Advanced Review

The idea of anthropogenic global climate change in the 20th century

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People had long speculated that human activities might affect a region's climate. But a developed conjecture that humanity might change the climate of the entire planet first appeared in 1896: a calculation that carbon dioxide from fossil fuel combustion could gradually warm the globe. Scientists soon rejected the idea. Most people thought it incredible that climate could change globally except on a geological timescale, pushed by forces far stronger than human activity. In midcentury, a few scientists revived the hypothesis of global warming. Meanwhile, the exponential growth of human activity, especially chemical pollution and nuclear armaments, was showing that humanity really could affect the entire atmosphere. Moreover, during the 1960s research suggested that small perturbations might lead to an abrupt change in the climate system. Although nobody expected serious impacts until the distant 21st century, some began to frame global warming not just as a scientific puzzle but as an environmental risk, a security risk, a practical policy question, an international relations issue, and even a moral problem. In the late 1970s a scientific consensus began to take shape, culminating around the end of the century in unanimous agreement among government representatives on essential points, although many uncertainties remained. Meanwhile, increasing media warnings of peril made most of the literate world public aware of the issue, which had deep implications for the human relationship with nature. Skepticism persisted, correlated with aversion to regulation. The majority of the world public were now concerned, but disinclined to take action. *WIREs Clim Change* 2010 1 67–81

Of all the ideas that took hold during the 20th century, the belief that humans can severely change the entire planet's climate stands among the most significant and astonishing. At the start of the century, a few scientists had begun to speculate that a human influence on global climate might become significant in the remote future. By the end of the century, a majority of the world's citizens thought it likely that humanity was already causing an observable climate change. They were mainly thinking about global warming caused by fossil fuel combustion, but they had come to believe more generally that in various ways, both inadvertently and deliberately, people were seriously altering not just their own regional circumstances but the vast planetary atmosphere as a whole. This perception of global climate as a human artifact has been central in a profound change, as great as any since the spread of agriculture, in how we conceive the human relationship with the natural world.

In the 19th century the concept of 'climate' referred to the 'condition (of a region or country)'—as the Oxford English Dictionary put it—regarding atmospheric phenomena such as temperature or dryness, i.e., the long-term average of weather. By its very definition, then, climate was conceived as local, and static on the scale of a human lifetime. Since antiquity people had wondered whether human activities like deforestation might slowly change the climate of a particular region, and the discovery of the ice ages had shown that climate could change radically on a planetary scale. But neither the hand-waving speculations about gradual regional shifts nor the hard evidence of greater changes in the distant past seemed of any practical significance. Hardly worth considering was the notion that a planet-wide change could be caused by humans: *anthropogenic global* climate change, the subject of this essay.

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DOI: 10.1002/wcc.006

Ideas about a human impact on the entire planet changed because of developments in both scientific and popular thinking. Neither could diverge far from the other. Even the boldest scientist would not devote many years to a topic that everyone else dismissed as fantasy. On the other hand, the views of attentive citizens were strongly influenced by what scientists came to believe. In the mid-20th century, new avenues for ideas opened up, and the late decades of the century saw a parade of evidence that an anomalous global warming was underway, which theorists linked to human activities. By 2001, climate scientists and government officials could announce a consensus on the central question: it was highly likely that humanity was changing the global climate. But the topic had become associated with deep political and cultural meanings, and scientific evidence could not impose a consensus among the public at large.

SPECULATIONS ABOUT A HUMAN INFLUENCE (1896–1960)

Since antiquity people had wondered whether they might change their local climate, e.g., by cutting down forests or draining swamps.[1,2] In the 19th century this became a matter of public and even official interest. But scientists disagreed on whether a given change in land use would bring more rain or less. By the last decade of the century, scientific opinion had turned decisively against any belief in a human influence on climate; no plausible theory had been developed for how it could happen, and the evidence was against it (even the deforestation of Eastern North America had apparently failed to affect the region's weather). The idea lingered in the public mind, among many other scientific speculations about matters of no immediate concern.[3–6]

These debates about possible regional effects did not touch on global climate change. Nobody had seriously proposed that humans could affect the physical state of the planet as a whole. After all, there were barely a billion and a half humans scattered around the planet, mostly peasants relying on brute muscle power. People scarcely imagined that their industry and agriculture, so puny among the vast natural forces, could upset the 'balance of nature' that governed the planet as a whole.

Reinforcing this assumption was a belief that any large-scale climate change must be almost imperceptibly slow. A few writers speculated about regional shifts like an increase in dryness that had supposedly laid low Near Eastern civilizations, but if such shifts had existed at all they had advanced over the course of generations. The ice ages uncovered by 19th century geologists had seen far greater changes across far wider regions. But they seemed to have unfolded gradually over dozens of millennia. At the opening of the 20th century, people who offered conjectures about such large-scale climate changes looked to the buildup or decay of mountain ranges, the evolution of the Sun's properties, alterations in the orbital elements of the planet, and other sluggish geophysical phenomena. Geologists in particular were convinced that nature operates only through processes that were the same in the past as in the present, and thus the same in the present as in the past, maintaining an equilibrium that could be shifted only gradually by the most immense physical forces. These scientific opinions reflected a view of 'Nature' as stable and supra human—a belief that lay deep in most human cultures, traditionally tied up with faith in a divinely ordered universe.

