9

Global Warming?

The Early Twentieth Century

As man is now changing the composition of the atmosphere at a rate which must be very exceptional on the geological time scale, it is natural to seek for the probable effects of such a change. From the best laboratory observations it appears that the principal result of increasing atmospheric carbon dioxide . . . would be a gradual increase in the mean temperature of the colder regions of the earth.

—G. S. Callendar (1939)

In the first half of the twentieth century, most scientists did not believe that increased CO_2 levels would result in global warming. It was thought that at current atmospheric concentrations, the gas already absorbed all the available long-wave radiation; thus any increases in CO_2 would not change the radiative heat balance of the planet but might augment plant growth. Other mechanisms of climatic change, although highly speculative, were given more credence, especially changes in solar luminosity, atmospheric transparency, and the Earth's orbital elements.

By the 1950s, as temperatures around the Northern Hemisphere reached early-twentieth-century peaks, global warming first found its way onto the public agenda. Concerns were expressed in both the scientific and popular press about rising sea levels, loss of habitat, and shifting agricultural zones. Amid the myriad mechanisms that could possibly account for climatic changes, several scientists, notably G. S. Callendar, Gilbert Plass, Hans Suess, and Roger Revelle, focused on possible links between anthropogenic CO_2 emissions, the geochemical carbon cycle, and climate warming.

A Plethora of Speculative Theories

By 1900, most of the chief theories of climate change had been proposed, if not yet fully explored: changes in solar output; changes in the Earth's orbital geometry; changes in terrestrial geography, including the form and height of continents and the circulation of the oceans; and changes in atmospheric transparency and composition, in part due to human activities.[1] Of course, there were many others. New climate theories were being proposed and new work was being done on heat budgets, spectroscopy, and the rising CO_2 content of the atmosphere. Evidence for glaciation in low latitudes was explained by Wladimir Köppen and Alfred Wegener as the result of continents drifting northward under climate zones controlled mainly by latitude.[2] Although this theory was not widely accepted by geologists, it is now seen as a first step in paleoclimatic reconstruction. In the 1930s, the Serbian astronomer and geophysicist Milutin Milankovic, building on earlier work, outlined a comprehensive "astronomical theory of the ice ages" that viewed them as caused by periodic changes in the Earth's orbital elements.[3] Atmospheric heat budgets were constructed early in the twentieth century by William Henry Dines and George Clark Simpson, among others.[4] Measurements of infrared radiation at longer wavelengths, including the eight-to-twelve micron atmospheric "window," and at finer band resolutions, were completed in the 1930s.[5] In 1938, G. S. Callendar read a paper to the Royal Meteorological Society that argued that CO_2 from fossil fuel consumption had caused a modest but measurable increase in the Earth's temperature of about one-quarter of a degree in the previous fifty years.[6] All these issues, especially whether the Earth would experience a new ice age or would become warmer, were perennially debated, but no single causal mechanism was universally accepted.

William Jackson Humphreys, author of *Physics of the Air* and a strong proponent of the theory that volcanic dust was the leading cause of ice ages, did not consider any of the current theories adequate: "Change after change of climate in an almost endless succession, and even additional ice ages, presumably are still to be experienced, though . . . when they shall begin, how intense they may be, or how long they shall last no one can form the slightest idea."[7] Echoing Rudyard Kipling's "nine and sixty ways of making tribal lays," the climatologist C. E. P. Brooks quipped, "There are at least nine and sixty ways of constructing a theory of climatic change, and there is probably some truth in quite a number of them."[8] In a similar lighthearted vein, two prominent oceanographers, David B. Ericson and Goesta Wollin, wryly observed: "It has been estimated that a new theory to explain continental glaciations has been published for every year that has passed since the first recognition of the evidence for past glaciation."[9] Most scientists of the time supported only one of the major mechanisms of climatic change; some grudgingly admitted that other mechanisms might play a secondary role.

In 1950, Brooks, who had spent much of his career attempting to sort out the "nine and sixty" theories of climate change, published a selective annotated bibliography on the subject in the first volume of the new journal *Meteorological Abstracts and Bibliography* (table 9-1 is adapted from this work).[10]

Five years after compiling this bibliography, Brooks presented his opinions on the "present position of theories of climatic change" in the *Meteorological Magazine*. He considered variations of solar radiation, "either alone or combined with some other cause," to be a "first favorite," although he had to admit that such theories were, at present,

Table 9-1. Climate change theories as classified by Brooks (1950).

Changes in elements of the Earth's orbit:
- Adhémar (1842), Croll (1864, 1875), Drayson (1873), Ekholm (1901), Spitaler (1907), Milankovic (1920, 1930, 1941)

Changes of solar radiation:
- Dubois (1895), Simpson (1930, 1934, 1939–40), Himpel (1937), Hoyle and Lyttleton (1939)

Lunar-solar tidal influences: Pettersson (1914)

Elevation of land masses — mountain building:
- Lyell (1830–33), Wright (1890), Ramsay (1909–10, 1924), Brooks (1926, 1949)

Changes in atmospheric circulation:
- Harmer (1901, 1925), Gregory (1908), Hobbs (1926), Flint and Dorsey (1945)

Changes in oceanic circulation:
- Croll (1875), Hull (1897), Chamberlin (1899), Brooks (1925), Lasareff (1929),

Changes in continent-ocean distribution:
- Czerney (1881), Harmer (1901, 1925), Gregory (1908), Brooks (1926), Willis (1932)

Changes in atmospheric composition:
- Arrhenius (1896), Chamberlin (1897, 1899), Ekholm (1901), Callendar (1938, 1939)

