

THE DISCOVERY OF THE RISK OF GLOBAL WARMING

An accidental confluence of old interests and new techniques led a few scientists in the 1950s to realize that human activity might be changing the world's climate.

Spencer R. Weart

It is now a century since Svante Arrhenius published the idea: As human activity puts ever more carbon dioxide into the atmosphere, global warming becomes ever more likely. (See figure 1 and the box on page 36.) His paper attracted notice, and one might suppose that knowledge of the so-called “greenhouse effect” has grown steadily ever since.¹ But that is not in fact how the science proceeded. During more than half a century after 1896 almost nothing of value was learned about global warming. Only in the late 1950s did scientists at last begin to regard it as a serious possibility, indeed a potential danger.

Not that climate change itself had been ignored; even the general public paid attention to that. By the late 1930s it was common knowledge that the world had been warming up. Grandfathers were saying that the younger generation had it easy: none of those early frosts and daunting blizzards of bygone times. And in fact, as one magazine put it in 1951, “The old-timers are right—winters aren’t what they were.” The evidence was largely anecdotal. Rivers failed to freeze over as formerly, glaciers retreated, and fish were found north of their former haunts. But detailed analysis of temperature statistics also seemed undeniably to show a rise.² (See figure 2.)

Nobody was worried. It seemed reasonable that weather moves in cycles, temperatures rising and falling slightly over decades and centuries. If we happened to be in for a spell of warming, so much the better! A *Saturday Evening Post* article was typical in supposing that “vast new food-producing areas will be put under cultivation farther north.” Such talk attracted little interest, for it was merely speculation about some remote future century. And as *Time* magazine said, “Meteorologists don’t know whether the present warm trend is likely to last 20 years or 20,000 years.”³

By the early 1960s much had changed. Many scientists had become seriously concerned that warming might be no mere phase of a modest natural cycle but the onset of an accelerating climb, unprecedented and foreboding. This shift of understanding and attention may eventually be regarded as one of our century’s pivotal scientific developments. Yet as we shall see, it was largely a matter

of luck—a byproduct of work aimed at entirely different questions.

Callendar: The climate of the 1930s

The pioneering 1896 work of Arrhenius had been reinforced independently by the American Thomas C. Chamberlin over the next few years, but nobody else took up the matter and both men turned to other topics. There were many forces other than carbon dioxide bearing on climate: the intrinsic variations of solar radiation suggested by the sunspot cycle, the variations of incoming radiation indicated by calculations of changes in Earth’s orbit, dust from volcanic eruptions, spontaneous shifts in the pattern of ocean currents, and more. Alongside these, carbon dioxide seemed to most scientists a distinctly minor and unlikely influence. Few thought that any act of humanity could possibly make for more than a minor addendum to the mighty forces of astronomy and geology. The standard view of climate change held up through the 1940s was neatly summarized by an authoritative textbook. “We can say with confidence,” it declared, that climate “is not influenced by the activities of man except locally and transiently.”⁴

This view had been challenged, but only by a single individual—not even a well-known meteorologist. Guy Stewart Callendar listed himself as a “steam technologist to the British Electrical and Allied Industries Research Association” when he delivered a paper to the Royal Meteorological Association in London in 1938. After sorting through old measurements of atmospheric carbon dioxide, Callendar asserted that since the 1890s the level had increased by some 10%. This rise, he insisted, could explain the warming during the same period.⁵

Most meteorologists dismissed these calculations with a few condescending remarks. The carbon dioxide data seemed far too unreliable to sustain Callendar’s claims that the level was rising. Data aside, those who paid attention to the question of climate change (and they were few) believed that carbon dioxide from fossil fuels could not possibly have much influence. It was a matter of simple physical principles.

