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FREQUENTLY ASKED QUESTIONS ABOUT THE SCIENCE OF CLIMATE CHANGE

2008 UPDATE

Canada

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ABOUT THE SCIENCE OF CLIMATE CHANGE

2008 Update

Atmospheric Science Assessment and Integration Section

Science and Technology Branch

Environment Canada

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PREFACE

Canadians frequently ask questions that indicate considerable public confusion about many aspects of climate change science. Some of this confusion stems simply from the fact that the climate system is extremely complex. Understanding how the Earth's climate changes over time in response to different factors requires an understanding of the whole of the earth system: the atmosphere, the oceans, the land and all the living things within these parts and the interactions among them all. Some of the confusion may also stem from the fact that there are many different sources of information available on climate change science and not all of these tell the same story. It is a significant challenge for anyone not reading the primary scientific literature on an ongoing basis to know what to consider 'sound science' and what not.

This document was first published in 2002 to provide reliable, credible responses to the most frequently heard questions and arguments about climate change science. Responses are based on fundamental, well-accepted principles of physics, on the highly acclaimed international science assessment reports of the *Intergovernmental Panel on Climate Change* (IPCC), and on recent peer-reviewed scientific papers. In the initial publication, responses were consistent with the Third Assessment Report of the IPCC, published in 2001. This update also includes results from the many new papers and reports published since then, particularly the recently released Fourth Assessment Report of the IPCC, published in 2007. Specific references are provided for diagrams and for responses where specific values are introduced.

This document is intended primarily for those with some prior knowledge of the climate change issue and in particular for those who themselves are involved in educating others about climate change science. However, by providing both a simple response and a more detailed technical explanation for each question, it is our hope that this document will be of value to a wide readership.

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A. General Overview: What is Climate Change?

A.1 What is climate and how does it differ from weather?

Response: Climate describes average day-to-day weather for a specific location or region experienced over an extended period of time. In many respects, climate is what we can expect, and weather is what we get. For example, the climate of Edmonton indicates that we should expect maximum temperatures on an average day in January to reach -8°C. However, in January 2007, actual daily maximum temperatures varied from a low of -20.3°C on January 13 to a high of +4.3°C on January 18.

Explanation: Weather in any particular location or region can change from hour to hour, day to day, season to season, and year to year. Such changes include shifts in temperature, snow and rainfall, winds, and clouds. They are caused by a complex interplay of various factors, including rapid shifts in global wind patterns, slower variations in ocean conditions, and seasonal changes in the amount of sunshine. Averaging over an extended period of time – usually at least 30 years – allows the characterization of weather we might expect at that location or region. Such climate statistics can also be used as a reference for assessing the probability of getting weather that significantly differs from these averages, including the risk of extreme weather events.

A.2 What is climate change?

Response: Climate change is a long-term shift or alteration in the climate of a specific location, region or the entire planet. The shift is measured by changes in some or all of the features associated with average weather, such as temperature, wind patterns and precipitation. It can involve both changes in average weather conditions and changes in how much the weather varies about these averages. “Climate change” is distinguished from “climate variability” by the persistence of the change over time so that a measurable difference is observed between two periods of time.

Explanation: At the global scale, climate change occurs in response to a change in the amount of energy flowing into or out of the Earth’s climate system. This occurs when something alters either the amount of the sun’s radiation absorbed by the Earth’s atmosphere and surface, or the amount of heat radiation emitted from the Earth’s surface and atmosphere to space (see Figure A.4). The climate system responds to this imbalance in energy input versus output by warming or cooling until a radiation energy balance is restored. Since the factors that cause the initial change in the energy balance push or ‘force’ the climate to change, these factors are generally referred to as ‘climate forcings’. Colloquially, positive forcings are often referred to as ‘warming factors’ while negative forcings are called ‘cooling factors’. Climate forcings can be natural phenomena or can arise from human activities.

The factors that affect regional climate change are much more complex. That is because, in addition to being affected by global climate change, regional climates are also affected by a myriad of other factors operating on smaller time and space scales, and by changes in wind and ocean patterns due to internal fluctuations of the climate system.

A.3 What is the difference between climate change and global warming?

Response: Global warming (as well as global cooling) refers specifically to a sustained warming (cooling) of the global average surface temperature. Global warming is often misunderstood to imply that the world will warm uniformly. In fact, it will affect the climate of one region very differently from another. As a result, some areas of the world will warm more, while others will warm less than the average. Some areas may even cool. Furthermore, an increase in average global temperature will also cause changes in other aspects of the climate system, such as precipitation and winds, affecting weather patterns around the world. In other words, global warming is only one aspect of climate change. Hence, the term ‘climate change’ more clearly describes the situation that the world is facing today.

Explanation: The initial response of the Earth’s atmosphere to a ‘climate forcing’[1] is a change in flow of solar and heat energy through the atmosphere that in turn causes temperatures at the surface, in the atmosphere and within the oceans to change. However, these changes in temperature are more rapid over land than water, and can cause changes in many other aspects of the climate. For example, warmer temperatures would cause more evaporation, higher concentrations of water vapour in the atmosphere, changes in cloud cover and in rain or snowfall, more snow and ice melt, and changes in winds and ocean currents, and so forth. Many of these secondary changes also affect temperature, resulting in a complex interplay of different processes that may amplify the increase in temperature in some regions and moderate changes, or even cause cooling, in others. In other words, a climate forcing that causes global warming also causes many other aspects of the climate to change in complex ways. Therefore, the term ‘climate change’[2] is the more accurate description of how the climate system responds to a forcing.

[1] *See A.2 for a description of climate forcing.*

[2] *The term ‘climate change’ is used preferentially throughout this document. The term ‘global warming’, when it is used, refers specifically to the increase in global average surface temperature.*

A.4 What is the “greenhouse effect” and how does it influence the climate system?

Response: The greenhouse effect describes the role of the atmosphere in insulating the planet from heat loss, much like a blanket on our bed insulates our bodies from heat loss. The small concentrations of “greenhouse gases” within the atmosphere that cause this effect allow most of the sunlight to pass through the atmosphere to heat the planet. However, these gases absorb much of the outgoing heat energy radiated by the Earth itself, and return much of this energy back towards the surface. This keeps the surface much warmer than if these gases were absent. This process is referred to as the ‘greenhouse effect’ because, in some respects, it resembles the role of glass in a greenhouse. The greenhouse effect makes the Earth livable. Without it, the Earth would be too cold to support life as we know it.

Explanation: The Earth is heated by sunlight. In turn, the Earth radiates heat energy out to space. It is this balance between incoming solar (shortwave) radiation and outgoing infrared (longwave) radiation that determines the temperature of the Earth. However, gases and solid and liquid particles within the atmosphere, as well as properties of the Earth’s surface, affect the flow of solar and heat energy by reflecting, scattering or absorbing and re-radiating some of it. About 31% of the incoming sunlight is reflected back to space by clouds and the Earth’s surface. The remainder of the solar energy warms the Earth’s surface, oceans and atmosphere. Much of the harmful ultraviolet part of sunlight is absorbed in the stratosphere by ozone (O_3). Thus, the ozone layer not only protects the Earth’s ecosystems from harm, it also retains a portion of the sun’s energy in the upper atmosphere. However, while some atmospheric particles can absorb significant amounts of solar energy, most gases within the atmosphere absorb very little, allowing most of the Sun’s energy to pass through to warm the surface. The warmed Earth then emits heat energy (infrared radiation) back towards space. Most of this outgoing radiation is absorbed by clouds and molecules of greenhouse gases in the lower atmosphere. These re-radiate the energy in all directions, some back towards the surface and some upward, where other molecules higher up can absorb the energy again. This process of absorption and re-emission is repeated until the energy escapes from the atmosphere to space. Since much of this heat energy has been recycled downward, surface temperatures become much warmer than if the greenhouse gases were absent from the atmosphere. This natural process is known as the greenhouse effect. Without naturally occurring greenhouse gases, such as water vapour, CO_2, CH_4 and N_2O, the Earth’s average temperature would be -19°C instead of +14°C, or 33°C colder. Over the past 10,000 years (the period since the end of the most recent glaciation), the amount of these greenhouse gases in our atmosphere has been relatively stable. Then a few centuries ago, their concentrations began to increase due to human activities. This has enhanced the natural greenhouse gas effect, and caused the Earth’s climate to change.

Reference: Le Treut et al., 2007

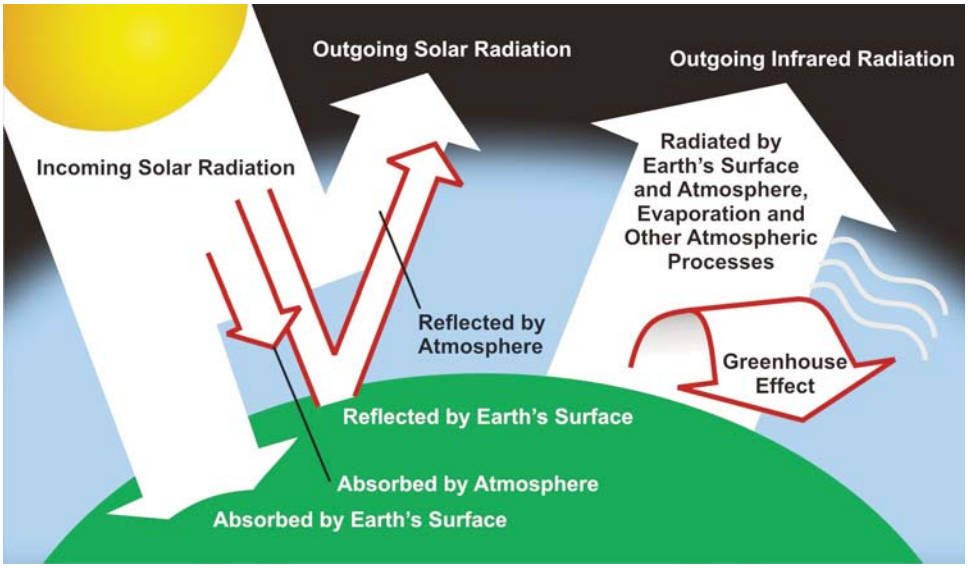

Figure A.4. A simple diagram of the natural greenhouse effect. Naturally occurring greenhouse gases in the atmosphere insulate the Earth from heat loss. The Earth's average temperature is much warmer than it would otherwise be because of the natural greenhouse effect. In a stable climate, the net solar energy absorbed by the Earth's atmosphere, surface and oceans is, on average, equal to the net heat energy returned back to space by the Earth's surface and atmosphere. Enhancing the greenhouse effect will alter the Earth's energy balance and will have a warming effect on Earth's climate (Environment Canada, 2007a).

A.5 What are the primary gases that produce the natural greenhouse effect and what are their relative roles?

Response: Important naturally occurring greenhouse gases include water vapour, CO_2, CH_4, O_3 and N_2O. Without the natural greenhouse effect, Earth's average temperature would be -19°C instead of +14°C, or 33°C colder. About two thirds of the natural greenhouse effect is from water vapour. Another one quarter is due to CO_2.

Explanation: Water vapour is the single most important absorber of the outgoing long-wave infrared radiation. If the radiative effects of other greenhouse gases are ignored, water vapour is responsible for roughly 60 to 70% of the natural greenhouse effect, while CO_2 alone would make up only about 25%. However, the atmospheric concentration of water vapour varies in response to changes in temperature and other factors such as changes in soil moisture and vegetation. The total amount of water vapour in the atmosphere will increase under a warmer climate as a result of the atmosphere's increased ability to hold more water vapour before it becomes saturated and condenses the water vapour into raindrops or snowflakes. Furthermore, warmer surface temperatures will result in more evaporation of surface moisture into water vapour. The tight coupling between atmospheric temperature and atmospheric water vapour is the reason why changes in water vapour are considered a climate feedback rather than a climate forcing. The water vapour feedback is positive, meaning the increase in water vapour will cause additional absorption of infrared radiation, further enhancing the greenhouse effect.

References: Le Treut et al., 2007; Shine et al., 1990.

A.6 What causes climate change?

Response: Changes in climate can be caused both by natural events and processes and by human influences. Key natural factors include changes in the intensity of sunlight reaching the Earth and in the concentration of volcanic dust (which reflects and scatters sunlight) in the stratosphere. Both of these factors alter the amount of sunlight that is absorbed by the Earth's climate system. Changes in atmospheric concentrations of greenhouse gases due to natural processes have also contributed to past changes in climate. Key human influences include emissions of gases and particles that affect the atmospheric concentrations of greenhouse gases, cause O_3 depletion in the stratosphere and create regional air pollution. Land use change due to expansion of agriculture, urbanization and other factors are also contributors. Most of these human influences affect the amount of heat energy escaping to space, although some also change the amount of sunlight reflected to space.

Explanation: Any factor that affects the balance between the amount of radiative solar energy absorbed by the Earth's climate system and the radiative heat energy released back to space pushes the climate towards a new state, and hence is a climate forcing. One example of a climate forcing that has been a regular feature of the Earth's climatic history is the changing annual and/or seasonal intensity of sunlight reaching the Earth. Some changes, like the large 100,000-year glacial-interglacial swings detected in polar ice core data and ocean sediments, appear to be caused by cyclic variations in the Earth's orbit around the Sun. These orbital changes affect both the distance between the Sun and the Earth and the angle of Earth's exposure to sunlight. Such long-term cycles can cause changes in average global surface temperatures on the order of 4 to 7°C between glacial and interglacial periods. For the past 10,000 years, the Earth has been in the warm interglacial phase of such a cycle. Other cycles in solar intensity are caused by changes in the amount of energy released from the Sun itself. These solar activity cycles can be on much shorter time scales, with the shortest being the well-known 11-year sunspot cycle. Finally, other natural changes in climate forcings include large eruptions of volcanoes, which can sporadically increase the concentration of atmospheric particles for short periods of time, temporarily blocking out more sunlight. However, the magnitudes of naturally induced changes in climate during the current interglacial period have been much smaller than those caused by the long orbital cycles. Within the past several thousand years, for example, net changes in average global surface temperatures due to natural climate forcings appear to have been within a range of about 1°C.

Most scientists are now convinced that human activities are also changing the climate. The main cause of such change is the increasing atmospheric concentration of greenhouse gases. Particularly important is the increase in CO_2, which is released by humans primarily through the burning of fossil fuels (coal, oil and natural gas) and through deforestation. An increase in greenhouse gases enhances the natural greenhouse effect and leads to an increase in the Earth's average surface temperature. Emissions of other polluting gases and particles into the atmosphere can also be significant. However, many of these do not stay in the atmosphere long, and hence their roles in influencing climate change may be large at a regional scale but relatively modest when averaged globally. Some of these can also have opposing climate forcing effects. Dark, sooty aerosols, for example, tend to absorb both solar and heat radiation energy, and cause a warming influence. On the other hand, sulphate aerosols reflect and scatter incoming sunlight, both directly and by altering the amount and brightness of clouds, and tend to cool the climate. While the immediate effects of such aerosols will be felt primarily within the industrialized regions from where most emissions originate, aerosols can also indirectly alter average global temperatures and wind currents. Human-induced depletion of O_3 in the stratosphere also tends to cool the Earth's surface (see B.11). Finally, land use change can alter the albedo of the Earth's surface, making it either more or less reflective. In this way, changing land use can contribute to climate change.

A.7 Is there any evidence that past changes in greenhouse gas concentrations have been linked to climate change?

Response: Yes. For example, the relationship between greenhouse gases and climate change is strongly supported by the analyses of ice samples taken from deep within ice sheets in Antarctica and Greenland. These samples provide excellent archives of fossilized air bubbles trapped within the ice, and thereby provide a record of the variations in concentrations of atmospheric greenhouse gases over hundreds of thousands of years. The relative concentrations of different oxygen and hydrogen isotopes in the ice itself can also indicate how regional air temperatures have changed over time. These analyses indicate that the atmospheric concentrations of CO_2, CH_4 and N_2O have remarkably strong correlations with the air temperature over Antarctica and Greenland.

Explanation: Studies of polar ice cores have demonstrated that atmospheric greenhouse gas concentrations are linked to changes in past climate. The latest scientific analyses of ice core samples from Antarctica, for example, provide records of climate and greenhouse gas variations over the last 650,000 years. As shown in the accompanying figure, there is good agreement between these records. During glacial periods, average local temperatures in Antarctica were some 10°C colder than today, while CO_2, CH_4 and N_2O concentrations dropped to their lowest values of 200 parts per million (ppm), 400 parts per billion (ppb) and 220 ppb, respectively. During warm interglacials, when temperatures were similar to or slightly warmer than today, gas concentrations rose to 300 ppm, 700 ppb and N_2O ->280 ppb, respectively. These records also indicate that the current concentration of CO_2, CH_4 and N_2O are unprecedented for the last 650,000 years. There are also indications that, over million-year time scales, the Earth's climate was warm during periods of high CO_2 concentrations and much cooler during low CO_2 concentration periods, providing additional evidence of the tight coupling between greenhouse gas concentrations and climate. Current scientific understanding is that while changes in solar forcing were likely to have initiated climate warming or cooling, changes in greenhouse gas concentrations strongly amplified the initial change in climate.

