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Concerns about climate change and the role of fossil fuel use

Donald J. Wuebbles [*], Atul K. Jain

Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801 USA

Abstract

The greenhouse effect, the ability of certain gases like carbon dioxide and water vapor to effectively trap some of the reemission of solar energy by the planet, is a necessary component to life on Earth; without the greenhouse effect, the planet would be too cold to support life. However, human activities are increasing the concentration of carbon dioxide and several other greenhouse gases, resulting in concerns about warming of the earth by 1–5°C over the next century. Recent increases in global averaged temperature over the last decade already appear to be outside the normal variability of temperature changes for the last thousand years. A number of different analyses strongly suggest that this temperature increase is resulting from the increasing atmospheric concentrations of greenhouse gases, thus lending credence to the concerns about much larger changes in climate being predicted for the coming decades. It is this evidence that led the international scientific community through the Intergovernmental Panel on Climate Change (IPCC) to conclude (after a discussion of the remaining uncertainties) "Nonetheless, the balance of the evidence suggests a human influence on global climate". More recent findings have further strengthened this conclusion. Computer-based models of the complex processes affecting the carbon cycle have implicated the burning of fossil fuels as a major factor in the past increase in concentrations of carbon dioxide. These models also suggest that, without major policy or technology changes, future concentrations of CO_2 will continue to increase largely as a result of fossil fuel burning. This paper reviews the current understanding of the concerns about climate change and the role being played by fossil fuel use. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Climate change; Greenhouse effect; Greenhouse gases

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1. Introduction

Climate is defined as the typical behavior of the atmosphere, the aggregation of the weather, and is generally expressed in terms of averages and variances of temperature,

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[*] Corresponding author.

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precipitation and other physical properties. The greenhouse effect, the ability of certain gases like carbon dioxide and water vapor to effectively trap some of the reemission of solar energy by the planet, is a necessary component to life on Earth; without the greenhouse effect, the planet would be too cold to support life. However, human activities are increasing the concentration of carbon dioxide and several other greenhouse gases, resulting in concerns about warming of the earth by 1–5°C over the next century. Recent increases in global averaged temperature over the last decade already appear to be outside the normal variability of temperature changes for the last thousand years. A number of different analyses strongly suggest that this temperature increase is resulting from the increasing atmospheric concentrations of greenhouse gases, thus lending credence to the concerns about much larger changes in climate being predicted for the coming decades. It is this evidence that led the international scientific community through the Intergovernmental Panel on Climate Change (IPCC) to conclude, after a discussion of remaining uncertainties, "Nonetheless, the balance of the evidence suggests a human influence on global climate". More recent findings have further strengthened this conclusion. Computer-based models of the complex processes affecting the carbon cycle have implicated the burning of fossil fuels by an ever-increasing world population as a major factor in the past increase in concentrations of carbon dioxide. These models also suggest that, without major policy or technology changes, future concentrations of CO_2 will continue to increase largely as a result of fossil fuel burning. This paper briefly reviews the state of the science of the concerns about climate change that could result from fossil fuels and other human-related emissions.

2. The changing climate

There is an extensive amount of evidence indicating that the earth's climate has warmed during the past century (see Table 1). Foremost among this evidence are compilations of the variation in global mean sea surface temperature and in surface air

Table 1
Summary of trends in observed climatic variables [11,28]

Variable	Analysis period	Trend or change
Surface air temperature and SST	1851–1995	0.65 ± 0.15°C
Alpine glaciers	Last century	Implies warming of 0.6–1.0°C in alpine regions
Extent of snowcover in the NH	1972–1992	10% decrease in annual mean
Extent of sea ice in the NH	1973–1994	Downward since 1977
Extent of sea ice in the SH	1973–1994	No change, possible decrease between mid 1950s and early 1970s
Length of the NH growing season	1981–1991	12 ± 4 days longer
Precipitation	1900–1994	Generally increasing outside tropics, decreasing in Sahel
Heavy precipitation	1910–1990	Growing in importance
Antarctic snowfall	Recent decades	5–20% increase
Global mean sea level	Last century	1.8 ± 0.7 mm/year

temperature over land and sea. Supplementing these indicators of surface temperature change is a global network of balloon-based of atmospheric temperature since 1958. As well, there are several indirect or *proxy* indications of temperature change, including satellite observations (since 1979) of microwave emissions from the atmosphere, and records of the width and density of tree rings. The combination of surface-, balloon-, and satellite-based indicators provides a more complete picture than could be obtained from any given indicator alone, while proxy records from tree rings and other indicators allow the temperature record at selected locations to be extended back for a thousand years. Apart from temperature, changes in the extent of alpine glaciers, sea ice, seasonal snow cover, and the length of the growing season have been documented that are consistent with the evidence that the climate is warming. Less certain, but also consistent, changes appear to have occurred in precipitation, cloudiness, and interannual temperature and rainfall variability.

Thermometer-based measurements of air temperature have been systematically recorded at a number of sites in Europe and North America as far back as 1760. However, the set of observing sites did not attain sufficient geographic coverage to permit a rough computation of the global average land temperature until the mid-19th century. Land-based, marine air, and sea surface temperature datasets all require rather involved corrections to account for changing conditions and measurement techniques. Analyses of these records indicate a global mean warming from 1851 to 1995 of about 0.65 ± 0.05°C [1,2].

As shown in Fig. 1, the increase in temperature has occurred in two distinct periods. The first occurred from roughly 1910–1945, while the second is since 1976. Recent warming has been about 0.2°C per decade. Very large changes have occurred in the last decade, with 1998 being the warmest year in the global temperature record. The highest 10 years in global surface temperature have been since 1980, with eight of them occurring in the last 11 years.

In addition to limited sampling of temperature with altitude through balloon-borne instruments, satellite-based sensors, known as microwave sounding units (MSUs), are being used to examine global temperature changes in the middle troposphere (mainly the 850–300 HPa layer), and in the lower stratosphere ($\sim$50–100 HPa). None of the channels sample at the ground. The MSU measurements have been controversial because some earlier versions of the satellite dataset had indicated a cooling in the lower troposphere in contrast to the warming from the ground-based instruments. However, several errors and problems (e.g., due to decay in the orbit of the satellite) with the MSU data have been found, and the latest analyses of MSU corrected for these problems show a warming (about 0.1°C per decade), albeit somewhat smaller than that found at the ground [3]. These analyses also suggest that the cooling effect of decreasing ozone in the lower stratosphere (as a result of chlorine and bromine from human-related emissions of chlorofluorocarbons and other halocarbons) may have led to the difference in upper tropospheric and ground-level temperature trends.

