Topic 2 – Causes of change
(15 May 2007)

2.1 Emissions of greenhouse gases

Anthropogenic emissions of greenhouse gases have increased during the period 1970-2004 at an average annual rate of 0.69 Gt CO_2-equivalent. Population and GDP growth are the dominant factors contributing to the observed growth in CO_2 emissions. Developed (Annex I) countries have higher per capita greenhouse gas emissions but a lower carbon intensity of GDP than developing (non-Annex I) countries. {WGIII 1.3}

Between 1970 and 2004, global emissions of CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, weighted by their Global Warming Potential, have increased by 70% (24% between 1990 and 2004), from 29 to 49 Gt CO_2-eq (Figure 2.1a). CO_2 emissions have grown between 1970 and 2004 by about 80% (28% between 1990 and 2004) and it is the dominant gas accounting for 77% of total anthropogenic greenhouse gas emissions in 2004 (Figure 2.1). {WGIII 1.3, TS 1, SPM}

BOX 2.1: Carbon dioxide-equivalent (CO_2-eq) emissions and concentrations

Greenhouse gases differ in their warming influence (radiative forcing) on the global climate system. These warming influences may be expressed through a common metric based on the radiative forcing of CO_2.

- **CO_2-equivalent emission** is the amount of CO_2 emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a well mixed greenhouse gas or a mixture of well mixed greenhouse gases. The equivalent CO_2 emission is obtained by multiplying the emission of a well-mixed greenhouse gas by its Global Warming Potential for the given time horizon. For a mix of greenhouse gases it is obtained by summing the equivalent CO_2 emissions of each gas. Equivalent CO_2 emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply exact equivalence of the corresponding climate change responses (see WGI 2.10).
- **CO_2-equivalent concentration** is the concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases.

Global greenhouse gas emissions grew by 0.69 Gt CO_2-eq annually during the 25 year period of 1970 to 2004. However, the rate of growth was very high during the recent ten year period of 1995-2004 at 0.92 Gt CO_2-eq annually, compared to 0.45 Gt CO_2-eq annually during the previous period of 1970-1994. {WGIII TS 1, Figure TS.1a}

Global anthropogenic greenhouse gas emission trends

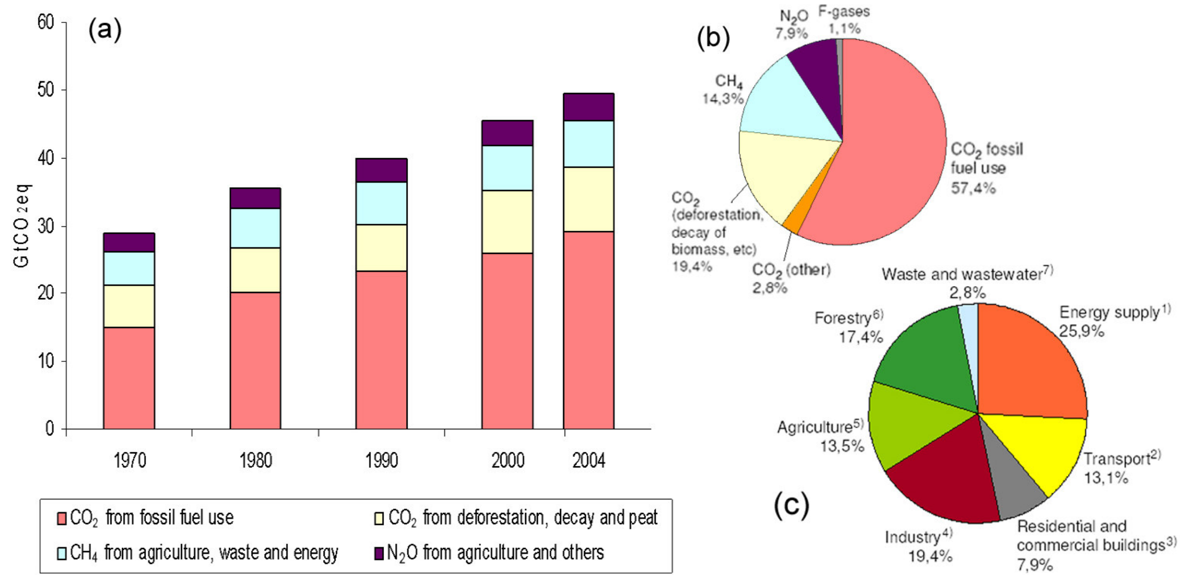

Figure 2.1. (a) Global anthropogenic greenhouse gas emissions trends, 1970 to 2004 (F–gases accounting for around 1% excluded from this figure). (b) Share of different anthropogenic greenhouse gases in 2004. (c) Share of different sectors in total anthropogenic greenhouse gas emissions in 2004. {WGIII Figures TS 1a, TS 1b, TS 2b}