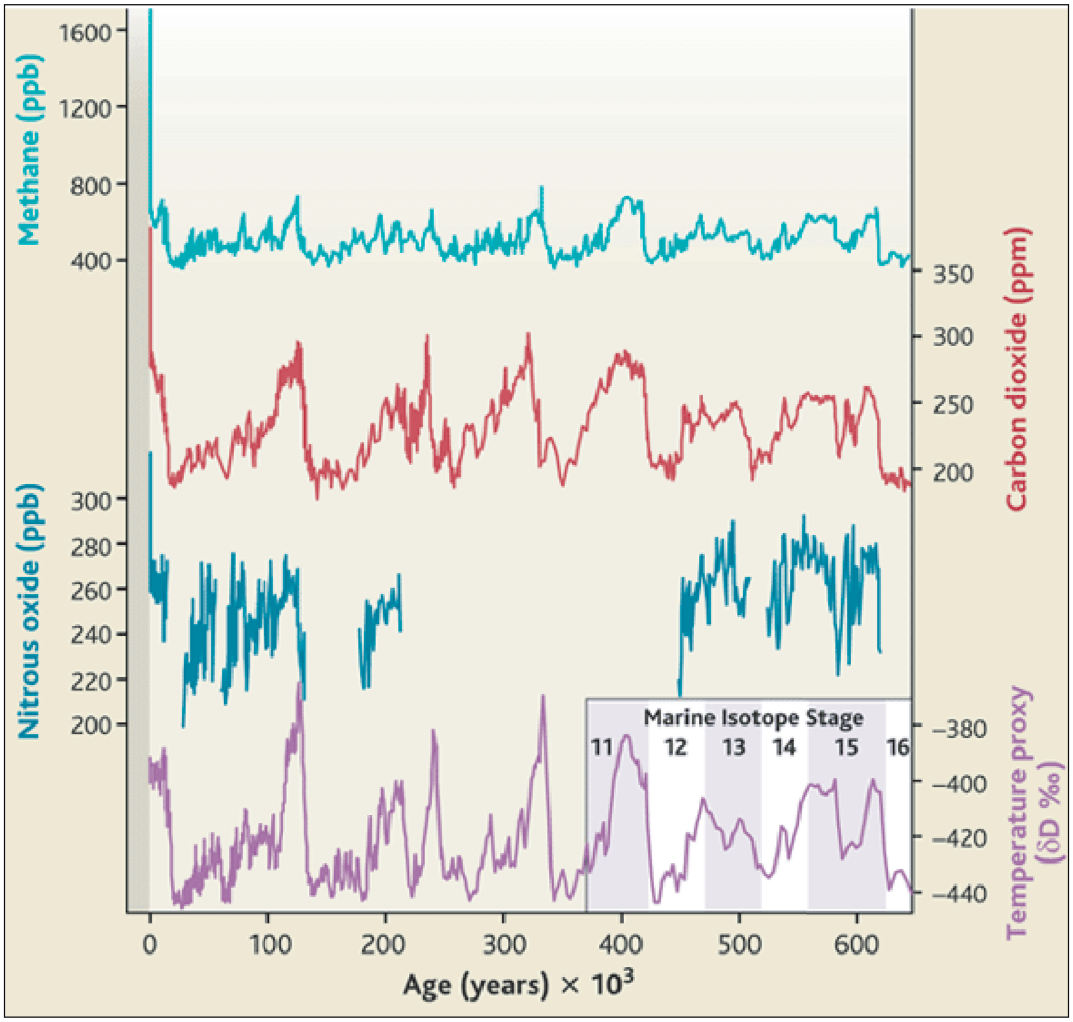

Figure A.7. The greenhouse gas (CO_2, CH_4, and N_2O) and deuterium (δD) records for the past 650,000 years from the European Project for Ice Coring in Antarctica (EPICA) ice core sample and other ice cores, with marine isotope stage correlations (labelled at lower right) for stages 11 to 16. δD, a proxy for air temperature, is the deuterium/hydrogen ratio of the ice, expressed as a per mil deviation from the value of an isotope standard. More positive values indicate warmer conditions. Data for the past 200 years from other ice core records and direct atmospheric measurements at the South Pole are also included (Brook, 2005).

A.8 Ice core data indicate that, during glacial-interglacial cycles, changes in CO_2 concentrations lag those in polar temperatures. Doesn't this indicate that climate change causes CO_2 concentrations to change, not the other way around?

Response: Studies of ice core records indeed indicate that in the past, changes in CO_2 concentrations appear to have been a response to changes in climate, not the initial cause. However, there is clear evidence that the initial changes in climate, believed to be triggered by variations in the Earth's orbit around the Sun, resulted in a rapid release of greenhouse gases, particularly CO_2, that substantially enhanced the initial warming. In fact, model studies suggest that approximately half of the magnitude of the 4 to 7°C global temperature swing between glacial and interglacial periods can be attributed to greenhouse gas feedbacks.

Explanation: Analyses of polar ice core samples have demonstrated that, during the 650,000 years of that record, changes in CO_2 were never the initial cause of the slow swings in climate from glacial to interglacial conditions. Such swings appear to have been triggered by changes in the Earth's orbit around the Sun. However, the initial changes in climate appear to have caused a rapid increase in the release of CO_2, CH_4 and N_2O from various natural sources. The prime source of CO_2 emissions was likely the deep oceans. This response appears to have been so rapid that any lag between temperature change and CO_2 response was on the order of several centuries to one millennium – rapid on geological time scales. Climate model simulations demonstrate that the full magnitude of temperature changes cannot be explained solely by the climate forcing due to orbital changes. Rather, the responsive changes in greenhouse gas concentrations appear to have contributed about 50% of the change in climate. This, in turn, provides evidence of the important role of greenhouse gases in the climate system, and that increases in their concentrations due to direct emissions by humans would also cause the climate to warm.

Reference: Jansen et al., 2007.

B. Human Influences on the Atmosphere

B.1 How much have concentrations of the primary greenhouse gases increased in recent years?

Response: By 2005, concentrations of CO_2 had increased 36% above pre-industrial levels of the mid-18th century, those of CH_4 by 148%, while N_2O increased by 18%. Current concentrations of these gases appear to be unprecedented in at least the past 650,000 years. There is clear evidence that these increases are mostly due to human activities, particularly the burning of fossil fuels for transportation, heating and electricity, and land use change. The rise in CO_2 accounts for more than two thirds of the enhancement of the greenhouse effect that these changes have caused to date.

Explanation: Data from cores extracted from polar ice sheets contain fossilized air bubbles that provide samples of the chemical composition of the atmosphere in the distant past. These indicate that the atmospheric concentration of CO_2 did not exceed about 300 parts per million by volume (ppm) over the entire 650,000-year record, and that it remained between 260 and 280 ppm during the last 10,000 years (the current interglacial period) until about 250 years ago when it began to rise. By 2005, atmospheric CO_2 concentration had increased to 379 ppm, with most of that increase occurring during the past 50 years. Meanwhile, concentrations of CH_4 and N_2O have increased from pre-industrial levels of 715 parts per billion by volume (ppb) and 270 ppb to about 1774 ppb and 319 ppb, respectively. Collectively, these three gases have increased the intensity of the natural greenhouse effect by 2.3 watts per metre squared (W/m^2)[3] with 1.66 W/m^2 of that due to CO_2 alone.

Reference: Forster et al., 2007.

[3] *One W/m^2 of global climate forcing might be approximated by the effect of placing one 100 W light-bulb at 10 meter intervals around the entire surface area of the Earth, with all the energy generated by the bulbs being converted to heat energy.*

B.2 How have other greenhouse gas concentrations changed in recent years?

Response: In addition to CO_2, CH_4, and N_2O, a number of other atmospheric greenhouse gases have been increasing in abundance. Concentrations of O_3 in the lower atmosphere (troposphere), for example, have increased significantly in industrialized regions of the world, relative to pre-industrial levels. Meanwhile, chemical engineering activities have also created a suite of other new greenhouse gases that were largely absent in the pre-industrial atmosphere. Particularly important are the long-lived halocarbon gases, which now have atmospheric concentrations in the tens to hundreds of parts per trillion (ppt). While the concentrations of these new greenhouse gases are as yet very low relative to the primary greenhouse gases, they are very powerful greenhouse gases and, once released, can remain in the atmosphere for centuries to millennia. To date, increases in tropospheric O_3 and halocarbons have collectively enhanced the natural greenhouse effect by about 0.7 W/m^2 – adding another 30% to the climate forcing caused by increases in the abundance of the three primary greenhouse gases.

Explanation: While tropospheric O_3 does occur naturally, it has a very short lifetime. Therefore, pre-industrial concentrations of O_3 were very low. Emissions of gases that contribute to the chemical production of O_3 (known as O_3-precursors), such as nitrogen oxides, carbon monoxide and hydrocarbons, have dramatically contributed to increased tropospheric O_3 concentrations over many industrialized regions of the world. Model studies suggest that these increases, averaged globally, have likely enhanced the greenhouse effect by an estimated 0.35 W/m^2

Meanwhile, a range of other greenhouse gases (particularly halocarbons and sulphur hexafluoride) have been generated by human chemical engineering and industrial processes. Although their concentrations remain very low, they are powerful greenhouse gases. For example, for some of these gases, an increase of their presence in the atmosphere by 1 kg can enhance the natural greenhouse effect by the same amount as the emission of tens of thousands of kg of CO_2. The halocarbons alone have increased the natural greenhouse effect by 0.34 W/m^2 even though they are present in only minute amounts (parts per trillion) in the atmosphere. Some of these halocarbons also cause excessive destruction of O_3 in the stratosphere (in the ozone layer). Since O_3 is a greenhouse gas, its decline in the stratosphere also slightly decreases the net greenhouse effect by offsetting the effects of other greenhouse gases by -0.05 W/m^2. Due to the fact that stratospheric O_3 decline results in increased exposure of life and materials at the Earth's surface to harmful ultraviolet radiation, production and use of the O_3 depleting halocarbons are now restricted under the Montreal Protocol[4].

Reference: Forster et al., 2007.

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[4] *The Montreal Protocol is part of an international agreement to control the production and emission of substances that contribute to the depletion of O_3 in the stratosphere. These substances include a number of halon gases, particularly chlorofluorocarbons, hydrochlorofluorocarbons, and chlorocarbons, that are also potent greenhouse gases. However, other halons that do not contribute to O_3 depletion, such as fluorocarbons, are not controlled under the Montreal Protocol.*

B.3

How do scientists know that the atmospheric build up of greenhouse gases is due to human activity?

Response: A number of factors clearly point to the role of human activities as the primary source of observed increases in greenhouse gas concentrations. For example, the current rate of increase in concentrations correlates well with changes in the rate of human emissions, and is unprecedented in many millennia of atmospheric history. Furthermore, trends in ratios of carbon isotopes in atmospheric CO_2 and in the distribution of CO_2 in the atmosphere are consistent with emissions from human sources. Similar evidence demonstrates the role of humans in increases in the other greenhouse gases.

Explanation: The rapid rise in greenhouse gas concentrations during the past century is consistent with trends in human emissions, and unprecedented in at least the last 650,000 years and likely in the past 20 million years (see Figure A.7). Furthermore, the concentration of CO_2 molecules in the atmosphere containing the radioactive carbon 14 atom (after adjustment for atomic explosion testing activities in the 1950s) is declining. This is consistent with increased emissions of CO_2 from burning of coal, oil and natural gas, all of which contain 'old' carbon that has no carbon 14. Changes with time in ratios of carbon 13 and carbon 12 in oceans are also consistent with human emissions, as is the north-south latitudinal gradient in atmospheric concentrations of CO_2. Finally, carbon budget models, which can now reproduce the global carbon cycle quite accurately, point to human emissions. In fact, increased uptake and storage of CO_2 by the Earth's terrestrial biosphere and oceans have helped remove about half of the related emissions into the atmosphere from human sources. Similar studies have been undertaken for CH_4 and N_2O, which also indicate a major human contribution. However, the exact magnitude of the human role in increases in these gases is less clear because of the uncertainty surrounding the many biological processes involved in both their natural and human emissions. Finally, trace gases such as the halocarbons and sulphur hexafluoride have no significant natural sources. There is strong evidence that changes in their concentrations are entirely caused by human emissions.

B.4

Which human activities contribute the most greenhouse gases to the atmosphere?

Response: The burning of fossil fuels – primarily coal, oil and natural gas - currently accounts for between 70 and 90% of all human emissions of CO_2. Fossil fuels are used for transportation, manufacturing, heating, cooling, electricity generation, and other applications. The remainder of the CO_2 emissions comes from human land use activities — ranching, agriculture and the clearing and degradation of forests. For other greenhouse gases, primary sources include the production and transport of fossil fuels, agricultural activities, waste management and industrial processes.

Explanation: Between 2000 and 2005, humans released more than 26 billion tonnes of CO_2 into the atmosphere per year through the burning of fossil fuels for energy. CO_2 emissions associated with land use change, although far more uncertain than those due to fossil fuel combustion, have been roughly estimated at 6 billion tonnes per year. Some, but not all of these land use emissions are being offset by growth of new forests and improved soil management in some regions of the world.

CH_4 emissions occur both naturally and as a result of human activities. CH_4 is the second most significant greenhouse gas, next to CO_2. Rice cultivation, cattle and sheep ranching, and decaying material in landfills all release CH_4, as do coal mining, oil drilling operations, and leaky gas pipes. N_2O comes from both natural sources and human activities. Fossil fuel combustion, industrial practices, and agricultural practices (including the use of chemical fertilizers) all contribute to N_2O emissions. The industrial production of chlorofluorocarbons (CFCs) and other halocarbons - used in refrigeration, air conditioning, and as solvents - have added other greenhouse gases, but many of these sources are gradually being eliminated under the Montreal Protocol agreement because they deplete the stratospheric ozone layer (see B.2). O_3 in the troposphere (the lower part of the atmosphere), in addition to being a key ingredient of smog, is also a greenhouse gas. It is primarily produced as a result of chemical reactions involving highly reactive gases such as nitrogen dioxides, carbon monoxides and hydrocarbons that are released from transportation and industrial sources. Since these gases contribute to O_3 production, they are commonly known as O_3 precursors.

In Canada, about 37% of all greenhouse gas emissions in 2005 were caused by the production of energy for use by Canadians and for exports. These energy-related emissions are almost equally divided between the production of electricity from the combustion of fossil fuels and the exploration and production of coal, oil and natural gas for the energy market. Another 27% was produced by the transportation of goods and people across Canada - whether by truck, car, airplane, train, boat or other means. Mining, manufacturing and industrial processes added another 16%. Non-electrical use of energy in the residential, commercial and institutional sector contributed about 11%, land use, forestry and agricultural activities about 5%, and waste management almost 4%.

Similar sources of emissions occur in other countries, although the ratios differ with the type of economy, culture and climate.

Reference: Environment Canada, 2007b.

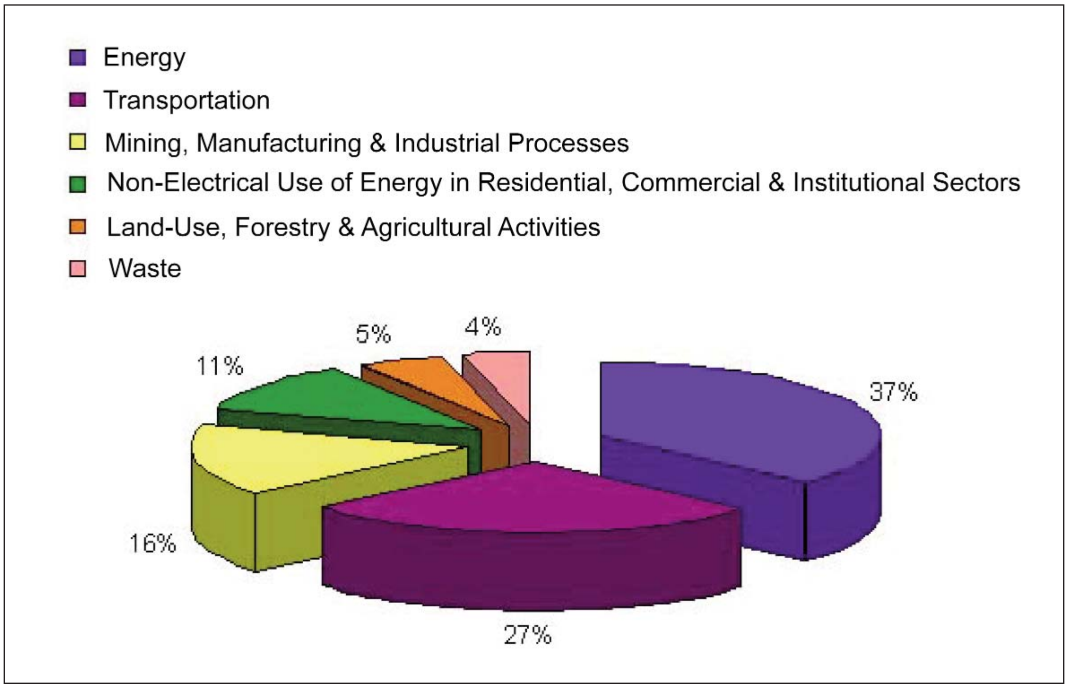

Figure B.4. Canadian greenhouse gas emissions by sector (2005 data). The Energy sector includes Electricity and Heat Generation, Fossil Fuel Industries and Fugitive Emissions. The Mining, Manufacturing and Industrial Processes sector combines energy-related and direct emissions (including from solvent use) (based on Table: Sectoral Greenhouse Gas Emission Summary, Environment Canada, 2007b).

B.5 Since greenhouse gases only represent such a small fraction of the atmosphere, how can changes in their concentrations have a significant effect on the global climate?

Response: Collectively, greenhouse gases constitute less than 1% of the volume of the atmosphere. However, most greenhouse gases are very effective in absorbing heat escaping from the Earth and keeping it trapped (much like a blanket on a bed). It takes only small amounts of these gases to significantly change these insulating properties of the atmosphere.

Explanation: Ninety-nine percent of the dry atmosphere consists of nitrogen and oxygen, which are relatively transparent to sunlight and to infrared energy radiated by the Earth. Hence, they have little effect on the flow of sunlight and heat energy through the air. By comparison, the atmospheric gases that cause the Earth's natural greenhouse effect total less than 1% of the atmosphere. However, these gases (including water vapour) collectively increase the Earth's average surface temperature from -19°C to +14°C - a difference of about 33°C. Furthermore, because the concentrations of these gases in the atmosphere are so low, it is possible for human emissions to have a significant effect on them. For example, during 2000-2005, human emissions of CO_2 from fossil fuel combustion and land use change amounted to roughly 32 billion tonnes per year. Over the next century, human emissions are expected to increase the concentration of CO_2 in the atmosphere from about 0.038% today to almost certainly 0.06% (about double that of pre-industrial levels), and possibly to 0.09% (a tripling). Since the production of each molecule of CO_2 removes one molecule of oxygen from the atmosphere, a doubling of CO_2 concentrations would only reduce the volume of oxygen in the atmosphere from 20.95% to about 20.92%. That is, because the volume of oxygen is much larger, the same human activities have very little effect on its concentrations.

B.6 Since most of the CO_2 released into the atmosphere each year comes from natural sources, how can our actions significantly change its atmospheric concentration?

Response: Over thousands of years, the large natural emissions of CO_2 into the atmosphere by oceans and land ecosystems have been almost perfectly offset by the large amounts of CO_2 removed from the atmosphere through natural processes such as photosynthesis and ocean absorption. These processes are part of the natural carbon cycle on Earth. Human emissions have upset this balance. Just as a relatively small deficit in a household financial budget, repeated over time, can cause a large debt to accumulate, this imbalance has caused a large accumulation of additional CO_2 in the atmosphere.

Explanation: Human emissions of CO_2 into the atmosphere, currently estimated at about 32 billion tonnes annually, represent approximately 6% of the average natural flow of CO_2 into the atmosphere through plant and soil respiration and venting from the surface waters of the oceans (a total of about 550 billion tonnes each year). However, natural emissions are offset by natural absorption processes such as the uptake of CO_2 by plant photosynthesis, as well as absorption by the oceans. Like a bank account, changes in the amount of CO_2 in the atmosphere (the "balance" of the global carbon budget) are determined by the net average difference between inflow (emissions, or 'sources') and outflow (uptake, or 'sinks'), not by the magnitude of the flows themselves. Air samples from the distant past, trapped as bubbles within ice buried deep within the Greenland and Antarctic polar ice sheets, can provide good indicators of how this 'balance' has changed over the past 650,000 years. These provide clear evidence that, during the pre-industrial period of the current interglacial (the past 10,000 years), the atmospheric concentration of CO_2 varied by only a few percent from an average value of 280 parts per million (ppm). This implies that the natural carbon budget was, on average, well balanced (i.e. on average, inflow equalled outflow) during this time period. This, together with other sources of evidence, indicates that the cumulative effect of a relatively small but persistent and increasing imbalance introduced into the carbon budget by humans is the principle cause of the 36% increase in CO_2 concentrations noted over the past several centuries.

Reference: Forster et al., 2007.

