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).

The Carbon Dioxide Greenhouse Effect

In the 19th century, scientists realized that gases in the atmosphere cause a "greenhouse effect" which affects the planet's temperature. These scientists were interested chiefly in the possibility that a lower level of carbon dioxide gas might explain the ice ages of the distant past. At the turn of the century, Svante Arrhenius calculated that emissions from human industry might someday bring a global warming. Other scientists dismissed his idea as faulty. In 1939, G.S. Callendar argued that the level of both carbon dioxide and temperature had been rising, but most scientists found his arguments implausible. It was almost by chance that a few researchers in the 1950s discovered that global warming truly was possible. In the early 1960s, C.D. Keeling measured the level of carbon dioxide in the atmosphere: it was rising fast. Researchers began to take an interest, struggling to understand how the level of carbon dioxide had changed in the past, and how the level was influenced by chemical and biological forces. They found that the gas plays a crucial role in climate change, so that the rising level could gravely affect our future. (This essay covers only developments relating directly to carbon dioxide, with a separate essay for Other Greenhouse Gases. For related theoretical issues, see the essay on Simple Models of Climate.)

Like many Victorian natural philosophers, John Tyndall was fascinated by a great many questions. While he was preparing an important treatise on "Heat as a Mode of Motion" he took time to consider geology. Tyndall had hands-on knowledge of the subject, for he was an ardent Alpinist (in 1861 he made the first ascent of the Weisshorn). Familiar with glaciers, he had been convinced by the evidence—hotly debated among scientists of his day—that tens of thousands of years ago, colossal layers of ice had covered all of northern Europe. How could climate possibly change so radically?

One possible answer was a change in the composition of the Earth's atmosphere. Beginning with work by Joseph Fourier in the 1820s, scientists had understood that gases in the atmosphere might trap the heat received from the Sun. This was the effect that would later be called, by an inaccurate analogy, the "greenhouse effect." (*For explanation of the science, see the separate essay on Simple Models of Climate.*) The equations and data available to 19th-century scientists were far too poor to allow an accurate calculation. Yet the physics was straightforward enough to show that a bare rock at the Earth's distance from the Sun should be far colder than the Earth actually is. Tyndall set out to find whether there was in fact any gas that could trap heat rays. In 1859, his careful laboratory work identified several gases that did just that. The most important was simple water vapor (H_2O). Also effective was carbon dioxide (CO_2), although in the atmosphere the gas is only a few parts in ten thousand.[1]

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[1] Tyndall (1861).

Greenhouse Speculations: Arrhenius and Callendar

The next major scientist to consider the question was another man with broad interests, Svante Arrhenius in Stockholm. He too was attracted by the great riddle of the prehistoric ice ages. In 1896 Arrhenius completed a laborious numerical computation which suggested that cutting the amount of CO_2 in the atmosphere by half could lower the temperature in Europe some 4-5°C (roughly 7-9°F)—that is, to an ice age level. But this idea could only answer the riddle of the ice ages if such large changes in atmospheric composition really were possible. For that question Arrhenius turned to a colleague, Arvid Högbom. It happened that Högbom had compiled estimates for how carbon dioxide cycles through natural geochemical processes, including emission from volcanoes, uptake by the oceans, and so forth. Along the way he had come up with a strange, almost incredible new idea.

It had occurred to Högbom to calculate the amounts of CO_2 emitted by factories and other industrial sources. Surprisingly, he found that human activities were adding CO_2 to the atmosphere at a rate roughly comparable to the natural geochemical processes that emitted or absorbed the gas. The added gas was not much compared with the volume of CO_2 already in the atmosphere—the CO_2 released from the burning of coal in the year 1896 would raise the level by scarcely a thousandth part. But the additions might matter if they continued long enough.[1] (By recent calculations, the total amount of carbon laid up in coal and other fossil deposits that humanity can readily get at and burn is some ten times greater than the total amount in the atmosphere.) So the next CO_2 change might not be a cooling decrease, but an increase. Arrhenius made a calculation for doubling the CO_2 in the atmosphere, and estimated it would raise the Earth's temperature some 5-6°C.[2]

Arrhenius did not see that as a problem. He figured that if industry continued to burn fuel at the current (1896) rate, it would take perhaps three thousand years for the CO_2 level to rise so high. Högbom doubted it would ever rise that much. One thing holding back the rise was the oceans. According to a simple calculation, sea water would absorb 5/6ths of any additional gas. (That is roughly true over a long run of many thousand years, but Högbom and Arrhenius did not realize that if the gas were emitted more rapidly than they expected, the ocean absorption could lag behind.) Anyway temperatures a few degrees higher hardly sounded like a bad idea in chilly Sweden. Another highly respected scientist, Walter Nernst, even fantasized about setting fire to useless coal seams in order to release enough CO_2 to deliberately warm the Earth's climate.[3]

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[1] Högbom (1894); the essentials are quoted by Arrhenius (1896), pp. 269-73; see also Berner (1995); for further background, see Arrhenius (1997).

[2] He also did computations for 1.5-, 2.5- and 3-fold increases. Arrhenius (1896), 266; see Crawford (1996), chap. 10; Crawford (1997); reprinted with further articles in Rodhe and Charlson (1998).

[3] Nernst also noted that the additional CO_2 would fertilize crops. James Franck, interview by Thomas Kuhn, p. 6, Archive for History of Quantum Physics, copies at AIP and other

Arrhenius brought up about the possibility of future warming in an impressive scientific article and a widely read book. By the time the book was published, 1908, the rate of coal burning was already much higher than in 1896, and Arrhenius suggested warming might appear wihin a few centuries rather than millenia. Yet here as in his first article, the possibility of warming in some distant future was far from his main point. He mentioned it only in passing, during a detailed discussion of what really interested scientists of his time — the cause of the ice ages. Arrhenius had not quite discovered global warming, but only a curious theoretical concept.[1]

An American geologist, T. C. Chamberlin, and a few others took an interest in CO_2. How, they wondered, is the gas stored and released as it cycles through the Earth's reservoirs of sea water and minerals, and also through living matter like forests? Chamberlin was emphatic that the level of CO_2 in the atmosphere did not necessarily stay the same over the long term. But these scientists too were pursuing the ice ages and other, yet more ancient climate changes—gradual shifts over millions of years. Very different climates, like the balmy age of dinosaurs a hundred million years ago, puzzled geologists but seemed to have nothing to do with changes on a human time scale. Nobody took much interest in the hypothetical future warming caused by human industry.

