THIS IS THE TEXT OF AN ESSAY IN THE WEB SITE *"THE DISCOVERY OF GLOBAL WARMING"* BY SPENCER WEART, HTTP://WWW.AIP.ORG/HISTORY/CLIMATE. **JUNE 2007**. HYPERLINKS WITHIN THAT SITE ARE NOT INCLUDED IN THIS FILE. FOR AN OVERVIEW SEE THE BOOK OF THE SAME TITLE (HARVARD UNIV. PRESS, 2003). COPYRIGHT © 2003-2007 SPENCER WEART & AMERICAN INSTITUTE OF PHYSICS.

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.

The story in a nutshell: From ancient times people suspected that human activity could change the climate. For example, in the 19th century many Americans believed that cutting down forests brought more rainfall to a region. The discovery of ice ages in the distant past proved that

[1] Schindler (1999).

climate could change all by itself, and radically. But what caused these changes—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, and not the most plausible. Scientists found good reason to believe that our emissions could not change the climate. Anyway 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 1961 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. A 1967 calculation suggested that average temperatures might rise a few degrees within the next century. The next century seemed far off, however, and the calculations were plainly speculative. Groups of scientists that reviewed the issue saw no need for any policy actions, although they did draw official attention to the need for a greater research effort.

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 and Antarctic ice sheets. 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 evidently begun to rise again. International panels of scientists began to warn that the world should take active steps to cut greenhouse gas emissions. The scientists' claims about climate change first caught wide public attention in the summer of 1988, the hottest on record till then. (Most years since then have been hotter.) But the many scientific uncertainties, and the sheer complexity of climate, made for vehement debate over what actions, if any, governments should take. Corporations and individuals who opposed all government regulation spent large sums to convince people that there was no problem at all.

Scientists intensified their research, organizing programs on an international scale. The world's governments 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 managed to establish a consensus, phrased so cautiously that scarcely any expert 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.

(These essays originally ended with the developments of mid 2001, but I have made annual updates. Be warned that this introduces distortions that cannot be avoided in doing a sort of journalism without the perspective of history.)

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 intergovernmental panel reaffirmed that in a report published in 2007, but they 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). Although only a small fraction of this warming had happened so far, predicted effects were already becoming visible in some regions—more deadly heat waves, rising sea level, stronger floods and droughts, the spread of tropical diseases and the decline of sensitive species. (Expected impacts are summarized at the end of the essay on Impacts.)

Scientists meanwhile improved their understanding of some less probable but more severe possibilities. On the one hand, an abrupt change in ocean circulation seemed unlikely in the next century or two. On the other hand, there were signs that disintegrating ice sheets could bring harm sooner and more severely than most scientists had expected. Worse, new evidence showed that the warming was itself starting to cause changes that would generate still more warming.

The political news was a little better. The scientists who had predicted back in the 1980s that by the end of the century the world would be warmer were now demonstrably correct, and the press and other elites began to trust them. Many of the public did continue to doubt, supported by a tiny minority of scientists who clung to earlier views from ideological conviction or sheer stubbornness. But an ever larger number of individuals, government units, and corporate entities realized 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.)

Using the site

Getting around: There are two sorts of essays here. Lengthy ones tell the history of some major development, such as computer modeling or international negotiations. Shorter ones delve more deeply into a particular topic—partly because it had an important impact, and partly to show some typical details of what was going on behind the scenes. At the end of most essays you will find links suggesting related supplementary essays (as enrichment) and major essays (as a path to continue through the main story).

In each essay, on the right of the text you will see links to essays about other topics. Follow forward an arrow to see how the events you are reading about gave something **=>TO** the other topic. Follow back an arrow to track influence **<=FROM** the other topic (*this is where you'll find the more complete account of a development*). A double arrow **<=>** shows **MUTUAL** interaction.

Numbered notes, e.g., [12] give references. Notes shown thus: [12] have some informative text in addition. You can click on the note to see text and references, and once there you can click on a reference to reach the item in the bibliography. To return from the bibliography, use your browser's **Back** button.

To start in, if you are interested especially in *the social connections* of climate studies you might start, for example, with the facts of the Modern Temperature Trend. From there you could proceed to the long essays on The Public and Climate and U.S. Government: The View from Washington, followed by International Cooperation. For *the scientific story*, a good starting-point is the keystone essay on the basic discoveries about The Carbon Dioxide Greenhouse Effect, followed by studies of Past Cycles: Ice Age Speculations and attempts to explain changes with Simple Models of Climate. For *basic information and current developments*, see the page of links and bibliography.

Utilities: There is a Table of Contents (site map)... Milestones are listed in a Timeline ... For recent developments and current understanding, see sections on Events After 1988... Historians and climate scientists should be sure to read the Introduction on Methods and Sources and are urged to contribute your thoughts including comments and corrections to sweart@aip.org ... References are listed in the bibliography. In lieu of an index, note the Site Search function