One of the hypotheses called attention to the chemical composition of the atmosphere. Minor constituents like water vapor and carbon dioxide gas (CO_2) had been found to intercept heat radiation.[7] Theorists pointed out that the result would be what later came to be named (misleadingly) a 'greenhouse effect,' an obstruction in the outflow of radiant energy that keeps the planet's surface warmer than it would be without an atmosphere.[8] If the composition of the atmosphere was to change—e.g., if over the course of many millennia the emission of gases from the world's volcanoes increased or decreased—it could eventually change the planet's temperature. Was this the solution to that famous scientific problem, the origin of ice ages? Attracted by the puzzle, a prominent Swedish physical chemist, Svante Arrhenius, calculated how much cooling would result from cutting the atmosphere's CO_2 level in half.

A colleague, Arvid Högbom, brought Arrhenius a strange new thought. Högbom had calculated that human factories and other industrial activities were adding CO_2 to the atmosphere at a rate that was comparable to the natural processes. To be sure, the gas released from the burning of coal in the year 1896 would raise the level in the atmosphere by scarcely a thousandth part, but over the course of centuries it might build up to a significant level.[9–11] Arrhenius attempted to calculate the consequences of doubling the CO_2 in the atmosphere, and in 1896 announced it would raise the Earth's temperature some 5–6°C.[10,12–15] A little extra warmth some centuries in the future did not sound like a bad idea in chilly Sweden. A few people went farther; e.g., Nils Ekholm speculated that we might someday be

able to regulate the planet's temperature to suit our needs.[16]

The notion that humans might alter the globe's climate, inadvertently or even deliberately, was able to emerge at this time because it fitted the optimistic temper of the age. In this astounding era of X-rays, electricity, and radium, who could say where technology would lead next? Many believed that in the centuries to come, scientists and engineers would vanquish poverty, turn deserts into gardens, and craft countless wonders to benefit our race.

Futuristic visions aside, a handful of scientists took a mild interest in greenhouse warming as a topic for research. By 1910 they all set it aside. Arrhenius's idea looked implausible on several grounds. In particular, laboratory measurements seemed to prove that in the part of the infrared spectrum where CO_2 interfered with radiation, the existing CO_2 and also water vapor were already blocking the radiation so thoroughly that more gas could make little difference: the absorption was 'saturated.' Moreover, Arrhenius had overlooked many important phenomena, such as how cloudiness might change if the Earth got a little warmer and thus more humid. Given the universal belief in a self-stabilizing 'balance of nature,' it seemed probable that cloudiness would increase until it reflected enough sunlight to maintain the status quo. Another geophysical stabilizer was seawater, for a simple calculation showed that the oceans would absorb most of the gas that we added to the atmosphere.

This dismissal of any human influence was part of a larger conviction that all of biology was irrelevant to the global atmosphere. The air and its weather were governed by physical forces apparently far mightier than the meter or so of organic matter that covered some patches of the planet's surface.

A few people began to think otherwise in the 1920s. The most profound was the Russian geochemist Vladimir I. Vernadsky. His work mobilizing industry during the First World War had helped him to realize that the volume of materials produced by human industry was approaching geological proportions. Analyzing biochemical processes, he concluded that the oxygen, nitrogen, and CO_2 that make up the Earth's atmosphere are put there largely by plants and other living creatures. Beyond this he saw a new and still greater force coming into play: intelligence. A few scientists, mainly in the Soviet Union, followed his lead and began to study how living creatures affect the chemistry of the Earth's surface. But most who read Vernadsky's visionary pronouncements about humanity as a geological force saw it as mere romantic rambling.[17–19]

Arrhenius's idea meanwhile lived a shadowy afterlife. Textbooks and popular articles that discussed theories of climate often mentioned anthropogenic greenhouse warming if only to rehearse the arguments against it. After all, none of the many other theories of climate change had won broad respect. Thus, among the small fraction of the world's population that took a strong interest in science, a good many people were vaguely aware of speculations about future anthropogenic warming.

In the 1930s, grandfathers recalling the bitter winters of their youth in the late 19th century drew attention to a warming trend in regions around the North Atlantic. The trend, widely reported in the media, was confirmed by studies of weather records. Experts saw this as just part of the mysterious 'cycles' that affected regional and global climates; nobody could say whether it would continue for a decade or for a century, but presumably it would eventually reverse.

An English engineer, Guy Stewart Callendar, dissented. His own statistical studies of temperature records not only confirmed the trend but indicated it was global. Meticulously evaluating old measurements of atmospheric CO_2 concentrations, Callendar concluded that over the past century the level had risen by about 10%. This, he insisted, was the cause of the observed warming, and the warming would increase in future centuries as fossil fuel emissions continued. He also showed reasons to question the claim that adding more of the gas could scarcely affect the flow of radiation. Callendar's work, done for no compensation but the pleasures of science and in defiance of conventional opinion, single-handedly revived the moribund theory. Climatology textbooks and articles of the 1940s and 1950s routinely included a brief reference to his studies.[20–22]

Most meteorologists, however, gave Callendar's work scant credence. Human activities were in fact too small in the first half of the 20th century to noticeably affect the global climate. Until the mid-1950s hardly anyone remarked that population and industrialization were exploding in exponential growth, or if they did notice it, recognized its prodigious significance.[23] Between the start of the 20th century and its end the world's population would quadruple, and the use of fossil fuel energy by an average person would triple, making a 12-fold increase in the rate of emission of CO_2. Yet the First World War and Great Depression brought people in industrialized nations to worry about a possible *decline* in their populations and industries. As for the less-developed nations: they were expected to stay that way for another century or so. Through

the 1940s, among the few who noticed the idea of anthropogenic global global warming at all, nearly everyone framed it as an unlikely hypothesis about distant future centuries.