Experts could dismiss the hypothesis because they found Arrhenius's calculation implausible on many grounds. In the first place, he had grossly oversimplified the climate system. Among other things, he had failed to consider how cloudiness might change if the Earth got a little warmer and more humid.[2] A still weightier objection came from a simple laboratory measurement. A few years after Arrhenius published his hypothesis another scientist in Sweden, Knut Ångström, asked an assistant to measure the passage of infrared radiation through a tube filled with carbon dioxide. The assistant ("Herr J. Koch," otherwise unrecorded in history) put in rather less of the gas in total than would be found in a column of air reaching to the top of the atmosphere. The assistant reported that the amount of radiation that got through the tube scarcely changed when he cut the quantity of gas back by a third. Apparently it took only a trace of the gas to "saturate" the absorption—that is, in the bands of the spectrum where CO_2 blocked radiation, it did it so thoroughly that more gas could make little difference.[3]

Still more persuasive was the fact that water vapor, which is far more abundant in the air than carbon dioxide, also intercepts infrared radiation. In the crude spectrographs of the time, the smeared-out bands of the two gases entirely overlapped one another. More CO_2 could not affect

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repositories..

[1] Arrhenius (1896); revised calculations, finding a somewhat lower effect, were given in Arrhenius (1901); popularization: Arrhenius (1908), chap. 2.

[2] The following discussion to ca. 1960 is taken with minor changes from a published study that includes some additional discussion and references, Weart (1997).

[3] Ångström (1900).

radiation in bands of the spectrum that water vapor, as well as CO_2 itself, were already blocking entirely.[1]

These measurements and arguments had fatal flaws. Herr Koch had reported to Ångström that the absorption had not been reduced by more than 0.4% when he lowered the pressure, but a modern calculation shows that the absorption would have decreased about 1% —like many a researcher, the assistant was over confident about his degree of precision.[2] But even if he had seen the 1% shift, Ångström would have thought this an insignificant perturbation. He failed to understand that the logic of the experiment was altogether false.

The greenhouse effect will in fact operate even if the absorption of radiation were totally saturated in the lower atmosphere. The planet's temperature is regulated by the thin upper layers where radiation does escape easily into space. Adding more greenhouse gas there will change the balance. Moreover, even a 1% change in that delicate balance would make a serious difference in the planet's surface temperature. The logic is rather simple once it is grasped, but it takes a new way of looking at the atmosphere—not as a single slab, like the gas in Koch's tube (or the glass over a greenhouse), but as a set of interacting layers. *(The full explanation is in the essay on Simple Models.)* The subtle difference did not occur to anyone for many decades, if only because hardly anyone thought the greenhouse effect was worth their attention. For after Ångström published his conclusions in 1900, the few scientists who had taken an interest in the matter concluded that Arrhenius's hypothesis had been proven wrong. Theoretical work on the question stagnated for decades, and so did measurement of the level of CO_2 in the atmosphere and its absorption of radiation.[3]

A few scientists dissented from the view that changes of CO_2 could have no effect. An American physicist, E.O. Hulburt, pointed out in 1931 that investigators had been mainly interested in pinning down the intricate structure of the absorption bands (which offered fascinating insights into the new theory of quantum mechanics) "and not in getting accurate absorption coefficients." Hulburt's own calculations supported Arrhenius's estimate that doubling or halving CO_2 would

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[1] Ångström (1900), pp. 731-32; Abbot and Fowle (1908), pp. 172-73; for spectrographs, e.g., Weber and Randall (1932).

[2] Koch had only a thermocouple to measure heat across the entire infrared spectrum. He accurately reported that about 10% of the radiation from a 100°C black body was absorbed in his tube, and that at lower pressure at most 9.6% was absorbed, whereas in fact it must have been about 9%. For the modern calculation I thank Raymond T. Pierrehumbert.

[3] Fleming (2000), p. 301; for early measurements and additional background and references, see Mudge (1997). Ångström's argument was immediately accepted in for example, *Monthly Weather Review* (1901); a leading expert dismissing CO_2 because of saturation was Humphreys (1913), pp. 134-35, although while denying that doubling the amount in the atmosphere would "appreciably affect the total amount of radiation actually absorbed," he did note that it would "affect the vertical distribution or location of the absorption," Humphreys (1920), p. 58; on CO_2 saturation, Schaefer (1905), p. 104.

bring something like a 4°C rise or fall of surface temperature, and thus “the carbon dioxide theory of the ice ages... is a possible theory.”[1] Hardly anyone noticed this paper. Hulburt was an obscure worker at the U.S. Naval Research Laboratory, and he published in a journal, the *Physical Review*, that few meteorologists read. Their general consensus was the one stated in such authoritative works as the American Meteorological Society’s 1951 *Compendium of Meteorology*: the idea that adding CO_2 would change the climate “was never widely accepted and was abandoned when it was found that all the long-wave radiation [that would be] absorbed by CO_2 is [already] absorbed by water vapor.”[2]

Even if people had recognized this was untrue, there were other well-known reasons to deny any greenhouse effect in the foreseeable future. These reasons reflected a nearly universal conviction that the Earth automatically regulated itself in a “balance of nature.” Getting to specifics, scientists repeated the plausible argument that the oceans would absorb any excess gases that came into the atmosphere. Fifty times more carbon is dissolved in sea water than in the wispy atmosphere. Thus the oceans would determine the equilibrium concentration of CO_2, and it would not easily stray from the present numbers.

