also a short lifetime, it will have a large GWP on a 20 year scale but a small one on a 100 year scale. Conversely, if a molecule has a longer atmospheric lifetime than CO₂ its GWP will increase with the timescale considered.

Carbon dioxide has a variable atmospheric lifetime, and cannot be specified precisely. Recent work indicates that recovery from a large input of atmospheric CO₂ from burning fossil fuels will result in an effective lifetime of tens of thousands of years. Carbon dioxide is defined to have a GWP of 1 over all time periods.

Methane has an atmospheric lifetime of 12 ± 3 years and a GWP of 72 over 20 years, 25 over 100 years and 7.6 over 500 years. The decrease in GWP at longer times is because methane is degraded to water and CO₂ through chemical reactions in the atmosphere.

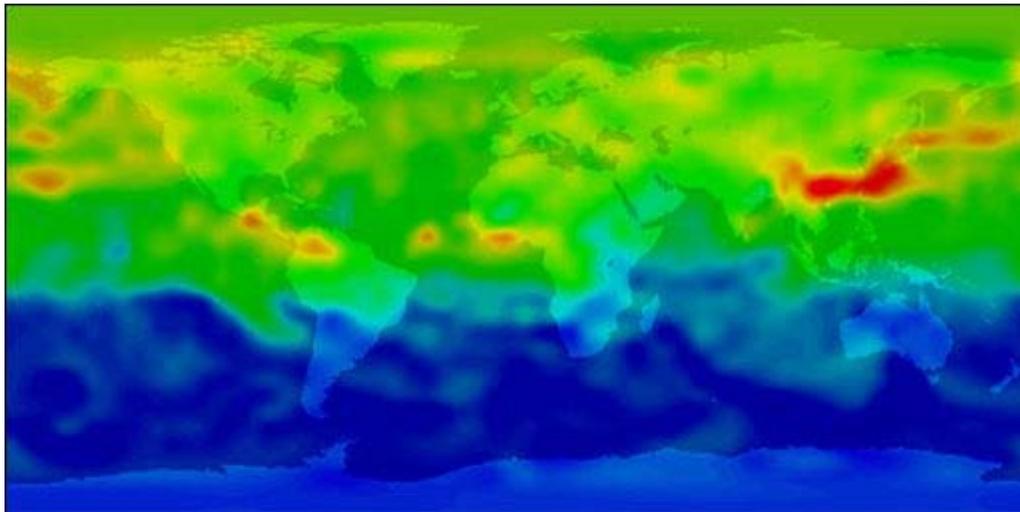
Examples of the atmospheric lifetime and GWP relative to CO₂ for several greenhouse gases are given in the following table:

Atmospheric lifetime and GWP relative to CO₂ at different time horizon for various greenhouse gases.

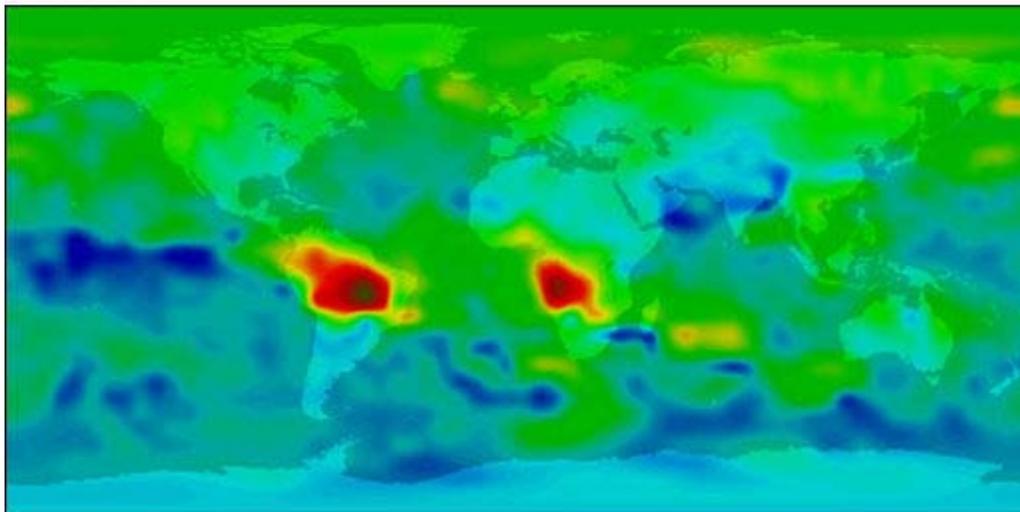
Gas name	Chemical formula	Lifetime (years)	Global warming potential (GWP) for given time horizon		
			20-yr	100-yr	500-yr
Carbon dioxide	CO ₂	See above	1	1	1
Methane	CH ₄	12	72	25	7.6
Nitrous oxide	N ₂ O	114	289	298	153
CFC-12	CCl ₂ F ₂	100	11 000	10 900	5 200
HCFC-22	CHClF ₂	12	5 160	1 810	549
Tetrafluoromethane	CF ₄	50 000	5 210	7 390	11 200
Hexafluoroethane	C ₂ F ₆	10 000	8 630	12 200	18 200
Sulphur hexafluoride	SF ₆	3 200	16 300	22 800	32 600
Nitrogen trifluoride	NF ₃	740	12 300	17 200	20 700

The use of CFC-12 (except some essential uses) has been phased out due to its ozone depleting properties. The phasing-out of less active HCFC-compounds will be completed in 2030.

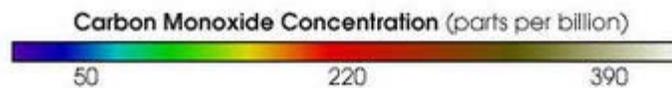
Related effects



April 30, 2000



October 30, 2000



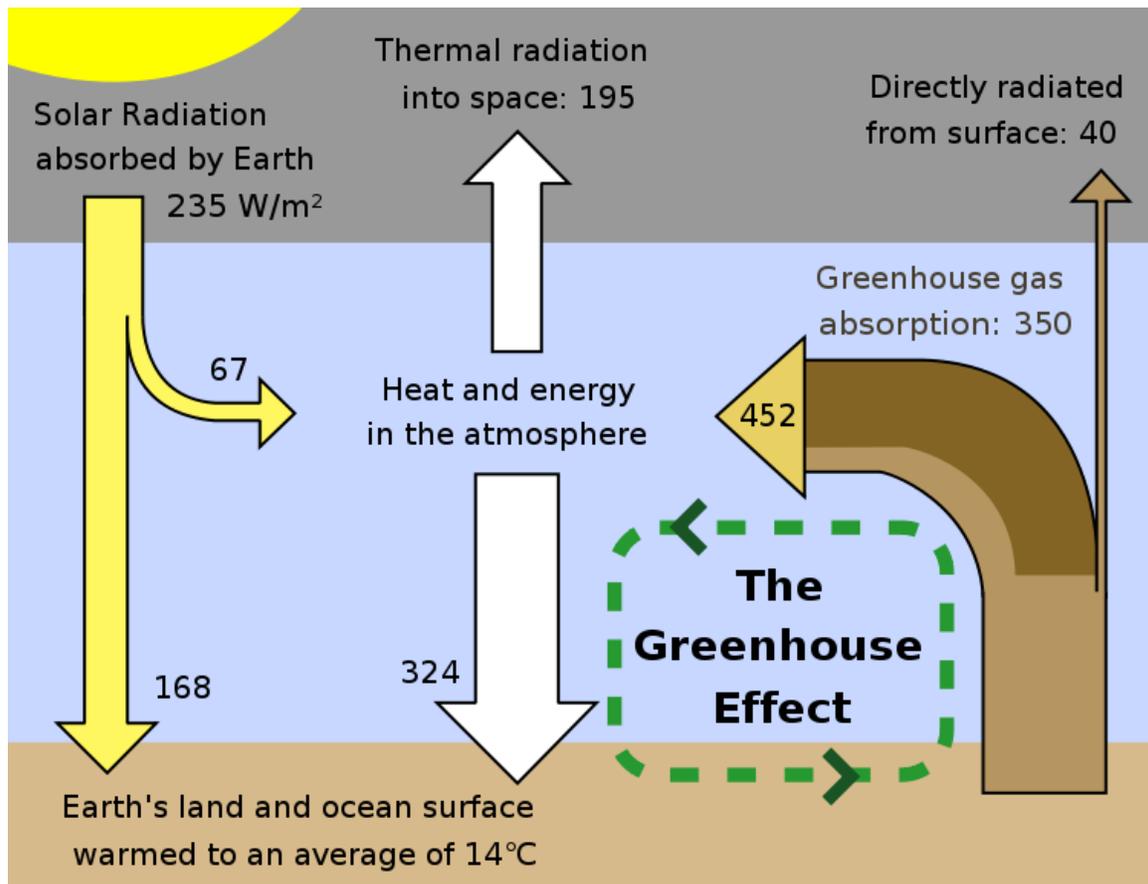
MOPITT 2000 global carbon monoxide

Carbon monoxide has an indirect radiative effect by elevating concentrations of methane and tropospheric ozone through scavenging of atmospheric constituents (e.g., the hydroxyl radical, **OH**) that would otherwise destroy them. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to carbon dioxide. Carbon monoxide has an atmospheric lifetime of only a few months and as a consequence is spatially more variable than longer-lived gases.

Another potentially important indirect effect comes from methane, which in addition to its direct radiative impact also contributes to ozone formation. Shindell *et al.* (2005) argue that the contribution to climate change from methane is at least double previous estimates as a result of this effect.

Chapter- 4

Greenhouse Effect



A representation of the exchanges of energy between the source (the Sun), the Earth's surface, the Earth's atmosphere, and the ultimate sink outer space. The ability of the atmosphere to capture and recycle energy emitted by the Earth surface is the defining characteristic of the greenhouse effect.

The **greenhouse effect** is a process by which thermal radiation from a planetary surface is absorbed by atmospheric greenhouse gases, and is re-radiated in all directions. Since part of this re-radiation is back towards the surface, energy is transferred to the surface and the lower atmosphere. As a result, the temperature there is higher than it would be if direct heating by solar radiation were the only warming mechanism.

Solar radiation at the high frequencies of visible light passes through the atmosphere to warm the planetary surface, which then emits this energy at the lower frequencies of infrared thermal radiation. Infrared radiation is absorbed by greenhouse gases, which in turn re-radiate much of the energy to the surface and lower atmosphere. The mechanism is named after the effect of solar radiation passing through glass and warming a greenhouse, but the way it retains heat is fundamentally different as a greenhouse works by reducing airflow, isolating the warm air inside the structure so that heat is not lost by convection.

The greenhouse effect was discovered by Joseph Fourier in 1824, first reliably experimented on by John Tyndall in 1858, and first reported quantitatively by Svante Arrhenius in 1896.

If an ideal thermally conductive blackbody was the same distance from the Sun as the Earth is, it would have a temperature of about 5.3 °C. However, since the Earth reflects about 30% (or 28%) of the incoming sunlight, the planet's effective temperature (the temperature of a blackbody that would emit the same amount of radiation) is about -18 or -19 °C, about 33°C below the actual surface temperature of about 14 °C or 15 °C. The mechanism that produces this difference between the actual surface temperature and the effective temperature is due to the atmosphere and is known as the greenhouse effect.

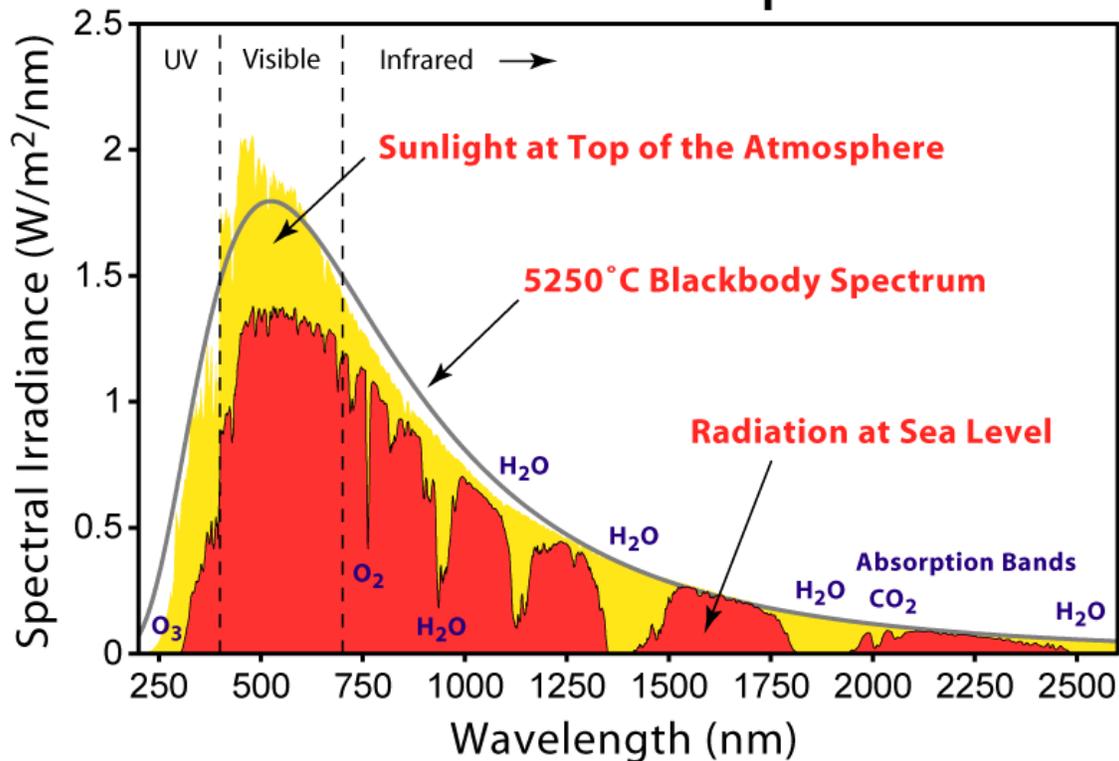
Global warming, a recent warming of the Earth's surface and lower atmosphere, is believed to be the result of a strengthening of the greenhouse effect mostly due to human-produced increases in atmospheric greenhouse gases.

Basic mechanism

The Earth receives energy from the Sun in the form UV, visible, and near IR radiation, most of which passes through the atmosphere without being absorbed. Of the total amount of energy available at the top of the atmosphere (TOA), about 50% is absorbed at the Earth's surface. Because it is warm, the surface radiates far IR thermal radiation that consists of wavelengths that are predominantly much longer than the wavelengths that were absorbed. Most of this thermal radiation is absorbed by the atmosphere and re-radiated both upwards and downwards; that radiated downwards is absorbed by the Earth's surface. This trapping of long-wavelength thermal radiation leads to a higher equilibrium temperature than if the atmosphere were absent.

This highly simplified picture of the basic mechanism needs to be qualified in a number of ways, none of which affect the fundamental process.

Solar Radiation Spectrum



The solar radiation spectrum for direct light at both the top of the Earth's atmosphere and at sea level

- The incoming radiation from the Sun is mostly in the form of visible light and nearby wavelengths, largely in the range 0.2–4 μm , corresponding to the Sun's radiative temperature of 6,000 K. Almost half the radiation is in the form of "visible" light, which our eyes are adapted to use.
- About 50% of the Sun's energy is absorbed at the Earth's surface and the rest is reflected or absorbed by the atmosphere. The reflection of light back into space—largely by clouds—does not much affect the basic mechanism; this light, effectively, is lost to the system.
- The absorbed energy warms the surface. Simple presentations of the greenhouse effect, such as the idealized greenhouse model, show this heat being lost as thermal radiation. The reality is more complex: the atmosphere near the surface is largely opaque to thermal radiation (with important exceptions for "window" bands), and most heat loss from the surface is by sensible heat and latent heat transport. Radiative energy losses become increasingly important higher in the atmosphere largely because of the decreasing concentration of water vapor, an important greenhouse gas. It is more realistic to think of the greenhouse effect as applying to a "surface" in the mid-troposphere, which is effectively coupled to the surface by a lapse rate.

- Within the region where radiative effects are important the description given by the idealized greenhouse model becomes realistic: The surface of the Earth, warmed to a temperature around 255 K, radiates long-wavelength, infrared heat in the range 4–100 μm . At these wavelengths, greenhouse gases that were largely transparent to incoming solar radiation are more absorbent. Each layer of atmosphere with greenhouse gases absorbs some of the heat being radiated upwards from lower layers. To maintain its own equilibrium, it re-radiates the absorbed heat in all directions, both upwards and downwards. This results in more warmth below, while still radiating enough heat back out into deep space from the upper layers to maintain overall thermal equilibrium. Increasing the concentration of the gases increases the amount of absorption and re-radiation, and thereby further warms the layers and ultimately the surface below.
- Greenhouse gases—including most diatomic gases with two different atoms (such as carbon monoxide, CO) and all gases with three or more atoms—are able to absorb and emit infrared radiation. Though more than 99% of the dry atmosphere is IR transparent (because the main constituents— N_2 , O_2 , and Ar—are not able to directly absorb or emit infrared radiation), intermolecular collisions cause the energy absorbed and emitted by the greenhouse gases to be shared with the other, non-IR-active, gases.
- The simple picture assumes equilibrium. In the real world there is the diurnal cycle as well as seasonal cycles and weather. Solar heating only applies during daytime. During the night, the atmosphere cools somewhat, but not greatly, because its emissivity is low, and during the day the atmosphere warms. Diurnal temperature changes decrease with height in the atmosphere.

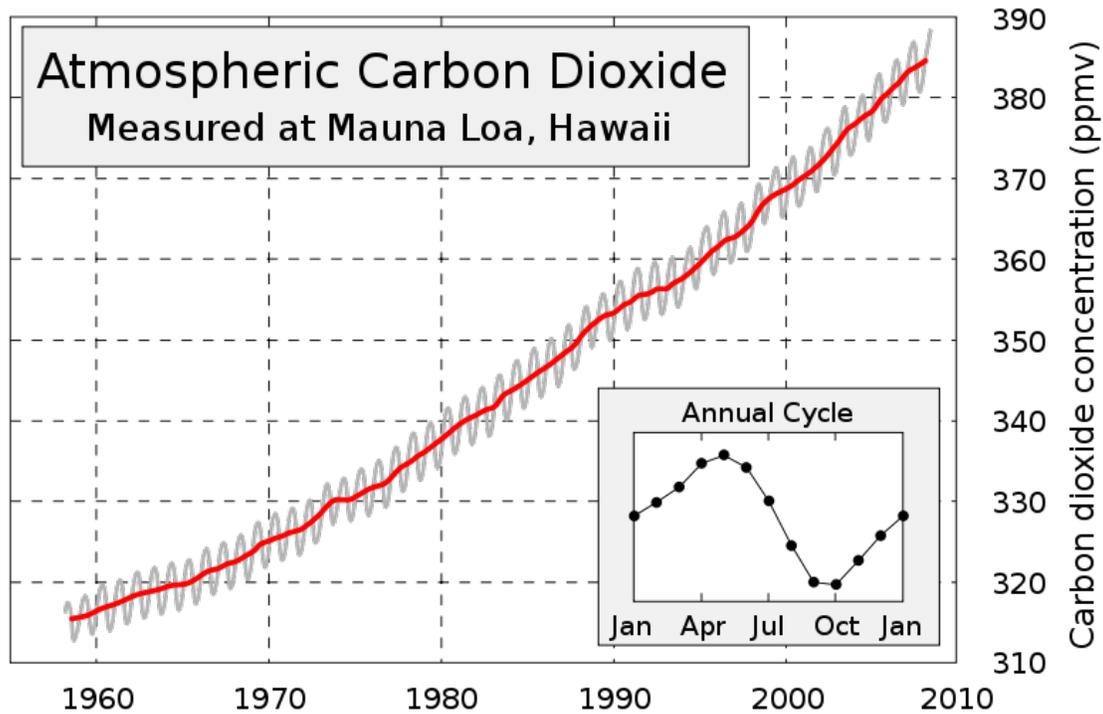
Greenhouse gases

By their percentage contribution to the greenhouse effect on Earth the four major gases are:

- water vapor, 36–70%
- carbon dioxide, 9–26%
- methane, 4–9%
- ozone, 3–7%

The major non-gas contributor to the Earth's greenhouse effect, clouds, also absorb and emit infrared radiation and thus have an effect on radiative properties of the atmosphere.

Role in climate change



The Keeling Curve of atmospheric CO₂ concentrations measured at Mauna Loa Observatory.

Strengthening of the greenhouse effect through human activities is known as the enhanced (or anthropogenic) greenhouse effect. This increase in radiative forcing from human activity is attributable mainly to increased atmospheric carbon dioxide levels.

CO₂ is produced by fossil fuel burning and other activities such as cement production and tropical deforestation. Measurements of CO₂ from the Mauna Loa observatory show that concentrations have increased from about 313 ppm in 1960 to about 389 ppm in 2010. The current observed amount of CO₂ exceeds the geological record maxima (~300 ppm) from ice core data. The effect of combustion-produced carbon dioxide on the global climate, a special case of the greenhouse effect first described in 1896 by Svante Arrhenius, has also been called the Callendar effect.

Because it is a greenhouse gas, elevated CO₂ levels contribute to additional absorption and emission of thermal infrared in the atmosphere, which produce net warming. According to the latest Assessment Report from the Intergovernmental Panel on Climate Change, "*most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*".

Over the past 800,000 years, ice core data shows unambiguously that carbon dioxide has varied from values as low as 180 parts per million (ppm) to the pre-industrial level of

270ppm. Paleoclimatologists consider variations in carbon dioxide to be a fundamental factor in controlling climate variations over this time scale.

Real greenhouses



A modern Greenhouse in RHS Wisley

The "greenhouse effect" is named by analogy to greenhouses. The greenhouse effect and a real greenhouse are similar in that they both limit the rate of thermal energy flowing out of the system, but the mechanisms by which heat is retained are different. A greenhouse works primarily by preventing absorbed heat from leaving the structure through convection, i.e. sensible heat transport. The greenhouse effect heats the earth because greenhouse gases absorb outgoing radiative energy and re-emit some of it back towards earth.

A greenhouse is built of any material that passes sunlight, usually glass, or plastic. It mainly heats up because the Sun warms the ground inside, which then warms the air in the greenhouse. The air continues to heat because it is confined within the greenhouse, unlike the environment outside the greenhouse where warm air near the surface rises and mixes with cooler air aloft. This can be demonstrated by opening a small window near the roof of a greenhouse: the temperature will drop considerably. It has also been demonstrated experimentally (R. W. Wood, 1909) that a "greenhouse" with a cover of

rock salt (which is transparent to infra red) heats up an enclosure similarly to one with a glass cover. Thus greenhouses work primarily by preventing convective cooling.

In the greenhouse effect, rather than retaining (sensible) heat by physically preventing movement of the air, greenhouse gases act to warm the Earth by re-radiating some of the energy back towards the surface. This process may exist in real greenhouses, but is comparatively unimportant there.

