Sophie's Planet

Dear Young People,

I am writing for the sake of all young people, and I hope to communicate with those of you of high school and college age. You must be concerned about your future, and hopefully also about the future of your nation and your planet.

You have the potential to affect all of those futures. That is a bold assertion – it may seem like a homily for a graduation ceremony. I wish to persuade you that it is not only a plausible goal, but that it is essential that you alter the course upon which older generations have set us.

No doubt you know that global climate is changing. Moreover, political polarization and disaffection within and among nations is rising. Life prospects for youth, in many nations, are not improving.

These matters are interrelated. While these threats are not being addressed effectively, nevertheless a basis for optimism emerges – if the global situation is assessed objectively and if the issues are well understood. "Well understood" is the key phrase here.

Is there any reason you should believe that *I* can help you understand these matters?

The best reason I can offer is that I am trained in scientific objectivity, and so done by a master, Prof. James Van Allen at the University of Iowa. I will always try to make clear the rationale for my conclusions, warn you when subjective and political factors may be involved, and leave ultimate conclusions to you.

I describe where I came from, so you can assess what prejudices that might introduce.

I am of the generation that followed what has been termed the 'greatest generation.' I was born before the United States entered World War II, but I was not yet five years old on what we called V-J Day, Victory in Japan. We had a giant bonfire that evening, in front of the Court House in Denison, Iowa, as we burned worn-out rubber tires that had been collected to support the war effort. We children ran about with sparklers, miniature fireworks on a stick. Adults were happy but war-weary; many homes had Armed Forces service banners in their windows, with blue stars for family members serving in the war and golds star if family members died in the war.

I grew up in the era of Presidents Truman, Eisenhower and Kennedy. Our government invested in infrastructure and in its youth. College was not expensive, and it was not difficult for me to emerge from college without any debt. It was a time of opportunity and high expectations, with a positive view of the future. Each generation expected to be better off than the one before.

Trained in space sciences, I was fortunate to get a position in NASA, where I led development of an experiment to go to the planet Venus. However, even before our spacecraft arrived at Venus, I realized that there was a more interesting planet, our home planet, Earth, whose atmosphere was changing before our eyes. What would be the consequences of that, I wondered?

I proposed and received funding for a project to investigate how the changing atmosphere would alter our climate. Eventually this led to opportunities to testify about climate change to the

United States Congress in the 1980s. The predictions that we made then about climate change have proven to be accurate.

Considerable hullabaloo followed my congressional testimonies in 1988 and 1989. This was in part because of annoyance of some scientists who felt that I was speaking out too soon, and in part because I objected to edits of my testimony by government censors. Emerging from that imbroglio, I realized that I preferred to stick to scientific research. I would leave climate communications to others who were more capable at it and enjoyed it.

That seemed to work well for 15 years. However, by 2004 I was concerned that a gap had grown between what I perceived as the dangerous level of atmospheric greenhouse gases and the levels that were being talked about as plausible targets by governments and most scientists. Lax targets provided an excuse for governments to let global fossil fuel emissions continue to rise, while making promises for reduced emissions down the road, by the middle of the 21st century.

Thus, when I was invited to give a public talk in 2004, I decided to use the opportunity to make a strong statement about the threat of climate change and to encourage people to vote for candidates who would address the matter. Not being a good public speaker, I prepared diligently for the talk, which was planned for delivery in Washington, DC. However, the sponsor got cold feet, so Prof. Van Allen kindly arranged for a Distinguished Lecture at the University of Iowa.

My talk had no discernible impact. I was trying to make the climate story clearer, not fully realizing that the issues about climate change were more political than scientific.

The period 2004-2008 was a turning point in my career, as I was drawn out of pure climate science by young people – first by my grandchildren and then by college students at Virginia Tech and other universities. In considering the planet that we are leaving for young people, I was forced to think more broadly, not just about climate, but about energy systems and economics.

Connecting climate, energy and economics is not rocket science. Economists inform us that an economy is most efficient and strong if prices are honest. Thus when climate science informs us that carbon emissions impose a growing cost on society, an effective way to address this is via a simple, transparent, rising carbon fee. I gave a comprehensive public talk as the Bjerknes lecture at the annual meeting of the American Geophysical Union in San Francisco, in late 2008. Additionally I described the policy implications in a letter to President-elect Obama.

Again, I had no significant influence. President Obama's climate policy was late, ineffectual and partisan, focused on regulations and subsidies. Obama owed his election, in large part, to young people, and he was well-intentioned. Unfortunately, good intentions are not enough.

My education continued to broaden in the past 10 years, as I worked both within the government and outside the government. From 2008-2013 I continued to work 40 hours per week for NASA, focusing on climate research, and 40 hours per week as a private citizen, preparing the science case for lawsuits against the government and supporting citizens' groups. The most important of these groups is Citizens Climate Lobby (CCL), which is using the democratic process to try to affect policy, writing op-eds and letters-to-the-editor, and continually visiting the offices of Senators and Representatives. CCL now has more than 90,000 members and is growing.

In 2013 I resigned from the government to form the Climate Science, Awareness and Solutions program in the Columbia University Earth Institute. Some of the best relevant scientists in the world agreed to work with us to produce peer-reviewed papers describing the situation faced by young people, future generations, and nature, and propose the actions that are needed to stabilize climate and provide a bright future[123].[1,2,3] These papers provide the scientific basis for legal action against governments and the fossil fuel industry for violating the rights of young people.

Today we stand at a dangerous point in history. The public is fed up with government. Washington and other capitals are awash in influence peddling. 'Drain the swamp' is a universal cry.

The public, in its frustration, is driven to extreme political positions. Media provide echo chambers for right and left extremes, increasing hatred of the other side. Fighting the other side becomes paramount, extending from election to election, with no time in between for governance. Compromise and good governance have become almost impossible.

Both sides have legitimate issues. If you belong to one camp or the other, please take a minute now to consider just one issue of the other side, as I will do here.

People on the right say that we now have an Administrative State in the United States. There is more than a grain of truth in that claim. I call it a Bureaucratic State. Even NASA, one of our most effective agencies, has become a bureaucracy, wasting taxpayer money. I will describe how the Washington swamp caused this to happen. We also have a Secret Government, which, among other things, encourages and carries out overthrow of other governments. These overseas adventures cost lives and treasure while generating hatred for America. Our Secret Government is protected by a rule that prohibits any citizen from even saying that they ever provided technical advice to the Secret Government. This rule is functioning more to protect the Secret Government, rather than to protect the public. I am able to write the chapter 'If I Did It' because I worked for decades for the government, thus gaining some understanding of its major parts. I realize that in today's world it is essential to have accurate intelligence to protect ourselves and our way of life, but we must demand better civilian control over the Secret Government. People on the right have a good basis for their concern about government overreach.

People on the left say that our government favors the wealthy and powerful. There is more than a grain of truth in that claim. Billionaire Warren Buffett notes that his secretary pays a higher tax rate than he does. The tax code is riddled with loopholes designed for special interests, while the wage earner cannot escape high income tax rates. Should corporations have the rights of people, corporations with pockets so deep that they can buy elections? Clearly, the rich and the powerful do have greater access to the Whitehouse and to Congress, much greater.

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[1] Hansen, J., P. Kharecha, M. Sato, V. Masson-Delmotte, F. Ackerman, D. Beerling, P.J. Hearty, O. Hoegh-Guldberg S.L. Hsu, C. Parmesan, J. Rockstrom, E.J. Rohling, J. Sachs, P. Smith, K. Steffen, L. Van Susteren, K. von Schuckmann, and J.C. Zachos, 2013: Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLOS ONE*, **8**, e81648.

[2] Hansen, J., M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G. Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormay, B. Donovan, E. Kandiano, K. von Schuckmann, P. Kharecha, A.N. Legrande, M. Bauer, and K.W. Lo, 2016: Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous *Atmos. Chem. Phys.*, **16**, 3761-3812. doi:10.5194/acp-16-3761-2016.

