PUBLIC POLICY
SOURCES

NUMBER 80 / JUNE 2004

The Science Isn't Settled

The Limitations of Global Climate Models

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A FRASER INSTITUTE OCCASIONAL PAPER

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Editing, design and typesetting: Kristin McCahon and Lindsey Thomas Martin

Printed and bound in Canada.
ISSN 1206–6257.

Date of issue: June 2004

Executive summary

Computerized models of the earth's climate are at the heart of the debate over how public policy should respond to climate change. Global climate models (GCMs)—also called general circulation models—attempt to predict future climatic conditions starting with a set of assumptions about how the climate works and guesses about what a future world might look like in terms of population, energy use, technological development, and so on.

Analysts have pointed out, however, that many of the assumptions used in modeling the climate are of dubious merit, with biases that tend to project catastrophic warming, and have argued that climate models have many limitations that make them unsuitable as the basis for developing public policy. This paper examines two major limitations that hinder the usefulness of climate models to those forming public policy.

No "reality check"

First, to decide if future climate change may be significant, projections should be compared to actual climate trends and variations using collected climate data for the last century or more. This comparison cannot be done rigorously as our knowledge of how (or if) the climate is changing now is based on a data record with the following deficiencies.

Climate records are dominated by a high density of measurements from a small portion of the earth's land surface. Only the continental United States and western Europe have many closely spaced stations that have operated for well over 100 years. Few observations are available from sparsely inhabited land areas or in ocean areas except from islands and shipping lanes.

Many important global climate records are too short to convey information about long-term trends. For example, Environment Canada's record that ostensibly covers the second largest country on earth is only scientifically valid and official from 1948. In fact, there are fewer stations in Canada today than there were in 1960.

Land surface temperature records are biased by the "urban heat island effect." In 1952 T.J. Chandler found that Greater London was much warmer than the surrounding countryside. Failure to account for local warming in cities led to some claims of dramatic warming in the 1980s and 1990s and, while adjustments are made today and the predictions of warming significantly reduced, some researchers believe the adjustments to be inadequate.

The upper air temperature record disagrees with the surface record. Temperatures above the surface are measured by weather balloon instruments and by satellites. Weather balloons have been launched routinely for over 50 years but few observations are made in many areas of the world. Starting in 1978, satellites have taken temperatures down through the atmosphere over the entire globe. Theoretically, the lower part of the atmosphere should warm at about the same rate as the surface, which has warmed rapidly since the late 1970s. However, both weather balloon and satellite data sets show much less warming in the lower atmosphere than at the surface, although recent examination of all data sets has resulted in adjustments that reduce the disagreements.

To summarize the first major limitation, climate trends using any source of observed data, including surface stations, weather balloons, and satellites, are uncertain due to short length of the records and because of the need for adjustments to correct for artificial discontinuities such as instrument or satellite changes. However, there is general consensus that there has been global surface warming around 0.6° C or 1° F since the late 1800s. The warming was concentrated into two periods from 1910 to 1945 and since 1976, with cooling around 0.2° C or 0.3° F between 1945 and 1976.

No crystal ball

The second limitation upon the usefulness of climate models in the formation of public policy is that future climate trends are projected, not by simply extrapolating recent trends, but by using climate models with deficiencies that make the projected trends very unreliable.

Climate models oversimplify many poorly understood climate processes. Assumptions and parameters are adjusted in different modeling efforts until the model produces estimates that are within what the modelers believe to be plausible. For example, thunderstorms are too small to appear in even an advanced climate model but account for almost all of the rainfall in many tropical areas. Models estimate rainfall from thunderstorms by simple rules called "parameterizations," that may give realistic amounts of rainfall in some areas but not in others.

Results from models are contradictory. Different climate models, or the same model run with different assumptions, produce significantly different results when the same data is run through them. The result of most interest is the "climate sensitivity," which estimates the amount of atmospheric warming that would occur from a doubling of carbon-dioxide levels. Models that realistically depict the climate trends of the last 100 years or so may still produce sensitivity values ranging anywhere from 1.5°C to 4.5°C.

Models fail to account for aerosols properly because their microscopic effects are not fully understood. Aerosols are particles (both natural and man-made) in the atmosphere. Some aerosols reflect solar radiation and cause cooling. Other aerosols absorb radiation and warm one layer of the atmosphere, while shading and cooling lower layers and the surface. Aerosols produce indirect effects by making it either easier or more difficult for clouds to form, and for precipitation to fall. Aerosols can also make both clouds and snow surfaces darker. Models are currently based on the assumption that the cooling effect from reflective particles is much larger than the warming effect from absorption of sunlight by dark particles.

Scenarios of future concentrations of greenhouse gases are based on dubious assumptions about the future. These scenarios depend on other models of projected growth of population, economies, and energy use. Some projections are so dubious that MIT's Dr. Richard Lindzen, a lead author of one of the IPCC science reports, has referred to them as "children's exercises." As researchers Ian Castles, formerly the head of Australia's national office of statistics, and David Henderson of the Westminster Business School and formerly the chief economist of the OECD, point out, when estimating potential future climate changes, IPCC's modelers inappropriately compared future estimates of GDP in terms of exchange rates rather than purchasing power parity. This produces GDP estimates that are significantly inflated, leading to estimates of greenhouse-gas producing activity that are similarly inflated. Castles observes that if such assumptions are correct, then the average income of South Africans will have overtaken that of Americans by a very wide margin by the end of the century. Because of this economic error, the IPCC scenarios of the future also suggest that relatively poor developing countries such as Algeria, Argentina, Libya, Turkey, and North Korea will all surpass the United States.

Canada's ratification of the Kyoto protocol, if it is treated seriously and attempts are made to reduce Canada's greenhouse gas emissions by nearly 30% in the next few years (the estimated reduction required of Canada), is likely to have a major impact on the future of the Canadian economy and the allocation of scarce environmental resources. That ratification relied largely on frightening scenarios generated by computer climate models that are simply not sophisticated enough to serve as meaningful guides to instituting public policy. Though politicians such as Environment Minister David Anderson claim that "the science is solid," even a cursory inspection of the many problems with computer climate models suggests it is anything but.

Recommendations

- Reexamine the science of climate change and stop grounding policy in the output of computer models of limited utility. Models are primarily useful to scientists to determine what is known and not known about climate processes. Therefore, they only suggest probabilities, not certainties, about the future.

- Acknowledge that published scenarios of future greenhouse gas concentrations are skewed toward unlikely high growth in emissions and, therefore, climate models using these scenarios will tend to project unrealistically large warming.

- Acknowledge that models cannot accurately predict the absolute amount of warming (or other climate change) resulting from a particular scenario of greenhouse gas concentrations.

- Acknowledge that the effect on global climate of implementing a particular action will be extremely slow to occur. If the action involves only one country, the effect on global climate may be undetectable, even after a century. Policies that produce worthwhile emissions reductions will certainly require international cooperation over a long period.

- Recognize that some climate changes (both natural and human-caused) are climate surprises, or events that are not anticipated in advance (and, by definition, are not properly incorporated into models). Any climate surprise in a future projection from a model is probably an error because of the many assumptions and simplifications in models.

- Perform full and transparent economic and risk analyses of the costs and effectiveness of proposed greenhouse gas control actions, including alternatives.

- Redirect some of the resources currently being allocated based on a model-based focus on greenhouse gas emission reductions toward research efforts to improve the state of weather and climate forecasting. In the next few years, the main improvements are likely to be better forecasts of the regional effects of recurring variations such as El Niño.

- Allocate some resources toward researching probabilities of different outcomes. The projected global average surface warming from 1990 to 2100 has a large range of 1.4° to 5.8° C or about 3° to 10° F (IPCC, 2001: 13), with no probability distribution specified. However, the possible range of greenhouse gas concentration scenarios is included as an uncertainty along with the genuine scientific uncertainties.

- Redirect some of the resources currently focused on greenhouse gas mitigation to research programs that will help Canadians adapt to climate change regardless of origin. For example, research efforts to predict economic impacts of climate change tie together chains of assumptions and uncertainties prematurely. Climate impacts depend on projected climate changes, which in turn depend on greenhouse gas concentrations, which depend on an emissions scenario, which finally depends on the path of development of society. Because of uncertainties, it is not valid to say: “An impact of business as usual in 2100 will be a certain number of dollars of flooding damage from sea level rise.” However, it is legitimate and important to estimate the impacts of coastal flooding with a certain sea level rise or effects on Great Lakes shipping due to changed ice cover from a specific amount of warming, regardless of the cause of the rise in the sea level or the warming.

I remember my friend Johnny von Neumann used to say, "with four parameters I can fit an elephant and with five I can make him wiggle his trunk."

—Enrico Fermi, quoted by Freeman Dyson in "A Meeting with Enrico Fermi" (*Nature* 427 (January 2004): 297.

Introduction

Imagine basing American or Canadian economic policy for the next hundred years on a simple computer model developed from an inadequate database in which one variable is arbitrarily doubled while most others are arbitrarily kept constant. Further, consider using such a model despite the fact that it is known to omit key elements that shape economic trends. Finally, imagine using such a model despite copious evidence showing that all previous model outputs were incorrect. This is essentially what the government of Canada did when it chose to rely on computerized models of the earth's climate in deciding to ratify the Kyoto Protocol on climate change.

