Chapter 15. Greenhouse Giants

The greenhouse effect was described in Chapter 10 in comparing the Goldilocks planets: Venus, Mars and Earth. The greenhouse effect was understood qualitatively two centuries ago, as 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, heating 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,[2] additionally warming Earth’s surface.

If Earth had no atmosphere, and still 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. That 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, usually called ‘global warming,’ is surely small compared with this natural greenhouse effect. Can the smaller human-made effect really be important? That question has a long history.

Eunice Foote, an American amateur scientist, inventor, and women’s rights campaigner[3] is the first person known to have made climate-specific experiments with individual gases. She filled glass cylinders with each gas, including carbon dioxide and moist air, and measured temperature changes of the gases when the tubes were placed in the sun and in the shade.

Her 1856 paper,[4] *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 especially 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 even though absorption of sunlight by CO_2 has a negligible effect on Earth’s surface temperature; indeed, it may even cause a slight global cooling of surface air. Absorption of sunlight by CO_2 reduces solar heating of the ground and surface air, where the heating has a greater “efficacy” in raising surface air temperature.[5]

Eunice Foote (1819-1888) deserves recognition for initiating investigation of individual gases, as the first scientist to infer that carbon dioxide and water vapor are important gases affecting Earth’s temperature, and as recognizing the potential importance of CO_2 in affecting long-term climate change.[6] Unfortunately, no photograph or portrait of Foote seems to have survived.

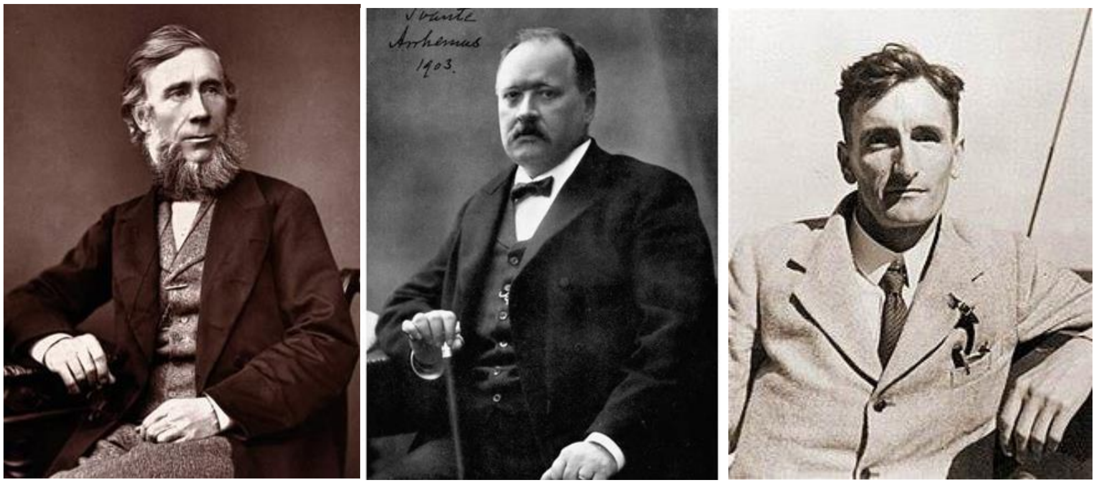

Fig. 15.1. John Tyndall, Svante Arrhenius, and Guy Callendar

John Tyndall, an Irish physicist, is the father of the greenhouse effect, in the sense that he made the greatest contributions to the science. Tyndall converted qualitative statements of Fourier and others into quantitative science through an impressive body of research and laboratory data[7], and he communicated his understanding in a language accessible to everyone.

Tyndall had keen physical insight and made fundamental laboratory measurements with water vapor and carbon dioxide that 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 vapor 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 wrote with elegance about the atmosphere acting as a "blanket." His other metaphor, that the dam must eventually overflow and "give back to space all that we receive from the sun," refers to the most fundamental concept, conservation of energy: Earth must eventually radiate to space the same amount of energy that 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[8]:

> *Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. However this may be, the facts above cited remain; 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 of his own proposition. In correspondence[9] of 1 June 1866, he stated that changes in radiative properties alone were unlikely to be the root causes of glacial periods. Data that became available more than 100 years later would reveal 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 will cause warming; but the question remains, how much?

