The Discovery of Global Warming

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Introduction:

A Hyperlinked History of Climate Change Science

"To a patient scientist, the unfolding greenhouse mystery is far more exciting than the plot of the best mystery novel. But it is slow reading, with new clues sometimes not appearing for several years. Impatience increases when one realizes that it is not the fate of some fictional character, but of our planet and species, which hangs in the balance as the great carbon mystery unfolds at a seemingly glacial pace."
— *D. Schindler*(1)

It is an epic story: the struggle of thousands of men and women over the course of a century for very high stakes. For some, the work required actual physical courage, a risk to life and limb in icy wastes or on the high seas. The rest needed more subtle forms of courage. They gambled decades of arduous effort on the chance of a useful discovery, and staked their reputations on what they claimed to have found. Even as they stretched their minds to the limit on intellectual problems that often proved insoluble, their attention was diverted into grueling administrative struggles to win minimal support for the great work. A few took the battle into the public arena, often getting more blame than praise; most labored to the end of their lives in obscurity. In the end they did win their goal, which was simply knowledge.

The scientists who labored to understand the Earth's climate discovered that many factors influence it. Everything from volcanoes to factories shape our winds and rains. The scientific research itself was shaped by many influences, from popular misconceptions to government funding, all happening at once. A traditional history would try to squeeze the story into a linear text, one event following another like beads on a string. Inevitably some parts are left out. Yet for this sort of subject we need *total history,* including all the players — mathematicians and biologists, lab technicians and government bureaucrats, industrialists and politicians, newspaper reporters and the ordinary citizen. This Web site is an experiment in a new way to tell a historical story. Think of the site as an object like a sculpture or a building. You walk around, looking from this angle and that. In your head you are putting together a rounded representation, even if you don't take the time to inspect every cranny. That is the way we usually learn about anything complex.

You can start with the following 10-minute overview. Or skip down to advice on using this site. This and all other files are available in a printable format (but you'll miss the hyperlinks and the most recent updates).

The story in a nutshell: People have long suspected that human activity could change the local climate. For example, ancient Greeks and 19th-century Americans debated how cutting down forests might bring more rainfall to a region, or perhaps less. But there were larger shifts of climate that happened all by themselves. The discovery of ice ages in the distant past proved that climate could change radically over the entire globe, which seemed vastly beyond anything mere humans could provoke. Then what did cause global climate change — was it variations in the heat of the Sun? Volcanoes erupting clouds of smoke? The raising and lowering of mountain ranges, which diverted wind patterns and ocean currents? Or could it be changes in the composition of the air itself?

In 1896 a Swedish scientist published a new idea. As humanity burned fossil fuels such as coal, which added carbon dioxide gas to the Earth's atmosphere, we would raise the planet's average temperature. This "greenhouse effect" was only one of many speculations about climate change, however, and not the most plausible. Scientists found technical reasons to argue that our emissions could not change the climate. Indeed most thought it was obvious that puny humanity could never affect the vast climate cycles, which were governed by a benign "balance of nature." In any case major change seemed impossible except over tens of thousands of years.

In the 1930s, people realized that the United States and North Atlantic region had warmed significantly during the previous half-century. Scientists supposed this was just a phase of some mild natural cycle, with unknown causes. Only one lone voice, the amateur G.S. Callendar, insisted that greenhouse warming was on the way. Whatever the cause of warming, everyone thought that if it happened to continue for the next few centuries, so much the better.

In the 1950s, Callendar's claims provoked a few scientists to look into the question with improved techniques and calculations. What made that possible was a sharp increase of government funding, especially from military agencies with Cold War concerns about the weather and the seas. The new studies showed that, contrary to earlier crude estimates, carbon dioxide could indeed build up in the atmosphere and should bring warming. Painstaking measurements drove home the point in 1960 by showing that the level of the gas was in fact rising, year by year.

Over the next decade a few scientists devised simple mathematical models of the climate, and turned up feedbacks that could make the system surprisingly variable. Others figured out ingenious ways to retrieve past temperatures by studying ancient pollens and fossil shells. It appeared that grave climate change could happen, and in the past had happened, within as little as a few centuries. This finding was reinforced by computer models of the general circulation of the atmosphere, the fruit of a long effort to learn how to predict (and perhaps even deliberately change) the weather. Calculations made in the late 1960s suggested that average temperatures would rise a few degrees within the next century. But the next century seemed far off, and the models were preliminary. Groups of scientists that reviewed the calculations found them plausible but saw no need for any policy action, aside from putting more effort into research to find out for sure what was happening.