If somehow the oceans failed to stabilize the system, organic matter was another good candidate for providing what one scientist called “homeostatic regulation.”[3] The amount of carbon in the atmosphere is only a small fraction of what is bound up not only in the oceans but also in trees, peat bogs, and so forth. Just as sea water would absorb more gas if the concentration increased, so would plants grow more lushly in air that was “fertilized” with extra carbon dioxide. Rough calculations seemed to confirm the comfortable belief that biological systems would stabilize the atmosphere by absorbing any surplus. One way or another, then, whatever gases humanity added to the atmosphere would be absorbed—if not at once, then within a century or so—and the equilibrium would automatically restore itself. As one respected expert put it baldly in 1948, “The self-regulating mechanisms of the carbon cycle can cope with the present influx of carbon of fossil origin.”[4]

Yet the theory that atmospheric CO_2 variations could change the climate was never altogether forgotten. An idea so simple on the face of it, an idea advanced (however briefly) by outstanding figures like Arrhenius and Chamberlin, had to be mentioned in textbooks and review articles if only to refute it. Arrhenius’s outmoded hypothesis persisted in a ghostly afterlife.

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[1] Hulburt (1931), quote p. 1876; note also Simpson (1928b), who finds CO_2 adds a correction—but only a small one—to water vapor absorption.

[2] Brooks (1951), p. 1016.

[3] Redfield (1958), 221. The atmospheric elements he addressed were oxygen and other elementary gases, not carbon.

[4] Hutchinson (1948), quote p. 228; see also Hutchinson (1954), 389-90; another example: Eriksson and Welander (1956), 155.

It found a lone advocate. Around 1938 an English engineer, Guy Stewart Callendar, took up the old idea. An expert on steam technology, Callendar apparently took up meteorology as a hobby to fill his spare time.[1] Many people, looking at weather stories from the past, had been saying that a warming trend was underway. When Callendar compiled measurements of temperatures from the 19th century on, he found they were right. He went on to dig up and evaluate old measurements of atmospheric CO_2 concentrations. He concluded that over the past hundred years the concentration of the gas had increased by about 10%. This rise, Callendar asserted, could explain the observed warming. For he understood that even if the CO_2 in the atmosphere did already absorb all the heat radiation passing through, adding more gas would change the height in the atmosphere where the absorption took place. That, he calculated, would make for warming.

As for the future, Callendar estimated, on flimsy grounds, that a doubling of CO_2 could gradually bring a 2°C rise in future centuries. He hinted that it might even trigger a shift to a self-sustaining warmer climate (which did not strike him as a bad prospect).[2] But future warming was a side issue for Callendar. Like all his predecessors, he was mainly interested in solving the mystery of the ice ages.

Callendar's publications attracted some attention, and climatology textbooks of the 1940s and 1950s routinely included a brief reference to his studies. But most meteorologists gave Callendar's idea scant credence. In the first place, they doubted that CO_2 had increased at all in the atmosphere. The old data were untrustworthy, for measurements could vary with every change of wind that brought emissions from some factory or forest.[3] If in fact CO_2 was rising, that could only be detected by a meticulous program stretching decades into the future.[4] The objections that had been raised against Arrhenius also had to be faced. Wouldn't the immense volume of the oceans absorb all the extra CO_2? Callendar countered that the thin layer of ocean surface waters would quickly saturate, and it would take thousands of years for the rest of the oceans to turn over and be fully exposed to the air.[5] But nobody knew the actual turnover rate, and it seemed that the oceans would have time to handle any extra gases. According to a well-known estimate published in 1924, even without ocean absorption it would take 500 years for fuel combustion to double the amount of CO_2 in the atmosphere.[6]

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[1] (Obituary) (1965).

[2] Callendar (1938); see also Callendar (1940); Callendar (1939); Callendar (1949).

[3] For bibliography on CO_2 measurements and ideas to 1951, see Stepanova (1952); criticism: Slocum (1955); Fonselius et al. (1956); however, some evidence for a gradual increase was summarized by Junge (1958); measurements are reviewed by Bolin (1972); From and Keeling (1986).

[4] E.g., it "may require a period of [data] collection of many decades to detect the real trends" according to Eriksson and Welander (1956).

[5] Callendar (1940).

[6] Lotka (1924).

There was also the old objection, which most scientists continued to find decisive, that the overlapping absorption bands of CO_2 and water vapor already blocked all the radiation that those molecules were capable of blocking. Callendar tried to explain that the laboratory spectral measurements were woefully incomplete.[1] Some other scientists too kept an open mind on the question. But it remained the standard view that, as an official U.S. Weather Bureau publication put it, the masking of CO_2 absorption by water vapor was a "fatal blow" to the CO_2 theory. Therefore, said this authority, "no probable increase in atmospheric CO_2 could materially affect" the balance of radiation.[2]

Most damaging of all, Callendar's calculations of the greenhouse effect temperature rise ignored much of the real world's physics. In particular, any rise in temperature would allow the air to hold more moisture, which could mean more clouds. Callendar admitted that the actual climate change would depend on interactions involving changes of cloud cover and other processes that no scientist of the time could reliably calculate. Few thought it worthwhile to speculate about such dubious questions, where data were rudimentary and theory was no more than hand-waving. Better to rest with the widespread conviction that the atmosphere was a stable, automatically self-regulated system. The notion that humanity could permanently change global climate was implausible on the face of it, hardly worth a scientist's attention.[3]

The scientists who brushed aside Callendar's claims were reasoning well enough. (Subsequent work has shown that the temperature rise up to 1940 was, as his critics thought, mainly caused by some kind of natural cyclical effect, not by the still relatively low CO_2 emissions. And the physics of radiation and climate was indeed too poorly known at that time to show whether adding more gas could make much difference.) Yet if Callendar was mistaken when he insisted he could prove global warming had arrived, it was a fortunate mistake.

Research by definition is done at the frontier of ignorance. Like nearly everyone described in these essays, Callendar had to use intuition as well as logic to draw any conclusions at all from the murky data and theories at his disposal. Like nearly everyone, he argued for conclusions that mingled the true with the false, leaving it to later workers to peel away the bad parts. While he could not prove that global warming was underway, he had given reasons to reconsider the question. We owe much to Callendar's courage. His claims rescued the idea of global warming from obscurity and thrust it into the marketplace of scientific ideas. Not everyone dismissed his claims. Their very uncertainty attracted scientific curiosity.

