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.

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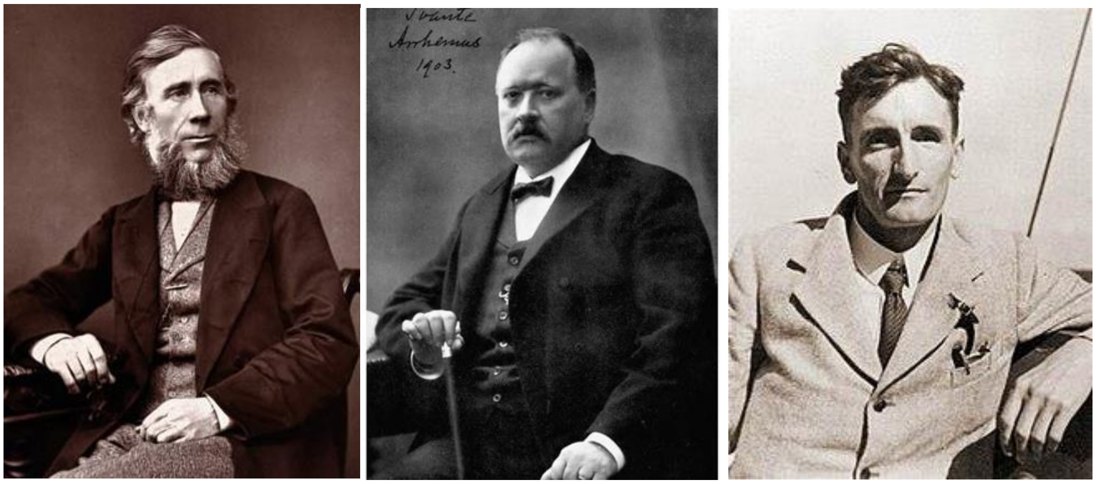

Fig. 15.1. John Tyndall, Svante Arrhenius, and Guy Callendar

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

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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 remarkably prescient, 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

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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.

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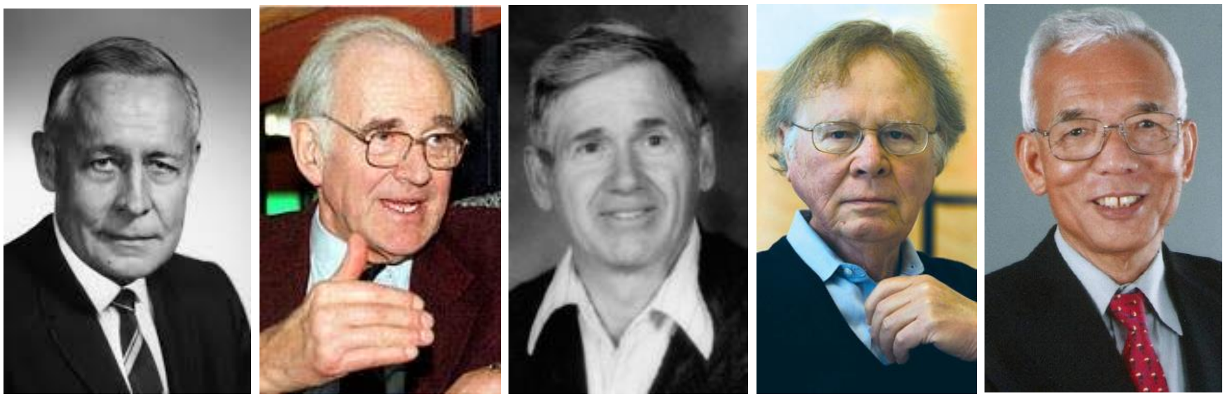

Fig. 15.2. Roger Revelle, Bert Bolin, David Keeling, Wally Broecker, Syukuro Manabe

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.

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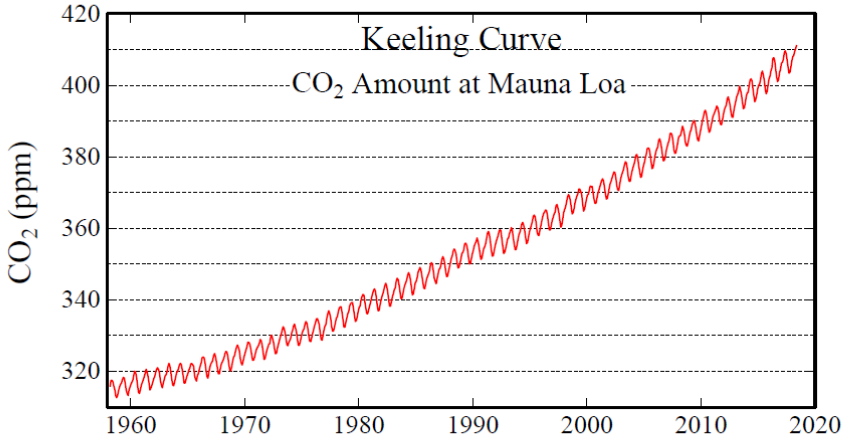

Fig. 15.3. Keeling curve today

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.