The 1910–1945 warming primarily occurred in the Northern Atlantic. In contrast, the most recent warming has primarily occurred at middle and high latitudes of the Northern Hemisphere continents in winter and spring, while the northwest portion of the Northern Atlantic and the central North Pacific Oceans has shown year-around cooling. Signifi-

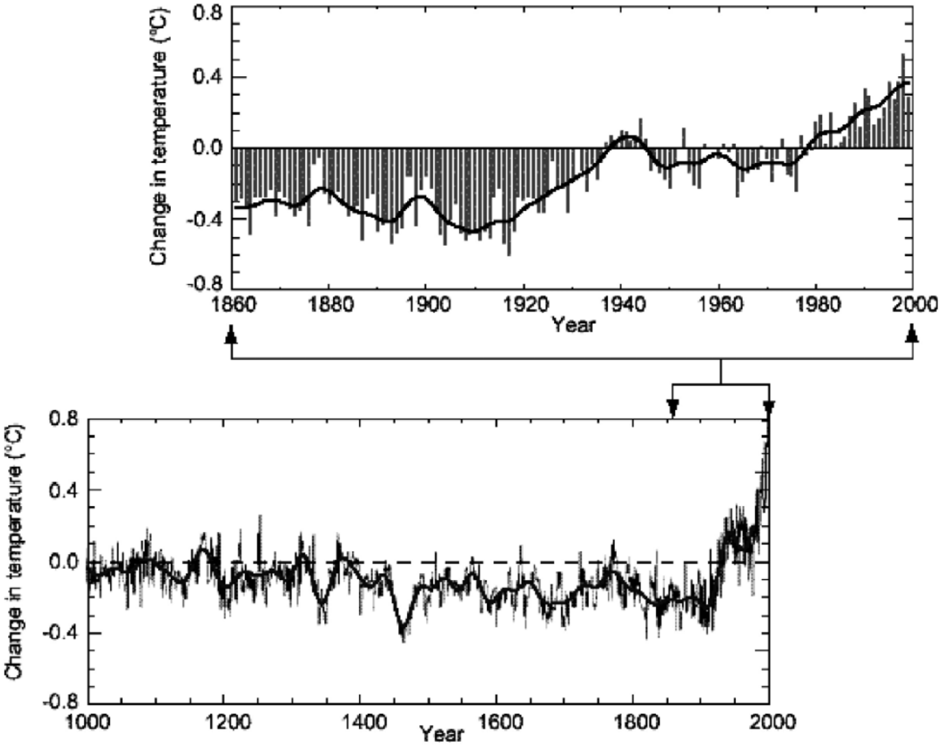

Fig. 1. Variations of the earth's surface temperature for the last 1000 years. The top panel shows the combined annual land-surface and sea-surface temperature anomalies for 1861–1999, relative to the average of the 1961–1990 period. This figure is an update by P.D. Jones of the analysis previously done for IPCC [10]. The bottom panel shows the Northern Hemispheric temperature reconstruction over the last 1000 years from proxy data in combination with the instrumental data record [4].

cant regional cooling occurred in the Northern Hemisphere during the period from 1946–1975.

Proxy temperature indicators, such as tree ring width and density, the chemical composition and annual growth rate in corals, and characteristics of annual layers in ice cores, are being used at a number of locations to extend temperature records back as much as a thousand years [4,5]. As seen in Fig. 1, the reconstruction indicates the decade of the 1990s has been warmer than at any time during this millennium and that 1998 was the warmest year in the 1000-year record [4]. Using a different approach, based on underground temperature measurements from boreholes, Huang et al. [6] found temperature changes over the last 500 years that are very similar to the trend in Mann et al. [4]. The basic conclusion is the same, that the late-20th century warming is unprecedented in the last 500–1000 years.

Recent studies (for example, Refs. [7–9]) with state-of-the-art numerical models of the climate system have been able to match the observed temperature record well but only if they include the effects of greenhouse gases and aerosols. These studies indicate that natural variability of the climate system and solar variations are not sufficient to explain the increasing temperatures in the 1980s and 1990s. However, natural variability and variations in the solar flux are important in fully explaining the increase in temperature in the 1910–1945 period. Emissions from large volcanic eruptions resulting in sulfate aerosols and other aerosols in the lower stratosphere are also important in explaining some of the short-term variations in the climate record.

3. Human factors in climate change: gases and aerosols

Without human intervention, concentrations of many atmospheric gases would be expected to change slowly. Ice core measurements of the gases trapped in ancient ice bubbles indicate this was the case before the last century. However, since the beginning of the industrial age, emissions associated with human activities have risen rapidly. Agriculture, industry, waste disposal, deforestation, and especially fossil fuel use have been producing increasing amounts of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and other important gases. Due to increasing emissions, atmospheric levels of these greenhouse gases have been building at an unprecedented rate, raising concerns regarding the impact of these gases on climate. Some of the gases, such as CFCs, are also responsible for large observed depletions in the natural levels of another gas important to climate, ozone. Of these gases, two, carbon dioxide and methane, are of special concern to climate change. These two gases are discussed in some detail in the sections below. Under the international Montreal Protocol, emissions of CFCs and other halocarbons are being controlled and their atmospheric concentrations will gradually decline over the next century. Emissions leading to atmospheric concentrations of sulfate and other aerosol particles are also important to climate change and are further discussed below. Unless stated otherwise, most of the discussion below is based on the most recent IPCC and WMO international assessments [10,11] of global change, with concentrations and trends updated as much as possible, particularly from data available from National Oceanic and Atmospheric Administration's Climate Monitoring and Diagnostics Laboratory (NOAA CMDL).

3.1. Carbon dioxide

Carbon dioxide has the largest changing concentration of the greenhouse gases. It is also the gas of most concern to analyses of potential human effects on climate. Accurate measurements of atmospheric CO_2 concentration began in 1958. The annually averaged concentration of CO_2 in the atmosphere has risen from 316 ppm (parts per million, molar) in 1959 to 364 ppm in 1997 [12], as shown in Fig. 2. The CO_2 measurements exhibit a seasonal cycle, which is mainly caused by the seasonal uptake and release of atmospheric CO_2 by terrestrial ecosystems. The average annual rate of increase over the whole time period is about 1.2 ppm or 0.4% per year, with the rate of increase over the last decade being about 1.6 ppm/year. Measurements of CO_2 concentration in air trapped in ice cores indicate that the pre-industrial concentration of CO_2 was approximately 280 ppm. This data indicates that carbon dioxide concentrations fluctuated by

