Substantia
An International Journal of the History of Chemistry

Firenze University Press
www.fupress.com/substantia

Citation: R. M. Baum Sr. (2019) Taking the Earth's temperature: 200 years of research has established why the Earth is as warm as it is and how burning fossil fuels is making it warmer. *Substantia* 3(2) Suppl. 1: 27-42. doi: 10.13128/Substantia-264

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Taking the Earth's temperature:

200 years of research has established why the Earth is as warm as it is and how burning fossil fuels is making it warmer

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Abstract. Because of the threat of global warming due to the build-up of atmospheric carbon dioxide from burning fossil fuels, energy use is the central factor in creating a sustainable future. Anthropogenic climate change is real, but climate change deniers insist that carbon pollution is not a threat and that the science behind climate change is flimsy at best and a sham at worst. In fact, efforts to understand Earth's climate and why the planet's temperature is what it is date back to the early 19th century, and I review that history in this paper. Earth's atmosphere was first likened (inaccurately, as it turns out) to a greenhouse in the 1820s; CO_2 was first shown to be a greenhouse gas in the 1860s; the idea that burning fossil fuels could change the Earth's temperature was proposed in the late 19th century; the concentration of CO_2 in the atmosphere was first shown to be inexorably rising in the 1950s. The science of climate change has a long and distinguished pedigree.

Keywords. Greenhouse gases, global warming, climate change, fossil fuels, carbon dioxide.

INTRODUCTION

Energy consumption is by far the most important factor in determining whether humanity can transition to a sustainable economic system in the 21st century. Burning fossil fuels powered the Industrial Revolution and, in a mere 200 years, transformed civilization. Civilization as we know it is entirely dependent on burning fossil fuels—which are, in fact, fossilized sunshine—cheaply. Humans burn fossil fuels on the cheap because we treat the atmosphere as a free dumping ground for the waste products of combustion, primarily carbon dioxide (CO_2).

For many years, economists and others thought the supply of fossil fuels would place limits on economic growth. Books were written on "peak oil"—when the amount of petroleum extracted from the Earth would begin an inevitable decline as oil fields were depleted.[1] It turns out that that's probably not the case. Enough fossil-fuel resources—petroleum, natural gas, and coal—are left on Earth for us to keep the economic engines that have powered 200 years of exponential growth going for another 200 or 300 years or so.

Earth's climate, however, will not tolerate humans continued unrestrained fossil fuel use. The buildup of atmospheric CO_2—from 280 ppm at the beginning of the Industrial Revolution to more than 400 ppm today[2]—is already forcing the climate to change. Earth's temperature is increasing due to the buildup of CO_2 and other greenhouse gases, many of them associated with fossil fuel production and use.

Among scientists, there is no doubt that anthropogenic climate change is real. However, a determined cadre of climate change deniers insists that carbon pollution is nothing but propaganda, that climate scientists are engaged in an elaborate conspiracy to demonize fossil fuels and line their pockets with research grants. One persistent thread in the deniers' claims is the suggestion that climate change is a relatively new idea cooked up by left-leaning scientists and politicians bent on strangling economic growth. Nothing could be further from the truth. Scientists have been pondering the question of why the Earth's temperature is what it is for 200 years. That the Earth's atmosphere plays a role in regulating the planet's temperature was first proposed in the 1820s. Carbon dioxide was first shown to be a greenhouse gas—able to absorb infrared radiation—in the 1860s. The idea that burning fossil fuels could ultimately change Earth's climate was proposed in the late 19th century; the first calculation on the potential impact of CO_2 on climate was published in 1896. Climate change has a long and distinguished scientific pedigree.

It should be noted that while the terms "greenhouse gases" and "greenhouse effect" are now firmly embedded in the vernacular concerning climate change and that a number of 19th century scientists made allusions to a greenhouse or a blanket when discussing the influence of Earth's atmosphere on the planet's surface temperature, the term "greenhouse effect" was not used until 1901 by the Swedish scientist Nils Ekholm. Perhaps unfortunately, as will be discussed further, a greenhouse is not an accurate analogy for how gases like carbon dioxide are warming the Earth.

ENERGY BALANCE

Why is the temperature at the surface of the Earth what it is? The French mathematician and physicist Joseph Fourier (1768–1839) addressed the question in the early 1800s as part of his more general work on heat flow. Fourier is best known for his work on discontinuous functions, work that is the foundation of what is known today as the Fourier transform. He also made seminal experimental and theoretical contributions to our understanding of energy flow in various substances.

Fourier thought that there were three sources of energy that contributed to Earth's surface temperature: solar radiation, which is unevenly distributed across Earth's surface and gives rise to the diversity of climates; energy from interstellar space, essentially from the stars; and energy from Earth's interior, which he thought to be relatively minor.[3,4,5] The most important energy source was the sun. When the light from the sun strikes the Earth and warms it, why doesn't the planet just keep getting hotter? Fourier reasoned that the Earth must be radiating invisible heat—infrared radiation—back into space to achieve a net energy balance.

Treating the Earth as a black body being heated by sunlight, Fourier calculated that its temperature would be significantly lower than it is. Fourier thought, incorrectly, that the difference was likely made up by energy from interstellar space. However, he also speculated that the atmosphere might be transparent to sunlight impinging on the planet but that it somehow impeded the outward flow of heat from the planet back into space. In one analogy, he compared the heating of the atmosphere to the action of a heliothermometer, an instrument designed and used by Horace Benedict de Saussure (1740–1799) in the 1770s to study the variability of the intensity of solar radiation with altitude. The device consists of a small wooden box lined by a layer of

Figure 1. Joseph Fourier (1768–1830); Credit: www.bridgemanimages.com.

blackened cork and fitted with three panes of glass separated by air spaces. The similarity of a heliothermometer to a greenhouse and Fourier's reference to it are what gives rise to the suggestion that Fourier was the first to liken Earth's atmosphere to a greenhouse, although he never used that term.

In fact, it's a little bit tricky to unearth Fourier's precise thinking about this subject. Fourier's 1827 disquisition "Mémorie sur les temperatures du globe terrestre et des espaces planétaires" ("Memoir on the temperature of the earth and planetary spaces"), often cited to support the link between Fourier and the greenhouse effect, may well have been a public presentation rather than a formal scientific paper. It contains no equations or formal calculations. As James R. Fleming points out in "Joseph Fourier, the 'greenhouse effect', and the quest for a universal theory of terrestrial temperatures,"[6] the 1827 article "has been mentioned repeatedly as being the first reference in the literature to the atmospheric 'greenhouse effect.' Here I will review the origins of this practice and demonstrate that most of these citations are unreliable, misdirected and anachronistic. While there are indeed greenhouse analogies in Fourier's writings, they are not central to his theory of terrestrial temperatures, nor are they unambiguous precursors of today's theory of the greenhouse effect." Nevertheless, Fourier clearly stimulated others to investigate the factors that determined the Earth's temperature.

One such scientist was Claude S. M. Pouillet (1790–1868), who in the 1830s developed a pyrheliometer and made the first quantitative measurements of the solar constant. In his 1838 article,[7,8] "Mémoire sur la chaleur solaire, sur le pouvoir rayonnants et absorbants de l'air atmosphérique, et sur la temperature de l'espace" ("Memoir on solar heat, on the radiating and absorbing powers of the atmospheric air, and on the temperature of space"), Pouillet credits Fourier as being "the first who has had the idea of regarding the unequal absorption of the atmosphere as exercising an influence on the temperature of the soil."