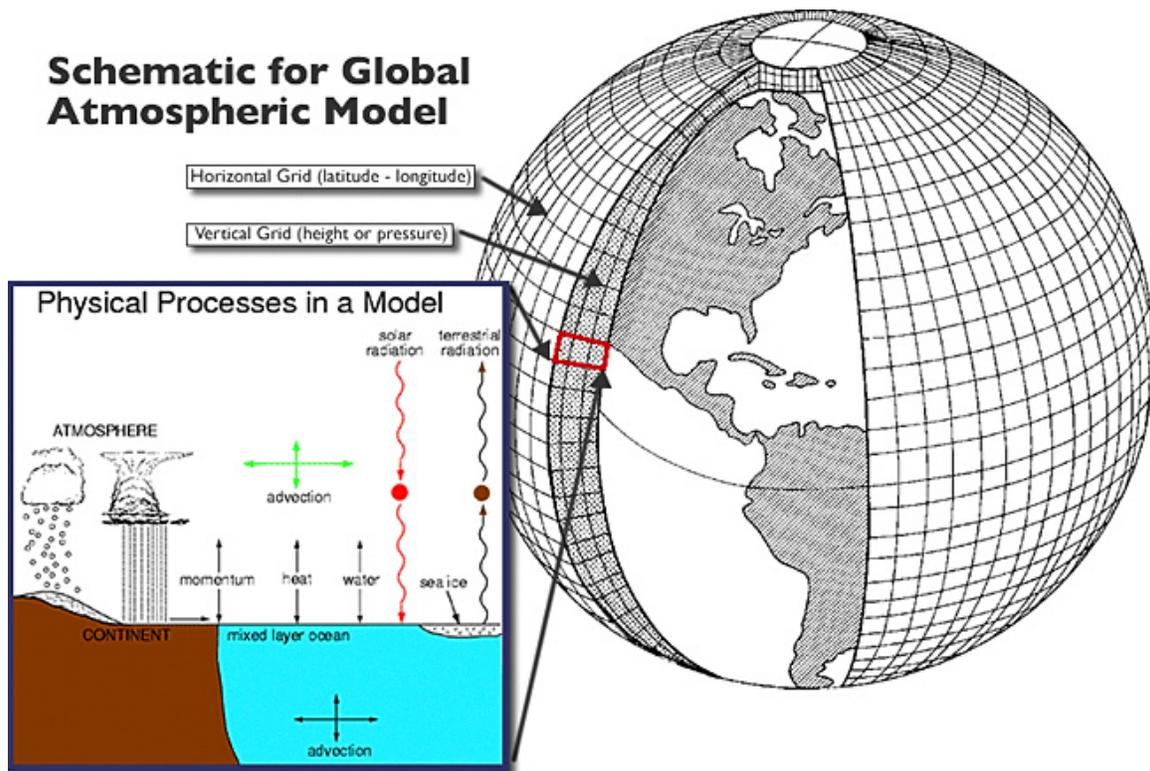
Bodies other than Earth

In our solar system, Mars, Venus, and the moon Titan also exhibit greenhouse effects. Titan has an anti-greenhouse effect, in that its atmosphere absorbs solar radiation but is relatively transparent to infrared radiation. Pluto also exhibits behavior superficially similar to the anti-greenhouse effect.

A runaway greenhouse effect occurs if positive feedbacks lead to the evaporation of all greenhouse gases into the atmosphere. A runaway greenhouse effect involving carbon dioxide and water vapor is thought to have occurred on Venus.

Chapter- 5

Global Climate Model



Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To “run” a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. The winds, heat transfer and other quantities are only used to compute a final result so they do not need to correspond to real world conditions, and in some numerical schemes fictitious quantities are introduced.

A **General Circulation Model (GCM)** is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). These equations are the basis for complex computer programs commonly used for

simulating the atmosphere or ocean of the Earth. Atmospheric and Oceanic GCMs (AGCM and OGCM) are key components of **Global Climate Models** along with sea ice and land-surface components. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change. Versions designed for decade to century time scale climate applications were originally created by Syukuro Manabe and Kirk Bryan at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. These computationally intensive numerical models are based on the integration of a variety of fluid dynamical, chemical, and sometimes biological equations.

History

In 1956, Norman Phillips developed a mathematical model which could realistically depict monthly and seasonal patterns in the troposphere, which became the first successful climate model. Following Phillips's work, several groups began working to create general circulation models. The first general circulation climate model that combined both oceanic and atmospheric processes was developed in the late 1960s at the NOAA Geophysical Fluid Dynamics Laboratory. By the early 1980s, the United States' National Center for Atmospheric Research had developed the Community Atmosphere Model; this model has been continuously refined into the 2000s. In 1986, efforts began to initialize and model soil and vegetation types, which led to more realistic forecasts. Coupled ocean-atmosphere climate models such as the Hadley Centre for Climate Prediction and Research's HadCM3 model are currently being used as inputs for climate change studies. The importance of gravity waves was neglected within these models until the mid 1980s. Now, gravity waves are required within global climate models in order to properly simulate regional and global scale circulations, though their broad spectrum makes their incorporation complicated.

Atmospheric vs Ocean models

There are both atmospheric GCMs (AGCMs) and oceanic GCMs (OGCMs). An AGCM and an OGCM can be coupled together to form an atmosphere-ocean coupled general circulation model (CGCM or AOGCM). With the addition of other components (such as a sea ice model or a model for evapotranspiration over land), the AOGCM becomes the basis for a full climate model. Within this structure, different variations can exist, and their varying response to climate change may be studied (e.g., Sun and Hansen, 2003).

Modeling trends

A recent trend in GCMs is to apply them as components of Earth System Models, e.g. by coupling to ice sheet models for the dynamics of the Greenland and Antarctic ice sheets, and one or more chemical transport models (CTMs) for species important to climate. Thus a carbon CTM may allow a GCM to better predict changes in carbon dioxide concentrations resulting from changes in anthropogenic emissions. In addition, this approach allows accounting for inter-system feedback: e.g. chemistry-climate models

allow the possible effects of climate change on the recovery of the ozone hole to be studied.

Climate prediction uncertainties depend on uncertainties in chemical, physical, and social models. Progress has been made in incorporating more realistic chemistry and physics in the models, but significant uncertainties and unknowns remain, especially regarding the future course of human population, industry, and technology.

Note that many simpler levels of climate model exist; some are of only heuristic interest, while others continue to be scientifically relevant.

Model structure

Three-dimensional (more properly four-dimensional) GCMs discretise the equations for fluid motion and integrate these forward in time. They also contain parameterisations for processes - such as convection - that occur on scales too small to be resolved directly. More sophisticated models may include representations of the carbon and other cycles.

A **simple general circulation model (SGCM)**, a minimal GCM, consists of a dynamical core that relates material properties such as temperature to dynamical properties such as pressure and velocity. Examples are programs that solve the primitive equations, given energy input into the model, and energy dissipation in the form of scale-dependent friction, so that atmospheric waves with the highest wavenumbers are the ones most strongly attenuated. Such models may be used to study atmospheric processes within a simplified framework but are not suitable for future climate projections.

Atmospheric GCMs (AGCMs) model the atmosphere (and typically contain a land-surface model as well) and impose sea surface temperatures (SSTs). A large amount of information including model documentation is available from AMIP. They may include atmospheric chemistry.

- AGCMs consist of a dynamical core which integrates the equations of fluid motion, typically for:
 - surface pressure
 - horizontal components of velocity in layers
 - temperature and water vapor in layers
- There is generally a radiation code, split into solar/short wave and terrestrial/infrared/long wave
- Parametrizations are used to include the effects of various processes. All modern AGCMs include parameterizations for:
 - convection
 - land surface processes, albedo and hydrology
 - cloud cover

A GCM contains a number of prognostic equations that are stepped forward in time (typically winds, temperature, moisture, and surface pressure) together with a number of

diagnostic equations that are evaluated from the simultaneous values of the variables. As an example, pressure at any height can be diagnosed by applying the hydrostatic equation to the predicted surface pressure and the predicted values of temperature between the surface and the height of interest. The pressure diagnosed in this way then is used to compute the pressure gradient force in the time-dependent equation for the winds.

Oceanic GCMs (OGCMs) model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model. For example, the standard resolution of HadOM3 is 1.25 degrees in latitude and longitude, with 20 vertical levels, leading to approximately 1,500,000 variables.

Coupled atmosphere-ocean GCMs (AOGCMs) (e.g. HadCM3, GFDL CM2.X) combine the two models. They thus have the advantage of removing the need to specify fluxes across the interface of the ocean surface. These models are the basis for sophisticated model predictions of future climate, such as are discussed by the IPCC.

AOGCMs represent the pinnacle of complexity in climate models and internalise as many processes as possible. They are the only tools that could provide detailed regional predictions of future climate change. However, they are still under development. The simpler models are generally susceptible to simple analysis and their results are generally easy to understand. AOGCMs, by contrast, are often nearly as hard to analyse as the real climate system.

Model grids

The fluid equations for AGCMs are discretised using either the finite difference method or the spectral method. For finite differences, a grid is imposed on the atmosphere. The simplest grid uses constant angular grid spacing (i.e., a latitude / longitude grid), however, more sophisticated non-rectangular grids (e.g., icosahedral) and grids of variable resolution are more often used. The "LMDz" model can be arranged to give high resolution over any given section of the planet. HadGEM1 (and other ocean models) use an ocean grid with higher resolution in the tropics to help resolve processes believed to be important for ENSO. Spectral models generally use a gaussian grid, because of the mathematics of transformation between spectral and grid-point space. Typical AGCM resolutions are between 1 and 5 degrees in latitude or longitude: the Hadley Centre model HadCM3, for example, uses 3.75 in longitude and 2.5 degrees in latitude, giving a grid of 96 by 73 points (96 x 72 for some variables); and has 19 levels in the vertical. This results in approximately 500,000 "basic" variables, since each grid point has four variables (u, v, T, Q), though a full count would give more (clouds; soil levels). HadGEM1 uses a grid of 1.875 degrees in longitude and 1.25 in latitude in the atmosphere; HiGEM, a high-resolution variant, uses 1.25 x 0.83 degrees respectively. These resolutions are lower than is typically used for weather forecasting. Ocean resolutions tend to be higher, for example HadCM3 has 6 ocean grid points per atmospheric grid point in the horizontal.

For a standard finite difference model, uniform gridlines converge towards the poles. This would lead to computational instabilities and so the model variables must be filtered along lines of latitude close to the poles. Ocean models suffer from this problem too, unless a rotated grid is used in which the North Pole is shifted onto a nearby landmass. Spectral models do not suffer from this problem. There are experiments using geodesic grids and icosahedral grids, which (being more uniform) do not have pole-problems. Another approach to solving the grid spacing problem is to deform a Cartesian cube such that it covers the surface of a sphere.

Flux correction

Some early incarnations of AOGCMs required a somewhat *ad hoc* process of "flux correction" to achieve a stable climate (not all model groups used this technique). This resulted from separately prepared ocean and atmospheric models each having a different implicit flux from the other component than the other component could actually provide. If uncorrected this could lead to a dramatic drift away from observations in the coupled model. However, if the fluxes were 'corrected', the problems in the model that led to these unrealistic fluxes might be unrecognised and that might affect the model sensitivity. As a result, there has always been a strong disincentive to use flux corrections, and the vast majority of models used in the current round of the Intergovernmental Panel on Climate Change do not use them. The model improvements that now make flux corrections unnecessary are various, but include improved ocean physics, improved resolution in both atmosphere and ocean, and more physically consistent coupling between atmosphere and ocean models.

Convection

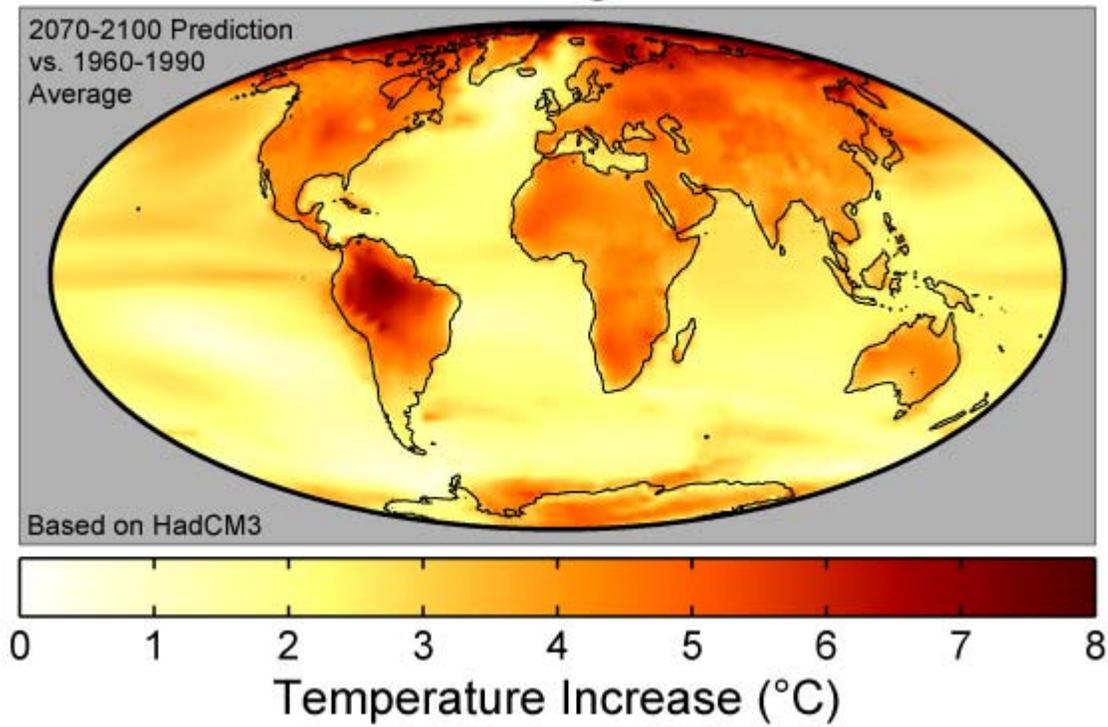
Moist convection causes the release of latent heat and is important to the Earth's energy budget. Convection occurs on too small a scale to be resolved by climate models, and hence must be parameterised. This has been done since the earliest days of climate modelling, in the 1950s. Akio Arakawa did much of the early work and variants of his scheme are still used although there is a variety of different schemes now in use. The behavior of clouds is still poorly understood and is parametrized.

Output variables

Most models include software to diagnose a wide range of variables for comparison with observations or study of atmospheric processes. An example is the 1.5 metre temperature, which is the standard height for near-surface observations of air temperature. This temperature is not directly predicted from the model but is deduced from the surface and lowest-model-layer temperatures. Other software is used for creating plots and animations.

Projections of future climate change

Global Warming Predictions



Shows the distribution of warming during the late 21st century predicted by the HadCM3 climate model (one of those used by the IPCC) if a business-as-usual scenario is assumed for economic growth and greenhouse gas emissions. The average warming predicted by this model is 3.0 °C.

Coupled ocean-atmosphere GCMs use transient climate simulations to project/predict future temperature changes under various scenarios. These can be idealised scenarios (most commonly, CO₂ increasing at 1%/yr) or more realistic (usually the "IS92a" or more recently the SRES scenarios). Which scenarios should be considered most realistic is currently uncertain, as the projections of future CO₂ (and sulphate) emission are themselves uncertain.

The 2001 IPCC Third Assessment Report figure 9.3 shows the global mean response of 19 different coupled models to an idealised experiment in which CO₂ is increased at 1% per year. Figure 9.5 shows the response of a smaller number of models to more realistic forcing. For the 7 climate models shown there, the temperature change to 2100 varies from 2 to 4.5 °C with a median of about 3 °C.

Future scenarios do not include unknowable events - for example, volcanic eruptions or changes in solar forcing. These effects are believed to be small in comparison to GHG forcing in the long term, but large volcanic eruptions, for example, are known to exert a temporary cooling effect.

Human emissions of GHGs are an external input to the models, although it would be possible to couple in an economic model to provide these as well. Atmospheric GHG levels are usually supplied as an input, though it is possible to include a carbon cycle model including land vegetation and oceanic processes to calculate GHG levels.

Emissions scenarios

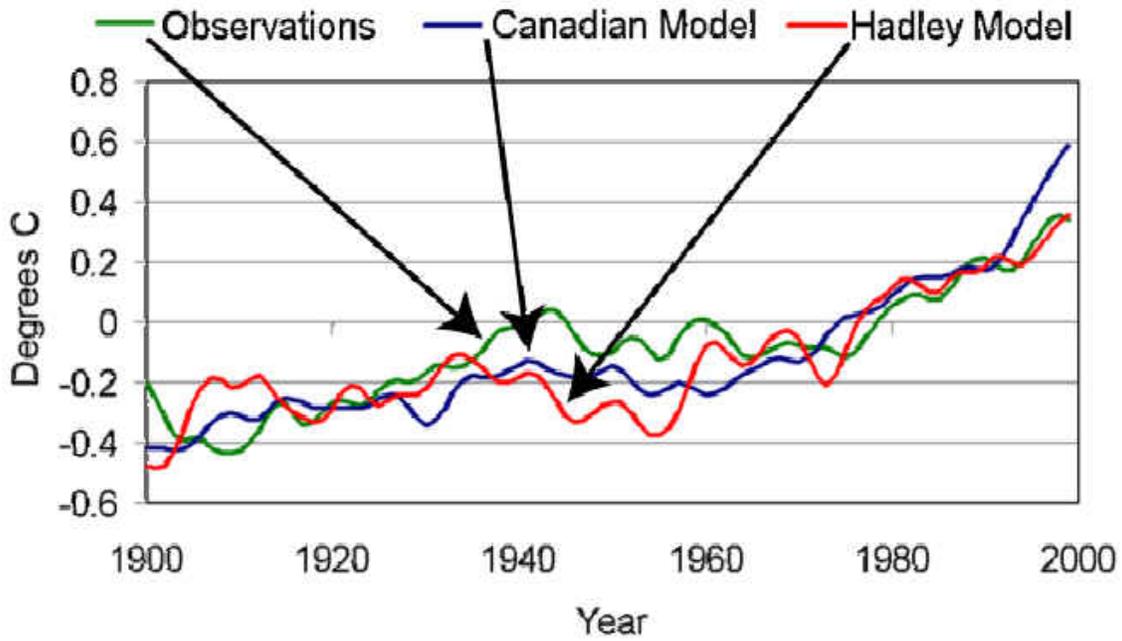
For the six SRES marker scenarios, IPCC (2007:7-8) gave a "best estimate" of global mean temperature increase (2090-2099 relative to the period 1980-1999) that ranged from 1.8 °C to 4.0 °C. Over the same time period, the "likely" range (greater than 66% probability, based on expert judgement) for these scenarios was for a global mean temperature increase of between 1.1 and 6.4 °C.

Pope (2008) described a study where climate change projections were made using several different emission scenarios. In a scenario where global emissions start to decrease by 2010 and then decline at a sustained rate of 3% per year, the likely global average temperature increase was predicted to be 1.7 °C above pre-industrial levels by 2050, rising to around 2 °C by 2100. In a projection designed to simulate a future where no efforts are made to reduce global emissions, the likely rise in global average temperature was predicted to be 5.5 °C by 2100. A rise as high as 7 °C was thought possible but less likely.

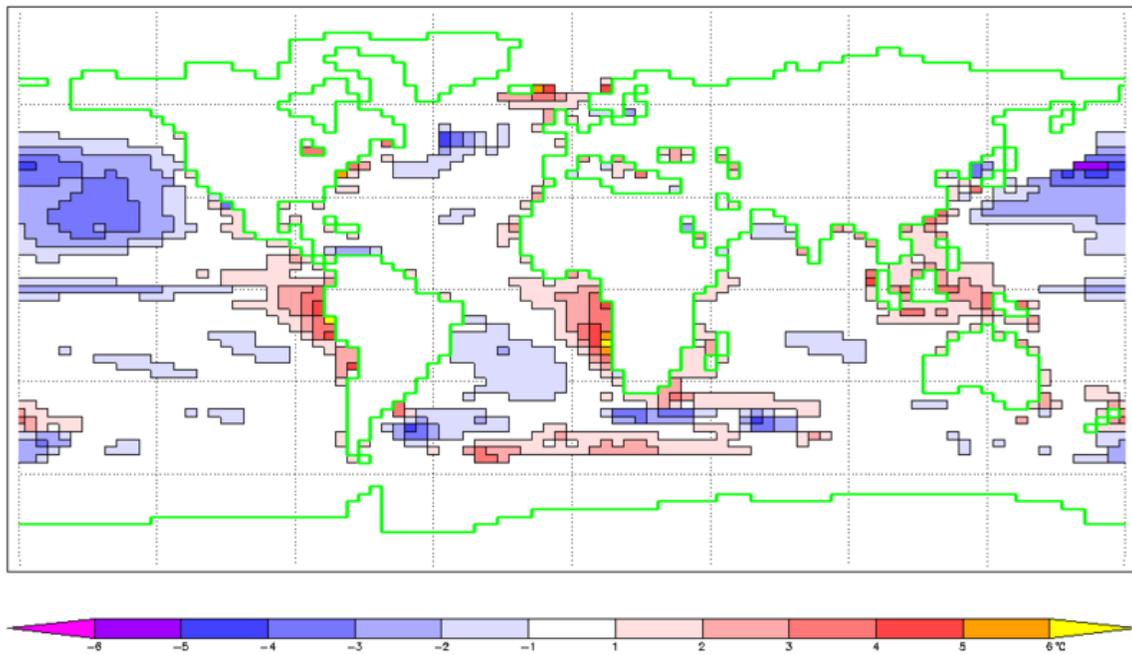
Sokolov *et al.* (2009) examined a scenario designed to simulate a future where there is no policy to reduce emissions. In their integrated model, this scenario resulted in a median warming over land (2090-2099 relative to the period 1980-1999) of 5.1 °C. Under the same emissions scenario but with different modeling of the future climate, the predicted median warming was 4.1 °C.

Accuracy of models that predict global warming

Mean Temperature Anomalies (Global)

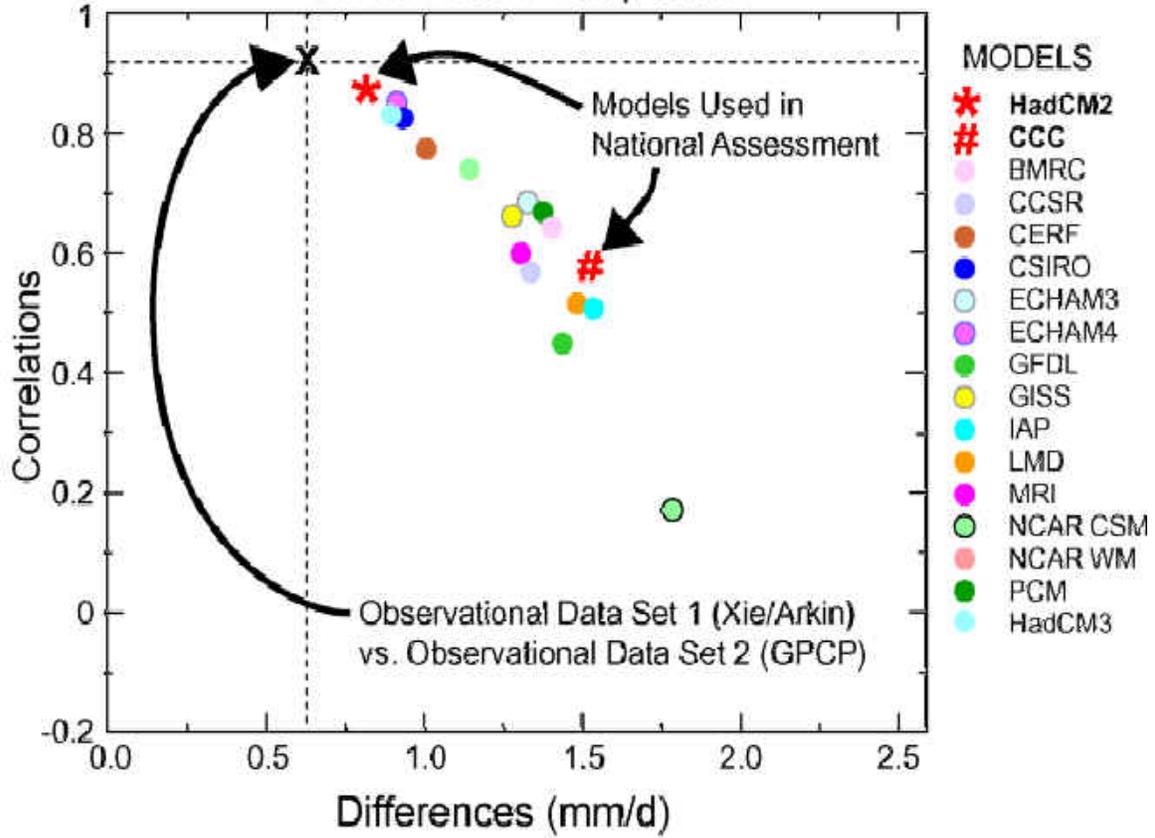


Mean global temperatures from observations and two climate models



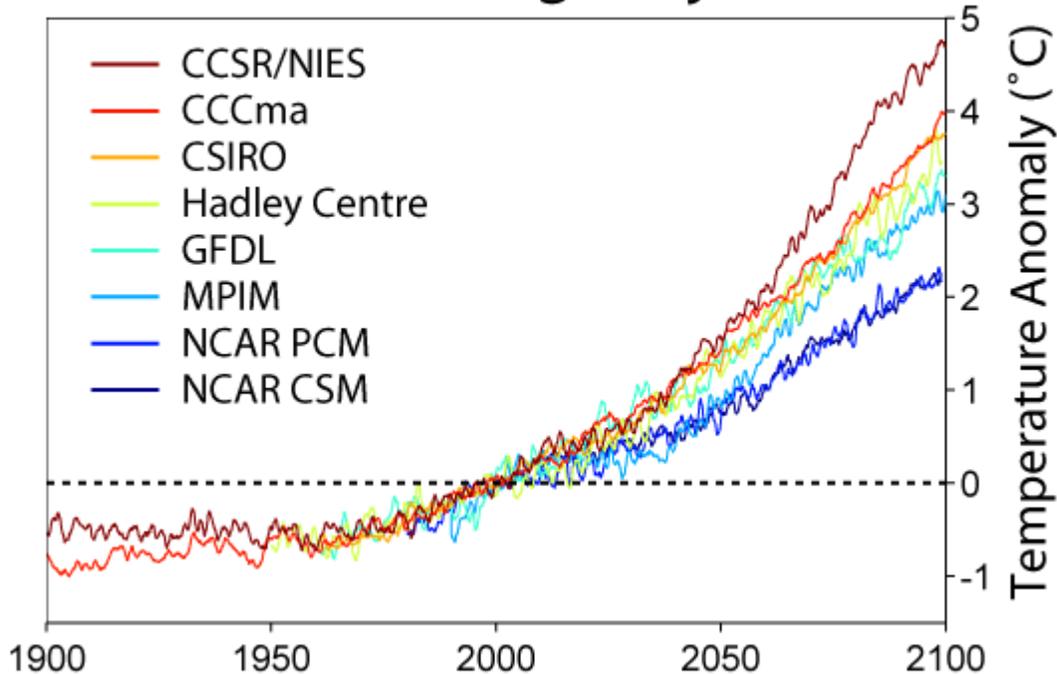
SST errors in HadCM3

MODEL PERFORMANCE OVER NORTH AMERICA Annual Mean Precipitation



North American precipitation from various models

Global Warming Projections



Temperature predictions from some climate models assuming the SRES A2 emissions scenario

AOGCMs represent the pinnacle of complexity in climate models and internalise as many processes as possible. However, they are still under development and uncertainties remain. They may be coupled to models of other processes, such as the carbon cycle, so as to better model feedback effects. Most recent simulations show "plausible" agreement with the measured temperature anomalies over the past 150 years, when forced by observed changes in greenhouse gases and aerosols, but better agreement is achieved when natural forcings are also included.

