Aerosols: Volcanoes, Dust, Clouds and Climate

Haze from small particles surely affected climate, but how? Old speculations about the effects of smoke from volcanoes were brought to mind in the 1960s, when urban smog became a major research topic. Some tentative evidence suggested that aerosols emitted by human industry and agriculture could change the weather. A few scientists exclaimed that smoke and dust from human activities would cause a dangerous global cooling. Or would pollution warm the atmosphere? Theory and data were too feeble to answer the question, and few people even tried to address it. Among these few, the uncertainties fueled vigorous debates, in particular over how adding aerosols might change the planet's cloud cover. Starting in the late 1970s, powerful computers got to work on the ferociously complex calculations, helped by data from volcanic eruptions. But there were so many difficulties in both theory and data that aerosol effects were persistently the largest source of uncertainty in estimates of future warming. It was clear, however, that pollution was significantly delaying, and masking, the coming of greenhouse effect warming, and that restricting pollution would accelerate the warming.

In 1783 a volcanic fissure in Iceland erupted with enormous force, pouring out cubic kilometers of lava. Layers of poisonous ash snowed down upon the island. The grass died; three-quarters of the livestock starved to death, followed by a quarter of the people. A peculiar haze shadowed western Europe for months. Benjamin Franklin, visiting France, noticed the unusual cold that summer and speculated that it might have been caused by the volcanic "fog" that visibly dimmed the sunlight.[1]

Better evidence came from the titanic 1883 explosion of Krakatau (Krakatoa) in the East Indies, which sent up a veil of volcanic dust that reduced sunlight around the world for months. The planet had so few weather stations that scientists were unable to learn for sure whether the eruption affected the average global temperature. But from then on, scientific reviews of climate change commonly listed volcanoes as a natural force that might affect large regions, perhaps the entire planet. Looking at temperatures after major volcanic eruptions between 1880 and 1910, a few scientists believed they could see a distinct temporary cooling. (The most impressive confirmation came late in the 20th century, when examination of older records showed that

[1] Franklin (1784). First to suggest the connection was a French naturalist, Mourgue de Montredon, in a 1783 communication to the Académie royale de Montpelier.

the1815 eruption of Tambora, scarcely noted at the time outside Indonesia, had affected the world's climate much more than Krakatau. Crops were frozen as far away as New England.)[1]

Perhaps the smoky skies in an era of massive volcanic eruptions were responsible for the ice ages, or had even killed off the dinosaurs by cooling the Earth?[2] This image of climate change became familiar in popular as well as scientific thinking. In the 1950s, experts noted that the Northern Hemisphere had been getting warmer over the last several decades, a time when volcanoes had been relatively quiet, whereas the preceding century had experienced a number of huge eruptions and had been severely colder.[3]

The climate scientist J. Murray Mitchell, Jr. took up the question, with the help of improved data on how minuscule particles (aerosols) moved through the upper atmosphere. Studies of fallout from nuclear bomb tests had shown that fine dust injected into the stratosphere would linger for a few years, but would not cross from one hemisphere to the other. With that in mind, Mitchell pored over global temperature statistics and put them alongside the record of volcanic eruptions. In 1961, he announced that large eruptions caused a significant part of the irregular variations in average annual temperature in a given hemisphere. On the other hand, average temperatures had fallen since 1940, a period in which the world had seen few major eruptions. Mitchell concluded that the recent cooling was an "enigma." He thought it might signal a new phase of a decades-long "rhythm," the sort of cycle that generations of climatologists had tried to winkle out of their data.[4]

Maybe aerosol science itself could solve the enigma. If it was plausible that volcanic emissions could alter the climate, what about particles from other sources? Meteorologists recognized that dust and other tiny airborne particles could have important influences. Simple physics theory suggested that such aerosols should scatter radiation from the Sun back into space, cooling the Earth. Through the first half of the 20th century, measurements and theory were inadequate to

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[1] Krakatau's effects were seen only on subtracting supposed effects of the sunspot cycle, Abbot and Fowle (1913). The classic study Symons (1888). Tambora: Stothers (1984).

[2] A principal exponent of the view that volcanoes dominated climate change was W.J. Humphreys, see Humphreys (1913); Humphreys (1920), repeated in the 3rd (1940) edition, pp. 587-618.

[3] Wexler (1952), p. 78.

[4] Mitchell (1961). On fallout studies he cites a 1960 Defense Atomic Support Agency report by A.K. Stebbins; rhythm: Mitchell (1963), p. 180.

say anything about that.[1] Speculation gradually came to focus on something that people were beginning to recognize as a major source of atmospheric particles: human activity.

Aerosols as Global Pollution (1920s-1960s)

Hints that human emissions made a difference in the atmosphere went back to measurements by the pioneering oceanographic vessel *Carnegie* and other ships on voyages between 1913 and 1929. Analysis of the sea air showed a long-term decrease in its conductivity, a decrease which seemed to be caused by smoke and gases from ships and perhaps from industry on land. "Thus we see," a researcher concluded, "that like a living thing, the conductivity of the lower atmosphere finds survival increasingly difficult in our modern industrial age."[2] Still, a 1953 review concluded that scientists simply did not know whether pollution had significantly affected the transmission of solar radiation.[3]

There was little prospect of getting an answer. Nobody had foreseen the need for a series of uniform measurements over the decades to show what was happening on a global scale. There existed only a few indirect indications, like the *Carnegie*'s measurements of air far out at sea. It happened that some astronomical observatories had kept regular records of the clarity of the air at their sites. But nobody took on the challenge of hunting down such data and trying to correct the numbers for local changes such as the growth of a nearby city. As late as 1977, one expert lamented that "the time and energy put into discussion perhaps outweigh the time and energy which have been put into measurements."[4] Worse, since air pollution seemed to be a problem only near the cities and factories where it was emitted, nobody had studied the relationship between pollution on the one hand and the chemistry of the global atmosphere on the other. The two fields engaged two different groups of investigators.

Aerosols not only intercepted sunlight, but might also affect climate by helping to create clouds. Research early in the century had shown that clouds can only form where there are enough "cloud condensation nuclei" (CCNs), tiny particles that give a surface for the water droplets to condense around. In the 1950s, scientists began to consider whether people might be able to deliberately change their local weather by injecting materials into the atmosphere to help clouds form. "Seeding" clouds with silver iodide smoke, in hopes of making rain, became a widespread commercial enterprise. Less visible to the public were government studies of the use of aerosols

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[1] It "would be necessary to bring [dust] into the scheme" of a complete calculation, but "that will not be attempted," in the most comprehensive effort at calculation, Richardson (1922), p. 45, see p. 59; discussed in Nebeker (1989), pp. 93-94; Ångström (1929); another speculation (first suggested by H. Shapley in 1921) was that long-term climate changes might come when the Earth passed through clouds of interstellar dust. Hoyle and Lyttleton (1939); Himpel (1947); Krook (1953).

[2] Wait (1946), p. 343.

[3] Wexler (1953), pp. 94-95.

[4] Twomey (1977b), p. 290.

as a weapon of climatological warfare, to inflict droughts or blizzards on an enemy. For good or ill, it was becoming plausible that aerosols emitted on an industrial scale could alter the climate of an entire region.

Perhaps we were already doing something like that inadvertently. In the early 1960s, Walter Orr Roberts, a prominent astrophysicist at the University of Colorado, noticed that something was changing in the broad and sparkling skies above Boulder. Roberts had a long-standing interest in climate. One of the things that had driven his career in astrophysics was a hope of connecting climate with sunspot cycles; he had been especially impressed by the terrible drought of the 1930s, which he had seen firsthand when he drove through the Dust Bowl on his way to Colorado. Aerosols stayed on his mind.

One morning as he was talking with a reporter from the *New York Times* Roberts pointed out the jet airplane contrails overhead. He predicted that by mid afternoon they would spread and thin, until you couldn't tell the contrails from cirrus clouds. They did, and you couldn't.[1] The *Times* made it a front-page story (Sept. 23, 1963). "Until recently, Dr. Roberts explained, cirrus clouds were thought to be more of an effect than a cause of weather conditions. But data from balloon and satellite experiments now suggest... [clouds] may trap enough heat beneath them to affect the weather." Since jets evidently made cirrus clouds, they "might be altering the climate subtly along major air routes."

The idea was controversial, like anything that sounded like "cloud seeding." Many scientists believed that seeding with particles could cause rain only under unusual conditions—or never. The "cloud chamber" studies around the start of the 20th century, which had shown that clouds could not condense in very pure air, did not seem significant. Most scientists believed that there were always plenty of nuclei in the air, from sources like soil dust stirred up by the wind and salt crystals from ocean foam. Therefore clouds would form wherever the temperature and humidity were right. Nobody had carefully tested this assumption. The theory of how particles affected clouds was complex beyond reckoning, and field tests were too costly to pursue far, especially since their results turned out to be contradictory and confusing. Scientists avoided the intractable study of cloud formation. As one of them later recalled, they viewed tiny particles mainly "as air-quality indicators."[2]

By the early 1960s, however, the question of human influence on clouds was starting to attract at least some scientific attention. Roberts's observation of contrails was joined by other hints that various types of anthropogenic aerosols—microscopic solid particles or droplets of chemicals produced by human activity—might indeed increase the amount of cloud cover. A 1966 study of satellite photos of the oceans found linear clouds that might have been seeded by smoke from

[1] On Roberts: Levenson (1989), p. 98. Reporter: John A. Osmundsen, personal communication; contrail studies are reviewed by Barrett and Landsberg (1975); one of the first observations was the brief report of Georgi (1960).