It took barely a decade for thinking to reverse. One factor was a growing awareness of the dangers of atmospheric pollution. In the 1930s smoke from factories was a welcome sign of prosperity. But in the 1950s, as the world economy soared and life expectancy in industrialized countries lengthened, there began a historic shift from worries about poverty to worries about chronic health conditions. 'Killer smogs' emerged as a present danger.[24,25] Another thing that drew attention to human influences on the air was exciting news about manipulating weather. During the 1950s, the press prominently reported attempts to make rain by 'seeding' clouds with silver iodide smoke. Scientists speculated about other technical tricks, such as spreading a cloud of particles at a selected level in the atmosphere to interfere with solar radiation. Journalists and science fiction authors announced that in a not distant future we might alter climates over entire nations to their benefit. Or perhaps to their harm. As the Cold War got underway, U.S. and Soviet agencies devoted significant funds to secret research into ways to strike an enemy with drought or storms, and respected scientists publicly warned about the approach of 'climatological warfare.' It had become plausible that by putting materials into the air, humans could alter climate on a grand scale.[26–28] Even decades later, when poll-takers asked people about causes of climate change, many thought first of advanced technological feats, ranging from spaceship launches to nuclear explosions.[29]

The staggering advent of nuclear energy in 1945 stood at the center of the change in thinking. Suddenly nothing seemed beyond human power. Experts speculated that we might soon be able to use salvoes of atomic bombs to control the weather. At the same time, scientists warned that a nuclear war could destroy civilization if not all life on the planet. No matter whether technology could turn deserts into gardens, it could demonstrably turn gardens into deserts! Impacts could be global: opponents of nuclear armaments pointed to the horrors of radioactive fallout drifting invisibly everywhere.[30] From about 1953 until open-air nuclear testing ceased in the mid-1960s, many in the public blamed the faraway tests for almost any unseasonable heat or cold, drought or flood. In a magazine article laying out the evidence that global temperatures had been rising, the authors remarked that 'Large numbers of people wonder whether the atomic bomb is responsible for it all.'[31]

Humans were introducing unnatural technologies, spreading pollution everywhere! Would 'Mother Nature' pay us back for our attacks upon 'her'?[30] That fear was nothing new, for many tribal peoples attributed weather disasters to human misdeeds: the community was being punished because someone had violated a taboo. Just so was the Flood of Noah called down upon humanity by our sins. Chinese dynasties were shaken when people blamed devastating floods on the corruption of the mandarins; European communities met droughts by declaring days of public penance. The advent of nuclear weapons put a stamp of technological reality on this old fear that our errors could damage our world.

The increased belief in the power of technology may have cleared the way for a closer look at Callendar's claims (Callendar himself continued to correspond with other scientists). Or perhaps the reconsideration was a chance consequence of major advances in radiation theory and instrumentation and digital computers. In any case, the physicist Gilbert Plass took up the question. In 1956 he showed, more convincingly than Callendar had been able to do, that the old supposed proof that the absorption of infrared radiation was 'saturated' was a complete misunderstanding of how radiant energy works its way through the atmosphere. Plass calculated that doubling the CO_2 level would bring a 3-4° rise; assuming emissions would continue at the current rate, he expected about one degree of warming per century. Other scientists found that Plass's calculation, like Arrhenius's, was too crude to give reliable numbers. But they also saw that the possibility of greenhouse warming could no longer be dismissed.[32,33]

Another supposed proof that humans could not cause greenhouse warming had relied on the fact that the oceans absorb CO_2. Learning of Plass's work, the oceanographer Roger Revelle took a close look at seawater. To be sure, eventually most of the carbon that humanity added to the air would end up precipitated on the sea floor—but how long was eventually? In 1957, Revelle calculated that it would take a few centuries for the oceans to absorb CO_2 added to the atmosphere, and remarked that the accumulation of gas 'may become significant during future decades if industrial fuel combustion continues to rise exponentially.'[34] Two Swedish meteorologists, Bert Bolin and Erik Eriksson, clarified Revelle's cryptic chemical argument and proceeded to a striking calculation: with industrial production climbing exponentially, the atmospheric CO_2 level would rise by 25% as early as the year 2000.[35]

Revelle had meanwhile been talking about global warming with science journalists and government

officials, saying that humanity was inadvertently undertaking a great 'experiment' on the atmosphere. He suggested that the rise of CO_2 might turn Southern California and Texas into 'real deserts,' and that the melting of Arctic ice could let the Soviet Union become an important maritime power by the 21st century.[36] Everyone understood this was sheer speculation. To understand what was actually happening, Revelle hired a young geochemist, Charles David Keeling, to measure the concentration of gas in the atmosphere around the world. Revelle's simple aim was to establish a baseline 'snapshot,' averaging over the large variations found from place to place and from time to time. After a couple of decades, somebody could come back, take another snapshot, and see if the global CO_2 concentration had risen. Keeling did better than that. In 1960, after only 2 years of painstaking measurements, he announced that he had detected a rise of the CO_2 level.[37–39] It was these measurements that at last made anthropogenic global climate change a significant topic for scientific research and public consideration.