The Speculations Vindicated (1950-1960)

The complacent view that CO_2 from human activity could never become a problem was overturned during the 1950s by a series of costly observations. This was a consequence of the

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[1] Callendar (1941).

[2] Russell (1941), 94.

[3] For additional discussion and references, see Weart (1997).

Second World War and the Cold War, which brought a new urgency to many fields of research. American scientists enjoyed massively increased government funding, notably from military agencies. The officials were not aiming to answer academic questions about future climates, but to provide for pressing military needs. Almost anything that happened in the atmosphere and oceans could be important for national security. Among the first products were new data for the absorption of infrared radiation, a topic of more interest to weapons engineers than meteorologists.

The early experiments that sent radiation through gases in a tube, measuring bands of the spectrum at sea-level pressure and temperature, had been misleading. The bands seen at sea level were actually made up of overlapping spectral lines, which in the primitive early instruments had been smeared out into broad bands. Improved physics theory and precise laboratory measurements in the 1940s and after encouraged a new way of looking at the absorption. Scientists were especially struck to find that at low pressure and temperature, each band resolved into a cluster of sharply defined lines, like a picket fence, with gaps between the lines where radiation would get through.[1] The most important CO_2 absorption lines did not lie exactly on top of water vapor lines. Instead of two overlapping bands, there were two sets of narrow lines with spaces for radiation to slip through. So even if water vapor in the lower layers of the atmosphere did entirely block any radiation that could have been absorbed by CO_2 , that would not keep the gas from making a difference in the rarified and frigid upper layers. Those layers held very little water vapor anyway. And scientists were coming to see that you couldn't just calculate absorption for radiation passing through the atmosphere as a whole, you had to understand what happened in each layer—which was far harder to calculate.

Digital computers were now at hand for such calculations. The theoretical physicist Lewis D. Kaplan decided it was worth taking some time away from what seemed like more important matters to grind through extensive numerical computations. In 1952, he showed that in the upper atmosphere, adding more CO_2 must change the balance of radiation significantly.[2]

But would adding carbon dioxide in the upper layers of the air significantly change the surface temperature? Only detailed computations, point by point across the infrared spectrum and layer by layer up through the atmosphere, could answer that question. By 1956, such computations could be carried out thanks to the increasing power of digital computers. The physicist Gilbert N. Plass took up the challenge of calculating the transmission of radiation through the atmosphere, nailing down the likelihood that adding more CO_2 would increase the interference with infrared radiation.[3] Going beyond this qualitative result, Plass announced that human activity would raise the average global temperature "at the rate of 1.1 degree C per century."

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[1] Martin and Baker (1932); for review, see Smith et al. (1968), pp. 476-483.

[2] Kaplan (1952); for other workers see, e.g., Möller (1951), pp. 46-47.

[3] Plass (1956b); see also Plass (1956c).

The computation, like Callendar's, paid no attention to possible changes in water vapor and clouds, and overall was too crude to convince scientists. "It is almost certain," one authority scolded, "that these figures will be subject to many strong revisions."[1] Yet Plass had proved one central point: it was a mistake to dismiss the greenhouse effect with spectroscopic arguments. He warned that climate change could be "a serious problem to future generations"—although not for several centuries. Following the usual pattern, Plass was mainly interested in the way variations in CO_2 might solve the mystery of the ice ages. "If at the end of this century the average temperature has continued to rise," he wrote, then it would be "firmly established" that CO_2 could cause climate change.[2]

None of this work met the argument that the oceans would promptly absorb nearly all the CO_2 humanity might emit. Plass had estimated that gas added to the atmosphere would stay there for a thousand years. Equally plausible estimates suggested that the surface waters of the oceans would absorb it in a matter of days.[3] Fortunately, scientists could now track the movements of carbon with a new tool—the radioactive isotope carbon-14. This isotope is created by cosmic rays in the upper atmosphere and then decays over millennia. The carbon in ancient coal and oil is so old that it entirely lacks the radioactive isotope. In 1955, the chemist Hans Suess reported that he had detected this fossil carbon in the atmosphere.

The amount that Suess measured in the atmosphere was barely one percent, a fraction so low that he concluded that the oceans were indeed taking up most of the carbon that came from burning fossil fuels. A decade would pass before he reported more accurate studies, which showed a far higher fraction of fossil carbon. Yet already in 1955 it was evident that Suess's data were preliminary and insecure. The important thing he had demonstrated was that fossil carbon really was showing up in the atmosphere. More work on carbon-14 should tell just what was happening to the fossil carbon.[4]

Suess took up the problem in collaboration with Roger Revelle at the Scripps Institution of Oceanography. (Some other carbon-14 experts attacked the topic independently, all reaching much the same conclusions.) From measurements of how much of the isotope was found in the air and how much in sea water, they calculated the movements of CO_2 . It turned out that the ocean surface waters took up a typical molecule of CO_2 from the atmosphere within a decade or so. Radiocarbon data also showed that the oceans turned over completely in several hundred years, an estimate soon confirmed by evidence from other studies.[5] At first sight that seemed fast enough to sweep any extra CO_2 into the depths.

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[1] Rossby (1959), p. 14; the chief critic was Kaplan (1960).

[2] Plass (1956d), quotes on 306, 311, 315, 316; see also Plass (1959); Plass (1956e); Plass (1956a).

[3] Plass (1956a); Dingle (1954).

[4] Suess (1955); see also Suess (1953); a confirmation: Münnich (1957); Revision: Houtermans et al. (1967), see p. 68.

[5] Revelle and Suess (1957); Craig (1957a); Arnold and Anderson (1957).

But Revelle had been studying the chemistry of the oceans through his entire career, and he knew that the seas are not just salt water but a complex stew of chemicals. These chemicals create a peculiar buffering mechanism that stabilizes the acidity of sea water. The mechanism had been known for decades, but Revelle now realized that it would prevent the water from retaining all the extra CO_2 it took up. A careful look showed that the surface layer could not really absorb much gas—barely one-tenth the amount a naïve calculation would have predicted.

