Degrees of Certainty

STEPHEN H SCHNEIDER

Debate in the media over global warming often mixes what is well known with what is speculative, thereby leading to an artificially confusing impression that scientists share no consensus of the probable magnitude, timing, and potential seriousness of the environmental and societal consequences of the documented and well-understood buildup of various greenhouse-enhancing gases in the atmosphere. Indeed, widespread concern exists over the plausibility of temperature increases of 1 to 5°C in the 21st century, and that the mid to upper part of that range could imply dramatic restructuring of ecosystems or communities. I discuss the difficulty in interpreting the 0.5 ± 0.2°C 20th century warming trend as "proof" of greenhouse-gas–induced global warming in light of possible climatic-change causal factors such as industrial aerosols, natural fluctuations, or changes in solar output. How to act is controversial, and economic model results showing potential abatement costs of carbon taxes are discussed.

SCIENTISTS TOO OFTEN SHARE RESPONSIBILITY with the media for not clearly communicating complex science issues to the public. Most members of the general public, as well as many officials in government, do not recognize that most scientists spend the bulk of their time arguing about what they do not know. Most scientists consider discussions of well-accepted, proven ideas as "old hat" and not worth our time. That attitude is not without merit, however, for the scientific method operates on the basis of constant questioning, particularly for issues that are not yet well-validated. But if the public and its representatives do not understand our process and its focus on not-yet-resolved issues, they will not easily interpret what has been called the "dueling scientists" debate over global warming, regardless of whether the scientists are ideologically driven. We simply have to spend more time making clear the distinctions among what is well-known and accepted by most knowledgeable scientists, what is known with some degree of reliability, and what is highly speculative.

The public debate on global warming rarely separates those components, thereby leaving the false impression that somehow the scientific community is in overall intellectual disarray. In fact, the 15-year-old often-reaffirmed U S National Academy of Sciences consensus estimate of 1.5 to 4.5°C global average warming if CO_2 were to double still reflects the best estimate from a wide range of current climate models[6] and ancient climatic eras.[7] The Earth has not been >1 to 2°C warmer than now during the 10 000-year era of human civilization. The previous ice age, in which mile-high ice sheets stretched from New York to Chicago to the Arctic, was "only" 5°C colder than the current 10 000-year-old interglacial epoch we now enjoy. This 1.5 to 4.5°C warming range still includes those studies that recently halved the best guess on warming from >4°C to 2.5°C. Perhaps some new discovery next week will push it back up again, but even if not, that enduring 1.5 to 4.5°C warming consensus still remains.

Changes of this magnitude could dramatically alter accustomed climatic patterns, affecting agriculture, water supplies, disease patterns, ecosystems, endangered species, severe storms, sea level, and coastal flooding.

Unless scientists communicate what they know along with what they do not know, the public policy process is subverted in an endlessly confusing debate that inadequately represents the actual nature of informed opinion. It is difficult for the media to do what sometimes I wish they would: back off their concept of "balance" in favor of the concept of "perspective." If an issue is complicated, it is not enough to give equal inches or minutes to "all sides"—a practice that often leaves the public more confused than before,