[3] Hansen, J., M. Sato, P. Kharecha, K. von Schuckmann, D.J. Beerling, J. Cao, S. Marcott, V. Masson-Delmotte, M.J. Prather, E.J. Rohling, J. Shakun, P. Smith, A. Lacis, G. Russell, and R. Ruedy, 2017: Young people's burden: requirement of negativeCO2 emissions. *Earth Syst. Dynam.*, **8**, 577-616, doi:10.5194/esd-8-577-2017.

The problems are bipartisan. The problems are not solved by replacing one party with the other. I will provide numerous examples showing that both parties are at fault.

Democracy can still work. Making democracy work has always been hard. Yet democracy has the advantage that it is possible to have a peaceful revolution, a revolution without guns.

Founders of the American government, who signed the Declaration of Independence and framed the Constitution, anticipated that occasionally a revolution would be needed. That time has arrived.

The revolution should restore government of the people, by the people, for the people. The revolution should come from the center. It requires a new political party in the United States, which should be based on bedrock principles of the American Constitution.

As a name, I would suggest the American Party. Its slogan: 'Make America America Again'.

Here I should give a few words about my rationale and my prejudices.

First, as a scientist, I recognize that many of our issues are global. Climate change, for example, cannot be addressed by the United States alone. Cyber security, terrorism, pandemics – I could go on – there are many matters that require global cooperation to avoid or minimize problems.

Second, my perspective is affected by having grown up in the aftermath of World War II. The United States exerted leadership in establishing the United Nations, the Universal Declaration of Human Rights, and numerous organizations such as the World Bank. It was not a zero sum game. Standards of living rose almost worldwide.

Some people will argue that the situation is different now, that my perspective is outdated. I believe, more than ever, that issues are global and American leadership is crucial.

Yes, there are problems with international organizations. Parts of the United Nations are ineffectual or even corrupt. These should be fixed, and the United States has the clout to help see that they are fixed. There is no plausible alternative that will work, in my opinion.

Time is running out. You do not have time to repeat my mistakes. I hope you can learn from my experience. I will not hold back relevant information. You can judge what is helpful.

Don't waste your time in the shouting match between the political extremes. Nor can you learn much that is useful by listening within a single echo chamber.

I am sorry that we older people are leaving problems for you. I do not mean that we will desert you – we will keep doing what we can. For example, I am trying to provide science for lawsuits against governments and the fossil fuel industry, which will help put pressure on the system.

I am heartened that many of you are standing up for your rights. Of course it is not enough to demand solutions. You will need to understand what will work and demand that, and perhaps work on those solutions yourselves.

One of the things that I learned in science is that understanding a problem is 90 percent of the solution. Your planet and your future depend upon your understanding and your actions.

Jim Hansen

Chapter 1. Ancestry

Hansens are of Danish extraction, I always thought.

It is true that my father's grandparents, Ingvert and Karen Hansen, emigrated from Denmark in 1860. Ingvert, born in Ribe County, Lihme, in rural Denmark in 1836 was a Lutheran, like most Danes. At age 19 he was converted to the Latter Day Saint (LDS) religion[4] by Mormon missionaries. He served four years as a Mormon missionary while he worked as a carpenter in Denmark. At age 23 he married Karen Petersen of Holme, Denmark, and in 1860 they used her small inheritance to pay for their trip to America, where they hoped to contribute to the building of Zion, the Promised Land.

Ingvert, Karen and 729 other 'Saints', converted Danish, Swiss and English Mormons, set sail in May 1860 from Liverpool on the William Tapscott, a three-deck sail ship usually used for freight. With unfavorable winds, the trip took 35 days on rough seas, during which 10 passengers died, 9 marriages occurred and four babies were born, one of these to Ingvert and Karen. They named their first child William Tapscott Bell, after the ship's captain James Bell, which may have helped assure that the newborn was declared an American citizen by the captain. The captain had sole authority to declare whether a child was born close enough to shore to be a citizen. The most arduous leg of their journey, by oxcart from Omaha to Utah, required 2½ months. They reached Salt Lake City in October 1860.

Ingvert's carpenter tools, carried from Denmark, aided their pioneer struggles in the forbidding Utah landscape. But Ingvert and Karen became disillusioned with Brigham Young's version of the Latter Day Saint church, especially its polygamy (more precisely polygyny, plural wifism). From an apostate Mormon, Alex McCord, they learned about a smaller offshoot of the Latter Day Saint church, the Reorganized Church of Jesus Christ of Latter Day Saints, RLDS[5], with members located mainly on the eastern banks of the Missouri River in Iowa and Missouri.

The RLDS church described by McCord was closer to what the Hansens thought they were joining when they left Denmark. So in 1864, now with three children, Ingvert and Karen set out with their oxen on the Mormon Trail in reverse. Their goal, on the advice of McCord, was to homestake in western Iowa, which in 1864 was prairie, tallgrass prairie, with trees or tree groves growing mainly along the streams.

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[4] The LDS movement arose during an early 19th century period of Protestant religious revival, which some scholars relate to rejection of the rationalism of the Enlightenment or Age of Science and Reason. I believe it indicates that science and reason alone do not satisfy the need of many people for a spirituality that provides strength and helps give meaning to their lives. Joseph Smith founded the LDS movement in western New York after he had visions in which Smith claimed God instructed him not to join any of the existing churches. Smith said that an angel showed him the location of golden plates with writing that he translated, with divine assistance, to a new sacred text, the Book of Mormon, which he published in 1830 as a complement to the Bible. As Smith's following grew, local opposition forced repeated moves of the group, eventually to a small town in Illinois that they named Nauvoo. Nauvoo's population reached a peak of about 14,000 rivaling that of Chicago, but renewed tensions with non-Mormons resulted in the murder of Joseph Smith by a mob in 1844. The largest group of Mormons accepted Brigham Young as the new prophet and leader and emigrated with him to the Utah Territory. Under Young the LDS Church openly practiced polygyny, which Smith had instituted in Nauvoo. The LDS Church officially ended plural marriage in 1890, and today members who practice it are excommunicated. The LDS Church has extended its reach internationally via a vigorous missionary program, growing to a membership of about 15 million.

[5] The RLDS church changed its name to Community of Christ in 2001. It reports about 250,000 members today.

Upon reaching southwest Iowa Ingvert and Karen settled in Gallands Grove[6], in the northwest corner of Shelby County 15 miles southwest of Denison. A majority of the settlers already in the Grove were Mormons who had been driven from their homes around Nauvoo[1], Illinois, but had decided not to follow the Morman leader Brigham Young to Utah. The Hansens were nearly penniless, but according to Shelby County history, Alex McCord made it known that the Hansens were "hard workers, good credit, and needed help in getting settled".

The homestead may have appeared to be Eden compared to Utah, but it was hilly, rocky land, difficult to plow. Some years the crops were lost to a grasshopper plague, chinch bugs, or drought and dust storms. It wasn't all bad, though: chickens and pigs fattened on the grasshoppers. Ingvert and Karen never strayed far from the Grove. The eighth of their 11 children was James Edward Hansen, my grandfather, known as Jim Hansen.

Only 25 percent of the blood in my veins comes from my grandfather, Jim Hansen. Another 25 percent is from his wife, Katherine (Kate) Von Tersch. Kate was daughter of Johan Von Tersch and Mary Wilwerding, immigrants from Westphalia, Germany and Belgium, respectively. While Jim's parents were carving a farm out of the woods, in Gallands Grove, Kate's parents settled on nearby prairie land. Jim and Kate had eight children, the second being James Ivan Hansen, my father. So, from my father, my siblings and I are 25 percent Danish, 12½ percent German, and 12½ percent Belgian.

My oldest sister, Donna Hansen Stene, compiled this information in *The Hansen Family*[7]. Her subsequent work on our mother's ancestry does not yield such precise genealogy, because of the longer history of our mother's family in the United States.