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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. 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[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 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

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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.

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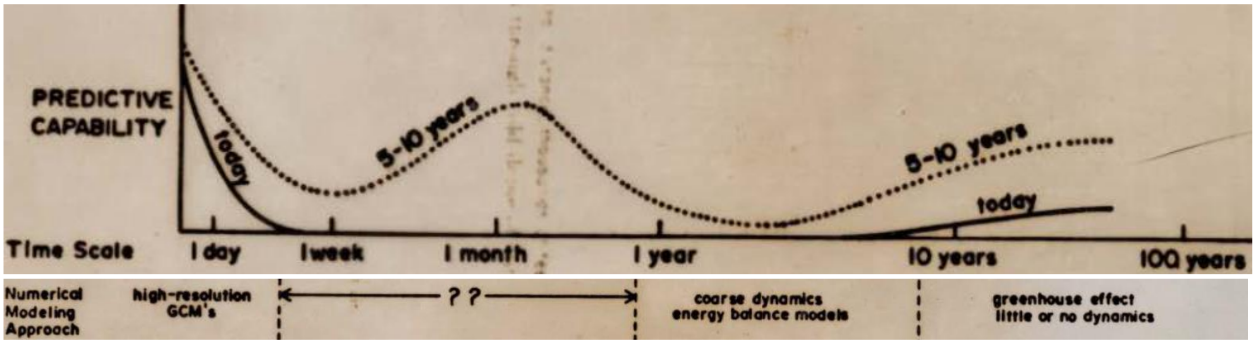

Fig. 16.1. Chart used to discuss Farmers' Forecast and End-of-Century climate problems.

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.

Jastrow hoped that research on the Farmers' Forecast provided a reason for NASA to continue to support GISS, as an institute in New York City, with the weather project relocated to Greenbelt.

The chart shows climate "predictive capability" as a function of the length of the forecast, both the capability existing "today" (the late 1970s) and the potential predictability in 5-10 years assuming aggressive deployment of relevant global observations and development of global climate models. Such a rapid improvement of forecasting ability was unrealistic, and NASA managers would likely recognize that, but they would not object to ambitious goals.

The accuracy of local weather forecasts was not good in the 1970s. Predictions were usually accurate for a day or so, at best, and not reliable for longer lead times. It was realized that the chaotic aspect of atmospheric motions, as described by Ed Lorenz[24], would always prevent reliable local forecasts at time scales beyond a week or two. Jastrow drew an optimistic curve for increasing weather predictability in 5-10 years, assuming accurate global satellite observations and improved high-resolution weather models.

Dr. Jastrow discussed the weather end of this diagram first, the short time scales, to help explain the diagram. The time scale is increasingly compressed toward longer time scales, and the nature of predictability changes as the time scale increases. For time scales of a few weeks to a few months, the Farmers' Forecast period, prediction of weather on a specific day is not possible or needed. Instead, the goal is knowledge of what week is best to plant or harvest and of whether a season is going to be wetter than normal or drier than normal.

Dr. Jastrow argued that high predictability of average weather was possible on the Farmers' Forecast time scale, because atmospheric boundary conditions such as sea surface temperature patterns, soil moisture and snow cover, would affect the average weather on those time scales. Anomalies in these boundary conditions could be observed at the time of forecast, and the model would compute or specify how these anomalies changed in the future.

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Finally, Dr. Jastrow argued that there was also significant predictability at the "end-of-century" time scale. On such long time scales the interest is not in specific year-to-year changes, such as those caused by El Niños, which are unpredictable so far ahead. Instead, the interest is in long-term global and regional climate change caused by factors such as changes of atmospheric composition, land use, solar irradiance and the level of volcanic activity.

Dr. Jastrow's chart showed great optimism about potential predictability, especially on the time scale of the Farmers' Forecast. Improved predictability was the carrot that Dr. Jastrow was proffering. He argued that the economic benefits are greatest for a good seasonal forecast.