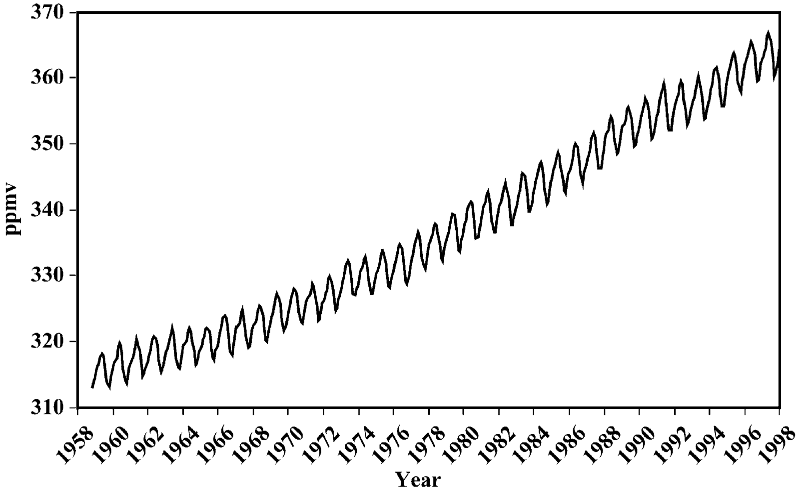

Fig. 2. Observed monthly average CO_2 concentration (ppmv) from Mauna Loa, Hawaii [12]. Seasonal variations are primarily due to the uptake and production of CO_2 by the terrestrial biosphere.

± 10 ppm around 280 ppm for over a thousand years until the recent increase to the current 360 ppm, an increase of over 30%.

Why has the atmospheric concentration of CO_2 increased so dramatically? Analyses with models of the atmosphere–ocean–biosphere system of the carbon cycle, in coordination with observational analyses of the isotopes of carbon in CO_2, indicate that human activities are primarily responsible for the increase in CO_2. Two types of human activities are primarily responsible for emissions of CO_2: fossil fuel use, which released about 6.0 GtC into the atmosphere in 1990, and land use, including deforestation and biomass burning, which may have contributed about 1.6 ± 1.0 GtC in addition to that from fossil fuels. Evaluations of carbon releases from vegetation and soils based on changes in land use indicate that land use decreased carbon storage in vegetation and soil by about 170 Gt since 1800. The added atmospheric CO_2 resulting from human activities is redistributed within the atmospheric, oceanic, and biospheric parts of the global carbon cycle, with the dynamics of this redistribution determining the corresponding rise in atmospheric CO_2 concentration. In the future, as the amount of CO_2 increases in the atmosphere and in the ocean, it is expected that the oceans will take up a smaller percentage of the new emissions. Analyses of the carbon budget previously had implied that a mismatch existed between observed levels of CO_2 and known loss processes. This discrepancy suggested that a missing carbon sink has existed during recent decades. This sink now appears to be largely explained through increased net carbon storage by the terrestrial biomass stimulated by the CO_2 fertilization effect (increased growth in a higher CO_2 concentration atmosphere) [13].

Carbon dioxide is emitted when carbon-containing fossil fuels are oxidized by combustion. Carbon dioxide emissions depend on energy and carbon content, which ranges from 13.6 to 14.0 MtC/EJ for natural gas, 19.0–20.3 MtC/EJ for oil, and 23.9–24.5 MtC/EJ for coal. Other energy sources such as hydro, nuclear, wind, and solar have no direct carbon emissions. Biomass energy, however, is a special case. When biomass is used as a fuel, it releases carbon with a carbon-to-energy ratio similar to that of coal. However, the biomass has already absorbed an equal amount of carbon from the atmosphere prior to its emission, so that net emissions of carbon from biomass fuels are zero over its life cycle.

Human-related emissions from fossil fuel use have been estimated as far back as 1751. Before 1863, emissions did not exceed 0.1 GtC/year. However, by 1995 they had reached 6.5 GtC/year, giving an average emission growth rate slightly greater than 3% per year over the last two and a half centuries. Recent growth rates have been significantly lower, at 1.8% per year between 1970 and 1995. Emissions were initially dominated by coal. Since 1985, liquids have been the main source of emissions despite their lower carbon intensity. The regional pattern of emissions has also changed. Once dominated by Europe and North America, developing nations are providing an increasing share of emissions. In 1995, non-Annex I (developing countries; includes China and India) nations accounted for 48% of global emissions.

Future CO_2 levels in the atmosphere depend not only on the assumed emission scenarios, but also on the transfer processes between the major carbon reservoirs, such as the oceans (with marine biota and sediments) and the terrestrial ecosystems (with land use changes, soil and forest destruction). Recent work for the new IPCC assessment show, based on projections of fossil-fuel use and land use changes, that the concentration of CO_2 are expected to increase well above current levels by 2100 (75–220% over pre-industrial concentrations). As discussed later, none of these scenarios leads to stabilization of the CO_2 concentration before 2100.

3.2. Methane

Although its atmospheric abundance is less than 0.5% that of CO_2, on a molecule by molecule basis, a molecule of CH_4 is approximately 50 times more effective as a greenhouse gas in the current atmosphere than CO_2. When this is combined with the large increase in its atmospheric concentration, methane becomes the second most important greenhouse gas of concern to climate change. Based on analyses of ice cores, the concentration of methane has more than doubled since preindustrial times. In year 1997, the globally averaged atmospheric concentration of methane was about 1.73 ppmv [14].

Continuous monitoring of methane trends in ambient air from 1979 to 1989 indicates that concentrations had been increasing at an average of about 16 ppb ($\sim$ 1% per year). During much of the 1990s, the rate of increase in methane appeared to be declining. Although the cause of the longer-term global decline in methane growth is still not well understood, it may be that much of the earlier rapid increase in methane emissions from agricultural sources are now slowing down. However, in 1998 the CH_4 growth rate increased to about 10 ppb/year (Fig. 3b). There are some indications that this increase in the growth rate may be due to a response of emissions from wetlands in the Northern Hemisphere responding to warm temperatures. In 1999, the growth rate decreased to about 5 ppb/year (Dlugokenckey, NOAA CMDL, private communication, 2000).

