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POLICY IN AN UNCERTAIN CLIMATE: THE SCIENCE OF CLIMATE CHANGE

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INTRODUCTION

The politics surrounding environmental issues are often very partisan, painting the issues in black and white terms. They frequently pit the interests of one sector of society against another. In such politically charged circumstances, scientific studies are often used as ammunition in a war for public opinion. The issue of climate change is a good example of the manipulation of science for political gains. It is also a perfect example of a situation in which science cannot provide all the answers.

The science of climate change is essentially observational. There is only one Earth, and so it is impossible to do controlled experiments by manipulating one and not the other in the normal manner of testing a hypothesis. In trying to understand the Earth's climate, scientists therefore have to form a hypothesis and observe whether or not reproductions of past climates – short- or long-term – are consistent with it. Often this involves using computer-generated models that try to mimic the current understanding of climate processes. These models are then used to try and predict future climate change. Given that our reconstructions of past climates, computer models and estimates of the future composition of the atmosphere are all less than perfect, the politics of climate change are bound to continue to operate in a sea of uncertainty where individual studies will be used to support or tear down a point of view. Confusing the issue further is the fact that the science of climate change is very complicated.

That being said, a number of observations made by science regarding climate and the greenhouse effect suggest that an enhanced greenhouse effect is a real possibility that humans should be worried about. This paper discusses some of the science used to understand climate change as well as some of the major conclusions that have been drawn.

BACKGROUND

A. Factors Affecting Climate

1. Orbital Changes: Milankovitch Theory

Both the orbit of the Earth around the sun and the angle of the axis on which the Earth spins change over very long periods of time. The angle of the Earth's axis changes between 22º and 25º on a 41,000-year cycle, with the smaller angle producing cooler summers and milder winters. The timing of the closest approach to the sun in the Earth's elliptical orbit changes on a 22,000-year cycle. When the closest approach is in July, seasons are more severe. The shape of the elliptical orbit changes on cycles of 100,000 and 400,000 years which influences the importance of changes in orbital timing. The interaction of these orbital changes, known as Milankovitch cycles, is thought to be the driving force behind periods of glaciation. When the angle of the axis is low, the closest approach to the sun is in January and the ellipse is less round; in this configuration, summers in the northern hemisphere are cooler and allow for the accumulation of snow. According to Milankovitch theory, the average amount of sunlight hitting the Northern hemisphere (particularly north of 65º) is projected to increase gradually for the next 25,000 years and no combination of orbital changes leading to glaciation is expected for the next 100,000 years. Although orbital eccentricity seems to be primarily responsible for glaciation, the resulting changes in energy inputs are weak and require amplification in order to cause the temperature to drop sufficiently. Both the feedbacks associated with ice sheet reflectance and atmospheric CO_2 have been suggested as amplification mechanisms.

2. The Greenhouse Effect

The sun's energy is absorbed by the earth's surface and transformed into heat, which then radiates back toward space. The absorption of some of this heat by gases in the atmosphere results in the atmosphere being approximately 33°C warmer than it would be in their absence. This trapping of heat by the atmosphere has been called the greenhouse effect, without which human life on this planet would not be possible. The main greenhouse gas (GHG) is water which, while highly variable, constitutes approximately 3% of the atmosphere and has been estimated to be responsible for ⅔ of the greenhouse effect in the lower part of the atmosphere known as the troposphere. Carbon dioxide (CO_2) is responsible for approximately

25% of the tropospheric greenhouse effect. Other important GHGs are methane and nitrous oxide. The effect of changes in carbon dioxide concentrations on the greenhouse effect are thought to be amplified by feedbacks on the amount of water in the atmosphere. A slight warming as a result of an increase in CO_2 could increase evaporation and therefore the amount of water in the atmosphere thereby causing more warming. Human activity is thought to be responsible for enhancing the greenhouse effect which may result in increased temperatures beyond that which would naturally occur.

3. Solar Irradiation

The amount of energy put out by the sun varies over time and might therefore be expected to have an impact on climate. It is only with the advent of satellite technology, however, that this effect has been confirmed. The 11-year sunspot cycle has been associated with temperature change, particularly in the upper levels of the atmosphere, but only after signal processing removed such large effects as the Pinatubo eruption. Similar variations in surface temperature measurements over the past century have also been seen after analysis for human and volcanic effects. Speculation has also been made regarding a lower solar output and the cooling episode around 1645 to 1715 known as the Little Ice Age.