The largest growth in CO_2 emissions between 1970 and 2004 has come from power generation, road transport and industry, with the residential and commercial buildings and land use, land-use change and forestry and agriculture sectors growing at a lower rate. When the sectoral sources of greenhouse gases are considered (Figure 2.1c), in 2004, energy supply accounted for 26% of emissions, followed by industry (19%), forest (17%), agriculture (14%), transport (13%), residential and commercial buildings (8%) and waste (3%). {WGIII 1.3}

CO_2 emissions, population, GDP and total primary energy supply have all grown during the period 1970 to 2004. The effect on global emissions of the decrease in global energy intensity (-33%) during 1970 to 2004 has been smaller than the combined effect of global income growth (77%) and global population growth (69%); both drivers of increasing energy-related CO_2 emissions. The long-term trend of a declining carbon intensity of energy supply reversed after 2000. {WGIII 1.3}

Differences in terms of per capita income, per capita emissions, and energy intensity among countries remain significant. In 2004 UNFCCC Annex I countries held a 20% share in world population, produced 57% of world Gross Domestic Product based on Purchasing Power Parity (GDP_{ppp}), and accounted for 46% of global greenhouse gas emissions (Figure 2.2). {WGIII 1.3}

Distribution of regional greenhouse gas emissions by population and GDP_{PPP}

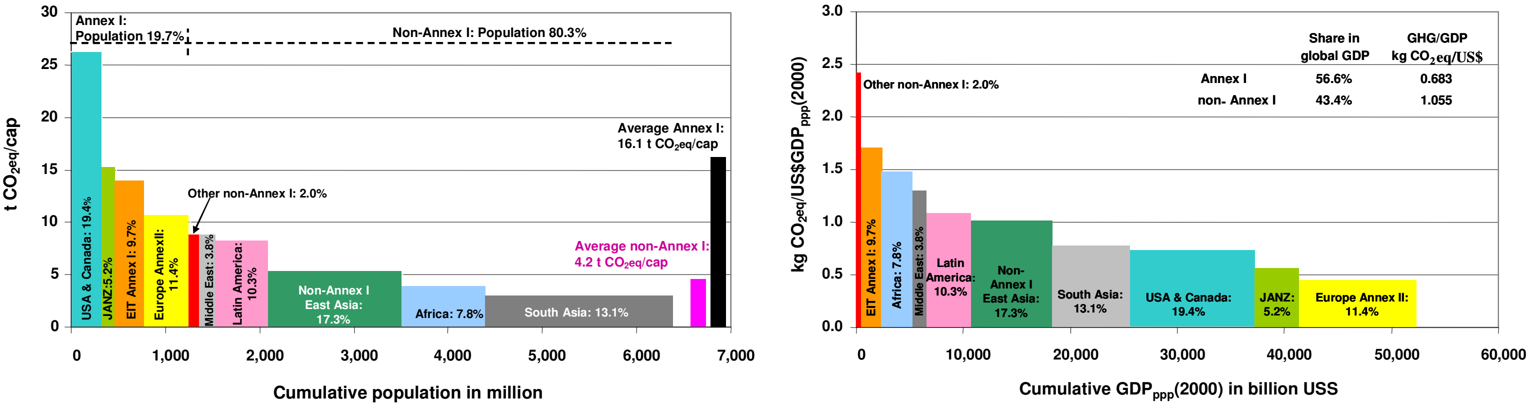

Figure 2.2. (a) Distribution of regional per capita greenhouse gas emissions according to the population of different country groupings in 2004 (see glossary for definition of country groupings). (b) Distribution of regional greenhouse gas emissions per US$ of GDP_{PPP} over the GDP of different country groupings in 2004. {WGIII Figures TS 4a and 4b}

2.2 Drivers of climate change

Changes in the atmospheric concentration of greenhouse gases and aerosols, in solar radiation and in land surface properties affect the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. These are drivers of climate change. The resulting positive or negative changes in energy balance due to these factors are expressed as radiative forcing[1], which is used to compare warming or cooling influences on global climate. {WGI TS.2}

