Chapter 31. Aerosols

Charney was right, the aerosol story is weird. It is also important. When citizens finally force political leaders to act to prevent climate catastrophe, it will become clear 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 drop, 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 mixed 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 aerosol climate forcing today is estimated to be of order -0.5 W/m^2, uncertain by a factor of two, so its 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'll never solve it," said Charney.

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.

The global observations must be complemented by including aerosol modeling in global climate models. Reasonably good progress is being made in 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 top two 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 understanding of electromagnetic theory – even van de Hulst was impressed. Cairns, originally from the U.K., came to GISS as a post-doc from the University of Rochexter with the rare quality of combined theoretical and experimental talent, a crucial quality for the sake of extracting the 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.

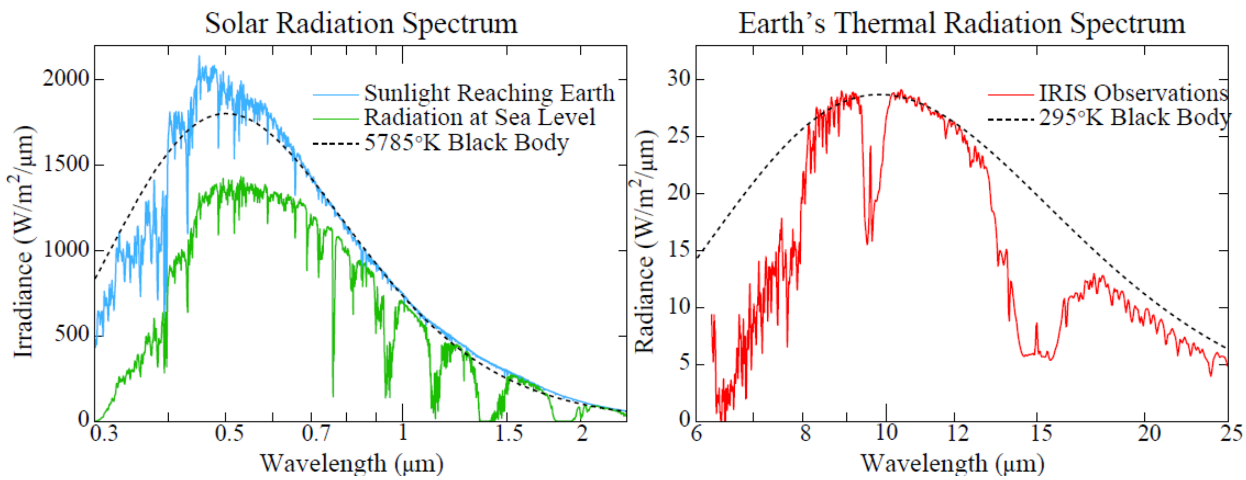

Fig. 31.1. Sunlight reaching Earth and reaching the ground for clear sky conditions (left). Thermal (heat) radiation to space measured from a satellite over the Sahara desert (right).

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 human-made 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."

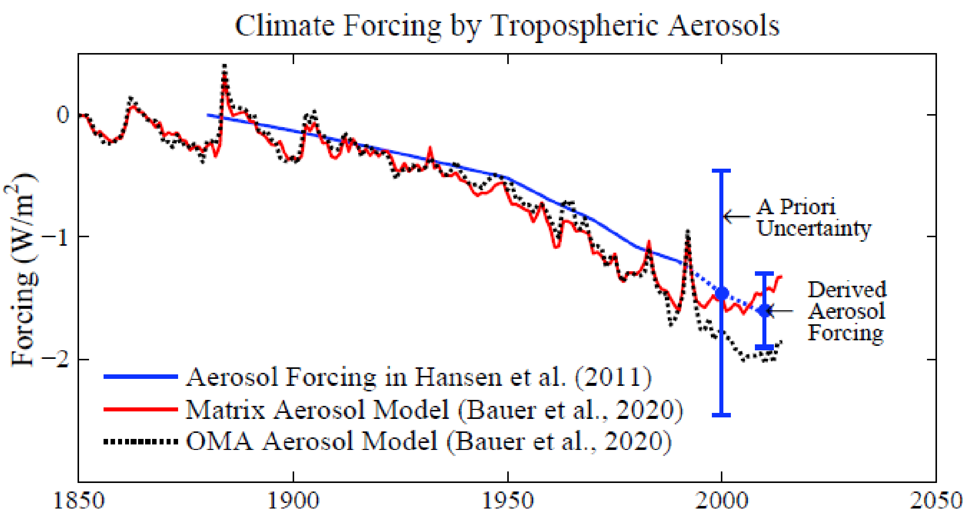

Fig. 31.2. Aerosol forcing scenarios and value in 2010 based on Earth's energy imbalance.

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. 31.2). 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, greater negative forcing 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 only 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 chapters.

[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.