4. Aerosols

Most aerosols, or fine particulate matter or droplets, will tend to reflect sunlight back to space and thus create a cooling effect. Such an effect was seen with the increase in atmospheric aerosols caused by the eruption of Mount Pinatubo in the 1990s. However, aerosols that are dark in colour (i.e., soot) will tend to absorb light and change it to heat thus having a warming effect. The burning of fossil fuels can produce both reflective aerosols and soot. Computer models which mimic climate tended to overestimate the temperature increase due to the build-up of greenhouse gases until the cooling aerosols were taken into account.

5. Albedo

The Earth's albedo is essentially the amount of light that is reflected back to space. Very light surfaces such as snow and white clouds increase the reflectance and thus diminish heat production, while dark surfaces such as evergreen trees and open water tend to absorb more light and transform it to heat. The Earth's albedo has the potential to create many feedback loops. For instance, the less ice, the less energy is reflected causing more heat production, which in turn will cause ice to diminish further. The interaction of a warming atmosphere and its capacity to hold water and form clouds (thus increasing reflectance and/or heat absorption) is one of the least-understood feedbacks in relation to predictions of future climate. Albedo also complicates analysis of forest cover. Theoretically, northern forests may extend their range as the Earth warms. This will trap more CO_2 but the darker surface area of the forest, particularly in winter, may convert more light to heat.

6. Internal Variability

The above "external" factors can cause natural variation in the Earth's long-term climate. Variation in climate can also be caused by changes within the climate system of the Earth. Such variation can be caused by, for instance, the manner by which heat is transferred around the globe. This is called internal variation and includes such episodic changes in oceanic and atmospheric circulation as the oceanic El Niño-Southern Oscillation (ENSO) and the atmospheric North Atlantic Oscillation (NAO) phenomena.

THE WARMING EARTH

A. Surface Instrumental Record

People have been recording surface temperature using various forms of thermometers for more than 150 years. Extrapolating these point measurements to average global surface temperatures is no easy task. In addition, the further back in time one goes, the more limited the historical data coverage becomes. Estimating global averages requires some relatively complicated mapping of measured temperatures to grids and then interpolation into blank grid boxes and weighting the measurements in some manner. Different methods of extrapolating from point measurements to global averages have, however, led to quite similar results.(1)

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(1) For a more complete discussion of the temperature records for surface, satellite and balloon, see:

a) The Intergovernmental Panel on Climate Change, Working Group I Technical Summary available at: http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

b) National Research Council, *Reconciling Observations of Global Temperature Change*, National Academy Press, Washington, January 2000, available at: http://books.nap.edu/books/0309068916/html/R1.html#pagetop.

In the past 100 years, there have been two episodes of warming in the surface record: 1900 to 1945 and 1976 to 2000. The intermediate period included a time of slight cooling. Overall, the past 100 years have seen a rise in average temperature of 0.6 ± 0.2ºC. The average, however, does not tell the whole story because various parts of the globe have experienced different changes. For instance, parts of the eastern United States have, on average, remained unchanged over the past 100 years while northwestern Canada and Scandinavia have warmed between 0.4 and 0.6ºC per decade. As well, in an emerging trend, land temperatures are increasing faster than ocean surface temperatures. Also, the mean daily minimum land temperature has been increasing at approximately twice the rate of the mean daily maximum land temperature for the past 50 years. During the day, the atmosphere is better mixed than at night. The greater warming measured at night therefore would suggest that the temperature at the surface has been warming at a faster rate than the atmosphere as a whole.

1. The Urban Heat Island Effect

One of the most frequently cited limitations of the surface instrumental record is contamination due to the urban heat island effect. Many instrumental records are from areas that have incurred a lot of land-use change over their history that would lead to a heating of the surrounding land. It has therefore been suggested that the observed general warming trend is the result of this effect and that no warming has really occurred. A comparison of rural and urban locations appears to show that this effect may be the cause of about one-tenth of the observed warming. Warming has also occurred over the oceans, which would clearly not suffer from this problem.

B. Balloon and Satellite Data

Although balloons have been launched since 1958 with thermometers to measure atmospheric air temperature at different altitudes, the measurements suffer from being even less comprehensive than the surface record. Balloon measurements of tropospheric temperature are in reasonable agreement with surface temperature trends up to about 1979. After this point, however, surface temperature seems to continue to increase at 1.5 ± 0.05ºC per decade while the tropospheric temperatures show a trend of 0.05 ± 0.1ºC – a significant difference.