One argument noted that the oceans contain 50 times as much carbon dioxide as the atmosphere. It seemed logical to conclude that, as a classic monograph by Alfred Lotka announced in 1924, “The sea acts as a vast equal-

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FIGURE 1. SVANTE ARRHENIUS (seated on the table in the front row) in Spitsbergen, Norway, seeing off an Arctic balloon expedition in 1896. In that year Arrhenius calculated that human activity, by adding carbon dioxide to the atmosphere, could substantially warm the globe. His main aim, however, was to offer a theory of how a *decrease* of carbon dioxide might explain past ice ages. (Photograph courtesy of the Royal Swedish Academy of Sciences.)

izer," taking up 95% of all the carbon dioxide that enters the atmosphere, so that fluctuations "are ironed out and moderated." One expert, Kurt Buch, remarked in 1955 that this ocean uptake of carbon dioxide was the main objection that could be raised to Callendar's claims.⁶

There was something more than science that brought Lotka and his followers to see the oceans as a reliable regulator. Almost everyone during those years believed in the natural world's propensity to automatically compensate in the direction of a self-sustaining "balance." The belief seemed well-founded on millions of years of geological history; very few noticed that the situation was changing as human industry attained the magnitude of a geological force.

If humanity ever did transform the face of the Earth, most people thought that would surely be for the better. Lotka was typical when he optimistically declared that the ability to burn the world's fossil carbon gave us a grand opportunity, and "we shall presently be carried on the crest of the wave into a safer harbor," a world of "practically imperishable" resources and "universal prosperity." Such frank faith in technology continued to dominate attitudes into the 1950s.⁷

There was also a more narrowly scientific objection to global warming, cited by experts on the rare occasions when the matter came up. Soon after the turn of the century, Arrhenius's conclusions had been thrown into doubt by laboratory measurements of the way tubes containing carbon dioxide blocked the transmission of infrared radiation. It turned out that in a length of tube containing

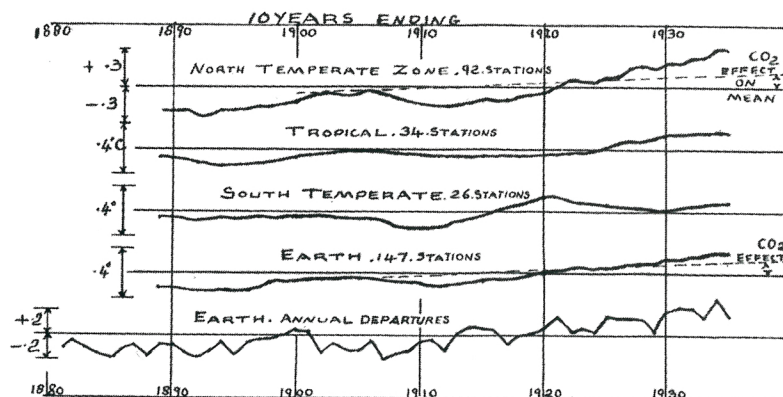
as much gas as would be found in a column through the atmosphere, the amount of radiation that was intercepted scarcely changed if the quantity of gas was cut in half or doubled. That meant saturation: Even a small amount of carbon dioxide blocked radiation so thoroughly, within its spectral bands, that adding more gas could make little difference.

A still more influential objection was that water vapor, which is much more abundant than carbon dioxide, blocks infrared radiation in these same spectral bands. More carbon dioxide could not affect atmosphere that was already opaque due to water vapor. This view was reflected in such authoritative publications as the American Meteorological Society's 1951 *Compendium of Meteorology*. The theory that carbon dioxide would change the climate, it said, "was never widely accepted—and was abandoned when it was found that all the long-wave radiation [that might be] absorbed by CO₂ is [already] absorbed by water vapor." The recent global increase of temperature was a normal fluctuation, said the *Compendium*, by no means related to human activities.⁸

The most striking feature of these discussions is how thin the arguments were and how fragile their empirical foundation. For example, in 1938 Callendar had to cite papers of 1905 and 1911 for data on infrared absorption. Into the early 1950s hardly anyone had taken the trouble to measure the intensity of the absorption bands; only the *positions* of lines mattered to physicists engaged in quantum and molecular studies.

As for theoretical work on climate change, few authors

FIGURE 2. GLOBAL RISE IN TEMPERATURE, as it showed up in statistical studies of the late 1930s. To these graphs of 10-year moving average temperatures (in °C), Guy Stewart Callendar added a crude estimate of a "CO₂ effect," the temperature rise he thought due to carbon dioxide generated by burning fossil fuels. (From G. S. Callendar in ref. 2.)