B.7 Don't volcanoes naturally release far more CO_2 into the atmosphere each year than humans?

Response: No. On a global scale, volcanoes release less than 1% of human emissions of CO_2 and hence are a minor contributor to changes in its atmospheric concentration. In any case, emissions from volcanoes have always been part of the natural cycle, which has been in approximate balance for many millennia prior to the industrial revolution.

Explanation: Estimates by volcanic experts with the U.S. Geological Survey suggest that volcanoes collectively release about 150 million tonnes (Mt) of CO_2 into the atmosphere each year. By comparison, humans annually emit more than 26 *billion* tonnes (Gt) of CO_2 from fossil fuel combustion alone, and another 6 or so Gt of CO_2 from activities that contribute to deforestation, forest degradation and other types of land use change. That is more than 100 times as great as volcanic emissions.

Mount Etna, in Sicily, is believed to be the largest single volcanic emitter of CO_2, estimated at 25 Mt of CO_2 per year. By comparison, emissions from Mount St. Helens following its eruption several decades ago were less than 2 Mt of CO_2/year.

However, it should be noted that some volcanic eruptions can have an important effect on climate by releasing large volumes of sulphate aerosols into the stratosphere. These aerosols contribute to the reflection of incoming sunlight for several years. Since they can remain in the stratosphere for several years – until they are removed through gravity - they can cause a short-lived but significant global cooling.

Reference: Gerlach, 1991.

B.8 Doesn't water vapour dominate the natural greenhouse effect, and thus make the effect of changes in the concentrations of other greenhouse gases insignificant?

Response: No. While the presence of water vapour in the atmosphere causes about two-thirds of the natural greenhouse effect, changes in its concentration are determined primarily by changes in atmospheric temperature and related effects on the hydrological cycle. As increases in other greenhouse gases warm the atmosphere and surface, the amount of water vapour also increases, amplifying the initial warming effect of the other greenhouse gases. Water vapour therefore provides a strong positive feedback to other climate forcings, but is not an initiating factor in climate change.

Explanation: Water vapour is indeed the most significant greenhouse gas within the atmosphere. If the effects of all greenhouse gases other than water vapour were ignored, the natural greenhouse effect would be about 60 to 70% of observed values, compared to about 25% if only CO_2 were present. However, humans have little direct effect on water vapour concentrations. Rather, its concentrations respond to changes in temperature and other natural atmospheric processes. Warmer atmospheric temperatures, whether caused by increased greenhouse gas concentrations or other causes, increase the amount of water vapour that the atmosphere can hold. Likewise, warmer surface temperatures increase the rate of evaporation of water from land ecosystems and ocean surfaces. Much of the water from increased evaporation comes down again as increased precipitation, but some remains in the atmosphere as water vapour. During recent decades, for example, a rise in global temperatures has been accompanied by an increase in global precipitation and a rise in moisture content of the atmosphere over many parts of the world. This increase in water vapour also affects other aspects of the climate system, particularly clouds. Most scientists agree that the overall effect of the direct and indirect feedbacks caused by increased water vapour content of the atmosphere significantly enhances the initial warming that caused the increase - that is, it is a strong positive feedback. However, the magnitude of this effect depends on where the increases take place within the atmosphere. If these occur in atmospheric regions where air is already near saturation levels, the additional effect is small. If, on the other hand, it occurs in dry air like that over deserts or in the upper troposphere, the effect can be very large. Most models suggest that the enhancement effect, globally, will be quite large (in the order of 60% of the initial climate forcing). However, this feedback is very complex, and its magnitude remains one of the key uncertainties in climate models.

References: Shine et al., 1990; Forster et al., 2007.

B.9 Don't human emissions of aerosols cool the climate and therefore offset emissions of greenhouse gases?

Response: Many of the same human activities that release greenhouse gases also release aerosols of various kinds into the atmosphere. These aerosols include sulphate and sooty aerosols, biomass burning particles and soil dust. In addition to directly reflecting or absorbing sunlight, they can alter cloud processes. Some aerosols, like soot, cause warming while others, particularly sulphates, cause cooling. However, because they only stay in the atmosphere for days to weeks, their effects on climate are strongest within the regions near their source and only remain as long as emissions continue. These effects are not well understood. Most studies indicate that, while aerosols have caused a significant climate forcing at the global scale during the past century, it has been secondary to that of the greenhouse gases. Because emissions of these aerosols are now being controlled in many countries to reduce local air pollution, the relative effect of greenhouse gases on the future climate is expected to be much more important than that of aerosols.

Explanation: Aerosols are small solid particles and liquid droplets released into the atmosphere through many of the same human activities that release greenhouse gases. These include sulphate aerosols and soot from the burning of fossil fuels, biomass aerosols from the burning of vegetation, and mineral dust from agricultural activities Some, like soot, are dark and thus absorb sunlight and warm the atmosphere. Others, like sulphate aerosols, reflect sunlight and cause cooling. (Both also absorb outgoing heat radiation, which has a warming effect; however, this effect is small compared to solar radiation effects.) Finally, these aerosols can also make clouds brighter and last longer. Since, unlike long-lived greenhouse gases, aerosols only remain in the lower atmosphere for days to weeks, they do not spread around the world but remain concentrated in and downwind of industrial or agricultural regions. Because they are not evenly distributed, their effect is much greater in some parts of the world than others, and hence they have a complex effect on climate that includes changes in circulation and in cloud characteristics as well as local areas of warming and cooling.

Globally, some of the warming and cooling effects of different aerosols cancel each other out. While very uncertain, their net effect has likely been a cooling of about -1.2 W/m^2. Hence, these aerosols have 'masked' some of the effects of rising greenhouse gas concentrations (estimated at about 3 W/m^2). If their emissions were to stop overnight, they would quickly disappear, unmasking the full effect of the rising greenhouse gas concentrations.

Many countries have already undertaken programs to reduce the emissions of these aerosols or their precursors to improve local air quality, and so their concentrations are decreasing in most industrialized regions. However, they continue to increase in other industrializing regions. It is likely that these regions will also need to curtail emissions in the future to protect local air quality. Experts estimate that the role of aerosols will be far less than that for greenhouse gases in the decades to come.

Reference: Forster et al., 2007.

B.10 I've heard that global dimming may have offset the warming effect of increasing greenhouse gas concentrations. Is this true?

Response: Global dimming is a popular term referring to a reduction in the amount of sunlight reaching the Earth's surface. Such reductions were observed between 1961 and 1990 at many monitoring stations around the world. Since the early 1990s, however, solar irradiation at the surface has again increased. While some argue that this may be due to a brighter Sun, various studies indicate that these trends are concentrated around large urban centres and are closely linked to changes in cloud cover and in the concentrations of aerosols within the atmosphere. Hence global dimming and brightening are, in many respects, simply a result of the changes in aerosol concentrations, not an independent source of climate forcing.

Explanation: Researchers have in the past reported a reduction of downward solar radiation observed at land stations around the world between 1961 and 1990 of about 1.3% per decade. Some experts have referred to this trend as global dimming. Since 1990, the radiation level has recovered at a similar rate. However, these measurements by themselves do not indicate whether these changes are caused by changes in the intensity of solar radiation reaching the Earth – and hence a natural solar forcing – or by changes in aerosol and cloud concentrations that change the amount of sunshine reaching the Earth's surface.

Recent improvements in data sources and analyses indicate that the latter appears to be the case. First, data from satellites and other methods of measuring the intensity of solar radiation reaching the outer atmosphere suggest little long-term change over the past 50 years. Second, recent thorough analyses of the surface radiation data, using a larger network of stations than used in earlier studies, show that the surface solar radiation trends are primarily associated with stations near large urban centres and are much less evident or absent in rural station data. Furthermore, satellite data also suggest that reduced cloud cover may be a factor in the recent 'brightening'. Hence, global dimming and brightening appear to be a consequence of air pollution and/or long-term cloud variability, not a direct climate forcing. As noted in B.9, changing concentrations of aerosols, in addition to affecting local air quality, have offset part of the enhanced greenhouse effect over the past century. However, their significance as a climate forcing is expected to become progressively minor relative to future projections of greenhouse gas concentrations.

Reference: Trenberth et al., 2007.

B.11 How do stratospheric ozone depletion and climate change affect each other?

Response: Although stratospheric O_3 depletion and climate change are different atmospheric issues, they are interlinked in a number of ways. First, the stratospheric O_3 depletion issue is focused on changes to the ozone layer and with the increase in harmful ultraviolet radiation reaching the Earth's surface. However, because O_3 absorbs solar radiation and is also a greenhouse gas, changes in its concentration also affect the Earth's energy balance and hence climate. Depletion of O_3 in the stratosphere causes a negative radiative forcing, that is, a cooling influence on climate. The magnitude of this cooling over the past few decades is small – enough to offset about 2% of the warming effect of increases in other well-mixed greenhouse gases. Second, climate change can also impact on O_3 depletion. An enhanced greenhouse effect cools the stratosphere, and thus affects O_3 chemistry at this altitude. Experts predict that future climate change will delay the expected recovery of the ozone layer in the Earth's polar regions as the controls of the Montreal Protocol are implemented. Finally, the halocarbons that contribute to stratospheric O_3 depletion are also potent greenhouse gases. Collectively, these have contributed about 10% of historical greenhouse gas forcing. While measures adopted under the Montreal Protocol have now curtailed the growth of their concentrations in the atmosphere, some of the gases being used by industry to replace the CFCs are also important greenhouse gases and are therefore of concern.

Explanation: High frequency ultraviolet C radiation from the sun breaks apart oxygen molecules in the stratosphere to form O_3 and release heat. Once formed, stratospheric O_3 absorbs incoming solar ultraviolet B radiation, contributing to additional heating of the atmosphere at that level. A decrease in stratospheric O_3 therefore cools the stratosphere (because there is less absorption of incoming solar radiation) and increases the amount of ultraviolet radiation that enters the troposphere and reaches the Earth's surface. Increased ultraviolet radiation at the Earth's surface is an environmental concern primarily because of related human health effects such as skin cancer, increased risk of harm to biota and the damage it can cause to materials.

However, stratospheric O_3 is also a greenhouse gas. Therefore, depletion of O_3 in the stratosphere also means less absorption of longwave radiation from the Earth's surface, which contributes to cooling of the stratosphere. The net effect of stratospheric O_3 depletion on the net global radiation balance over the past few decades has been a very weak cooling influence – now estimated at about -0.05 W/m^2. This offsets only about 2% of the positive forcing caused by well mixed greenhouse gases since preindustrial periods.

Successful reduction of O_3-depleting chemicals in the atmosphere as a result of international mitigative action under the Montreal Protocol is expected to allow a slow recovery of the global ozone layer over the next 50 years. However, temperatures of the stratosphere are also important in O_3 chemistry. In this regard, there are concerns about how increases in greenhouse gas concentrations will impact on ozone layer recovery. While increases in concentrations of well-mixed greenhouse gases warm the lower atmosphere, they also contribute to stratospheric cooling, as more heat is retained in the troposphere that would otherwise warm the stratosphere. It is recognized that the cooling of the stratosphere is equally due to the loss of O_3 and the increase in greenhouse gases. This general cooling of the stratosphere due to increases in the concentrations of well-mixed greenhouse gases is expected to reduce the rate of gas-phase O_3 destruction in much of the stratosphere and hence aid ozone layer recovery. But in polar regions during winter seasons, cold stratospheric temperatures can cause the formation of polar stratospheric clouds that enhance the rate of O_3 depletion. In polar regions, further stratospheric cooling could enhance the risks of O_3 depletion.

Finally, the halocarbons that cause O_3 depletion (CFCs, HCFCs and other gases) are also potent greenhouse gases. In fact, a halocarbon molecule can be many thousands of times more efficient at absorbing radiant energy emitted from the Earth than a molecule of CO_2. Although concentrations of halocarbons are much lower than the primary greenhouse gases, their increases over the period 1750–2000 have contributed a positive direct radiative forcing of about 0.34 W/m^2, which represents about 13% of the total radiative forcing to date from well-mixed greenhouse gases. Actions taken under the Montreal Protocol have led to the replacement of CFCs with HCFCs, HFCs, and other substances. Since HCFCs have a relatively high O_3 depletion potential and global warming potential, it was decided by the Parties to the Montreal Protocol, in September 2007, to accelerate the phase-out of production and consumption of HCFCs by a full decade in an effort to reduce their impact on the ozone layer and combat global warming. Because the substances replacing CFCs have lower potency as greenhouse gases, and because total halocarbon emissions have decreased, the combined effect on radiative forcing of annual emissions of all these gases between 1990 and 2000 has decreased by two-thirds.

References: Fergusson, 2001; Baldwin and Dameris, 2007.

B.12 What other human activities affect the climate?

Response: Humans also affect the climate by changing the reflectivity of the Earth's surface through activities such as land use change (globally, a slight net cooling effect) and the production of persistent water vapour contrails from aircraft exhausts (a slight warming influence). These effects are believed to be relatively small compared to those for greenhouse gases.

Explanation: Deforestation, reforestation, desertification, soil cultivation and urbanization are all human activities that can affect the characteristics of the Earth's surface, particularly its albedo (that is, its ability to reflect sunlight back to space). These albedo effects are complex, and can vary by location and season. For example, replacing forests in mid-latitudes with agricultural fields can decrease albedo in the spring and fall (when the bare soils that are darker than the original forest canopy are exposed to the Sun) but increase albedo in winter (when the fields are covered with snow, which is brighter than the original forest canopy). Studies suggest that these effects can have important local impacts on climate. However, recent analyses suggest that the net global effect is secondary to that of past changes in greenhouse gas concentrations, particularly since the land area involved is a relatively small area of the total Earth's surface. In its latest assessment, the IPCC (Intergovernmental Panel on Climate Change) estimates a net global cooling since pre-industrial times due to these albedo effects of between 0 and -0.4 W/m^2. Exhaust contrails from aircraft also have a complex role in absorbing both incoming solar and outgoing infrared radiation. The net effect, on a global scale, is estimated to be a very small warming force of about 0.01 W/m^2, relative to pre-industrial times.

Reference: Forster et al., 2007.

B.13 What is the net effect of all past human activities on our climate?

Response: Experts are very confident that the net average effect on global surface temperatures of all human activities since 1750 AD has been one of warming. However, there is less confidence in the exact magnitude of this warming influence. Best estimates suggest that the net radiative forcing is about 1.6 W/m^2. This net effect takes into account both warming and cooling influences on climate.

Explanation: As illustrated in the accompanying figure, experts have considerable confidence in the net global radiative effects of increased atmospheric concentrations of the long-lived greenhouse gases. That for CO_2 is estimated at between 1.5 and 1.8 W/m^2, while CH_4, N_2O and the halocarbons appear to have contributed another 0.9 to 1.1 W/m^2. However, the net effect of other human activities remains much more uncertain. For example, the net cooling effect of rising aerosol concentrations, allowing for both direct radiative effects as well as indirect effects through related changes in cloud properties, could be as strong as -2.7 W/m^2 and as weak as -0.4 W/m^2. Likewise, the estimates for the warming influence of rising concentrations of O_3 in the troposphere vary from 0.25 to 0.65 W/m^2.

However, experts are very confident that, when all these human influences are added together, the net effect has been a warming. Although the best estimate for a positive radiative forcing causing this warming is about 1.6 W/m^2, this could be as low as 0.6 W/m^2 or as high as 2.4 W/m^2.

Reference: Forster et al., 2007.

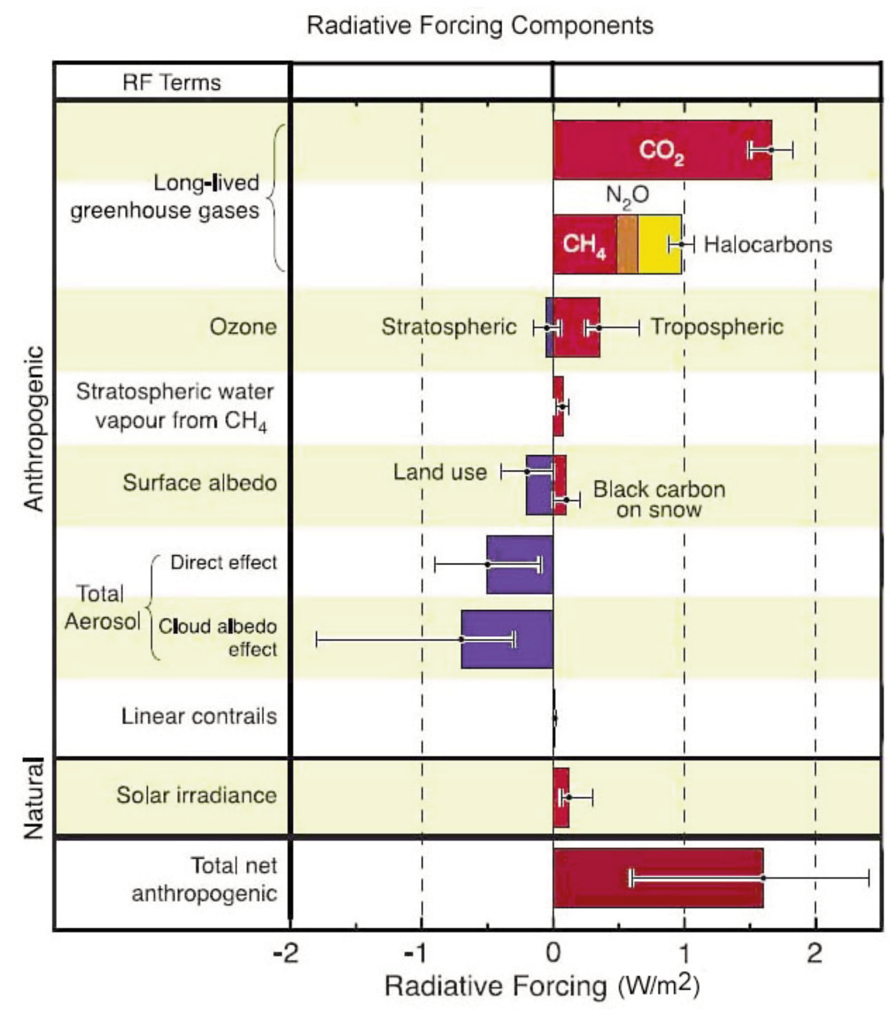

Figure B.13. Magnitude of various types of anthropogenic (produced by humans) climate forcings in 2005 relative to pre-industrial conditions. That for concurrent solar forcing is also included for comparison. Positive forcings lead to warming of climate and negative forcings to cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value (Based on Figure SPM.2, IPCC, 2007a).

C. Detecting and Attributing Climate Change

C.1 Has the world warmed?

Response: Yes, unequivocally so. During the 100-year period between 1906 and 2005, the global average temperature at the Earth's surface has warmed by about 0.74°C. There are also many other indicators of a warming world. These include warming of the lower atmosphere and the upper layers of the world's oceans, rising temperatures in terrestrial soils, melting mountain glaciers, retreating sea ice and snow cover, rising sea levels, and shifts in distribution of many species of plants and animals (see Figure C.1).