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (Figure 2.3). The global increases in carbon dioxide concentrations are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture. {WGI 2.3, 7.3, SPM}

The global atmospheric concentration of CO_2 increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. The annual CO_2 concentration growth-rate was larger during the last 10 years (1995-2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960-2005 average: 1.4 ppm per year) although there is year-to-year variability in growth rates. This increase in concentration growth rate in CO_2 is broadly consistent with the increase in CO_2 emission rates. {WGI 2.3, 7.3, SPM; WGIII 1.3}

The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and is 1774 ppb in 2005. Growth rates have

[1] *Radiative forcing* is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to pre-industrial conditions defined at 1750 and are expressed in Watts per square metre ($W m^{-2}$).

declined since the early 1990s, consistent with total emissions being nearly constant during this period. {WGI 2.3, 7.4, SPM}

The global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005. {WGI 2.3, 7.4, SPM}

Changes in greenhouse gases from ice-core and modern data

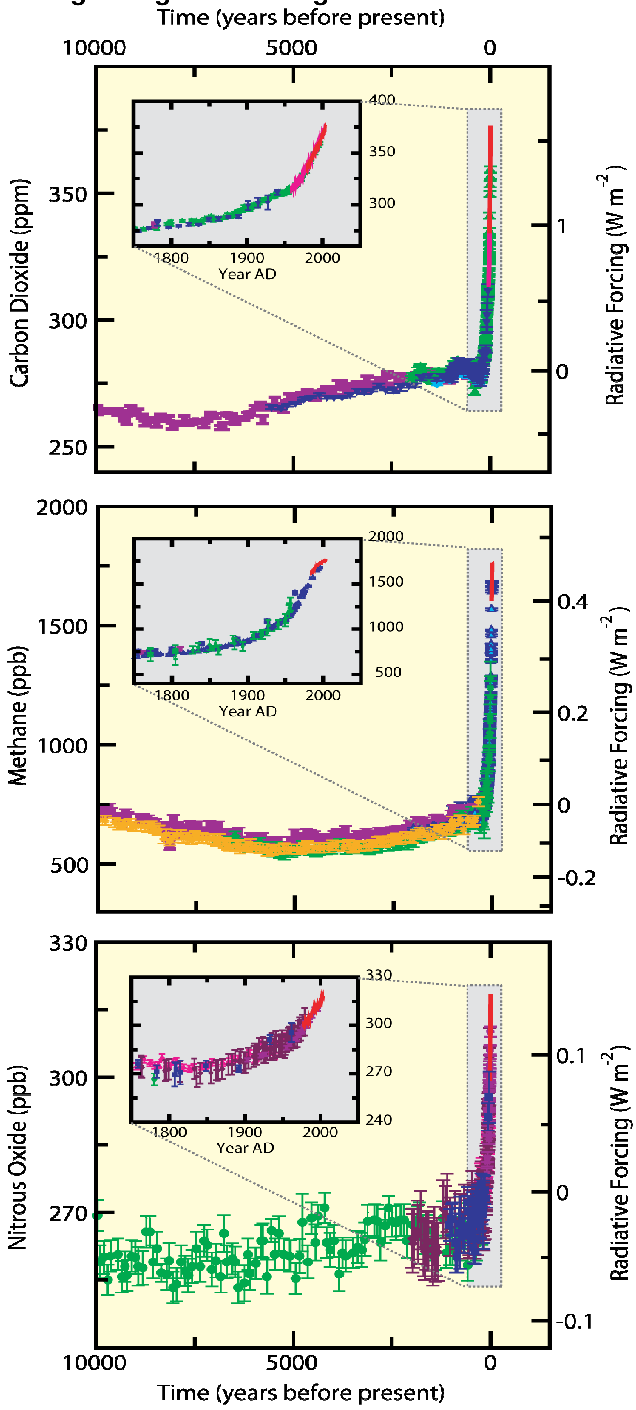

Figure 2.3. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {WGI Figure SPM-1}

There is *very high confidence* that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W m^{-2} (Figure 2.4). {WGI 2.3, 6.5, 2.9, SPM}