My mother's parents, John Ray and Florence Longenecker, immigrated to Iowa from Pennsylvania. The Rays immigrated to Pennsylvania from Oirville Alsace Lorraine. Alsace Lorraine is in France today, but it is a region that was fought over for centuries and was alternately German and French. Our branch of the Longeneckers lived in the Emmental valley of Switzerland where they were Anabaptist Evangelicals before moving to the Palitinate in southwestern Germany from whence our ancestors emigrated to Pennsylvania in the 1700s. There they were initially Mennonites, but joined the River Brethen movement that developed in the Susquehanna valley region. From there Joshua Longenecker and family emigrated to Iowa.

Ancestral bloodlines described in the preceding paragraph refer to the father of John Ray and the father of Florence Longenecker. The mothers of John and Florence contribute equally to the blood in my veins. Their origins are summarized by my sister Donna as: John's mother (Switzerland and elsewhere) and Florence's mother (Netherlands, Scotland and elsewhere).

Considering the contributions of Germany to the population of Alsace Lorraine and to the relevant part of Switzerland, I conclude that there probably is more German blood than Danish blood flowing in my veins. This will be of some small interest, at least to me, when I later consider the roles of Germany and the United States in creating the climate debacle that young people face today.

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[6] Abraham Galland was the first white settler in Shelby County, building a log cabin in Gallands Grove in 1847.
[7] The Hansen Family, C.S. Stene and D.H. Stene, 389 pp., Library of Congress CCN:2009902650, 2009.

We do not know much about the pioneer, my Great Grandfather Ingvert Hansen. His only surviving writings, of which we are aware, are a diary for parts of the travel from Denmark. We know that his farming in the "hardscratch" Grove soil was arduous, but he had five sons to help with the farming, as well as six daughters to help his wife, Karen. He likely retained his strong religious bent, as he eventually became the presiding Elder in the RLDS church in the Grove.

Our best source of information about Ingvert's character, my sister suggests, may be the inscription on his gravestone, which reads: "An honest man's the noblest work of God."

One story from Ingvert's pioneer days has been passed down the generations. It's about Yellow Smoke, Chief of the Omaha Indians.

> *Chief Yellow Smoke was the keeper of the Sacred Pole, the centerpiece of ceremonies, subject of sacred songs, and symbol of the tribe's well-being. Yellow Smoke's name came from the yellow smoke stain on the pole, which was displayed in the Smithsonian Museum in Washington, D.C., and now rests with the Omaha Tribe at Macy, Nebraska, according to the Crawford County History website.*
>
> *Yellow Smoke often visited the farms of Ingvert and his neighbor, John McIntosh. McIntosh was one of the first settlers in Shelby County, in 1849. Yellow Smoke called McIntosh the "Mormon Chief*[8]*." It is possible that McIntosh and Ingvert tried to convert Yellow Smoke to the Mormon faith, as both Joseph Smith and Brigham Young advocated that approach. In any case, Yellow Smoke expressed a desire to be buried "like a white man" in the Grove. He got his wish much sooner than he would have wanted.*
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> *The most reliable account of Yellow Smoke's demise, in my opinion, is the story passed from Ingvert to later Hansen generations. Sparsely settled western Iowa changed rapidly in the second half of the 1860s when a railroad was built across the state, reaching Council Bluffs in the fall of 1866. The town of Dunlap on the Boyer River several miles west of Gallands Grove sprang into existence in 1967, after the town was platted by a railroad company*[9],[10]*. Chief Yellow Smoke took a liking to gambling and drinking with white men in Dunlap.*

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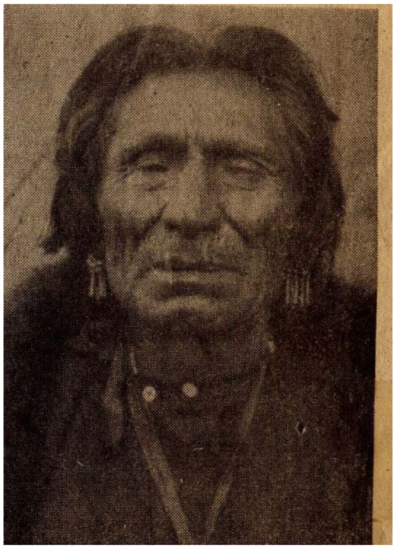
[8] I do not know of McIntosh's official position in the Latter Day Saint church or the RLDS, which was established in 1859. Ingvert eventually became the Presiding Elder. For decades RLDS had a log cabin church, but in 1880 a frame building was erected at a cost of $1300, likely making use of Ingvert's skill as a carpenter.

[9] According to Harrison County history the land by the Chicago & Northwestern railroad on which Dunlap was built was awarded by the government to "the great railroad king" John J. Blair. The Flair Town Lot and Land Company platted the town in June 1867, naming the town for George Dunlap, a railroad official. The second building constructed in Dunlap, in 1867, according to Harrison County history, was a saloon named 'Respectable Place', which likely was the place Yellow Smoke received his mortal injury.

[10] History of Harrison County, Iowa : its people, industries and institutions, with biographical sketches of representative citizens and genealogical records of many of the old families



Yellowsmoke photograph from newspaper article handed down by our father. The article described Yellowsmoke as between six feet and six feet two inches in height and weight 200-230 pounds.

> *According to my ancestors, Yellow Smoke was mortally wounded after demanding his winnings from a card game, the winnings being 75 cents. An argument and scuffle ensued during which Yellow Smoke was struck on the head. The blow crushed his skull. Yellow Smoke managed to reach Gallands Grove, four miles east of Dunlap, where Omaha Indians were encamped, but he died several days later and was buried in the Grove.*
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> *An article in the New York Times on 5 December 1868 says that after Yellow Smoke was struck and injured on the evening of 27 November "He succeeded in getting to where there were several hundred Indians encamped, about four miles east of town. He expired on Wednesday morning." Wednesday was 2 December 1868. The 5 December Times story also notes "The Chief was always noted for being very friendly and strictly honorable. His band comprises some 1,500 warriers, who according to reports are gathering in fast and are greatly excited. Yellow Smoke was buried yesterday."*
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> *According to my father, Yellow Smoke was buried on Ingvert's property. William Hansen, Ingvert's oldest son, acquired the larger part of Ingvert's property, and passed the land on to his son, Billy. William, born on the boat on the way to America, was 8½ years old when Yellow Smoke was murdered. According to William's son Billy, Yellow Smoke was buried under a tree on Ingvert's property, and subsequently they were never allowed to plow close to the tree, because of the grave. An article in the 15 June 1978 Harlan Tribune says that Indians continued to visit the grave and camp on the sacred ground as late as 1922. That article suggests that the grave may have been on the 'Mormon Chief' John McIntosh property, but I believe that the information passed from William to Billy is more credible than a newspaper article discussing what they describe as a "legend."*

There are other, uncomplimentary, stories about Chief Yellow Smoke, which I will note in due course. When combined with several other pieces of information, the Yellow Smoke story has a significant impact on my thinking. I believe that it may affect yours, too, but we must defer the discussion to a later chapter.