[2] "Plenty of nuclei," "air-quality": Twomey (1980), p. 1459.

ships. Another study, tracking rainfall downwind from paper mills, suggested that humans were causing more precipitation inadvertently than by deliberate cloud seeding.[1] These were not global but local or regional effects, and speculative at best.

Another line of thinking about the effects of dust from human activities addressed pollution that settled on ice and snow. Could that lower their reflectivity enough to change the climate? The idea was inspired by one of those quirky speculations that both harassed and stimulated climate scientists—a suggestion that "dusting of the ice caps" by volcanoes and soil blown off of dry lands had caused the irregular changes in sea-level that had been recorded in historic times.[2] This was only one of countless theories of climate change, and did not get much credence or attention.

Roberts's tentative ideas about clouds did get a chance to catch sustained attention. The opportunity was a growing public concern over the U.S. government's plans to build a fleet of supersonic transport airplanes. Hundreds of flights a year would inject water vapor and other exhaust into the high, thin stratosphere, where natural aerosols were rare and any new chemical might linger for years. Some scientists feared that the flights would seriously affect the climate.[3] A 1970 review by a panel of experts warned that aircraft were already polluting the stratosphere with hydrocarbons and sulfur and nitrogen compounds, all of which might interfere with radiation directly as well as increasing cloudiness. They reported that high cirrus clouds had in fact increased in the United States since the 1940s. The effects of aircraft on climate might be significant, they concluded—indeed particles emitted by a fleet of supersonic transports might alter the stratosphere as much as a volcanic eruption. But a calculation of the actual effects was still far beyond reach.[4] Such work was admittedly closer to plausible story-telling than scientific rigor.

Aerosol science was just emerging as a field standing on its own. Like many other fields it had gotten a strong impetus from warfare, where smokes, poison gases, and disease-carrying aerosols could be mortal concerns. The field first began to coalesce during the Second World War, and its first handbook was based on studies done under the Manhattan Project.[5] After the war rainmaking jumped to the top of the list of practical interests, but it was too intractable and

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[1] Conover (1966); mills: Hobbs et al. (1970), see p. 89.

[2] Bloch (1965); human impact was emphasized by Landsberg (1970).

[3] New York Times, May 1, 1965, p. 1. Aircraft were estimated to increase cirrus over as much as 5% of the worlds's skies, which "is not negligible," according to Bryson and Wendland (1970), p. 137; repeated in Bryson and Wendland (1975), p. 146. There were also concerns about exhaust from space shuttle flights.

[4] Wilson and Matthews (1971), p. 9, see Machta and Carpenter (1971); another major group effort found that while supersonic transports appeared to be harmless, the effect was close enough to the threshold of harm to merit concern. Pollack et al. (1976a); in 1999 a scientific panel concluded that aircraft would contribute roughly 5% of the human influence on climate by the year 2050, IPCC (1999).

[5] United States (1950); see Benarie (2000).

controversial for most aerosol specialists. Still less were they interested in tackling the physics of clouds or the physics of radiation high in the atmosphere—topics that were dauntingly intractable and remote from any useful application. Concern over fallout from nuclear weapons tests motivated some research (not always openly published) that was potentially relevant to climate. Most aerosol specialists, however, were far more interested in the practical problems of air at ground level, especially public and occupational health. And these problems, involving dust and pollution, "had no glamour to offer for young researchers," as one pioneer admitted. The field's first journal (named, naturally enough, the *Journal of Aerosol Science*) was not founded until 1970, and the editor remarked that even then "academic status has not been achieved."[1]

The people who were coming together to form an aerosol science community were mostly scattered among industrial and government laboratories. In these organizations, as the new journal's editor remarked, "it is extremely difficult for a scientist to concentrate over the many years which are necessary for the mastery of a subject."[2] Many of the aerosol experts were kept busy studying local air pollution, driven by rising public dismay over urban smogs. Chemists were drawn in during the 1950s to analyze the smog of Los Angeles, which turned out to be a fascinating (and sometimes lethal) mixture of chemicals as well as solid particles. Meanwhile other aerosol experts worked on industrial processes like "clean rooms" for manufacturing electronics, and still others investigated military problems such as the way particles scattered laser light. These researchers had only occasional contact with their colleagues in different areas of the proto-field of aerosol science, and still less with anyone in other fields of science that might relate to climate.[3]

Most of the aerosol scientists' attention went to "pollution" particles that fell out of the atmosphere (or were washed out by rain) within a few days. But other microscopic particles could linger longer and travel farther. Entire regions were intermittently hazed over, raising questions about possible world-wide effects. Already in 1958, one expert had remarked that "there can no longer be any sharp division between polluted and unpolluted atmospheres."[4] It was some time before many others recognized how far pollution spread beyond cities. Understanding came only after people studying smog set up a network of stations that regularly monitored the atmosphere's turbidity (haziness). In 1967, Robert McCormick and John Ludwig

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[1] "glamour": Gerhard Kaspar in Preining and Davis (2000), p. 392; "academic": Davies (1970).

[2] Davies (1970); Othmar Preining (personal communication) writes that an aerosol scientific community began forming in the mid 1960s, following the publication of Fuchs (1964); see Preining and Davis (2000), pp. 9, 148-49, 393. The American Association of Aerosol Science was formed only in 1981. A journal "Atmospheric Environment," founded 1967, dealt only with pollution.

[3] For a review of aerosol history, see Charlson (1998).

[4] Junge (1958), p. 95. He asserted that "unpolluted areas... no longer exist" in Western Europe and the northeastern United States (p. 101), but was not thinking of pollution great enough to alter climate.

of the National Center for Air Pollution Control in Cincinnati reported a gradual increase in the general turbidity over regions spanning a thousand kilometers. Further checks of the record of turbidity turned up hints of increases even in remote areas like Hawaii and the North and South Poles.[1] Could humanity's emissions be affecting the global climate, not in some abstract future but right now?

Although these studies were not widely noted at the time, they contributed to, and at the same time responded to, a broad change of public thinking. This had started with observations that radioactive fallout and chemical pesticides could be found far from the places where they were emitted. The world's oceans and air could no longer be seen as a virtually infinite dumping-ground. Fewer and fewer people believed that the atmosphere could safely absorb (as one aerosol expert acidly put it) "any effluents which mankind might see fit to disgorge into it."[2] Through the early 1960s, ideas about human influence on the global climate had focused on greenhouse effect warming caused by industrial emissions of carbon dioxide gas (CO_2). At the time the effect seemed no more than a fuzzy speculation. Adding to the uncertainty, weather experts were just now confirming that a world-wide cooling trend had been underway for a decade or so. McCormick and Ludwig suggested that the cooling trend itself might be due to human activities.

Reid Bryson, a University of Wisconsin meteorologist, joined the discussion. In 1962, while flying across India en route to a conference, he had been struck by the fact that he could not see the ground—his view blocked not by clouds but by dust. Later he saw similar hazes in Brazil and Africa. The murk was so pervasive that local meteorologists took it for granted and failed to study it. Bryson realized, however, that the haze was not some timeless natural feature of the tropics. He was seeing smoke from fields set on fire by the growing population of slash-and-burn farmers, and dust from over-grazed lands turning to desert. The effects of ever more widespread farming and grazing, together with pollution from industry, seemed large enough to alter the climate of a region or even the entire planet. At a 1968 "Symposium on Global Effects of Environmental Pollution" that met in Dallas, Texas, Bryson impressed his colleagues with a chart that showed how rising levels of dust in the Caucasus correlated with the rising output of the Russian economy. He went on to speculate that a rapid and world-wide rise of atmospheric turbidity would cause temperatures to fall. Calling for more intense study, Bryson and a collaborator wrote that they "would be pleased to be proved wrong. It is too important a problem to entrust to a half-dozen part-time investigators."[3]

Concern grew when studies showed that recent decades had seen a great increase in the amount of aerosols in the lower atmosphere ("troposphere"). The air over the North Atlantic was twice as dirty in the late 1960s as it had been in the 1910s, suggesting that the natural processes that

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[1] McCormick and Ludwig (1967); Bryson (1967); for establishment of network in 1960-61, see Flowers et al. (1969).

[2] Twomey (1977b), p. 1.

[3] Symposium: Singer (1970); Bryson and Wendland (1970), quote p. 137; see also Bryson (1968). India: Bryson (1967), p. 53. Impressed: Peterson et al. (2008), p. 1328.

washed aerosols out of the atmosphere could not keep up with human emissions.[1] As a back-page *New York Times* item (Oct. 18, 1970) reported, "This is disturbing news for those weather experts who fear that air pollution, if it continues unchecked, will seriously affect the climate..."

But how much of the haze was really caused by humans? In 1969 Murray Mitchell pushed ahead with his statistical studies of temperatures and volcanoes. He calculated that about two-thirds of the cooling that had been progressing in the Northern Hemisphere since 1940 was due to a few recent volcanic eruptions. He concluded that "man has been playing a very poor second fiddle to nature as a dust factory."[2] Other respected climatologists agreed that volcanic dust could account for a substantial part of the temperature variations in the last century or so. The most impressive work was done by the British meteorologist Hubert Lamb, who burrowed through many kinds of historical records to compile a "Dust Veil Index." His tables revealed a telling connection between dust and cooler temperatures. But if the experts now agreed that volcanic explosions could affect temperature, they disagreed on how strong the effect was.[3]

One thing scientists were coming to agree on was that the problem was significant enough to merit a sustained attack. Mitchell for one, even while denying that human aerosols had done much so far, thought they could become significant within a few decades. McCormick and Ludwig told a *New York Times* reporter (June 9, 1970) that their experiments proved that fine particles could noticeably reduce the sunlight reaching the surface of the Earth. Their main message was a call for better monitoring of turbidity. "What we are trying to do," Ludwig added, "is get scientists' curiosity and concern aroused."