Satellite measurements of tropospheric temperature have been available since 1979. Satellites measure temperature with an instrument called a microwave sounding unit (MSU) which measures radiation emitted directly by the upper troposphere, centred at about 7 km above the Earth's surface. The amount of microwave radiation detected is directly proportional to the temperature. Unfortunately, temperature measured in this manner at this altitude is somewhat contaminated by the lower stratosphere which is expected to show cooling with atmospheric change, not warming. To correct for this effect, two measurements are made at different sounding angles that are then subtracted. This yields a temperature centred at about 4 km above the Earth's surface. Despite the necessity for mathematical correction of the MSU data (particularly between satellites), the data are very accurate and match those from balloon measurements over the past 20 years.

C. Satellites versus Thermometers

The difference between the surface temperature and the balloon and satellite measurements over the past 20 years has led to a great deal of debate. Some argue that the only surface temperatures that can be trusted are those of highly advanced countries such as the United States. All other readings could be tainted by bad calibrations of measuring instruments, for example. By selectively ignoring large sections of the surface temperature record on the basis that the instrumentation could be faulty, those who believe that the earth is not warming significantly have used these selective measurements to bolster their case. This arises in part because the more northerly latitudes are ignored, areas which the surface record shows are warming to a greater extent than the average.

The discrepancy between the surface temperature record and the troposphere is also troubling because current understanding of atmospheric processes suggests that the troposphere should warm as the result of increased greenhouse gases. Thus if the surface temperature and tropospheric temperatures are both correct, the difference poses a challenge to the understanding of atmospheric processes. The general thinking now is to accept the discrepancy as real and not to throw out the surface data as the result of the relatively short record of 20 years of satellite measurements. There are many other corroborating measures of surface temperature, which have lead to this conclusion, some of which are discussed in the following section.

D. Other Measures of Surface Temperature

1. Boreholes

Over time, the heat at the surface of the earth diffuses into the ground. By digging a hole in the ground to a depth of 10 m, one can measure the temperature at different depths and, by making calculations based on heat diffusion rates through the ground, one can extrapolate back to form a history of surface temperatures. One such study – which examined 358 boreholes in Eastern North America, central Europe, southern Africa and Australia[(2)] – found that temperatures have increased 0.5ºC in the past 100 years, in close agreement with the surface temperature record.

2. The Oceans

For many years, climate experts were puzzled because their models were predicting greater warming of the atmosphere than was being measured. In 2000, a published study, which used millions of historical deep ocean temperature records, showed that the top 300 m of the oceans had warmed by 0.31ºC over the 50 years of data.[(3)] This finding was widely viewed as the discovery of at least some of the missing warming. It is also difficult to conceive of an ocean warming in the absence of surface warming. The warming of the oceans is largely responsible for the small but measurable increase in global sea level rise.

3. Ice

In 1999, a published paper suggested that the ice over the deep water Arctic had thinned by 40% in less than three decades.[(4)] This was widely cited as proof of the dramatic effects of global warming. The data, however, were largely taken at a single locale and at only two time points. Further study seems to suggest that this apparent thinning was probably the result of ice movement rather than melting; another submarine study over a more extensive, but still limited, area reported no measurable thinning.

Satellite data, however, show conclusively that the Arctic ice has indeed shrunk by about 3% per decade between 1978 and 1998; in addition, the amount of ice that survived the

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(2) Henry Pollack *et al.*, "Climate Change Record in Subsurface Temperatures: A Global Perspective," *Science*, vol. 282, 1998, p. 279.

(3) Sydney Levitus *et al.*, "Warming of the World Ocean," *Science*, vol. 287, 2000, p. 2225.

(4) D.A. Rothrock *et al.*, "Thinning of the Arctic sea-ice cover," *Geophysical Research Letters* 26, 1999, p. 3469.

summer thaw decreased by 14% in those 20 years.[5] Although part of this ice thickness change could be attributed to changes in the wind patterns in the Arctic, the rest was attributed to global warming.[6]

Satellite measurements analyzed by the Global Land Ice Measurement from Space project of the U.S. Geological Survey also show that glaciers are shrinking worldwide. Laser measurements of the Greenland ice sheet show that the edges are shrinking. Some Antarctic glaciers are also melting. A 2001 Canada/Denmark study concluded that the Greenland ice sheet could be shrinking faster than previously estimated.[7]

4. Biological Changes

Satellite evidence shows that the growing season in Eurasia has increased by 18 days between 1981 and 1999 and 12 days in North America during the same time period. In areas where growth was not limited by lack of water, increased temperatures were associated with increased greening of ecosystems.[8] Other changes associated with warming temperatures such as the time of egg laying by birds have also been observed. Changes in the Arctic can be seen, for example, in a dramatic change in algae as a result of ice changes in some terrestrial aquatic systems.