ELABORATION OF IDEAS AND EVIDENCE (1961–1980)

As Keeling's curve of the CO_2 level extended, inexorably higher year after year, it became increasingly impressive. It did not strike everyone as ominous. At this point and on through the following decades, many people in colder regions looked forward to a bit of warming (Russians in particular figured that it would benefit their nation). Anyway climate changes would become significant no earlier than the 21st century—which from 1960 seemed very distant.

Up to this point, nobody had written more than a few sentences about what a future warming might mean in practical terms. Anthropogenic global climate change was framed, if not as *mere speculation*, then as an obscure *scientific puzzle*, a hypothesis awaiting proof or refutation. A different approach began to emerge in 1963 at a meeting convened by the private Conservation Foundation. 'Conservation' was the traditional term for an outlook that was evolving into 'environmentalism,' centered on the growing recognition that human activities such as pesticide and other chemical pollution could damage vital ecosystems on a vast scale. Participants in the meeting (including Keeling, Plass, and Eriksson) began to frame anthropogenic global climate change as an *environmental risk*—something 'potentially dangerous' to biological systems, including humanity itself. The group could scarcely say what dangers might await a century ahead. The clearest impact they noted was that rising temperatures would melt many of the world's glaciers, raising the sea level and flooding coastal areas.[40]

The scientists' concern about impacts spread, catching the attention of the U.S. President's Scientific Advisory Committee. In 1965, these scientists reported that by 2000 the rising CO_2 level might produce climate changes that, they remarked laconically, 'could be deleterious from the point of view of human beings.'[41] A landmark study on 'Man's Impact on the Global Environment,' conducted at the Massachusetts Institute of Technology in 1970, suggested that greenhouse warming might bring 'widespread droughts, changes of the ocean level, and so forth.'[42] A meeting in Stockholm the following year came to similar conclusions, and added that we might pass a point of no return if the Arctic Ocean's ice cover disappeared.[43]

Most climate scientists, however, stuck by the belief that climate was dominated by gradual natural processes; what really interested them was the natural cycle of ice ages. By the mid-1970s they pinned down the nature of the cycles. It was not massive geological forces that set the timing, but minuscule shifts in the Earth's orbit.[44–46] Meanwhile, new geological evidence showed that global temperatures had not always varied gradually over hundreds of millennia, as the textbooks had it, but sometimes dipped or soared over a few thousands of years if not faster. All this reinforced new theoretical ideas about the instability of complex systems. Mikhail Budyko in the Soviet Union, Edward Lorenz and William Sellers in the United States, and others calculated that, thanks to feedbacks, a minor perturbation of forces might cause the climate system to tip relatively quickly from one state to another. That made it easier to believe that human activities could trigger such a change. And as Lorenz and others found, it might be a hair-trigger: the timing of a shift might be flatly unpredictable.[47–51]

If humanity inadvertently caused a dangerous greenhouse warming, couldn't technology reverse it? Schemes of deliberate 'geoengineering' to alter regional climates had been accumulating for decades. For example, in the 1950s Soviet engineers had speculated about throwing a dam across the Bering Strait and pumping water from the Arctic Ocean into the Pacific; that would draw warmer water from the Atlantic to melt the Arctic ice pack and warm up Siberia. In the 1960s, Budyko and others speculated about how people might bring a similar warming by strewing soot across the Arctic snow and ice to absorb solar energy. An actual attempt at climatological warfare was undertaken by the U.S. military in Asia in 1967–1972: extensive cloud seeding intended to increase rainfall and bog down

the North Vietnamese Army's supply line in mud.[52] And if we wanted to reverse global warming, the U.S. Presidential panel of 1965 speculated that we might, e.g., spread some material across the oceans to reflect more sunlight or sow particles high in the atmosphere to encourage the formation of reflective clouds. Back-of-the-envelope arithmetic suggested that such steps were entirely feasible.[41] However, the panel and other scientists recognized that the climate system was so complex that nobody could predict confidently that a given action would be beneficial. Further, any intervention would probably harm some regions even as it helped others, provoking international conflict. All these arguments would be repeated and elaborated in following decades.

The idea that particles in the atmosphere could profoundly change climate was pursued especially by the meteorologist Reid Bryson. He had noted that the world's ever more extensive farming and grazing as well as industry raised ever more dust and smoke. These emissions resembled the aerosols from great volcanic eruptions, which had been found to temporarily dim sunlight and cool the entire planet. In the early 1970s, Bryson issued public warnings that the balance of climate could be tipped by what he called 'the human volcano.'[53] Other studies found that the amount of aerosols in the atmosphere was indeed increasing rapidly.[54] As a back page *New York Times* item (October 18, 1970, p. 92) reported, 'This is disturbing news for those weather experts who fear that air pollution, if it continues unchecked, will seriously affect the climate and perhaps bring a new ice age.'