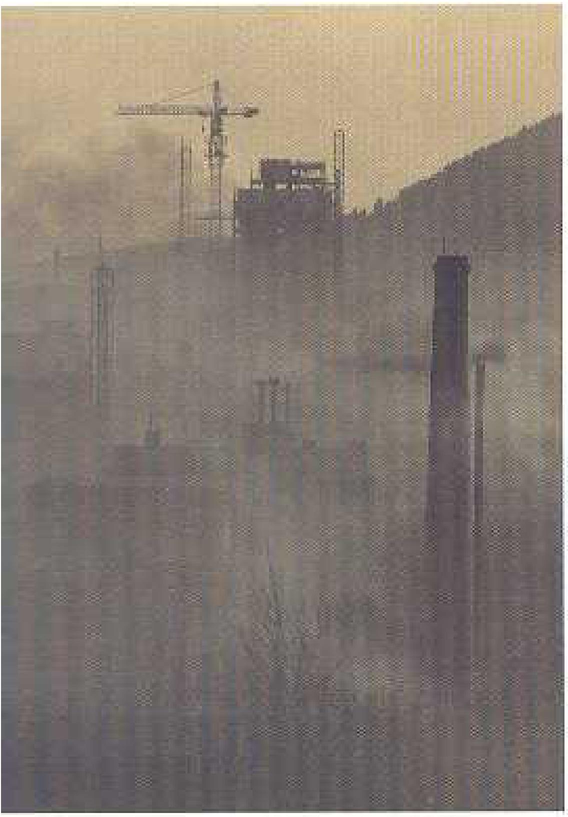

Figure 1.
Qingdao, Shandong Province, People's Republic of China, 1987. In 1898, China ceded Qingdao to Germany for 99 years, along with the right to build the Shandong railway and to work the coal mines for 14 km on either side of the railway line.
BRUCE DALE

particularly if the "sides" that are left out are the middle: the bulk of experts, ie, the people who created the established consensus.

Moreover, that established consensus must be stated in terms of probabilities, because very few scientists—myself included—would say they believe the future climate will be in or out of the 1.5 to 4.5°C warming range for certain. Rather, most believe this range to be reasonably probable. Therefore, if scientific opinion is to be communicated accurately, it must be by converting issues into probabilistic terms and providing perspective on the range of views rather than by conducting an entertaining but misleading debate among the most extreme of the dueling scientists—or occasionally stretched beyond caricature in editorials or articles by polemicists and ideologues. What counts, then, is the nature of the evidence and the spectrum of opinions of a broadly representative group of experts,[eg,6,13] not simply a few highly visible debaters with extreme views.

What Does Comprise a Consensus on Global Warming?

Just to illustrate the point that much is already known, I offer the following list of global-warming–related points accepted by a very large fraction of the relevant expert communities. One good source for discussion on the following points is the recent National Research Council's study on global warming and its implications.[13] (Following each of these statements is my own estimate of the likelihood of the statement turning out to be true.)

- ▶ GREENHOUSE GASES—H_2O, CO_2, CH_4, N_2O, CFC—trap infrared radiative energy in the lower atmosphere. ▶ CERTAIN
- ▶ THE NATURAL GREENHOUSE EFFECT from clouds, water vapor, CO_2, and CH_4 is responsible for some 33°C of natural surface temperature warming. ▶ CERTAIN
- ▶ HUMANS HAVE ALTERED the natural greenhouse effect by adding 25% more CO_2, 100% more CH_4, and a host of other greenhouse gases such as N_2O and CFC since the Industrial Revolution. ▶ CERTAIN
- ▶ ADDED GREENHOUSE GASES from human activities should have added some 2 to 3 W of infrared radiative energy over every square meter of Earth. This is well-established based on our considerable knowledge of the structure of the atmosphere and on extensive validation from satellites and other measurements—even though the extra 2 to 3 W cannot be directly measured yet. ▶ VIRTUALLY CERTAIN
- ▶ EARTH HAS IN FITS AND STARTS, warmed up by ~0.5°C over the past century; the 1980s is the warmest decade on record and 1990, 1991, and 1988 (in order) the warmest years on record. (The warmth of individual years varies with instrument method used—eg, these records are from the surface network of thermometers, not radiosound or satellite instruments.) ▶ VERY LIKELY
- ▶ ALTHOUGH NO HIGHLY SIGNIFICANT (ie, at the often-cited 99% statistical confidence limit) cause-and-effect statements between the observed warming and the buildup of human-induced greenhouse gases can be credibly asserted for at least another decade or 2, the likelihood that the 0.5°C 20th century warming trend is wholly a natural phenomenon is small (ie, I would estimate perhaps a 10 to 20% chance). ▶ LIKELY
- ▶ MOST CLIMATIC MODELS PROJECT A WARMING of several degrees or so in the next 50 years given standard ("business as usual") greenhouse-gas emission scenarios, and they portend a potential long-term (ie, AD 2100 to 2200) warming commitment as high as 5 to 10°C (eg, IPCC[6]). ▶ GOOD CHANCE, AT LEAST AN EVEN BET

CFC = chlorofluorocarbons
CH_4 = methane
CO_2 = carbon dioxide
H_2O = water
N_2O = nitrous oxide
SO_2 = sulfur dioxide