Gallands Grove and surrounding areas changed enormously during the first two generations of settlers. We have no writings by Ingvert or his wife Karen describing their Iowa homestead. However, the Grove, about 15 miles southwest of Denison, Iowa, is near adjoining corners of four counties, Crawford, Shelby, Harrison and Monona. Historical data sites for these four counties provide helpful information, especially a 488 page history of Harrison County[9] that contains reminisces of several early pioneers, including D.W. Butts and Sally Young:

> *Pioneer Butts decried the loss of the deep-rooted 6-foot prairie grass that, except for the occasional tree grove, once covered western Iowa, noting that the prairie grass was succeeded by 2-foot "tame grass" and weeds. He wrote "The grass, the natural product of this valley, was so high and luxuriant for miles and miles that horsemen might hide from each other at a distance of two hundred yards. Quite as surprising as this true statement is the rapid change by which this tall grass disappeared very quickly after the white man appeared with cattle and crowded out the deer and the elk and the red men. We expected to see the range gradually reduced, but were hardly prepared to see it go down from six feet to two feet in a few years. However, the wild hay of this section has been a mine of wealth to many, and it is yet to those who had the foresight to save it from the flock and plow. Forty years ago this part of the state was noted for grass and hay, as it is now for corn and hogs!"*
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> *Pioneer Sally Young wrote "We located in this county in 1850 and found, as we thought, the garden of Eden, a vast prairie of beautiful flowers and a great abundance of wild fruits. At this time the country was very thinly settled, our nearest neighbors being six miles away." She complained about the flies and mosquitoes, but continued " There were oceans of game, tons of fall acids in the shape of plums and grapes. The thousands of deer which roamed up and down the valley…were to be had at the little cost of shooting and dressing, and gave to the larder all, yea, perhaps, better than is now experienced by many, who at present live in this, what is termed the land of plenty. Great droves of wild turkeys lined the skirts of the interior timber track, and honey was far more plentiful then than now."*

Modern agriculture is succeeding in feeding a large population. Yet it has flaws that affect human health and the environment. There is something to be learned from natural tallgrass prairie. For now, we only note that there are potential improvements to current agricultural practices that would help restore biological diversity and increase soil productivity while also storing more carbon in the soil, changes that would help limit human-made climate change.

D.W. Butts wrote of "red men," who were called Indians when I was a boy, or American Indians when corrected by our school teachers, or Native Americans today. By the late 1800s Native Americans in western Iowa had been moved to the less productive land west of the Missouri River. Let us finish our initial remarks about Native Americans with one poignant paragraph from the Harrison County history[9], titled there as "Indian Troubles"

> *"The last difficulty with Indians in this part of the country was in 1885, when a band of about three hundred were in the habit of crossing the Missouri river into Harrison county. They were quite friendly, but annoyed the citizens very much by pilfering stock and poultry. To put a stop to this the whites, twenty in number, assembled and met the band when they had crossed the river. The twenty whites captured the three hundred Indians, loaded their bows and arrows into wagons and took them over the county line at Honey Creek, Pottawattamie county. The Indians were half starved, and the humane white people gathered together and*

> *raised a fund with which a steer was bought and given the Indians, who seemed to greatly appreciate the act of kindness. After the feast, the day following, they went over the river to their homes in eastern Nebraska."*

Kindness of the humane white people is a matter of perspective. Continual forced displacement of Native Americans, with near genocidal results, is now an historical fact that cannot be altered. However, I will suggest that there are potential actions to minimize climate change and climate impacts that could be designed with Native Americans to usefully restore some natural environment. We must defer this topic until we have described the climate situation.

I struggled to write the next chapters of this book. I wanted to describe my life growing up in Denison, Iowa. Denison was a wonderful place to grow up. Our mother told us many times how lucky we were, and she was right.

Yet I also needed to understand more about my parents' struggles and pressures they were under as they tried to provide for their family. I dug into the 390 page *The Hansen Family*[6] written by my oldest sister, Donna Hansen Stene, and her husband, as well as 62 pages of unpublished vignettes[11] on our childhood written by my second oldest sister, Eleanor Hansen Maiefski, who was the story-teller in our early days of raucous child-filled bedrooms. Their stories raised more questions, which led to hundreds of e-mail exchanges with all of my siblings. Their detailed remembrances and frank assessments have been most helpful to my understanding.

As I learned more about events before I was born, it seemed that my parents had inherited a situation with odds stacked against them. Was that bad luck? A failure of their parents, the generation after Pioneers Invert and Karen Hansen? I needed to know about my grandparents.

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[11] *Surviving After the Great Depression*, Eleanor Hansen Maiefski, 62 pages, unpublished.

Greenhouse warmings of Mars, Earth and Venus are about 5°C, 33°C and 500°C.

Chapter 13. Runaway Greenhouse

The Goldilocks planets, Mars, Venus and Earth, too cold, too hot, and just right, provide a nice set of planets to illustrate the greenhouse effect. The surface temperature of each planet is determined by the amount of solar energy it absorbs and by its atmospheric composition.

Physics of the greenhouse effect is simply energy balance: a planet must send back to space, in the form of heat radiation, the same amount of energy that it absorbs from sunlight. We know the amount of absorbed solar energy – from the Sun's measured irradiance and the planet's measured albedo, which is the fraction of incident sunlight that the planet reflects away.

Calculation of the planetary temperature required to radiate this absorbed energy is trivial if the planet has no atmosphere. The Stefan-Boltzmann law gives the radiation to space in that case, with the radiation proportional to the fourth power of temperature. This law was deduced by Josef Stefan in 1879 on the basis of laboratory measurements by the Irish physicist John Tyndall and derived from thermodynamic theory by Ludwig Boltzmann in 1884.

Gases or airborne particles that absorb heat (infrared) radiation act like a blanket, limiting the heat escaping to space. As a result, the surface must be warmer than calculated with the Stefan-Boltzmann law, in order for the planet to send the required amount of energy back to space.

Mars' atmosphere is so thin that almost all of the heat radiation from the ground goes straight through the atmosphere to space. Therefore Mars' surface temperature is only a few degrees warmer than the temperature calculated from the Stefan-Boltzmann law. Specifically, Mars requires a surface temperature of only about minus 50 degrees Celsius (-50°C) in order to radiate back to space the energy that it absorbs from the Sun. The temperature -50°C is about 60 degrees below zero Fahrenheut (-60°F). Mars is, indeed, too cold for bears or humans.

Earth is more complex than Mars, because Earth has a thicker atmosphere of gases, clouds and aerosols. Tyndall made meticulous measurements of the radiation properties of many atmospheric gases.[12] He found that the main constituents of Earth's atmosphere, the diatomic molecules nitrogen (N_2) and oxygen (O_2), are transparent to both visible light and infrared radiation, but the triatomic molecules, water vapor (H_2O) and carbon dioxide (CO_2), are strong absorbers of infrared radiation.[13] We will learn more about remarkable John Tyndall later.

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

[13] Their triatomic structure results in vibrational energy states that are excited by infrared photons.

Earth absorbs 70% of the energy it receives from the Sun. If Earth had no atmosphere, its temperature would need to be about -18°C (about 0°F) to radiate that amount of energy back to space, according to the Stefan-Boltzmann law. In reality, Earth's average surface temperature is a pleasant +15°C (59°F). So Earth's greenhouse effect is 33°C (almost 60°F).

Venus absorbs only 23% of incident sunlight, because of its thick, complete cloud cover. As a result, it requires a planetary radiating temperature of only -45°F (-43°C) to radiate that energy back to space. However, the Venus surface temperature is more than 450°C, hot enough to melt lead! The greenhouse effect on Venus is about 500°C (900°F)!

The main reason for the huge greenhouse effect on Venus was revealed by the Venera spacecraft. The surface pressure on Venus is about 90 bars and the atmospheric composition is almost entirely CO_2. Other constituents, specifically the small amount of water vapor, the clouds, and sulfur dioxide (SO_2), in that order, contribute, but CO_2 is responsible for about two-thirds of the greenhouse effect on Venus.[14]

So the three Goldilocks planets nicely illustrate weak, moderate and strong greenhouse effects. But how did the planets get to the present situations? What are the implications for future climate change on Earth? Can Earth end up like Venus, as a lifeless hothouse? My description of runaway greenhouse on Earth in my first book, *Storms of My Grandchildren*, had a flaw that I want to correct, so I will make the greenhouse story clearer here.

Venus suffered a runaway greenhouse effect that reached a terminal state, the 'baked crust' greenhouse. Baked crust? How does that work? Venus was doomed to a baked crust, and a permanent climatic hell, as soon as it lost its ocean. But let's back up a step first.

The crust is the outer layer of a solid planet such as Venus or Earth, like the skin on an apple. Continents are tectonic plates, which are mobile in this viscous outer layer. South and North America, for example, are sliding westward at a rate of about an inch per year, overriding the thinner crust under the Pacific Ocean.