Svante Arrhenius, a Swedish physicist and physical chemist, took up Tyndall's challenge: to quantify how sensitive global temperature is to a specified climate forcing (see Chapter 10).

The Sun causes maximum heating at Earth's surface, because of the atmosphere's transparency to sunlight. Because of the blanketing of heat radiation by greenhouse gases, convection as well as radiation carries the energy upward to a level at which the energy can be radiated to space. Convection, rising and sinking air, 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 spectrum. Therefore, radiation to space arises from all altitudes in the atmosphere. On average the altitude from which the energy emerges is about 5.5 km. Not surprisingly, the temperature at this altitude is close to -18°C, the temperature that a solid body requires in order to radiate the 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 present 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. [10] 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. A geometric increase of CO_2 is required to yield a linear increase of absorption. In other words, an equal increase of absorption occurs with each doubling of CO_2 amount. He then made elaborate energy balance calculations, which required a year of his time. From these he estimated that doubling atmospheric CO_2 would cause a warming between 4.9°C and 6.1°C, depending on latitude and season. This first estimate of 'climate sensitivity' suffered from errors in Langley's measurement and other approximations in a complex calculation.

Arrhenius later improved upon his first analysis, obtaining a global climate sensitivity[11] of 4°C for doubled CO_2 and 8°C for quadrupled CO_2. This improved estimate of Arrhenius turned out to be within the range found in modern studies, as I discuss further below.

Knut Angstrom, another Swedish scientist, disputed Arrhenius in 1900, arguing that CO_2 absorption bands are 'saturated', i.e., they absorb nearly all the radiation within narrow spectral regions and negligible energy elsewhere.[12] Therefore additional CO_2 would have little effect.

Band saturation actually was accounted for in Arrhenius' empirical evaluation. Saturation is the reason that the warming effect is not linear in CO_2 amount. Even at wavelengths where the absorption is saturated at Earth's surface, absorption is not saturated higher in the atmosphere. Radiation is absorbed and reemitted throughout the atmosphere, with escape to space occurring at the level above which there is little chance of absorption. 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, causing a planetary energy imbalance and thus a warming that restores energy balance.

Arrhenius' estimate of climate sensitivity in his 1908 book was realistic, and he 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 partly due to his estimate that 5/6 of the emissions would be taken up quickly by the ocean.

Arrhenius saw the CO_2 effects as being beneficial, helping the world feed its growing population: "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."

As long as climate effects of CO_2 remained theoretical, they would not be an issue of concern to the public. Broader interest in the topic would require evidence of ongoing global change.

Guy S. Callendar, a British engineer, believed that he found that evidence in 1938. Callendar used records from 147 weather stations around the world to estimate that global temperature increased by about 0.3°C between 1880 and the early 1930s.[13] This was a bit larger than the 0.2°C warming that he calculated as the expected warming from increasing atmospheric CO_2.

Callendar's work on both temperature and atmospheric CO_2 amount was careful. Because of his engineering training, he paid close attention to difficulties in obtaining accurate measurements. He was able to discriminate among the various attempts to measure atmospheric CO_2, and he correctly inferred the approximate magnitude of the CO_2 increase over the prior half-century.

Callendar's claim that atmospheric CO_2 was increasing markedly was at odds with understanding of the carbon cycle, which implied that the ocean would quickly take up most of the fossil fuel CO_2 emissions. This mystery would not be solved until 1957. Still later, measurements on bubbles of ancient air trapped in Greenland and Antarctic ice cores proved that Callendar's estimate of CO_2 growth since the late 1800s was accurate.

Callendar, like Arrhenius, concluded that future warming would be 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, 1905). In any case the return of the deadly glaciers should be delayed indefinitely."

In the next 40 years after Callendar's 1938 paper, until the late 1970s, there was no discernable global warming, despite a factor of five increase of annual fossil fuel CO_2 emissions. Absence of global warming in a period of such rapidly growing emissions required an explanation if the estimates of climate sensitivity of Arrhenius were in the right ballpark.

