Chapter 31. Aerosols

Charney was right, the aerosol story is weird. It is also important. When the public and political leaders finally understand the climate situation, they will realize that we must manage Earth's energy balance. Greenhouse gases and aerosols are the two big factors that determine our planet's energy balance and the direction of future climate change.

Most attention so far has been on greenhouse gases. Aerosols also deserve attention.

Indeed, aerosol properties are better known on Venus than on Earth. Let me explain. Astronomers once claimed that the light from the planets – reflected sunlight – was unpolarized. However, that was because the measurement error in their data was a few percent. When Bernard Lyot, a French astronomer, invented a polarimeter with an accuracy approaching 0.1 percent, he discovered a beautiful curve for the degree polarization as a function of the phase (Earth-Sun-Venus) angle as Venus and Earth traveled in their orbits about the Sun.

My post-doc research showed that the Venus polarization curve carried the signature of a Venus "rainbow." Some of the sunlight incident on Venus clouds is refracted into the cloud drops, bounces off the back of the particle, and emerges in the direction of Earth. I also found that the refraction angle changed slightly with the wavelength of light. Polarization data was the principal information that led to identification of the cloud composition as sulfuric acid.[1,2]

Our polarimeter on the Pioneer Venus orbiter spacecraft was able to look at a given area on Venus from different perspectives. Kiyoshi Kawabata and Larry Travis analyzed the data, showing that the sulfuric acid cloud drops, which had a narrow size distribution with mean radius just over 1 micron, were imbedded in a haze of even smaller particles of the same composition, probably the product of a recent volcanic eruption on Venus.

Earth has several aerosol types, with a range of radiative properties. Aerosol albedo – the fraction of light hitting the particle that is reflected – affects the amount of sunlight absorbed by Earth. Sulfuric acid – an abundant human-made aerosol arising from sulfur in fossil fuels – has albedo near unity, scattering all the light incident upon it. Black soot – from burning of biomass or fossil fuels – is at the other extreme, strongly absorbing sunlight and thus heating the air.

Most human-made aerosols increase the albedo of Earth and reduce sunlight reaching the ground. Therefore the overall direct effect of aerosols is to cause a cooling of Earth's surface. This global average climate forcing today is estimated to be of order -0.5 W/m^2, uncertain by a factor of two, so it's value is probably in the range -0.25 to -1 W/m^2.

However, aerosols have a larger, indirect, effect on Earth's energy balance: aerosols alter cloud properties. Aerosols are nuclei on which water vapor can condense to form cloud drops. If the abundance of aerosols increases because of human emissions, the number of cloud droplets in a cloud increases. More cloud drops result in smaller cloud particles because available water vapor is fixed. Smaller particles, given a fixed water volume, present a larger cross-sectional area to sunlight, thus causing a higher cloud albedo. This "Twomey effect"[3] is confirmed by observations. For example, satellite images reveal ship tracks of brightened clouds where ships are pumping aerosols into the atmosphere. The magnitude of the global negative (cooling) forcing is very uncertain, with estimates ranging from -0.3 to -1.8 W/m^2.

There is a second indirect aerosol effect on clouds: smaller cloud particles are also believed to prolong the lifetime of clouds by slowing the production of raindrops. This Albrecht effect[4] is even more difficult to quantify than the Twomey effect.

There are other complications. We noticed an aerosol effect on clouds in our climate modeling experiments, which we dubbed the semi-direct aerosol effect.[5] Absorbing aerosols, such as black soot, cause a local heating of the air that reduces cloud cover. The reduction of cloud cover increases absorption of sunlight by Earth, thus increasing the warming effect of black soot.

Charney had reappeared. His statements are in quotation marks.

"**Whoa, this aerosol problem is complex.** It seems that you will never solve it."

It is solvable, but it requires global observations focused on the aerosol-cloud problem. We need global monitoring of aerosol and cloud microphysics, and their effects on solar and thermal radiation. By microphysics I mean the size distribution of particles, particle shape and refractive index – information that is related to the chemical composition of the particles.

These global observations must be complemented by aerosol modeling within a global climate model. Reasonably good progress is being made in the aerosol modeling. It is the global data that are missing. We should have Keeling-like global monitoring of aerosols and clouds.

The needed observations were understood about 30 years ago. We proposed a small satellite to collect the data in 1989, as a complement to the large NASA Earth Observing System (EOS). The required data were described in detail at a workshop "Long-term Monitoring of Global Climate Forcings and Feedbacks" and published as NASA Conference Publication 3234.[6]

We developed a peerless polarimetry team at GISS – the two top people in the world, Michael Mishchenko and Brian Cairns, who worked together selflessly. Mishchenko came to GISS as a young immigrant from the Ukraine with unmatched depth of understanding of electromagnetic theory – even van de Hulst was impressed. Cairns, originally from the U.K., came to GISS as a post-doc with the rare quality of combined theoretical and experimental talent, a crucial quality for the sake of extracting the great amount of information in high precision polarimetry.

Michael and Brian showed that polarization measurements from a satellite with accuracy of order 0.1 percent can yield 10 parameters defining the microphysics of aerosol and cloud particles.[7] Cairns confirmed these claims with measurements from aircraft.

"**You mean that a single instrument, a polarimeter,** can determine the climate forcing by human-made aerosols?"

It can measure aerosols, but not, by itself, define aerosol climate forcing. A high-precision polarimeter observing a given region from a range of angles in several spectral bands between the near-ultraviolet and near-infrared can define 10 parameters characterizing the aerosols, clouds and the ground in the field-of-view. That will yield aerosol properties, and we can study how those properties change over time as the human or natural aerosol sources change.

However, aerosol climate forcing also depends on how aerosols alter clouds. The polarimeter measures cloud albedo and microphysics in the cloud top region, but we also need to know how aerosols alter cloud cover and cloud temperature. So the polarimeter is accompanied by a Michelson interferometer and a high resolution camera on our proposed small satellite.

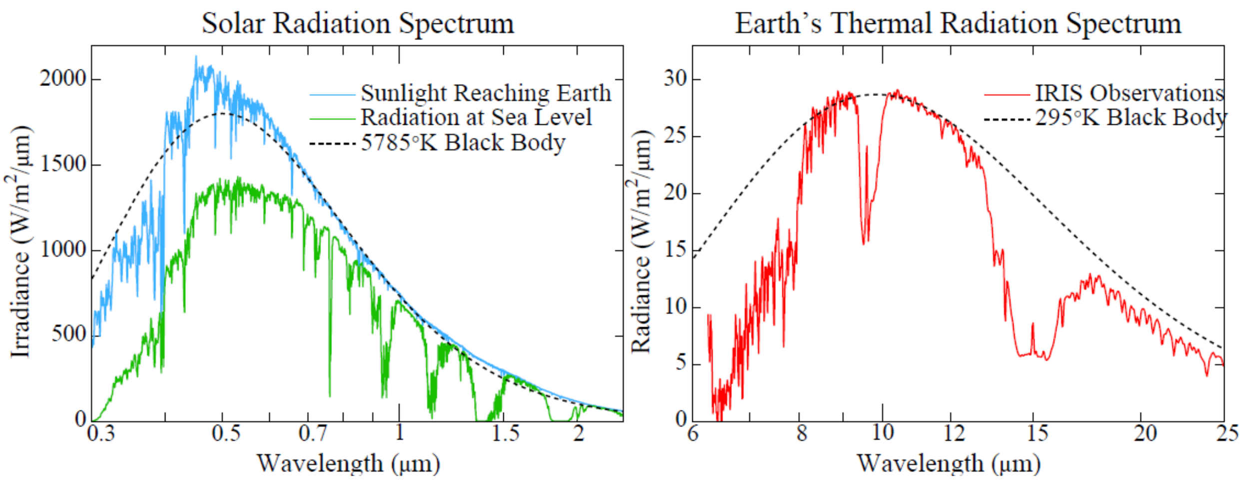

Fig. 31.1. Sunlight reaching Earth and reaching the ground for clear sky conditions (left). Thermal (heat) radiation to space measured from a satellite over the Sahara desert (right).

The interferometer is a standard instrument, well-tested on planetary missions. It measures the thermal infrared spectrum between about 6 and 40 microns with moderate spectral resolution and a coarse spatial resolution (about 5-10 kilometers) matching that of the polarimeter. In other words, it measures the wavelength dependence of the heat radiation emitted to space by Earth.

Ozone, water vapor, liquid water and ice all have absorption features in the infrared spectrum. Thus the Michelson interferometer allows measurement of ozone, water vapor, and temperature, as well as cloud temperature, opacity, ice or water phase, and cloud particle size.

"It seems that you are measuring much more than aerosols."

For sure. Most mechanisms for climate change – climate forcings and feedbacks – operate by affecting the solar radiation absorbed by Earth or the outgoing terrestrial radiation. Aerosols are the big unknown forcing. The major feedbacks are water vapor, clouds and surface albedo. All of these are revealed in the reflected solar radiation and emitted heat radiation.

Our instruments measure these two spectra in optimum fashion. Information in reflected solar radiation requires only coarse spectral resolution – about 10 bands from the ultraviolet to the infrared, including an oxygen absorption band and weak and strong water vapor bands – because the principal information is in precise polarimetry. In contrast, the information in thermal spectra is primarily in the strength of absorption lines.

Both instruments are proven on planetary missions. They are small – each about 20 kilograms – and inexpensive as satellite instruments go. They provide the potential to maintain long-term monitoring of climate forcings and feedbacks, analogous to Keeling's CO_2 monitoring.

Our proposal was to put these instruments on their own small satellite – Climsat – so that orbits could be optimized for viewing geometry. Full sampling of the diurnal and seasonal cycle of radiation can be obtained with two of these small satellites: one in a sun-synchronous[8] polar orbit and one in an inclined precessing orbit.

"Sounds great, but you failed for 40 years to initiate the measurements? Weren't you a NASA manager? Couldn't you devise a plan in 40 years? Isn't NASA the can-do agency?"

That's a bigger issue – although it is related to Climsat and aerosols. However, your criticism is valid. Aerosols were my area of expertise. I should have been able to make the case for the measurements that were needed. The story of repeated failures to get the measurements is depressing. I summarized the story on a few pages. You can read them on your trip home.

Let's consider what we do know now about aerosols, or think that we know. It is based largely on models and indirect inferences, rather than aerosol observations.

The Intergovernmental Panel on Climate Change (IPCC) assesses the climate situation for the United Nations in a huge report delivered every five to seven years. It's an arduous task – we must thank those scientists who prepare the report, which goes through numerous reviews.

There are now scores of global climate models (GCMs) in national laboratories and universities all around the world. It's a matter of national pride. Also, nations want to examine the issues with their own scientists, because, it is feared, efforts to limit climate change might be costly.