No model – whether a wind tunnel model for designing aircraft, or a climate model for projecting global warming – perfectly reproduces the system being modeled. Such inherently imperfect models may nevertheless produce useful results. In this context, GCMs are capable of reproducing the general features of the observed global temperature over the past century.

A debate over how to reconcile climate model predictions that upper air (tropospheric) warming should be greater than surface warming, with observations some of which appeared to show otherwise now appears to have been resolved in favour of the models, following revisions to the data.

The effects of clouds are a significant area of uncertainty in climate models. Clouds have *competing* effects on the climate. One of the roles that clouds play in climate is in cooling the surface by reflecting sunlight back into space; another is warming by increasing the

amount of infrared radiation emitted from the atmosphere to the surface. In the 2001 IPCC report on climate change, the possible changes in cloud cover were highlighted as one of the dominant uncertainties in predicting future climate change.

Thousands of climate researchers around the world use climate models to understand the climate system. There are thousands of papers published about model-based studies in peer-reviewed journals - and a part of this research is work improving the models. Improvement has been difficult but steady (most obviously, state of the art AOGCMs no longer require flux correction), and progress has sometimes led to discovering new uncertainties.

In 2000, a comparison between measurements and dozens of GCM simulations of ENSO-driven tropical precipitation, water vapor, temperature, and outgoing longwave radiation found similarity between measurements and simulation of most factors. However the simulated change in precipitation was about one-fourth less than what was observed. Errors in simulated precipitation imply errors in other processes, such as errors in the evaporation rate that provides moisture to create precipitation. The other possibility is that the satellite-based measurements are in error. Either indicates progress is required in order to monitor and predict such changes.

A more complete discussion of climate models is provided by the IPCC TAR chapter 8, Model Evaluation (2001).

- The model mean exhibits good agreement with observations.
- The individual models often exhibit worse agreement with observations.
- Many of the non-flux adjusted models suffered from unrealistic climate drift up to about 1°C/century in global mean surface temperature.
- The errors in model-mean surface air temperature rarely exceed 1 °C over the oceans and 5 °C over the continents; precipitation and sea level pressure errors are relatively greater but the magnitudes and patterns of these quantities are recognisably similar to observations.
- Surface air temperature is particularly well simulated, with nearly all models closely matching the observed magnitude of variance and exhibiting a correlation > 0.95 with the observations.
- Simulated variance of sea level pressure and precipitation is within ±25% of observed.
- All models have shortcomings in their simulations of the present day climate of the stratosphere, which might limit the accuracy of predictions of future climate change.
 - There is a tendency for the models to show a global mean cold bias at all levels.
 - There is a large scatter in the tropical temperatures.
 - The polar night jets in most models are inclined poleward with height, in noticeable contrast to an equatorward inclination of the observed jet.
 - There is a differing degree of separation in the models between the winter sub-tropical jet and the polar night jet.

- For nearly all models the r.m.s. error in zonal- and annual-mean surface air temperature is small compared with its natural variability.
 - There are problems in simulating natural seasonal variability.(2000)
 - In flux-adjusted models, seasonal variations are simulated to within 2 K of observed values over the oceans. The corresponding average over non-flux-adjusted models shows errors up to about 6 K in extensive ocean areas.
 - Near-surface land temperature errors are substantial in the average over flux-adjusted models, which systematically underestimates (by about 5 K) temperature in areas of elevated terrain. The corresponding average over non-flux-adjusted models forms a similar error pattern (with somewhat increased amplitude) over land.
 - In Southern Ocean mid-latitudes, the non-flux-adjusted models overestimate the magnitude of January-minus-July temperature differences by ~5 K due to an overestimate of summer (January) near-surface temperature. This error is common to five of the eight non-flux-adjusted models.
 - Over Northern Hemisphere mid-latitude land areas, zonal mean differences between July and January temperatures simulated by the non-flux-adjusted models show a greater spread (positive and negative) about observed values than results from the flux-adjusted models.
 - The ability of coupled GCMs to simulate a reasonable seasonal cycle is a necessary condition for confidence in their prediction of long-term climatic changes (such as global warming), but it is not a sufficient condition unless the seasonal cycle and long-term changes involve similar climatic processes.
- Coupled climate models do not simulate with reasonable accuracy clouds and some related hydrological processes (in particular those involving upper tropospheric humidity). Problems in the simulation of clouds and upper tropospheric humidity, remain worrisome because the associated processes account for most of the uncertainty in climate model simulations of anthropogenic change.

The precise magnitude of future changes in climate is still uncertain ; for the end of the 21st century (2071 to 2100), for SRES scenario A2, the change of global average SAT change from AOGCMs compared with 1961 to 1990 is +3.0 °C (4.8 °F) and the range is +1.3 to +4.5 °C (+2 to +7.2 °F).

Forecasts of climate change are inevitably uncertain. Even the degree of uncertainty is uncertain, a problem that stems from the fact that these climate models do not necessarily span the full range of known climate system behavior.

Relation to weather forecasting

The global climate models used for climate projections are very similar in structure to (and often share computer code with) numerical models for weather prediction but are nonetheless logically distinct.

Most weather forecasting is done on the basis of interpreting the output of numerical model results. Since forecasts are short—typically a few days or a week—such models do not usually contain an ocean model but rely on imposed SSTs. They also require accurate initial conditions to begin the forecast—typically these are taken from the output of a previous forecast, with observations blended in. Because the results are needed quickly the predictions must be run in a few hours; but because they only need to cover a week of real time these predictions can be run at higher resolution than in climate mode. Currently the ECMWF runs at 40 km (25 mi) resolution as opposed to the 100-to-200 km (62-to-120 mi) scale used by typical climate models. Often nested models are run forced by the global models for boundary conditions, to achieve higher local resolution: for example, the Met Office runs a mesoscale model with an 11 km (6.8 mi) resolution covering the UK, and various agencies in the U.S. also run nested models such as the NGM and NAM models. Like most global numerical weather prediction models such as the GFS, global climate models are often spectral models instead of grid models. Spectral models are often used for global models because some computations in modeling can be performed faster thus reducing the time needed to run the model simulation.

Computations involved

Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. They are used for a variety of purposes from study of the dynamics of the climate system to projections of future climate.

All climate models take account of incoming energy as short wave electromagnetic radiation, chiefly visible and short-wave (near) infrared, as well as outgoing energy as long wave (far) infrared electromagnetic radiation from the earth. Any imbalance results in a change in temperature.

The most talked-about models of recent years have been those relating temperature to emissions of carbon dioxide. These models project an upward trend in the surface temperature record, as well as a more rapid increase in temperature at higher altitudes.

Three (or more properly, four since time is also considered) dimensional GCM's discretise the equations for fluid motion and energy transfer and integrate these over time. They also contain parametrisations for processes—such as convection—that occur on scales too small to be resolved directly.

Atmospheric GCMs (AGCMs) model the atmosphere and impose sea surface temperatures as boundary conditions. Coupled atmosphere-ocean GCMs (AOGCMs, e.g. HadCM3, EdGCM, GFDL CM2.X, ARPEGE-Climat) combine the two models.

Models can range from relatively simple to quite complex:

- A simple radiant heat transfer model that treats the earth as a single point and averages outgoing energy
- this can be expanded vertically (radiative-convective models), or horizontally
- finally, (coupled) atmosphere–ocean–sea ice **global climate models** discretise and solve the full equations for mass and energy transfer and radiant exchange.

This is not a full list; for example "box models" can be written to treat flows across and within ocean basins. Furthermore, other types of modelling can be interlinked, such as land use, allowing researchers to predict the interaction between climate and ecosystems.

Box models

Box models are simplified versions of complex systems, reducing them to boxes (or reservoirs) linked by fluxes. The boxes are assumed to be mixed homogeneously. Within a given box, the concentration of any chemical species is therefore uniform. However, the abundance of a species within a given box may vary as a function of time due to the input to (or loss from) the box or due to the production, consumption or decay of this species within the box.

Simple box models, i.e. box model with a small number of boxes whose properties (e.g. their volume) do not change with time, are often useful to derive analytical formulas describing the dynamics and steady-state abundance of a species. More complex box models are usually solved using numerical techniques.

Box models are used extensively to model environmental systems or ecosystems and in studies of ocean circulation and the carbon cycle.

Zero-dimensional models

A very simple model of the radiative equilibrium of the Earth is:

$$(1 - a)S\pi r^2 = 4\pi r^2 \epsilon \sigma T^4$$

where

- the left hand side represents the incoming energy from the Sun
- the right hand side represents the outgoing energy from the Earth, calculated from the Stefan-Boltzmann law assuming a constant radiative temperature, T , that is to be found,

and

- S is the solar constant - the incoming solar radiation per unit area—about $1367 \text{ W}\cdot\text{m}^{-2}$

- a is the Earth's average albedo, measured to be 0.3.
- r is Earth's radius—approximately 6.371×10^6 m
- π is the mathematical constant (3.141...)
- σ is the Stefan-Boltzmann constant—approximately $5.67 \times 10^{-8} \text{ J} \cdot \text{K}^{-4} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
- ϵ is the effective emissivity of earth, about 0.612

The constant πr^2 can be factored out, giving

$$(1 - a)S = 4\epsilon\sigma T^4$$

Solving for the temperature,

$$T = \sqrt[4]{\frac{(1 - a)S}{4\epsilon\sigma}}$$

This yields an average earth temperature of 288 K (15 °C; 59 °F). This is because the above equation represents the effective *radiative* temperature of the Earth (including the clouds and atmosphere). The use of effective emissivity and albedo account for the greenhouse effect.

This very simple model is quite instructive. For example, it easily determines the effect on average earth temperature of changes in solar constant or change of albedo or effective earth emissivity. Using the simple formula, the percent change of the average amount of each parameter, considered independently, to cause a one degree Celsius change in steady-state average earth temperature is as follows:

- Solar constant 1.4%
- Albedo 3.3%
- Effective emissivity 1.4%

The average emissivity of the earth is readily estimated from available data. The emissivities of terrestrial surfaces are all in the range of 0.96 to 0.99 (except for some small desert areas which may be as low as 0.7). Clouds, however, which cover about half of the earth's surface, have an average emissivity of about 0.5 (which must be reduced by the fourth power of the ratio of cloud absolute temperature to average earth absolute temperature) and an average cloud temperature of about 258 K (−15 °C; 5 °F). Taking all this properly into account results in an effective earth emissivity of about 0.64 (earth average temperature 285 K (12 °C; 53 °F)).

This simple model readily determines the effect of changes in solar output or change of earth albedo or effective earth emissivity on average earth temperature. It says nothing, however about what might cause these things to change. Zero-dimensional models do not address the temperature distribution on the earth or the factors that move energy about the earth.

Radiative-Convective Models

The zero-dimensional model above, using the solar constant and given average earth temperature, determines the effective earth emissivity of long wave radiation emitted to space. This can be refined in the vertical to a zero-dimensional radiative-convective model, which considers two processes of energy transport:

- upwelling and downwelling radiative transfer through atmospheric layers that both absorb and emit infrared radiation
- upward transport of heat by convection (especially important in the lower troposphere).

The radiative-convective models have advantages over the simple model: they can determine the effects of varying greenhouse gas concentrations on effective emissivity and therefore the surface temperature. But added parameters are needed to determine local emissivity and albedo and address the factors that move energy about the earth.

Links:

- "Effect of Ice-Albedo Feedback on Global Sensitivity in a One-Dimensional Radiative-Convective Climate Model"

Higher Dimension Models

The zero-dimensional model may be expanded to consider the energy transported horizontally in the atmosphere. This kind of model may well be zonally averaged. This model has the advantage of allowing a rational dependence of local albedo and emissivity on temperature - the poles can be allowed to be icy and the equator warm - but the lack of true dynamics means that horizontal transports have to be specified.

EMICs (Earth-system Models of Intermediate Complexity)

Depending on the nature of questions asked and the pertinent time scales, there are, on the one extreme, conceptual, more inductive models, and, on the other extreme, general circulation models operating at the highest spatial and temporal resolution currently feasible. Models of intermediate complexity bridge the gap. One example is the Climber-3 model. Its atmosphere is a 2.5-dimensional statistical-dynamical model with $7.5^\circ \times 22.5^\circ$ resolution and time step of 1/2 a day; the ocean is MOM-3 (Modular Ocean Model) with a $3.75^\circ \times 3.75^\circ$ grid and 24 vertical levels.

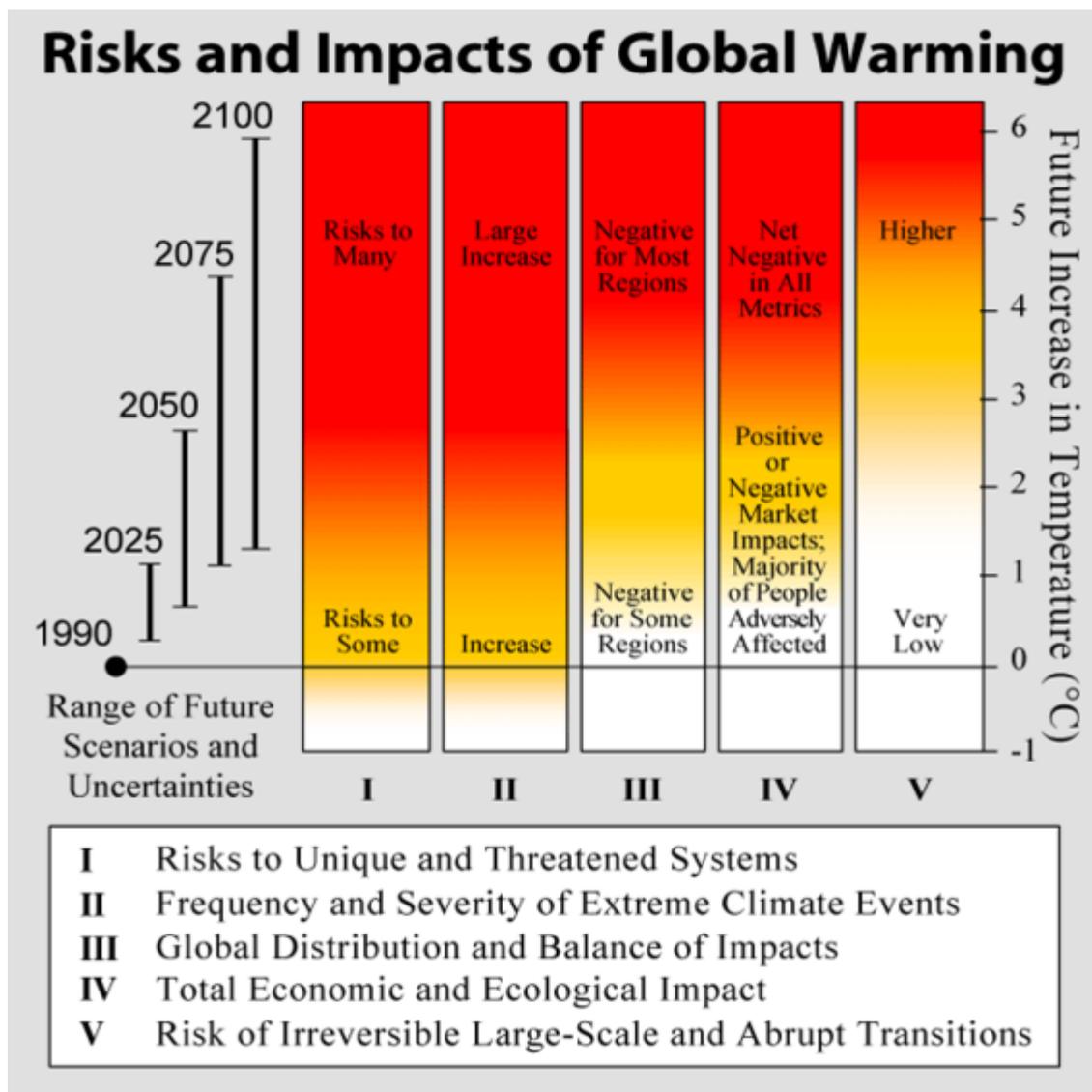
Climate modellers

A climate modeller is a person who designs, develops, implements, tests, maintains or exploits climate models. There are three major types of institutions where a climate modeller may be found:

- In a national meteorological service. Most national weather services have at least a climatology section.
- In a university. Departments that may have climate modellers on staff include atmospheric sciences, meteorology, climatology, or geography, amongst others.
- In national or international research laboratories specialising in this field, such as the National Center for Atmospheric Research (NCAR, in Boulder, Colorado, USA), the Geophysical Fluid Dynamics Laboratory (GFDL, in Princeton, New Jersey, USA), the Hadley Centre for Climate Prediction and Research (in Exeter, UK), the Max Planck Institute for Meteorology in Hamburg, Germany, or the Institut Pierre-Simon Laplace (IPSL in Paris, France). The World Climate Research Programme (WCRP), hosted by the World Meteorological Organization (WMO), coordinates research activities on climate modelling worldwide.

Chapter- 6

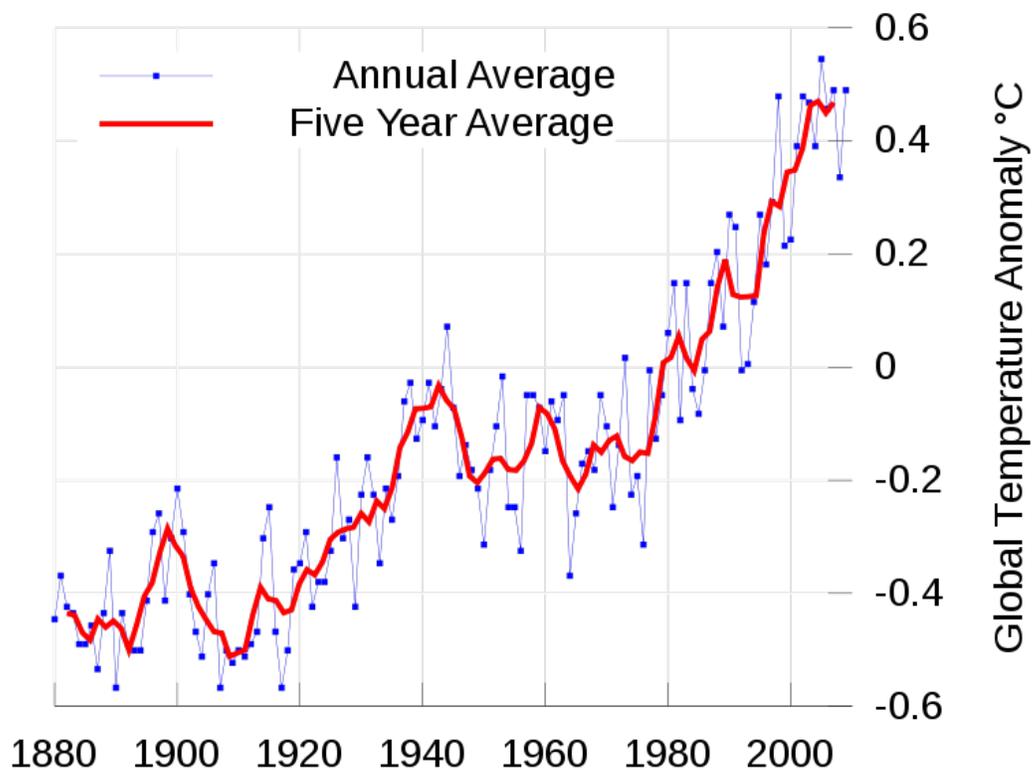
Effects of Global Warming



Graphical description of risks and impacts of climate change by IPCC (2001). A revision of this figure by Smith *et al.* (2009) shows increased risks.

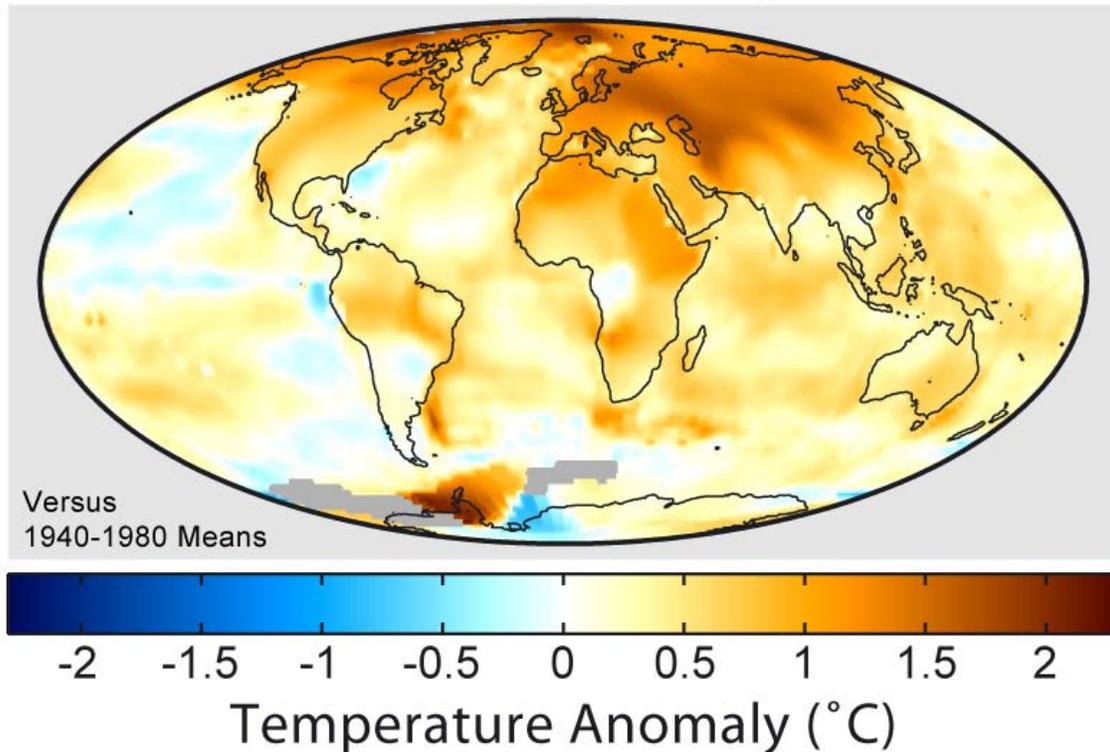
This article is about the **effects of global warming** and climate change. The effects, or impacts, of climate change may be physical, ecological, social or economic. Evidence of observed climate change includes the instrumental temperature record, rising sea levels, and decreased snow cover in the Northern Hemisphere. According to IPCC (2007a:10), "[most] of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in [human greenhouse gas] concentrations". It is predicted that future climate changes will include further global warming (i.e., an upward trend in global mean temperature), sea level rise, and a probable increase in the frequency of some extreme weather events. Signatories of the United Nations Framework Convention on Climate Change have agreed to implement policies designed to reduce their emissions of greenhouse gases.