Volcanic dust in the atmosphere:
- Humphreys (1913, 1920), Abbot and Fowle (1913)

Cosmic dust theory: Hoyle and Lyttleton (1939), Himpel (1947)

Sunspot theory
- Czerny (1881), Huntington (1915), Huntington and Visher (1922),

Polar migration and continental drift theory:
- Kreichgauer (1902), Wegener (1920), Köppen and Wegener (1924)

"almost entirely hypothetical with little or no evidence to support them." Other causes were given short shrift. In his opinion, orogenesis and changes of land and sea distribution were not widely accepted, changes in the elements of the Earth's orbit and inclination of the axis were "rather out of favor," and changes in atmospheric composition, given the assumed insufficiency of CO_2 to absorb infrared radiation, "now reduce almost entirely to the effects of volcanic dust."[11]

In his 1956 article in the popular journal *Weatherwise*, respected meteorologist Hans Panofsky located the question of climatic changes on a vast spectrum of atmospheric fluctuations that ranged from seconds (turbulence) to millions of years. Pointing out that the shorter period fluctuations of the atmosphere are not due to a single cause, Panofsky thought it reasonable that longer period climatic changes might also have multiple explanations. His classification of the most important types of climatic change theories included changes in the Earth's crust, astronomical influences, and changes in atmospheric composition.[12]

Panofsky selected three theories involving changes in the Earth's crust for further examination: migration of the Earth's axis, mountain building, and volcanism. His article did not mention Alfred Wegener's theory of continental drift. Polar wandering, which he traced to Joseph Adhémar, assumes that the Earth's axis has taken different positions relative to the crust. The main difficulty of this theory is that polar shifts would produce glaciation in different regions of the globe at different times, while the evidence seemed to indicate simultaneous advance and retreat of the glaciers. Mountain building, a preferred mechanism of Charles Lyell and many other geologists, may produce glaciation over the longest time scales, but Panofsky considered simple diastrophism inadequate to explain the ice ages of the past million years. Climate changes caused by the reduction of solar insolation following the injection of volcanic dust high into the atmosphere was (as noted earlier) a favored mechanism of William Jackson Humphreys. Historic eruptions have indeed measurably reduced solar radiation and temperatures, at least for several years following the events, but Panofsky was not convinced that volcanism was sufficient to cause widespread glaciation.

Panofsky next reviewed theories of astronomical influence, including variations in solar luminosity and the Earth's orbit. Changes in solar output were favored by many climatologists and astronomers, perhaps influenced by C. G. Abbott's measurements of the varying "solar constant." Panofsky found no evidence that the Sun was a variable star, especially if the effect of atmospheric absorption at all wavelengths was taken into account. The theory that the Sun may occasionally increase its luminosity due to encounters with clouds of interstellar dust seemed both ad hoc and quantitatively inadequate. Panofsky noted two basic (and opposing) opinions on the climatic effects of a hotter Sun: One school believed it would cause a direct temperature rise and *decreased* glaciation; the other school thought it would cause a greater pole-to-equator temperature gradient, increased atmospheric circulation, increased evaporation, increased precipitation, and *increased* glaciation.

Although orbital changes, as calculated by Milankovic, were not widely accepted in the 1950s as causes of climatic change, Panofsky thought they caused important changes in solar insulation that would alter atmospheric dynamics as well as climate. He presented the following arguments in favor of this mechanism: (1) Variations in the obliquity of the ecliptic, the angle between the plane of the Earth's orbit and the plane of the equator, result in greater contrasts between seasons. When the obliquity is large this could lead to increased temperature gradients, a more energetic general circulation, and perhaps an ice age. (2) Variations in eccentricity of the Earth's orbit can result in significant differences between solar insolation received by the Earth at perihelion and aphelion. (3) The precession of the equinoxes causes systematic variations in the seasons. Currently the Earth is closest to the Sun in January; in ten thousand years this will occur in July. Currently the northern hemisphere has less contrast between winter and summer than the southern hemisphere; this will be reversed in ten thousand years.

Most of Panofsky's contemporaries favored a combination of solar activity and mountain building as the causes of major climatic changes. Panofsky himself favored the orbital theory combined with mountain building.

Doubts about CO_2

In 1899, Nils Eckholm, an early and eager spokesman for anthropogenic climate control, pointed out that at present rates, the burning of pit coal could double the concentration of atmospheric CO_2. This would "undoubtedly cause a very obvious rise of the mean temperature of the Earth." By controlling the production and consumption of carbonic acid, he thought humans would be able to "regulate the future climate of the Earth and consequently prevent the arrival of a new Ice Age." Eckholm, like his lifelong friend and colleague Svante Arrhenius, thought that warmer was better. An increasing concentration of CO_2 would counteract the expected deterioration of the climate of the northern and Arctic regions, as predicted by James Croll's astronomical theory of the Ice Age.[13]

Soon, however, the efficacy of CO_2 as an infrared absorber was challenged. In 1900 Knut Angström concluded that CO_2 and water vapor absorb infrared radiation in the same spectral regions. The amount of carbon dioxide in the atmosphere was thought to be equivalent to a column of the pure gas 250 centimeters in length at STP. Experiments done in 1905 demonstrated that a column of carbon dioxide fifty centimeters long was ample for maximum absorption. Any additional CO_2, it was argued, would have little or no effect.