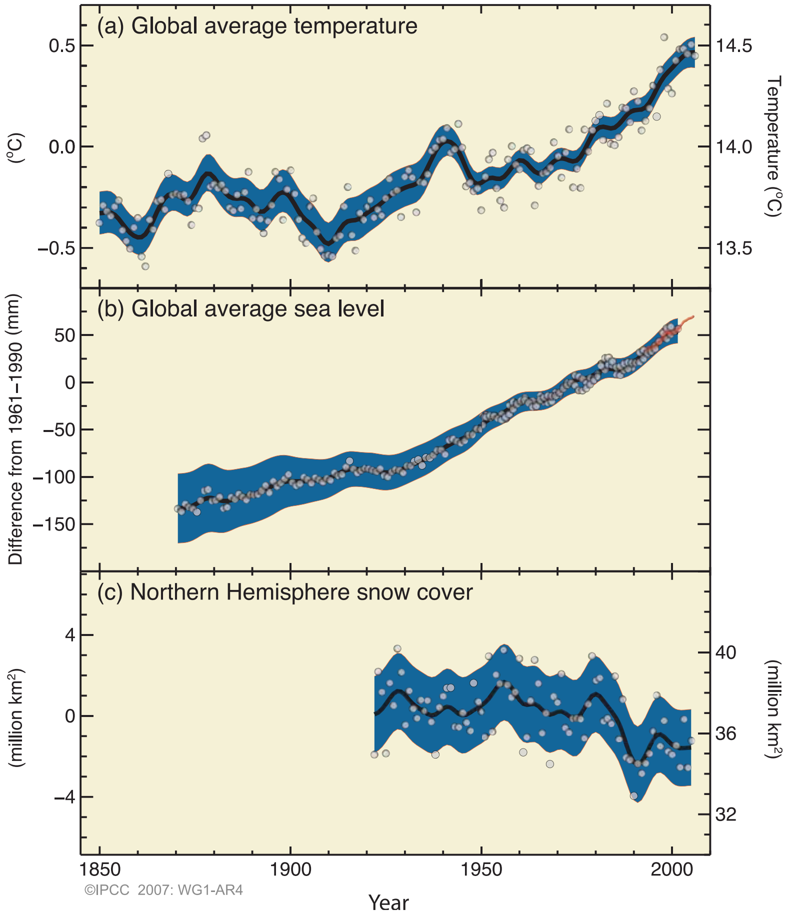

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Figure C.1. Global surface temperature records, adjusted for biases due to changing observing practices and influences such as urbanization, show that recent temperatures are significantly warmer than temperatures one century ago. Furthermore, the rate of warming appears to be accelerating. Sea level is also rising, while Northern Hemisphere snow cover is receding (Figure SPM.3, IPCC, 2007a).

Explanation: Experts in global temperature trend analyses report that, during the 100 years ending in 2005, global average surface temperature has warmed by at least 0.56°C, and possibly by as much as 0.92°C, with a best estimate of 0.74°C. The linear trend for the last 50 years of this record is about 0.13°C per decade, about twice that for the entire 100 years. Eleven of the 12 years between 1995 and 2006 are the warmest on record since the beginning of the global instrumental record some 150 years ago.

It is important to note, however, that these trends refer to global average surface warming. In some areas, particularly over continents, the magnitude of warming has been several times greater than the global average. In Canada, for example, there has been an increase in average annual temperature of about 1.4°C over the period 1948-2007. On the other hand, in a few areas around the world, temperatures have actually cooled.

A variety of other climate variables also provide supporting evidence of a warming climate. These include: a warming of the lower 6km of the atmosphere similar to that at the surface; a rise in average ocean temperatures down to a depth of 3000m; a 5% reduction in the extent of spring snow cover in the Northern Hemisphere since the late 1960s; a coincident reduction in Northern Hemisphere lake ice cover seasons; a reduction in Arctic annual average sea ice cover since the late 1970s of about 8% and a considerable decline in sea ice thickness; an 8cm global sea-level rise since 1960; an increase in global heat content in the Earth's soils, its cryosphere and its oceans since adequate measurements began in the 1950s; and a decrease in the frequency of cold days and nights and an increase in the frequency of hot days and nights, and heat waves, since the 1950s.

References: Trenberth et al., 2007; Lemke et al., 2007; Environment Canada, 2008.

C.2 How are the global average temperature records developed?

Response: The records for global average surface temperature are based on data collected over the past 150 or so years at thousands of weather and climate stations on land areas around the world, by ships at sea, or more recently by ocean data buoys. These data are carefully averaged over the entire globe in a manner that avoids biases towards regions with high concentrations of data. Although some areas of the world had very sparse or no coverage during the early part of the record, and there are a number of other problems associated with using these data to estimate global temperature trends, experts have worked for many decades on addressing these concerns.

Explanation: Daily temperature data have been recorded at thousands of weather and climate stations around the world for most of the past century, with many of these station records extending back in time to 1850 and earlier. These temperatures are recorded at a height approximately one metre above the ground surface. In addition, crew members from ships navigating the world's oceans have been collecting daily temperatures for both sea surface waters and air at the level of the ship's deck. Many of these records, particularly those for the 19th century, were logged from British naval vessels. More recently, ocean data buoys have also provided additional data. There are several teams of experts within the international research community that have devoted considerable efforts at developing a comprehensive picture of the change in average surface temperatures around the world from these data. To do so, they must develop statistical techniques for properly averaging the data, addressing significant data gaps, and correcting for other problems associated with how the data have been collected. Since these groups use different techniques, the results differ slightly. However, this also helps to improve confidence in the results.

The corrections and adjustments that need to be made to the data are significant. For example, the abundance of good quality data is generally far greater in southern Canada, the USA and western Europe than in many other parts of the world, particularly for the 19th century. Some parts of the world, such as much of Africa and Antarctica, have very little data, even today. Methods of developing global temperature trends need to address this geographic imbalance in the data. Experts also screen the data to remove stations that are unreliable. These include stations in urban centres that have been influenced by the effect of urbanization on local temperatures. They also adjust the data, where possible, for influences caused by changes in recording methods or location of the station.

To average the selected data, the experts divide the Earth's surface into a grid of equal sized regions and develop one composite record for each of these by using advanced techniques for averaging the available data within that area when there are multiple records and for interpolating from adjacent grid areas when there are no data. Experts continue to make improvements in their methodologies, and test them against other data sources to determine how successful they are. While there are continuing uncertainties associated with the trend analyses that emerge from these data compilations, for the past century these now appear to be constrained to about +/- 0.2°C.

References: Folland et al., 2001; Trenberth et al., 2007.

C.3 Is the temperature record reliable?

Response: Yes, the data used to calculate global temperature trends provide a good indication of how our climate is changing. As required for proper use of data from all monitoring programs, the climate data used to estimate the global temperature trend are first subjected to quality control procedures and evaluated for systematic sources of error. In addition to deleting records with major errors or nonclimatic influences and correcting others where the error is readily identifiable, climate scientists also compare the instrumental climate records with those derived from other sources. To allow for any remaining non-climate factors affecting these records, experts provide a margin of error in their estimates. They state with high confidence that the global average surface temperature during the 1906-2005 period has risen by at least 0.56°C, and not more than 0.92°C.

Explanation: One method of dealing with random errors that occur at single stations is to average the temperature values over many stations. Global temperature analyses use many thousands of stations, and hence such random errors are largely removed through averaging. Systematic changes that are unrelated to climate but that can affect many or all of the records at the same time or in the same way are more difficult to remove. These include changes in observed values due to urban heat island effects, large-scale changes in instrumentation, changes in the density of recording stations, or a systematic shift in the location of instruments at weather stations. These can be at least partially addressed through careful analysis and adjustments. In undertaking the global trend analyses, climate experts have made careful allowance for a number of such systematic influences, including the heat island effect (see Figure C.3), the change in observing processes on ships, and other non-climatic influences on observations. There remains solid evidence that the warming of the recent decades is real and global. Furthermore, surface temperature records are in good agreement with the long-term trends apparent in radiosonde measurements and satellite data collected for the lower 6km of the atmosphere during recent decades. They also agree with evidence from tree rings, and with information obtained from bore holes drilled into the Earth's surface in different parts of the world. Finally, they are also consistent with concurrent trends towards reduced global snow cover, glacier retreats and other indicators of a warming world. However, because of the uneven global distribution of observation sites, climate records are still dominated by land data obtained in the Northern Hemisphere. Considering these uncertainties, the science community estimates that the Earth's surface has, on average, warmed by 0.74 ± 0.18°C over the past 100 years.

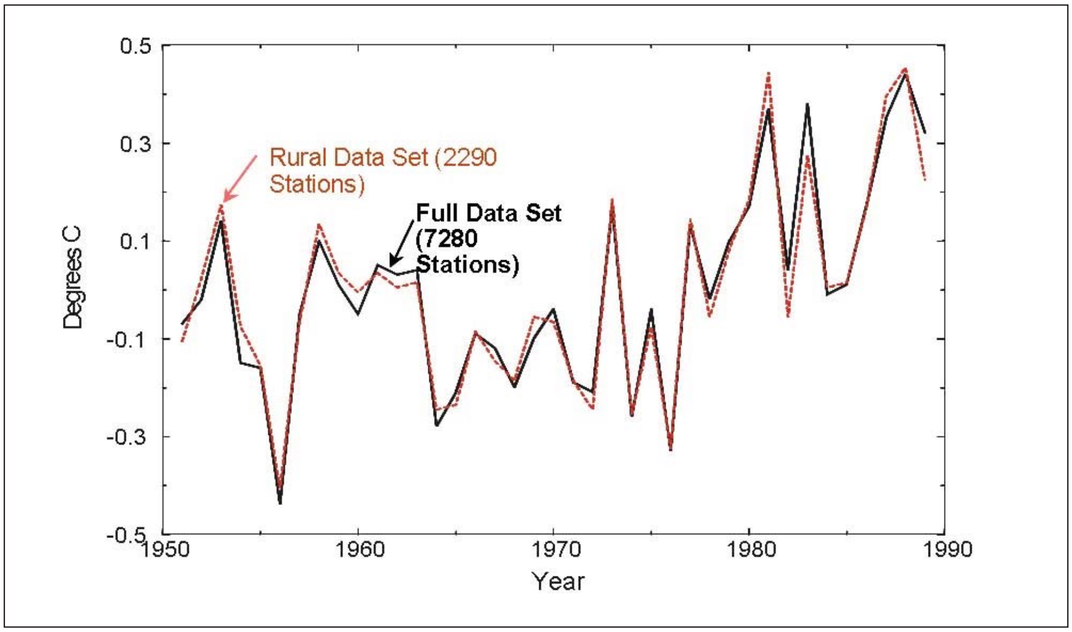

Figure C.3. Comparison between temperature trends of the full corrected land data set used in global temperature trend analysis and a subset of rural stations suggests there is very little residual effect of urbanization remaining in the data (Peterson et al., 1999).

C.4 How unusual has recent warming been?

Response: Although the observed average global warming of 0.74°C during the past 100 years seems modest, its significance can be assessed against reconstructed climates for the Earth's surface for previous centuries and even millennia. Such comparisons indicate that, at least for the Northern Hemisphere, the second half of the 20th century was likely the warmest 50-year period of at least the past 1300 years. Furthermore, climate model studies indicate that it is very difficult to replicate the climate trends of the past millennium without including the role of anthropogenic climate forcings.

Explanation: Researchers have indirectly collected information about past climates from various indicators such as tree rings, ice cores and ocean corals. Individually, these indicators provide information on only some aspects of hemispheric climate. Tree rings, for example, are useful indicators of average temperatures during growing seasons in mid-latitudes, or of precipitation changes in arid regions. Ice cores provide information on temperatures in cold regions, while ocean corals can help reconstruct temperatures in tropical ocean climates. Analysts can use statistical techniques to combine these various information sources into a single hemispheric temperature reconstruction. There has been considerable debate in recent years about the reliability of such reconstructions (often referred to as the 'hockey stick' debate since the reconstructions show a relatively stable millennium (the shaft) followed by a rapid warming over the 20th century (the blade)). However, recent assessments by teams of experts have concluded that, at least for the Northern Hemisphere, the second half of the 20th century was very likely the warmest in the past 500 years, and likely in the past 1300 years.

Paleoclimate model simulations are broadly consistent with the reconstructed Northern Hemisphere temperatures over the past 1000 years. These simulations also indicate that the rise in surface temperatures since 1950 *very likely* cannot be reproduced without including anthropogenic greenhouse gases in the climate forcings[5] used in the model. Furthermore, it is *very unlikely* that this warming was merely a recovery from a pre-20th century cold period. There is less confidence in similar conclusions for the Southern Hemisphere, since the available data for that region is as yet very sparse.

References: National Research Council, 2006; Jansen et al., 2007.

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[5] *See A.2 for description of climate forcing.*

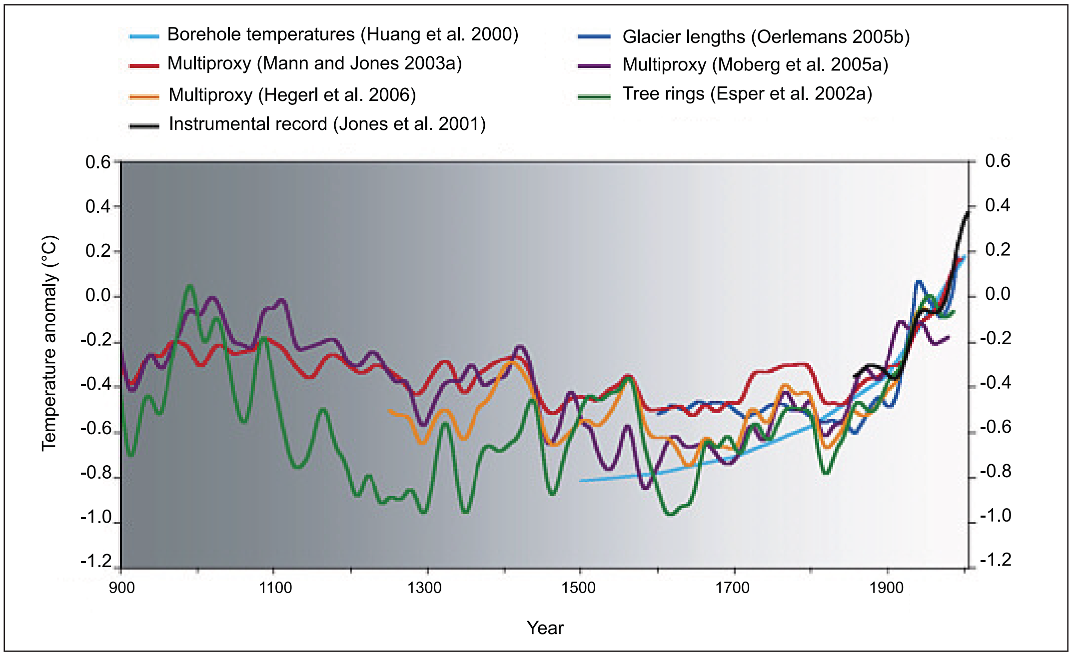

Figure C.4. Various studies have used proxy indicators of past temperatures, including tree rings, ice cores and corals, to reconstruct Northern Hemisphere temperatures over the past several millennia. While there is disagreement on the magnitude of hemispheric temperature variations prior to the 20th century, these studies, and other evidence, indicate that the late 20th century warmth is unprecedented in the context of at least the last millennium (Figure S.1, National Research Council, 2006).

C.5 How do scientists examine the question of what caused the warming?

Response: Scientists have studied possible causes of climate change for many years. These causes include changes in solar radiation, the effect of volcanic eruptions on climate, and the role of greenhouse gases and aerosols that humans release into the atmosphere. Researchers have been able to reconstruct, with varying degrees of confidence, how these different forces for climate change have varied over the past decades and centuries. Climate models are then used to simulate how these different climate forcing factors should have affected the global climate over space and time. By comparing the expected response of the climate to different forcings with that which actually occurred, researchers are able to attribute the causes of global changes in climate, including the recent warming, with considerable confidence. The conclusion of such work is that most of the warming of the past 50 years has been due to human influences. However, attributing changes at the regional scale, where natural climate variability becomes more significant, is much more difficult.

Explanation: Anything that causes a persistent change in the radiative balance between incoming solar and outgoing infrared radiation at the top of the atmosphere is, in essence, a force causing the Earth's climate to change, hence a 'climate forcing'. There are four broad categories of climate forcings that operate on time scales relevant to human lifetimes: i) changes in solar irradiation at the top of the atmosphere; ii) changes in the concentrations of aerosols and cloud particles within the atmosphere that reflect and scatter incoming solar radiation back to space and absorb outgoing heat radiation; iii) changes in the Earth's surface that affect both the amount of incoming solar radiation reflected back to space at the surface and the amount of heat energy released from the surface towards space; and iv) changes in the concentration of greenhouse gases that absorb and retain outgoing heat radiation.

Researchers have used tree rings, ice cores and other proxy indicators to help reconstruct past changes in most of the key climate forcings, including those due to solar radiation, changes in volcanic aerosol concentrations in the atmosphere, and changes in concentrations of greenhouse gases and of anthropogenically generated aerosols in the atmosphere. However, the impacts of these changes in forcings on climate involve many complex feedbacks within the climate system that require the most sophisticated climate models to properly simulate. Such simulations can estimate the pattern of change, vertically, horizontally and in time, that might be expected for each of the forcings individually and in combination with each other. By comparing these simulation results with observed patterns, experts can help identify which combination of factors have, for example, likely caused the global scale warming of recent decades. Results indicate that global trends of the past century cannot be explained if only natural climate forcings are considered. However, there is good agreement when anthropogenic forcings are included (see Figure C.5). In fact, the evidence supports the conclusion that most of the warming during the past 50 years was due to human influences. Similar attributions are now also available at the continental scale. However, because of the much greater variability of climate at the regional scale and the higher complexity of regional feedbacks, attribution of changes at this scale to specific global forcings is, in general, not yet feasible.

Reference: Hegerl et al., 2007.