Pouillet regarded light rays and heat rays to be fundamentally different—"the rays of heat and of light may derive their origins from the same source, be emitted at the same time, and coexist in the same pencil of rays, but they preserve a distinctive character"—and as such could be thought of differently in how they interact with matter. This allows him to view the atmosphere as being "diathermanous," meaning that light rays can pass through the atmosphere without heating it while heat rays are absorbed by it and warm it. Thus, he writes:

> *With regard to the solar heat no doubt exists: we know that in traversing diathermanous substances it is less absorbed than the heat which is derived from different terrestrial sources, the temperature of which is not very high. It is true that we have been able to make the experiment only upon liquid or solid diathermanous screens; but we regard it as certain that the atmospheric stratum acts in the manner of screens of this kind, and that consequently it exercises a greater absorption upon the terrestrial than upon the solar rays.*

That is, some component of the atmosphere absorbs heat emanating from the Earth's surface resulting in an overall warming of the planet. Neither Fourier nor Pouillet had any idea what that component of the atmosphere might be.

OF GLACIERS AND ICE AGES

Questions about the Earth's temperature also were stimulated in the first half of the 19th century by the then radical idea that the Earth had experienced numerous ice ages during its history. Geologists had taken note of large boulders scattered across much of Europe far from the mountains from which they had originated. How did they get there? One explanation was Noah's Flood. Another was violent volcanic activity. Jean de Charpentier (1786–1855), a German-Swiss mining engineer and geologist who studied Swiss glaciers, proposed that these so-called erratics had been carried to their locations by glaciers that had once been much more extensive than at that time.[9] He did not know how the glaciers had formed, moved, or what had happened to them.

Credit for the idea of ice ages is somewhat controversial.[10] The German botanist Karl Friedrich Schimper (1803–1867) studied mosses growing on erratics and, like Charpentier, wondered where the boulders had come from and concluded that they had been carried by ice. Schimper spent the summer of 1836 in the Swiss Alps with his former university friend Louis Agassiz (1807–1873) and Charpentier and together they developed the theory of successive glaciations covering much of northern Europe, Asia, and North America. Schimper coined the term "ice age" ("eiszeit" in German) in 1837. The same year, Agassiz, already renowned for his work in paleontology, presented the theory to the Helvetic Society. The theory was not well received as it conflicted with then current ideas about Earth's climate history. In 1840, Agassiz published a two-volume work "Études sur les glaciers" ("Studies of Glaciers").[11]

The question, of course, was, if the idea of global ice ages was correct, what could possibly have caused the Earth's climate to shift so drastically to allow such massive ice sheets to form? It is a question that has still not been completely answered.

John Tyndall (1820-1893), an Irish chemist and physicist, had a keen interest in glaciers and in heat flow. He was a careful and precise experimenter who had made his reputation with his studies of diamagnetism in the early 1850s.[12] He was also an accomplished mountaineer who had made close studies of glaciers. In addition to a number of papers on glaciers—he coauthored "On the Structure and Motion of Glaciers" with Thomas Huxley in 1857—he wrote "Glaciers of the Alps: Being a narrative of excursions and ascents, an account of the origin and phenomena of glaciers, and an exposition of the physical principles to which they are related" in 1860.

Tyndall began his experiments on the absorption of heat by gases in early 1859. His biographer, Roland Jackson, writes:

> *His interest had a long gestation. … He had considered the topic for several years; he read Macedonio Melloni's work on the absorption of heat by liquids and solids around 1850, and frequently discussed the issue with friends. His work on glaciers rekindled that interest. He had explored the existence of air bubbles in ice, the conduction of heat through ice, and the formation of flower-shaped structures in ice by a focused beam of light. Now his attention turned to the atmosphere, to examine its interaction with solar and terrestrial radiation, and to investigate the remarkable condition of temperature in mountain regions. His aim was to do for gases what Melloni had done for liquids and solids. There was further motivation. He was convinced that not only the physical but also the chemical composition of substances—and specifically their molecules—played a part previously unrecognized in radiation and absorption. He would be probing the nature of molecules themselves using radiation.*[13]

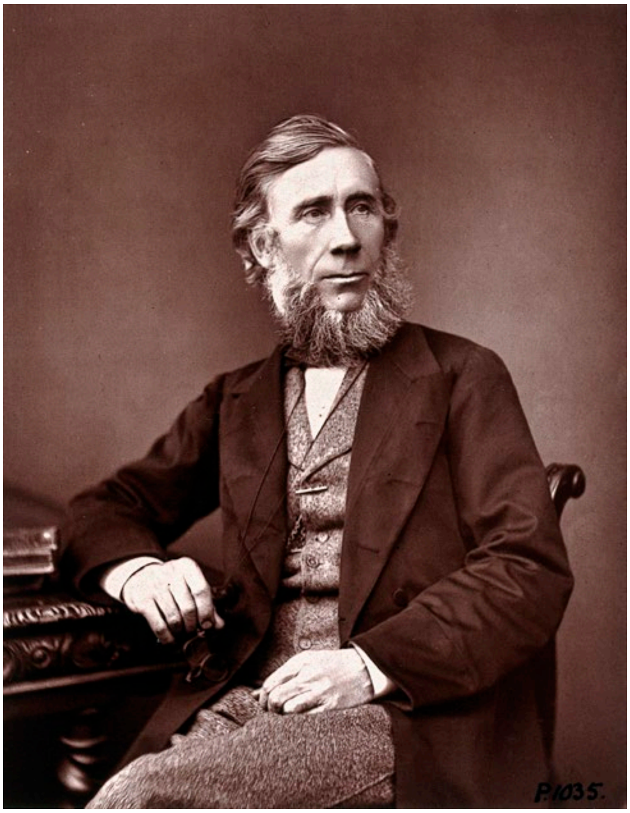


Figure 2. John Tyndall (1820–1893). Credit: Wellcome Collection, CC BY.

Tyndall's skill as an experimentalist allowed him to succeed where Melloni had failed in measuring how different gases interacted with heat radiation. Tyndall built the first differential spectrometer.[14] It consisted of a long tube that he filled with the gas under study. The ends of the tube were capped with slabs of rock salt, which is transparent to infrared radiation. A precision heat source emitted radiation that traversed the tube and interacted with the gas before entering one cone of a differential thermopile. Another heat source emitted exactly the same amount of radiation directly into the other cone of the thermopile. The thermopile was connected to a galvanometer, which measured small voltage differences. A voltage measurement indicated that the gas under study had attenuated the passage of radiation down the tube.

Tyndall quickly discovered that dry air is transparent to heat radiation and that both water vapor and carbon dioxide absorbed it. He announced his results to the Royal Society and followed with a "Discourse" to the Royal Institution, "On the transmission of heat of different qualities through gases of different kinds."[15] He had demonstrated that a number of gases absorbed heat, although the only one he specified in his report was "coal gas," a mixture of carbon monoxide and methane. He concluded: "Thus the atmosphere admits of the entrance of the solar heat; but checks its exit, and the result is a tendency to accumulate heat at the surface of the planet."

