The Realization of Global Warming

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Perhaps better than any other issue, global warming exemplifies how scientific data and its interpretations affect the whole of society. Most politicians will state their view on climate change, and as such we tend to think of it as an entirely political issue. Phrases like 'greenhouse effect,' 'ozone hole,' and 'carbon cycle' are so politicized that their scientific merit sometimes seems dependent on whether the speaker is a Republican or Democrat. Many Americans have lost track of the argument among this political jargon and bureaucratic red tape, choosing to go on with their lives as normal. Others have become 'green,' or more aware and conscientious of the environment. So what exactly does it mean to be aware of global warming? To legions of scientists, awareness of global warming has been a long and treacherous journey, fraught with years of data collection and interpretation. What follows is a short glimpse into how scientists determined that the Earth is warming.

Before jumping into the story, it's best to know the how global warming stands among scientists today. First, 140 years of data and reconstructions of the last 1,000 years of weather patterns make clear that the Earth is warmer now than it has been in the last millennia. The question now is just how much of a role humankind plays in this warming? Are we its sole cause, plunging the Earth into a climate catastrophe? Or are we adding to an already natural warming trend that will result in significant but tolerable weather change? Or, as many critics of global warming contend, are scientists just 'scaremongering' and refusing to admit that our emissions are being deposited away into the natural carbon 'sinks' (ocean bottoms and terrestrial vegetation) and that life will go on as normal? Here is where the term 'global warming' becomes tricky. Depending on who's talking, it can mean all of the above. With such imprecise use of terms, it's pretty easy to just give up and peg global warming as non-scientific.

But that would be mistaken. Global warming research is very scientific. Something helpful to keep in mind is that 'global warming' is a buzzword that represents a lot of scientific ideas about climate change. The science is complex. Many computer models have the Earth warming in the range of 0.5°C to 6°C, but this is just a global average, and it would not be distributed evenly throughout the world. Many scientists agree that some regions of the Earth will become colder. With the rest of the world experiencing higher temperatures, though, many catastrophes could arise. Glaciers could melt into the ocean, forever losing their supply of fresh water and significantly raising ocean levels. Life cycles of plants and animals could be disrupted, and growing seasons might be disrupted by irregular weather cycles. All of this is well supported science, but it can easily be taken out of context to be seen as non-scientific. Clearly, a lot of confusion exists in the public's mind over global warming.

1. Many people only consider how scientific knowledge influences society through the technology that is developed using that knowledge. How does the idea of global warming illustrate that scientific knowledge itself may impact society?

The effects of global warming are potentially catastrophic for some components of the biosphere. So understanding it and its causes is crucial. Global warming is tied to the greenhouse effect. Around 1830, Fourier, a mathematician, came to the conclusion that the Earth's atmosphere holds in heat, much like glass panels of greenhouses that provide ideal growing habitats for plants year-round. If the Earth had no atmosphere, its surface temperature (heated only by the direct radiation of the sun) would be around the freezing point of water.

The greenhouse effect has everything to do with the types of gases making up the atmosphere. Most gases react with only a very small portion of the light spectrum. Nitrogen (N_2) and oxygen (O_2) make up close to 99% of the Earth's atmosphere. In the late 1850s the noted British physicist John Tyndall analyzed the gases of the Earth's atmosphere one by one. He determined that nitrogen and oxygen do not absorb infrared heat radiation that rises from a warmed surface. But he determined that three gases in the Earth's atmosphere do hold in heat radiation. These gases are water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3). Unlike nitrogen and oxygen, these greenhouse molecules all have three atoms. This gives them a special property. Whereas nitrogen, oxygen, water vapor, carbon dioxide and ozone are all transparent to sunlight, the greenhouse gases trap a portion of the heat radiation reflected from a heated surface. As he described

Charles Keeling photo courtesy of Harmon Craig it: “As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial [infrared] rays, produces a local heightening of the temperature at the Earth's surface.”

On Venus, carbon dioxide makes up 96% of its atmosphere and is responsible for temperatures over 400°C. On the Earth, the greenhouse gases make up less than 1% of our atmosphere and maintain an average temperature of 14°C. Tyndall had the insight that if the amount of carbon dioxide in our atmosphere dropped even a little, the change could cool the planet. He also suggested this might be a possible explanation for ice ages. Interestingly, he appears not to have considered the consequences of a rise in carbon dioxide levels. At the time, his explanation worked to describe one way in which surface temperature was maintained on the Earth's surface, and nobody considered that booming industry could one day trip the climatic balance.

