# Chapter 15. Greenhouse Giants

**The greenhouse effect** is described in Chapter 10 on the Goldilocks planets: Mars, Venus, and Earth. The greenhouse effect was understood qualitatively two centuries ago; there are numerous references to it in the literature during the first half of the 19th century. Joseph Fourier, a French mathematician and physicist, wrote[1] in 1824: "The temperature [of Earth's surface] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in re-passing into the air when converted into non-luminous heat." Fourier was describing the natural greenhouse effect. Sunlight readily penetrates Earth's atmosphere and heats the surface. In contrast, heat (infrared radiation) from Earth's surface is largely absorbed by the atmosphere, with some of this energy radiated back to the surface. Thus, the atmosphere acts like a blanket,[I] additionally warming Earth's surface.

If Earth had no atmosphere, and absorbed 70 percent of incident sunlight as it does today, its temperature would need to be -18°C to emit enough infrared radiation to yield energy balance. But the blanket of greenhouse gases forces Earth to warm to a point that the radiation emitted to space equals the absorbed solar energy. This results in the actual surface temperature of +15°C. So, the natural greenhouse effect on Earth is 33°C, which is about 60°F. Absent the greenhouse effect, Earth would be uninhabitably cold. Any human-made increase of global temperature, called "global warming," is surely small compared with this natural greenhouse effect. Can the much smaller human-made effect really be important? That issue has a long history.

**Eunice Foote,** an American amateur scientist, inventor, and women's rights campaigner[II] is the first person known to have made climate-specific experiments with individual gases. She filled glass cylinders with each gas and measured temperature change of the gases when the tubes were placed in sunlight or in the shade. Her 1856 paper,[2] *Circumstances affecting the Heat of the Sun's Rays*, begins "My investigations have had as their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun." She showed that a cylinder filled with moist air, and one filled with $CO_2$, warmed by tens of degrees Fahrenheit when placed in sunlight. She concluded "An atmosphere of that gas [$CO_2$] would give to our earth a high temperature; and if, as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted." Foote's conclusion, that $CO_2$ warms Earth is correct, but the mechanism is not absorption of sunlight by $CO_2$. Although $CO_2$ weakly absorbs sunlight, the effect of that absorption on surface temperature is slight.[3]

Eunice Foote (1819-1888) deserves recognition for initiating investigation of the role of individual gases in affecting Earth's temperature, for insight correctly perceiving the key role of $CO_2$ in affecting long-term climate, and for a lifetime of social and scientific contributions. Recent rediscovery of her contributions led to an incorrect assertion that she deserved credit for discovery of the infrared greenhouse effect of $CO_2$, the actual mechanism by which $CO_2$ and

[I] The blanket analogy is imperfect, as are "greenhouse" and "automobile with windows rolled up" analogies, which all include restrictions on heat transfer by other processes such as convection and conduction (Chapter 10).
[II] Eunice Foote was on the editorial committee for the 1848 Seneca Falls Convention, the first women's rights convention, and she helped prepare the proceedings for publication.