As an adjunct to the IPCC climate assessment, there are climate model intercomparisons.[9] Because of the large number of models, it is not quite like your Woods Hole meeting in which you met with a handful of the best scientists, had insightful discussions, and wrote a report. Instead, each modeling group makes standard simulations and provide results to a data center, where the data are made available to the entire community for study. It's a useful approach.

"**I must leave soon, so please get to the point.** Can the climate models simulate observed climate change? What is the aerosol climate forcing used in the models?"

That's what's interesting. Most models can produce global warming over the past century that resembles observed global warming, but they achieve this using a wide variety of aerosol forcing histories. Commonly they use a smaller negative aerosol forcing than aerosol experts suggest, and they may even exclude the aerosol indirect effect entirely.

In a sense, there is a disconnect between the IPCC chapters written by aerosol experts and the chapters written by global climate modelers. Aerosol experts believe that humanmade aerosols produce a negative (cooling) forcing of the order of $-1.5\ W/m^2$, including both the direct effect of aerosols and indirect effect on clouds.

Yes, there is large uncertainty in the aerosol forcing, especially the indirect effect. Nevertheless, this discrepancy between the aerosol physics and the climate models increased my suspicion that there is a flaw in the global climate models, at least in the most prominent models.

My suspicion was aroused by the long time that it took for the surface temperature in our GISS climate model to approach its equilibrium response to a doubled CO_2 forcing – it took centuries. Then I examined other major climate models and found that they were just as slow to respond, or even slower. This suggests that the models mix heat too efficiently from the wind-mixed surface layer of the ocean into the deeper ocean.

"**Let's see, if a climate model mixes heat into the deeper ocean too rapidly** the surface warming will be too small. Therefore the modeler must use a climate forcing that is larger than the true, real-world, climate forcing to achieve a modeled surface warming that agrees with observations. They do this by understating the negative aerosol forcing."

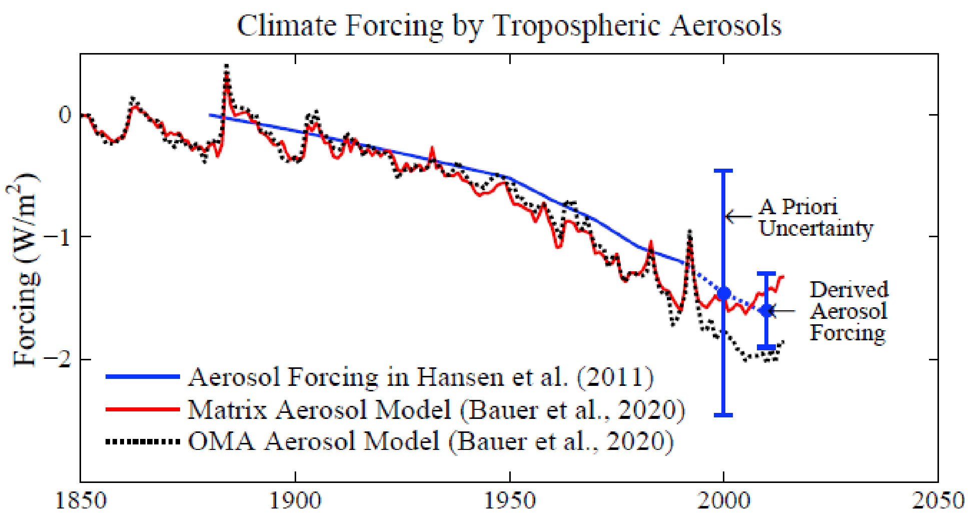

Fig. 31.2. Aerosol forcing scenarios and value in 2010 based on Earth's energy imbalance.

Precisely so, Sherlock, at least that was my interpretation. Today I have almost ironclad proof of that interpretation. You will be glad to know that oceanographers initiated a fantastic data collection program – several thousand "Argo" floats, distributed around the global ocean. They periodically dive to a depth of two kilometers, slowly rise to the surface while measuring temperature and salinity, and radio the data to a satellite.

So now we have a good measure of increasing ocean heat storage. That is one strong constraint on climate models. A second constraint is provided by observed global warming.

Pitted against these constraints are three major uncertainties in the models: climate sensitivity, aerosol forcing, and ocean mixing. But one of these – climate sensitivity – is known quite well: paleoclimate data informs us that climate sensitivity is about 3-4°C for doubled CO_2.

If we assume 3°C climate sensitivity, we have two unknowns and two constraints. That allows us to solve for the recent aerosol climate forcing. It was -1.6 W/m^2 in 2010 (Fig. 31.1). If the true sensitivity is 4°C, the aerosol forcing would be a bit larger (more negative).

"That seems reasonable, but I want to understand what you did, and I want to know more about the Argo data. I must come back again, but explain quickly what's in Fig. 31.2."

The blue curve is the aerosol forcing that we employed in the simplified global climate model that we employed in our analysis of Earth's energy imbalance.[10] As described in section 14.3 of that paper, the aerosol forcing was from an aerosol model of Dorothy Koch that employed global fuel use data and Tica Novakov's estimates for temporal changes in fossil fuel technologies.

The shape of the aerosol curve, increasing as fossil fuel use increased, is probably realistic, but the magnitude of the forcing is very uncertain. We estimated that in year 2000 the total aerosol forcing was probably in the range -0.5 to -2.5 W/m^2. However, by using the constraints from the observed Earth energy imbalance in 2010 and observed global warming of the past century, we deduced that the aerosol climate forcing was -1.6 ± 0.3 W/m^2 in 2010.

That result was obtained under the assumption that the fast feedback climate sensitivity is 3°C for doubled CO_2. Up-to-date analyses of paleoclimate data (Chapter 25) imply that the fast feedback climate sensitivity is probably in the range 3 to 4°C for doubled CO_2. If the real world fast feedback sensitivity is closer to 4°C, the inferred aerosol forcing may approach -2 W/m^2.[11]

Fig. 31.2 also shows the aerosol climate forcing in recent climate simulations with the GISS global climate model that included interactive aerosol-climate physics. With interactive aerosol physics, the aerosol forcing is estimated by subtracting a simulation that excludes the aerosol physics. This procedure causes the noisy nature of the aerosol forcing in the figure.

Two alternatives for the aerosol physics, OMA and Matrix, were employed, as explained in their paper.[12] Lead author Susanne Bauer suggests that the Matrix model is perhaps closer to reality.

"If the aerosol models are realistic, are global aerosol measurements still needed?

Aerosol models are probably in the right ballpark, but only because we know where the ballpark is. Models need to yield enough aerosols to keep global warming close to observations. That's not the desired way to do science or the way forward. We need to understand various aerosol types and their effects on clouds so that we can correctly interpret ongoing climate change and provide sound scientific direction to guide future climate policy. That requires real-world data.

In the period 2015-2020 global warming accelerated. The growth rate of greenhouse gas climate forcing increased a bit in that period, but not enough to account for observed warming. I believe it is likely, as Susanne Bauer's models suggest, that the human-made aerosol forcing reached its maximum negative value and the aerosol forcing is now rising toward less negative values.

We need to know and understand such things based on aerosol and cloud observations. We need to know where aerosol changes are occurring and the aerosol types. Such knowledge will help us manage restoration of a healthy climate.

"Manage restoration of a healthy climate? Yikes. I'm not sure that's a message that I want to be taking back. You seem to suggest interfering with nature?"

We *are* interfering with nature, big time. I'm suggesting that we minimize our interference. Our biggest interference is the disruption of Earth's energy balance,

Earth is now out of energy balance by almost 1 W/m^2. That's huge. It's driving global warming at a rate probably much faster than any time in Earth's history,[13] putting unprecedented pressures on nature. We need to stop this human-caused drive with urgency, but without panic. We need to understand the actions that will minimize the chance that we push a critical system past a point of no return, such as locking in disintegration of a large ice sheet.

Like it or not, we are turning the control knobs on both greenhouse gas and aerosol climate forcings. It would be foolish to try to control the ship by turning one of the knobs, while the other knob is spinning in our ignorance.

Reducing greenhouse gas forcing is urgent, but even with full attention and global cooperation that knob will be turned slowly because of CO_2's long lifetime and fossil fuel infrastructure. Aerosols fall out in days, if the source is removed. They also can be in regions of our choice, where they do little if any harm and possibly lots of good – but we need good understanding.

"It's sounds like you have a plan. I want to hear it, but I have to go now. Can you give me the page that describes the aerosol story that you find too depressing to talk about?"

Sorry, it turned out to be a little more than a page. It's two short chapters.

Chapter 32. Battlestar Galactica

Mission to Planet Earth seemed perfect for NASA. Measuring and deciphering natural and human-made global change is a complex task. A view from space is essential to monitor change on the 510,000,000 square kilometers of Earth's surface.

Global observations from space are only part of what is required. We also need measurements on the ground and in the ocean and atmosphere. Data interpretation depends on small-scale models of processes and global models to integrate all processes. Models and interpretations should be tested for the range of climates in Earth's rich paleoclimate history.

NASA managed a complex mission to Venus brilliantly, with an orbiting spacecraft, entry probes, theoretical studies, and models. Scientists determined the nature and scale of the Pioneer Venus mission before it was even presented to engineers. Richard Goody and Don Hunten published the mission concept in *Science* magazine to be sure that NASA understood what was needed and to give the larger scientific community an opportunity to comment on the plan.[14]

In contrast, spacecraft plans for Mission to Planet Earth were hatched in the dark. Spacecraft plans were set before the scientific community had a chance to assess the science, required measurements, and the implications for instruments, satellite size and orbits.

Battlestar Galactica sprang from the minds of a handful of people within the walls of the NASA Headquarters building in Washington, DC. Battlestar Galactica is not the NASA name. It is a name we at the Goddard Institute and others used after we were stunned by the initial plans: about 20 instruments, some as large as automobiles on each of two giant platforms.

A lot happened between 1982 – when Richard Goody and Mike McElroy persuaded NASA Deputy Administrator Hans Mark of the need for a Mission to Planet Earth to carry out a broad-based scientific study of natural and human-made global change – and the 1989 emergence of the NASA Earth Observing System (EOS). EOS was the space observations component of Mission to Planet Earth. Hans Mark left NASA in 1984 to become Chancellor of the University of Texas system. Space Science influence on Mission to Planet Earth declined.

What followed was a tragedy, in my view. It was surely harmful to our institute and specific individuals, but it was also harmful to humanity. A mission strategy was set in motion that prevented the public from having timely quantitative knowledge of the full causes of climate change and the options to minimize adverse effects of climate change.