Warming or Cooling? (Early 1970s)

A few scientists did have their curiosity and concern aroused to the point where they pursued a modest number of studies in the early 1970s. They failed to find solid evidence for a global increase of turbidity. But the studies did confirm that there were regional hazes—episodes of pollution spreading a thousand kilometers or so downwind from industrial centers.[4] Everyone now admitted that human pollution was growing headlong. While Mitchell continued to insist that humanity was "an innocent bystander" in the cooling of the past quarter-century, in 1971 he calculated that our emissions might begin to cause substantial cooling after the end of the century.[5] Other scientists claimed that the increase of aerosols was important already, perhaps

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[1] Cobb and Wells (1970); see also Hodge (1971).

[2] Mitchell at meeting of AAAS, Boston, Dec. 1969, as cited by Landsberg (1970); quote: Mitchell (1970), p. 153, from a 1968 symposium.

[3] "It seems probable that present changes of the Earth's temperature are determined mainly by... the level of volcanic activity," concluded Budyko (1969), p. 613; on the other hand, Lamb concluded that "volcanic dust is not the only, and probably not the main, influence," Lamb (1970); skepticism held up publication of this paper for five years, see Lamb (1997), p. 189.

[4] Barrett and Landsberg (1975), pp. 42-43, 48.

[5] Mitchell (1971b), quote p. 713.

even more of a concern than CO_2. But nobody trusted anyone else's calculations, which were in fact much too crude to give reliable answers. Adding to the uncertainty, Mitchell gave plausible arguments that aerosols could produce a *warming* effect. It depended on how much they absorbed or reflected radiation coming down from the Sun, and how much they trapped heat radiation rising up from the Earth's surface. It also depended on the height in the atmosphere where the aerosols floated, and on whether they floated above bright regions like deserts (which reflect sunlight) or dark ones like the oceans (which absorb sunlight).[1]

S. Ichtiaque Rasool and Stephen Schneider entered the discussion with a pioneering numerical computation. (This was the first atmospheric science paper by Schneider, who would become a well-known commentator on global warming. As an engineering graduate student, he had been alerted to environmental issues when he heard a talk by the biologist Barry Commoner, warning that pollution could trigger either an ice age or global warming.)[2] Rasool and Schneider, like Mitchell, recognized that aerosols might not cool the atmosphere but warm it; the tricky part was to understand how aerosols absorbed radiation. Their calculation gave cooling as the most likely result. Estimating that dust in the global atmosphere might have doubled already during the century, and might double again in the next fifty years, they figured that this might cool the planet by as much as 3.5°C.

That could be disastrous, especially in view of some simplified calculations just published by others which suggested that the climate system could be very sensitive to small changes of temperature. Rasool and Schneider also believed the greenhouse effect would not counteract the cooling, since according to their model, adding even a large amount of CO_2 would bring little warming. The dip caused by aerosols, they exclaimed, "could be sufficient to trigger an ice age!" In fact their equations and data were rudimentary, and scientists soon noted crippling flaws (as did Schneider himself, see below). But if the paper was wrong, what did aerosols in fact do?[3]

Another stimulus to work on aerosols came from a spacecraft that reached Mars in 1971 and found the planet enveloped by a great dust storm. The dust had caused the Martian atmosphere to

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[1] If exponential growth continued, Mitchell foresaw a 1°C greenhouse effect temperature rise by 2000, followed by accelerating cooling as aerosols accumulated faster than CO_2. Mitchell (1970); "In my opinion, man-made aerosols... constitute a more acute problem than CO_2," Landsberg (1970).

[2] Kaiser (2000).

[3] This globally averaged model didn't allow for changes in convection or clouds, and got only 2°C of warming for an eightfold rise of CO_2, an error soon corrected by other calculations. Also, the ice-age scenario came from an exponential rise of aerosols beyond anything possible. Rasool and Schneider (1971), quote p. 138, with references to work of Budyko and Sellers; they calculated the doubling of dust from data reported by Hodge (1971); see confirmation and priority claim by Barrett (1971); criticism: Charlson et al. (1972); Weare et al. (1974); Chylek and Coakley (1974); Kellogg et al. (1975); Schneider and Mass (1975); possible warming was calculated by Wang and Domoto (1974).

warm up substantially—an undeniable demonstration that aerosols could profoundly affect climate.[1] New studies confirmed how aerosols could affect a planet's reflectivity, by scattering and absorbing sunlight and by catching infrared rays coming up from the surface. Yet the calculations were still too uncertain to say for sure whether the net result would be to increase or decrease the reflectivity, whether dust would cool the Earth or warm it.

Beyond the direct effects of aerosols absorbing or scattering radiation, an even tougher puzzle remained: how did particles help create particular types of clouds? And beyond that loomed the enigmatic question of how a given type of cloud might affect the temperature. Depending on whether clouds were thick or thin, and where they floated in the atmosphere, they might bring some amount of cooling, by reflecting sunlight, or they might even bring warming, by trapping heat radiation in a sort of greenhouse effect. The one sure thing was that aerosols could make a difference to climate, and perhaps a big difference.

Bryson felt more certain than most about the effects of aerosols, and more worried. His studies of the distant past had convinced him that the climate had sometimes veered dramatically in the span of a single century. Could a similar cataclysm befall our civilization? Weren't the deadly 1973 droughts in Africa and South Asia a sign that we were destroying our climate with pollution?[2] In 1974, Bryson noted that humans emitted aerosols mostly in northern mid-latitudes, just where the recent cooling trend was most evident. He suggested that the pattern of pollution would change the gradient of temperature from equator to pole. A change of only a few tenths of a degree in this gradient, he calculated, could shift the entire general pattern of atmospheric circulation. That might alter, for example, the annual monsoon that was crucial for the peoples of India and the African Sahel. "Our climatic pattern is fragile rather than robust," he warned.[3] Bryson was taking his concerns to the public. The entire balance of climate could be tipped, he said, by what he called "the human volcano." (He meant our emissions of aerosol particles and chemicals, not CO_2. The amount of the gas coming from volcanoes was negligible, barely as much in a century as what human industry emitted each year.)

To the confusion of onlookers, an entirely different prediction about cooling was meanwhile emerging from an entirely different field of science. New data on past ice ages showed that they followed a remarkably regular schedule. The warmest part of a cycle typically lasted barely ten thousand years, so it seemed likely that the Earth was now past the peak of the current cycle and was scheduled to descend into another glacial epoch. (Decades later it was learned that the current cycle is atypical and might last considerably longer, but nobody at the time could guess that.) In the natural course of things the temperature would fall gradually over the next few thousand years. But perhaps human emissions were getting large enough to interfere with the

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[1] Also, it was suggested that such dust storms might initiate a radical warming by darkening the polar ice caps. Sagan et al. (1973).

[2] Bryson (1973).

[3] Bryson (1974), quote p. 756; for earlier mention, see Bryson (1973), p. 9.

natural process. Would greenhouse gases prevent the projected cooling? Or would pollution accelerate it?

Newspapers and television in the early 1970s were regularly running stories on the appalling droughts in the Sahel and elsewhere, and the public was starting to worry about climate change. Would more dust and gases of human origin afflict us with even more deadly droughts or floods? That depended critically on the effects of aerosols. The scientists who had studied this recondite topic began to feel the public eye upon them, and they debated their technical questions with heightened intensity. They increasingly saw that it was theoretically possible for a small change of conditions to bring large changes of climate. But it would be another three decades before computer models of climate became good enough to confirm that industrial pollution had indeed contributed to the Sahel drought.[1] Few experts were more than halfway convinced by Bryson's argument that the "human volcano" was liable to cause a disastrous global cooling.

The prominent meteorologist William W. Kellogg, for one, told a 1975 World Meteorological Organization symposium not to worry. He noted that industrial aerosols, and also the soot from burning debris where forests were cleared, absorbed sunlight strongly—after all, smog and smoke are visibly dark. They would thus retain heat. He calculated that the chief effect of human aerosols would be regional warming (but he admitted that the calculation relied on properties that were poorly known). Anyway, as Kellogg also pointed out, rains washed aerosols out of the lower atmosphere in a matter of weeks. Eventually the warming due to the increase in CO_2—a gas that lingered in the atmosphere for centuries—must necessarily dominate the climate.[2]

Similarly, Stephen Schneider and a collaborator improved his rudimentary model, correcting his earlier overestimate of cooling (see above) by checking against the effects of dust from volcanoes. They got a decent match to temperatures over the past thousand years, after they added an estimate for changes of solar intensity. The model now predicted that "CO_2 warming dominates the surface temperature patterns soon after 1980."[3] Only a few people pointed out that pollution might cancel out some of the greenhouse warming, delaying the time when it would become obvious.[4]

Bryson and his co-workers continued to insist that smoke from burning fossil fuels and forest clearing had a powerful cooling effect. After all, the haze visibly dimmed the solar radiation that reaches the surface. They expected pollution would more than balance the effects of increased CO_2, since the more fuel humanity burned, the more aerosols were emitted along with the gas.

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[1] Rotstayn and Lohmann (2002); Chiang and Friedman (2012).

[2] Kellogg made a distinction between effects of aerosols over land (cooling) or sea (not necessarily cooling), but held that the pollutants were mostly over land. Kellogg et al. (1975); Bryson's theory of cooling was "almost the opposite of the true situation," Kellogg said at a 1980 international workshop, Kellogg (1980), p. 282.

[3] Schneider and Mass (1975a).

[4] E.g., Barrett and Landsberg (1975), pp. 53, p. 77.

Taking everything into account, they calculated that "an expected slight decrease in surface temperature" was already underway.[1] Bryson would not concede that his group's observations, analysis of data, and theoretical understanding were too uncertain to produce a definitive answer. The real value of this work was not in the purported findings, but in the way it forced scientists to pay attention to a topic that was indeed highly important.