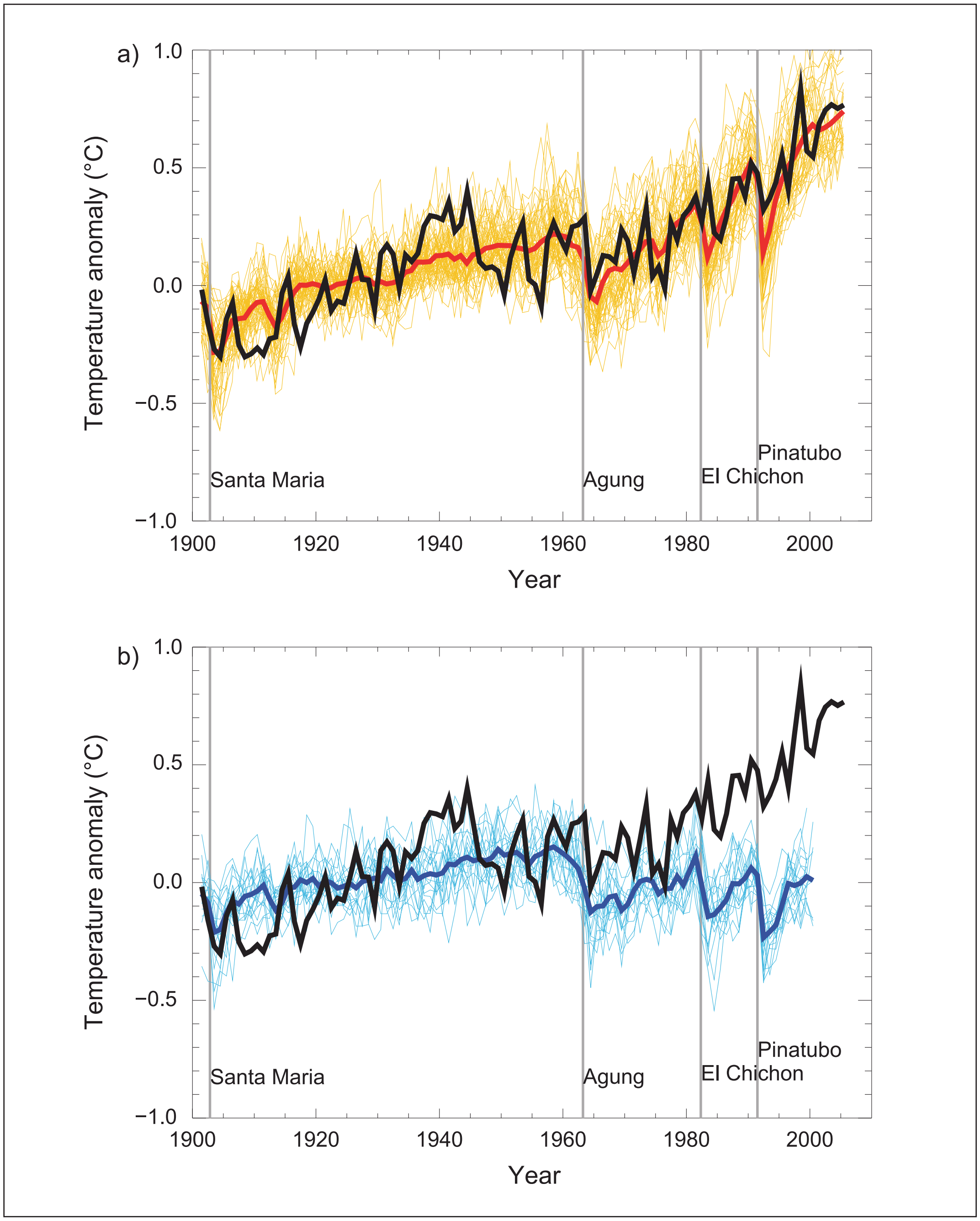

Figure C.5. Comparison of global mean surface temperature anomalies (change in temperature relative to 1901-1950 period) from observations (thin black line) with those estimated by climate model simulations forced with a) natural and human factors and b) natural influences only. Results both illustrate how well models can replicate observed climate change when forced with all leading causes of change and how poorly they replicate observed changes when only natural forcings are included (Fig. 9.5, Hegerl et al., 2007).

C.6 Could changes in cosmic radiation from outer space have caused the warming?

Response: No. While some scientists have hypothesized that changes in cosmic radiation could change global cloud cover, and hence surface temperatures, observational data of cloud cover in recent decades do not support this. Over the past two decades when global warming has been strong, the trend in cosmic ray intensity has been in the opposite direction to that required to explain the warming.

Explanation: Cosmic radiation consists of energetic particles, such as protons and small atomic nuclei, that originate from outer space, bombarding the Earth's atmosphere. It has been hypothesized that changes in cosmic radiation could have been a dominant influence on Earth's climate over the past 500 million years. Furthermore, it is suggested that, if such processes could affect climate on multi-million year time scales, they might also do so on century time scales. The hypothesis is that cosmic radiation can ionize aerosols within the atmosphere, and thus affect cloud formation processes. Since clouds generally have a cooling effect on climate (by reflecting solar radiation), some scientists have speculated that during periods with relatively high levels of cosmic radiation, more clouds would form and the Earth should cool. Conversely, fewer cosmic rays should lead to a warmer Earth. However, studies conducted to date do not support this hypothesis. Analyses of observational data over recent decades show no linkage between fluctuations in cosmic radiation and global cloud cover. Furthermore, over the past two decades there is evidence that both cosmic ray fluxes and surface temperatures have been increasing. That is, the trend in cosmic ray intensity has been in the opposite direction to that required to explain the increasing temperature trend. In fact, variations in global temperature over the past century are well explained by changes in anthropogenic and other natural factors, namely changes in greenhouse gas and aerosol concentrations, in solar radiation and volcanic eruptions (see C.5).

References: Rahmstorff et al., 2004; Forster et al., 2007; Lockwood and Frölich, 2007.

C.7 Can solar irradiance changes have caused the warming of the past century?

Response: Changes in solar irradiance can explain part of the warming, particularly in the early part of the 20th century. However, average sunshine reaching the Earth has not changed significantly over the past 50 years, and therefore cannot explain the rapid warming of recent decades.

Explanation: Solar irradiance undergoes an approximate 11-year sunspot[6] cycle, varying from minimum to maximum sunspot numbers on the Sun's surface and back again. However, while these cycles may be a contributing factor to decadal variability of climate, they do not significantly affect long-term climate trends unless the nature of the cycle itself changes. There is considerable evidence to indicate that the amplitude of the sunspot cycle slowly became larger over the past few centuries, until about 1950. Radiation experts estimate that this may have caused a small positive (warming) radiation imbalance at the top of the atmosphere over the past century of, at most, a few tenths of a W/m^2, or about 10% of that due to increasing greenhouse gas concentrations (see Figures B.13 and C.8). However, although this forcing has varied over the past 50 years, first decreasing then increasing, its long-term average over that period has changed very little. Therefore, it is not considered a significant contributor to the rapid warming of recent decades.

References: Hansen et al., 2005; Forster et al., 2007.

[6] *A sunspot is a region on the Sun's surface that is marked by a lower temperature and appears darker than its surroundings.*

C.8 What is the role of volcanoes in the recent warming?

Response: Volcanic eruptions periodically eject aerosols into the stratosphere where they can remain for several years. This can have a short-term cooling effect on the climate because these volcanic aerosols reflect sunlight. Average concentrations of these aerosols can also change over longer periods of time as the frequency and intensity of volcanic eruptions varies over time. Therefore, volcanic aerosols can also become a long-term climate forcing. This forcing causes a cooling effect when the average concentrations rise above the long-term average (because of increased reflection of sunlight) and a warming effect when they decline below the long-term average (since they now reflect less sunlight than normal). Such a decline occurred between 1900 and 1950, likely contributing to warming of the globe during the early 20th century. However, an increase in the number of large volcanic eruptions in recent decades has reversed this trend. While such eruptions have significantly affected global climates for short periods of time, they cannot explain the recent warming trend. Rather, the rise in average volcanic aerosol concentrations in recent decades should have caused a cooling trend.

Explanation: Sulphur gases released during large volcanic eruptions can cause a dramatic increase in the concentrations of sulphate aerosols in the stratosphere, where they reflect incoming sunlight back to space. This can have a large and abrupt cooling effect on the Earth's surface temperatures. For any given eruption, the cooling is short lived, since these aerosols only remain in the atmosphere for a few years before settling back to the Earth's surface. However, during periods of time with frequent large eruptions, the average concentrations of these aerosols (and hence cooling influence) are higher than during periods of time with fewer eruptions. Between 1900 and 1950, there was a decline in the frequency of large volcanic eruptions and in the mean concentration of related aerosols. This contributed to the warming of the early 20th century. However, in recent decades, such eruptions have become more frequent, once again increasing the net cooling effect (see Figure C.8).

Reference: Hegerl et al., 2007.

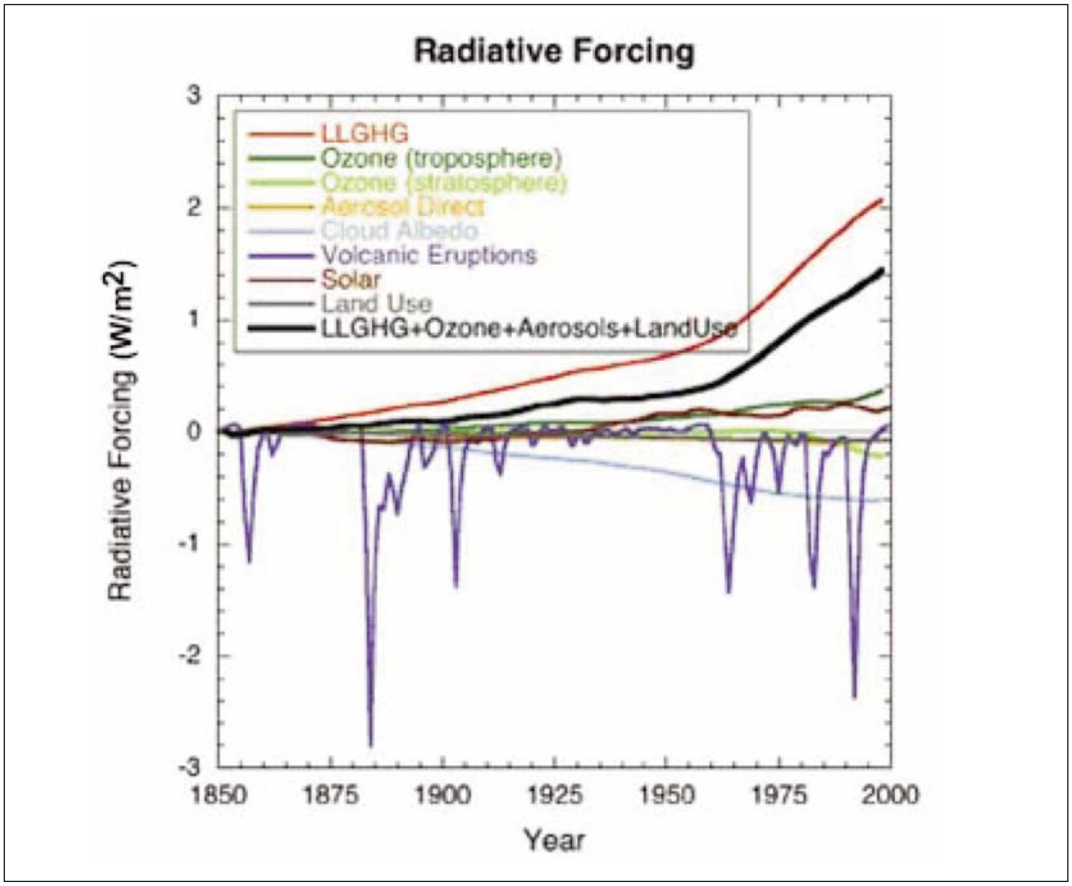

Figure C.8. Changes in natural and anthropogenic climate forcings since 1850. The cooling influence (negative forcing) of volcanic eruptions over the second half of the 20th century is shown clearly here, as is the strong warming influence (positive forcing) from long-lived greenhouse gases (LLGHG) (Fig 2.23 upper panel, Forster et al., 2007).

C.9 Why do scientists point to greenhouse gases and anthropogenic aerosols as the reason for recent warming?

Response: While climate model simulations that include only the natural forcings of the climate system due to variations in solar radiation and volcanic aerosol concentrations project that the Earth should have cooled in recent decades, simulations that include changing concentrations of greenhouse gases and human-induced atmospheric aerosols replicate the recent warming remarkably well. Furthermore, the vertical, horizontal and temporal patterns of observed changes in temperature agree with the pattern expected due to these human factors, and not with those due to natural forcings. Finally, the unusualness of the recent warming within the past millennia also suggests that human factors are a likely cause for the recent warming.

Explanation: There are a variety of indicators that have led scientists to agree that most of the warming during the past 50 years is very likely due to the effects of rising greenhouse gas concentrations, partially masked by concurrent influences of anthropogenic aerosol emissions (which have a cooling effect). First, model simulations using natural forcings due to solar and volcanic activities only, cannot explain the recent warming (see Figure C.5). In fact, all else being equal, these should have caused a cooling. Second, the unusual nature of the recent trends within the context of climate variability of the past two millennia indicate that they are also unlikely due to the combination of natural forcings and natural variability. Third, the recent trends are remarkably similar to those simulated by climate models when forced by human-induced changes in greenhouse gas and aerosol concentrations. Finally, the spatial pattern (or 'fingerprint') of change is very similar to that expected due to the human forcings, but not the natural ones. This pattern is a composite of a relatively uniform warming due to rising greenhouse gas concentrations and a cooling influence from industrial aerosol emissions that is highly variable from region to region, particularly in the Northern Hemisphere.

Reference: Hegerl et al., 2007.

C.10 A large increase in temperature occurred in the early part of this century when emissions of CO_2 and other greenhouse gases were still relatively low. However, temperatures actually cooled in the 1950s and 1960s when these emissions began to increase rapidly. Doesn't this contradict the idea that increased greenhouse gas emissions will cause warmer climates?

Response: Rising concentrations of greenhouse gases is only one of a number of factors that affect the climate system. Other factors important on decadal and longer time scales include natural forcings due to solar and volcanic activity, human emissions of aerosols (particularly sulphates), and natural internal variability of the climate system. The short period of slight cooling in mid-century appears to be at least partially linked to a period of rapidly rising aerosol concentrations that coincided with a cool phase in natural decadal climate variability. Since then, acid rain control measures have helped to reduce aerosol concentrations in the Western Hemisphere, while greenhouse gas concentrations continue to increase rapidly. Hence, the role of greenhouse gas forcing has become increasingly dominant relative to that due to aerosols. As shown in Figure C.5, models can now replicate that pattern of change with time remarkably well.

Explanation: During the first half of the century, increasing solar radiation intensity, declining volcanic aerosol concentrations and human activities (particularly those causing a rise in greenhouse gas concentrations) were all contributors to the modest rise in observed global average surface temperature (see Figure C.5). However, from the mid-20th century to about 1980, anthropogenic emissions of sulphates into the atmosphere over North America and Europe rose rapidly. These aerosols reflect sunlight and their increased concentrations caused rapid regional cooling at the surface that affected global temperatures and offset much of the warming caused by rising greenhouse gas concentrations. Greenhouse gas emissions also increased more rapidly during the same period, but climate system response times to changes in greenhouse gas concentrations are slower than for aerosols. Furthermore, the North Pacific and North Atlantic Oceans underwent a period of regional surface cooling in the 1950s and 1960s as part of a long-term multi-decadal natural climate oscillation. This combination of natural variability and sulphate cooling appears to have been enough to offset the enhanced greenhouse effect – which was still relatively modest at the time. During the 1980s, most of the industrialized world began stringent acid rain control programs that helped to decrease sulphate aerosol concentrations over North America and Europe. Since aerosols have very short atmospheric residence time, these controls quickly reduced their concentrations and hence their cooling influence on regional climates. Furthermore, the cool phase of the ocean cycles ended, and greenhouse gas concentrations continued to increase rapidly. When these factors, together with solar and volcanic forcings, are incorporated into climate model simulations, results confirm that they can explain the decadal pattern over temperature change during the past century – including the slight cooling in mid-century and the rapid rise since.

Reference: Hegerl et al., 2007.

C.11 Has natural climate variability over time scales of several decades contributed to the recent warming trend?

Response: Climate oscillations that occur every few decades or so as a result of natural variability internal to the climate system are an important factor in short-term regional climate trends. However, when averaged over multiple decades, and over continental to global scales, variations caused by these oscillations largely average out. Therefore, while oscillations are likely a factor in enhanced warming in regions like the Arctic, they cannot adequately explain the observed magnitude of multi-decadal warming at continental and larger scales.

Explanation: The Earth's atmosphere and oceans constantly undergo oscillations that can significantly affect regional climates on decadal and multi-decadal time scales. These oscillations represent variability internal to the climate system. The best known of these is the El Niño/La Niña cycle, officially called the El Niño Southern Oscillation (ENSO). The trend in regional surface temperatures over, for example, a 20-year period can be significantly influenced by such oscillations. The recent warming in the Arctic, for example, is likely attributable in part to a change in the Arctic Oscillation, which is also linked to the North Atlantic Oscillation. Likewise, recent warming in the North Pacific also appears to have been influenced by a change in phase of the Multi-Decadal Pacific Oscillation. However, when averaged over hemispheric and multi-decadal time scales, many of these natural variations average out. Thus, the observed global warming over the past 50 years appears to be primarily due to forcings external to the climate system, not internal climate system variability. The unusualness of recent warming when compared to variability over the past millennium further supports this conclusion.

Reference: Hegerl et al., 2007.

C.12 Despite the overall global warming during the 20th century, some argue that current average temperatures are still lower than during warm periods experienced in the past, such as the Medieval Warm Period. Doesn't this suggest that current increases are likely due to natural causes, and therefore of no real concern?

Response: As noted in C.4, although the observed warming of 0.74°C during the past 100 years seems modest, comparisons with reconstructed climates for the Northern Hemisphere for previous centuries show that the second half of the 20th century was likely the warmest 50-year period of at least the past 1300 years, at least in the Northern Hemisphere. This period includes the interval often referred to as the Medieval Warm Period. Furthermore, climate model studies indicate that it is very difficult to replicate the climate trends of the past millennium without including the role of anthropogenic climate forcings. Experts therefore conclude that the trends of the past 50 years are indeed very significant and very unlikely to be due to natural causes.

Explanation: Researchers have indirectly collected information about past climates from various indicators such as tree rings, ice cores and ocean corals. These indicate that, for at least the Northern Hemisphere, the second half of the 20th century was likely the warmest 50 year period in at least the past 1300 years. Furthermore, the 1990s was the warmest single decade. By comparison, the Medieval Warm Period of about 1000 years ago appears to have been warm in regions surrounding the North Atlantic but not in other parts of the Northern Hemisphere. Average temperatures for the entire hemisphere during that period were cooler than that for the past century (see Figure C.4). Proxy data for the Southern Hemisphere are as yet too sparse to make similar conclusive comparisons in that region. However, paleoclimate scientists have also made some approximations of global temperatures further back in time. These suggest that temperatures experienced during the peak of the current interglacial period some 6,000 to 8,000 years ago were about 1°C warmer than today, and that temperature variations within this range have occurred on thousand-year time scales since then. This suggests that some of the recent warmings could be due to natural causes.

As shown in Figure C.4, climate model studies indicate that, during the first half of the 20th century, a significant part of the warming is, in fact, likely due to a combination of increased solar radiation, decreased volcanic dust in the atmosphere and rising greenhouse gas concentrations. However, during the past 50 years, solar intensity has not shown a significant long-term trend and more frequent major volcanic eruptions have, on average, increased the level of volcanic dust in the atmosphere with time. Thus, the combined effects of the natural causes for change, by themselves, would have caused cooling during that period. In contrast, the observed climate record shows a rapid warming in recent decades consistent with that expected due to human influences. Therefore, while temperature changes during the whole of the past century are due to a combination of natural and human factors, that for the past 50 years is very likely due primarily to human influences.

References: Hegerl et al., 2007; Jansen et al., 2007.

D. Predicting Climate

D.1 How do we predict climate change?

