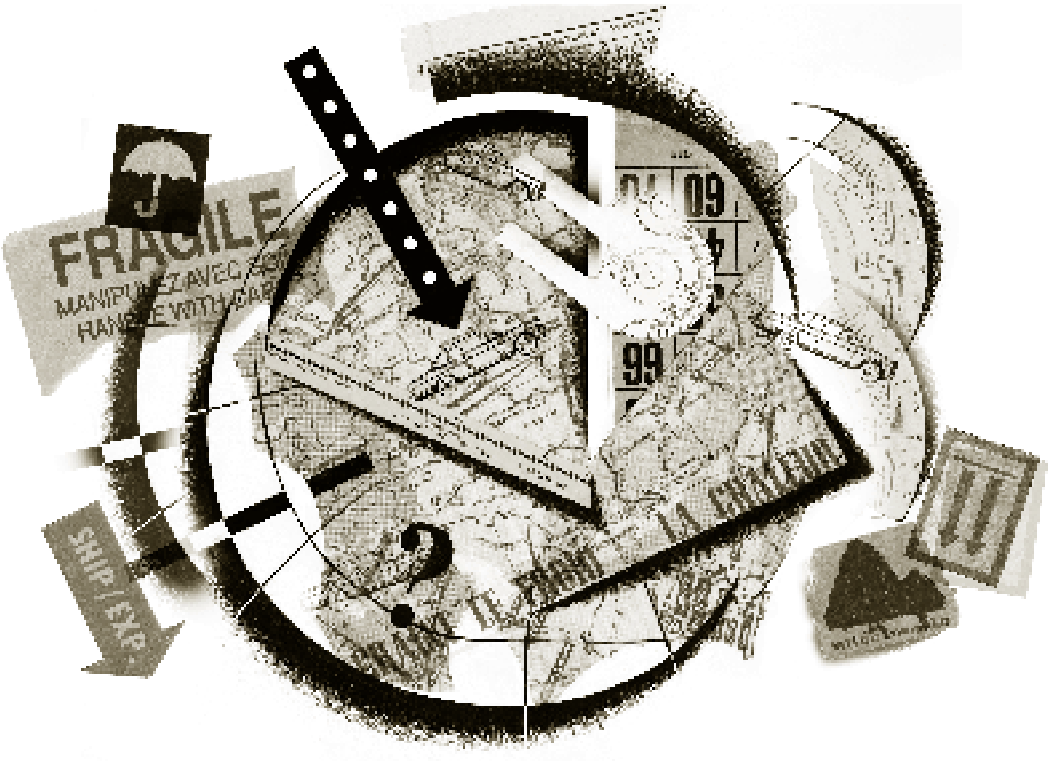
The Science of Climate Change

What Do We Know?



BY **GORDON MCBEAN, ANDREW WEAVER** AND **NIGEL ROULET**

ABSTRACT ▶ The greenhouse effect is a natural process that keeps the earth at a temperature which makes it a livable planet. The combined evidence of increased atmospheric concentrations of greenhouse gases, observed changes in the climate itself such as increased global mean temperature, and modeling experiments has led to credible scientific assessments of climate change. Through these assessments climate change has managed to become an issue in policy agendas. Although there are uncertainties surrounding projections of how human activities will affect the climate in the future, increasingly competent computer models have convinced the scientific community that there will be not only higher temperatures to deal with, but also more intense precipitation events and magnified warming in countries in high latitudes such as Canada. Nevertheless, uncertainties need to be reduced before the detailed refinement of response strategies can be done. For example, we need a clearer understanding of the spatial and temporal variations in climate change, especially of extreme events, before being able to refine response strategies.

RÉSUMÉ ▶ L’effet de serre est un processus naturel maintenant la Terre à une température qui la rend habitable. On a pu effectuer des évaluations scientifiques crédibles des changements climatiques en se fondant à la fois sur l’augmentation des concentrations de gaz à effet de serre dans l’atmosphère, sur les changements observés dans le climat lui-même — l’augmentation de la température moyenne de la planète, notamment — et sur des expériences réalisées sur des modèles. Ce qui a fait des changements climatiques un nouvel enjeu pour les politiques. Bien qu’il reste des incertitudes quant aux projections relatives à l’impact qu’auront à l’avenir les activités humaines sur le climat, les résultats obtenus grâce à des modèles sur ordinateur de plus en plus perfectionnés ont convaincu la communauté scientifique qu’en plus de l’élévation de la température, il faudra tenir compte de l’intensification des précipitations et d’un important réchauffement des contrées situées à des latitudes élevées comme le Canada. Néanmoins, avant de penser à raffiner les interventions stratégiques, il faut commencer par atténuer ces incertitudes. Nous devons, par exemple, parvenir à une meilleure compréhension des variations spatiales et temporelles des changements climatiques, particulièrement des phénomènes exceptionnels. (Traduction : **www.isuma.net**)

ILLUSTRATIONS : ALAIN RENO

Climate, ecosystems and humans have evolved together on this planet. From a hot inhospitable planet at the beginning, Earth has become what we know today—a planet inhabited by over six billion people, with a wide range of flora and fauna. Over the history of human habitation, climate has played a major role in determining the development of societies and cultures. We need only to think back to the earliest people of Canada and their probable migration here during the last Ice Age, which provided a land bridge from Asia. And to the first Viking settlers of Greenland, who arrived about 1100 years ago during a relatively mild climatic period over the North Atlantic, and who later perished during harsher climatic times. More recently, we have felt the impact of climate during the dust bowl of the 1930s.