Given what scientists now know about the greenhouse effect, it might seem like anybody studying the environment should have immediately realized that the Earth must be affected by man-made pollutants. The story, however, isn't that simple. Most of the evidence of global warming comes in bits and pieces, relying on gritty (and often obsessive) researchers going to the ends of the Earth to study the most obscure ecosystems. They came from disciplines as diverse as their topic – oceanography, geophysics, astronomy, physics, chemistry, and others. Once they collected their data, the hardest journey lay ahead of them. What did the numbers mean? Were humans making things worse? And at what point, if evidence supported a human influence on global warming, should scientists warn the public and politicians? Like most science ideas, global warming was not “discovered” in a single instance or a single experiment. The idea developed and had been supported by research over a long period of time.

2. Real science is neither divided nor isolated into the neat divisions often found in school science. Evidence for global warming comes from several different scientific disciplines. How does knowledge that is supported from several science disciplines add credibility to that knowledge?

In 1896, the Swedish scientist Svante Arrhenius, who received one of the first Nobel prizes in chemistry, argued that the Earth's climate could be alternating between 'ice ages' and warming periods based on the introduction or depletion of carbon dioxide in the atmosphere. For example, a period of intense volcanic activity would put a lot of carbon dioxide into the atmosphere, and cause a warming. If these volcanoes then went dormant for a long enough time, the planet could cool and cause an ice age. But Arrhenius went further. He wrote in the London, Edinburgh, and Dublin Philosophical Magazine of April, 1896 that “We are evaporating our coal mines into the air.” He noted that human activity adding large quantities of carbon dioxide to the air must be causing “a change in the transparency of the atmosphere.”

Very few scientists specialized in climatology in the early 1900s, and those that did often did so as a hobby. As physics and chemistry underwent 'revolutions' in thinking with relativity theory, quantum mechanics, and atomic theory, climatologists kept making their 'short time' predictions for farmers and almanacs. To those who kept an eye on the sky, carbon dioxide was no more important than any other gas that made up the atmosphere. Then in 1938, Guy Stewart Callendar went before the Royal Meteorological Society to present his argument that contemporary calculations of carbon dioxide in the atmosphere happened to be higher than those in the previous century. This rise in carbon dioxide, he said, could be the cause of warming on the Earth. Perhaps, even, modern industry had contributed to this rise with its belching smoke stacks and mechanized vehicles. Far from being a climatologist, Callendar was a steam engineer, and he relied on old, rudimentary information. His ideas were heard by the Society, but not well received.

The state of climatology changed almost overnight with World War II. Historian Spencer Weart describes what it was like before the war: “Climatology could hardly be scientific when meteorology itself was more art than science. The best attempts to use physics and mathematics to describe weather – or even simple, regular features of the planet's atmosphere like the trade winds – had gotten nowhere.” American entrance into World War II on two sides of the globe placed a huge emphasis on knowing weather patterns and predicting trends. Willing participants were tossed into crash courses on meteorology. Money poured into the coffers. Generals fantasized about one day controlling the weather, seeding clouds from airplanes and bringing rain down upon enemies at just the right time. Of course, this never occurred, but the intense research into the Earth's climate paid huge dividends.

In the mid-1950s, two researchers began studying carbon dioxide levels in the atmosphere. David Keeling, a post-doctoral student at Caltech, had been tenaciously measuring carbon dioxide levels in various areas of the country beginning in spring 1955. An outdoors lover, Keeling had decided against working in a chemistry lab in favor of working in an emerging field called geochemistry. From May to September of that year he collected carbon dioxide samples while camping with his wife and newborn son at sites in the Western United States. While camping at Yosemite, they ran into problems with hungry deer. One night he heard noise outside the tent.

I rummaged around, grabbed my flashlight, looked out, and the flashlight was just like a policeman's apprehending a suspect. Two big eyes, looking right at me! It was that darn mule deer (or another just like it) and he had my research notebook between his teeth. And as soon as I got him started he ran off into the woods with the notebook.

Keeling rushed out of the tent and amazingly found his notebook, the pages showing the teeth marks of the deer.

> **!** **Note that scientists choose a particular field of study because of their academic interests, but also because of what they find personally enjoyable. Many people reject a career involving science, wrongly thinking that all scientists work solely in a laboratory. In actuality, scientists work in all sorts of settings.**

By 1958 Keeling had collected and analyzed an enormous amount of data and determined that two invisible carbon dioxide cycles exist. The first is a local daily cycle. As the sun rises, photosynthetic organisms begin taking in carbon dioxide. Respiration occurs day and night, but a net drop in carbon dioxide occurs during the day due to the greater rate of photosynthesis. At night, carbon dioxide levels return to the same level as the previous night. The second cycle occurs over the entire planet during the course of a year. Whereas respiration occurs all during the year, photosynthesis primarily occurs from around April through October, peaking in June. So the Earth's carbon dioxide levels rise and fall during the year.