An explosion of understanding related to CO_2 and climate began with the International Geophysical Year (IGY). The origin of IGY traces to a meeting of several scientists, including Sydney Chapman and Lloyd Berkner in James Van Allen's living room in March 1950.[14] Prior International Polar Years, in 1882-1883 and 1932-1933, showed the value of international cooperation in gathering global data. These scientists suggested that it was time for a worldwide Geophysical Year, in part because of recent advances in rocketry, radar and computing.

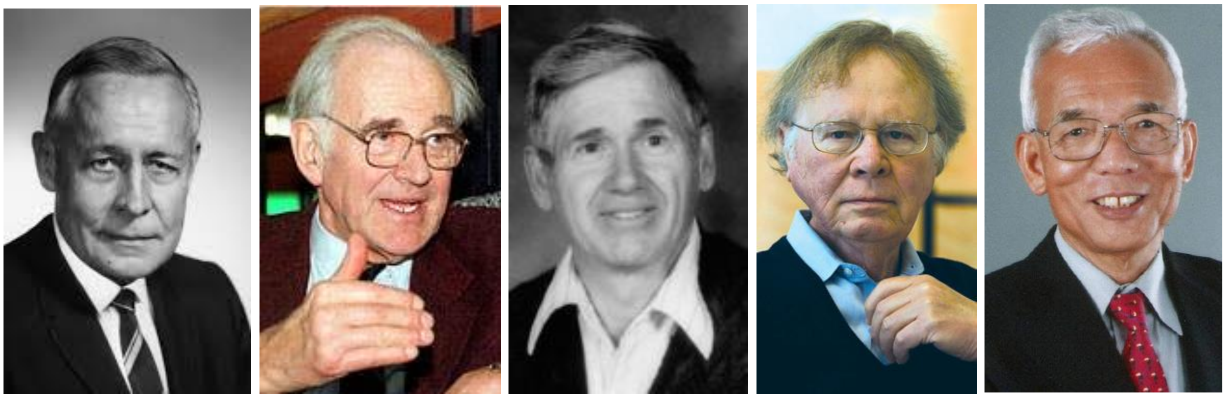

Fig. 15.2. Roger Revelle, Bert Bolin, David Keeling, Wally Broecker, Syukuro Manabe

Berkner and Chapman obtained approval of the International Council of Scientific Unions for the IGY for the 18 months, July 1957 through December 1958, coinciding with the next period of maximum solar activity. More than 70 nations eventually cooperated in the IGY. 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, to the surprise of many, especially in the United States. 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.

Major achievements of the International Geophysical Year included discovery of the Van Allen radiation belts and verification that there was a continuous system of submarine mid-ocean ridges encircling the globe.[15] These discoveries were part of a broad collection of data that helped to initiate a comprehensive overview of global geophysical phenomena.

Roger Revelle and Hans Suess altered the course of the CO_2 climate story in 1957 with a paper[16] 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 was that the increase of CO_2 in the air from fossil fuel burning has a 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.[17]

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 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.

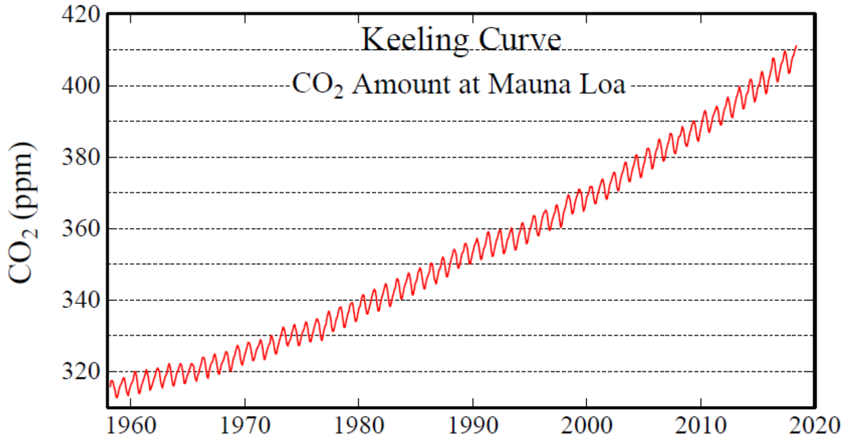

Fig. 15.3. Keeling curve today

The ocean, to a good approximation, 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 about 4 kilometers (about 2½ miles) is mixed with the surface layer by the ocean's overturning circulation on time scales of centuries to millennia.