All the individuals in this story were well intentioned. My objective is not to cast blame, which I would deserve much of, but rather to expose the nature of how things work in our government, even in the more effective agencies. Perhaps it will point us toward needed changes.

The Earth Observing System became the focus at NASA Headquarters. Principal people defining the program were Burt Edelson, Shelby Tilford and Dixon Butler.

Edelson's background was in telecommunications satellite technology with Comsat Corporation. Edelson was the college roommate of James Beggs – NASA Administrator from July 1981 to December 1985. Beggs hired Edelson to be NASA's Associate Administrator for Space Science and Applications when NASA was struggling to find a purpose for the expensive Space Shuttle.

Tilford and Butler had been involved in NASA ozone research. Their backgrounds were fitting preparation for programmatic leadership at NASA Headquarters. Work at Headquarters – facilitating acquisition of funding from Congress and dispersing funds to NASA Centers and universities – is not attractive to most scientists. Yet good management is crucial for mission success, and NASA historically has done well in finding people who excel in this service.

Successful program management demands extensive interaction with the scientific community, especially in early mission definition. That interaction was inadequate for the Earth Observing System. Mission definition may have been affected by directions from the highest levels at NASA, but nevertheless interviews of Tilford and Butler for the NASA Oral History Project[15] expose a shockingly constrained approach to mission definition in the years following the impressive Woods Hole workshop in 1982. Scientists were consulted about data needs, but the scientific community did not have a chance to assess and alter the basic spacecraft strategy.

Edelson and Tilford initially proposed huge polar-orbiting platforms to be carried to orbit by the Space Shuttle, likely requiring multiple launches with platform segments bolted together in space by astronauts. They did not understand that the energy needed for launch into polar orbit was too great for the Shuttle and a large platform. After realizing that the Shuttle had little role in the program, they continued to plan on large polar platforms with 12-24 instruments.

It is fine to examine such a concept for Earth observations, but it is crucial to seek scientific review and encourage alternative proposals. The scientific method requires skepticism of any first proposition. The truth is that we seldom get things right with our first concept. The absence of such scrutiny seems inconceivable for a program with a $50B price tag.[16] Failure to have an open early conceptual review dogged Mission to Planet Earth throughout its lifetime.

In stark contrast to their tight in-house definition of planned space hardware, Tilford and Butler did an exceptional job of encouraging input on the nature of Earth science research to be pursued by Mission to Planet Earth. They had strong motivation to court the scientific community. Congress would never pick up the tab if the scientific community did not bless the project.

Tilford's choice of Francis P. Bretherton to chair the Earth Systems Science Committee, formed in 1983, was brilliant. Bretherton had been President of the University Corporation for Atmospheric Research and simultaneously Director of the National Center for Atmospheric Research in the 1970s. Bretherton gave up administration in 1980 and returned to research.

Bretherton is a genius. Look up Bretherton Equation in Wikipedia for an example of his ability in mathematics and physics. He used that nonlinear partial differential equation to study weakly-nonlinear wave dispersion. Don't worry about what that means.

Bretherton's parents gave him the middle name Patton. It fit. He had to marshal troops from disciplines that did not normally communicate with each other. Complexity of the Earth system was emerging. For example, a farmer fertilizing his field to improve crop yield, by affecting nitrogen fixation,[17] alters the amount of nitrous oxide (N_2O) emitted to the atmosphere. Nitrous oxide, popularly known as laughing gas, has a lifetime of about a century, more than enough time for much of it to waft into the stratosphere. There it causes chemical reactions that destroy ozone, which then allows more ultraviolet radiation to reach Earth's surface. Increased UV radiation affects plants as well as humans. See the complex feedback loops in the Earth system! Soil scientists must work with stratospheric chemists to understand the system.

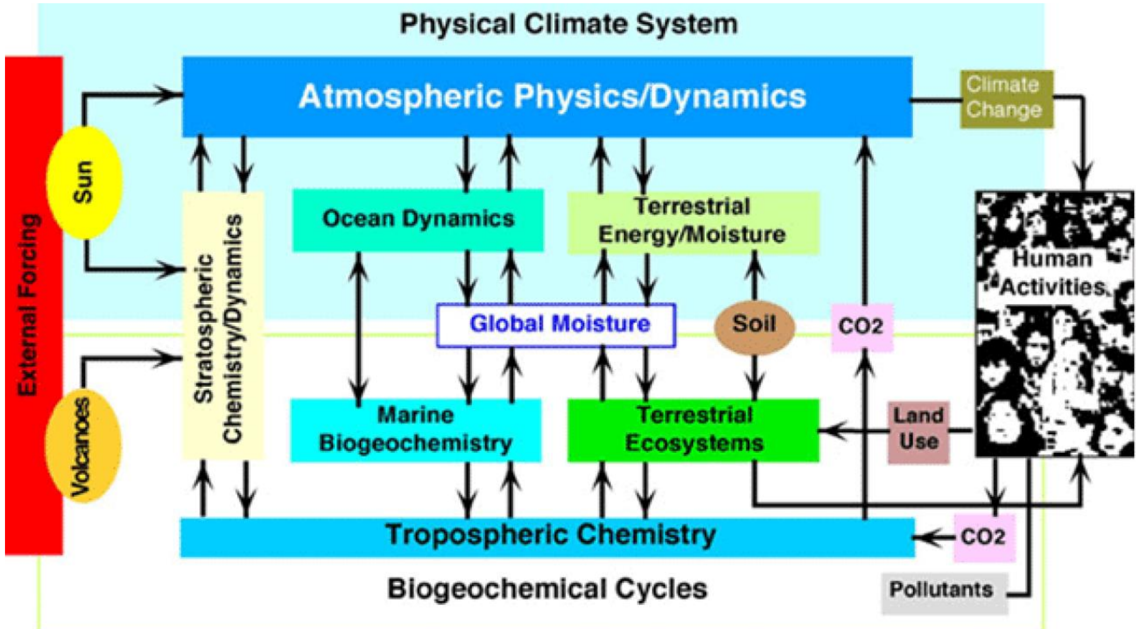

Fig. 32.1. Simplified "Bretherton Wiring Diagram."[18]

Bretherton spoke in a loud authoritative voice that avoided the need for electronic amplification. His normal volume was described as "one Bretherton." When he wanted to explain an important point or if he got excited his voice rose, and he was sometimes warned "Francis, you are at two Brethertons!" Nobody minded that he dominated a meeting: he knew what he was talking about, tried to be in good humor, expressed emotion, and was often self-deprecating.

The main objective of the Earth System Science ("Bretherton") Committee was to produce a document describing the Earth system to help scientists and agencies understand how the many research areas fit into a global picture. It took years. A coherent summary of such a complex system requires the overall story to exist in one brain. That brain was Bretherton's. He often assigned himself the task of writing the summary of a section, which he sent to Committee members and other relevant people with some comments punctuated by "Whew!"

A preliminary document was produced in 1986 and the final version, *Earth System Science: A Closer View*, in 1988. The report of more than 200 pages includes a complex "wiring diagram" summarizing how Earth systems are interconnected and the simplified version in Fig. 32.1. The simplified Bretherton Wiring Diagram became an iconic summary of Earth's climate system, including natural and human-made forcings that drive climate change. The diagram was a useful tool that aided communication with students, policymakers and interested public.

It was a propitious moment, in 1988, for NASA to propose Mission to Planet Earth. How could Congress fail to provide funding, given ongoing dramatic climate events? Indeed, at the end of the year Time Magazine declared Earth to be "Person of the Year."

NASA issued an Announcement of Opportunity, anticipating new funds from Congress in 1989, soliciting proposals for satellite instruments and interdisciplinary science investigations of the principal global change issues. We prepared two proposals at the Goddard Institute.

One proposal, with Larry Travis as principal investigator, was a polarimeter to measure aerosol and cloud properties. A polarimeter is the only known remote sensing approach capable of defining the climate forcing by aerosols.

Our second proposal, for which I was the principal investigator, was an interdisciplinary study of the global carbon, energy, and water cycles. In other words, our topic was the entire Bretherton diagram. We asserted credibility based on composition of our team, which included Tony Del Genio, Inez Fung, Andy Lacis, Michael Prather, David Rind, Bill Rossow and Peter Stone.

However, we were distressed by the specific NASA plans for an Earth Observing System (EOS), which was dominated by huge satellite platforms in sun-synchronous polar orbits. A large platform is slow to construct and likely to experience delays and cost overruns that tend to squeeze out research and delay progress in the science.

We felt that priorities were backward. First there should be investment in brainpower – especially students and post-docs – as happened at the origin of NASA space science. Next are measurements that provide information soon. Some critical data can be obtained quicker with small satellites. Some measurements are best if made from a non-polar orbit.[19]

Bill Rossow, Inez Fung and I were probably the ones most responsible for questioning mission strategy. Our opinions became well known because Bill and Inez worked extensively with scientists at other organizations and I attended regular staff meetings at Goddard Greenbelt.

Our criticisms were not appreciated. Gerry Soffen, Project Scientist for the Mission to Planet Earth at Greenbelt, and my supervisor, Vince Salomonson, told me to hold any criticisms until Congress fully funded the program. That would be too late, I argued – we needed to question the program strategy before it was set in concrete.

Gerry Soffen called me a few days before the winning proposals for Mission to Planet Earth were to be announced. Our proposed science investigation of carbon, energy and water cycles was "just below the cutoff line and would not be funded." His explanation: Bob Dickinson's proposal, with objectives similar to ours, received a higher rating from a review panel. That did not surprise me. Soft-spoken Bob Dickinson, expert in everything from stratospheric dynamics to vegetation in climate models, was widely considered to be the smartest person in the field.

Gerry said that I must meet with Shelby Tilford. Tilford had absolute control on where the line was drawn; I could probably persuade him to move it down. That, too, was believable. Shelby operated like a tsar. A sign on his desk read: "The Golden Rule, he who has the gold rules."

Gerry's suggestion may have been an independent friendly gesture on his part, with Shelby unaware of it. However, to me it felt like an effort to silence our criticisms. I also doubted that a review committee would rate us that low.

The day before the NASA announcement Gerry called again. He was frantic. Why had I not contacted Tilford? This was our chance for funding; how could we survive without it? I said that perhaps we would seek funding from EPA or the Department of Energy. Gerry was perplexed and angry. From that point on our relationship was frigid.

Both of our proposals were selected: the polarimeter and the carbon, energy, and water cycles investigation. The title of the latter study was simplified to "The Theory of Everything" for our name tags when the 500 winning principal and co-investigators[20] got together for the first time at a week-long meeting at Goddard Space Flight Center in March 1989.