Most of the studies were not even addressing all the key problems. Ideas about human emissions focused on an image of dark smog and smoke obscuring the sky. Some scientists pointed out, however, that such direct effects of particles interfering with radiation could be outweighed by indirect effects. They emphasized new observations that nuclei for the condensation of water droplets into rain or snow were sparse under natural conditions. Thus "the most sensitive" leverage point for pollution particles might be their role as cloud condensation nuclei. "Although the changes are small," one scientist remarked, "the long-term effect on climate can be profound." Conceivably the clouds would reflect away so much sunlight that the whole climate system would flip into a new ice age.[2] An important 1975 review panel concluded that the impact of particles on global temperatures "cannot be reliably determined," for it depended on many factors that were scarcely known. Warning that the particle load in the atmosphere might rise another 60% by the end of the century, they called (in the usual fashion of study groups) for further study.[3]

So it continued, as some scientists concluded that aerosols would cause warming, others expected cooling, still others expected no significant global effect, and canny observers understood that none of them could calculate a reliable result. One widely noted example was a survey of dusty days in Arizona by Sherwood Idso and Anthony Brazel, who concluded that additional aerosols from human activity would warm the Earth. They urged people to abandon any thought that industrial pollution would serve as a brake on CO_2 greenhouse warming. Critics promptly tried to poke holes in the study's limited data.[4] Another group analyzed global weather statistics, found that the recent drop in temperatures was restricted to northern latitudes, and argued that this demonstrated a cooling effect of industrial particle emissions, which were far greater in the Northern Hemisphere. This approach too was quickly criticized, for lack of enough data on Southern Hemisphere temperatures.[5] Many other studies invoked physical models, data, and the history of volcanic eruptions and the ice ages as they debated the relation of particle size

[1] Bryson and Dittberner (1976); see the challenge by Woronko (1977) and reply, Bryson and Murray (1977).

[2] "Perhaps the most sensitive," Hobbs et al. (1974); "profound," referring to Budyko's 1969 paper, Twomey (1974).

[3] GARP (1975), quote p. 44; they cite Mitchell (1973); aerosol effects were "lost in the noise": Barrett and Landsberg (1975), p. 72.

[4] Idso and Brazel (1977); Herman et al. (1978).

[5] Damon and Kunen (1976); Damon and Kunen (1978).

to albedo (reflectivity), clouds, and temperature. Like most aspects of climate studies, only even more so, progress on aerosol impacts would require help from many different fields.[1]

In 1977 some light was cast into the shadows by Sean Twomey at the University of Arizona's Institute of Atmospheric Physics. (The name of the institute hints how scientists were regrouping to attack complex questions involving the environment.) Twomey showed that reflection of sunlight from clouds depends on the number of nuclei in a curiously intricate way. Adding particles would normally create more water droplets, and thus thicker light-reflecting clouds. Past some point, however, the drops might fall as rain and the clouds would disappear altogether. On the other hand, if there were a great many nuclei the water could end up not as raindrops but as myriads of tiny droplets—a long-lasting mist. And as Twomey also showed, the amount of reflection and absorption depended strongly on the average size of the droplets (with smaller mist droplets there is more surface area for a given amount of water).

In short, adding more aerosol particles might either raise or lower cloud reflectivity, depending on quite a variety of factors. Overall, for thin clouds Twomey calculated that added pollution would increase the reflectivity (and thus cool the climate), whereas for thick clouds absorption would dominate (hence warming). He concluded that since thin clouds are most common, the net effect of human pollution should be to cool the Earth.[2]

This did not close the debates. As another pioneer recalled, "Twomey's insights were largely ignored by the climate modeling community—perhaps because it seemed unlikely that such a simple analysis could capture the behavior of such a complex object as a cloud."[3] Besides, to figure out the effects on the world's climate, in principle you would need to start with a map of the globe showing for each region the amount of every type of smoke and dust particle and industrial pollutant in each layer of the atmosphere. Next you would have to calculate the direct interaction of each type of particle or chemical molecule with sunlight, and also calculate the effects of each type in forming various types of clouds, and finally calculate how each kind of cloud interacted with visible and infrared sunlight. Little was known about any of this.

The debates made one thing clear: climate change could not be properly understood without a better grasp of aerosol effects. When scientists made theoretical calculations of scattering, the results were often at odds with field and laboratory measurements. It was not clear whether the theories or the measurements were wrong—if not both. Much more work would have to be done

[1] For example: Baldwin et al. (1976); Pollack et al. (1976b); Shaw (1976); Ninkovich and Donn (1976); Herman et al. (1978); aerosols "can hardly have a significant effect" except regionally: Kellogg (1980).

[2] Twomey (1977a); Twomey (1977b); Twomey (1977c); see also Twomey (1974) (which showed that while very few nuclei would inhibit precipitation, so would very many, multiplying droplets too small to fall as rain); for brief review and further references on aerosols and precipitation, see Rosenfeld (2000), p. 1793.

[3] Toon (2000), p. 1763.

to get even the most basic data, such as how the various kinds of particles of various sizes scattered or absorbed light of various wavelengths. Several groups undertook these measurements in the 1970s, using instruments that, like so much in aerosol science and the rest of geophysics, could be traced back to a military application.

All this was only the most simple, basic-physics aspect of aerosols. Studies increasingly confirmed that there were more complex ways that particles would surely affect the climate. A surprising example showed up in the 1974 international GATE experiment, in which scores of research ships and aircraft crisscrossed the tropical Atlantic. They found that when winds blew dust from the Sahara desert over the ocean, significant changes in weather and the radiation balance could be seen all the way to the American coast.[1]

The best clues of all came from observing how volcanic eruptions acted on climate. Historical research covering the past two centuries was confirming a distinct, if weak, pattern of global cooling in the few years following each major eruption.[2] Better still, dust from volcanoes and other sources was found in layers of ancient ice, drilled from the frozen plateaus of Greenland and Antarctica. The dust in the ice cores correlated with Lamb's volcanic "Dust Veil Index" and extended much farther back. Temperatures too could be read from the layers of ice, and analysis showed that through the past hundred millennia, dustier air had correlated with cooler polar regions. To be sure, that might only mean that cooler periods were windier, bringing dust from afar. But it seemed likely that volcanoes did have a direct impact on climate. (Later, more comprehensive studies tended to confirm that. For example, a dearth of major eruptions over several centuries may have helped cause a "Medieval Warm Period" that affected large parts of the planet—notably the North Atlantic region, when the Vikings benefitted from a benign climate to establish a colony in Greenland—although changes in solar activity were probably at least as important.)[3]

None of this supported the claims that we risked hurling ourselves into a new ice age—claims more common in excited news articles than in the scientific literature. Few scientific papers were published in the early 1970s on any topic related to climate change on a human time-scale, that is, faster than the thousands of years that most scientists thought glacial ages took to evolve. Only a small fraction of these few papers projected cooling within a century or two. During the second half of the 1970s the pace picked up as scientists published several dozen papers about century-scale global climate change. Some of these papers discussed cooling and warming factors without coming to a conclusion, but more than half projected that greenhouse warming would dominate. A study of the peer-reviewed articles of the period found that "global cooling was never more than a minor aspect of the scientific climate change literature of the era."[4]

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[1] Kondratyev (1981); Ginsburg and Feigelyson (1980).

[2] E.g., "A significant dip in temperature can be found within a few years after the major eruption dates..." according to Taylor et al. (1980), p. 175.

[3] Hamilton and Seliga (1972). Recent studies: Bauer et al. (2003).

[4] Peterson et al. (2008), p. 1331.

(Decades later, as noted below, scientists with far better data and computer models concluded that industrial haze along with volcanoes had indeed helped to depress Northern Hemisphere temperatures for a few decades in the mid 20th century, while warming from the accumulated greenhouse gases began to dominate in the 1980s.)

By the late 1970s hardly any scientist was arguing that cooling was likely to become severe. The major industrial nations had put "clean air" laws in place. Given that particles were washed out of the lower atmosphere in weeks, pollution was not going to double and redouble as some had feared. Moreover, improved computer models of climate had convinced many that CO_2 added to the atmosphere must bring a global warming. The effect would be increasing rapidly along with the relentless rise of CO_2, which humanity was emitting far more rapidly than anything could remove it from the atmosphere.

Sulfates, Soot and Clouds (mid 1970s-1980s)

As scientists calculated the physics of aerosols more accurately, they realized they could not figure out any way that smoke and dust particles from an eruption could cause long-term effects on temperature; they should drift to the ground or be rained down in a few weeks. Then how did volcanoes affect climate for a year or even two? The answer was hidden in something else thrown into the air.

When thinking about aerosols, the public and most scientists had attended chiefly to the visible and obvious. That meant the fine carbon soot making up smoke from factories, slash-and-burn forest clearing, and natural forest fires; mineral dust from dried-out soil (perhaps increased by human agriculture); and other solids such as salt crystals from ocean foam. When scientists thought about climate change that volcanic eruptions might cause, they chiefly considered the minute glassy dust particles that snowed down thousands of miles downwind from an eruption.[1] Well into the 1970s, meteorologists concerned with aerosols mostly continued to assume they were dealing with such coarse mineral particles. However, anyone looking at city smog—or smelling it—might guess that chemicals could be a main component of a haze. The intense studies of urban smog that began in the 1950s focused the attention of a few scientists on the production and evolution of simple chemicals.

One of the most important of these molecules was sulfur dioxide, SO_2. Emitted profusely by volcanoes as well as by industries burning fossil fuels, SO_2 rises in the atmosphere and combines with water vapor to form minuscule droplets and crystals of sulfuric acid and other sulfates. The particles reflect some of the radiation coming from the Sun and absorb some of the heat radiation rising from the Earth's surface.