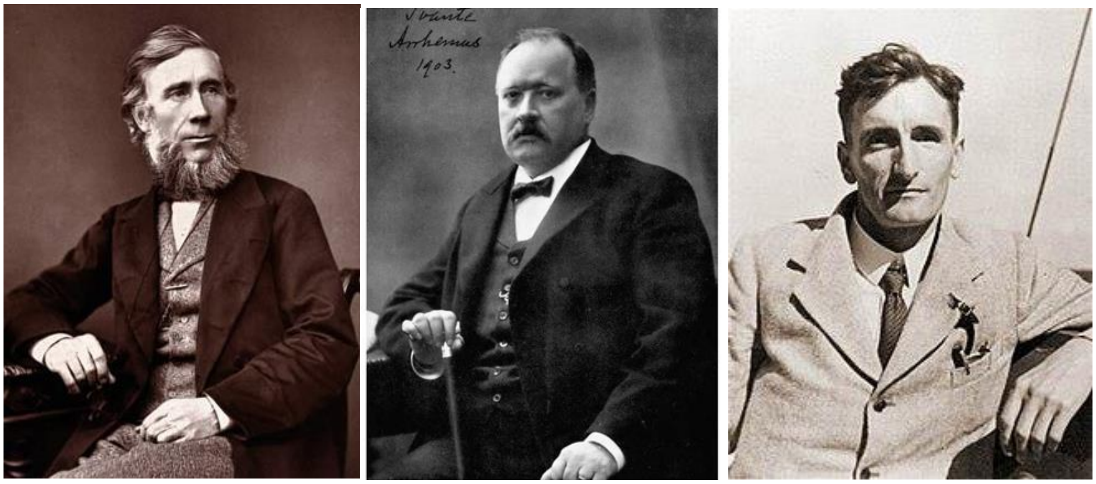


**Fig. 15.1. John Tyndall, Svante Arrhenius, and Guy Callendar**

other greenhouse gases operate.[4] Foote surely would be embarrassed by the manufactured contretemps. She deserves acclaim for her many accomplishments, but, unfortunately, no authentic photograph or portrait of her seems to have survived.

**John Tyndall, an Irish physicist,** converted qualitative statements about the greenhouse effect into quantitative science through an extensive body of laboratory data[5], and he communicated in a language accessible to everyone. Tyndall's laboratory measurements with water vapor and carbon dioxide established the experimental basis for the greenhouse effect. He realized the impact of these gases in keeping Earth's surface warm, writing (ibid. pp. 423-424):

> "This aqueous vapour is a blanket more necessary to the vegetable 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. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost. The aqueous vapour constitutes a dam, by which the temperature at the earth's surface is deepened: the dam, however, finally overflows, and we give to space all that we receive from the sun."

Tyndall's statement that greenhouse gases act as a "blanket" was elegant and useful. His other metaphor, that the dam eventually overflows to "give back to space all that we receive from the sun," refers to conservation of energy: Earth must radiate to space as much energy as it receives from the Sun. Tyndall, like Foote, had an inkling that changes of greenhouse gases may account for known climate changes during Earth's history, stating in his 1861 Bakerian lecture[6]:

> *Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. …they (greenhouse gases) constitute true causes (of climate change), the extent alone of the operation remaining doubtful.*

Tyndall was speculating about the ice ages. As required by the scientific method, he remained skeptical and sensed that something more was needed to explain the ice ages. In correspondence[7] of 1 June 1866, he stated that changes in radiative properties alone were unlikely to be the root causes of glacial periods. More than 100 years later, new data revealed that Tyndall was correct in both his original speculation and his cautionary correspondence about root causes, as we will see. Tyndall's final phrase in the quotation immediately above foreshadows the principal issue in climate science: climate sensitivity. The physics is clear, he says, increased greenhouse gases cause warming; but how much?

**Svante Arrhenius, a Swedish physicist and physical chemist,** took up Tyndall's challenge: to quantify climate sensitivity. The Sun causes maximum heating at Earth's surface because of the atmosphere's transparency to sunlight. Blanketing of heat radiation by greenhouse gases results in convection, as well as radiation, carrying energy upward to a level where heat can be radiated to space. Convection establishes a temperature gradient in Earth's atmosphere, with temperature falling off with height on average by about 6°C per kilometer of altitude.

Absorption by gases, mainly water vapor and carbon dioxide, occurs across the entire spectrum of Earth's infrared (heat) radiation, but absorption is not uniform across this wavelength range. Therefore, radiation to space arises from all altitudes in the atmosphere. On average, the altitude at which radiation to space emerges is about 5.5 km. Not surprisingly, temperature at 5.5 km altitude is close to -18°C, the temperature at which a solid body radiates the amount of energy that Earth absorbs from the Sun. The temperature difference between this altitude and the surface is about 33°C (5.5 km × 6°C/km), which is the greenhouse effect on Earth.