Humphreys used these results to argue that a doubling or halving of CO_2, as proposed by Arrhenius, would make no difference in the amount of infrared radiation absorbed by the atmosphere and could not appreciably change the average temperature of the Earth or be at all effective in the production of marked climatic changes. Such negative assessments of CO_2 were amplified by Charles Greely Abbot and his assistant F. E. Fowle, Jr., who insisted on the primacy of water vapor as an infrared absorber.[14]

T. C. Chamberlin considered Humphreys's view "absurd" and found the contention of Abbot and Fowle "strange." He thought their positions were in direct violation of the "fundamental principle of spectroscopy that each element radiates or absorbs its own lines exclusively."[15] He considered CO_2 an "innocent party" in the matter and did not approve of Abbot "throw[ing] so much (cold) water vapor over so worthy a member of the atmospheric family." It was Chamberlin's view that each atmospheric constituent interacted with all others and all were ultimately controlled by diastrophism, "the most basal and independent agency" of atmospheric change.[16]

Doubts about CO_2 continued, however. In 1929, G. C. Simpson pointed out that it was "now generally accepted that variations in carbon-dioxide in the atmosphere, even if they do occur, can have no appreciable effect on the climate." He provided three reasons why this was so: "(1) [T]he absorption band of carbon-dioxide is too narrow to have a significant effect on terrestrial radiation; (2) the current amount of atmospheric CO_2 exerts its full effect and any further addition would have little or no influence; (3) the water vapor absorption band overlaps and dominates the CO_2 band."[17] The third edition of Humphreys's *Physics of the Air* appeared in 1940, and an article on climatic change in the *U.S.D.A. Yearbook* for 1941 echoed his negative assessment of CO_2:

> Much has been written about varying amounts of carbon dioxide in the atmosphere as a possible cause of glacial climates. The theory received a fatal blow when it was realized that carbon dioxide is very selective as to the wavelengths of radiant energy it will absorb, filtering out only such waves as even very minute quantities of water vapor dispose of anyway. No possible increase in atmospheric carbon dioxide could materially affect either the amount of insolation reaching the surface or the amount of terrestrial radiation lost to space.[18]

One investigator allowed that the equilibrium of the carbon cycle might be disturbed over periods of several centuries, causing temperature fluctuations, but pointed out that the quantity of CO_2 produced by photosynthesis in three days was greater than that produced by industrial activity in a year. C. E. P. Brooks, writing in the *Compendium of Meteorology* (1951), observed that the CO_2 theory of climate change, advanced by Arrhenius and Chamberlin, “was never widely accepted and was abandoned when it was found that all the long-wave radiation absorbed by CO_2 is also absorbed by water vapour.” He considered the recent rise in both CO_2 and global temperature as documented by Callendar to be nothing more than a “coincidence.”[19]

Concerning changes in atmospheric composition, Panofsky's 1956 article focused on the effects of increased levels of carbon dioxide and increased cloudiness. The radiative effects of CO_2 were well known by this time, but its meteorological effects were not. Panofsky was quite skeptical of the overall efficacy of CO_2 as an agent of climatic change, noting, "Carbon dioxide is such a good absorber in a narrow band of the radiation spectrum, that neither a reduction nor an increase of the existing amount of carbon dioxide would have much effect on the temperature of the atmosphere." He mentioned Arrhenius's hypotheses that a fifty percent reduction of CO_2 might reduce the Earth's temperature by four degrees Celsius, leading to widespread glaciation, but he agreed with T. C. Chamberlin's objection that the oceans contain many times more CO_2 than the atmosphere and could easily correct any CO_2 deficit. He also accepted Chamberlin's view that the slow turnover of ocean water occurring over tens of thousands of years might possibly withdraw and supply atmospheric CO_2 in amounts sufficient to trigger glacial and interglacial periods. Panofsky, representing most meteorologists of the time, was not convinced that "the general rise in temperature in the last 100 years" could be explained by increased industrial activity and carbon emissions, since this theory "omits the possible storage of the additional carbon dioxide in the oceans." Admitting that unknown, internal changes in the atmosphere *might* be operative, Panofsky rightly pointed out the lack of knowledge of the complex interrelationships among atmospheric composition, solar insolation, cloudiness, evaporation, ocean circulation, and glaciation.[20]

G. S. Callendar and Anthropogenic CO_2

Beginning in 1938, the role of anthropogenic carbon dioxide in climate change was reevaluated. G. S. Callendar, a British steam engineer, acknowledged the "checquered history" of the CO_2 theory: "[I]t was abandoned for many years when the prepondering influence of water vapour radiation in the lower atmosphere was first discovered, but was revived again a few years ago when more accurate measurements of the water vapour spectrum became available." Noting that humans had long been able to intervene in and accelerate natural processes, Callendar pointed out that humanity was now intervening heavily in the slow-moving carbon cycle by "throwing some 9,000 tons of carbon dioxide into the air each minute."[21]

Guy Stewart Callendar was born in 1897, the second son of Professor Hugh Longbourne Callendar, F.R.S., and Victoria Mary Stewart. He was educated at St. Paul's School and City and Guilds Engineering College, London. He assisted his father's experiments on steam at high temperatures and pressures at the Royal College of Science from 1923 to 1929 and lectured on the subject following his father's death in 1930. He continued his steam research under the patronage of the British Electrical and Allied Industries Research Association, which represented turbine manufacturers. His research included investigations on the efficiencies of various batteries, particularly fuel cells. From 1942 to 1957, he was a member of the research staff of the Ministry of Supply at Langhurst and subsequently at London. His avocation was meteorology, and he published numerous articles on terrestrial temperature fluctuations and trends in the *Quarterly Journal of the Royal Meteorological Society*, *Tellus*, and *Weather*. He was a member of the Glaciological Society, and he was elected a fellow of the Royal Meteorological Society and served on its council. He died suddenly in October 1964.[22]