E. Summary

Average global surface temperatures have increased by about 0.6ºC in the past 100 years. Although the satellite data of tropospheric temperatures do not show the same increase as the surface temperatures over the past 20 years, many other lines of evidence support the surface temperature measurements. The Intergovernmental Panel on Climate Change (IPCC), after comparing the measured increase in temperature with proxy data of annual temperatures (e.g., tree-ring data, ice-cores and corals) has concluded that there is between 66% and 90% certainty that the observed rate and duration of the temperature increase is larger than at any time in the past 1,000 years. Even sceptics of greenhouse warming are beginning to accept that the Earth is warming up.

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(5) Ola Johannessen *et al.*, "Satellite Evidence for an Arctic Sea Ice Cover in Transformation," *Science*, vol. 286, 1999, p. 1937.

(6) Konstantin Vinnikov *et al.*, "Global Warming and Northern Hemisphere Sea Ice Extent," *Science*, vol. 286, 1999, p. 1934.

(7) W.S.B. Paterson and Niels Reeh, "Thinning of the ice sheet in northwest Greenland over the past forty years," *Nature* 414, 2001, p. 60.

(8) L. Zhou *et al.*, "Variations in Northern Vegetation Activity Inferred from Satellite Data of Vegetation Index During 1981 to 1999," *Journal of Geophysical Research*, 2001.

WHY WORRY ABOUT CARBON DIOXIDE?

As described above, there are many factors that affect climate such as solar insolation, aerosols and the long-term changes in the orbit of the Earth around the sun along with natural changes in the greenhouse effect. Because CO_2 makes up only 0.035% of the atmosphere, it seems reasonable to ask why there should be any concern associated with doubling or even quadrupling this level.

A. Paleoclimates

1. Ice Cores

As snow falls and accumulates in the large ice sheets of the north and south poles, it traps air within the spaces between flakes. This air remains largely unchanged over time and CO_2 concentrations can be measured from air extracted from the cores taken of the ice. The water that makes up the snow also contains information. One of these cores, called the Vostok ice core, contains a record going back 420,000 years.

Water is made up of hydrogen and oxygen. Hydrogen, as with most elements, is present in a number of weights, or isotopes. The most common has an atomic weight of one, but a small percentage has an atomic weight of two (deuterium). When water evaporates, it is easier for a lighter molecule to evaporate than a heavier one, and this effect is greater at lower temperatures. This means that water in the air over an ocean contains relatively more of the lighter hydrogen at cooler temperatures. The hydrogen signal in snow formed from this water and layered in polar ice sheets therefore acts like a thermometer in time.

In the past, the correlation between the hydrogen thermometer and the concentration of CO_2 was considered very high, and therefore many people believed that CO_2 and temperature were closely linked over the past 150,000 years or so. Despite the correlation, there were some substantial deviations from the pattern, which cast doubt on the link. Now, however, new corrections to the data set from the Vostok ice core that account for variations in climate at the area where the water evaporated have made the correlation even tighter. Over the past 150,000 years, it was found that CO_2 and the hydrogen thermometer have been tightly linked. Statistically speaking, almost 90% of the variation in the hydrogen thermometer was explained by changes in CO_2. Over the period from 150,000 years ago to 350,000 years ago, the correlation was 84%. From a scientific point of view, such a tight linking in such a complex system is remarkable and strongly suggests that carbon dioxide is an important causative factor of climate. The results of a 2001 study of the number of pores in fossilized leaves, which varies with the CO_2 concentration at which the plants are grown, suggest that CO_2 and temperature have been associated for the past 300 million years.(9)

2. Foraminifera

Foraminifera are small organisms that live in the ocean and produce a shell of calcite. In a similar manner to the changes in hydrogen isotopes described above, the relative abundance of oxygen isotopes in the calcite shells is dependent on the temperature at which the calcite is formed. When the foraminifera die, they sink; sediment cores can then be analyzed to estimate the temperature at which the calcite shell was formed.