Some people, like the UK's Sir David King claim that global warming is a more serious threat to the world than terrorism (BBC, 2004). Canadian Minister of Environment David Anderson also elevates global warming above terrorism as a world-wide threat. (Ljunggren, 2004). Public misunderstanding about global warming also stems from the way the issue is presented in popular accounts. Dr. Freeman Dyson, Professor Emeritus of Physics at the Institute for Advanced Study at Princeton University, expresses it concisely.

> The way the problem is presented to the public is seriously misleading. The public is led to believe that the carbon dioxide problem has a single cause and a single consequence. The single cause is fossil fuel burning, the single consequence is global warming. In reality there are multiple causes and multiple consequences. (Dyson, 1999)

Like most governments that present public policy on global warming, the government of Canada primarily bases its stance on the reports of the IPCC. But politicians clearly do not realize that the major conclusions of the IPCC's reports are not based on hard evidence and observation but rather largely upon the output of assumption-driven computer models, especially global climate models or general circulation models (GCMs).

Some consider atmospheric scientist Norman Phillips' 1955 model of the atmosphere the first crude GCM. Others place the beginning, especially of misconceptions about the validity of the models, with Dr. Syukuro Manabe of the Geophysical Fluid Dynamics laboratory in Princeton (Caffrey, 1997). He tried to remind people that he was not predicting climate with his models but merely trying to understand it as a fluid dynamic process. Despite his cautions, activists and politicians claimed his model results actually predicted earth's future climate. Global circulation models gradually became more sophisticated as computing power and capacity increased until the model of NASA's Goddard Institute of Space Studies (GISS) reached a level of perceived sophistication that made models the focus of climate science. GISS modeler Dr. James Hansen also gave the hypothesis of human-induced (i.e. "anthropogenic") global warming dramatic impetus with his appearance before the 1988 United States Senate Committee on global warming chaired by then-Senator Al Gore. At that hearing he testified that he was 99% sure that global warming was due to humans and caused by one greenhouse gas (GHG) in particular, carbon dioxide (CO_2).

A review of the literature, however, suggests there are significant problems with the physics of GCMs and climate data inputs to the models as well as questionable assumptions built into climate models.

Problems with the physics of GCMs

Some of the physical processes that should be included in global circulation models (GCMs)[1] are wind, radiation, clouds, precipitation, exchanges of moisture between air and sea, energy and momentum, exchanges of moisture between air and land, soil moisture, ground water, chemistry (particularly O_3 and CO_2), aerosols, ocean temperature, salinity and currents, sea ice, snow, glaciers, vegetation, and ocean biota. But understanding each of these processes is hampered by severe problems, including a lack of data, a lack of knowledge of the mechanisms involved, a lack of computer capacity to model the phenomena properly, and a rudimentary understanding of the interactions and feedbacks among all of these phenomena. Consequently, the data that is finally used in the GCMs are very crude estimates. For example, assessing the interactions between the boreal forest and climate began only a few years ago (Hogg, 1995).

Estimates of radiative forcing

Figure 1 shows 12 identified components of climate that could drive the atmosphere toward greater or lesser heat retention. The heat retention of each factor is called "radiative forcing," and the height of each bar is the "central estimate" of the radiative forcing of each factor in watts per square meter, comparing the earth in 2000 with the preindustrial period around 1750. For example, the first bar represents long-lived greenhouse gases in the lower atmosphere. Gases added to the air since 1750 are estimated to trap nearly 2.5 watts per square meter of solar energy, which would tend to warm the earth about the same as if greenhouse gases stayed unchanged but the sun brightened enough to provide 2.5 more watts per square meter near the earth's surface. For comparison, full sunlight just above the atmosphere is 1,368 watts per square meter but, because the earth is a sphere instead of a disc, the average sunlight is one fourth this amount, or 342 watts per square meter. The earth, air, and clouds reflect about 30% of incoming energy, so the amount of heat energy absorbed is 236 watts per square meter (Willson, 1997). So, added greenhouse gases so far have an effect equivalent to a 1% brighter sun. The last bar in figure 1, labeled "Solar," indicates that scientists estimate that the sun has actually brightened since 1750 but only by about 0.1% (or 0.3 watt per square meter). A bar extending below zero represents a cooling effect. For example, the "Stratospheric ozone" bar indicates that scientists estimate that ozone depletion in the stratosphere allows about 0.1 watt per square meter of atmospheric heat energy to escape to space.

In figure 1, nine of the 12 potential drivers are assigned low or very low confidence, meaning that scientists are quite unsure of the magnitude of the warming or cooling effect of estimated changes in those factors. For each factor, the vertical line (with "X" or "O" at the ends) shows the range of estimates of the amount of the effect of that factor. Factors without bars are so uncertain that it is not possible to state a "central estimate." Mineral dust both absorbs and reflects energy, and there is no consensus about whether the increase in mineral dust has caused warming or cooling on a global basis. The "tropospheric aerosol indirect effect (1st type)" is the possibility that adding particles might increase the reflectiveness of clouds (because cloud water droplets form on particles), and there is great uncertainty about the size of this effect or whether this effect exists at all.

Figure 1 is actually incomplete because scientists continue to identify additional factors that may affect climate as they change. Some of these factors are volcanic eruptions, water vapour, the amount of cloudiness—this would be called the "tropospheric aerosol indirect effect, 2nd type") heat stored in the ocean, and heat stored in land.

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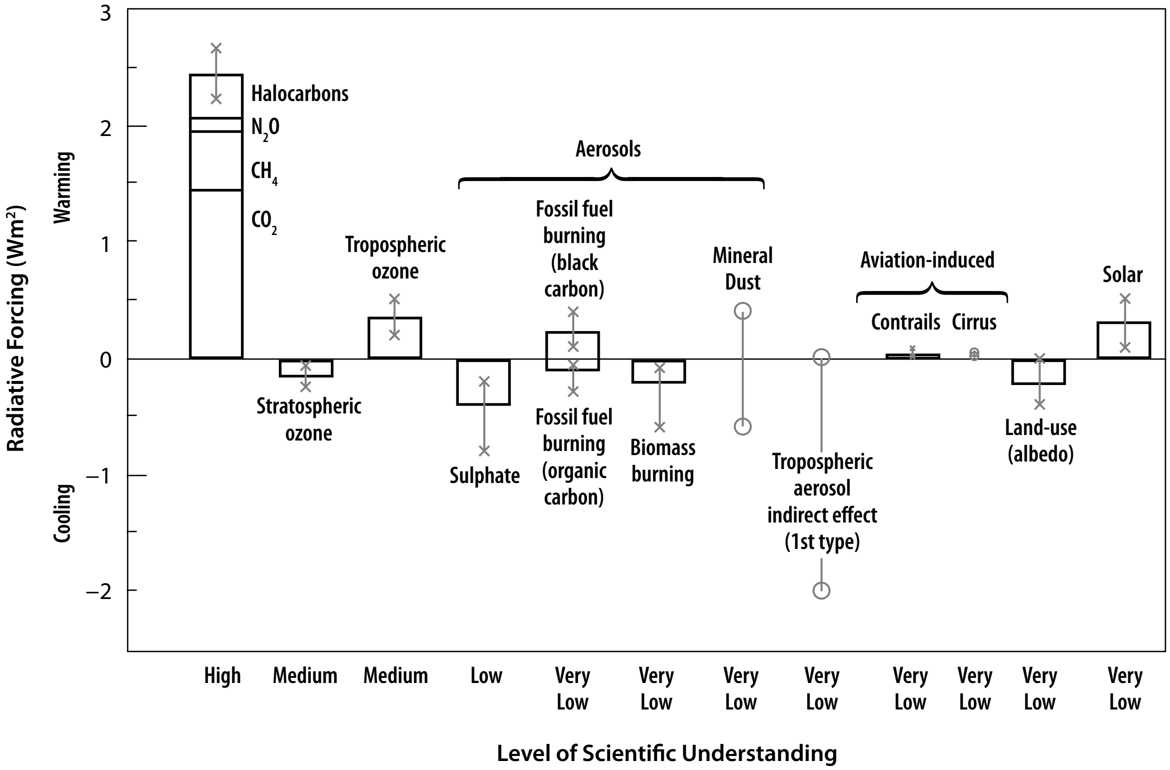
(1) See Appendix, page 21 for more details about how a GCM depicts the global climate and is used to project climate changes that may occur as greenhouse gases and other factors change.

Figure 1: Level of confidence assigned to identified components of climate change



Source: Houghton et al., 2001: 8.

Inadequacy of GCMs

Three examples that highlight the inadequacy of global circulation models are their handling of water vapour, clouds, and aerosols.

Water vapour

Even though water vapour makes up 97% of all greenhouse gases by volume, it is almost completely ignored by climate models, which focus primarily on CO_2 and methane. Only recently have attempts been made to consider the effects of water vapour as a greenhouse gas in models (NOAA, 1997). The crucial issue is whether the average relative humidity stays constant, which means that a warmer atmosphere would contain more water vapour. This seems logical but an alternative theory states that, with additional evaporation in a warmer climate, storms will become stronger and will rain out most of the additional vapour. This uncertainty is the main reason that climate models project warming ranging from 1.5° C to 4.5° C with doubled carbon dioxide.