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- Natural, *sustained, globally averaged* rates of surface air-temperature change (eg, from the breakup of the last ice age 15 000 years ago to the full establishment of our current interglacial age some 5000 to 8000 years ago) are typically ~1°C/1000 years. On the other hand, even the minimum projected human-induced rates of climate change are on the order of 1°C/100 years up to a potentially catastrophic rate of 5°C/100 years—the latter being some 100 times faster than typical sustained globally-averaged rates of climate change to which human civilization evolved, and the current distribution of species and ecosystems emerged. ▶ VERY LIKELY
- MOST FOREST SPECIES "MIGRATE" at rates of at most 1 km/y, and would not be able to "keep up" with temperature changes at a rate of several degrees centigrade per century without human intervention to transplant them (ie, ecological engineering).[4] ▶ VERY LIKELY
- DIFFERENT SPECIES (eg, specific kinds of trees, insects, birds, or mammals) would all respond differently to projected climatic changes. For example, birds can migrate rapidly but the vegetation some birds need for survival habitat would respond only very slowly (over centuries). This implies a possible tearing apart of the structures of communities of plants, insects, and animals (eg, T L Root[20]) at rates that exceed clear historic or geologic metaphors (eg, R W Graham and E C Grimm[6]). ▶ LIKELY
- CURRENT ENGINEERING AND ECONOMIC PRACTICES in terms of building standards, automobiles, power production, or manufacturing are very retarded relative to the energy efficiency of best available technologies or techniques. Many studies[eg,13,15] show that from 10 to 40% reductions in current CO_2 emissions in the United States could result in long-term costs at or below current rates of expenditure for the equivalent energy services if current inefficient practices and infrastructures were replaced by state-of-the-art, proven efficient practices and equipment. ▶ VERY LIKELY

Figure 2.
Although air-pollution levels have recently improved, surgical masks are worn by those troubled by the still-high pollution levels on Honshu Island, in Tokyo, Japan.
DAVID ALLAN HARVEY

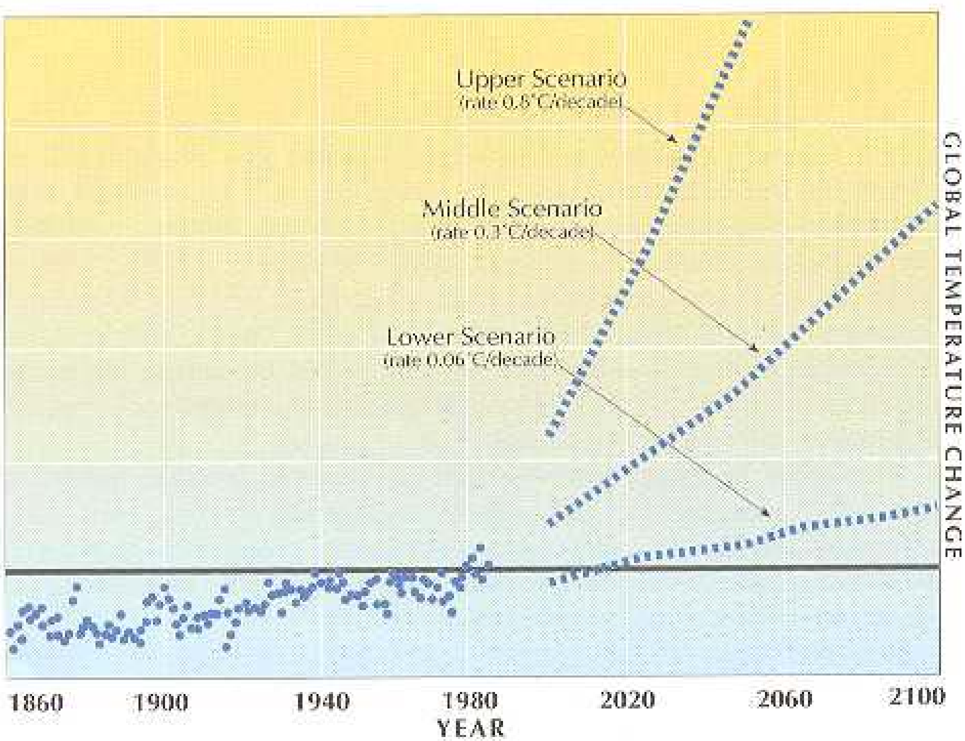

Figure 3.
Three scenarios for global temperature change to 2100 derived from combining uncertainties in future trace greenhouse-gas projections with those of modeling the biotic and climatic response to those projections. Sustained global temperature changes beyond 2°C (3.6° F) would be unprecedented during the era of human civilization. The middle to upper range represents climatic changes at a 10 to 100 times faster pace than long-term natural average rates of change.[9]