The carrot was important. We needed more funding, if GISS was to be viable. The $500K per year that NASA Headquarters agreed to provide GISS after departure of the weather program to Greenbelt hardly covered institutional costs and commitments that Dr. Jastrow had made, commitments that he said were needed to "keep the doors open."

NASA Headquarters had left open the possibility that we could propose additional research for additional funding. Dr. Jastrow was suggesting that the potential for a Farmers' Forecast was so great that Headquarters should supply greater funding for research on it. Dr. Jastrow's chart had "??" for the numerical modeling approach that should be used for the Farmers' Forecast.

My interest was in what Dr. Jastrow called End-of-Century predictions. My proposal to the stratospheric research program at NASA Headquarters had been approved. The funding helped support development of the coarse resolution climate model. Specifically, it allowed me to pay the salary of Gary Russell, who did not want to move to Maryland with Halem's weather modeling group.

We were still early in our work on the three-dimensional (3-D) coarse resolution model, so I did not have results for end-of-century climate simulations. All that I could show were calculations that we had done with a simple 1-D (vertical column) climate model, while we were working on the 3-D climate model.

These calculations were for the natural climate experiment that was playing out over our heads in 1963 when Andy and I were taking the Ph.D. qualifying examination. Now we could use the measurements that we had made on a cold winter night in Iowa in 1963 as the moon was obscured by the sulfate aerosols produced by the massive eruption of Mount Agung on the island of Bali, Indonesia.

The idea was to use this volcanic eruption as a natural climate experiment. The stratospheric aerosols produced by the Agung eruption reflected sunlight to space, reducing solar heating of Earth so much that it should have a discernable cooling effect on Earth.

Benjamin Franklin had the idea a bit earlier than us. Franklin wondered whether excessively cold weather in the early 1780s might be a result of an incessant "dry fog" that was prevalent then, especially in Europe. The dry fog was believed to be a result of continuing volcanic eruptions near Iceland, which poured out lava and sulfurous gases. The Sun's rays were so enfeebled by this dry fog that, when collected in the focus of a "burning glass," according to Franklin, they could "scarce kindle brown paper."

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Franklin's idea, that volcanic aerosols reduced solar heating, was plausible, but he lacked the scientific tools and data needed to investigate the idea. We had fairly good global data for the stratospheric aerosols produced by the Agung eruption, which was the largest eruption in the past 50 years, so Agung provided a useful test of the climate models we were developing.

Earth is heated by the Sun at an average rate of about 240 W/m^2, averaged over the entire planet, thus averaged over day and night.[25] Based on our 1963 lunar eclipse data and other data, we could estimate that the Agung aerosols reflected about 1 percent of the sunlight striking Earth at the time of maximum stratospheric aerosol amount. Thus the maximum (negative, cooling) forcing by the aerosols was about – 2.4 W/m^2. The forcing slowly diminished over the next year as the aerosols descended into the lower atmosphere and were washed out.

When we put the aerosol data into our 1-D energy-balance model, the calculated temperature changes following the eruption were in good agreement with observed temperature changes in Earth's stratosphere and at the surface. We submitted a paper to *Science* in the summer of 1977, and it was published in early 1978.[26]

Robert Frosch, the NASA Administrator, read our paper. Frosch was unusual for a NASA Administrator, being a top-flight scientist as well as an engineer, with a Ph. D. in theoretical physics. Frosch contacted Ichtiaque Rasool, chief scientist in NASA Earth Sciences, and recommended that NASA be prepared to make appropriate observations at the next large volcanic eruption.

Frosch's interest was useful for Jim Pollack and his colleagues at NASA Ames Research Center, helping them get support for aircraft instrumentation. They were ready to obtain measurements of volcanic aerosols after the eruptions of El Chichón in 1982 and Pinatubo in 1991.

Frosch's interest in the Mount Agung paper did not result in new funding to GISS. However, Jastrow, Cooper and climate program managers at Headquarters were all aware of Frosch's reference to our paper. This helped to buy us some time to work on our climate model.

We needed a 3-D Global Climate Model (GCM). A GCM is an essential tool for climate studies because it lets climate processes interact. GCMs are based on basic physical principles: conservation of energy, mass and momentum, plus the ideal gas law defining the relation between atmospheric temperature, pressure and number density of gas molecules in the air. GCMs are complex because of source and sink terms in these conservation equations, and because of the complicated nature of water.

There is a separate equation for conservation of water, but keeping track of water is challenging because of phase transitions that occur between water vapor, liquid water and ice. The climate model needs sub-models for clouds, precipitation, soil moisture, rivers, lakes, and so on.