Clouds

Because clouds form on a microscopic level, models "parameterize" the formation and dissipation of clouds in a very simple way that attempts to compute the proportion of each box in the model's three-dimensional grid that is filled with clouds. Even when a model is "tuned" to compute a realistic amount of cloudiness in today's climate, there is no assurance that the parameter values will produce realistic cloudiness in a changed climate.

Aerosols

Aerosols include all kinds of particles in the air, ranging from water droplets in clouds to the sulphur-bearing droplets emitted in airplane exhaust to dust thrown into the atmosphere by volcanoes. Particulate concentrations vary greatly over time. As recently as 1972, H.H.Lamb introduced the first attempts at recording the influence of particulates on incoming solar radiation with the Dust Veil Index (DVI) (Lamb, 1972). Lamb was primarily concerned with dust from volcanoes, as the impacts of volcanoes like Tambora in Indonesia in 1815 on the climate are well documented (in eastern Canada and New England, 1816 is still called the "year with no summer") and the Pinatubo eruption in 1991 caused global cooling for about two years. Researcher Vincent Gray also underlines the importance of aerosols: "The effects of aerosols, and their uncertainties, are such as to nullify completely the reliability of any of the climate models" (Gray, 2002: 47). Experts attributing global warming to human-induced (i.e. "anthropogenic") sources exploited this lack of knowledge about aerosols by adding sulfates to their modeled atmosphere. This was done to compensate for the contradiction between their models and the actual temperature. Though models predicted that CO_2 increases would invariably drive temperatures up, global average temperatures actually went down from 1945 to 1976 while man-made CO_2 increased. The discrepancy was first explained by sulfates from human sources blocking sunlight and offsetting the warming caused by CO_2. The problem is that, after 1976, temperatures began to rise though levels of sulfates did not decrease. Recent alarmist predictions of warming up to 5.8° C (about 10° F) from 1990 to 2100 (Houghton et al., 2001: 2-3) are based on the highest emission scenarios and the assumption that the cooling effect from the current level of air pollution cancels out almost all of the warming effect from greenhouse gas. If air pollution is cleaned up, these models say the aerosol cooling effect will be removed and warming will rapidly accelerate.

Consider the conclusion of Gates et al. (including Benjamin Santer, editor of the IPCC's report) in their analysis of the results of atmospheric models.

> From the analysis presented here and elsewhere, it is clear that much further work is needed to significantly reduce the errors of the atmospheric GCMs . . . It should be recalled that a model's errors are defined with respect to observational data that are in many cases of limited quality and coverage, although the data used here are in many cases the most appropriate and accurate available. (Gates et al., 1998)

A 1999 press release from the US National Academy of Sciences summed up the findings of their report on the data that is the basis of the climate models like this: "Deficiencies in the accuracy, quality and continuity of the records . . . place serious limitations on the confidence that can be placed in the research results" (U.S National Academy of Sciences, 1999: 29). The press release continued: "There is today no comprehensive system designed to observe and document climate variability or climate changes." They also see the situation getting worse in the future:

> Without immediate action to prevent the deterioration of some essential observing systems, the ability of the climate research community to provide over the next decade the objective scientific information required for informed decision making will be seriously compromised. (U.S National Academy of Sciences, 1999: 29)

Problems with physics in climate models may explain why they often fail to match up with real-world measurements. For example, while cooling has been observed in the North Atlantic and parts of eastern Canada for the last 25 to 30 years, most climate models do not simulate the cooling properly (Khandekar, 2000).

Problems with the data in GCMs

Models are only as good as the data and assumptions that go into them, a truism beautifully expressed by the well-known acronym, “Garbage in, Garbage out” (GIGO). The US National Research Council’s report, *Climate Change Science: An Analysis of Some Key Questions*, notes that

> [a] major limitation of these model forecasts for use around the world is the paucity of data available to evaluate the ability of coupled models to simulate important aspects of past climate. In addition, the observing system available today is a composite of observations that neither provide the information nor the continuity in the data needed to support measurements of climate variables. (US National Research Council, 2001: 26)

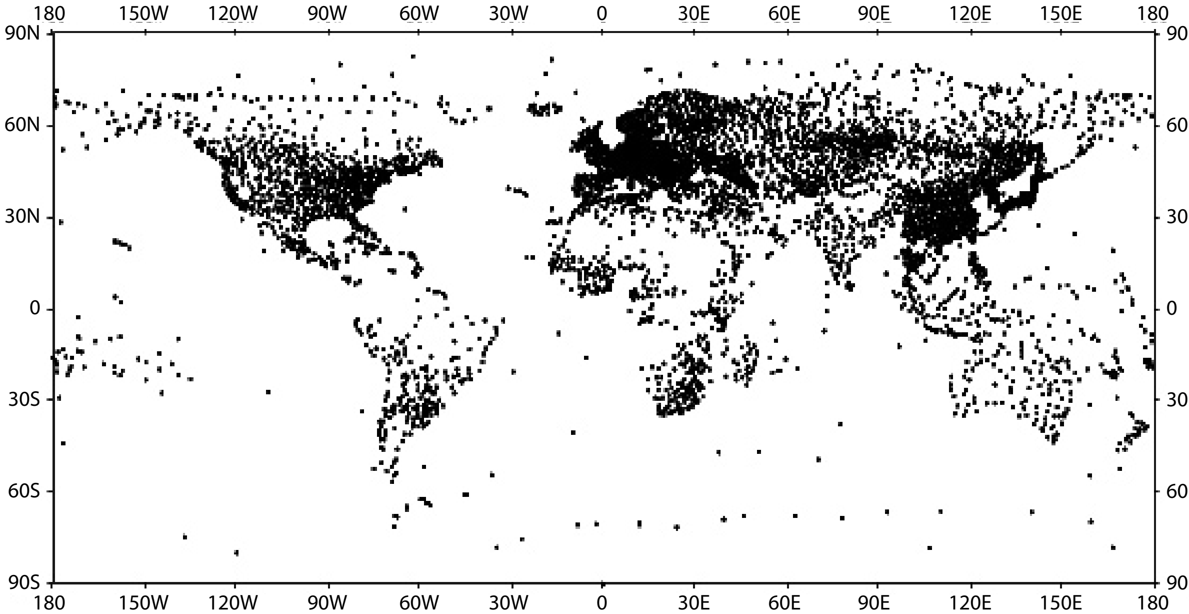
GCMs are based on global climate data that are inadequate to the task of adequately representing the earth’s climate: the surface record covers very little of the world and is biased toward eastern North America and western Europe (figure 2).

Record of surface temperatures

Figure 2 shows the concentration of surface records but it also shows that vast areas of the world have few stations. There are few ocean stations, yet oceans cover 70% of the earth’s surface. Deserts and mountains cover 38% of the land surface yet there are few stations. The vast boreal and tropical forests are almost unmeasured, as are the Arctic, Antarctic, and sub-Arctic regions. What records exist are usually limited in length. There are one or two records for Antarctica over 50 years in length; most records only began in 1957.

Surface temperature records for the world are inadequate to determine the average annual temperature of the earth. The uncertainty in the global “normal”

Figure 2: Distribution of the approximately 8,000 weather stations



Source: United States National Center for Atmospheric Research (1996). *An Introduction to Atmospheric and Oceanographic Datasets*, NCAR Technical Note NCAR/TN-404+IA, <http://www.cgd.ucar.edu/cas/tn404/text/tn404_1.html>: figure 3.4.

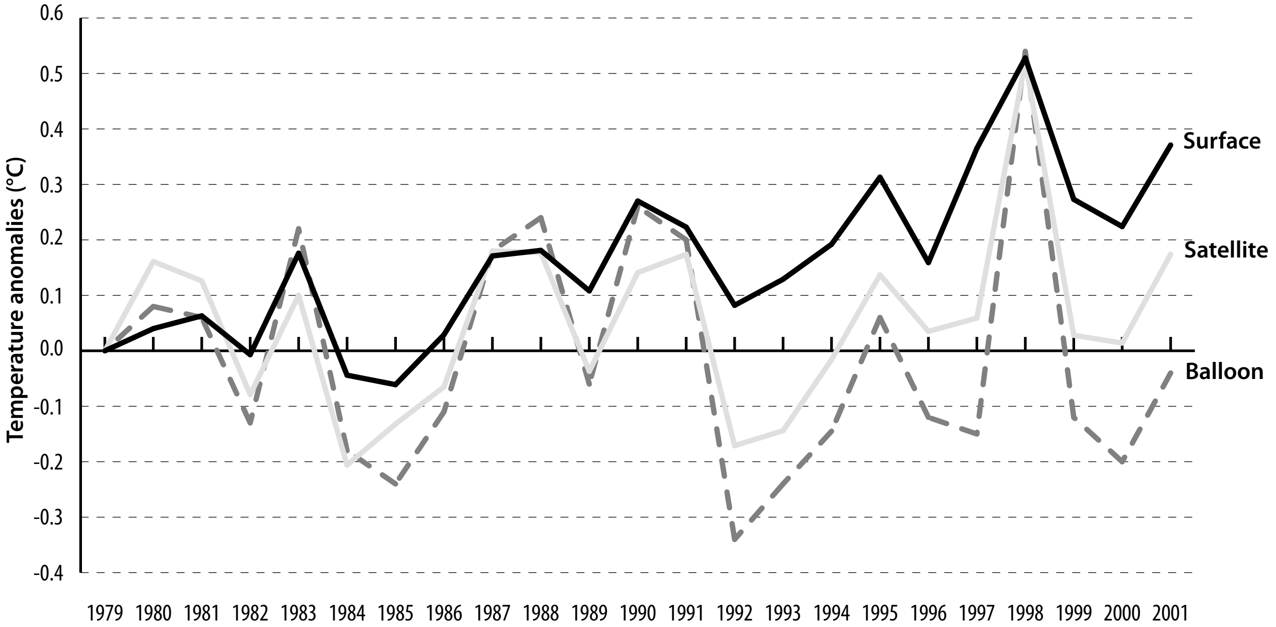
surface temperature—estimated to be 13.9° C or 57.0° F (Menne, 2000), a decrease from an earlier estimate of 15° C or 59° F—is almost twice as large as the estimated global warming in the last 100 years, about 0.6° C or 1° F (IPCC, 2001: 2–3) because of the difficulty in determining temperatures in data-sparse mountain areas and the Antarctic. The estimate of warming is fairly accurate, just like an estimate of the rate of population growth in an area where the total population is not known, but the uncertainty in the "normal" temperature causes difficulties in validating the results of computer models because a model fills in the gaps and may not be realistic.

