Topic 2 – Causes of change
(31 August 2007)

This topic considers both natural and anthropogenic drivers of climate change including the chain from greenhouse gas (GHG) emissions to atmospheric concentrations to radiative forcing[3] to climate responses and effects.

2.1 Emissions of long lived GHGs

The radiative forcing of the climate system is dominated by the long-lived GHGs, and this section considers those whose emissions are covered by the UNFCCC.

Global total anthropogenic GHG emissions have grown by 70% between 1970 and 2004, from 28.7 to 49 GtCO_2-equivalent (weighted by their 100-year Global Warming Potentials). {WGIII 1.3, SPM}

CO_2 emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 Gt per annum, and represented 77% of total anthropogenic GHG emissions in 2004 (Figure 2.1). The rate of growth of CO_2-eq emissions was much higher during the recent ten year period of 1995-2004 (0.92 GtCO_2-eq per year) than during the previous period of 1970-1994 (0.43 GtCO_2-eq per year). {WGIII 1.3, TS.1, SPM}

Carbon dioxide-equivalent (CO_2-eq) emissions and concentrations

GHGs differ in their warming influence (radiative forcing) on the global climate system due to their radiative properties and their different lifetimes in the atmosphere. 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 time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The equivalent CO_2 emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon.[4] For a mix of GHGs 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 GHGs but does not imply the same climate change responses (see WGI 2.10).
- **CO_2-equivalent concentration** is the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.

[3] *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).

[4] This report uses 100-year GWPs and numerical values consistent with the UNFCCC.

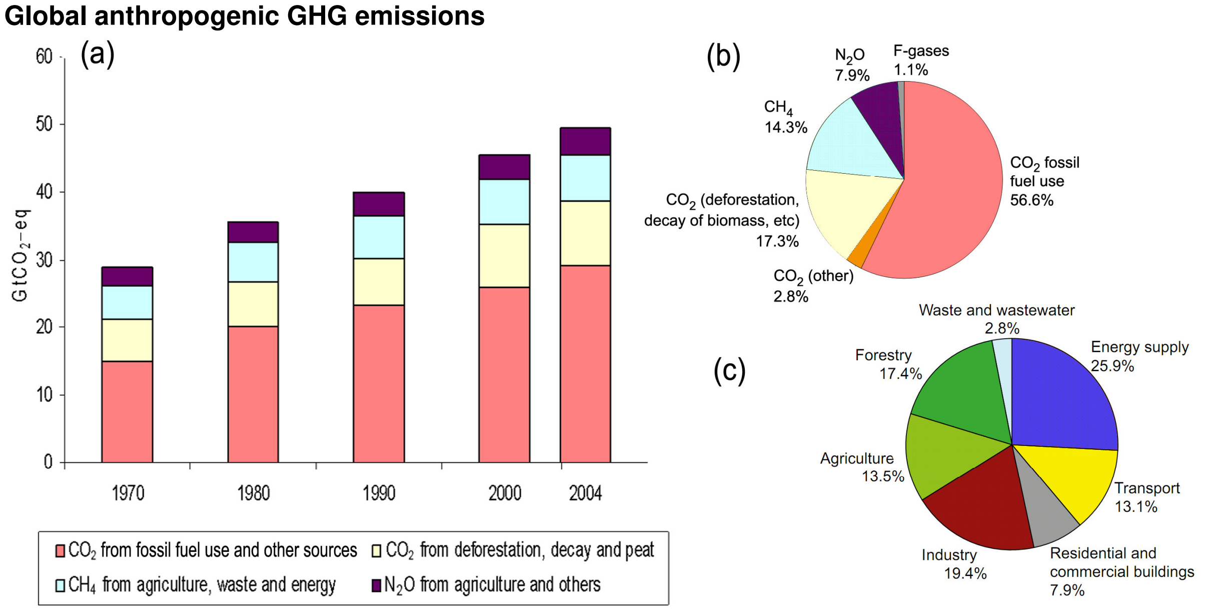

Figure 2.1. (a) Global emissions of principal anthropogenic GHGs between 1970 and 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in CO_2-eq (forestry includes deforestation). {WGIII Figures TS 1a, TS 1b, TS 2b}