Response: The primary tool used by scientists to predict how climate will change in the future is the climate model. These models are developed using the most advanced physics and mathematics available today. Because of the large number of mathematical calculations involved, climate simulations with these models require the most powerful computers available to operate efficiently. Models are first tested against observed climates and climates of the past to ensure they can adequately simulate real climates. Once they have passed these and other tests, they are used to project future climates for various scenarios of future greenhouse gas and aerosol emissions. The difference between the recent past/actual climate and the future climate gives us the magnitude of the climate change. Although model evaluations have shown some significant disagreements between observed and simulated climates at regional scales, the advanced models of today can replicate the global and continental scale patterns and trends quite well. Hence, modellers are confident that they can provide useful indicators of how the climate will respond to continued human interference with the climate system.

Explanation: The climate models used to predict future climates are based on well-accepted physical principles of science and a wealth of scientific observations of the climate system. Complex mathematical equations are used within the models to describe how these principles affect the interactions of land, sea, ice and air, which together determine the Earth's climate. These models are then operated on very large computers to simulate how the climate behaves. Models are first tested to see how well they can describe today's climate, and most are now able to describe the main features of the climate system quite accurately. There are, however, significant regional differences apparent in most models, both because the spatial and temporal resolutions of the models are too coarse to capture all the important regional interactions of the climate system and because some of these interactions are as yet inadequately understood. Computing power remains a primary limitation to how much climate system detail can be added into the models. The models are then also run for climates of the past, including the last 100 years, the peak Holocene climate of 6,000 years ago, and the last glacial maximum of 18,000 years ago. Most advanced models now simulate these quite well, particularly for the past 100 years. Finally, there are also model inter-comparison studies that seek to understand where and why the model results differ. Over the past four decades of climate model evolution, the confidence in their performance has continually improved. While there are still significant uncertainties in model performance, there is considerable confidence that they can help provide useful advice on future climate change.

Reference: Meehl et al., 2007.

D.2 How will natural climate forcing factors affect the climate system over the next century?

Response: The two primary natural forces for change, external to the climate system, are changes in solar irradiance and emissions of sulphate aerosols by volcanic eruptions. While the well-known 11-year sunspot cycle contributes to short-term climate variability, longer term changes in solar behaviour are not well understood or predictable. However, changes are unlikely to significantly exceed that observed during the past century – currently estimated to have been a net warming influence of about 0.1 W/m^2. This is an order of magnitude less than that for forcing due to rising greenhouse gas concentrations over the same time period. Likewise, episodic sulphate emissions into the stratosphere from volcanic eruptions can have significant cooling effects on climate (up to -3 W/m^2) for a few years after an eruption. However, the long-term trend in related aerosol loading in the stratosphere, while poorly understood, appears to be low. Hence, the combined role of these two forcings is expected to be low relative to the projected forcing of future emissions of greenhouse gases. Internal oscillations of the climate system, particularly those related to ocean circulation, can also contribute significantly to decadal and interdecadal climate variability. However, there is no evidence that they will contribute to a long-term trend in climate over the next century. Therefore, experts predict with confidence that rising greenhouse concentrations will be the dominant factor in climate change over the coming century.

Explanation: The fundamental source of all energy entering into the Earth's climate system is radiation from the Sun. Therefore, variation in solar output is an important radiative forcing agent. Satellite observations since the late 1970s show relative variations of total solar irradiance at the top of the Earth's atmosphere over the past two solar 11-year activity cycles of about 0.1%, which is equivalent to a variation in radiative forcing of about 0.2 W/m^2. This also has an important effect on the concentration of O_3 in the stratosphere, which in turn can influence climate (see Figure B.13). However, while the longer term trends in irradiance remain uncertain, experts generally agree that solar forcing likely contributed to global warming during the first half of the 20th century but was not a significant factor in the second half. Net forcing over the entire century due to solar irradiance changes is estimated at +0.12 W/m^2. Although long-term behaviour of the Sun is uncertain and largely unpredictable, there are no indications that changes in the next century will be significantly larger than this, or whether it will be positive or negative.

Volcanic activity can inject large amounts of sulphur-containing gases (primarily sulphur dioxide) into the stratosphere, which are transformed into sulphate aerosols. These aerosols enhance the reflection of sunlight to space, causing a cooling of the Earth's surface and lower atmosphere. This cooling forcing can last for a few years before the aerosols are removed through gravity, and can be large. That for the Mt. Pinatubo eruption in 1991, for example, is estimated to have peaked at -3 W/m^2. However, while volcanic behaviour over the next century is largely unpredictable, it is unlikely that these episodic events will be significantly different from those of the past few centuries. Therefore, while contributing to the year-to-year variability of climate, volcanic emissions are unlikely to significantly contribute to trends in climate over the next century.

Natural climate variations internal to the climate system can also occur, largely as a result of complex interactions between components of the climate system. Particularly important in this regard is oscillations within the coupled atmosphere-ocean component of the climate system, such as the El Niño-Southern Oscillation (ENSO), the North Atlantic/Arctic Oscillation and the Pacific Decadal Oscillation. However, while their influence can be significant on decadal time scales, particularly at the regional scale, these internal climate fluctuations generally average out over time. Over the next century, they will continue to contribute to the natural variability of climate but are not expected to affect long-term trends.

Reference: Meehl et al., 2007.

D.3 What are the projections for climate forcing due to changes in greenhouse gases and tropospheric aerosol concentrations over the next century?

Response: Future climate forcing due to greenhouse gas and aerosol emissions is very dependent on how human society will evolve over time, and what decisions are taken to reduce such emissions. Currently, the net human contribution to climate forcing since pre-industrial times is estimated at 1.6 W/m^2 (see B.13). However, relevant 'business-as-usual' scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) suggest that, by 2100, forcing due to rising greenhouse gas concentrations could increase by an additional 2.1 to 7.3 W/m^2. That is, net forcing by 2100 relative to pre-industrial levels could be about two to five times that of today.

By comparison, the projected forcing from changes in emissions of sulphates, sooty aerosols and organic carbon aerosols is relatively small – varying between -0.1 and +0.2 W/m^2.

Explanation: Under the future projections for greenhouse gas concentrations for 2100 developed in the IPCC Special Report on Emissions Scenarios (SRES), CO_2 concentrations will rise to between 540 and 970 ppm, compared to about 280 ppm in the pre-industrial era (year 1750) and 379 ppm in the year 2005. For CH_4 the projected concentrations range from about 1550 ppb to 3700 ppb, compared to about 715 ppb in 1750 and about 1774 ppb in 2005. For N_2O, the range of projected concentrations is between 350 and 450 ppb, compared to 270 ppb in 1750 and 319 ppb in 2005. Concentrations of tropospheric O_3 and a number of other secondary greenhouse gases are also expected to increase. By comparison, because of measures to control local air pollution, the rise in emissions of aerosols will be much less. The human contribution to climate forcing to date is estimated to be 1.6 W/m^2. The net effect of these projected increases in greenhouse gas concentrations is a further rise in climate forcing of between 2.1 W/m^2 (SRES B1) and 7.25 W/m^2 (SRES A1F1).

Aerosol concentrations considered in the SRES scenarios include those for sulphates, aerosols released through biomass-burning, fossil fuel black carbon (or soot) and fossil fuel organic carbon. Some of these aerosols (e.g. sulphates and fossil fuel organic carbon) have a cooling effect, while others (soot and aerosols from biomass burning) have a warming influence. At the regional scale, the SRES scenarios include the possibility of both increases and decreases in anthropogenic aerosol emissions, depending on the extent of fossil-fuel use and policies to abate local air pollution. Since emissions are expected to continue to increase in some regions and decrease in others, the regional distribution of future aerosol forcing is expected to change significantly from that of today. However, in all of the six illustrative SRES scenarios, global sulphate aerosol concentrations decrease. This would result in global warming relative to present day. The net direct effect of projected changes in all four aerosol types varies between a cooling of -0.1 W/m^2 and a warming of 0.2 W/m^2.

References: IPCC, 2000; Ramaswamy et al., 2001; Meehl et al., 2007

D.4 How much is the Earth expected to warm over the next 100 years?

Response: Without coordinated action to reduce greenhouse gas emissions, global average surface temperature is likely to increase by between 1.1 and 6.4°C by the year 2100 relative to 1990. This range considers both uncertainties related to future increases in greenhouse gas concentrations (uncertainty related to human demographics and behaviour) and the disagreement between climate models with respect to how much or rapidly the climate system will respond to such increases (scientific uncertainty). But even if greenhouse gas concentrations are stabilized, temperatures will continue to rise for centuries after stabilization because of the delay in ocean and ice response to climate forcing.

Explanation: The most optimistic temperature projection provided by the IPCC in its Fourth Assessment is based on the SRES B1 emission scenario, a scenario that envisions a mid-century peak in global population, a rapid shift toward a service and information economy and the extensive use of clean energy technologies by 2100. When a large number of climate models provide projections based on this emission scenario, and additional information about carbon cycle feedbacks in the climate system are taken into account, the lowest estimate of warming by 2100 considered likely to occur is a warming of 1.1°C above current levels. The most pessimistic case is for the SRES scenario A1FI, a scenario that is distinguished by its assumption of continued intensive use of fossil fuels throughout the 21st century. Based on this scenario, the highest estimate of warming by 2100 considered likely to occur is 6.4°C above current levels. These results, and those presented in Figure D.4, demonstrate clearly that the magnitude of warming that will occur over this century will be strongly influenced by how society evolves over this time period and the consequent emissions of greenhouse gases and aerosols.

Since most greenhouse gases remain in the atmosphere for a long time, the effects of past emissions will persist for centuries even if greenhouse gas emissions from human activities were to stop immediately. Estimates from climate models suggest that even if atmospheric concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.6°C would be expected by the end of the century with slow additional warming in the centuries beyond. It is important to note that temperature changes will occur unevenly around the world. Land will warm more than oceans, high latitudes more than low latitudes, and winter at middle-to-high latitudes more than summer. In Canada, the annual mean temperature could increase between 5 and 10°C over the next century.

Reference: Meehl et al., 2007

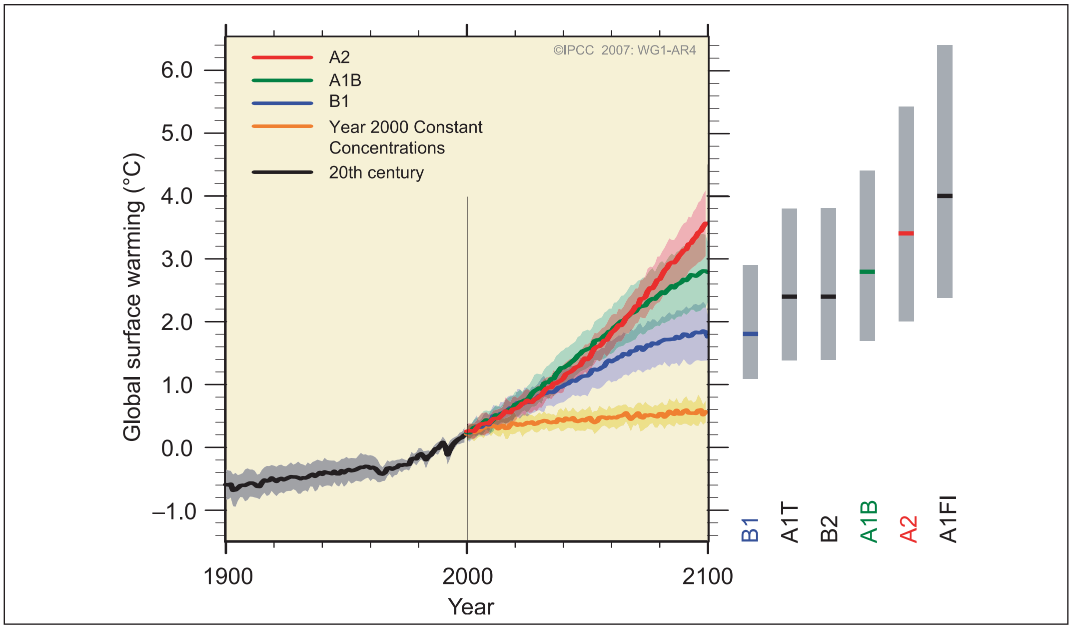

Figure D.4. Projected range of increase in global average surface temperature over the next century compared to changes during the past 100 years. Results are presented separately for experiments using different scenarios of how emissions of greenhouse gases and aerosols will change in the future (scenarios B1, A1T, B2, A1B, A2, A1FI). Solid coloured lines are average results from a number of global climate models, while the shading around each line represents modelling uncertainty. The grey bars at the right indicate the best estimate and likely range of global surface warming by 2100 for six emission scenarios (Figure SPM.5, IPCC, 2007a).

D.5 Why is there more than a 5°C range in the amount of global warming projected?

Response: Any projection of climate change carries an associated uncertainty, which arises from two primary sources: i) inadequacies in climate model performance due to computing power limitations and inadequate scientific understanding and/or representation of climate processes and variability within these models; and ii) the inherent uncertainty in the demographic and socio-economic factors that determine future emissions of greenhouse gases and aerosols in the atmosphere. When these scientific and demographic uncertainties are combined in model simulations, they result in a range of more than 5°C in the magnitude of likely warming projected for 2100, extending from the most optimistic IPCC projection of a 1.1°C warming to its most pessimistic projection of a 6.4°C warming.

Explanation: One of the primary reasons for uncertainty is scientific. For example, inadequate understanding of atmospheric and oceanic processes and/or limitations in how these can be described in mathematical terms that can be simulated by climate models limit the accuracy of any estimate of the climate response to radiative forcing. Limited computing power, which forces modellers to choose between lower resolution and a simpler mathematical description of climate processes, is also an important factor. As a result, different climate models used in projecting future climates employ various ways to formulate important components like clouds or sea ice, which can lead to different estimates of climate variables.

The second primary cause for uncertainty in future climate projections is the predictability of future emissions of greenhouse gases and aerosols. Such emissions are determined by how rapidly human populations and economies will grow in future decades, how efficiently societies will use energy, the type of energy they use and how human use of land is likely to change. These are uncertainties about future social behaviour, rather than about the climate system. During the first half of the 21st century, the scientific uncertainty associated with climate modelling is the primary cause of uncertainty in climate projections. However, the uncertainty in demographic behaviour and related implications for emission scenarios dominate the uncertainties for the second half of the century.

Reference: Meehl et al., 2007.

D.6 Which climate processes and feedbacks contribute most to differences in model simulations of climate sensitivity to climate forcing?

Response: One of the most important causes of uncertainty between different climate model simulations of climate sensitivity[7] relates to how the role of water vapour, clouds and other aspects of the water cycle in atmospheric radiative processes are described in these models. This is in part due to the highly variable nature of these parameters, both in space and time, and to the inadequate observations and understanding of hydrological processes in the upper troposphere. However, it is also very difficult to adequately describe these processes, which take place at physical scales that range from the micrometres to kilometres, in mathematical equations that describe climate processes at model resolutions of hundreds of kilometres. Other significant sources of uncertainty in climate model results include the role of snow and sea ice as climate feedbacks, description of ocean circulation and related heat flux processes, and carbon cycle feedbacks.

[7] Climate sensitivity refers to the magnitude of temperature response of the global climate system to a climate forcing caused by a doubling of CO_2 concentrations once the climate system has come to a new equilibrium state. Experts suggest that this sensitivity is likely to range between 2 and 4.5°C per CO_2 doubling.

Explanation: Clouds and water vapour play very important roles in modifying the flow of solar and infrared energy through the atmosphere and in the transport of energy around the planet. Water vapour is an important greenhouse gas that amplifies changes in climate caused by other factors. When water vapour is formed, it also converts a lot of energy into latent heat that can be released again far from its origin when the water vapour once again is condensed into water droplets that form clouds. Clouds both reflect incoming sunlight and absorb outgoing radiation, with the net effect of these offsetting energy flux processes being dependent on the type of cloud, its altitude and the nature of the underlying surface below the cloud. Furthermore, because of limited observations in the middle to upper troposphere, water vapour and cloud processes in these regions are poorly understood. Many of these processes also occur at the microphysical scale, and can vary vertically and horizontally from one metre to the next. As a result, these processes are extremely difficult to describe accurately in mathematical equations used in climate models that have resolutions on the scale of hundreds of kilometres. Different models use different schemes to do so, each with its limitations and advantages.

Sea ice and snow cover also play important roles in climate processes, particularly at the regional scale, because of their capacity to reflect sunlight and to insulate the land and ocean surfaces below from heat loss to the atmosphere during cold seasons. However, the presence or absence of snow and ice is directly related to the temperature freezing threshold, and hence sensitive to even minor changes in surface temperatures. Furthermore, the effect of ocean sea ice is modified by ocean dynamics, the presence of leads and polynyas[8] in the ice pack and other variables. Again, there are significant differences in how modelling groups describe these processes.

Both the rate of ocean heat uptake and the response of ocean circulation to climate change are important variables that govern climate system inertia and hence the rate of atmospheric warming. There remain significant differences in how well models can simulate these processes.

Another important feedback is the global carbon cycle. Climate change will affect the health and distribution of ecosystems and the frequency of wild fires, both of which affect the flux of carbon into and out of the atmosphere. This in turn affects how much of the CO_2 released by human emissions will remain in the atmosphere. Likewise, changes in ocean circulation and productivity in response to climate change can affect net ocean uptake of atmospheric CO_2. The magnitude of these carbon cycle feedbacks on the climate system remain uncertain but most are expected to be positive, meaning they will increase the magnitude of the global temperature response to any given change in greenhouse gas forcing.

Reference: Randal et al., 2007; Kharin et al., 2007.

[8] Leads and polynyas are open water areas that can form within the ice pack. In winter, these open water areas are an important source of heat and moisture flow into the cold atmosphere above.

D.7 How are we to believe the temperature projections of climate models when their various forecasts for future climate differ so much?

Response: While the models disagree on the details of future climate change, there is general agreement on the continental scale pattern and significance of expected future changes in temperature, particularly over the next few decades. Hence, while they cannot provide detailed predictions of how climates will change, they are useful tools for providing projections with respect to the direction and approximate magnitudes of such change.

Explanation: Various models use alternative techniques for describing how different components of the climate system function. Furthermore, there is significant natural variability within the climate system, so that experiments with the same model that have identical forcings but slightly different starting points can be expected to show different details in their results. Consequently, there are significant differences between model experiments in the details about the nature and rate of future climate change. However, all models agree that the warming will be significant and likely unprecedented in human history, that continents will warm more than oceans, and that high latitudes will warm more than low latitudes.

Reference: Meehl et al., 2007.

D.8 How reliable are the models used to predict future changes in other climate indicators such as precipitation?

Response: Global climate model projections are useful indicators of the direction and significance of expected changes in a broad range of climate variables at global and continental scales as global temperatures rise. For example, they consistently project an accelerated global hydrological cycle and related rise in total annual average precipitation, an increase in the intensity of precipitation, more intense summer droughts in mid-continent regions, a shift in storm tracks, a slow-down in global ocean circulation, and a decline in sea ice and snow extent in mid- to high latitudes and at high altitudes.