Most of the record of surface temperatures covers less than 50 years and only a few stations are as much as 100 years old. Environment Canada claims that its record is valid from 1948 but even that is debatable when you consider how few stations there are in the vast Arctic and sub-Arctic regions. The extent of the problem is manifest in the preface to Environment Canada's official publication, incorrectly titled *Canadian Climate Normals 1951-1980*.

> No hourly data exists in the digital archives before 1953; the averages appearing in this volume have been derived from all available "hourly" observations, at the selected hours, from 1953 to 1980 inclusive. The reader should note that many stations have fewer than the 28 years of record in the complete averaging. (Atmospheric Environment Services, 1984: 1)

The most complete temperature record is likely that for the continental United States for the period from 1880 to the present. This record shows warming from 1880 to 1940 when human production of carbon dioxide was low. From 1940 to 1976, the production of carbon dioxide increased dramatically, but temperatures in the United States decreased on average. Since then temperatures have increased only slightly despite a reported rise in carbon dioxide levels (NCDC, 2004).

Figure 3: Temperature anomalies from surface, satellite, and balloon records



Notes: Data from the three sources has been adjusted to create a common starting point; averaging period from which anomaolies are calculated: surface: 1961–1990; satellite: 1979–1998; balloon: 1958–1977. Spike in data for 1998 is a result of El Niño.
Sources: **Surface**—Parker, D.E., P.D. Jones, A. Bevan, and C.K. Folland (1994). "Interdecadal Changes of Surface Temperature since the Late 19th Century." *Journal of Geophysical Research* 99: 14373–99 (and updates). **Satellite**—Christy, J.R., R.W. Spencer, and W.D. Braswell (2000). "MSU Tropospheric Temperatures: Data Set Construction and Radiosonde Comparisons." *Journal of Atmospheric and Oceanic Technology* 17,1153–70 (and updates). **Balloon**—Angell, J. K. (1988). "Variations and Trends in Tropospheric and Stratospheric Global Temperature 19582/8/0287." *Journal of Climate* 1: 1296–313 (and updates).

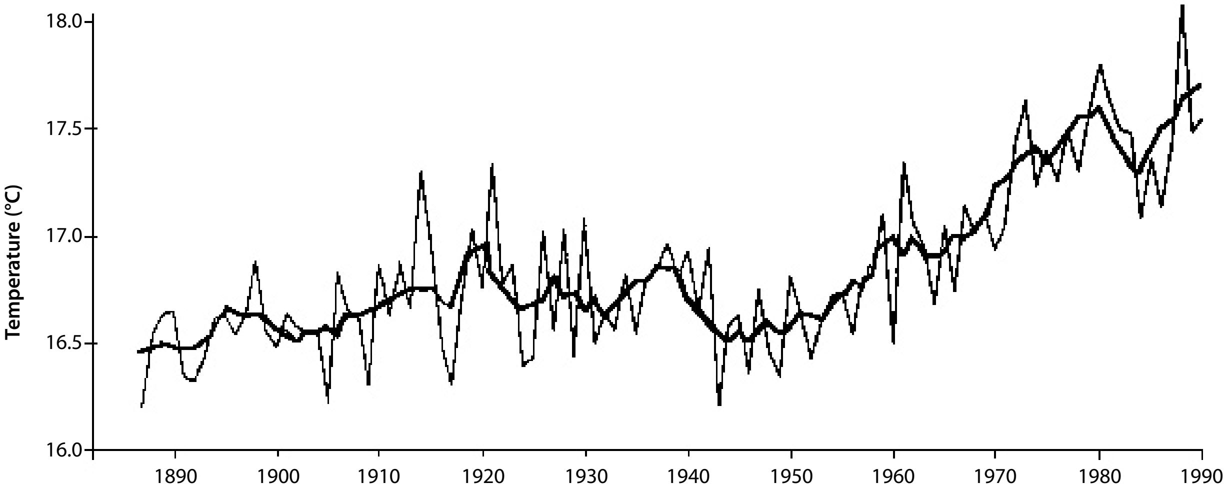
Record of temperatures above the surface

These problems are compounded by the fact that the above surface record is even worse: there is very little empirical data for most parts of the atmosphere though most models have at least 20 vertical layers.

The only reliable, sufficiently distributed, data is from earth-orbiting satellites that are able to survey the entire world atmosphere. It is revealing that, while these temperature measurements agree with those taken by weather balloons, they disagree considerably with the surface record (figure 3). Although satellite data show practically no global temperature change since measurements began in 1978 (only 0.07° C per decade in the lower troposphere, according to Dr. John Christy, Professor and Director, Earth System Science Center at the University of Alabama), this information is not used as a basis for GCMs because this is thought to be too short a time interval to be considered meaningful (Christy et al, 2000). One wonders if the satellite record would be dismissed so easily if it showed significant warming.

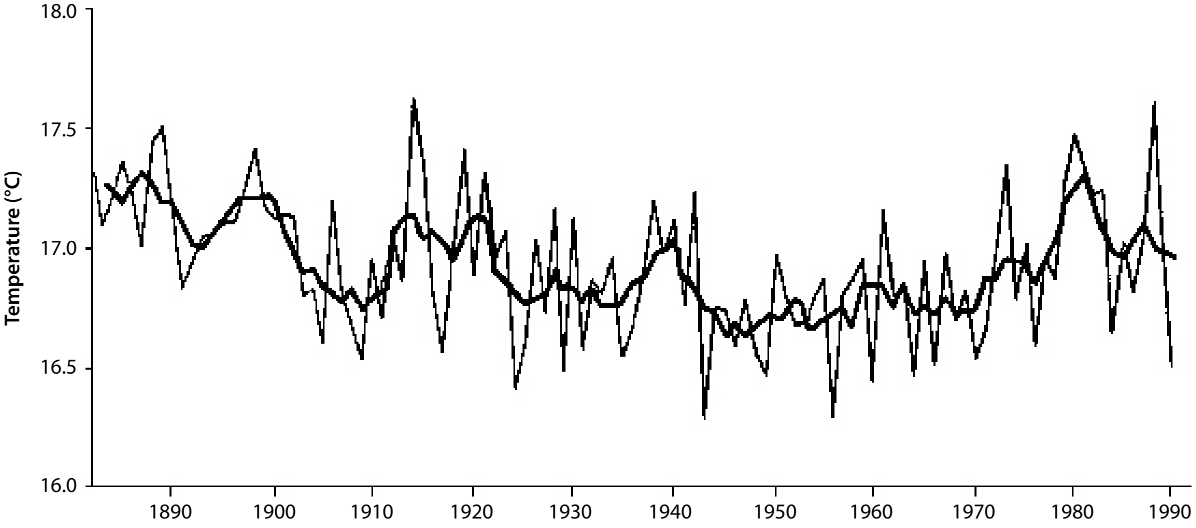
A study of Australian temperature records illustrates an even more significant problem. While six of their urban meteorological stations show dramatic warming after 1950 (figure 4a), 27 rural stations show no such trend (figure 4b). This difference is almost certainly caused by the "urban heat island effect," a phenomenon first measured by T.J. Chandler in 1952 for London, England. Most meteorological stations in western Europe and eastern North America are located at airports on the edge of cities but have been enveloped by urban expansion. Although climate modelers have made adjustments to compensate for the urban heat island effect other researchers have shown their adjustments are inadequate (Kalnay and Ming, 2003).

Figure 4a: Mean temperatures in the six Australian capital cities, 1890 to 1990



Note: The postwar temperature increase is due to the increase in the number of cars that allowed people to live further from the city centre. The city thus encompassed the airports and the thermometers at the weather station.
Source: Hughes, W.S. (1991). *The Australian Record on Global Warming*. Tasman Institute.

Figure 4b: Mean temperatures in 27 rural stations in Australia, 1890 to 1990



Source: Hughes, W.S. (1991). *The Australian Record on Global Warming*. Tasman Institute.