Our climate model did not yet include a dynamical ocean model that could move heat from one location to another, but we did include the heat capacity of the upper layer of the ocean that is mixed rapidly by waves. The thermal inertia of this ocean layer is needed so that the computed surface temperature has a realistic seasonal cycle.

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Coarse resolution was our savior, but the community's bugaboo. When Kiyoshi's initial simulations revealed that 8×10 degree resolution yielded a realistic atmospheric circulation, I was euphoric. It meant that we could do useful climate simulations on our old (1967) computer.

Moore's Law is the remarkable empirical fact, noted by Intel co-founder Gordon Moore in 1965, that the number of transistors that can be packed into a given space approximately doubles every two years. Computer speeds increased at a similar rate, at least for a few decades.

Of course, to take advantage of Moore's Law you must buy a new computer regularly. By 1977 our 1967 computer was five doublings behind state-of-the-art, a factor of 32.

The 8×10 model, with Texas-size grid-boxes (500 miles across), was almost eight times faster than the 4×5 model. Ten boxes covered the contiguous 48 states in the U.S., but Texas, Florida and Maine stuck out into three additional boxes. A gridbox surface could be part land and part ocean, with atmosphere-surface interactions computed separately for land and ocean fractions.

David Rind looked at the simulations in detail. He found that the 8×10 model had recognizable high and low pressure systems, but they did not move as fast as real storms. A real-world storm might start in the Gulf of Mexico, move up the East Coast, and end up near Norway. In our model the storms tended to poop out when they reached New England, but another storm would form to carry heat poleward. Because the poleward transport of heat is driven by the temperature gradient, the model found a way, albeit imperfectly, to move the heat.

This is an example of the benefit of the careful treatment of the fundamental equations by Akio Arakawa and Gary Russell. Of course, we needed to be aware of the model's limitations due to its coarse resolution, but we had a tool that was useful for many purposes.

Such coarse resolution is not good for weather forecasting, which requires accurate tracking of the motions of individual high- and low-pressure systems. Nor was it likely that such resolution would be useful for the Farmers' Forecast.

We did a set of forecast experiments with our coarse-resolution model. We made seasonal simulations with and without inclusion of observed sea surface temperature (SST) anomalies at the beginning of the season. The model runs that included the SST anomalies produced slightly more accurate temperature anomalies during the following three months than the set of model runs that did not include the initial SST anomalies.

I showed this result during a visit by Dr. Cooper. Dr. Jastrow described it glowingly as a first step toward his Farmers' Forecast, implying that we would keep improving the model and input data as needed for a better forecast.

That was a problem. Forecasting experiments based on SST anomalies were trivial, requiring only addition of observed SST anomalies to the climate model's SST climatology – the SST distribution computed by the model. If we wanted to do better, we needed a model that could compute changing SSTs and other slowly changing boundary conditions such as soil moisture and vegetation health. There were bigger groups with far greater resources already working on those things. We would continue to work on improvements in our global climate model, but not with expectation of competing with other groups in what amounted to long-range weather forecasts. Instead, my focus was on the "end of century" problem – long-term climate change. We had better make progress on that before the next visit by Dr. Cooper or other NASA brass.

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Meanwhile, a great opportunity arose. Bob Schiffer, head of the climate program at NASA Headquarters, was interested in finding a role for NASA in the CO_2 climate problem. We had a suggestion: add a dynamic ocean model to the budding GISS climate model, and keep track of the carbon in the ocean, including the transfer of fossil fuel CO_2 into the ocean.

There was an ongoing scientific puzzle: a "missing carbon sink." The amount of fossil fuel CO_2 injected into the atmosphere was known accurately. The increase of CO_2 in the air was measured accurately by Dave Keeling, and found to be only 60 percent of the fossil fuel source. Much of the other 40 percent was surely going into the ocean, but Wally Broecker argued persuasively that the ocean was not taking up that much CO_2.

Other scientists looking at data on deforestation, which was another CO_2 source, and regrowth of vegetation, which is a CO_2 sink, could not account for the fossil fuel CO_2 that was not appearing in the air. We wanted to look at the problem with a global transport model, including carbon isotopes, and try to help resolve the mystery of the missing sink.

We included Wally Broecker as a co-investigator because he was the world's leading expert on ocean geochemistry and we wanted his advice. However, the proposal would also be a way to get money to pay for Wally's students without hamstringing GISS research programs.