Svante Arrhenius and the 'Greenhouse Effect'

The first extensive discussion of how climate might be changed by adding carbon dioxide to the atmosphere was published in 1896 by Svante Arrhenius, a Swedish scientist known for discoveries in physical chemistry. His starting point was the idea, first proposed by Joseph Fourier in 1827, that the Earth is kept warm because the atmosphere traps heat as if under a pane of glass. The process, now commonly called the "greenhouse effect," is actually nothing like the complex processes of a greenhouse. Molecules of gas in the atmosphere intercept infrared radiation rising from the Earth's surface; some of the absorbed energy is re-radiated back to the surface, overall keeping the Earth warmer than if it had no atmosphere. The gas chiefly responsible for this is water vapor. But in 1859 John Tyndall found that other gases such as methane and carbon dioxide also block infrared radiation.

Arrhenius undertook lengthy calculations of how carbon dioxide intercepts radiation in the atmosphere. He announced that doubling the amount of carbon dioxide would raise the planet's average surface temperature some 5–6 °C, while halving the amount of gas would lower the temperature about as much. In fact, his laborious calculations were almost worthless. Not only were the spectroscopic data available to Arrhenius inadequate, but he was unable to make more than a crude estimate of crucial feedback effects. For example, on a warmer Earth the oceans would evaporate more water vapor, which would additionally intercept outgoing infrared radiation, but would also make more clouds and snow that would deflect incoming solar radiation. Even with modern supercomputers such complexities can barely be understood. At best, Arrhenius had shown that the effect might be of a significant order of magnitude.

Arrhenius owed the most surprising feature of his paper to the geologist Arvid Högbom, a Swedish colleague. Högbom had pointed out that the amount of carbon dioxide released by humans burning coal was comparable to the amount that circulates naturally. Arrhenius speculated that eventually civilization might release enough of the gas to create a warmer climate—which in chilly Scandinavia sounded like an excellent idea. But that was not expected for centuries to come, if ever. Through the following half-century most scientists dismissed the entire theory as implausible.

attempted anything beyond a few sentences of qualitative argument, stressing their personal choice of a particular subset of the many factors involved. In the handful of papers that tried to do more, it is a melancholy experience to see ingenious approximations and lengthy calculations (carried out laboriously with mechanical calculators) based on such primitive assumptions that the results could win little credence even at the time.

If the question of climate change was pursued in a generally inadequate fashion, it was largely because the topic held an out-of-the-way position within the scientific community. Well into the 1950s, climatology remained much as it had been for the previous half-century and more: a minor branch of meteorology devoted to the compilation of data. A climatologist was somebody who *described* climate—usually at ground level. The enterprise was valued mainly for the services it rendered to agriculture, civil engineering and the like.

For these practical aims, it was normally thought sufficient to gather and process extensive weather statistics. "We can safely accept the past performance as an adequate guide for the future," wrote a leading climatologist in 1946.⁹ To such experts, climate was, by definition, nothing more than a summation of daily weather—and the study of weather was itself far from a developed science. Nobody could calculate even such plain facts as the nature of the trade winds. Given the obvious and all-but-insuperable obstacles that stood in the way of numerical conclusions about any aspect of climate, and the prevailing attitude that warming could not possibly amount to much in any case, what ambitious scientist could want to devote years of effort to the subject?

Plass and Revelle: Overturning objections

The first blow to this dismissive view came from progress in infrared spectroscopy. Greatly improved techniques proliferated widely in the 1940s, driven by military and industrial interest as much as by purely scientific curiosity. Laboratory and theoretical studies, during the Second World War and after, revised the old measurements with gases in a tube. In those tubes the spectral lines had been broadened by the sea-level gas pressure. It now became clear that in the rarified upper atmosphere, such a smear of overlapping lines may resolve into a sort of picket fence, with gaps between the pickets where radiation can slip through. It was also found that the most important carbon dioxide absorption lines did not lie right on top of water absorption lines—and especially not if you looked at how radiation was intercepted layer by layer: The stratosphere was now known to be bone-dry.

A few people looked to see what the new knowledge might mean for meteorology. Among them was Gilbert



FIGURE 3. HANS SUESS showed in 1955 that a fraction of the carbon dioxide in the atmosphere comes from fossil fuels; he used the fact that the carbon-14 in coal and oil has long since decayed away. Although his first crude data falsely showed a very low level of fossil carbon dioxide, Suess had opened up the question to direct measurement. (1972 photograph from Hans Suess Papers, MSS 199, Mandeville Special Collections, Library, University of California, San Diego.)