The uncertainties in temperature projections over the next century range over a factor of 10 (Figure 3). Including together, uncertainty from human behavioral activities that create greenhouse-gas emissions, biological factors that influence the carbon cycle, and physical factors such as the "feedback effects" of clouds or ice, leads to the differences seen on Figure 3.[9]

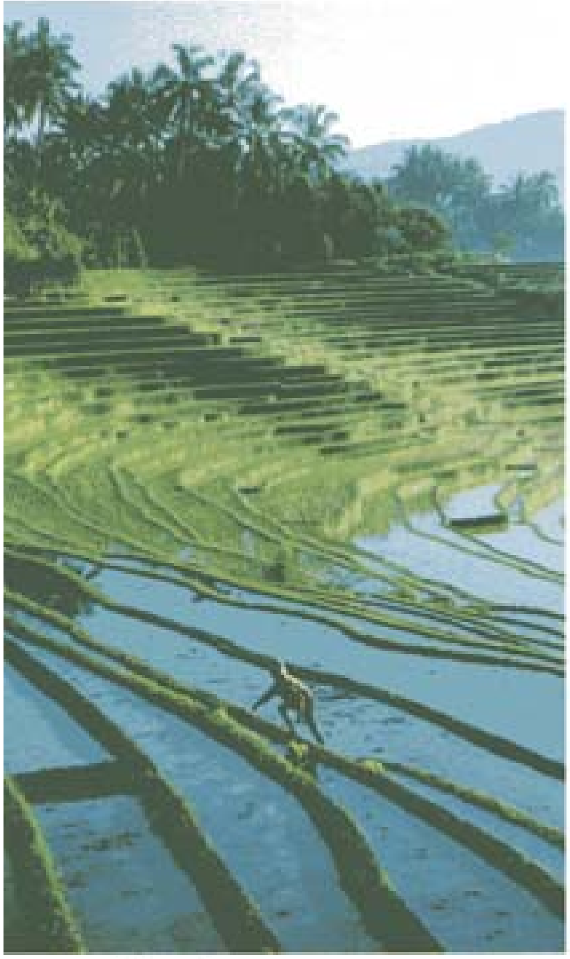

Figure 4.
Terraced rice fields on the island of Bali are common. Taking advantage of the run-off from nearby mountains, these fields produce as many as 3 crops a year with centuries-old irrigation systems.
CHARLES O'REAR

Figure 5. (opposite page)
Chisso Company, Minamata, Japan, 1971.
JAMES L STANFIELD

What Is Known with Some Reliability?

A major criticism of global warming has been the imperfect match between the erratic warming of the Earth and the relatively smooth increase in greenhouse gases over the past 100 years. It has been alleged that the temperature trends in the 20th century cannot be attributed to greenhouse-gas buildup, because most of the warming in the 20th century took place between 1915 and the 1940s, followed by a cooling at the very time the global greenhouse gases began to build up rapidly. Then, from the mid-1970s to 1992 there has been a dramatic warming, with the past 12 years of surface temperature containing over a half dozen of the warmest years on record.

Unfortunately, we cannot rule out some possible role for other potential climatic influences or "forcings" as they are called. Among these forcings are: sunspot activity or atmospheric particles from volcanic eruptions, industry, automobiles, and agriculture (Figures 1,2,4,5). It has long been known that most of these particles, for example, tend to cool the planet, counteracting any greenhouse effect, at least regionally.