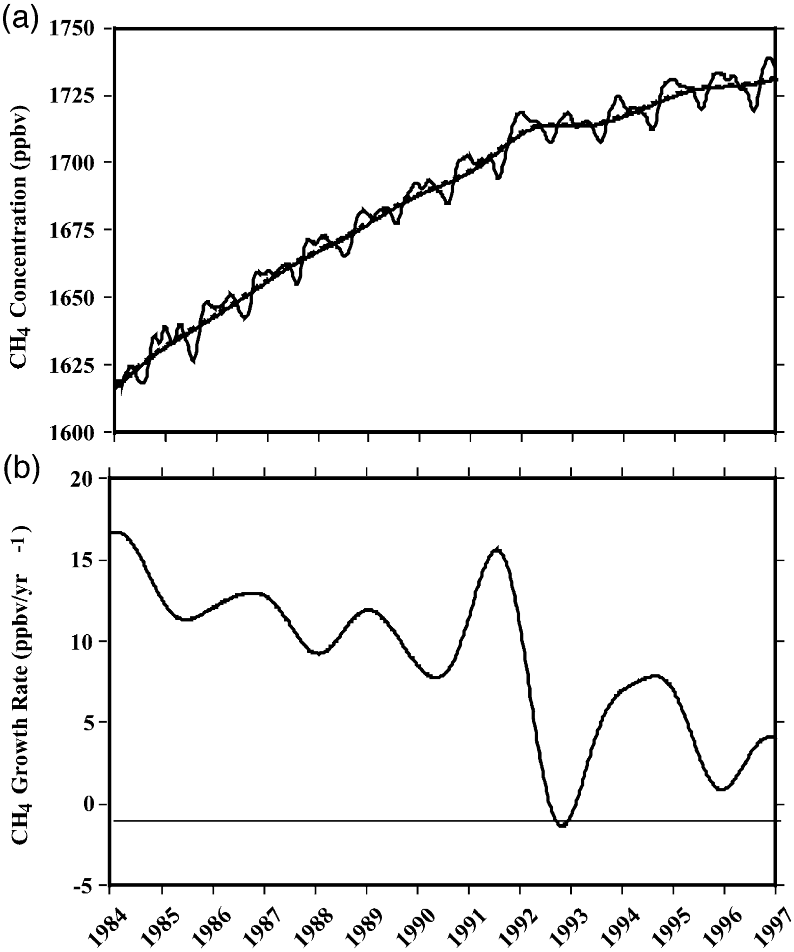

Fig. 3. (a) Globally averaged atmospheric CH_4 concentrations (ppbv) derived from NOAA Climate Monitoring Diagnostic Laboratory air sampling sites [14]. The solid line is a deseasonalized trend curve fitted to the data. The dashed-line is a model (that accounts for CH_4 emissions and loss in the atmosphere) estimated calculated trend that fit to the globally average values. (b) Atmospheric CH_4 instantaneous growth rate (ppbv/year) which is the derivative with respect to the trend curve shown in above panel.

Methane emissions come from a number of different sources, both natural and anthropogenic. One type of human related emissions arises from biogenic sources from agriculture and waste disposal, including enteric fermentation, animal and human wastes, rice paddies, biomass burning, and landfills. Emissions also result from fossil fuel-related methane sources such as natural gas loss, coal mining, and the petroleum industry. Methane is emitted naturally by wetlands, termites, other wild ruminants, oceans, and hydrates. Based on recent estimates, current human-related biogenic and fossil fuel-related sources for methane are approximately 275 and 100 $TgCH_4$/year while total natural sources are around 160 $TgCH_4$/year.

3.3. Sulfuric and other aerosols

Emissions of sulfur dioxide and other gases can result in the formation of aerosols that can affect climate. Aerosols affect climate directly by absorption and scattering of solar radiation and indirectly by acting as cloud condensation nuclei (CCN). A variety of analyses indicates that human-related emissions of sulfur, and the resulting increased sulfuric acid concentrations in the troposphere, may be cooling the Northern Hemisphere sufficiently to compensate for a sizable fraction of the warming expected from greenhouse gases. As the lifetime in the lower atmosphere of these aerosols is typically only about 1 week, the large continual emissions of the aerosol precursors largely determine the impact of the aerosols on climate. Large volcanic explosions can influence climate for periods of 1–3 years through emissions of sulfur dioxide, and the resulting sulfate aerosols, into the lower stratosphere.

Over half of the sulfur dioxide, SO_2, emitted into the atmosphere comes from human-related sources, mainly from the combustion of coal and other fossil fuels. Most of these emissions occur in the Northern Hemisphere. Analyses indicate that anthropogenic emissions have grown dramatically during this century. Other SO_2 sources come from biomass burning, from volcanic eruptions, and from the oxidation of di-methyl sulfide (DMS) and hydrogen sulfide (H_2S) in the atmosphere. DMS and H_2S are primarily produced in the oceans. Atmospheric SO_2 has a lifetime of less than a week, leading to the formation of sulfuric acid and eventually to sulfate aerosol particles. Gas-to-particle conversion can also occur in cloud droplets; when precipitation does not soon occur, the evaporation of such droplets can then leave sulfate aerosols in the atmosphere.

Other aerosols are also important to climate. Of particular interest are the carbonaceous aerosols or black carbon (soot) aerosols that are absorbers of solar and infrared radiation, and can thus add to the concerns about warming.

4. Radiative forcing and climate change

A perturbation to the atmospheric concentration of an important greenhouse gas, or the distribution of aerosols, induces a radiative forcing that can affect climate. Radiative forcing of the surface-troposphere system is defined as the change in net radiative flux at the tropopause due to a change in either solar or infrared radiation or both [10]. Generally, this net flux is calculated after allowing for stratospheric temperatures to re-adjust to radiative equilibrium. A positive radiative forcing tends on average to warm the surface; a negative radiative forcing tends to cool the surface. This definition is based on earlier climate modeling studies, which indicated an approximately linear relationship between the global mean radiative forcing at the tropopause and the resulting global mean surface temperature change. However, recent studies of greenhouse gases (e.g., Ref. [15]) indicate that the climatic response can be sensitive to the altitude, latitude, and nature of the forcing.

The resulting change in radiative forcing can then drive changes in the climate. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing tends to cool the surface. Changes in radiative forcing can occur either as a result of natural phenomena or due to human activities. Natural causes for significant changes in radiative forcing include those due to changes in solar luminosity or due to concentrations of sulfate aerosols following a major volcanic eruption. Human-related causes include the changes in atmospheric concentrations of greenhouse gases and in aerosol loading discussed earlier.

4.1. Explaining the past record

As shown in Fig. 4, analyses of the direct radiative forcing due to the changes in greenhouse gas concentrations since the beginning of the Industrial Era give an increase of about 2.3 W m^{-2}. To put this into perspective, a doubling of CO_2 from pre-industrial levels would correspond to about 4 W m^{-2}; climate models studies indicate this would give a 1.5–4.5°C increase in global temperature. Approximately 0.5 W m^{-2} of the increase has occurred within the last decade. By far the largest effect on radiative forcing has been the increasing concentration of carbon dioxide, accounting for about 64% of the total change in forcing. Methane has produced the second largest change in radiative forcing of the greenhouse gases.