So how did Arrhenius obtain an estimate of the sensitivity of Earth's temperature to a change of atmospheric $CO_2$? He needed to know the change in infrared absorption as $CO_2$ amount changes. He used infrared measurements by American astronomer Samuel Langley of the full moon.[8] The amount of $CO_2$ traversed by moonlight decreased as the moon rose in the sky. Arrhenius saw that $CO_2$ absorption did not change linearly with $CO_2$ amount. Instead, a geometric increase of $CO_2$ was needed to yield a linear increase of absorption. In other words, an equal increase of absorption occurs with each doubling of $CO_2$ amount. Arrhenius then made elaborate energy balance calculations to estimate that doubling atmospheric $CO_2$ would cause a warming between 4.9°C and 6.1°C, depending on latitude and season. He later revised his analysis[9] to a global climate sensitivity of 4°C for doubled $CO_2$ and 8°C for quadrupled $CO_2$.

Knut Angstrom, another Swedish scientist, disputed Arrhenius, arguing that $CO_2$ absorption bands are "saturated," i.e., they absorb nearly all the radiation within narrow spectral regions and negligible energy elsewhere.[10] Therefore, he said, additional $CO_2$ would have little effect. In fact, Arrhenius' evaluation accounted for band saturation. Even at wavelengths where absorption is saturated at Earth's surface, absorption is not saturated at higher levels in the atmosphere. Radiation escape to space occurs at the level above which there is little chance of absorption. Thus, added $CO_2$ causes the "emission to space level" to be at greater altitude, and because it is colder at higher levels, radiation to space is reduced. The resulting energy imbalance – more energy coming in than going out – causes global warming to restore energy balance.

Arrhenius realized that fossil fuel burning would cause atmospheric $CO_2$ to increase, but he thought it would take several centuries before warming would be significant. This conclusion was due partly to his estimate that 5/6 of the emissions would be taken up quickly by the ocean. Arrhenius saw global warming as being beneficial: "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 more abundant crops than at present, for the benefit of rapidly propagating mankind."

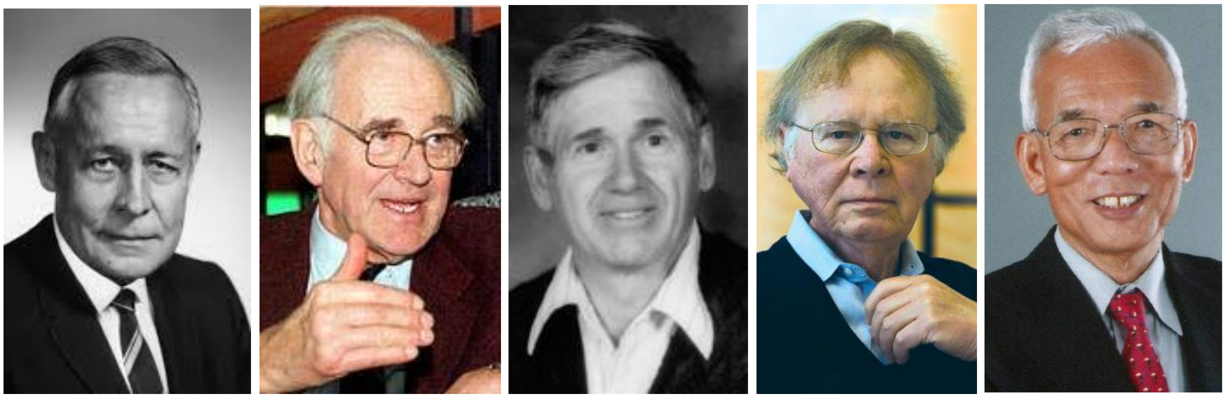

**Fig. 15.2. Roger Revelle, Bert Bolin, David Keeling, Wally Broecker, Syukuro Manabe**

As long as climate effects of $CO_2$ remained theoretical, global warming would not be a concern of the public. Broader interest in the topic would require evidence of ongoing global change.