Until very recently, the oxygen thermometer from foraminifera suggested that the tropical seas have been much cooler than arctic seas at a time of high atmospheric CO_2. Such anomalies have been used to question the link between CO_2 and atmospheric temperature. Further analysis, however, suggests that much of the oxygen signal in the foraminifera from this time was changed through a process called diagenesis,(10) a process unlinked to sea surface temperatures. The analysis of foraminifera, microscopically confirmed to have not undergone diagenesis, suggests that the divergence of temperature and the oxygen thermometer was in fact the result of diagenesis. If this is a widespread phenomenon, then the foraminiferal record would confirm the correlation between CO_2 and temperature.

Despite the remarkable long-term correlation between CO_2 and temperature, evidence suggests that there have been times in the past where the patterns of CO_2 and temperature have deviated. Although further analysis is needed to verify these anomalies, it is also not terribly surprising that other factors come into play. Five hundred million years ago, for instance, the continents were in different positions than they are today. As well, correlations must be seen for what they are. A statistical correlation does not mean a causal relationship and it is possible that changes in temperature affect CO_2 rather than the other way around, or both values may be changing at the same time in response to some other factor. There are, however, mechanistic reasons to believe that CO_2 may be a primary factor in climate change.

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(9) Gregory J. Retallack, "A 300-million-year record of atmospheric carbon dioxide from fossil plant cuticles," *Nature* 411, 2001, p. 287.

(10) Diagenesis is a process in which the calcite shell is corroded and calcite subsequently recrystallizes. The recrystallization process will reflect the cooler subsurface temperatures rather than the surface temperatures where the original shell was formed.

B. Carbon Dioxide and the Greenhouse Effect

1. Trends in Atmospheric Carbon Dioxide

For at least 800 years before 1800, the atmosphere contained a constant 280 parts per million (ppm) CO_2. By 1900, this had increased to about 290 ppm, by 1950 to 300 ppm and it now stands at approximately 370 ppm. The increase is the result of the burning of fossil fuels and land-use changes. The IPCC has concluded that today's concentration of CO_2 has not been exceeded in the past 420,000 years and is likely exceptional for the past 20 million years.

The concentration of CO_2 has not risen steadily. The atmospheric concentration of CO_2 is determined by CO_2 being added to and taken out of the atmosphere. Variations in the amount being absorbed by land and oceans have created variation in the net rate at which CO_2 is increasing. In fact, almost half of the estimated amount of CO_2 released by human activity has ended up in the forests or the oceans, although how long it will stay there is unknown.

2. CO_2 and Temperature: Making the Link

The enhanced greenhouse theory states that the increasing amount of CO_2 should trap more energy in the atmosphere and thereby cause it to warm. The surface temperature is certainly warming, but firming the link between CO_2 and warming requires showing that CO_2 is indeed trapping more energy. A comparison over time of outgoing radiation being re-emitted from the earth, as measured by satellite, confirmed that changes in greenhouse gases in the atmosphere were causing more energy to be trapped in the atmosphere. CO_2 absorbs energy at certain wavelengths and it was shown in this study that the Earth was emitting more of the long wave energy at these wavelengths in 1970 than it was in 1997.[(11)]

3. Computer Models

Computer models that use the mechanisms of climate change to drive their outputs (as opposed to simply fitting the models to observed data) are becoming more sophisticated and better able to mimic past climates. The models can be used to help understand the influence of external and internal factors on climate as well as in distinguishing between natural and anthropogenic (i.e., the result of human activity) causes of change. In one such

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(11) John Harries *et al.*, "Increases in Greenhouse Forcing Inferred from the Outgoing Longwave Radiation Spectra of the Earth in 1970 and 1997," *Nature* 410, 15 March 2001.

model, the inclusion of anthropogenic factors over the period of 1963 to 1993 – a period that had three major volcanic (cooling) eruptions – was necessary for the model to fit the observed temperature trends. Equally, the cooling period between 1945 and 1965 was not reproduced by anthropogenic factors alone but required natural factors.(12)