Explanation: All models project that both surface evaporation and total annual global precipitation will rise (consistent with an accelerated hydrological cycle in a warmer world), although they disagree by how much. Zonally, most agree that high latitudes will become significantly wetter, consistent with a poleward shift in storm tracks across mid-latitudes. In mid-latitudes, many regions will likely experience a decrease in precipitation in summer. Most models also project that when it does rain or snow, more of this precipitation will fall as intense events. For example, over North America, the one in twenty year extreme rainfall event will likely, by 2100, occur about once every ten years. However, in many regions, the duration between rainfall events will also likely increase. As a result, in mid-continent regions the duration and intensity of summer droughts are also expected to increase.

Changes in air temperature and in precipitation also affect temperatures and salinity of ocean surface waters, factors which play an important role in water density and ocean circulation. Most model simulations project a significant decrease in overturning of waters in the Atlantic Ocean by as much as 50%, and hence a weakening of the warm Atlantic Gulf stream. Both sea ice extent and thickness are projected to decline, with some models projecting complete loss of summer sea ice in the Arctic by the latter half of the 21st century. Over land areas, all models agree that the season for snow cover will become shorter, and the extent of snow cover will decrease significantly.

However, because most of the above climate variables are influenced by a complex array of feedbacks to changes in temperature, the uncertainty about the magnitude and even the sign of related changes at the regional scale is much larger than that for temperature. Studies into the possible implications of climate change at this scale need to consider the full range of results from numerous state-of-the-art climate models to capture fully the range of possible outcomes.

Reference: Meehl et al., 2007; Kharin et al., 2007.

D.9 Models used for weather forecasting often can't even properly predict the weather for the next few days. How can we expect credible predictions from climate models for decades and even a century into the future?

Response: Climate is *average* weather, which is more predictable than day-to-day and hour-to-hour weather changes. Weather behaviour is chaotic and often difficult to predict beyond a week or so into the future. By comparison, climate is largely determined by global and regional geophysical processes that change slowly. Hence, if these factors are properly understood and predictable, then the climate can be forecast far into the future with a significant degree of confidence.

Explanation: Day-to-day local weather is largely determined by atmospheric circulation, the formation of large-scale weather systems, and local convective processes. Because of the chaotic nature of the atmosphere, predictability decreases with time, and is quite poor beyond a week or so. Climate, on the other hand, represents average weather and its expected variability. These are determined by factors such as incoming solar radiation (which varies with latitude and time of year), the influence of prevailing characteristics of cloud cover, aerosols and other components of the atmosphere on the flow of the Sun's energy into the atmosphere and of heat energy out again, prevailing winds and other atmospheric conditions, and local geophysical conditions that, in general, change slowly and in a more predictable manner. Thus, while forecasters would be unable to predict day-to-day weather 6 months into the future, they can provide good approximations of the changes in seasonal climates because of known physical processes that cause conditions to change from winter to summer and back again. They can also provide estimates of the changes in probability of different kinds of weather events, such as sub-zero minimum temperatures, maximum temperatures in excess of 30°C, snow blizzards or thunderstorms. Likewise, climate models, when looking much farther into the future, project how the climate characteristics, averaged over several decades, might change in response to projected changes in the factors that determine the climate.

D.10 What are the projections for sea-level rise and how reliable are they?

Response: Experts project that the average global sea level will rise by between 18 and 59cm by 2100 based on a range of emission scenarios. This rise is primarily due to the combined effects of melting glaciers and the expansion of sea water as it warms. Sea levels will continue to rise centuries thereafter. On multi-century time scales, the melting and the dynamical collapse of ice sheets could become dominant factors, potentially raising sea levels by many metres. However, there remains high uncertainty about the magnitude and timing of such responses. Likewise, there are substantially larger differences in model projections of regional changes in sea level, compared to the global mean change.

Explanation: As the oceans warm, the sea water within them expands. This alone could cause sea levels to rise between 10 and 41cm by 2100, depending on how much the Earth's surface warms and how rapidly the excess surface heat penetrates into the ocean. Furthermore, mountain glaciers and small ice caps around the world are expected to continue to melt, adding another 7 to 17cm to the ocean level as the melt water runs off to sea. Finally, slow changes in polar ice sheet thickness and extent could modify sea levels. However, positive contributions from the Greenland and West Antarctic ice sheets are likely to be significantly offset by snow accumulation in East Antarctica. The net ice sheet contribution to sea levels over the next century is therefore expected to be small, with estimates ranging between a decrease of 9cm to an increase of 9cm. Experts indicate that the combination of these factors could cause a sea-level rise by 2100 of between 18 and 59cm. It should be noted that this range does not incorporate a sea level response to carbon cycle feedbacks in the climate system. Since such feedbacks are expected to be positive, enhancing the global mean temperature response to a given emission scenario, the upper end of the range of estimated sea-level rise could be an underestimate. Similarly, the range in projected sea-level rise of between 18 to 59cm does not include the possibility of rapid changes in ice flow rates from the ice sheets.

In subsequent centuries, continued ocean warming and enhanced melting of the Greenland ice sheet are likely to cause further sea-level rise. Even if atmospheric CO_2 concentrations are successfully stabilized by 2100, continued thermal expansion of ocean waters would likely add another 20-40cm to sea levels by 2200. If a global warming beyond about 2°C above the pre-industrial level were sustained for millennia, this could lead to irreversible melting of the Greenland Ice Sheet with an associated sea-level rise of about 7m.

On the other hand, changes in the volume of the Antarctic ice sheets are expected to be less significant, primarily because increased snowfall over the ice sheet domes under a warmer climate would likely more than offset increased discharge at the ice sheet margins. There remains, however, a possibility of a sudden surging and eventual collapse of the West Antarctic Ice Sheet (see D.11). Total dissipation of the West Antarctic Ice Sheet would add 5m or more to global sea levels.

Reference: Meehl et al., 2007.

D.11 How likely are abrupt catastrophic changes in climate?

Response: Possible abrupt, catastrophic changes in the climate system include a collapse of the West Antarctic Ice Sheet, a shut-down of the deep Atlantic Ocean circulation system that causes the Gulf Stream and a rapid positive carbon cycle feedback triggered by melting of frozen hydrates underneath the ocean floor. Most experts agree that the risks of such potentially catastrophic events within the next century are very low. However, the risks become increasingly significant as the rate and magnitude of future global warming increase.

Explanation: Studies of the Earth's climate history demonstrate that abrupt and catastrophic changes in climate have occurred in the past, particularly during periods of climate transition between cold and warmer states. For example, there is evidence that an abrupt release of CH_4 from thawing hydrates below the ocean floor may have caused a sudden and large climate warming many millions of years ago. Likewise, during the latter part of the last glacial period and the subsequent deglaciation, abrupt shutdown of the deep Atlantic Ocean circulation system (which brings warm tropical water northward at the surface - the so-called Gulf Stream - and returns cold waters southward through deep ocean currents) occurred at regular intervals. These events, likely triggered by sudden periodic releases of freshwater, glacial ice or melt waters into the North Atlantic, appear to have caused changes in temperatures around the North Atlantic of as much as 10°C within a few decades. Finally, there is evidence that the West Antarctic ice sheet is unstable and could, if exposed to intense warming, begin to rapidly surge into the Southern Ocean. Such a disintegration of the ice sheet could raise global sea levels by up to 1m per century, and 5 to 6m when fully depleted. In contrast, both the East Antarctic and Greenland ice sheets are dynamically much more stable and change much more gradually (see D.10).

There remains a large degree of uncertainty about the mechanisms involved in such events, and hence also about the likelihood or time scales of such transitions. That is because the climate system involves many processes and feedbacks that interact in complex and non-linear ways. These interactions can give rise to thresholds in the climate system that can be crossed if the system is perturbed sufficiently. Although identification of such thresholds is very difficult, there is concern that such disastrous surprises could happen again if the climate is pushed too rapidly towards warmer conditions. Model studies suggest that the more rapid the rise in greenhouse gases and in related global temperatures, the greater the risks of such extreme global scale events. Once such events occur, it would take centuries to millennia for the climate system to recover. Most experts agree that the risks of such catastrophic events occurring within the next century are very low, although depending on the magnitude of global warming within the next century, essentially irreversible (on human time scales) and catastrophic processes could be triggered.

References: Meehl et al., 2007; Zhang, 2003.

D.12 Have we underestimated the future change in climate?

Response: International assessments of the risks of climate change have focused on the outputs of coupled climate models forced with projected changes in greenhouse gas and aerosol concentrations derived from IPCC SRES emission scenarios. These suggest that it is unlikely that warming by 2100 will be less than 1.1°C or greater than 6.4°C. However, some studies have suggested that these results underestimate the potential magnitude of the climate system's response to radiative forcing. For example, a strong positive feedback in the global carbon cycle because of vegetation response to warmer climates and altered precipitation patterns could significantly add to the magnitude of warming by 2100 projected in recent IPCC assessments. Likewise, abrupt climate system responses such as those discussed in D.11 could introduce surprises. Although these higher risk projections remain uncertain and controversial, they suggest that the upper range of IPCC projections for change by 2100 is more uncertain than the lower range. Hence, the magnitude of future climate change is more likely to be underestimated than overestimated.

Explanation: Experts have estimated a likely range for climate sensitivity to a doubling of CO_2 of 2 to 4.5°C. However, probability studies using thousands of simulations with simple coupled climate models using the full range of plausible climate system parameterizations have suggested a 5% probability that climate sensitivity could be less than 2°C per CO_2 doubling, and a similar probability that it could be greater than 8°C per doubling. Therefore, there is a real possibility that the upper limit for climate sensitivity could be greater than 4.5°C. Furthermore, some studies have projected that land ecosystems could become a significant source of CO_2 if major ecosystems become dry under warmer climates, and hence increasingly vulnerable to wildfire and enhanced soil respiration. This would cause atmospheric CO_2 concentrations to rise more rapidly than predicted by traditional analysis of the SRES scenarios, and accelerate climate change. There is also the possibility that Arctic sea ice cover could reach a threshold where it could disappear more rapidly than models project. This would also add to climate sensitivity since loss of ice cover is a positive feedback on the climate system. While the IPCC assessments suggest that global warming by 2100 will likely be in the range of 1.1 to 6.4°C, these and other lines of evidence suggest there is a risk that it could be larger.

Some experts have also suggested that, because of overestimation of the water vapour feedback effect, warming could be less than the lower end of the IPCC. However, both observational data and careful assessments of these theoretical arguments suggest this is unlikely.

At a minimum, it can be concluded that the risk of underestimating the magnitude and rate of future climate warming is probably greater than that of overestimation.

Reference: Meehl et al., 2007.

E. Impacts of Climate Change

E.1 Global temperatures have warmed by less than 0.8°C in the last 100 years. Such a change is much less than we get from one year to the next. What's the big deal?

Response: Natural variability in climate can cause large differences in conditions from one year to the next and one region to the next. However, the observed 0.74°C warming between 1906 and 2005 is a long-term trend in the *global average* of all these variations in space and time. Experts indicate the average Northern Hemispheric temperature during the past 50 years has likely been higher than at any other time during at least the past 1300 years. By comparison, it took only about 4 to 7°C of warming to cause the Earth to slowly change from the last glacial period some 15,000 years ago, when large volumes of ice covered what is now Canada, to the interglacial conditions that exist today.

Explanation: Natural variability in climate can cause one region of the world to warm several degrees relative to the preceding year, while another cools a similar amount. However, when such variability is averaged globally, much of this spatial variability is removed from the measurements. Likewise, averaging weather conditions over time also reduces the season-to-season and year-to-year variability of climate. The reported trends in temperature represent a *long-term* and *global* change. Experts indicate that the average Northern Hemispheric temperature over the past 50 years is now *very likely* higher than any similar period of the past 500 years, and *likely* without precedence in at least the past 1300 years (see Figure C.4). By comparison, the change in temperature between the last glacial maximum, which ended about 15,000 years ago, and today was about 4 to 7°C. That temperature change caused a transformation of the Canadian landscape from a large ice sheet several kilometres thick to today's mosaic of productive ecosystems.

Reference: Jansen et al., 2007.

E.2 What are the potential consequences of a few degrees of warming?

Response: Even a modest warming of global temperatures would significantly change global wind and precipitation patterns, and hence alter local weather behaviour around the world from that which we are used to. Some of these changes would be effectively irreversible. Since both ecosystems and human societies have adapted to the climates of today and the recent past, they will be ill-prepared to deal with the changes if these are too rapid to allow ecosystems and societies to adapt. For many developing countries, this may have very harmful effects on basic human needs for a place to live, food to eat and clean water to drink and on their ability to live healthy lives. For all countries, increased frequency of severe weather events will enhance the risk of weather-related disasters.

Explanation: Ecosystems evolve slowly in response to changes in the average conditions and variability of past weather. Many species, like most trees, respond very slowly, while others with shorter lifespans can respond and evolve more quickly. Since individual species will respond at different rates to changing environmental conditions, ecosystem function is likely to be disturbed since the relationships among species within ecosystems may be disrupted. Some species have unique climate niches that may disappear, leaving them vulnerable to extinction. Likewise, the socio-economic infrastructure and culture of human societies are closely adapted to the climate within which these evolved, and rapid climate change would make it difficult to adapt quickly. Experts also predict longer and more frequent extreme weather events such as heavy rains, droughts, floods, and severe storms that would significantly impact humans and natural ecosystems and increase the risk of weather-related economic disasters. For example, longer and more frequent heat waves will likely increase heat-stress-related deaths. More frequent and severe droughts are likely to increase the risk of famine, particularly in semi-arid and arid regions of the tropics and subtropics. Global warming is also expected to increase the potential transmission of infectious diseases such as malaria, dengue, and yellow fever through the expansion of the range in which disease-carrying organisms can survive.

The IPCC synthesized knowledge about the vulnerability of societies and ecosystems to the impacts of climate change into five 'reasons for concern' (see Figure E.2). Although there is uncertainty about temperature change thresholds at which different types of impacts will occur, there is, nonetheless, a lot of confidence in the general relationship of impacts becoming increasingly negative with increasing temperatures. Recent scientific evidence has strengthened the reasons for concern about climate change and provided support for some negative impacts occurring at lower thresholds of temperature change than previously thought.

Reference: IPCC 2007d.

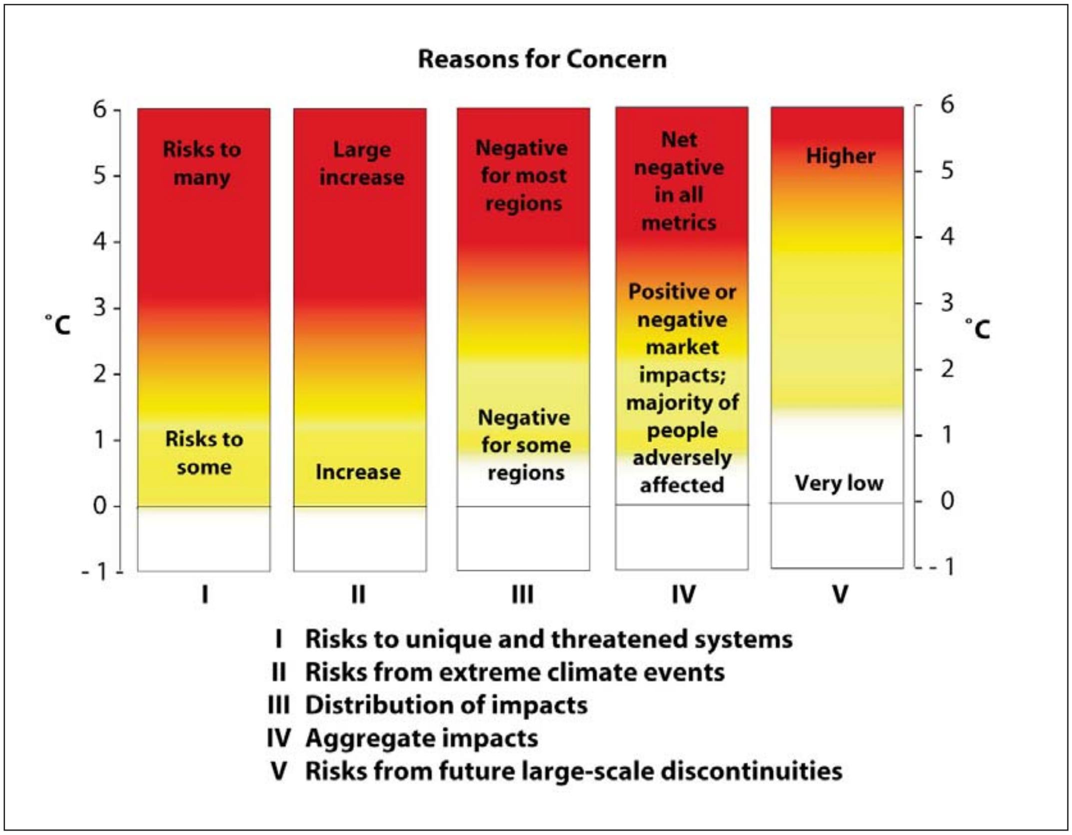

Figure E.2 Some negative impacts have already occurred in some regions in response to warming to date (e.g. increases in human mortality, loss of glaciers, increases in the frequency and/or intensity of extreme events). Modest warming could provide some benefits in some regions, but as global temperature increases, impacts are expected to become increasingly negative at all scales. (IPCC 2001, WGII Figure SPM-2, RH panel).

E.3 How will rising global sea levels affect people?

Response: Experts project that the average global sea level will rise 18 to 59cm by 2100 (see D.10). Because 50 to 70% of the world's population lives in low-lying coastal areas, millions of people are already vulnerable to coastal flooding due to storm surges. A sea-level rise within the above range would affect many millions more. Protective measures, such as dike building, can help to reduce the risks in some but not all areas, but would be costly.

Explanation: Today, many millions of people are already at risk from flooding in low-lying coastal areas, where 50 to 70% of the world's population lives. The combined effects of a significant rise in sea level and population growth in coastal areas would substantially increase this number. Adaptation measures, such as the installation or enhancement of protective sea walls and dikes, could help reduce the impacts on people. However, such measures would be costly. Estimates for protection of U.S. coastlines, for example, range from US$20 billion to US$150 billion.

Furthermore, even with the adoption of such protective measures, a modest sea-level rise of 40cm would still leave an estimated 80 million additional people vulnerable to coastal flooding during storm surges.

While Canadian coastlines are relatively rugged and hence less vulnerable to the impacts of sea-level rise than those of many other countries, some of the 240 000km of ocean coastline are low lying and/or soft and vulnerable to erosion. Highly sensitive regions of the Canadian coastline include much of the Maritime Provinces, a large part of the Beaufort Sea Coast and the Fraser Delta region of British Columbia.

References: Nichols et al., 2007; Natural Resources Canada, 2004.

E.4 The frequency and intensity of disasters related to extreme weather events appear to be increasing. Is this linked to climate change?

Response: It is very difficult to establish trends in weather-related disasters or to attribute recent disasters to specific causes. That is, the perceived increase in disasters in some parts of the world in recent years may be inaccurate or may be entirely natural. There is no clear evidence to suggest that recent disasters are already a consequence of global warming. However, studies suggest that the frequency and severity of many types of extreme weather events will change as the climate warms. Therefore, many of the current weather-related disasters may be viewed as examples of what can be expected more often in the future as the global climate continues to warm.