A supplementary essay on Revelle's Discovery tells this crucial story in full, as a detailed example of the complex interactions often found in geophysical research.

Revelle did not at first recognize the full significance of his work. He made a calculation in which he assumed that industry would emit CO_2 at a constant rate (like most people at the time, he scarcely grasped how explosively population and industry were rising). This gave a prediction that the concentration in the air would level off after a few centuries, with an increase of no more than 40%. Revelle did note that greenhouse effect warming "may become significant during future decades if industrial fuel combustion continues to rise exponentially." He also wrote that "Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."[1]

As sometimes happens with landmark scientific papers, written in haste while understanding just begins to dawn, Revelle's explanation was hard to grasp. Other scientists failed to see the point that was obscurely buried in the calculations, and continued to deny there was a greenhouse effect problem. In 1958, when Callendar published a paper to insist once again that CO_2 observations showed a steady rise from the 19th century, he noted Revelle's paper but still confessed that he did not understand why "the oceans have not been accepting additional CO_2 on anything like the accepted scale."[2] Finally in 1959 two meteorologists in Sweden, Bert Bolin and Erik Eriksson, caught on. They explained the sea water buffering clearly—so clearly that during the next few years, some scientists cited Bolin and Eriksson's paper for this decisive insight rather than Revelle and Suess's (only in later years was Revelle always cited for the discovery).[3] The central insight was that although sea water did rapidly absorb CO_2, most of the added gas would promptly evaporate back into the air before the slow oceanic circulation swept it into the abyss. To be sure, the chemistry of air and sea water would eventually reach an equilibrium—but that could take thousands of years. Arrhenius had not concerned himself with time-scales shorter than that, but geoscientists in the 1950s did.

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[1] Revelle and Suess (1957), pp. 18-20, 26.

[2] Callendar (1958), p. 246. Here Callendar was one of those who quickly picked up Revelle's "geophysical experiment" phrase. A typical denial of any future greenhouse effect problem was Bray (1959), see p. 228.

[3] Bolin and Eriksson (1959); example of paper citing Bolin & Eriksson but not Revelle: Mitchell (1961), p. 243; review citing them: Skirrow (1965), pp. 282-84, 308.

In the late 1950s a few American scientists, starting with Plass, tentatively began to inform the public that greenhouse gases might become a problem within the next few centuries. Revelle in particular warned journalists and government officials that greenhouse warming might come within the foreseeable future, and deserved serious attention. The stakes were revealed when Bolin and Eriksson pursued the consequences of their calculation to the end. They assumed industrial production would climb exponentially, and figured that atmospheric CO_2 would rise some 25% by the end of the century. That was a far swifter rise than anyone before had suggested. In 1962, a still stronger (although not widely heeded) warning was sounded by the Russian climate expert Mikhail Budyko. His calculations of the exponential growth of industrial civilization suggested a drastic global warming within the next century or so.

Once meteorologists understood that ocean uptake was slow, they found it possible that CO_2 levels had been rising, just as Callendar insisted.[1] Yet it was only a possibility, for the measurements were all dubious. By the mid 1950s, researchers were saying that it was important to measure, much more accurately, the concentration of CO_2 in the atmosphere.[2] A Scandinavian group accordingly set up a network of 15 measuring stations in their countries. Their only finding, however, was a high noise level. Their measurements apparently fluctuated from day to day as different air masses passed through, with differences between stations as high as a factor of two. Only much later was it recognized that their methods of analyzing the air had been inadequate, and responsible for much of the noise.[3] A leading authority summarized the scientific opinion of the late 1950s: "it seems almost hopeless to arrive at reliable estimates [of CO_2]... by such measurements in limited areas." To find if the gas level was changing, measurements would have to "be made concurrently and during a great number of years" at many locations.[4]

Charles David (Dave) Keeling held a different view. As he pursued local measurements of the gas in California, he saw that it might be possible to hunt down and remove the sources of noise. Technical advances in infrared instrumentation allowed an order of magnitude improvement over previous techniques for measuring gases like CO_2. Taking advantage of that, however, would require many costly and exceedingly meticulous measurements, carried out someplace far from disturbances. Most scientists, looking at the large and apparently unavoidable fluctuations in the raw data, thought such precision irrelevant and the instrumentation too expensive. But Revelle and Suess had enough funds, provided by the International Geophysical Year, to hire Keeling to measure CO_2 with precision around the world.

A supplementary essay tells the precarious story of Keeling's funding and monitoring of CO_2 levels as a detailed example of how essential research and measurements might be fed—or starved.

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[1] e.g., Mitchell (1961).

[2] Eriksson (1954).

[3] Fonselius et al. (1955); Fonselius et al. (1956); for critique, see From and Keeling (1986), p. 88, and passim for history of CO_2 measurements generally; also Keeling (1998), p. 43.

[4] Rossby (1959), p. 15; this is a translation of Rossby (1956).

Revelle's simple aim was to establish a baseline "snapshot" of CO_2 values around the world, averaging over the large variations he expected to see 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 average CO_2 concentration had risen. Keeling did much better than that with his new instruments. With painstaking series of measurements in the pristine air of Antarctica and high atop the Mauna Loa volcano in Hawaii, he nailed down precisely a stable baseline level of CO_2 in the atmosphere. In 1960, with only two full years of Antarctic data in hand, Keeling reported that this baseline level had risen. The rate of the rise was approximately what would be expected if the oceans were not swallowing up most industrial emissions.[1]

Lack of funds soon closed down the Antarctic station, but Keeling managed to keep the Mauna Loa measurements going with only a short hiatus. As the CO_2 record extended it became increasingly impressive, each year noticeably higher. Soon Keeling's curve, jagged but inexorably rising, was widely cited by scientific review panels and science journalists. It became the primary icon of the greenhouse effect.

Carbon Dioxide as the Key to Climate Change (1960s-1980s)

New carbon-14 measurements were giving scientists solid data to chew on. They began to work out just how carbon moves through its many forms in the air, ocean, minerals, soils, and living creatures. They plugged their data into simple models, with boxes representing each reservoir of carbon (ocean surface waters, plants, etc.), and arrows showing the exchanges of CO_2 among the reservoirs. The final goal of most researchers was to figure out how much of the CO_2 produced by human activity was sinking into the oceans, or perhaps was being absorbed by vegetation. But along the way there were many curious puzzles, which forced researchers to make inquiries among experts in far distant fields.