4. Other Greenhouse Gases

Other greenhouse gases such as methane, nitrous oxide and halocarbons have also been implicated in the enhanced greenhouse effect. As well, these have been shown to have decreased the amount of outgoing radiation from the Earth, thereby confirming a role in an enhanced greenhouse effect. In fact, these gases are far more powerful at trapping outgoing radiation than is CO_2, although methane does not reside in the atmosphere for as long. Methane lasts only about 12 years in the atmosphere while CO_2 lasts about 200 years. Over a 100-year period, methane has 21 times more capacity to trap energy than does carbon dioxide; nitrous oxide has 310 times the potential on a weight basis over the same time period. Massive outgassing of oceanic reserves of methane has been speculated to have caused some warming episodes in the past, but only after having been converted to CO_2. Some of the halocarbons such as perfluoromethane reside in the atmosphere for tens of thousands of years and therefore may affect climate well into the future.

Concentrations of methane and nitrous oxides have also been increasing as the result of human activity. The IPCC estimates that the change in energy trapped in the atmosphere between 1750 and 2000 due to methane was about one-third that of CO_2. The increase in methane seems to have slowed, and because its lifetime in the atmosphere is only 12 years it is unlikely to cause a lot of concern over the long term. Many of the halocarbons are decreasing as the result of regulations developed to deal with the fact that they are also implicated in depletion of the ozone layer. As well, carbon dioxide is more of a long-term concern because of the potential release from the burning of large fossil fuel deposits.

C. Summary

The scientific data suggesting that anthropogenic releases of CO_2 cause the globe to warm are compelling. For the past 420,000 years, and likely longer, global temperature has

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(12) Peter Stott, "External Control of 20th Century Temperature by Natural and Anthropogenic Forcings," *Science*, vol. 290, December 2000.

been in a virtual lock-step with atmospheric carbon dioxide concentrations. Atmospheric carbon dioxide is now on the rise as the result of human activity. As carbon dioxide has risen, so have the surface and oceanic temperatures. Mechanistic theory suggests that carbon dioxide can absorb outgoing radiation and therefore cause atmospheric temperature to rise. Satellite observations have confirmed that the increase in carbon dioxide has decreased outgoing radiation.

THE FUTURE

The headlines regarding climate change are often full of the potential devastating effects of a warming globe. Often they refer to rising sea levels and increased frequency of catastrophic weather events such as drought and violent storms. The big doomsday headlines suffer from being speculative and are often derived from what are termed worst-case scenarios of climate change.

According to another view, because horticulturalists use about 1,000 ppm CO_2 in greenhouses to enhance plant growth, we should actively encourage CO_2 emissions to create a greener Earth. This last hypothesis suffers from looking at CO_2 in isolation and assumes that there are no consequential effects on climate, an assumption that is becoming more and more difficult even for sceptics to support.

The problem is that formulating plans regarding what should be done about emissions requires predicting the future effects of climate change on agriculture, sea levels, and natural systems. Predicting future climate change, however, is where one encounters the greatest uncertainty because it involves estimating future atmospheric CO_2 concentrations and any accompanying changes in climate. Future atmospheric CO_2 concentrations will be dependent upon the level of CO_2 emissions and how the carbon biogeochemical cycle reacts to increased CO_2 and to climate change. Estimating the effects of atmospheric CO_2 on climate depends on how effective computer models are at predicting climate change.

A. Emissions

Predicting emissions will depend heavily on estimates of economic growth and the degree to which economic growth can be uncoupled from carbon sources. Among other things, this will involve estimates of population growth, assumptions about living standards within the population, assumptions about changing end-use efficiency of fossil fuel burning, and the introduction of new technologies. The IPCC has created a set of 35 different emission scenarios grouped into what it terms "story lines," ranging from massive economic growth and no restrictions on carbon-based fuels to scenarios which lead to far fewer emissions. Climate, however, does not react to emissions but to concentrations, which in turn are dependent on what happens to the CO_2 after it is emitted.

B. Sinks

Currently, the IPCC emission scenarios do not include feedbacks of climate change on the biogeochemical cycling of carbon, although attempts have been made to include these feedbacks in models of climate change. As discussed above, almost half of the emitted CO_2 to date has found its way into the oceans and into forests. These pools of CO_2 are called sinks, as long as there is a net movement of CO_2 into them. The capacity of these sinks is unknown; similarly, how long these sinks will remain as sinks is unknown, but it is unlikely to be long-term.