Explanation: A weather-related disaster can occur when society and/or ecosystems are unable to effectively cope with an extreme weather event. That is, both the extreme nature of the weather event and the sensitivity of ecosystems or society to that event are factors. The dramatic rise in damages in recent years due to such disasters may therefore be at least partly attributed to demographic factors, such as increased human population in vulnerable regions and increased wealth.

On the other hand, there are indications that there have also been increases in various types of extreme weather events, at least in some regions of the world. Yet, since these events, by definition, occur infrequently and irregularly, they are difficult to link to global causes. They may simply be the result of natural variations in climate. Experts agree it is still too early to be confident about a direct link between climate change and these extreme events. Furthermore, few events are without historical precedence. Most historical records of such events prior to the past few decades are also not very accurate.

However, in many respects, the trends towards more intense and unusual extremes for some types of weather and climate events in some regions in recent years are broadly similar to those projected by climate models and related studies. Therefore, while there is no hard proof to link recent disaster trends to climate change, many of these events can be considered as examples of what could happen more frequently in the future.

Reference: Hegerl et al., 2007.

E.5 Why would global warming lead to more frequent and extreme weather events?

Response: Higher temperatures lead to higher rates of evaporation and precipitation, more frequent heat waves, less frequent cold extremes, and generally more energy for storms. Model results can provide useful clues as to the direction and significance of such changes. However, the processes involved are complex and the changes in extremes are therefore still difficult to predict accurately.

Explanation: Most extreme events are complex responses to a number of factors, and hence their responses to warmer climates are difficult to assess. However, as the Earth warms, experts expect more frequent high temperature extremes and less frequent cold extremes, and that more precipitation will fall over shorter periods of time. This will likely increase the frequency of very heavy and extreme precipitation events, and of local flooding. Tornadoes and the intensity of thunderstorms and related extreme wind and hail events will also increase in some areas. It is also expected that many regions of the world will experience more frequent, prolonged, or more intense droughts due to more rapid evaporation from plants, soils, lakes, and reservoirs. Increasing atmospheric moisture could also increase the intensity and frequency of blizzards and snow storms in some colder locations. In more temperate latitudes, their frequency will likely decrease, but their intensity may rise. In effect, climate change will 'load the dice' with respect to the probability of occurrence of such extreme weather events. There is as yet little consensus on how global warming will affect other extreme weather events such as tropical storms, cyclones and typhoons, although the potential maximum intensity of such storms is expected to increase.

Reference: Meehl et al., 2007.

E.6 Will global warming take place gradually or rapidly?

Response: Most climate model studies suggest that the response of the climate to human influences will be gradual. However, there is evidence that the Earth's climate has undergone abrupt shifts in the past, primarily during periods of glacial climates or during major transitions of climate from one state to another. Similar abrupt changes, although unlikely within the next century, cannot be ruled out (see D.11).

Explanation: There is clear evidence from paleoclimate data that the climate system underwent large-scale abrupt changes in climate during the past glacial maximum and the deglaciation process between 10,000 and 15,000 years ago. These appear to occur when the climate system is in an unstable mode, and to have had major impacts on regional climates. Temperatures over Greenland, for example, have changed by as much as 10°C within a few decades. Such large, abrupt changes have not occurred during the past 10,000 years of stable Holocene climate. Some scientists, however, have expressed concern that a rapid, human-induced climate change could return the climate to an unstable condition and once again trigger such abrupt events. While such events are unlikely within at least the next century, that possibility cannot be ruled out. Abrupt events appear to be linked to changes in ocean circulation, and the risk of occurrence appears to increase with increasing rates of change in global climate. The consequences, should they occur, could be catastrophic, since rapid change allows little time for adaptation.

Reference: Jansen et al., 2007.

E.7 Wouldn't Canadians be better off with a warmer climate?

Response: For cold countries such as Canada, climate change can indeed provide some significant benefits. For example, warmer temperatures would reduce space heating costs and provide for longer, warmer growing seasons. When averaged over the entire country of Canada, these benefits could help offset some of the harmful effects caused by climate change provided the rate and magnitude of climate change are modest. However, if climate change is rapid or large, the risks of danger increase significantly, and the overall effect on countries like Canada would be increasingly negative, simply because it is more difficult to adapt to large or rapid change. Moreover, major negative impacts are projected for many of the developing countries of the world, even for modest changes in climate. These off-shore impacts can also have indirect yet significant negative consequences for Canadians (see E.8).

Explanation: Moderately warmer climates could provide benefits to some sectors of the economy or society, and to some regions of the world. For example, providing there is adequate moisture, longer and warmer growing seasons will increase productivity of agricultural crops, and warmer winters will reduce space heating costs in such countries and make it easier to navigate through ice-covered waters. Most of these benefits are due to changes in *average* temperatures.

However, other consequences of climate change are expected to be very harmful. These include: the combined effects of sea-level rise and ocean storm surges, which could be economically and ecologically devastating to some of Canada's coastal regions; enhanced summer drought conditions that could threaten agricultural production and natural ecosystems, and increase competition for water; increased intensity of summer rainfall, that would increase heavy flooding and erosion, sometimes in the same regions otherwise plagued by drought; and increased frequency of high summer temperature extremes that could stress both ecosystems and human populations.

The larger or more rapid the change in climate, the more difficult it will be to take advantage of the potential benefits, and the greater the risk of danger due to extreme events and other harmful changes. Thus, the concern is not about climate change of any particular kind, but about the possibility that rates and magnitudes of change will exceed human and ecological tolerance thresholds.

References: Field et al., 2007; Anisimov et al., 2007; Natural Resources Canada, 2004.

E.8 What are the primary reasons why Canadians should be concerned about climate change?

Response: While climate change will affect Canadian ecosystems and societies in many complex ways, the primary reasons why Canadians should be concerned are the effects of a warmer world on our northern environment and ecosystems, the economic and ecological consequences of longer and more severe droughts and the implications for life and property of more frequent and/or intense extreme weather events. Furthermore, Canadians should also be concerned about the impacts that climate change will have on other countries, especially those already exposed to severe problems of poverty, hunger and other health risks.

Explanation: Canadian ecological and social systems are well adapted to today's climate and weather patterns. Climate change will therefore affect almost every aspect of Canadian society and significantly alter the ecological patterns across the country. There are several aspects of such change that are of particular concern. First, warmer climates will melt snow, permafrost and sea ice across Canada's northern regions, dramatically altering the environment that current ecosystems and northern residents depend upon. While Arctic marine transportation may eventually become easier, over-land transportation that relies on frozen grounds will be increasingly curtailed, traditional cultures that rely on sea ice and frozen ground for pursuing hunting activities will be jeopardized, and ice-dependent animal species may become increasingly threatened with decline and possible extinction. In southern Canada, the primary concerns are related to extreme climate and weather events, particularly extended droughts, increased severe local floods and major wind events.

Canada also has had a long and admirable history of helping those in need in other countries of the world. Experts argue that the global need for assistance will increase dramatically under warmer climates, even for modest rises in temperature (see E.2 and E.3). Hence, Canada will likely be called upon to extend help to these victims through direct aid, through assistance in resolving related conflicts within and between countries, and by accepting those people who are displaced from their home countries because of the loss of property and homes or by related social unrest.

References: Field et al., 2007; Anisimov et al., 2007; Natural Resources Canada, 2004.

E.9 It has been suggested that, within 50 years, warmer climates will cause Halifax's climate to be similar to that of Boston today, Toronto's like that of Kentucky, and Vancouver's like that of San Francisco. What's so bad about that?

Response: Ecosystems, culture and socioeconomic infrastructures in Canada have been shaped by the local climate of today and the recent past. Changing infrastructure to suit warmer climates and associated changes in weather may be very costly. If climate change occurs rapidly, the process of adaptation becomes increasingly difficult, costly, and potentially unsuccessful, leading to risks of major disasters. The same is true for the natural environment.

Explanation: The past development of the infrastructure of Canadian cities, transportation systems, agricultural practices and other social and economic well-being activities have been significantly influenced by the past conditions of local climates. For example, most Canadian winter sport facilities and activities are dependent on the presence of snow and ice. Storm sewers and drainage systems in Canadian cities are based on, among other things, local rainfall characteristics, and residential and commercial buildings are designed for temperate to cold climates. Likewise, agriculture, water resource management and flood control infrastructures are based on current growing season and water resource characteristics. Many of these structures and activities require long lead times in order to prepare for future changes in climate. Hence, the more rapid the change in climate, the greater the potential mismatch of cultural, social and economic infrastructures with altered climate conditions, and the greater the risk of failure to adapt, and of negative consequences of climate change.

E.10 Reports indicate that warmer global temperatures will cause some of the largest changes in northern countries such as Canada. Does this mean we are much more at risk of danger than countries near the equator?

Response: No. Climate models, indeed, indicate that the magnitude of climate change in Canada will probably be greater than in many other countries. However, because our current Canadian climate regularly undergoes large changes from week to week, season to season, and year to year, Canadians may be better prepared to deal with climate variability and climate change than those living in less variable climates. Furthermore, modest warming will give us some benefits that will help offset some of the harmful effects (although the benefits and harm may be experienced by different regions, economic sectors or communities). As a people, we may be less vulnerable to climate change than many others, particularly those living in poor tropical countries. However, within every country, there are communities and sectors of the economy more vulnerable than the population or economy as a whole.

Explanation: Models suggest that changes in temperature will be greatest at high continental latitudes and in winter. However, natural climate fluctuations are also greatest in these regions, and in winter. Hence, ecosystems and societies which have developed in these regions, in general, also have a greater tolerance for change, and may be more adaptable to the large changes predicted for future decades. As in any other region, the rate of climate change will be a key determinant in our ability to adapt to the coming changes. Since cold temperatures are a limitation to many ecosystems and socio-economic activities in Canada, warmer climates are expected to bring many benefits. That said, the warming of the Arctic is expected to bring about such dramatic changes that residents of the North, and species within northern ecosystems, are expected to face many serious challenges in the coming years. Canada is a relatively wealthy nation, however, with a social infrastructure that can help Canadians to adapt more readily. By contrast, societies of many developing countries in low latitudes already have a marginal existence and have less access to such resources. This can make them vulnerable to even very small changes in climate. Thus, while the large changes for Canada projected by models may result in significant impacts within Canada, many of which will be negative, Canadians may be better able to cope with the consequences of climate change than residents of many developing countries.

F. Scientific Credibility and Human Response

F.1 It seems that there are always conflicting stories about climate change appearing in the media. Is there no agreement among scientists about climate change?

Response: The vast majority of scientists studying climate change agree that the basis for concern is scientifically sound. Although there may be individual scientists who disagree with this consensus and whose opinions may be featured in stories in the media, it is important to consider what scientific support there is for their arguments. The best approach is to refer to the peer reviewed published literature, since a key test for credibility is whether a paper has successfully gone through a process of peer review (review by scientists with relevant expertise).

Explanation: Each year, there are several thousand new scientific papers published in peer-reviewed journals on topics related to climate change. Each paper adds a small increment to the large body of knowledge already available. Since the global climate system is very complex, these papers involve many different scientific disciplines, and are focused on a broad range of processes and causes of climate change. Some processes involve negative feedbacks that reduce the initial climate response; others involve positive feedbacks that amplify it. Some causes for change, whether natural or human, tend to cool climate, while others induce warming. Each new scientific paper has to be put in context with all that has preceded it. The best approach for evaluating the implications of new science is through periodic assessments of the scientific literature. Such assessments will focus on recent findings and will place them in context with what was known and understood about an issue previously. The best known process for assessing the scientific literature on climate change is that undertaken by the Intergovernmental Panel on Climate Change (IPCC).

Sometimes, a new scientific paper may be published that appears to contradict established wisdom. Such a result would be intrinsically of special interest to any scientist. Normal scientific process would see such results get intense scrutiny by other scientists and there would be further research undertaken aimed at replicating the results. This process of verifying and replicating new results takes time and sometimes the concurrent debate among scientists is mistaken by non-scientists to mean there is some important disagreement among scientists. Generally, this is not the case. In the field of climate change, there is certainly debate about the details, and the need to better understand the particulars of how the climate system will respond to increases in greenhouse gases is what drives ongoing research efforts. However, the background science upon which concern about climate change is based is much less controversial. A good summary of such background information was recently provided in the Fourth Assessment Report released by the Intergovernmental Panel on Climate Change in 2007.

References: IPCC, 2007c; IPCC, 2007d.

F.2 I understand there are thousands of scientists who argue that we know too little about climate change, and that it is therefore premature to respond. Who are these dissenters and are they credible?

Response: The numbers often quoted with respect to dissenting scientists are not supported by the published literature in scientific fields related to the study of climate change. Very few of the dissenters publish scientific research papers in those journals in which the majority of papers on climate change are published, that is, in the forum where scientific discussions should occur. It is important to pay attention to the field of work and level of expertise of those acting as sources of information in the climate change discussion. Review by scientists with relevant expertise is a good measure of credibility.

Explanation: Over time, as scientific evidence in support of human-induced climate change has grown, the arguments put forth by dissenters have changed. While some dissenters may still argue that the global warming trend is not real and that the human influence on climate is not yet apparent - arguments easily refuted by published peer-reviewed science – many now focus their arguments on the projected rate and consequences of future climate change which they claim are exaggerated. There are some scientists who do argue that the science about climate change is uncertain enough that much more research is needed before measures to substantially reduce greenhouse gas emissions are taken. Whether or not to act in the face of uncertainty is not a scientific issue, but rather a policy decision, one which requires a risk management approach. Scientists can, however, provide advice about the nature of the risks and impacts that may be associated with different magnitudes of global warming (and related climatic changes). Most of the dissenters with credible scientific backgrounds generally agree with the fundamental science underlying the concern about climate change.

F.3 With so much uncertainty about future climate change, why don't we hold off on any reductions in CO_2 emissions until we are better able to better predict what will happen?

Response: The scientific concern about climate change is well-founded. Many of the remaining uncertainties are related to the details of the consequences of global climate change. Scientists are in general confident that the basis for concern about climate change is scientifically sound, that humans are largely responsible for the change in climate during the past 50 years, that the risks of danger due to projected changes in climate are real and significant. Unrestrained increases in atmospheric greenhouse gas concentrations would be catastrophic. The only way to stabilize atmospheric greenhouse gas concentrations is to reduce global emissions of these gases. When and how this should be done is a policy decision but the fact that the climate system responds slowly to changes in emissions makes it prudent that we begin precautionary action now.

Explanation: While there is uncertainty as to the magnitude and rate of climate change, particularly at the regional level, scientists generally agree that rates of change over the next century will almost certainly be greater than anything experienced on Earth during the past 10,000 years. More significantly, the change could be as large as that experienced during the deglaciation at the end of the last ice age, but more than 10 times as fast – an experiment on the climate system with risky consequences. Furthermore, because of the long delay in the response of the climate system to changes in radiative forcing, by the time all the evidence is in it may be too late to avoid significant danger. Given that there is considerable inertia in both society and the global climate system – the former to changes in cultural behaviour and in technological restructuring, the latter to changes in radiative forcing - early action is prudent. The scientific community has recommended precautionary action that will reduce the risks by slowing down the potential rate of climate change.

F.4 Is it too late to stop climate change?

Response: Scientists agree that the current warming trend cannot be stopped or reversed. However, it can be slowed down to allow biological systems and human society more time to adapt.

Explanation: There are two reasons why further climate change is already unavoidable. First, there is a lot of inertia in the climate system mainly because of the slow response of oceans. This means that the oceans have not yet fully warmed to the level they will eventually reach under current greenhouse gas concentrations, and are still somewhat cooling off the atmosphere. Even the atmospheric response to current greenhouse gas concentrations is not yet fully realized. If all emissions stopped today, the oceans would continue to warm for a number of decades until they finally reached a new equilibrium. Second, while global emissions of greenhouse gases can be slowed down, it will take time for transition from a fossil-fuel-based global economy to alternatives. Further emissions and incremental warming are therefore unavoidable. The fact that some additional climate change is unavoidable means that adapting to climate change is a necessity. Mitigative actions are likewise essential, to slow down and eventually stop the rise in global emissions. As long as the atmospheric concentration of greenhouse gases increases, there will continue to be a 'positive forcing' – a warming effect – on climate. To stabilize atmospheric concentrations of greenhouse gases will require a reduction of global greenhouse gas emissions.

F.5 Isn't it more important to tackle air pollution first, since the risks it poses to our health are more immediate?

Response: Air pollution issues such as smog and acid rain are indeed of immediate concern, while the more serious impacts of climate change are further in the future. However, there are multiple and complex linkages between climate change, smog and other local air pollution concerns that suggest that there are many benefits to addressing these issues at the same time. First, the key ingredients of smog also have important roles in the climate system. O_3, for example, is a greenhouse gas that contributes to global warming. Likewise, sooty aerosols absorb sunlight and add to local warming. In contrast, sulphate aerosols reflect sunlight and alter local cloud properties, both of which tend to cool the climate. Most importantly, all of these substances are directly or indirectly released through many of the same human activities that release long-lived greenhouse gases such as CO_2. Second, climate change can affect O_3 chemistry, since chemical reactions are influenced by both atmospheric temperatures and the amount of sunlight. Ecosystems and societies that are affected by smog may already be stressed due to climate change, and the combined effects may lower the critical thresholds for catastrophic loss. For example, an elderly person already stressed by high temperatures during a heat wave could suffer additional respiratory stress in association with high smog concentrations.

Explanation: The combustion of fossil fuels and other industrial sources of greenhouse gas emissions are also important sources of the precursors to tropospheric O_3 and the particulate matter that contribute to local air pollution, particularly smog. Furthermore, while O_3 is a particularly harmful component of smog, it is also a greenhouse gas that is estimated to be the third largest contributor to historical enhancement of the greenhouse effect. Sooty aerosols within smog absorb incoming solar radiation and thereby contribute to global warming. Reducing these aerosol emissions would both reduce urban smog and global warming. On the other hand, some of the other particulates within smog, particularly sulphate aerosols, reflect sunlight and alter cloud properties. These effects tend to cool climate. Measures to reduce their emissions to improve local air quality tend to increase warming.

Since sunlight and air temperatures are important factors in surface O_3 chemistry, rising temperatures and changes in cloud cover due to climate change will affect O_3 chemistry, and hence smog intensity. Furthermore, changes in wind direction and in precipitation frequency and intensity will affect O_3 transport and the efficiency of particulate removal by precipitation.

Finally, smog causes serious health impacts, including significant increases in mortality from cardiovascular and cardio-pulmonary diseases as well as cancer. It also damages vegetation. In general, the combined effects of multiple stresses from climate change and air pollution will increase the likelihood of exceeding critical thresholds for ecological stress tolerance, increasing the chance of related morbidity and mortality, particularly amongst the most vulnerable.

All of these linkages between climate change and air pollution speak to the need for a coordinated response to 'atmospheric change' which would take into consideration how actions to improve any one environmental problem would affect other issues. Where there are common sources of multiple pollutants, such as the combustion of fossil fuels, there are multiple benefits to reducing such activities.

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