Tyndall continued his research on gases into the 1860s.[16] He showed that water vapor, CO_2, and numerous hydrocarbons absorbed heat radiation and that absorption was proportional to density for small amounts of a gas. Why were oxygen and nitrogen such poor absorbers of radiant heat? As Jackson summarizes:

> *Tyndall thought that this might be due to their existence as single atoms—although we now know them to be diatomic—and that the far stronger power of other substances, such as water, carbon dioxide, and coal gas, was*

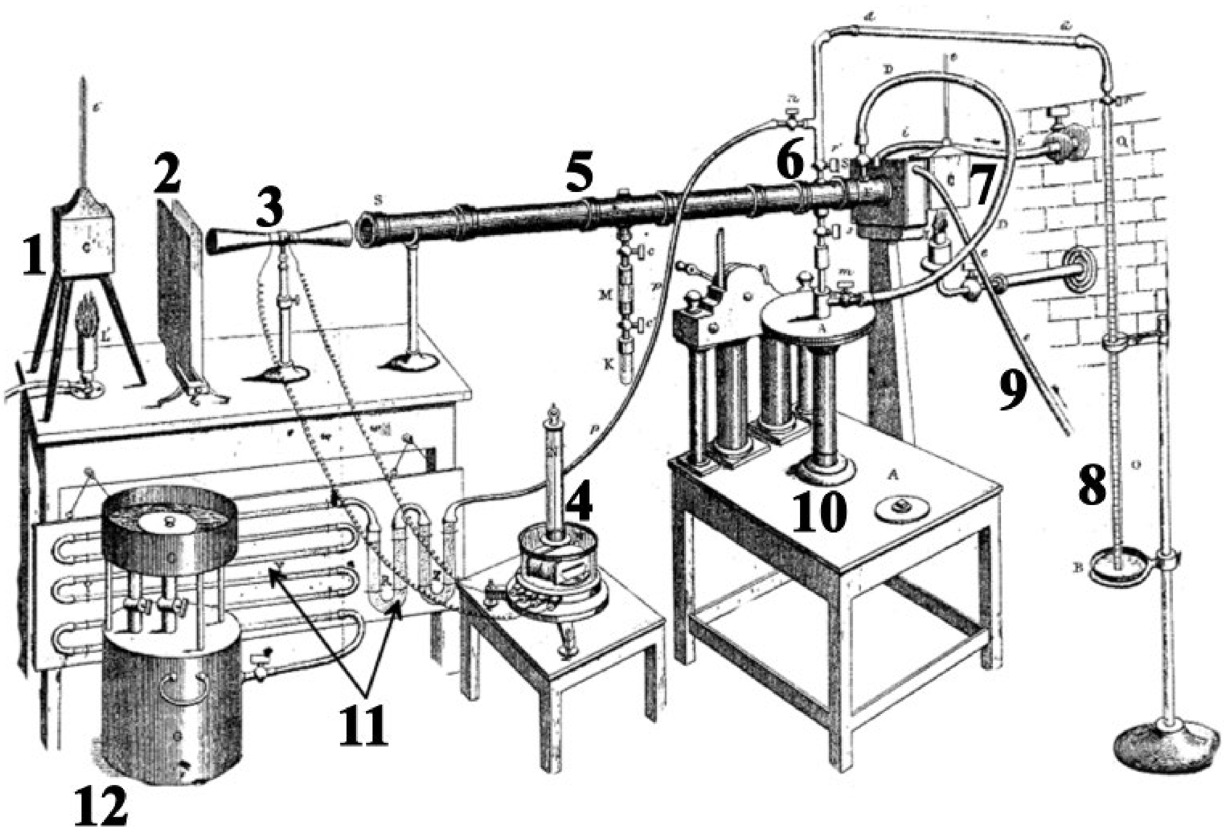


Figure 3. 1: Heat source. 2: Heat screen. 3: Thermopile, with conical reflectors. 4: Galvanometer. 5: Brass tube with rock salt plugs at each end. The tube contains the gas that is under study. 6: Gas enters tube. 7: Heat source. 8: Manometer. 9: Circulating cold water solves a heat conduction issue. 10: Vacuum pump. 11: The gas or gas mixture can pass through some filtration process beforehand. 12: Container of gas or gas mixture to be studied.

> *due to their molecular structure as oscillating systems of atoms. These compound molecules, Tyndall imagined, 'present broad sides to the ether,' unlike the simple individual spherical atoms. They have more sluggish motions, so tend to bring the period of oscillation into synchrony with the slower undulations of radiant heat compared to those of visible light.*[17]

Tyndall realized that water vapor, because of its relatively high atmospheric concentration compared to other trace gases, was the most influential absorber of heat radiation in the atmosphere. In an 1863 Royal Institution Discourse "On radiation through the earth's atmosphere," he stated: "This aqueous vapor is more necessary to the vegetative life of England than clothing is to man. Remove for a single summer night the aqueous vapor from the air which overspreads this country and you would assuredly destroy every plant capable of being destroyed by a freezing temperature."[18]

Tyndall went on to probe the nature of heat radiation, which he referred to as "black" or "obscure" heat, beginning to break down the idea that visible light and heat are fundamentally different phenomena. He showed that heat radiation could be focused, that it could set paper ablaze, and that it could make metal glow with visible light, a phenomenon he referred to as "calorescence," a counterpoint to "fluorescence." In a presentation to the Royal Society in 1865, he showed that the maximum heat in the spectrum of an electric lamp was beyond the visible red.[19]

Interestingly, although Tyndall's work has long been recognized as seminal in our understanding of the interaction of the atmosphere and solar radiation, he was not the first person to show experimentally that a trace constituent of the atmosphere could absorb infrared radiation. In 2010, Raymond P. Sorenson, a retired petroleum geologist, discovered the work of Eunice Foote (1819–1888), an American scientist who in 1856 reported that water vapor and carbon dioxide absorbed heat radiation and in doing so warmed the atmosphere.[20] Foote speculated that a higher concentration of CO_2 could have been the cause of a much warmer climate earlier in Earth's history. Foote's paper, "Circumstances affecting the heat of the sun's rays," was presented in August 1856 at the 10th annual meeting of the American Association for the Advancement of Science by John Henry, the founding director of the Smithsonian Institution. Foote subsequently published a paper, "On the heat of the Sun's rays" in the November 1856 issue of the *American Journal of Science & Arts* with a note that it had been presented at the AAAS meeting.[21]

Foote's experimental apparatus, only vaguely described in her paper, was crude compared to Tyndall's. Unlike Tyndall, Foote did not expose gases only to long-wavelength radiation, which is the basis of the greenhouse effect. Nevertheless, in a recent paper, Jackson concludes that Foote "does seem to have been the first person to notice the ability of carbon dioxide and water vapour to absorb heat, and to make the direct link between the variability of these atmospheric constituents and climate change. For that she deserves proper recognition, even if she was not able to explore, and perhaps did not recognize, the distinction between solar radiation and radiated heat from the earth".[22]

HOW COLD? HOW WARM?

Tyndall had concluded that Earth would be a frozen wasteland without the greenhouse warming provided by water vapor, but he didn't calculate what the Earth's temperature would, in fact, be without that cloak. Nor did he try to calculate what change in atmospheric CO_2 levels could bring on an ice age.

The Swedish chemist, physicist, and mathematician Svante Arrhenius (1859–1927) is primarily remembered for his research on the conductivities of electrolytes, work for which he won the 1903 Nobel Prize in chemistry; and the concept of an activation energy, an energy barrier that must be overcome before two molecules will react.

However, as with Tyndall and many other 19th century natural philosophers/scientists, Arrhenius' intellect ranged widely. It was this diversity of talents and interests that led him to embark on what some now view as his greatest achievement, the mathematical analysis of the influence of CO_2 on the Earth's energy budget as detailed in his now-famous paper, "On the influence of carbonic acid [carbon dioxide] in the air upon the temperature on the ground."[23] While the work is now regarded as a seminal contribution to climate science, it was not recognized as such when it was published or for many years thereafter.

Arrhenius was a founding member of Stockholm Physics Society, which drew a wide range of scientists to its fortnightly meetings to discuss topics ranging from physics to chemistry, meteorology, geology, and astrophysics, including the ice ages and what caused them.[24] It was through meetings of the society that Arrhenius formed a close collaboration with Arvid Högbum (1857–1940), a geologist who studied the geochemical carbon cycle of the Earth, especially how atmospheric CO_2 is influenced by the oceans, vegetation, and formation of carbonates. Högbum believed that atmospheric CO_2 levels varied widely over geologic time and likely influenced climate.