Principal investigators each had several minutes to describe their study. I knew that many scientists shared our concerns about EOS, so I used part of my time to raise two issues. First, investment in development of scientific brainpower and in research was underfunded relative to funding of hardware. Second, NASA made major decisions about observing systems before asking help of advisory committees, which could then only tinker around the edges.

Naively, I hoped to get open discussion of these issues. It did not happen. The organizers did not want such, and no other scientists joined the criticism. After I sat down, Gerry Soffen walked up from behind, put his hand on my shoulder and whispered: "You will never be allowed to speak at an EOS meeting again!"

What had gone wrong? Larry Travis described the problem as my "habit of blurting out the truth." The blurting part was right, for sure. That I lacked rhetorical skills was an understatement. I did not have the abilities to lead discussion of concerns that must have been felt by others. My lack of oral communication ability had not been a severe handicap in space science, because of authoritative leaders such as Don Hunten, Richard Goody and Tom Donahue, and NASA leaders such as Hans Mark and Tom Young, who listened to the science experts.

Perhaps such leaders could have made a difference for Earth science; perhaps they could have implemented a Mission to Planet Earth along the lines contemplated – and aspired to – at the 1982 Woods Hole meeting chaired by Richard Goody (Chapter 23). Perhaps not.

A powerful, growing, force opposed any efforts to have science requirements drive resource allocation. I hope that exposure of this force may help taxpayers and political leaders contemplate and define a better approach.

Chapter 33. Climsat: A Proposal

NASA is inspirational. The National Aeronautics and Space Act of 1958 established NASA with its first objective "the expansion of human knowledge of the earth and phenomena in the atmosphere and space." Space science is NASA's very essence.

I was in awe of NASA leadership in 1981, when I was chosen to direct the NASA Goddard Institute for Space Studies. Tom Young, the Goddard Director, had been the storied director of the complex Mars Lander Mission. Hans Mark, NASA Deputy Administrator – running NASA on a day to day basis – had been chairman of Nuclear Engineering at the University of California in Berkeley, director of NASA's Ames Research Center, and Secretary of the Air Force.

NASA differed from the Department of Energy and EPA. Research funding from these latter agencies often was suddenly terminated, depending on the politics of the U.S. Administration. NASA seemed to be more scientific and reliable.

Our experiment on the Galileo Jupiter Mission came under fire during the two years just before I became GISS Director. Galileo was managed by the Jet Propulsion Laboratory in California. When the Galileo project ran into budgetary and spacecraft cost problems, the project manager decided to delete our instrument from the mission. I blanketed the planetary science community with memos[21] explaining the importance of our measurements for issues such as the abundance of gases on Jupiter relative to their abundance on the Sun. Tim Mutch, the NASA Associate Administrator for Space Sciences, in an unusual move, overruled the Galileo project manager and restored our experiment to the Galileo mission. Science seemed to rule in NASA.

NASA was changing in the 1980s, however. Tragically, Tim Mutch was killed in October 1980 in an accident in the Himalayas.[22] Tom Young left NASA in 1982 to join Martin Marietta Corporation, where, after a few years, he was President and Chief Operating Officer. Hans Mark left NASA in 1984 to become Chancellor of the University of Texas system. Noel Hinners, Goddard Director in the mid-1980s, left NASA in 1989 to join the Martin Marietta Corporation.

By the late 1980s I was no longer in awe of NASA management. Still, if we stuck to our guns, I thought that science would win in the end – we would achieve the needed climate measurements.

In this chapter I list – chronologically, without emotion – our efforts to initiate Keeling-like, inexpensive, long-term monitoring of global climate forcings and feedbacks, including measurement of the global aerosol climate forcing.

1. I wrote a letter[23] to Dixon Butler to clarify my criticisms at the EOS workshop. Dixon's reaction was publicly supportive, as Eliot Marshall reported in an article[24] in *Science* on 16 June 1989, but it did not lead to substantial change of NASA Headquarters plans for EOS.

The method of selecting and funding proto-scientists is crucial. A staffer for Senator John Glenn, the first American to orbit Earth, asked me to speak with Senator Glenn about "NASA priorities." I decided to focus my comments on the need to develop young brainpower in Earth Science analogous to the support Space Science received in the 1960s. After a letter exchange[25] with Prof. Van Allen, I gave my oral recommendation to Senator Glenn and sent a letter to Senator Gore. I also handed a copy of this letter (including the handwritten note at the bottom of page 1) to Senator Tim Wirth at a meeting in Sundance, Utah, held by Robert Redford. I suggested that post-docs be selected in a national competition administered, say, by the National Research Council with post-docs allowed to choose the university or government laboratory for their research and with post-doc positions renewable for up to three years.

That suggestion never made headway. Congress funded the EOS program and NASA allocated part of the funding to selected EOS investigators. This approach provides support for students and post-docs of the selected EOS scientists, but it fails to cast a nation-wide net that provides equal opportunity for all young people, comparable to what we had in the 1960s.

2. In December 1989 I attended a "roundtable" discussion in Senator Gore's office. Senator Barbara Mikulski was co-host. The purpose was to advise the Senators on NASA's Mission to Planet Earth, the wider U.S. Global Change Research Program, and the still wider International Geosphere-Biosphere Program. There were about 10 scientists, including Francis Bretherton, Tom Lovejoy, Gordon MacDonald, Mike McElroy, Sherry Rowland and George Woodwell.[26] Senator Mikulski left after an hour, but the meeting continued several hours.

Senator Gore was impressive in leading the discussion, taking notes, and summarizing each topic in lay language. He produced a list of 23 "Principal Scientific Inquiries," which his staffer Rick Adcock sent to the participants in inviting us to a second roundtable.

We discussed Gore's 23 topics at GISS. Most of the topics could be organized as parts of the global energy, water or carbon cycles described in our EOS proposal. For each of the three cycles we made tables of science objectives, required observations, and accuracy requirements.

Is climate changing? What are the causes? Answers require quantitative understanding of the energy cycle. Observations are needed in three categories: forcings (greenhouse gases, aerosols, solar irradiance, ground albedo), feedbacks (clouds, water vapor, ice, snow), and diagnostics (planetary energy balance, atmospheric temperature, ocean temperature and salinity).

Observations must continue for decades, the time scale for climate change. Some data were already being acquired by NOAA operational weather satellites, weather stations, or other monitoring, such as Keeling's CO_2 stations. The missing data, we concluded, were best obtained from small, relatively inexpensive, satellites, which made long-term monitoring feasible.

Three instruments needed for this satellite monitoring were selected for the Earth Observing System (EOS): our Earth Observing Scanning Polarimeter (EOSP), the Stratospheric Aerosol and Gas Experiment (SAGE), and the Earth Radiation Budget (ERB) instrument. These instruments could be accommodated on a small satellite.

Could EOS obtain the needed climate observations? No, not in our opinion. EOS as approved by Congress had observations from two polar platforms in syn-synchronous orbits and the Space Station.[27] Clouds, aerosols and other climate variables change during the day, but the EOS platforms observe at a fixed time of day. It was unlikely that multi-billion dollar platforms could continue to be replaced on multi-decade climate time scales.

Optimum calibration and adequate sampling of climate data can be obtained by two spacecraft: one in sun-synchronous polar orbit one in an inclined precessing orbit. This could be one small satellite in inclined orbit plus the three instruments on the EOS platform. However, it is more sensible to make two copies of the small satellite. It is expensive to integrate the instruments onto the complex EOS platform, the platform may take a decade to build, the small climate

	Existing Source	Proposed Source
Climate Forcings		
Greenhouse gases		
CO_2	G	
CFCs	G	
CH_4	G	
N_2O	G	
O_3 (profile)	–	SAGE
stratospheric H_2O	–	SAGE
Aerosols		
tropospheric	–	EOSP
stratospheric	–	SAGE
Solar Irradiance	X	
Surface Reflectivity	O (poorly calibrated)	EOSP
Climate Feedbacks		
Clouds		
cover	O, W	
height (temperature)	O	
optical depth	O	
particle size	–	EOSP
water phase	–	EOSP
Tropospheric H_2O (profile)	O, W (lower troposphere)	SAGE
Sea Ice Cover	O	
Snow Cover/Vegetation	O	
Ocean Heat Exchange (vertical mixing & horizontal divergence)	S, X	
Climate Diagnostics		
Radiation Budget	–	ERB
Temperature		
upper air	W, O	
surface air	W	
ground	O	
sea surface	S, O	
ocean, internal	S	
Precipitation	W, O, X	

Data source key: O = operational satellite system, X = experimental satellites (e.g., TRMM), W = operational weather station network, G = other ground stations and aircraft, S = ships and buoys. SAGE = Stratospheric Aerosol and Gas Experiment. EOSP = Earth Observing Scanning Polarimeter. ERB = Earth Radiation Budget scanner.

Note: Climate parameters that have more than one role—for example, forcing and feedback—are listed under their dominant influence.

Table 32.1. Principal global climate forcings, feedbacks and diagnostics.

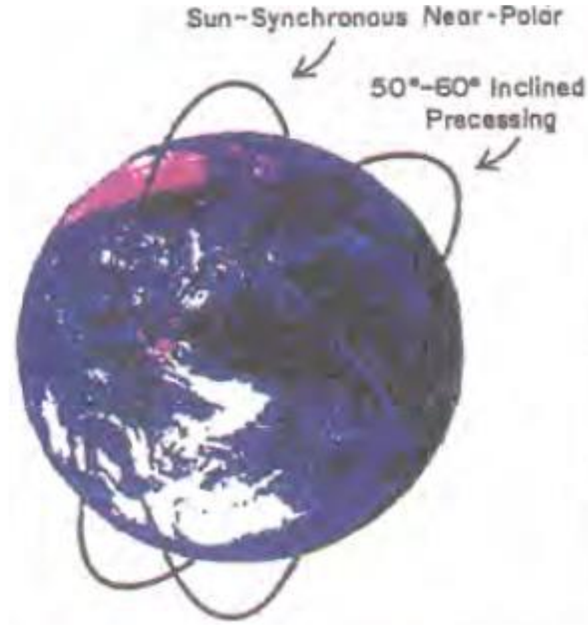

Fig. 33.1. Climsat orbits.

instruments would likely have low priority in platform design and operations, and the platform may be difficult to replace at time of instrument or mission failure.

My main area of research was the energy cycle. I felt comfortable that I could explain the table describing the energy cycle at Gore's second roundtable. I would use that table to rationalize a proposal for small satellite observations.

3. On 31 January 1990 Senator Gore had his second roundtable. I introduced the energy cycle table, but my discussion was too elaborate. Senator Gore interrupted me "with all due respect Dr. Hansen," suggesting that I write up the detailed concept as a homework assignment.