To the considerable surprise of atmospheric scientists, studies in the early 1960s suggested that sulfuric acid and other sulfate particles were the most significant stratospheric aerosols. This was

[1] Humphreys (1940), p. 595; Junge (1952).

something that could linger high in the air for years, like the fine fallout particles injected by nuclear weapon tests. The sulfate haze was in fact especially thick for a few years following a huge volcanic eruption in 1963, when Mount Agung in Indonesia blasted some three million tons of sulfur into the stratosphere. That was an order of magnitude more sulfur than human industry produced in a year, and most specialists thought human emissions of sulfates must be comparatively unimportant.[1] Flights in the stratosphere in the early 1970s (part of a huge government effort to study whether airplanes might harm the ozone layer) conclusively confirmed that the principal aerosol there was droplets of sulfuric acid, presumably from volcanoes.[2]

Outside the smoggy cities, haze was commonly assumed to be a "natural background" from soil particles and the like, with occasional extra material from volcanoes. That was challenged in 1976 by two leading experts, Bert Bolin and Robert Charlson. Analyzing air purity data collected by government agencies, they showed that sulfate aerosols from industrial centers measurably affected wide regions downwind. Sulfates dimmed the sunlight not only in cities but across much of the eastern United States and western Europe. This confirmed what McCormick and Ludwig had reported a decade earlier, a widespread haze somehow connected with urban smog.[3]

Bolin and Charlson drove their point home with some calculations. Although they repeatedly admitted that the data were fragmentary, and the theory so oversimplified that they could be off by a factor of ten, their results strongly indicated that sulfates were a significant factor in the atmosphere. Indeed among all the aerosols arising from human activity, sulfates played the biggest role for climate. The old view of aerosols as simply a dust of mineral particles had to be abandoned. In fact the haze was a mixture of the dust with tinier chemical droplets.

Still, the effect seemed minor. Bolin and Charlson figured that human sulfate emissions noticeably affected scarcely one percent of the Earth's surface. The sulfates were cooling the Northern Hemisphere by scarcely one-tenth of a degree. Most scientists thought that was negligible (even if the calculations were accurate, which seemed unlikely). They continued to assume that the problem of human aerosols was strictly local, or at worst regional. Bolin and Charlson themselves, however, noted that sulfate emissions were climbing steeply. They warned that "we are already approaching the time when the magnitude of the indirect effects of increasing use of fossil fuel may be comparable to the natural changes of the climate over decades and centuries."[4]

Sulfates were a new worry for the scientists who were concerned about future climates. That included in particular the Russian expert Mikhail Budyko. In 1974, he suggested that if global

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[1] Wilson and Matthews (1971), pp. 279-80, 283-84.

[2] Barrett and Landsberg (1975), pp. 44-45.

[3] Bolin and Charlson (1976); for other studies of regional haze, see Husar and Patterson (1980).

[4] Bolin and Charlson (1976), p. 50.

warming became a problem, we could cool down the planet by burning sulfur in the stratosphere, which would create a haze “much like that which arises from volcanic eruptions.” He calculated that just a few airplane flights a day would suffice.[1] That kind of freewheeling speculation was about all one could do at this point in thinking about sulfates.

The question attracted few workers, if only because the prospects were poor for solid, publishable studies. For one thing, the amount and type of aerosols (unlike CO_2) varied greatly from region to region. For another, their net effect on the radiation balance depended on the angle of sunlight (the low-angle illumination of Arctic zones doesn’t interact with clouds in the same way as the plunging rays of the tropics). And so forth. The only thing likely to get anywhere would be a full-scale computer attack.

In the mid 1970s, when some groups managed at last to develop computer models that plausibly connected climate to the level of greenhouse gases, a few groups tried to apply these models to study the effects of aerosols. First they needed reasonably accurate information on the spectrum of aerosols normally in the atmosphere—the sulfuric acid droplets, salt crystals, rock dust, soot, and so forth. What were the sizes of the particles, their chemical composition, and their effects on radiation at various heights in the atmosphere? There were far fewer observations than the scientists needed, but some approximate numbers were laboriously worked out in a form usable for modeling studies.[2] The scientists also had to give up their preoccupation with the smog-ridden lower atmosphere, considering also the clear stratosphere. A few extra particles there, lingering for months, could make a big difference to the passing radiation. Despite daunting theoretical complexities and ignorance of many aerosol properties, the enterprise made progress. Different groups of modelers, using different techniques, converged on some tentative ideas.

The first big idea was confirmation that the formation of clouds was not already saturated by natural aerosols. Thus adding some particles to the atmosphere should noticeably affect climate. The second big idea was that the net effect of adding aerosols, an effect which could now be reliably calculated, was to increase the planet’s reflectivity and thus bring modest cooling.[3]

Especially impressive was work published in 1978 by a NASA group under James Hansen, studying how climate had changed after the 1963 Mount Agung eruption. They found that the changes calculated by their simple model corresponded in all essential respects—including timing and approximate magnitude—to the observed global temperature changes. Hansen undertook the study mainly to check that his climate modeling was on the right track. But the

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[1] I have not seen the original Russian language publications, including Budyko (1974a); Budyko (1974b); see Budyko and Korol (1975); Budyko (1977), pp. 239-41; quote from Geophysical Abstracts B (1977), p. 63, an English summary of Budyko and Drozdov (1976).

[2] E.g., Toon and Pollack (1976).

[3] Harshvardhan and Cess (1976); Harshvardhan (1979); Charlock and Sellers (1980); for an overview, see Hansen et al. (1980).

results also showed that "contrary to some recent opinions," volcanic aerosols could significantly cool the surface.[1]

Another sign that sulfates mattered came literally from another planet—Venus. The hellish greenhouse effect that astronomers observed there could not be caused by CO_2 alone, and during the 1970s, sulfuric acid was identified as a main force in the planet's atmosphere.[2] Another telling sign came from a 1980 study of Greenland ice cores. The level of sulfuric acid in the layers of ice pointed directly to ancient volcanic eruptions. Where clusters of giant eruptions were found, there had been episodes of cooling ("which further complicates climatic predictions," the authors remarked).[3]

The feeling that scientists were getting a handle on aerosols was strengthened in 1981 when Hansen's group fed their computer model a record of modern volcanic eruptions. They combined the temporary cooling effect of volcanoes with estimates of changes due to solar variations and, especially, to the rising level of CO_2. The net result fitted pretty well with the actual 20th-century temperature curve, adding credibility to their model's prediction of future global warming.[4] (This result was robust: vastly more sophisticated computer models at the end of the 20th century continued to get a good match to modern temperature fluctuations if, and only if, they added together eruptions, solar activity, and the rise of greenhouse gases. Adding industrial aerosol pollution would further improve the match.)[5]

The cooling effect of sulfates was confirmed by computer studies that took advantage of a colossal explosion of the Mexican volcano El Chichón in 1982. From this event scientists learned more about the effects of volcanic aerosols, one of them declared, "than from all previous eruptions combined." Satellite observations of clouds that were affected by the eight million tons of sulfur aerosols blown into the upper air could be matched with a noticeable cooling of regions beneath the clouds.[6] Alongside the progress in dealing with volcanoes came increasing evidence that the natural background of aerosols always present in the atmosphere also tended to cause mild cooling. The first calculation that many experts accepted as reasonably accurate gave a year-in, year-out global cooling effect of 2-3°C (roughly 4-5°F).[7]

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[1] A one-dimensional model. Hansen et al. (1978); see also the approximate calculation by Pollack et al.(1976b); Charlock and Sellers (1980); recent opinions: e.g., B.J. Mason, see Gribbin (1976).

[2] The Venus greenhouse was invoked regarding the importance of sulfuric acid in Hansen et al. (1978).

[3] Hammer et al. (1980).

[4] Hansen et al. (1981); see also Bryson and Goodman (1980) (eyeball comparison going back to the 1880s); Gilliland (1982b).

[5] Stott et al. (2000).

[6] Hofmann (1988), quote p. 196. The paper includes a historical review of 1980s work.

[7] Coakley et al. (1983).

These calculations, however, dealt only with the effects of aerosols directly on radiation. They included cloud cover (if they calculated it at all) as a simple consequence of the moisture in the atmosphere. But since the 1960s, a few scientists had pointed out that the direct effects of aerosols might be less important than their indirect effects on clouds. This was the kind of thing Walter Orr Roberts had talked about, when he had pointed to cirrus clouds evolving from jet contrails. These clouds had seemed a temporary, local phenomenon. Now some wondered whether human emissions, by adding nuclei for water droplets, might be causing more cloudiness world-wide?

These speculations had been reinvigorated in 1979, when a pair of scientists at the University of Utah had managed to insert aerosols and cloudiness in a reasonable way into a basic radiation-balance computer model. The researchers confessed that their calculation was massively uncertain. But if the worst case was correct, then increased cirrus clouds could lower the Earth's surface temperature several degrees. It was another case of scientists warning that we might "initiate a return to ice age conditions."[1] Other scientists, in particular Hansen's group, doubted that aerosols could be so powerful. While admitting that nobody knew how to model cloud feedbacks reliably, they concluded that aerosols from human activity and even from volcanoes could not produce enough cooling to halt the "inevitable" warming by greenhouse gases.[2]

Progress would depend upon more accurate knowledge of the intricate chemistry of the atmosphere. In the 1980s, aerosol physicists and atmospheric chemists finally established close contacts. It was becoming clear that the most important aerosols humanity produced were not dust and smoke particles, but products of chemical reactions of the gases we emitted, an almost unknown topic. As usual, recognition of an important area of ignorance drove rapid improvements in measuring instruments and also in theory (which by now was done mostly through computer models).