Plass, a theoretical physicist working with a laboratory group at Johns Hopkins University, engaged in studies relating to the transfer of infrared radiation through the atmosphere. Plass noticed an opportunity to apply the new laboratory measurements and the new theoretical understanding of linewidths to the question of climate change. He announced preliminary results in 1953, but a full-scale calculation only became possible in 1955 when he got access to one of the new digital computers. His results put it beyond doubt that adding carbon dioxide to the atmosphere would mean more infrared radiation would be intercepted.¹⁰

Still, that would happen only if carbon dioxide really was accumulating—but wouldn't the oceans soak it up as fast as it was produced? The first direct evidence on that question came from carbon-14 studies. It had become possible to detect this isotope with exquisite sensitivity, and its presence in the atmosphere had become important for dating Egyptian mummies and the like. In 1955, chemist Hans Suess (see figure 3) reported he had detected in the atmosphere the fossil carbon produced by burning fuels. But his conclusion was not what one would expect from current understanding, for his data were scanty and preliminary. The amount of fossil carbon, Suess declared, was so low that the oceans must be swallowing up most

of the new carbon dioxide.¹¹

The matter would not rest there, thanks especially to Roger Revelle, director of the Scripps Institute of Oceanography in California (see figure 4). Revelle was just then looking into problems that turned out to be relevant to the question of ocean uptake of carbon dioxide. That question could be split into two factors: first, the chemistry of gas absorption in surface waters; and second, the mixing of these surface waters into the whole volume of the oceans. Revelle had taken an interest in both questions off and on since the 1930s, but his interest redoubled as a result of studies he was undertaking in connection with tests of nuclear weapons in the Pacific Ocean.

Preparing for the 1946 tests at Bikini atoll, scientists under Revelle's direction had looked into the chemistry of seawater in coral reefs. Something about it puzzled him, and into the mid-1950s many pages of calculations may be found among his unpublished papers. The basic chemistry seemed to be well known. Studies in the 1930s had established the key data—the partial pressure of carbon dioxide in seawater as a function of alkalinity and so forth. But seawater is a complex chemical system (boron ions, for example, play an important buffering role), with subtleties that had significance nobody grasped. The confusion was so great that a scientist, reviewing the question, reported in 1957, "Recent estimates of the residence time of a molecule of carbon dioxide in the atmosphere, before entering the sea, range from 16 hours to the order of 1,000 years."¹²

And once a molecule did enter the ocean, what then? The length of time it takes for the thin layer of surface water to be buried in the depths was also unknown. This too was of heightened interest to Revelle in 1955. A vehement public debate had broken out over radioactive fallout from bomb tests. Japan was in an uproar over the threat to its fishing, and the Atomic Energy Commission needed to know where fallout wound up. Of even greater interest to Revelle were proposals to deliberately bury nuclear wastes at the bottom of the ocean. The circulation of ocean waters had become a matter of national importance.

Revelle noticed an opportunity to attack the problem by working on the carbon-14 data, collaborating with Suess. Indeed other carbon-14 experts—Harmon Craig, as well as James Arnold in collaboration with Ernest Anderson—had struck upon the same opportunity and begun work. They all agreed to cooperate and publish simultaneously, and it turned out that the results in the three drafts were similar. As Revelle and Suess put it, "the average lifetime of a CO₂ molecule in the atmosphere before it is dissolved into the sea is of the order of 10 years." The authors also all estimated that the oceans



turned over completely in several hundred years.¹³

These rates seemed fast enough to sweep any extra carbon dioxide into the depths. That comfortable conclusion fitted with another result derived from carbon isotope data, a result Revelle and Suess stated unequivocally: "Most of the CO_2 released by artificial fuel combustion since the beginning of the industrial revolution must have been absorbed by the oceans." There remained some anomalies, but those could be handled by assuming that some carbon dioxide was absorbed by terrestrial biomass such as trees or peat bogs (so little was known of this absorption that it could be used virtually as a free parameter).