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It is interesting to compare Earth with our neighboring planets, Venus and Mars. In the absence of other factors, the surface temperatures of these planets would reflect their distance from the sun, but measurements show that the average surface temperatures are very different. The average temperature of Venus is about 525°C, of Earth, about 15°C and of Mars, about —50°C. All are hotter than expected but the difference is, by far, the largest for Venus. From one point of view this is surprising since Venus' atmosphere is more than 90 percent carbon dioxide and so thick that the sun can hardly be seen from the surface. The so-called greenhouse effect is the explanation for these warmer temperatures. When the sun's radiation is absorbed by the surface of these planets, the surface re-emits heat radiation which travels up into the atmosphere and is absorbed by molecules of greenhouse gases (water vapour, carbon dioxide (CO_2), methane (CH_4), etc.). These gases in turn re-emit energy both up and down, warming the lower layers of the atmosphere and the surface, in effect acting as a blanket. From outer space, the planet "looks" cooler, corresponding to the temperature of the upper layers of gases that are radiating to space because the greenhouse effect traps heat radiation, thus raising surface temperatures. The greenhouse effect is widely accepted as the reason why the surfaces of planets are warmer than they would be otherwise. The effect for Earth is to move the average temperature from below freezing to nicely above (a 33°C increase), making the planet livable. The Earth's natural greenhouse effect (as existed prior to human interference) is dominated by water vapour (about 65% of effect) and carbon dioxide (25%). Global concerns about future climate change have to do with how increases in atmospheric concentrations of greenhouse gases, as a result of human activities, will enhance the natural greenhouse effect and increase the Earth's temperature.

History of the science of global warming

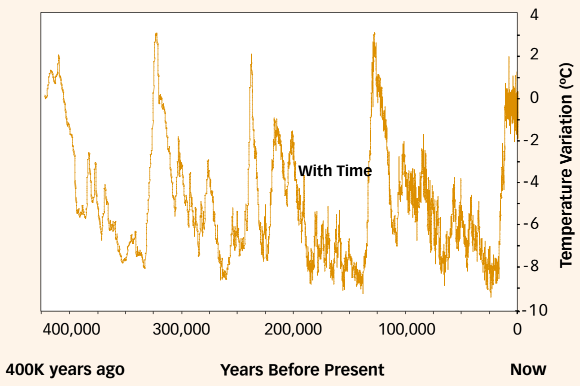
A common misconception is that the link between increasing levels of atmospheric CO_2 and global warming has only recently been realized. While Dr. James Hansen of NASA's Goddard Institute for Space Studies is often credited in the media as being the "father of climate change theory,"[1] this now famous testimony to the U.S. Senate occurred nearly 100 years after the link was drawn between CO_2 and the Earth's temperature.[2] In 1824, Jean-Baptiste-Joseph Fourier, a well-known French mathematician, wrote a paper entitled *General remarks on the temperature of the terrestrial globe and planetary spaces*.[3] In this work Fourier hypothesized that the atmosphere blocks outgoing radiation from the Earth and re-radiates a portion of it back, thereby warming the planet, i.e., the greenhouse effect. The Swedish Nobel Laureate, Svante Arrhenius, drew upon this and other earlier work to develop in 1896 the first theoretical model of how atmospheric CO_2 affects the Earth's temperature.[4]

In a seminal paper in 1957, Roger Revelle and Hans Suess of the Scripps Institute of Oceanography argued that the oceans could not absorb the human emissions of CO_2 as fast as they were being produced. They noted that this would leave the human-released CO_2 in the atmosphere for centuries and stated: "Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future." They further stated that "we are returning to the atmosphere and oceans the concentrated organic carbon stored in the sedimentary rocks over hundreds of millions of years."[5]

The first sophisticated atmospheric modeling studies aimed at investigating the climatic consequences of increasing atmospheric CO_2 were conducted at the U.S. NOAA Geophysical Fluid Dynamics Laboratory. Imbedded within the abstract of a paper written by the renowned Suki Manabe and colleague Richard Weatherald was the conclusion: "According to our estimate, a doubling of the CO_2 content in the atmosphere has the effect of raising the temperature of the atmosphere (whose relative humidity is fixed) by about 2°C."[6] As noted below, this early work yielded a projection consistent with recent studies.

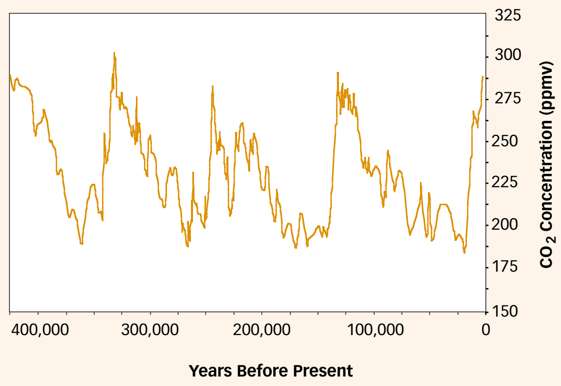
By the early 1980s, the issue of climate change began to move from the scientific to policy agendas. Several scientific assessments of the relationship between CO_2 and climate began to appear (e.g., U.S. National Academy of Sciences, National Research Council, *CO_2 and Climate: A Scientific Assessment* and *Changing Climate*, published in 1979 and 1983, respectively). On the international scene, it is apparent that a series of conferences and reports organized by the

FIGURE 1a
Variation with Time of the Vostok Isotope Temperature Record



Source: J.R. Petit et al., "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica," *Nature*, Vol. 399 (1999), pp. 429-436.