One important finding in the early 1980s was that human chemical emissions tended to turn into sulfate particles whose sizes fell exactly within the range most effective for scattering sunlight. Thanks to research on atmospheric quality sponsored by environmental protection agencies, scientists increasingly agreed that regional sulfate hazes were a serious issue. Since the mid 1970s, studies had proved that such hazes could significantly dim sunlight for thousands of kilometers downwind from the factories. But the effect on the rest of the planet's climate, if any, remained debatable.[3]

The need to resolve the problem was driven home by undeniable evidence that dimming of sunlight by aerosols was increasing all across the Northern Hemisphere. One estimate, which few

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[1] Freeman and Liou (1979), p. 283.

[2] Hansen et al. (1981), p. 960, "inevitable" p. 966.

[3] E.g., Husar and Patterson (1980) (listing 1970s studies); Ball and Robinson (1982); for useful reviews, see Charlson and Wigley (1994); Charlson (1998).

believed, put the reduction as high as 18% per decade.[1] A 1980 study claimed that stratospheric aerosols were increasing by about 9% each *year*. Even in the Arctic, where the immense empty landscapes promised only pristine air, scientists were startled to find a visible haze of pollutants drifting up from industrial regions. There was so much soot that some speculated it might alter the northern climate.[2]

(*I have seen it myself.* Backpacking in the Sierra Nevada and the Canyonlands, decades after my first visits to these magnificent places, the views of distant cliffs and of the stars are never as sparkling clear as I was once used to seeing.)

New Complexities

Talk of cooling from aerosols took a spectacular turn in 1983. A group of scientists, most of whom had already been studying aerosols, went public with warnings of an unexpected danger. If the blasts of a nuclear war injected smoke and dust into the atmosphere, a lethal "nuclear winter" might envelop the planet. The Russian meteorologist Kirill Kondratyev went on to point a finger at the nitrates (NOx) that weapons tests had already been put into the atmosphere. These had produced aerosols which, he surmised, might have been responsible for the decreased transparency of the atmosphere, and thus the cooling, observed during the 1960s.[3] Only think how much cooling might follow a thousand nuclear explosions! Launching a nuclear strike would be literally suicidal, even if the other side never struck back. Other scientists disagreed, setting off a vehement public debate.

An even more horrendous effect of aerosols had been proposed back in 1980 by Walter and Luis Alvarez: the extinction of the dinosaurs when a giant meteor struck the Earth 65 million years ago. Calculations showed that dust from an asteroid impact could have fatally cooled the planet.[4] All this was sharply contested by other scientists. The leading alternative that they developed to explain the doom of the dinosaurs was a series of gargantuan volcanic eruptions. That just showed another way that aerosols could change climate on an apocalyptic scale.[5]

The "nuclear winter" and dinosaur extinction controversies contributed almost nothing to scientific study of ordinary climate change. But they encouraged a planetary-scale viewpoint, and sharpened awareness of the mortal fragility of the Earth's climate. Especially aroused was the aerosol community, or rather the scattering of researchers in diverse specialties who were

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[1] Peterson et al. (1981).

[2] Each year: Hofmann and Rosen (1980). "Arctic Haze, an aerosol showing a strong anthropogenic chemical fingerprint," Shaw (1982); scientists "startled": Kerr (1981). Already in the 1950s, J. Murray Mitchell had guessed the haze was caused by distant industries.

[3] Kondratyev (1988), pp. 179-95.

[4] Alvarez et al. (1984); Wolbach et al. (1985).

[5] McLean (1985).

gradually coalescing into a community. The furious controversies encouraged them to communicate with one another, and with meteorologists and other climate scientists.

Turning back to the way routine pollution might affect climate, scientists were slowly hacking a way through the jungle of complexities. A few meteorologists gradually worked out the implications of Twomey's studies, noticing how increasing emission of aerosols could create lingering misty clouds that might reflect enough sunlight to offset the warming expected from greenhouse gases.[1] It was hard to know whether nature really acted according to these difficult calculations, and most experts paid little heed. After all, even massive direct cloud seeding had never been proven capable of doing much, despite decades of experiments. As Twomey admitted in 1980, "clear field verification has not been obtained" for various key predictions.[2]

Finally in 1987 a dramatic visible demonstration convinced many scientists that the theory deserved respect. Satellite pictures of the oceans displayed persistent clouds reflecting sunlight above shipping lanes—a manifest response to ship-stack exhaust. Aerosols could indeed create clouds, enough to outweigh the particles' direct interactions with radiation. (Later studies showed there were inconsistencies, as usual with aerosols; in some cases emissions from ships made for more cloudiness, in some cases less. But even where there were no ship tracks at all, it turned out that the ships' exhaust affected the water content of the air in a way that brought cooling. Studies of shipping lanes would become an important tool for quantifying aerosol effects.)[3] Meanwhile, careful data gathering was making it clear that the dominant source of the atmosphere's sulfate aerosols came from human activities, not natural systems.[4] Nevertheless, many scientists continued to think of aerosols as "local" pollution and worried little about global implications.

The closer scientists thought they were getting to definite answers, the more they noticed additional factors that they ought to figure in. For example, studies of the surprising dwindling of ozone over Antarctica (the "ozone hole") revealed in 1985 that crucial reactions took place on the surface of ice crystals floating high in the atmosphere. Scientists had dismissed surface reactions

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[1] More pollution divided the water among more and hence smaller droplets, which not only made clouds linger (by inhibiting precipitation) but would also raise the reflectivity of the clouds and lower their absorption of solar radiation, keeping them cool and further lengthening their lifetime. Twomey (1980); the effect of aerosols in increasing cloud lifetimes and thus reflection, especially over the oceans where nuclei are rare, was worked out particularly by Albrecht (1989); "...the climatic effect is quite comparable to that of increased carbon dioxide, and acts in the opposite direction." Twomey et al. (1984).

[2] Twomey (1980), p. 1461; he went on to report a verification at a single site, Twomey et al. (1984).

[3] Coakley et al. (1987); Radke et al. (1989). For cloudiness probably due to nitrates, see Lawrence and Crutzen (1999). Inconsistencies: e.g., Ackerman et al. (2000). Effects where no ship tracks visible: Manshausen et al. (2022). Tool: e.g., Durkee et al. (2000) , Christensen and Stephens (2011).

[4] Schwartz (1988).

on particles as unlikely to make much difference for the chemical structure of the upper atmosphere. Now they saw the reactions were yet another set of complex problems that they would have to investigate. Even more troublesome was the fact that any climate change would alter the natural background emission of aerosols. For example, if deserts expanded (whether from direct human activity or climate change) there would be more airborne dust. Meanwhile pollution studies showed that altering the amount of one type of aerosol in the air would start a chain of reactions that would alter the distribution of sizes and other key characteristics of other aerosols. And these subtle calculations themselves, one author warned, “do not do justice to the complexities of the real atmosphere.”[1]

On top of all that, there could be biological feedbacks. The most intriguing suggestion was that the nuclei for condensation of clouds in the pure air over the oceans might come primarily from dimethylsulfide (DMS) molecules, whose chief source was living plankton. Warmer seas might make for more plankton (or less?) and thus more clouds (or less?). It was another feedback dependent on temperature which might stabilize the climate—or might not. It would take decades of research to show, and even then only tentatively, that the effect was too small to make much difference.[2]

Even if researchers set aside such issues, and even if they could resolve all the problems of cloud formation, they would still be far from knowing precisely how aerosols might affect climate. Few studies had even taken into account the fact that human activity emitted far more aerosols in some places than in others, so that the commonly used global averages could hardly represent the real situation. In some regions there would be too many particles to make normal clouds, in other regions too few. The properties of the aerosols themselves would be different in humid and dry regions. Yet climate scientists mostly continued to treat aerosols as a globally uniform background, mainly of natural origin. Atmospheric chemistry, observations of regional haze, and climate models were still such different fields that it was hard for any one person to assemble a coherent story.[3]

Calculating Aerosol Effects (1990s)

By 1990, scientists understood that human activity produced somewhere between a quarter and a half of all the aerosol particles in the lower atmosphere, including industrial soot and sulfates, smoke from debris burned when forests were cleared, and dust from semi-arid lands turned to agriculture or over-grazed. The consequences, if any, were entirely uncertain—”at this stage neither the sign nor magnitude of the proposed climatic feedback can be quantitatively

[1] White (1986), quote p. 1671.

[2] Charlson et al. (1987) (the “CLAW” hypothesis); Ayers and Cainey (2007).

[3] Joseph (1984); Charlson et al. (1992), p. 425.

estimated."[1] Interest remained focused on greenhouse gases, which were expected to dominate climate change sooner or later.

Some scientists, however, did realize they had to take into account what the recent increase in aerosols meant for climate. Hansen called for better monitoring and more studies.[2] Experts increasingly admitted that global climate change was not a matter of CO_2 alone. It came from a variety of effects ("forcings") on incoming and outgoing radiation due to a variety of gases and aerosols. A leader in the work remarked that it was this shift of viewpoint—looking at changes in the energy balance rather than attempting to calculate surface temperature changes—that made meaningful global calculations possible. He added that the calculations "would not have been possible without an enormous amount of work measuring the actual properties of atmospheric aerosols."[3] Workers in the various fields that dealt with aerosols increasingly exchanged information and ground out observations and computations. Dramatic advances in laboratory instrumentation made it possible to measure microscopic particles one by one, providing context for a new wealth of sophisticated satellite observations. Specialists began to pin down the most important characteristics of aerosol particles, from the regions where different kinds were emitted to the ways they interacted chemically.