Here the matter might have rested, but Revelle's parallel work on seawater chemistry had left him with uncertainties. By early 1956 he had realized that it was not enough to say that a typical CO_2 molecule went into the ocean within ten years. You must also ask, would it *stay* there or diffuse back into the air? How much *additional* CO_2 could sea water in fact hold? Revelle now made the calculation. He was using known data, but he was now applying it to a question that nobody had thought it worth the trouble to work through. He wrote up his result in a few demure words, as if reminding scientists of something they already knew: "Because of the peculiar buffer mechanism of sea water . . . the increase in the partial CO_2 pressure is about 10 times higher than the increase of the total CO_2 concentration of sea water when CO_2 is added and the alkalinity remains constant." In other words, the water would adjust to match a higher concentration of CO_2 molecules in the atmosphere through a cascade of changes in the concentrations of various ions; it turned out that to readjust the balance, the surface layer would not need to absorb much gas—barely one-tenth the amount a naïve calculation would predict.¹⁴

Revelle's brief paragraph has since become famous while the rest of the paper is forgotten. Indeed, if one reads the paper carefully, the paragraph virtually contradicts the thrust of the rest. It was an afterthought: On the copy in Revelle's archives at Scripps the paragraph is visibly an addition, Scotch-taped onto the original draft. Revelle himself, although he had privately advised his



FIGURE 4. ROGER REVELLE began his career as an oceanographer (top, about 1936), studying the chemical interaction of carbon dioxide with seawater. Taking up the subject again decades later (bottom, about 1958), he realized that the absorption is much slower than he and others had supposed. (Scripps Institute of Oceanography photographs, courtesy of the AIP Emilio Segrè Visual Archives; top photo by Eugene LaFond.)

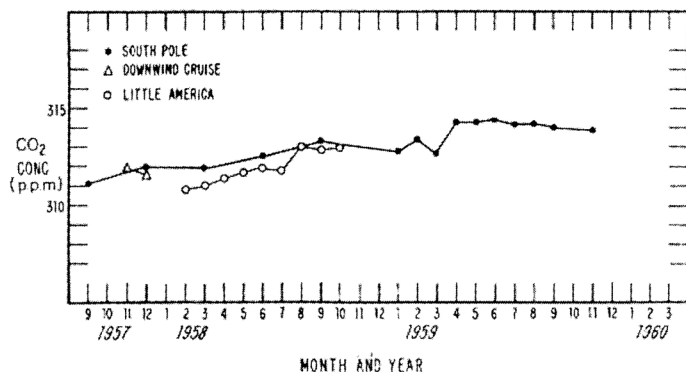


FIGURE 5. RISING LEVEL OF CARBON DIOXIDE in the atmosphere, as first reported in 1960 by Charles Keeling. An increase was visible after only two years of measurements in Antarctica. Previous measurements were bedeviled by random variations in measured carbon dioxide levels. Keeling succeeded by using a recording spectrophotometer, an instrument others had thought more sensitive—and expensive—than necessary for such work. (From C. Keeling, *Tellus* 12, 200, 1960.)

collaborators that “80% of the CO_2 added to the atmosphere will stay there,” did not make much of this discovery. It took several years for the small community of geophysicists to realize that the oceans could not be relied upon to absorb all the carbon dioxide that human industry was pouring forth.¹⁵

Keeling: A conclusion and a beginning

Even before Revelle’s findings were assimilated, the tide was moving toward a suspicion that global warming was a possibility, and indeed a problem. The new, more anxious attitude could be sensed, for example, in a 1959 *Scientific American* article by Plass. Although calculations at this time were based on highly uncertain approximations, Plass boldly predicted that the world’s temperature would rise more than 3 °F by the end of the century. What would that mean? Plass only remarked mildly that this would allow a conclusive test of the carbon dioxide theory. But the magazine’s editorial staff offered a more ominous picture: a photograph showing coal smoke belching from factories. The caption read, “Man upsets the balance of natural processes by adding billions of tons of carbon dioxide to the atmosphere each year.”¹⁶

Foul contamination, the balance of nature upset—the tenor of public discourse was changing. Factory smoke was becoming less an emblem of prosperity than of dangerous pollution. Moreover, industrial pollution was no longer seen as restricted to particular places, where local problems would eventually wither away as humanity grew more enlightened. Less optimistic views were beginning to emerge, prodded in the first place by outcries against the world-wide distribution of nuclear fallout, and reinforced by worries about DDT and other new chemicals. By the late 1950s, misgivings about human uses of technology, with passionate warnings that we might harm living creatures everywhere, were becoming widespread. Severe global climate change, caused by human activity, now began to sound plausible.