FIGURE 1b
CO_2 Concentration in the Vostok Ice Core



Source: J.R. Petit et al., "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica," *Nature*, Vol. 399 (1999), pp. 429-436.

United Nations Environment Programme (UNEP), the International Council of Scientific Unions (ICSU) and the World Meteorological Organization (WMO), were especially influential. The Second Joint UNEP/ICSU/WMO International Assessment of the Role of Carbon Dioxide and other Greenhouse Gases in Climate Variations and Associated Impact, which took place in October 1985 in Villach, Austria was particularly important in this regard.[7]

Looking at the past

As scientists analyzed the climate records of the past 400,000 years, as revealed from ice cores, they see many interesting things (Figure 1). The global mean temperatures and the concentrations of carbon dioxide have gone up and down together with a mix or superposition of very long-term (10s to 100s of thousands of years) through to very short-term (years to decades) variations. The long-term variations in climate are driven primarily by variations in Earth's orbit around the sun and the inclination of its North Pole, but analysis indicates that feedbacks through the greenhouse effect also play a significant role. During periods of glaciation (the Ice Ages), the global mean temperature was about 5°C colder than present (important to keep in mind this number when thinking about global mean temperature changes projected over the next 100 years) and there were periods during previous interglacials where the mean temperature was about one degree warmer. During this period of record, there seems to be upper and lower bounds on carbon dioxide concentrations: varying between 180 and 310 ppm (parts per million of carbon dioxide in the air). Analysis shows that the warm climates can't be maintained unless there are greenhouse gases to block outgoing radiation, and the cold climates can't be maintained unless there is a depletion of greenhouse gases.

Human activities are now, without question, changing the concentrations of greenhouse gases in the atmosphere. For about 10,000 years, prior to the 1800s (the pre-industrial period), global carbon dioxide concentrations were about 280 parts per million (ppm) with a variation of less than 10 percent; since then the concentration has risen 31 percent, to 368 ppm now (Figure 2), a value unprecedented in the last 400,000 years. This increase has been in direct relation to the increasing use of fossil fuels and to land changes by humans. Measurements of the changing isotopic ratios of atmospheric carbon dioxide are consistent with the injection of "old" carbon (from fossil fuel) that has different isotopic ratios. Over the same period, the atmospheric methane concentrations have more than doubled (more than a 100% increase).

Observational evidence of climate change

Several researchers around the world have independently put together global data sets of surface air temperatures from the instrumental record, using only non-urban locations or corrected urban data. Over the 20th century, the globally averaged surface air temperature has increased by about 0.6±0.2 °C. Most of this warming has occurred during two periods: 1910-1945 and 1976-2000. Very recently, proxy data from, for example, boreholes, corals, tree rings have allowed for reconstructions of northern hemisphere temperature back to 1000 AD. Reconstructed and instrumental records agree remarkably over their common period. In the last 1,000 years the 20th century is the warmest century, the 1990s the warmest decade and the top 10 warmest years in descending order are: 1998, 1997, 1995, 1990, 2000, 1999, 1991, 1994, 1988, 1983, 1987. A recent U.S. National Academy of Sciences Report has reaffirmed the validity of the global surface temperature record,[8] and new published scientific studies are now showing warming trends in satellite and surface-based data sets of about 0.13°C per decade.

A common misconception is that global warming implies warming everywhere by about the same amount. This is not

The ice core record reveals that the current concentrations of CO_2 and CH_4 are much higher than what has been experienced on Earth for the last 400,000 years.

the case and there are, in fact, regions where the Earth has cooled over the 20th century. Regional warming is either amplified or reduced through local feedbacks. In general, the warming is much larger over land compared to oceans as the oceans have a higher heat capacity and can store heat to great depths. Warming is also generally larger at high latitudes than at low latitudes, due to the existence of a powerful positive feedback involving the albedo (reflectivity) of snow and ice. As snow and ice cover retreat, as has been observed over the 20th century, especially since 1979, the land surface darkens and so does not reflect as much solar radiation back to space. In the case of sea ice, the observed reduction in areal extent also exposes more of the ocean to the atmosphere, thereby allowing the warming of the atmosphere through heat loss from the ocean. The warming is also amplified in the winter, and to a lesser extent spring, over land since the snow albedo effect is largest at this time of year. In addition, the warming trend over land since 1950, on average, has been about twice as fast at night compared to the day.

It is not possible to provide an exhaustive discussion of all the observed changes in the climate since the start of the 20th century so we refer the reader to the recent reports of the Intergovernmental Panel on Climate Change. It is important to note that the observed changes in the climate system are internally consistent with each other, as well as with physical intuition, without needing to appeal to complicated climate models.

Climate change detection and attribution

Since the climate system varies both through *natural*, internal processes as well as in response to variations in *external* forcing (e.g., solar changes, volcanic emissions, greenhouse gases), the detection of climate change involves looking, in a statistically significant sense, for the emergence of a signal above the background noise of natural climate variability. Attribution involves specifically assigning a cause for the detected signal to human activities, variations in other external forcing, or a combination of both.