Another part of our proposal was to investigate climate sensitivity. We had initiated a doubled CO_2 experiment with our 3D GCM. The experiment was not complete – even with near-Texas-size grid-boxes the model was slow on our computer – but it looked interesting. Our model seemed to yield almost twice as much global warming as Manabe had found in his most recent climate model experiments.

We proposed to complete this $2\times CO_2$ experiment. We would analyze model diagnostics to investigate what physical processes were causing our model to yield greater warming than Manabe had found. We would also compare our model with real world data to help assess the reliability of the model.

We wrote still another proposal, for cloud studies. Clouds were the most uncertain climate feedback. If the world became warmer, would cloud cover increase or decrease? Would clouds move to higher altitudes? Cloud changes may be the biggest factor affecting how sensitive climate is to forcings such as increased CO_2. We proposed to use satellite observations to assess the realism of cloud distributions computed in climate models.

I submitted both the CO_2 and cloud proposals to NASA Headquarters on 1 July 1979. Jule Charney somehow got a copy of the CO_2 proposal, probably from our co-investigator Peter Stone, a colleague of Charney at MIT.

Charney's interest in our CO_2 proposal would turn out to make all the difference to the future of our climate program, and to the future of the Goddard Institute for Space Studies.

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Jule Charney

Chapter 17. Charney's Puzzle: How Sensitive is Earth?

President Jimmy Carter was concerned about growing United States dependence on oil from the Middle East. On 18 April 1977, just three months after assuming the Presidency, he delivered an *Address to the Nation on Energy* while sitting in the White House, wearing a sweater, with the White House thermostat turned down.

Oil and gas supplies are limited, President Carter said, so "we need to shift to plentiful coal" and "we must start now to develop the new, unconventional sources of energy that we will rely on in the next century." Carter would also put solar panels on the White House, but fossil fuels were, and still are, the source of most energy in the United States and the world as a whole.

Conventional fossil fuels are oil, gas and coal that can be readily extracted from large deposits in the ground without special effort and expenditure of energy. Unconventional energies include tar sands and "tight" gas and oil deposits that are extracted by high pressure hydraulic fracturing (fracking) of rock formations. Coal gasification is another unconventional fuel. It takes energy to extract these fuels, so they are more carbon-intensive than conventional fossil fuels, that is, they emit more CO_2 per unit of useful energy for the consumer.[27] Unconventional fossil fuels also produce regional pollution, including expanding plumes of polluted groundwater.

"We've always been proud of our leadership in the world. Now we have a chance again to give the world a positive example," President Carter concluded.

Indeed. United States actions matter. Between 1915 and 1950 the United States emitted 45 percent of global fossil fuel emissions, with the almost 200 other nations emitting 55 percent. By 1977 emissions from other nations had climbed, but during Carter's presidency U.S. annual emissions were still more than one-quarter of global annual emissions.

Carter's Science Adviser, Frank Press, requested advice from Philip Handler, the President of the National Academy of Sciences. The charge to the Academy was broad, ending:

> ***"To summarize in concise and objective terms our best present understanding of the carbon dioxide/climate issue for the benefit of policymakers."***

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The charge was a license to provide broad advice on energy policy. It was clear that President Carter needed advice on climate. Fourteen years had passed since the 1965 PSAC CO_2 study headed by Roger Revelle. Understanding of the climate issue had advanced.

Phil Handler chose a stellar group of atmospheric physicists, meteorologists and oceanographers for the Academy study: Akio Arakawa, D. James Baker, Bert Bolin, Jule Charney, Robert Dickinson, Richard Goody, Cecil Leith, Henry Stommel and Carl Wunsch. Charney, a pioneer in dynamic meteorology with great insight into climate physics and an infectious enthusiasm for the science, was a perfect chair for the study. Handler presumably chose Charney and consulted with him on committee membership.

Charney chose to focus the Academy study on climate sensitivity. This was consistent with the limited time for the study: the group met for five days, 23-27 July 1979. Charney continued to consult with study group members and other scientists in the following weeks before completing a 33-page report.[28]

Charney's narrow focus was ingenious, yielding clear definition of the core scientific issue in global climate change. His sharp focus provided a quantitative framework for thinking about climate sensitivity. The value of Charney's framework has not diminished over time.

CO_2 in the air was observed to be increasing rapidly. Keeling's data showed that CO_2 had passed 335 ppm (parts per million), was increasing more than 1 ppm per year, and the rate of growth was increasing as annual fossil fuel use continued to increase. It was known that a lot of fossil fuels were present in the ground, so, if fossil fuel use continued to increase, airborne CO_2 at some point would be twice as great as the preindustrial level, estimated to be about 280 ppm.