Very recently, R J Charlson and colleagues[1] picked up on this old debate[eg,2,21,24] of the cooling potential of human emissions of SO_2 (largely from burning sulfur-contaminated oil or coal) and added some quantitative insights. They concluded that sulfuric acid aerosol particles (a form of smog) could both directly and indirectly (by brightening clouds) reflect enough sunlight away so as to nearly compensate for the extra human-caused greenhouse-effect surface-layer heating from CO_2, CH_4, and CFC over most of the Northern Hemisphere landmasses since the 1960s. Since this reflection of sunlight is a daytime phenomenon but the addition of greenhouse gases is a day and night effect, scientists (see, for example R A Kerr[10]) recently have begun to project that the SO_2 effect combined with the anticipated global warming from greenhouse-gas emissions would, at least over land in the Northern Hemisphere, result in a nighttime warming trend. Recently, T R Karl and colleagues[11] noted that over the United States, the former Soviet Union, and China (precisely those places most affected by SO_2 emissions), recent (ie, within the past 30 years) warming trends were indeed largely at night. While 30 years is too little time to allow any confident conclusions, these latest results add (not subtract as some critics have contended) to the confidence that greenhouse-gas buildup equivalent to a doubling of CO_2 would eventually warm the Earth by some 1.5 to 4.5°C. This is all noted in the recent update of the Intergovernmental Panel on Climate Change report.[8]

Finally, for 2 reasons we should take little comfort from the possibility that sulfuric acid particles will "save us" from global warming. First, such chemicals are principal ingredients of acid rain (Figures 19 & 20) and health-threatening smog. Second, aerosols are, as many have noted for decades[eg,23,24] a regional phenomenon, whereas "greenhouse" heat-trapping effects are spread fairly uniformly over the globe. Thus, even if on a hemispheric average sulfur aerosols were to exactly reject as much extra solar heat to space as greenhouse gases trapped heat in the infrared wavelengths near the surface, this situation would not be a cancellation of climatic effects, since the cooling would be in very patterned half-continent-sized intense patches, whereas the heating would be relatively more evenly distributed around the hemisphere. The likely result would be a distortion of normal heating patterns, such as the land–ocean thermal contrast. Such distortions would likely lead to regional climatic anomalies (ie,

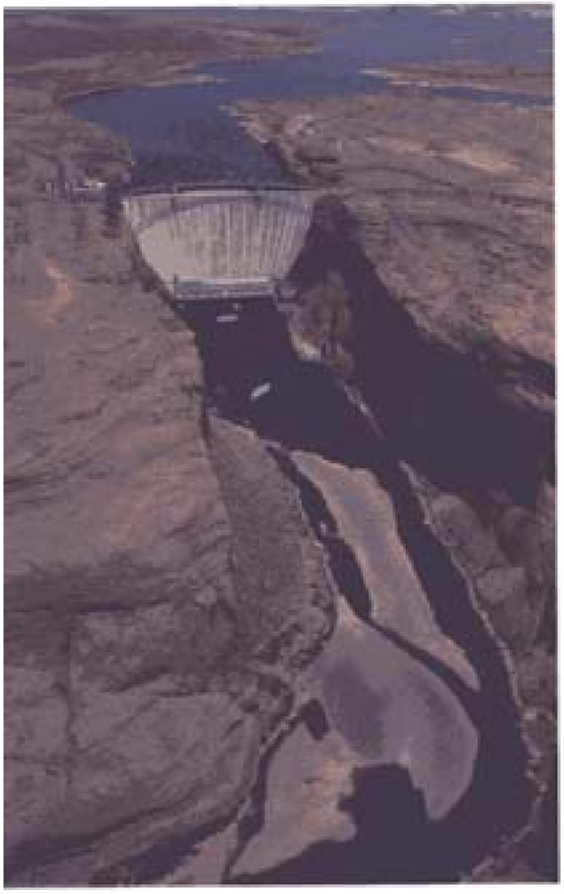

Figure 6.
Drought affects this Colorado River site at Lake Powell and Glen Canyon Dam, near Page, Arizona.
KERBY SMITH

Table 1. The Sensitivity and Adaptability of Human Activities and Nature

Human Activity and Nature	Low Sensitivity	Sensitive; Adaptation at Some Cost	Sensitive Adaptation Problematic
Industry and Energy	■		
Health	■		
Farming		■	
Managed forests and grasslands		■	
Water resources		■	
Tourism and recreation		■	
Settlement and coastal structures		■	
Human migration		■	
Political tranquility		■	
Natural landscapes			■
Marine ecosystems			■