In the early 1970s, the rise of environmentalism raised public doubts about the benefits of human activity for the planet. Curiosity about climate turned into anxious concern. Alongside the greenhouse effect, some scientists pointed out that human activity was putting dust and smog particles into the atmosphere, where they could block sunlight and cool the world. Moreover, analysis of Northern Hemisphere weather statistics showed that a cooling trend had begun in the 1940s. The mass media (to the limited extent they covered the issue) were confused, sometimes predicting a balmy globe with coastal areas flooded as the ice caps melted, sometimes warning of the prospect of a catastrophic new ice age. Study panels, first in the U.S. and then elsewhere, began to warn that one or another kind of future climate change might pose a severe threat. The only thing most scientists agreed on was that they scarcely understood the climate system, and much more research was needed. Research activity did accelerate, including huge data-gathering schemes that mobilized international fleets of oceanographic ships and orbiting satellites.

Earlier scientists had sought a single master-key to climate, but now they were coming to understand that climate is an intricate system responding to a great many influences. Volcanic eruptions and solar variations were still plausible causes of change, and some argued these would swamp any effects of human activities. Even subtle changes in the Earth's orbit could make a difference. To the surprise of many, studies of ancient climates showed that astronomical cycles had partly set the timing of the ice ages. Apparently the climate was so delicately balanced that almost any small perturbation might set off a great shift. According to the new "chaos" theories, in such a system a shift might even come all by itself — and suddenly. Support for the idea came from ice cores arduously drilled from the Greenland ice sheet. They showed large and disconcertingly abrupt temperature jumps in the past.

Greatly improved computer models began to suggest how such jumps could happen, for example through a change in the circulation of ocean currents. Experts predicted droughts, storms, rising sea levels, and other disasters. A few politicians began to suspect there might be a public issue here. However, the modelers had to make many arbitrary assumptions about clouds and the like, and reputable scientists disputed the reliability of the results. Others pointed out how little was known about the way living ecosystems interact with climate and the atmosphere. They argued, for example, over the effects of agriculture and deforestation in adding or subtracting carbon dioxide from the air. One thing the scientists agreed on was the need for a more coherent research program. But the research remained disorganized, and funding grew only in irregular surges. The effort was dispersed among many different scientific fields, each with something different to say about climate change.

One unexpected discovery was that the level of certain other gases was rising, which would add seriously to global warming. Some of these gases also degraded the atmosphere's protective ozone layer, and the news inflamed public worries about the fragility of the atmosphere. Moreover, by the late 1970s global temperatures had begun to rise again. Many climate scientists had become convinced that the rise was likely to continue as greenhouse gases accumulated. By around 2000, some predicted, an unprecedented global warming would become apparent. Their worries first caught wide public attention in the summer of 1988, the hottest on record till then. (Most since then have been hotter.) An international meeting of scientists warned that the world should take active steps to cut greenhouse gas emissions.

The response was vehement. Corporations and individuals who opposed all government regulation began to spend many millions of dollars on lobbying, advertising, and "reports" that mimicked scientific publications, in an effort to convince people that there was no problem at all. Environmental groups, less wealthy but more enthusiastic, helped politicize the issue with urgent cries of alarm. But the many scientific uncertainties, and the sheer complexity of climate, made room for limitless debate over what actions, if any, governments should take.

Here's what all scientists agreed they knew by 1988

To stay at a constant temperature, the Earth must radiate as much energy as it receives from the Sun. We receive this energy mostly as visible light which warms the surface. Being much cooler than the Sun, the Earth radiates most of its energy as infrared rays. A calculation using basic laws of physics shows that a planet at our distance from the Sun, emitting the same total amount of energy as it receives, will have a temperature well below freezing. Then why is the actual average surface temperature higher, about 14°C? Infrared radiation beaming up from the surface is intercepted by "greenouse" gas molecules in the lower atmosphere, and that keeps the lower atmosphere and the surface warm. The radiation that finally escapes is mostly emitted from higher levels of the atmosphere, levels that are indeed well below freezing (-18°C, for details see the essay on simple models).

The nitrogen and oxygen gases that make up most of the atmosphere don't intercept infrared radiation. The most important greenhouse gases are water vapor and carbon dioxide (CO_2). The level of carbon dioxide in the atmosphere was observed to be rising rapidly, and the only reasonable explanation was that this was due to the enormous emissions from human activities.

A rather straightforward calculation showed that doubling the level of carbon dioxide in the atmosphere... which would arrive in the late 21st century if no steps were taken to curb emissions... should raise the temperature of the surface roughly one degree C. However, a warmer atmosphere would hold more water vapor, which ought to cause another degree or so of warming. Beyond that the calculations got problematic. Cloudiness was likely to change in ways that could either enhance or diminish the warming, and scientists did not understand the complex processes well. Moreover, humanity was emitting ever increasing amounts of smoke and other pollution; again scientists were not sure how this might affect climate. Only better observations and computer models could attempt to project the outcome.

Scientists intensified their research, organizing programs on an international scale. Was the global temperature rise due to an increase in the Sun's activity? Solar activity began to decline, but the temperature soared faster than ever. Did computer models reproduce the present climate only because they were tweaked until they matched it, making them worthless for calculating a future climate change? Improved models successfully predicted the temporary cooling due to a huge volcanic explosion in 1991 and passed many other tests. In particular, the modelers could now reproduce in detail the pattern of warming, changes in rainfall, etc. actually observed in different regions of the world over the past century. Nobody had been able to build a model that matched the historical record and that did *not* show significant warming when greenhouse gases were added.