The largest growth in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry, while residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate. The sectoral sources of GHGs in 2004 are considered in Figure 2.1c. { WGIII 1.3, SPM}

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, Figure SPM 2, SPM}

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 GHG emissions (Figure 2.2). {WGIII 1.3, SPM}

Regional distribution of GHG emissions by population and by GDP_{PPP}

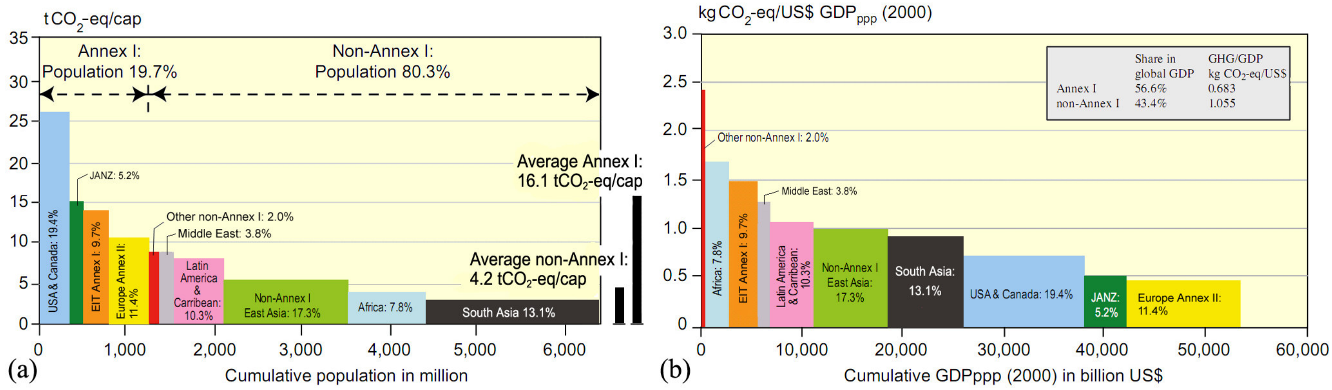

Figure 2.2. (a) Distribution of regional per capita GHG emissions according to the population of different country groupings in 2004 (see appendix for definitions of country groupings). (b) Distribution of regional GHG emissions per US$ of GDP_{PPP} over the GDP of different country groupings in 2004. {WGIII Figures SPM 3a, b}

2.2 Drivers of climate change

Changes in the atmospheric concentration of GHGs and aerosols, in solar radiation and in land surface properties are drivers of climate change. They affect the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed as radiative forcing[3], which is used to compare warming or cooling influences on global climate (Figure 2.4). {WGI TS.2}

Human activities result in emissions of four long-lived GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O) and halocarbons (a group of gases containing fluorine, chlorine or bromine). Atmospheric concentrations of GHGs increase when emissions are larger than natural removal processes.

Global atmospheric concentrations of CO_2, CH_4 and N_2O 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 atmospheric concentration of CO_2 in 2005 exceeds by far the natural range over the last 650,000 years. The global increases in CO_2 concentrations are due primarily to fossil fuel use and land-use change, while those of CH_4 and N_2O are due primarily 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. {WGI 2.3, 7.3, SPM; WGIII 1.3}

The global atmospheric concentration of CH_4 has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and was 1774 ppb in 2005. Growth rates have declined since the early 1990s. {WGI 2.3, 7.4, SPM}

The global atmospheric N_2O concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005. {WGI 2.3, 7.4, SPM}

Many halocarbons (including hydrofluorocarbons) have increased from a near zero pre-industrial background concentration, primarily due to human activities. {WGI 2.3, SPM; SROC SPM }