Volcanoes and mountain building occur along the edges of the continental plates, continually pouring volatile gases, including CO_2, into the atmosphere. On a planet with an ocean, the CO_2 gets put back into the crust rather quickly – that is, if you consider a few thousand years to be quick, which it is for a planet billions of years old. The mechanism for extracting CO_2 from the air is the weathering process and chemical reactions in the ocean, which ultimately deposit the CO_2 as limestone on the ocean floor. We will consider weathering more when we examine ways to speed up this natural process, so as to remove human-made CO_2 from the air.

On a planet without an ocean, like the Venus of today, CO_2 from volcanoes stays in the air, building up to a huge amount – the crustal CO_2 is 'baked' into the atmosphere. There is so much CO_2 in the air that the surface pressure, about 90 bars, i.e., 90 times the surface pressure on Earth, would crush a human being, if he or she were not already fried to a cinder.

How did Venus lose its ocean? Will Earth lose its ocean? That depends. The story is pretty easy to understand.

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[14] Pollack, J.B., Toon, O.B. and Boese, R., Greenhouse models of Venus' high surface temperature, as constrained by Pioneer Venus measurements, J. Geophys. Res., 85, A13, 8223-8231, 1980.

Our Sun, and the planets orbiting about it, formed 4.6 billion years ago from a swirl of gas, ice and dust in a spiral arm of our Galaxy, the Milky Way. Planetary formation will be a focus topic in the Galileo chapter, but for the moment, let's just note that Venus, because it is less massive than Earth and closer to the Sun, but not too close, was able to capture and retain water, but not as much water as Earth captured.

Venus, when it was young, had enough water to form an ocean, but the ocean was not nearly as deep as the ocean on Earth. As Venus aged, it lost its ocean, which, as already mentioned, is a prerequisite for a planet to experience the extreme 'baked-crust' runaway greenhouse.

How can a planet lose its water? The molecules in the air are all jostling about, bumping into each other, moving faster when the gas is hotter, the smallest ones gaining the fastest speed after bumping into heavy ones. In the upper fringes of the atmosphere solar ultraviolet radiation continually breaks up (dissociates) molecules. Hydrogen, the lightest atom, moves the fastest, and sometimes, before it recombines with another atom or molecule, it shoots out into space, escaping the planet's gravity. When hydrogen atoms that were part of water molecules fly off into space, the amount of water on the planet decreases, as the oxygen atoms left behind combine with other elements or with themselves, thus forming the oxygen molecule O_2.

How much water did young Venus have? We know that pretty well, based mainly on Pioneer Venus measurements of the amount of deuterium in the Venus atmosphere. Deuterium, sometimes called 'heavy hydrogen', is an isotope of hydrogen. Isotopes of any given element all have nearly the same physical and chemical properties, except they differ in mass because they have different numbers of neutrons in the nucleus. A normal hydrogen atom has only a proton in its nucleus, but deuterium has a proton and a neutron. So deuterium is about twice as heavy as normal hydrogen. Because it is heavy, it cannot easily escape to space.

Pioneer Venus found that the deuterium amount on Venus was about 1 percent of total hydrogen. That is a big enrichment compared to the initial deuterium amount on Venus, which was believed to be only 50 parts per million (ppm) of total hydrogen. Based on these data, Mike McElroy and colleagues[15] concluded that Venus initially had enough water to form a layer 8 meters thick, if it covered the entire planet. This was a lower limit because some deuterium probably also escaped.

Moreover, the Galileo mission to Jupiter found that the deuterium proportion of hydrogen on Jupiter was only 25 ppm, not 50 ppm. Jupiter's gravitational field is too strong to allow even hydrogen to escape, so 25 ppm is a good estimate of the primordial deuterium abundance in the solar nebulae that formed the planets. Therefore McElroy's estimate of the initial water on Venus should be increased to at least 16 meters, which is about half of 1 percent of the amount of water on Earth today.

Sixteen meters of water is still a lot of water to be lost via hydrogen escape. That much water could not have escaped if the Venus atmosphere had a "cold trap" like the one on Earth. The upper troposphere on Earth, at a height of about 10 miles, is so cold that it 'wrings out' almost all the water. When air mixes upward from Earth's lower atmosphere it must pass through this cold trap. The upwelling air is then so dry that it delivers very little water to the outer fringes of the atmosphere. Water cannot escape the planet, at least not a significant amount of water.

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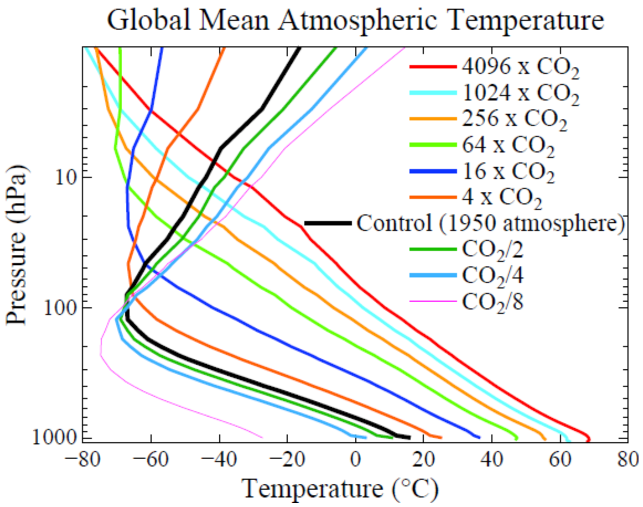
[15] McElroy, M.B., M.J. Prather and J. Rodriquez, Escape of hydrogen from Venus, Science 215, 1614-1615, 1982.



Global mean temperature profile for successive doublings of atmospheric CO_2.

Yet Venus' ocean escaped, we know from deuterium. How could that be, when a cold trap was expected to exist on Veuns?[16,17] Andy Ingersoll[18] suggested a solution to this conundrum: a runaway greenhouse. He argued, that, if a planet were warm enough for water to be a major constituent of the atmosphere, the greenhouse effect would force continuous evaporation of surface water, and convection would carry water vapor to altitude, leading to more water being available for dissociation by ultraviolet light in the upper atmosphere.

In effect, Ingersoll was saying: if the climate forcing is large enough, so the atmospheric temperature is high enough, so the water vapor mixing ratio is large enough, the resulting blocking of infrared heat transport will force a pumping of water vapor into the upper atmosphere, where the hydrogen can escape. This is not really a Rube Goldberg machine, it is pretty simple, but it needs to be tested with realistic calculations. Ingersoll assumed that water absorbed at all wavelengths, while actually it has absorption bands and windows, i.e., some spectral regions in which it is quite transparent. Also the transport of water vapor upward should be calculated using a realistic description of moist convection in a global climate model.

Such calculations[19], shown in the above figure, confirm Ingersoll's thesis. The climate forcing in this case was successive doublings of atmospheric CO_2 amount, but similar results would follow if the forcing were increased solar irradiance. Each CO_2 doubling provides an additional forcing of about 4 W/m^2. Thus $1024\times CO_2$ is 10 doublings, a forcing of about 40 W/m^2.

The climate model control run had Earth's atmosphere and distance from the Sun, thus solar heating of the planet was about 240 W/m^2. If the planet were moved to the orbit of Venus, where solar irradiance is twice as large as at Earth, and if the reflection of sunlight (albedo) of the planet was 30% as it is for Earth (early Venus would not be expected to have sulfuric acid clouds), the solar forcing relative to our control run would be about 240 W/m^2. We infer that no cold trap existed on Venus, and its modest ocean was lost to space. Once the ocean was gone,

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[16] Sagan, C., The radiation balance of Venus, Cal Tech JPL Tech. Rept. 32-34, 23 pp., 1960.

[17] Gold, T., Outgassing processes on the moon and Venus, in The Origin and Evolution of Atmospheres and Oceans, Eds. Brancazio & Cameron, New York, Wiley, 249-256, 1964.