Overview



Global mean surface temperature difference from the average for 1880-2009

1999-2008 Mean Temperatures



Mean surface temperature change for the period 1999 to 2008 relative to the average temperatures from 1940 to 1980

Over the last hundred years or so, the instrumental temperature record has shown a trend in climate of increased global mean temperature, i.e., global warming. Other observed changes include Arctic shrinkage, Arctic methane release, releases of terrestrial carbon from permafrost regions and Arctic methane release in coastal sediments, and sea level rise. Global average temperature is predicted to increase over this century, with a probable increase in frequency of some extreme weather events, and changes in rainfall patterns. Moving from global to regional scales, there is increased uncertainty over how climate will change. The probability of warming having unforeseen consequences increases with the rate, magnitude, and duration of climate change. Some of the physical impacts of climate change are irreversible at continental and global scales. With medium confidence, IPCC (2007b:17) concluded that with a global average temperature increase of 1–4°C, (relative to 1990–2000) partial deglaciation of the Greenland ice sheet would occur over a period of centuries to millennia. Including the possible contribution of partial deglaciation of the West Antarctic Ice Sheet, sea level would rise by 4–6 m or more.

The impacts of climate change across world population will not be distributed evenly (Smith *et al.*, 2001:957). Some regions and sectors are expected to experience benefits while others will experience costs. With greater levels of warming (greater than 2–3°C by

2100, relative to 1990 temperature levels), it is very likely that benefits will decline and costs increase (IPCC, 2007b:17). Low-latitude and less-developed areas are probably at the greatest risk from climate change (Schneider *et al.*, 2007:781). With human systems, adaptation potential for climate change impacts is considerable, although the costs of adaptation are largely unknown and potentially large. In a literature assessment, Schneider *et al.* (2007:792) concluded, with high confidence, that climate change would likely result in reduced diversity of ecosystems and the extinction of many species.

Definition of climate change

This article refers to reports produced by the IPCC. In their usage, "climate change" refers to a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties, and that persists for extended periods, typically decades or longer (IPCC, 2007d:30). The climate change referred to may be due to natural causes or the result of human activity.

Physical impacts

This section describes some physical impacts of climate change. For some of these physical impacts, their effect on social and economic systems are also described.

Effects on weather

Increasing temperature is likely to lead to increasing precipitation but the effects on storms are less clear. Extratropical storms partly depend on the temperature gradient, which is predicted to weaken in the northern hemisphere as the polar region warms more than the rest of the hemisphere.

Extreme weather

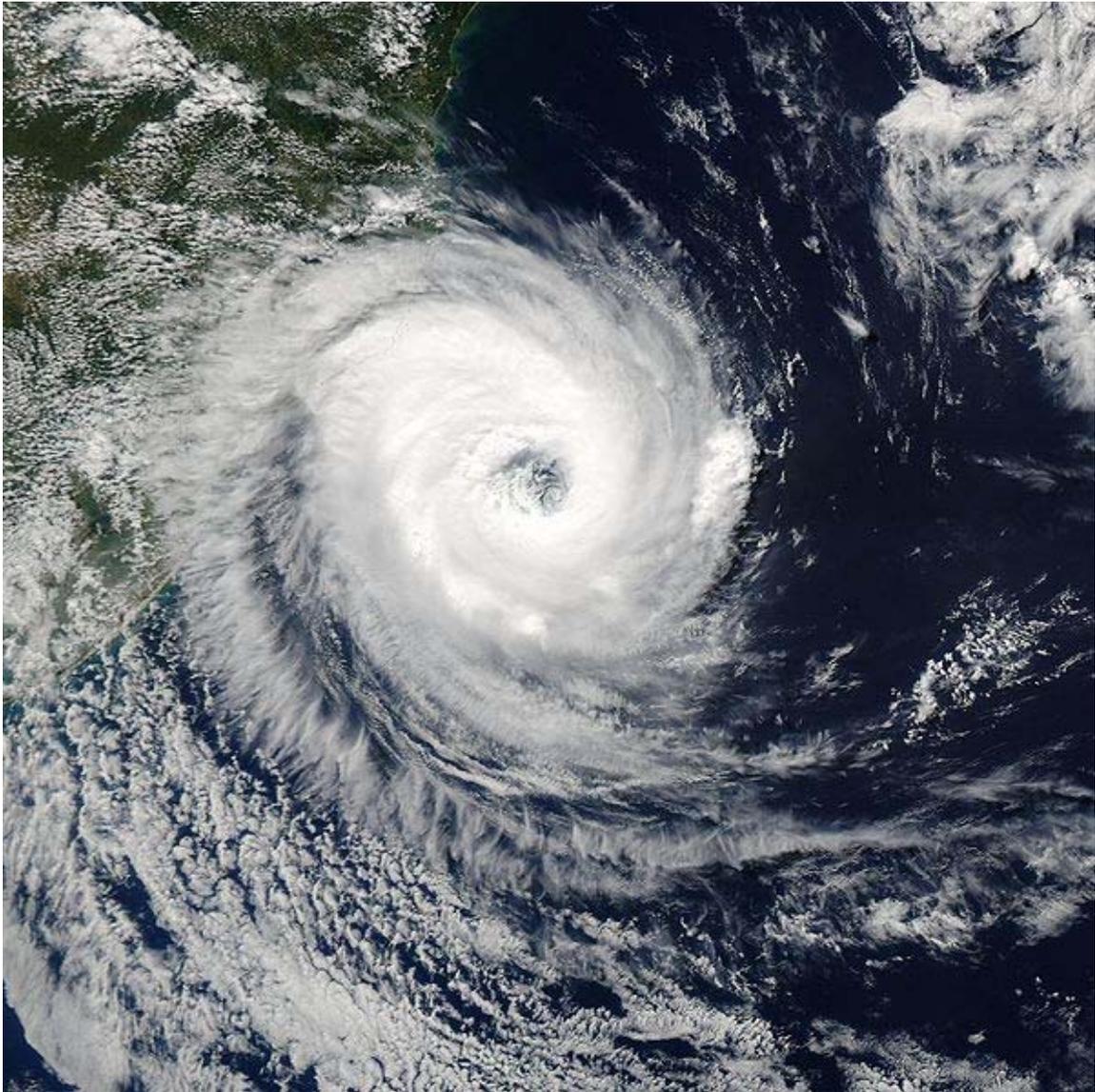
IPCC (2007a:8) predicted that in the future, over most land areas, the frequency of warm spells or heat waves would very likely increase. Other likely changes are listed below:

- Increased areas will be affected by drought
- There will be increased intense tropical cyclone activity
- There will be increased incidences of extreme high sea level (excluding tsunamis)

Increased freshwater flow

Research based on satellite observations, published in October, 2010, shows an increase in the flow of freshwater into the world's oceans, partly from melting ice and partly from increased precipitation driven by an increase in global ocean evaporation. The increase in global freshwater flow, based on data from 1994 to 2006, was about 18%. Much of the increase is in areas which already experience high rainfall. One effect, as perhaps experienced in the 2010 Pakistan floods, is to overwhelm flood control infrastructure.

Local climate change



The first recorded South Atlantic hurricane, "Catarina", which hit Brazil in March 2004

Regional effects of global warming vary in nature. Some are the result of a generalised global change, such as rising temperature, resulting in local effects, such as melting ice. In other cases, a change may be related to a change in a particular ocean current or weather system. In such cases, the regional effect may be disproportionate and will not necessarily follow the global trend.

There are three major ways in which global warming will make changes to regional climate: melting or forming ice, changing the hydrological cycle (of evaporation and precipitation) and changing currents in the oceans and air flows in the atmosphere. The coast can also be considered a region, and will suffer severe impacts from sea level rise.

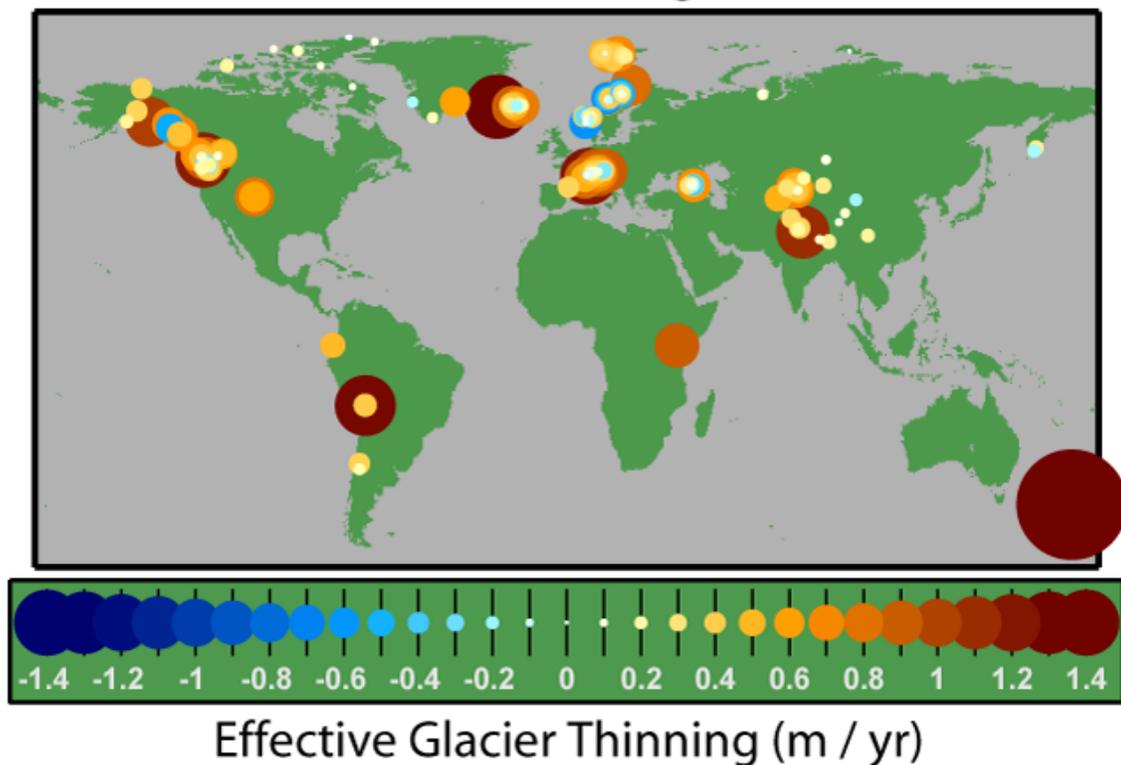
Biogeochemical cycles

Climate change may have an effect on the carbon cycle in an interactive "feedback" process. A feedback exists where an initial process triggers changes in a second process that in turn influences the initial process. A positive feedback intensifies the original process, and a negative feedback reduces it (IPCC, 2007d:78). Models suggest that the interaction of the climate system and the carbon cycle is one where the feedback effect is positive (Schneider *et al.*, 2007:792).

Using the A2 SRES emissions scenario, Schneider *et al.* (2007:789) found that this effect led to additional warming by 2100, relative to the 1990-2000 period, of 0.1 to 1.5 °C. This estimate was made with high confidence. The climate projections made in the IPCC Fourth Assessment Report of 1.1 to 6.4 °C account for this feedback effect. On the other hand, with medium confidence, Schneider *et al.* (2007) commented that additional releases of GHGs were possible from permafrost, peat lands, wetlands, and large stores of marine hydrates at high latitudes.

Glacier retreat and disappearance

Mountain Glacier Changes Since 1970



A map of the change in thickness of mountain glaciers since 1970. Thinning in orange and red, thickening in blue.

IPCC (2007a:5) found that, on average, mountain glaciers and snow cover had decreased in both the northern and southern hemispheres. This widespread decrease in glaciers and ice caps has contributed to observed sea level rise. With very high or high confidence, IPCC (2007d:11) made a number of predictions relating to future changes in glaciers:

- Mountainous areas in Europe will face glacier retreat
- In Latin America, changes in precipitation patterns and the disappearance of glaciers will significantly affect water availability for human consumption, agriculture, and energy production
- In Polar regions, there will be reductions in glacier extent and the thickness of glaciers.

Oceans

The role of the oceans in global warming is a complex one. The oceans serve as a sink for carbon dioxide, taking up much that would otherwise remain in the atmosphere, but increased levels of CO₂ have led to ocean acidification. Furthermore, as the temperature of the oceans increases, they become less able to absorb excess CO₂. Global warming is projected to have a number of effects on the oceans. Ongoing effects include rising sea levels due to thermal expansion and melting of glaciers and ice sheets, and warming of the ocean surface, leading to increased temperature stratification. Other possible effects include large-scale changes in ocean circulation.

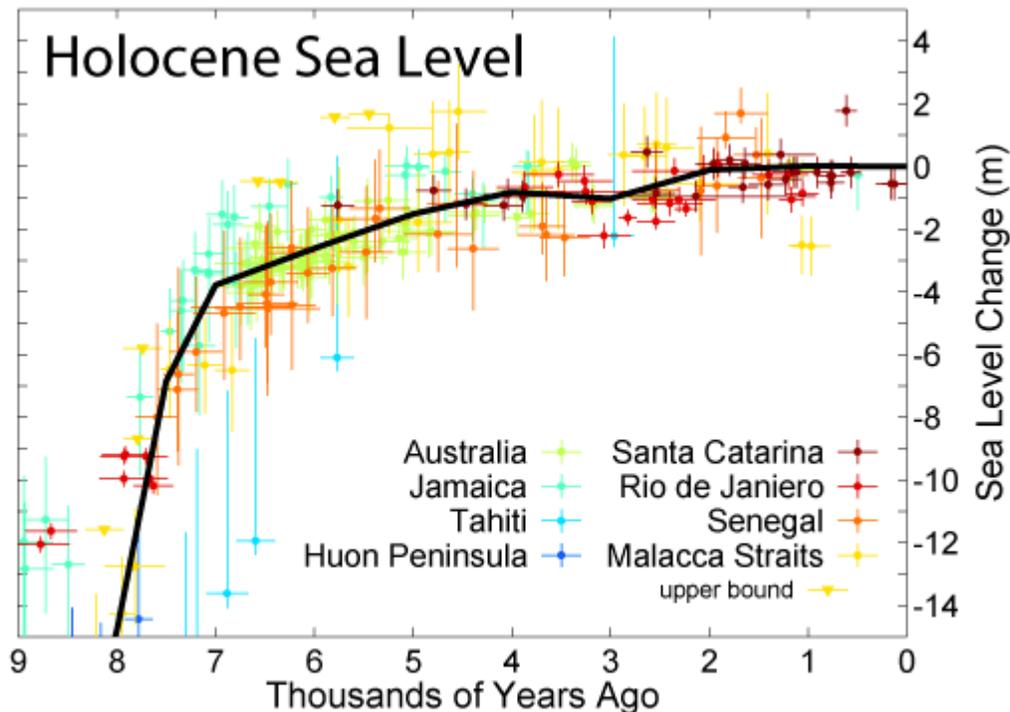
Acidification

Dissolving CO₂ in seawater increases the hydrogen ion (H⁺) concentration in the ocean, and thus decreases ocean pH. Caldeira and Wickett (2003) placed the rate and magnitude of modern ocean acidification changes in the context of probable historical changes during the last 300 million years. Since the industrial revolution began, it is estimated that surface ocean pH has dropped by slightly more than 0.1 units (on the logarithmic scale of pH; approximately a 30% increase in H⁺), and it is estimated that it will drop by a further 0.3 to 0.5 units (more than doubling ocean H⁺ concentrations) by 2100 as the oceans absorb more anthropogenic CO₂.

Oxygen depletion

The amount of oxygen dissolved in the oceans may decline, with adverse consequences for ocean life.

Sea level rise



IPCC (2007a:5) reported that since 1961, global average sea level had risen at an average rate of 1.8 [1.3 to 2.3] mm/yr. Between 1993 and 2003, the rate increased above the previous period to 3.1 [2.4 to 3.8] mm/yr. IPCC (2007a) were uncertain whether the increase in rate from 1993 to 2003 was due to natural variations in sea level over the time period, or whether it reflected an increase in the underlying long-term trend.

IPCC (2007a:13, 14) projected sea level rise to the end of the 21st century using the SRES emission scenarios. Across the six SRES marker scenarios, sea level was projected to rise by 18 to 59 cm (7.1 to 23.2 inches). This projection was for the time period 2090-2099, with the increase in level relative to average sea levels over the 1980-1999 period. Due to a lack of scientific understanding, this sea level rise estimate does not include all of the possible contributions of ice sheets.

Temperature rise

From 1961 to 2003, the global ocean temperature has risen by 0.10 °C from the surface to a depth of 700 m. There is variability both year-to-year and over longer time scales, with global ocean heat content observations showing high rates of warming for 1991 to 2003, but some cooling from 2003 to 2007. The temperature of the Antarctic Southern Ocean rose by 0.17 °C (0.31 °F) between the 1950s and the 1980s, nearly twice the rate for the world's oceans as a whole. As well as having effects on ecosystems (e.g. by melting sea ice, affecting algae that grow on its underside), warming reduces the ocean's ability to absorb CO₂.

Social systems

Food supply

Climate change will impact agriculture and food production around the world due to: the effects of elevated CO₂ in the atmosphere, higher temperatures, altered precipitation and transpiration regimes, increased frequency of extreme events, and modified weed, pest, and pathogen pressure (Easterling *et al.*, 2007:282). In general, low-latitude areas are at most risk of having decreased crop yields (Schneider *et al.*, 2007:790). With low to medium confidence, Schneider *et al.* (2007:787) concluded that for about a 1 to 3°C global mean temperature increase (by 2100, relative to the 1990-2000 average level) there would be productivity decreases for some cereals in low latitudes, and productivity increases in high latitudes. With medium confidence, global production potential was predicted to:

- increase up to around 3°C,
- very likely decrease above about 3 to 4°C.

Most of the studies on global agriculture assessed by Schneider *et al.* (2007:790) had not incorporated a number of critical factors, including changes in extreme events, or the spread of pests and diseases. Studies had also not considered the development of specific practices or technologies to aid adaptation.

Health

Human beings are exposed to climate change through changing weather patterns (temperature, precipitation, sea-level rise and more frequent extreme events) and indirectly through changes in water, air and food quality and changes in ecosystems, agriculture, industry and settlements and the economy (Confalonieri *et al.*, 2007:393). According to a literature assessment by Confalonieri *et al.* (2007:393), the effects of climate change to date have been small, but are projected to progressively increase in all countries and regions.

With high confidence, Confalonieri *et al.* (2007:393) concluded that climate change had altered the seasonal distribution of some allergenic pollen species. With medium confidence, they concluded that climate change had:

- altered the distribution of some infectious disease vectors
- increased heatwave-related deaths

With high confidence, IPCC (2007d:48) projected that:

- the health status of millions of people would be affected through, for example, increases in malnutrition; increased deaths, diseases and injury due to extreme weather events; increased burden of diarrhoeal diseases; increased frequency of cardio-respiratory diseases due to high concentrations of ground-level ozone in

- urban areas related to climate change; and altered spatial distribution of some infectious diseases.
- climate change would bring some benefits in temperate areas, such as fewer deaths from cold exposure, and some mixed effects such as changes in range and transmission potential of malaria in Africa. Overall, IPCC (2007d:48) expected that benefits would be outweighed by negative health effects of rising temperatures, especially in developing countries.

With very high confidence, Confalonieri *et al.* (2007:393) concluded that economic development was an important component of possible adaptation to climate change. Economic growth on its own, however, was not judged to be sufficient to insulate the world's population from disease and injury due to climate change. The manner in which economic growth occurs was judged to be important, along with how the benefits of growth are distributed in society. Examples of other important factors in determining the health of populations were listed as: education, health care, and public-health infrastructure.

Specific health impacts

Malnutrition

With high confidence, Confalonieri *et al.* (2007) projected that malnutrition would increase due to climate change. This link is associated with climate variability and change (Confalonieri *et al.*, 2007). Drought reduces variety in diets and reduces overall consumption. This can lead to micronutrient deficiencies.

The World Health Organization (WHO) (referred to by Confalonieri *et al.*, 2007) conducted a regional and global assessment to quantify the amount of premature morbidity and mortality due to a range of factors, including climate change. Projections were made over future climate change impacts. Limited adjustments for adaptation were included in the estimates based on these projections. Projected relative risks attributable to climate change in 2030 varied by health outcome and region. Risks were largely negative, with most of the projected disease burden due to increases in diarrhoeal disease and malnutrition. These increases were primarily in low-income populations already experiencing a large burden of disease.

Extreme events

With high confidence, Confalonieri *et al.* (2007) projected that climate change would increase the number of people suffering from death, disease and injury from heatwaves, floods, storms, fires and droughts.

Floods and weather disasters

Floods are low-probability, high-impact events that can overwhelm physical infrastructure and human communities (Confalonieri *et al.*, 2007). Major storm and flood disasters have occurred in the last two decades.

The impacts of weather disasters is considerable and unequally distributed. For example, natural disasters have been shown to result in increased domestic violence against - and post-traumatic stress disorders in – women. In terms of deaths and populations affected, floods and tropical cyclones have the greatest impact in South Asia and Latin America. Vulnerability to weather disasters depends on the attributes of the person at risk, including where they live and their age, as well as other social and environmental factors. High-density populations in low-lying coastal regions experience a high health burden from weather disasters.

Heatwaves

Hot days, hot nights and heatwaves have become more frequent (Confalonieri *et al.*, 2007). Heatwaves are associated with marked short-term increases in mortality. For example, in August 2003, a heatwave in Europe resulted in excess mortality in the range of 35,000 total deaths.

Heat-related morbidity and mortality is projected to increase (Confalonieri *et al.*, 2007). The health burden could be relatively small for moderate heatwaves in temperate regions, because deaths occur primarily in susceptible persons.

Drought

The effects of drought on health include deaths, malnutrition, infectious diseases and respiratory diseases (Confalonieri *et al.*, 2007). Countries within the "Meningitis Belt" in semi-arid sub-Saharan Africa experience the highest endemicity and epidemic frequency of meningococcal meningitis in Africa, although other areas in the Rift Valley, the Great Lakes, and southern Africa are also affected (Confalonieri *et al.*, 2007). The spatial distribution, intensity, and seasonality of meningococcal (epidemic) meningitis appear to be strongly linked to climate and environmental factors, particularly drought. The cause of this link is not fully understood.

Fires

In some regions, changes in temperature and precipitation are projected to increase the frequency and severity of fire events (Confalonieri *et al.*, 2007). Forest and bush fires cause burns, damage from smoke inhalation and other injuries.

Infectious disease vectors

With high confidence, Confalonieri *et al.* (2007) projected that climate change would continue to change the range of some infectious disease vectors. Vector-borne diseases (VBD) are infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies, and blackflies (Confalonieri *et al.*, 2007). There is some evidence of climate-change-related shifts in the distribution of tick vectors of disease, of some (non-malarial) mosquito vectors in Europe and North America. Climate change has also been implicated in changes in the breeding and migration dates of several bird species. Several species of wild bird can act as carriers of human pathogens as well as of vectors of infectious agents.

Dengue

It is possible^d that climate change will increase the number of people at risk of dengue (Confalonieri *et al.*, 2007). Based on the expert judgement of Confalonieri *et al.* (2007), this projection had about a two-in-ten chance of being correct. Dengue is the world's most important vector-borne viral disease (Confalonieri *et al.*, 2007). Several studies have reported associations between dengue and climate, however, these associations are not entirely consistent.

Malaria

The spatial distribution, intensity of transmission, and seasonality of malaria is influenced by climate in Sub-saharan Africa (Confalonieri *et al.*, 2007). Rainfall can be a limiting factor for mosquito populations and there is some evidence of reductions in transmission associated with decadal decreases in rainfall. The effects of observed climate change on the geographical distribution of malaria and its transmission intensity in highland regions remains controversial. There is no clear evidence that malaria has been affected by climate change in South America or in continental regions of the Russian Federation. There is still much uncertainty about the potential impact of climate change on malaria at local and global scales.