Following Eckholm's lead, Callendar examined the role of anthropogenic carbon dioxide in the climate warming experienced during the early decades of the twentieth century (see fig. 10-1). His first article on this subject appeared in 1938. It was followed by articles in successive years on the carbon dioxide content of the atmosphere through the ages, on the current amount of atmospheric carbon dioxide, and on the infrared absorption properties of CO_2. Callendar published articles on the influence of carbon dioxide on climate in 1949 and 1957, reported on the present climatic fluctuation and on a series of important pre–Mauna Loa measurements of atmospheric carbon dioxide in 1958 and, in 1961, reviewed the relationship between temperature trends and CO_2 in light of recent work by others.[23]

In 1938, Callendar pointed out that fuel combustion had generated some one hundred fifty billion tons of carbon dioxide in the previous half century, and that three-quarters of it had remained in the atmosphere—an increase of six percent in the CO_2 concentration from 1900 to 1936. Callendar's radiative model calculated "sky radiation" emitted by water vapor and CO_2 in the thirteen- to sixteen-micron band. This is one factor in what is now called greenhouse forcing. As the density of gases increased in the model, the total sky radiation increased, and the height of the effective atmospheric radiating surface decreased. With a hypothesized doubling of the CO_2 concentration, Callendar's model predicted only a small increase in the total sky radiation. This was because radiation from higher, cooler layers of the atmosphere was effectively screened off. Using the best available data for fossil fuel combustion, Callendar calculated that downward or sky radiation generated by these emissions could account for sixty percent of the half-degree-Celsius-per-century rate of temperature increase being measured by meteorological stations. A doubling of CO_2 in his model resulted in an increase in the mean temperature of two degrees Celsius. Callendar noted, however, that the effect of carbon dioxide might be "considerably greater than supposed."

Warmer, however, was still better. Callendar concluded, much as Arrhenius had three decades earlier, "that the combustion of fossil fuel, whether it be peat from the surface or oil from ten thousand feet below, is likely to prove beneficial to mankind in several ways, besides the provision of heat and power." He cited as examples the importance of small increases of mean temperature at the northern margin of cultivation and the idea that the growth of plants is directly proportional to an increase of the partial pressure of carbon dioxide. "In any case," he concluded, "the return of the deadly glaciers should be delayed indefinitely."[24]

During the discussion of this article at the Royal Meteorological Society, Sir George Clark Simpson, who advocated a theory based on changes in solar radiation, pointed out that the atmosphere was not in a state of radiative equilibrium and that convection and other air movements would have to be taken into account. These sentiments were echoed by David Brunt and C. E. P. Brooks. Simpson regarded the recent rise of CO_2 content and temperature as coincidental and pointed to other complicating factors. John Henry Coste questioned the reliability of the early measurements of CO_2 concentration and temperature. Callendar responded by saying that the measurements he used, taken at Kew Observatory, were "probably very accurate."[25] He realized the extreme complexity of the atmospheric heat budget, but noted that "if any substance is added to the atmosphere which delays the transfer of low temperature radiation, without interfering with the arrival or distribution of the heat supply, some rise of temperature appears to be inevitable in those parts which are furthest from outer space." In other words, *the greenhouse effect is real.*[26]

Callendar's 1939 article, "The Composition of the Atmosphere through the Ages," is an account of the atmospheric carbon cycle over geological time. The article contains an early statement of the now familiar claim that humanity is conducting a "grand experiment" and has become an "agent of global change." Callendar considered it a "commonplace" that humanity had sped up natural processes and had interfered with the carbon cycle. According to Callendar, "[t]he five years 1934–38 are easily the warmest such period at several stations whose records commenced up to 180 years ago." The article ends with an argument linking the one–degree Fahrenheit rise in temperature from 1900 to 1938 to the concurrent increase in industrial emissions of carbon dioxide.[27]

INSERT Fig. 9-1. Rising temperatures, 1858 to 1939 (Callendar)

In 1941, Callendar published a review of spectroscopic measurements on the absorption bands of CO_2 and the effect of pressure broadening on line widths. Of note is his diagram of the infrared spectrum, clearly showing the atmospheric window at eight to twelve microns and the absorption bands of CO_2, H_2O, N_2O, and O_3.

INSERT Fig. 9-2. Atmospheric spectrum in the infrared (Callendar)

All this fit well with Callendar's stated research agenda, which was to "reconsider the difficult problem of the effect of changes in the amount of carbon dioxide on the temperature of the atmosphere with the aid of the much more accurate absorption values given here."[28]

A discussion of this article at the Royal Meteorological Society revealed significant changes in opinion caused by Callendar's work. Brunt thought Callendar had made it clear that "CO_2 absorption was rather more important than had been thought in the past." The noted geophysicist Sidney Chapman pointed out, as Tyndall had known a century earlier, that the polyatomic gases in the atmosphere were the chief absorbers and emitters of radiation and suggested that meteorologists should conduct an organized research program on atmospheric radiation.[29]

Callendar's 1949 article, "Can Carbon Dioxide Influence Climate?" provided the following values from various sources for the observed CO_2 content of the atmosphere:

Date	Observed CO_2 content (ppm)
Pre-1900	290
1910	303
1922	305
1931	310
1935	320

These figures indicated a ten percent rise in observed CO_2 content in the previous thirty-five years. One might predict from this about a twenty-five percent increase in CO_2 per century. Callendar noted, however, that the *rate* of CO_2 increase had been accelerating recently, perhaps due to the expansion of industry.[30]

In his 1958 article on the amount of carbon dioxide in the atmosphere, Callendar provided a chart of the CO_2 levels in the free air of the North Atlantic region since 1870 (figure 9-3) and a full discussion of its implications.[31] He called the solid line the "fuel line" noting that the rise of fossil fuel emissions was in "close agreement" with the rise in measured ambient CO_2 concentrations. He considered this agreement possibly coincidental, but potentially significant, pending the outcome of further investigations.