Nevertheless, Senator Gore liked the idea of small satellites, which he hoped would be able to acquire data soon. The EOS platforms were not expected to provide data for at least 6-8 years. Could small satellites be faster than the large EOS platforms? "Yes," I said.

However, roundtable participation had been expanded. Two new members, Berrien Moore of the University of New Hampshire and Jeff Dozier of the University of California, were prominent EOS scientists. Moore was chairmen of the EOS Payload Advisory Committee, which was allowed to offer advice on possible rearrangement of observations on the EOS platforms. Dozier took leave from his university to help with implementation of the EOS program at Goddard Space Flight Center.

One of these new participants interjected that a small satellite could not be launched much faster than the scheduled time for EOS platform launch. He was correct, given that NASA had become slower and slower in project execution. NASA was no longer the can-do agency of the 1960s. However, that lethargy would make the large EOS platforms take even longer.

Small satellites had advantages in addition to quicker launch: lower cost, optimal orbits, and ease of replacing a failed satellite. However, the difficulty in obtaining approval for such a small satellite approach became evident during a break in the roundtable meeting.

Mike McElroy tapped me on the shoulder and asked me to walk with him down the august hallway of the Senate Russell office building. He wanted to tell me of a conversation with Shelby Tilford at a recent dinner. Tilford was upset about some things that had been said about EOS at the first Gore roundtable – he was aware of specific statements of participants. McElroy asked Tilford if there was "a mole at the meeting?" Shelby flushed and shot back "Watch it, McElroy, or you will end up in the same box as Hansen!"

Tilford's comment did not surprise me. We were aware that neither NASA Headquarters nor Goddard Space Flight Center managers appreciated criticism of EOS. Yet we thought that we might still alter the EOS observing plans if we made the scientific case clear enough.

4. I met with GISS staff members to discuss this situation. We agreed that the best approach was to shine a bright light on plans for climate observations, their inadequacies, and the potential for small satellites. I had been invited to write an article for *Issues in Science and Technology* criticizing EOS plans. Instead, Bill Rossow, Inez Fung and I would write an article about the potential for small satellites to obtain data complementary to EOS polar platform measurements.

We titled the article[28] "*The Missing Data on Global Climate Change*" with subtitle "A pair of small, inexpensive satellites could help answer pressing questions about projected warming trends." We included the energy cycle table (Table 32.1) to help explain needed observations.

We stressed that these proposed small satellites, dubbed Climsats, were complementary to the EOS platforms. Large EOS instruments could observe with high spatial and spectral resolution, making EOS well-suited for process studies relevant to climate and other global change issues. We reiterated this position in our closing paragraphs:

"We are aware that our advocacy of a small satellite mission inevitably leaves the impression that we are undermining support for the larger EOS mission. But we see the small satellites and polar platforms as complementary rather than mutually exclusive. There is good justification for both systems. The real danger, in our opinion, is that essential climate measurements and accompanying research will be held hostage to the rate of progress of the much larger EOS program, which is still only one component of Mission to Planet Earth."

I sent the draft paper to about 50 scientists, including many EOS investigators. The response was largely positive. Negative criticisms were mainly, if not entirely, from scientists who were receiving funding from EOS. Piers Sellers, one of the top Earth scientists at Goddard Space Flight Center, told me that he was pressured to join in writing a negative criticism of our paper. He refused, but said "whew, it's getting too hot."

A letter-to-the-editor[29] in the Wall Street Journal, with Francis Bretherton as first author, defended the importance of the EOS mission. That letter correctly described our small satellite proposal as complementary to the EOS mission. I testified on this topic at a hearing on Mission to Planet Earth held in the United States Senate on 6 September 1990.[30]

Don Hunten must have thought that I was beleaguered. He sent a note: "You have many vocal critics, a few of whom are even entitled to an opinion. You also have lots of silent supporters, among whom I count myself, and I even think that I know something about the subject. We miss you at PV and Galileo meetings, but the role you have set yourself is important to all of us. Keep up the good work!"

5. On 7 August 1990 I met with my supervisor. He seemed tense. Two papers sat on his desk: (1) the publication approval form for our *Missing Data on Global Climate Change* paper, and (2) my Senior Executive Service (SES) performance plan. He said that I should have asked publication approval earlier, because he objected to two statements in the paper: (1) that with small satellites "the overall results can be improved while we avoid the dangers of having all of our eggs in one large basket," and (2) "The real danger, in our opinion, is that essential climate measurements and accompanying research will be held hostage to the rate of progress of the much larger EOS program." I said that there was still time to alter the paper, but I could not change those statements, which were the essence of the paper.

He said that he would approve publication because he "didn't want our argument to get into the newspapers," but our paper was "not something an SESer should be doing." Therefore he added to my performance plan a requirement to "Enhance and strengthen the role of GISS within NASA as a positive and collaborative programmatic entity." I initialed that change, even though, I argued, we were loyal to NASA and I had taken our reservations about EOS up the chain of command to the level of Associate Administrator Len Fisk.[31]

My supervisor said that NASA management, both at Headquarters and at Goddard, was upset that I was "fighting NASA a third time." Surprised, I asked: "what were the first two?"

The first "fighting NASA" was my 1988 testimony to Congress. The House of Representatives requested that I testify on the same subject that I had testified to the Senate on 23 June. NASA Headquarters insisted that Ichtiaque Rasool testify in my stead. A House staffer called me, saying that they would threaten to have an empty chair with my name on it, if I was willing to testify. Frank McDonald, a Goddard astrophysicist and respected member of the National Academy of Sciences, called me, saying that he was the Acting Director of Goddard (the Director had left for the day). Frank's advice was that I would be wise to "duck it," to allow Rasool to testify. I thought about it over the weekend. Rasool was certain to disagree with my testimony and he could state that most of the scientific community agreed with him.[32] That could wipe out any value of my 23 June testimony. I let the House Committee use the empty chair threat, and I was allowed to testify. I repeated the exact testimony of 23 June.

The second "fighting NASA" was my objection to changes in my 1989 testimony requested by OMB. NASA bureaucrats wanted me to be compliant with OMB wishes. My first response was that these bureaucrats were not "real NASA." Then I remembered an argument I had made at the most recent Goddard management "retreat": as civil servants we owe allegiance to taxpayers and scientific accuracy. My actions were consistent with that duty.

Our disagreement about what constituted "real NASA" flared up again at the next assessment of my performance, in January 1991. After I got home I wrote a 4-page single-spaced letter to my supervisor on the topic "real NASA," with a copy to the Goddard Director. I concluded that it would be irresponsible if I did not take the issue about the inadequacy of EOS to the highest level I could reach, implicitly comparing this to the responsibility of NASA engineers to warn the highest level of a perceived danger in launching the Space Shuttle.

6. Why continue to detail this Climsat saga? It exposes fixable government problems. I took the story to high levels – the NASA Administrator and the White House (the Vice President) – without effect. That's not surprising. The problems emanate down from the highest levels.

That's good, in one sense. If the government were filled with lethargic or incompetent people, that would be hard to fix. But the fact is that the NASA troops – and government employees in other agencies that I interacted with – are hard-working competent people. The problem is that they are constrained to work in an increasingly bureaucratic, inefficient system.

Neither political party in the United States makes a serious effort to reduce bureaucracy and increase government vitality. On the contrary, both parties have increased the politization and inefficiency of government agencies. I refer not to blatant politization during the Trump administration, but rather to gradual change over the past half century. Thus, young people inherit an expensive government that does not serve the public as well as it should.

The public can affect this situation via political parties, their platforms and elections – as I will argue in a later chapter. I realize the difficulty in addressing government inefficiency, but difficult problems can be solved if they are well-defined. My NASA experience provides clear evidence that helps to define the problem.

However, I need to finish this book. So I will summarize events and my opinions.

7. The Washington swamp is not hopeless. Yes, Washington is full of lobbyists and our Senators and Representatives are beholden to special interests. Incumbent political parties refuse to fix this problem because the situation is lucrative. Elected Congresspeople realize that they have joined an elite social class with a good lifestyle and guaranteed post-government "consulting" pay from the special interests. They lose interest in campaign finance reform.

Young people have shown that social media allow election of a political candidate without the need for money from special interests. That potential provides a tool to break the stranglehold that special interests have on our government, possibly via a third political party. American citizens yearn for an alternative that rejects special interest funding. More on that topic later.

Here I only wish to note that the "troops" in Washington are not the problem. Young people do not come to Washington with the idea of working for a crook or for someone who is simply milking the tax-paying public. Young people coming to Washington tend to be idealistic.

I have a positive impression of Congressional staffers and other government employees. In general, they are enthusiastic and try to get best results for the public. Indeed, that was true of Jack Fellows, the OMB professional who was criticized for editing my 1989 Senate testimony. After I learned his identity, we met for lunch in a cafeteria in the New Executive Office Building, which is nominally part of the White House. Although I believe it is wrong that the Administration is allowed to alter the testimony of scientists, I readily agreed that Fellows edits of my testimony were consistent with the views of most of the scientific community at that time.[33] I may not have entirely persuaded Fellows of my conclusions about human-caused climate change, but our views on the science actually were not very different.

After my 1988 testimony an earmark of $1.6M for climate research at GISS appeared in the NASA budget proposed by a Congressional Committee. If that earmark survived budget passage, I was sure that NASA would reduce other funding to GISS. Our budget would become a political football. Given inevitable political oscillations, we would end up firing people as we had in 1981, when the Department of Energy terminated funding for our CO_2 research. So I asked Rafe Pomerance to find out who inserted the $1.6M and have it removed. It was removed.

Then, somehow, $15M for Climsat appeared in the NASA budget in 1991. I did not request it. I do not know who put it there, but it was most likely a Congressional staffer[34] or Jack Fellows. Our 1990 paper on Climsat in *Issues in Science & Technology* had received a lot of attention; the commentary was favorable, except from some NASA-funded researchers. I would welcome funding for a Climsat project, funding that would go to aerospace contractors for construction of the satellite and launch vehicle and to Goddard engineers for oversight of the project. The question was whether NASA Headquarters and Goddard would welcome a Climsat project.

7. In October 1991 I received a call from Goddard Director Klineberg's office. Could I come to his office to discuss plans for the Tropical Rainfall Measuring Mission (TRMM)? He thought that TRMM provided an opportunity to fly our polarimeter (EOSP) to measure aerosols.

That idea could be dismissed out of hand because the tropical orbit of the TRMM satellite would limit observations to low latitudes. Human-made aerosols originate mainly at middle latitudes. We needed *global* measurements of aerosols and other climate forcings and feedbacks.