Meanwhile, Gilbert Plass had been working close by at Lockheed Martin. He had been researching heat-seeking missiles when he took up studying the absorption of energy by carbon dioxide. After running his calculations through the company computer, in 1956 he claimed that human activity could raise temperatures by 1.1°C per century. Hearing of each other's work, they teamed up and headed to the Scripps Oceanography Institute to study the absorption of carbon dioxide by ocean water. What they determined was that the ocean did absorb some carbon and send it to the bottom, but only 1/10 as much as previously thought. The remaining carbon had to go somewhere else.

'Carbon sinks' are locations where carbon is naturally processed or stored away. For example, ocean water will absorb some carbon, and over a very long time of cycling, the carbon will be sent to the depths, where it will not contribute to global warming. The world's flora is another carbon sink. Trees and grasses take in carbon dioxide through the process of photosynthesis. However, vegetation can take in only so much carbon dioxide. So, if output of carbon dioxide is great enough, it will overpower the natural 'carbon cycle' and become permanently entrenched in the atmosphere, where it becomes a trap for heat. The science of the 1950s had brought this possibility to the table – that the industry so loved by mankind might be overburdening the carbon cycle and raising the carbon dioxide levels of the atmosphere.

Meanwhile, the problem of ice ages still had not been solved. By now, Swedish researchers were drilling into ice cores and carefully extracting pollen samples, which revealed what kinds of plants inhabited an area at particular times in Earth's history. Other researchers were dating tree fragments from ice sheets. All of them continued to arrive at a 20,000 year cycle of warming and cooling. Nobody could figure out, though, just how this could happen. While this physical mechanism remained a mystery, many agreed that the ice ages could have ended within 1,000 years – a rate which astounded many climatologists who preferred to believe these dramatic changes took much longer.

> **!** **Note that many different sources of evidence are being collected by different researchers. Yet they are independently interpreting their data to mean the Earth has approximately 20,000 year cycles of warming and cooling. Confidence in this idea grows with consistent independent interpretation of multiple data sources. Yet without a well-supported theory to explain this 20,000 year relationship, scientists are not satisfied. This illustrates the importance of theories in science. Theories provide an explanation for regularities in the natural world.**

By 1965, enough scientists had been concerned about the situation that they met in Boulder, Colorado, at the National Center for Atmospheric Research. They titled their meeting "Causes of Climate Change." As a group, they concluded that the Earth's climate was not self-stabilizing, meaning that external influences (such as mankind) could cause striking changes. David Keeling, meanwhile, continued collecting carbon dioxide samples. Plotting his data, he determined that while the Earth's carbon dioxide levels rise and fall each year in an ongoing cycle, the overall trend in the curves is higher levels of carbon dioxide each year. This is referred to as a Keeling curve (Figure 1).

While climatology boomed from an influx of researchers and money, it perhaps best benefited from new digital computers. These computers did the dirty work of crunching thousands of numbers and forecasting models. These computers, however, accidentally gave a great

FIGURE 1

An example of a Keeling Curve measuring atmospheric CO_2.

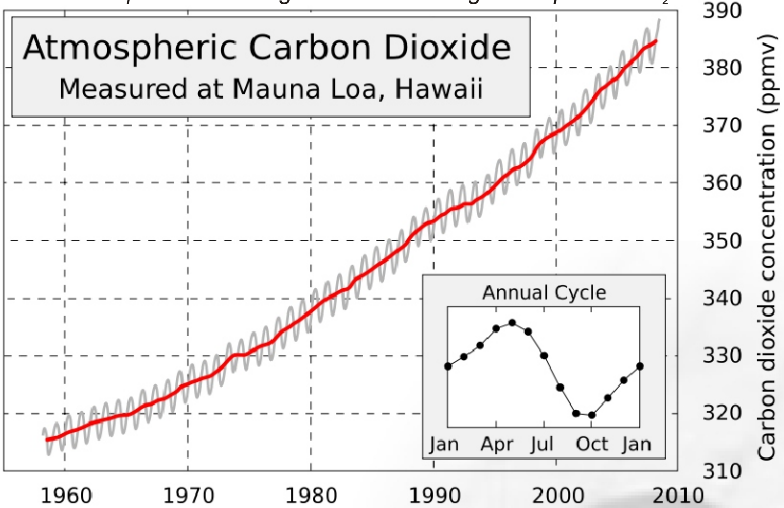

Image created by Robert A. Rohde / Global Warming Art.

insight to climatologists. Researchers realized that if they truncated numbers – say plugging in .002 for .0024959 – the computer would produce very different forecasts than if they had used the full number. At first researchers thought this meant that they needed to have the most accurate data possible to prevent error. Then something very important dawned on them. What if these very slight changes actually represented just how narrowly balanced the environment was? What if all that was required to change the environment over time was a very small change in carbon dioxide levels? These small changes, they realized, could account for the speedy changes between ice ages.