Charney defined an idealized gedanken problem: how much would global temperature increase if the amount of CO_2 in the air doubled from its preindustrial amount? Such a doubling would likely occur in the 21st century, if there were no efforts to constrain fossil fuel use.

The problem was idealized in several ways for the sake of being a tractable, well-defined problem. The global warming was defined as that which exists after the planet returns to near-equilibrium with space, in response to the planetary energy imbalance created by the added CO_2.

The report suggested that delay in attaining full warming could be as much as "a few decades." We now know that the study group greatly underestimated the delay caused by the ocean's thermal inertia. They also did not seem to recognize that the delay time is a very strong function of climate sensitivity, a matter that was not clarified until the mid-1980s.

The lag in climate response has important practical implications. It causes human-made climate change to be an intergenerational matter. One generation can cause climate change that becomes large only during later generations. Because of the importance of this climate change lag, we defer discussion of it to a later chapter, where we can be quantitative.

Climate feedbacks were a principal topic of the Charney report. Charney did not explicitly divide feedbacks into the categories of fast feedbacks and slow feedbacks, but the nature of the Charney study and report implicitly led to such a framework for analysis.

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Consider first the "no feedback" case. If the amount of CO_2 in the air is doubled and everything else is held fixed, how much will Earth's surface temperature increase? The increased CO_2 makes the atmosphere more opaque in the infrared part of the spectrum. Thus, radiation to space occurs from greater altitudes, where it is colder. The amount of radiation to space is therefore reduced, and the planet is out of energy balance: less energy is emitted to space than is received from the Sun. So, Earth warms until energy balance is restored. The radiation calculation is tedious because absorption of infrared radiation by CO_2 varies with wavelength; therefore, in effect, we must do calculations at all wavelengths in the infrared spectrum and add up the results. Everyone gets the same answer, if they do the radiation calculation accurately. Earth's surface and lower atmosphere must warm about 1.2°C (2.2°F) to restore energy balance with space.

Thus, the no-feedback climate sensitivity is about 1.2°C for $2\times CO_2$. Doubled CO_2 is a forcing of about 4 W/m^2, so the no-feedback sensitivity can also be stated as 0.3°C per W/m^2. The conclusion seems to be that climate is not very sensitive – if there are no feedbacks.

However, if the world warms up 1.2°C, that will cause other things to change. Those changes, called climate feedbacks, can either amplify or diminish the no-feedback climate sensitivity.

Jule Charney was delighted that our model gave a different global warming than Manabe's. Charney had a predilection for 3-D GCMs. He was instrumental in development of these models based on the fundamental equations for atmospheric structure and motions, and he knew that global models were needed to study how climate feedbacks interacted. Results from more than one model were useful. Different results from different models provided Charney an opportunity to investigate causes of the differences and try to quantify uncertainties in model predictions.

Charney invited me to give a presentation on our results during their workshop at the Woods Hole Oceanographic Institute in Massachusetts. Fortunately, from my perspective, the workshop occurred while I was running our first Summer Institute on Climate and Planets, which was more than a fulltime activity and provided an excuse not to go to Woods Hole. I was still trying to understand climate change and our budding global model, and I was not eager to reveal my ignorance before Charney's stellar committee. Robert Dickinson, for example, was recognized to be a genius; he knew everything that I knew about climate feedbacks, and much more.

Instead, we scheduled a telecon on which I answered questions from Charney and his committee; When Charney called, he said that I was a voice from a black box on their meeting room table. In addition, after their workshop ended, Charney sent Arakawa to work with us several days, studying our computer output to try to understand our model and its simulated climate response.

Manabe's latest model yielded a climate sensitivity of 2°C for $2\times CO_2$, while our model gave almost 4°C. Charney called a few times after the workshop, while he was finishing the report, and we discussed some of the possible reasons for the difference.

Clouds were likely one reason. Manabe specified the cloud distribution in his model to make it as realistic as practical and he kept the clouds the same in the $2\times CO_2$ simulation. Clouds were computed in our model, occurring in atmospheric layers and at times when the air became saturated. Some cloud types tend to occur at a given temperature, so in the $2\times CO_2$ world as the atmosphere warmed these clouds moved to higher altitude. It is colder at the greater altitude, so the clouds radiate less energy to space than they would if they had stayed at the same altitude. In

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Manabe's model, with fixed cloud heights, these clouds are hotter and radiate more energy to space. Also the cloud cover decreased slightly in our 2×CO_2 world, which increased the amount of sunlight absorbed by Earth.