I sensed something untoward in Klineberg's suggestion, so I asked GISS satellite experts, Bill Rossow and Larry Travis, to accompany me. As I suspected, Klineberg thought of a flight of our instrument on TRMM as an alternative to Climsat, thus making the Climsat $15M funding available. We rejected his idea because it provided only a tiny fraction of our data needs. Bill had useful suggestions for the TRMM mission, which kept the meeting reasonably cordial.

A month later I was back in Klineberg's office advocating for Climsat. Klineberg said that Climsat must be endorsed by the Berrien Moore committee and he noted – perceptively – that they would not endorse anything Shelby Tilford did not want. I responded that we would have a workshop to define climate data needs, inviting the best relevant scientists in the country.

8. In January 1992 I met with my supervisor. He was distraught. My midterm performance rating was "minimally satisfactory" – D on an A, B, C, D, F scale. Senior Executive Service members usually get either an A or a B. With a D, I should plan to give up being GISS Director and revert to research; my supervisor encouraged that.

I had struck out, he said. Strike 1: failure to ask early publication approval of our paper for *Issues in Science and Technology*. Strikes 2 and 3: failure to get his approval for the agenda and participants for our planned Climsat workshop.

Consequently, he reduced the GISS travel budget and we would not be allowed to hire any civil servants. Michael Prather was leaving GISS for a professorship at the University of California in Irvine, but we would not be allowed to refill his position. Renewal of the upcoming GISS building lease with Columbia University might not be supported.

There was still time for me to try to raise my performance assessment before the final rating in the summer. I decided that, instead, I would continue to plan the Climsat workshop with the participants and agenda that I judged to be best. If I were demoted, that would provide an opportunity to shine a light on issues about the path that NASA was on.

9. In February 1992 we held the Climsat workshop at GISS. Our proposed payload for the Climsat mission included a spectacular improvement over the payload discussed in our 1990

Issues in Science and Technology paper. Instead of an Earth Radiation Budget (ERB) instrument we included a Michelson Interferometer (MINT).

We realized from data sampling studies[35] that it is not practical to measure Earth's energy imbalance caused by greenhouse gases to the accuracy needed for climate analyses. A more practical and accurate way is to continue and enhance monitoring of global ocean temperature.

Climsat, with MINT, had optimum measurement of the spectra of both reflected solar radiation and Earth's emitted heat radiation, as shown in Fig. 31.1. The solar spectrum is covered from the near-UV to the near-IR in a dozen bands with polarization measured to 0.1 percent accuracy. The thermal spectrum is measured with high wavelength-to-wavelength precision between 6 and 40 microns (a micron is one millionth of a meter) with moderate spectral resolution.

MINT measures cloud properties, surface temperature, and atmospheric water vapor, ozone and temperature in four atmospheric layers. The polarimeter (EOSP) measures aerosol and cloud particle properties and ground reflectance. A third instrument, the Stratospheric Aerosol and Gas Experiment (SAGE), measures stratospheric aerosols and gases with very high vertical resolution by observing the Sun and Moon as they are occulted by Earth's atmosphere.

The Climsat rationale and instruments are described in a report Long-Term Monitoring of Global Climate Forcings and Feedbacks[36]. The MINT and EOSP instruments are small and well-proven on planetary missions. SAGE had proven predecessor instruments on Earth satellites.

Richard Somerville handed me a note near the end of the Climsat workshop as he headed to the elevator with his suitcase. I opened the note a few minutes later – it said that he was about to meet with Shelby Tilford and he would strongly recommend Climsat to Tilford.

I jumped up and ran down the stairs to the guard's desk. Too late. Somerville had just left in a taxi. I slumped into a chair. Somerville was chairman of a NASA Earth Sciences Advisory Committee. His committee's recommendation would mean more than that of Berrien Moore's committee, but Tilford would not call a meeting if he anticipated a Climsat recommendation.

"Oh well," I thought. A positive recommendation would not alter Tilford's position. I was in a box. We probably would have to wait until circumstances had changed.

10. In April 1992 Dan Goldin became the NASA Administrator. On his first day on the job he gave a talk[37] to the NASA troops. While listening in my office I nearly fell off my chair when he said "Let me just digress from the written words and say: when you have a concern feel free that NASA is an open system to express those concerns. If you have an idea, before you go take that idea forward, why don't you test it, do some peer review, five of your peers. Peer review is probably the most severe thing you could do. It's more difficult than a review by your boss. If you make it through that peer review, and a consensus builds, take it forward and don't let anybody in the organization stop you, go to your boss, talk about it, see if there's some consensus there, take it as high in the organization as it has to go, and if it has to come to my office, I'll stay night and day, I'll stay weekends but I plan to listen. And I fully expect each of your bosses to encourage you to take it forward and not to stop you. NASA is an open book and I deeply and firmly believe it from the bottom of my heart and I want that each of you believes that, so I really, truly want you to participate."

Goldin was sincere, but he had big problems with the Space Shuttle and Space Station. Goddard was just one of 10 NASA Centers and GISS was less than one percent of Goddard. There were five layers of management between me and Goldin – and all these layers opposed Climsat.

Opposition to Climsat stemmed in part from fear that it would reduce support for EOS, but that explanation is insufficient by itself. When I met former Goddard Director Noel Hinners in 1991 he shook his head and said, as close as I can remember, "Why don't they simply adopt Climsat as part of Mission to Planet Earth? It would help in assuring funding from Congress."

Part of the opposition to Climsat, I felt, was reaction to my clumsy criticisms of EOS at its inaugural meeting in 1989. How could I erase that stumble? It was hard because I was certain that my criticisms were valid. The best chance to clarify the climate monitoring story probably was to circulate the draft Climsat report widely. I sent it to more than 100 people.

11. On 28 July 1992 I met my supervisor for my performance review. To my surprise he had raised the rating from D (minimally satisfactory) to B (highly successful). Nevertheless, I submitted my already-prepared written response and requested higher level review. I wrote a comment "I do not object to my rating, but the appraisal process has revealed issues of vital importance to NASA, which I feel should be reviewed at the Office of the Administrator."

My 23-page response detailed my experience in the prior few years. I presented evidence relevant to two important matters. First, NASA falsely claimed that EOS would provide the information that policymakers required to make decisions about global warming. Second, NASA was abusing the advisory process, destroying its value for critical review. The first problem was largely a result of the second: failure of the advisory process. Advisory groups included scientists funded by NASA, and the permitted range of advice was limited.

Goddard Director Klineberg agreed to set up a meeting for me with the Administrator. Time for our discussion would be limited, so I prepared a document for Administrator Goldin prior to the meeting. The document was essentially the material that I attached to my performance review, but I removed the name of my supervisor. He was a religious, rigorously honest person. He was doing exactly what his superiors wanted. It was the NASA bureaucracy that was at fault.

I also sent a note[38] to five leading, relevant scientists including a three-page summary of the two issues that I would raise with Goldin, and I asked if I could give their names if Goldin wanted to discuss these topics further. All of them responded positively and I spoke with most, if not all, of them to get their advice about the topics of the meeting.

12. On 21 September 1992 I met with Administrator Goldin. He had locked in his safe the document that I sent! I don't remember his exact explanation for that, but he said or implied that some people at NASA Headquarters would consider the document to be incendiary.

One topic of our discussion was my assertion that EOS plans failed to deliver on the promise to solve the issues about natural and human-made climate change. I used solar irradiance – which EOS ignored -- as an example. Continuity of solar monitoring should be high priority. Goldin agreed that it should be measured by a small satellite.

This introduced the main topic: corruption of the NASA advisory process. Most advisory committee members were funded by NASA. I suggested that he ask the National Academy of

Sciences to form a group to review Mission to Planet Earth and EOS. He said that he would talk with the President of the Academy about that possibility within the next few days.

I did not mention Climsat. Instead, I invited him to visit GISS, where we could brief him on the science of long-term climate change and the observations needed for understanding. He promised to visit soon. When I returned to GISS there was a message from Goldin's assistant that he would visit GISS on 13 October.

Goldin soon cancelled his plan to visit GISS. According to John Perry, assistant to the President of the National Academy of Sciences, the Academy never received a request from Goldin to review Mission to Planet Earth.

Goldin chose his own reviewers. Down-sizing of EOS occurred several times during 1989-1992, because the Bush Administration would not accept its large price tag – the last down-sizing was after Goldin became Administrator. Ed Frieman – Director of Scripps Institution of Oceanography – headed reviews of the down-sizing during Goldin's tenure.

I presented Climsat to Frieman's committees during the final two down-sizings. They were favorably inclined toward Climsat, as indicated in Frieman's letter to me, but in each case NASA Headquarters informed the committee that there was no room in the budget for Climsat despite the fact that budget changes from one downsize to another amounted to billions of dollars. In answer to Frieman's question to me – about whether Climsat alone could satisfy climate research needs – I said that the polar platform was also needed for high-resolution climate process studies.

Tilford and Fisk had no interest in Climsat. They declined the $15M that Congress put in the NASA budget for Climsat, signing it over to the Department of Energy, which claimed that it would have a small satellite program. They never did – I'm not sure how they used the money.

13. On 12 March 1993 I received a phone call from the director of a large astrophysics laboratory at Goddard. He was on the same organizational level as my supervisor.

The astrophysical director had decided – even though he feared that it may be "career-suicidal" – to organize a mass protest against Goldin. Goldin was a "madman," he said, who had "uniformly alienated everybody." Goldin had moved Len Fisk to a ceremonial position of Chief Scientist, which meant that Fisk lost control of the Space and Earth Science budget.

The astrophysical director's plan was to take a group of scientists to inform Vice President Gore of the situation and seek Goldin's removal as NASA Administrator. He asked me to lead this delegation, because, he said, I was the only one he knew with an entrée to the Vice President.

The other end of the phone went silent as I erupted. My lack of eloquence was compensated by emotion as I unloaded my opinion and experiences. I agreed that Goldin could be abrasive, but he seemed to me to be sincere in his intent to solve basic problems that developed since NASA's early "can do" days. EOS compared to Pioneer Venus as night to day. Goddard engineers loved the idea of working on an innovative small satellite project to investigate climate change, but Klineberg nixed any such effort, because, he said, the "Administration" did not want to see Climsat progress. I asked Klineberg who was the "Administration?" President Bush? OMB? No, it was simply Tilford, backed by Fisk. When I complained to Fisk that EOS was a fake climate mission, that it had no plans to measure the largest unknown natural forcing – the sun's brightness – or the largest unknown human-made forcing – aerosols – Fisk had no answer.

Besides I had already given Gore positive comments about Goldin. On 12 May 1992 Senator Gore and Carl Sagan took a "Joint Appeal of Science and Religion on the Environment" to the United States Senate, where I was asked to give the talk on climate change. Over coffee before the presentations, Gore asked me about Goldin, because he had received criticisms of Goldin from Earth scientists. My response was that Goldin realized that NASA needed reform, was saying all the right things, and I hoped that he would be given a chance to succeed.