**Guy S. Callendar,** a meticulous British engineer, found such evidence in 1938,[11] but his data for global temperature change and atmospheric $CO_2$ would raise new questions. Callendar used records from 147 weather stations around the world to estimate that global temperature increased about 0.3°C between 1880 and the early 1930s. By itself, this warming[12] seemed consistent with the expected effect of increasing $CO_2$. However, during the next 40 years, as human emissions of $CO_2$ from fossil fuel burning increased by a factor of five, almost no further warming occurred. Something else had to be occurring, something that we are only beginning to quantify and understand today.

Callendar's engineering expertise allowed him to discriminate among disparate attempts to measure $CO_2$. He concluded that $CO_2$ had increased over the prior 50 years, but here, too, the results were puzzling: the $CO_2$ increase was larger than he expected. Like Arrhenius, Callendar believed that most of the $CO_2$ emitted in burning fossil fuels should have been taken up by the ocean. The mystery survived until 1957, the International Geophysical Year (IGY), which ignited an explosion of understanding of geophysical processes.[13]

**Roger Revelle and Hans Suess** altered the course of the $CO_2$ climate story in 1957 with a paper[14] in *Tellus*. The abstract of the paper is misleading, as it states "…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 ocean." The crucial insight from their analysis, in fact, was that $CO_2$ added to the air by fossil fuel burning has a much more difficult time getting into the ocean than prior analyses suggested. Ocean chemistry is a complex soup. Technically, ocean water is a buffered solution that resists a change in acidity. This buffering reduces the net flux of fossil fuel $CO_2$ into the ocean.

Bert Bolin and Erik Eriksson soon realized that Revelle and Suess made an approximation for ocean mixing that caused a severe underestimate of the importance of the buffering effect.[15] Revelle and Suess treated the entire ocean as a well-mixed volume. It is worth clarifying why that is a bad approximation. Ocean mixing, we will find later, is a crucial physical phenomenon

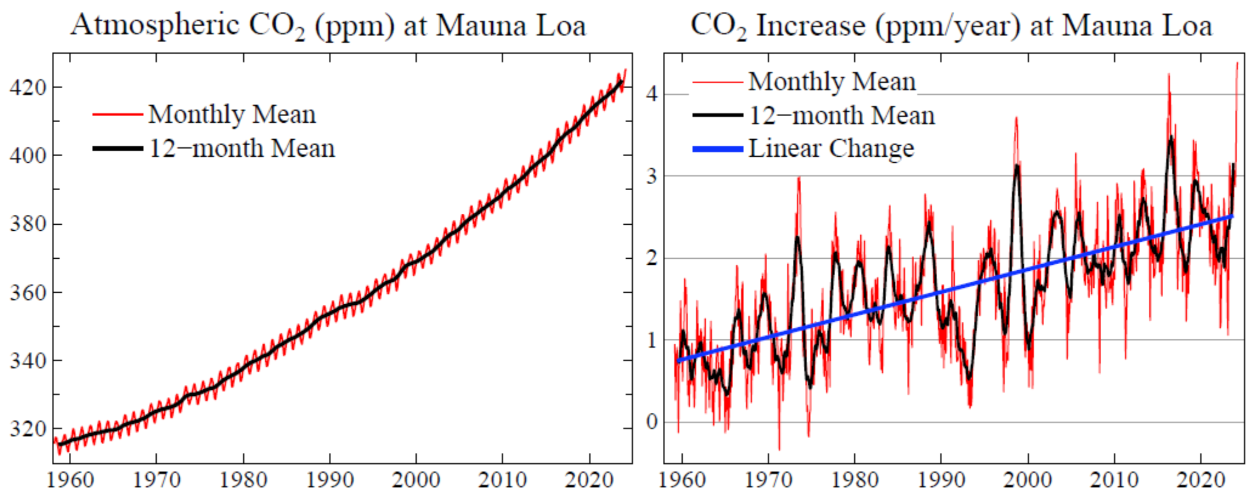

**Fig. 15.3. Keeling curve: $CO_2$ at Mauna Loa, Hawaii, including 12-month running mean.**

affecting not only ocean chemistry, but also the response time of climate to human perturbations, as well as the strategies and chances of success of human efforts to avoid climate catastrophe.