INSERT Fig. 9-3. CO_2 concentration in North Atlantic air, 1870-1956 (Callendar)

By 1961, Callendar had completed his remarkable series of essays on atmospheric warming and anthropogenic CO_2. He concluded that the trend toward higher temperatures was significant, especially north of the forty-fifth parallel; that increased use of fossil fuels had caused a rise of the concentration of

CO_2 in the atmosphere of about seven percent from pre-1920 levels; and that increased sky radiation from the extra CO_2 was linked to the rising temperature trend. Although he was an amateur meteorologist, Callendar's work, contrary to the assertions of some, was not "largely ignored because of World War II," nor was he quite the obscure figure some make him out to be.[32] In 1944, Gordon Manley noted Callendar's valuable contributions to the study of climatic change. A decade later, Gilbert Plass and Charles Keeling consulted with Callendar before beginning their research programs. In 1953, Hans Suess, one of the founders of radiocarbon dating, pointed out that according to Callendar,

> The average CO_2 concentration in the atmosphere has increased over the past 50 years by approximately 10 percent. This can be seen from a comparison of CO_2 analyses of air carried out in the 19th century with those of more recent years . . . this increase corresponds very closely to the amount of carbon dioxide added to the atmosphere by artificial coal combustion.

Suess and Roger Revelle even referred to rising levels of atmospheric CO_2 caused by industrial fuel combustion as the Callendar effect.[33]

The Public Agenda on Warming

Global warming was on the public agenda in the late 1940s and early 1950s, as Northern Hemisphere temperatures reached an early-twentieth-century peak (see figure 10-1). Hans Ahlmann, a climatologist at Stockholm University, reported in the *Geographic Journal* that Iceland had experienced a 1.3-degree Celsius warming from the period 1872–1925, when the average annual temperature was 4.1 degrees, to the period 1926–47, when the average annual temperature had risen to 5.7 degrees. His article contained photographs documenting the retreat of the Áobrekke glacier since 1869.[34] In 1950, based on his analysis of meteorological records, the meteorologist Hurd C. Willet told the Royal Meteorological Society that the global temperature trend was "significantly upward" since 1885, with most of the warming occurring north of the fiftieth parallel.[35] Subsequent studies confirmed that from 1890 to 1940, the mean thickness of Arctic ice decreased by about thirty percent, and the area covered decreased by as much as fifteen percent; the intensity of the global circulation increased markedly, and the Earth became warmer—ten degrees warmer in the Norwegian Sea.[36]

In the 1950s, several developments combined to increase public awareness of geophysical issues. Many people were certain that atmospheric nuclear testing was changing the Earth's weather. Weather bureau officials dismissed such speculation, arguing that the impact of the tests on the atmosphere was primarily local and temporary. Radioactive fallout posed far more insidious dangers to human health and environmental quality. Radioactive materials in the environment, however, provided new tools for ecologists and geophysicists to trace the flow of materials through the biosphere, atmosphere, and oceans. The International Geophysical Year (IGY), in 1957–58, provided an organizational and financial boost to academic geophysics, including meteorology. The successful launch of the Soviet IGY satellite *Sputnik*, however, combined with the failure of the U.S. Vanguard launch vehicle program, precipitated a crisis in public confidence, a "race" to close a perceived missile gap, and an increase in Cold War tensions. Newsweek announced a weather modification "Race with the Reds," and some even wanted to use weather control as a weapon of war.[37]

Concerns were also being expressed in the popular press about changing climates, rising sea levels, loss of habitat, and shifting agricultural zones. In 1950, the *Saturday Evening Post* asked, "Is the World Getting Warmer?" The article cited three January thaws in succession on the Penobscot River near Old Town, Maine, an unprecedented event that marooned the Indians living on an island and prompted the state to build a new bridge across the river. Average February temperatures in Spitzbergen, Norway, had risen seven degrees in twenty-six years. Hans Ahlmann believed this climatic fluctuation was the first in history that we could "measure, investigate, and possibly also explain." He was of the opinion that "if older people say that they have lived through many more hard winters in their youth, they are stating a real fact." Thomas Jefferson would have concurred. In fact, there is little that is actually new or unique in popular climate discourse. Topics of climatic speculation cited in the article included a warmer planet; rising sea levels; shifts of agriculture; the retreat of the Greenland ice cap and other glaciers; changes in ocean fisheries, perhaps due to changes in the Gulf Stream; and the migration of millions of people displaced by climate change. Ahlmann was concerned about the unprecedented rate of change. He pointed out that the climate was now changing so fast that "each new contribution to the subject is out of date almost as soon as it is published." Perhaps he also meant to say that *climatology* was experiencing unprecedented rates of change.[38]

The famous cartoonist Virgil Partch (a.k.a. VIP) illustrated contemporary climate concerns in *Today's Revolution in Weather!*, a 1953 compilation of news items on weather extremes and global warming. These concerns included sea level rise, migration of plant and animal species, regional winners and losers, and psychological and social influences of climatic change (figures. 9-4a, b, c, d). The compiler, economic forecaster William J. Baxter, predicted a climate-induced real estate boom in the north and advised, "Go north-west young man."