Changes in the amounts of sulfate, nitrate, and carbonaceous aerosols induced by natural and human activities have all contributed to changes in radiative forcing over the last century. The direct effect on climate from sulfate aerosols occurs primarily through the scattering of solar radiation. This scattering produces a negative radiative forcing, and has resulted in a cooling tendency on the earth's surface that counteracts some of the warming effect from the greenhouse gases. In the global average, increases in amounts of carbonaceous aerosols, which absorb solar and infrared radiation, have likely counteracted some of the effect of the sulfate aerosols. Aerosols can also produce an indirect radiative forcing by acting as condensation nuclei for cloud formation. There is

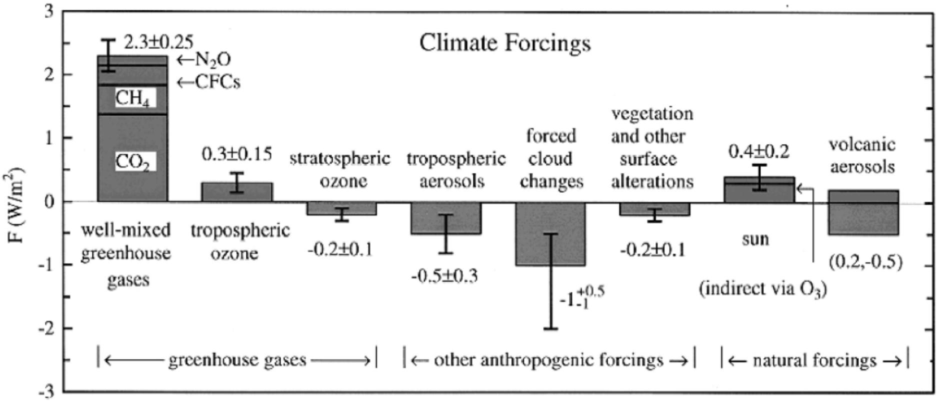

Fig. 4. Estimated change in globally and annually averaged anthropogenic radiative forcing (W m^{-2}) resulting from changes in concentrations of greenhouse gases and aerosols from the pre-industrial time to 1998 and to natural changes in solar output from 1850 to 1998. The error bars show an estimate of the uncertainty range. Based on Hansen et al. [16].

large uncertainty in determining the extent of radiative forcing that has resulted from this indirect effect, as indicated in Fig. 4.

Changes in tropospheric and stratospheric ozone also affect climate, but the increase in tropospheric ozone over the last century and the decrease in stratospheric ozone over recent decades have had a relatively small combined effect on radiative forcing compared to CO_2. The radiative forcing from the changes in amount of stratospheric ozone, which has primarily occurred over the last few decades primarily as a result of human-related emissions of halogenated compounds containing chlorine and bromine, is generally well understood. However, the changes in concentrations of tropospheric ozone over the last century, and the resulting radiative forcing, are much less well understood.

Changes in the solar energy output reaching the earth are also an important external forcing on the climate system. The Sun's output of energy is known to vary by small amounts over the 11-year cycle associated with sunspots and there are indications that the solar output may vary by larger amounts over longer time periods. Slow variations in the earth's orbit, over time scales of multiple decades to thousands of years, have varied the solar radiation reaching the earth, and have affected the past climate. As shown in Fig. 4, solar variations over the last century are thought to have had a small but important effect on the climate, but are not important in explaining the large increase in temperatures over the last few decades.

Evaluation of the radiative forcing from all of the different sources since pre-industrial times indicates that globally averaged radiative forcing on climate has increased. Because of the hemispheric and other inhomogeneous variations in concentrations of aerosols, the overall change in radiative forcing is much greater or much smaller at specific locations over the globe.

Any changes induced in climate as a result of human activities, or from natural forcings like variations in the solar flux, will be superimposed on a background of natural climatic variations that occur on a broad range of temporal and spatial scales. Analyses to detect the possible influence of human activities have had to take such natural variations into consideration. As mentioned earlier, however, recent studies suggest that the warmer global temperatures over the last decade appear to be outside the range of natural variability found in the climate record for the last 400–1000 years.

4.2. Projecting the future changes

In order to study the potential implications on climate from further changes in human-related emissions and atmospheric composition, a range of scenarios for future emissions of greenhouse gases and aerosol precursors has been produced by the IPCC Special Report on Emission Scenarios (SRES) for use in modeling studies to assess potential changes in climate over the next century for the current IPCC international assessment of climate change. None of these scenarios should be considered as a prediction of the future, but they do illustrate the effects of various assumptions about economics, demography, and policy on future emissions. In this study, we investigate four SRES "marker" scenarios, labeled A1, A2, B1, and B2, as examples of the possible effect of greenhouse gases on climate. Each scenario is based on a narrative storyline, describing alternative future developments in economics, technical, environmental and social dimensions. Details of these storylines and the SRES process can be found elsewhere [9,17]. These scenarios are generally thought to represent the possible range for a business-as-usual situation where there has been no significant efforts to reduce emissions to slow down or prevent climate changes.

Fig. 5 shows the anthropogenic emissions for four of the most important gases to concerns about climate change, CO_2, CH_4, N_2O, and SO_2. Carbon dioxide emissions span a wide range, from nearly five times the 1990 value by 2100 to emissions that rise

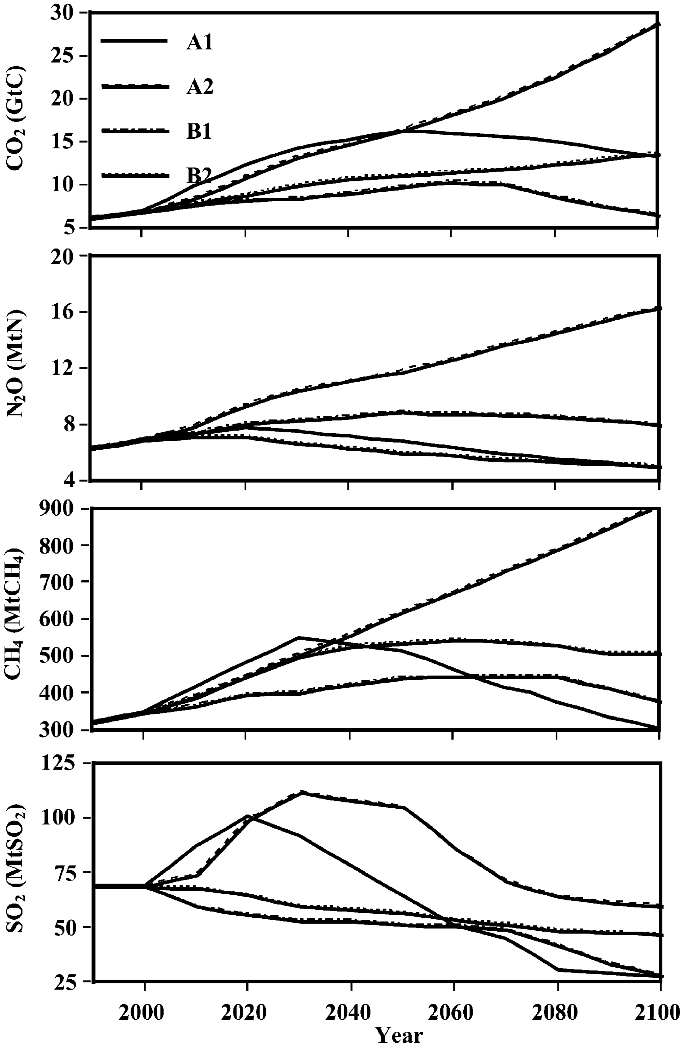

Fig. 5. Anthropogenic emissions in the SRES marker scenarios for CO_2, CH_4, N_2O, and SO_2. Note that the SRES emission values are standardized such that emissions from 1990 to 2000 are identical in all scenarios.