During the 1960s, these tentative contacts among almost entirely separate research communities developed into ongoing interchanges. Scientists who studied biological cycles of elements such as nitrogen and carbon (typically supported by forestry and agriculture interests) got in touch with, among others, geochemists (typically in academic retreats like the Scripps Institution of Oceanography in La Jolla, California). This emerging carbon-cycle community began to talk with atmospheric scientists who pursued interests in weather and climate prediction (typically at government-funded laboratories like the National Center for Atmospheric Research in Boulder, Colorado, or the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey). One valuable example of this crossover of interests was a calculation published by Princeton computer specialists in 1967: the first reasonably solid estimate of the global temperature change that was likely if the amount of CO_2 in the atmosphere doubled.[2]

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[1] The paper also described the seasonal cycle of CO_2 emissions. Keeling (1960); in the 1970s, it was found that the 1959-1960 rise had been exaggerated by an unusual natural release of the gas related to an El Niño event. Keeling (1998); for the history, see also Keeling (1978).

[2] Manabe and Wetherald (1967).

Even before that, in 1965, a prestigious group of scientists had suggested with remarkable foresight that "By the year 2000 the increase in atmospheric CO_2... may be sufficient to produce measurable and perhaps marked changes in climate." But most scientists at this time were scarcely concerned about CO_2 as an agent of future global warming. They addressed the gas as simply one component in their study of biological, oceanographic or meteorological systems.[1] Most stuck with the old assumption that the Earth's geochemistry was dominated by stable mineral processes, operating on a planetary scale over millions of years. People did not easily grasp how sensitive the Earth's atmosphere was to biological forces—the totality of the planet's living activity—to say nothing of the small fraction of that activity affected by humanity.

Leading scientists continued to doubt that anyone needed to worry at all about the greenhouse effect. The veteran climate expert Helmut Landsberg stressed in a 1970 review that little was known about how humans might change the climate. At worst, he thought, the rise of CO_2 at the current rate might bring a 2°C temperature rise over the next 400 years, which "can hardly be called cataclysmic."[2] Meanwhile Hubert H. Lamb, the outstanding compiler of old climate data, wrote that the effects of CO_2 were "doubtful... there are many uncertainties." The CO_2 theory, he pointed out, failed to account for the numerous large shifts that he had uncovered in records of climate from medieval times to the present. Many agreed with Lamb that a "rather sharp decline" of global temperature since the 1940s put the whole matter in question.[3]

> *Up to this point, about 1970, I have described a central core of CO_2 atmospheric research, which only occasionally interacted with other subjects. During the 1970s, the greenhouse effect became a major topic in many overlapping fields. The description of these studies is distributed among all the topical essays. The remainder of this essay covers only the developments most directly related to the gas CO_2 itself.*

Research on changes in the atmosphere's CO_2 had been, almost by definition, identical to research on the greenhouse effect. But in the late 1970s and early 1980s, calculations found that other gases emitted by human activities also have a strong greenhouse effect—sometimes molecule for molecule tens or hundreds of times greater than CO_2. Global climate change could not be properly studied without taking into account methane, emitted by both natural and artificial sources, and various other industrial gases. Nevertheless most of the scientific interest continued to revolve around CO_2.

Carbon cycle studies proliferated. A major stimulus was a controversy that erupted in the early 1970s and stubbornly resisted resolution. National economic statistics yielded reliable figures for how much CO_2 humanity put into the air each year from burning fossil fuels. The measurements of the annual increase by Keeling and others showed that less than half of the new carbon could be found in the atmosphere. Where was the rest? Oceanographers calculated how much of the

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[1] President's Science Advisory Committee (1965); Hart and Victor (1993), passim.

[2] Landsberg (1970).

[3] Lamb (1969), p. 245.

gas the oceans took up, while other scientists calculated how much the biosphere took up or emitted. The numbers didn't add up—some of the carbon was "missing." Plainly, scientists did not understand important parts of the carbon cycle. Looking at large-scale climate changes, such as between ice ages and warm periods, they turned up a variety of interactions with climate involving plant life and ocean chemistry. The papers addressing these topics became increasingly complex.

Some scientists took up the old argument that fertilization of plant life by additional CO_2, together with uptake by the oceans, would keep the level of gas from rising too sharply. Keeling, however, warned that by the middle of the next century, plants could well reach their limit in taking up carbon (as every gardener knows, beyond some point fertilization is useless or even harmful). Further, there would eventually be so much CO_2 in the ocean surface waters that the oceans would not be able to absorb additional gas as rapidly as at present.[1] He kept refining and improving his measurements of the CO_2 level in the atmosphere to extract more information. The curve did not climb smoothly, but stuttered through a large seasonal cycle, plus mysterious spells of faster and slower growth. It was only over a long term, say a decade, that the rise was clearly as inexorable as a tide.[2] Meanwhile, computer models were coming into better agreement on the future warming to be expected from increased CO_2. And global temperatures began to rise again. It was getting increasingly difficult for scientists to believe that the greenhouse effect was no cause for worry.

An especially convincing finding came from holes arduously drilled into the Greenland and Antarctic ice caps. The long cylinders of ice extracted by the drills contained tiny bubbles with samples of ancient air—by good fortune there was this one thing on the planet that preserved CO_2 intact. Group after group cut samples from cores of ice in hopes of measuring the level. For two decades, every attempt failed to give consistent and plausible results. Finally reliable methods were developed. The trick was to clean an ice sample scrupulously, crush it in a vacuum, and quickly measure what came out. In 1980, a team published findings that were definite, unexpected, and momentous.