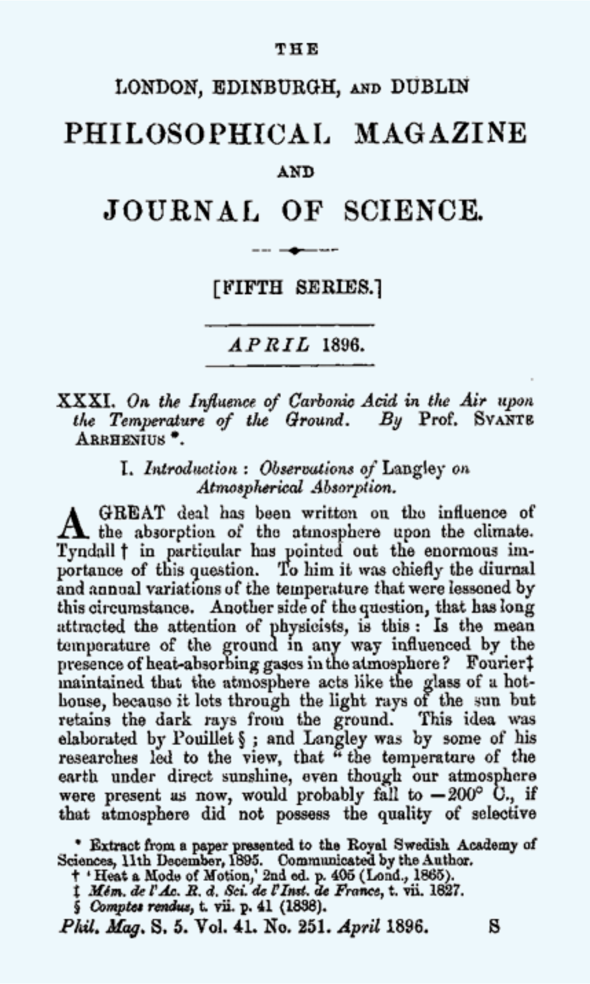
Why focus on CO_2 when water vapor is much more prevalent in the atmosphere and a much more influential greenhouse gas? Arrhenius realized that Earth is a wet planet. Water cycles in and out of the atmosphere continuously. CO_2, by contrast, remains in the atmosphere

Figure 4a. Svante Arrhenius (1859–1927). Credit: University Archives, Universität Würzburg.

for centuries. It acts as a "control knob" that sets the level of atmospheric water vapor. If atmospheric CO_2 levels dropped substantially, Earth's temperature would fall only slightly at first. But this lower temperature would result in less water vapor in the atmosphere, further lowering the Earth's temperature.

Arrhenius embarked on the laborious effort to develop equations to quantify how much atmospheric CO_2 would have to vary to bring about changes, both warmer and colder, that could explain the ice ages. As Thomas R. Anderson, Ed Hawkins, and Philip D. Jones point out in their paper "CO_2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models": [25]

> *The calculations involved balancing the radiative heat budget (thereby assuming a state of equilibrium), namely solar radiation arriving at the Earth's surface (including the effects of albedo from clouds and the Earth's surface) and the subsequent absorption of re-emitted infrared radiation by the atmosphere. Calculating this absorption required integration across the different wavelengths that encompass the absorption spectrum of CO_2 and water vapor, as well as integrating across different zenith angles … and the corresponding path lengths associated with incoming and outgoing radiation.*



THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. By* Prof. SVANTE ARRHENIUS[*].

I. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall[†] in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier[‡] maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet[§]; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

[*] Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
[†] 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
[‡] *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
[§] *Comptes rendus*, t. vii. p. 41 (1838).

Phil. Mag. S. 5. Vol. 41. No. 251. *April* 1896. S

Figure 4b. First page of Arrhenius' groundbreaking paper.

By his own admission, the calculations were laborious, taking up a year of his time. In his 1896 paper, he wrote: "I should certainly have not undertaken these tedious calculations if an extraordinary interest had not been connected with them." It is possible that he immersed himself in the work as an emotional escape from personal problems. That year, he went through a painful divorce after only two years of marriage from Sofia Rudbeck, a former student, losing not only his wife but custody of their young son.

Arrhenius made calculations for six scenarios, with CO_2 levels at 0.67, 1.0, 1.5, 2.0, 2.5, and 3.0 times the levels in the atmosphere at that time. His work showed that doubling or halving the amount of CO_2 would result in warming or cooling the Earth by 5–6 °C. To lower the temperature the 4–5 °C needed to bring on an ice age, he wrote, would require CO_2 to drop to 0.62–0.55 of its 1896 level.

What of global warming? Arrhenius wasn't too concerned because he thought it would require 3,000 years for humans burning coal to double the atmospheric level of CO_2. Nor did he necessarily consider global warming such a bad outcome. In his 1908 book "Worlds in the Making," which was written for a nontechnical audience, Arrhenius wrote:

> *We often hear lamentations that the coal stored up in the earth is wasted by the present generation without any thought of the future. … We may find a kind of consolation in the consideration that here, as in every other case, there is good mixed in with the evil. By the influence of the increasing percentage of carbonic acid in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the earth, ages when the earth will bring forth much more abundant crops than at present, for the benefit of rapidly propagating mankind.*[26]

Arrhenius' friend and collaborator, the Swedish meteorologist Nils Ekholm (1848–1923), expressed a similar sentiment, saying that if "the present burning of pit-coal continues for some thousand years, it will undoubtedly cause a very obvious rise in the mean temperature of the earth," and that, with this impact, coupled with humans tapping other sources of CO_2, "it seems possible that man will be able efficaciously to regulate the future climate of the earth and consequently prevent the arrival of a new ice age".[27]

As it turns out, the temperature changes that Arrhenius calculated are somewhat higher than the currently accepted range of 1.5–4.5 °C of warming that would result from doubling atmospheric CO_2.[28] Nevertheless, his accomplishment was remarkable given the tools and data at his disposal.

One argument raised against Arrhenius' conclusions on the effects of atmospheric CO_2 is important because it was widely accepted at the time and because it is still raised by climate change deniers. Not long after Arrhenius published his results, another Swedish scientist, Knut Ångström (1857–1910), who published the first infrared absorption spectrum of CO_2, argued that his work showed that the infrared absorption bands of the gas were completely saturated in the lower atmosphere. That is, the trace CO_2 already in the atmosphere was absorbing all of the infrared radiation that it was capable of absorbing, and that, therefore, adding more CO_2 could not change the Earth's energy balance.[29]

Arrhenius strongly rejected Ångström's argument,[30] but many other influential scientists of the day did not. As a result, practically no one took seriously Arrhenius' idea that burning coal and other fossil fuels could eventually result in a warmer Earth, and no one paid much attention to the concentration of CO_2 in the atmosphere. The fallacy in Ångström's reasoning is that it treats the atmosphere with regard to infrared radiation as a single slab, much like the panes of glass in a greenhouse. In point of fact, this is where the greenhouse metaphor as an explanation of global warming breaks down.

For the purposes of absorbing infrared radiation, the atmosphere must be viewed as consisting of many layers which get thinner, drier, and colder at higher and higher altitudes. Earth's temperature is controlled by these thin upper layers where radiation escapes easily into space. Adding CO_2 to these layers does change the planet's energy balance. As infrared radiation leaving the surface of the Earth moves up through the layers of the atmosphere, some of it is absorbed at each layer. The layer of air radiates some of the energy back toward Earth's surface and some toward higher layers. In the topmost layers where heat radiation from lower layers slips easily through into space, adding CO_2 means the layer will absorb more radiation and warm, thus shifting to even higher layers where radiation escapes into space. Adding greenhouse gases to the atmosphere effectively increases the pathlength infrared radiation takes before escaping into space, changing the equilibrium of energy arriving and departing the planet. Instead of the metaphor of a greenhouse, a more accurate analogy is that adding CO_2 and other infrared absorbers to the atmosphere has the effect of placing a thicker blanket around the Earth. (Which, like all metaphors for atmospheric dynamics, isn't entirely accurate, either.)