and then fall to near their 1990 value. N_2O and CH_4 emission scenarios reflect these variations and have similar trends. However, global sulfur dioxide emissions in 2100 have declined to below their 1990 levels in all scenarios, because rising affluence increases the demand for emissions reductions. Note that sulfur emissions, particularly to mid-century, differ fairly substantially between the scenarios. Also, the new scenarios for sulfur emissions are much smaller than earlier analyses (e.g., Ref. [10]), largely as a result of increased recognition worldwide of the importance of reducing sulfate aerosol effects on human health, on agriculture, and on the biosphere.

In this study, the global climate change consequences of SRES scenarios were calculated with the reduced form version of our Integrated Science Assessment Model (ISAM) [18,19]. The model consists of several gas cycle sub-models converting emissions of major greenhouse gases to concentrations and energy balance climate model for the atmosphere and ocean, and a sea level rise model. In this study, updated radiative forcing analyses [20] for various greenhouse gases have been used. Based on results from the carbon cycle submodel within ISAM, Fig. 6 shows the derived changes in concentrations of carbon dioxide for the four scenarios. Over the next century, CO_2 concentrations continue to increase in each scenario, reaching concentrations from 548 to 806 ppm. Even though emissions decline in some of the scenarios, the long atmospheric lifetime of CO_2 results in continued increases in concentration over the century.

The upper panel of Fig. 7 shows the derived globally averaged radiative forcing as a function of time for various SRES marker scenarios. Calculated radiative forcing increases to 7 W m^{-2} by 2100 for high scenario A2 and 4.7 W m^{-2} for low scenarios B1 and B2 relative to the beginning of the Industrial Era. As a result, each of the scenarios implies a significant warming tendency. Direct effects of aerosols are included in this analysis but indirect effects and effects on ozone are not considered.

The response of the climate system to the changes in radiative forcing is determined by the climate sensitivity defined as the equilibrium surface temperature increase for doubling of atmospheric CO_2 concentration. This parameter is intended to account for all the climate feedback processes not modeled explicitly. The middle panel of Fig. 7

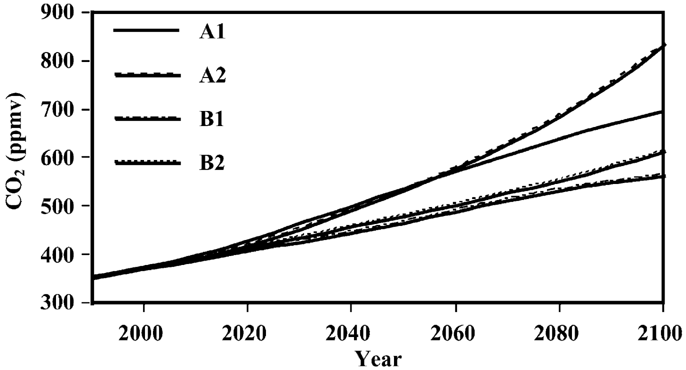

Fig. 6. Integrated Science Model (ISAM) estimated CO_2 concentrations for the SRES marker scenarios.

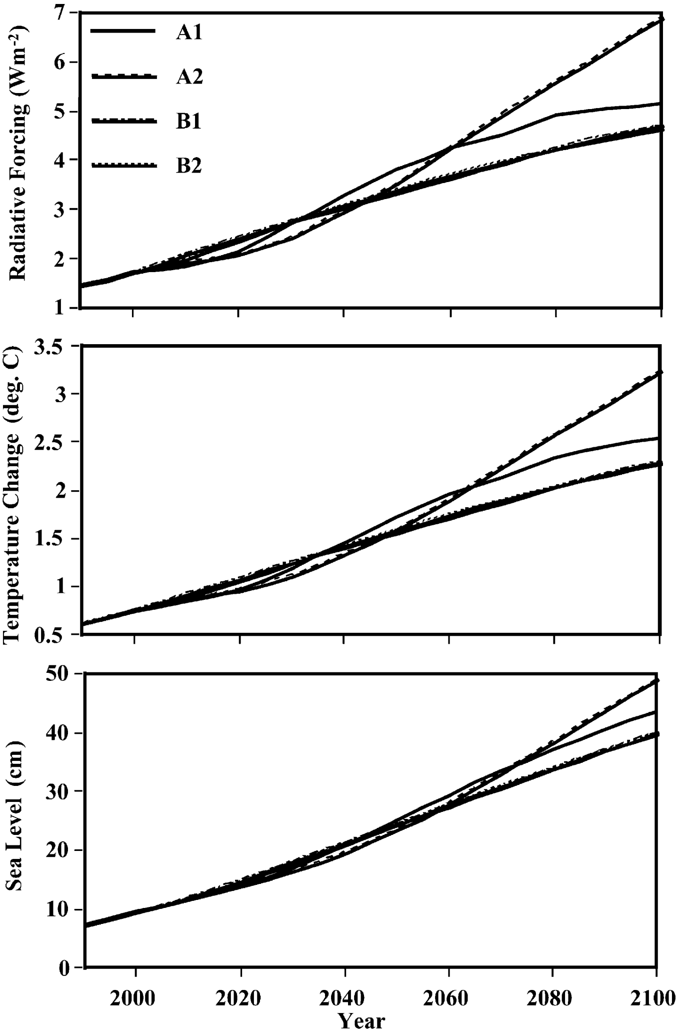

Fig. 7. ISAM estimated change in radiative forcing, change in globally averaged surface temperature, and sea-level rise for the SRES marker scenarios. The temperature change is estimated a climate sensitivity of 2.5°C for a doubling of CO_2; this sensitivity appears to best represent the climate sensitivity of current climate models [10].

shows the model-calculated changes in global mean surface temperature for the various SRES scenarios assuming a central value for the climate sensitivity of 2.5°C. For the four scenarios, surface temperature is projected to increase by about 1.8–2.6°C by 2100 relative to 1990 for this assumed climate sensitivity. The full range of uncertainty in the climate sensitivity would be presented by a broader range of 1.5–4.5°C for a doubling of CO_2 concentration [10]. Accounting for this uncertainty, the scenarios would give an increase in surface temperature of about 1.3–5°C for the four scenarios. The bottom panel of Fig. 7 shows the derived sea level rise for the four scenarios. The difference in future sea level scenarios is much smaller as compared to the temperature scenarios. This is because the sea level rise has a much stronger memory effect due mainly to the large thermal inertia of the ocean and, hence, long time scale of the ocean response.