[18] Ingersoll, A.P., The runaway greenhouse: a history of water on Venus, J. Atmos. Sci., 26, 1191-1198, 1969.

[19] Hansen, J., M. Sato, G. Russell and P. Kharecha, Climate sensitivity, sea level and atmospheric carbon dioxide, *Phil. Trans. Roy. Soc. A.* **371**, 20120294, 2013; see Figure 7.

the CO_2 belching from volcanoes stayed in the atmosphere and Venus was on its way to being a baked-crust permanent hothouse.

Earth's runaway greenhouse, the one that could occur soon if we allow it to happen, will not be the terminal baked-crust greenhouse. Let us assume that we are so foolish as to keep burning fossil fuels to the point that we quadruple atmospheric CO_2. Global warming would be of the order of 10°C, according to the above simulations and confirmed by Earth's history. The change of the atmospheric temperature profile would allow more water vapor to be pumped to the upper atmosphere, so the rate of hydrogen escape would increase. However, within several millennia the weathering process will draw down most of the excess CO_2 in the air, depositing the carbon on the ocean floor as limestone. The amount of water lost from the ocean to space in that period will be negligible. Burning fossil fuels cannot lead to a baked crust runaway greenhouse.

A terminal baked-crust runaway, requiring loss of the ocean, can occur on Earth on the billion year time scale. Our Sun, an ordinary star, is increasing in brightness by about 10 percent per billion years.[20] A 10 percent increase of solar irradiance causes a climate forcing equivalent to five doublings of CO_2, a CO_2 increase by a factor of 32. That changes the temperature profile enough to increase the flux of hydrogen into space, which begins to affect the ocean volume.

If that worries you about the future of humanity, assuming that humanity still exists in a billion years (fat chance, at the rate we are going), put your mind at ease. An advanced civilization could easily shield the Earth or perhaps even push the planet to a greater distance from the Sun.

Our real concern should be the runaway greenhouse that can occur if high fossil fuel emissions continue. Consider the extreme of quadrupling CO_2, which could cause global warming of the order of 10°C. The tropics would be uninhabitable, as would the subtropics in the warm season. All of today's coastal cities would be lost to rising seas. Migration pressures might make the world ungovernable.

Such a result should be preposterous, considering the fact that technological cooperation among the major world powers could readily initiate a rapid phasedown of emissions. However, the present idiotic political trend toward every-nation-for-itself and damn the consequences for young people, leaves open the possibility, if not the likelihood, of climate runaway disaster.

In *Storms of My Grandchildren*, extraterrestrial visitors to Earth in 2525 found a lifeless planet. Such an outcome is conceivable, given the potential chaos accompanying the greenhouse runaway that is possible on the 500 year time scale. The flaw in *Storms* is that the visitors witnessed boiling tropical oceans. That physical state in not possible on a 500-year time scale. That sentence should be eliminated or altered. A boiling ocean will not happen until Earth gets to a baked crust runaway. And that will take a very, very long time.

Planetary science was my love for years. Like other researchers, I said that planetary studies help us understand Earth better. That rationale helps justify why taxpayers should fund planetary missions. And it is true. However, Earth was not my main interest. This was about to change.

It is not as if a light bulb suddenly turned on. That is not how it works. It took several steps, through the weather, and the ozone, and an enthusiastic, persuasive young post-doc.

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[20] Sackmann, I.J., A. Boothroyd, and K. Kraemer, Our sun III: present and future, *Astrophys. J.* **418**, 457-468, 1993.

Chapter 20. Greenhouse Giants

Joseph Fourier, a French mathematician and physicist, wrote[21] 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. Most wavelengths of sunlight penetrate the cloud-free atmosphere, heating Earth's 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. In other words, the atmosphere acts like a blanket, warming the surface.

Earth must radiate back to space as heat the same amount of energy that it absorbs from the sun. The atmospheric blanket of greenhouse gases forces Earth to warm to a degree that the radiation emitted to space equals the absorbed solar energy. If Earth had no atmosphere, and still absorbed 70 percent of incident sunlight as it does today, its (blackbody) temperature would need to be only -18°C. Actual surface temperature of Earth is +15°C.

Thus the natural greenhouse effect on Earth is 33°C, about 60°F. Without this greenhouse effect, Earth would be uninhabitably cold. A supposed human-made increase of global temperature, usually called 'global warming,' is surely small compared with the natural greenhouse effect. Can the smaller human-made effect really be important? That question has a long history.

John Tyndall, an Irish physicist, is the father of the greenhouse effect and global warming, in the sense that he made the greatest contributions to the science and our understanding of it. Tyndall converted the qualitative statements of Fourier and others into quantitative science through an enormous body of research and laboratory measurements[22], and he communicated his developed understanding in a language everyone could understand.

Tyndall had keen physical insight about climate, and he made the fundamental measurements that established the science. He realized the dominant impact of atmospheric water vapor in keeping Earth's surface warmer than it otherwise would be, writing (ibid, p. 423):

> "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."

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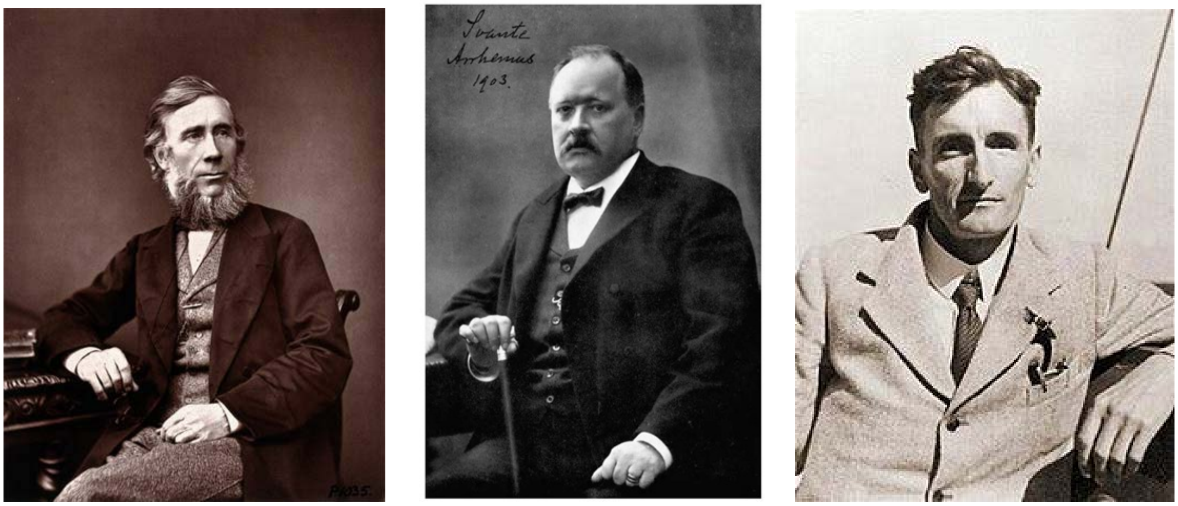
[21] Fourier, J., Remarques generals sur les temperatures du globe terrestre et des espaces planetaires, Annal Chim. Phys., 27, 136-167, 1824.

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



John Tyndall, Svante Arrhenius and Guy Callendar. Tyndall Image credit: Wellcome Library

Tyndall wrote with elegance, but also with the clarity of a physicist, about the importance of water vapor in keeping Earth's surface warmer than it would be in the absence of that gas, which acts 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 radiate to space the same amount of energy that it receives from the Sun.

Tyndall properly credited earlier researchers, De Saussure, Fourier, Pouillet and Hopkins with the concept for the greenhouse effect, that such gases are transparent to sunlight but absorb heat (infrared) radiation. However, Tyndall deserves full credit for the laboratory work that established the experimental basis for the greenhouse effect.