The ocean can be thought of as consisting of two layers. The upper 100 meters of the ocean is well-mixed, stirred by the wind. The remainder of the ocean, with average depth 4 kilometers (2½ miles) is mixed with the surface layer by the ocean's overturning circulation on time scales of centuries to millennia. The combination of chemical buffering and slow exchange between the mixed layer and deeper ocean causes fossil fuel $CO_2$ to have a long lifetime in the air. It requires centuries and millennia for human-made $CO_2$ to be taken up by the ocean.

Revelle's insight was revealed in his summary statement: "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." Revelle saw an opportunity to study geophysical processes, but he also warned of future perils. He speculated that in the 21st century the greenhouse effect might exert "a violent effect on the earth's climate" (quote in 28 May 1956 *Time Magazine*). He thought the temperature rise might eventually melt the Greenland and Antarctic ice sheets, which would raise sea levels enough to flood coastlines, and in 1957 he told a congressional committee that the greenhouse effect might someday turn Southern California and Texas into deserts.

The 1957-58 International Geophysical Year[III] provided an opportunity to obtain important data. Revelle seized that opportunity. Using funds from the United States Committee for the IGY and other sources, he hired a young post-doc from the California Institute of Technology to come to the Scripps Institution of Oceanography to carry out a world survey of atmospheric $CO_2$.

**Charles David ("Dave") Keeling** proved to have the dogged determination needed for that job. Keeling's task was to find instrumentation capable of accuracy an order of magnitude better than prior work. He had to hunt down all potential significant errors in the instrument. He succeeded. Keeling's precise data yielded a beautiful curve for atmospheric $CO_2$ amount as a function of time, described today as the "Keeling curve." Keeling intuited, brilliantly, that data from two carefully selected points on Earth would be very informative. The places Keeling picked were a volcanic mountain in Hawaii and the South Pole. The Hawaii site sampled air arriving from the

[III] The International Geophysical Year extended 18 months, from July 1957 through December 1958.

Pacific Ocean, largely free of local pollution. The South Pole site was even more isolated, yet even there it was necessary to be aware of emissions from local machinery.

The annual cycle in the Keeling curve is easy to understand. Atmospheric $CO_2$ at Mauna Loa decreases in the spring and summer as growing vegetation in the Northern Hemisphere sucks $CO_2$ from the air, and $CO_2$ increases in the fall and winter as plant litter decomposes. As the data record passed the 12-month mark, a long-term $CO_2$ increase became apparent. Later this increase was proven to be largely from fossil fuel burning. At the South Pole the seasonal variation was smaller and the long-term $CO_2$ growth trailed the rise in the Northern Hemisphere. These were understandable consequences of the mixing time of the global atmosphere and the fact that fossil fuel use and vegetation growth were larger in the Northern Hemisphere. The annual increase of $CO_2$ is now a factor of three greater than when Keeling initiated his measurements.

**Wally Broecker and Syukuro Manabe** led the scientific community to fundamental advances in defining the climate change story in the years following the IGY. The breadth of Broecker's expertise was unrivalled, as he was the acknowledged authority in ocean geochemistry while also among the world leaders in paleoclimate studies. Broecker's intellectual depth, curiosity, and outgoing personality were effective in spurring the scientific community to relevant studies.[IV] Manabe was the authority on the radiative processes that drive climate change. He developed simplified models to study climate processes and, together with oceanographer Kirk Bryan, the most comprehensive atmosphere-ocean climate models.

In 1965 the President's Science Advisory Committee (PSAC) delivered a report[16] on pollution to President Lyndon Johnson. Johnson signed a statement accepting the report, decrying air, soil and water pollution, and saying that he would give priority to increasing the number of scientists and engineers working on pollution control. It is highly unlikely that he read the report in detail. Perhaps he was even unaware that one of the 11 pollution subpanels was on $CO_2$ and climate.