There has been major debate on whether there is evidence for human-caused change in climate over the past century; i.e., is there a "smoking gun"? In its Second Assessment Report (SAR) in 1995, the IPCC concluded that: "the balance of evidence suggests a discernible human influence on global climate."[9]

This cautious statement represented the consensus view of those scientists involved at the time. It was based on the results of only a few detection and attribution studies available then. Since 1996, there have been many more published works firming up the science behind this statement. As a result, much stronger statements were included in the IPCC Third Assessment Report (2001), which concluded "unequivocally" that the Earth's climate is changing and that: "There is now new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[10]

Late last year, Peter Stott and his colleagues from the Hadley Centre in the United Kingdom published a paper[11] in which they reported on the most comprehensive model simulations to date of the climate of the 20th century. They found that natural forcing agents (solar forcing and volcanic emissions) produced a gradual warming to about 1960 followed by a return to late 19th-century temperatures, consistent with the gradual change in solar forcing throughout the 20th century and a resumption of volcanic activity during the past few decades. This could not, however, account for the warming in recent decades. Similarly, anthropogenic forcing alone (greenhouse gases and sulphate aerosols) was insufficient to explain the 1910-1945 warming, but was necessary to simulate the warming since 1976. In addition, the use of anthropogenic forcing alone did not capture the slight cooling that occurred between the two periods of rapid warming. Only the combined forcing was able to reproduce much of the observed decadal scale variation in global mean temperature and was also able to capture with some fidelity the large-scale spatial structure of the observed changes. Stott et al. showed that when combined, these signals explained approximately 80 percent of the observed interdecadal variance of global mean temperature.

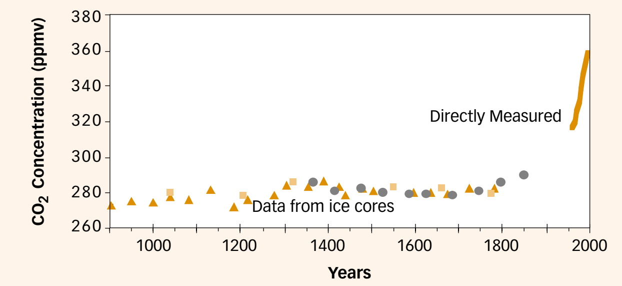
The cycles of the greenhouse gases

The evidence, based on direct measurements, is irrefutable that the concentrations of the greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased substantially over the last 40 years, and continue to increase today (see Table 1). The ice core record reveals that the current concentrations of CO_2 and CH_4 are much higher than what has been experienced on Earth for the last 400,000 years. The relations between the biogeochemical cycles that control greenhouse gas and other climatically important atmospheric concentrations and the climate are complex and interdependent.

The concentrations of the greenhouse gases in the atmosphere are controlled by the exchanges of chemical

FIGURE 2

Trends in CO_2 Concentrations (Past 1000 years)



Note: Atmospheric concentrations of carbon dioxide over past 1000 years, estimated from ice cores and directly measured.

Extreme weather or climate events are important from a policy perspective as they cause the most stress on adaptation strategies for climate change.

compounds among the terrestrial system, the ocean and the atmosphere. Carbon dioxide (CO_2) and methane (CH_4) are both part of the global carbon cycle, but since they are produced in quite different environments, they are usually treated separately. To examine the controls on the atmospheric concentration of CO_2 it is important to frame the questions within the context of a specific time interval. Over millions of years its concentration is largely controlled by the geologic cycling of carbon in the silicate carbonate cycle. To explain changes in concentration over shorter time intervals such as glacial cycles, the biology of land ecosystems and dynamics and chemistry of the oceans become the dominant controls. On the time interval of the last few hundreds years, there is strong evidence that human activities are the principal cause of the changes in concentration of CO_2 and CH_4.

From both a scientific perspective and that of controlling atmospheric concentrations, it is important to know how long a typical molecule or particle of a gases or aerosol will remain in the atmosphere—this is usually called the "atmospheric residence" or "life time." The residence times of individual greenhouse gases and aerosols vary considerably due to natural removal mechanisms (see Table 1 for the greenhouse gases). Tropospheric (in the lower 10 km of the atmosphere) aerosols, for example, stay in the atmosphere only a few days as they are effectively washed out by precipitation. Stratospheric (above 10 km) aerosols, such as those released during volcanic eruptions, can stay in the atmosphere for up to a few years since they must first descend, through gravity, into the troposphere before they can be washed out.

On the time scale of contemporary climate change there are three reservoirs that are important in the global carbon cycle: the atmosphere, the terrestrial biosphere that comprises soils and vegetation, and the surface ocean water where the CO_2 is mostly dissolved and in equilibrium with the atmosphere. These reservoirs are roughly equal in size, between 750 and 2100 GtC [12] (Figure 3). The annual exchange between the atmosphere and the land and ocean surface is relatively large: approximately 60 and 90 GtC yr^{-1}, respectively. This means the reservoirs can turn over a mass equivalent to what they store within five years in the case of the atmosphere and approximately 20 years for the surface ocean and land. The current increase in atmospheric CO_2 concentration results from two major changes in this relatively rapid cycling of carbon. The largest change comes from the combustion of fossil fuels. From the perspective of the contemporary carbon cycle this amounts to the insertion of "old" carbon into the atmosphere from geologic carbon reservoirs which have a turnover time of hundreds on millions of years. Since there is no geologic process to remove this carbon on the time scale of its release, the approximately 6.3 GtC yr^{-1} of combusted geologic carbon is added to the quickly changing (or fast) components of the carbon cycle. Measurements of the atmospheric concentration show that only 3.2 GtC yr^{-1} remains in the atmosphere and the rest must be taken up by the ocean or terrestrial systems. As a result, the concentration of CO_2 is increasing in the atmosphere, the ocean and the terrestrial biosphere.