Tyndall even had an inkling that changes of greenhouse gases may account for known climate changes, stating in his 1861 Bakerian lecture[23]:

> *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[24] on 1 June 1866, he stated that changes in radiative properties alone were unlikely to be the root causes of glacial epochs. Tyndall had neither the tools nor the data needed to interpret the root causes of the ice ages. Tools and 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 sentence 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 how much?

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

[24] 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.

Svante Arrhenius, a Swedish physicist and physical chemist, took up Tyndall's challenge, that is, he tried to quantify how sensitive global temperature is to a specified climate forcing. Thanks in good part to the extensive laboratory measurements of Tyndall, Arrhenius had a good grasp of the nature of the problem.

Earth's atmosphere and surface are heated by the sun, with maximum heating at the ground, because of the atmosphere's transparency to sunlight. Earth must radiate an equal amount of energy to space, but because of the blanketing of Earth's thermal radiation by greenhouse gases, energy is carried upward in Earth's atmosphere by both radiation and convection. Convection, rising and sinking air, establishes a vertical temperature gradient in Earth's atmosphere, temperature falling off with height, an average of about 6°C per kilometer of altitude.

Absorption by gases, mainly water vapor and carbon dioxide, is ubiquitous across the entire spectrum of Earth's infrared (heat) radiation, but absorption is by no means uniform across this wavelength spectrum. High variability of absorption with wavelength implies that heat 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 (18°C below zero), the temperature that a solid body requires in order to radiate the energy that Earth absorbs from the Sun. Also 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.

This general picture was already clear to Arrhenius, but not the quantitative data I just provided. 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 changed. He used infrared measurements by American astronomer Samuel Langley of the full moon. 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. He correctly inferred that 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 very 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.[25] This first estimate of 'climate sensitivity' (global warming in response to doubled CO_2) 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[26] 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. The basic physics, understood for well over 100 years, is that more CO_2 molecules trap more radiation in the lower layers of the atmosphere. As Tyndall aptly stated, more greenhouse gases, are a thicker blanket that makes the surface warmer.

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[25] 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.

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

Knut Angstrom, another Swedish scientist, in 1900 disputed Arrhenius, arguing that CO_2 absorption bands are 'saturated', i.e., they absorb essentially all of the radiation within narrow spectral (wavelength) regions and negligible energy elsewhere.[27] Therefore, he suggested, additional CO_2 would have little effect.

The effect of band saturation actually was accounted for in Arrhenius empirical evaluation. Partial saturation of absorption bands is a reason that the warming effect is not linear in CO_2 amount, as Arrhenius correctly deduced. Even at wavelengths where the absorption is saturated at Earth's surface, the absorption is not saturated higher in the atmosphere, thus the added CO_2 still affects the planet's energy balance by causing the emission to space to emerge from a higher level. 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 believed that it would be several centuries before warming from fossil fuel burning would be significant. This conclusion was partly due to his estimate that 5/6 of the emissions were taken up quickly by the ocean.

Moreover, Arrhenius saw the CO_2 effects as beneficial, helping the world to 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.[28] 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. He published more than a dozen papers on the topics. Perhaps because of his engineering training, he paid special attention to the difficulties in obtaining accurate measurements. He was capable of discriminating among the various attempts that had been made to measure atmospheric CO_2, and he correctly inferred the approximate magnitude of the CO_2 increase over the prior half-century.

Callendar's insistent 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, just before precise monitoring of CO_2 was initiated as one of the advances in earth sciences initiated during the

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[27] Angstrom, K.: Ueber die bedeutung des wasserdampfes und der kohlensaure bei der absorption der Erdatmosphare, Annalen der Physik, 308, 720-732, 1900.

[28] Callendar, G.S.: The artificial production of carbon dioxide and its influence on temperature, Quar. J. Roy. Meteorol. Soc., 64, 223-240, 1938.

International Geophysical Year. Decades later, measurements on bubbles of ancient air trapped in ice cores proved that Callendar's estimate of CO_2 growth since the late 1800s was accurate.

Despite his realization that CO_2 was increasing rapidly, Callendar, too, concluded that the future warming from fossil fuel CO_2 was likely to be beneficial to humankind: "…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, as I will discuss.

An explosion of understanding related to CO_2 and climate began with the International Geophysical Year (IGY), well before global warming was clearly detected. The origin of IGY traces to a meeting of several top scientists, including Sydney Chapman and Lloyd Berkner in James Van Allen's living room in March 1950.[29] Prior International Polar Years, in 1882-1883 and 1932-1933, showed the value of international cooperation in gathering global data. These scientists suggested that the time was right for a worldwide Geophysical Year, in part because of recent advances in rocketry, radar and computing.

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. After several failed launch attempts with Vanguard rockets, an approach derived from small sounding rockets, Werner von Braun persuaded President Eisenhower to use a U.S. Army missile for the Explorer program. Within a few months, on 1 February 1958, Explorer 1 was launched, but it was the third Earth satellite, after Sputnik 2, launched 3 November 1957. The U.S. launched Vanguard 1 on 17 March 1958. The space race was on. NASA was formed on 29 July 1958. Thousands of young people, received NASA funding for graduate study, including Andy, Larry 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.[30] These discoveries, however, were only a part of a broad collection of data that helped to initiate a comprehensive overview of global physical phenomena.

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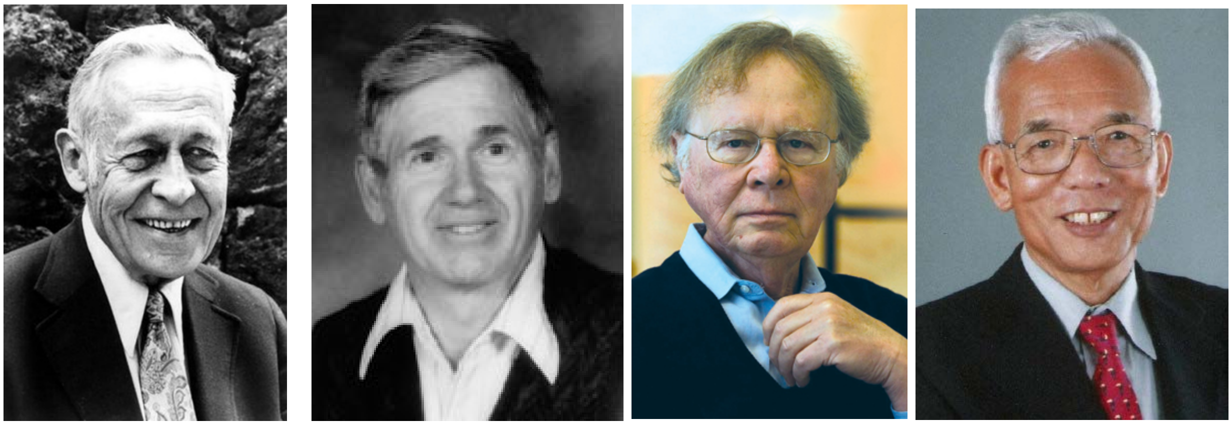
[29] Forestner, A.: James Van Allen:The First Eight Billion Miles, p. 124, University of Iowa Press, 322 pp., 2007.

[30] Discovery of this mountain chain, the largest on Earth, encircling the globe provided critical information confirming the concept of 'continental drift.' The theory of plate tectonics, that Earth's outer shell is divided into several plates that glide over Earth's mantle, the more fluid rocky layer above Earth's core, was soon developed.



Roger Revelle, David Keeling, Wally Broecker, Syukuro Manabe

Roger Revelle altered the course of the CO_2 climate story in 1957, as he realized the implications of carbon isotope data that he reported in a paper[31] in Tellus co-authored with Hans Suess. The abstract of the paper is a bit 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."