THE OCEANS AS A CO_2 SINK

There were other substantive objections to Arrhenius' argument that CO_2 could influence Earth's climate. One was related, in a way, to Ånström's objection that the CO_2's infrared absorption was saturated in the lower atmosphere. CO_2 absorbs infrared radiation in a few narrow bands while water vapor's infrared absorption bands are broad and largely overlap those of CO_2. Thus, this reasoning went, more CO_2 in the atmosphere could not affect the absorption of radiation already entirely absorbed by water vapor. This argument, although widely accepted, fails for the same reason Ångström's objection fails: what is critical is the CO_2 in the dry, cold upper layers of the atmosphere. Moreover, in the thin upper atmosphere the absorption lines of both molecules narrow and become better defined, and here the overlap between the two spectra is not complete.

Yet another argument raised against Arrhenius was that the oceans would absorb the vast majority of CO_2 released by all sources. It was known that there is 50 times more CO_2 dissolved in the oceans than is present in the atmosphere. However, the dynamics of the equilibrium between atmospheric CO_2 and CO_2 dissolved in ocean water are complicated and were not well understood. Most scientists simply assumed that ocean water represented an essentially infinite reservoir for the CO_2 humans were pouring into the atmosphere from burning fossil fuels. Earth's climate, the argument went, was a self-regulating system that naturally remained at equilibrium.

These objections to the notion of anthropogenic climate change mitigated against research into the field for most of the first half of the 20th century. There simply didn't seem to be much point in probing what was an inherently complex system because the consensus was that there wasn't anything to discover. Scientists are loath to waste their time on questions that have already been answered.

Guy Stewart Callendar (1898–1964) did not subscribe to the consensus view and developed data to challenge it. A British steam engineer with a lifelong passion for a wide variety of scientific topics, Callendar took up meteorology and climatology as a hobby.[31] Callendar compiled temperature records from the late nineteenth century through the 1930s and detected a warming trend over a 50-year period. He also evaluated old measurements of atmospheric CO_2 concentrations and, although these were crude, concluded that the concentration of the gas had increased by 6% between 1880 and 1935 and that this could account for the observed warming. The increased atmospheric CO_2, he argued, was consistent with combustion of fossil fuels which had added about 150 billion tons of the gas to the atmosphere, about three quarters of which, he estimated, remained there. He published his findings in a 1938 paper "The artificial production of carbon dioxide and its influence on temperature".[32]

The opening paragraphs of Callendar's paper neatly summarize the then-accepted consensus and his own challenge to it:

> *Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climate and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale.*
> *In the following paper I hope to show that such an influence is not only possible, but is actually occurring at the present time.*

Figure 5. Guy Stewart Callendar (1898–1964). Credit: Copyright University of East Anglia, used by permission.

> *It is well known that the gas carbon dioxide has certain strong absorption bands in the infra-red region of the spectrum, and when this fact was discovered some 70 years ago it soon led to speculation on the effect which changes in the amount of the gas in the air could have on the temperature of the earth's surface. In view of the much larger quantities and absorbing power of atmospheric water vapor it was concluded that the effect of carbon dioxide was probably negligible, although certain experts, notably Svante Arrhenius and T.C. Chamberlin, dissented from this view.*

Callendar did not accept the idea that the oceans would absorb most of the CO_2 being produced by burning fossil fuels. He felt that the relatively shallow surface waters of the oceans would become rapidly saturated with CO_2 and that it would take thousands of years for the ocean water to turn over and be fully exposed to the atmosphere.

Callendar published numerous papers on climate change, infrared radiation, and the carbon cycle between 1938 and his death in 1964. His ideas, however, were not taken seriously throughout much of that time by mainstream climate scientists. But his model was surprisingly accurate, given the resources he had at hand. A 2016 analysis of Callendar's work by Anderson, Hawkins, and Jones asked, "What, then, would Callendar have projected for global temperature rise during the twentieth century if he had correctly anticipated the increase in atmospheric CO_2, as well as taking into consideration the other greenhouse gases and aerosols?" Using Callendar's equations, they showed that he would have predicted an increase in heating of "0.52 °C which is somewhat on the low side compared to the observed rise of 0.6 °C … a consequence of Callendar's model … not taking account of climate feedbacks (other than water vapour) that amplify warming. … Nevertheless, we conclude that Callendar's model, in conjunction with realistic forcing, performs remarkably well when used to project climate warming during the twentieth century". [33]

As Anderson, Hawkins, and Jones note in their paper, a source of uncertainty in Callendar's calculations was the role of the ocean as a reservoir for CO_2. Callendar believed that the oceans did not absorb all of the CO_2 being produced by burning fossil fuels, but he had not demonstrated it. That task fell to one of the seminal figures of twentieth century climate science, Roger Revelle (1909–1991), director of the Scripps Institute of Oceanography in San Diego, and his Scripps collaborator, Hans Seuss (1909–1993).

Before moving to Scripps to work with Revelle in 1956, Seuss worked at the U.S. Geological Survey in Washington, D.C. No one at the time knew whether CO_2 from burning fossil fuels was adding to the total amount of CO_2 in the atmosphere. Suess, working in collaboration with Harold Urey's laboratory at the University of Chicago, undertook a study of the concentration of ^{14}C in wood harvested in the early 1950s compared to wood from the nineteenth century, prior to the advent of the industrial revolution. ^{14}C is continuously being produced in the atmosphere by cosmic rays interacting with ^{14}N. Plants absorb the ^{14}C and incorporate it into their tissues. Because ^{14}C has a half-life of only 5,730 years, however, fossil fuels contain an undetectable amount of the isotope. If CO_2 from burning fossil fuels were accumulating in the atmosphere, it should be reflected as a relative decrease in the amount of ^{14}C in the modern wood compared to the nineteenth century wood.

Seuss' work showed that this was, indeed, the case. The ^{14}C concentrations in four nineteenth century wood samples varied only slightly, not more than 0.12%, Seuss reported. By contrast, results for the modern wood "showed marked variations, always in the direction of a lower ^{14}C content," suggesting to Seuss "relatively large local variations of CO_2 in the atmosphere derived from industrial coal combustion".[34]

At Scripps, Revelle and Seuss worked to determine the average lifetime of a CO_2 molecule in the atmosphere. Their 1957 paper, "Carbon Dioxide Exchange Between the Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 during the Past Decades," in a sense, marks the beginning of the modern age of climate science. The paper's abstract concisely summarizes the situation humans faced:

> *From a comparison of C^{14}/C^{12} and C^{13}/C^{12} ratios in wood and in marine material and from a slight decrease of the C^{14} concentration in terrestrial plants over the past 50 years it can be concluded that the average lifetime of a CO_2 molecule in the atmosphere before it is dissolved into the sea is of the order of 10 years. This means 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.*
> *The increase in atmospheric CO_2 from this cause is at present small but may become significant during future decades if industrial fuel combustion continues to rise exponentially.*[35]

Revelle had studied ocean chemistry throughout his career. He realized that absorption of CO_2 by sea water was a complex process buffered by the various species the molecule adopts when it goes into solution—carbonate ion (CO_3^{2-}), bicarbonate ion (HCO_3^-), and protonated carbonic acid ($H_3CO_3^+$)—and that the combination of dissociation constants limits how fast CO_2 can enter the ocean.