A small amount of the carbon added to the surface reservoirs (ocean surface, plants, surface soils) leaks out of the system and goes into longer-term storage. For example, as carbon dioxide accumulates in the upper ocean through gas transfer between the atmosphere and the ocean, biological processes, the "biological pump," become more effective and move carbon down into the ocean. This removal, in turn,

FIGURE 3

The Global Carbon Cycle (1990s)

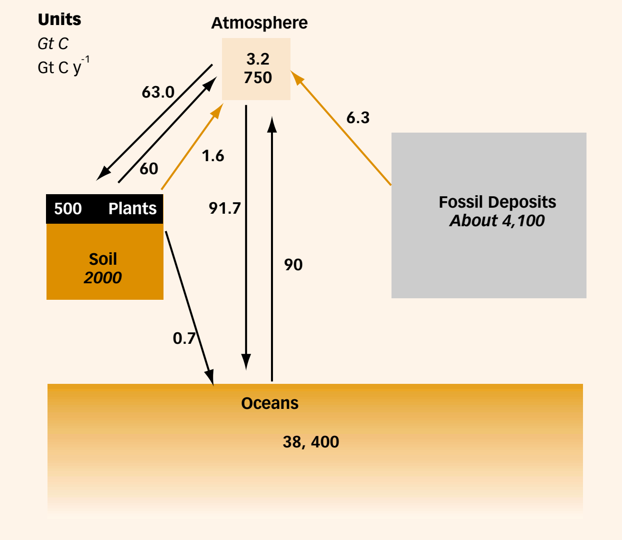


TABLE 1

Examples of greenhouse gases that are affected by human activities (from IPCC 2001)

	CO_2 Carbon dioxide	CH_4 Methane	N_4O Nitrous oxide	CFC-11 Chlorofluorocarbon	HFC-23 Hydrofluorocarbon	CF4 Tetrafluoromethane
Pre-industrial concentration	280 ppm	700 ppb	270 ppb	0	0	0
Concentration in 1998	365 ppm	1745 ppb	314 ppb	286 ppt	14 ppt	80 ppt
Rate of change	1.5 ppm/y	7.0 ppb/y	0.8 ppb/y	-1.4 ppt/y	0.55 ppt/y	1 ppt/y
Atmospheric lifetime	5-200 y	12 y	114 y	45 y	260 y	>50,000 y

The next generation of climate models will have to be effectively coupled to the biogeochemical cycles that largely control the concentration of the greenhouse gases.

involves the deeper ocean as an intermediate step and leads to the eventual accumulation of carbon in the sedimentary deposits at the ocean floor. Although the transfer across the ocean surface can take place relatively quickly, this process alone would soon saturate that region and the oceanic uptake from the atmosphere would stop. The biological pump and other processes move more slowly and hence the effective time scale for carbon uptake from the atmosphere into the oceans is decades to a few centuries (Table 1), depending on the state and rates of change of the systems.

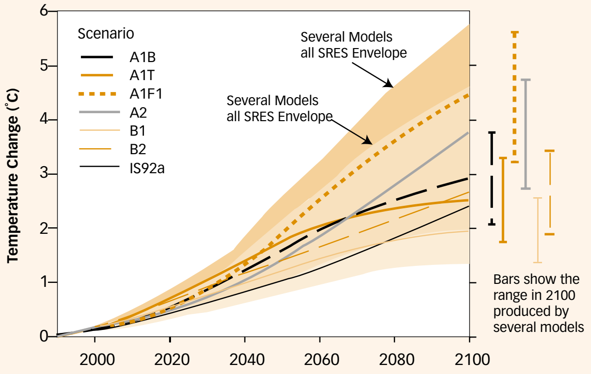
The difficulty in assessing the role of the terrestrial biosphere in the carbon cycle is that the land conversion of forest ecosystems to agricultural ecosystems, mainly in the tropics, results in a net release of CO_2, while the re-growth of forests on abandoned agricultural land, mainly in the temperate regions, results in a net uptake of CO_2. There is a large uncertainty in the estimate of the net effect of the land use changes but the current consensus is they result in a net release 1 and 2 GtC yr^{-1} to the atmosphere. There is indirect evidence from many different sources that the huge forests of the temperate and boreal zones are currently acting as a sink for CO_2, absorbing more CO_2 than is released through land use change. The explanation for this sink is not clear but it could result from a combination of a response to climate change and/or natural variability, to the higher concentration of CO_2 which can enhance plant growth, and the inadvertent supply of nitrogen, a nutrient that usually limits forest growth, through atmospheric deposition from the long-range transport of pollutants.

While CO_2 gets most of the attention, two others gases, methane (CH_4) and nitrous oxide (N_2O), account for at least 20 percent of the estimated warming since 1850. Humans are the dominant factor in the global methane cycle accounting for over 60 percent of the annual emission to the atmosphere of 540 Tg CH_4 yr^{-1}.[13] Wetlands are the only significant natural source of CH_4 (120–150 Tg), while the main sources from human activity are the production of rice in agricultural wetlands, livestock, landfills, exploration and transmission on natural gas, and coal mining. Unlike CO_2, CH_4 is a chemically reactive gas and is removed from the atmosphere relatively rapidly through chemical oxidation with the result being the production of ozone (O_3) in the lower part of the atmosphere. O_3 is also a powerful greenhouse gas so there is a secondary effect from CH_4 emissions. Since CH_4 is removed relatively rapidly compared to CO_2 or N_2O any attempt to reduce its emission would result in some positive benefit in a short period of time. There is evidence, though the record is still too short to place a greater deal of confidence in the trend, that the atmospheric concentrations of CH_4 are beginning to stabilize, albeit at 2.5 times the concentration prior to 1800.