A paper by researchers from the University of Oxford and the University of Florida published in Nature in May 2010 concluded that claims that a warming climate has led to more widespread disease and death due to malaria are largely at odds with the evidence, and that "*predictions of an intensification of malaria in a warmer world, based on extrapolated empirical relationships or biological mechanisms, must be set against a context of a century of warming that has seen marked global declines in the disease and a substantial weakening of the global correlation between malaria endemicity and climate.*"

Other infectious diseases

There is good evidence that diseases transmitted by rodents sometimes increase during heavy rainfall and flooding because of altered patterns of human-pathogen-rodent contact (Confalonieri *et al.*, 2007).

Projections

With very high confidence, Confalonieri *et al.* (2007) concluded that climate change would have mixed effects on malaria. Malaria is a complex disease to model and all of the published models assessed by Confalonieri *et al.* (2007) had limited parameterization of some key factors. Parameterization is used in climate models because the resolution of models is insufficient to resolve some physical processes (Randall *et al.*, 2007). Given this limitation, models assessed by Confalonieri *et al.* (2007) projected that, particularly in Africa, climate change would be associated with geographical expansions of the areas suitable for *Plasmodium falciparum* malaria in some regions, and contractions in other regions. Projections also suggested that some regions would experience a longer season of transmission. Projections suggested expansions in vector species that carry dengue for parts of Australia and New Zealand.

Diarrhoeal diseases

With medium confidence, Confalonieri *et al.* (2007) concluded that climate change would increase the burden of diarrhoeal diseases. Childhood mortality due to diarrhoea in low-income countries, especially in Sub-Saharan Africa, remains high (Confalonieri *et al.*, 2007). This is despite improvements in care. Several studies have shown that transmission of enteric pathogens is higher during the rainy season. Some studies have found that higher temperature was strongly associated with increased episodes of diarrhoeal disease in adults and children in Peru. The WHO study, referred to earlier, projected that climate change would increase the burden of diarrhoeal diseases in low-income regions by approximately 2 to 5% in 2020 (Confalonieri *et al.*, 2007).

Ground-level ozone

With high confidence, Confalonieri *et al.* (2007) projected that climate change would increase cardio-respiratory morbidity and mortality associated with ground-level ozone. Ground-level ozone is both naturally occurring and is the primary constituent of urban smog (Confalonieri *et al.*, 2007). Ozone in smog is formed through chemical reactions involving nitrogen oxides and other compounds. The reaction is a photochemical reaction, meaning that it involves electromagnetic radiation, and occurs in the presence of bright sunshine and high temperatures. Exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis and other respiratory diseases, and with premature mortality.

Background levels of ground-level ozone have risen since pre-industrial times because of increasing emissions of methane, carbon monoxide and nitrogen oxides (Confalonieri *et al.*, 2007). This trend is expected to continue into the mid-21st century.

Cold-waves

It is expected that^b climate change will bring some health benefits (Confalonieri *et al.*, 2007). It is expected that these benefits will be outweighed by negative climate change effects.

Cold-waves continue to be a problem in northern latitudes, where very low temperatures can be reached in a few hours and extend over long periods (Confalonieri *et al.*, 2007). Reductions in cold-deaths due to climate change are projected to be greater than increases in heat-related deaths in the UK (Confalonieri *et al.*, 2007).

Water resources

In a literature assessment, Kundzewicz *et al.*. (2007:175) concluded, with high confidence, that:

- the negative impacts of climate change on freshwater systems outweigh the benefits. All of the regions assessed in the IPCC Fourth Assessment Report (Africa, Asia, Australia and New Zealand, Europe, Latin America, North America, Polar regions (Arctic and Antarctic), and small islands) showed an overall net negative impact of climate change on water resources and freshwater ecosystems.
- Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater. With very high confidence, it was judged that many of these areas, e.g., the Mediterranean basin, western USA, southern Africa, and north-eastern Brazil, would suffer a decrease in water resources due to climate change.

Migration and conflict

An argument can be made that rising ethnic conflicts may be linked to competition over natural resources that are increasingly scarce as a result of climate change (Wilbanks *et al.*, 2007:365). According to a literature assessment by Wilbanks *et al.*. (2007:365), other factors need to be taken into account. It was suggested that major environmentally influenced conflicts in Africa have more to do with the relative abundance of resources, e.g., oil and diamonds, than with resource scarcity. On this basis, Wilbanks *et al.*. (2007:365) suggested that predictions of future conflicts due climate change should be viewed with caution.

With high confidence, Schneider *et al.*. (2007:787) predicted that stresses such as increased drought, water shortages, and riverine and coastal flooding would affect many local and regional populations. With medium confidence, it was predicted that these stresses would lead, in some cases, to relocation within or between countries. This might have the effect of exacerbating conflicts, and possibly impose migration pressures.

Zhang *et al* also concluded that climate change drives conflict.

Aggregate impacts

Aggregating impacts adds up the total impact of climate change across sectors and/or regions (IPCC, 2007d:76). The impacts of climate change across world population will not be distributed evenly (Smith *et al.*, 2001:957). IPCC (2007b:17) found that for increases in global mean temperature of less than 1-3 °C above 1990 levels, some impacts were projected to produce benefits in some places and sectors, and produce costs in other places and sectors. For some low-latitude and polar regions, net costs were projected for small increases in temperature. According to IPCC (2007b:17), a temperature increase of greater than about 2-3 °C would very likely result in all regions either experiencing reductions in net benefits or increases in net costs.

Regions

Some regions are likely to be especially affected by climate change (IPCC, 2007d:9):

- The Arctic, because of high rates of projected warming.
- Africa, especially in the sub-Saharan region. This is due to the continent's low capacity to adapt to climate change and projected impacts.
- Small islands, due to high exposure of population and infrastructure at risk to sea-level rise and increased storm surge.
- Asian megadeltas, due to large populations and high exposure to sea-level rise, storm surge and river flooding.

Within other areas, some people are particularly at risk, such as the poor, young children and the elderly.

Biological systems

With very high confidence, Schneider *et al.* (2007:792) concluded that regional temperature trends were already affecting species and ecosystems around the world. In a literature assessment, Rosenzweig *et al.* (2007:81) concluded that over the last three decades, human-induced warming had likely had a discernable influence on many physical and biological systems.

Schneider *et al.* (2007:792) concluded, with high confidence, that climate change would result in the extinction of many species and a reduction in the diversity of ecosystems.

- **Terrestrial ecosystems and biodiversity:** With a warming of 3°C, relative to 1990 levels, it is likely that global terrestrial vegetation would become a net source of carbon (Schneider *et al.*, 2007:792). With high confidence, Schneider *et al.* (2007:788) concluded that a global mean temperature increase of around 4°C (above the 1990-2000 level) by 2100 would lead to major extinctions around the globe.

- **Marine ecosystems and biodiversity:** With very high confidence, Schneider *et al.* (2007:792) concluded that a warming of 2°C above 1990 levels would result in mass mortality of coral reefs globally.
- **Freshwater ecosystems:** Above about a 4°C increase in global mean temperature by 2100 (relative to 1990-2000), Schneider *et al.* (2007:789) concluded, with high confidence, that many freshwater species would become extinct.

Abrupt or irreversible changes

Abrupt climate change

Abrupt climate change is defined as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems (CCSP, 2008a). There is the possibility of a rapid change in glaciers, ice sheets, and hence sea level. Predictions of such a change are highly uncertain due to a lack of scientific understanding. Modeling of the processes associated with a rapid ice sheet and glacier change could potentially increase future projections of sea level rise.

The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the Earth's climate system, characterized by a northward flow of warm, salty water in the upper layers of the Atlantic and a southward flow of colder water in the deep Atlantic (CCSP, 2008b, p. 5). Potential impacts associated with MOC changes include reduced warming or (in the case of abrupt change) absolute cooling of northern high-latitude areas near Greenland and north-western Europe, an increased warming of Southern Hemisphere high-latitudes, tropical drying, as well as changes to marine ecosystems, terrestrial vegetation, oceanic CO₂ uptake, oceanic oxygen concentrations, and shifts in fisheries (Schneider *et al.*, 2007). According to a assessment by the US Climate Change Science Program (CCSP, 2008b, p. 5), it is very likely that the strength of the AMOC will decrease over the course of the 21st century. Warming is still expected to occur over most of the European region downstream of the North Atlantic Current in response to increasing greenhouse gases, as well as over North America. Although it is very unlikely that the AMOC will collapse in the 21st century, the potential consequences of such a collapse could be severe.

Irreversibilities

An irreversible change is one where that change, once set in motion, cannot be reversed, at least over some specified timescale, e.g., centuries to millennia (Goldemberg *et al.*, 1996, p. 22). Climate change is likely to lead to some irreversible impacts (IPCC, 2007d). One example of a potentially irreversible impact of climate change is damage to ecosystems.

Footnotes

The IPCC report that is referred to in this article uses specific and quantitative language to describe uncertainty (Ahmad *et al.*, 2001). This language is intended to provide an indication of the level of confidence that IPCC authors have about a particular finding. The qualitative language used to describe uncertainty has a quantitative scale associated with it. The quantitative values for qualitative terms are intended to ensure that confidence levels are interpreted correctly. This is because qualitative statements, e.g., using the word "likely," can be interpreted differently in quantitative terms (Moss and Schneider, 2000, p. 44).

Quantitative values for confidence statements made in the IPCC Fourth Assessment Report are listed below (IPCC, 2007). These quantitative values are subjective probabilities that reflect the expert judgement of IPCC authors:

- ^a Very high confidence: At least 9 out of 10 chance of being correct
- ^b High confidence: About 8 out of 10 chance
- ^c Medium confidence: About 5 out of 10 chance
- ^d Low confidence: About 2 out of 10 chance
- ^e Very low confidence: Less than a 1 out of 10 chance

Chapter- 7

Adaptation to Global Warming

Adaptation to global warming and climate change is a response to climate change that seeks to reduce the vulnerability of natural and human systems to climate change effects. Even if emissions are stabilized relatively soon, climate change and its effects will last many years, and adaptation will be necessary. Climate change adaptation is especially important in developing countries since those countries are predicted to bear the brunt of the effects of climate change. That is, the capacity and potential for humans to adapt (called adaptive capacity) is unevenly distributed across different regions and populations, and developing countries generally have less capacity to adapt (Schneider *et al.*, 2007). Adaptive capacity is closely linked to social and economic development (IPCC, 2007). The economic costs of adaptation to climate change are likely to cost billions of dollars annually for the next several decades, though the amount of money needed is unknown. Adaptation will be more difficult for larger magnitudes and higher rates of climate change.

Another policy response to climate change, known as climate change mitigation (Verbruggen, 2007) is to reduce greenhouse gas (GHG) emissions or enhance the removal of these gases from the atmosphere (enhancing carbon sinks). Even the most effective reductions in emissions, however, would not prevent further climate change impacts, making the need for adaptation unavoidable (Klein *et al.*, 2007). In a literature assessment, Klein *et al.* (2007) assessed options for adaptation. They concluded, with very high confidence, that in the absence of mitigation efforts, the effects of climate change would reach such a magnitude as to make adaptation impossible for some natural systems, e.g., ecosystems. For human systems, the economic and social costs of unmitigated climate change would be very high.

Effects of Climate Change

The projected effects for the environment and for human life are numerous and varied. The main effect is an increasing global average temperature. This causes a variety of secondary effects, namely, changes in patterns of precipitation, rising sea levels, altered patterns of agriculture, increased extreme weather events, the expansion of the range of tropical diseases, the opening of new trade routes.

Potential effects include sea level rise of 110 to 770 mm (0.36 to 2.5 feet) between 1990 and 2100, repercussions to agriculture, possible slowing of the thermohaline circulation,

reductions in the ozone layer, increased intensity and frequency of extreme weather events, lowering of ocean pH, and the spread of tropical diseases such as malaria and dengue fever.

A summary of probable effects and recent understanding can be found in the report made for the IPCC Third Assessment Report by Working Group II. The 2007 contribution of Working Group II detailing the impacts of global warming for the IPCC Fourth Assessment Report has been summarized for policymakers.

Necessity for adaptation

In the Feb. 8, 2007 issue of Nature, a team of science policy experts argue that adapting to climate change would be a more effective means of dealing with global warming than reducing emissions of greenhouse gases.

National Academy of Sciences

One prominent attempt to address adaptation was a 1991 report by the American National Academy of Sciences, "Policy Implications of Greenhouse Warming." The National Academy report cautioned that agricultural adaptation will be essential in a greenhouse world.

IPCC Working Group II

IPCC Working Group II argues that mitigation and adaptation should be complementary components of a response strategy to global warming. Their report makes the following observations:

1. Adaptation is a necessary strategy at all scales to complement climate change mitigation efforts.
2. Those with the least resources have the least capacity to adapt and are the most vulnerable
3. Adaptation, sustainable development, and enhancement of equity can be mutually reinforcing.

Adaptation is a necessary strategy

Because of the current and projected climate disruption precipitated by high levels of greenhouse gas emissions by the industrialized nations, adaptation is a necessary strategy at all scales to complement climate change mitigation efforts because we cannot be sure that all climate change can be mitigated. And indeed the odds are quite high that in the long run more warming is inevitable, given the high level of GHGs in the atmosphere, and the (several decade) delay between emissions and impact.

Adaptation has the potential to reduce adverse impacts of climate change and to enhance beneficial impacts, but will incur costs and will not prevent all damages. Extremes,

variability, and rates of change are all key features in addressing vulnerability and adaptation to climate change, not simply changes in average climate conditions.

Human and natural systems will to some degree adapt autonomously to climate change. Planned adaptation can supplement autonomous adaptation, though there are more options and greater possibility for offering incentives in the case of adaptation of human systems than in the case of adaptation to protect natural systems.

Disadvantaged nations

The ability of human systems to adapt to and cope with climate change depends on such factors as wealth, technology, education, infrastructure, access to resources, management capabilities, acceptance of the existence of climate change and the consequent need for action, and sociopolitical will. Populations and communities are highly variable in their endowments of these attributes, with Developing nations being among those worst-placed to adapt to global warming.

Mutual reinforcement

Many communities and regions that are vulnerable to climate change are also under pressure from forces such as population growth, resource depletion, and poverty. Policies that lessen pressures on resources, improve management of environmental risks, and increase the welfare of the poorest members of society can simultaneously advance sustainable development and equity, enhance adaptive capacity, and reduce vulnerability to climate and other stresses. Inclusion of climatic risks in the design and implementation of national and international development initiatives such as polar cities can promote equity and development that is more sustainable and that reduces vulnerability to climate change.

Mitigation

Yohe *et al.* (2007) assessed the literature on sustainability and climate change. With high confidence, they suggested that up to the year 2050, an effort to cap GHG emissions at 550 ppm would benefit developing countries significantly. This was judged to be especially the case when combined with enhanced adaptation. By 2100, however, it was still judged likely that there would be significant climate change impacts. This was judged to be the case even with aggressive mitigation and significantly enhanced adaptive capacity.

Tradeoffs and economics

Adaptation and mitigation can be viewed as two competing policy responses, with tradeoffs between the two. The other tradeoff is with climate change impacts. In practice, however, the actual tradeoffs are debatable (Schneider *et al.*, 2001). This is because the people who bear emission reduction costs or benefits are often different from those who pay or benefit from adaptation measures.

Economists, using cost-benefit analysis, have attempted to calculate an "optimal" balance of the costs and benefits between climate change impacts, adaptation, and mitigation (Toth *et al.*, 2001). There are difficulties in doing this calculation, for example, future climate change damages are uncertain, as are the future costs of adaptation.

Also, deciding what "optimal" is depends on value judgements made by the economist doing the study (Azar, 1998). For example, how to value impacts occurring in different regions and different times, and "non-market" impacts, e.g., damages to ecosystems (Smith *et al.*, 2001). Economics cannot provide definitive answers to these questions over valuation, and some valuations may be viewed as being controversial.

Some reviews indicate that policymakers are uncomfortable with using the results of this type of economic analysis (Klein *et al.*, 2007). This is due to the uncertainties surrounding cost estimates for climate change damages, adaptation, and mitigation. Another type of analysis is based on a risk-based approach to the problem. Stern (2007) (referred to by Klein *et al.*, 2007), for example, used such an approach. He argued that adaptation would play an important role in climate policy, but not in an explicit trade-off against mitigation.

UNFCCC

In the United Nations Framework Convention on Climate Change (UNFCCC), which most countries are Parties to (UNFCCC, n.d.), countries have made commitments to assist those most vulnerable in adapting to climate change (Banuri *et al.*, 1996, p. 98). The Clean Development Mechanism (CDM), set up as part of the Kyoto Protocol to the Framework Convention, is the main source of income for the UNFCCC Adaptation Fund. This fund was established in 2007 (World Bank, 2010, pp. 262–263). The CDM is subject to a 2% levy, which could raise between \$300 million and \$600 million over the 2008-12 period. The actual amount raised will depend on the carbon price.

Although established under the Kyoto Protocol, the Adaptation Fund has been very slow to operationalize and has not as yet (August 2010) disbursed any funding. The call for Proposals was issued in April 2010

Institution of Mechanical Engineers

In February 2009, the Institution of Mechanical Engineers (UK) issued a report in which they expressed pessimism about the ability of any international agreement, such as Kyoto Treaty to reduce carbon emissions. While it did not dismiss mitigation policy all together, it stated that they are "realistic enough to recognise that global CO₂ emissions are not reducing and our climate is changing so unless we adapt, we are likely to face a difficult future."

Conceptualising adaptation

Adaptation can be defined as adjustments of a system to reduce vulnerability and to increase the resilience of system to change, in this case in the climate system. Adaptation occurs at a range of inter-linking scales, and can either occur in anticipation of change (anticipatory adaptation), or be a response to those changes (reactive adaptation). Most adaptation being implemented at present is responding to current climate trends and variability, for example increased use of artificial snow-making in the European Alps. Some adaptation measures, however, are anticipating future climate change, such as the construction of the Confederation Bridge in Canada at a higher elevation to take into account the effect of future sea-level rise on ship clearance under the bridge.

Adaptive capacity and vulnerability are important concepts for understanding adaptation; vulnerability can be seen as the context in which adaptation takes place, and adaptive capacity is the ability or potential of a system to respond successfully to climate variability and change, in order to reduce adverse impacts and take advantage of new opportunities. Those societies that can respond to change quickly and successfully have a high adaptive capacity. High adaptive capacity does not necessarily translate into successful adaptation. For example the adaptive capacity in W. Europe is high, and the risks of warmer winters increasing the range of livestock diseases was well documented, but many parts of Europe were still badly affected by outbreaks of the Bluetongue virus in livestock in 2007.

Adaptive capacity is driven by factors operating at many different interlinked scales, and it is important to understand the ways in which the different drivers of adaptive capacity interact. Physical constraints are important, but in most cases it is social processes which increase or decrease adaptive capacity; it can be said that adaptive capacity is socially constructed. The social drivers of adaptive capacity are varied but may include broad structures such as economic and political processes, as well as processes which operate at a very local scale, such as access to decision-making and the structure of social networks and relationships within a community. Adaptive capacity at a local scale is constrained by larger scale processes. For example a farmer's adaptive capacity will not only depend on access to resources (both physical and social) within the community which allow a crop to be grown successfully, but also the effect of macro-scale economic processes on the price received for the crop. Gender is another factor which is important in determining adaptive capacity constrain adaptive capacity and vulnerability, for example women may have participation in decision-making, or be constrained by lower levels of education.

The social construction of adaptive capacity is very important when thinking about the risks and impacts of a changing climate. It is not just the change in climate which will affect vulnerability and livelihoods, but the way that these changes are negotiated through complex social systems. A 10% decrease in rainfall may be acceptable and manageable to members of a community who have access to improved agricultural techniques, or whose livelihoods are in some way diversified, whereas marginalised members of the community may not be able to cope with these changes. Adaptation can be seen as a

social and institutional process that involves reflecting on and responding to current trends and projected changes in climate.

Both temporal and spatial scales are very important in thinking about adaptation, as is the frame of reference taken for looking at adaptation. Much adaptation takes place in relation to short-term climate variability, however this may cause maladaptation to longer-term climatic trends. For example the expansion of irrigation in Egypt into the W. Sinai desert due to a period of higher river flows is a maladaptation when viewed in relation to the longer term projections of drying in the region). Adaptations at one scale can also create externalities at another by reducing the adaptive capacity of other actors. This is often the case when broad assessments of the costs and benefits of adaptation are examined at smaller scales and it is possible to see that whilst the adaptation may benefit some actors, it has a negative effect on others.

It is clear from the literature that people have always adapted to a changing climate and that coping strategies already exist in many communities, for example changing sowing times or adopting new water-saving techniques. Traditional knowledge and coping strategies must be maintained and strengthened, otherwise adaptive capacity may be weakened as local knowledge of the environment is lost. Strengthening these indigenous techniques and building upon them also makes it more likely that adaptation strategies will be adopted, as it creates more community ownership and involvement in the process. In some cases however this will be not be enough to adapt to new conditions which are outside the range of those previously experienced, and new techniques will be needed.

Criteria for assessing responses

James Titus identifies the following criteria that policy makers should use in assessing responses to global warming:

- Economic Efficiency: Will the initiative yield benefits substantially greater than if the resources were applied elsewhere?
- Flexibility: Is the strategy reasonable for the entire range of possible changes in temperatures, precipitation, and sea level?
- Urgency: Would the strategy be successful if implementation were delayed ten or twenty years?
- Low Cost: Does the strategy require minimal resources?
- Equity: Does the strategy unfairly benefit some at the expense of other regions, generations, or economic classes?
- Institutional feasibility: Is the strategy acceptable to the public? Can it be implemented with existing institutions under existing laws?
- Unique or Critical Resources: Would the strategy decrease the risk of losing unique environmental or cultural resources?
- Health and Safety: Would the proposed strategy increase or decrease the risk of disease or injury?
- Consistency: Does the policy support other national state, community, or private goals?

- Private v. Public Sector: Does the strategy minimize governmental interference with decisions best made by the private sector?

Costs

The United Nations Development Programme estimated that an additional USD 86 billion per year would be needed in 2015.

According to UNFCCC estimates in 2007, costs of adaptation to climate change would cost \$49–171 Billion per annum globally by 2030, of which a significant share of the additional investment and financial flows, USD 28-67 billion would be needed in 2030 in non-Annex I Parties. This represents a doubling of current official development assistance (ODA).

This estimate has been critiqued by Parry *et al.* (2009), in a joint study by IIED and the Grantham Institute, which argues that the UNFCCC estimate underestimates the cost of adaptation to climate change by a factor of 2 or 3. Moreover, sectors such as tourism, mining, energy and retail were not included in the UNFCCC estimate.

The more recent World Bank Study on the 'Economics of Adaptation to Climate Change' found that the costs of adaptation would be in the range of \$75–100 Billion per year between 2010 and 2050; with higher estimates under the wetter global scenario than the drier scenario, assuming that warming will be about 2 degrees by 2050.

The benefits of strong, early action on mitigation considerably outweigh the costs. The Copenhagen Accord was agreed on in order to create a commitment by developed countries to provide:

new and additional resources...approaching USD 30 billion for the period 2010- 2012 with balanced allocation between adaptation and mitigation... [and] in the context of meaningful mitigation actions and transparency on implementation, developed countries commit to a goal of mobilizing jointly USD 100 billion dollars a year by 2020 to address the needs of developing countries.
—Copenhagen Accord

However, a key point of contention between states at the UNFCC Copenhagen Climate Summit was who was to foot the bill and if aid is to be given, how is it to affect other levels of development aid. The concept of **additionality** has thus arisen and the EU has asked its member states to come up with definitions of what they understand additionality to mean, the four main definitions are:

1. Climate finance classified as aid, but additional to (over and above) the '0.7%' ODA target;
2. Increase on previous year's Official Development Assistance (ODA) spent on climate change mitigation;

3. Rising ODA levels that include climate change finance but where it is limited to a specified percentage; and
4. Increase in climate finance not connected to ODA.

The main point being that there is a conflict between the OECD states budget deficit cuts, the need to help developing countries adapt to develop sustainably and the need to ensure that funding does not come from cutting aid to other important Millennium Development Goals.

Adaptation mechanisms

Scheraga and Grambsch identify 9 fundamental principles to be considered when designing adaptation policy.

1. The effects of climate change vary by region.
2. The effects of climate change may vary across demographic groups.
3. Climate change poses both risks and opportunities.
4. The effects of climate change must be considered in the context of multiple stressors and factors, which may be as important to the design of adaptive responses as the sensitivity of the change.
5. Adaptation comes at a cost.
6. Adaptive responses vary in effectiveness, as demonstrated by current efforts to cope with climate variability.
7. The systemic nature of climate impacts complicates the development of adaptation policy.
8. Maladaptation can result in negative effects that are as serious as the climate-induced effects that are being avoided.
9. Many opportunities for adaptation make sense whether or not the effects of climate change are realized.