In the depths of the last ice age, the level of CO_2 in the atmosphere had been as much as 50% lower than in our own warmer times. (These Greenland measurements were later called into question, but the dramatically lower ice-age level was quickly confirmed by other studies.)[3] Pushing forward, by 1985 a French-Soviet drilling team at Vostok Station in central Antarctica had produced an ice core two kilometers long that carried a 150,000-year record, a complete ice age cycle of warmth, cold and warmth. They found that the level of atmospheric CO_2 had gone up and down in remarkably close step with temperature.[4]

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[1] The partial pressure of CO_2 in sea water would grow and the chemical buffering would change. Keeling (1973), p. 291.

[2] E.g., Keeling et al. (1976).

[3] Berner et al. (1980); Delmas et al. (1980); Neftel et al. (1982); Shackleton et al. (1983).

[4] Lorius et al. (1985); see also Barnola et al. (1987); Genthon et al. (1987).

The Vostok core, an ice driller declared, “turned the tide in the greenhouse gas controversy.”[1] At the least it nailed down what one expert called an “emerging consensus that CO_2 is an important component in the system of climatic feedbacks.” More generally, he added, it showed that further progress would “require treating climate and the carbon cycle as parts of the same global system rather than as separate entities.”[2] The rise and fall of temperature was tied up in a complex way with interlocking global cycles involving not just the mineral geochemistry of CO_2 in air and sea water, but also methane emissions, the growth and decay of forests and bogs, changes of the plankton population in the oceans, and still more features of the planet’s biosphere.

All through these decades, a few geologists had continued to pursue the original puzzle raised by Tyndall and Chamberlin—had changes of CO_2 been responsible for the greatest of climate changes? These were the vast slow swings, lasting tens of millions of years, between eras like the age of dinosaurs with summer-like climates almost from pole to pole, and eras like our own when continental ice caps waxed and waned. There was no consensus about the causes of these grand shifts, and it was nearly impossible to reliably measure the atmosphere many millions of years back. Nevertheless, by the 1980s, scientists turned up evidence that CO_2 levels had been elevated during the great warm eras of the past.

Lines of thinking converged to emphasize the importance of the greenhouse effect. For decades geologists had been puzzled by a calculation that astrophysicists insisted was indisputable: the Sun had been dimmer when the Earth was young. Billions of years ago the oceans would have been permanently frozen, if not for high CO_2 levels. Astrophysical theory showed that as the Sun had consumed its nuclear fuel it had gradually grown brighter, yet somehow the Earth’s temperature had remained neither too cold nor too hot to sustain life. The best guess was that CO_2 acted as a thermostat for the planet. Volcanoes presumably put the gas into the atmosphere at a fairly constant rate. But chemical processes run faster at higher temperatures, so on a warmer Earth the weathering of rocks would take up CO_2 faster. As the rocks erode, rivers carry the soil into the seas, where the carbon eventually winds up in compounds deposited on the seabed. Thus a rough self-sustaining balance is maintained among the forces of volcanic emissions, greenhouse warming, weathering, and ocean uptake.[3] To be sure, the system might take thousands if not millions of years to stabilize after some great disturbance.

Such great disturbances—even a totally glaciated “snowball Earth”—were not a fantasy of oversimplified models. Geologists turned up evidence that more than half a billion years ago the oceans had actually frozen over, if not entirely than mostly. That seemed impossible, for how could the Earth have escaped the trap and warmed up again? There was at least one obvious way (but it was only obvious once someone thought of it, which took decades). Over many thousands of years, volcanoes would have continued to inject CO_2 into the atmosphere. There the gas would have accumulated, since it could not get into the frozen seas. Eventually a colossal greenhouse

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[1] Mayewski and White (2002), pp. 39, 77.

[2] Sundquist (1987).

[3] Walker et al. (1981).

effect might have melted the ice.[1] All this was speculative, and proved little about recent climates. But it added to the gathering conviction that CO_2 was the very keystone of the planet's climate system—a system by no means as cozily stable as it appeared.

Another unusual disturbance had begun. The proof was in the Vostok team's 1987 report of their analysis of ice cores reaching back some 160,000 years, through the entire previous glacial period and into the warm time before. (And the drill was still only partway down; by the time they stopped drilling a dozen years later, the team had recovered ice going back 400,000 years, through four complete glacial cycles.) The CO_2 levels in their record got as low as 180 parts per million in the cold periods and reached 280 in the warm periods, never higher.[2] But in the air above the ice, the level of the gas had reached 350—far above anything seen in this geological era. It was still climbing exponentially, at a rate that doubled every 30-35 years.

After 1988

During the 1990s, further ice core measurements indicated that during past glacial periods, temperature changes had *preceded* CO_2 changes by several centuries. Was it necessary to give up the simple hypothesis that had attracted scientists ever since Tyndall in the 19th century—that changes in CO_2 were a simple and direct cause of ice ages? Some scientists doubted that the time lag could be measured so precisely, but most of the evidence pointed to a lag.[3] It seemed that rises or falls in carbon dioxide levels had not initiated the glacial cycles.

In fact most scientists had long since abandoned that hypothesis. In the 1960s, painstaking studies had shown that subtle shifts in our planet's orbit around the Sun (called "Milankovitch cycles") set the timing of ice ages. The amount of sunlight that fell in a given latitude and season varied predictably over millenia, altering how long snow lingered in the spring, which crucially affected how much sunlight was absorbed.The fact that carbon dioxide levels lagged behind the orbital effect should have been no surprise. But now this could be seen as the first step in a powerful feedback cycle. For even a small change in the gas level would bring further changes in the global heat balance, which would in turn alter the gas level, which... and so forth. This suggested how tiny shifts in the Earth's orbit could be amplified into the enormous swings of glacial cycles.

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[1] Also, the discovery in the late 1970s that life is sustained at hot springs in the deep ocean showed that the continuous fossil record of sea life did not rule out the possibility that the oceans had frozen. Studies include Berner et al. (1983); Kasting and Ackerman (1986); for review, Crowley and North (1991); more recently, Hoffmann et al. (1998); the term "snowball Earth" was coined by Joseph Kirschvink: Kirschvink (1992); earlier Manabe called it "White Earth" according to Gleick (1987), p. 332; for references and popular-level discussion, see Ward and Brownlee (2000).

[2] Genthon et al. (1987); Petit et al. (1999).