5. Potential impacts of climate change

In the previous sections, we briefly discussed projected changes in climate as a result of current and potential human activities. There are many uncertainties in our predictions, particularly with regard to the timing, magnitude, and regional patterns of climate change. At this point, potential changes in climate globally are better understood than the changes that could occur locally or regionally. However, the impacts of interest from climate change are primarily local to regional in scale. Nevertheless, scientific studies have shown that human health, ecological systems and socioeconomic sectors (e.g., hydrology and water resources, food and fiber production, and coastal systems, all of which are vital to sustainable development) are sensitive to changes in climate as well as to changes in climate variability. Recently, a great deal of work has been undertaken to assess the potential consequences of climate change [21]. This recent study has assessed how systems would respond to future projections of climate change. Here, we restrict our discussion to only a brief overview.

5.1. Ecosystems

Ecosystems both affect and are affected by climate. As carbon dioxide levels increase, the productivity and efficiency of water use by vegetation may also increase. As temperature warms, the composition and geographical distribution of many ecosystems will shift as individual species respond to changes in climate. As vegetation shifts, this will in turn affect climate. Vegetation and other land cover determine the amount of radiation absorbed and emitted by the earth’s surface. As the earth’s radiation balance changes, the temperature of the atmosphere will be affected, resulting in further climate change. Other likely climate change impacts from ecosystems include reductions in biological diversity and in the goods and services that ecosystems provide society.

5.2. Water resources

Climate change may lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources. Reduced rainfall and increased evaporation in a warmer world could dramatically reduce runoff in some areas, significantly decreasing the availability of water resources for crop irrigation, hydroelectric power production, and industrial/commercial and transport uses. Other regions may see increased rainfall. In light of the increase in artificial fertilizers, pesticides, feedlots excrement, and hazardous waste dumps, the provision of good quality drinking water is anticipated to be difficult.

5.3. Agriculture

Crop yields and productivity is projected to increase in some areas, at least during the next few decades, and decrease in others. The most significant decreases are expected in the tropics and subtropics, which contain the majority of the world's population. The decrease could be so severe as to cause increased risk of hunger and famine in some locations that already contain many of the world's poorest people. These regions are particularly vulnerable, as industrialized countries may be able to counteract climate change impacts by technological developments, genetic diversity, and maintaining food reserves.

Livestock production may also be affected by changes in grain prices due to pasture productivity. Supplies of forest products such as wood during the next century may also become increasingly inadequate to meet projected consumption due to both climatic and non-climatic factors. Boreal forests are likely to undergo irregular and large-scale losses of living trees because of the impact of projected climate change. Marine fisheries production is also expected to be affected by climate change. The principal impacts will be felt at the national and local levels.

5.4. Sea level rise

In a warmer climate, sea level will rise due to two primary factors: (i) the thermal expansion of ocean water as it warms, and (ii) the melting of snow and ice from mountain glaciers and polar ice caps. Over the last century, the global-mean sea level has risen about 10–25 cm. Over the next century, current models project a further increase of 25–100 cm in global-mean sea level for typical scenarios of greenhouse gas emissions and resulting climate effects (IPCC, 2000). A sea level rise in the upper part of this range could have very detrimental effects on low-lying coastal areas. In addition to direct flooding and property damage or loss, other impacts may include coastal erosion, increased frequency of storm surge flooding, salt water infiltration and, hence, pollution of irrigation and drinking water, destruction of estuarine habitats, damage to coral reefs, etc. Little change is expected to occur in the Antarctic over the next century, but if there were to be any major melting, it would potentially increase sea level by large amounts.

5.5. Health and human infrastructure

Climate change can impact human health through changes in weather, sea level and water supplies, and through changes in ecosystems that affect food security or the geography of vector-borne diseases. The IPCC study [22] dealing with human health issues found that most of the possible impacts of global warming would be adverse.

In terms of direct effects on human health, increased frequency of heat waves would increase rates of cardio-respiratory illness and death. High temperatures would also exacerbate the health effects of primary pollutants generated in fossil fuel combustion processes and increase the formation of secondary pollutants such as tropospheric ozone. Changes in the geographical distribution of disease vectors such as mosquitoes (malaria) and snails (schistosomiasis) and changes in life-cycle dynamics of both vectors and infective parasites would increase the potential for transmission of disease. Non-vector-borne diseases such as cholera might increase in the tropics and sub-tropics because of climatic change effects on water supplies, temperature and microorganism proliferation. Concerns for climate change effects on human health are legitimate. However, impacts research on this subject is sparse and the conclusions reached by the IPCC are still highly speculative.

Indirect effects would also result from climatic changes that decrease food production would reduce overall global food security and lead to malnutrition and hunger. Shortages of food and fresh water and the disruptive effects of sea level rise may lead to psychological stresses and the disruption of economic and social systems.

6. Pathways to policy considerations

Worldwide concern over climate change and its potential consequences has led to consideration of international actions to address this issue. These actions fall into two broad categories: an adaptive approach, in which people change their lifestyle to adapt to the new climate conditions; or a preventive or “mitigation” approach, in which attempts are made to minimize human-induced global climate change by removing its causes. While it is not our intention here to consider or examine the range of possible policy options, it is important to discuss recent international activities that have resulted in a number of recommendations for emission reductions.

In Rio de Janeiro in 1992, the United Nation Framework Convention on Climate Change (UNFCC) agreed to call for the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system....” [23]. While specific concentration levels and time paths to reach stabilization for greenhouse gases had not been stated, analyses of illustrative scenarios for future CO_2 concentrations have given some guidance as to what is required to reach CO_2 stabilization at various levels [24,25]. Fig. 8 shows the calculated allowable emission levels over time which ultimately stabilize atmospheric CO_2 at levels ranging from 350 to 750 ppmv. These calculations were made with the carbon cycle component of our Integrated Science Assessment Model [18] discussed above. From this figure it is clear that, regardless of the stabilization target, global CO_2 emissions initially can continue to increase, would have to reach a maximum some time in the next century, and eventually must begin a long-term decline that continues through the remainder of the analysis period.