The combination of the chemical buffering effect and the 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 International Geophysical Year presented an opportunity to obtain important measurements. 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 help carry out a world survey of atmospheric CO_2.

Charles David 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 Pacific Ocean, largely free of local pollution. The South Pole site was even more isolated, yet 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.

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.[18]

Manabe was the authority on the radiative processes that drive climate change, and he developed both 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[19] 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[20] 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 what many people today would describe as "mad scientist" implausible geoengineering countermeasures? Was the purpose to draw attention to the seriousness of human-made global warming? Or did this constitute 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.

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[21] presented a comprehensive general circulation model of the atmosphere with a realistic hydrologic cycle. Manabe and Richard Wetherald[22] used a one-dimensional climate model to explore important processes affecting climate change and climate sensitivity. Manabe and Kirk Bryan[23] published the first results from a coupled ocean-atmosphere general circulation model.

So Manabe had a decade head-start on us. Furthermore, computer capacity of his lab, NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) located at Princeton University, was much greater than ours at GISS. GFDL was NOAA's premier climate modeling laboratory, so they could anticipate continual improvement of 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 a useful role for our modeling approach?

We were in trouble at GISS, and I knew it. We had an old computer and little funding to cover salaries, let alone purchase a new computer.

Jastrow's gambit was the Livermore supercomputer proposition. Dr. Jastrow thought that access to a supercomputer might let us compete with the big modeling centers, GFDL and NCAR, so I dutifully assigned four of the five programmers borrowed from Halem's group to work on reprogramming the GISS weather model to run on the supercomputer at Livermore.

My interest, however, was in a different approach, the coarse resolution global modeling that I had proposed to Rasool. The objective was a model we could run for long time scales, a model that could yield 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. It was clear that we were headed for a showdown.

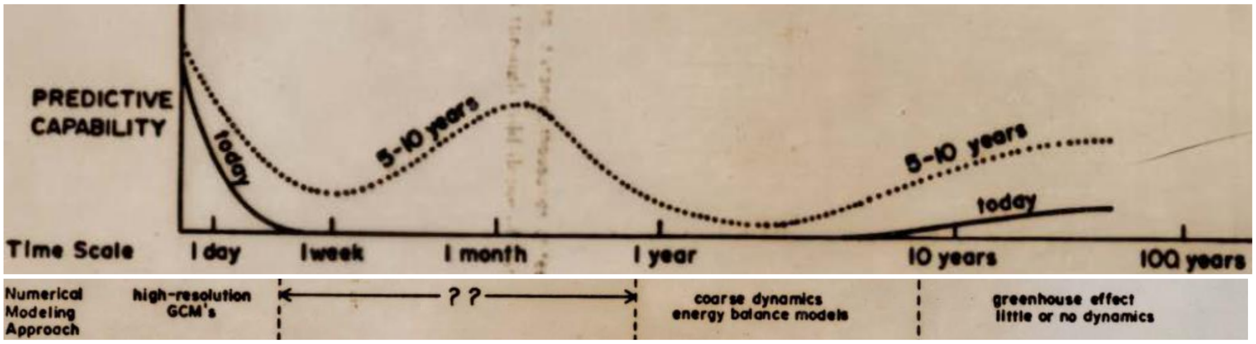

Fig. 16.1. Chart used to discuss Farmers' Forecast and End-of-Century climate problems.

Chapter 16. Farmers' Forecast vs. End-of-Century

The Farmers' Forecast was the focus of Dr. Jastrow's pitch to Dr. Cooper. I still have the chart he used. It has yellowed with age over the past 40-plus years. By Farmers' Forecast, he meant long-range forecasting, weeks and months in advance, the timeline segment in which modeling approaches are missing. Dr. Jastrow was superb at making technical material clear to a lay audience or to higher level NASA management. Accurate long-range forecasts would have great economic value for farmers, helping them decide when and what to plant.