The global accounting of N_2O is the most uncertain of the three main greenhouse gases. N_2O is a by-product of the nitrogen cycle. Nitrogen in the form of N_2 accounts for 78 percent of the composition of the atmosphere. A very small portion of that inert gas is fixed (changed) into forms that are biologically available. In the natural system this fixation occurs through bacteria and legumes, but human activity now results in an equal amount of fixation, primarily as a by-product of combustion and the production of nitrogen fertilizer. Because nitrogen is so important in biological processes and is naturally in such short supply, the nitrogen cycle is relatively tight with most being returned to the atmosphere as N_2, but a small amount of N_2O leaks out along the pathways of the nitrogen cycle and is emitted to the atmosphere. With larger amounts of nitrogen being cycled, the leakage of N_2O has increased. There are some industrial processes that also involve the production and release of N_2O. N_2O is naturally broken down in the atmosphere primarily by sunlight (photodissociation) and has a typical atmospheric lifetime of 114 years.

Much of the research over the last two decades on the biogeochemical cycles has focused on delineating the sinks and the sources of the greenhouse gases, but there has also been a tremendous increase in the understanding of the processes that control the rate and magnitude of their exchange. There are strong feedbacks, some positive and some negative, among climate, CO_2 and biogeochemical cycling. The concentration of CO_2 controls, in part, the photosynthetic rate of land plants, the chemical diffusion of CO_2 across the air-ocean interface and the chemical reactions in the surface of the ocean. Climate affects the rate of photosynthesis and respiration of land plants and the rate of soil carbon decomposition, mainly through temperature and moisture. Temperature also affects the amount of CO_2 that can be dissolved in water and the mixing of ocean waters that is critical in determining the surface concentrations. The interrelationships between climate and biogeochemical cycling mean that understanding and modelling the direct sources of greenhouse gases is only part of the challenge; we also need to build models that contain these feedbacks. The importance of incorporating these feedbacks has recently been demonstrated in the results of the U.K. Hadley Centre model simulations where a simplified carbon cycle was coupled to a climate model. In a transient simulation their results indicate that the concentration of CO_2 was approximately 250 ppm higher (for the same emissions scenario) and the temperature approximately 1°C warmer by 2100 than when climate and the carbon cycle were not coupled. These results provide food for thought, since the primary cause for the extra increase in CO_2 was the conversion of the terrestrial biosphere from a small sink in the first half of the 21st century to a large source in the second half primarily through the release of carbon initially stored in the soils. However, this is the result of only one carbon model coupled to one general climate model. The challenge that this experiment has presented is that the next generation of climate models will have to be effectively coupled to the biogeochemical cycles that largely control the concentration of the greenhouse gases.

FIGURE 4
Temperature Change



Notes: Model projected global annual mean temperature change relative to 1990 under a wide range of scenarios. The dark shading gives the range using all 35 scenarios and the average model climate sensitivity. The light shading extends this range by calculating the spread from each model independently. Note that in all cases, warming is projected even though in B1, emissions of CO_2 and CH_4 are assumed to drop substantially below 1990 levels (Figure 7). (IPCC, 2001)

Projections of climate change

Global climate models (GCM) have evolved considerably over the years and are continually being further improved, both in terms of resolution and through the inclusion of new, sophisticated, physical parameterizations. They consist of an atmospheric component, developed through decades of research in numerical weather prediction, coupled to ocean and sea ice models. All GCM include a land surface scheme and some now allow the terrestrial vegetation to respond to a changing climate. Climate models are not used to predict weather, but rather the slow mean change of average weather and its statistics. They are built on the physical principles that we believe govern the various components of the climate system. Before a climate model is deemed useful for future climate projections, it must be satisfactorily tested against the present-day and transient 20th century climate. GCM simulations of past climates (e.g., 6,000 and 21,000 years ago) are also used to evaluate a model's performance against available reconstructions. Deficiencies in a model found through this evaluation process are documented, and attempts are then made to reduce or eliminate them.

Scenarios of future emissions

Any projection of future climate change fundamentally requires assumptions to be made as to what future emissions of greenhouse gases and aerosols will be. These in turn are determined by making assumptions on future economic and population growth, technological change, energy use, etc. Clearly it is difficult if not impossible to make accurate projections of these socio-economic factors out over 100 years. As such, the IPCC put forth a number of scenarios of future emissions under a wide range of possible story lines of socio-economic and technological change in the future. For the IPCC SAR, six such scenarios were developed (IS92a-f). For the recent IPCC TAR, 35 scenarios were prepared.

Several of the possible scenarios lead to projected reductions of greenhouse gases emissions over the 21st century but due to the long atmospheric lifetime of CO_2, the atmospheric concentration is still increasing at 2100. Several other scenarios lead to continued growth in emissions while others suggest that emissions continue to increase in the short term but eventually start to come down. None of the individual scenarios can be termed "correct" since each is as equally plausible or implausible as the other. To produce a range of possible climate outcomes, it is therefore advisable to integrate coupled models under as many of the scenarios as possible. It has, however, not yet been possible for comprehensive GCM to run century long integrations using all scenarios, solely due to the lack of available computing time. Nevertheless, several groups around the world have run their GCM for a number of these scenarios. The climate sensitivity, defined to be the equilibrium global mean warming corresponding to a doubling of atmospheric CO_2, obtained from the comprehensive models can be used in simpler models with the full range of scenarios to get estimates of global surface air temperature changes and sea level rise over the next century.

It is important to note that, as the atmospheric concentration of CO_2 does not respond quickly to changes in CO_2 emissions, the climate itself also does not respond instantly to changes in greenhouse gas concentrations. Generally, the oceans respond slowly, on times scales of decades to centuries and slow any climate response. Unlike the case for changes from glacial to interglacial periods which occurred on the timescales of millennia, thereby allowing the Earth system time to equilibrate with changes in the greenhouse gas concentrations and radiative energy, the current rate of change is very rapid. As such, there is inevitable warming in store as the Earth system attempts to equilibrate with the higher levels of greenhouse gases. In terms of global warming, therefore, the real policy question that needs to be addressed is what do we as a society consider to be an acceptable level of future warming.