In the early 1990s, Charlson and others worked to persuade aerosol experts that sulfates could cause significant cooling, simply by scattering back incoming solar radiation. The effects of sulfate particles through stimulating cloudiness were harder to estimate, but appeared to add still more cooling. In a pioneering 1991 calculation, Charlson and his allies concluded that the scattering of radiation by humanity's sulfate emissions was roughly counterbalancing the CO_2 greenhouse warming in the Northern Hemisphere—the two were comparable in magnitude but of opposite sign. In retrospect, this was the key paper for establishing the net effect of aerosols on the planet's heat balance. The calculation, however, was admittedly full of uncertainties.[4]

In 1991 Mount Pinatubo in the Philippines exploded. A mushroom cloud the size of Iowa burst into the stratosphere, where it deposited some 20 million tons of SO_2, more than any other 20th-century eruption. Hansen's group saw an opportunity in this "natural experiment." It could provide a strict test of computer models. From their calculations they boldly predicted roughly half a degree of average global cooling, concentrated in the higher northern latitudes and lasting a couple of years.[5] Exactly such a temporary cooling was in fact observed.

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[1] Quote from chapter on "Greenhouse gases and aerosols" by R.T. Watson et al., IPCC (1990), p. 32.

[2] Hansen and Lacis (1990).

[3] R. Charlson, personal communication, 2002.

[4] "Comparable to but opposite in sign to the current greenhouse forcing by increased CO_2 to date," Charlson et al. (1991); the first, primitive version was Charlson et al. (1990). Key paper: Bolin (2007), p. 254.

[5] Hansen et al. (1992).

Human pollution of the atmosphere should do the same, for although black soot particles absorbed radiation and would bring some warming, the cooling from cloud formation and sulfates seemed likely to outweigh that. Most scientists now agreed that aerosols emitted by the "human volcano" had indeed acted like an ongoing Pinatubo eruption, offsetting some of the greenhouse warming.

Papers published in 1992 concluded that the smoke from slash-and-burn farming of tropical forests might have been enough all by itself to cancel a large share of the expected warming. Other scientists reported that the direct effect of sulfates blocking sunlight "completely offsets the greenhouse effect" in the most industrialized regions. Yet another team estimated that the indirect action of sulfates, making clouds darker, could have a still stronger cooling effect.[1] As one expert remarked, "the fact that aerosols have been ignored means that projections may well be grossly in error."[2] Thus efforts to restrict sulfate emissions, however important that might be for reducing acid rain and other unhealthy pollution, might hasten global warming.

Computer modelers returned to their simulations of global temperature, and found they could get curves that matched the observations since the 1860s quite closely provided they included increases in sulfate aerosols as well as CO_2. The key paper, constructed at the Hadley Centre for Climate Prediction and Research in the United Kingdom, took a model that coupled the atmosphere and oceans and ran it through the centuries as the CO_2 level rose, once without aerosols and once with them. The latter was clearly a better match to the actual historical record. Published in 1995, the result made a strong impression on scientists.[3]

Because aerosol pollution was greater in some regions than others, whereas CO_2 levels were about the same everywhere, modelers tried using that to disentangle the two influences.[4] To be sure, there was a risk that with aerosol effects poorly understood, the modelers might merely be adjusting their numbers until they reproduced the climate data, overlooking other possible factors. But the new results incorporating aerosols did give, for the first time ever, a plausible and consistent accounting of the main features of 20th-century climate. In particular, it was now confirmed that industrial pollution had been a strong factor in the mid-century dip of Northern Hemisphere temperatures. As Bryson had speculated back in the 1970s, the effects of aerosol emissions from human industry were comparable to the effects of a large volcanic eruption. These results played a major role in a 1995 announcement by the Intergovernmental Panel on Climate Change (IPCC) that human influence on climate had become "discernible." Scientists might have been convinced of global warming a decade earlier if they had been quicker to grasp the cooling effect of aerosols.

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[1] Smoke: Penner et al. (1992); similarly, Charlson et al. (1992), which is cited much more often than the 1991 Charlson et al. paper; see Kerr (1992). Direct effect calculation: Kiehl and Briegleb (1993), quote from abstract; indirect effect calculation: Jones et al. (1994).

[2] Wigley (1994).

[3] Mitchell et al. (1995); IPCC (1996a), chap. 8.

[4] Taylor and Penner (1994).

The reprieve from warming would be temporary. As CO_2 and other greenhouse gases inexorably accumulated in the atmosphere, they were overtaking the effects of aerosol pollution—which was no longer climbing. The IPCC's next report, issued in 2001, pointed out how industrialized nations were taking steps to reduce pollution, as people slowly realized that restricting emissions from burning fossil fuels could save countless lives. Considering various possibilities, the panel reported a high upper limit for where greenhouse warming might go during the 21st century: if the use of fossil fuels continued to expand at a breakneck pace while pollution controls restricted aerosols, global temperatures might shoot up nearly 6°C.[1]

A minority of experts dissented from the panel's confidence that the improved computer models gave solid information. The critics warned that "given the present uncertainties in aerosol forcing, such improvement may only be fortuitous."[2] To clear up the uncertainties, scientists needed better information not only on how aerosols interacted with weather, but also on just what kinds of aerosols human activity stirred up and just where the winds blew them.[3] None of that was measured well enough.

Persistent Uncertainties (2000-)

The old discussion of whether pollution brought warming or cooling was still yielding surprises. In particular, evidence turned up that much more soot ("black carbon") was puffing into the air than had been suspected. For example, a team under Veerabhadran Ramanathan deploying ships, aircraft and balloons in the Indian Ocean in 1999 detected a huge drifting "brown cloud." It was a miasma caused by human activity, expanded from the haze that Bryson had noticed while flying over India a third of a century earlier. (Later called the "Asian brown cloud" extending to Indonesia and China, the haze included diesel exhaust and smoke from stoves burning cow dung or charcoal as well as smoke from factories and fires to clear farmland.) Hansen now drew attention to the warming potential of such pollutants. To be sure, the dark smokes shaded the surface and thus made for cooling. But higher in the atmosphere the soot absorbed radiation so thoroughly, according to his group's new calculations, that on balance it added strongly to global warming.[4]

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[1] IPCC (2001a). A review of aerosols and the 1950s-60s global temperature dip: Hegerl et al. (2019).

[2] Ledley et al. (1999), p. 458; Singer (1999) also notes uncertainty about aerosol effects.

[3] E.g., on increased dust, see Andreae (1996).

[4] Satheesh and Ramanathan (2000), discussed in *Wall Street Journal*, May 6, 2003, p. 1; Hansen et al. (2000b); "The magnitude of the direct radiative forcing from black carbon itself exceeds that due to CH_4, suggesting that black carbon may be the second most important component of global warming after CO_2 in terms of direct forcing," Jacobson (2001). Subsequently Hansen and Nazarenko (2004) argued that decreased reflection of sunlight from snow and ice dirtied by soot gave another significant contribution to global warming.

Cutting this sort of pollution could not only reduce damage to local and global climates, but also prevent hundreds of thousands of premature deaths from respiratory illnesses. Some scientists argued that before going all out to restrain greenhouse gases, the world should attack the rightly despised smokes, the most ancient form of technological pollution.[1]

Later, beginning around 2002, climatologists were surprised by evidence that hazes were having an even bigger effect than they had supposed. As far back as 1989, Atsumu Ohmura in Switzerland had published evidence that sunlight had been growing dimmer globally throughout the 20th century. Like the other indications of widespread turbidity noted above, Ohmura's work had attracted little attention, even though some computer modelers had begun to worry that their models did not seem to include enough aerosol absorption. Now evidence turned up by other scientists convinced many experts that the Northern Hemisphere, at least, had seen a dimming of 10 percent or more—much more than most experts had thought, indeed probably great enough to affect agriculture. Aerosol pollution was the only plausible cause. "There could be a big gorilla sitting on the dining table, and we didn't know about it," Ramanathan admitted in 2004.

Many aerosol specialists now suspected that they had badly underestimated how strongly greenhouse warming had been held back by the cooling effect of aerosols. That had given the world "a false sense of security" about global warming, the respected atmospheric scientist Paul Crutzen warned in 2003. For the "global dimming" trend was not really global but regional, and since the 1980s it had flattened out or even reversed in some regions. Nobody could be sure why, but a likely cause was the pollution controls that many industrialized nations were imposing to reduce sulfates. Europe, which had the strictest controls, was the main region where the sunlight was now significantly brighter. Dimming was still getting stronger over China and other developing nations, but these nations were laying plans to clean up their air. Experts began to worry that eventually this would bring a "global brightening," so that temperatures would rise faster than the standard greenhouse warming calculations predicted. Meanwhile some studies proposed that changes in cloudiness were partly responsible for how much sunlight was reaching the surface. Whatever was happening, it was more obvious than ever that the world urgently needed better measurements of aerosols, and better models for how they blocked sunlight.[2]

Large uncertainties also remained in figuring how aerosols interacted with gases, and above all with water vapor, to increase reflectivity (the main "indirect effect" or "Twomey effect").

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[1] Hansen et al. (2000b); Andreae (2001).

[2] Ohmura and Wild (2002) and Roderick and Farquhar (2002) drew attention to the summary of evidence in Stanhill and Cohen (2001); Ohmura and Lang (1989). For "gorilla" and more see Kenneth Chang, "Globe Grows Darker as Sunshine Diminishes 10% to 37%," *New York Times,* May 13, 2004. Reversal: Wild et al. (2005); Pinker et al. (2005); Stanhill (2007). Underestimates: Anderson et al. (2003); Crutzen quoted Pearce (2003); brightening: Ohring et al. (2008). A 2005 analysis of satellite measurements indicated a disturbingly strong aerosol effect, Bellouin et al. (2005). On regional effects through 2007 see Wang et al. (2009). Updates: Solomon et al. (2011); Hatzianastassiou et al. (2012); IPCC (2021a) § 7.2.2.3.