While the reductions in emissions in the stabilization scenarios are projected to lead to measurable decreases in the rate of increase in CO_2 concentrations, no specific commitments to achieve this goal were made until the December 1997 meeting of the Conference of Parties to the FCCC in Kyoto, Japan [26]. At that meeting, developed nations agreed for the first time to reduce their emissions of greenhouse gases by an average of 5.2% below 1990 levels. Emission targets range from a return to baseline year emissions for most Eastern European countries up to an 8% reduction for the European Union. Emission limits for the US under the Kyoto Protocol consist of a 7%

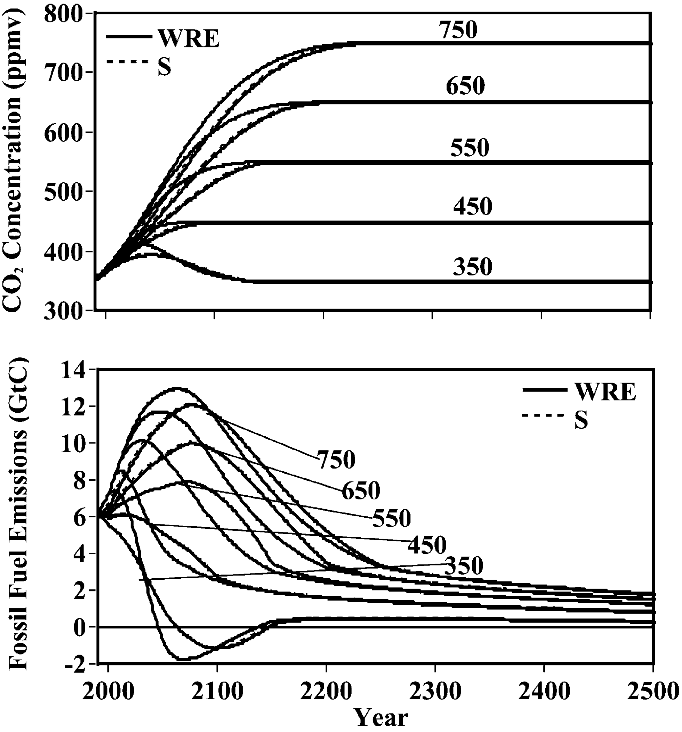

Fig. 8. CO_2 concentration stabilization profiles and associated fossil CO_2 emissions. The "S" and "WRE" pathways are defined in Enting et al. [24] and Wigley et al. [25].

reduction below baseline year emission levels. The baseline year relative to which emission reductions are determined is 1990 for CO_2, CH_4 and N_2O, and the choice of either 1990 or 1995 for HFCs, PFCs and SF_6. Mitigation actions can include reductions in any of six greenhouse gases: CO_2, CH_4, N_2O, halocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexaflouride (SF_6).

However, should this protocol enter into force in the US (which is currently responsible for 25% of the world's greenhouse gas emissions), and even if its terms were renewed throughout the remainder of the 21st century, it would not achieve the goal of the UNFCC. As Fig. 9 clearly shows, the long-term effect of the Kyoto Protocol is small. This is due to the fact that Kyoto only legislates emission controls for developed or industrialized nations. In the past, a move towards industrialization has been accompanied by an enormous increase in greenhouse gas emissions. Although emissions from the developed countries listed in the Kyoto Protocol currently account for the majority of global greenhouse gas emissions, most developing nations are already moving towards industrialization. If their relationship between greenhouse gas emissions, fossil fuel use and industrialization follow the paths of other developed nations, emissions from currently developing nations are projected to equal emissions from currently developed nations by 2020 and far surpass them by the end of the century.

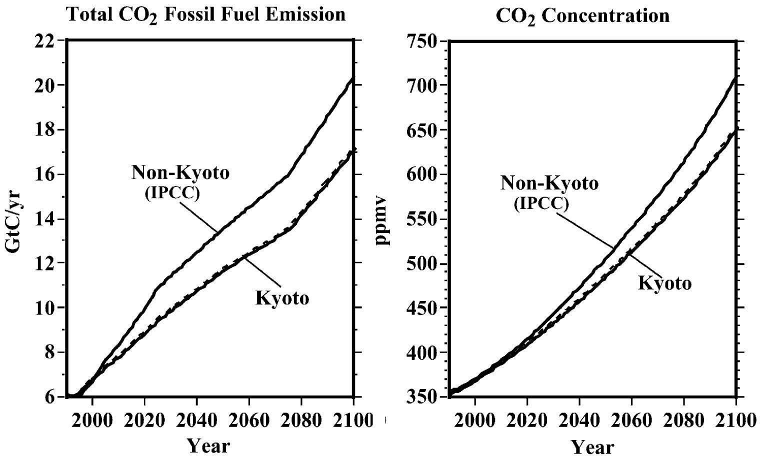

Fig. 9. Global fossil CO_2 emissions and concentrations where countries follow the various emissions limitations proposed under the Kyoto Protocol. Global emissions and concentrations under no-limitations in a business-as-usual scenario are also given for comparison.

Thus, emissions from developed nations will make up a smaller and smaller part of the climate change problem as we proceed further into the coming century. For this reason, Kyoto controls on currently developed countries are not enough if we want to prevent dangerous climate change impacts. At the same time, countries in the process of industrialization have the right to be allowed to develop into industrialized nations with higher standards of living and greater wealth. The challenge facing the world community today is how to allow nations the right of development while successfully preventing “dangerous anthropogenic interference with the climate system”.

Kyoto is important as the first concrete step in international cooperation. However, stabilizing radiative forcing will require much larger reductions that can only be fully supplied by CO_2 emissions [27] from all nations. The future emphasis on CO_2 emission reductions from developed and developing countries highlights the importance of energy and transportation technologies that do not emit CO_2 and technologies such as efficiency improvements or carbon capture and sequestration that provide mechanisms by which fossil fuels can continue to play an important role in future global energy systems without concurrent emissions growth.

7. Conclusions

Human activities already appear to be having an impact on climate. The latest evaluation for future global warming by 2100, relative to 1990, for a business-as-usual set of scenarios based on varying assumptions about population and economic growth is 1.3 to almost 5°C. Potential economic, social and environmental impacts on ecosystems, food production, water resources, and human health could be quite important, but require much more study. A certain degree of future climatic change is inevitable due to human activities no matter what policy actions are taken. Some adaptation to a changing climate will be necessary. However, the extent of impacts and the amount of adaptation will depend on our willingness to take appropriate policy actions. The consensus grows that we must follow a two-pronged strategy to conduct research to narrow down uncertainties in our knowledge, and at the same time, take precautionary measures to reduce emissions of greenhouse gases.

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