Projections of future temperature change

Using the range of climate sensitivities from coupled GCM, simple climate models and all emissions scenarios, one arrives at a range of projected 2100 warming, relative to 1990, of 1.4-5.8°C (Figure 4). This range, reported in the IPCC TAR, is higher than the 1.0-3.5°C range reported in the SAR simply because a wider range of scenarios (35 rather than 6) were used to capture a more diverse range of possible socio-economic assumptions leading to a more diverse range of future emissions. Also, generally, the newer scenarios yield lower sulphur dioxide emissions (and, hence, less cooling from the resulting direct and indirect effects of the aerosols). It is important to note that the IPCC estimates of climate sensitivity, based on GCM, have not changed significantly. Global warming was not suddenly expected to double (a confusion which arose because the upper bound was raised from 3.5 to 5.8°C); climate models have not become more uncertain (a confusion which arose because the spread between maximum and minimum projected warming had increased from 2.5 to 4.4°C). Very simply, for a more diverse range of emission scenarios, the climate models projected a more diverse range of possible future climates.

While it is not meaningful to pick a particular place on the Earth's surface and say unequivocally that it will warm by a certain amount over the next century, a number of key conclusions can be drawn. First, land areas warm more than do ocean areas due to the greater heat capacity of the ocean. Second, the interior of the continents warm more than the coasts as they are further away from the ocean. Third, the west coast at northern mid-latitudes tends to warm less than the east coast as the former is more influenced by the ocean since the prevailing winds are from west to east. Fourth, the high latitudes warm more than the lower latitudes due to powerful albedo feedbacks associated with retreating snow and sea ice. As noted earlier, an additional positive feedback arising from retreating sea ice is that the ocean is no longer insulated from the atmosphere and so can warm it from below. Fifth, the northern hemisphere warms more than the southern hemisphere as there is more land there. Enhanced warming is also projected in the winter months relative to the summer.

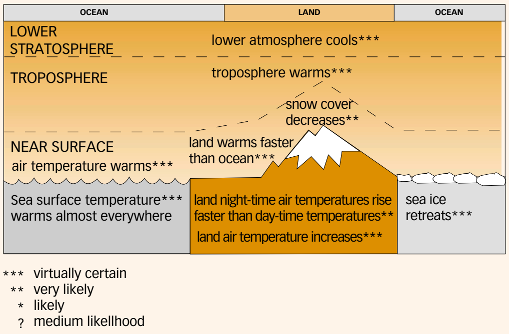
Figure 5 summarizes the projected changes for the end of the 21st century with an assigned level of confidence (virtually certain: >99% probability; very likely: 90-99% probability; likely: 66-90% probability; medium likelihood: 33-66% probability). Certain phenomena are not shown in Figure 5 as they are either not resolved, or there is a disagreement between models as to what might occur. Tornadoes, thunder days, hail, lake and river ice melt, for example, are not resolved in coarse resolution climate models so no assessment can be made as to their future changes.

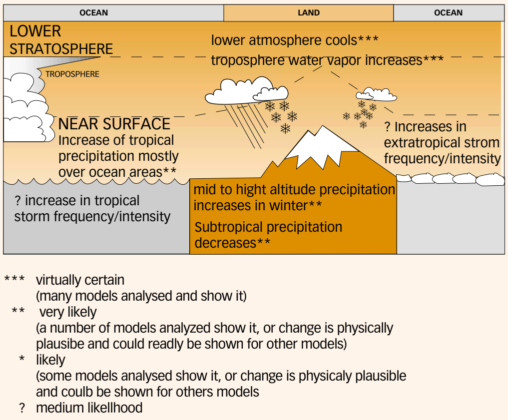
Extreme events and the possibility of surprises

Extreme weather or climate events are important from a policy perspective as they cause the most stress on adaptation strategies for climate change. Adaptation strategies aimed exclusively at dealing with a slow mean change in climate could be ineffective if they do not also account for projected changes in climate and weather statistics associated with the projected mean climate change. The IPCC (IPCC 2001) undertook a systematic analysis of observed changes in extreme weather and climate events over the 20th century and their projected change over the 21st century (summarized in Table 2, reproduced from IPCC, 2001).

Rapid transitions between fundamentally different climate regimes have commonly occurred over the last 400,000 years,[14] inspiring scientists to try and grapple with their possible likelihood of future occurrence. Two specific climate change surprises have been given special attention.