Methods of adaptation

Examples of adaptation include defending against rising sea levels through better flood defenses, and changing patterns of land use like avoiding more vulnerable areas for housing.

Enhancing adaptive capacity

In a literature assessment, Smit *et al.* (2001) concluded that enhanced adaptive capacity would reduce vulnerability to climate change. In their view, activities that enhance adaptive capacity are essentially equivalent to activities that promote sustainable development. These activities include:

- improving access to resources
- reducing poverty
- lowering inequities of resources and wealth among groups

- improving education and information
- improving infrastructure
- improving institutional capacity and efficiency

Adaptation through local planning

Local land use and municipal planning represent important avenues for adaptation to global warming. These forms of planning are recognised as central to avoiding the impacts of climate related hazards such as floods and heat stress, planning for demographic and consumption transition, and plans for ecosystem conservation. This type of planning is different from the National Adaptation Programs of Action (NAPAs) which are intended to be frameworks for prioritizing adaptation needs. At the local scale, municipalities are at the coal face of adaptation where impacts are experienced in the forms of inundation, bushfires, heatwaves and rising sea levels.

Cities are planning for adapting to global warming and climate change. The New York Times began a series of articles on this subject with Chicago's adaptation initiatives being highlighted. Projects include changing to heat tolerant tree varieties, changing to water permeable pavements to absorb higher rainfalls and adding air conditioning in public schools. New York and other cities are involved in similar planning.

Adaptation through local planning occurs in two distinct modes. The first is strategic planning, which is important but not unique to local governments. At the local scale it fosters community vision, aspirational goals and place-making, along with defining pathways to achieve these goals. The second form is land-use planning, and is focused on the allocation of space to balance economic prosperity with acceptable living standards and the conservation of natural resources. Although these two types of planning are quite different in practice, and in many cases are managed by different departments, we propose that both are highly important to climate change adaptation, and can contribute to achieving adaptation at the local scale. Significant constraints are recognised to hinder adaptation through planning, including limited resources, lack of information, competing planning agendas and complying with requirements from other levels of government.

Agricultural production

A significant effect of global climate change is the altering of global rainfall patterns, with certain effects on agriculture. Extended drought can cause the failure of small and marginal farms with resultant economic, political and social disruption.

However, such events have previously occurred in human history independent of global climate change. In recent decades, global trade has created distribution networks capable of delivering surplus food to where it is needed, thus reducing local impact. There are also several ways to adapt to and minimize the disruptive effects of rainfall patterns.

Drought tolerant crop varieties

Agriculture of any kind is strongly influenced by the availability of water. Climate change will modify rainfall, evaporation, runoff, and soil moisture storage. Changes in total seasonal precipitation or in its pattern of variability are both important. The occurrence of moisture stress during flowering, pollination, and grain-filling is harmful to most crops and particularly so to corn, soybeans, and wheat. Increased evaporation from the soil and accelerated transpiration in the plants themselves will cause moisture stress. As a result, there will be a need to develop crop varieties with greater drought tolerance.

More spending on irrigation

The demand for water for irrigation is projected to rise in a warmer climate, bringing increased competition between agriculture—already the largest consumer of water resources in semi-arid regions—and urban as well as industrial users. Falling water tables and the resulting increase in the energy needed to pump water will make the practice of irrigation more expensive, particularly when with drier conditions more water will be required per acre.

Rainwater storage

One strategy involves adapting urban areas to increasingly severe storms by increasing rainwater storage (domestic water butts, unpaved gardens etc.) and increasing the capacity of stormwater systems (and also separating stormwater from blackwater, so that overflows in peak periods do not contaminate rivers).

According to English Nature, gardeners can help mitigate the effects of climate change by providing habitats for the most threatened species, and/or saving water by changing gardens to use plants which require less.

Weather control

Russian and American scientists have in the past tried to control the weather, for example by seeding clouds with chemicals to try to produce rain when and where it is needed. A new method being developed involves replicating the urban heat island effect, where cities are slightly hotter than the countryside because they are darker and absorb more heat. This creates 28% more rain 20–40 miles downwind from cities compared to upwind. On the timescale of several decades, new weather control techniques may become feasible which would allow control of extreme weather such as hurricanes.

The World Meteorological Organization (WMO) through its Commission for Atmospheric Sciences (CAS) has issued a "STATEMENT ON WEATHER MODIFICATION" as well as "GUIDELINES FOR THE PLANNING OF WEATHER MODIFICATION ACTIVITIES" in 2007, stating among others that "Purposeful augmentation of precipitation, reduction of hail damage, dispersion of fog and other types of cloud and storm modifications by cloud seeding are developing technologies which are

still striving to achieve a sound scientific foundation and which have to be adapted to enormously varied natural conditions."

Damming glacial lakes

Glacial lake outburst floods may become a bigger concern due to the retreat of glaciers, leaving behind numerous lakes that are impounded by often weak terminal moraine dams. In the past, the sudden failure of these dams has resulted in localized property damage, injury and deaths. Glacial lakes in danger of bursting can have their moraines replaced with concrete dams (which may also provide hydroelectric power).

Geoengineering

In a literature assessment, Barker *et al.* (2007) described geoengineering as a type of mitigation policy. IPCC (2007) concluded that geoengineering options, such as ocean fertilization to remove CO₂ from the atmosphere, remained largely unproven. It was judged that reliable cost estimates for geoengineering had not been published.

The Royal Society (2009) published the findings of a study into geoengineering. The authors of the study defined geoengineering as a "deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming" (p. ix). According to the study, the safest and most predictable method of moderating climate change is early action to reduce GHG emissions.

Scientists such as Ken Caldeira and Paul Crutzen, suggest geoengineering techniques, which can be employed to change the climate deliberately and thus control some of the effects of global warming. These include:

- Solar radiation management may be seen as an adaptation to global warming. Techniques such as space sunshade, creating stratospheric sulfur aerosols and painting roofing and paving materials white all fall into this category.
- Hydrological geoengineering - typically seeking to preserve sea ice or adjust thermohaline circulation by using methods such as diverting rivers to keep warm water away from sea ice, or tethering icebergs to prevent them drifting into warmer waters and melting. This may be seen as an adaptation technique, although by preventing Arctic methane release it may also have mitigation aspects as well.

Assisting disadvantaged nations

In 2000, there was a proposal made at the Sixth Conference of Parties to the UN Framework Convention on Climate Change that called for the creation of an Adaptation Fund of \$1 billion per year for developing countries, especially the least developed and small island states, to enable them to combat the consequences of climate change.

Many scientists, policy makers and the IPCC Fourth Assessment Report have agreed that disadvantaged nations, especially in the global south need more attention to the negative impacts of climate change. These regions are highly populated and people have generally lower adaptive capacity. A balance, however, between development and climate change mitigation and adaptation needs to be found.

In the global south, national governments are largely responsible for formulation and implementation of the adaptation plan, from local to the national level. In this context, a contradictory situation exists. National governments attach high priority to development policies and plans not climate change. Development agendas are driven by pre-existing problems such as poverty, malnutrition, food insecurity, availability of drinking water, indebtedness, illiteracy, unemployment, local resource conflicts, lower technological development etc. Here, it is important to recognize that if climate change phenomenon is not properly understood and coping strategies such as mitigation and adaptation are not adopted on timely manner, climate change impacts will exacerbate these pre-existing problems.

Hence, there is a need of exploring strategies of integration between the climate change plans and development plans in the global south. This integration should include principles such as social justice and equity, inclusion of marginal population in decision making, women's participation and promotion of social cohesion. Inclusion of these principles will not only promote mitigation and adaptation to climate change but will also make development more distributive.

Collaborative research from the Institute of Development Studies draws links between adaptation and poverty to help develop an agenda for pro-poor adaptation that can inform climate-resilient poverty reduction. Adaptation to climate change will be "ineffective and inequitable if it fails to learn and build upon an understanding of the multidimensional and differentiated nature of poverty and vulnerability". Poorer countries tend to be more seriously affected by climate change, yet have reduced assets and capacities with which to adapt. This has led to more activities to integrate adaptation within development and poverty reduction programmes. The rise of adaptation as a development issue has been influenced by concerns around minimising threats to progress on poverty reduction, notably the MDGs, and by the injustice of impacts that are felt hardest by those who have done least to contribute to the problem, framing adaptation as an equity and right issue.

Adaptation Finance

The aggregate of current climate change adaptation programs will not raise enough money to fund adaptation to climate change. There are, however, several programs and proposals to finance adaptation to climate change in developing countries. The United Nations Framework Convention on Climate Change runs a program called the Global Environmental Facility, which provides some funding for adaptation to least developed countries and small island states. Under the GEF umbrella, the GEF Trust Fund, the Least Developed Countries Fund, and the Special Climate Change Fund operate to carry out the climate change adaptation financing goals of the GEF. There are several other climate

change adaptation finance proposals, most of which employ official development assistance or ODA. These proposals range from a World Bank program, to proposals involving auctioning of carbon allowances, to a global carbon or transportation tax, to compensation-based funding. Other proposals suggest using market-based mechanisms, rather than ODA, such as a vulnerability reduction credit (VRC) or a program similar to the Clean Development Mechanism, to raise private money for climate change adaptation. The Copenhagen Accord, the most recent global climate change agreement, commits developed countries to goal of sending \$110 billion to developing countries in assistance for climate change mitigation and climate change adaptation through 2020. This agreement, while not binding, would dwarf current amounts dedicated to adaptation in developing countries.

Adaptation measures by country

Numerous countries have held inquiries into, planned, or started adaptation measures including Australia. The state of California has also issued a document titled "2009 California Climate Adaptation Strategy Discussion Draft" that summarizes the best known science on climate change impacts in seven specific sectors and provides recommendations on how to manage against those threats. Poorer communities have gotten help with climate adaptation in places like Bangladesh as well.

Chapter- 8

Global Warming Controversy

The **global warming controversy** is a variety of disputes regarding the nature, causes, and consequences of global warming. The disputed issues include the causes of increased global average air temperature, especially since the mid-20th century, whether this warming trend is unprecedented or within normal climatic variations, whether humankind has contributed significantly to it, and whether the increase is wholly or partially an artifact of poor measurements. Additional disputes concern estimates of climate sensitivity, predictions of additional warming, and what the consequences of global warming will be.

The controversy is significantly more pronounced in the popular media than in the scientific literature, where there is a strong consensus that global surface temperatures have increased in recent decades and that the trend is caused mainly by human-induced emissions of greenhouse gases. No scientific body of national or international standing disagrees with this view, though a few organisations hold non-committal positions.

History

Public opinion

The level of coverage that US mass media devoted to global warming "was minimal prior to 1988" but interest increased significantly after the drought of 1988, and related Senate testimony of James E. Hansen "attributing the abnormally hot weather plaguing our nation to global warming". Similarly, incipient coverage of climate change in the British press "changed at the end of 1988 ... stimulated by Margaret Thatcher's appropriation of the risks of climate change to promote nuclear energy and dismantle the coal industry ... but also by environmental organizations and political forces in opposition who demanded solutions that contrasted with the government's". All European Union member states ratified the 1997 Kyoto Protocol, and many European countries had already been taking action to reduce greenhouse gas emissions prior to 1990. For example, Margaret Thatcher advocated action against man-made climate change in 1988, and Germany started to take action after the Green Party took seats in Parliament across the 1980s. Substantial activity by NGOs took place as well. Both "global warming" and the more politically neutral "climate change" were listed by the Global Language Monitor as political buzzwords or catchphrases in 2005. In Europe, the notion of human influence on climate gained wide acceptance more rapidly than in many other parts of the world, most

notably the United States. A 2009 Eurobarometer survey titled "Europeans' Attitude Toward Climate Change" notes that, on the average, Europeans rate climate change as the second most serious problem facing the world today, between "poverty, the lack of food and drinking water" and "a major global economic downturn". 87% of Europeans consider climate change to be a "very serious" or "serious" problem, while 10% "do not consider it a serious problem".

There has been a debate among public commentators about how much weight and media coverage should be given to each side of the controversy. Andrew Neil of the BBC stated that "There's a great danger that on some issues we're becoming a one-party state in which we're meant to have only one kind of view. You don't have to be a climate-change denier to recognise that there's a great range of opinion on the subject".

The authors of the 2010 book Merchants of Doubt accuse climate change "skeptics" of trying to sow seeds of doubt in public opinion in order to halt any meaningful social or political progress to reduce the impact of human carbon emissions. The fact that only half of the American population believe that global warming is caused by human activity could be seen as a victory for these so-called skeptics. One of the authors' main arguments is that most prominent scientists who have been voicing opposition to the near-universal consensus are being funded by industries, such as automotive and oil, that stand to lose money by government actions to regulate greenhouse gases.

A compendium of poll results on public perceptions about global warming is below.

Statement	% agree	Year
<i>(USA)</i> Global Warming is very/extremely important	49	2006
<i>(International)</i> Climate change is a serious problem.	90	2006
<i>(International)</i> Human activity is a significant cause of climate change.	79	2007
<i>(USA)</i> It's necessary to take major steps starting very soon.	59	2007
<i>(USA)</i> The Earth is getting warmer because of human activity	49	2009

In 2007 a report on public perceptions in the UK by Ipsos MORI reported that

- There is widespread recognition that the climate, irrespective of the cause, is changing - 88% believe this to be true.
- However, the public is out of step with the scientific community, with 41% believing that climate change is being caused by both human activity and natural processes. 46% believe human activity is the main cause.
- Only a small minority reject anthropogenic climate change, while almost half (44%) are very concerned. However, there remains a large proportion who are yet to be fully persuaded and hold doubts about the extent of the threat.
- There is still a strong appetite among the public for more information, and 63% say they need this to come to a firm view on the issue and what it means for them.
- The public continue to externalize climate change to other people, places and times. It is increasingly perceived as a major global issue with far-reaching

consequences for future generations - 45% say it is the most serious threat facing the World today and 53% believe it will impact significantly on future generations. However, the issue features less prominently nationally and locally, indeed only 9% believe climate change will have a significant impact upon them personally.

The Canadian science broadcaster and environmental activist, David Suzuki, reports that focus groups organized by the David Suzuki Foundation showed the public has a poor understanding of the science behind global warming. This is despite recent publicity through different means, including the films *An Inconvenient Truth* and *The 11th Hour*.

An example of the poor understanding is public confusion between global warming and ozone depletion or other environmental problems.

A 15-nation poll conducted in 2006 by Pew Global found that there "is a substantial gap in concern over global warming – roughly two-thirds of Japanese (66%) and Indians (65%) say they personally worry a great deal about global warming. Roughly half of the populations of Spain (51%) and France (46%) also express great concern over global warming, based on those who have heard about the issue. But there is no evidence of alarm over global warming in either the United States or China – the two largest producers of greenhouse gases. Just 19% of Americans and 20% of the Chinese who have heard of the issue say they worry a lot about global warming – the lowest percentages in the 15 countries surveyed. Moreover, nearly half of Americans (47%) and somewhat fewer Chinese (37%) express little or no concern about the problem".

A 47-nation poll by Pew Global Attitudes conducted in 2007 found that "Substantial majorities 25 of 37 countries say global warming is a 'very serious' problem".

There are differences between the opinion of scientists and that of the general public. A 2009 poll by Pew Research Center found that "[w]hile 84% of scientists say the earth is getting warmer because of human activity such as burning fossil fuels, just 49% of the public agrees". A 2010 poll in the UK for the BBC showed "Climate scepticism on the rise". Robert Watson found this "very disappointing" and said that "We need the public to understand that climate change is serious so they will change their habits and help us move towards a low carbon economy".

Related controversies

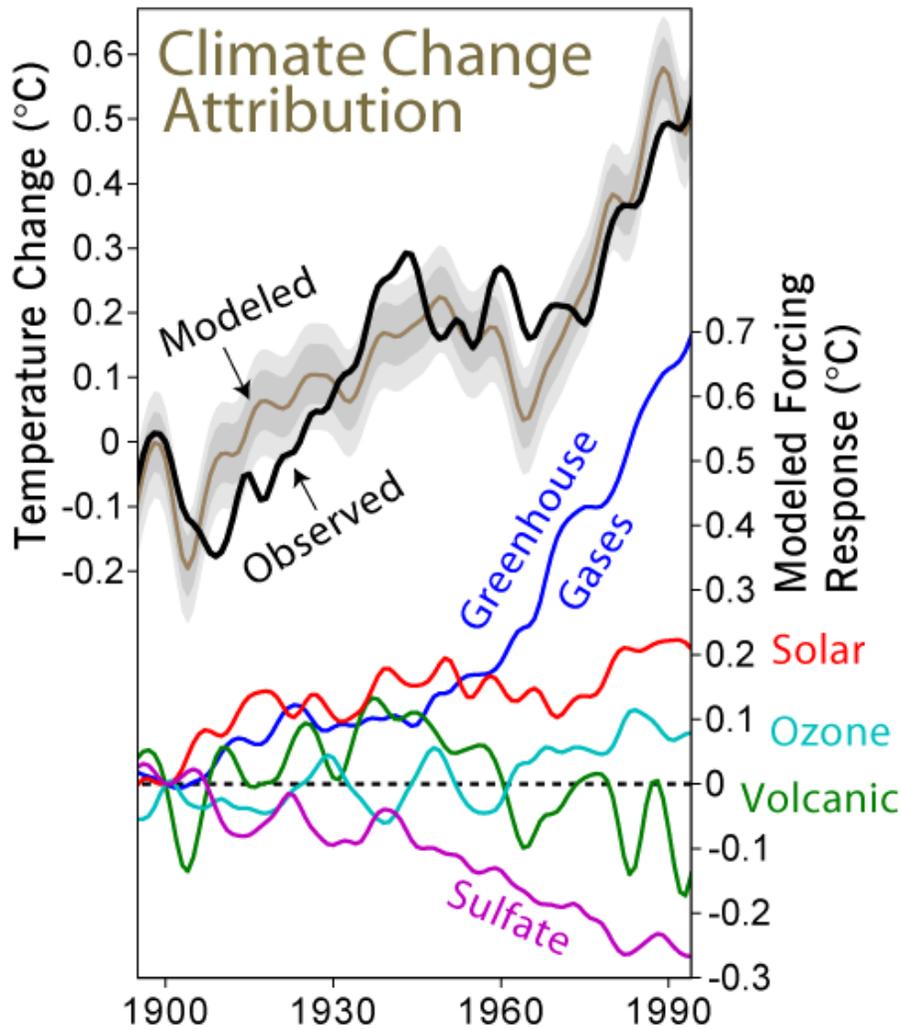
Many of the critics of the consensus view on global warming have disagreed, in whole or part, with the scientific consensus regarding other issues, particularly those relating to environmental risks, such as ozone depletion, DDT, and passive smoking. Chris Mooney, author of *The Republican War on Science*, has argued that the appearance of overlapping groups of skeptical scientists, commentators and think tanks in seemingly unrelated controversies results from an organized attempt to replace scientific analysis with political ideology. Mooney claims that the promotion of doubt regarding issues that are politically, but not scientifically, controversial became increasingly prevalent under the

Bush Administration and constituted a "Republican war on science". This is also the subject of a 2004 book by environmental lawyer Robert F. Kennedy Jr. entitled *Crimes Against Nature: How George W. Bush and Corporate Pals are Plundering the Country and Hijacking Our Democracy*. Another book on this topic is *The Assault on Reason* by former U.S. Vice-President Al Gore. Earlier instances of this trend are also covered in the book *The Heat Is On* by Ross Gelbspan.

Some critics of the scientific consensus on global warming have argued that these issues should not be linked and that reference to them constitutes an unjustified ad hominem attack. Political scientist Roger Pielke, Jr., responding to Mooney, has argued that science is inevitably intertwined with politics.

The mainstream scientific position, and challenges to it

The finding that the climate has warmed in recent decades and that human activities are already contributing adversely to global climate change has been endorsed by every national science academy that has issued a statement on climate change, including the science academies of all of the major industrialized countries.



Reproduction of the temperature record using historical forcings

Attribution of recent climate change discusses how global warming is attributed to anthropogenic GHGs.

On the assertion of consensus

Environmental groups, many governmental reports, and the media in many countries often state that there is virtually unanimous agreement in the scientific community in support of human-caused global warming. Among opponents of the mainstream scientific assessment, some claim that there is consensus on humans having an effect on climate without universal agreement about the quantitative magnitude of Anthropogenic global warming (AGW) relative to natural forcings and its harm to benefit ratio. Other opponents dismiss it altogether, or highlight the dangers of focusing on only one viewpoint in the context of what they say is unsettled science, or point out that science is based on facts and not on opinion polls.

Environmental journalist George Monbiot revealed that a list titled "500 Scientists Whose Research Contradicts Man-Made Global Warming Scares" published in 2007 by the Hudson Institute and distributed by the Heartland Institute included numerous scientists who had demanded to be removed from the list. The institute refused requests by scientists to have their names removed, stating that the scientists "have no right—legally or ethically—to demand that their names be removed from a bibliography composed by researchers with whom they disagree."

A 2010 paper in the Proceedings of the National Academy of Sciences analysed "1,372 climate researchers and their publication and citation data to show that (i) 97–98% of the climate researchers most actively publishing in the field support the tenets of ACC outlined by the Intergovernmental Panel on Climate Change, and (ii) the relative climate expertise and scientific prominence of the researchers unconvinced of ACC are substantially below that of the convinced researchers". Judith Curry has said "This is a completely unconvincing analysis", whereas Naomi Oreskes said that the paper shows that "the vast majority of working [climate] research scientists are in agreement [on climate change]... Those who don't agree, are, unfortunately—and this is hard to say without sounding elitist—mostly either not actually climate researchers or not very productive researchers". Jim Prall, one of the coauthors of the study, acknowledged "it would be helpful to have lukewarm [as] a third category".

On the authority of the IPCC

The "standard" view of climate change has come to be defined by the reports of the IPCC, which is supported by many other science academies and scientific organizations. In 2001, sixteen of the world's national science academies made a joint-statement on climate change, and gave their support for the IPCC

Opponents have generally attacked either the IPCC's processes, people or the Synthesis and Executive summaries; the scientific reports attract less attention. Some of the controversy and criticism has originated from experts invited by the IPCC to submit reports or serve on its panels. For example, Richard Lindzen has publicly dissented from IPCC positions.

Christopher Landsea, a hurricane researcher, said of "the part of the IPCC to which my expertise is relevant" that "I personally cannot in good faith continue to contribute to a process that I view as both being motivated by pre-conceived agendas and being scientifically unsound", because of comments made at a press conference by Kevin Trenberth of which Landsea disapproved. Trenberth said that "Landsea's comments were not correct"; the IPCC replied that "individual scientists can do what they wish in their own rights, as long as they are not saying anything on behalf of the IPCC" and offered to include Landsea in the review phase of the AR4. Roger Pielke, Jr. commented that "Both Landsea and Trenberth can and should feel vindicated... the IPCC accurately reported the state of scientific understandings of tropical cyclones and climate change in its recent summary for policy makers".

In 2005, the House of Lords Economics Committee wrote that "We have some concerns about the objectivity of the IPCC process, with some of its emissions scenarios and summary documentation apparently influenced by political considerations". It doubted the high emission scenarios and said that the IPCC had "played-down" what the committee called "some positive aspects of global warming". The main claims of the House of Lords Economics Committee were rejected in the response made by the United Kingdom government and by the Stern Review.

Speaking to the difficulty of establishing scientific consensus on the precise extent of human action on climate change, John Christy, a contributing author, wrote:

Contributing authors essentially are asked to contribute a little text at the beginning and to review the first two drafts. We have no control over editing decisions. Even less influence is granted the 2,000 or so reviewers. Thus, to say that 800 contributing authors or 2,000 reviewers reached consensus on anything describes a situation that is not reality.

He added:

I've written a number of papers about the precision of our climate records. The impact of Kyoto-like proposals will be too small for we scientists to measure due to the natural variations of climate and the lack of precision in our observing system. In other words we will not be able to tell lawmakers with high confidence that specific regulations achieve anything in terms of climate in this country or the world. Additionally, the climate system is immensely complicated and really cannot be tweaked for a predictable outcome.