The combined radiative forcing due to increases in CO_2, methane, and nitrous oxide is +2.3 [+2.1 to +2.5] W m^{-2}, and its rate of increase during the industrial era is *very likely* to have been unprecedented in more than 10,000 years (Figures 2.3 and 2.4). The CO_2 radiative forcing increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years. {WGI 2.3, 6.4, SPM}

Anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of -0.5 [-0.9 to -0.1] W m^{-2} and an indirect cloud albedo forcing of -0.7 [-1.8 to -0.3] W m^{-2}. Aerosols also influence cloud lifetime and precipitation. {WGI 2.4, 2.9, 7.5, SPM}

Changes in solar irradiance since 1750 are estimated to have caused a radiative forcing of +0.12 [+0.06 to +0.30] W m^{-2}, which is less than half the estimate given in the Third Assessment Report. {WGI 2.7, SPM}

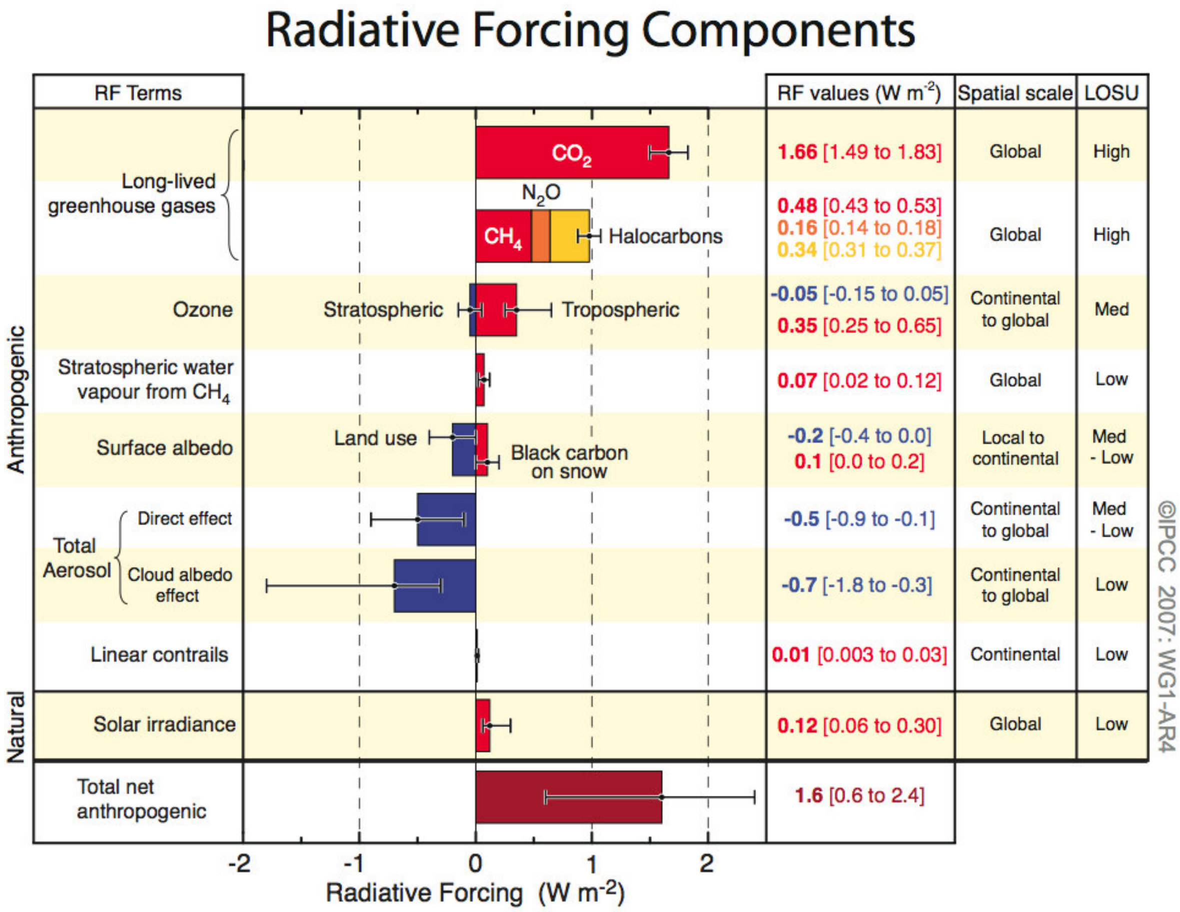

Figure 2.4. Global-average radiative forcing (RF) estimates and ranges in 2005 with respect to 1750 for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term and can cool the climate for a few years. {WGI Figure SPM-2}