Changes in GHGs from ice core and modern data

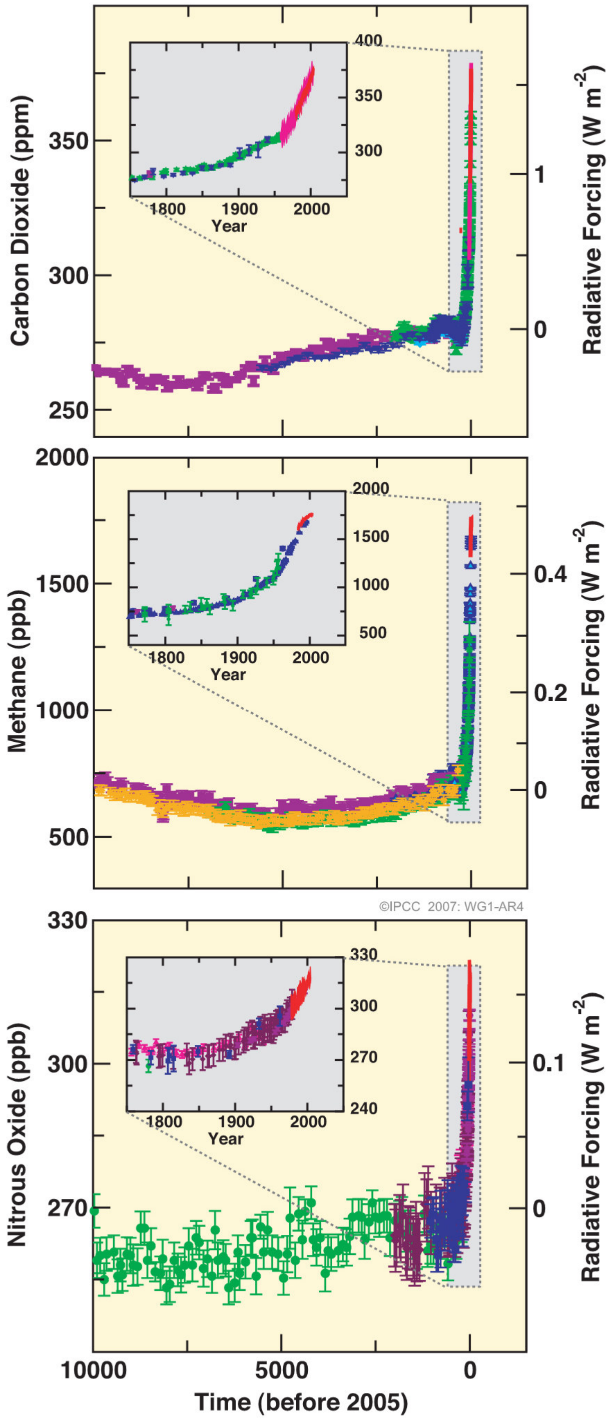

Figure 2.3. Atmospheric concentrations of CO_2, CH_4 and N_2O over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings relative to 1750 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, CH_4 and N_2O 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 but these are considered to be part of the climate response rather than radiative forcings. {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 TAR. {WGI 2.7, SPM}