The subdued astrophysical director asked whether Goddard Director Klineberg was part of the problem. I paused – I believed that I was speaking to an emissary of Klineberg – then said that I thought Klineberg should be capable of working with a new "Administration" at Headquarters.

I was concerned about what other scientists were telling Gore about NASA and Goldin, so I sent a letter to Gore reiterating my opinion about the need for reform within NASA. Gore did not respond to this letter, so I have no indication that it affected his opinions.

14. On 21 April 1993 Goldin finally visited GISS. He scheduled it for two hours. We planned one hour for GISS overall science and one hour for Climsat, with our usual approach: brief introductions and presentations, with enough time for free discussion around a conference table. This approach was usually effective because several staff members were articulate.

Goldin was 15 minutes late, left the room twice to make phone calls, and seemed uninterested. Inez Fung's summary: "it was as if he had been told to visit GISS and did not want to be here."

On 7 September 1993 Vice President Gore announced a plan to "Reinvent" Government. He would attack the bureaucracy, red tape, unwieldy rules and regulations. NASA welcomed this – it seemed to be just what was needed for Goldin's "faster, better, cheaper" goals.

On 4 November 1993 I met Goldin.[39] He confided about the difficulty of changing NASA Centers. He tried to decrease Goddard's workforce by 200 people, he said, but was promptly called by the White House. Instead of telling me who called him, he said "let your mind wander over the possibilities." I knew he was referring to Vice President Gore, who was close to Barbara Mikulski, who famously protected the budget of what she described as "my Goddard." Goldin was frustrated. "No Darwinian" is possible, he said: the budget is almost entirely allotted to big NASA Centers, protected by their Senators. Goldin complained that the Goddard budget had increased from $1B per year to $2.5B per year. In 2020 it is about $5B per year.

It took decades for NASA rocketry to figure out the Darwinian process. After NASA's own ability to launch astronauts "went to ground," seed money was provided for private industry competition, eventually yielding Elon Musk's Space X and inexpensive launches. Something analogous is needed for science missions.

Goldin visited GISS a few times in 2000 and 2001 – his final two years at NASA – accompanied by NASA Chief Scientist, Kathie Olsen. Goldin was more relaxed then. We had our usual GISS style of meeting, sitting around the conference table in meetings that lasted a few hours.

The first EOS platform had finally been launched in December 1999. EOS carried instruments that the EOS payload committee claimed would measure aerosols. Goddard and JPL each had instruments on EOS that supposedly measured aerosols. In reality, they could not measure either the aerosol climate forcing or the cloud feedback.

Goldin became incensed at this failure of NASA Earth Sciences. In one meeting in the GISS conference room he ordered Associate Administrator Ghassem Asrar to fly our polarimeter. Too late. Goldin was replaced by Vice President Dick Cheney's golfing partner, Sean O'Keefe.

15. On 12 June 2003 I gave a presentation on climate change to the White House Council on Environmental Quality (CEQ) at the invitation of CEQ chairman Jim Connaughton, who was the most powerful person in the Bush White House on climate change issues. Kathie Olsen, who had become the Associate Director of the Office of Science and Technology Policy (OSTP), was in the audience. Olsen, in other words, was deputy to President Bush's Science Adviser.

The largest uncertainty about ongoing and future climate change is caused by the absence of measurements of aerosols and their effect on clouds, I noted. Kathie Olsen asked about the status of the NASA aerosol measurements that Goldin had ordered. Answer: the NASA bureaucracy dropped the idea as soon as Goldin was gone.

I don't know who called whom next, except that I got a call from NASA Headquarters. They had changed their minds and would fly a polarimeter to measure aerosols. The satellite mission, named Glory, had a high-precision (0.1% accuracy) polarimeter and a solar irradiance monitor.

That was a shotgun marriage. Although I advocated the solar measurement for years and in my talk at CEQ, the solar irradiance monitor should be on its own easily-replaceable small satellite.

The natural marriage is a polarimeter with a Michelson interferometer, as defined in our Climsat document. The satellite should include a simple "cloud camera," an imager to accurately define cloud cover in the field of view of the two science instruments. An image avoids the need to "use up" several of the channels of the two science instruments to determine cloud cover. All channels can instead be used to extract greater information on clouds, aerosols, and gases.

Nevertheless, the Glory mission[40] would be a big step toward better understanding of aerosols and likely would lead to an eventual Climsat-like follow-on mission. Work on Glory would keep technical polarimetry expertise alive and progressing during the extended time needed for NASA to move from big EOS-like satellites to modern faster-better-cheaper satellites.

I kept my distance from Glory. A Goddard old-timer told me that my name and the Climsat name still invoked strong resentment at both Goddard and Headquarters, because of a belief that our criticisms had contributed to downsizing of the EOS platforms and budget.

Michael Mishchenko and Brian Cairns developed an unrivaled capability to extract information from scattered sunlight. Michael – principal investigator for the polarimeter on Glory -- was the world leader in scattering theory; he developed exact solutions for scattering by particles of arbitrary shape. Brian was cognizant of the theory and the leader in instrument development, measurements from aircraft, and development of data processing algorithms.

16. On 4 March 2011 the Glory spacecraft sat atop a Taurus XL rocket at Vandenberg Air Force Base in California. Glory had traveled a long road to the launch pad. NASA removed Glory from their budget after Kathie Olsen left OSTP. However, Orbital Science Corporation, which had been selected to provide the launch vehicle, appealed to their Congresspeople, who succeeded in restoring Glory to the NASA budget.

Fig. 33.2. The Glory spacecraft, housed under the nose cone, waited at sunset, and finally blasted off at 2:09 AM on 4 March 2009.

Michael Mishchenko had invested a large fraction of his career in the Glory mission. He had been at Vandenberg on 23 February when the launch was scrubbed because of a malfunction in ground support equipment. He returned and waited nervously at 2 AM on 4 March for the next launch attempt. His concern was heightened, because the prior Taurus launch – of the Orbiting Carbon Observatory (OCO) in 2009 – had failed: the nose cone didn't separate from the spacecraft, thus dragging down the spacecraft to crash into the Pacific Ocean near Antarctica.

NASA had put Taurus launches on hold for two years yet was unable to find the cause for the 2009 launch failure. The rocket, spacecraft and nose cone were all the same for Glory as for OCO, but it was decided to go ahead with the Glory launch. At 2:09 AM on 4 March 2011 Taurus was launched. Two minutes and 58 seconds later the command was sent for the nose cone to separate and fall away. No separation occurred. Glory crashed into the Antarctic Ocean.

Michael was understandably depressed when he came into my office the next day. We talked about the possibility of a replacement satellite. NASA initiated work on a replacement for OCO promptly after its launch failure, but would we receive equal treatment? It seemed unlikely.

I was also thinking about something that Michael didn't know about. He had been nominated for induction into the National Academy of Sciences, but preliminary voting came up short despite his spectacular publication record. In the physics section of the Academy there was a strong emphasis on the number of "home runs" – discoveries in science – hit by the candidate. That issue would be taken care of, I was certain, after Michael had a chance to analyze data from Glory. Michael and Brian Cairns had shown that the polarimeter could yield 10 parameters defining the microphysics of aerosol and cloud particles.[41] I could not help thinking about Michael's home runs, lying on the floor of the Southern Ocean.

17. We had to try again. Aerosols are a big uncertainty in projections of climate change. We must understand aerosol-cloud effects for the purpose of safely guiding Earth back to the climate of a century ago. A climate cooler than today is required to maintain global shorelines, preserve species, keep low latitudes habitable and comfortable, and lower the frequency and severity of climate extreme events to the level of natural climate variability.

Someone suggested that I meet Pete Worden – Director of NASA Ames Research Center – who shared our preference for use of small satellites. Independently, the subject of potentially working with NASA Ames came up during a staff meeting of the heads of Goddard Earth Science laboratories. Our supervisor cautioned us against working with NASA Ames, summarizing the reason as: "they can't be trusted." NASA Ames was contrasted with the other NASA Center in California, the Jet Propulsion Laboratory (JPL).

Goddard and JPL are large NASA Centers. Both Goddard and JPL need to have responsibility for missions in the billion-dollar class to support their large work forces. Their managements achieved an accommodation emphasizing cooperation. In effect they agreed to divide the pie in institutional responsibility for future missions, and there would be opportunities for Goddard instruments to be included on JPL missions and vice versa.

However, NASA policy and the NASA Administrator encourage cooperation among all NASA Centers. I accepted an invitation to give a seminar at NASA Ames on my next trip to the West Coast and had lunch with Pete Worden. We agreed on the need for small inexpensive satellite missions and decided to encourage collaborations among our scientists.

When NASA announced the possibility of proposals for small satellite missions with a cost cap of $95M, this was a great opportunity to demonstrate the ability to measure aerosols and clouds from a small satellite at low cost. The polarimeter and interferometer were each less than or about 20 kilograms in mass. The spacecraft bus and the launch vehicle could be substantially smaller than those used for the Glory mission.[42]

Before our proposal was ready for submission, Pete Worden informed Goddard about our proposal. I should have warned Pete. Goddard management managed to have our proposal prohibited from the competition. I realized then that it was time to retire from NASA.

I have not tried to put together details and dates of this last effort. That would not be easy, because, beginning in 2006, I became involved in what some media called "climate activism." This only amounted to common-sense reaction to requests from people concerned about climate change, but it was sufficiently time-consuming that I had no time to write middle-of-the-night notes on my NASA activities. Instead I wrote Communications on the extracurricular activity that I put on my Columbia University website.

18. **Summary**. Pete Worden left NASA not long after I left. Michael Mishchenko tried hard but was unable to get NASA Headquarters to support a replacement polarimeter for the one deposited in the Southern Ocean.[43]

Michael Mishchenko may have been the best physicist in NASA. He died in 2020 at age 60. Michael was always enthusiastic and loved science, but sometimes downcast in his final years. The NASA system failed him, as he was unjustifiably criticized by higher level management. Michael's sin was that, seemingly without fear, he spoke truth as he saw it, and he saw it with a clarity that evaded ordinary scientists. Specifically, in his papers and in scientific meetings he showed that the Goddard and JPL aerosol measurements on EOS gave inconsistent results and were incapable of defining the aerosol climate forcing. As Michael's immediate supervisor, I bear more responsibility than others. I should have been able to defend him better and to see that his talents were more fully utilized. For sure, we were outnumbered. I believed that science and time were on our side, but time is a precious commodity, and it was squandered in trying to do too many things at once.