Carbon has been released out of long-term storage (millions of years) as fossil fuels into a cycle that is measured in hundreds of years. The forest sink is thought to arise because of a longer growing season, higher photosynthetic rates and, most importantly, the reforestation of abandoned unproductive agricultural land. Rising CO_2 increases rates at which plants use it in the process called photosynthesis and so may increase the movement of CO_2 into forests. Longer-term field experiments in which areas of forest were incubated in high CO_2 seem to suggest that this effect is only short-lived in some forest systems. Also respiration, and therefore CO_2 emissions from forests, is widely thought to increase with temperature, although probably to a lesser degree than short-term laboratory experiments have estimated. The total capacity for reforestation is also limited. If all forests that have been cut in the past were replaced, the atmospheric levels of CO_2 might be brought down by some 50 ppm – only a small proportion of the levels that may one day be reached if the current emission rates remain unchecked.

The oceans are absorbing about one-quarter of the emitted CO_2, but once again there are many unknowns about the exact nature of the sink. Carbon may be absorbed by micro-organisms which then subsequently sink into the deep oceans, or it may simply dissolve and remain in the upper surfaces until it moves into the polar regions where the cold water sinks into the deeper oceans. The amount of CO_2 moving into the deep oceans and into long-term storage as rock is unknown. In addition, as oceans warm, their capacity to dissolve CO_2 decreases.

Thus, sinks and the feedback of climate change on them are not well understood. Although they have had a mitigating effect on CO_2 concentrations, the effect is unknown and of probable limited capacity and duration. Understanding them, however, is essential in predictions of atmospheric CO_2 over the next century.

C. General Circulation Models

General circulation models are the computer models that climatologists use to imitate the Earth's climate. They are becoming more robust at reproducing past climates, and recent advances are able to create the different rates of temperature increase over land and oceans. However, they are not yet sophisticated enough to predict local effects. Unfortunately, it is the local effects that count, particularly when it comes to adapting to climate change. As one commentator has put it, the devil is in the details. That the global average temperature will rise is of little help to policy-makers in Europe if melting fresh water stops the Gulf Stream and causes Europe to become cold, as apparently has happened in the past.

D. Summary

The future of climate change is really where the debate lies at this point. As has been pointed out, although the mechanisms of climate change are far better understood and more robust now than at the time of the IPCC's second report, the third report – released in February 2001 – contains a greater possible range of temperature change than does the second.(13) Thus, while understanding has increased, uncertainty regarding the future has also increased. What the overall global temperature change will be and what local effects it will have are still relatively unknown. Some have suggested that climate change from CO_2 will, on the whole, be beneficial. Uncertainty, however, cuts both ways, and it is possible that climate change, particularly on a local level, will have devastating effects. The IPCC has therefore recommended a precautionary approach to dealing with CO_2 emissions.

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(13) Richard Kerr, "Global Warming: Rising Global Temperature, Rising Uncertainty," *Science*, vol. 292, April 2001, p. 192.

POLICY IN AN UNCERTAIN WORLD

Politicians are now being forced to make difficult decisions based on uncertain, but potentially devastating, scenarios of the future climate, a climate at least partially under human control. A variety of suggestions have been made to help in the formation of appropriate policy, at least in the short term, that involve both mitigating and adapting to climate change. In the long term, there is little doubt that carbon-free energy sources must be incorporated to reduce emissions of CO_2.

A. Mitigation

The main effort towards mitigation has been the work on the Kyoto Protocol. In 1992, more than 100 countries ratified the United Nations Framework Convention on Climate Change (FCCC). Using the IPCC's initial 1990 report as a basis of discussion, the FCCC stated that, despite the well-acknowledged uncertainties involved in predictions, a precautionary approach should be taken, and greenhouse gas (GHG) emissions should be stabilized at 1990 levels by the year 2000. In 1995, the parties agreed to work toward a binding agreement. In 1997, at the third follow-up meeting of those who signed the Convention (Third Conference of Parties, or COP 3), the parties agreed in the Kyoto Protocol to reduce average GHG emissions by a further 5.2% between 2008 and 2012.

The Kyoto Protocol has had a lot of difficulties since its signing in 1997. One of the main criticisms is that it has a limited capacity to address mitigation. Even if emissions are reduced to 5.2% of 1990 levels, CO_2 concentrations will continue to rise, only at a slightly reduced rate. In addition, the mechanisms that countries would be able to use for reductions were the subject of much debate and have only recently been finalized. Canada has emphasized using its forests as sinks while the European community has tried to emphasize energy use efficiency. It has also been suggested the costs of conforming to the protocol are too high. Citing the high costs and the lack of developing nation participation, the United States of America pulled out of official negotiations in the winter of 2001. Other countries decided to continue, and the tentative political agreement reached in Bonn in July 2001 was put into practical language at COP 7 in Marrakech in November 2001.