Going into the 1970s, fuel resources were being used at unprecedented rates. In 1972, the entire world felt a significant change in the climate. Droughts ravaged Africa and millions starved. The Soviet Union couldn't harvest its crops. The monsoons missed India. The media clamored for answers, and the only people who seemed to have them were those studying climatology. The scientists, in turn, were unsure of what to say, but many of them felt pressed to say that the climate could change in as little as 100 years. Citizens reacted, and the first Earth Day was held, and they pressed national governments to ban chlorofluorocarbons, an ingredient in aerosol cans discovered to be one of the worst greenhouse gases.

Meanwhile, scientists found themselves struggling. Suddenly reporters and politicians wanted concrete answers they didn't have. National tensions made exchanging data a hassle. Money still came, but the funds were earmarked for short-term weather prediction, the kind seen on television. Few people were concerned about the long-term, and even scientists didn't know what to say could happen in the next hundred or thousand years.

In 1973, Nick Shackleton measured radioactive potassium from a long core taken in the Indian Ocean. He determined that the Earth did indeed have warming and cooling cycles of 20,000 and 40,000 years, with a dominant cycle happening every 100,000 years or so. This agreed with modern astronomical calculations of the Earth's 'wobble' in its rotational axis, so scientists were forced to conclude that the 'precession of the equinoxes' did indeed have something to do with climate change. The question, again, was how did a small change in light intensity make such a dramatic change?

The answer was called 'feedback processes.' Essentially, the precession of equinoxes caused a slight change in global temperature, which was then amplified by other physical processes. If the change in temperature was enough to melt ice sheets, these ice sheets might then float into the ocean, becoming enormous mirrors that reflected light back into space and cooled the Earth. When the precession was over, the ice would melt and temperatures would rise again. Other feedback processes exist, but this was just one example.

3. Much of the scientific knowledge essential for understanding our climate and global warming was developed through what is called basic or pure research. This kind of research is done solely to learn more about the natural world with little thought of how it might be applied to society. Some people think that all scientific research should be targeted solely toward known societal concerns (called applied research). How does the history of global warming research illustrate that both pure and applied research should be supported for the benefit of society?

By the 1980s, global warming had become a topic on public opinion polls. One-third of the American population had heard of the 'controversial' idea. Still, accurate determinations were hard to come by. It seemed as if every small thing in the world affected the weather, so much that in 1979 Ed Lorenz posed to the American Association for the Advancement of Science his famous question: “Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?” Despite the seeming impossibility of forecasting long-term weather trends, they still had some stand-bys to rely on. For example, tornado and hurricane season came at the same time every year. Despite all the complexities, scientists realized some trends must hold. And in 1980, Jim Hansen determined a trend that nobody wanted to hear: that over the 20th century, global temperatures had risen by an average of 0.2°C. Furthermore, scientists came to realize a harrowing fact, described by historian Spencer Weart:

> **Any greenhouse warming would be masked not only by random natural variations and industrial pollution, but also by some fundamental planetary physics. If anything added heat to the atmosphere, much of it would be absorbed into the upper layer of the oceans. While that was warming up, perception of the problem would be delayed. [A] panel of experts had explained the effect in 1979: 'We may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable.'**

In 1986, the Climatic Research Unit at the British University of East Anglia compiled all the data on surface temperature they could get and concluded that the three warmest years on record had all come in the 1980s. Previous research had focused primarily on carbon dioxide. New research made clear that methane was actually a worse greenhouse gas by a factor of twenty. The product of bacteria breaking down organic material, the main sources of natural methane was undrained rice paddies and cattle. Researchers soon realized that the levels of methane in the atmosphere had climbed by 11% in the 1980s alone. They then realized another feedback process that could happen. If ice sheets melted to reveal swampy peat moss environments, the subsequent release of methane would enhance warming and thereby release more methane to create a “positive feedback.” Indeed, the environment did seem precariously balanced.

It's clear how global warming wasn't just 'discovered' one day, but put together piece by piece over a very long time. There is no question that the Earth is warming, because it's within its natural cycle to warm. The question is how much of this warming can be attributed to humans, and whether it is harmful and reversible. Right now, virtually every Earth scientist agrees that humans are adding carbon dioxide and methane and other greenhouse gases to the atmosphere at a dangerous level, a level which might not be reversible. The scientists arguing against global warming tend not to be Earth scientists, and are often idolized by non-scientists for their stand against their peers. Given the history, it should be clear that scientists who deny global warming are denying over a hundred years of painstakingly accumulated evidence. This is an important fact to remember as global warming is taken up by politicians in the coming years.

4. Many people wrongly think that scientific knowledge comes from scientists following a rigid step-by-step scientific method when doing research. This misconception wrongly leads to another misconception that the value of a scientific claim can only be made through a controlled experiment. Global warming is just one of many well-established science ideas that defy investigation by means of a controlled experiment. How might the public's view that all scientific knowledge should come from controlled experiments cause them to reject human beings' impact on global warming?

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