2.3 Feedbacks and climate sensitivity

The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of CO_2 concentrations. It is *likely* to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values. {WGI 8.6, 9.6, Box 10.2, SPM}

Feedbacks can amplify or dampen the response to a given forcing. Direct emission of water vapour by human activities makes a negligible contribution to radiative forcing. However, as global mean temperatures increase, tropospheric water vapour concentrations increase and this represents a key positive feedback but not a forcing of climate change. Water vapour changes represent the largest feedback affecting equilibrium climate sensitivity and are now better understood than in the Third Assessment Report. Cloud feedbacks remain the largest source of uncertainty. Spatial patterns of climate response are largely controlled by climate processes and feedbacks. For example, sea ice albedo feedbacks tend to enhance the high latitude response. {WGI 2.8, 8.6, 9.2, TS 2.1.3, 2.5, SPM}

Warming tends to reduce land and ocean uptake of atmospheric CO_2, increasing the fraction of anthropogenic emissions that remains in the atmosphere. This positive carbon cycle feedback leads to larger atmospheric CO_2 increases and greater climate change for a given emissions scenario, but the strength of this feedback effect varies markedly among models. {WGI 7.3, TS 5.4, SPM}

2.4 Attribution of climate change

Attribution evaluates whether observed changes are quantitatively consistent with the expected response to external forcings and inconsistent with alternative physically plausible explanations. {WGI TS.4, SPM}

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. This is an advance since the TAR's conclusion that "most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations" (Figure 2.5). {WGI 9.4, SPM}

The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is *extremely unlikely* that global temperature change of the past fifty years can be explained without external forcing, and *very likely* that it is not due to known natural causes alone. During this time, the sum of solar and volcanic forcings would be *likely* to have produced cooling, not warming. Warming of the climate system has been detected in changes in surface and atmospheric temperatures, and in temperatures of the upper several hundred metres of the ocean. The observed pattern of tropospheric warming and stratospheric cooling is *very likely* due to the combined influences of greenhouse gas increases and stratospheric ozone depletion. It is *likely* that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place. {WGI 2.9, 3.2, 3.4, 4.8, 5.2, 7.5, 9.4, 9.5, 9.7, TS 4.1, SPM}