The costs of mitigation, particularly when predictions of climate change still hold considerable uncertainty and given that the achievement of Kyoto goals will have only a limited impact on emissions, have been an argument against efforts to reduce emissions. However, others have argued that if the environmental and health costs of burning fossil fuels are included (internalized), there are in fact financial benefits to mitigating CO_2 emissions.(14) Such a recognition has already been made in heavily polluted cities, particularly in China where a great effort is now being made to move to cleaner fuels and away from coal, which has virtually choked cities in the past. In recognition of the limitations of the Kyoto Protocol, negotiations towards further action are planned to begin in 2005.

It has also been suggested that, although they may have limited effects in the long term, mitigating emissions of methane and nitrous oxide, as well as halocarbons, would be the easiest and most efficient initial mitigation response. Methane is largely produced by agricultural activities as well as natural gas leaks and leakage from landfill sites. Nitrous oxide is also largely produced from agricultural activity. Halocarbons are used in the refrigeration industry. These are all far more effective heat absorbers per kilogram than CO_2, and changes in land and waste management as well as halocarbon use may be more easily and cheaply achieved than having to focus on carbon emissions associated with the burning of fossil fuel.

B. Adaptation

In the absence of scientific certainty regarding future climate, and assuming that our capacity to mitigate against emissions – at least in the short term – is limited, it has also been suggested that programs to adapt to climate change would be easier and help improve people's lives even in the absence of any climate change.(15) With the world population growing, extreme climate events will increasingly impact on human activity without any change in the frequency of extreme events. Particularly in developing nations, land-use management has been poor, making people even more susceptible to extreme events. Hurricane Mitch, when it stalled over Latin America, had devastating results in large part because land-use management had stripped

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(14) Luis Cifuentes *et al.*, "Climate Change: Hidden Health Benefits of Greenhouse Gas Mitigation," *Science*, vol. 293, 2001, p. 1221; Giulio De Leo *et al.*, "The Economic Benefits of the Kyoto Protocol," *Nature* 413, October 2001, p. 478.

(15) David Sarewitz and Roger Pielke Jr., "Breaking the Global Warming Gridlock," *The Atlantic*, July 2000.

the land of the capacity to absorb its impact. Therefore, if land management had been improved and people had moved away from vulnerable areas, the human impact would have been greatly reduced. Improving agricultural practices to store more water in the soil would also help to adapt to drier conditions. After massive flooding in China, forestry has been virtually banned and reforestation programs have been implemented.

CONCLUSION

There is now strong evidence that humans are warming the globe by altering the composition of the atmosphere, particularly by increasing CO_2 concentrations. The effects of this are uncertain, but could be devastating. The response to climate change, however, has been hindered by a partisan battle in which scientific studies have been used as ammunition by both sides.

Climate change is inevitable. Historical records have shown, for instance, that European settlers arrived on the prairies of North America at a fortunate time. The past 200 years have been relatively wet and amenable to agriculture compared to the previous 1,000 years. An adaptive response to potential climate change is therefore a wise course of action no matter what the predictions of human impact on the environment.

One of the main concerns regarding mitigation is the cost. By focusing on mitigation strategies that have ancillary health and other economic benefits such as moving toward cleaner-burning fuels and higher energy efficiency, the costs can certainly be reduced. Some even estimate that there will be net financial benefits associated with emission reductions. Although there may be benefits to reducing CO_2 emissions to society as a whole and to certain sectors of the economy, costs may be incurred elsewhere. Strategies to lessen the impact of these costs will likely be required to gain the political will to act.

For the past 420,000 years, atmospheric concentrations of CO_2 and global temperature have been highly correlated. The level of CO_2 that human activity has caused, through the mobilization of very old pools of fossil fuels, is higher than any in the past 420,000 years and probably the past 20 million years. There is also strong mechanistic theory, confirmed by observation, that CO_2 leads to energy being trapped in the atmosphere. Even in the absence of certainty regarding the future effects of atmospheric CO_2 on climate, it is reasonable to ask whether or not continuing to increase atmospheric CO_2 through the burning of fossil fuels is sustainable.