Radiative forcing components

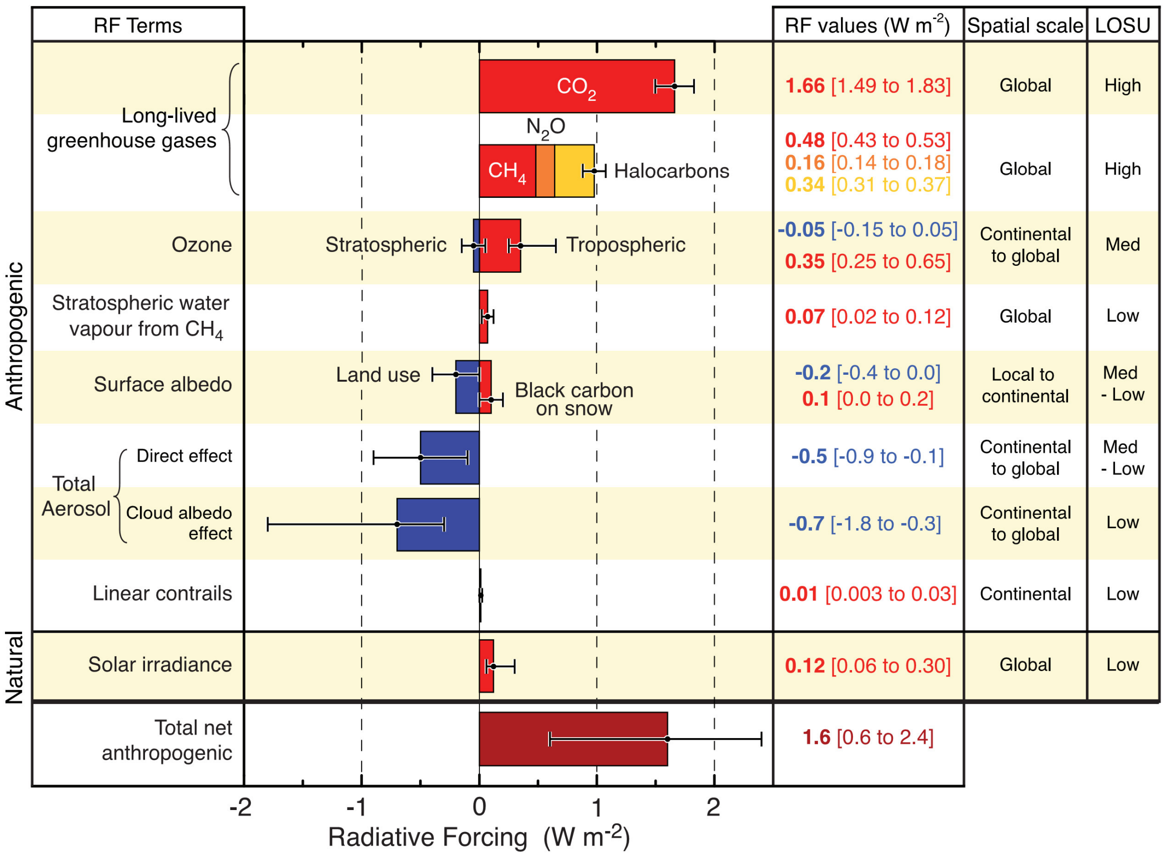

Figure 2.4. Global-average radiative forcing (RF) in 2005 (best estimates and 5-95% uncertainty ranges) with respect to 1750 for CO_2, CH_4, N_2O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term for a few years following an eruption. {WGI Figure SPM.2}

2.3 Climate sensitivity and feedbacks

The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration. 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 (a greenhouse gas) by human activities makes a negligible contribution to radiative forcing. However, as global average temperature increases, 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 TAR. 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 terrestrial ecosystem 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; WGII 4.4}

2.4 Attribution of climate change

Attribution evaluates whether observed changes are quantitatively consistent with the expected response to external forcings (e.g. changes in solar irradiance or anthropogenic GHGs) 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 GHG concentrations.[5] 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 GHG 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 climate change of the past 50 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 *likely* 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 GHG increases and stratospheric

[5] Consideration of remaining uncertainty is based on current methodologies.

ozone depletion. It is *likely* that increases in GHG 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