On December 10, 2008, a report was released by the U.S. Senate Committee on Environment and Public Works Minority members, under the leadership of the Senate's most vocal global warming skeptic Jim Inhofe. The timing of the report coincided with the UN global warming conference in Poznań, Poland. It claims to summarize scientific dissent from the IPCC. Many of the claims about the numbers of individuals listed in the report, whether they are actually scientists, and whether they support the positions attributed to them, have been disputed.

While some critics have argued that the IPCC overstates likely global warming, others have made the opposite criticism. David Biello, writing in the *Scientific American*, argues that, because of the need to secure consensus among governmental representatives, the IPCC reports give conservative estimates of the likely extent and effects of global warming. *Science* editor Brooks Hanson states in a 2010 editorial: "The IPCC reports have underestimated the pace of climate change while overestimating societies' abilities to curb greenhouse gas emissions". Climate scientist James E. Hansen argues that the IPCC's conservativeness seriously underestimates the risk of sea-level rise on the order of meters—enough to inundate many low-lying areas, such as the southern third of Florida. Roger A. Pielke Sr. has also stated that "Humans are significantly altering the global climate, but in a variety of diverse ways beyond the radiative effect of carbon dioxide. The IPCC assessments have been too conservative in recognizing the importance of these human climate forcings as they alter regional and global climate".

Henderson-Sellers has collected comments from IPCC authors in a 2007 workshop revealing a number of concerns.

Greenhouse gases

Attribution of recent climate change discusses the evidence for recent global warming. Correlation of CO₂ and temperature is not part of this evidence. Nonetheless, one argument against global warming claims that rising levels of carbon dioxide (CO₂) and other greenhouse gases (GHGs) do not correlate with global warming.

- Studies of ice cores show that carbon dioxide level variations follow 600 +/- 400 years after temperature variations. Recent warming is followed by carbon dioxide levels with only a 5 months delay. The time lag has been used to argue that the current rise in CO₂ is a *result* of warming and not a cause. While it is generally agreed that variations before the industrial age are mostly timed by astronomical forcing, a main part of current warming is found to be timed by anthropogenic releases of CO₂, having a much closer time relation not observed in the past (thus returning the argument to the importance of human CO₂ emissions). Analysis of carbon isotopes in atmospheric CO₂ shows that the recent observed CO₂ increase cannot have come from the oceans, volcanoes, or the biosphere, and thus is not a response to rising temperatures as would be required if the same processes creating past lags were active now.
- Carbon dioxide accounts for about 390 parts per million by volume (ppm) of the Earth's atmosphere, increasing from 284 ppm in the 1830s to 387 ppm in 2009. Carbon dioxide contributes between 9 and 26% of the natural greenhouse effect.
- In the Ordovician period of the Paleozoic era (about 450 million years ago), the Earth had an atmospheric CO₂ concentration estimated at 4400ppm (or 0.44% of the atmosphere), while also having evidence of some glaciation. Modeling work has shown that it is possible for local areas at elevations greater than 300–500 meters to contain year-round snow cover even with high atmospheric CO₂ concentrations. A 2006 study suggests that the elevated CO₂ levels and the glaciation are not synchronous, but rather that weathering associated with the uplift and erosion of the Appalachian Mountains greatly reduced atmospheric greenhouse gas concentrations and permitted the observed glaciation.

As noted above, climate models are only able to simulate the temperature record of the past century when GHG forcing is included, being consistent with the findings of the IPCC which has stated that: "Greenhouse gas forcing, largely the result of human activities, has very likely caused most of the observed global warming over the last 50 years"

The "standard" set of scenarios for future atmospheric greenhouse gases are the IPCC SRES scenarios. The purpose of the range of scenarios is not to predict what exact course the future of emissions will take, but what it may take under a range of possible population, economic and societal trends. Climate models can be run using any of the scenarios as inputs to illustrate the different outcomes for climate change. No one

scenario is officially preferred, but in practice the "A1b" scenario roughly corresponding to 1%/year growth in atmospheric CO₂ is often used for modelling studies.

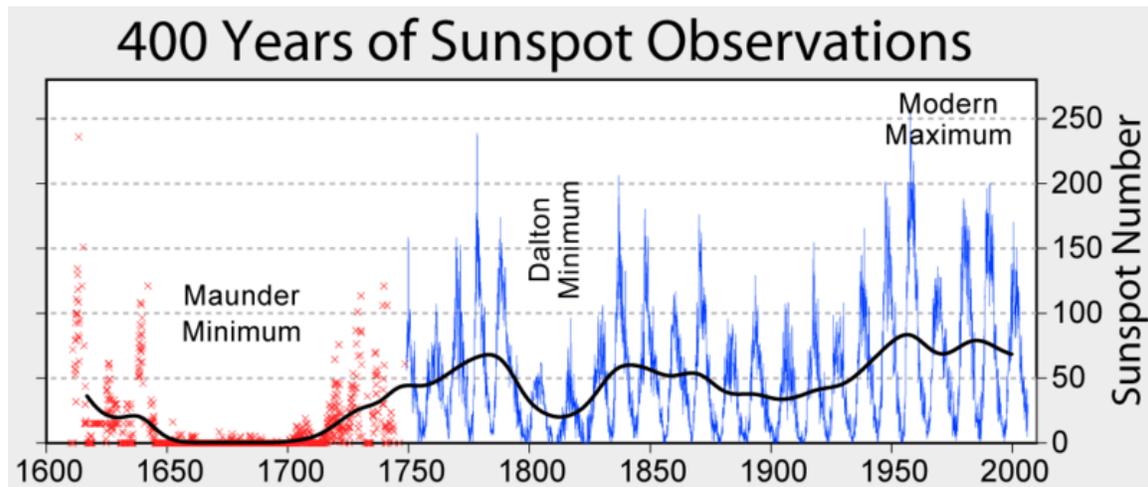
There is debate about the various scenarios for fossil fuel consumption. Global warming skeptic Fred Singer stated that "some good experts believe" that atmospheric CO₂ concentration will not double since economies are becoming less reliant on carbon.

However, The Stern report, like many other reports, notes the past correlation between CO₂ emissions and economic growth and then extrapolates using a "business as usual" scenario to predict GDP growth and hence CO₂ levels, concluding that:

Increasing scarcity of fossil fuels alone will not stop emissions growth in time. The stocks of hydrocarbons that are profitable to extract are more than enough to take the world to levels of CO₂ well beyond 750ppm with very dangerous consequences for climate change impacts.

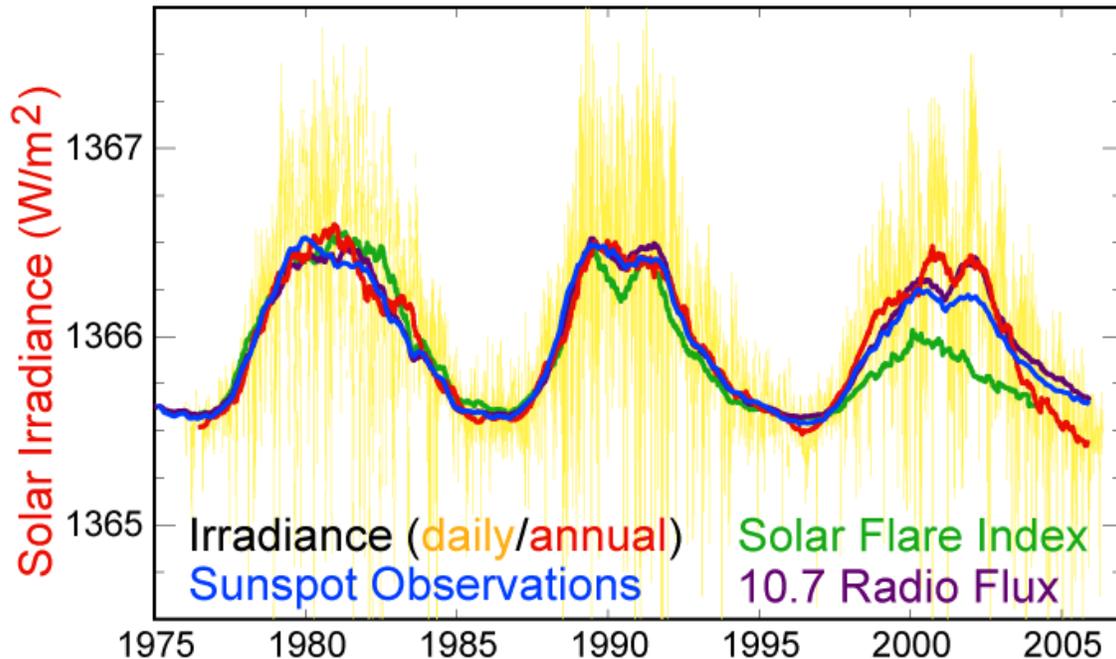
According to Lawrence Livermore National Laboratory, "the earth would warm by 8 degrees Celsius (14.4 degrees Fahrenheit) if humans use the entire planet's available fossil fuels by the year 2300".

Solar variation



400 year history of sunspot numbers

Solar Cycle Variations



Last 30 years of solar variability

Scientists opposing the mainstream scientific assessment of global warming express varied opinions concerning the cause of global warming. Some say only that it has not yet been ascertained whether humans are the primary cause of global warming; others attribute global warming to natural variation; ocean currents; increased solar activity or cosmic rays. The consensus position is that solar radiation may have increased by 0.12 W/m² since 1750, compared to 1.6 W/m² for the net anthropogenic forcing. The TAR said, "The combined change in radiative forcing of the two major natural factors (solar variation and volcanic aerosols) is estimated to be negative for the past two, and possibly the past four, decades". The AR4 makes no direct assertions on the recent role of solar forcing, but the previous statement is consistent with the AR4's figure 4.

A few studies claim that the present level of solar activity is historically high as determined by sunspot activity and other factors. Solar activity could affect climate either by variation in the Sun's output or, more speculatively, by an indirect effect on the amount of cloud formation. Solanki and co-workers suggest that solar activity for the last 60 to 70 years may be at its highest level in 8,000 years; Muscheler *et al.* disagree, suggesting that other comparably high levels of activity have occurred several times in the last few thousand years. Muscheler *et al.* concluded that "solar activity reconstructions tell us that only a minor fraction of the recent global warming can be explained by the variable Sun". Solanki *et al.* concluded "that solar variability is unlikely to have been the dominant cause of the strong warming during the past three decades", and that "at the most 30% of the strong warming since then can be of solar origin".

Another point of controversy is the correlation of temperature with solar variation.

Mike Lockwood and Claus Fröhlich reject the claim that the warming observed in the global mean surface temperature record since about 1850 is the result of solar variations. Lockwood and Fröhlich conclude that "the observed rapid rise in global mean temperatures seen after 1985 cannot be ascribed to solar variability, whichever of the mechanisms is invoked and no matter how much the solar variation is amplified.

Aerosols forcing

The "pause" in warming from the 1940s to 1960s is generally attributed to cooling effect of sulphate aerosols. More recently, this forcing has (relatively) declined, which may have enhanced warming, though the effect is regionally varying. Another example of this is in Ruckstuhl's paper who found a 60% reduction in aerosol concentrations over Europe causing solar brightening:

[...] the direct aerosol effect had an approximately five times larger impact on climate forcing than the indirect aerosol and other cloud effects. The overall aerosol and cloud induced surface climate forcing is $\sim +1 \text{ W m}^{-2} \text{ dec}^{-1}$ and has most probably strongly contributed to the recent rapid warming in Europe.

On the reliability of temperature records

Instrumental temperature record

Skeptics have questioned the accuracy of the instrumental temperature record on the basis of the urban heat island effect, the quality of the surface station network and what they view as unwarranted adjustments to the temperature record.

Skeptics contend that stations located in more populated areas could show warming due to increased heat generated by cities, rather than a global temperature rise. The IPCC Third Assessment Report acknowledges that the urban heat island is an important *local* effect, but cites analyses of historical data indicating that the effect of the urban heat island on the *global* temperature trend is no more than 0.05 °C (0.09 °F) degrees through 1990. More recently, Peterson (2003) found no difference between the warming observed in urban and rural areas.

Parker (2006) found that there was no difference in warming between calm and windy nights. Since the urban heat island effect is strongest for calm nights and is weak or absent on windy nights, this was taken as evidence that global temperature trends are not significantly contaminated by urban effects. Pielke and Matsui published a paper disagreeing with Parker's conclusions.

More recently, Roger A. Pielke and Stephen McIntyre have criticized the US instrumental temperature record and adjustments to it, and Pielke and others have criticized the poor quality siting of a number of weather stations in the United States. In

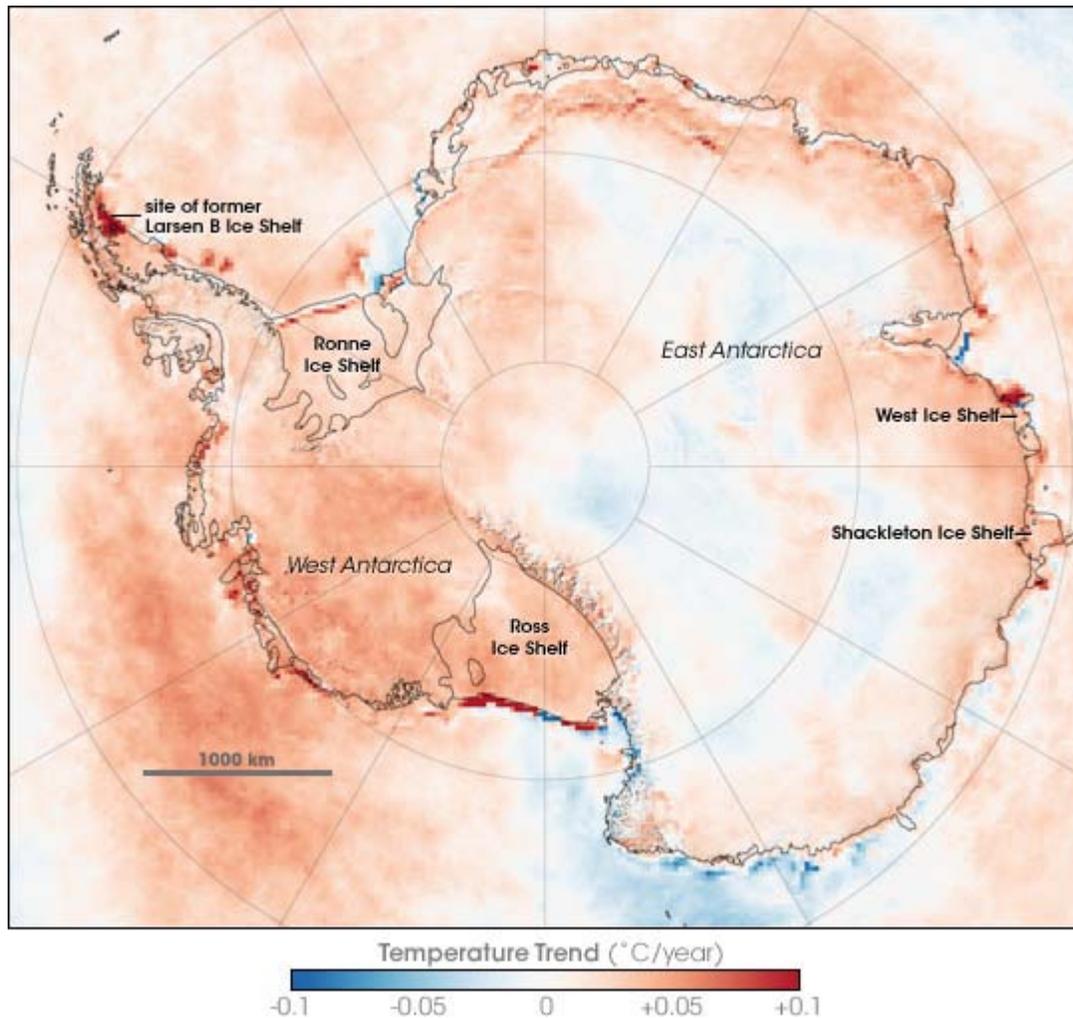
response, Anthony Watts began a volunteer effort to photographically document the siting quality of these stations. Based on the work of Watts, Stephen McIntyre has completed a reconstruction of U.S. temp history using only those weather stations identified so far as meeting the requirements to be CRN level 1 (excellent) or level 2 (good) stations. The higher quality stations indicate the warmest years in the U.S. were 1934 and 1921, followed by 1998 and 2006. McIntyre has made all of his methods, data and code available for others to reproduce his findings. McIntyre's analysis has not been published in the peer-reviewed literature.

Joe D'Aleo and other climate skeptics have also suggested that the NOAA and GISS temperature records show a warming trend due to the reduction of the number of weather stations used to calculate the average world temperature. He states that this is done by cherry picking weather stations in order to show a warming trend. Specifically, it is claimed that large regions of the temperature record are derived from other weather stations in the region. For example, Bolivia, a landlocked and high-altitude country, has its temperature derived from lower-altitude areas in the Amazon Basin and in Peru.

Tropospheric temperature record

General circulation models and basic physical considerations predict that in the tropics the temperature of the troposphere should increase more rapidly than the temperature of the surface. A 2006 report to the U.S. Climate Change Science Program noted that models and observations agreed on this amplification for monthly and interannual time scales but not for decadal time scales in most observed data sets. Improved measurement and analysis techniques have reconciled this discrepancy: corrected buoy and satellite surface temperatures are slightly cooler and corrected satellite and radiosonde measurements of the tropical troposphere are slightly warmer. Satellite temperature measurements show that tropospheric temperatures are increasing with "rates similar to those of the surface temperature", leading the IPCC to conclude that this discrepancy is reconciled.

Antarctica cooling



Antarctic Skin Temperature Trends between 1981 and 2007, based on thermal infrared observations made by a series of NOAA satellite sensors. Skin temperature trends do not necessarily reflect air temperature trends.

Various individuals, most notably writer Michael Crichton, have asserted that Antarctic temperature measurements contradict global warming. Observations unambiguously show the Peninsula to be warming. The trends elsewhere show both warming and cooling but are smaller and dependent on season and the timespan over which the trend is computed. Climate models predict that future trends in Antarctica are much smaller than in the Arctic.

To the extent that a controversy exists it is confined to the popular press and blogs; there is no evidence of a related controversy within the scientific community. Peter Doran, the lead author of the paper cited by Crichton, stated that "... our results have been misused as "evidence" against global warming by Crichton in his novel 'State of Fear'..." Others, for example RealClimate, agree there is no contradiction.

Climate sensitivity

Equilibrium climate sensitivity refers to the equilibrium change in global mean surface temperature (ΔT_s) following a unit change in the radiative forcing (RF).

(ΔT_s): $\Delta T_s = \lambda RF$, where λ is the climate sensitivity parameter

Climate sensitivity usually is expressed as the increase in global mean temperature resulting from a doubling of atmospheric CO₂. This value is estimated by the IPCC Fourth Assessment Report as "likely to be in the range 2 to 4.5 °C with a best estimate of about 3 °C".

Using a combination of surface temperature history and ocean heat content, Stephen E. Schwartz has proposed an estimate of climate sensitivity of 1.9 ± 1.0 K for doubled CO₂, revised upwards from 1.1 ± 0.5 K. Grant Foster, James Annan, Gavin Schmidt, and Michael E. Mann argue that there are errors in both versions of Schwartz's analysis. Astronomer Nir Shaviv also has computed a value for climate sensitivity of 0.35 ± 0.09 °K / (W/m²), which is consistent with a variety of historical datasets. Petr Chylek and co-authors have also proposed low climate sensitivity to doubled CO₂, estimated to be 1.6 K ± 0.4 K.

Infrared iris hypothesis

Richard Lindzen proposed an Infrared Iris hypothesis of compensating meteorological processes that tend to stabilize climate change. Roy Spencer et al. discovered "a net reduction in radiative input into the ocean-atmosphere system" in tropical intraseasonal oscillations that "may potentially support" the idea of an "Iris" effect, although they point out that their work is concerned with much shorter time scales. Other analyses have found that the iris effect is a *positive* feedback rather than the negative feedback proposed by Lindzen.

Internal radiative forcing

Roy Spencer hypothesizes there is an "Internal Radiative Forcing" affecting climate variability,

[...] mixing up of cause and effect when observing natural climate variability can lead to the mistaken conclusion that the climate system is more sensitive to greenhouse gas emissions than it really is. . . . it provides a quantitative mechanism for the (minority) view that global warming is mostly a manifestation of natural internal climate variability.

[...] low frequency, internal radiative forcing amounting to little more than 1 W m⁻², assumed to be proportional to a weighted average of the Southern Oscillation and Pacific Decadal Oscillation indices since 1900, produces ocean temperature behavior similar to that observed: warming from 1900 to 1940, then slight cooling through the 1970s, then

resumed warming up to the present, as well as 70% of the observed centennial temperature trend.

Spencer's hypothesis has not been published in a peer-reviewed journal.

Temperature predictions

Conventional predictions of future temperature rises depend on estimates of future GHG emissions and the climate sensitivity. Models referenced by the Intergovernmental Panel on Climate Change (IPCC) predict that global temperatures are likely to increase by 1.1 to 6.4 °C (2.0 to 11.5 °F) between 1990 and 2100. Others have proposed that temperature increases may be higher than IPCC estimates. One theory is that the climate may reach a "tipping point" where positive feedback effects lead to runaway global warming; such feedbacks include decreased reflection of solar radiation as sea ice melts, exposing darker seawater, and the potential release of large volumes of methane from thawing permafrost.

An example of a prediction that has been tested comes from 1959, when Dr. Bert Bolin, in a speech to the National Academy of Sciences, predicted that by the year 2000, there would be a 25% increase in carbon dioxide in the atmosphere compared to the levels in 1859. This prediction has proved to be an underestimate. The actual increase by 2000 was about 29%.

Some scientists, such as David Orrell or Henk Tennekes, say that climate change cannot be accurately predicted. Orrell says that the range of future increase in temperature suggested by the IPCC rather represents a social consensus in the climate community, but adds that "we are having a dangerous effect on the climate".

A 2007 study by David Douglass and coworkers concluded that the 22 most commonly used global climate models used by the IPCC were unable to accurately predict accelerated warming in the troposphere although they did match actual surface warming, concluding that "projections of future climate based on these models should be viewed with much caution". This result contrasts a similar study of 19 models which found that discrepancies between model predictions and actual temperature were likely due to measurement errors.