INSERT Figs. 9-4 a, b, c, d. Four global warming cartoons, 1953 (Virgil Partch)

Why was the climate getting warmer? Scientists, inspired by Callendar, began to investigate in greater detail the linkages between rising CO_2 levels and rising temperatures. His early results were revised and extended by the work of others, notably Gilbert Plass, an infrared physicist who developed an early computer model of infrared radiative transfer and published a number of articles on carbon dioxide and climate between 1953 and 1959.

Gilbert Plass

Gilbert Plass built bridges—between the physics of infrared absorption and the geochemistry of the carbon cycle and between geophysics and computer modeling. According to Plass, "all sorts of things came together." New detailed spectroscopic measurements of the absorption bands of water vapor, carbon dioxide, and ozone; new information on the carbon cycle and industrial emissions; and newly available digital computers meant that more realistic models of radiative transfer would soon replace the older, graphical approximations. Plass's new carbon dioxide theory meant that old objections, like those of Humphreys, were no longer valid.[39]

Gilbert Norman Plass was born in Toronto, Ontario, on March 22, 1920. He received a B.S. from Harvard University in 1941, where he recalled that his courses on geology, chemistry, and physics provided an interdisciplinary foundation for his later work. He was particularly impressed by the experimental techniques of John Strong, one of his physics professors. Plass received his Ph.D. in physics from Princeton University in 1947 and worked as an associate physicist at the Metallurgical Laboratory (Manhattan District) of the University of Chicago from 1942 to 1945. He became an instructor of physics at Johns Hopkins University in 1946 and was subsequently promoted to assistant and then associate professor. At Hopkins he conducted research on infrared radiation with funds provided by the Office of Naval Research. During his sabbatical year, at Michigan State University in 1954–55, he gained access to a large computer and realized it offered the perfect way to construct a better model of radiative transfer. In 1955, Plass moved out of academics, serving for a year as a staff scientist with Lockheed Aircraft Corporation. He then joined the advanced research staff of the aeronutronic division of the Ford Motor Company. Ford provided him with excellent laboratory facilities where he could continue his experimental work on infrared physics. In 1960, he became manager of the research lab at Ford's theoretical physics department and a consulting editor of the journal *Infrared Physics*. In 1963, he accepted a position as the first professor of atmospheric and space science at the Southwest Center for Advanced Studies (now the University of Texas, Arlington) where he remained for five years. In 1968, he arrived at Texas A&M University, where he served as professor of physics and head of the department. He is the author of *Infrared Physics and Engineering* (1963).[40] Plass is well known for his research in radiative transfer and planetary atmospheres, especially infrared absorption and emission by molecules and the carbon dioxide theory of climate. He also worked on nuclear fission and neutron physics, electromagnetic and gravitational action at a distance, electron emission, and electrostatic electron lenses. As of this writing, he is retired and living in Bryan, Texas.

Before the advent of numerical models of radiative transfer that included the detailed infrared spectrum of CO_2 and water vapor, meteorologists used a simplified atmospheric radiation chart and tables developed by Walter M. Elsasser in 1942 and Arent Bruinenberg in 1946.[41] The Elsasser Chart assumed that CO_2 was a perfect "black body" absorber at all altitudes, but only for wavelengths between 13.1 to 16.9 microns. Other simplifying assumptions were made for water vapor.[42]

Plass used his more sophisticated theory to warn that accumulation of carbon dioxide in the atmosphere from anthropogenic sources could become a serious problem in the near future. He pointed out in 1956 that humanity was conducting a large-scale experiment on the atmosphere, the results of which would not be available for several generations: "If at the end of this century, measurements show that the carbon dioxide content of the atmosphere has risen appreciably and at the same time the temperature has continued to rise throughout the world, it will be firmly established that carbon dioxide is an important factor in causing climatic change."[43] According to the IPCC scientific assessment, published in 1995, "[t]he balance of evidence suggests a discernible human influence on global climate."[44] Many would say that the uncontrolled "experiment" pointed out by Callendar in 1939 and revisited by Plass in 1956 has been verified.

Roger Revelle

Roger Revelle, statesman of science and public policy, convinced himself that he was the "granddaddy" of the theory of global warming.[45] Although this claim cannot be supported historically, the popular press and many geophysicists have kept the notion alive. A survey of the obituary notices of Roger Revelle reveals his considerable reputation in this area. The *New York Times* referred to him as "an early predictor of global warming"; the *Boston Globe* called him the "grandfather of the greenhouse effect" and the "godfather of global warming"; and his hometown paper, the San Diego County edition of the *Los Angeles Times*, began its front page coverage as follows: "Roger Revelle, the internationally renowned oceanographer who warned of global warming 30 years before greenhouse effect became a household term, died Monday of complications related to a heart attack. He was 82."[46]

Such renown may be attributed in part to Revelle's family ties, social standing, and the high academic, administrative, and political positions he held at the University of California at San Diego (UCSD), Harvard University, and in the federal government. G. S. Callendar was, after all, just a "steam engineer," and Gilbert Plass was a junior professor who moved to industry just as his articles on CO_2 and climate were appearing in the scholarly journals. In contrast, in his lifetime Revelle attained god like status at his home institution and served on national climate panels such as the National Academy of Sciences Climate Research Board and the Committee on Climate of the American Association for the Advancement of Science.