Revelle and Seuss were very aware of the implications of their work. They pointed out in their paper that the United Nations had estimated in 1955 that during the first decade of the 21st century fossil fuel combustion could produce CO_2 equal to 20% of that then in the atmosphere, which they estimated was something like two orders of magnitude greater than the rate of CO_2 production from volcanoes. The scientists famously wrote:

> *Thus 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.*

THE KEELING CURVE

Revelle and Seuss concluded their paper with a focus on some of what still needed to be understood to know whether humans were changing earth's climate:

> *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.*

The opportunity did indeed exist and Revelle would set in motion a profoundly important set of measurements to answer what seemed to be a fundamental question: Was the concentration of atmospheric CO_2 increasing because of use of fossil fuels?

In fact, an even more fundamental question needed to be answered: What was the atmospheric concentration of CO_2? The literature stated that the concentration was about 300 ppm by volume, but published values ranged from 250 to 550 ppm. Atmospheric scientists had even proposed using CO_2 concentrations as tags to track different air masses.[36]

Revelle was one of the founders of the International Geophysical Year (IGY) in 1957–58, an international effort involving 67 countries collaborating to make geophysical measurements over an 18-month period in 11 earth sciences, including meteorology and oceanography. Revelle hired a young California Institute of Technology postdoc, Charles David Keeling (1928–2005), to nail down the atmospheric concentration of CO_2 and monitor it over time to establish whether humans were changing the composition of Earth's atmosphere.

Keeling was an ideal choice for the work. He had received his Ph.D. in chemistry with a minor in geology from Northwestern University in 1953. His thesis had been in polymer chemistry and he had received job offers from a number of chemical companies on the East Coast, which, to his thesis advisor's consternation, he had turned down. In a charming 1994 extended autobiographical sketch,[37] Keeling wrote: "I had trouble seeing the future this way. I wrote letters offering my services as a Ph.D. chemist exclusively to geology departments west of the North American continental divide. In general, I received back polite declining letters, but I got two offers." He accepted one of them, an invitation from Harrison Brown (1917–1986) to become his first postdoctoral fellow in the newly established geochemistry department at Caltech.

At Caltech, Keeling developed instrumentation and carried out field observations to test an idea of Brown's: that the concentration of carbonate in ground water could be estimated by assuming that the water is in equilibrium with both limestone ($CaCO_3$) and atmospheric CO_2. He did the field work in the pristine environment of Big Sur on the central California coast. Keeling quickly discovered that the water in the stream he was monitoring was supersaturated with CO_2 and therefore not amenable to Brown's equilibrium hypothesis. He focused his attention on measurements of CO_2 in air because they showed an intriguing diurnal pattern: the air contained more CO_2 at night than during the day and the $^{13}C/^{12}C$ ratios in night and day air suggested that, during the day, plants at some sites reabsorbed CO_2 previously released into the air locally the night before. He also found that air in the afternoon always had nearly the same amount of CO_2, about 310 ppm, while concentrations at night were quite variable and always higher than during the day.

Keeling's studies eventually resulted in job offers from the Weather Bureau in Washington, D.C., and from Revelle at Scripps. Once again, he chose the west and work in open spaces to the east and a cramped basement office. He moved to Scripps in August 1956.

In the year leading up to the advent of the IGY in July 1957, Keeling established CO_2 monitoring stations at the weather observatory on Mauna Loa in Hawaii at an altitude of about 3,000 meters and at a U.S. weather station on the coast of Antarctica. The measurements were made with a highly precise, continuously recording infrared gas analyzer. Keeling had insisted on instrumentation with a precision of 0.1 ppm, which some critics thought unnecessary as they anticipated that atmospheric CO_2 concentrations would be highly variable.

A number of issues arose at Mauna Loa in the fall of 1957 that prevented data from being collected. Data collected in 1958 were somewhat patchy due to electrical outages and other issues, but a clear trend was evident: CO_2 concentration increased from January until May and then

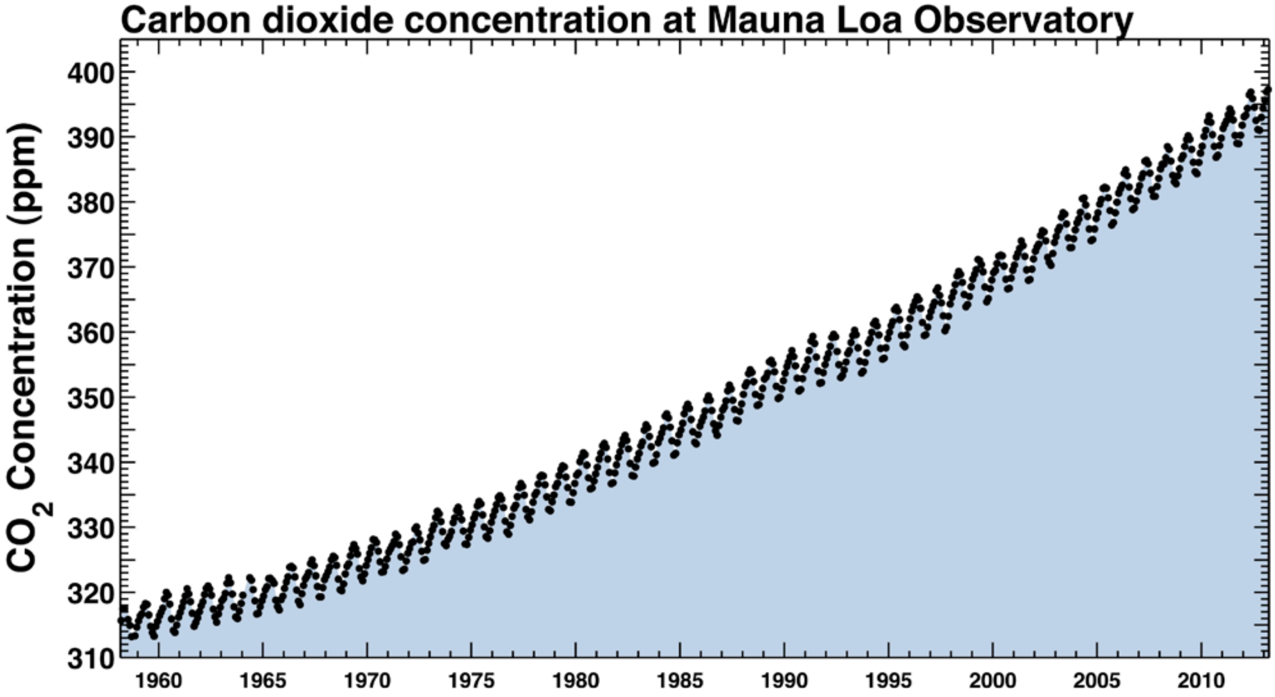


Figure 6. The Keeling Curve through 2019. Courtesy Ralph Keeling, Scripps Institute of Oceanography.

began a steady decrease that lasted until late September when the trend reversed and the concentration began to increase once again. The variation was not insignificant, on the order of 6 ppm from the summer peak to the winter minimum. As Keeling writes: “The maximum concentration at Mauna Loa occurred just before the plants in temperate and boreal regions put on new leaves. At Mauna Loa the regular season pattern almost exactly repeated itself during the second year of measurements. … We were witnessing for the first time nature’s withdrawing CO_2 from the air for plant growth during the summer and returning it each succeeding winter.”

One other trend was immediately clear from the data: the atmospheric concentration of CO_2 was steadily increasing at a rate of 0.7 ppm per year.[38] Human beings, through their ravenous thirst for energy, were slowly but surely changing the chemical makeup of the atmosphere.