Through the 1970s journalists continued to indulge in sensational talk about the risk of abrupt cooling. In the public mind, the impact of human emissions got mixed up with an entirely separate scientific projection: some experts calculated that in the absence of human influences, orbital shifts in the natural course of the current ice-age cycle would bring a gradual cooling over future millennia.[55] In the 1970s, few scientists published peer-reviewed papers about any climate change faster than the thousands of years that glacial ages apparently took to evolve. Of those few papers, only a small fraction concluded that anthropogenic cooling was likely; others discussed cooling and warming factors without coming to a conclusion, and more than half thought it likely that greenhouse warming would eventually dominate.[56] All the experts confessed, however, that this was guesswork; it would take decades of effort to work out a reliable answer. Journalists reported this confession, and the public well understood that no scientific consensus existed. Yet a consensus was emerging on one point. As a 1977 *Readers' Digest* article put it, regardless of whether a scientist saw a likelihood of global warming, or cooling, or (most likely) neither, 'All scientists agree that a new factor has entered the game of climate change, a ''wild card'' never there before—man himself.'[57]

Progress toward a consensus would depend on digital modeling of the general circulation of the atmosphere. This enterprise was advancing rapidly, thanks to headlong improvements in computers and hard work by a growing number of modeling groups in the United States and Europe. In the mid-1960s, a team in Princeton under Syukuro Manabe had begun to produce moderately plausible models of global climate, confronting the long-standing doubts about cloudiness by at last incorporating humidity in a physically plausible way. It occurred to Manabe to check how the model would respond to a doubling of the CO_2 level. He calculated that would raise global temperature roughly 2°C.[58–60] This was the first time a greenhouse warming calculation included enough of the essential factors to seem reasonable to many experts.

Such research began to look more important in the early 1970s, when a series of weather disasters, the oil-fueled 'energy crisis,' and the rise of environmentalism as a mass movement put greenhouse warming on the political agenda. Advocates of nuclear reactors had already been citing the dangers of greenhouse gas emissions as a reason to buy their technology. That prompted the coal industry and other corporations dependent on fossil fuels to regard talk of greenhouse warming as a threat to their own interests. CO_2 emissions became one of the side issues occasionally raised in the increasingly passionate debates over choices among energy technologies.[61] Thus, some began to frame anthropogenic global climate change as an *economic policy question*, worthy of the attention of corporations and politicians. It was becoming a matter of political controversy whether the computer predictions of greenhouse warming should be trusted.

In 1979 the U.S. National Academy of Sciences convened a panel, chaired by veteran meteorologist Jule Charney, to look into climate models. They found that any model capable of reproducing something vaguely like the present climate showed a rise in global temperature when its CO_2 level was raised. The Charney panel announced they had rather high confidence that as the CO_2 level doubled the planet would warm up by about three degrees, plus or minus 50% (i.e., 1.5–4.5°C).[62]

Up to this point scientists had expected that climate change, if it happened at all, would bring no serious impacts until well into the 21st

century—which still seemed far away. But now a few began to argue that terrible droughts in the African Sahel and elsewhere could already be blamed on overgrazing or aerosol emissions.[63] Media exaggerations prompted public suspicion that anthropogenic climate change was showing its face in every local weather disaster. Although some experts continued to insist that higher levels of CO_2 would overall be benign, the tendency was to expect the worst. For example, a 1974 study commissioned by the U.S. Central Intelligence Agency concluded that if the next few decades brought a radical global climate shift (they had cooling in mind), we could expect mass migrations, perhaps even wars as starving nations fought over the remaining resources.[64] That framed anthropogenic global climate change as a *security risk*.

Concern strengthened as evidence emerged that greenhouse warming was not just a matter of fossil fuel combustion. Several studies indicated that (as Callendar had already suggested in 1939) land-use changes might also be globally significant. For example, in 1976 Bolin broke with his earlier view that plants are not a major source of CO_2. He estimated that tropical deforestation and the decay of plant matter in soils damaged by agriculture were adding CO_2 to the atmosphere at something like a quarter of the rate added by fossil fuels.[65] In fact scientists had only crude guesses for the global budget of carbon going into and out of the atmosphere, biosphere, and oceans. A long-lasting controversy arose over the numbers, inspiring many studies of the biological exchanges of carbon.[66–68] The outcome was a new recognition of the geochemical significance of living creatures—not least ourselves.

In 1980 a NASA group headed by Veerabhadran Ramanathan published surprising estimates of the contribution to global warming from miscellaneous gases—methane, nitrates, ozone, and others emitted by industry and by agricultural sources such as fertilizer. In particular, each molecule of methane gas (CH_4) turned out to have a greenhouse effect more than 20 times that of a molecule of CO_2. Methane comes mainly from living creatures, e.g., bacteria in rice paddies, wetlands and the stomachs of domestic animals; as the human population expanded, so did these emissions.[69,70] It seemed that the long-overlooked 'trace' gases might collectively contribute roughly as much as CO_2 did to global warming.[71,72] The implication was shocking: global warming would come on twice as fast as the previous calculations for CO_2 alone had predicted. The 21st century was approaching swiftly.