Global and continental temperature change

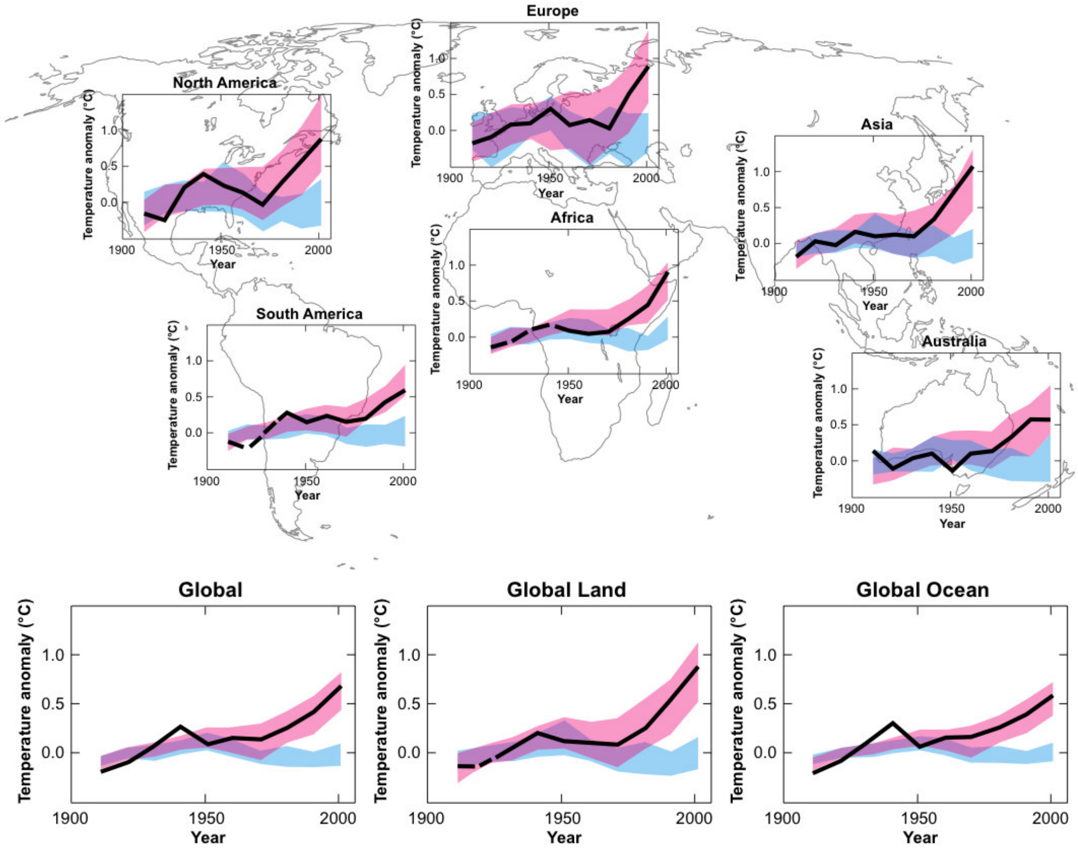

Figure 2.5. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906-2005 (black line) plotted against the centre of the decade and relative to the corresponding average for the 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 model simulations from 14 climate models using both natural and anthropogenic forcings. {WGI Figure SPM-4}

It is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica (Figure 2.5). {WGI 3.2, 9.4, SPM}

Antarctica has insufficient observational coverage to make a continent scale assessment. The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are simulated by models that include anthropogenic forcing. No coupled global climate model that has used natural forcing only has reproduced the continental mean warming trends in individual continents (except Antarctica) over the second half of the 20th century. {WGI 3.2, 9.4, TS 4.2, SPM}

Difficulties remain in reliably simulating and attributing observed temperature changes at smaller scales. On these scales, natural climate variability is relatively larger making it harder to distinguish changes expected due to external forcings. Uncertainties in local forcings and feedbacks also make it difficult to estimate the contribution of greenhouse gas increases to observed small-scale temperature changes. {WGI 8.3, 9.4, SPM}

Discernible human influences now extend to other aspects of climate, including temperature extremes and wind patterns. {WGI 9.4, 9.5, SPM}

Anthropogenic forcing is *likely* to have contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns in both hemispheres. However, the observed changes in the Northern Hemisphere circulation are larger than simulated in response to 20th century forcing change. Temperatures of the most extreme hot nights, cold nights and cold days are *likely* to have increased due to anthropogenic forcing. It is *more likely than not* that anthropogenic forcing has increased the risk of heat waves. {WGI 3.5, 3.6, 9.4, 9.5, 10.3, SPM}

It is *very likely* that the response to anthropogenic forcing contributed to sea level rise during the latter half of the 20th century. There is some evidence of the impact of human climatic influence on the hydrological cycle, including the observed large-scale patterns of changes in land precipitation over the 20th century. It is *more likely than not* that human influence has contributed to a global trend towards increases in drought in the second half of the 20th century. {WGI 3.3, 5.5, 9.5, TS 4.1, TS.4.3}

At the global scale, anthropogenic warming over the last three decades has *likely* had a discernible influence on observed changes in many physical and biological systems. {WGII 1.4}

A small number of studies have linked responses in some physical and biological systems (including glacier retreat, global runoff, spring phenology of plants and animals in the Northern Hemisphere, and wildfires in Canada) directly to anthropogenic climate change using climate, process, and statistical models. Further, a global-scale assessment of the consistency of the observed changes in physical and biological systems described in section 1.2 and observed warming shows that it is *very likely* that the observed changes in many systems cannot be explained entirely due to natural variability or other confounding non-climate factors. Taken together with evidence of significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica, these show that it is *likely* that anthropogenic warming over the last three decades has had a discernible influence on many natural systems. {WGI 3.2, 9.4, SPM; WGII 1.4, SPM}

Limitations and gaps prevent more complete attribution of the causes of observed natural system responses to anthropogenic warming. There are few studies directly linking global climate model simulations with observed effects. At the regional scales that are relevant for the study of system responses, natural temperature variability is larger relative to the changes due to external forcing. Many impacts studies are limited to shorter timescales than the 50-year timescale over which the attribution of surface temperature changes has been assessed. There are other non-climate factors that may have contributed to the observed system changes in some regions. {WGII 1.2, 1.3, 1.4, SPM}