Here I followed the Climsat story up to the present – to 2020 – for the sake of making the story comprehensible. In following chapters I revert to a chronological account from the 1990s. I must develop several additional stories before drawing conclusions about climate change and related government policies. However, the Climsat story by itself exposes things about our government that young people need to know, things that are fixable.

NASA Centers, to a substantial degree, have become self-licking ice cream cones. Pete Worden originated that description of a system whose main purpose is to sustain itself. Pete tried to do something about it. He wanted to open NASA Ames to high tech Silicon Valley companies and innovation. He believed that faster, better, cheaper was possible. What frustrated his efforts; why did he leave NASA? I have been too busy in climate research and policy-related work to investigate. NASA troops know that reform is needed, but specific, heart-felt suggestions they send up the chain-of-command do not stem the tide of an increasingly stultifying bureaucracy.

Resurrection of a revitalized NASA is important for young people, for the nation, and for the planet. I believe the United States President and Congress should ask a nonpartisan commission to assess NASA and report recommendations. The United States has great universities, freedom of thought provided by a democracy, and a well-financed private sector. We should be able to do better, and it need not be expensive – the present NASA budget of $20-25B per year is less than half of one percent of the national budget.

The commission could consider and make recommendations about such fundamental problems as politization of NASA, pork barrel distribution of NASA funds, and the archaic civil service system for employees. Noel Hinners, former Goddard Director, realized that the relation between NASA Centers and Headquarters was "too cozy."[44] Management of NASA Centers and NASA science programs should be separate, he thought. Hinners wanted to propose that as part of NASA reforms when he was asked to serve on the Rogers Commission investigating the Challenger accident that killed seven astronauts, but higher ups overruled Hinners.

Hinners is no longer alive. We need a commission while it can still take advantage of the NASA experiences of people like Dan Goldin and Pete Worden. It should seek participation of people in the private sector, such as Elon Musk, and academia. NASA funding could be used to seed projects competitively proposed in which NASA Center facilities are available to and shared with the private sector and universities.

Reimagining NASA should start with a mission statement. When NASA troops were allowed to participate, they chose as the first line "to understand and protect the home planet," but that was removed by a political appointee. A nonpartisan agreement on NASA's mission is needed.

[1] Young, A.T., Are the clouds of Venus sulfuric acid?, Icarus, 18, 564-582, 1973.
[2] Hansen, J.E., and J.W. Hovenier: Interpretation of the polarization of Venus. *J. Atmos. Sci.*, **31**, 1137-1160, 1974.
[3] Twomey, S., Pollution and the planetary albedo, *Atmos. Environ*. **8** (12), 1251–56, 1974. The cross-sectional area of a particle, which determines the amount of scattered radiation, is proportional to the square of the particle radius, while the volume of water is proportional to the cube of the radius. Thus it is easy to show that the cloud albedo increases as the particle number increases. See https://en.wikipedia.org/wiki/Twomey_effect.
[4] Albrecht, B.A., Aerosols, cloud microphysics, and fractional cloudiness, *Science*, **245,** 1227–30, 1989. See also https://en.wikipedia.org/wiki/Albrecht_effect
[5] Hansen, J., M. Sato and R. Ruedy, Radiative forcing and climate response, *J. Geophys. Res.*, **102**, 6831-64, 1997.
[6] Hansen, J., W. Rossow and I. Fung (Eds.), *Long-Term Monitoring of Global Climate Forcings and Feedbacks*. NASA CP-3234, National Aeronautics and Space Administration, 1993.
[7] Mishchenko, M.I., B. Cairns, G. Kopp, C.F. Schueler, B.A. Fafaul, J.E. Hansen, R.J. Hooker, T. Itchkawich, H.B. Maring, and L.D. Travis, 2007: Accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission. *Bull. Amer. Meteorol. Soc.*, **88**, 677-691, doi:10.1175/BAMS-88-5-677.
[8] From a sun-synchronous orbit a given area on Earth's surface is always observed at the same time of day.
[9] Eyring, V., S. Bony, G.A. Meehl, C. A. Senior, B. Stevens, R.J. Stouffer and K.E. Taylor: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, 2016.
[10] Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann: Earth's energy imbalance and implications. *Atmos. Chem. Phys.*, **11**, 13421-13449, 2011.
[11] The inferred aerosol forcing does not change much as the assumed equilibrium climate sensitivity increases above 3°C per CO_2 doubling because the climate response is not much different during the first few decades after the forcing is introduced, if the climate sensitivity is high. Most of the human-made forcing is recent.
[12] Bauer, S.E., K. Tsigaridis, G. Faluvegi, M. Kelly, K.K. Lo, R.L. Miller, L. Nazarenko, G.A. Schmidt and J. Wu: Historical (1850-2014) aerosol evolution and role on climate forcing using the GISS ModelE2.1 contribution to CMIP6, J.Adv.Mod.EarthSyst. 12, e2019MS001978, 2020.
[13] The sharpest known warming spike in Earth's history, Paleocene-Eocene Thermal Maximum (PETM, Chapter 25), was driven by a forcing that increased at least 10 times more slowly than the human-made forcing has increased in the past half century; the global warming rate in the PETM likely would have been similarly slower.
[14] Management of the Galileo mission to Jupiter was not quite as lustrous. The tortuous 20-year time-scale of the Galileo mission was in part a result of political decisions including use of the Space Shuttle to launch the spacecraft.
[15] Johnson Space Center, Earth System Science, oral histories.
[16] $50B was the cost estimate in 1989 for 30-year program in 1989 dollars, which exceeds $100B in 2020 dollars.
[17] Nitrogen fixation converts nitrogen in the air to ammonia (NH_3) or related nitrogenous compounds, especially by certain microorganisms, as part of the nitrogen cycle. Nitrogen is a critical element for plant growth. It is a major component of chlorophyll needed for photosynthesis and of amino acids, the key building blocks of proteins.
[18] National Research Council, *Earth System Science: A Closer View*. Washington, National Academies Press, 1988.
[19] The Earth Observing System had two platforms, both in sun-synchronous orbits with subsatellite track close to the poles with equator-crossing times at the same time of day every orbit, one of the platforms with equator-crossing time in mid-morning, the other in mid-afternoon.
[20] Almost 500 proposals were submitted in response to NASA's 1988 Announcement of Opportunity. NASA approved 30 instruments for development and 29 interdisciplinary science investigations.
[21] Don Hunten used parts of these memos for the paper summarizing Galileo mission objectives and thus included me as a co-author of that paper: Hunten, D.M., L. Colin, and J.E. Hansen: Atmospheric science on the Galileo mission. *Space Sci. Rev.*, **44**, 191-240, 1986.
[22] Eckelmann, F.D., Memorial to Thomas A. Mutch., 1980.
[23] Letter to Dixon Butler, EOS Program Scientist, NASA, Washington, DC 20546, 27 March 1989.
[24] Marshall, E., Bringing NASA Down to Earth, Science, 244,1248-1251, 1989.
[25] Letter exchange with Prof. James Van Allen, University of Iowa, September 1989.
[26] I no longer have the invitation letter to the December 1989 roundtable, but the expanded list of invitees to the January 1990 meeting was D. James Baker, Francis Bretherton, James Hansen, Tom Lovejoy, Gordon MacDonald, Mike McElroy, Irving Mintzer, William Moomaw, George Woodwell, Berrien Moore, Steve Schneider, Steve Leatherman, Karl Wunsch, Sherry Rowland and Jeff Dozier.
[27] The low latitude orbit of the Space Station is limiting, astronauts can disturb precise pointing of instruments, and cost is added by the requirement to assure that the instruments provide no risk to the astronauts.
[28] Hansen, J., W. Rossow and I. Fung: The missing data on global climate change. *Issues Sci. Tech.*, **7**, 62-69, 1990.

[29] Bretherton, F., et al.: Planet Earth – Help is on the Way, Wall Street Journal, 9 August 1990.
[30] Hansen, J., Remarks on Mission to Planet Earth, Federation of American Scientists, U.S. Senate, 6 Sept. 1990.
[31] Fisk listened steely-eyed and unsmiling during a 75-minute discussion in his office on 17 January 1990, but I could not alter his support for Tilford's large platform EOS.
[32] Kerr, R.A., Hansen vs. the World on the Greenhouse Threat, *Science* **244**, 1041-1043, 1989.
[33] Kerr, R.A., Hansen vs. the World on the Greenhouse Threat, *Science* **244**, 1041-1043, 1989.
[34] I had lunch once, in 1990, with Richard Malow and Jeff Lawrence, two powerful congressional staffers; it was arranged by Rafe Pomerance, who said that it was at their request. As we were parting after lunch one of them asked if I had a recommendation for the NASA budget. Perhaps they expected me to say "Climsat," but I said "put TRMM back in." Tilford had removed the Tropical Rainfall Measuring Mission for the sake of grabbing funds for EOS, even though TRMM had been planned for more than a decade. My nighttime notes (I had trouble sleeping in those years and often got up to write a record of events or plans) imply that I had lunch once, in 1992, with Kevin Kelley, another powerful staffer, but I do not have notes from a meeting with him.
[35] We had global data from two sources: the International Satellite Cloud Climatology Project and our global climate model simulations. We sampled these data sets at the places and times observable from specific spacecraft orbits to find the error introduced by incomplete global coverage for different orbit choices.
[36] Hansen, J., W. Rossow and I. Fung, *Long-Term Monitoring of Global Climate Forcings and Feedbacks*, NASA CP-3234, 91 pages, 1993.
[37] Goldin, D.S., NASA Administrator Address to Employees, 01 April 1992.
[38] Faxed note and 3-page attachment sent to Peter Stone; the same note and attachment were sent to Michael McElroy,,Gerald North, Carl Sagan and Warren Washington.
[39] My notes don't explain the occasion, but I believe it was outdoors on the Goddard Greenbelt campus. His intent seemed to be to confide that the White House was frustrating his effort to use "Darwinian" (competition) to spur his plans for a faster, better, cheaper NASA.
[40] Mishchenko, M.I., B. Cairns, G. Kopp, C.F. Schueler, B.A. Fafaul, J.E. Hansen, R.J. Hooker, T. Itchkawich, H.B. Maring and L.D. Travis: Accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission. *Bull. Amer. Meteorol. Soc.*, **88**, 677-691, 2007.
[41] Ibid.
[42] Glory used a spacecraft salvaged from a cancelled mission. Refurbishment of that spacecraft bus was costly and resulted in a heavy satellite with a mission cost exceeding $400M.
[43] NASA did support construction of a new solar irradiance monitor and the prior solar mission lasted far beyond its expected lifetime, so an unbroken record of the Sun's brightness is continuing.
[44] Hinners, N., NASA Oral History Project, 2010. Direct link to relevant comments in the document.