Forecasts confidence

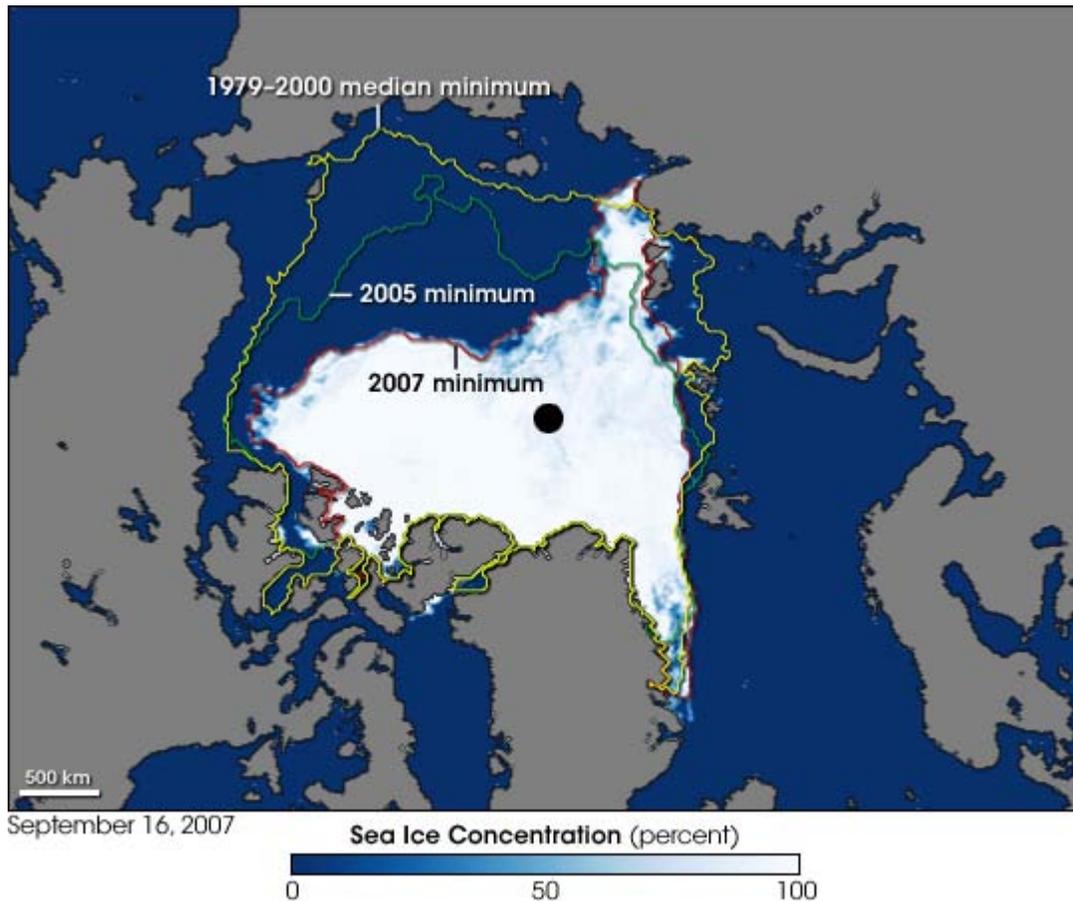
The IPCC states it has increased confidence in forecasts coming from General Circulation Models or GCMs. Chapter 8 of AR4 reads:

There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation). Over several decades of development,

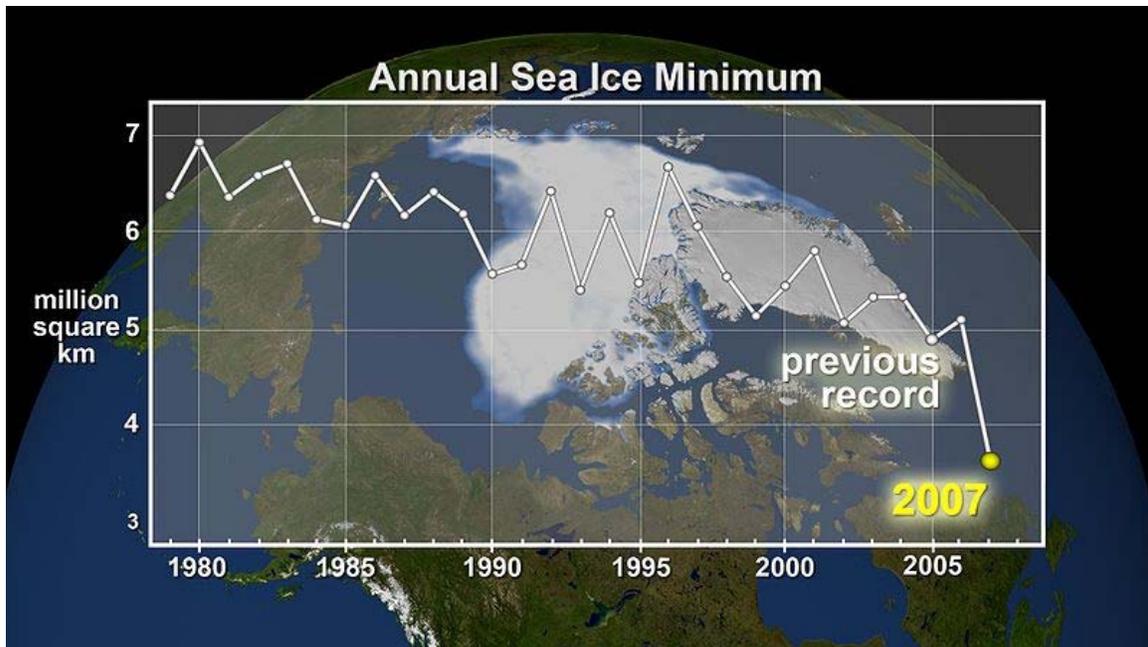
models have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases.

Certain scientists, skeptics and otherwise, believe this confidence in the models' ability to predict future climate is not earned.

Arctic shrinkage



Arctic Sea ice as of 2007 compared to 2005 and also compared to 1979-2000 average



Northern Hemisphere ice trends

One unsettled question related to temperature rises is if or when the Arctic sea may become ice-free in the summer (winter sea ice remains in all scenarios). Mark Serreze, the director of US National Snow and Ice Data Center, following the record low in 2007, stated "If you asked me a couple of years ago when the Arctic could lose all of its ice then I would have said 2100, or 2070 maybe. But now I think that 2030 is a reasonable estimate".

Data archiving and sharing

Scientific journals and funding agencies generally require authors of peer-reviewed research to archive all of the data necessary to reproduce their research. If another scientist attempts to reproduce the research and needs additional data, authors are expected (with few exceptions) to provide the data, metadata, methods and source code that may be necessary.

David Legates has claimed that Mann, Bradley and Hughes 1998, famous for its hockey stick-shaped historic temperature reconstruction, serves as an example of climate scientists not abiding by these policies and suggested that legislators might ultimately take action to enforce them.

Bets between scientists

A prediction market on climate futures, like other kinds of futures markets, could be used to establish the market consensus on climate change. There has been sporadic betting activity outside of a market framework. British climate scientist James Annan proposed bets with global warming skeptics concerning whether future temperatures will increase.

Two Russian solar physicists, Galina Mashnich and Vladimir Bashkirtsev, accepted the wager of US\$10,000 that the average global temperature during 2012-2017 would be lower than during 1998-2003. Annan first directly challenged Richard Lindzen. Lindzen had been willing to bet that global temperatures would drop over the next 20 years. Annan claimed Lindzen wanted odds of 50-1 against falling temperatures. Lindzen, however, claims that he asked for 2-1 odds against a temperature rise of over 0.4 °C. *The Guardian* columnist George Monbiot challenged Myron Ebell of the Competitive Enterprise Institute to a GB£5,000 bet of global warming versus global cooling. Annan and other proponents of the consensus state they have challenged other skeptics to bets over global warming that were not accepted, including Annan's attempt in 2005 to accept a bet that had been offered by Patrick Michaels in 1998 that temperatures would be cooler after ten years.

Political



The Washington Monument illuminated with a message from Greenpeace criticizing American environmental policy

In the U.S. global warming is often a partisan political issue. Republicans tend to oppose action against a threat that they regard as unproven, while Democrats tend to support actions that they believe will reduce global warming and its effects through the control of greenhouse gas emissions. Recently, bipartisan measures have been introduced.

Climatologist Kevin E. Trenberth stated:

The SPM was approved line by line by governments[...]. The argument here is that the scientists determine what can be said, but the governments determine how it can best be

said. Negotiations occur over wording to ensure accuracy, balance, clarity of message, and relevance to understanding and policy. The IPCC process is dependent on the good will of the participants in producing a balanced assessment. However, in Shanghai, it appeared that there were attempts to blunt, and perhaps obfuscate, the messages in the report, most notably by Saudi Arabia. This led to very protracted debates over wording on even bland and what should be uncontroversial text... The most contentious paragraph in the IPCC (2001) SPM was the concluding one on attribution. After much debate, the following was carefully crafted: "In the light of new evidence, and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse-gas concentrations".

As more evidence has become available over the existence of global warming debate has moved to further controversial issues, including:

1. The social and environmental impacts
2. The appropriate response to climate change
3. Whether decisions require less uncertainty

The single largest issue is the importance of a few degrees rise in temperature:

Most people say, "A few degrees? So what? If I change my thermostat a few degrees, I'll live fine." ... [The] point is that one or two degrees is about the experience that we have had in the last 10,000 years, the era of human civilization. There haven't been--globally averaged, we're talking--fluctuations of more than a degree or so. So we're actually getting into uncharted territory from the point of view of the relatively benign climate of the last 10,000 years, if we warm up more than a degree or two.

The other point that leads to major controversy—because it could have significant economic impacts—is whether action (usually, restrictions on the use of fossil fuels to reduce carbon-dioxide emissions) should be taken now, or in the near future; and whether those restrictions would have any meaningful effect on global temperature.

Because of the economic ramifications of such restrictions, there are those, including the Cato Institute, a libertarian think tank, who feel strongly that the negative economic effects of emission controls outweigh the environmental benefits. They claim that even if global warming is caused solely by the burning of fossil fuels, restricting their use would have more damaging effects on the world economy than the increases in global temperature.

The linkage between coal, electricity, and economic growth in the United States is as clear as it can be. And it is required for the way we live, the way we work, for our economic success, and for our future. Coal-fired electricity generation. It is necessary. (Fred Palmer, President of Western Fuels Association)

Conversely, others feel strongly that early action to reduce emissions would help avoid much greater economic costs later, and would reduce the risk of catastrophic, irreversible

change. In his December 2006 book, *Hell and High Water*, energy technology expert Joseph J. Romm

discusses the urgency to act and the sad fact that America is refusing to do so...

Ultimately, however, a strictly economic argument for or against action on climate change is limited at best, failing to take into consideration other potential impacts of any change.

Council on Foreign Relations senior fellow Walter Russell Mead argues that the 2009 Copenhagen Summit failed because environmentalists have changed from "Bambi to Godzilla". According to Mead, environmentalist used to represent the skeptical few who made valid arguments against big government programs which tried to impose simple but massive solutions on complex situations. Environmentalists' more recent advocacy for big economic and social intervention against global warming, according to Mead, has made them, "the voice of the establishment, of the tenured, of the technocrats" and thus has lost them the support of a public which is increasingly skeptical of global warming.

Kyoto Protocol

The Kyoto protocol is the most prominent international agreement on climate change, and is also highly controversial. Some argue that it goes too far or not nearly far enough in restricting emissions of greenhouse gases. Another area of controversy is the fact that China and India, the world's two most populous countries, both ratified the protocol but are not required to reduce or even limit the growth of carbon emissions under the present agreement even though when listed by greenhouse gas emissions per capita, they have rankings of 121st largest per capita emitter at 3.9 Tonnes of CO₂e and 162nd largest per capita emitter at 1.8 Tonnes of CO₂e respectively, compared with for example the USA at position of the 14th largest per capita CO₂e emitter at 22.9 Tonnes of CO₂e. Nevertheless, China is the world's second largest producer of greenhouse gas emissions, and India 4th. Various predictions see China overtaking the US in total greenhouse emissions between late 2007 and 2010 and according to many other estimates, this already occurred in 2006.

Additionally, high costs of decreasing emissions may cause significant production to move to countries that are not covered under the treaty, such as India and China, claims Fred Singer. As these countries are less energy efficient, this scenario is claimed to cause additional carbon emissions.

In May 2010 the Hartwell Paper was published by the London School of Economics in collaboration with the University of Oxford. This paper was written by 14 academics from various disciplines in the sciences and humanities, and also some policies thinkers, and they argued that the Kyoto Protocol crashed in late 2009 and "*has failed to produce any discernable real world reductions in emissions of greenhouse gases in fifteen years.*" They argued that this failure opened an opportunity to set climate policy free from Kyoto and the paper advocates a controversial and piecemeal approach to decarbonization of the global economy. The Hartwell paper proposes that "*the organising principle of our effort*

should be the raising up of human dignity via three overarching objectives: ensuring energy access for all; ensuring that we develop in a manner that does not undermine the essential functioning of the Earth system; ensuring that our societies are adequately equipped to withstand the risks and dangers that come from all the vagaries of climate, whatever their cause may be".

The only major developed nation which has signed but not ratified the Kyoto protocol is the USA. The countries with no official position on Kyoto are mainly African countries with underdeveloped scientific infrastructure or are oil producers.

Funding for partisans

Both sides of the controversy have alleged that access to funding has played a role in the willingness of credentialed experts to speak out.

The Greenpeace research project ExxonSecrets, and George Monbiot writing in *The Guardian*, as well as various academics, have linked several skeptical scientists—Fred Singer, Fred Seitz and Patrick Michaels—to organizations funded by ExxonMobil and Philip Morris for the purpose of promoting global warming skepticism. Similarly, groups employing global warming skeptics, such as the George C. Marshall Institute, have been criticized for their ties to fossil fuel companies.

On February 2, 2007, *The Guardian* stated that Kenneth Green, a Visiting Scholar with AEI, had sent letters to scientists in the UK and the U.S., offering US\$10,000 plus travel expenses and other incidental payments in return for essays with the purpose of "highlight[ing] the strengths and weaknesses of the IPCC process", specifically regarding the IPCC Fourth Assessment Report.

A furor was raised when it was revealed that the Intermountain Rural Electric Association (an energy cooperative that draws a significant portion of its electricity from coal-burning plants) donated \$100,000 to Patrick Michaels and his group, New Hope Environmental Services, and solicited additional private donations from its members.

The Union of Concerned Scientists have produced a report titled 'Smoke, Mirrors & Hot Air', that criticizes ExxonMobil for "underwriting the most sophisticated and most successful disinformation campaign since the tobacco industry" and for "funneling about \$16 million between 1998 and 2005 to a network of ideological and advocacy organizations that manufacture uncertainty on the issue". In 2006 Exxon claimed that it was no longer going to fund these groups though that claim has been challenged by Greenpeace.

The Center for the Study of Carbon Dioxide and Global Change, a skeptic group, when confronted about the funding of a video they put together (\$250,000 for "The Greening of Planet Earth" from an oil company) stated, "We applaud Western Fuels for their willingness to publicize a side of the story that we believe to be far more correct than

what at one time was 'generally accepted'. But does this mean that they fund The Center? Maybe it means that we fund them!"

Donald Kennedy, editor-in-chief of *Science*, has said that skeptics such as Michaels are lobbyists more than researchers, and that "I don't think it's unethical any more than most lobbying is unethical", he said. He said donations to skeptics amounts to "trying to get a political message across".

A number of global warming skeptics, such as the following, assert that grant money is given preferentially to supporters of global warming theory. Atmospheric scientist Reid Bryson said in June 2007 that "There is a lot of money to be made in this... If you want to be an eminent scientist you have to have a lot of grad students and a lot of grants. You can't get grants unless you say, 'Oh global warming, yes, yes, carbon dioxide.'" Similar claims have been advanced by climatologist Marcel Leroux, NASA's Roy Spencer, climatologist and IPCC contributor John Christy, University of London biogeographer Philip Stott, *Accuracy in Media*, and Ian Plimer in his 2009 book *Heaven and Earth — Global Warming: The Missing Science*.

Richard Lindzen, the Alfred P. Sloan Professor of Meteorology at MIT, makes the specific claim that "[in] the winter of 1989 Reginald Newell, a professor of meteorology [at MIT], lost National Science Foundation funding for data analyses that were failing to show net warming over the past century". Lindzen also suggests four other scientists "apparently" lost their funding or positions after questioning the scientific underpinnings of global warming. Lindzen himself, however, has been the recipient of money from energy interests such as OPEC and the Western Fuels Association, including "\$2,500 a day for his consulting services", as well as funding from federal sources including the National Science Foundation, the Department of Energy, and NASA.

Controversy over most effective response to warming

In recent years some skeptics have changed their positions regarding global warming. Ronald Bailey, author of *Global Warming and Other Eco-Myths* (published by the Competitive Enterprise Institute in 2002), stated in 2005, "Anyone still holding onto the idea that there is no global warming ought to hang it up". By 2007, he wrote "Details like sea level rise will continue to be debated by researchers, but if the debate over whether or not humanity is contributing to global warming wasn't over before, it is now.... as the new IPCC Summary makes clear, climate change Pollyannaism is no longer looking very tenable".

"There are alternatives to its [(the climate-change crusade's)] insistence that the only appropriate policy response is steep and immediate emissions reductions.... a greenhouse-gas-emissions cap ultimately would constrain energy production. A sensible climate policy would emphasize building resilience into our capacity to adapt to climate changes.... we should consider strategies of adaptation to a changing climate. A rise in the sea level need not be the end of the world, as the Dutch have taught us". says Steven F. Hayward of American Enterprise Institute, a conservative think-tank. Hayward also

advocates the use of "orbiting mirrors to rebalance the amounts of solar radiation different parts of the earth receive"—the space sunshade example of so-called geoengineering for solar radiation management.

In 2001 Richard Lindzen in response to the question, "*Kyoto aside for a moment, should we be trying to reduce carbon dioxide emissions? Do our concerns about global warming require action?*" said "We should prioritize our responses. You can't just say, "No matter what the cost, and no matter how little the benefit, we'll do this". If we truly believe in warming, then we've already decided we're going to adjust...The reason we adjust to things far better than Bangladesh is that we're richer. Wouldn't you think it makes sense to make sure we're as robust and wealthy as possible? And that the poor of the world are also as robust and wealthy as possible?"

Others argue that if developing nations reach the wealth level of the United States this could greatly increase CO₂ emissions and consumption of fossil fuels. Large developing nations such as India and China are predicted to be major emitters of greenhouse gases in the next few decades as their economies grow.

The conservative National Center for Policy Analysis whose "Environmental Task Force" contains a number of climate change skeptics including Sherwood Idso and S. Fred Singer says, "The growing consensus on climate change policies is that adaptation will protect present and future generations from climate-sensitive risks far more than efforts to restrict CO₂ emissions".

The adaptation-only plan is also endorsed by oil companies like ExxonMobil, "ExxonMobil's plan appears to be to stay the course and try to adjust when changes occur. The company's plan is one that involves adaptation, as opposed to leadership", says this Ceres report.

Gregg Easterbrook characterized himself as having "a long record of opposing alarmism". In 2006, he stated, "based on the data I'm now switching sides regarding global warming, from skeptic to convert".

The Bush administration also voiced support for an adaptation-only policy. "In a stark shift for the Bush administration, the United States has sent a climate report [*U.S. Climate Action Report 2002*] to the United Nations detailing specific and far-reaching effects it says global warming will inflict on the American environment. In the report, the administration also for the first time places most of the blame for recent global warming on human actions—mainly the burning of fossil fuels that send heat-trapping greenhouse gases into the atmosphere". The report however "does not propose any major shift in the administration's policy on greenhouse gases. Instead it recommends adapting to inevitable changes instead of making rapid and drastic reductions in greenhouse gases to limit warming". This position apparently precipitated a similar shift in emphasis at the COP 8 climate talks in New Delhi several months later, "The shift satisfies the Bush administration, which has fought to avoid mandatory cuts in emissions for fear it would harm the economy. 'We're welcoming a focus on more of a balance on adaptation versus

mitigation', said a senior American negotiator in New Delhi. 'You don't have enough money to do everything'. The White House emphasis on adaptation was not well received however:

"Despite conceding that our consumption of fossil fuels is causing serious damage and despite implying that current policy is inadequate, the Report fails to take the next step and recommend serious alternatives. Rather, it suggests that we simply need to accommodate to the coming changes. For example, reminiscent of former Interior Secretary Hodel's proposal that the government address the hole in the ozone layer by encouraging Americans to make better use of sunglasses, suntan lotion and broad-brimmed hats, the Report suggests that we can deal with heat-related health impacts by increased use of air-conditioning ... Far from proposing solutions to the climate change problem, the Administration has been adopting energy policies that would actually increase greenhouse gas emissions. Notably, even as the Report identifies increased air conditioner use as one of the 'solutions' to climate change impacts, the Department of Energy has decided to roll back energy efficiency standards for air conditioners". Letter from 11 State Attorneys General to George W. Bush.

Some find this shift and attitude disingenuous and indicative of an inherent bias against prevention (i.e. reducing emissions/consumption) and for the prolonging of profits to the oil industry at the expense of the environment. "Now that the dismissal of climate change is no longer fashionable, the professional deniers are trying another means of stopping us from taking action. It would be cheaper, they say, to wait for the impacts of climate change and then adapt to them" says writer and environmental activist George Monbiot in an article addressing the supposed economic hazards of addressing climate change. Others argue that adaptation alone will not be sufficient.

To be sure, though not emphasized to the same degree as mitigation, adaptation to a climate certain to change has been included as a necessary component in the discussion early as 1992, and has been all along. However it was not to the *exclusion*, advocated by the skeptics, of *preventative* mitigation efforts, and therein, say carbon cutting proponents, lies the difference.

Political pressure on scientists

Many climate scientists state that they are put under enormous pressure to distort or hide any scientific results which suggest that human activity is to blame for global warming. A survey of climate scientists which was reported to the US House Oversight and Government Reform Committee noted that "Nearly half of all respondents perceived or personally experienced pressure to eliminate the words 'climate change', 'global warming' or other similar terms from a variety of communications". These scientists were pressured to tailor their reports on global warming to fit the Bush administration's climate change scepticism. In some cases, this occurred at the request of a former oil-industry lobbyist. In June 2008, a report by NASA's Office of the Inspector General concluded that NASA staff appointed by the White House had censored and suppressed scientific data on global

warming in order to protect the Bush administration from controversy close to the 2004 presidential election.

U.S. officials, such as Philip Cooney, have repeatedly edited scientific reports from US government scientists, many of whom, such as Thomas Knutson, have been ordered to refrain from discussing climate change and related topics. Attempts to suppress scientific information on global warming and other issues have been described by journalist Chris Mooney in his book *The Republican War on Science*.

Climate scientist James E. Hansen, director of NASA's Goddard Institute for Space Studies, claimed in a widely cited *New York Times* article in 2006 that his superiors at the agency were trying to "censor" information "going out to the public". NASA denied this, saying that it was merely requiring that scientists make a distinction between personal, and official government, views in interviews conducted as part of work done at the agency. Several scientists working at the National Oceanic and Atmospheric Administration have made similar complaints; once again, government officials said they were enforcing long-standing policies requiring government scientists to clearly identify personal opinions as such when participating in public interviews and forums.

The BBC's long-running current affairs series *Panorama* recently investigated the issue, and was told that "scientific reports about global warming have been systematically changed and suppressed".

On the other hand, some American climatologists who have expressed doubts regarding the certainty of human influence in climate change have been criticized by politicians and governmental agencies. Oregon Governor Ted Kulongoski publicly clarified that Oregon does not officially appoint a "state climatologist" in response to Oregon State University's George Taylor's use of that title. As a result of scientific doubts he has expressed regarding global warming, the Delaware Department of Natural Resources and Environmental Control reportedly attempted to remove David Legates from his office of Delaware State Climatologist. In late 2006, Virginia Governor Tim Kaine (D) reportedly began an investigation of Virginia State Climatologist and global warming skeptic Patrick Michaels.

Scientists who agree with the consensus view have sometimes expressed concerns over what they view as sensationalism of global warming by interest groups and the press. For example Mike Hulme, director of the Tyndall Centre for Climate Research, wrote how increasing use of pejorative terms like "catastrophic", "chaotic" and "irreversible", had altered the public discourse around climate change: "This discourse is now characterised by phrases such as 'climate change is worse than we thought', that we are approaching 'irreversible tipping in the Earth's climate', and that we are 'at the point of no return'. I have found myself increasingly chastised by climate change campaigners when my public statements and lectures on climate change have not satisfied their thirst for environmental drama and exaggerated rhetoric".

According to an Associated Press release on January 30, 2007,

Climate scientists at seven government agencies say they have been subjected to political pressure aimed at downplaying the threat of global warming.

The groups presented a survey that shows two in five of the 279 climate scientists who responded to a questionnaire complained that some of their scientific papers had been edited in a way that changed their meaning. Nearly half of the 279 said in response to another question that at some point they had been told to delete reference to "global warming" or "climate change" from a report".

Critics writing in the *Wall Street Journal* editorial page claim that the survey was itself unscientific.

In addition to the pressure from politicians, many prominent scientists working on climate change issues have reported increasingly severe harassment from members of the public. The harassment has taken several forms. The US FBI told *ABC News* that it was looking into a spike in threatening emails sent to climate scientists, while a white supremacist website posted pictures of several climate scientists with the word "Jew" next to each image. One climate scientist interviewed by *ABC News* had a dead animal dumped on his doorstep and now frequently has to travel with bodyguards.

Litigation

Several lawsuits have been filed over global warming. For example, *Massachusetts v. Environmental Protection Agency* before the Supreme Court of the United States allowed the Environmental Protection Agency to regulate greenhouse gases under the Clean Air Act. A similar approach was taken by California Attorney General Bill Lockyer who filed a lawsuit *California v. General Motors Corp.* to force car manufacturers to reduce vehicles' emissions of carbon dioxide. This lawsuit was found to lack legal merit and was tossed out. A third case, *Comer v. Murphy Oil USA, Inc.*, a class action lawsuit filed by Gerald Maples, a trial attorney in Mississippi, in an effort to force fossil fuel and chemical companies to pay for damages caused by global warming. Described as a nuisance lawsuit, it was dismissed by District Court. However, the District Court's decision was overturned by the United States Court of Appeals for the Fifth Circuit, which instructed the District Court to reinstate several of the plaintiffs' climate change-related claims on October 22, 2009. The Sierra Club sued the U.S. government over failure to raise automobile fuel efficiency standards, and thereby decrease carbon dioxide emissions.