THE QUEST FOR CONSENSUS (1981–2001)

By the early 1980s, all the main ideas about anthropogenic global climate change were in place. Originally advanced by a few scientists, they were now fully in the public arena. There would be some additions to understanding and reframing of the implications. But from here forward the most important history is about how scientists and the world public responded to the central ideas.

The question of global warming had become prominent enough to be included in some public opinion polls. A 1981 survey found that more than a third of American adults claimed they had heard or read about the greenhouse effect. Most of these people, however, would never have brought up the subject by themselves. Few understood how global warming was related to fossil fuels, let alone other sources of greenhouse gases. Among the world's many problems, it did not loom large.[73,74]

Among climate scientists, however, concern kept growing. Only an accumulation of arguments of different kinds could move a given scientist's opinion step by step up or down the scale that ranged from 'possible' through 'probable' to 'near certain.' The most persuasive evidence came from the ever more elaborate computer models. They were getting fairly skillful in their reproductions of past and present climates, so it seemed increasingly plausible that their projections of possible future changes should be taken seriously.[75–77] Meanwhile, a wholly different argument came unexpectedly from American, West European, and Soviet teams who drilled deep into the icecaps of Greenland and Antarctica. The ancient ice revealed that over past glacial cycles, the CO_2 and methane content of the atmosphere had risen and fallen in close conjunction with the rises and falls of temperature, pointing to strong feedbacks between greenhouse gases and climate.[78–83]

Adding to the concern were calculations that huge reservoirs of carbon were frozen in the deep permafrost layers of peat in northern tundras and clathrate ices under the seabed. Some speculated that global warming could melt those, leading to massive additional releases of CO_2 and methane. These were only two of a number of alarming ideas, raised from the 1980s on, about positive feedbacks: more greenhouse warming, thus more emissions, and so on up.[84,85]

Still more disturbing were statistical studies by British and American groups that showed that the actual global warming first noticed in the 1930s, which had paused between 1940 and the mid-1970s, had resumed with a vengeance. On average the world was

hotter in the 1980s than at any time as far back as good records went.[86,87] Some climate scientists believed that greenhouse warming was already manifest, but the majority exercised the caution appropriate to their trade. Much remained unknown about the changes in solar energy, aerosols, cloudiness, and many other influences on the climate system.

There were forces working to magnify this skepticism in the public mind. Corporations that feared government regulation of their emissions found allies in political conservatives who saw any claim about an environmental risk as left-wing agitation. During the 1980s, public opinion about global warming became polarized along political lines. The polarization was stronger in the United States than in Western Europe and Japan, where environmentalists were more in the political mainstream and industrialists fought regulation less fiercely.

Political polarization increased in 1983 when a group of respected atmospheric scientists announced a new risk to global climate. They warned that smoke from cities torched in a nuclear war would darken the atmosphere, bringing a long 'nuclear winter' that might jeopardize the survival of all humankind.[88] The apocalyptic image of a planet ravaged by nuclear war had been familiar for decades as a science fiction trope, but now explicit calculations offered a realistic mechanism. Even if, as soon emerged, a 'nuclear autumn' was a more likely outcome, it was now a sober prediction that our policies, driven by fear or greed or simple aggression, could cause an atmospheric catastrophe—as if in punishment for our wickedness.

That way of thinking spread more widely after 1985, when a British group announced their discovery of a 'hole' in the ozone layer over Antarctica. The cause proved to be a buildup of chlorofluorocarbon chemicals, produced in industrial processes and widely used by the public in spray cans. Loss of ozone would mainly mean more skin cancers and other biological harms, but many members of the public got ozone depletion confused with global warming. The true lesson was that human activity, something as simple as using a spray, could change the atmosphere seriously and quickly.[89]

A sense of danger was also spreading in the scientific community. A new breed of interdisciplinary 'impact' studies was showing that even a few degrees of warming might have harsh consequences.[90,91] The rise in greenhouse gases was liable to devastate the world's coral reefs, allow tropical diseases to invade new territory, kill off entire forests, and so forth. Still more troubling, new theoretical possibilities for feedbacks and instability kept turning up. For example, a modest shift in temperature and rainfall might plausibly cause a sudden reorganization of the entire circulation system of the oceans. Ice cores from Greenland showed that radical shifts of the climate system had in fact happened within a single decade in the past.[92–94]

When a 1987 international conference in Montreal imposed restrictions on ozone-destroying chemicals, it gave hope that the world's governments were capable of acting against threats to the atmosphere. Scientists followed up in 1988 with a large international conference in Toronto, where they reached consensus on a statement that anthropogenic changes in the atmosphere 'represent a major threat to international security and are already having harmful consequences over many parts of the globe.' For the first time, a group of prestigious scientists was calling on the world's governments to set strict targets for reducing greenhouse gas emissions. They had framed anthropogenic global climate change as an *international relations issue*.[95–99]

The Toronto Conference attracted wide publicity, helped by exceptional heat and drought that were much in the news in this summer of 1988. Meanwhile, Congressional testimony by NASA scientist James Hansen, who believed greenhouse warming was becoming visible in the global temperature record, was widely misunderstood as a claim that the weather disasters were a sign of anthropogenic global warming. Although most scientists thought it premature to make such claims, politicians paid more attention to the media. And editors were always happy when an assembly of experts like the Toronto Conference, or even a single expert like Hansen, gave them an opening to exclaim about a gathering crisis.[100–104] The issue's legitimacy was enhanced by attention from the politically powerful 'Greens' in Germany and elsewhere in continental Europe, and a decision by environmentalist organizations to concentrate on global warming. Like the media, environmentalist groups tended to focus on the most frightening scenarios.