Note: Sensitivity can be defined as the degree of change in the subject for each "unit" of change in climate. The impact (sensitivity times climate change) will thus be positive or negative depending on the direction of climate change. Many things can change sensitivity, including intentional adaptations and natural and social surprises, and so classifications might shift over time. For the gradual changes assumed in the National Academy of Sciences study, the panel believes these classifications are justified for the United States and similar nations.
Source: National Academy Sciences.[11]

unanticipated local or regional climatic events) even if the net hemispheric temperature changes were small as a result of the hemispheric-scale heating–cooling compensations. In short, we cannot "cure" global warming with SO_2 emissions and escape risk free.

An updated interim report of the Intergovernmental Panel on Climate Change acknowledged these uncertainties, while concluding once again that the 1.5 to 4.5°C warming range is quite likely to cover what the actual long-term temperature response to CO_2 doubling will be over the next 50 years or so.

But most scientists still agree that without 10 to 20 more years of thermometer, satellite, solar, atmospheric pollution, and volcanic observations it is difficult to pin anything down to 99% certainty.

Fortunately, we are now measuring energy output of the sun, eruptions of volcanoes, and pollution-generating activities, and can thus account better for their individual effects. Finally, in short, we are watching some of the other forcings. Thus, as greenhouse gases continue to build up in the future, if greenhouse warming does not take place at roughly the predicted rate during the 1990s and into the next century, then it will be possible to argue on the basis of some direct evidence that the effect predicted by current models is off base. Personally, I will be surprised if our current global "best guesses" prove to be off by >50%.

Indeed, speculative theory is not the principal reason that advocates of concern over the prospect of global warming—and I am unabashedly one of them—take their time and stand before groups such as Congressional committees and take their time with our concern. Rather, our concern is based on the validation exercises for models that we have built of the present and past climate, since these models can also be used to foreshadow the future. In fact, many aspects of these models have already been validated to a considerable degree, although not to the full satisfaction of any responsible scientist.

For example, we know from observations of nature that the last ice age, which was ~5°C colder on a global average than the present era, had CO_2 levels ~25% less than over thousands of years before the Industrial Revolution. CH_4, another very potent greenhouse gas, also was lower by about half relative to preindustrial levels.

Ice in Antarctica contains gas bubbles that are records of the atmospheric composition going back over 160 000 years. Cores drilled into the ice sheets show us that the previous interglacial warm age, some 120 000 to 130 000 years ago, had temperatures and CO_2 and CH_4 levels comparable to those in the present interglacial period.

The well-correlated change in these greenhouse gases and in planetary temperature over geological epochs is an empirical way to estimate the sensitivity of climate to greenhouse-gas concentration changes. Such studies find geological-scale temperature changes from greenhouse-gas variations roughly of the magnitude that one would expect based on projections from today's generation of computer models.[7] However, we still cannot assert that this greenhouse-gas–geological-temperature coincidence is proof that our models are quantitatively correct, since other factors were operating during the ice age–interglacial cycles. The best we can say is that the evidence is strong but circumstantial.

One related point to the ice age–interglacial cycles may be useful here. It typically takes tens of thousands of years to build up ice age glaciers,