Sea ice was another difference between our models. Manabe's control run (climate simulation with 1×CO_2) had less sea ice around Antarctica than the real world, while our control run had more sea ice than observed. The sea ice area decreases in the 2×CO_2 world, which is an amplifying feedback, because the ocean is much darker than sea ice, so it absorbs more sunlight. Because Manabe's model did not have as much sea ice as ours to begin with, the amplification of warming due to sea ice loss was less in Manabe's model than in our model.

Water vapor was the largest feedback in both models. The amount of water vapor that the air can hold is a strong function of temperature, as readily noticed in daily life. If we let outdoor air into the house in winter and heat it to room temperature, the relative humidity becomes very low even if it was snowing outside, which implies that the humidity outside was near 100 percent. Our models were similar in this calculation, but multiple amplifying feedbacks reinforce each other. Therefore, because the cloud and sea ice feedbacks were larger in our model, the water vapor increase in our model was larger than in Manabe's model.

Charney decided that his central estimate for climate sensitivity was 3°C for 2×CO_2, which was about the midpoint between the two GCM results. Discussion of feedbacks in the Charney report, aided by 1-D models, implied 2.4°C as the most likely sensitivity. However, Charney explained to me that he trusted the 3-D models more, because they allowed interactions among the feedbacks and included expected amplification of warming at high latitudes.

Choosing an uncertainty range was more difficult. Charney settled on 3 ± 1.5°C for expected equilibrium global warming due to doubled CO_2. That is a large range, a factor of three, from 1.5°C to 4.5°C. Furthermore, he later clarified that the estimate only meant that there was at least a 50 percent chance[29] that real world sensitivity was within the 1.5-4.5°C range!

Forty years later, the range would not be much narrower if it relied entirely on climate models. One problem with models is that we are never certain that all significant processes are included. Also some processes, such as cloud formation, are difficult to simulate, and a small change of cloud cover can have a large effect on the amount of solar energy absorbed by Earth.

Fortunately, Earth's climate history provides a way to assess climate sensitivity that is much more accurate, as we will discuss later. For now, let's consider the crucial time scale of climate processes, including "fast" and "slow" climate feedbacks, and also the ocean's role in delaying climate change.

Charney's climate sensitivity is the "fast-feedback" climate sensitivity, which includes the feedback effects of water vapor, sea ice, clouds, and natural aerosols. These feedbacks are described as fast because they are expected to change almost coincident with global temperature change. Water vapor is known to be a strongly amplifying feedback because the air holds more water vapor as it becomes warmer, and water vapor is an effective greenhouse gas. Sea ice feedback is also amplifying because sea ice cover decreases as Earth warms, thus replacing high-albedo sea ice with a darker ocean surface that absorbs more solar energy. Clouds and aerosols are the difficult part of the fast feedback problem. Aerosols by themselves are complex because

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there are several aerosol compositions[30] and each varies geographically. Moreover, aerosol and cloud particles are a complex continuum, as water vapor condenses on aerosols to initiate cloud drop formation. Aerosol-cloud modeling, which is still developing today, suggests that clouds are an amplifying feedback, but there is a wide disparity among different models. Charney was forced to accept a very large uncertainty in the net fast-feedback climate sensitivity.

Charney did not talk about slow feedbacks, but his idealized doubled CO_2 experiment implicitly assumed that Greenland and Antarctic ice sheets will not change much on a practical time scale, for example, during a human lifetime. Also, by doubling CO_2 and then keeping its amount fixed, he ignored the feedback that changed climate will have on GHG amounts. It was known that the time required for complete overturning of the deep ocean was of the order of 1000 years; thus, the penetration of temperature change to the deep ocean would take a long time and Charney ignored the effect of that ocean change on CO_2 emissions to the atmosphere. Other feedbacks were intentionally excluded by the assumption of fixed land surface properties. Charney's objective was a tractable experiment for models that existed in 1979. He realized that a more comprehensive study of feedbacks would be needed eventually.

Given enough time, warming will cause ice sheets to shrink and expose a darker surface that absorbs more sunlight, causing still more warming. Also, land surface properties will change in response to global warming. For example, some tundra areas – frozen ground – will melt, thus releasing greenhouse gases CO_2, CH_4 and N_2O. Also, forests will expand to higher latitudes in the Northern Hemisphere in a warmer world. It was realized that some of these feedbacks may not be so slow, but determination of their time scales was a problem for the future.