Keeling would continue measuring CO_2 at Mauna Loa for the remainder of his career, despite regular threats by various government agencies to cut his funding. Since Keeling’s death in 2005, the work has been supervised by Ralph Keeling, one of Keeling’s five children, who is the principal investigator for the Scripps Atmospheric Oxygen Research Group and the director of the Scripps CO_2 Program. The sawtooth, steadily rising plot of the CO_2 data is now known as the “Keeling Curve,” and has been called by many the single most important environmental data set of the twentieth century. On May 9, 2013, the CO_2 concentration on Mauna Loa passed 400 ppm for the first time, a dire milestone in human history.[39] In the long quest to understand why earth’s temperature is what it is and whether human beings could affect earth’s climate, two things were now clear: CO_2 is a potent greenhouse gas and burning fossil fuels was inexorably increasing its concentration in earth’s atmosphere. One critical question remained: was Earth’s climate heating up?

THE HOCKEY STICK

Accurate thermometer readings of Earth’s temperature extend back only to the 1880s. In the 1930s, Callendar believed that he had detected a slight increase in Earth’s temperature over the 50-year period covered by that temperature record. Many critics thought that Callendar was simply wrong in this conclusion. Others argued that, even if there had been an increase, it was part off the natural fluctuations one would expect of Earth’s complex climate system.

By the 1970s, the temperature record suggested a slight cooling trend over the previous several decades, and many observers declared that concerns about the buildup of CO_2 in the atmosphere were overblown. In 1975, Wallace Broecker (1931–2019), a distinguished climate scientist at Columbia University’s Lamont-Doherty Earth Observatory, published what would come to be recognized as a groundbreaking paper in *Science*, “Climate Change: Are We on the Brink of a Pronounced Global Warming?” that strongly challenged this view. Broecker wrote:

> *The fact that the mean global temperature has been falling over the past several decades has led observers to discount the warming effect of CO_2 produced by the burning of chemical fuels. In this report I present an argument to show that this complacency may not be warranted. It is possible that we are on the brink of a several-decades-long period of rapid warming. Briefly, the argument runs as follows. The ^{18}O record in the Greenland ice core strongly suggests that the present cooling is one of a long series of similar natural climatic fluctuations. This cooling has, over the last three decades, more than compensated for the warming effect produced by the CO_2 released into the atmosphere as a by-product of chemical fuel combustion. By analogy with similar events in the past, the present natural cooling will, however, bottom out over the next decade or so. Once this happens, the CO_2 effect will tend to become a significant factor and by the first decade of the next century we may experience global temperatures warmer than any in the last 1000 years.*[40]

Broecker’s paper proved to be prophetic, as global temperatures almost immediately began to climb and have continued to do so ever since. As his 2019 obituary in the *New York Times* pointed out, however, Broecker based his predictions “on a simplified model of the climate system, and he later realized … that some of his analysis had been flawed. He would later write a follow-up paper stating that, as accurate as his prediction turned out to be, ‘It was dumb luck.’”[41] Nevertheless, Broecker’s paper earned him the sobriquets “grandfather of climate science” and “father of global warming.”

Broecker’s analysis was theoretical. In his paper, he observed that, “Meteorological records of the mean global temperatures are adequate only over the last century. … From this record alone little can be said about the causes of climatic fluctuations. It is too short and may be influenced by pollution.” But was the temperature record really so inconclusive?

The National Aeronautics & Space Administration’s Goddard Institute for Space Studies (GISS) published its first global temperature analysis in 1987.[42] GISS scientist James Hansen (1941–) and coauthor Sergei Lebedeff analyzed surface air temperature data from meteorological stations from 1880–1985 and found that the temperature changes at mid- and high-latitude stations were highly correlated. "We find that meaningful global temperature change can be obtained for the past century, despite the fact that the meteorological stations are confined mainly to continental and island locations. The results indicate a global warming of about 0.5°–0.7 °C in the past century, with warming of similar magnitude in both hemispheres." They continued that a strong warming trend between 1965 and 1980 "raised the global mean temperature in 1980 and 1981 to the highest level in the period of instrumental records."

Hansen and Lebedeff updated their analysis a year later, reporting that, "Data from meteorological stations show that surface air temperatures in the 1980s are the warmest in the history of instrumental records. The four warmest years on record are all in the 1980s."[43]

On June 23, 1988, Hansen and other climate scientists testified on the possibility of anthropogenic climate change before the Senate Committee on Energy & Natural Resources. Hansen was more emphatic than any other witness, stating:

> *I would like to draw three main conclusions. Number one, the earth is warmer in 1988 than at any time in the history of instrumental measurements. Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect. And number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to affect the probability of extreme events such as summer heat waves.*[44]

While stressing that global climate models needed improvement, Hansen drew particular attention to the correlation between the observed warming in the temperature record and warming predicted by computer models of the climate. "Since there is only a one percent chance of an accidental warming of this magnitude, the agreement with the expected greenhouse effect is of considerable significance," he told the committee.

Although scientists had been discussing the possibility that CO_2 from burning fossil fuels could impact Earth's climate for decades, Hansen's Senate testimony marked a turning point in the public perception of the

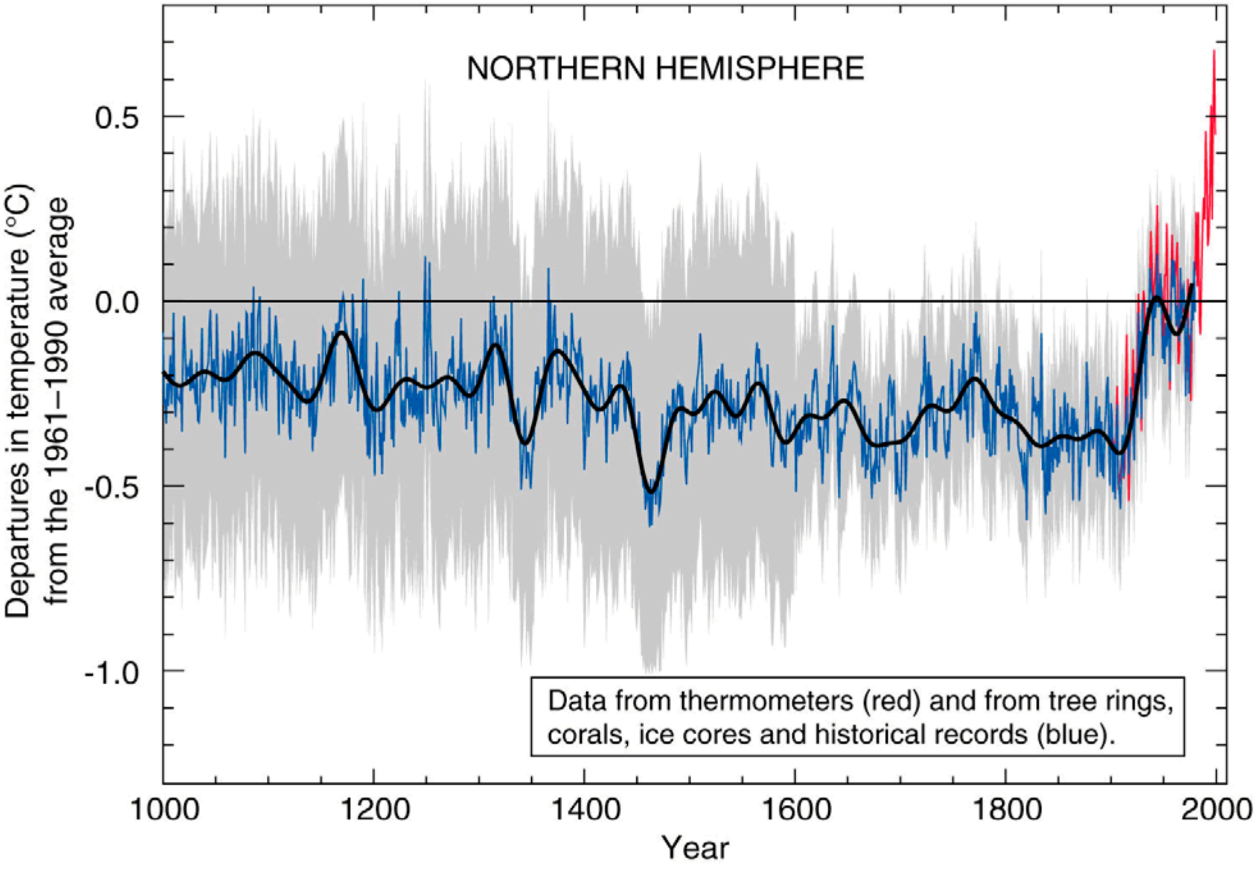


Figure 7. The Hockey Stick—time reconstructions (blue) and instrumental data (red) for Northern Hemisphere mean temperature. In both cases, the zero line corresponds to the 1902-80 calibration mean of the quantity. Courtesy Michael Mann.