Questionable assumptions

A global climate model (GCM) is a mathematical simulation, programmed into a computer, of complex, three-dimensional, atmospheric circulation (see the Appendix, page 21 for details). These mathematical models of the earth's atmosphere are based on the accumulated results of a series of smaller mathematical models representing different parts of the earth-atmosphere system. GCMs divide the atmosphere into a three-dimensional grid of "boxes." In one GCM, the boxes are stacked above the surface nine layers deep, and each box is about 2.5° of latitude wide, 3.75° of longitude in length and several kilometers high. Newer models can use smaller boxes and more layers. Some models extend the elements below the surface of the ocean as well but most work with what is called a "slab ocean," a single-layer ocean. When the models are run, climate is averaged within each element according to certain mathematical equations to simulate processes believed to be important in affecting climate: for example, solar radiation going into each box from the sun, and out of each box due to reflection and scattering by aerosols and gases, chemical transformations of molecules, and movement of parcels of air from one box to another.

There are three basic types of GCMs that are identified by the way they simulate the ocean and atmosphere-ocean interactions. Each GCM employs one of the following methodologies.

(1) The atmosphere is linked with an ocean that is a single, thin, fixed layer or slab.
(2) The atmosphere is linked to an ocean that incorporates ocean currents and heat transport.
(3) The most sophisticated models link three-dimensional models of the biosphere, atmosphere, and a layered ocean.

The volume of data and the number of calculations that can be accommodated for a given GCM are limited by computer capacity. Only the largest computers can attempt to deal with the third type of GCM and these most advanced models do not necessarily produce more accurate results because interactions, especially with the biosphere, are poorly known and therefore crudely represented in the models. Such models are important scientific learning tools, however, as they help to identify gaps in knowledge and to test hypotheses about the operation and relative importance of different factors. These models investigate questions such as whether plants may grow faster or larger as greenhouse gases increase, what effects on tree species may result from shifts in climate zones, whether plants and trees may absorb more or less carbon dioxide in the future, whether changes in ocean currents may change the absorption or release of atmospheric carbon dioxide, and how projections of warming may change as the biosphere reacts to the changes in greenhouse gases and the climate itself.

GCMs and reality

The major limitation of GCMs is that they fail to represent reality: the actual atmosphere is a continuous, fluid, constantly interacting gaseous envelope, while the models assume it is made up of discrete cubes of arbitrary dimensions determined by the computer's computational capacity. GCMs also assume that each cube interacts with the others in constant ways, especially at the interface between the surface and the atmosphere.

Consider the difficulties when ice is the surface. We know that Arctic air is warmed by heat transmitted through the ice from the much warmer water below, but there are no measures of how this varies over time or space. The area of the Arctic Ocean covered by ice varies from approximately 7 million km^2 in summer to 15 million km^2 in winter (Cavalieri et al., 2003). There are regions where a rectangle of 2.5° and 3.75° covers land, sea, and ice, each of which have radically different reflective properties, but the model must assume an average for the entire rectangle (CCPP-ARM, 2003).

As if all these problems with GCMs were not enough, some models essentially ignore solar variations. The sun emits energy in two forms, electromagnetic energy (heat and light) and corpuscular energy (particles of matter known as the "solar wind"). Research by Baliunas (Baliunas and Soon, 1997) and Labitzke (Labitzke and Van Loon, 1988) among others consistently shows a strong correlation between changes in solar activity and terrestrial temperature. The IPCC models, by contrast, assume that variations in electromagnetic energy are small and of little consequence (Houghton et al., 2001: 383–84).

IPCC climate forecasts also depend on scenarios that project trends in energy use and greenhouse gas emissions. It is becoming increasingly clear that most of these scenarios are exaggerated. The most recent IPCC scenarios (prepared in 1998) predicted carbon dioxide emissions from the use of fossil fuels rising 15% from 5.99 to 6.90 billion metric tons of carbon from 1990 to 2000 (Nakicenovic and Swart, 2000: see, for example, the 1990 and 2000 columns on p. 381), but recent estimates are that emissions rose 9% from 5.93 to 6.47 billion tons (United States Energy Information Administration, 2003). And there are more problems with the IPCC scenarios than their estimates of overall carbon dioxide emissions. Estimates of different greenhouse gas sources are also flawed. While the IPCC scenarios assumed that global coal consumption would rise between 4% and 31% during the 1990s, in one estimate coal consumption fell by about 7% during this period (Marland et al., 2003).

Economic elements of future scenarios are also problematic. As researchers Ian Castles, formerly the head of Australia's national office of statistics, and David Henderson of the Westminster Business School and formerly the chief economist of the OECD, point out, the IPCC modelers inappropriately compared future estimates of GDP in terms of exchange rates rather than purchasing power parity. This produces GDP estimates that are significantly inflated, leading to estimates of greenhouse-gas producing activities that are similarly inflated. Castle neatly illustrates the fallacy of this approach when he observes that even for the lowest emission scenarios used by the IPCC, the average income of South Africans will have overtaken that of Americans by a very wide margin by the end of the century (Castles, 2003: 22). The article goes on to explain that, because of this economic error, the IPCC scenarios of the future also suggest that relatively poor developing countries such as Algeria, Argentina, Libya, Turkey, and North Korea will all surpass the United States.

Finally, other researchers, including one of us (Green) as well as James Hansen (called "the father of global warming"), have criticized the IPCC's future scenarios for assumptions that current reality has already shown to be false or questionable, such as:

- there are no mid-course greenhouse gas reduction programs implemented between now and 2100;
- global deforestation is not abated;
- most energy production will be from carbon-based fuels;
- carbon dioxide emissions will nearly quadruple by 2100;
- methane emissions will more than double by 2100;
- carbon monoxide emissions will nearly triple by 2100;
- volatile organic carbon emissions will nearly triple by 2100; and
- fluorocarbon levels will rise dramatically by 2100, in some cases by two orders of magnitude (Green, 2000; Hansen, 2003).

A major weakness of the IPCC's and other computer model studies, as well as analyses by most environmental groups, is that they assume "business as usual." In reality, countries around the world are already implementing programs that will reduce emissions of greenhouse gases as a byproduct of controls on traditional air pollutants, while markets continue to demand the "decarbonization" of fuel as an aspect of competitiveness (Ausubel, 1996). Both governments and private conservation groups are taking action to slow deforestation. Emissions of methane, carbon dioxide, and fluorocarbons, as discussed above, are based on economic development, which was grossly over-predicted in most IPCC emission scenarios.

Summary of weaknesses in GCMs

Problems with the data

The database for the models, the surface, upper air, and ocean record, has the following weaknesses.

The database is dominated by a high density of measurements from a small portion of the earth's land surface. The only regions of the world with adequate density of stations are the continental United States and western Europe. Even for those regions most of the stations are in, or very close to, urban areas. The surface record has virtually no coverage of forests, deserts and polar regions, not to mention the oceans, that cover about 70% of our planet. Meaningful records only began in Antarctica in 1957.

Database is of short duration, mostly less than 50 years. Global average surface temperatures have been computed back to 1856 but the amount of data per year diminishes farther back in time. Temperature data for Toronto extends back to 1840 but Environment Canada's climate data covers the whole country only back to 1948. For variables besides surface temperature (such as precipitation, snowfall, cloud cover, sunshine, water vapour, and upper air temperature), global averages and trends must be computed from satellite observations, but suitable satellites observing the whole earth daily have only been orbiting since late 1978.

Database is distorted by urban heat islands. In 1952 T.J. Chandler measured the temperatures of Greater London and found them warmer than the surrounding countryside. This trend has been confirmed for most urban weather stations and was dramatically underscored by an Australian study comparing 100 years of record for urban and rural stations. Failure to account for the urban effect led to the claims of dramatic warming of the 1980s and 1990s and, while adjustments are made today and the predictions of warming significantly reduced, many researchers believe the adjustments to be inadequate (Kalnay and Ming, 2003).

The satellite record that gives total global coverage is at variance with the surface record. The satellite record of lower atmospheric temperatures since 1978 shows a very slight warming, in agreement with the weather balloon temperature record (United States National Atmospheric and Space Administration, 2003), but disagreeing with substantial warming at the surface. However, both satellites and weather balloon instruments have flaws. Each satellite lasts only a few years and problems in determining differences between satellites cause spurious jumps in the data that distort computed trends. Weather balloon instruments have become more sensitive, which cause discontinuities in trends as individual stations change instrument models every few years.

Difficulty in constructing equations for complex physical systems

There is a general inability to transform our understanding of the components of climate systems into mathematical equations. GCMs are an amalgam of computations for different segments of the atmosphere and so their outputs are only as accurate as the results of the calculations for each segment. The understanding of interactions is especially inadequate: for example, we only began to measure the interchange of energy and gases between the atmosphere and the vast boreal forest in the late 1990s. Although equations used in GCMs require that all components of the system be incorporated into the models to operate correctly, most still use crude estimates or omit variables entirely due to lack of empirical data.

Our knowledge of each component of the climate system is still limited. Such factors as soil moisture, sea ice, changes in albedo (the reflectivity of the earth's surface), and deep ocean circulation where energy and dissolved greenhouse gases can be stored for millennia are all essentially unmeasured (Edwards and Weart, 2003).

Data on climate components, such as rates of evaporation from the oceans, provide only crude and uncertain estimates, not hard numbers, as most people assume. Energy and gas interchanges between the atmosphere and the land or ocean surface are a major component of the earth's climate system yet there is little relevant empirical data and even less understanding (United States Government Accounting Office, 1995).