That may have been one reason that the scientific developments, although still highly tentative, sufficed to inspire more intense and costly investigation. Experts began to say that somebody ought to accurately measure the level of carbon dioxide in the atmosphere. Meanwhile new funding became available in connection with the International Geophysical Year. Revelle and Suess pushed for a major measurement program. To carry it out Revelle hired a young geochemist, Charles Keeling.

“Keeling’s a peculiar guy,” Revelle remarked long after. “He wants to measure CO_2 in his belly. He really never wanted to do anything else but measure CO_2 . And he wants to measure it with the greatest precision and the greatest accuracy he possibly can.” Technical advances in infrared gas instrumentation allowed an order of magni-

tude improvement in accuracy over previous results. Keeling campaigned for funds to buy the costly apparatus, then used it with utmost care. The original plan was simply to establish a baseline so that after a couple of decades somebody could come back and see if the level had risen. But Keeling was able to detect a rise by 1960 with a mere two years of measurements.¹⁷ (See figure 5.)

Keeling’s curve, climbing ominously higher each year, soon became well-known as an icon of the “greenhouse effect.” Concerned scientists and official groups began to issue warnings of potential problems. Global warming had become an issue. It has been studied with increasing intensity ever since. (See the box above.)

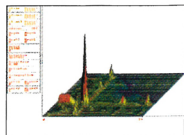
Sooner or later, scientists would have become aware of this issue, but the fact that it was recognized around 1960 owed much to happenstance. The story is not what one might imagine from the traditional textbook presentation of scientific progress—stepwise and cumulative construction of an answer to a question. In 1950 there hardly seemed to be a question at all. Indeed, but for Callendar’s idiosyncratic devotion to the issue, it would have been quite invisible. It was likewise with Plass, Suess, Revelle and Keeling: If just one of them had been a little less interested in the issue, a little less bold and persevering in its pursuit, then our understanding could have been long delayed.

The crucial things learned in the 1950s were not steps taken in a linear and logical sequence. After Callendar, each new result originated in a different subject area wholly remote from climate: development of infrared technology for weaponry, advances in the theory of spectral line widths, revision of ancient Egyptian chronology, con-

Global Warming Today

Since the early 1960s, virtually all scientists have accepted that the level of carbon dioxide in the atmosphere is rising, and that the extra gas must intercept some outgoing infrared radiation and so change the distribution of heat in the atmosphere. Answers have converged less easily for other questions: how rapidly the new carbon dioxide might be absorbed by biomass, and how climate will change after taking into account feedback involving evaporated water vapor, clouds and so on. (See the article by Jeffrey Kiehl, *PHYSICS TODAY*, November 1994, page 36.) It was only recently that painstaking international negotiations yielded a scientific consensus that we have probably begun to see global climate changes induced by human activity (see *PHYSICS TODAY*, August 1996, page 55). As for future changes, plausible estimates range from mild and manageable to abrupt and catastrophic. A prudent policy must somehow allow for either contingency.

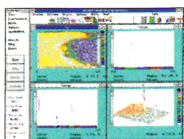
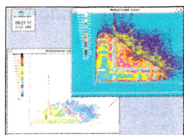
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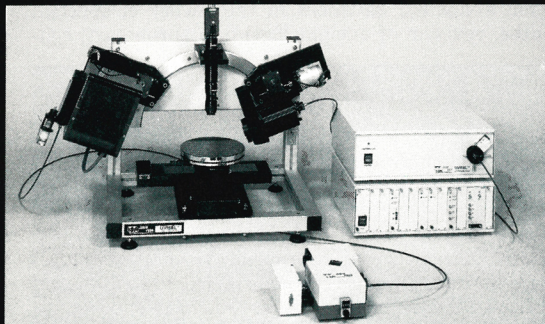
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cern about nuclear waste disposal, studies of seawater chemistry, and so forth. And prior to Keeling, every scientist who did a piece of work on global warming took up the matter as a mere side issue—an opportunity for a publication or two, a small detour from the main thrust of their work, which lay elsewhere and to which they soon returned. It was a matter of chance that each of these areas turned out to support some finding relating to global warming—scattered contributions which, when assembled at last, sounded an alarm for the possibility of grave danger.

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