In fact, the crucial insight of the Revelle and Suess analysis was that excess CO_2 in the air from fossil fuel burning has a much more difficult time getting into the ocean than prior simple calculations suggested. More precisely, fossil fuel CO_2 molecules can get into the ocean surface, but the ocean ejects almost as much CO_2 back to the atmosphere. Ocean chemistry is a complex soup. Technically, ocean water is a buffered solution that resists a change in acidity. This buffering effect reduces by about a factor of ten the net flux of fossil fuel CO_2 into the ocean. The ocean absorbs more of the fossil fuel CO_2 as water from deeper layers mixes to the surface, but deep mixing requires centuries. The resulting long time scale for uptake of fossil fuel CO_2 is the reason that fossil fuel burning poses a threat of large climate change.

Revelle's insight and communication ability came into play in a summary statement in the paper: "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 may have been thinking about the opportunity to study geophysical processes, but he also warned about future perils. He publicly speculated that in the 21st century the greenhouse effect might exert "a violent effect on the earth's climate" (as quoted by Time magazine in its 28 May 1956 issue). 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.

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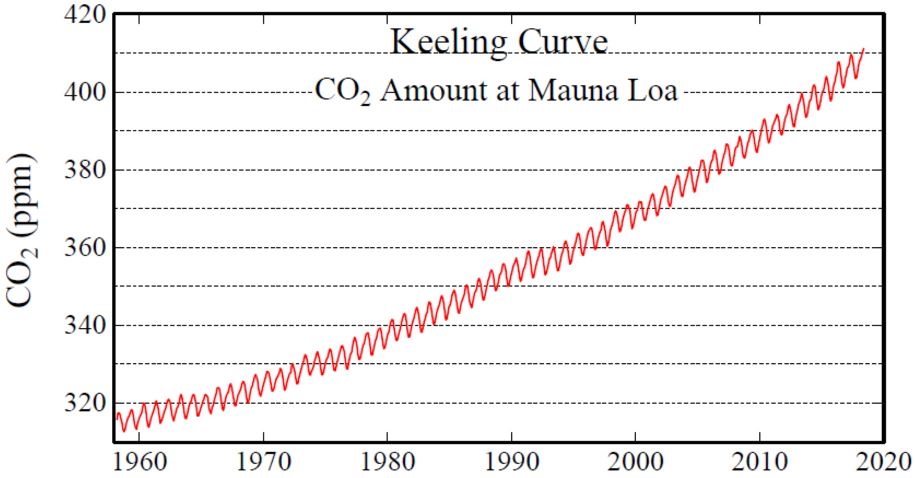
[31] Revelle, R. and Suess, H.E.: Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades, Tellus IX, 18-27, 1957.



Keeling curve today

The abstract of the Revelle and Suess paper concluded: “Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of exchange, and on possible fluctuations in terrestrial and marine organic carbon, are inadequate for accurate measurement of future changes in atmospheric CO_2. An opportunity exists during the International Geophysical Year to obtain much of the necessary information.”

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 would prove to have just the dogged determination needed for the job. Keeling’s first task was to find instrumentation capable of inherent accuracy at least an order of magnitude more precise than prior work, and he had to hunt down and understand the potential errors in operation of the instrument. He succeeded.

The result was analogous to that found by the brilliant French astronomer, Bernard Lyot, who improved the accuracy of polarimetry by an order of magnitude. Prior astronomers measuring the polarization of sunlight reflected by planets saw instrumental noise. Lyot looked at Venus and saw a beautiful smooth curve for polarization as the planet revolved around the Sun, a curve that was loaded with information waiting to be extracted.

So, too, Keeling was to find a beautiful smooth curve loaded with information, a curve for atmospheric CO_2 amount as a function of time, a curve described today as the ‘Keeling curve.’ Revelle’s idea, and his sales pitch to the IGY, concerned the need for global data on CO_2. Global measurements, or at least data for many places on Earth, are useful, but Keeling correctly intuited that data for two carefully selected points on Earth would be very informative.

The two place Keeling picked were high on a volcanic mountain in Hawaii and the South Pole. The Hawaii site, at a recently installed weather station on Mauna Loa, would sample air arriving from the broad Pacific Ocean that was largely free of local pollution. The South Pole site was even more isolated from industrial pollution, yet even there it was necessary to be cognizant of emissions from local machinery.

The official purpose of the measurements was to establish a baseline CO_2 amount for comparison with observations in later years. However, because of the high precision of the data, interesting results appeared almost immediately.

The beautiful annual cycle was easy to understand. Atmospheric CO_2 at Mauna Loa decreased in the spring and summer as growing vegetation in the Northern Hemisphere sucked CO_2 from the air, and CO_2 increased in the fall and winter as plant litter decomposed.

When the record length passed the 12-month mark, it became apparent that there was a secular, year-to-year, CO_2 increase, which later would be proven to be largely from fossil fuel burning. The amplitude of the annual cycle was less at the South Pole and the secular growth trailed that 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.

Keeling had a life-long fight to maintain support for continued CO_2 monitoring, despite its iconic status as a measure of global change. There is a strong bias in funding agencies against 'routine' monitoring, which program managers consider to be 'dull.'

This same problem, the difficulty in obtaining support to monitor critical climate quantities, dogged my scientific career and resulted in my greatest frustrations. I will return to this topic later, because it is a matter of great practical importance. Some of the most interesting and important science can be found in the temporal variations of these 'dull' quantities.

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. 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, he developed the most comprehensive atmosphere-ocean climate models.

In 1965 the President's Science Advisory Committee (PSAC), after 15 months deliberation and writing, delivered their report[32] on pollution to President Lyndon Johnson. Johnson signed a statement accepting the report, decrying air, soil and water pollution of all types, and saying that he would give high priority to increasing the numbers and quality of the scientists and engineers working on pollution control. It is unlikely that Johnson read the report; 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, other members being Wally Broecker, Harmon Craig, Dave Keeling and Joe Smagorinsky. Their 23-page report[33] 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

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[32] PSAC: *Restoring the Quality of Our Environment*, Report of Environmental Pollution Panel, White House, 1965.
[33] Revelle, R., et al, Appendix Y4 to PSAC (1965): Atmospheric Carbon Dioxide, pp. 111-133.

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 a ‘mad scientist’ implausible geoengineering countermeasure? Were they trying to draw attention to the seriousness of human-made global warming? Or was this a prescient recognition of the inability or unwillingness of governments to constrain fossil fuel emissions? Perhaps it is just as well that President Johnson did not read the report. We will return to the subject of countermeasures to global warming in due course.

By 1969 Syukuro Manabe and his colleagues had made major advances in modeling and understanding the global ocean-atmosphere system. Manabe, Smagorinsky, and Strickler[34] presented a comprehensive general circulation model of the atmosphere with a realistic hydrologic cycle. Manabe and Richard Wetherald[35] used a one-dimensional climate model to explore important processes affecting climate change and climate sensitivity. Manabe and Kirk Bryan[36] published the first results from a coupled ocean-atmosphere general circulation model.

Manabe had a decade head-start on us. Computer capacity of his lab, NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) located at Princeton University was much greater than ours at GISS. Furthermore, 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 Colorado-sized would not do. It likely would be hard for us to publish our model because of its coarse resolution.

My philosophy about climate models and computing differed from that of most of the community. Divergence began right away with my first proposal, in which I argued that coarse resolution could capture the most important features of the atmosphere’s general circulation.

Our idea was that with an efficient climate model we could put more emphasis on physics in the model. I did not see this as a replacement for the standard approach of seeking higher and higher resolution, but rather as a complement. Everyone does not need to follow the same approach.

The problem was that both Jastrow and Cooper, my boss and my boss’s boss, both believed in the standard approach. Nothing wrong with that. The best weather forecasts require that path. To understand why I did not want to go down that path, you need to know implications of Amdahl’s law and Moore’s law. Don’t worry, they are simple laws.

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[34] 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.
[35] Manabe, S. and Wetherald, R.T.: The effects of doubling the CO_2 concentration on the climate of a general circulation model, J. Atmos. Sci., 32, 3-15, 1975.
[36] Manabe, S. and Bryan, K.: Climate calculation with a combined ocean-atmosphere model, J. Atmos. Sci., 26, 786-789, 1969.