Questions were raised once again by detailed observations that confirmed the speculation that had first started scientists worrying back in the 1960s—cirrus clouds grew from jet contrails. Indeed the clouds measurably influenced the climate in regions beneath heavily traveled air routes.[1] Experts published widely divergent models for the formation of such clouds and their absorption of radiation. Controversial measurements published in 1995 claimed that clouds absorbed much more radiation than the conventional estimates said, raising a specter of "missing physics." As one researcher complained, "The complexity of this problem seems to grow with each new study." It was reasonable to expect that improvements in theoretical models and measuring techniques would eventually lead to a reconciliation (indeed within the next decade theory and observations would largely converge).

But there remained so many difficulties that Ramanathan remarked, "If I wake up with a nightmare, it is the indirect aerosol effect." The uncertainties raised serious doubts about the value of computer models, for most of them did not even try to calculate the indirect effect. Rather, modelers tended to use the effects of aerosols on clouds as a free parameter. They would adjust the numbers until their model fit other data such as the climate record of the past century. That was a shaky foundation. And the indirect effect was only one of several areas where new studies kept showing that, as Ramanathan and a colleague remarked, people were still "in the early stages of understanding the effects" of aerosols.[2]

This persistent ignorance about aerosols—their direct and indirect effects on radiation and cloudiness, and even their concentrations—was the largest single obstacle to attempts to predict future climate, especially if you tried to drill down to predictions for a given region. Funding agencies accordingly pushed vigorous and costly efforts to measure aerosol effects, and significant results accumulated in the early 21st century. In particular, the question Roberts had posed back in 1963 was answered—airplane contrails did trap significant heat. Indeed contrails were doing more to warm the planet than the greenhouse gases the airplanes emitted.[3]

Airplane flights were easy to count, but it was hard to know just what kinds of stuff was actually getting into the air in different regions around the globe. From the 1990s onward expeditions were mounted to measure both aerosols and clouds in far-flung regions. Meanwhile different

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[1] Boucher (1999) and other studies show contrails are significant, indeed they do more to warm the globe than the CO_2 gases the aircraft emit [Burkhard and Kärcher (2011)], but they are less important than other causes of climate change.

[2] Cess et al. (1995); Pilewskie and Valero (1995); Ramanathan et al. (1995); Li et al. (1995); see Kerr (1995b); "complexity:" Kiehl (1999), p. 1273; "nightmare:" Ramanathan quoted in Schrope (2000), p. 10, Not used in models: Knutti (2008)}; J. Hansen in particular raised serious doubts. "Early stages," Satheesh and Ramanathan (2000), p. 62; for an argument that there was nothing serious missing, see Hansen et al. (2000a), pp. 147-54. "Because nearly all recent studies show good agreement between observations and models, the dust of the CAA [cloud absorption anomaly] debate appears to be settling down," Li et al. (2003).

[3] Bock and Burkhardt (2019).

computer models still gave substantially different results. If some issues were settled, new puzzles appeared in theoretical papers or field studies to provoke new controversies and worries.

For example, in 2008 Ramanathan's group showed that black carbon aerosols had a much stronger warming effect than earlier calculations had estimated. Among other things, the calculations had not accounted for the combined effects of black carbon interacting with sulfate aerosols. A massive study published in 2013 went even further, asserting that in promoting global warming, black carbon was slightly ahead of methane gas, second only to CO_2. Policies to reduce these sooty emissions, everywhere from European diesel automobiles to East Asian cooking fires, would greatly benefit public health along with delaying global warming. On the other hand, some sources of soot, like burning off farm stubble, also produced aerosols that reflected sunlight and cooled the planet. Estimates of the influence of black carbon were controversial and researchers continued to struggle with the complexities of clouds and smog. In any case black carbon fell out of the atmosphere in a week or so, whereas greenhouse gases would linger for centuries.[1]

What if there remained other significant factors that had been overlooked, for example in estimates of the influence of sulfate aerosols? A few experts had been worrying for years that sulfates might have been more effective in holding back warming than computer modelers had figured. The rise of global pollution over the past century might have masked how sensitive the climate was to the rise of greenhouse gases. As nations continued to reduce their sulfate emissions, global temperatures might leap upward even faster than the IPCC reports predicted.

On the other hand, if the historical aerosol effects had been overestimated, then future temperatures might rise less than expected. In the 2010s different lines of evidence, such as observations from a "natural experiment" of sulfate emissions from an eruption in Iceland, showed that the effect of sulfates in "brightening" clouds was towards the lower end of estimates. That eased the fears that work to control pollution would release explosive global warming.

On *another* other hand, when new satellite methods to measure water droplet concentrations made it possible to separate the direct effects of aerosols from indirect feedbacks, it appeared that the power of aerosols to cool the planet by modifying clouds might be stronger than theorists had estimated. In addition, it seemed that wind-blown mineral dust from deserts had increased over the past century, another factor that had probably held back warming more than models allowed for. On yet another hand, measurements in Greenland ice cores found much more sulfates in past

[1] Black carbon: Ramanathan and Carmichael (2008); Bond et al. (2013); controversial: Wang et al. (2014). Sulfates: Schwartz and Andreae (1996); Schwartz et al. (2007).

centuries, quietly emitted by volcanoes, than scientists had supposed. Historical analyses might have exaggerated how far the recent human emissions had offset warming.

Some of the new findings involved such a tangle of processes that nobody could guess whether the result would be faster global warming, or slower. For example, wildfires were increasing globally, and some were so colossal that their smoke clouds penetrated into the stratosphere. The huge quantities of black carbon particles lingered for years, with "tremendous potential," researchers reported, to change things... somehow.[1]

Meanwhile, in 2015 the International Maritime Organization required ships to restrict their smokestack emissions of sulfates, and in 2020 they tightened the restrictions. The result was a prompt and sharp decrease in reflective clouds above major shipping lanes, big enough to raise suspicions that the sulfates could have been measurably retarding the rise in global temperature. This "experiment" reinforced the concerns of Hansen and some others who believed that the IPCC was seriously underestimating the indirect aerosol effect.

The uncertainty was partly due to the complexities of calculating the many processes in clouds, but it was still more due to a lack of global data. As always, computer models were only as good as the numbers fed into them, and across most of the planet there were no solid measurements of the ever shifting pollution and its effects on radiation. For decades Hansen, deeply engaged with aerosols throughout his career, had pushed NASA to build a satellite that would look at aerosols. Eventually NASA responded with the "Glory" mission, which launched in 2011—and failed to reach orbit. A replacement mission was originally scheduled for 2016, but suffered delays; the Trump administration, unfriendly to all climate science, attempted to kill the program altogether, but Congress restored funding. A satellite with instruments to measure aerosols ("PACE") was launched at last in 2024.

The efforts to measure aerosols and cloud formation around the globe were backed up by laboratory work. Most prominent was a 4-meter-tall chamber at CERN, the high-energy-physics center near Geneva. The chamber was built in 2009 to check out a hypothesis that cosmic rays had an important influence on aerosols, and hence on cloudiness, and hence on climate. When that influence turned out to be minor, the huge chamber was turned to other studies of cloud formation. For example, researchers found that significant aerosols came from chemical interactions involving organic molecules emitted by plants—it was one way that forests helped to

[1] Aerosols masking sensitivity: Andreae et al. (2005). Stevens (2017); Malavelle et al. (2017); Rosenfeld et al. (2019). Dust: Kok et al. (2023), Froyd et al. (2022); Greenland sulfates: Jongebloed et al. (2023); wildfires: Katich et al. (2023).

make clouds. There seemed no end to such surprises. As a researcher working on clouds in computer models complained, “We fix one problem and reveal another one.”[1]

The stubborn uncertainties afflicting aerosol studies were one of the chief reasons why predictions of future temperatures had a disturbingly large range. On top of this, it was uncertain how much people would rein in pollution globally, and doubly uncertain how this would play out in any given region, and thus how the local climate would change. Nevertheless, most experts felt that they had at least a rough idea of the gross effects. By 2020 they were confident that the sum of human aerosol emissions had a significant net cooling influence globally. Estimates of the magnitude of the cooling (both direct, and indirect through modifying clouds) ranged from fairly small to quite strong.

Since the 2015 “Paris Agreement,” the world’s governments had made specific pledges to reduce their CO_2 emissions. Calculations using figures in the IPCC’s 2021 report said that if all the promises were kept, global warming would most likely level off around 2.7°C above the pre-industrial level—a number much cited in news reports. The climate scientists themselves were far less precise; the IPCC calculated a possibility (perhaps 5%?) that the actual heating could reach five degrees. In 2023 a group led by Hansen reported an analysis of aerosol effects that claimed future heating would indeed approach that level. Other experts strongly disagreed, but the controversy served to draw attention to the very real risk of of utter catastrophe.[2]

Aerosol pollution had certainly delayed the appearance of greenhouse warming in some industrialized regions and perhaps everywhere. As pollution controls expanded while greenhouse gases inexorably accumulated, it was clear that dangerous global heating would advance all the faster.

Related:
General Circulation Models of the Atmosphere
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[1] Shipping emissions: Yuan et al. (2022); Hansen et al. (2023), cf. Hansen et al. (2011), Hansen et al. (2013), calling pollution restrictions a “Faustian bargain;” Bob Berwyn, “The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns,” *Inside Climate News* (Sept. 15, 2021), online at https://insideclimatenews.org/news/15092021/global-warming-james-hansen-aerosols/. Organic molecules:

[2] Uncertainties: e.g., Persad et al. (2022). IPCC (2021b), Fig. SPM.2; Hansen et al. (2023).