Revelle also had loyal colleagues at the Scripps Institution of Oceography (SIO) who were not shy about embellishing his reputation. One of them, the noted oceanographer Walter Munk, told an interviewer in 1990:

> For Roger, one scientific idea led to another. . . . Typical of this was the greenhouse effect, which he *really invented*, which he was the first to sense was happening, to consider the implications. . . . If it weren't for him getting the carbon dioxide observation started . . . there would be significant differences today at the highest levels of world governments in terms of how they approach global warming.[47]

Roger Randall Dougan Revelle was born March 7, 1909, in Seattle, Washington, and was raised in Pasadena, California. He earned a B.A. in geology from Pomona College in 1929 and a Ph.D. in 1936 from the University of California at Berkeley in conjunction with the SIO. Early in his graduate studies, in 1931, he married Ellen Virginia Clark, a member of the prominent Scripps publishing family and a grandniece of the original benefactors of the SIO. He was appointed as an instructor at Scripps after graduation. During World War II, he served as commander of the oceanographic section of the navy's Bureau of Ships and was involved in the establishment of the Office of Naval Research, where he became head of the geophysics branch in 1946. One of his projects there involved monitoring the effects on the ocean of the atomic bomb tests at Bikini Atoll.

Revelle returned to Scripps as a professor in 1948, working first as its associate director and, from 1951 to 1964, as its director. He held a number of prominent positions during this period, serving on the organizing committee of the IGY (1957–58), as president of the first International Oceanographic Congress (1959), and in the Kennedy administration as the science advisor to Secretary of the Interior Stewart Udall (1961–63). Under his administration, the SIO grew dramatically in size and reputation and became part of the USCD. He was disappointed in 1963, however, when he failed in his bid to become chancellor of UCSD, a campus he had done much to establish. He took a leave of absence and formally switched fields from oceanography to public policy. He became the founding director of the Center for Population Studies at Harvard University in 1964, where he supervised research on population issues in relation to economic and natural resources development. In 1975, he began splitting his time between

Harvard and UCSD; he returned to Scripps permanently in 1978. He continued to teach one undergraduate course at UCSD, met with students during office hours, and spent much of his time answering his correspondence. Among his many honors, he received the National Medal of Science in 1990 for his work on carbon dioxide and climate, oceanographic exploration, radiation in the marine environment, and global population and food studies. In 1991, he died of complications following cardiac arrest at the UCSD Medical Center, which he cofounded.[48]

Carbon Dioxide Exchange between Atmosphere and Ocean

In the mid-1950s, Revelle first became concerned about the increase in carbon dioxide in the atmosphere caused by the burning of fossil fuels. In 1957, he and Hans Suess, published an oft-cited article in *Tellus* on the exchange of carbon dioxide between the atmosphere and ocean. They began by citing Callendar, who maintained that most of the carbon dioxide produced by fossil fuel combustion had remained in the atmosphere (see figure 9-3), and that increasing levels of CO_2 may account for the recent warming in high latitudes. They also cited calculations by Plass, who found that a ten percent increase in atmospheric carbon dioxide would increase the average temperature by 0.36 degrees Celsius. As did T. C. Chamberlin at the turn of the century, Revelle and Suess thought that positive feedback processes, such as an increase in atmospheric water vapor content, could result in a more pronounced effect, but they emphasized that so little was known about the thermodynamics of the atmosphere that "it is not certain whether or how a change in infrared back radiation from the upper air would affect the temperature near the surface."[49]

The authors were concerned, however, about a possible increase in worldwide fuel and power consumption. They tabulated United Nations estimates of increasing concentrations of atmospheric CO_2 caused by exponentially increasing fossil fuel consumption. The U.N. figures indicated a worst-case seventy-four percent increase in atmospheric CO_2 concentration over preindustrial levels by the first decade of the twenty-first century. This would be about a sixty percent increase over the 1955 level. Based on these estimates and the observation that the production of industrial CO_2 is probably two orders of magnitude greater than the natural rate of CO_2 production from volcanoes, the authors ventured their memorable statement 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. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate."[50]

This statement is reminiscent of Plass's a year earlier and Callendar's statements earlier still.[51]

The balance of their essay is a calibration of the "carbon cycle" and an estimate of the sequestering of CO_2 in the atmosphere, oceans, biosphere, and lithosphere using C^{14} techniques pioneered by Suess. As did many others before them, notably Arvid Högbom and T. C. Chamberlin, Revelle and Suess reported ocean carbon reservoirs two orders of magnitude larger than those of the atmosphere, and carbonates in sediments two to three orders of magnitude larger than those of the ocean. Guesses about CO_2 exchange rates ranged over six orders of magnitude. Theirs was one hundred times larger than those used by Plass in 1956, yet ten thousand times smaller than that deduced by H. N. Dingle in 1954.[52] Clearly the carbon *fluxes* were not well known. This fact severely limited their conclusions.

Revelle and Suess thought that the Callendar effect, their term for a ten percent increase in atmospheric CO_2 concentration caused by industrial fuel combustion during the past century, was "quite improbable" on its own and was probably augmented by a number of factors. These included a slight increase of ocean temperature (not more than 0.05 degrees Celsius), a decrease in the carbon content of soils due to clearing of the forests and increased cultivation (shades of colonial America), and a possible change of organic matter in the oceans.[53] Using results published in the 1930s by Kurt Buch on the absorption of CO_2 by sea water and estimates of the average lifetime of a CO_2 molecule in the atmosphere of ten to thirty years, Revelle and Suess calculated secular increases in atmospheric CO_2 of only two to about ten percent *per centur*y. Their final estimates, a compromise between their own calculations and United Nations projections, was a twenty to forty percent increase by the end of the century. This, they said, would "allow a determination of the effects, *if any*, of changes in atmospheric carbon dioxide on weather and climate throughout the earth." With a rhetorical flourish, they pointed to current uncertainties and new work that needed to be done.

> Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of CO_2 exchange between the sea and the air, and between the air and the soils, and on possible fluctuations in marine organic carbon are insufficient to give an accurate base line for measurement of future changes in atmospheric CO_2. An opportunity exists during the International Geophysical Year to obtain much of the necessary information.[54]

Revelle and Suess concluded by acknowledging an article "on the same subject" in the same issue of *Tellus* by James R. Arnold and Ernest C. Anderson. These authors made several references to the "Suess effect," the recent secular decreases of C^{14} in the biosphere. They explained this effect by noting that industrial combustion of fossil carbon had now reached "truly geochemical proportions" and had exceeded natural production of current carbon by two orders of magnitude.[55] The matter, however, was far from settled.

During the IGY, Harry Wexler of the U. S. Weather Bureau succeeded in establishing a series of accurate measurements of carbon dioxide. Following a meeting with Revelle in October 1956, Wexler provided initial funding to the Mauna Loa Observatory for an infrared gas analyzer "to keep a continuous record of CO_2 at the Observatory."[56] These measurements were accurately and faithfully executed by Charles David Keeling, then an assistant research chemist at Scripps.[57] The measurements at Mauna Loa almost did not happen as planned, however. As Keeling recalls, "[Revelle] wouldn't sign my travel orders to go out and set up my measurements at the Mauna Loa Observatory because he wanted me to do it his way first."[58] "His way" was a geographical survey over large expanses of the ocean, based on an older notion that CO_2 varies by location. Wexler and Keeling prevailed, however, and Keeling recalled two decades later:

> The first unmistakable evidence of atmospheric CO_2 increase was furnished by continuous measurements made at [the Mauna Loa Observatory] and by measurements of flask samples collected periodically at the South Pole. These data, obtained in connection with the [IGY], were precise enough to indicate a rise in concentration in 1959 when compared with the results of the previous year. Further measurements have shown a persistent year-to-year increase.[59]

Since then, the Keeling curve, the famous saw-toothed curve of rising CO_2 concentrations, has become *the* environmental icon of the century (figure 9-5).

INSERT Fig 9-5. CO_2 concentrations, 1958-1990 (Keeling)

It is important to note, however, that measurements of the concentration of CO_2 in the atmosphere did not begin in 1958. They had been made, with varying degrees of accuracy, since the beginning of the nineteenth century by John Dalton and others. Callendar reported background measurements from as early as the 1870s in his essays and estimated that the concentration of CO_2 in the late nineteenth century was close to 290 parts per million. This result was later confirmed by Eric From and Charles Keeling.[60] It is also important to note that Callendar's curve (figure 9-3), which ends at about 325 parts per million in the mid-1950s, fits closely with the Keeling curve, which started at 315 parts per million in 1958.

Roger Revelle was a formidable figure in academic and political circles. By his own admission, however, he was not educated enough to tackle the modern rigors of the geophysical sciences he had done so much to promote. "I was never very well-educated," he told an interviewer in 1990 after President George Bush awarded him the National Medal of Science. "Geologists in those days didn't get much physics or mathematics." He called oceanography a "young man's game—not because it's physically demanding, but because it requires a lot of mathematics now."[61] His role in the global warming issue can largely be understood as an advocate for carbon cycle monitoring.[62]

The 1957 article of Revelle and Suess, so widely cited as launching Revelle's claim to being the father of the theory of the greenhouse effect, focused on geophysical and anthropogenic carbon sources and sinks. It was not a clarion call on the dangers of global warming. Clearly, it was the product of two separate authors—Suess's work on the carbon cycle as calibrated by C^{14} and Revelle's work on the chemistry of seawater. While it enhanced the luster of Revelle, publishing an article in *Tellus* was all in a day's work for Suess.

G. S. Callendar pointed out in 1961 that "this matter of atmospheric CO_2 increase is highly controversial at the present time, and several authors have expressed doubts as to the possibility of a CO_2 increase approaching the amount . . . added by fossil-fuel combustion."[63] He was referring to the 1957 article by Revelle and Suess in which they had stated that "most of the CO_2 released by artificial fuel combustion since the beginning of the industrial revolution must have been absorbed by the oceans." Clearly their work was not the dramatic turning point in our awareness of the risk of global warming that later authors perceived it to be.

In 1985, Revelle wrote a short, revisionist "scientific history of carbon dioxide" in which he *failed to mention the contributions of Callendar and Plass*. His account jumps from T. C. Chamberlin directly to areas of current concern.[64] Perhaps this omission was simply an oversight in a brief essay. More likely, it was based on Revelle's need to place himself at the center of the carbon dioxide theory of climate as a way of maintaining his larger-than-life legend.

Conclusion

Global warming and the carbon dioxide theory of climate change are not new issues. In the 1940s and 1950s, doubts about the efficacy of CO_2 as an agent of climatic change gave way to new theories and observations. Rising temperatures, expanding carbon emissions, new measurements of the radiative properties of trace gases, and new models of the Earth's heat budget and carbon cycle convinced a number of scientists that the carbon dioxide theory needed to be taken seriously. By the late 1940s and early 1950s, as Northern Hemisphere temperatures continued to rise, global warming was on the public agenda.

However, scientific work done in the mid-1950s did not seem to make much of an impression on the general public, whose awareness of climate issues seemed to rise and fall with the temperature trends. With the exception perhaps of Revelle's policy initiatives and Keeling's curve of CO_2 concentration, which continues its snakelike rise, early twentieth century concerns about global warming are not continuous with later climate research.