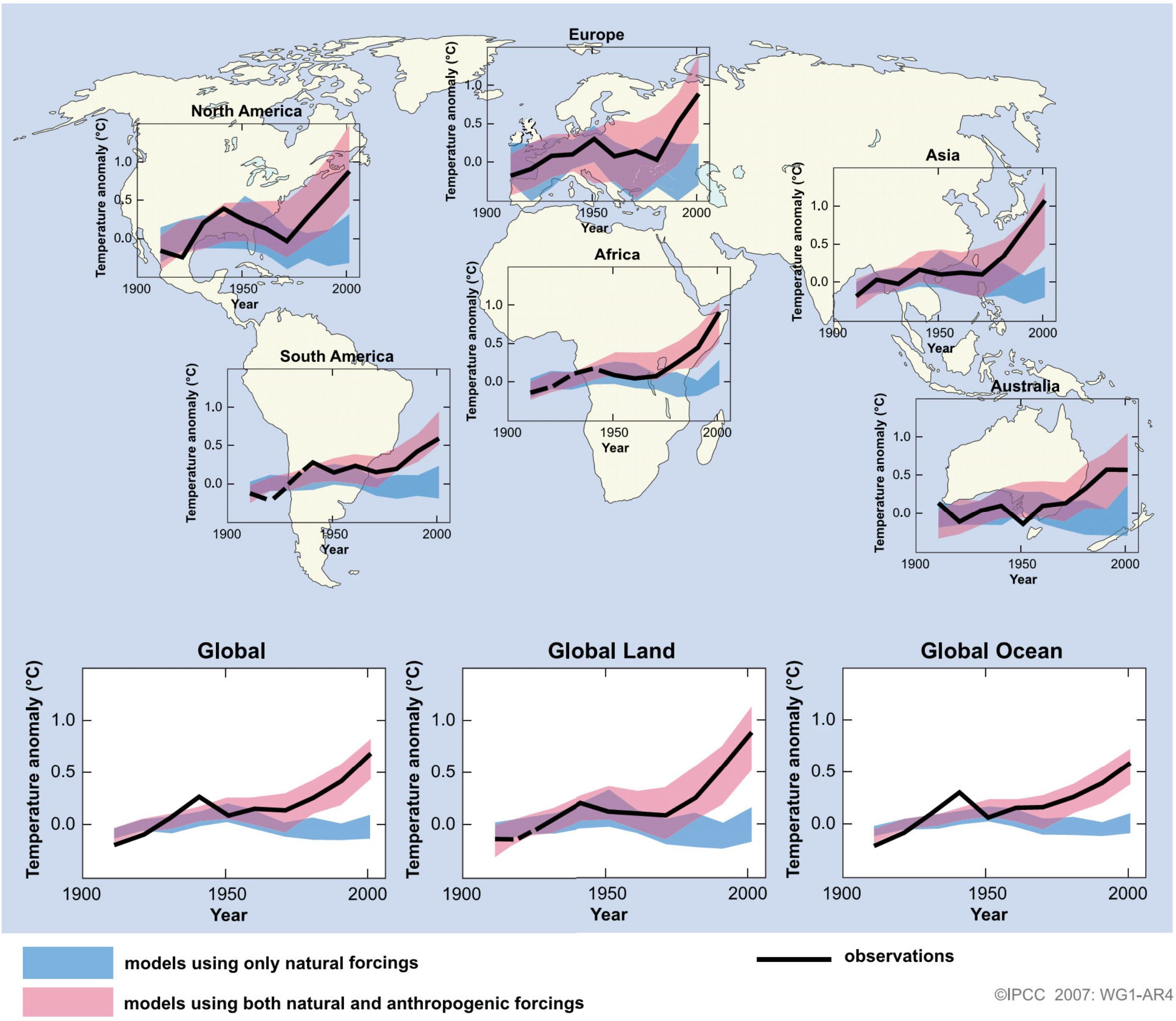

Figure 2.5. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906-2005 (black line) plotted against the centre of the decade 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 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[6] (Figure 2.5). {WGI 3.2, 9.4, SPM}

The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are only simulated by models that include anthropogenic forcing.

[6] Antarctica had insufficient observational coverage to make a continental-scale assessment.

No coupled global climate model that has used natural forcing only, has reproduced the continental mean warming trends in individual continents (except Antarctica[6]) 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, such as due to aerosols and land-use change, and feedbacks also make it difficult to estimate the contribution of GHG increases to observed small-scale temperature changes. {WGI 8.3, 9.4, SPM}

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

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. 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. {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 also 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 synthesis of studies strongly demonstrates that the spatial agreement between regions of significant warming across the globe and the locations of significant observed changes in many natural systems consistent with warming is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems. Modelling studies have linked some specific responses in physical and biological systems to anthropogenic warming, but only a few such studies have been performed. Taken together with evidence of significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica[6], 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. The available analyses are limited in the number of systems, length of records and locations considered. Natural temperature variability is larger at the regional than the global scale, thus affecting identification of changes to external forcing. At the regional scale, other factors (such as land-use change, pollution and invasive species) are influential. {WGII 1.2, 1.3, 1.4, SPM}