The $CO_2$ subpanel was blue ribbon. Chaired by Roger Revelle, it included Wally Broecker, Harmon Craig, Dave Keeling and Joe Smagorinsky. Their 23-page report[17] concludes: "The climatic changes that may be produced by the increased $CO_2$ content could be deleterious from the point of view of human beings." Without mention of possible efforts to limit the $CO_2$ increase, their next sentence continues: "The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored." They suggest deliberate change of Earth's albedo (reflectivity), noting: "Such a change in albedo could be brought about, for example by spreading very small reflecting particles over large oceanic areas." Further: "An early development of the needed technology might have other uses, for example in inhibiting the formation of hurricanes in tropical oceanic regions."

How should we interpret this instant leap to geoengineering countermeasures? Was the purpose to draw attention to the seriousness of human-made global warming? Was this prescient recognition of the unwillingness of governments to constrain fossil fuel emissions? We will return to the subject of deliberate countermeasures to global warming in due course.

[IV] Wally was the great grandfather of global warming and the straw that stirred the climate change drink. I regret that I did not finish this book in time to see his reaction to it.

**Syukuro Manabe and his colleagues**, by 1969, had made major advances in modeling and understanding of the global ocean-atmosphere system. Manabe, Smagorinsky, and Strickler[18] presented a comprehensive general circulation model of the atmosphere with a hydrologic cycle. Manabe and Richard Wetherald[19] used a one-dimensional climate model to explore processes affecting climate change and climate sensitivity. Manabe and Kirk Bryan[20] published the first results from a coupled ocean-atmosphere general circulation model.

Manabe had a decade head-start on our climate modeling at GISS. Furthermore, the computer capacity of his lab, NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) located at Princeton University, was much greater than ours. GFDL is NOAA's premier climate modeling laboratory, so they obtain continual improvements to their computing capability. Computer power, the research community seemed to agree, was the critical need to improve the realism of climate models. Dividing the world up in Texas-sized chunks, as we did, was a questionable approach. Was there even a useful role for our modeling approach?

**We were in trouble at GISS,** and I knew it. Our computer was old. We had little funding to cover salaries, and none to purchase a new computer. Jastrow's gambit was to use Livermore's supercomputers. He would have us compete with the big modeling centers, GFDL and NCAR. My interest, though, was a different approach, the coarse resolution global modeling that I had proposed to Rasool. My objective was a model we could run for long time scales and obtain results even on an old computer. That's the model Gary and the rest of us worked on. Given our tiny group, it was unlikely that we could successfully pursue both Jastrow's "Farmers' Forecast" and our long-term climate topic. We seemed to be headed for a showdown.

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[1] Fourier J. Remarques generals sur les temperatures du globe terrestre et des espaces planetaires. *Annal Chim Phys* **27**, 136-67, 1824.

[2] Foote E. Circumstances affecting the heat of the Sun's rays. *Amer J Sci Arts* **22**, 382-3, 1856

[3] Greater $CO_2$ slightly increases absorption of sunlight by Earth, but it reduces sunlight reaching the ground. The efficacy of a climate forcing is greatest for forcings near Earth's surface (Hansen J, Sato M, Ruedy R. Radiative forcing and climate response, *J Geophys Res* **102**, 6831-64, 1997; Efficacy of climate forcings. *J Geophys Res* **110**, D18104, 2005). Calculation of the net effect on the temperature profile of $CO_2$ sunlight absorption requires proper treatment of moist and dry convection in a 3-D world. The effect is small and has not engendered careful study.

[4] The Royal Society, perhaps in penitence for the long history of male chauvinism in science, published an article (Jackson R: Eunice Foote, John Tyndall and a question of priority, *Notes and Records of the Royal Society* **74**, 105-18, 2020) full of innuendos of a male conspiracy to rob Foote of rightful priority for discovery of the infrared greenhouse effect of $CO_2$. In fact, she did not obtain data useful for that purpose. Her data for measurements in sunlight, and a control in "the shade," included effects of diffuse sunlight, thermal emission, and other factors, making it indecipherable for that purpose. The Jackson article was preceded by and followed by articles in popular media with accusations, such as: McNeill L. This lady scientist defined the greenhouse effect but didn't get the credit, because sexism, *Smithsonian Magazine*, 5 December 2016. Foote did not pretend to investigate the actual infrared greenhouse effect; there is no merit in so mischaracterizing her impressive scientific contributions.