Polls showed that a majority of the public in the developed world was now aware of global warming, and worried about it. Of course, the public was used to seeing many kinds of apocalyptic warnings on their televisions; most people spent little time worrying about climate change, ranking the problem below daily issues like the economy or terrorism. Yet the growing acceptance of the reality of anthropogenic global warming had profound implications.

In 1900, people had seen nature as an expanse of wilderness surrounding their towns and fields. Whether nature was looked upon as a nurturing

environment for humanity or as a savage wasteland to be tamed and civilized, it stood outside and above human doings. By the 1980s, people were coming to see things the other way around: a 'wilderness' was a preserve surrounded and threatened by the machinery of civilization. And now the preserve itself was being overrun. Smog, ozone-destroying chemicals, greenhouse gases, and other kinds of pollution had entangled the air at every point on the globe with human agriculture and industry, indeed with each individual's daily consumption. In an influential book, nature writer Bill McKibben announced 'The End of Nature.' As he saw it, 'the *meaning* of the wind, the sun, the rain—of nature—has already changed.' Every cloud showed the imprint of human hands.[105] As a later writer put it, 'It was perfect weather for postmodernists: inescapably self-referential.'[106] To avoid universal punishment, McKibben and others called for radical changes in our lives: we must use public transport instead of inefficient cars, etc. They were framing anthropogenic global climate change as a *moral problem*.

The rising demands for regulating emissions worried conservative governments in the United States and elsewhere. They set up a mechanism for policy advice, an International Panel on Climate Change (IPCC), that would include not only scientists but official government representatives, and that moreover could issue no conclusion except by unanimous consent. It was a recipe for blandness if not paralysis. The first report of the IPCC, issued in 1990, was bland enough. The panel predicted (correctly, as it turned out) that it would take another decade before they could be confident whether greenhouse gas emissions would bring any temperature rise.[97,107]

No matter how else people framed it, climate change remained primarily a scientific puzzle. Thousands of scientists were now working to understand it, and their findings increasingly countered the objections raised by skeptics. To note one of many examples, independent computer modeling groups in California, Britain, and Germany all retroactively 'predicted' with reasonable accuracy the geographical pattern of atmospheric temperature changes at different levels of the atmosphere since the start of the century. The pattern of heating that the models calculated for the influence of greenhouse gases (the greenhouse 'signature') matched the observational data fairly well; patterns computed for solar energy changes or other proposed influences did not.[108,109] To be sure, there remained many problems. Everyone knew that cloudiness and aerosols in particular were poorly understood. But independent evidence pointed in the same direction as the models. In particular, the sensitivity of global temperature to the CO_2 level in the distant past was found to lie within the range the models claimed.[110] And through the 1990s the actual global temperature kept rising.

The unrelenting accumulation of evidence put the IPCC under pressure to reach a firm conclusion in its second report, due in 1995. The first panel had been criticized as too narrow; it was dominated by geophysicists, and nearly all of them came from a handful of wealthy nations. The IPCC's leaders responded by gradually including more experts from other disciplines—first the life sciences, followed by fields as distant as economics, each with its different approaches and opinions. Field geologists, e.g., in harmony with the fossil fuel industries where many of them worked, were often deeply skeptical about anthropogenic global warming. The IPCC also encouraged and even subsidized participation by scientists from less-developed nations. The panel was steadily organizing itself into an unprecedented mechanism for assembling scientific information and constructing summary statements.

Under the judicious chairmanship of Bert Bolin, in 1995 the representatives hammered out a unanimous consensus: not only was the world getting warmer, but 'the balance of evidence suggests' that humanity was exercising a 'discernible' influence on global climate.[108] The weaselly wording showed the strain of political compromises. Nevertheless, as a formal declaration by the assembled scientific experts and governments of the world, this was page-one news in many countries. The process resembled one observed historically in the emergence of parliaments: once a representative body has been created, it tends to gradually acquire status and ultimately a degree of power.

A prompt consequence of the IPCC's declaration was the 1997 Kyoto Protocol, in which most industrialized nations pledged to restrain their greenhouse gas emissions. Although in practical terms this turned out to be worth little more than most diplomatic promises, it constituted a comprehensive governmental endorsement of the idea that anthropogenic global climate change called for a serious response.

Many climate scientists were now taking an unequivocal or even activist stance on greenhouse warming. A smaller and dwindling number of skeptics opposed them. Their arguments were hardly ever published in peer-reviewed scientific journals, but mainly in conservative media and public-relations products funded by corporate and right-wing patrons, mostly in the United States. In the journals where climate scientists published their research,

anthropogenic global warming was treated as a well-established phenomenon.[111] When the IPCC issued its third report in 2001, concluding unanimously that it was 'likely' that greenhouse gases were bringing a sustained warming, it scarcely seemed like news.[112] Some did take note (especially in the intrinsically farsighted insurance industry), and began to frame anthropogenic global climate change as a *factor in practical decisions*.