Aerosols (atmospheric particles) are not accurately represented in climate models. Most models emphasize cooling from reflective particles and neglect warming from dark particles. Though levels of both light aerosols and dark aerosol are expected to diminish due to controls on air pollution, models predict greater warming as light aerosol levels decline due to pollution controls but do not consider that warming will be reduced as dark aerosols are controlled. (Michaels and Balling, 2000: 66).

Scientists still do not understand the complex interactions among the factors that affect climate, and so are unable to reproduce them. Yet understanding of these phenomena is essential in order to develop GCMs that provide useful predictions (Weart, 2003).

Conclusion and Recommendations

Many governments worldwide have based their national environmental programs and major economic decisions on the conclusions of global climate models (GCMs) developed and run by the IPCC. This is very unfortunate. The IPCC's alarmist predictions of future climate catastrophe are based on GCMs that, while useful in performing theoretical studies in academia, are completely unacceptable as a basis for policy making. Indeed, scientists like Dr. Richard Lindzen, a lead author of one of the IPCC's reports and the IPCC reports themselves warn against using their work as the basis of public policy.

Instead of moving ahead with the implementation of expensive and unproved Kyoto schemes based on the improper use of computer models, policy-makers should to make a sound "reality check" on the science of climate modeling. Claims that "the science is solid" by Kyoto's advocates such as Canada's environment minister, David Anderson, would be unimportant were it not that most of the public and the Media, believing such unfounded reassurances and the forecasts of GCMs,accept that we need a major effort to reduce greenhouse gases.

Recommendations

- Reexamine the science of climate change and stop grounding policy in the output of computer models of limited utility. Models are primarily useful to scientists to determine what is known and not known about climate processes. Therefore, they only suggest probabilities, not certainties, about the future.

- Acknowledge that published scenarios of future greenhouse gas concentrations are skewed toward unlikely high growth in emissions and, therefore, climate models using these scenarios will tend to project unrealistically large warming.

- Acknowledge that models cannot accurately predict the absolute amount of warming (or other climate change) resulting from a particular scenario of greenhouse gas concentrations. However, if a model is run using two realistic scenarios (with and without a proposed action), differences between the model-projected paths of climate change may be credible.

- Acknowledge that the effect on global climate of implementing a particular action will be extremely slow to occur. If the action involves only one country, the effect on global climate may be undetectable, even after a century. Policies that produce worthwhile emissions reductions will certainly require international cooperation over a long period.

- Recognize that some climate changes (both natural and human-caused) are climate surprises, or events that are not anticipated in advance (and, by definition, are not properly incorporated into models). Any climate surprise in a future projection from a model is probably an error because of the many assumptions and simplifications in models.

- Perform full and transparent economic and risk analyses of the costs and effectiveness of proposed greenhouse gas control actions, including alternatives. If an analysis is not performed in an open process, it is subject to the same pitfalls as the usual analyses performed to justify decisions such as tax policies, convention centers, or transit projects. An economic analysis that projects a very high cost (usually because the time table for the proposed action is too fast) should not be an excuse for taking no action but alternative actions (possibly international cooperation such as trading emissions credits or a gradual but longer-sustained improvement) may be more effective and less disruptive.

- Redirect some of the resources currently being allocated based on a model-based focus on greenhouse gas emission reductions toward research efforts to improve the state of weather and climate forecasting. In the next few years, the main improvements are likely to be better forecasts of the regional effects of recurring variations such as El Niño.

- Allocate some resources toward researching probabilities of different outcomes. The projected global average surface warming from 1990 to 2100 has a large range of 1.4° to 5.8° C or about 3° to 10° F (IPCC, 2001: 13), with no probability distribution specified. However, the possible range of greenhouse gas concentration scenarios is included as an uncertainty along with the genuine scientific uncertainties. For a policy-maker, it is more useful to know how the uncertainty range shifts with and without a proposed course of action.

- Redirect some of the resources currently focused on greenhouse gas mitigation to research programs that will help Canadians adapt to climate change regardless of origin. For example, research efforts to predict economic impacts of climate change tie together chains of assumptions and uncertainties prematurely. Climate impacts depend on projected climate changes, which in turn depend on greenhouse gas concentrations, which depend on an emissions scenario, which finally depends on the path of development of society. Because of uncertainties, it is not valid to say: "An impact of business as usual in 2100 will be a certain number of dollars of flooding damage from sea level rise." However, it is legitimate and important to estimate the impacts of coastal flooding with a certain sea level rise or effects on Great Lakes shipping due to changed ice cover from a specific amount of warming, regardless of the cause of the rise in the sea level or the warming.

Appendix—primer on global climate models

What is a global climate model and why would we use one?

In scientific parlance, a model is a mathematical description of important characteristics of a system. Models are used when it is impractical to perform experiments with the actual system one wishes to study, as is obviously the case with the climate. Global climate models (GCMs)—also called general circulation models—were created to help scientists to explore questions such as: "Would the climate have stayed constant if humans had not added certain gases to the atmosphere?"

Weather models

Weather models mathematically describe physical principles that control the weather, such as conservation of mass and energy. Just as climate is simply the long-term character of weather, a climate model simulates weather over an extended time—from a few weeks to thousands of years.

The weather at a given location and instant can be described by only a few quantities called variables. The six basic variables are temperature, pressure, wind speed (in three dimensions), and amount of water vapour. In the real world, differences in conditions between locations continuously cause forces and flows of energy and mass, which result in weather changes. The change in each variable is expressed mathematically by a "differential equation," so the weather everywhere in the world can theoretically be described using only six equations. Unfortunately, the variables are interrelated in such a complicated way that we cannot solve the equations mathematically to predict the future. In addition, we cannot possibly collect enough data to describe the weather at any instant—used as a starting point to make a forecast—over the whole world.

Even though we cannot describe the weather perfectly, usable daily forecasts can be made using a weather model that is simpler than the real world and data collected at a "reasonable" number of locations all around the world. Because the data and model are not complete or perfect, forecasts of the conditions at any location become more and more inaccurate after only a few days. Surprisingly, this is not a fatal hindrance for climate models. A climate model is a somewhat simplified weather model designed to simulate a long period in a reasonable amount of computer time. Only the long-term averages are of concern, not the day-to-day weather. Seasonal climate forecasting uses sea surface temperatures and other slowly changing factors to project whether an area is likely to be hotter or colder, or wetter or drier, than normal up to about a year in advance. Climate projections that are the subject of this paper are based on models that use measurements or projections of global greenhouse gases, land use (cropland versus forests, cities, and so on), and other factors to estimate changes in climate over periods of hundreds of years.

Any weather or climate model is constructed in a similar way. The model divides the atmosphere, oceans, and upper layers of soil into a three-dimensional grid. Starting with a "snapshot" of meteorological conditions such as temperature, wind, and so on in all grid boxes at a beginning time, the model repeatedly performs a two-step "marching" process to simulate the desired period, as though creating frames in an animated "three-dimensional" climate movie. In the first step, the model solves interlocking sets of equations within each grid box to compute the rates of change of the variables. In the second step, it extrapolates the changes forward a small step in time to produce a prediction of future weather variables in each grid box. This two-step procedure is repeated until the entire time period desired has been simulated. Model output can be displayed as a movie but usually only general statistics are collected.

There is no sharp distinction between weather and climate modeling although weather models usually simplify treatment of slowly changing phenomena, such as the formation or melting of sea ice.

What basic processes control the earth's climate?

Climate is simply the long-term character of weather. The two basic processes controlling the earth's climate are based on energy and motion. The long-term energy balance between sunlight and energy lost to space controls the global temperature. Motion of the air and ocean, which redistributes heat and controls local climate, is driven by heating differences. Other processes are described in a third category called feedbacks, where changes in the climate induce other changes in the environment that can increase or decrease the retention of heat in the atmosphere. The following brief summary illustrates some factors a climate model must simulate.

Energy processes

In the long run, the earth loses as much energy to space as it absorbs from the sun, an average of 236 watts per square meter (22 watts per square foot) (Willson, 1997). Solar energy warms the earth, and the earth emits energy back into space. The earth's "radiative temperature" that balances incoming and outgoing energy is –18° C (0° F) but the average surface temperature is 13.9° C (57° F) due to the natural greenhouse effect. Since air is nearly transparent to light, most sunlight reaches and heats the surface, which emits infrared energy. But greenhouse gases in the air absorb most infrared energy and, acting somewhat like the glass in a greenhouse, reflect much of it back toward the surface. Thus, heat is temporarily trapped before escaping to space—the natural greenhouse effect.