"Earth system sensitivity" is the terminology used for climate sensitivity when all feedbacks are included. As we will see, Earth's history reveals that the slow feedbacks, on net, are also amplifying, so Earth's climate is even more sensitive than indicated by Charney's analysis.

Conclusions of Charney's report ended with: "To summarize, we have tried but have been unable to find any overlooked or underestimated physical effects that could reduce the currently estimated global warmings due to a doubling of atmospheric CO_2 to negligible proportions or reverse them altogether. However, we believe it is quite possible that the capacity of the intermediate waters of the oceans to absorb heat could delay the estimated warming by several decades. It appears that the warming will eventually occur, and the associated regional climatic changes so important to the assessment of socioeconomic consequences may well be significant, but unfortunately the latter cannot yet be adequately projected."

The Preface to the Charney report, written by Verner E. Suomi, Chairman of the National Academy of Sciences Climate Research Board, states "The conclusions of this brief but intense investigation may be comforting to scientists but disturbing to policymakers. If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible. The conclusions of prior studies have been generally reaffirmed. However, the study group points out that the ocean, the great and ponderous flywheel of the global climate system, may be expected to slow the course of observable climatic change. A wait-and-see policy may mean waiting until it is too late."

Suomi correctly notes that the caveat about the delay caused by the ocean is not a benefit. It means that a "wait-and-see" approach by policymakers could be dangerous!

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The ultimate charge to NAS was: *"To summarize in concise and objective terms our best present understanding of the carbon dioxide/climate issue for the benefit of policymakers."* Does the report adequately inform policymakers? Suomi's words "…comforting to scientists but disturbing to policymakers…" are relevant. But did the report disturb policymakers? Were we, the scientific community, clear enough, strong enough, in our warnings to policymakers?

For my group, the chance to interact with Charney was a privilege and good fortune. Charney treated us with the respect accorded more established researchers, despite the coarse resolution and unpublished status of our climate model.

Charney's approval was noticed by NASA Headquarters. Publicity surrounding the Charney report included the fact that our model results were a prominent part of the report. It is likely that Charney's approbation played a role in the decision of NASA to fund both the CO_2 and cloud research proposals! We received $100K funding immediately for the CO_2 research and approval for $230K per year beginning the next fiscal year. The cloud research also was funded, beginning, if I remember right, at a level of $100K per year.

I had stopped work altogether on the Farmers' Forecast. I had ammunition for any dispute with Dr. Jastrow. Our model with coarse resolution did a good job of simulating the atmosphere's general circulation, consistent with our initial proposal that was guided by advice from atmospheric dynamist Prof. Peter Stone. I wanted to focus on the physics of long-term climate. Farmers' forecasting, essentially extended range weather forecasting, required a different focus.

Before any fight could occur, a referee stepped into the ring: the NASA Inspector General. He would alter our courses, both Jastrow's and mine.

The following two years were probably the best years of my research career. We had money for students and research associates, and I worked assiduously on a paper on CO_2 and climate. I thought we could say more than the Charney report had said about expected global warming.

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[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.

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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.

[24] Lorenz, E.N., Irregularity: A fundamental property of the atmosphere, *Tellus Ser. A*, **36**, 98-110, 1984.

[25] Solar irradiance at Earth averaged over the year is about 1361 W/m^2, but this is reduced by a factor of four when averaged over Earth's surface area, and only about 70 percent of the incident radiation is absorbed.

[26] Hansen, J.E., W.-C. Wang, and A.A. Lacis: Mount Agung eruption provides test of a global climatic perturbation. *Science*, **199**, 1065-1068, 1978.

[27] Bruckner, T and I.A.Bashmakov: Energy Systems, in Climate Change 2014, IPCC WG III, 2014.

[28] Charney, J., Arakawa, A., Baker, D., Bolin, B., Dickinson, R., Goody, R., Leith, C., Stommel, H., and Wunsch, C.: Carbon Dioxide and Climate: A Scientific Assessment, Natl. Acad. Sci. Press, Washington, DC, 33p, 1979.

[29] Conventional definition of the uncertainty range given by the number after "±" is 95 percent confidence that the true answer falls in that range. IPCC, however, uses 90 percent confidence and Charney used 50 percent.

[30] Including, e.g., VOCs (volatile organic compounds) produced by trees, sea salt produced by wind and waves, black and organic carbon produced by forest and grass fires, dust produced by wind and drought, and marine biologic dimethyl sulfide and its secondary aerosol products.

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