FIGURE 5


a) Temperature Indicators


b) Hydrological and Strom-Related indicators

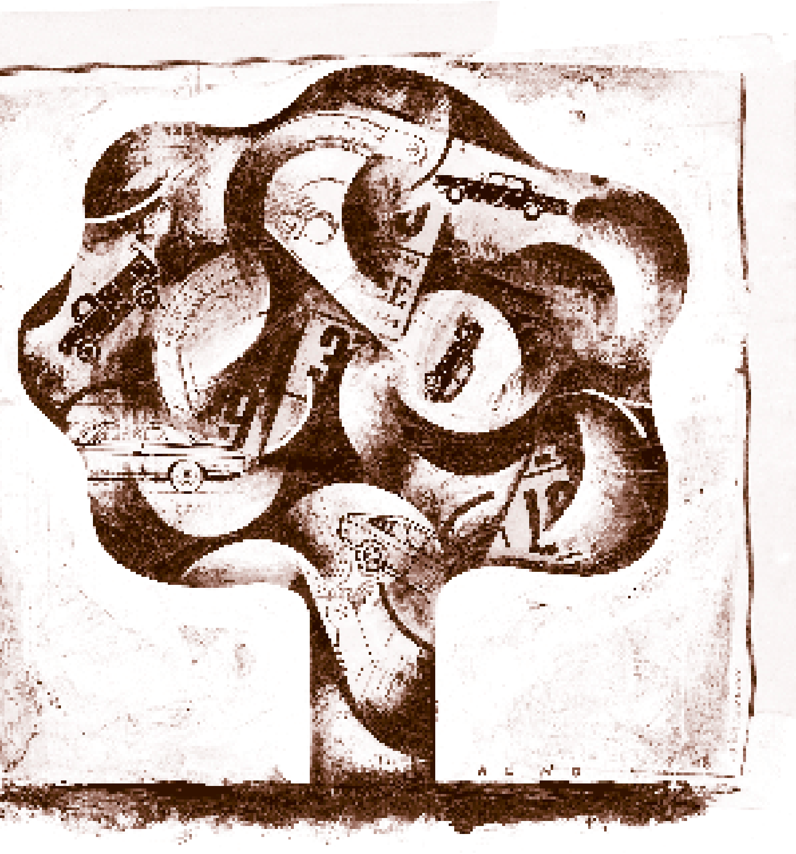


TABLE 2
Estimates of confidence in observed and projected changes in extreme weather and climate events

Changes in weather and climate	Confidence in observed changes (latter half of the 20th century)	Confidence in projected changes (during the 21st century)
Higher maximum temperatures and more hot days over nearly all land areas	Likely	Very likely
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely	Very likely
Reduced diurnal temperature range over most land areas	Very likely	Very likely
Increase of heat index (a measure of human discomfort) over land areas	Likely, over many areas	Very likely
More intense precipitation events	Likely, over many northern hemisphere mid- to high latitude land areas	Very likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, in a few areas	Likely, over most mid-latitude continental interiors (lack of consistent projections in other areas)
Increase in tropical cyclone peak wind intensities	Not observed in the few analyses available	Likely, over some areas
Increase in tropical cyclone mean and peak precipitation intensities	Insufficient data for assessment	Likely, over some areas

Note: Very likely (90–99% chance); likely (90% chance). Adapted from IPCC (2001), see endnote 10.

The first involves trying to determine the probability of a collapse of the West Antarctic ice sheet—an event that would lead to a 6m global sea level rise over a relatively short period of time. The second involves assessing the likelihood of a complete shutdown of the North Atlantic oceanic heat transfer system (involving warm water moving poleward at the surface, sinking at high latitudes and returning southward, as cold water, at depth, like a conveyor). If this were to transpire, the global oceanic deep circulation would be reorganized and the amount of heat transported northward in the North Atlantic by the ocean would be substantially reduced; this would affect the climate over land downwind of the ocean (i.e., Europe). In its Third Assessment Report, the IPCC (IPCC 2001) concluded that the former was very unlikely (1-10% chance) to occur over the 21st century but noted that it was too early to determine whether an irreversible change in the conveyor is likely or not over this same period.

Future directions for projections of future climate with models

In the IPCC Third Assessment Report, none of the international groups contributing projections of future climate had incorporated interactive terrestrial and oceanic carbon cycle models into their coupled models. A major thrust of international coupled modelling efforts over the next few years will be the development of a terrestrial and oceanic carbon cycle modelling capability for use in climate change projections on which policy will be based.

In the IPCC fourth assessment, likely to occur in five years, the leading climate models will include interactive terrestrial and ocean carbon cycles in which anthropogenic greenhouse gas and aerosol emissions, rather than concentration scenarios, will be specified. In addition, it is likely that these same models will allow both vegetation type and function to vary with the changing climate, thereby allowing important biological feedbacks within the climate system. We also believe that the state-of-the-art climate models will incorporate interactive atmospheric sulphur and ozone (tropospheric and stratospheric) cycles, which will allow for a more complete treatment of natural and anthropodenic radiative forcing of the climate system.

In the IPCC fifth assessment, probably in about 10 years, we envision that, rather than specifying future emissions of atmospheric aerosols and greenhouse gases, the state-of-the-art models will calculate these emissions internally through the interaction of coupled climate/socio-economic models. That is, emissions will be calculated internally under specified policy, technological, population growth and other socio-economic options.

Summary

To conclude, we know a lot about the climate system and feel comfortable about the general sense of projections of climate change, based on emission scenarios, over the next 100 years. The science is good enough to form a basis for political and social action. There still are, however, uncertainties that need to be reduced before the detailed refinement of response strategies can be done. Since a certain amount of climate change is inevitable, a major part of any response strategy will be adaptation and there is then need for a higher confidence on the spatial and temporal variations in climate change and, in particular, of extreme events.

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Endnotes

1. See, for example, P. Foster, “Global Warming: The Clouds Thicken,” *The National Post*, August 19, 2000; P. Holle, “Global Warming Fears Cool Off. Why Impose Questionable Constraints on Economic Growth,” The *Winnipeg Free Press*, January 27, 2001.
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12. Gt indicate a gigatonne, which is 1,000,000,000 or 109 tonnes. One tonne contains 1,000,000 grams, so a Gt = 10^{15} g, which is referred to as a Pg.
13. Tg is 10^{12} g.

14 P.U. Clark, A.J. Weaver and N.G. Pisias, “2001: Abrupt Climate Change,” *Nature*, submitted.