Motion processes

Global circulation patterns, driven by energy from heating and evaporation, spread tropical heat to higher latitudes and altitudes. Solar heating warms the air near the surface, which makes the atmosphere unstable as warm air rises. In simple terms, warm air rises near the equator and cold air sinks near the poles. The earth's rotation from west to east makes this circulation more complex. When air moves to a different latitude, its momentum is constant, so it moves more slowly than the surface if it moves toward the equator, or faster than the surface if it moves poleward. This effect is called the Coriolis force, which turns air to the right in the Northern Hemisphere. The Coriolis force is strongest near the poles and it decreases to zero at the equator. It is not the only force that governs the circulation pattern of fluids. Air moves counterclockwise (to the left) around a low pressure area in the Northern Hemisphere because of both Coriolis and pressure forces. At smaller scales, other forces such as friction and viscosity predominate. A few tornados rotate in the "wrong" direction, and water can flow down a drain either in a clockwise or counterclockwise direction. The earth's size and rotation rate produce six distinct "cells" of symmetrical circulation north and south of the equator, each about 30° of latitude wide. Outside the tropics, convergence between cells concentrates air flows a few miles above the surface into two jet streams from the west in each hemisphere. The Coriolis force is nearly zero near the equator. Convergence between the two tropical cells produces a band of thunderstorms called the Intertropical Convergence Zone (ITCZ). Because the Coriolis force is weak in the tropics, there is no strong jet stream above the ITCZ.

Daily weather in every location and season varies considerably from the idealized climate pattern. Friction between the atmosphere and the earth's surface creates sharp boundaries (warm and cold fronts) between contrasting air masses. Low-pressure areas form along the fronts, with intertwined paths of rising and sinking air. Mountains, and the irregular distribution of ocean and land, stir the air flow further. The earth's tilt on its axis causes seasonal cycles as well. The polar circulation expands in the winter hemisphere, the tropical circulation expands in the summer hemisphere, and the ITCZ (especially over land) moves north or south to be close to the latitude where the sun is vertical at noon.

Ocean circulation is driven by similar forces but heating stabilizes the ocean because warm water is buoyant. Water sinks if it becomes cold and salty due to evaporation or freezing (both processes leave salt behind), which creates a strong heat conveyor system as warm water flows in to replace the sinking water. The oceanic "conveyor belt" is called the thermohaline circulation. Areas of persistent sinking into the deep ocean are small, mainly around Greenland and Antarctica. Sinking water near Greenland generates currents from the southwest (the Gulf Stream and North Atlantic Drift), which keep the European climate much milder than other high latitude regions.

Feedback processes

Many factors affect climate indirectly through feedback processes. A negative feedback opposes the original change, which stabilizes the system. A positive feedback causes an additional change that amplifies the original change. Negative feedbacks, which are analogous to political checks and balances, are predominant in natural systems. Several major factors like the following can act as feedbacks.

Water

Water has a complex role in regulating the earth's temperature since it exists in three phases (vapour, liquid, and ice) and has a large heat capacity. Heat capacity is a measure of how much energy must be applied to a substance in order to change its temperature. It takes about one calorie to heat a gram of water by 1° C but only about 0.1 to 0.25 of a calorie to heat a gram of air or most common minerals. Each phase of water conducts, absorbs, and reflects energy differently. The energy involved in changing water from one phase to another is particularly large. Evaporation and melting absorb energy while condensation and freezing release energy. Energy absorbed in vapour or liquid water is called latent heat because it does not increase temperature until it is released. Latent heat carried away in water vapor is released and heats the air where the water condenses, providing energy for storms.

Water acts mostly as a negative climate feedback by absorbing or releasing energy in ways that slow the warming or cooling of adjacent air. Freezing and melting prolong the time an area stays close to freezing. Evaporation transports much tropical heat to higher altitudes and latitudes where the vapour condenses. Clouds have additional warming and cooling effects. Thin high clouds trap much of the earth's heat energy, causing warming, but thick and low clouds reflect most incoming sunlight, giving a cooling effect. The net effect of clouds, according to current estimates, is to cool the earth slightly. Because the heating and cooling effects are large and nearly equal, it is difficult to make measurements accurate enough to determine which effect predominates when averaged globally. It is especially difficult to determine how the heating and cooling effects will change as the climate changes (Houghton, 1997). In contrast, snow and ice act as a positive feedback because they reflect incoming sunlight: expanded snow and ice cover reflects more sunlight and prolongs cooling, while after snow or ice melts, the exposed dark surface absorbs more solar energy.

Aerosols

Aerosols are particles from processes such as dust storms, forest fires, use of fossil fuels, and volcanic eruptions. Aerosols that form around carbonaceous materials (soot) tend to absorb sunlight while aerosols made up mainly of sulfurous materials (sulfates) tend to reflect light. A large volcanic eruption cools the climate for several years by injecting sulfates into the stratosphere. Aerosols can have both direct and indirect feedback impacts. Particles in a dust storm, for example, directly absorb or reflect solar energy. This shades and cools the surface but also suppresses cloud formation, which allows more sunlight to reach and warm the surface. But clouds form by condensing on particles, so sulfate particle emissions can actually increase cloudiness, causing indirect cooling that may exceed the warming effect.

Land and oceans

Different surfaces absorb different amounts of solar energy. A forest absorbs up to 95% of sunlight but also can store much water. Sunlight increases evaporation, removing much of the heat as latent heat and often increasing clouds, which reflect sunlight. Therefore, a forest tends to moderate extremes of hot temperature. Grass and sand reflect more solar energy and retain less water than a forest, so such areas are heated more by sunlight and cool more at night due to radiative cooling. Water absorbs over 90% of incoming solar energy unless the sun is close to the horizon while snow and ice reflect most sunlight.

Solar energy heats mainly the top few centimeters of soil, which quickly heats the air. Over the ocean, wind stirring distributes absorbed heat through the mixed layer, approximately the top 100 meters (330 feet) of the ocean. The mixed layer stores about 28 times as much heat as the entire atmosphere, so the ocean and air above it change temperature slowly.

What factors cause the climate to change naturally?

Solar output

When the sun emits more energy, sunspots are numerous and the earth warms. Solar energy varies by about 0.1% over an 11-year solar cycle (Lean et al., 1995). From 1750 to 2000, the sun probably brightened by about 0.25% as the Little Ice Age ended (IPCC, 2001: 393). Much of the brightening occurred from about 1890 to 1960, followed by little change (Lean and Rind, 1995). Slight dimming, around 0.05%, is expected through about 2018 (Lean and Rind, 1995).

Orbit of the earth

There are three major orbital variations with very slow cycles lasting from 20,000 to over 100,000 years, caused mainly by the gravity of Jupiter. The orbit varies from circular to slightly elliptical, the date when the earth is closest to the sun precesses (moves forward through the year), and the tilt of the axis varies. These cycles have almost no effect on global annual sunlight but change solar intensity at each latitude and season. The Milankovitch hypothesis states that ice ages are favoured when combined cycles cause cool summers in high northern latitudes, which prevent snow from melting (Burroughs, 1992).

Greenhouse gases

Air bubbles in ice cores from Greenland and Antarctica (the thickest ice includes the last four ice ages) have been analyzed to reconstruct the time history of concentrations of several greenhouse gases (Petit, 1999). Greenhouse gases are less abundant during ice ages due to natural processes that are poorly understood (Houghton et al., 2001). While greenhouse gases are currently increasing due to human activities (so climate effects will lag the changes in greenhouse gases), in the recovery from the last ice age, warming occurred before the greenhouse gases increased (Fischer et al., 1999).

Albedo

The albedo of an object is the percentage of incoming solar radiation (insolation) that it reflects. The earth's albedo is about 30%, meaning that the earth is heated (mostly at the surface) by the 70% of solar energy that it absorbs. Albedo is an important factor in climate change, as discussed in the next few factors.

Cloud cover

An average cloud reflects 45% of incoming sunlight, ranging from a few percent for thin cirrus to over 90% for cumulonimbus (thunderstorm clouds) (Bryant, 2001). If a climate perturbation occurs, clouds could be a net negative or positive feedback. Warming a tropical ocean may form more thunderstorms but the shading would reduce heating (a negative feedback). If air flowing from the top of the storms produces many thin high clouds, not much sunlight is reflected and heat may be trapped under the high clouds, causing a positive feedback.

Volcanic eruptions

A large volcanic eruption injects reflective sulfate particles into the stratosphere. This cools at least one hemisphere (a tropical eruption usually affects both hemispheres) for a few years. In some geological eras, frequent volcanic activity probably caused prolonged cooling.

Dust

Dust absorbs some energy, which warms the top of the dust layer, but shades and cools the surface, making clouds less likely to form. Reduced cloudiness could offset the cooling but prolongs dryness and dustiness. Some types of particles attract water and make it easier to form clouds. In the last ice age, about 40 times as much dust was deposited onto Greenland as at present due to stronger winds over large deserts in North America (Bryant, 2001).

Vegetation and land surfaces

Surface changes may either amplify or counteract other climate change factors. A forest may absorb up to 95% of incoming solar energy while grass and bare soil are much more reflective. In a drought, incoming solar radiation usually increases due to reduced cloud cover, but plants reflect more energy as they become dry, which may restrain the warming. In the last ice age, surface changes in addition to the growth of ice sheets may have intensified the cooling. The global ocean area shrank by 8%, much of the newly exposed land had little vegetation, and many forest areas were replaced by bare soil (Clark and Mix, 2000). These three changes may have reflected as much solar radiation as the expanded ice sheets. Expansion or contraction of the deserts and the polar ice caps are factors that can trigger global climate change. An early theory by A.T. Wilson argued that expansion of the Antarctic ice sheet to approximately 50°S would reflect a critical 4% of the sunlight away from the earth (Lamb, 1977: 320).