[3] Shackleton (2000); changes of CO_2 preceding changes in ice sheet volume were reported in Shackleton and Pisias (1985).

There were many ways temperature or other climate features could influence the carbon dioxide level one way or another. Perhaps variations of temperature and weather patterns had caused land vegetation to release extra CO_2 or take it up... perhaps the oceans were involved through massive changes in their circulation or ice cover... or through changes in their CO_2-absorbing plankton, which would bloom or decline insofar as they were fertilized by minerals, which reached them from dusty winds, rivers, and ocean upwelling, all of which could change with the climate... or perhaps there were still more complicated and obscure effects.

A key point stood out. The cycling of carbon through living systems was not something to trifle with. In the network of feedbacks that made up the climate system, CO_2 was a potent amplifier. This did not prove by itself that the greenhouse effect was responsible for the warming seen in the 20th century. And it did not say how much warming the rise of CO_2 might bring in the future. What was now beyond doubt was that the greenhouse effect had to be taken very seriously indeed.[1]

By now there were a dozen teams around the world using computers to swallow and analyze every advance in observation or theory. As the 21st century arrived, the growing agreement among the rival teams, and the consistency of their models' results with many different kinds of observations, became overwhelmingly convincing. Scarcely any reputable expert now doubted that CO_2 and other greenhouse gases were at least partly responsible for the unprecedented warming that had struck the world since the 1980s. A final nail in the skeptics' coffin came in 2005, when a team compared computer calculations with long-term measurements of temperatures in the world's ocean basins (it was not in the air but the massive oceans, after all, that most of any heat added soon wound up). In each separate ocean basin, they showed a close match between observations of rising temperatures at particular depths, and calculations of where the greenhouse effect should appear . This was telling evidence that the computer models were on the right track. Nothing but greenhouse gases could produce the observed ocean warming—and other changes that were now showing up in many parts of the world, as predicted. ¶

The computations pinned down an imbalance. The Earth was now taking in from sunlight nearly a watt per square meter more than it was radiating back into space, averaged over the planet's entire surface. That was enough energy to cause truly serious effects if it continued. James Hansen, leader of one of the studies, called it "smoking gun" proof of greenhouse effect warming.[2]

Yet amid all the uncertainties about how carbon cycles operated, how much could we trust the computer models? Scientists are more likely to believe something if they can confirm it with an entirely independent line of evidence, preferably from somewhere nobody had looked before. Just such new evidence came up in the 1990s, thanks to an unexpected alliance of paleontology

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[1] Petit et al. (1999); IPCC (2001), p. 202; Lorius et al. (1990); Pälike et al. (2006) (detecting the carbon cycle feedback over millions of years).

[2] Barnett et al. (2005); Hansen et al. (2005).

and plant physiology. Studies of plant species that had changed little since the rise of the dinosaurs (magnolia for one) showed that if you exposed them to a higher level of CO_2, the structure of their leaves changed. Ancient fossil leaves showed just such changes. Several kinds of chemical studies confirmed that the level of the gas had swung widely over geological ages, and the temperature too.

Eventually geochemists and their allies managed to get numbers for the "climate sensitivity" in ancient eras, that is, the response of temperature to a rise in the CO_2 level. Over hundreds of millions of years, a doubled level of the gas had always gone along with a temperature rise of three degrees, give or take a couple of degrees. That agreed almost exactly with the numbers coming from many computer studies.

It was good to see that the models had not missed something huge. There seemed scant possibility of a runaway greenhouse catastrophe. What was less reassuring to notice what the climate had looked like in certain ancient times when CO_2 had stood at a high level... a level that humanity would eventually reach if we went on burning all available oil and coal. The Earth had been virtually a different planet, with tropical forests near the poles and sea levels a hundred meters higher. Worse, as one group pointed out, unchecked emissions seemed bound to bring not only "a warming unprecedented in the past million years," but changes "much faster than previously experienced by natural ecosystems..."[1]

If the planet warmed up by several several degrees during the 21st century, as paleontologists and computer modelers agreed was likely, what would be the consequences? This became the new center for most of the research. It was becoming clear that the consequences would be severe in many parts of the world, perhaps in some places catastrophic. (*See the separate essay on expected impacts of global warming.*)

Through all these discoveries, Keeling and others had kept on monitoring and analyzing the ongoing changes in atmospheric CO_2 levels. Since the 1980s, a cooperative international program had been measuring the gas at land stations around the world and along shipping lanes. The baseline continued to rise ominously, but not smoothly. There had been years when the world's atmosphere had gained one billion metric tonnes of the gas, while in other years it gained as much as six billion. How much did changes in the world's industries and agricultural practices affect the rate of the rise? Economic statistics allowed a good reckoning of how much gas humanity emitted in burning fossil fuels—and also of some significance, in the manufacture of cement—but the effects of deforestation and other land use changes were not so easy to figure.

Beyond that, how much did changes in the level of CO_2 reflect changes in the growth or decay of plants, perhaps related to some fluctuation in the oceans or on the Sun? What could one learn from the way the curve reacted to temporary climate changes brought on by El Niño events,

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[1] A recent review was Royer et al. (2007). Among many references: Berner(1991)(geochemical); Cerling (1991) (carbon in soils); McElwain and Chaloner (1995) (leaves); Royer et al. (2001); Hoffert and Covey (1992), quote p. 576.

volcanic eruptions, and so forth?[1] Further clues came from world-wide measurements of other biologically active gases, especially oxygen (the exacting techniques for measuring the tiny variations were pioneered by Keeling's son, Ralph Keeling).[2] Most of the "missing" carbon was finally located, with gradually increasing precision, in rapidly changing forests, soils, and other biological reservoirs.

The basic physics and chemistry of the problems raised by Tyndall were now well in hand. There were reliable calculations of the direct effects of CO_2 on radiation, of how the gas was dissolved in sea water, and other physical phenomena. Further progress would center on understanding the complex interactions of the entire planetary system, and especially living creatures... most of all, humans.

> *What can people do about global warming, and what should we do? See my Personal Note and Links.*

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[1] Keeling (1998).

[2] Keeling et al. (1993); Keeling et al. (1996b).