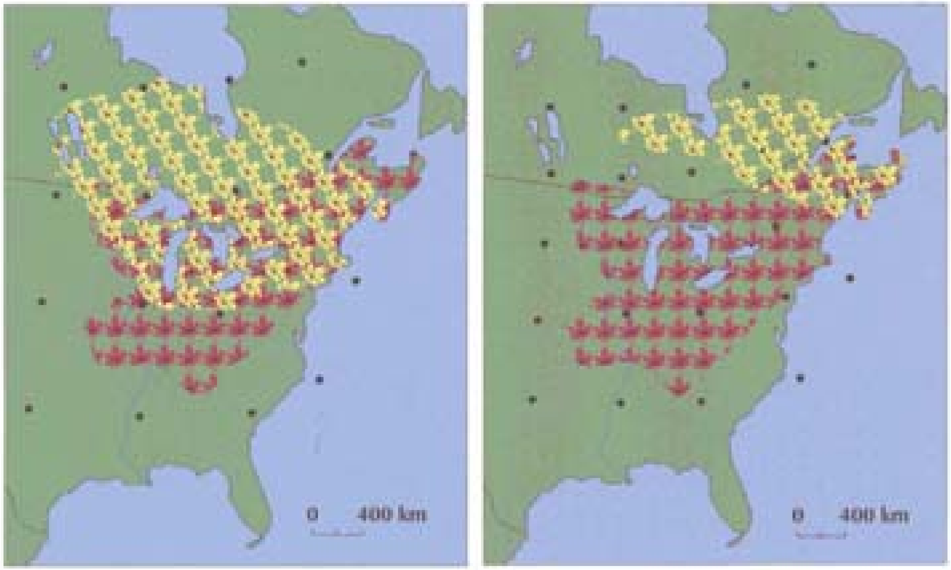

Figure 7.
Present geographical range of sugar maple (red leaves) and potentially suitable range under doubled CO_2 (yellow leaves). A. predictions use climate scenarios derived from the Goddard Institute for Space Studies general circulation model; B. predictions use climate scenarios derived from the Geophysical Fluid Dynamics Laboratory model. Gridpoints are sites of climatic data output for each model. [5]

but only ~10 000 years to deglaciate; and each warm interglacial epoch also lasts typically 10 000 years. Since our current interglacial is now ~10 000 years old, some have suggested that global warming is a good thing because it will hold back the next ice age. What this view ignores is that the time frame for natural interglacial to glacial transitions is tens of thousands of years, whereas the potential for global warming is 2 to 10°C warming in only a century or 2—a radical rate of climatic change relative to most sustained, natural global climate changes in geological history.

What Is Highly Speculative?

Any prediction of what climatologists call the detailed time-evolving, regional distribution of climatic anomalies is highly speculative. It is still tough to be confident in projecting where and when it will be wetter and drier—how many floods might occur in the spring in California, or forest fires in Wyoming or Siberia in August—although some plausible scenarios can be given (pp 180&181; Figures 18&21) . How much sea level will change is also speculative,[eg,22] with most estimates ranging from 0 to 1-m rise by 2100.

ECOLOGICAL IMPACTS: THE POTENTIALLY MOST SERIOUS CONSEQUENCE

Projecting the time required for regional climatic changes to evolve is still speculative, and so too is any confident assessment of the agricultural, hydrological, ecological, or health consequences of global warming. However, we can construct a variety of plausible specific scenarios of climatic changes over space and time and then ask: "So what?"[eg,16,25] Indeed, such exercises have led to conflicting assessments of the agricultural consequences (Table 1),[eg,13] but greater concern for the hydrological consequences[eg,26] and very serious concern for the ecological implication of most global warming scenarios (Figure 6).[17]

Figure 7 shows distribution of sugar maple trees (Figure 8) under 2 different estimates of climatic changes. The authors of this study noted that their estimates of changes in the ranges of this species did not account for the time it might take for the trees to migrate or the obstacles they might encounter in migration (eg, farms, cities, freeways, acid precipitation, air

Figure 8.
Sugar maple trees, near Algonquin Provincial Park, Ontario, Canada.
DAVID S BOYER

U S DEPARTMENT OF COMMERCE NATIONAL SEVERE STORMS LABORATORY

MICHAEL YADA, ABOVE
ROBERT W MADDEN, RIGHT

STEPHEN M DOWELL, ABOVE; HERRAL LONG, BELOW.

The growing record of climate anomalies in recent years has climatologists speculating that a pattern of detailed, time-evolved regional distribution of extreme weather is developing.

Examples of these recent anomalies are: violent tornados such as this one over East Roosevelt, Oklahoma (opposite page, above); torrential downpours like this one caused by a hurricane in Texas (opposite page, lower left; devastating hurricanes as illustrated by the ruins and remains on Dauphin Island, Alabama (opposite page, lower right); the notorious fire in Yellowstone National Park, Wyoming (above); and heavy snowstorms that leave cars mired in snow drifts in Perryburg, Ohio (left).