Atmospheric circulation and topography

Atmospheric circulation is affected by topography and the land-ocean distribution. In the last ice age, ice sheets grew to over 2.6 times the current volume and sea level dropped 130 meters (425 feet), increasing the land and ice volume above sea level by 56% (Clark and Mix, 2000). The ice cap centered on Hudson Bay was as large as Antarctica, which diverted storm tracks around it and affected air flows around the world.

Ocean circulation

Air moving over water quickly approaches the water temperature. Ocean currents transport very large amounts of heat and do not move much geographically (except in shallow areas where some passages were above sea level in ice ages) but fluctuate in strength. When the oceanic "conveyor belt" weakens and less salty water sinks near Greenland, Europe becomes colder because less warm water comes from the Caribbean.

Sea ice

Sea ice reflects most incoming solar energy. Ice insulates the surface, allowing the air to be much colder than the ocean. Evaporation from an ice-covered ocean is reduced, freezing causes surface water to become saltier and denser, and melting makes surface water fresher. All of these aspects of climate change if the amount of sea ice in an area changes. In the last ice age, occasional collapses of large portions of the ice cap over Canada covered much of the northern Atlantic with icebergs, reinforcing cooling for hundreds of years.

Chaotic characteristics

Weather is "chaotic" because a small initial uncertainty amplifies globally in a few weeks, so two starting conditions with imperceptible differences will eventually produce unrecognizably different weather maps. Although weather is "chaotic," climate is usually not chaotic because some general trends persist and may be forecast a year or so in advance. However, a chaotic feature of climate is that a small "push" may, in certain conditions, flip the climate into a very different state. The last few thousand years have been exceptionally stable but ice cores indicate that much of the last ice age alternated between a relatively mild and a very cold and windy state (about 6° C or 11° F colder around Greenland), with each state persisting around a thousand years and flipping to the other state in a few years (Bryant, 2001).

What are some mechanics of a simulation model?

To produce a forecast or simulation, a weather or climate model describes the earth as a grid, where each grid position is a specific location, and solves the equations on that grid at specific time intervals until the forecast or simulation is completed. However, in the atmosphere, each small "parcel" of air moves in response to forces, and it experiences continuous changes as it moves. A model needs to determine the weather at the grid locations (which do not move) at fixed times as the air passes by. A usable model requires a suitable grid and equations expressed in an appropriate form to be solved on that grid.

Describing the oceans, land, and atmosphere as a grid

The atmosphere and ocean are represented in models using a three-dimensional grid or lattice, with each grid point representing the volume of air or water (which could be called a grid box) closer to that point than to any other grid point. In one climate model, an average grid point represents an area about the size of Ohio (Pope, 2000). Small grid boxes allow more realism but require more computations because more grid boxes are needed to cover the earth. The most detailed short-term forecast models have grid boxes only a few miles square and can almost represent thunderstorms but it is not practical to use such a model for climate simulation. Some grids are irregular with closer spacing in certain areas;

for example, ocean grids along coastlines. The vertical grid interval is much smaller than the horizontal interval (20 to 30 layers are typically used), with layers usually closely spaced near the surface and around the tropopause, where large temperature and moisture changes in a small vertical distance are likely (The tropopause is the boundary between the troposphere and the stratosphere, about 5 miles above sea level near the poles, and 12 miles above sea level in the tropics).

Arranging equations for solution on a grid

The full set of differential equations is too complicated to solve exactly. However, any equation can be solved numerically (by using algebra, with a slight loss of accuracy) as a "finite difference" equation. A finite difference equation expresses rates of change (the unknown values) in terms of known variables at grid points. For example, the change in wind speed depends on pressures at nearby grid locations.

Running the model

Modeling is a four-dimensional problem, including time. Just as a movie contains many frames to represent the continuous action in a scene, a model "marches" forward in small time steps (in a typical climate model, each time step is a few minutes to a half hour) to simulate the weather or climate in a specified period. Starting with the values of all variables (temperature, wind, and so on) at each grid point at some instant, the model first solves all of the equations at each grid point to determine the rates of change of each variable, and then extrapolates the rates of change forward to predict the variables at the end of that time step. The two processes (solving equations at an instant and projecting the changes for a time step) are very suitable for parallel processing, where up to thousands of computer processors work simultaneously, since computations for each grid point are made separately.

The number of predictions required to simulate a day equals the number of grid points times the number of time steps in a day. One typical climate model makes over 6.3 million grid-point predictions per day of simulation, or about 2.3 trillion predictions to simulate 1000 years. Each grid-point prediction requires hundreds or thousands of computer computations. Weather forecasting and climate prediction have always motivated the development of faster computers with larger memory capacity because the number of calculations increases rapidly as resolution improves. The world's most powerful computer, the US$350 million "Earth Simulator" in Japan is testing a model with 15-kilometer grid boxes (still a little larger than a thunderstorm) and 96 layers in the atmosphere but even it could not model thousands of years of climate (or dozens of 200-year simulations) in a reasonable amount of time (IPRC Climate, 2004).

What inputs are used for climate modeling and where do they come from?

Inputs for a climate model include initial values of atmospheric, oceanic, and land-surface conditions and a scenario describing greenhouse gas levels and other variations.

Initial values

Starting a climate model is not as simple as supplying a "weather map" of available data at some chosen time because observations are not complete and small errors generate spurious results (when simulating the current or recent climate) or no observations are available (when simulating a past climate). While a forecast model must start with the most recent conditions to produce a useful forecast, a climate model only needs to start with a plausible situation that may not represent any actual day. Often, a climate model is "spun up" from an atmosphere and ocean at rest. As solar energy is supplied to the simulated planet, realistic weather patterns gradually build up with no data imbalances. While the atmosphere may appear realistic after a few months, a realistic ocean may require 100 years of simulation, so special techniques are used to accelerate the "spin up." The realism of the steady-state simulated climate is an important test of the model since it is not supplied with (for example) the correct global average temperature. The simulation may continue for a long time as a "control run" to ensure that the simulated climate does not slowly drift. The "spin up" data is discarded, and steady-state data is archived to start model runs without repeating the "spin up."

Scenarios

A scenario of external conditions and their time variations must also be supplied for models to function. To simulate the current climate (and to provide a "control run"), constant values of solar radiation, aerosols, and greenhouse gases are input. To simulate the last century or so (or even the last 100,000 years or more), trends of these factors, volcanic eruptions, and possibly other known changes are supplied. Concentrations of most greenhouse gases have been measured for a few decades and earlier concentrations can be estimated from bubbles trapped in glacier ice. Historical carbon dioxide emissions from the use of fossil fuels and cement production are fairly reliable, although two sources differ somewhat (United States Energy Information Administration, 2003; Marland et al., 2003). Emissions from changes in land-use such as deforestation are uncertain (Houghton and Hackler, 2002). There is little data about aerosol trends and whether cooling or warming effects predominate, so including these trends essentially amounts to adding an arbitrarily adjustable parameter that can be varied until the climate simulation appears realistic.

To simulate a future climate, a scenario of projected greenhouse gas concentrations and other forcing factors is supplied. Until recently, computer power was not sufficient to allow a long simulation with a realistic scenario. Four stages of development led to the current range of published scenarios.

(1) Early models could only simulate short periods and were run several times with fixed inputs depicting (for example) the present climate, doubled carbon dioxide, and the last ice age.

(2) Because the climate system does not instantly adjust to a radiative change, in the early 1980s a few models were run with instantaneous carbon dioxide doubling or a similar change to estimate the speed of adjustment of the atmosphere and ocean to a change.

(3) By the late 1980s, some model runs considered gradual changes in greenhouse gas concentrations, such as a 1% per year compounded growth of equivalent carbon dioxide (Stouffer et al., 1989). This growth rate has not occurred in reality. However, a scenario of 1% annual growth is still widely used to calibrate different models.

(4) Soon after the first model runs were made with simplistic greenhouse gas growth, detailed scenarios were published by the IPCC, specifying greenhouse gas emissions and concentrations, and other radiative forcing factors, from 1990 to 2100.

The IPCC's scenarios are widely used for standardized comparisons. In 1992, six scenarios were published including "business as usual" (Houghton et al., 1992) and 40 scenarios were published in 2000 (Nakicenovic and Swart, 2000). These scenarios are based on other published scenarios, United Nations' population and economic projections, and expert opinions concerning development and adaptation of new technologies. All scenarios assume growing prosperity and some increase in energy efficiency but no explicit actions to comply with emission reduction treaties; no scenario is a prediction or recommendation (Nakicenovic and Swart, 2000). A disproportionate number of the published scenarios have extremely high emissions growth rates.

A scenario specifies a time path of emissions but climate depends on greenhouse gas concentrations. A separate model projects concentrations by modeling processes that remove gases from the air. Knowledge of these processes is based on limited experiments. For example, certain plants may store more carbon in plant tissues with more carbon dioxide in the air. The chemical equilibrium between carbon dioxide in air and water can be measured in laboratory experiments but the rate of mixing of carbon dioxide into deep ocean currents must be modeled. Since the mid-1960s, the growth of carbon dioxide in the air has been about 42% of the total emitted by human activities because plants and oceans have absorbed the other 58%. A major uncertainty in projecting future concentrations is whether these carbon dioxide removal processes will continue to be effective.

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Acknowledgments

The authors would like to thank Chip Knappenberger of New Hope Environmental Services for providing the data for the chart of surface, satellite, and weather balloon temperature anomalies.