issue. NASA was 99% certain, Hansen had testified, that a warming trend was occurring and that humans were responsible. The June 24, 1988, front-page story in the New York Times on Hansen's testimony was entitled "Global Warming Has Begun, Expert Tells Senate."[45]

Temperature records go back only about 140 years. Climate change skeptics insisted that the changes Hansen was seeing were not, in fact, indicative of a long-term trend. Other scientists, however, were working to extend our understanding of the temperature of the Earth over much longer time spans, over hundreds and even thousands of years into the past. The field of paleoclimatology uses indirect evidence provided by "proxy climate data"—oxygen isotope ratios from ice cores, tree rings, deep ocean sediments, corals, and other natural data—to estimate temperature changes in the past.

In 1998, Michael E. Mann and Raymond S. Bradley of the Department of Geosciences at the University of Massachusetts and Malcolm K. Hughes of the Laboratory of Tree-Ring Research at the University of Arizona published "Global-Scale Temperature Patterns and Climate Forcing over the Past Six Centuries," in which they used proxy data networks to reconstruct Earth's temperature from 1400 to the present.[46] A year later, they extended the analysis over the entire past millennium in "Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations."[47]

In his book "The Hockey Stick and the Climate Wars,"[48] Mann describes the data set that resulted from this work:

> *Despite the uncertainties, my coauthors and I were able to draw certain important conclusions. We deduced that there had been a decline in temperature from a period running from the eleventh century through the fourteenth—a period sometimes referred to as the medieval warm period—into the colder Little Ice Age of the fifteenth to the nineteenth centuries. Think of this as the shaft of a hockey stick laid on its back. This long-term gradual decline in temperature was followed by an abrupt upturn in temperatures over the past century. Think of this as the blade.*

Mann and his colleagues used actual temperature measurements to fill in the plot from 1980 through 1999 as relatively few long-term proxy records had been updated since the early 1980s.

"Thus was born the hockey stick—though the term itself was actually coined later by a colleague in Prince-

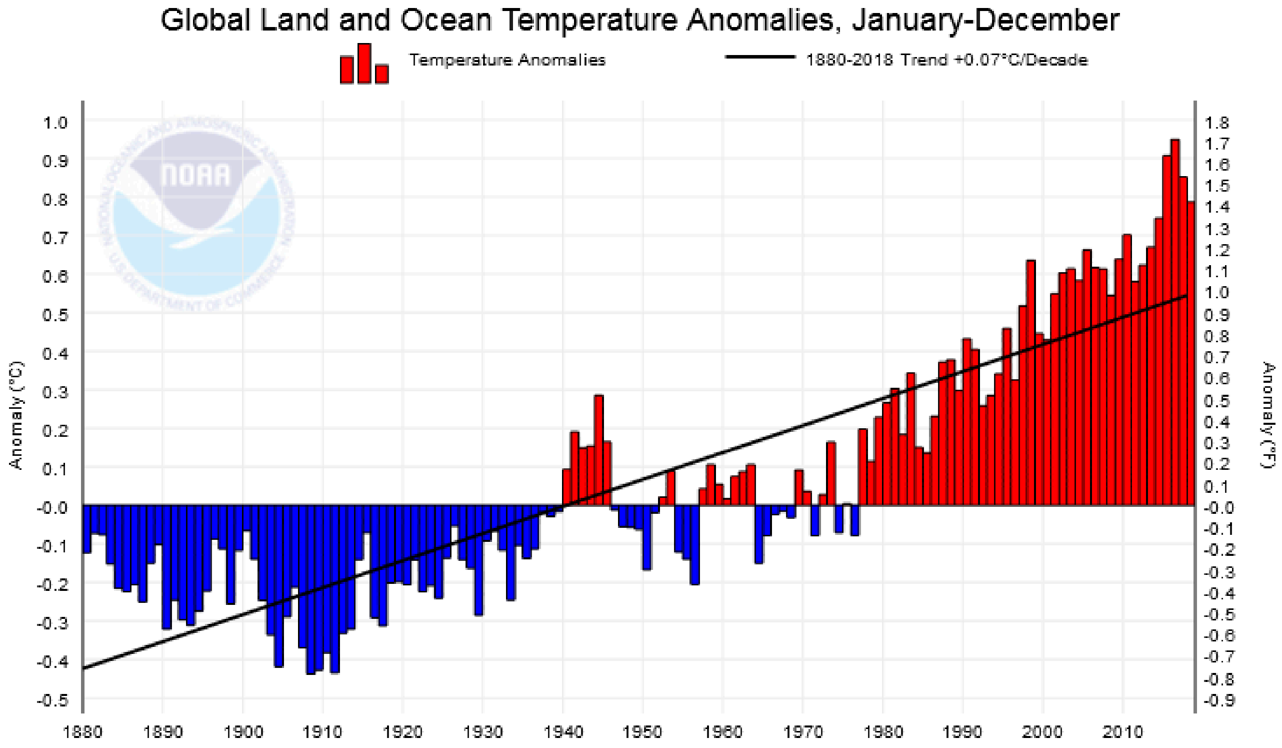


Figure 8. Graph of average annual global temperatures since 1880 compared to the long-term average (1901-2000). The zero line represents the long-term average temperature for the whole planet; blue and red bars show the difference above or below average for each year. National Oceanic & Atmospheric Administration.

ton," Mann writes. "It didn't take long for the hockey stick to become a central icon in the climate change debate. It told an easily understood story with a simple picture that a sharp and highly unusual rise in atmospheric warming was occurring on Earth."

CONCLUSION

For 20 years, the hockey stick has drawn the scorn of climate change deniers. They insisted the blade of the hockey stick flattened in the 2000s as Earth's temperature increase seemed to pause, albeit at an elevated level. Then the temperature began to increase again around 2010 and the blade still looks very much like a blade.

When James Hansen testified before the Senate, he pointed out that the 1980s were the warmest years in the historical record.

Those days are long gone. According to NOAA, 18 of the 19 warmest years on record have occurred in the twenty first century—the only outlier is 1998—and the past five years have been the warmest ever (Figure 8).[49] Ocean levels are rising because the oceans are being warmed and are expanding and the Greenland and Antarctic icecaps are melting; oceans are also acidifying as they absorb excess CO_2. The large-scale geophysical experiment that Revelle and Seuss pointed to in 1957 is now well underway and climate change denial is both intellectually indefensible and morally reprehensible.

Any notion of a sustainable economy in the 21st century must center on energy, specifically weaning humanity from fossil fuels. Other Earth resources are under stress and must also be attended to, but Earth's climate is not just under stress. It is careening toward catastrophe. A sustainable world requires many adaptations, but chief among them is for humans to learn to power civilization with energy sources other than fossil fuels, primarily the Sun. Humans will have to learn how to live off the sun in real time.

There is much work left to be done before Earth's climate is fully understood, but two hundred years of path-breaking research has made our dilemma clear.

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