Chapter 16 is undergoing revision.

---

[1] Fourier, J., Remarques generals sur les temperatures du globe terrestre et des espaces planetaires, Annal Chim. Phys., 27, 136-167, 1824.

[2] The blanket analogy, is imperfect, as are the "greenhouse" and "automobile with windows rolled up" analogies, which include limitation of heat transfer by other processes such as conduction and convection (see Chapter 10).

[3] 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.

[4] Foote, E.: Circumstances affecting the heat of the Sun's rays, Amer. J. Sci. Arts, 22, 382-383, 1856.

[5] Increasing atmospheric CO_2 slightly increases absorption of sunlight by Earth, but it reduces the amount of sunlight reaching the ground and surface air. The efficacy of climate forcings is greatest if the forcing occurs at or near Earth's surface (Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, **102**, 6831-6864, 1997; Hansen, J. et al.: Efficacy of climate forcings. *J. Geophys. Res.* **110**, D18104, 2005). Whether absorption of sunlight by CO_2 causes global warming or global cooling cannot be answered with a 1-D or toy climate model; the effect on the vertical temperature profile requires proper treatment of moist and dry convection in a 3-D global model. The effect is surely small and has not engendered careful study.

[6] 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, 105-118, 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 investigate the greenhouse effect, nor could others use her data for that purpose. Her data in "the shade," a control for the measurements in sunlight, 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. In fact, she did not even pretend to investigate the greenhouse effect; there is no merit in so mischaracterizing her impressive scientific contributions.

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

[8] Tyndall, J., On the absorption and radiation of heat by gases and vapours, Phil. Mag, 22, 169-194, 273-285, 1861.

[9] Fleming, J.R., 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, 121-123, 2009.

[10] Arrhenius, S.: On the influence of carbonic acid in the air upon the temperature of the ground, Phil. Mag., Ser. 5, Vol. 41, No. 251, 237-276, 1896.
[11] Arrhenius, S.: Worlds in the Making: The Evolution of the Universe, Harper & Brothers; freely available: https://archive.org/details/worldsinmakingev00arrhuoft, 1908.
[12] Angstrom, K.: Ueber die bedeutung des wasserdampfes und der kohlensaure bei der absorption der Erdatmosphare, Annalen der Physik, 308, 720-732, 1900.
[13] Callendar, G.S.: The artificial production of carbon dioxide and its influence on temperature, Quar. J. Roy. Meteorol. Soc., 64, 223-240, 1938.
[14] Forestner, A.: James Van Allen:The First Eight Billion Miles, p. 124, University of Iowa Press, 322 pp., 2007.
[15] Discovery of this mountain chain, the largest on Earth, encircling the globe provided information confirming the concept of 'continental drift' and sea floor spreading. The theory of plate tectonics, that Earth's outer shell is divided into several plates that ride over Earth's mantle, the more fluid rocky layer above Earth's core, was soon developed.
[16] Revelle, R. and Suess, H.E.: 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.
[17] Bolin, B. and E. Eriksson: 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.
[18] Wally died when this book was nearly finished. I will remember him as the scientist who had the greatest impact on the science – he was the straw who stirred the climate change drink and the great grandfather of global warming.
[19] PSAC: *Restoring the Quality of Our Environment*, Report of Environmental Pollution Panel, White House, 1965.
[20] Revelle, R., et al, Appendix Y4 to PSAC: Atmospheric Carbon Dioxide, pp. 111-133, 1965.
[21] Manabe, S., Smagorinsky, J. and Strickler, R.F.: Simulated climatology of a general circulation model with a hydrologic cycle, Mon. Wea. Rev., 93, 769-798, 1967.
[22] Manabe, S. and Wetherald, R.T.: Thermal equilibrium of the atmosphere with a given distribution of relative humidity, J. Atmos. Sci., 24, 241-259, 1967.
[23] Manabe, S. and Bryan, K.: Climate calculation with a combined ocean-atmosphere model, J. Atmos. Sci., 26, 786-789, 1969.