This could not get far, however, for predicting 'global warming' was a long way from predicting specific climate changes and their impacts. The IPCC had reached its consensus that warming was 'likely' only through grueling negotiations, haggling over every word. Almost the only other thing that all climate experts agreed on was that severe uncertainties remained. For example, data and theory remained inadequate to calculate the effects of aerosol pollution on climate beyond very broad limits. Nobody could be sure whether doubling the CO_2 in the atmosphere would raise the average global temperature a mere one degree or a catastrophic six degrees.

Worse, the *average* global temperature meant little: people wanted to know what could happen in their own region. Computer models tended to agree about some regions, e.g., that the American Southwest and the Mediterranean would get less rainfall, mountain snowpacks would dwindle, the Arctic would warm up fastest. But for many regions, little could be said with certainty. This did not prevent some individuals and organizations from exclaiming that the perils were terrible and imminent, while others insisted there were no risks whatsoever.

For most people, any connection to their business model or daily lives seemed remote. McKibben lamented that global warming 'has not registered in our gut.'[113] It was not just that the issue was still commonly framed as a scientific puzzle, although for many citizens that was enough to repel thought. Political conservatives and the industry-funded public relations effort in the United States continued working to keep people from framing global climate change as a 'problem.'[114,115] They insisted that global warming was not in fact underway. Or if it was, humans were not causing it. Or if we were, the net results would be benign. Or if not, new technologies would take care of it (by now there were scores of geoengineering proposals, ranging from prosaic reforestation to fantastic schemes to launch a sun shield into space). Many journalists, pursuing their ideal of 'unbiased' coverage, wrote 'balanced' stories that quoted the few skeptics as often as all the mainstream climate scientists. Both public and official opinion in the United States froze in place. The media in other nations tended to match the views of scientists more closely. The balance of public and official opinion in Europe, Japan, and leading developing nations steadily took global warming more seriously—although not seriously enough to install policies with serious economic consequences.[116,117]

CONCLUSION

In the last two decades of the 20th century, greenhouse warming became politically important enough to attract studies of public opinion. These found that everywhere a substantial minority felt deep concern about global warming, sometimes approaching despair; everywhere a minority of roughly comparable size steadfastly denied the problem; everywhere the majority of citizens felt increasingly substantial worries, but admitted they were ignorant about the issue and (especially in the United States) placed it low on their list of concerns. There was a wider range of views than ever on what 'anthropogenic climate change' meant in human terms, views that reflected deep-seated personal attitudes toward authorities, personal responsibility, risk-taking, and the natural world. During these same decades, the community of qualified scientists worked out a consensus as near certainty as could ever be reached for a system as complex as climate. It was a narrowly restricted consensus, addressing only the most general question, yet nonetheless significant: human emissions were making the world warmer, bringing serious risk at an accelerating pace.

At the start of the century, such a statement would have seemed absurd if not inconceivable. The reversal of opinion was due, in the first place, to the fact that human activities can indeed alter the global climate. But this fact became known only through the combined labors of thousands of scientists, painstakingly acquiring data and constructing computer models. Early in the century, hardly anyone saw a need for research on the topic, since prevailing views denied that living creatures could influence geophysical systems at all, let alone on a human timescale. Extensive research on the topic might have not have gotten underway until late in the century—perhaps not until anomalous global warming became manifest—but for the fact that prior to 1960 five scientists (Arrhenius, Callendar, Plass, Revelle, and Keeling) happened to take an interest in an odd hypothesis, and pursued it arduously with no reason to expect much reward. Thanks to them, a full-scale research effort could begin once the meteoric rise of population and industry and the advent of widespread pollution and nuclear weapons made plausible the idea of a

global human impact. From the 1970s forward this expanding research effort gradually persuaded scientists and other citizens that anthropogenic global climate change was underway. That belief and the striking rise of actual global temperature were key components in a prodigious transformation of the traditional relationship between nature and humanity.

Developments after 2001 are beyond the scope of this essay, but a few remarks are in order. Scientists found further reasons to worry about climate change within their own lifetimes. While it seemed unlikely that climate change could be radically abrupt, the risk was not negligible.[118] Actual impacts were showing up as predicted or sooner than predicted, from early spring flowering to a dwindling of the Arctic ice pack, impressing common people around the world.[119,120] The new findings showed that we still did not understand the climate system well, but it was increasingly hard to argue that the IPCC had exaggerated the risk; if anything, the panel seemed to have underestimated it.[121] Responses to the new findings ranged from contemptuous dismissal to despairing cries for radical policy change. Opinion tended to become more amenable to regulatory action, notably among elite political and business circles from the United States to China. Accepting that inadvertent anthropogenic global climate change was a reality, many people considered how civilization could keep itself from stressing the planetary environment beyond the point of safety.

NOTES

The references given here are in many cases only examples drawn from a far larger literature. This article is based on the on-line essays listed in the supplementary references as Weart, '*Discovery of Global Warming*,' where many more references may be found.

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