The physics of clouds and pollution remained too complex to work out exactly, and modeling teams that made different assumptions got somewhat different results. Most of them found a warming of around 3°C when the carbon dioxide level doubled, late in the 21st century. But some found a rise of 2°C or perhaps a bit less, a costly but manageable warming. Others calculated a 5°C rise or even more, an unparalleled catastrophe.

Meanwhile striking news came from studies of ancient climates recorded in Antarctic ice cores. For hundreds of thousands of years, carbon dioxide and temperature had been linked: anything that caused one of the pair to rise or fall had caused a rise or fall in the other. It turned out that a doubling of carbon dioxide had always gone along with a 3°C temperature rise, give or take a degree or two — a striking confirmation of the computer models, from entirely independent evidence.

The world's governments had created a panel to give them the most reliable possible advice, as negotiated among thousands of climate experts and officials. By 2001 this Intergovernmental Panel on Climate Change (IPCC) managed to establish a consensus, phrased so cautiously that scarcely any expert or government representative dissented. They announced that although the climate system was so complex that scientists would never reach complete certainty, it was *much more likely than not* that our civilization faced severe global warming. At that point the discovery of global warming was essentially completed. Scientists knew the most important things about how the climate could change during the 21st century. How the climate would actually change now depended chiefly on what policies humanity would choose for its greenhouse gas emissions.

Since 2001, greatly improved computer models and an abundance of data of many kinds strengthened the conclusion that human emissions are very likely to cause serious climate change. The IPCC's conclusions were reviewed and endorsed by the national science academies of every major nation from the United States to China, along with leading scientific societies and indeed virtually every organization that could speak for a scientific consensus. Specialists meanwhile improved their understanding of some less probable but more severe possibilities. On the one hand, a dangerous change in ocean circulation seemed unlikely in the next century or two. On the other hand, there were signs that disintegrating ice sheets could raise sea levels faster than most scientists had expected. Worse, new evidence suggested that the warming was itself starting to cause changes that would generate still more warming.

In 2007 the IPCC reported that scientists were more confident than ever that humans were changing the climate. Although only a small fraction of the predicted warming had happened so far, effects were already becoming visible in some regions — more deadly heat waves, stronger floods and droughts, heat-related changes in the ranges and behavior of sensitive species. (See the summary of expected impacts.) But the scientists had not been able to narrow the range of possibilities. Depending on what steps people took to restrict emissions, by the end of the century we could expect the planet's average temperature to rise anywhere between about 1.4 and 6°C (2.5 - 11°F).

Some people feared that the IPCC was too conservative; they insisted on emergency measures to avoid the risk of catastrophe if temperatures rose to the upper end of the projected range or even beyond. Others insisted that the IPCC was wholly mistaken; there was no need to worry. They pointed to a minority of scientists (scarcely any of them known for contributions to climate science) who held to the old conviction that human activity was too feeble to sway natural systems. Distrust of the climate experts was encouraged by corporations and political interests that opposed any government interference in the economy. However, the scientists who had been predicting for decades that by 2000 the world would be significantly warmer were now obviously correct. Science reporters, business leaders, government advisers and others increasingly believed them. An ever larger number of individuals, corporate entities, and government agencies at every level decided that something had to be done. They found that effective steps could be taken at surprisingly little cost, and many began to take them. (For a short summary of ideas on what we can do, see my personal note.)

What do we know today about how global temperature changes?

The temperature of the air near the surface has been measured by land, sea and satellite instruments, very accurately since the 1970s and fairly accurately since the late 19th century (black curve in GRAPH A, below). Four main influences are known, and combining these gives quite a good match to the observations (orange curve in A). The known influences are: irregular “El Niño” fluctuations in the upwelling of deep cold waters in the tropical Pacific Ocean, which cool or warm the air for a few years (purple curve in B); sulfate smog particles emitted in volcanic eruptions, such as El Chichón in 1982 and Pinatubo in 1991, which bring temporary cooling (blue curve); a quasi-regular cycle in the Sun’s activity that changes the radiation received at Earth (green curve); and human ("anthropogenic") changes — primarily emission of carbon dioxide from fossil fuels, but also other greenhouse gases and pollution such as smoke, and land-use changes such as deforestation (red curve). Theorists can calculate the actual influence of each factor, but only approximately. The authors of the model shown in the graph adjusted the weights to give the best fit to the observations. In particular, the global heating since the 1970s can be explained only by humanity’s greenhouse gas emissions. Note, for example, how the temperature trend in the first decade of the 21st century was generally flat because an upward push by anthropogenic forces was temporarily offset by a downward pull as solar activity decreased and the oceans absorbed more heat than usual from the atmosphere (sea water temperatures in fact continued to rise).