[5] Tyndall J. *Radiant Heat*, Longmans, Green, and Co., London, 1872 (available https://archive.org/stream/contributionsto01tyndgoog#page/n441/mode/1up).

[6] Tyndall J. On the absorption and radiation of heat by gases and vapours. *Phil Mag* **22**, 169-94, 273-85, 1861

[7] Fleming JR. Historical perspectives on climate change, Oxford University Press, 1998; quoted by Hulme, M., On the origin of 'the greenhouse effect': John Tyndall's 1859 interrogation of nature. *Weather* **64**, 121-3, 2009

[8] Arrhenius S. On the influence of carbonic acid in the air upon the temperature of the ground. *Phil Mag (Series 5)* **41 (251)**, 237-76, 1896

[9] Arrhenius S. *Worlds in the Making: The Evolution of the Universe*, Harper & Brothers; freely available: https://archive.org/details/worldsinmakingev00arrhuoft, 1908

[10] Angstrom K. Ueber die bedeutung des wasserdampfes und der kohlensaure bei der absorption der Erdatmosphare. *Annalen der Physik* **308**, 720-32, 1900

[11] Callendar GS. The artificial production of carbon dioxide and its influence on temperature. *Quar J Roy Meteorol Soc* **64**, 223-40, 1938

[12] Callendar, like Arrhenius, thought the warming was beneficial: "…increases of mean temperature would be important at the northern margin of cultivation, and the growth of favourably situated plants is directly proportional to the carbon dioxide pressure (Brown and Escombe, *Proc Roy Soc B* **76**, 1905). In any case the return of the deadly glaciers should be delayed indefinitely."

[13] Origin of IGY traces to a meeting of scientists, including Sydney Chapman and Lloyd Berkner, in Van Allen's living room in March 1950 (Forestner A. *James Van Allen: The First Eight Billion Miles*, p. 124, Univ. Iowa Press, 322 pp., 2007). They suggested it was time for a worldwide Geophysical Year, in part due to recent advances in rocketry, radar, and computing. Berkner and Chapman obtained approval of the International Council of Scientific Unions for an IGY of 18 months, July 1957 through December 1958, coinciding with the next maximum of solar activity. In July 1955 President Eisenhower announced that the U.S. would launch small Earth circling satellites as part of the IGY, and a few days later the Soviet Union announced plans to also launch a satellite. Sputnik 1, the first artificial Earth satellite, was launched on October 4, 1957. (I was a junior in high school then. Within months, after several failed launch attempts, the United States had its own satellites. The space race was on. NASA was formed on 29 July 1958. Thousands of young people received NASA funding for graduate study, including Andy Lacis, Larry Travis and me.) IGY achievements, including discovery of the Van Allen radiation belts and verification of a system of submarine mid-ocean ridges encircling the globe, helped provide an overview of global geophysical phenomena.

[14] Revelle R, Suess HE. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric $CO_2$ during the past decades. *Tellus* **IX** 18-27, 1957

[15] Bolin B, Eriksson E. Changes in the carbon dioxide content of the atmosphere and sea due to fossil fuel combustion, in *The Atmosphere and Sea in Motion*, Rossby Memorial Volume, Rockefeller Institute Press, 1959

[16] PSAC. *Restoring the Quality of Our Environment*, Report of Environmental Pollution Panel, White House, 1965

[17] Revelle R, *et al*. Appendix Y4 to PSAC: Atmospheric Carbon Dioxide, pp. 111-33, 1965

[18] Manabe S, Smagorinsky J, Strickler RF. Simulated climatology of a general circulation model with a hydrologic cycle. *Mon Wea Rev* **93**, 769-98, 1967

[19] Manabe S, Wetherald RT. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J Atmos Sci* **24**, 241-59, 1967

[20] Manabe S, Bryan K. Climate calculation with a combined ocean-atmosphere model, *J Atmos Sci* **26**, 786-9, 1969